Title: New views of cosmic gas from Atacama Cosmology Telescope observations of the millimeter sky

Speakers: William Coulton

Collection/Series: Cosmic Ecosystems

Subject: Cosmology

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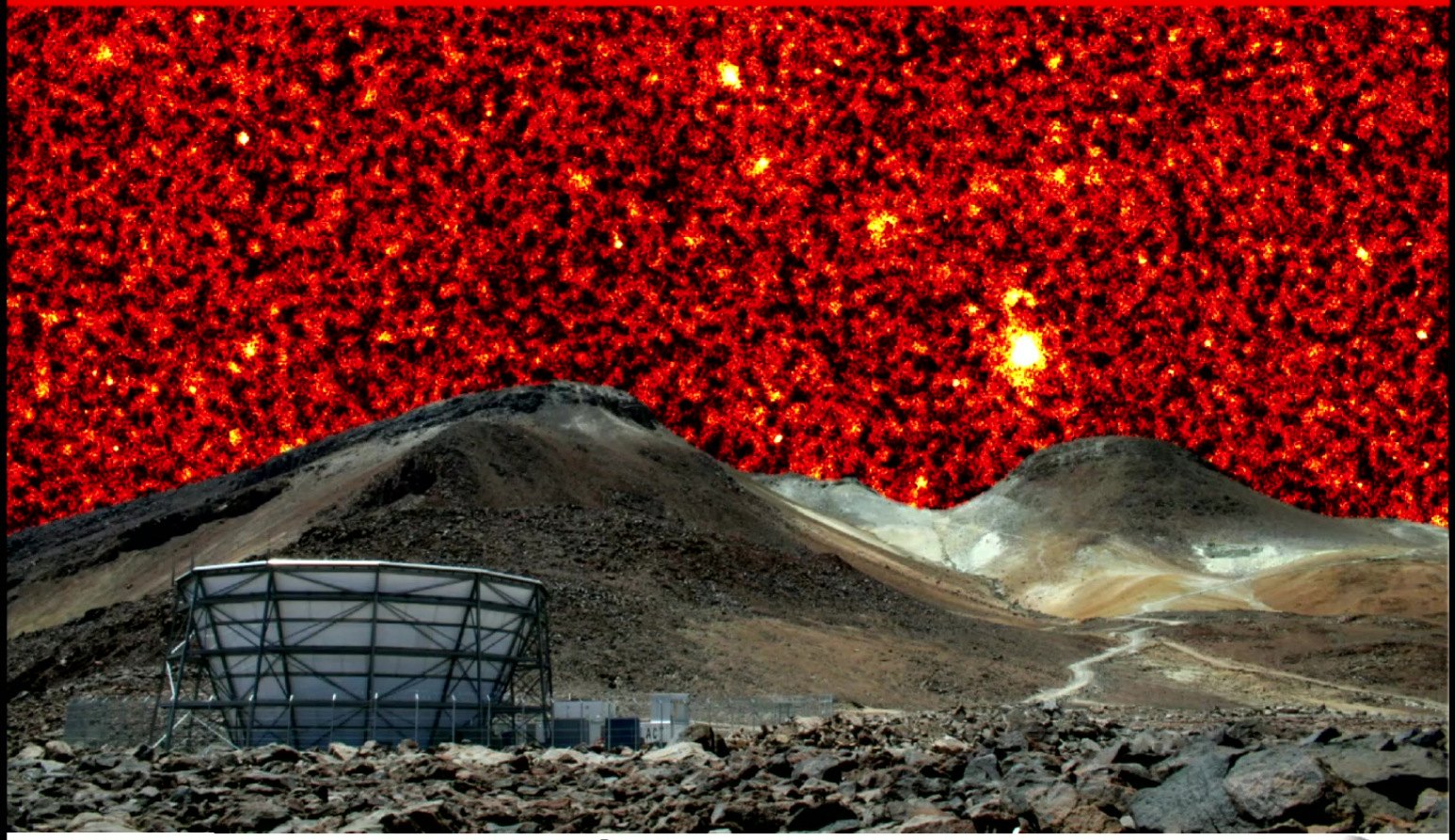
Abstract:

As cosmic microwave background photons travel through the Universe a small fraction of them interact with the intervening cosmic gas and thereby imprint the properties of this gas on our CMB observations. In this talk I will describe how data from the Atacama Cosmology Telescope can be used to isolate the signals arising from hot gas throughout the Universe and how the data can be used to measure both the integrated electron pressure and temperature of galaxy clusters. I will discuss how upcoming CMB experiments, such as the Simons Observatory, will allow us to improve our characterisation of the properties and evolution of cosmic gas.

New views of cosmic gas from Atacama Cosmology Telescope observations of the millimetre sky



UNIVERSITY OF CAMBRIDGE

William Coulton with Adri Duivenvoorden,
Lucas Kuhn, Zack Li and the ACT collaboration

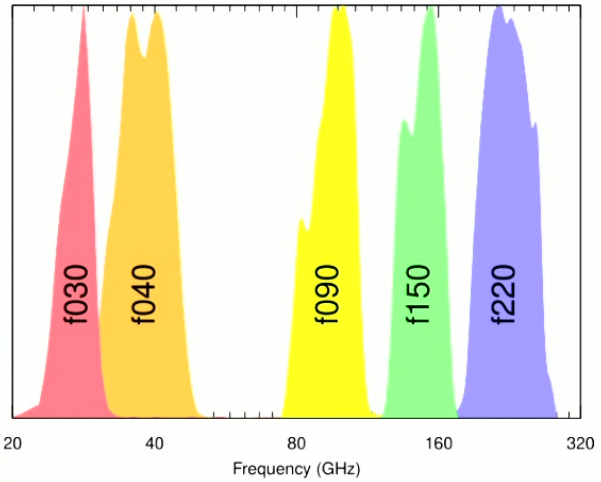
KICC

Cerro Toco - The Chilean CMB landscape

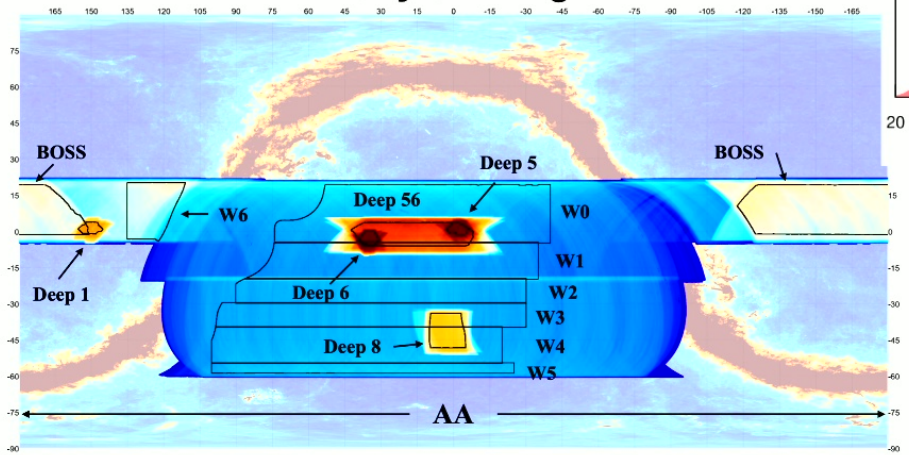
Atacama Cosmology Telescope (ACT)

