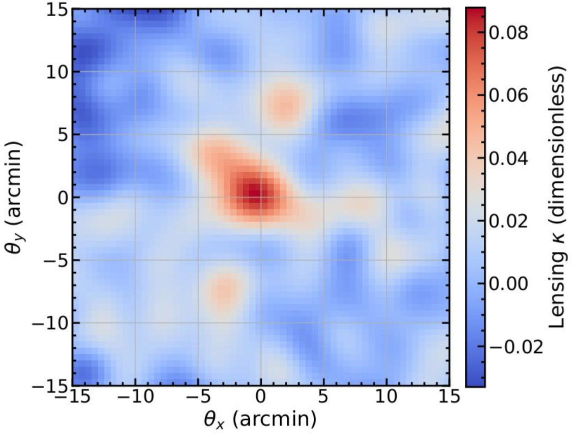


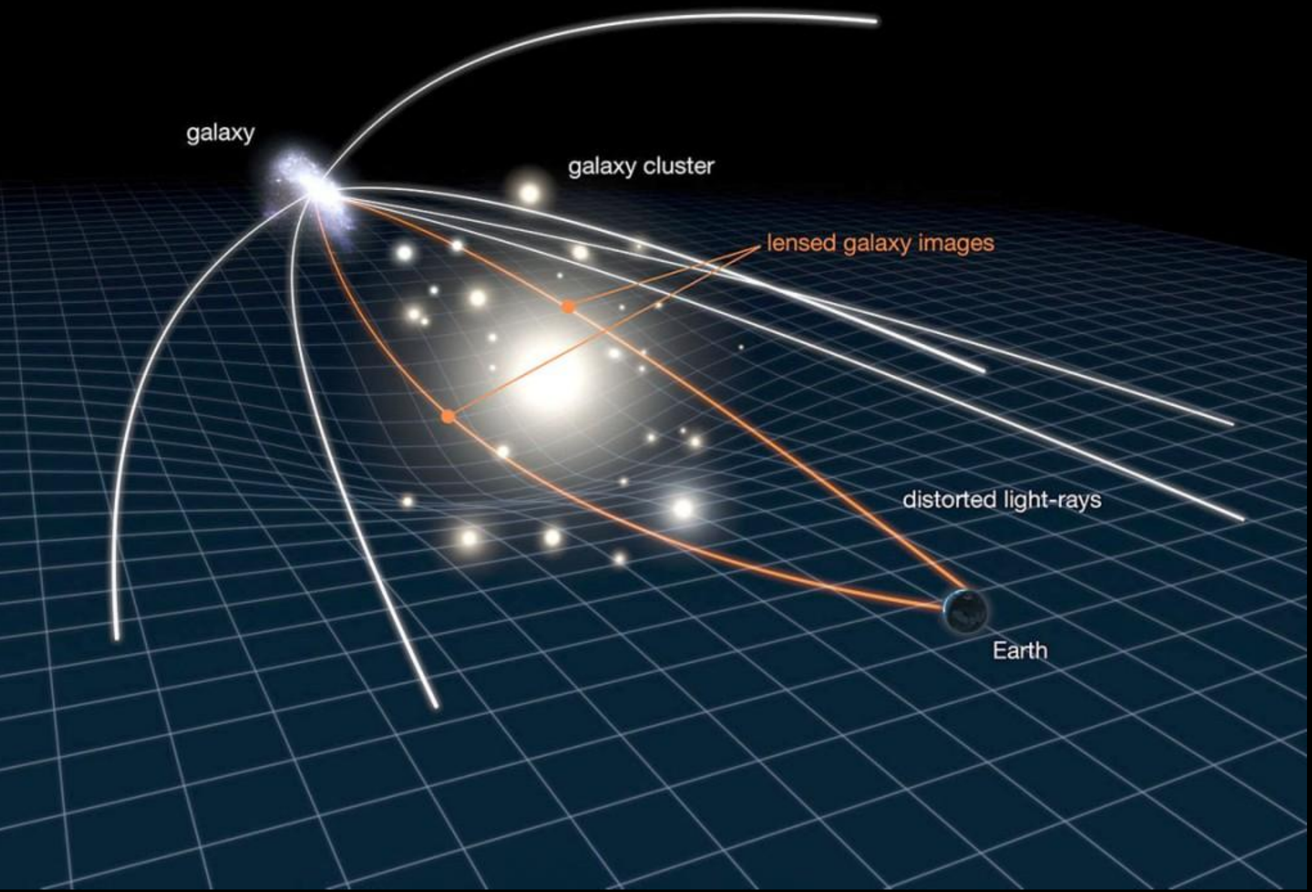
MM, Sifon, Battaglia et al ACT collaboration 2020,
to appear in ApJ Letters

High-z cluster lensing with the CMB as a backlight

Mathew Madhavacheril
Peebles Fellow, Perimeter Institute

ACT

Image: NASA/ESA



The CMB acts as a backlight for all lenses

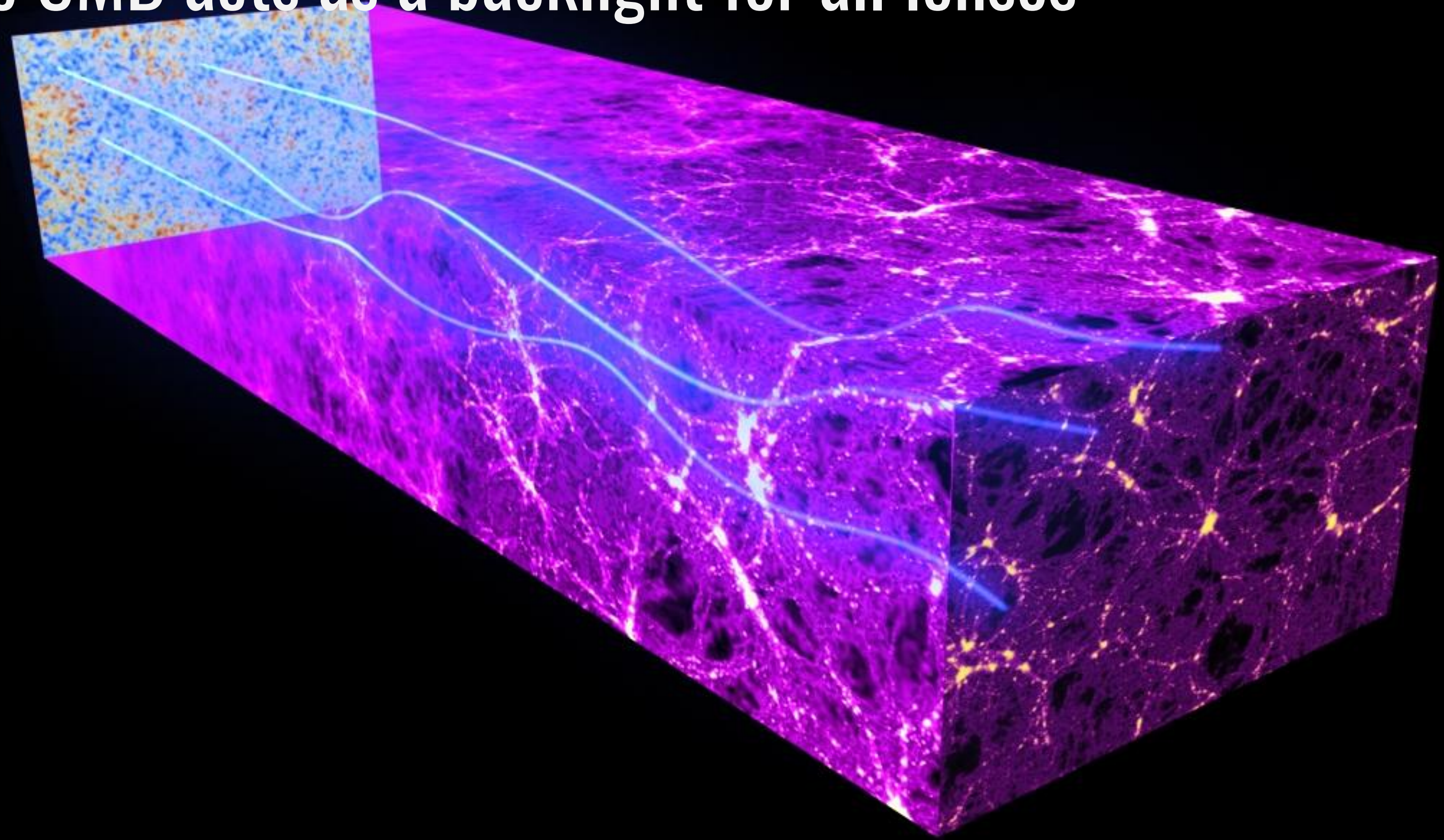
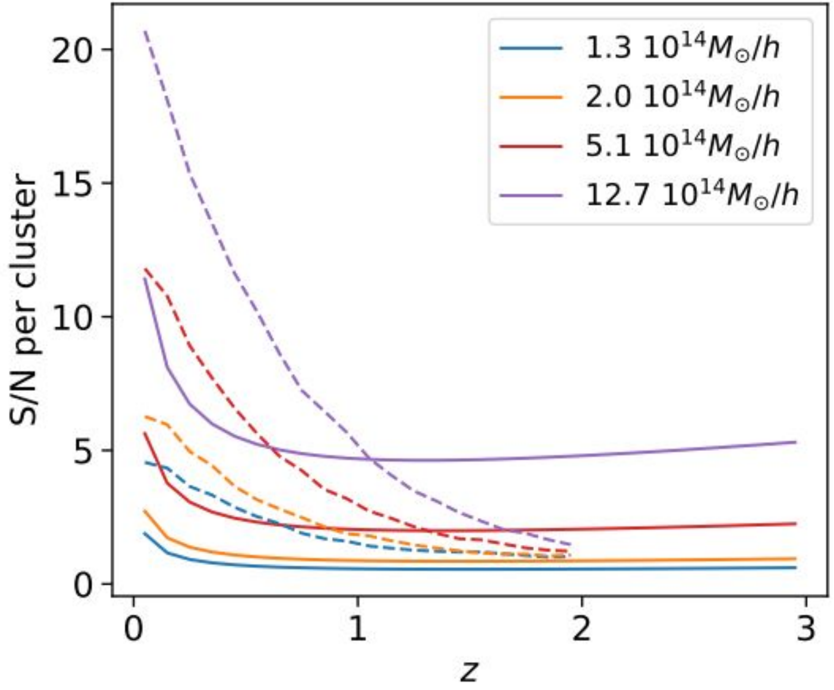


