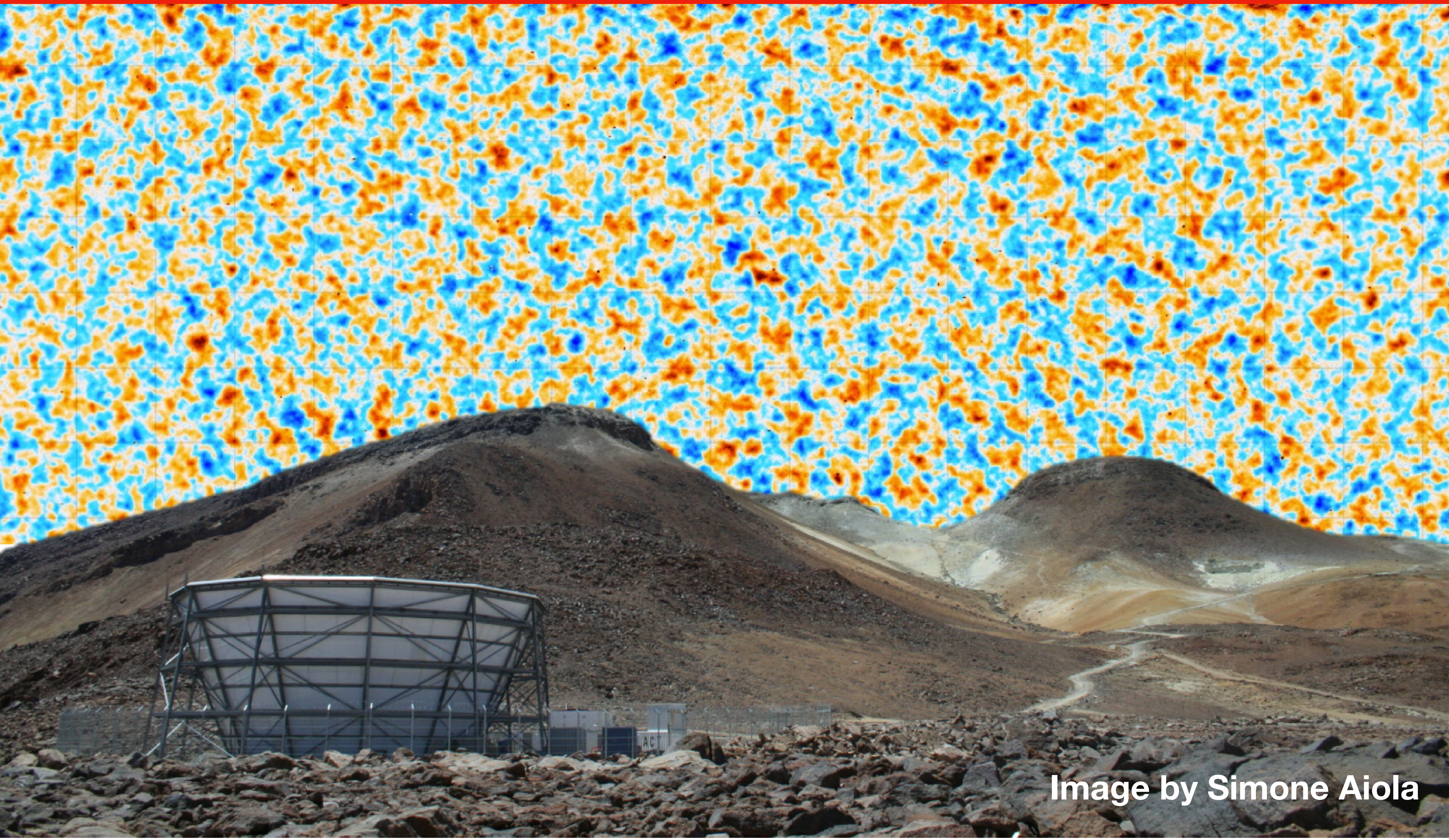
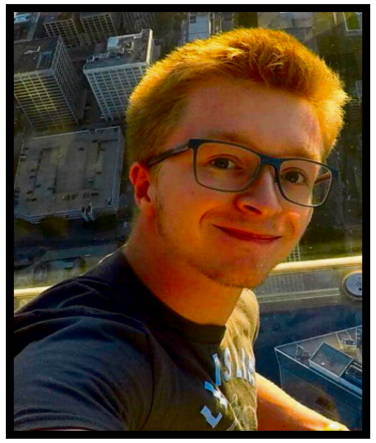
# Novel cosmological tests with precision CMB measurements




**William Coulton**

# Done in collaboration with

Alba Kalaja



David Baker

Alex Miranthis

Billy Lee

Zach Atkins

Leander Thiele

Thomas Flöss

Mat Madhavacheril

Gabriel Jung

Daan Meerburg

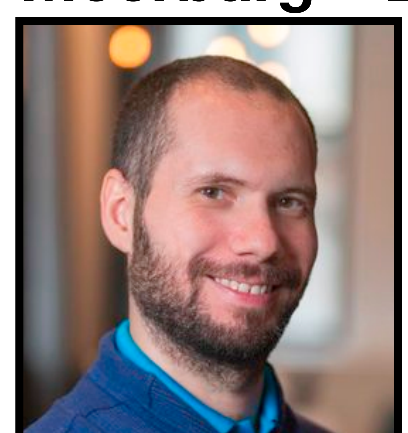
Adriaan Duivenvoorden

Colin Hill

Ben Wandelt

Licia Verde

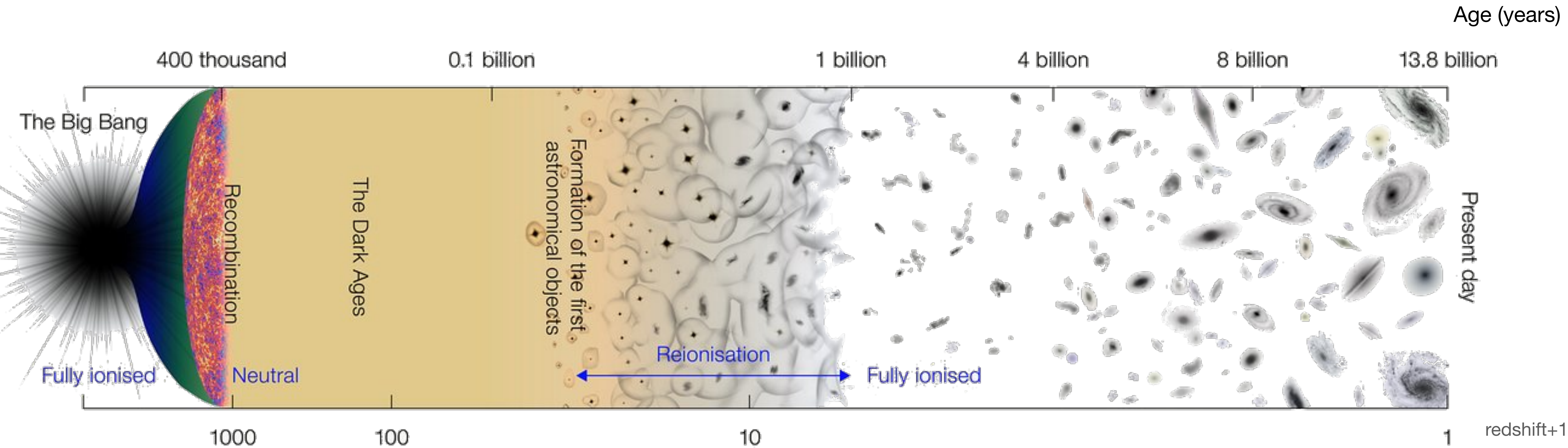
Anthony Challinor



Francisco Villaescusa-Navarro

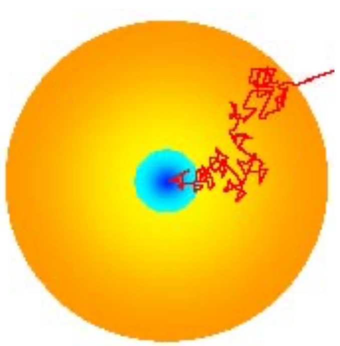
**The ACT and Simons Observatory collaborations and many more!**

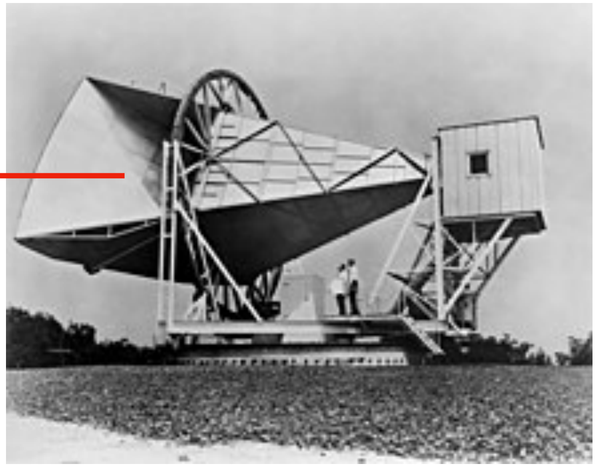
# The CMB!




**Opaque**

**Transparent**

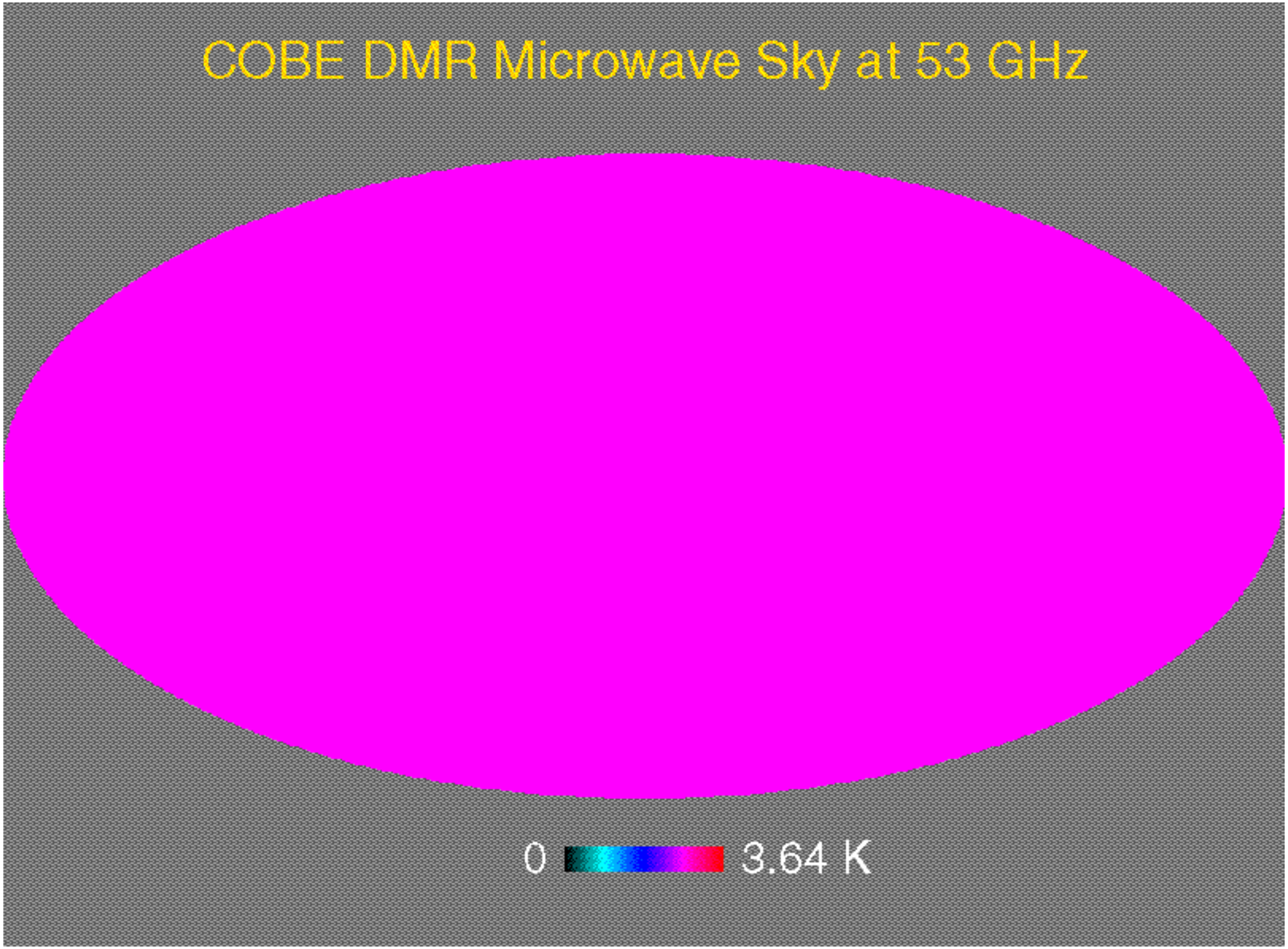






**Sources: ESA, wikipedia**

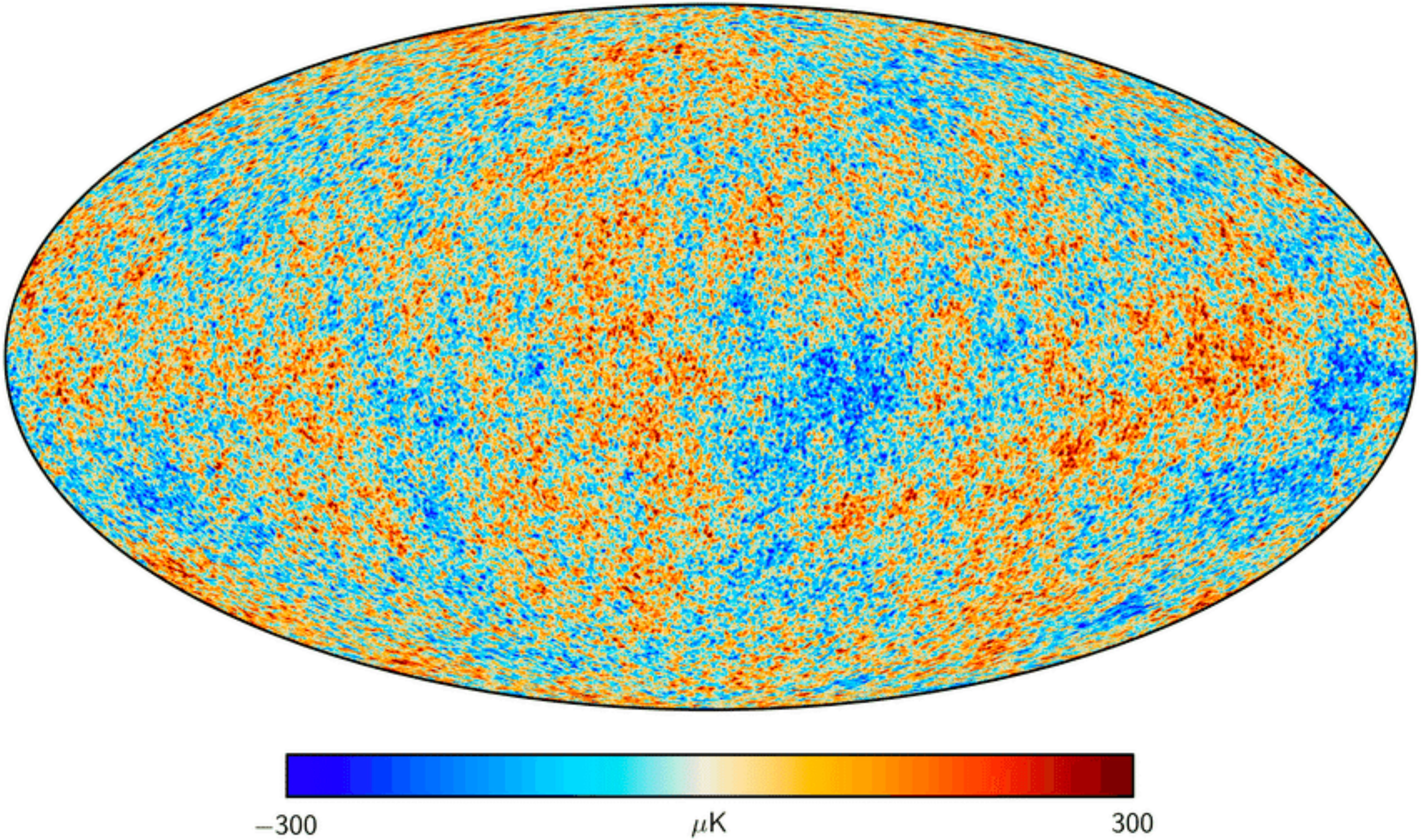
# The CMB!