2007 - 2022

Frequency Coverage



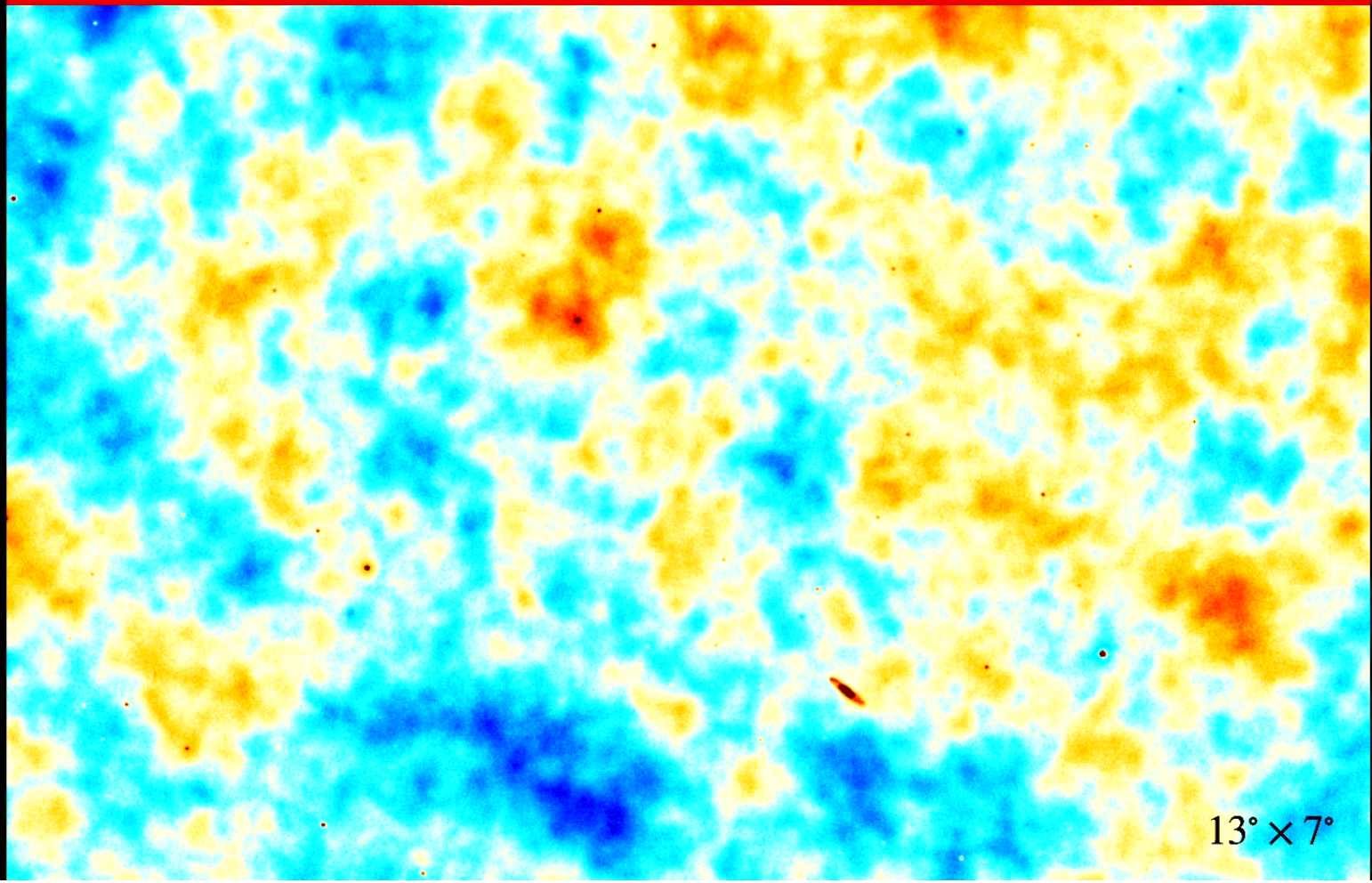
Sky Coverage



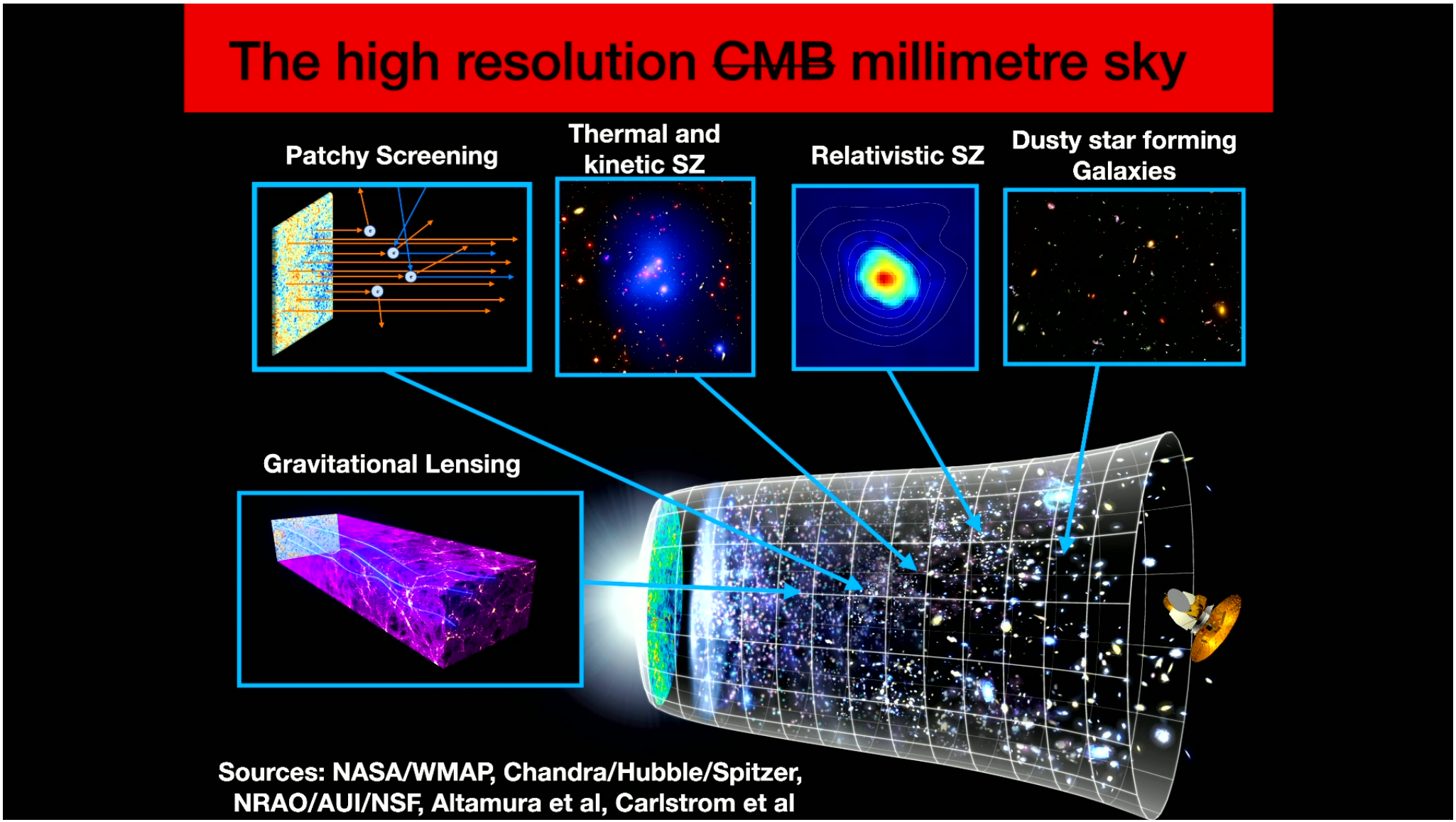
The Simons Observatory

The large aperture telescope:
1) ~6m primary
2) Frequency coverage from 30-280 GHz
3) ~10x the mapping speed of ACT!!

An extract from the latest ACT-Planck maps