Image: ESA/Planck

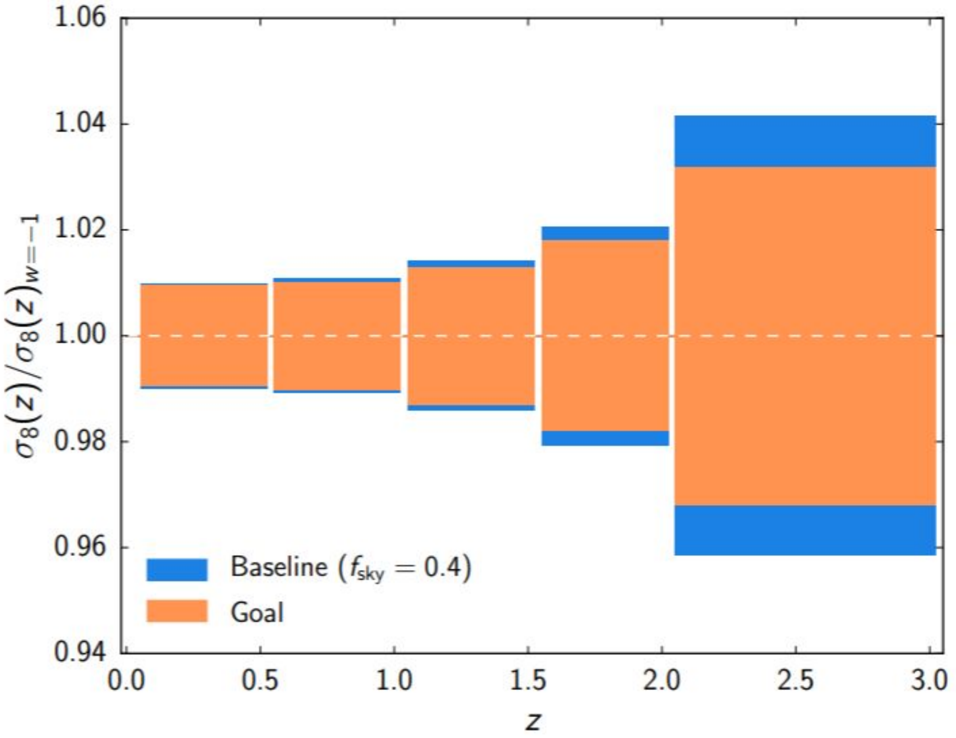
Supplements optical weak lensing info at high-z

MM, Battaglia, Miyatake 2017, PRD

- Alternative to **using galaxy shapes** for high-z clusters which have
  - Source redshift uncertainties
  - Shape measurement biases
  - Fewer galaxies behind higher redshift clusters



The potential:
Simons Observatory example -- calibrate SZ clusters with CMB lensing



Percent-level measurement of **σ_8(z)** in 5 redshift bins achievable with internal CMB halo lensing

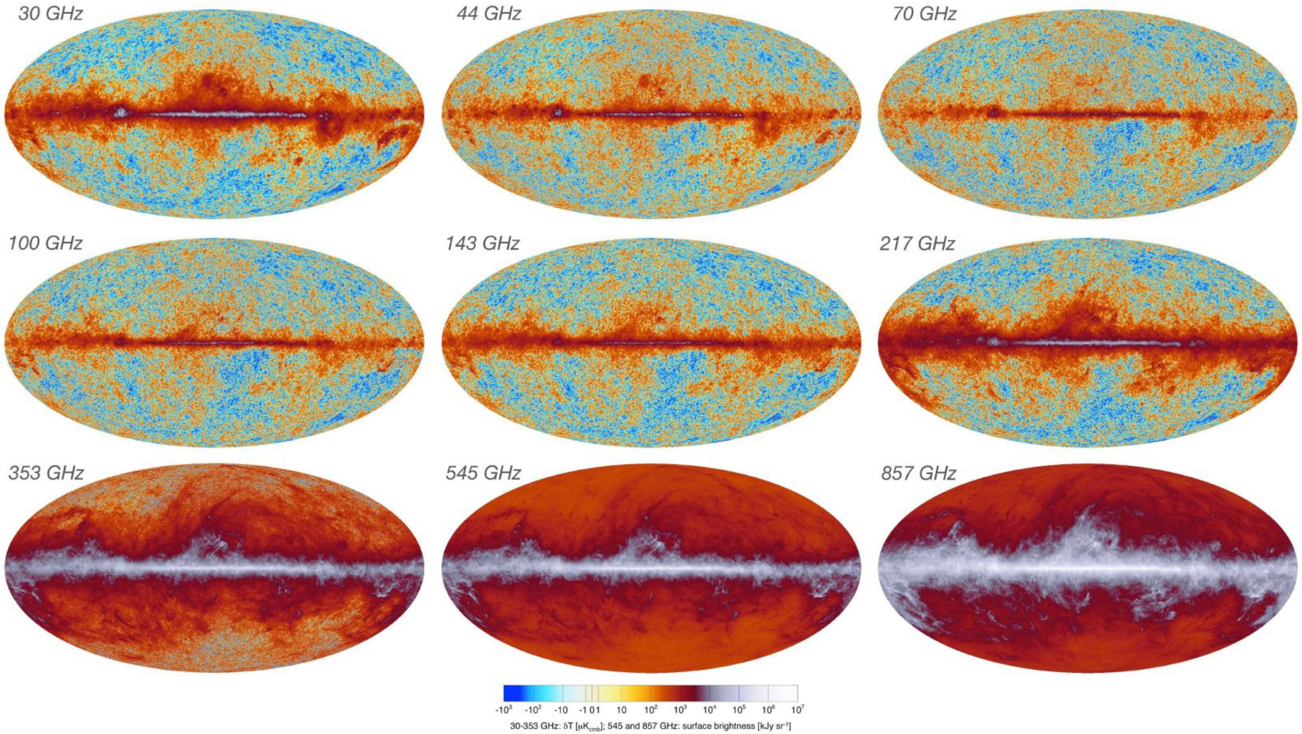
MM, Battaglia, Miyatake 2017,
arXiv:1708.07502, PRD