**Bennett et al (1996)**

# The CMB anisotropies

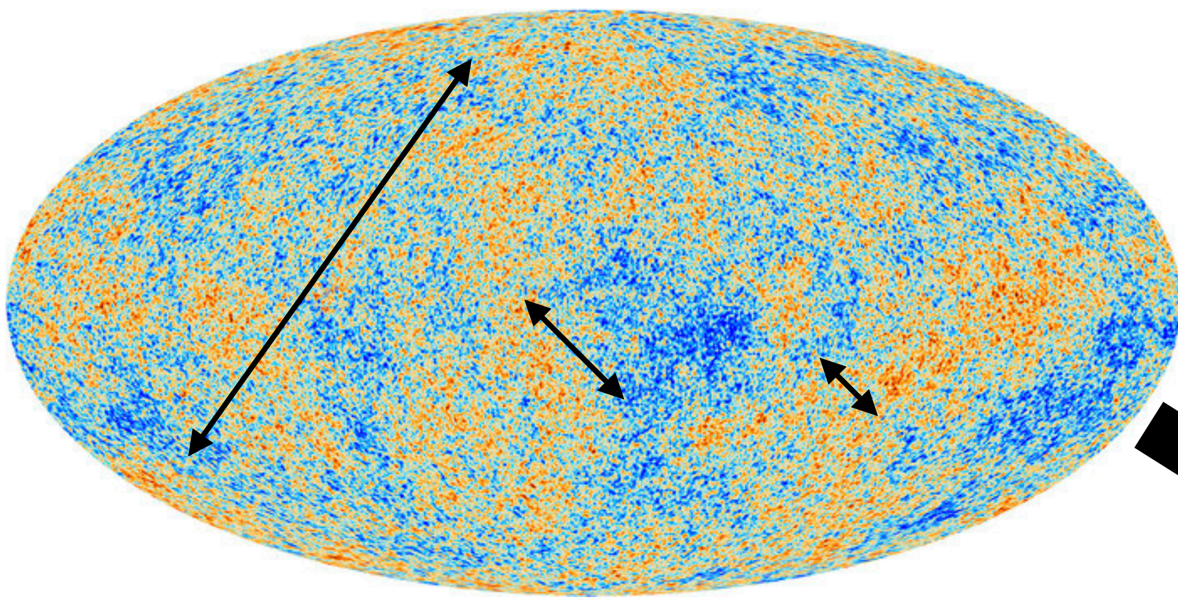




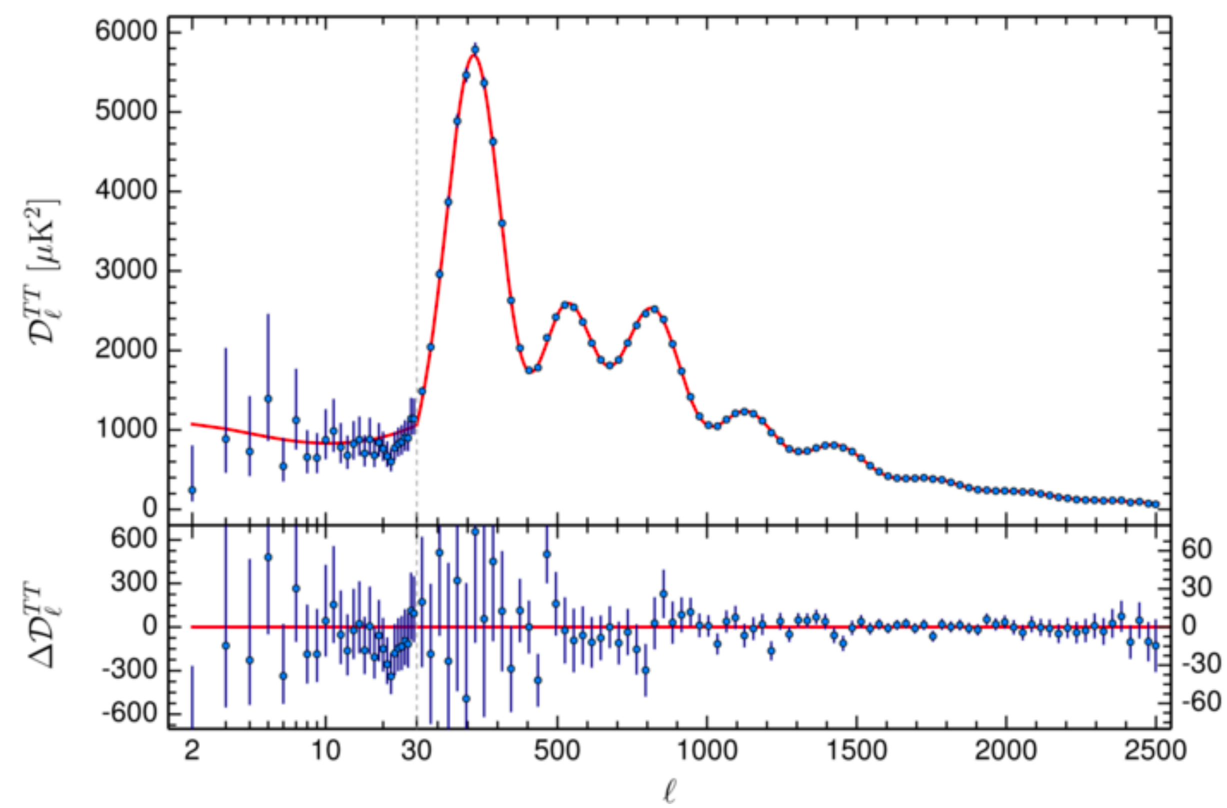

**Planck Satellite (ESA)**

# The leading approach

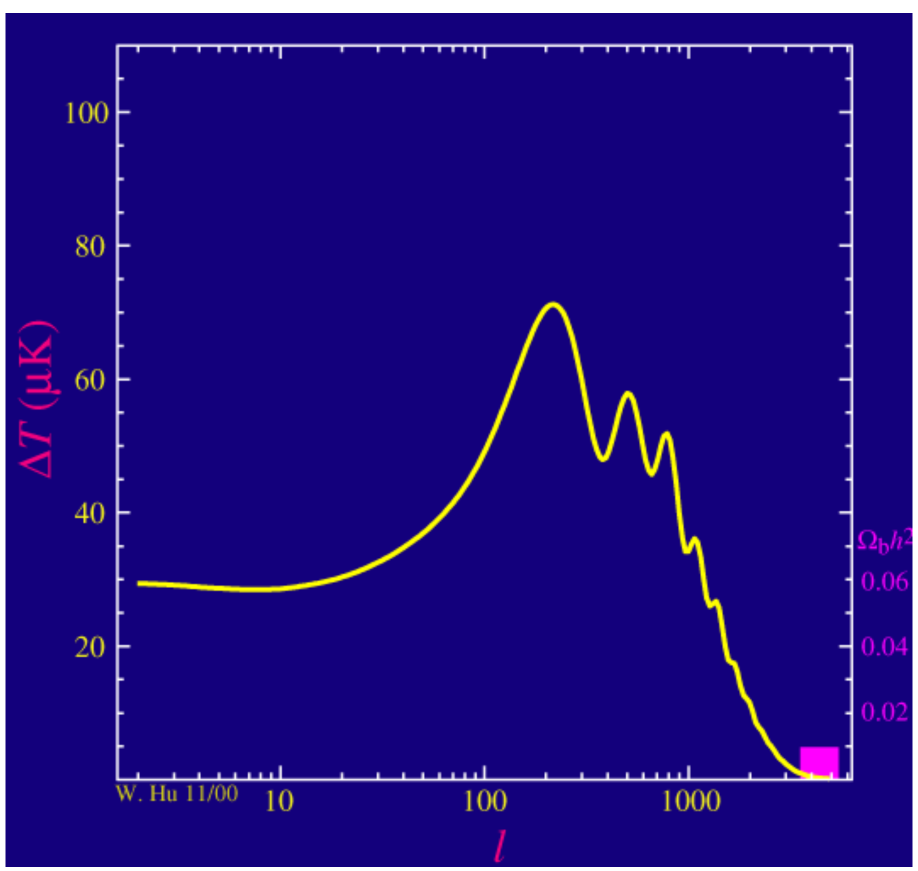
**Observations**



**CMB power spectrum**

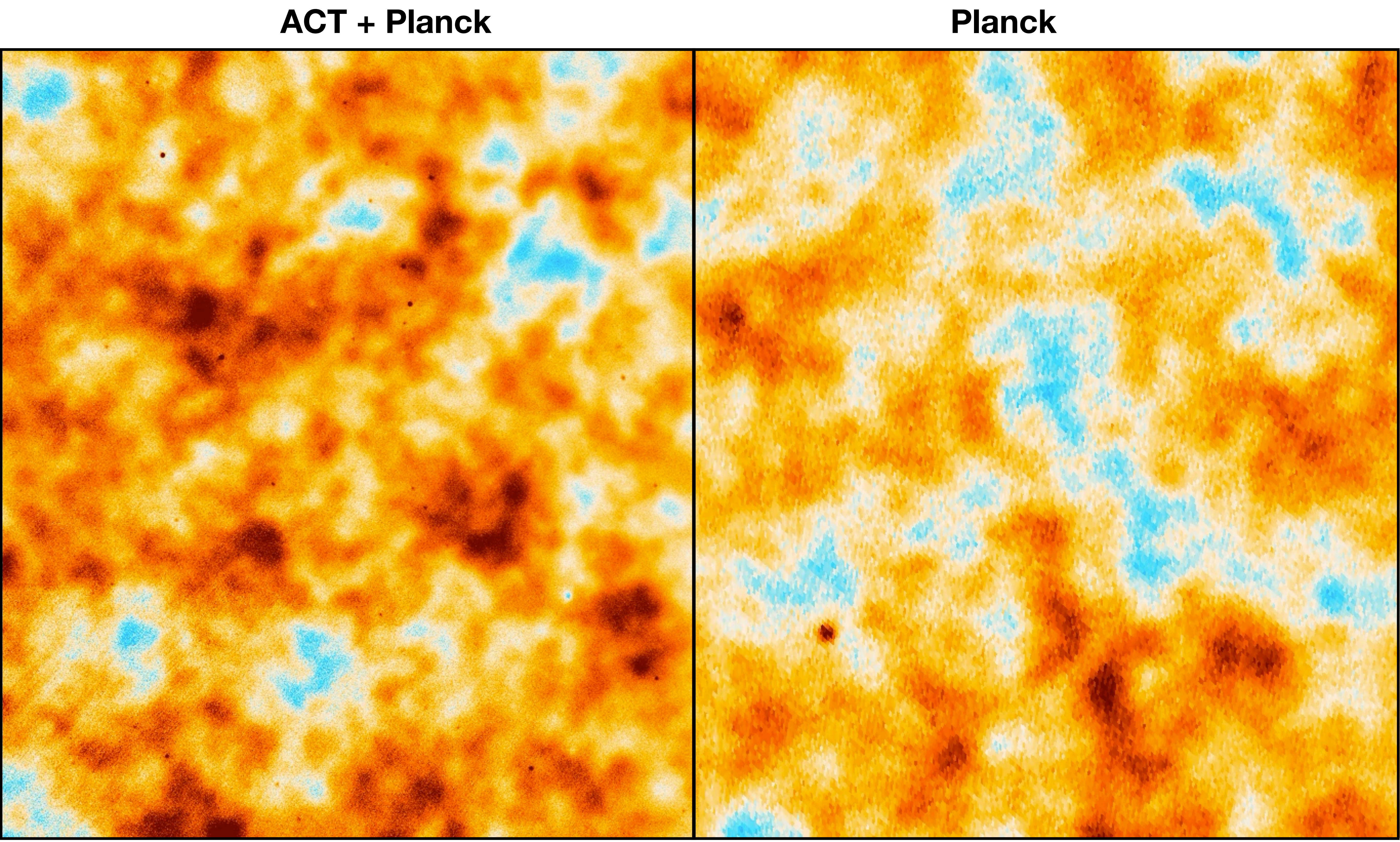



**Constrain the properties of the Universe**



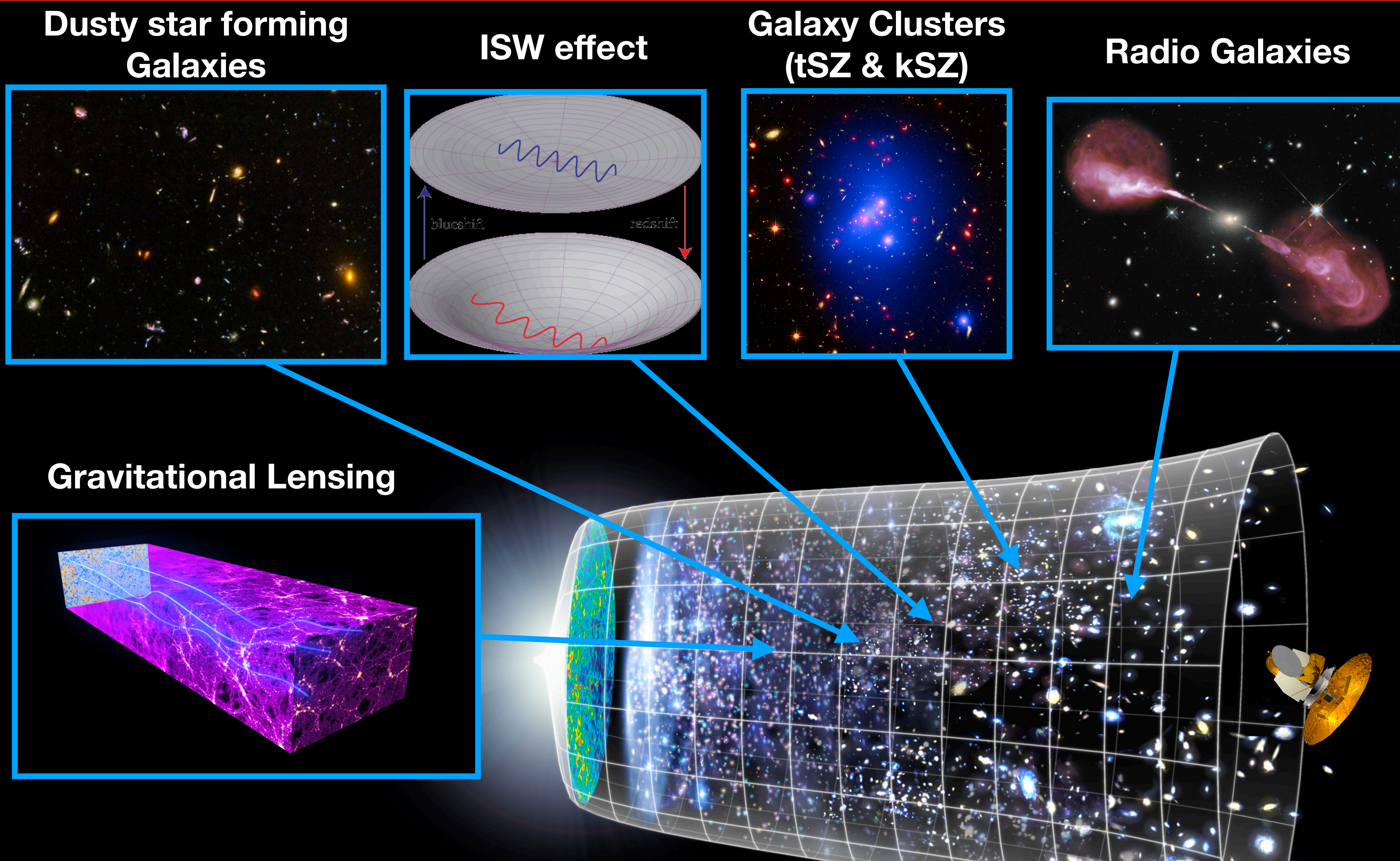

**Planck XX 2015, Planck V 2018, Buades 2015**

# The small scale millimeter sky



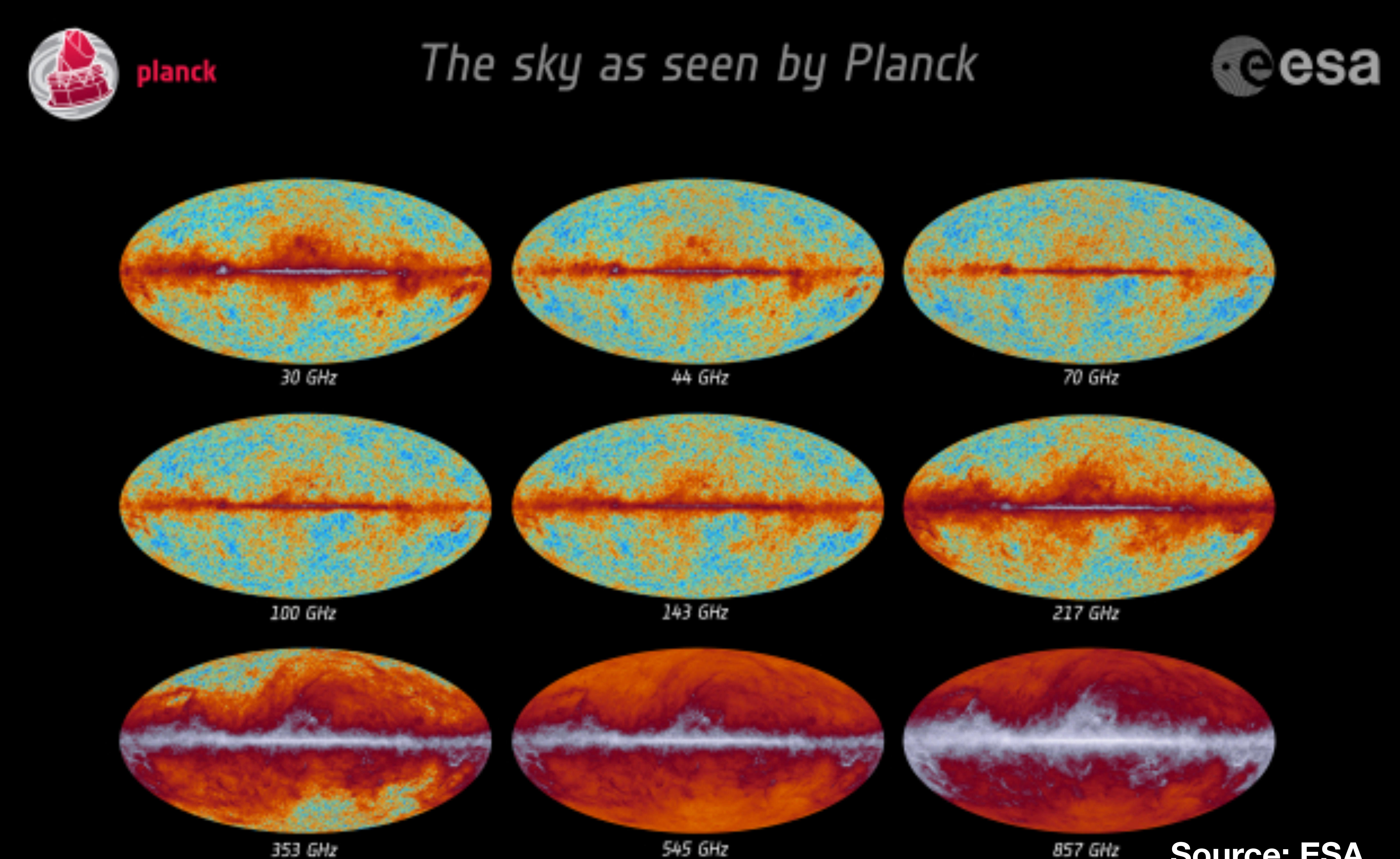

Source: Sigurd Naess and the ACTPol Collaboration

# The ~~CMB~~ millimeter sky




Sources: NASA/WMAP, Chandra/Hubble/Spitzer, NRAO/AUI/NSF

# The ~~CMB~~ millimeter sky

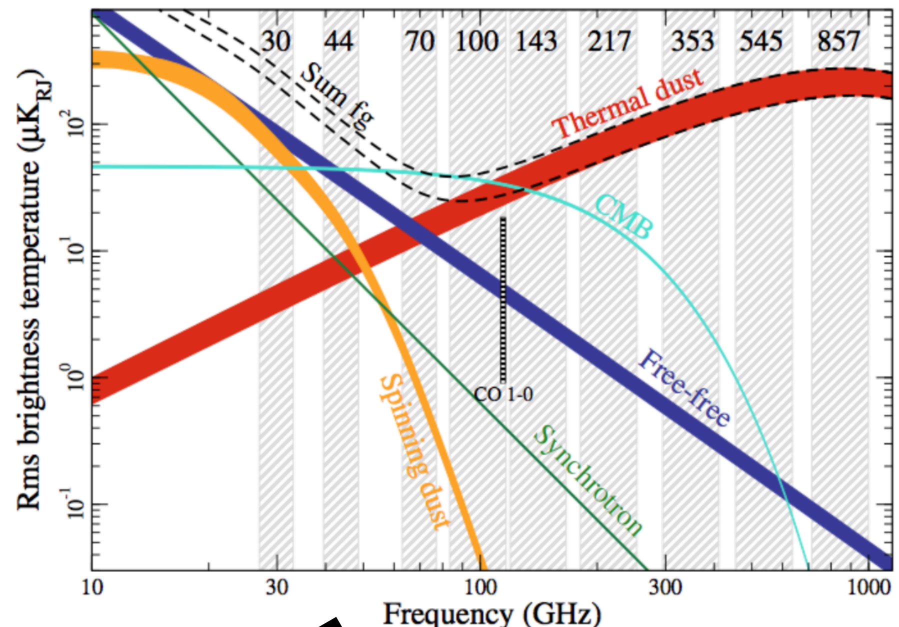



**Source: ESA**

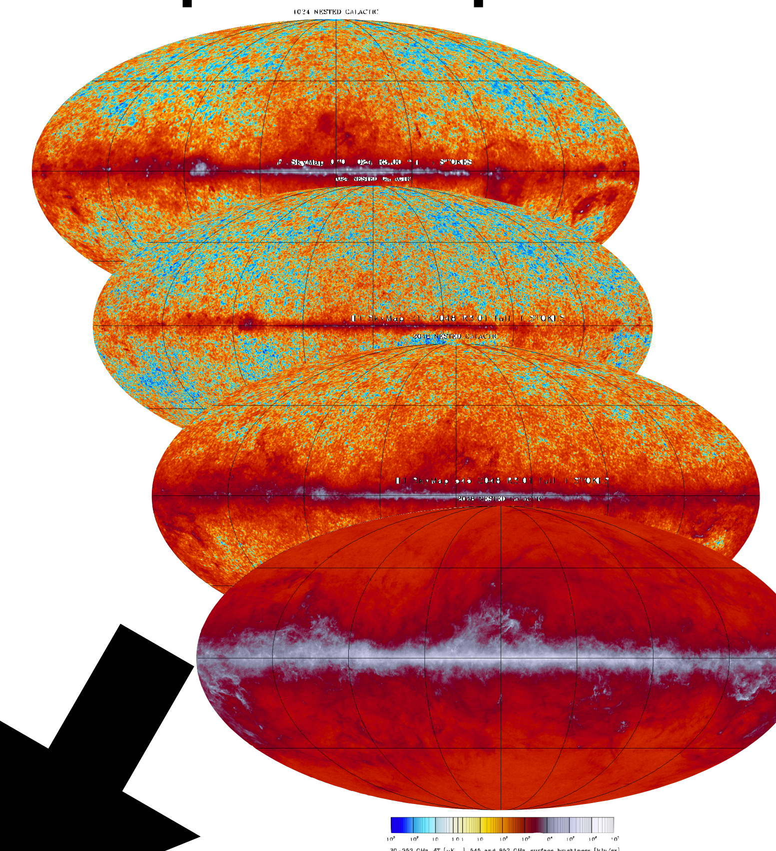
# Component Separation

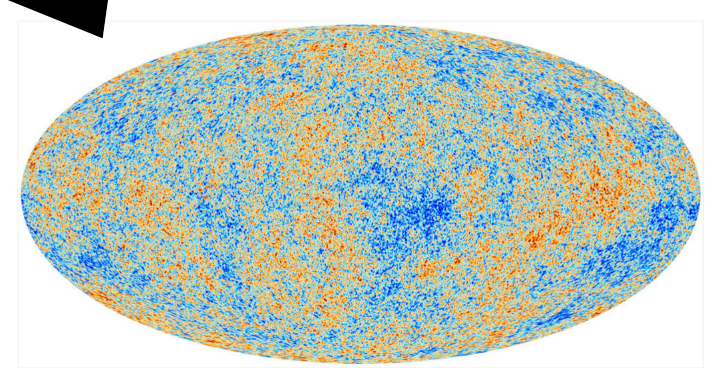
- The aim is to isolate signal of interest
- Utilize different spatial and frequency dependance of signals
- Combine different experiments with different noise/resolution etc
- Challenge:
  how to exploit different spatial properties of each component?

**Frequency dependence of the sky components**




**Statistical and Spatial Properties**



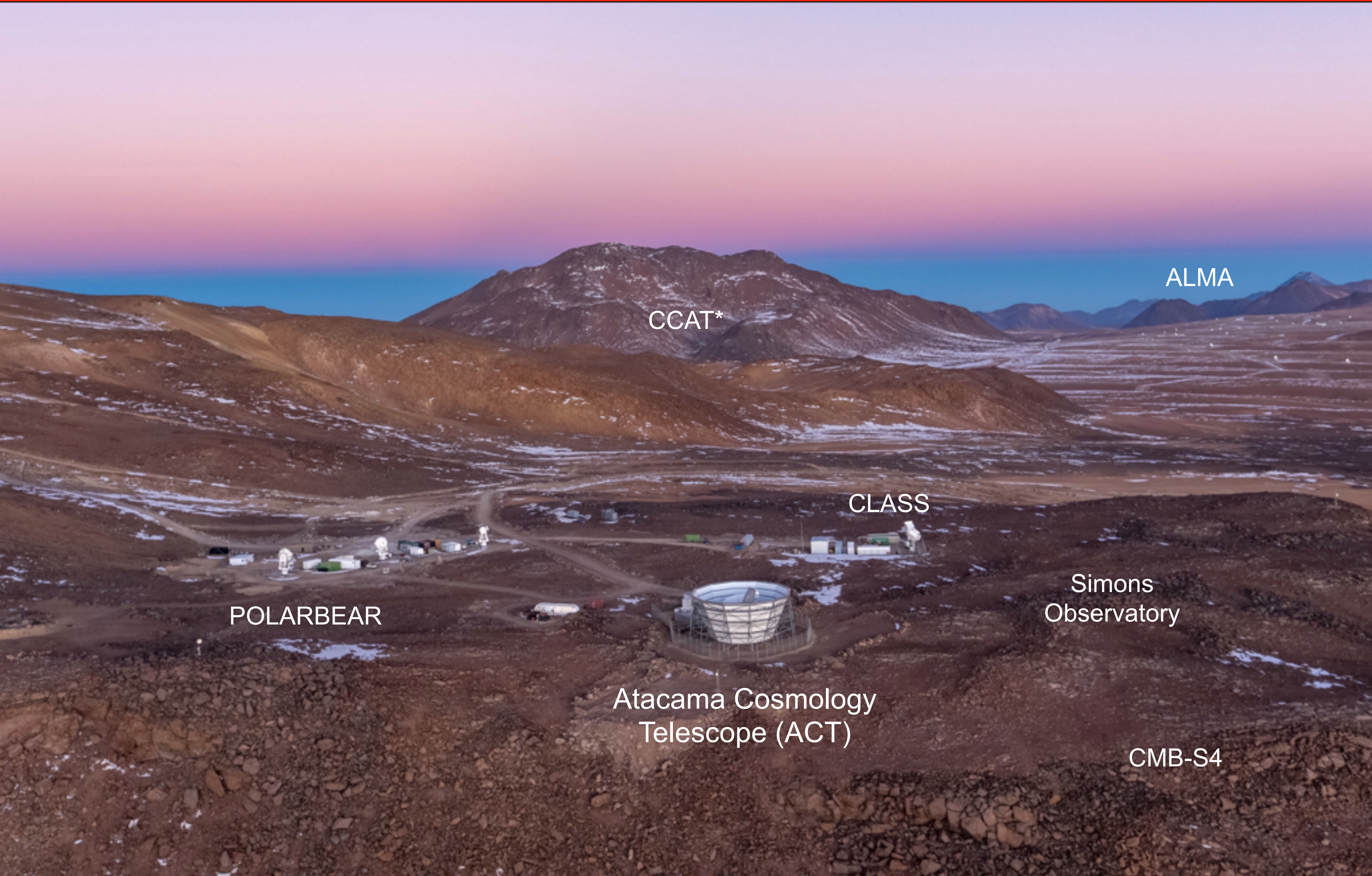


**Map of the signal of interest**



**Dickinson (2016), ESA**

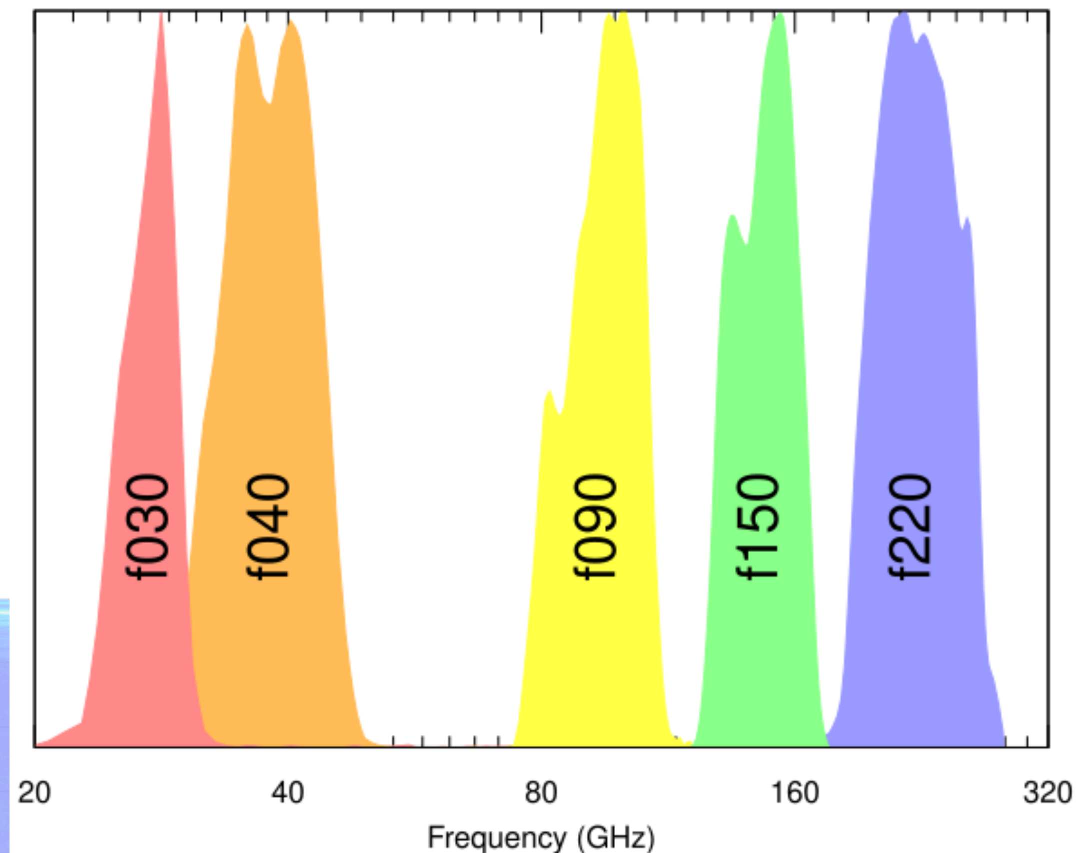
# Cerro Toco - The Chilean CMB landscape



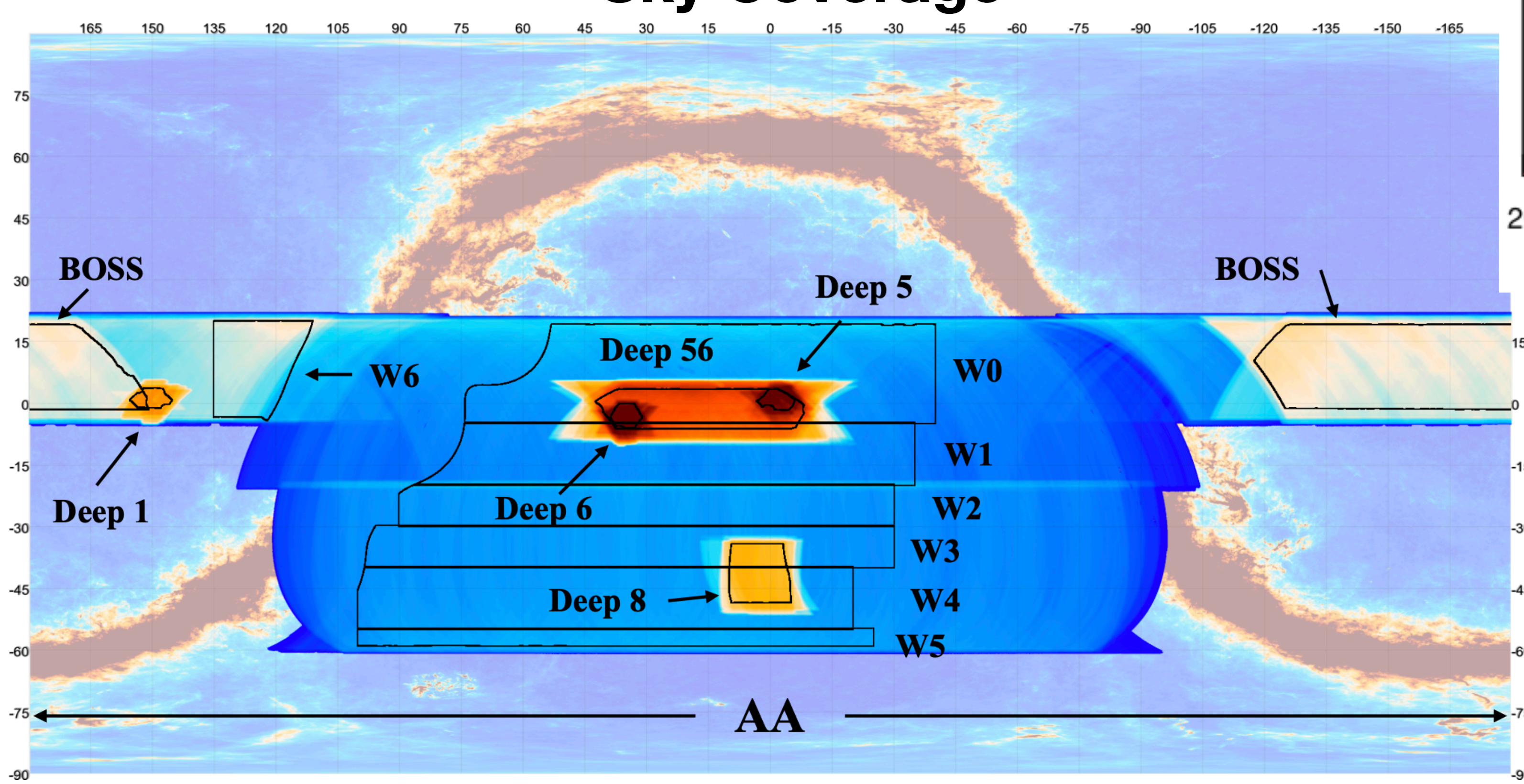
# Atacama Cosmology Telescope (ACT)

**2007 - 2022**

## Frequency Coverage




## Sky Coverage



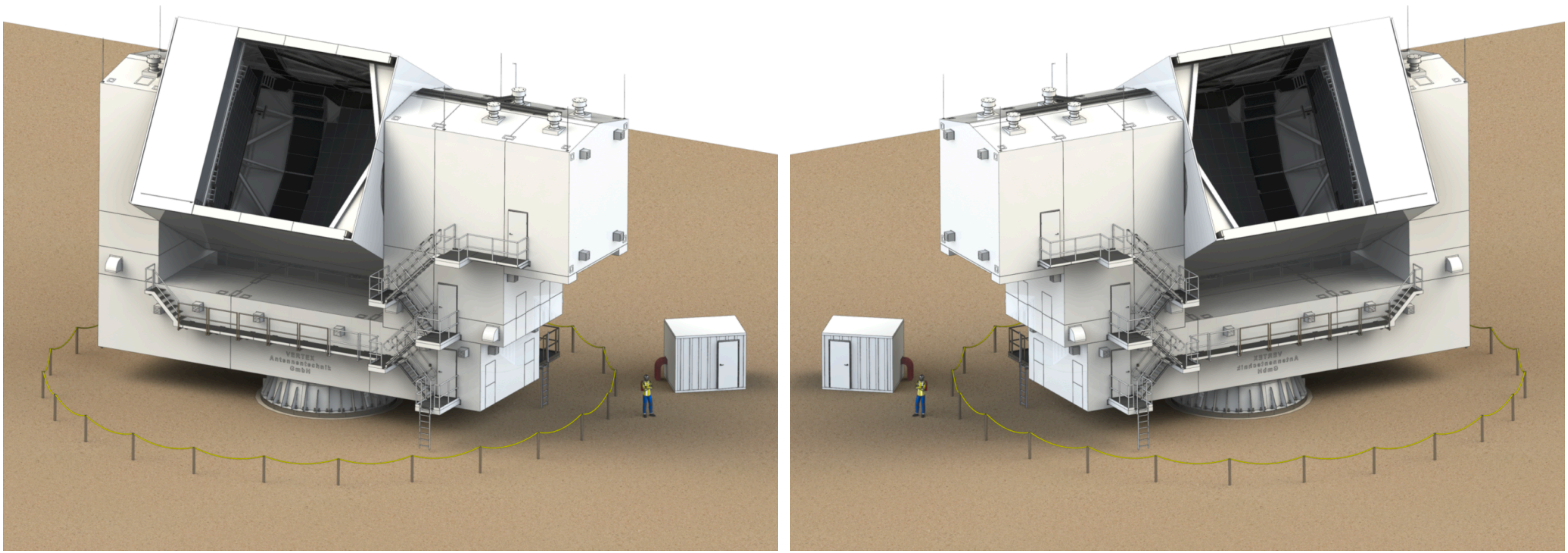
# Simons Observatory

Three (of 6!) Small Aperture Telescopes (SATs)
0.5m with 6 frequencies (30-280 GHz)