The high resolution ~~CMB~~ millimetre sky



Thermal Sunyaev Zeldovich effect

- Caused by inverse Compton scattering of CMB photons of hot electrons

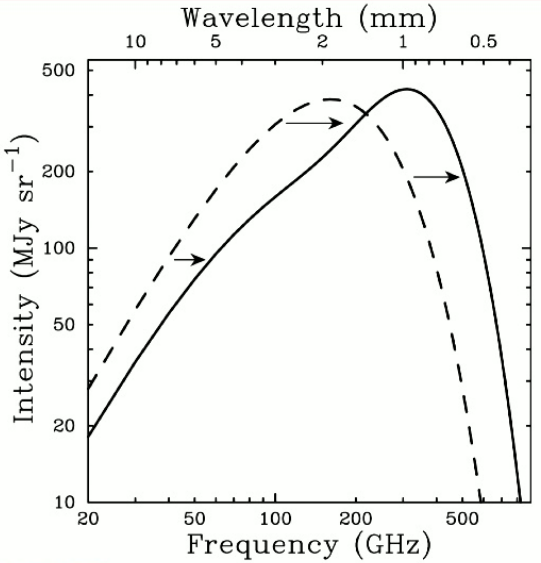
Frequency Response

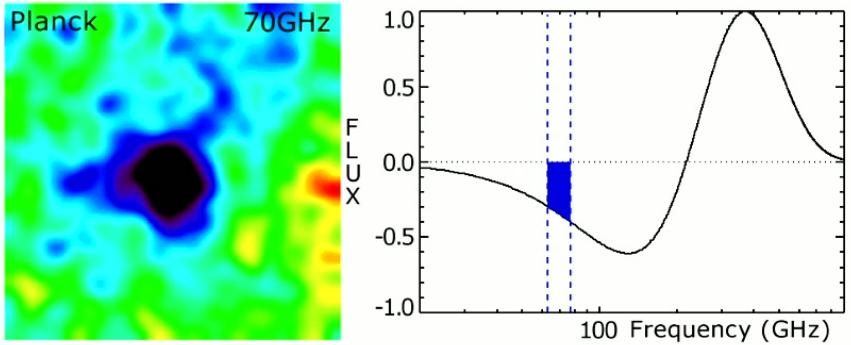
$$\delta I(\mathbf{n}, \nu) = g(\nu) y(\mathbf{n})$$

with:

$$y(\mathbf{n}) \propto \int \mathrm{d}l \, P_e(\mathbf{n}, l)$$

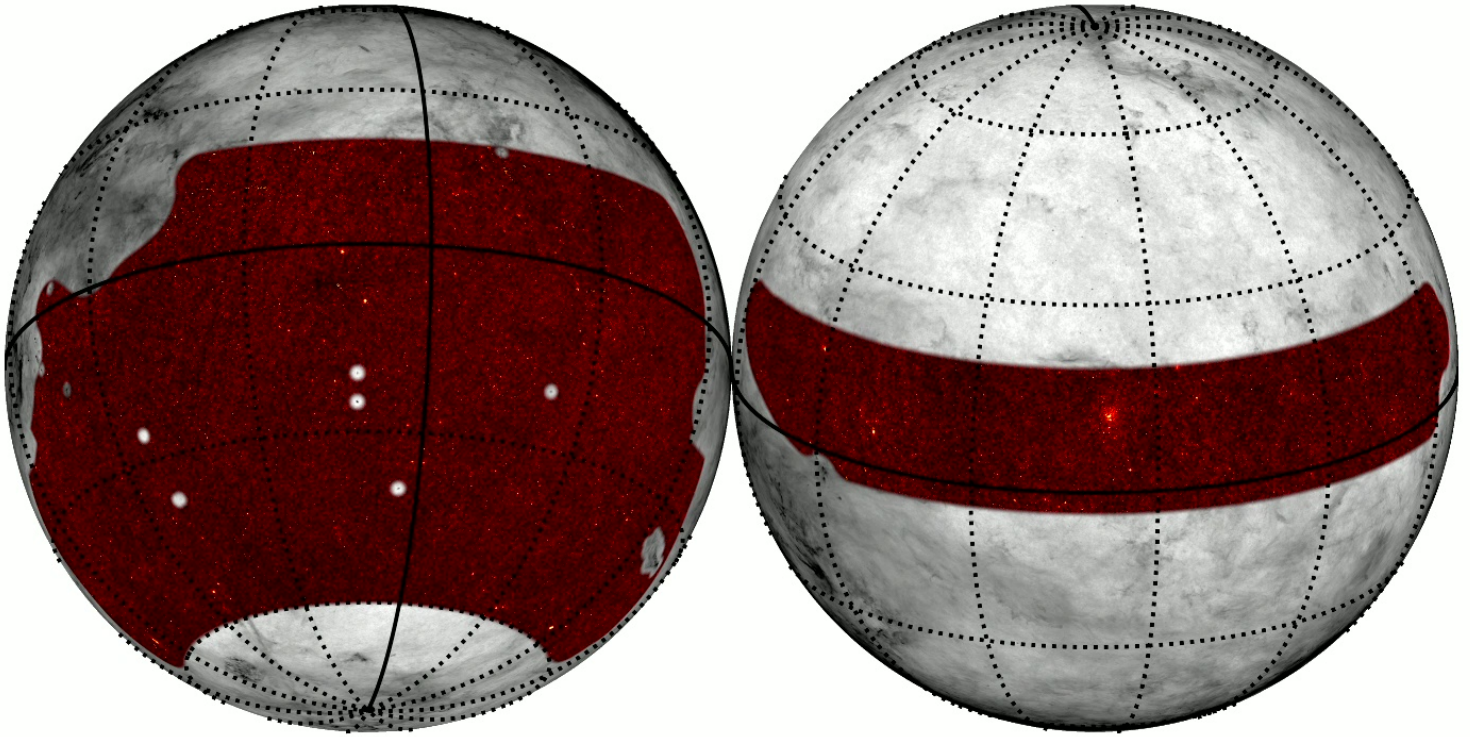
Electron Pressure





Source: Carlstrom et al (2002)

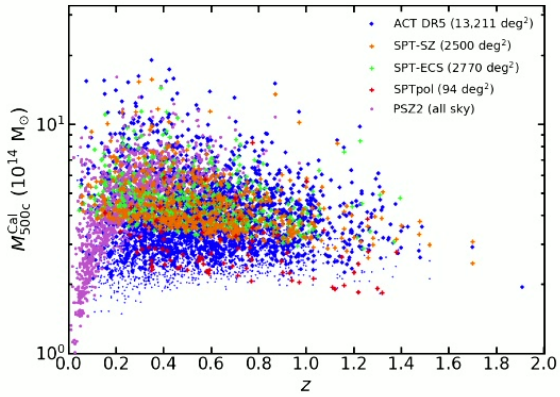
Our new Compton-y map



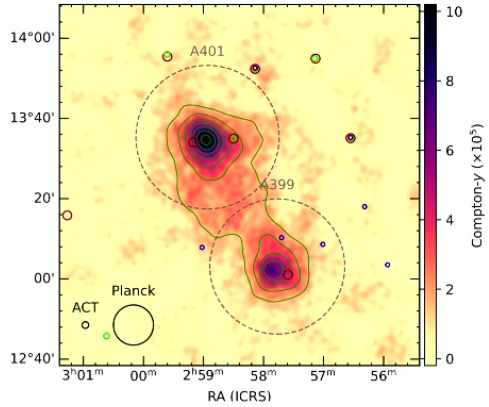
Coulton et al (2023)

A wealth of cosmological and astrophysical information

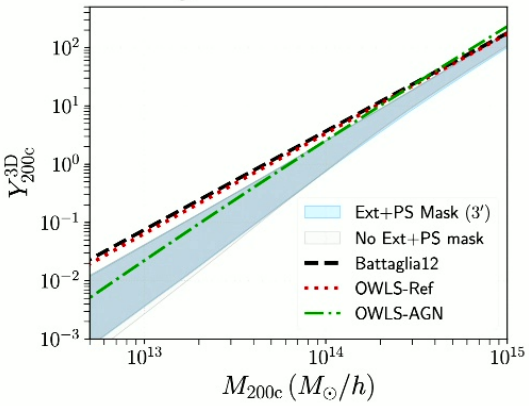
ACT has detected more than >9000 clusters!



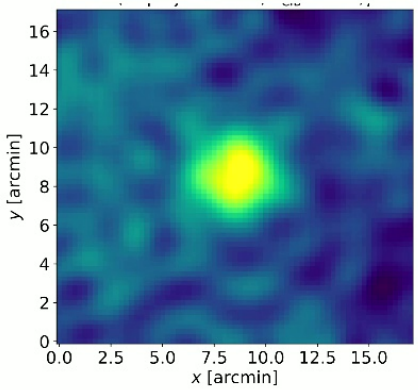
Study gas filaments



The gas-halo connection



The pressure around DESI galaxies



Hilton et al (2021),Hincks et al (2021), Isopi et al(2024), Liu et al (2025), Pandey et al (2025)

What is the relativistic Sunyaev Zeldovich (rSZ) effect?

- The usual tSZ formula:

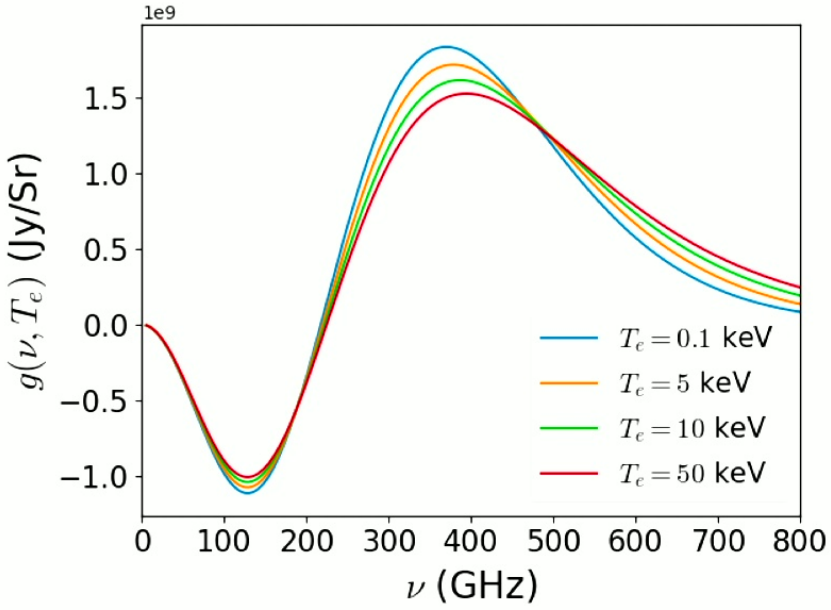
  $\delta I(\mathbf{n}, \nu) = g(\nu) y(\mathbf{n})$

  assumes non-relativistic electron ($T_e << m_e c^2/k_B$)

- X-ray measurements show that $T_e \gtrsim$ few keV !

- For relativistic electrons: $\delta I(\mathbf{n}, \nu, T_e) = g(\nu, T_e) y(\mathbf{n})$!