Simons Observatory collaboration (incl. MM)
arXiv:1808.07445, JCAP

1. How we measure this
2. Where we are now
3. Challenges

Planck

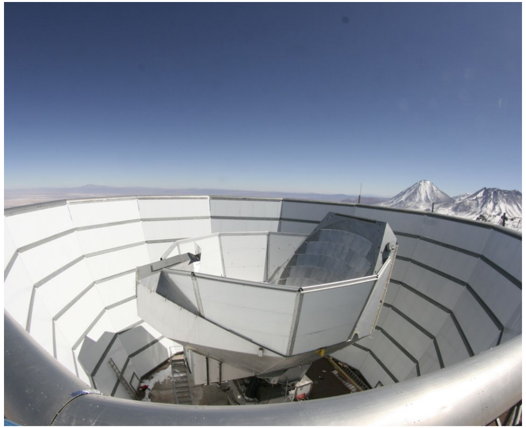
Final release 2018
fsky=70% for science
5-10 arcmin resolution



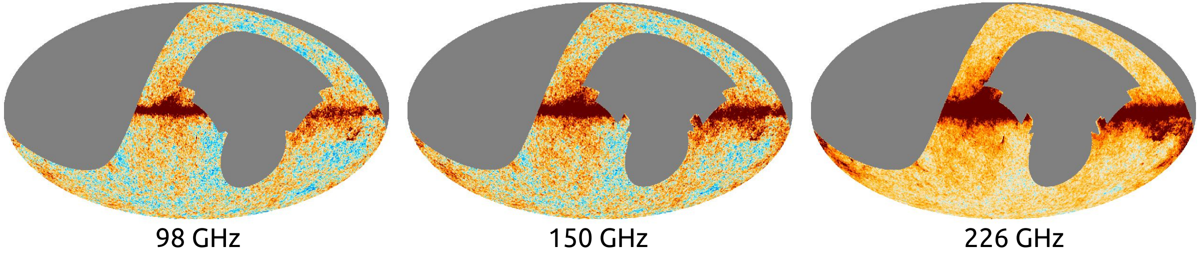
Temperature in 9 frequency bands
Polarization in 7 frequency bands

30 - 857 GHz

Atacama Cosmology Telescope (ACT)



Ongoing observations
2008-2021
fsky~30% for science
Noise 3-6x lower than Planck
1-2 arcmin resolution



High-resolution temperature and polarization in 3 frequency bands

98, 150, 226 GHz

Additional 2 frequency bands at 30 and 40 GHz started observing in 2020

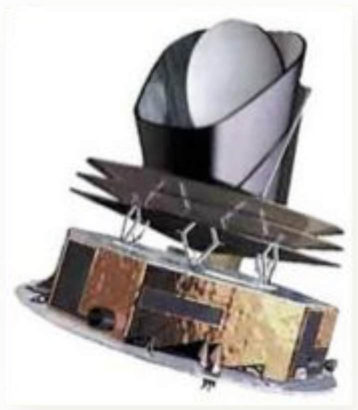
Many other ground-based experiments,
e.g. PolarBear, SPT, BICEP/KECK, CLASS

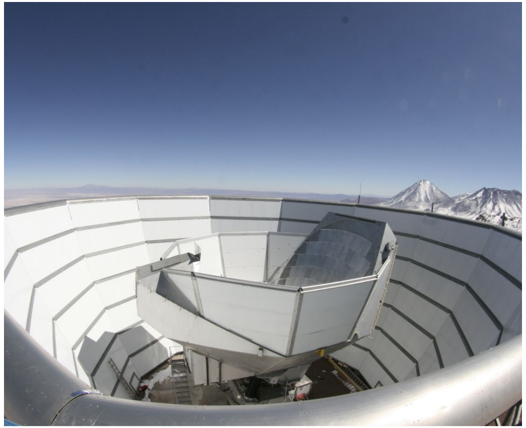
ACT is unique in its wide area coverage: it's **a cross-correlation machine**

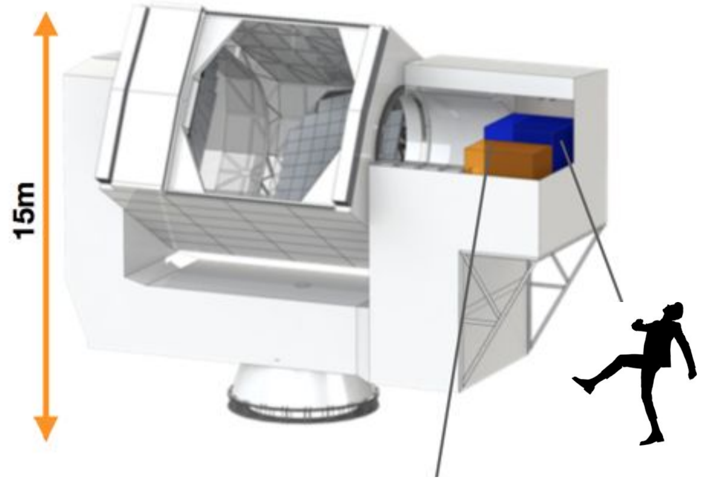
SO will also have three Small Aperture Telescopes for gravitational-wave search

Planck → ACT → Simons Observatory

Large Aperture Telescope







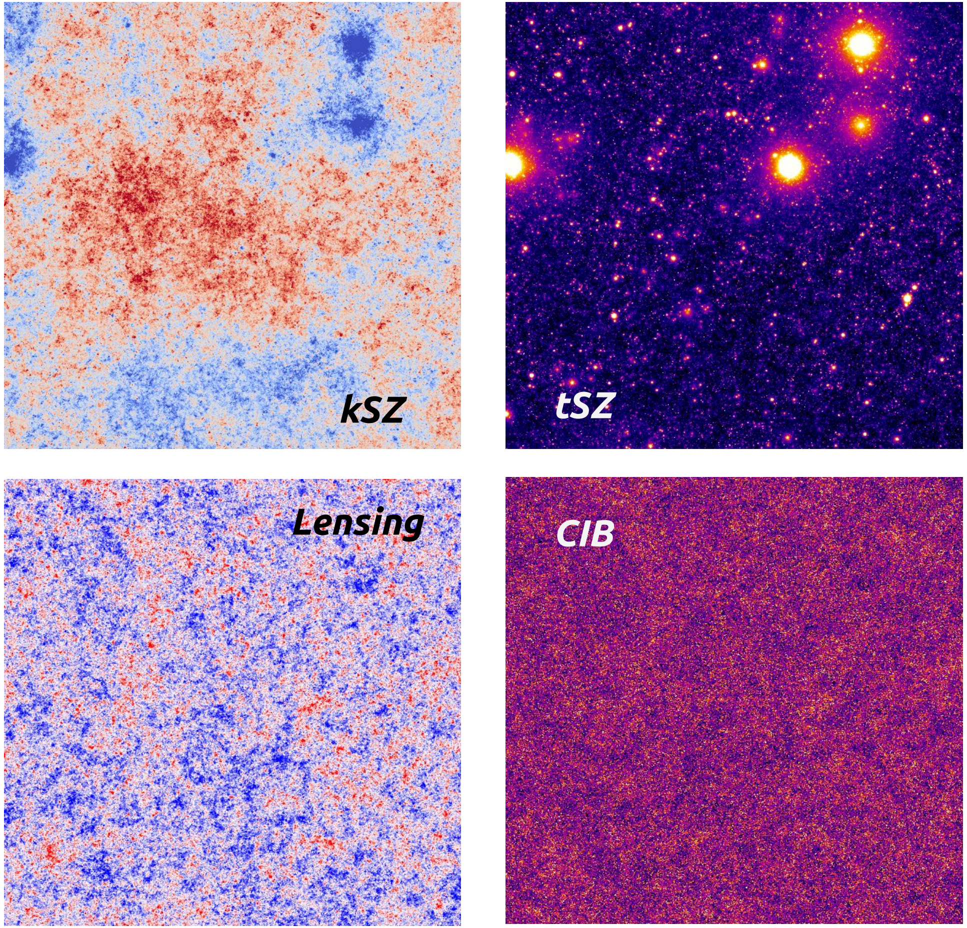
Final release **2018**
fsky=70% for science
5-10 arcmin resolution
9 bands from 30-857 GHz

Observations **2008-2021**
fsky~30% for science
Noise 3-6x lower than Planck
1-2 arcmin resolution
98, 150, 220 GHz (+30, 40 GHz soon)

Observations 2022-28
fsky ~40% for science
Noise 2-3 times < ACT
1-2 arcmin resolution
30, 40, 98, 150, 220, 270 GHz
Observing **from 2023 onwards**