Large Aperture Telescope (LAT)
~6m with 6 frequencies (30-280 GHz)

Image by: Anna Kofman

# CMB-S4



**CMB-S4 will also have small aperture telescopes + a large aperture telescope in the South Pole focused on B-modes and transients**

# Component one:
# the thermal Sunyaev Zel’dovich effect

# Thermal Sunyaev Zel'dovich effect

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

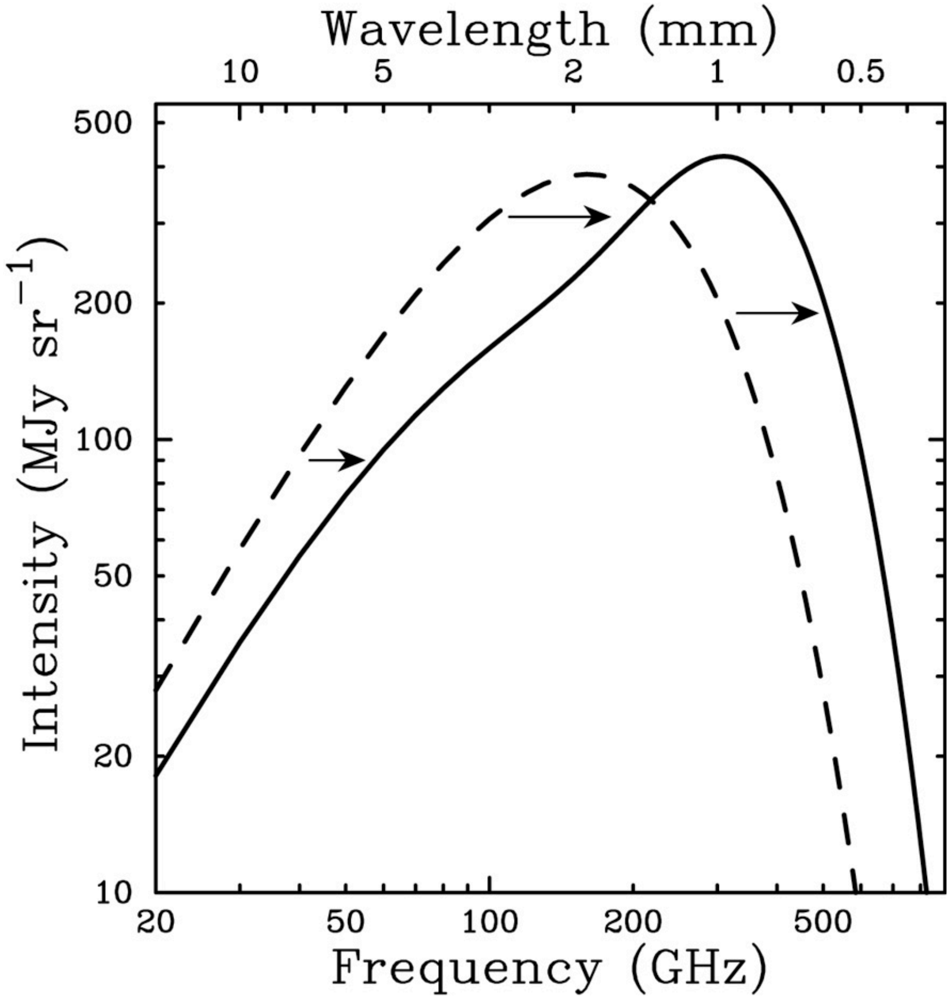
**Frequency Response**

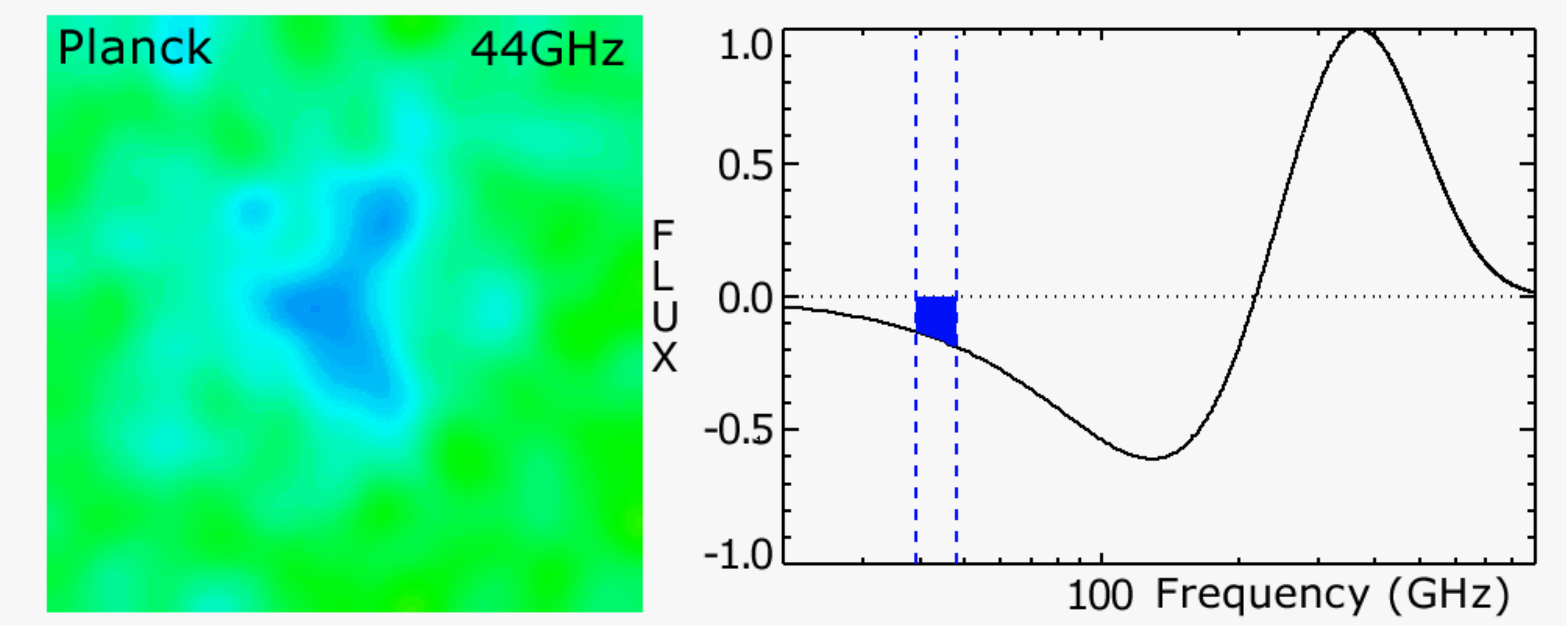
$$\delta I(\mathbf{n}, \nu) = g(\nu) y(\mathbf{n})$$

with:

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

**Electron Pressure**

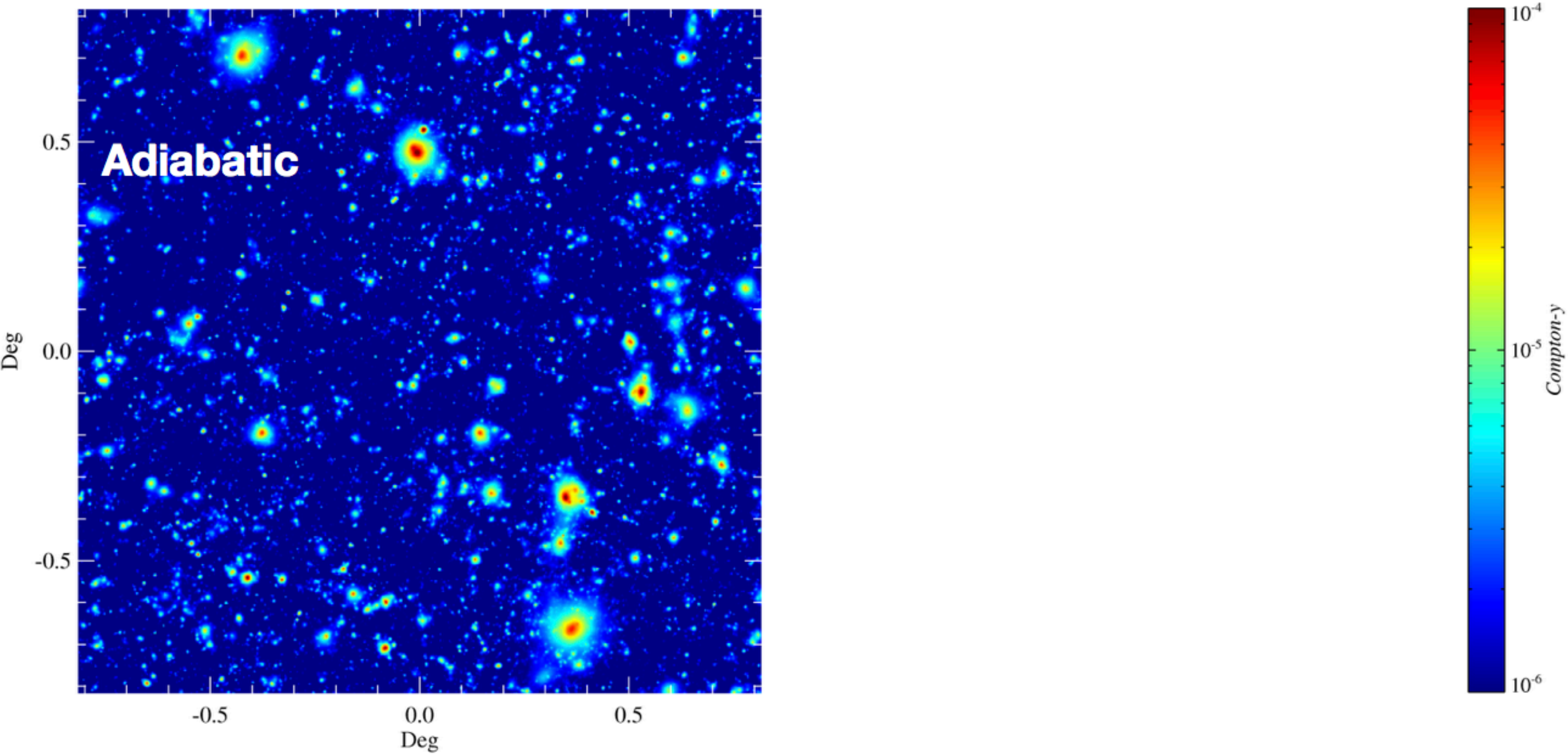



Source: Carlstrom et al (2002)

# What does the tSZ effect tell us?

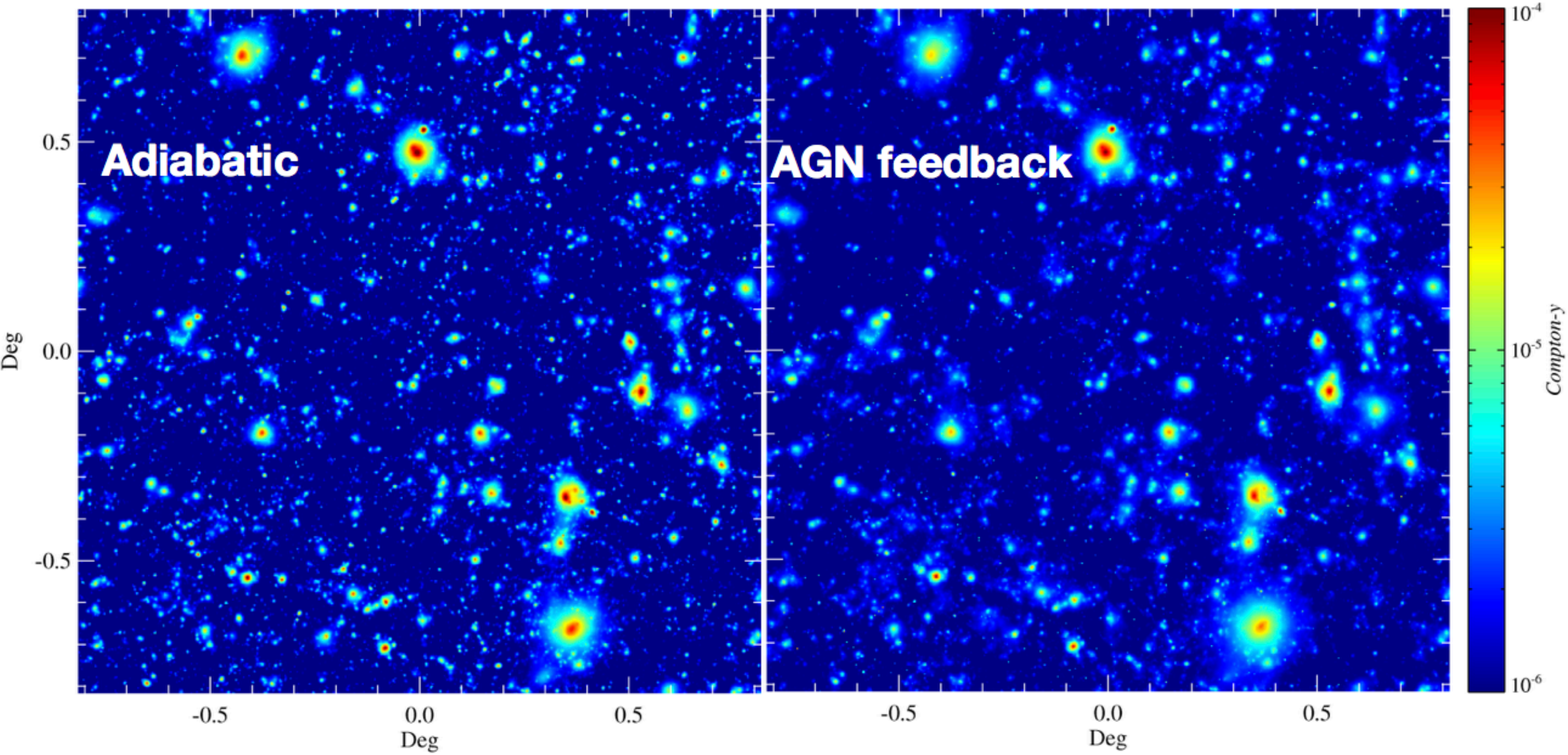
**Extracts from the Magneticum Pathfinder simulations**




**Dolag et al (2016)**

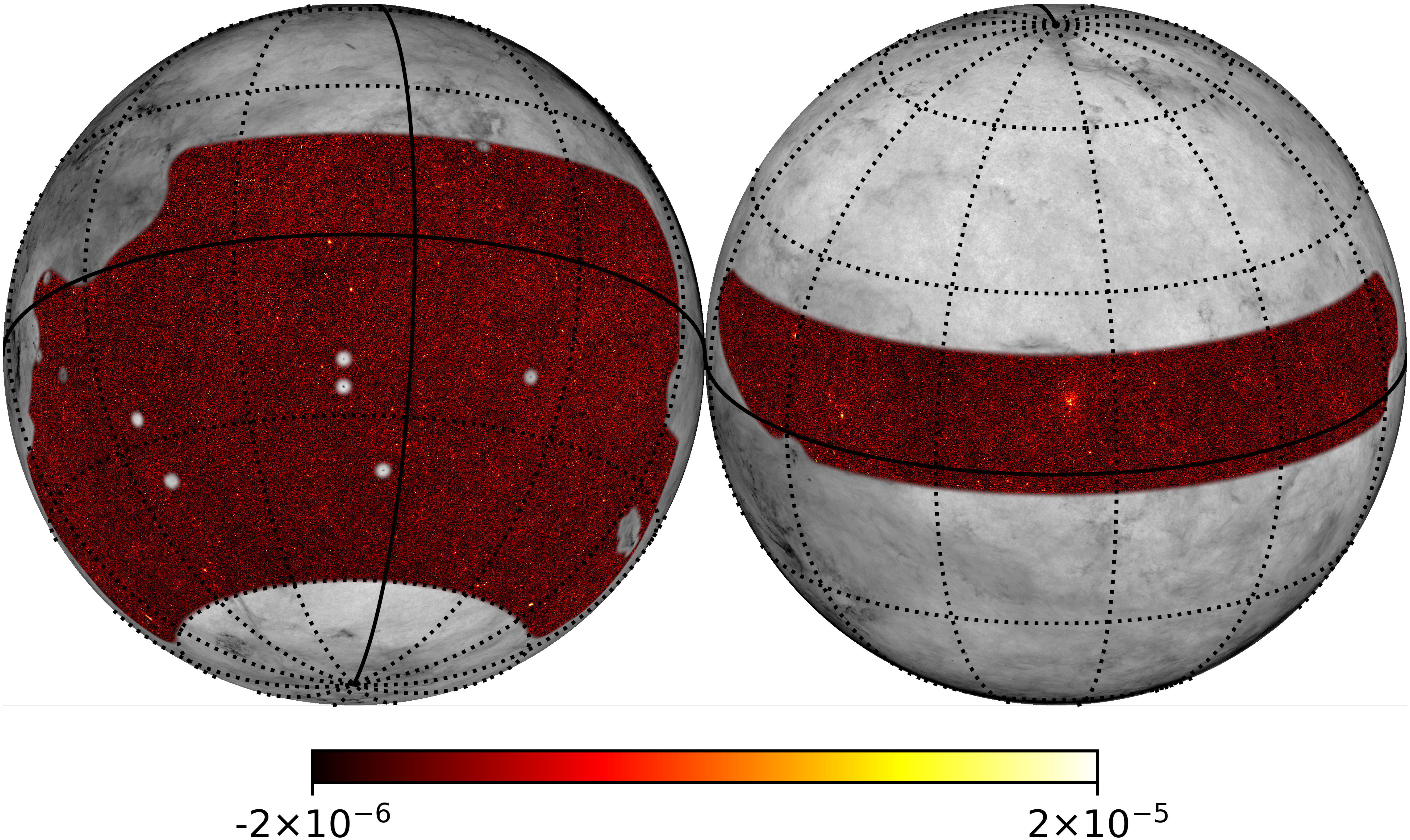
# What does the tSZ effect tell us?

**Extracts from the Magneticum Pathfinder simulations**




**Dolag et al (2016)**

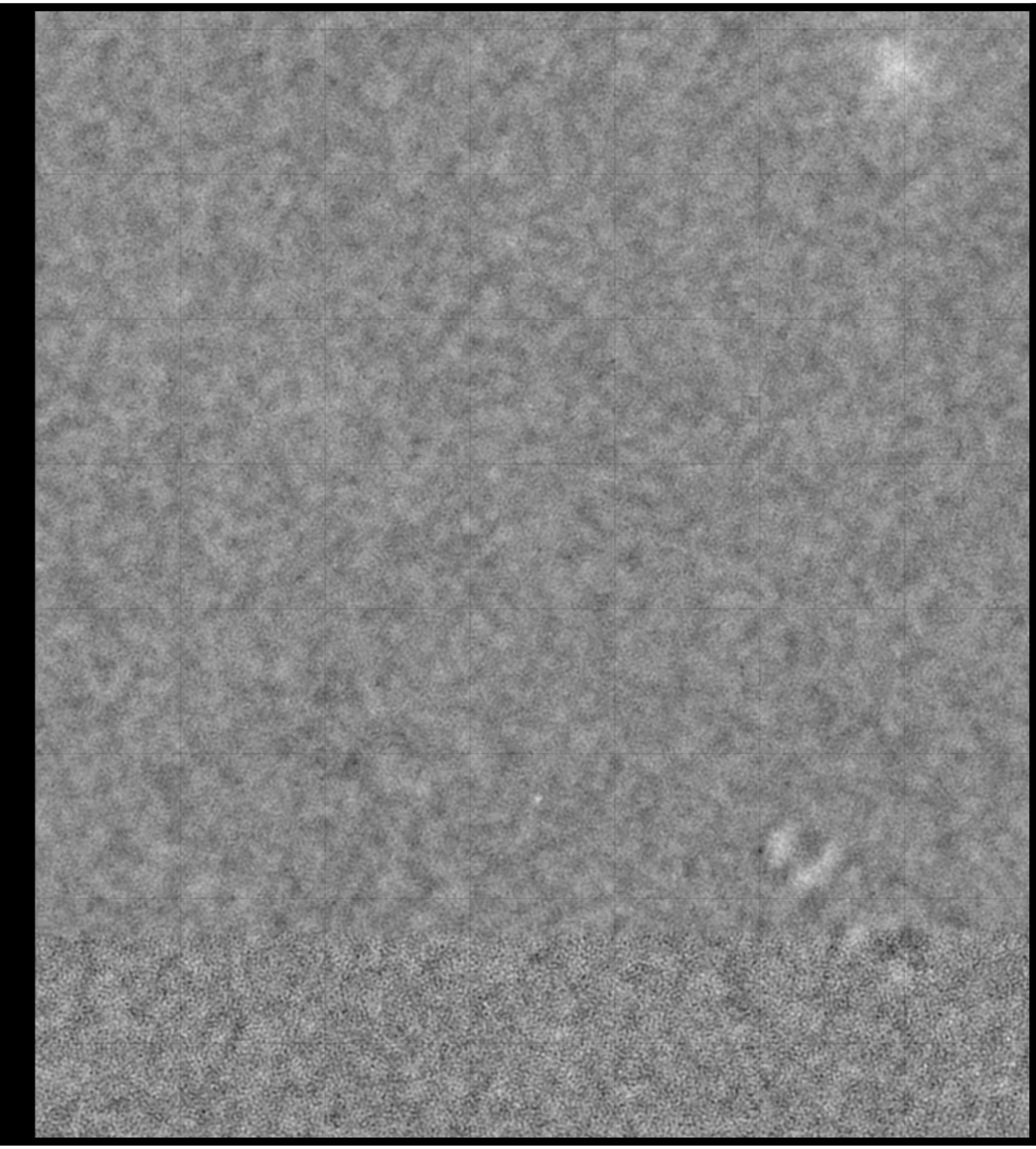
# Our new Compton-y map



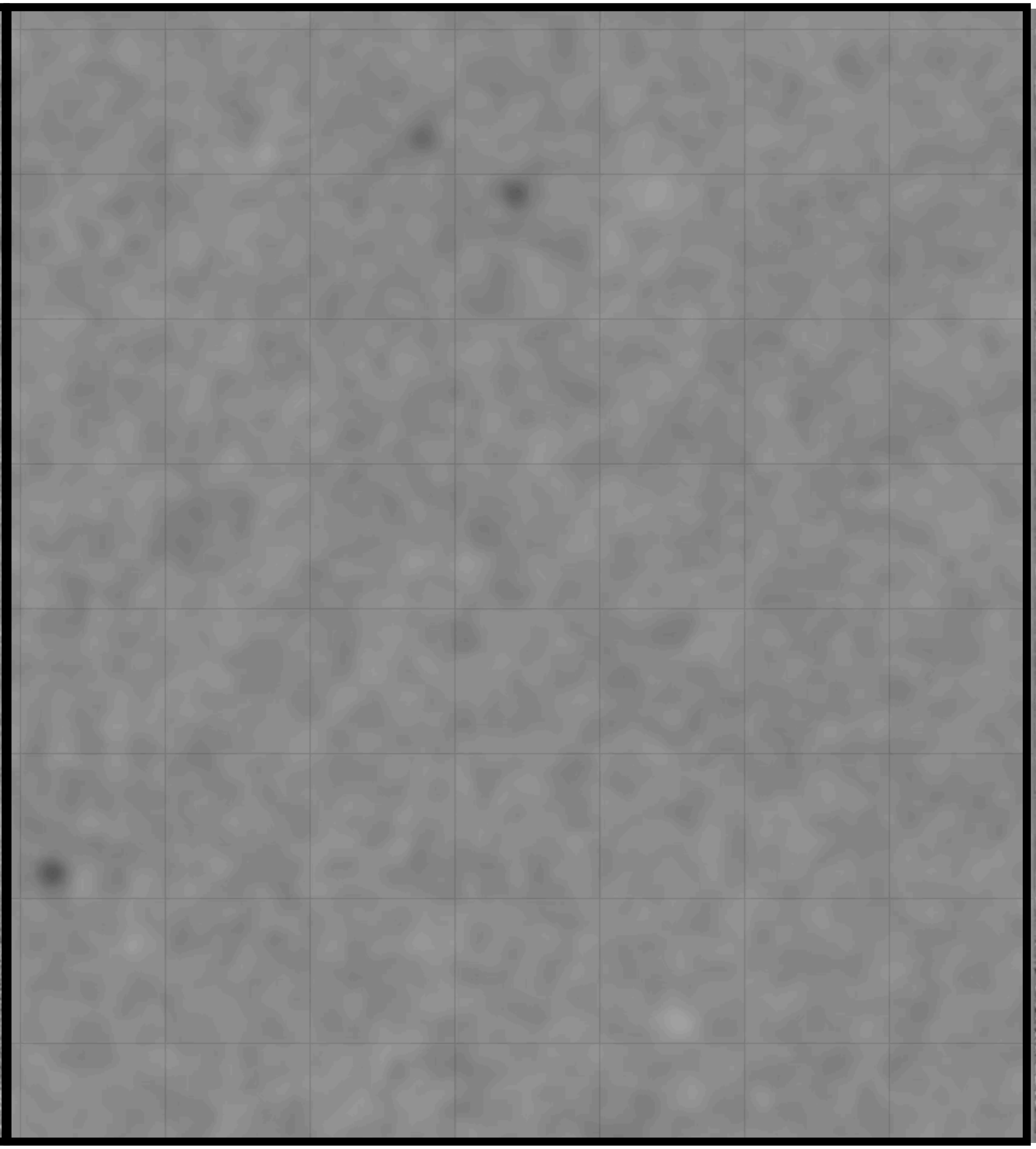

Coulton et al (2023)