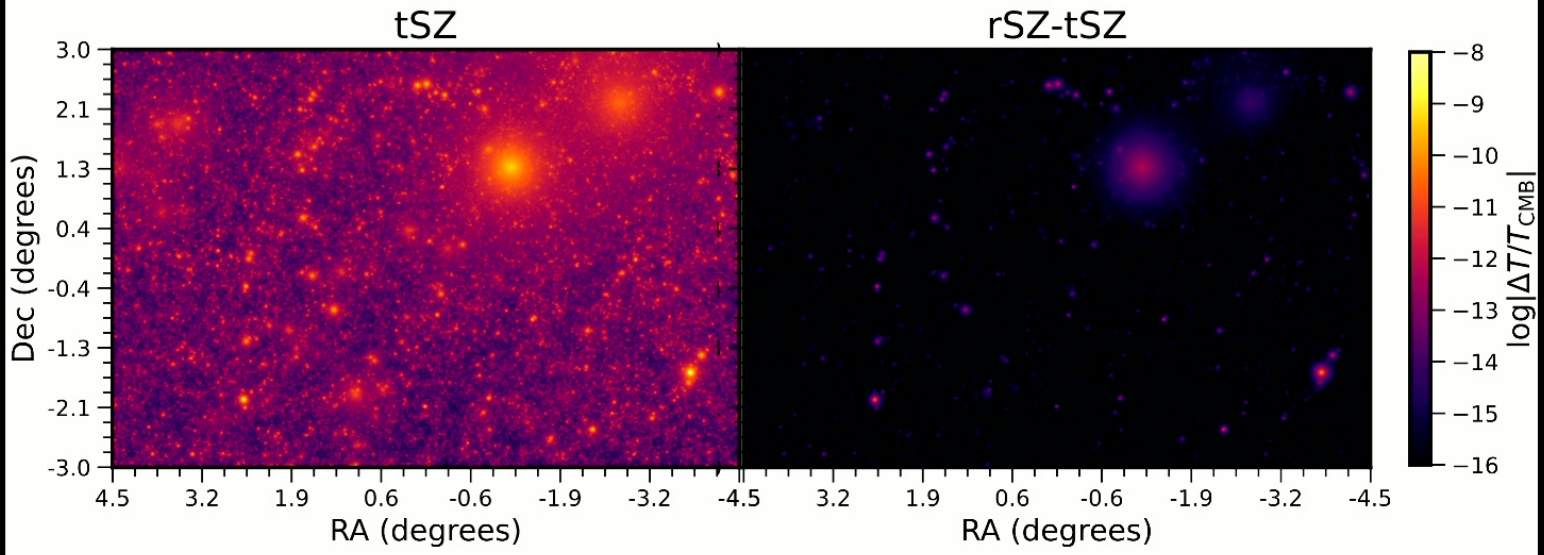
Relativistic SZ signature for electrons at different temperatures



How does this appear on the sky?

Lucas Kuhn

A simulated ~40 degree² patch of the sky



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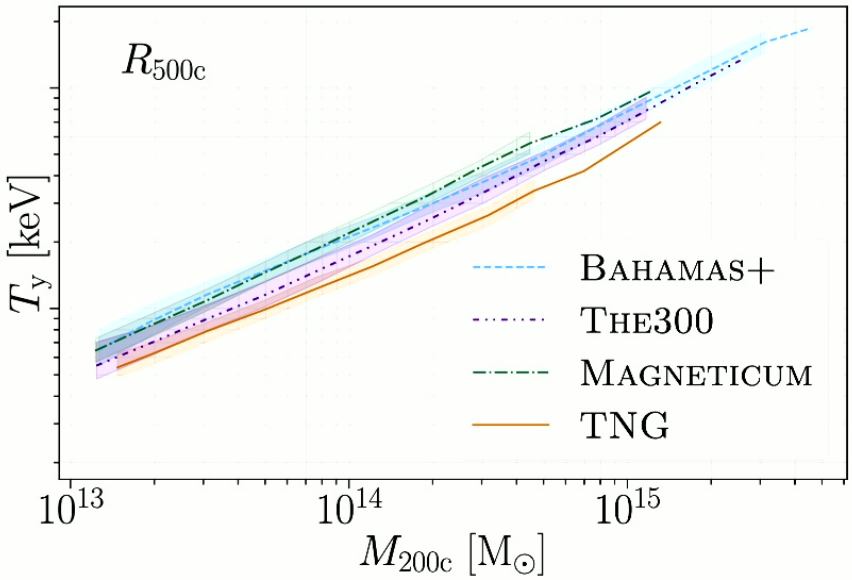
Kuhn et al (2025)

What can we learn from cluster temperatures?

- Cluster temperatures are a probe of the cluster's thermal history
- Especially interesting is their redshift evolution
- Can we push to high redshift?
- Can be used as a mass proxy for cosmology?

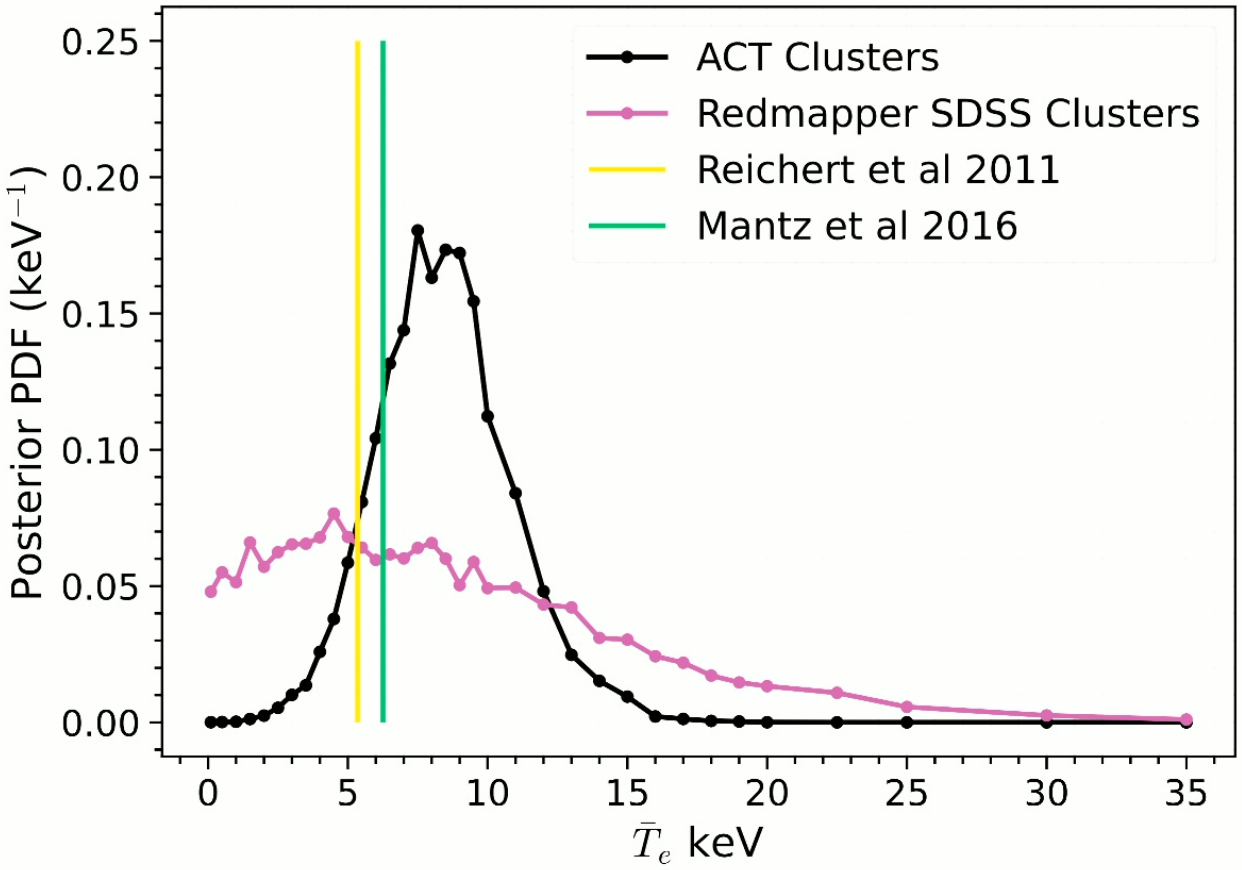
Temperature mass scaling relations for a collection of hydrodynamic simulations