CMB “secondaries”

including gravitational lensing



My favorite CMB secondaries

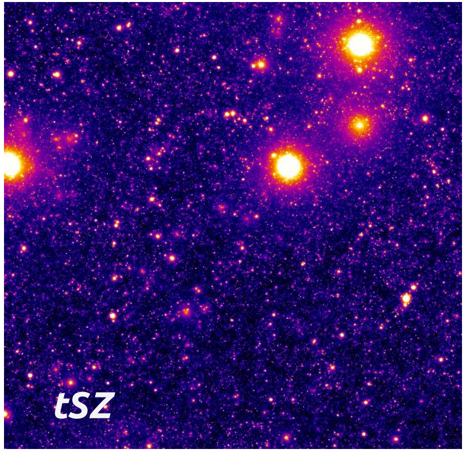
* These are simulated skies from the Websky Project
(Stein et al. 2020)

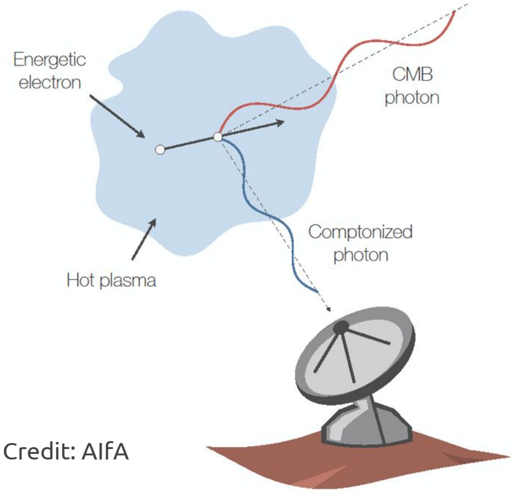
Thermal Sunyaev-Zel'dovich Effect

Inverse Compton scattering of CMB photons off hot clouds of free electrons

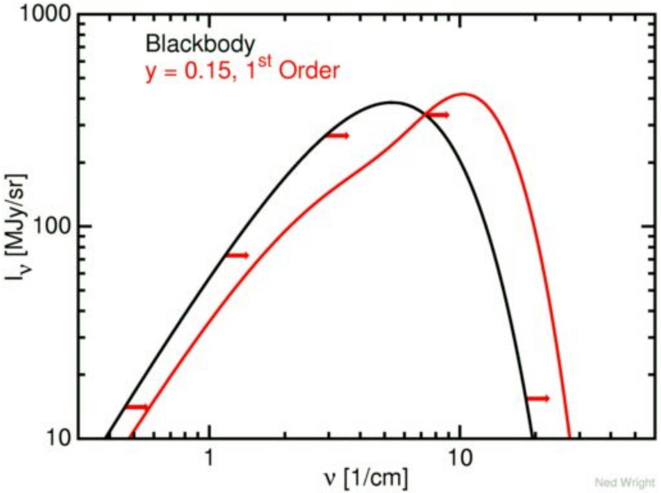
Probes free electron thermal pressure (hot gas)

y-distortion to photon spectrum.





Credit: AIfA



Thermal Sunyaev-Zel'dovich Effect

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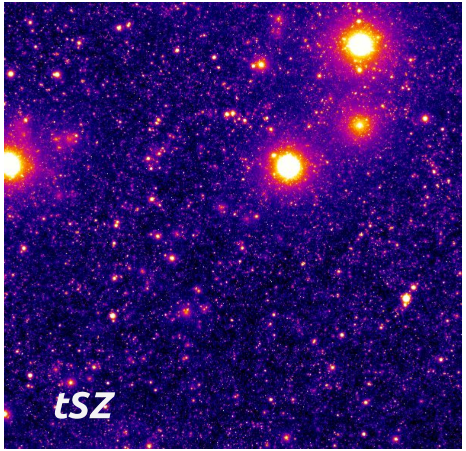
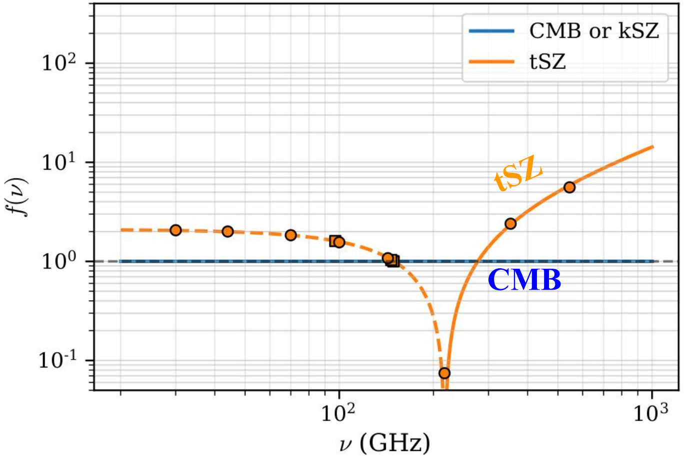
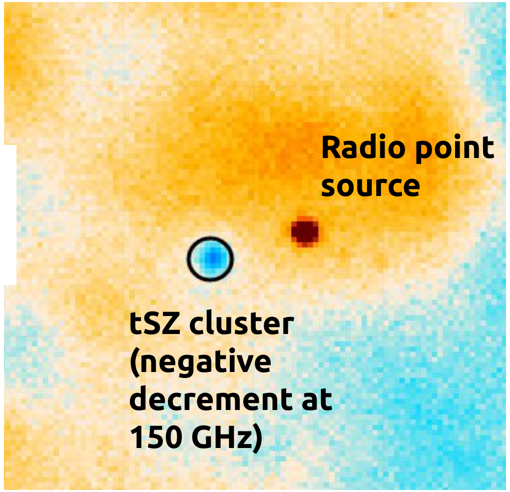
y-distortion to photon spectrum.

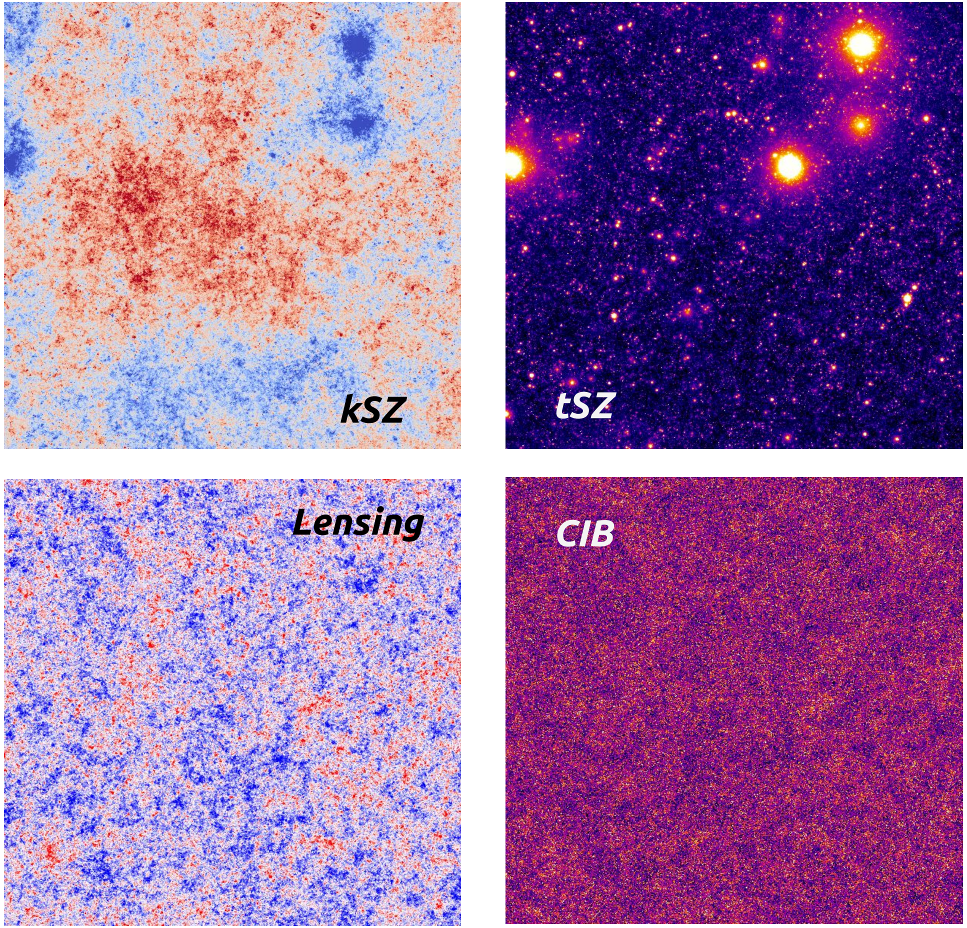




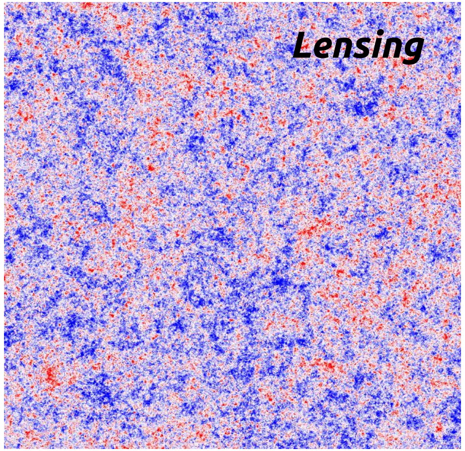
$$\frac{\delta T_{\mathrm{tSZ}}}{T_{\mathrm{CMB}}} = f(\nu)\,\tau \left(\frac{v_{\mathrm{thermal}}}{c}\right)^2 \propto \tau\, T_e$$