# The benefits of high resolution

**ACT & Planck NILC**



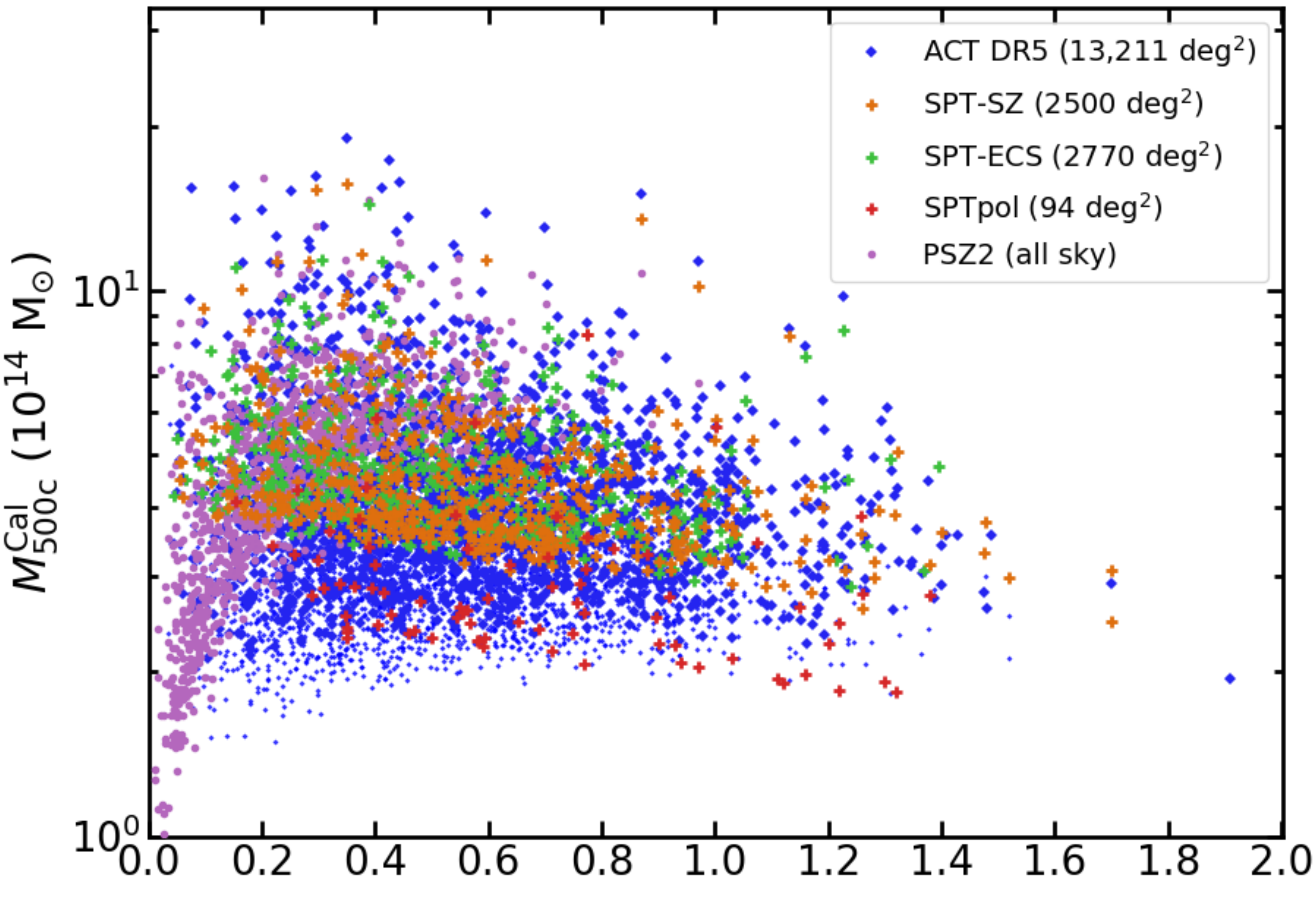
**Planck MILCA map**



# Cluster Count Cosmology!

**ACT DR5 has detected more than >4000 clusters!**

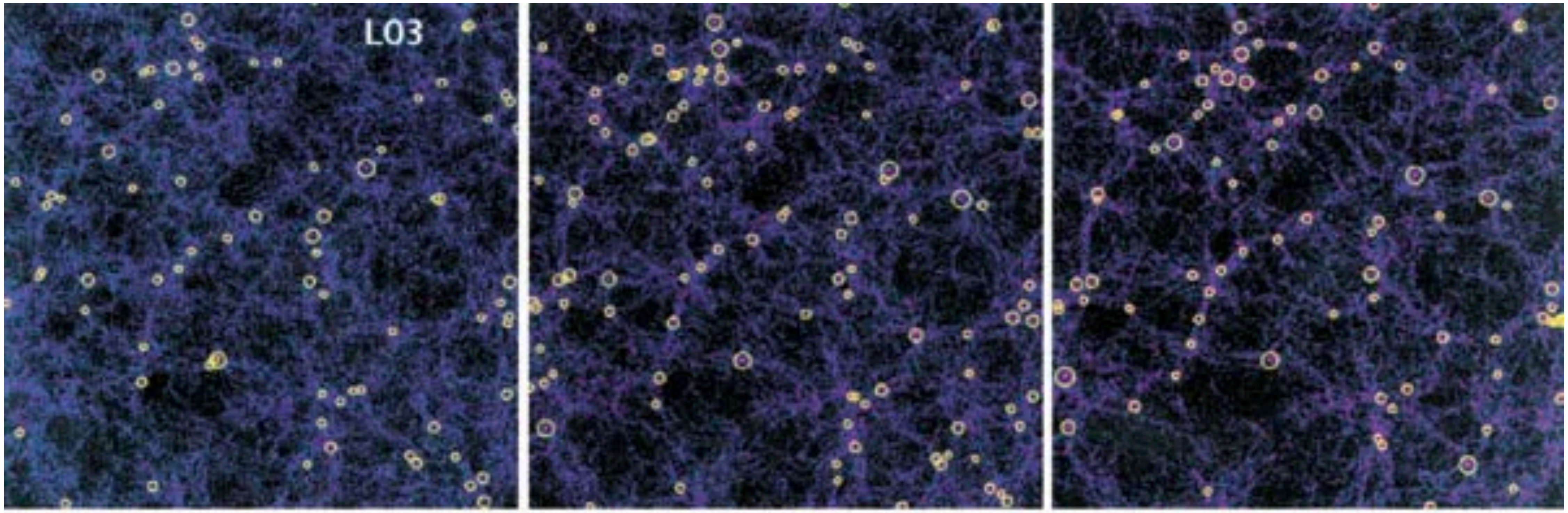
**Led by Matt Hilton**



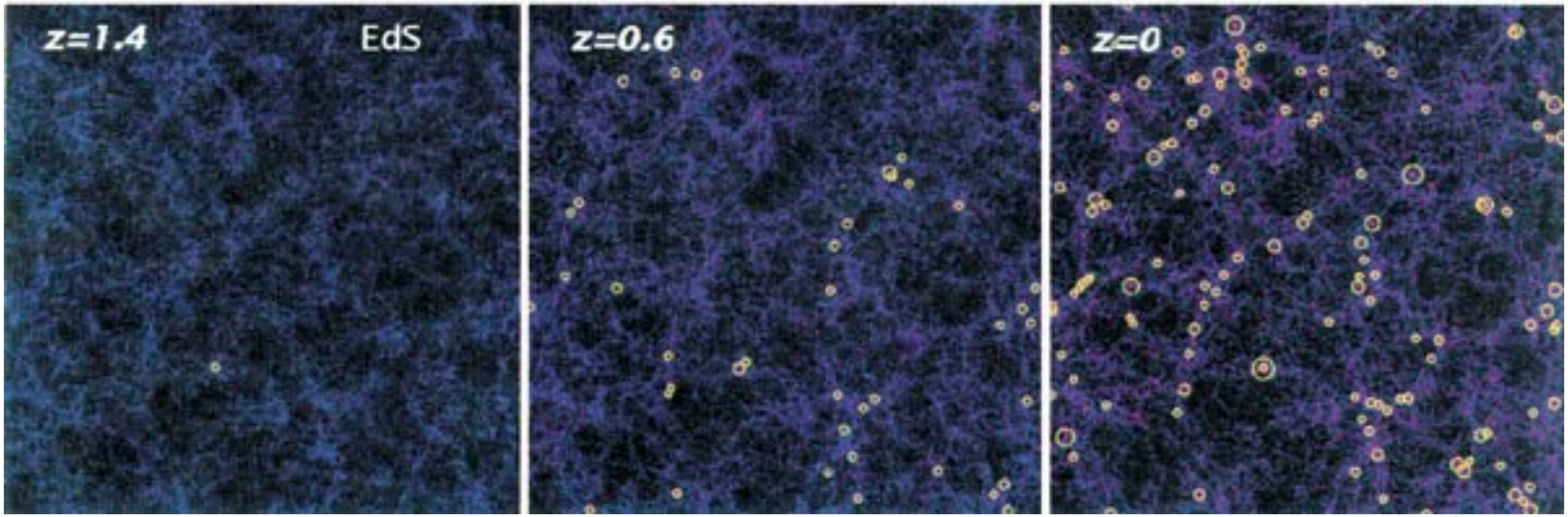

**Hilton et al (2021)**

# The power of cluster cosmology

Simulated Universe with Dark Energy



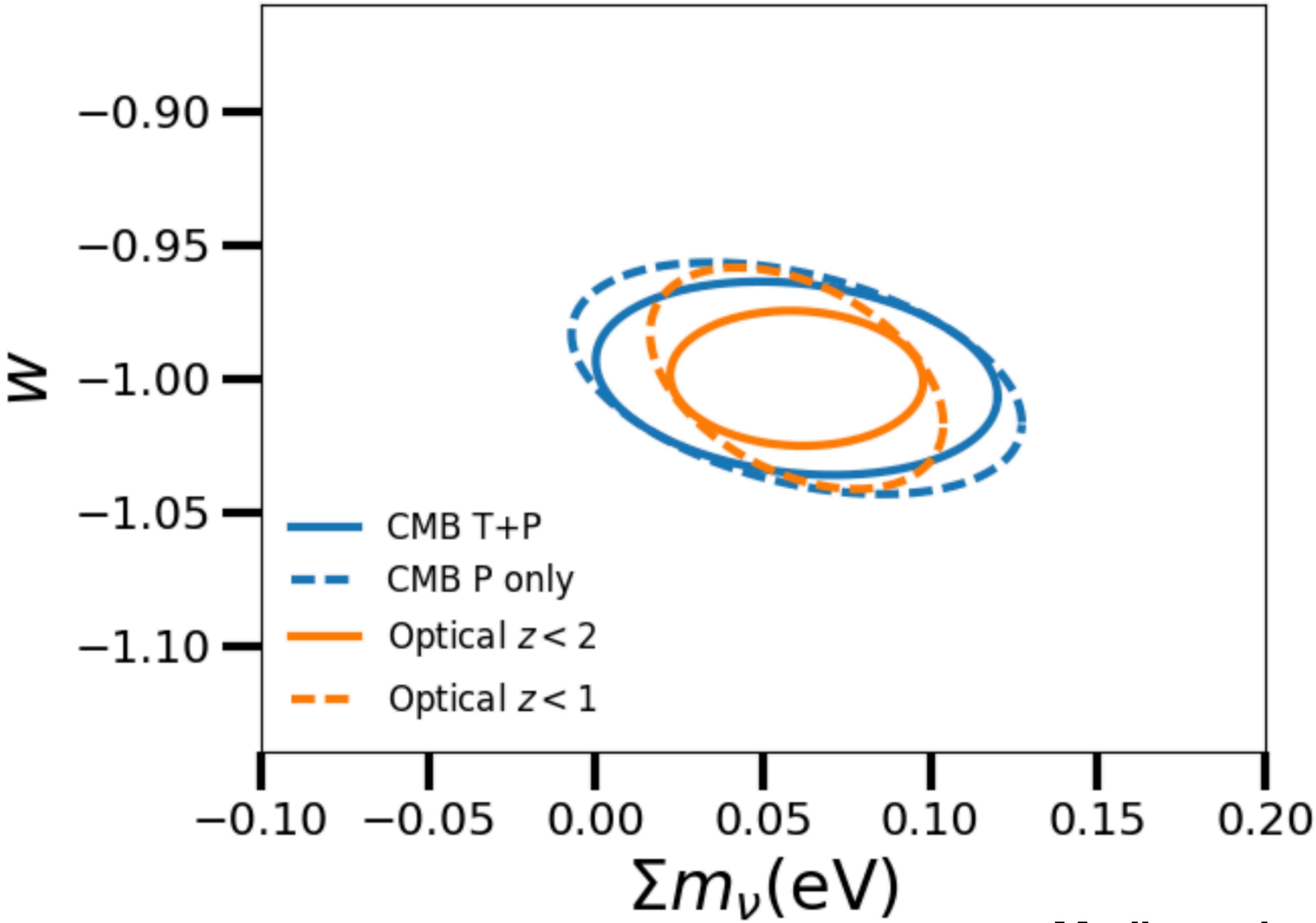

Simulated Universe without Dark Energy




Borgani & Guzzo (2001)

# Fundamental physics from cluster counts

**A forecast of how well we can constrain dark energy and the sum of the masses of neutrinos**

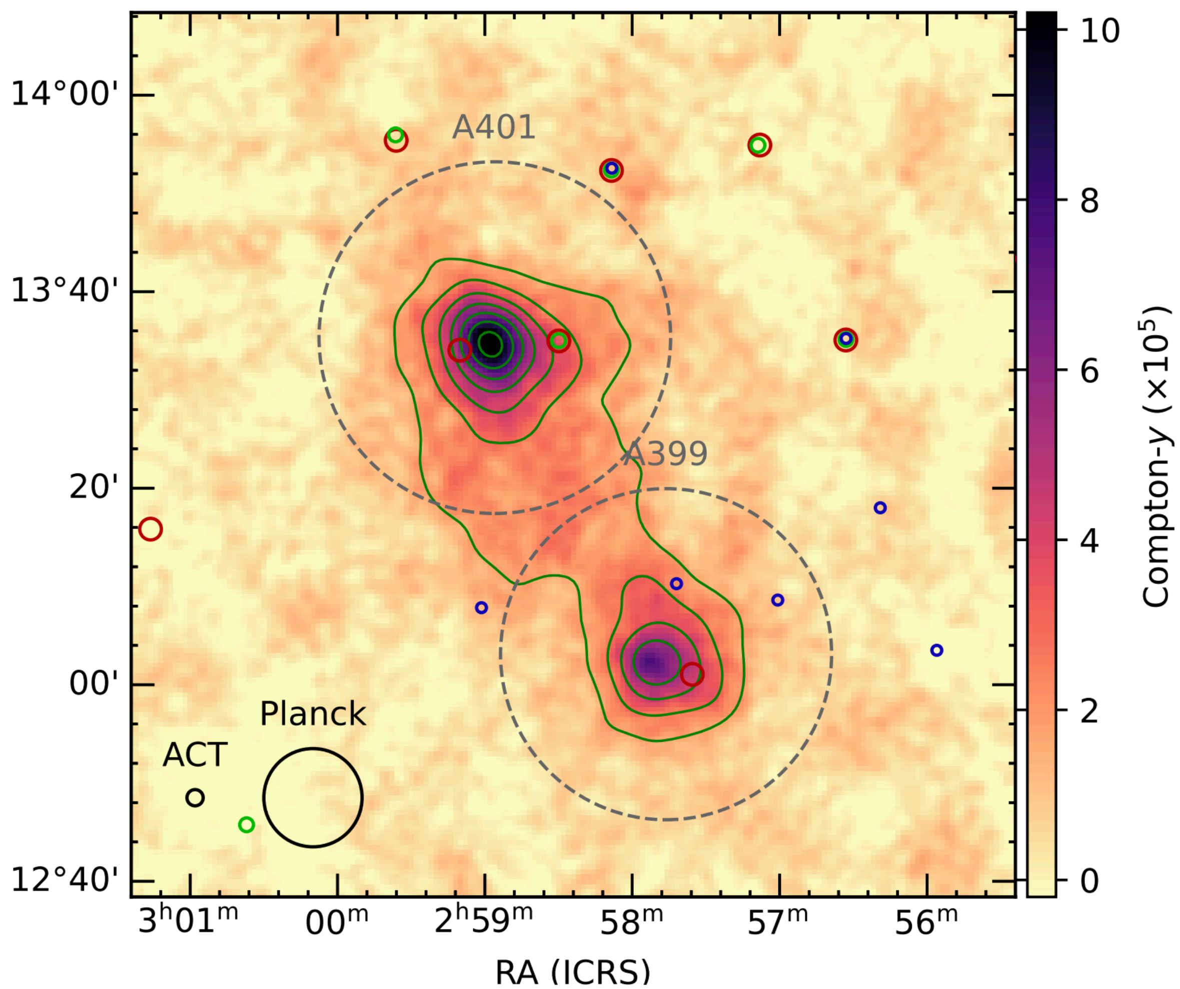



**Madhavacheril et al (2016)**

# Astrophysical Systematics

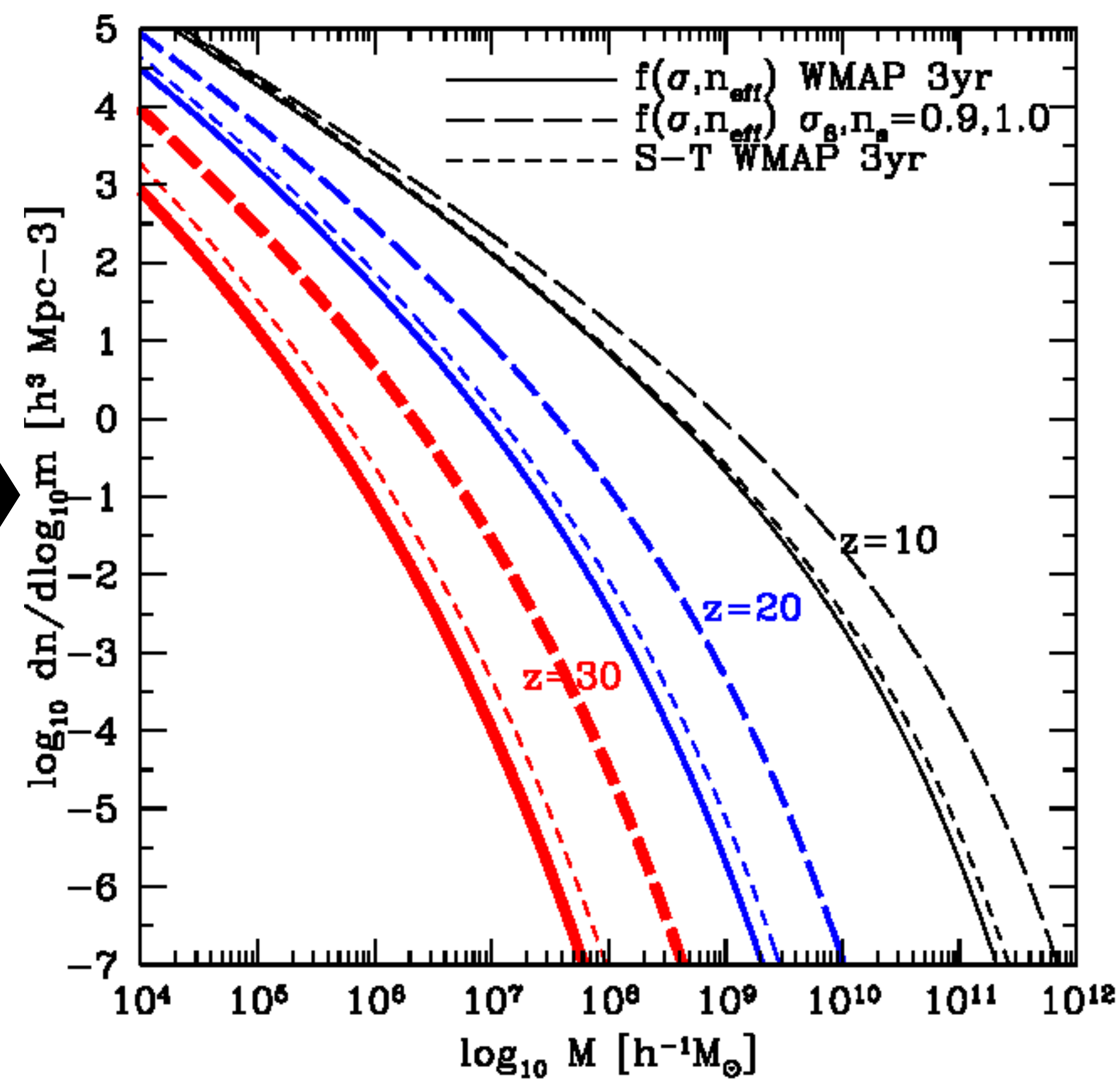
## How to connect the observables to the theory predictions?

**Observed: Integrated Pressure**




???

**Predicted: Counts per mass bin**



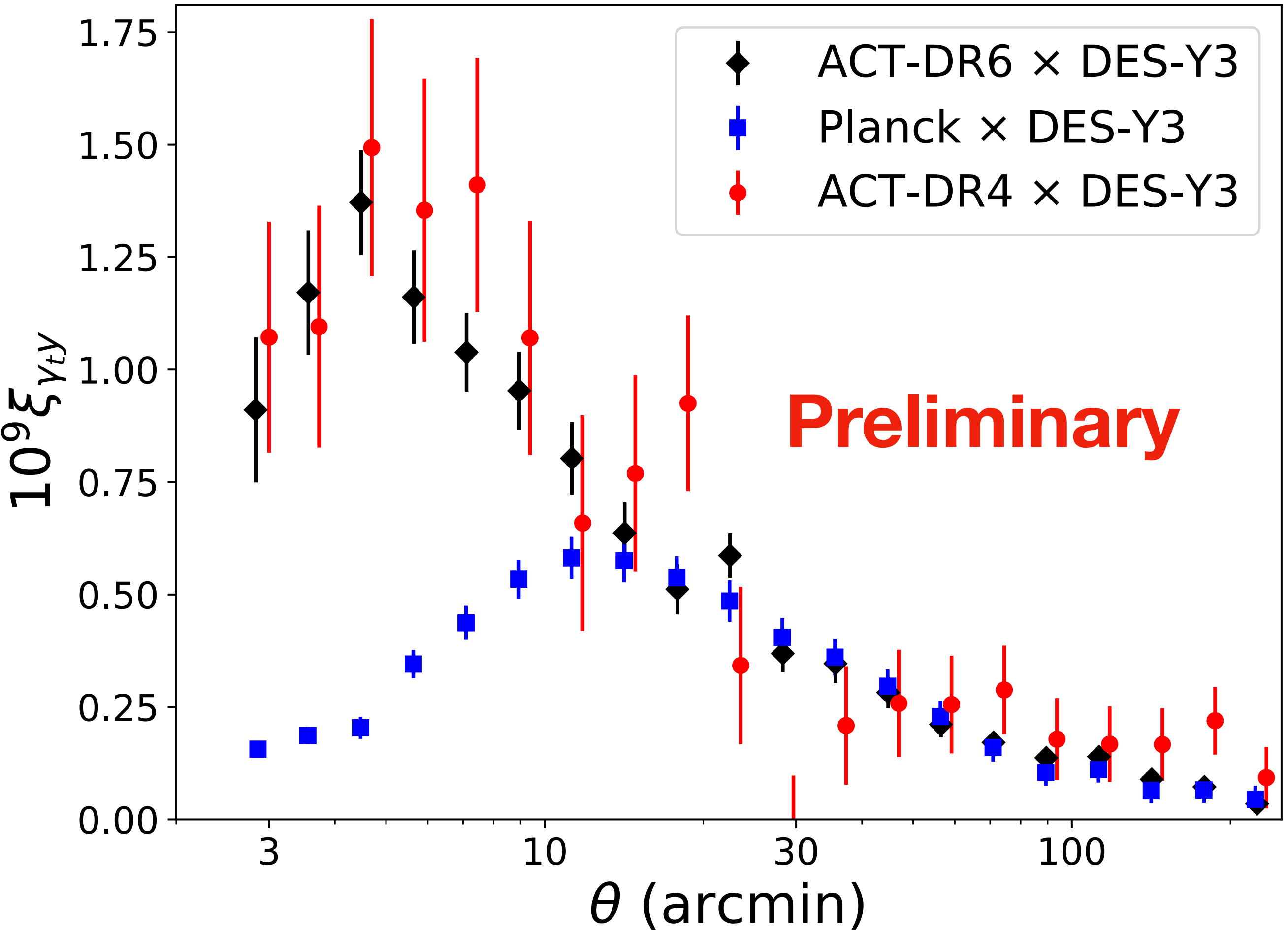

**Reed et al (2006)**

**Hincks et al (2021), Hincks et al inc. WRC (in prep)**

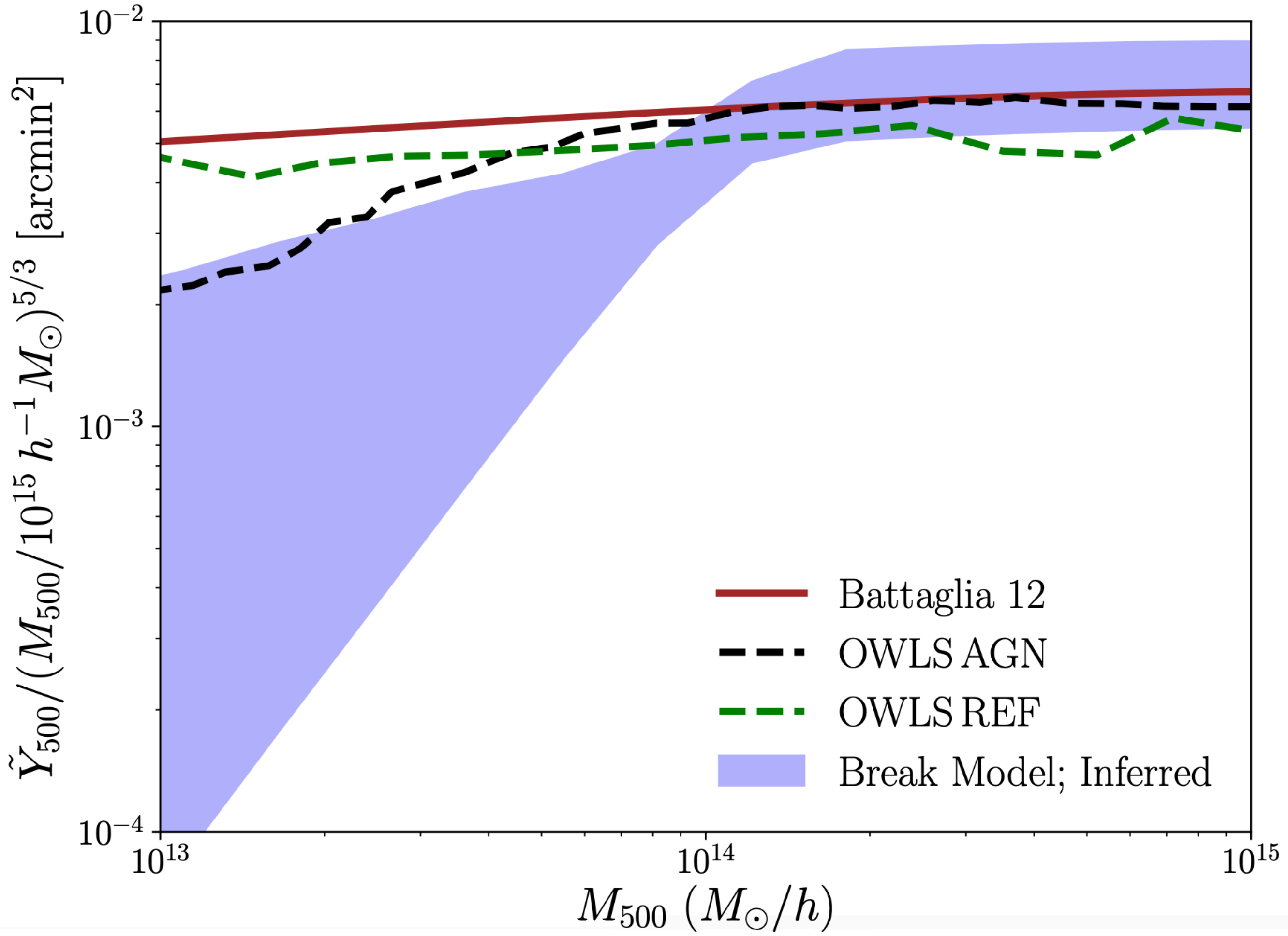
# Revealing the SZ-halo relation!