Lee et al (2022)

How well do we constrain the temperature?

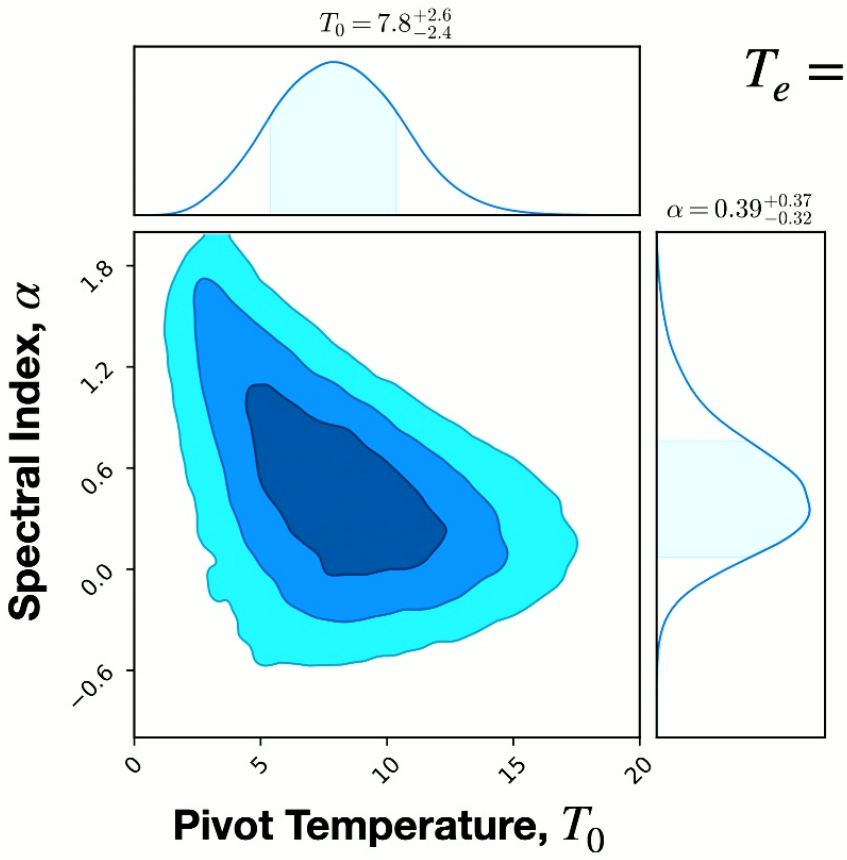
The mean temperature of the 4690 ACT clusters compared to other measurements



From profiles to physics

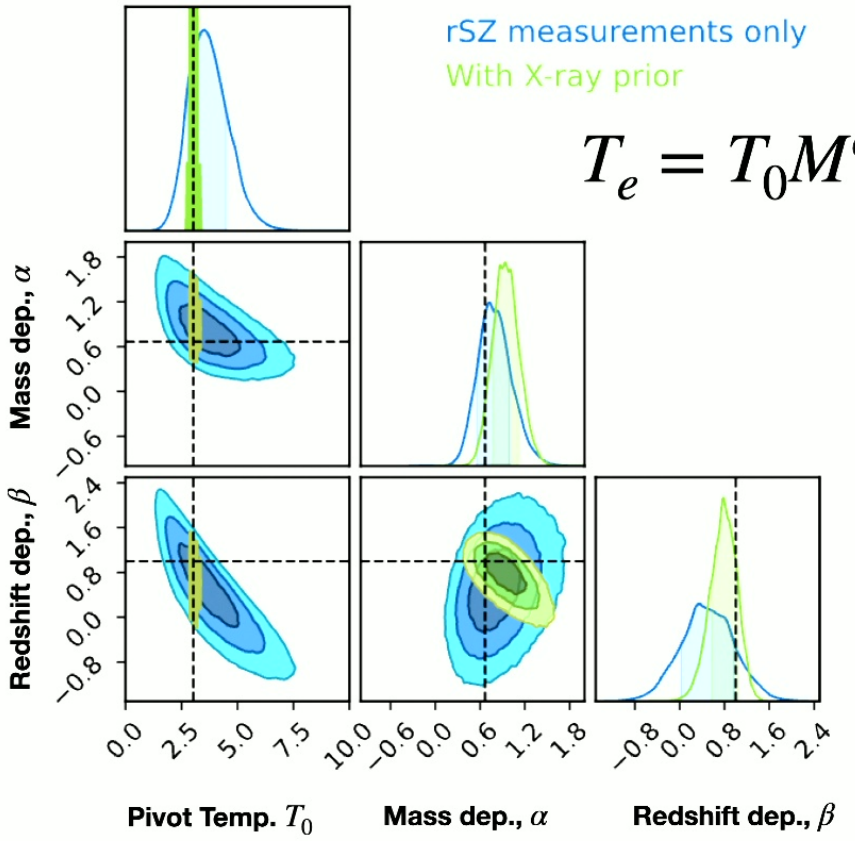
Instead of measuring the entire stack, we can subdivide and search for evolution