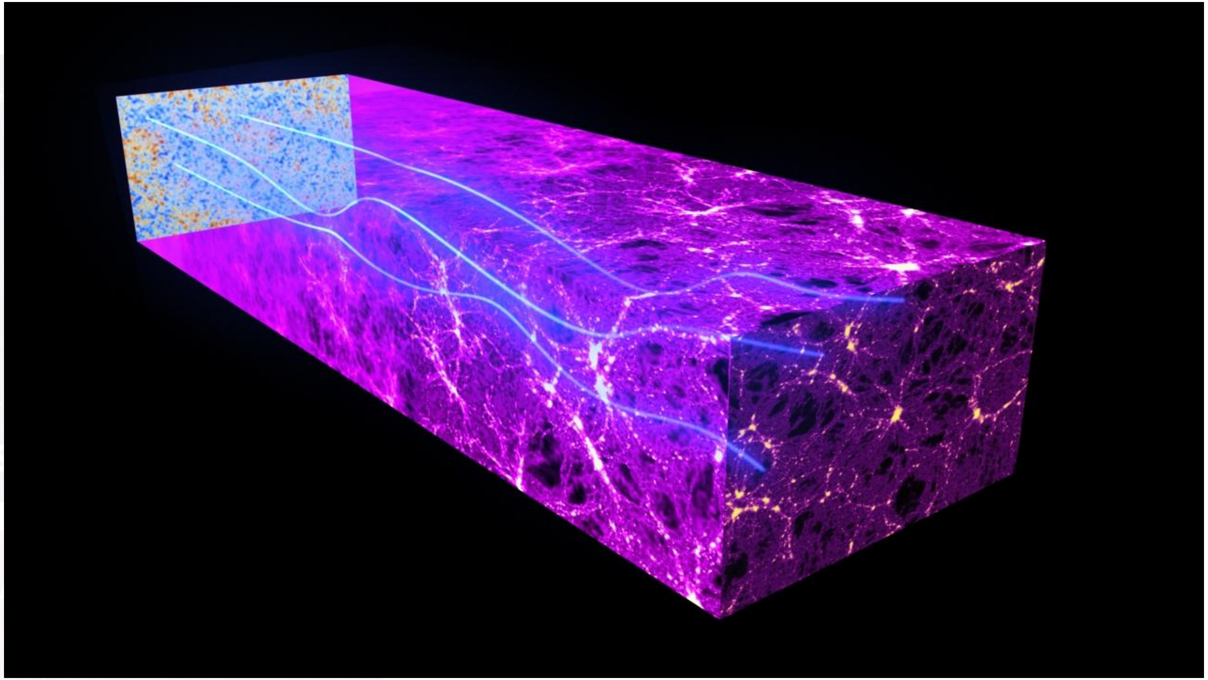
$$\tau \sim 10^{-3}, \quad \frac{v_{\mathrm{thermal}}}{c} \sim 0.1$$

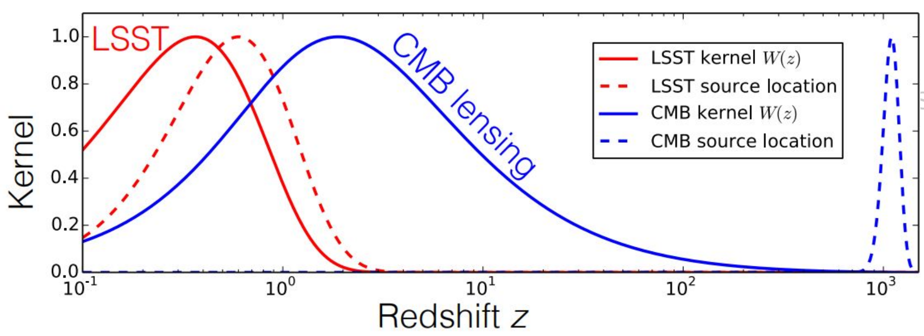



kSZ
tSZ
Lensing
CIB

Sensitive to projected
mass density, peak contribution
z ~ 1-2

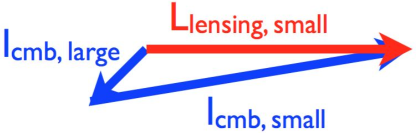


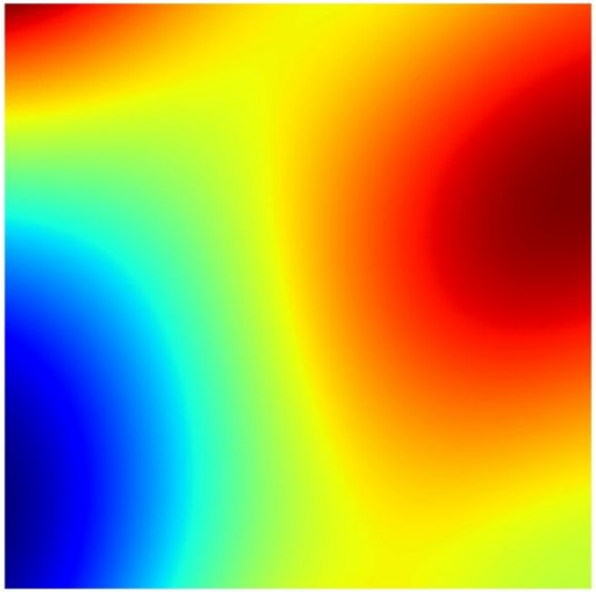




SA/Planck

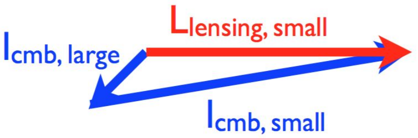
CMB lensing by halos

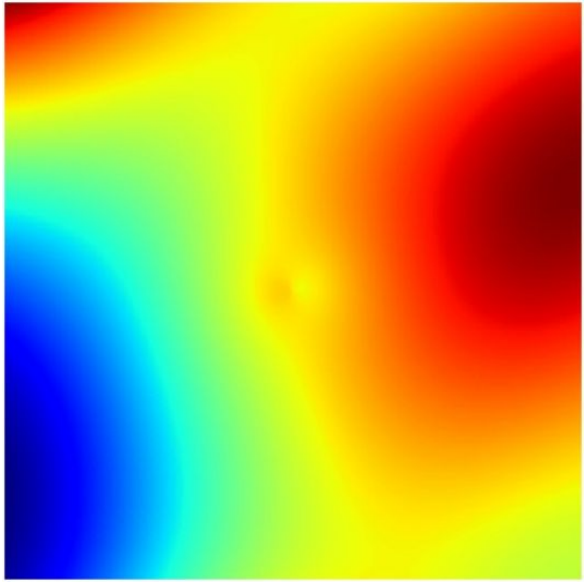




CMB has low power on small scales

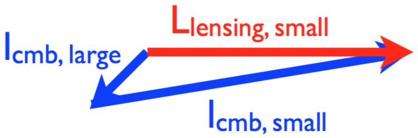
CMB lensing by halos

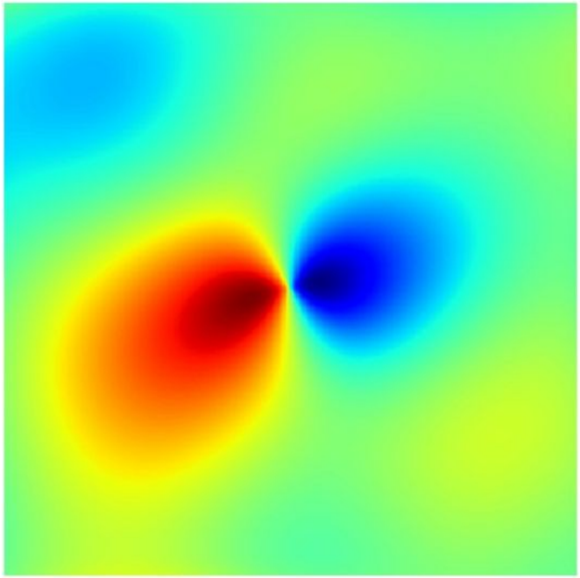




Super-Massive cluster
at z=1.0

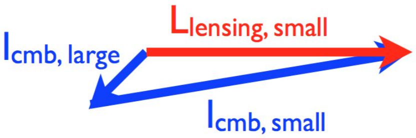
CMB lensing by halos





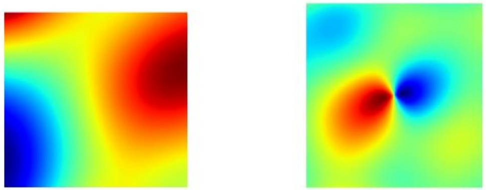
Difference is
dipole aligned with background gradient