Led by
Shivam Pandey

The cross correlation between Dark Energy Survey lensing and the ACT Compton-y map



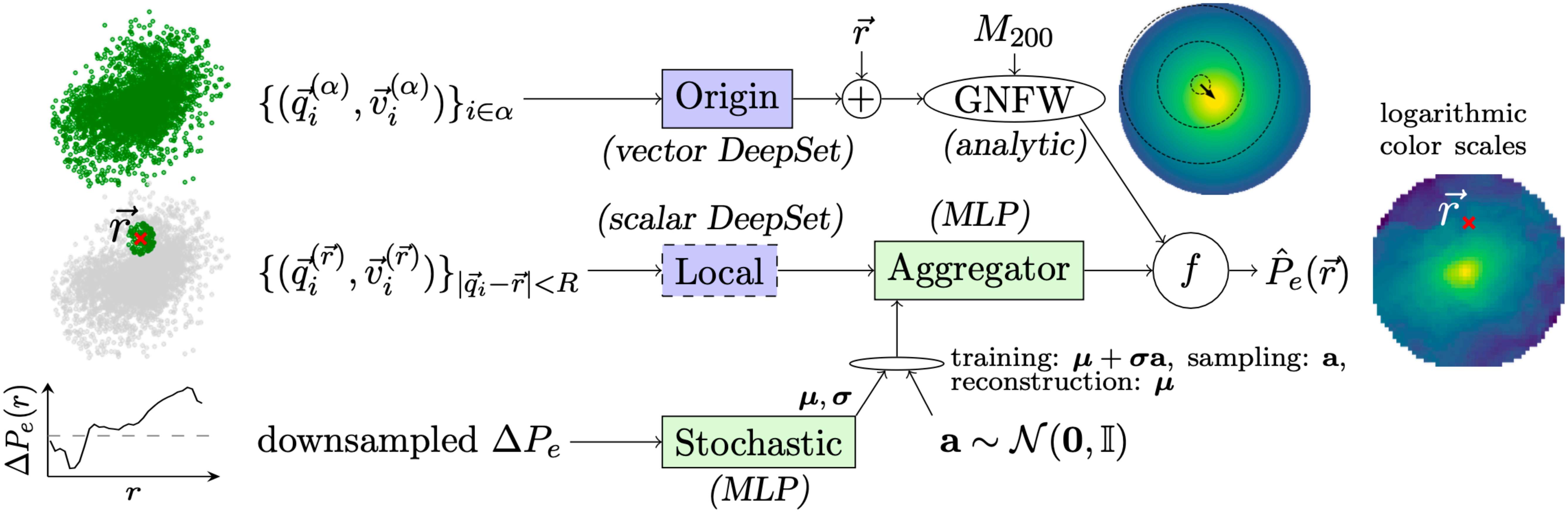

... reveals the impact of AGN feedback on the pressure of galaxy groups and clusters




Gatti et al (2022), Pandey et al (2022), Pandey et al inc. WRC (in prep)

# Connecting observations to physics?

**Led by Leander Thiele**




**Thiele et al inc. WRC (2022)**
**Lee et al inc. WRC (2023)**

# Component two:
# the relativistic Sunyaev Zeldovich effect

# What is the relativistic Sunyaev Zeldovich effect?

- The usual tSZ formula:

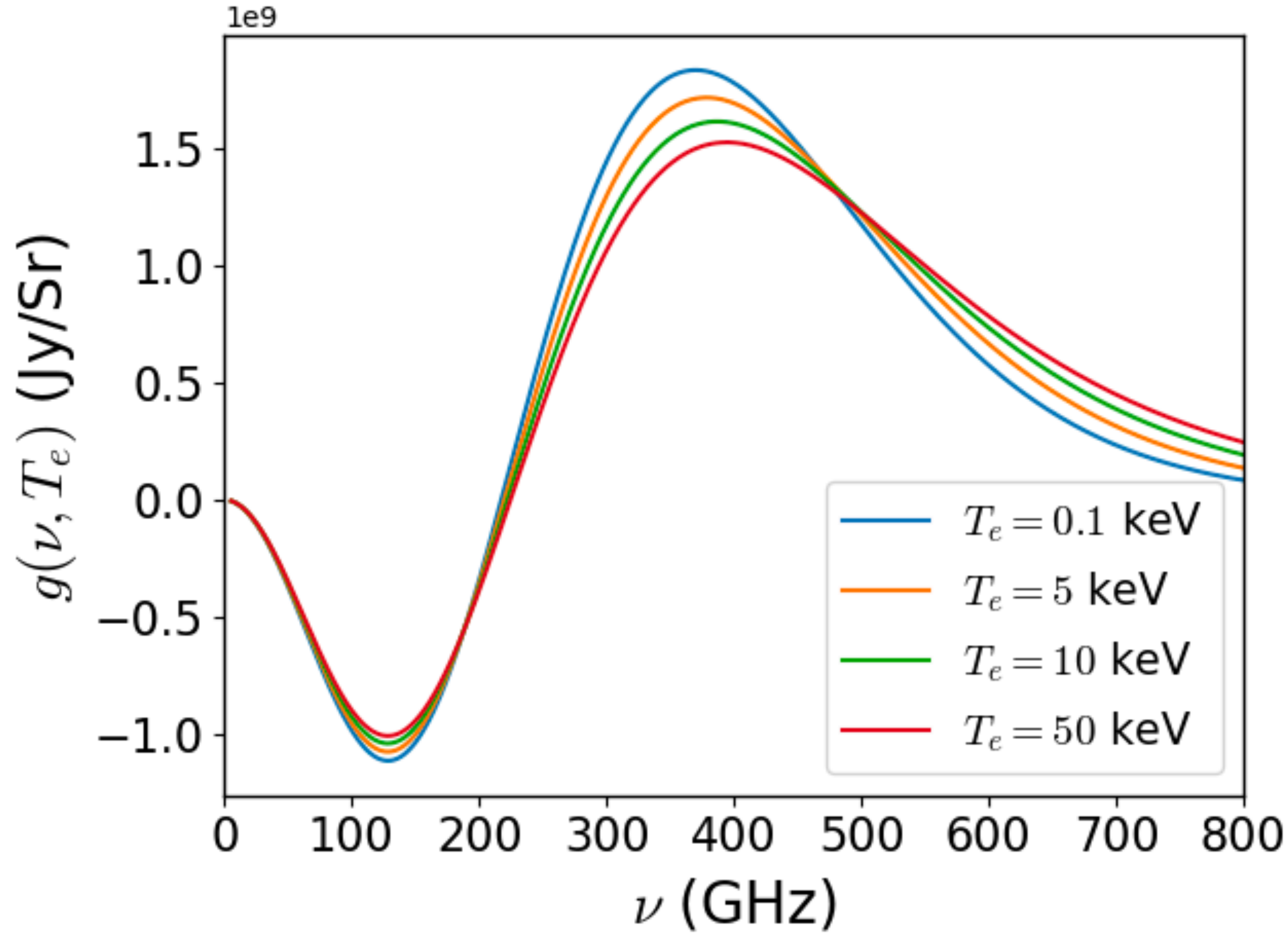
  $$\delta I(\mathbf{n}, \nu) = g(\nu) y(\mathbf{n})$$

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

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

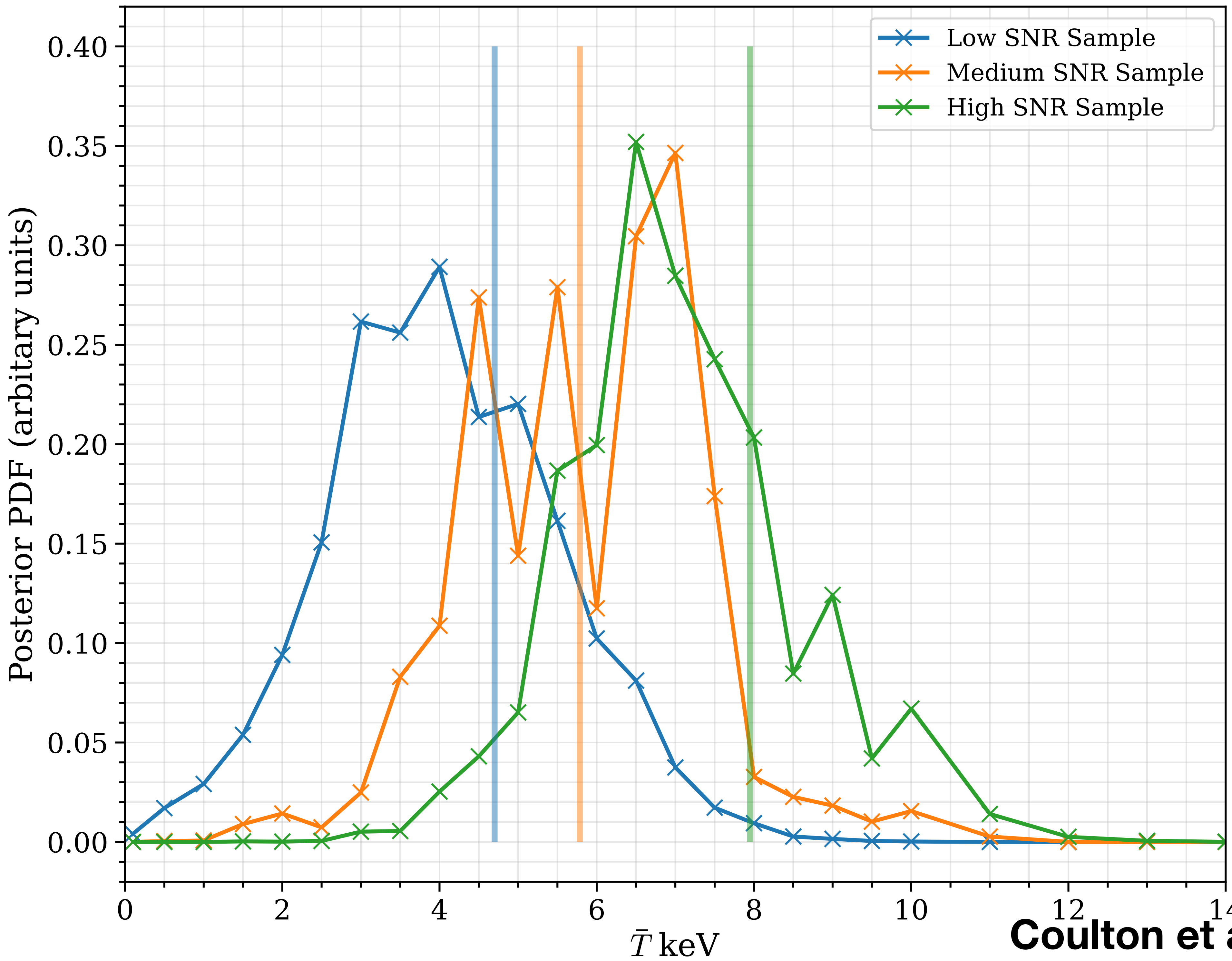
- For relativistic electrons: $\delta I(\mathbf{n}, \nu, T_e) = g(\nu, T_e) y(\mathbf{n})$!

**Relativistic SZ signature for electrons at different temperatures**



# What can we use it for?

**Measure mean cluster temperature (on simulations)!**




**Coulton et al (in prep.)**

# Coupling of different systematics

Relative gain uncertainties

Beam shape uncertainties

Polarization angle uncertainties

Beam frequency dependence uncertainties

Astrophysical contaminant uncertainties

Passband uncertainties

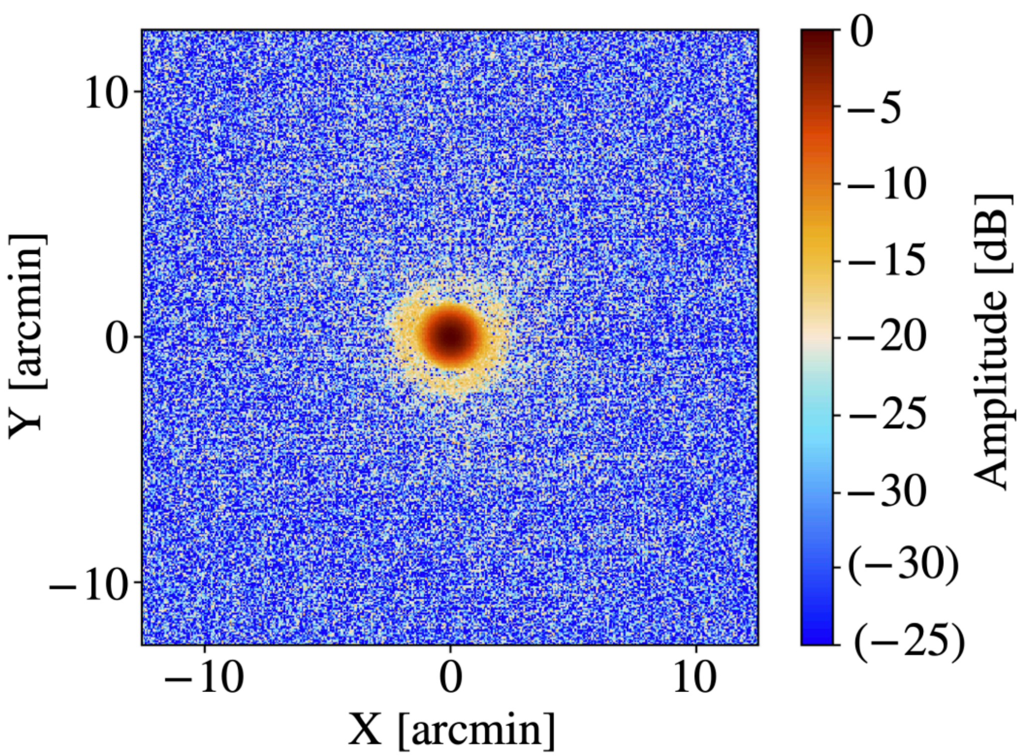
**Led by:**
**Adri Duivenvoorden**
**Tommy Alford**
**and Matthew Hasselfield**

# Into the weeds

**"Ideal beam"** $B(\theta)$

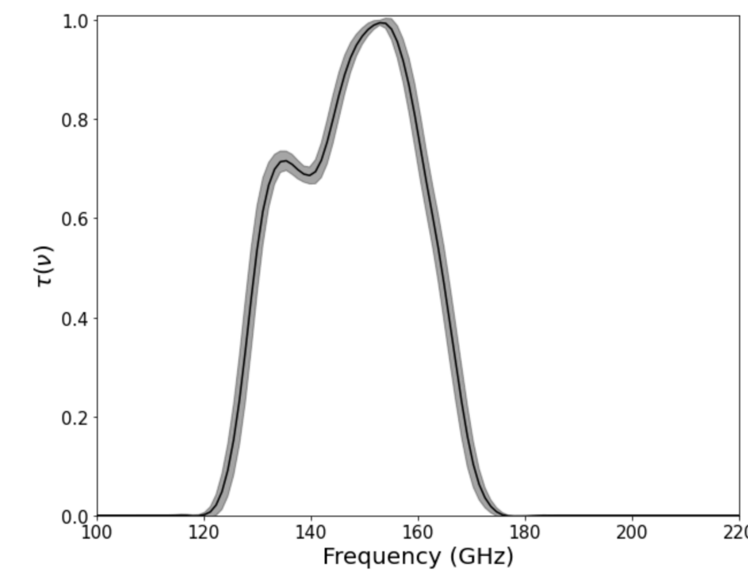
**Beam Freq. Dep.** $\mathrm{FHWM} \propto \lambda$

**The "effective beam"**

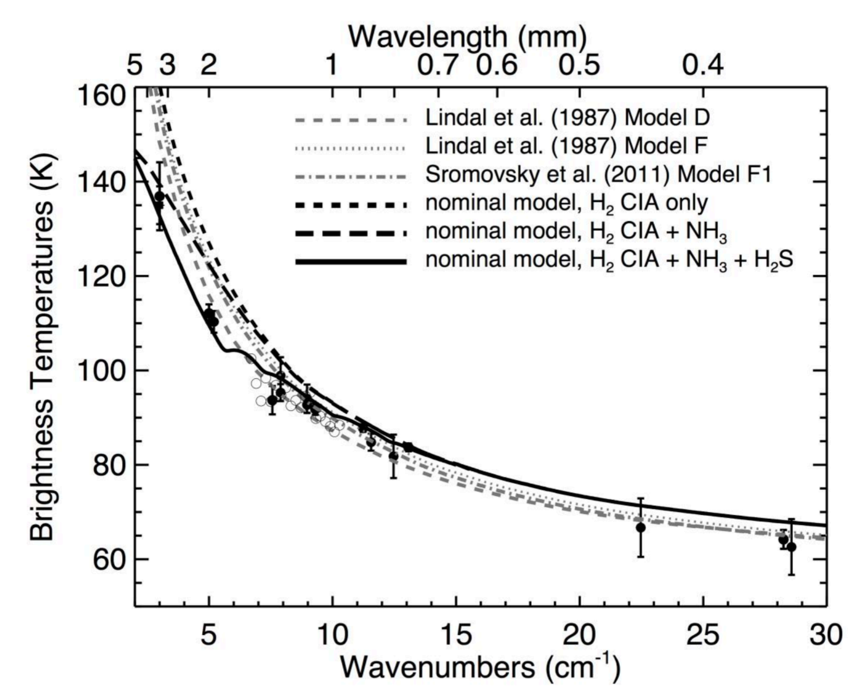



**Lungu et al (2021), Alford et al (in prep.)**

**Instrument Passband**




**Signal Spectrum**



# Component three:
# Gravitational lensing of the CMB

# Gravitational Lensing

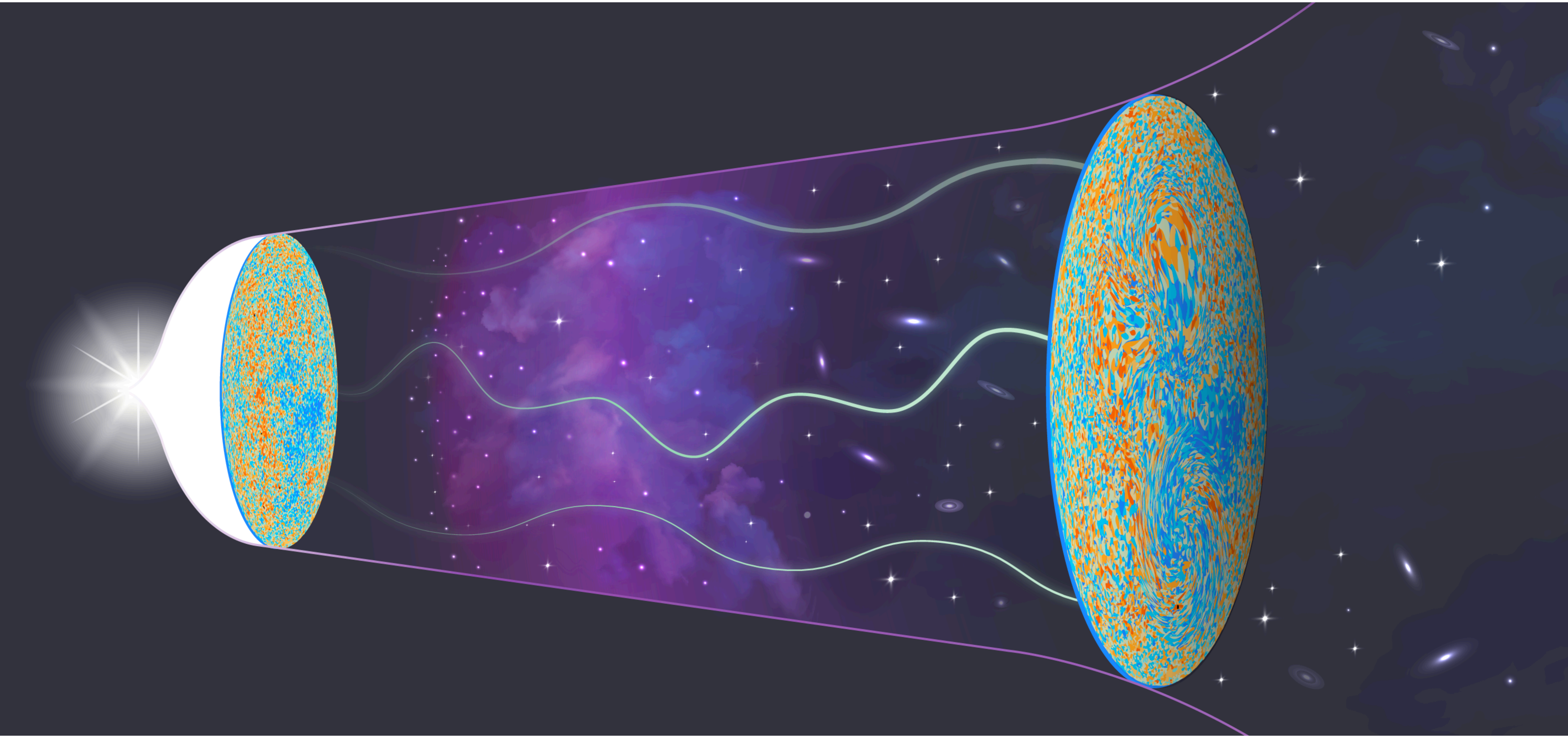
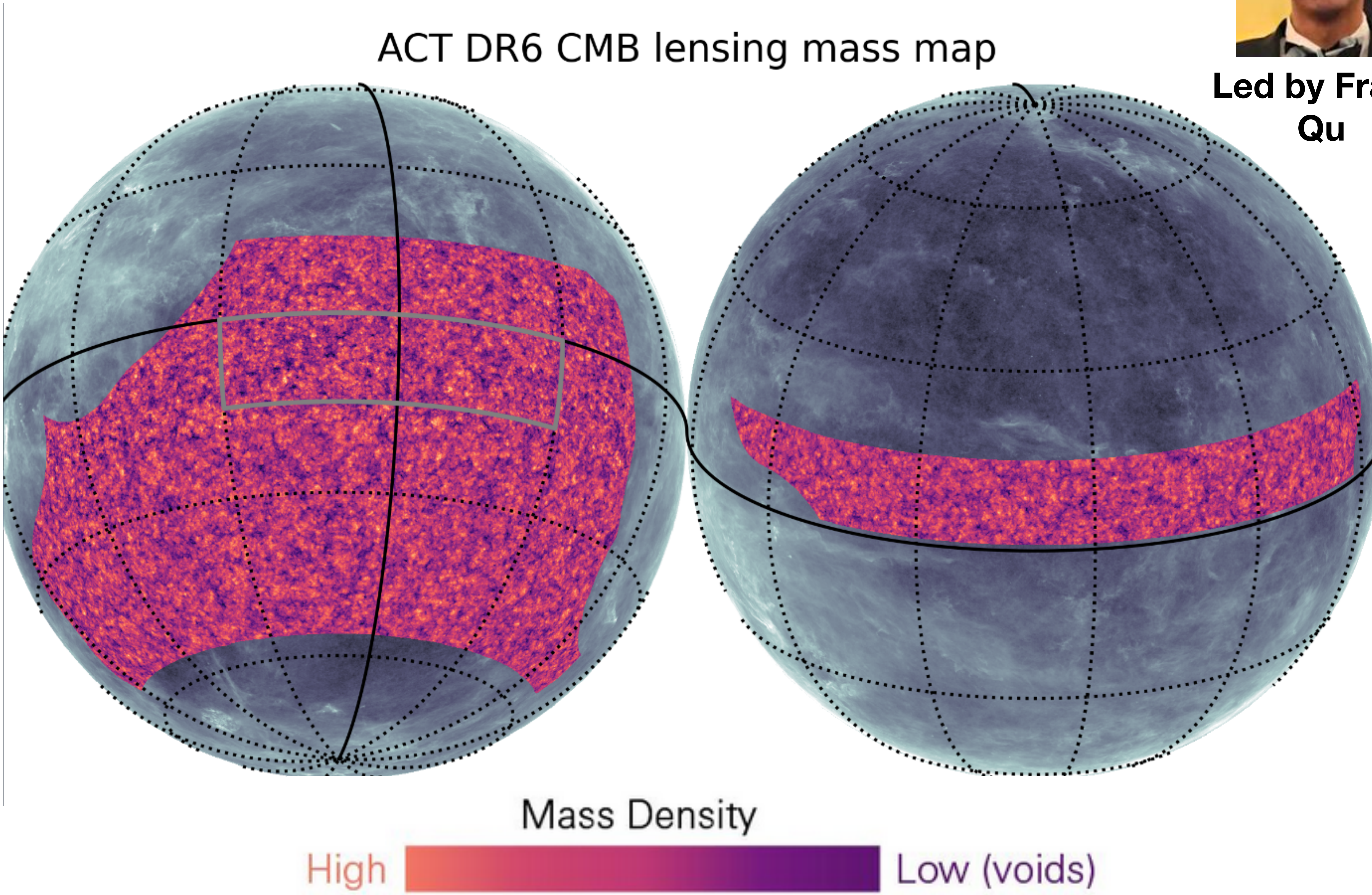


Image by: Lucy Reading-Ikkanda/Simons Foundation

# ACT lensing map

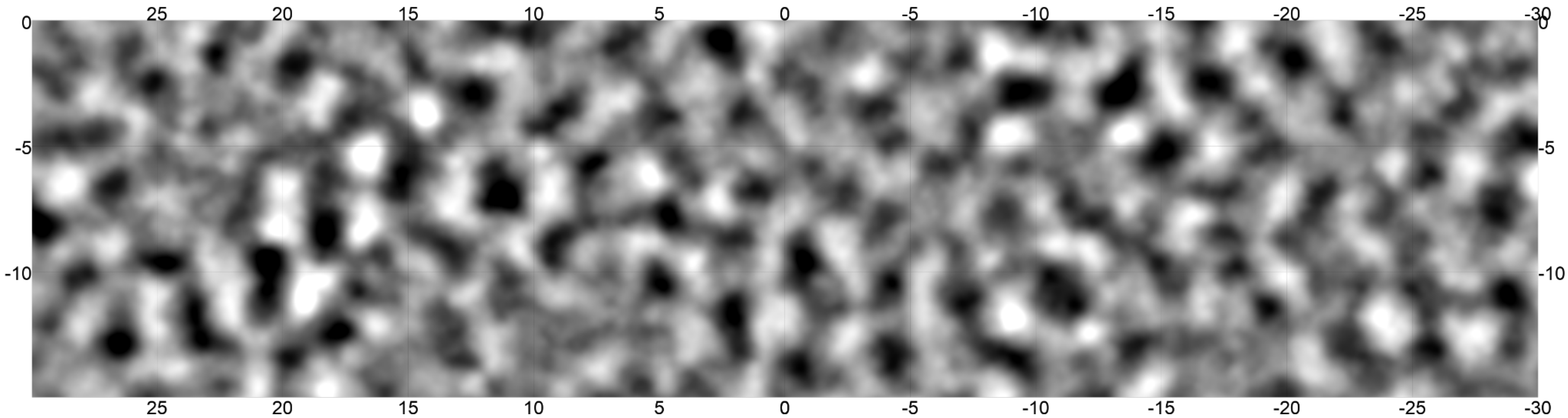
Led by Frank Qu




Qu et al inc. WRC (2023)

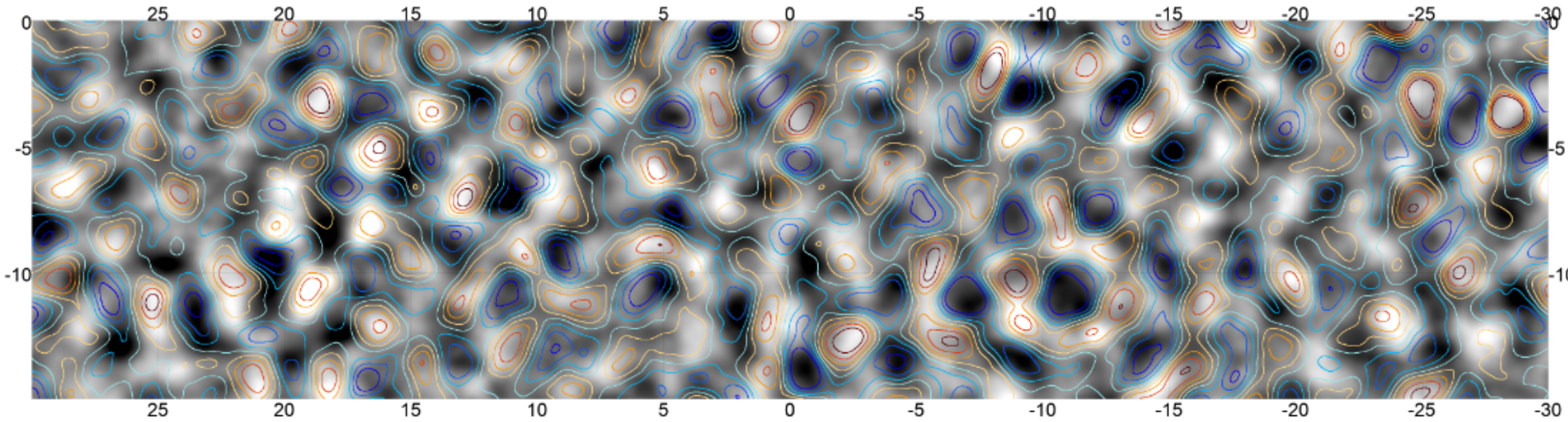
# Correlation by Eye!