$$T_e = T_0 \left(\frac{y_{500}}{y^0} \right)^{\alpha}$$



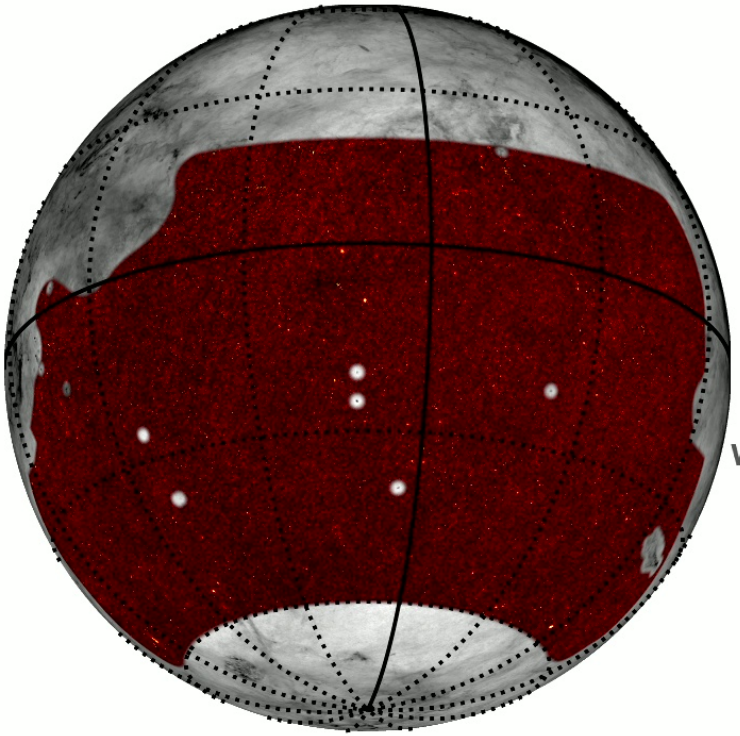
The future is (relatively) hot..

Forecast constraints on temperature-mass-redshift relations with Simons Observatory



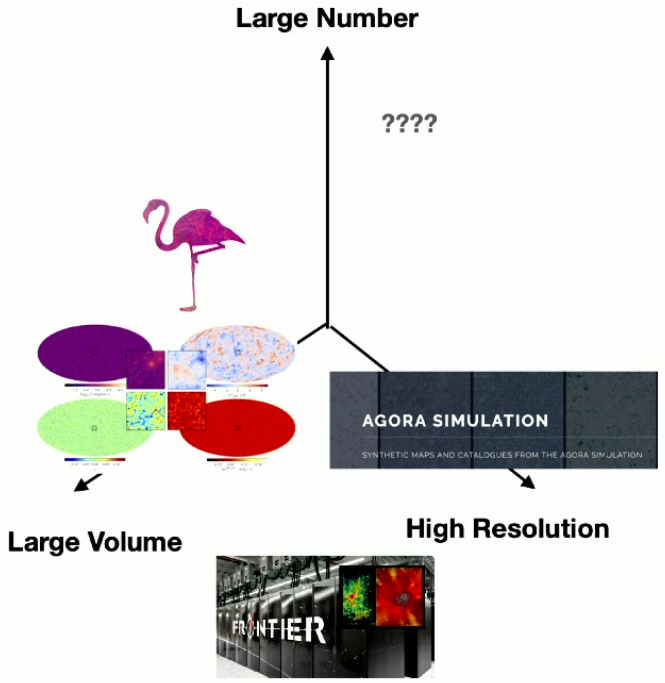
How do we interpret, analyse and validate observations?

CMB secondaries are inherently non-Gaussian



Websky

Simulations are a key tool!

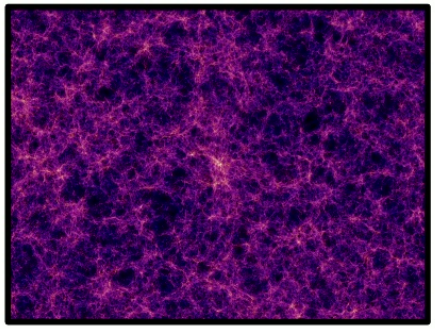


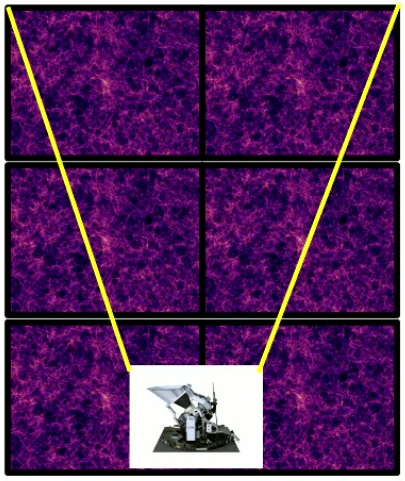
The backlight approach

High resolution, high fidelity dark matter simulations

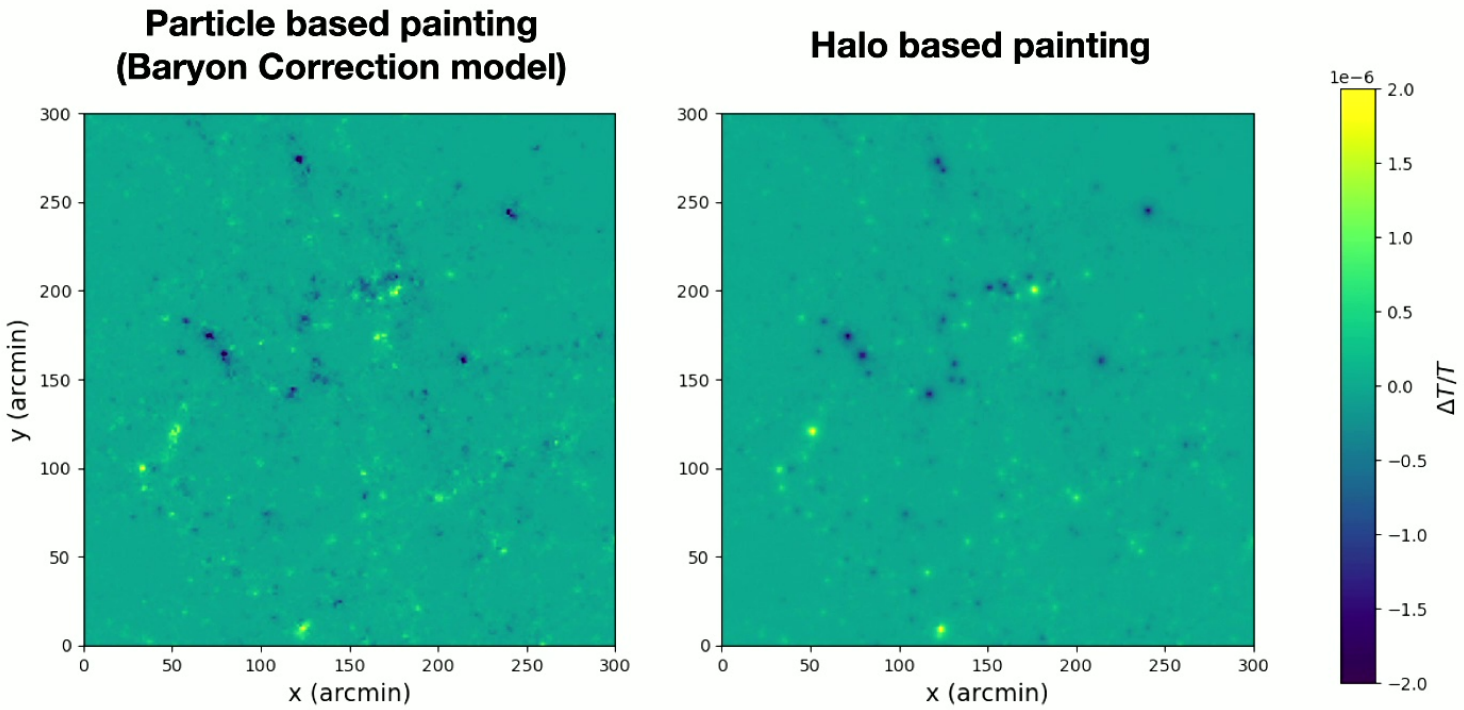
Tile box to cover the Universe and construct a light cone