Reconstructing halo lensing



Large-scale gradient Small-scale dipole

$$\hat{\kappa} \propto \vec{\nabla} \cdot \left[\left[\vec{\nabla} T \right]_{\text{low}} \left[T(\vec{\theta}) \right]_{\text{high}} \right]$$

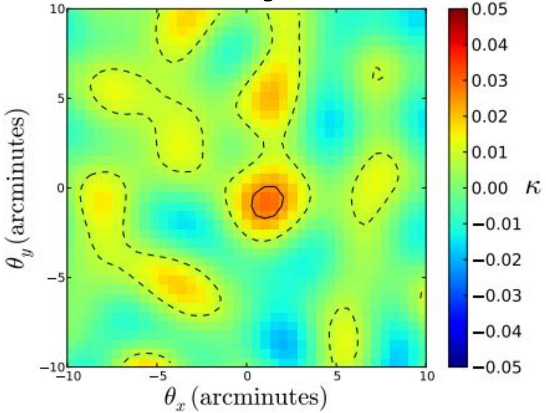


Hu, DeDeo, Vale 2007

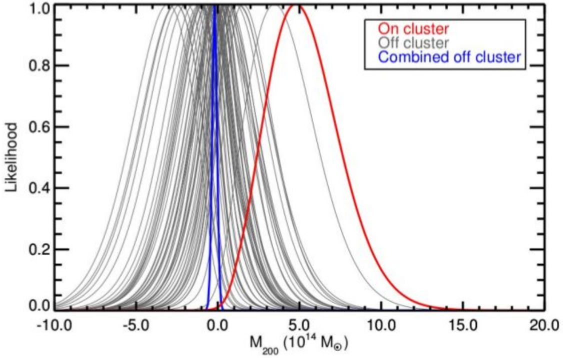
Quadratic estimator picture in real space

Measurement status

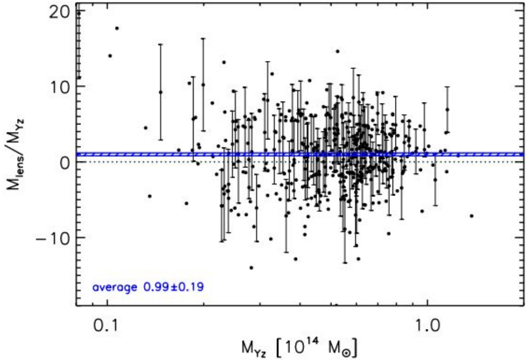
MM, Sehgal + ACTPol (PRL 2015)
3.2 sigma

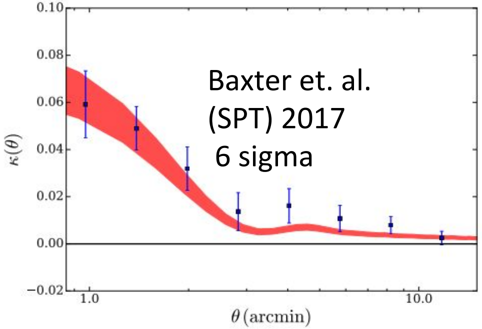


Baxter et. al (SPT) 2015
3 sigma

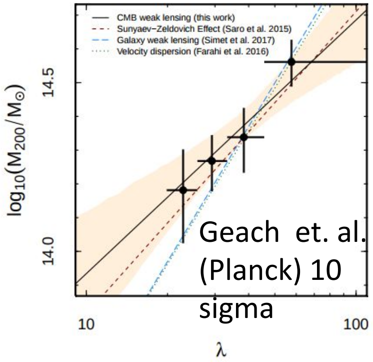


Planck 2015
5 sigma





Baxter et. al. (SPT) 2017
6 sigma



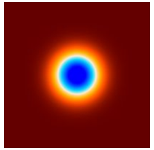
Geach et. al. (Planck) 10 sigma

Up to 10% measurements -- we're leaving few sigma regime for precision measurements

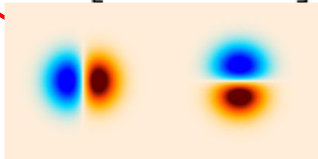
CMB Cluster lensing: bias from foregrounds like tSZ

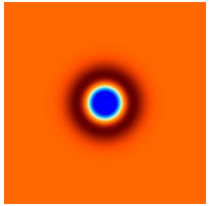
$$\kappa \approx \nabla.[T\nabla T]$$

$$T = T_L + F$$



$$\kappa \approx \nabla.[T_L\nabla T_L] + \nabla.[F\nabla F] + \cancel{\nabla.[T_L\nabla F] + \nabla.[F\nabla T_L]}$$