Zoom-in of 900 sq. deg. of 9400. sq. deg. mass map



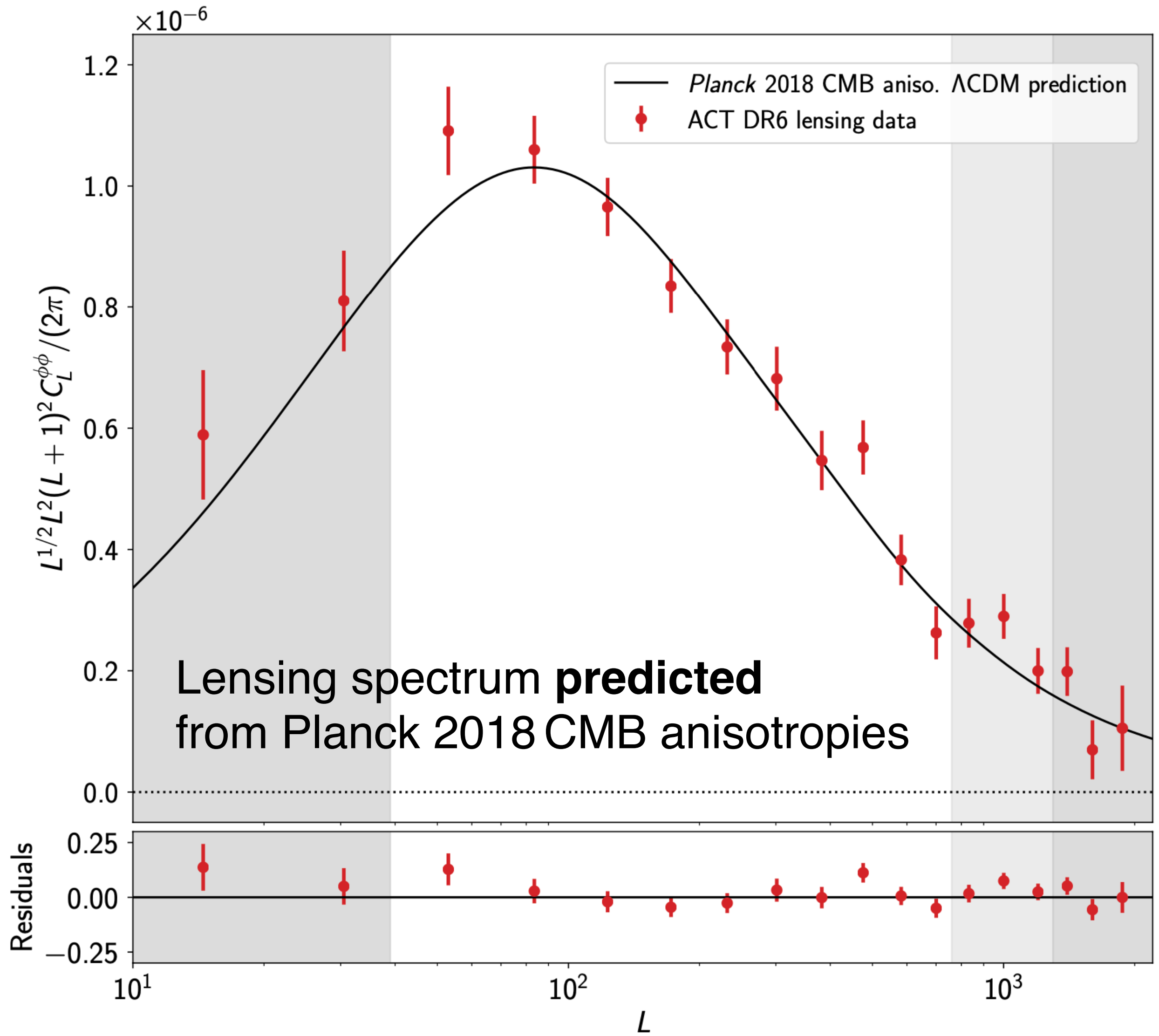
# Correlation by Eye!

Zoom-in of 900 sq. deg. of 9400. sq. deg. mass map with cosmic infrared background overlaid

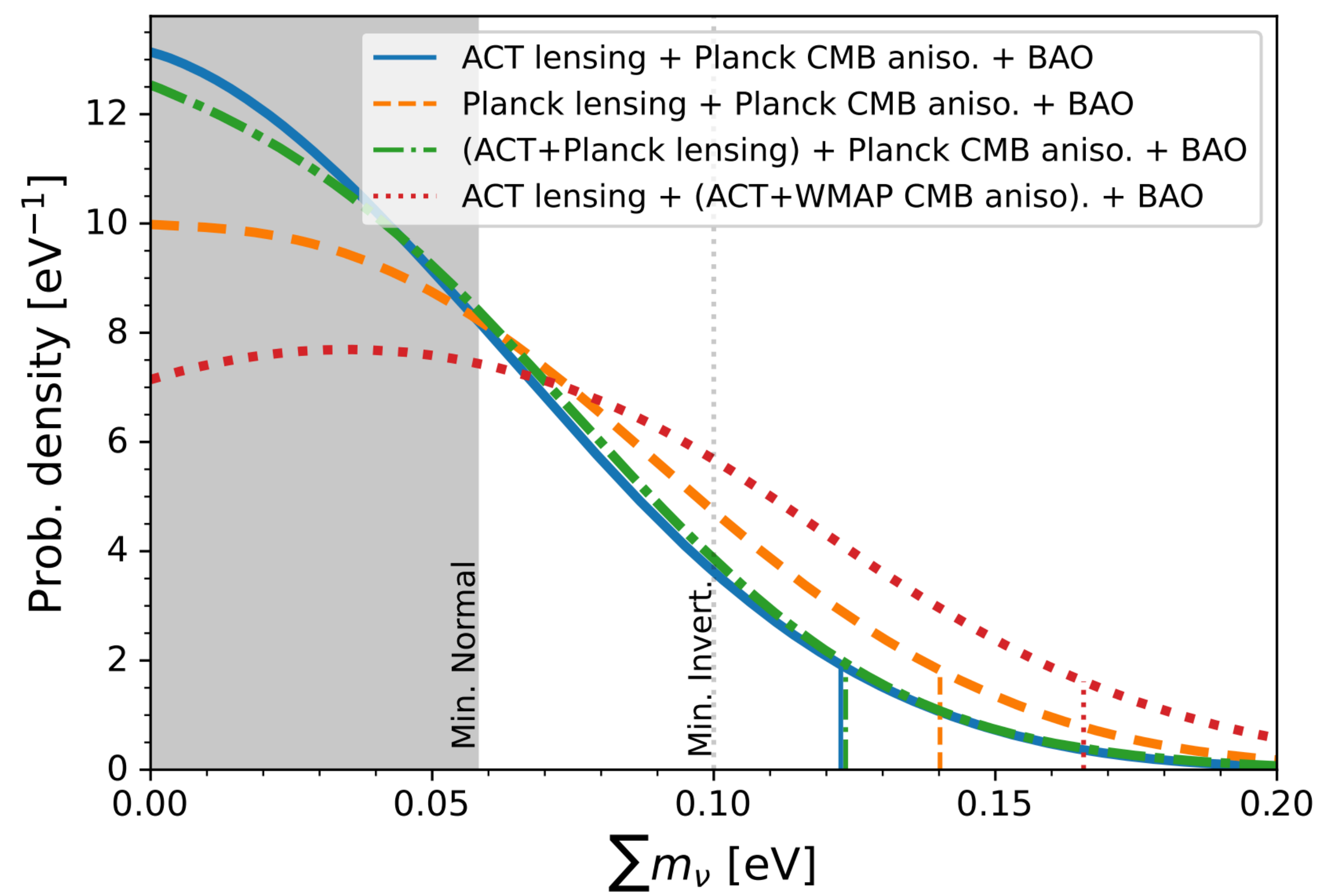


# Weighing in on $\sigma_8$

**Convergence Power spectrum**




**Cosmological Constraints**

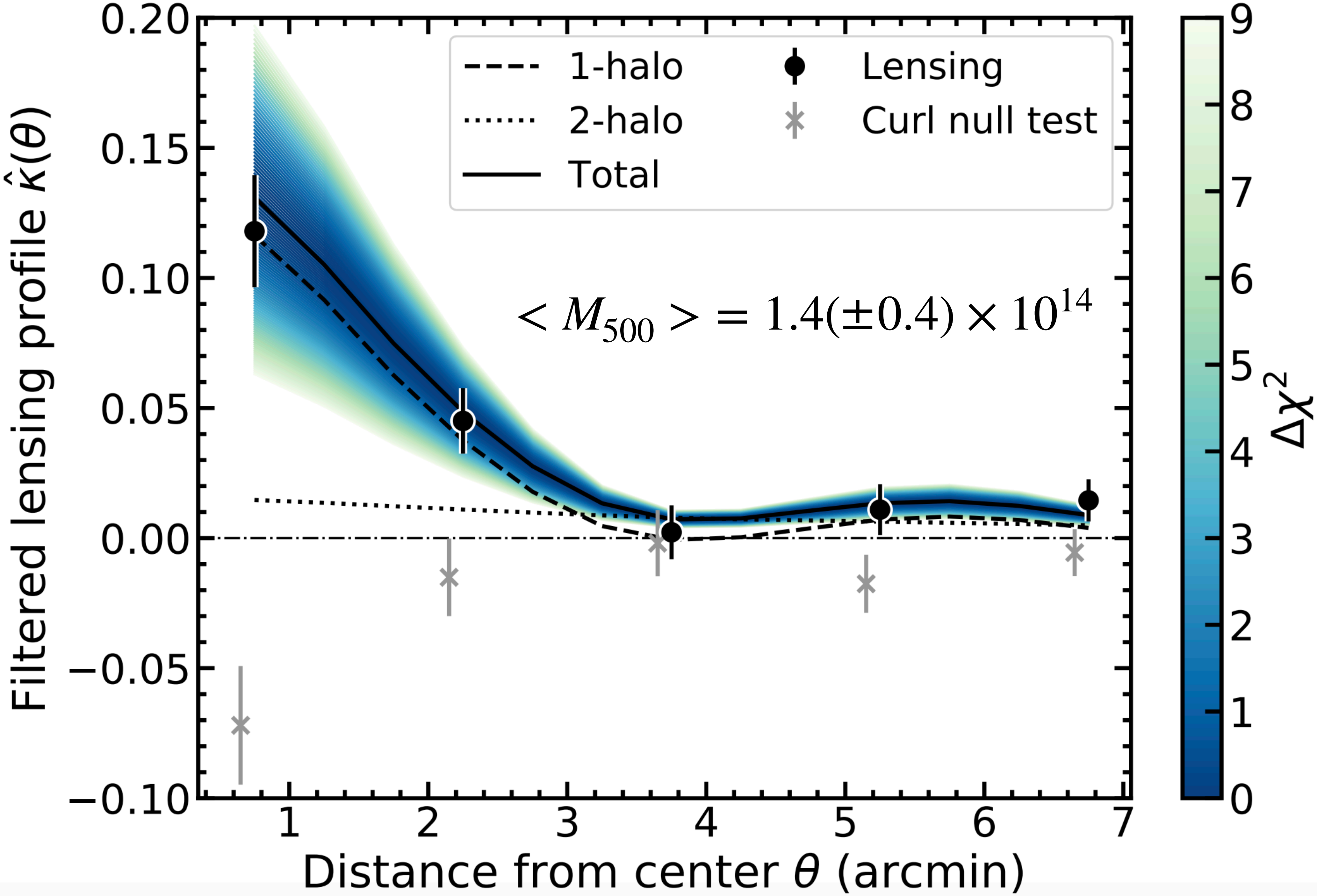



**See Farren et al (2023) for new lensing cross unWISE!**

**Madhavacheril et al inc. WRC (2023)**

# Weighing clusters

**Lensing profiles around the MaDCoWs Clusters at $z \approx 1$**




**Madhavacheril et al (2020) Lee et al including WRC (in prep.)**

# Component four:
# the patchy-screening effect

# What is the patchy-screening effect?

**A schematic of the patchy screening effect**

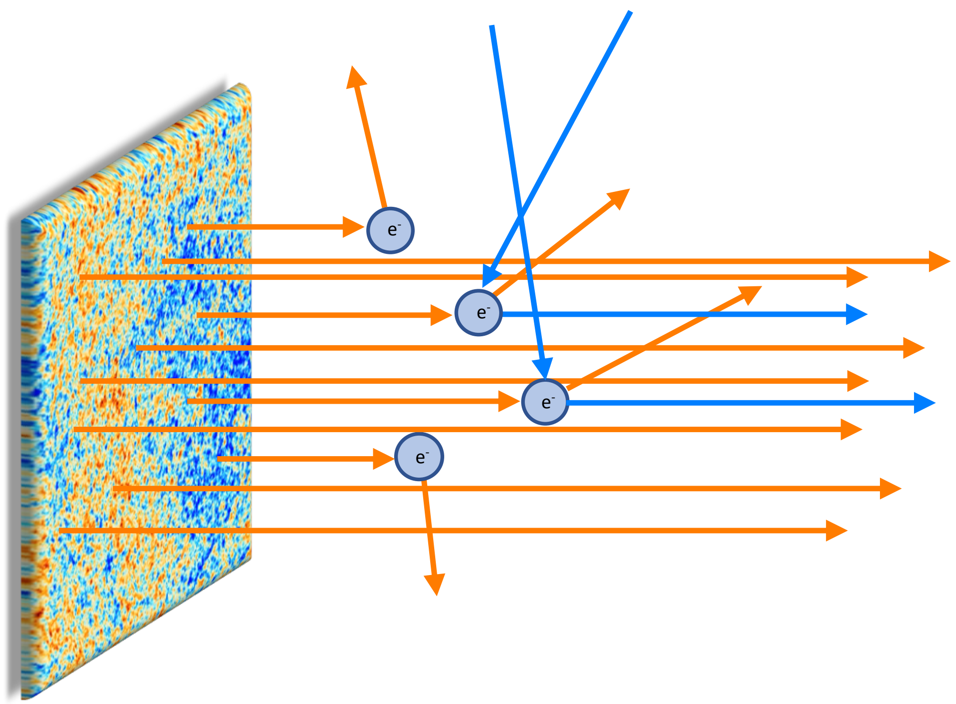
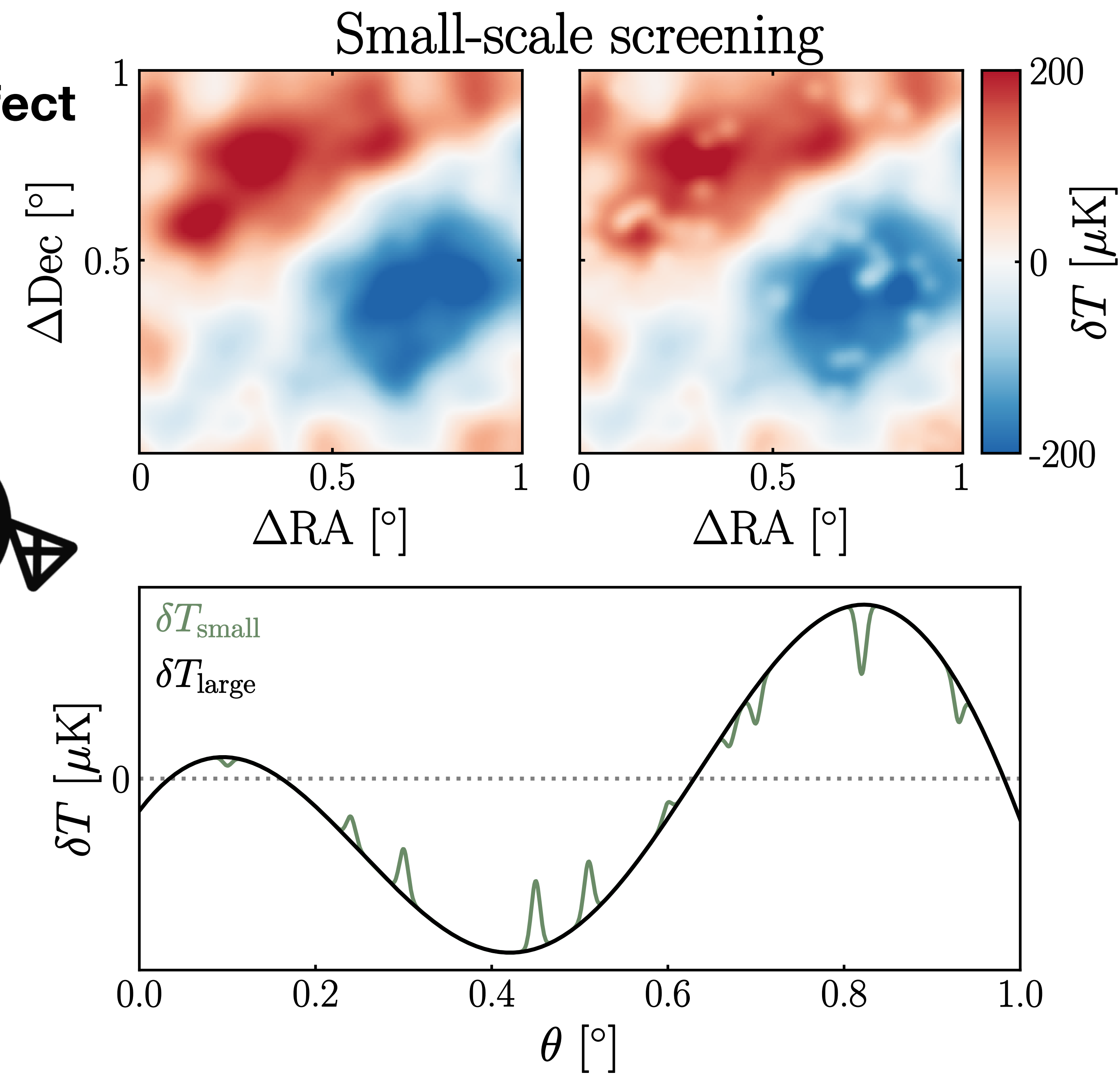


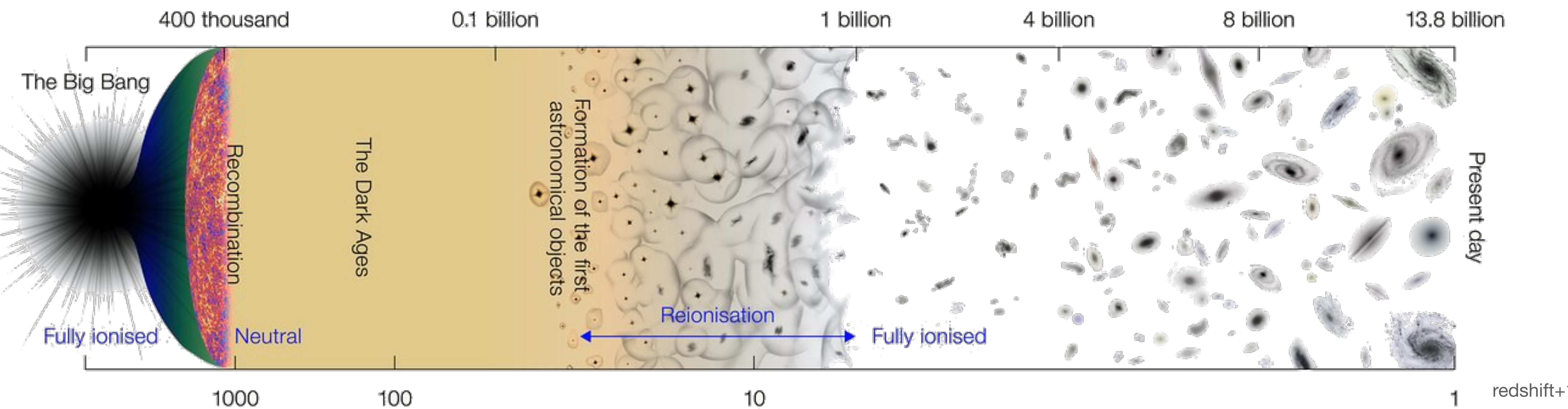

**Image by Alex Van Engelen**




**Schutt et al including WRC (2024)**

# When is the patchy-screening effect generated?

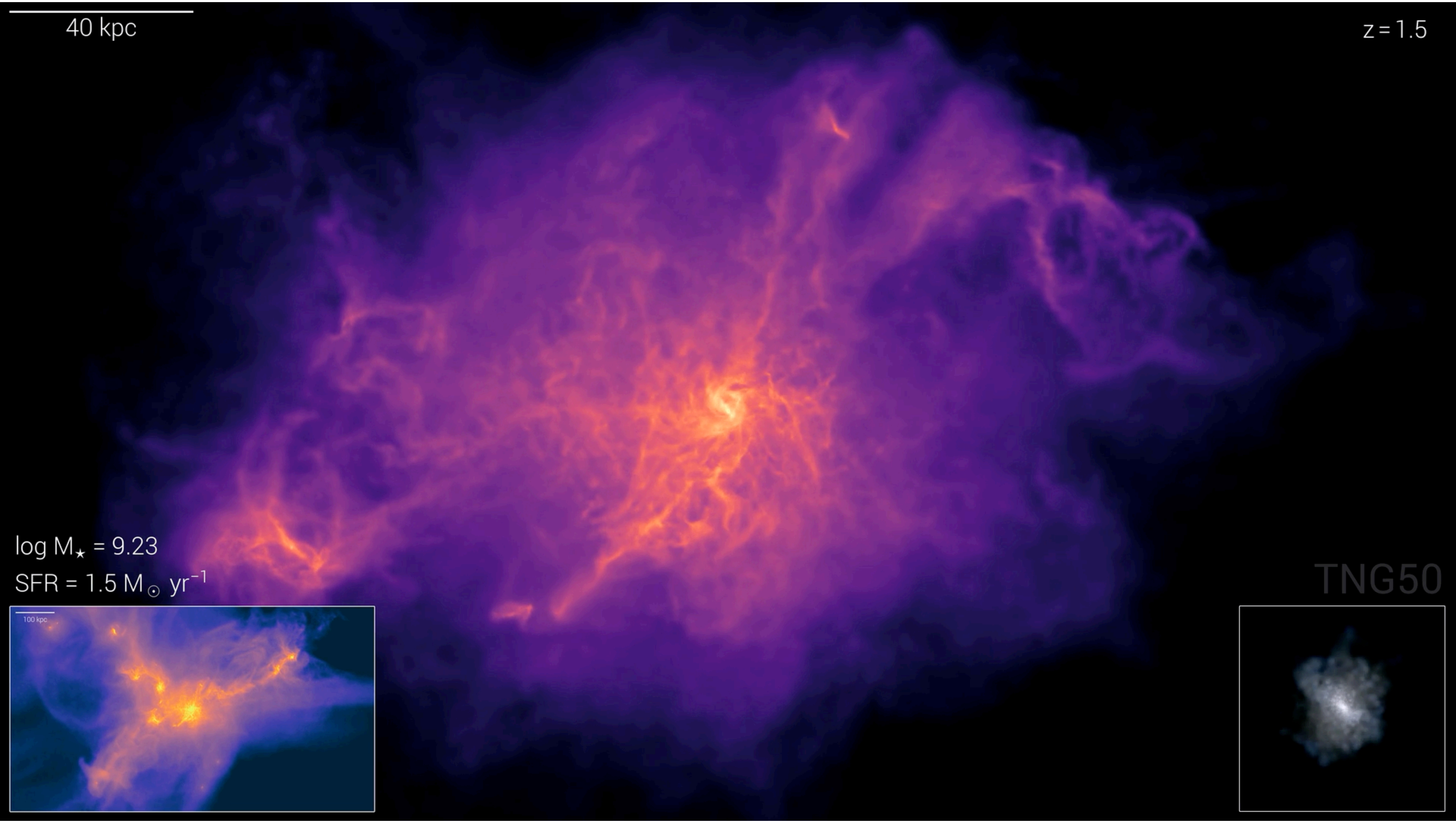
**O(1) fluctuations in free electron fraction at reionization**