“Paint” observables onto simulations





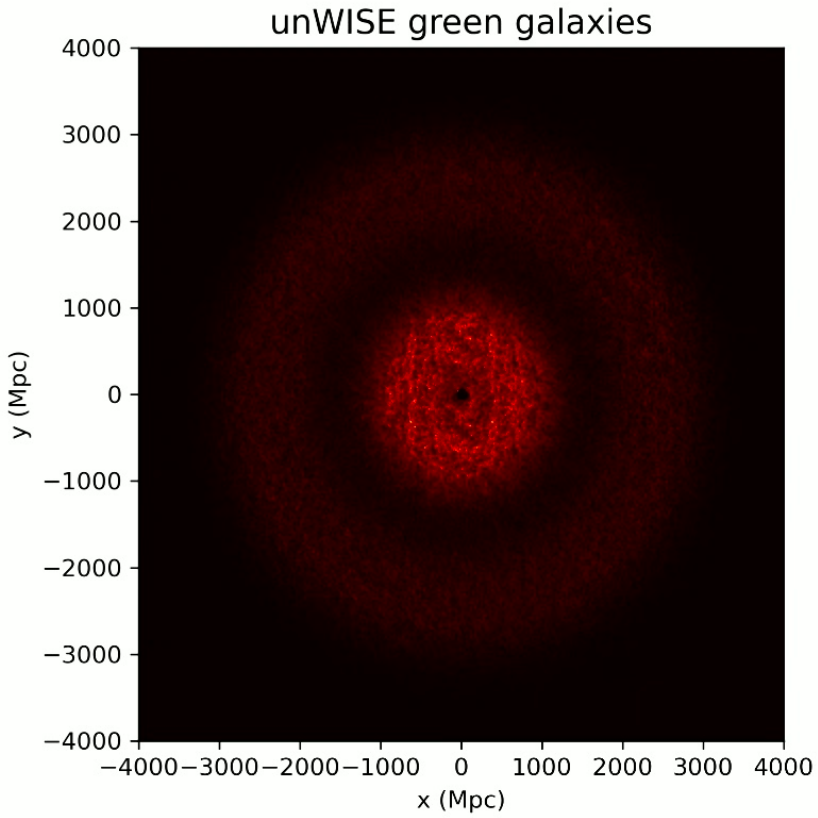
An example: mock kSZ maps



Can test importance of model assumptions: intrinsic scatter, ellipticity++
See Daisuke's talk

The backlight suite

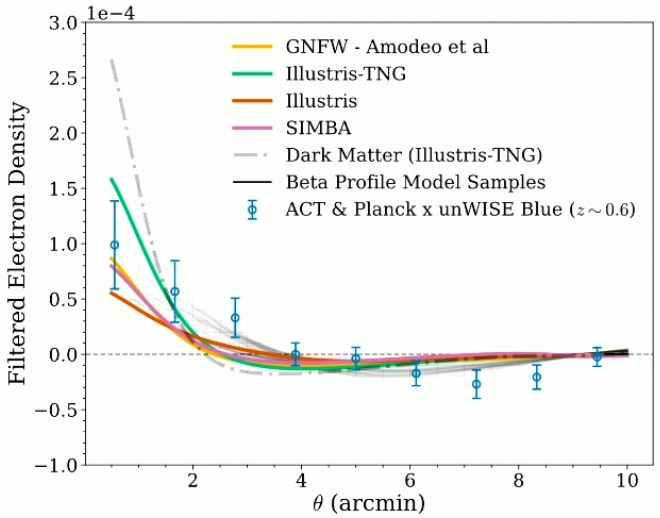
- Large number of simulations
  - Currently have ~250
    Goal: >1000
- Large range of observables (CMB, galaxy clustering, lensing++)
  - Talk to me about adding other observables
- Goal multiple “painting” methods
  - Currently a halo-based approach and a particle based approach



Gas probes beyond pressure….

Led by Jack Kwok and Bernardita Ried Guachalla

Integrated electron density constraints from patchy screening

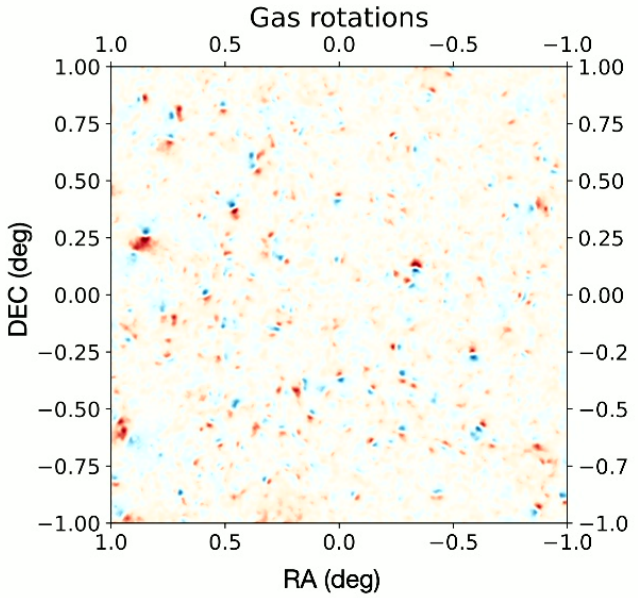


See talks by Jonah, Noah, Simone and Boryana

Coulton et al (2024)

Hadzhiyska et al. (2025), Sailer et al (2025)

Probing gas rotations with groups and clusters



Conclusions

- CMB secondaries contain a wealth of information on cosmic gas
  - With ACT, SPT ++, we have the sensitivity to make interesting gas measurements
- Publicly available ACT+Planck maps here
- Measuring the rSZ is hard!
  - Requires high resolution, low noise measurements … especially at high frequencies
  - A very precise characterisation of the instrument!
- We have made a $\sim 4\sigma$ measurement of the effect