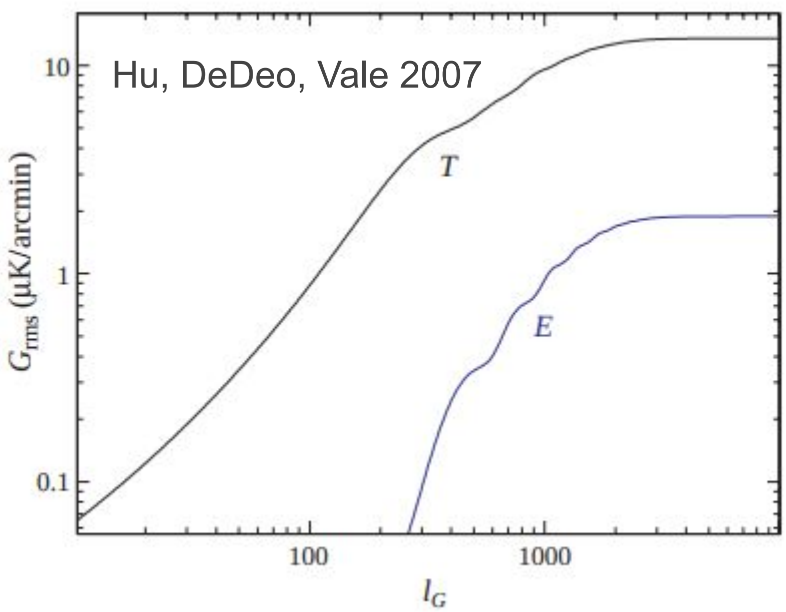




Bias originates from misestimated CMB gradient

MM, Hill, 2018, PRD

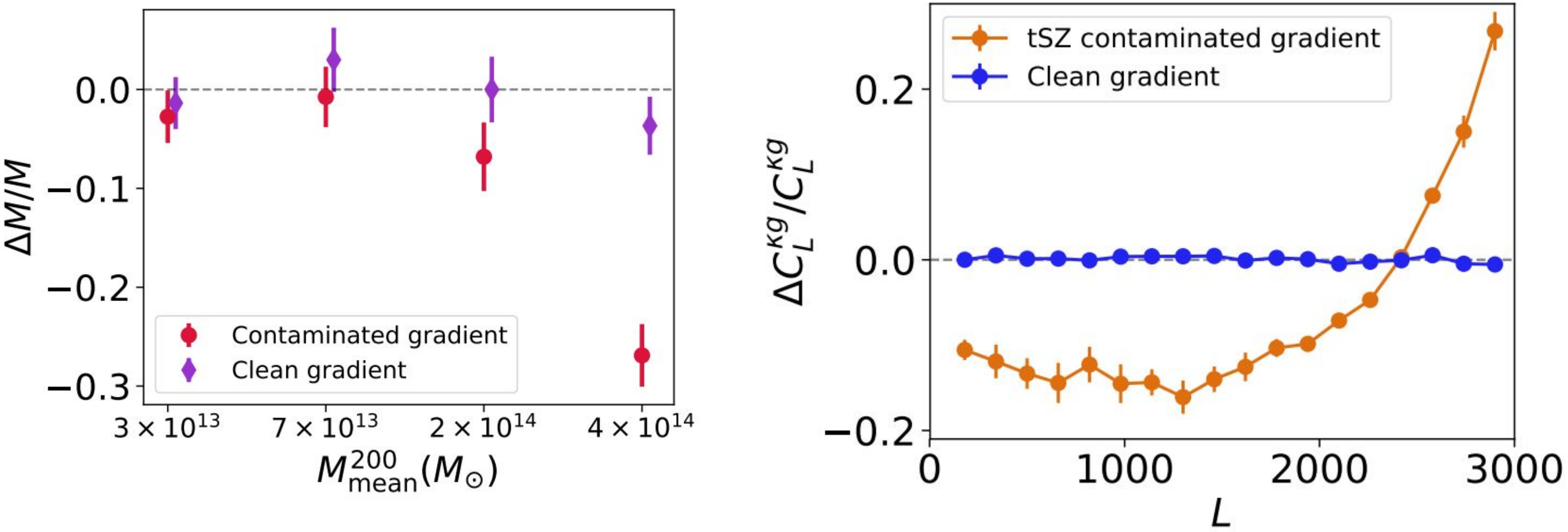
CMB Lensing: eliminating bias from foregrounds



- Gradient needs to be measured well only up to L=2000
- Planck component separated temperature (tSZ-free) maps good enough for gradient map!

$$\kappa \approx \nabla.[T_L \nabla T_L] + \cancel{\nabla.[F \nabla T_L]}$$

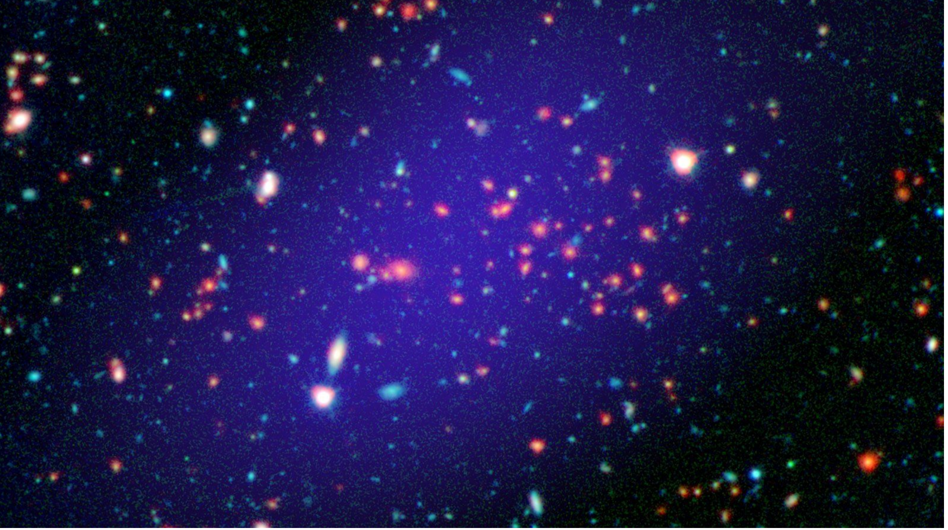
MM, Hill, 2018, PRD



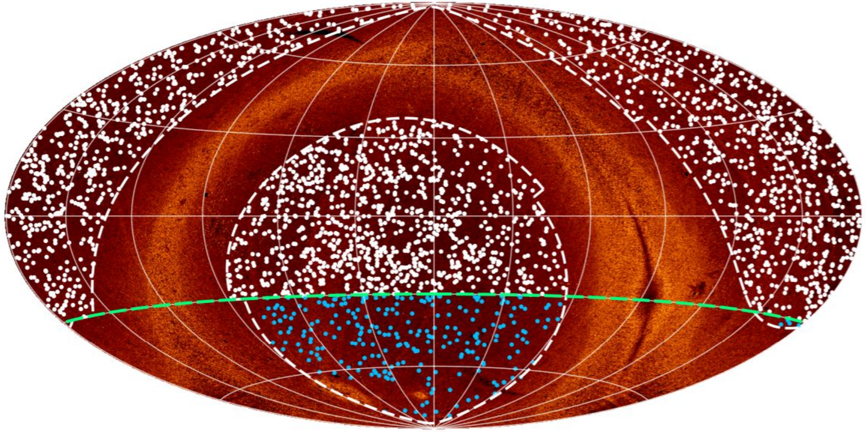
End-to-end simulations demonstrate gradient cleaning

Almost no loss in S/N when cleaning gradient alone with low-resolution multi-frequency data (Planck)

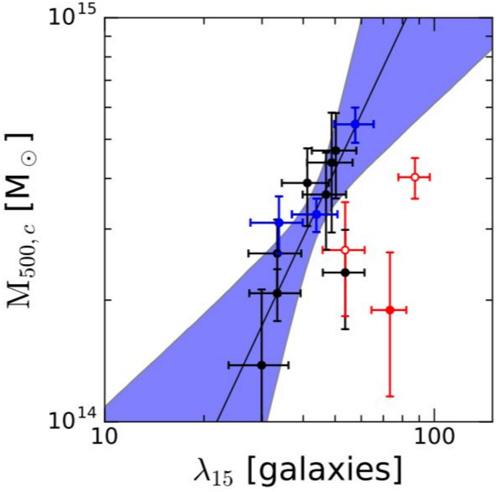
This technological advance (SZ bias-free, with no loss in SNR) allows us to push the CMB sensitivity to new levels



HST/Gemini/CARMA



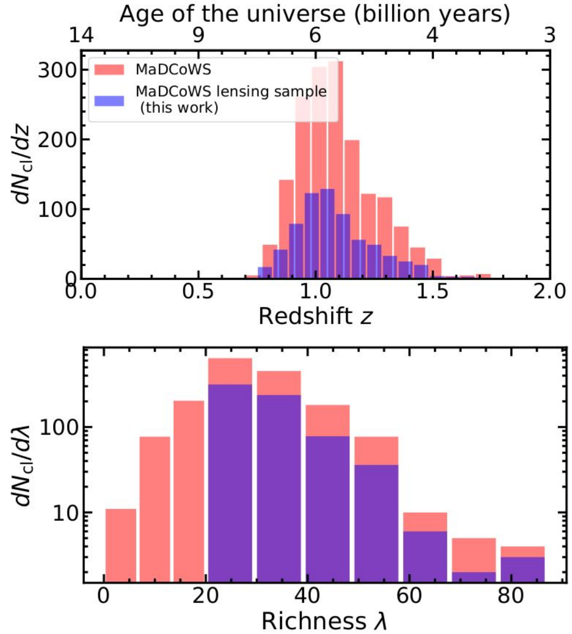
The MaDCoWs <z>=1 sample

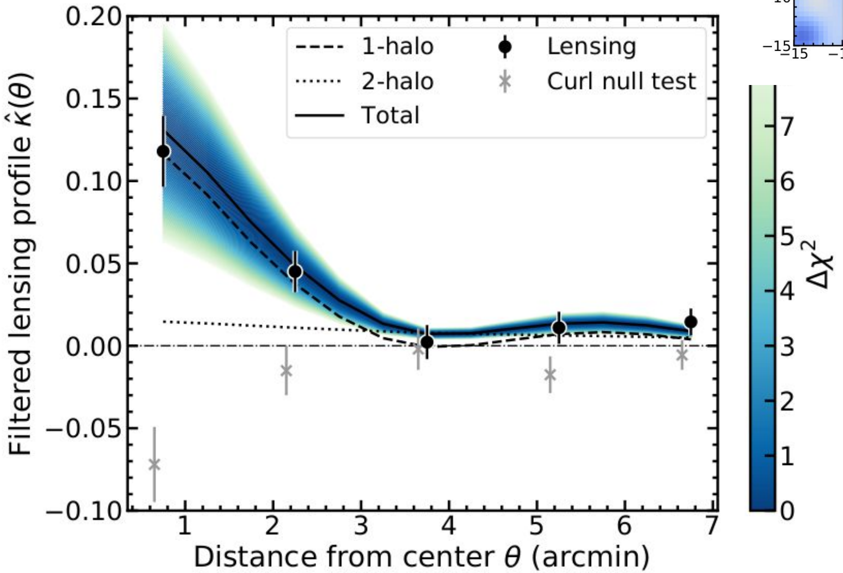


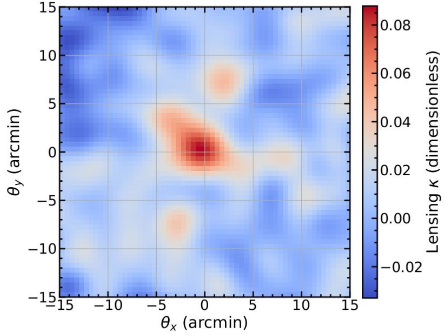
- Overdensities in all-sky WISE
- Followed up with Spitzer+PANSTARRS for photo-zs and richness
- sigma_z / (1+z) = 0.04, 5% outlier fraction
- ~1600 clusters
- SZ masses for a handful from CARMA
- 677 in the ACT footprint: can get a representative lensing measurement!

Galaxy cluster lensing at the highest redshift

MaDCoWs galaxy clusters; mass calibration with ACT CMB lensing





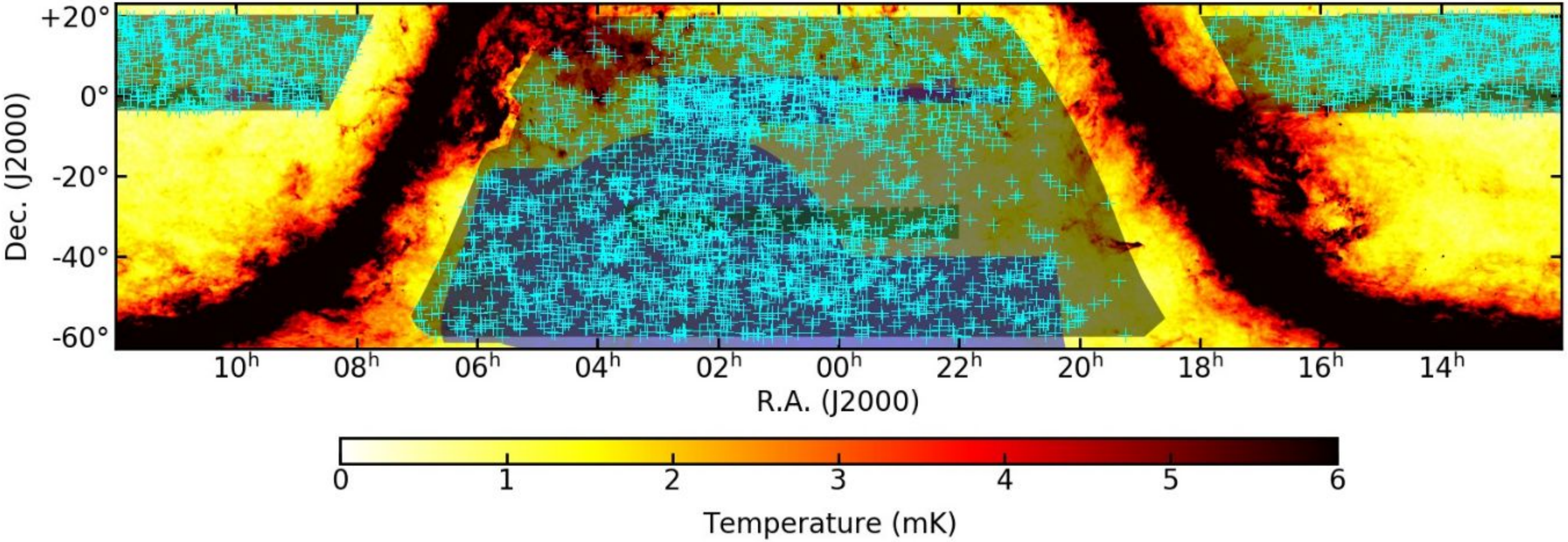


MM, Sifon, Battaglia et al 2020 (accepted to ApJ Letters)

Highlights power of CMB for high-z clusters
4 sigma mass constraint of 1.7 x 10^14 Msun with 677 clusters

Out now from ACT: largest tSZ cluster catalog (>4000 clusters)

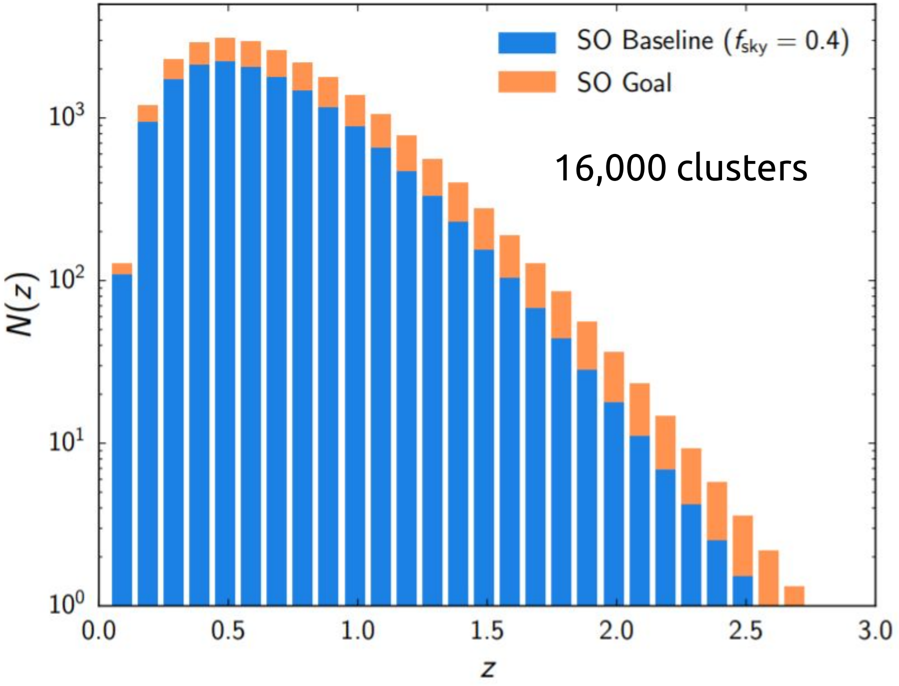
Hilton, Sifon, Naess, MM et al 2020

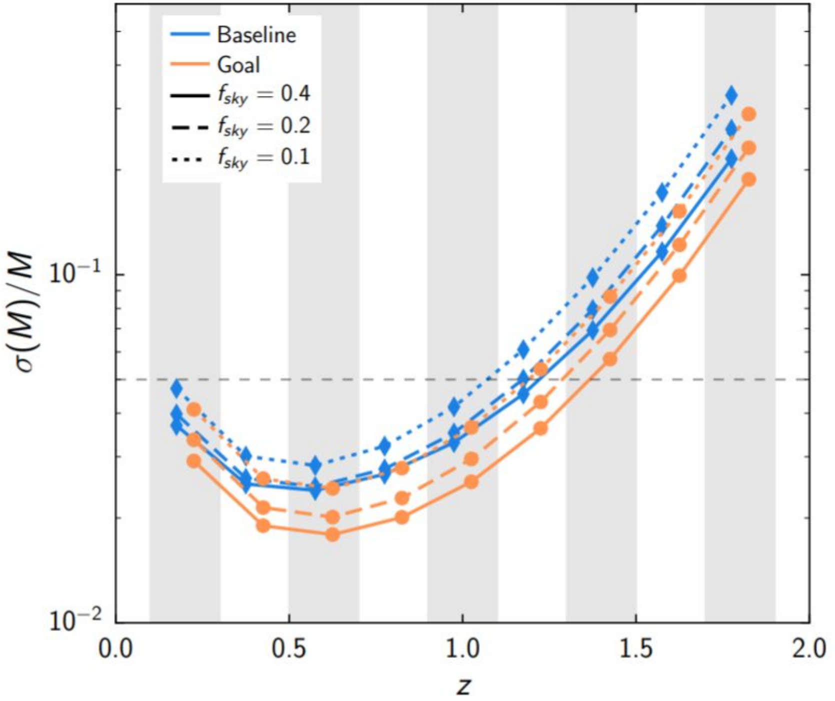


- Mass completeness of 2-4.5 x 10^14 Msun over fsky=0.3
- 872 new discoveries
- **221 clusters at z>1**

SZ clusters + CMB lensing mass calibration

Simons Observatory collaboration (incl. Madhavacheril)
arXiv:1808.07445





Summary

- Wide area high-resolution CMB surveys give you cluster mass calibration “for free”
- Supplements information at high-z for cluster cosmology
- New techniques developed to not be biased by astrophysical foregrounds
- CMB maps now deep enough to push high-z frontier beyond optical weak lensing capabilities
- Independent percent level constraints possible from CMB lensing in the next decade