**Large fluctuations in electron density around collapsed objects**

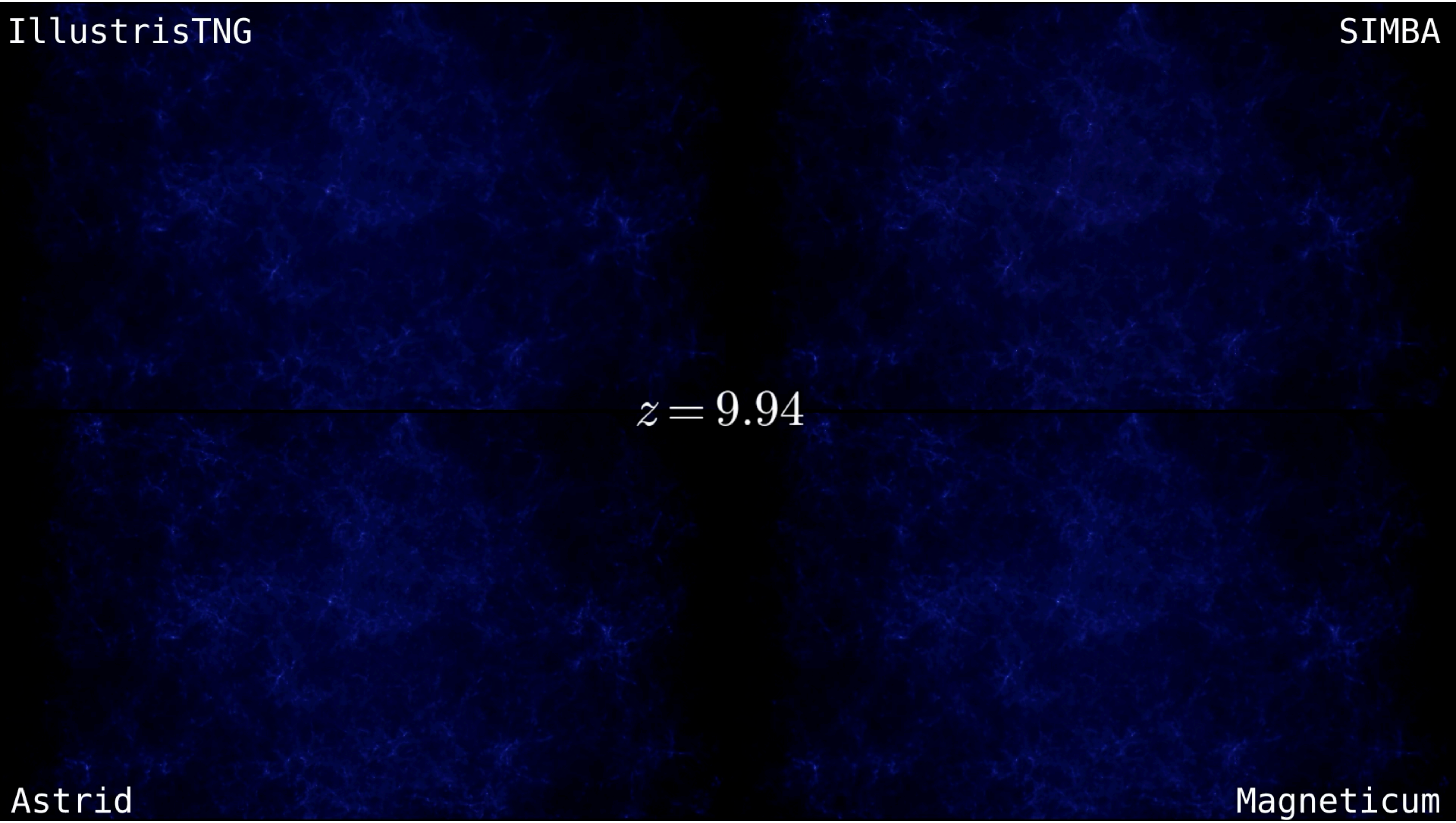
**Credit: ESO**

# The success of cosmological simulations




**Credit: IllustrisTNG collaboration**

# The challenges...

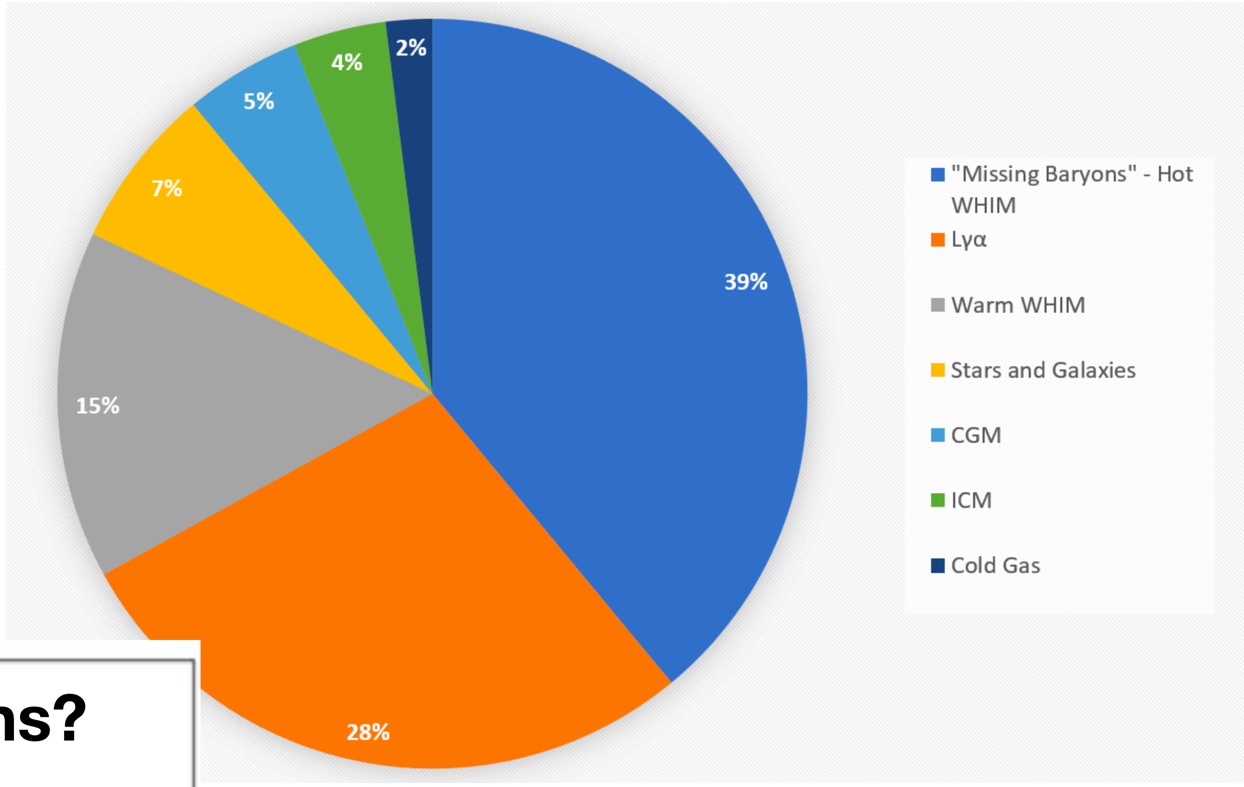


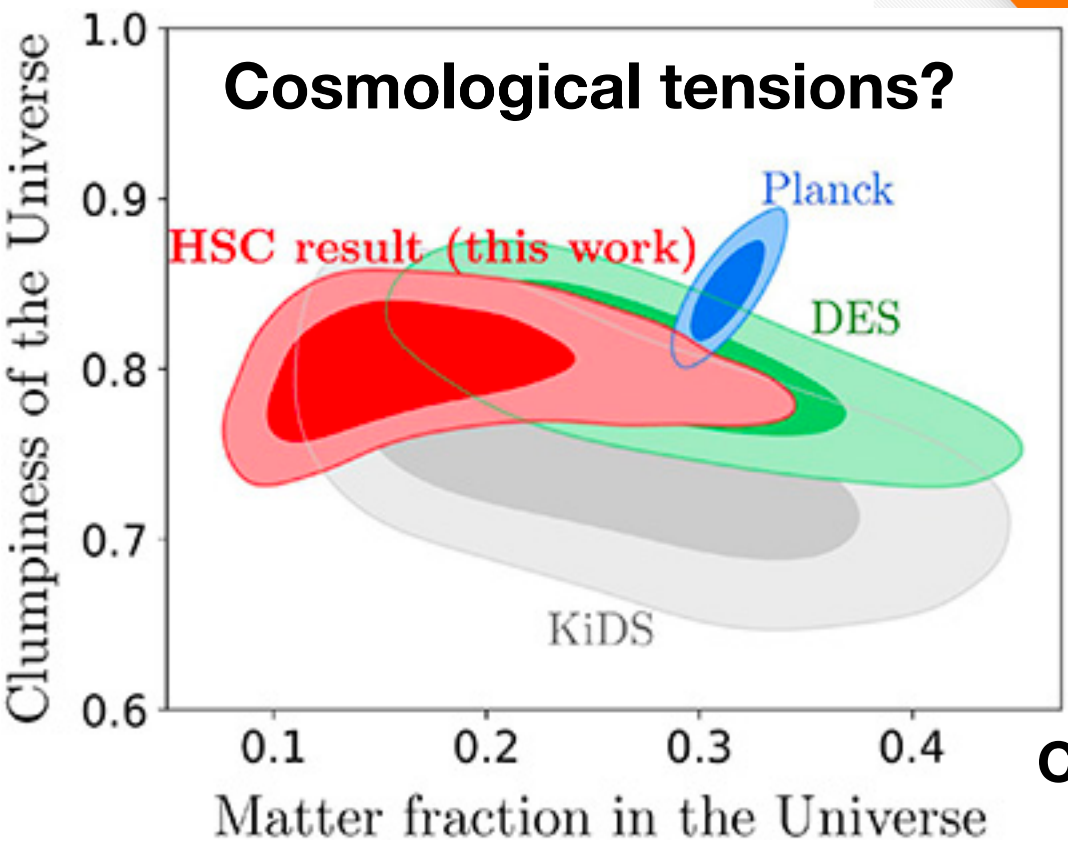

**Video by: Paco Villaescusa-Navarro**

# Why does this matter?

**Fates of galaxies**

**Missing baryons?**

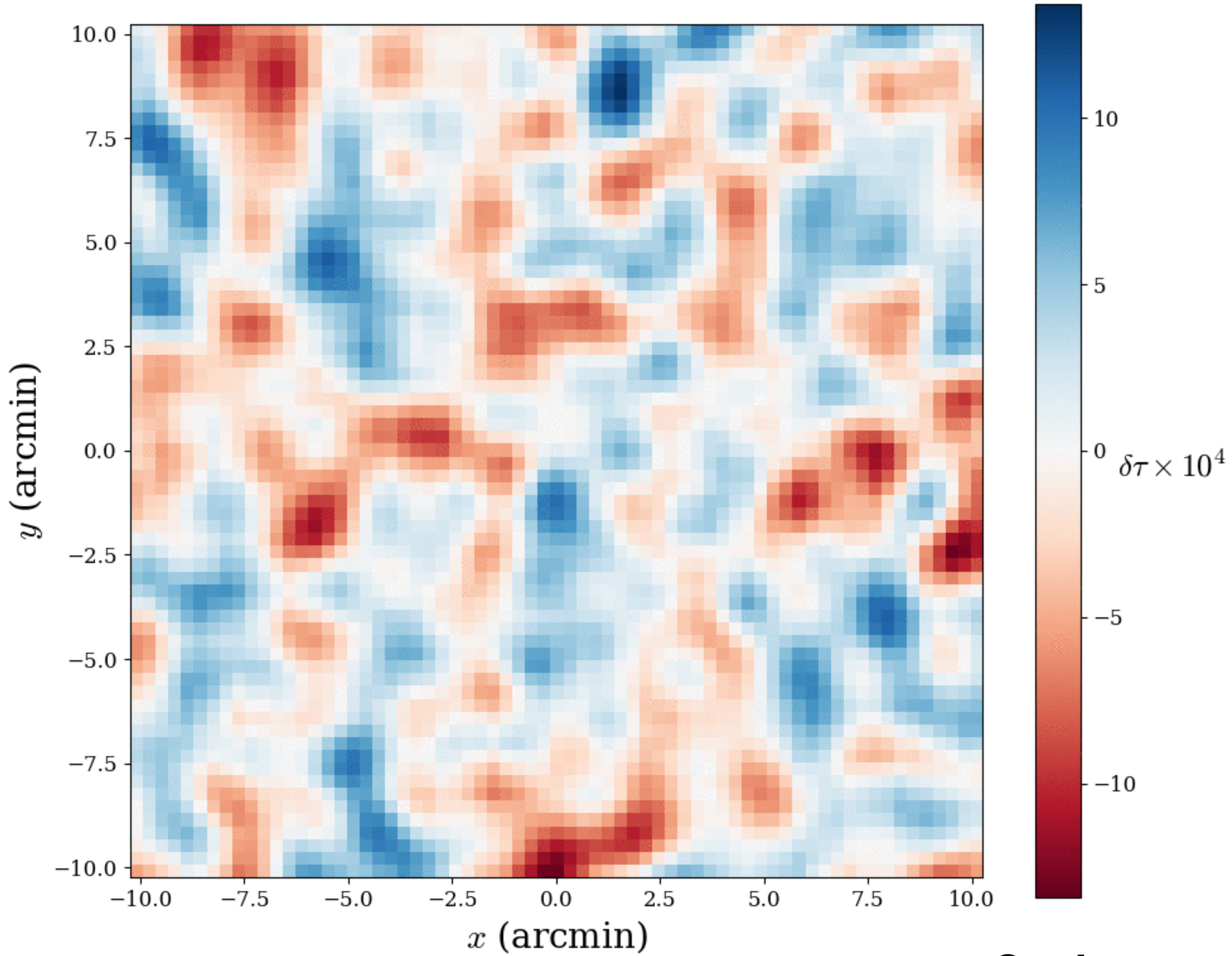



**Credit: C. Hikage, Nicastro et al (2018)**
**JWST**

# What do we measure?

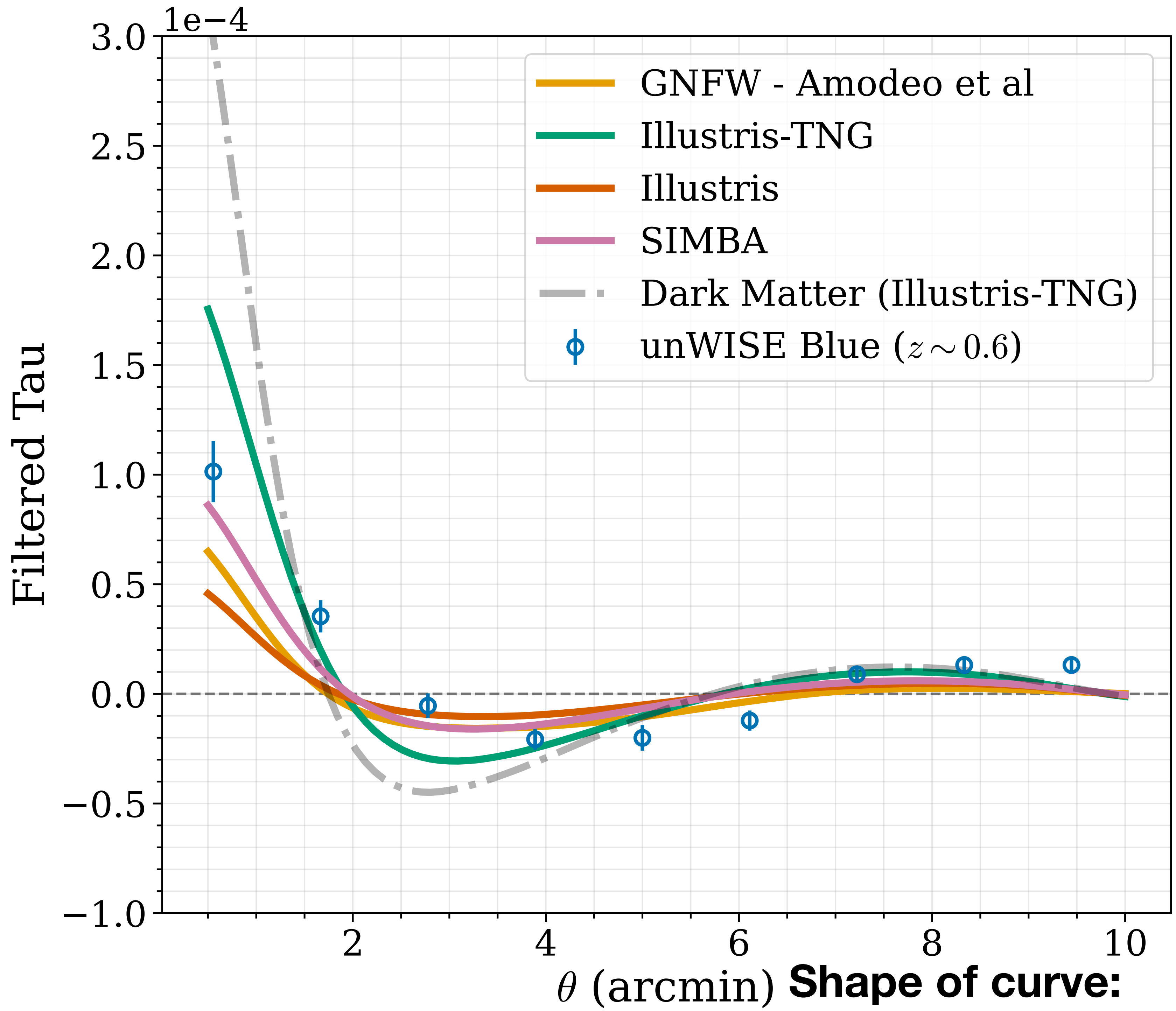
**Integrated electron profile around unWISE galaxies from ACT+Planck data**




**Coulton et al (2024)**

# What information does the late-time patchy-screening contain?

**Comparison of measured 1D profile to a set of theoretical models**




**Shape of curve:**

**1) Profile of free electrons**

**2) Filtering applied to CMB data**

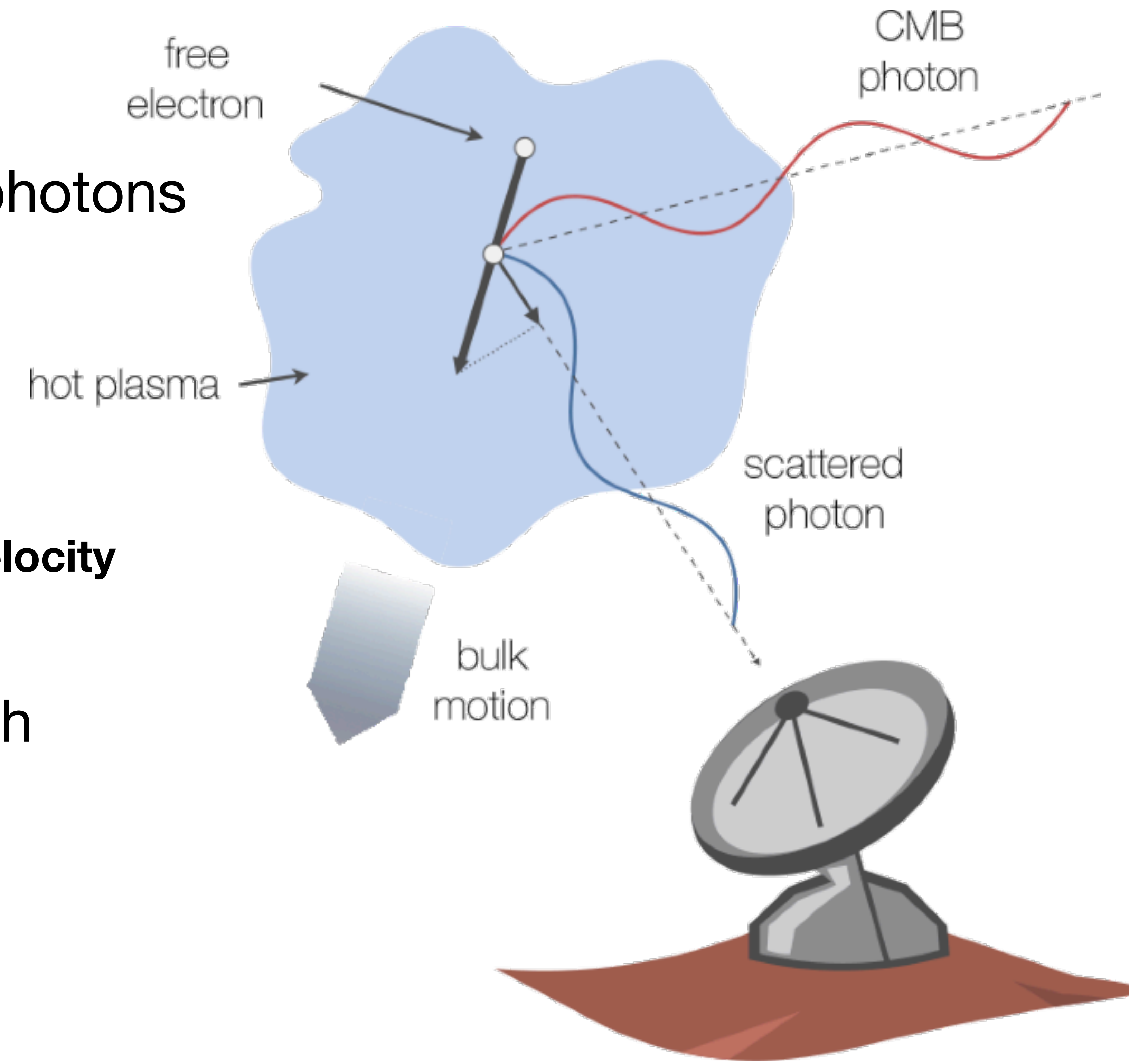
# Component five:
# the kinetic Sunyaev Zeldovich effect

# The kinetic Sunyaev Zeldovich Effect

- Doppler shifting of CMB photons

$$\frac{\Delta T(\mathbf{n})}{T_{\rm CMB}} \propto -\int \underbrace{\mathrm{d}\chi\delta_e}_{\text{Electron overdensity}} \mathbf{n} \cdot \underbrace{\frac{\mathbf{v}}{c}}_{\text{Bulk velocity}}$$

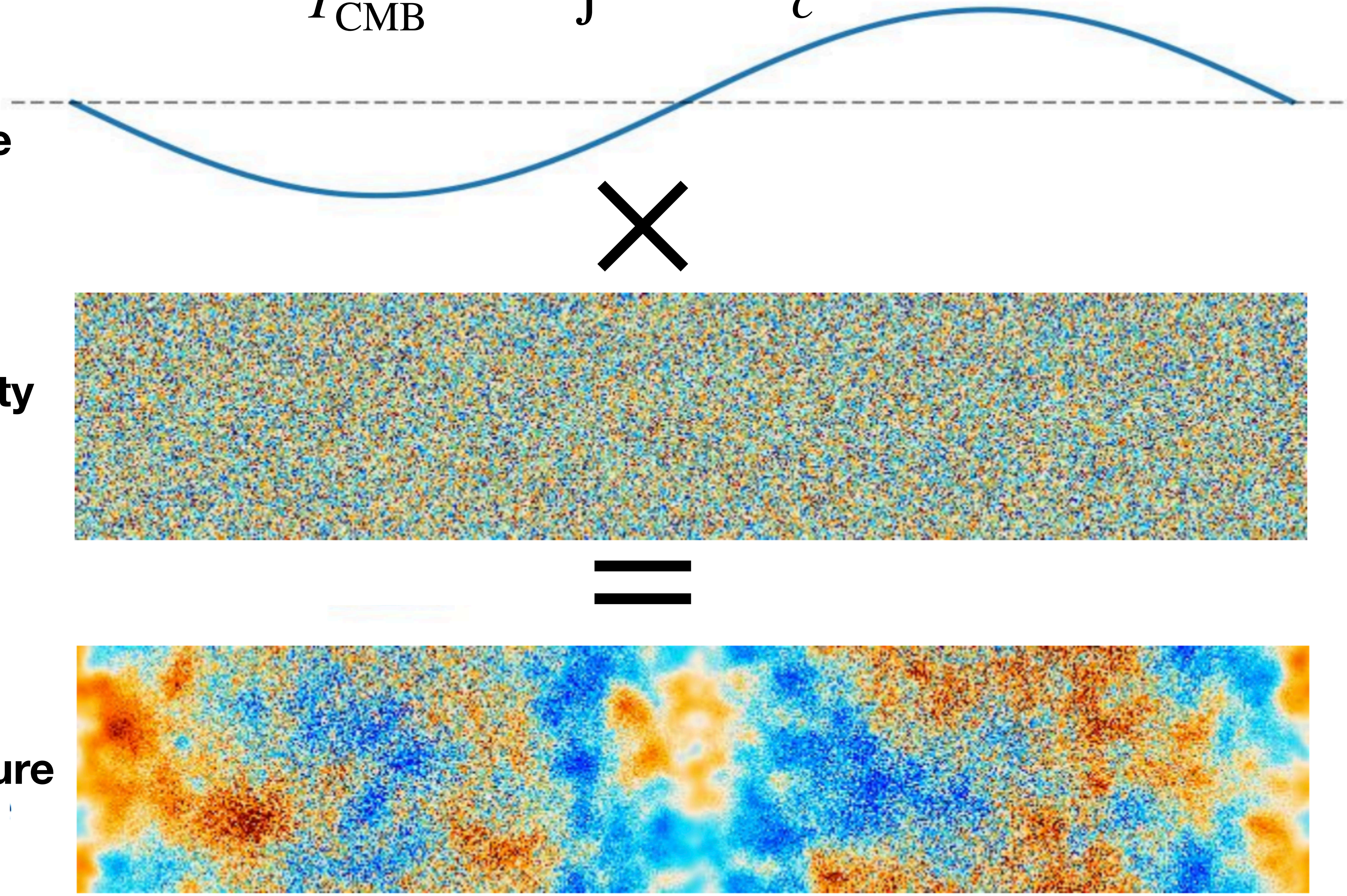
- Produces anisotropies with blackbody spectrum




**Source: Mroczkowski et al (2019 )**

# kSZ velocity reconstruction

$$\frac{\Delta T(\mathbf{n})}{T_{\rm CMB}} \propto -\int \mathrm{d}\chi \delta_e \mathbf{n} \cdot \frac{\mathbf{v}}{c}$$



Cosmic Velocity Mode

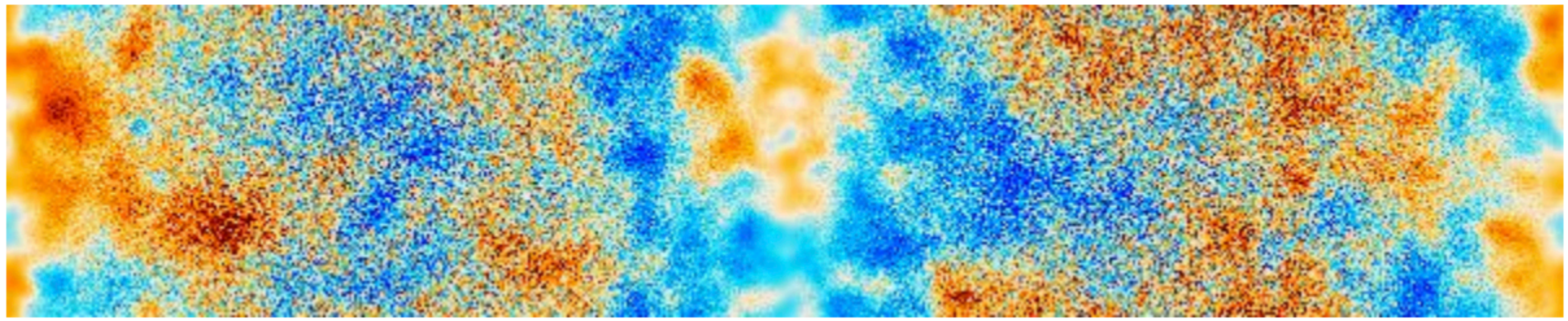
Electron density field

CMB Temperature Map

Madhavacheril (2019)
Smith (2019) ++

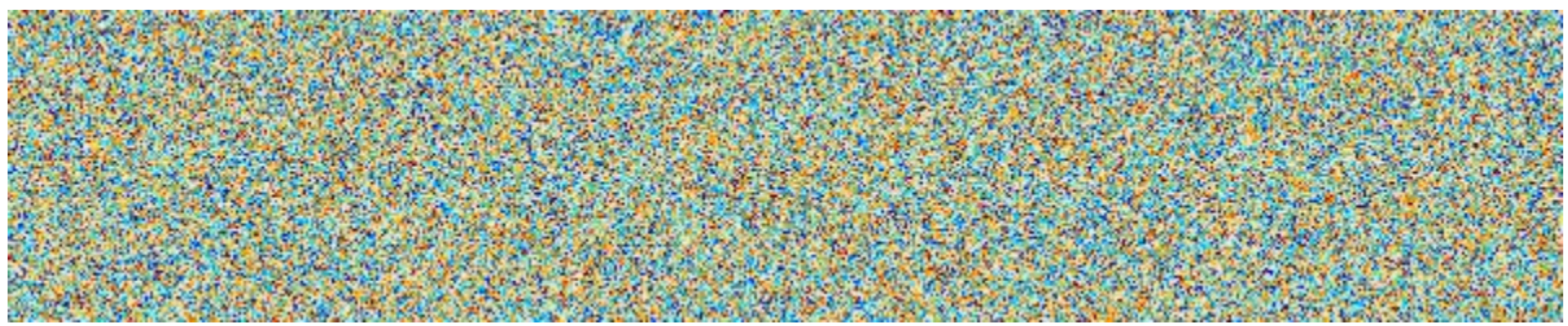
# kSZ velocity reconstruction

**Observed Map**



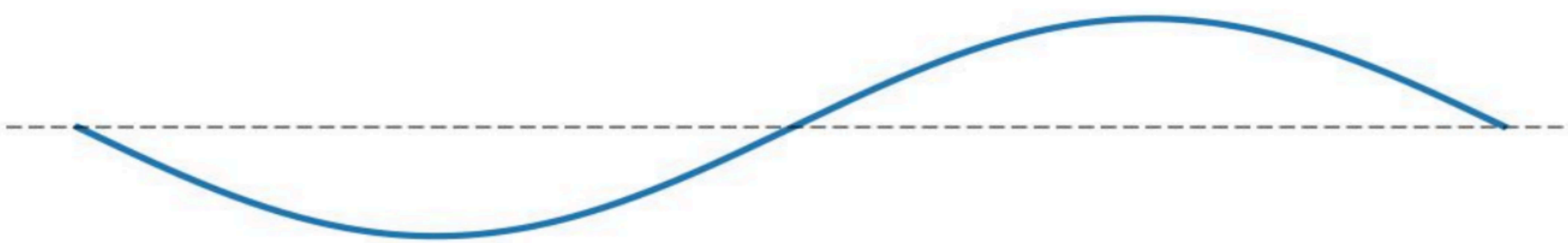
$\times$

**Tracer of Electron density field**



$=$

**Cosmic Velocity Mode**



$$\hat{v}(\mathbf{n}) \propto \Delta T(\mathbf{n})\, \delta_e(\mathbf{n}, z)$$

**Madhavacheril (2019)**
**Smith (2019) ++**

# Parity Violation in the Universe

- Parity violation is a feature of the standard model of particles

- In cosmology we typical only consider parity conserving Universes

- Recently there are two hints of parity violation in cosmology:

  - ‘Cosmic birefringence’ in Planck data

    **Minami and Komatsu (2021)**

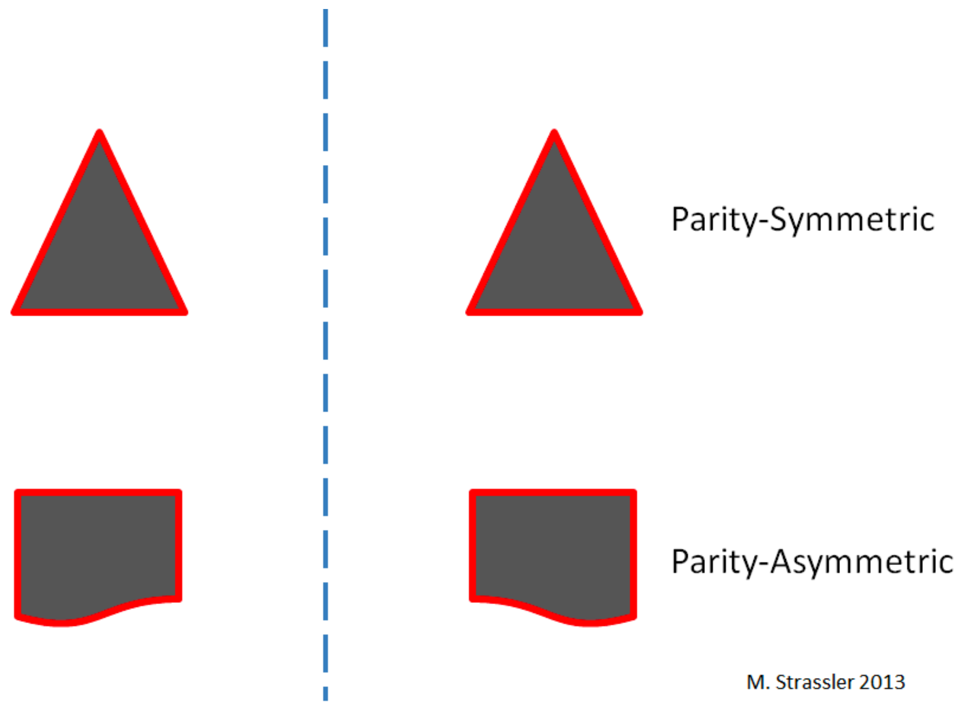
  - A hint of parity odd trispectrum in LSS

    **Hou et al (2022), Philcox (2022)**

**What is parity symmetry?**

$$\mathbf{P}: \begin{pmatrix} x \\ y \\ z \end{pmatrix} \mapsto \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix}.$$

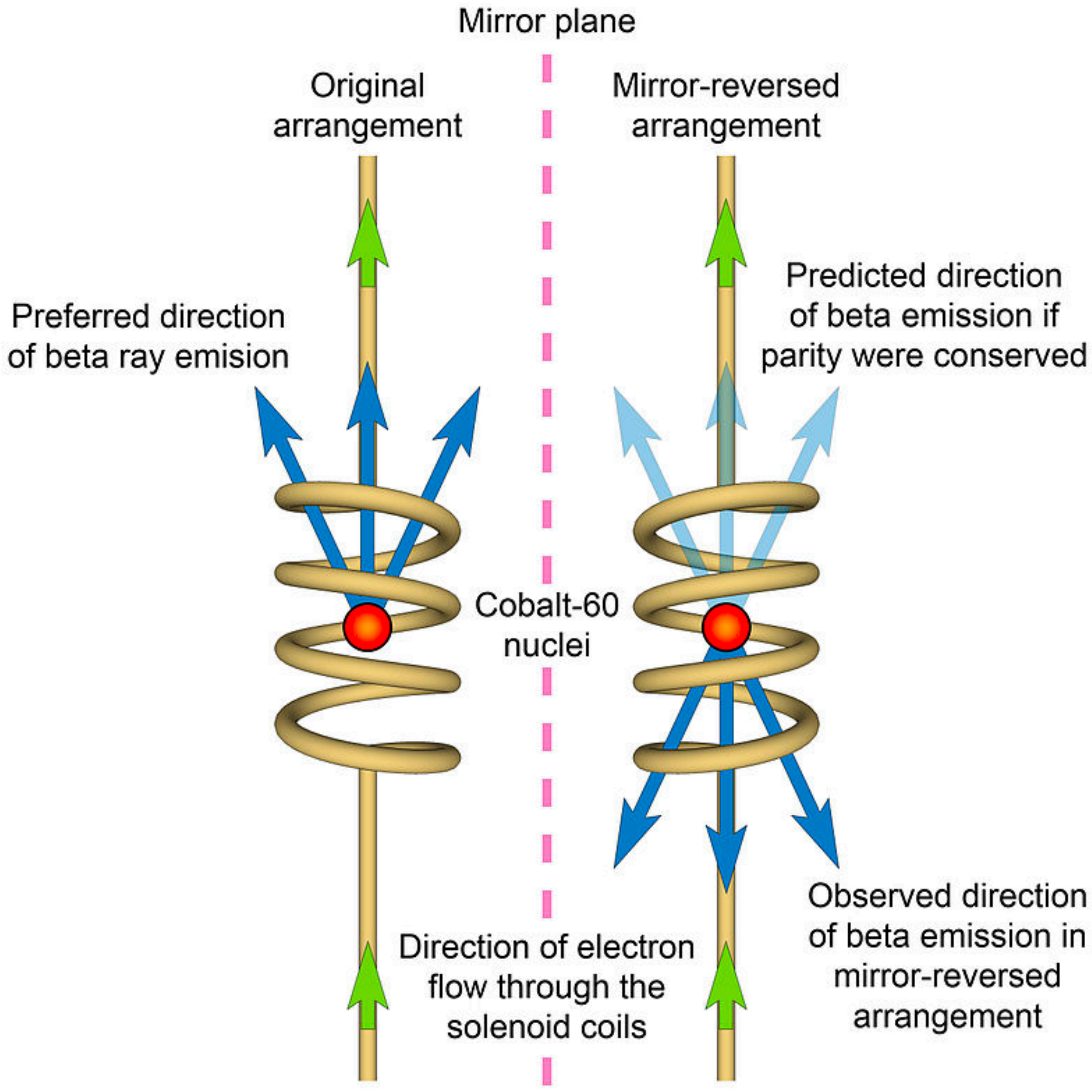
**An analogy to mirror symmetry:**



# New observables for parity

## A cosmic analogy…

### Wu experiment



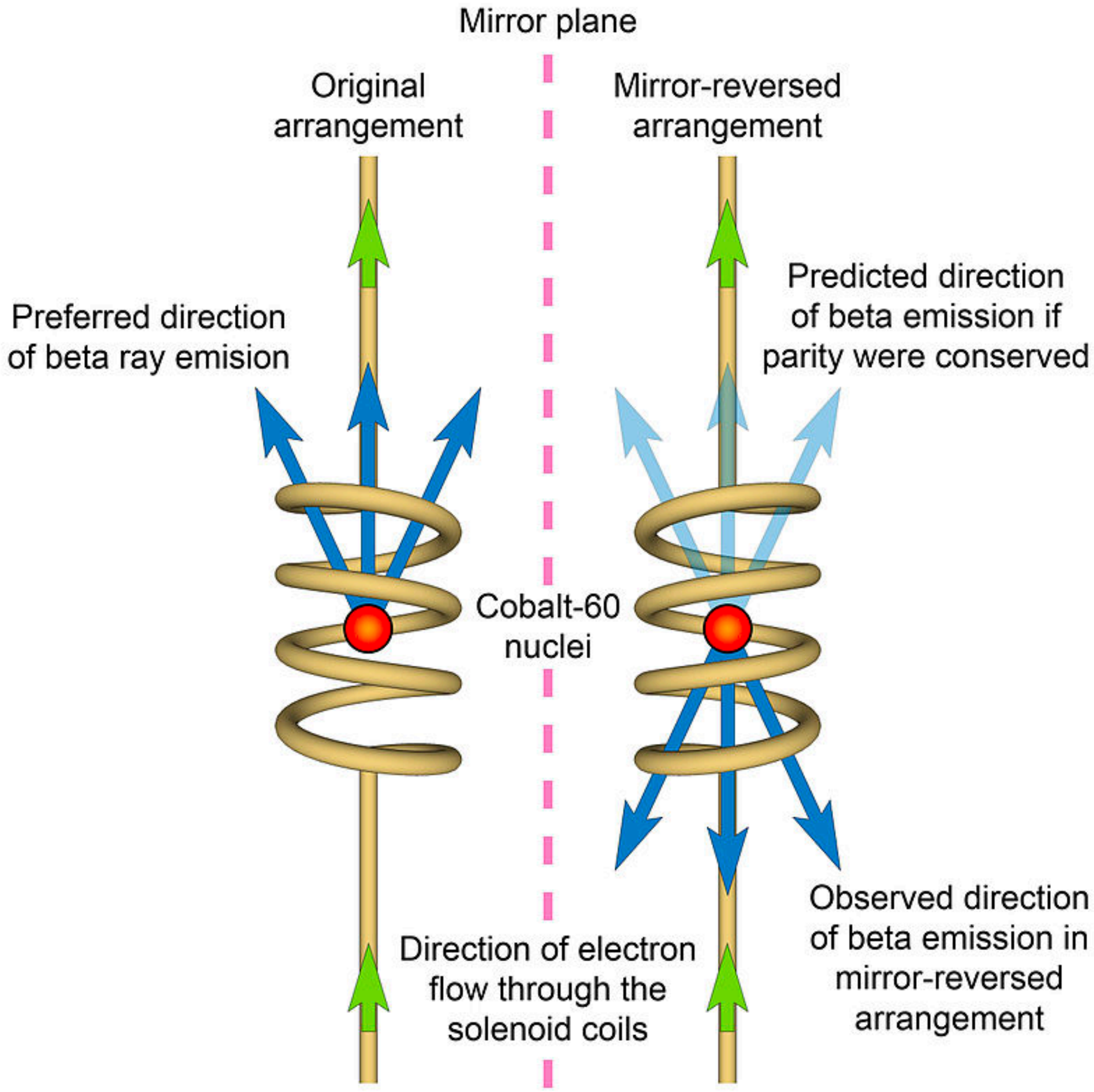



Images: Wikipedia

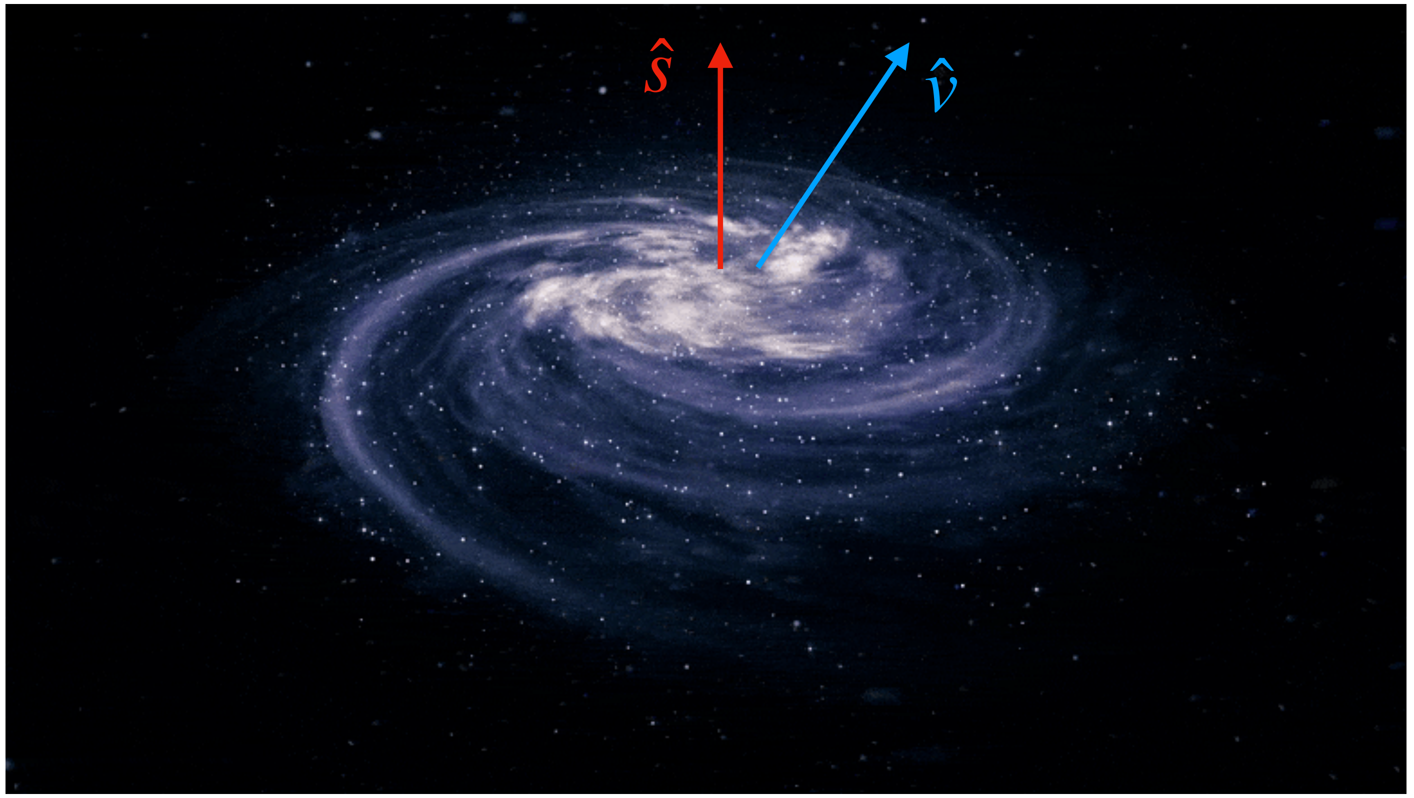
# New observables for parity

## A cosmic analogy…

**Wu experiment**

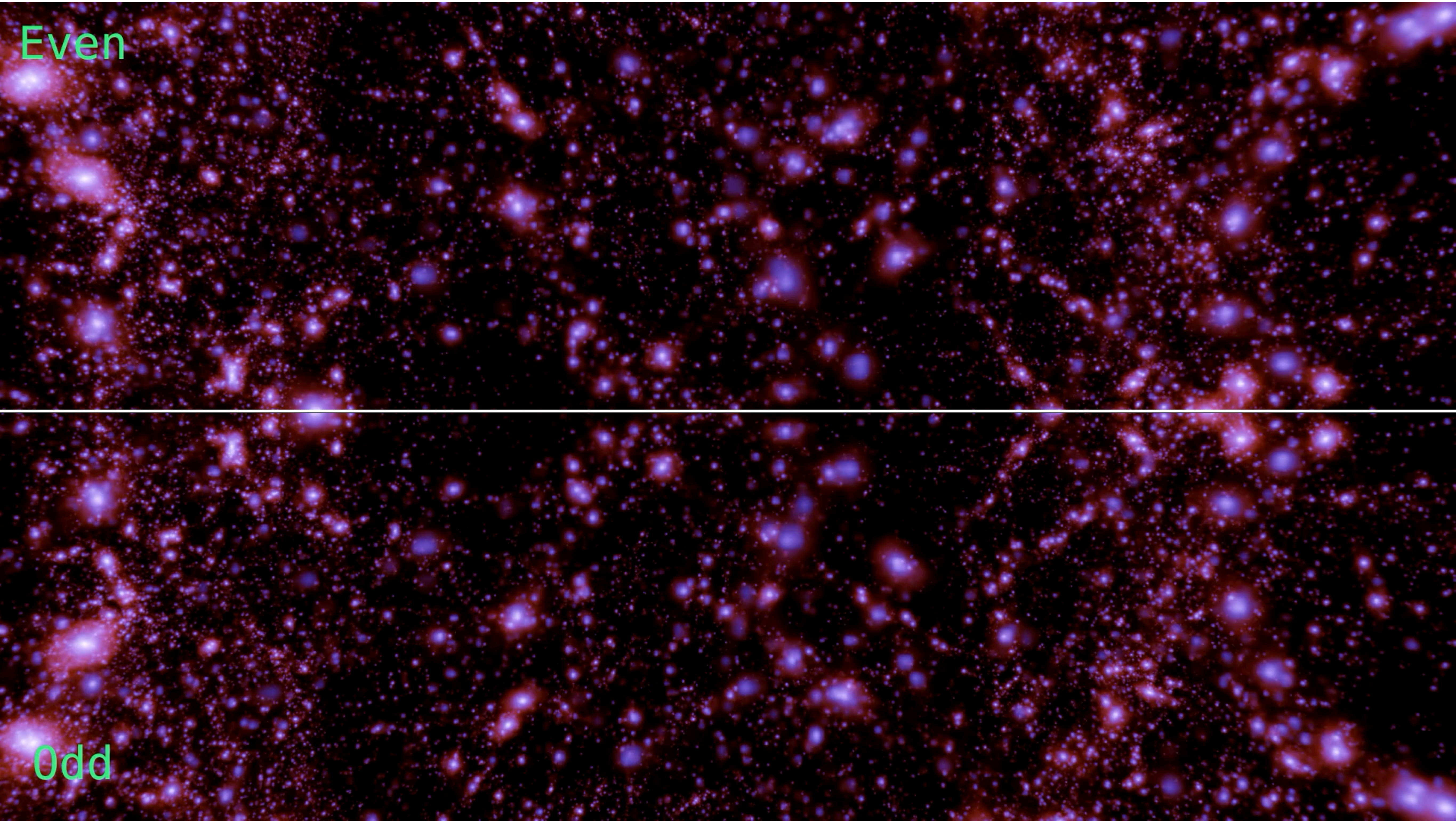



**Cosmological "Wu experiment"**




**Images: Wikipedia**

# Parity Violating PNG in Quijote-Odd

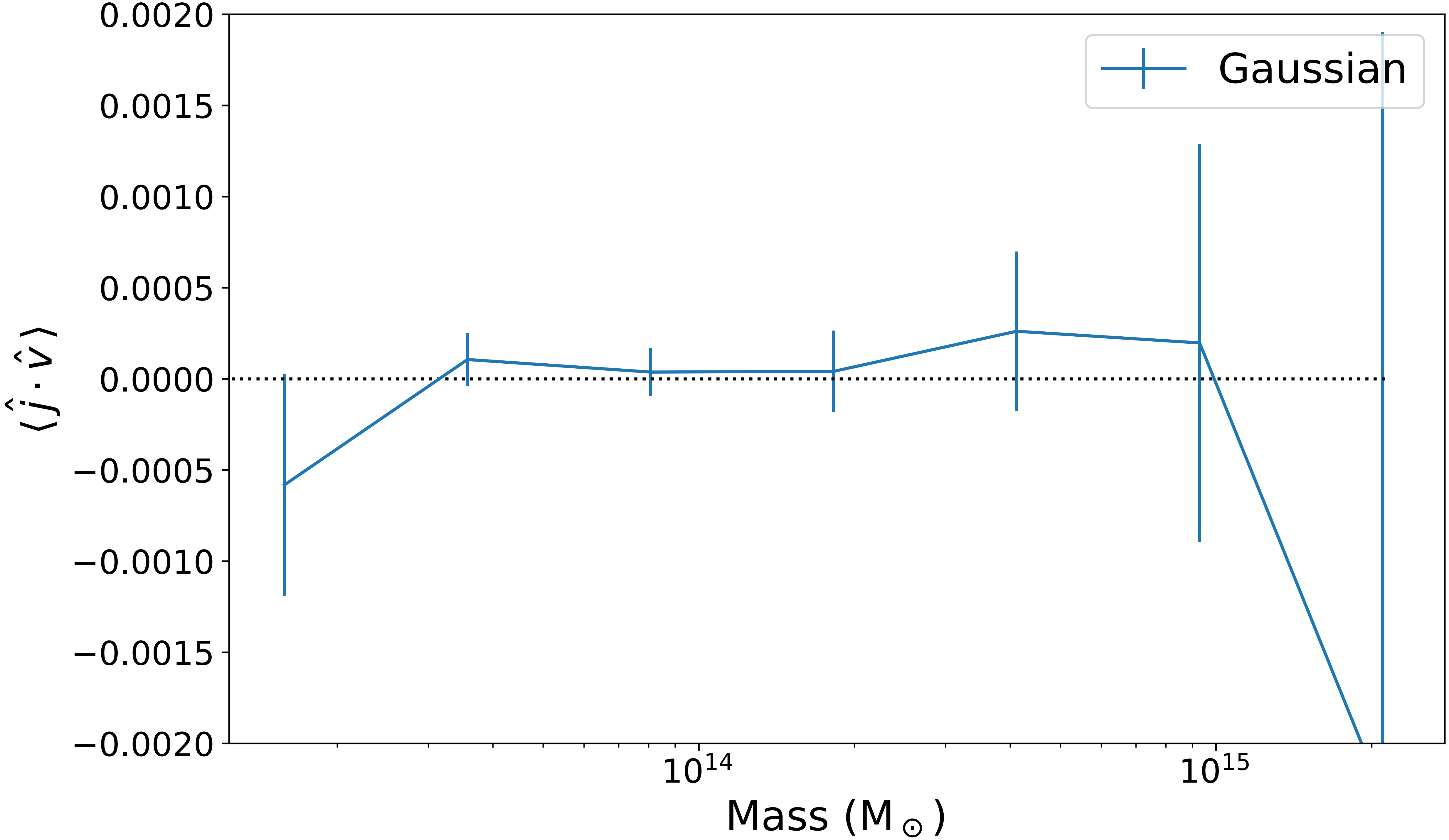





**Coulton, Philcox and Villaescusa-Navarro (2023)**

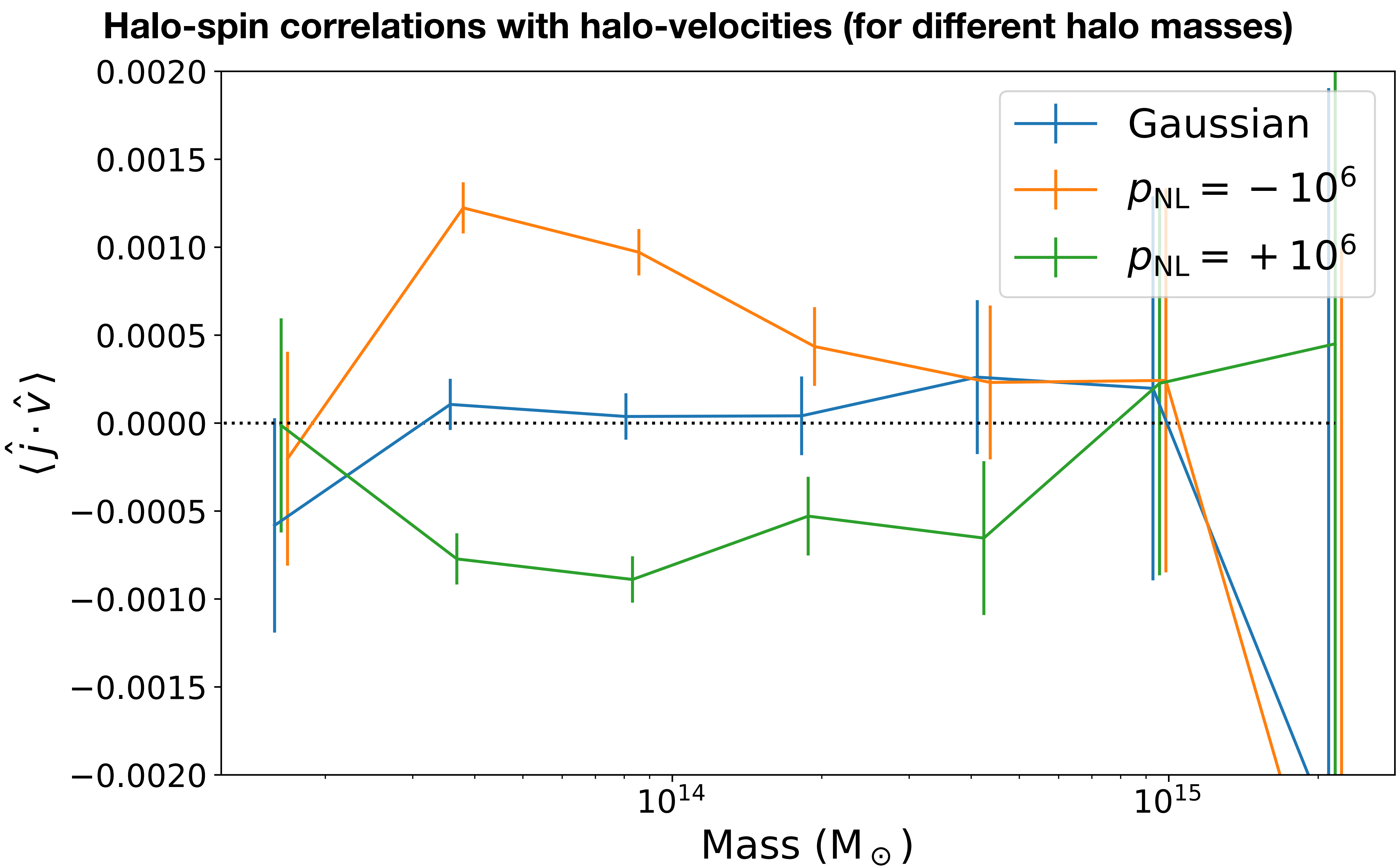
# The "Cosmological Wu Experiment"

**Halo-spin correlations with halo-velocities (for different halo masses)**




**Coulton, Philcox and Villaescusa-Navarro (2023)**

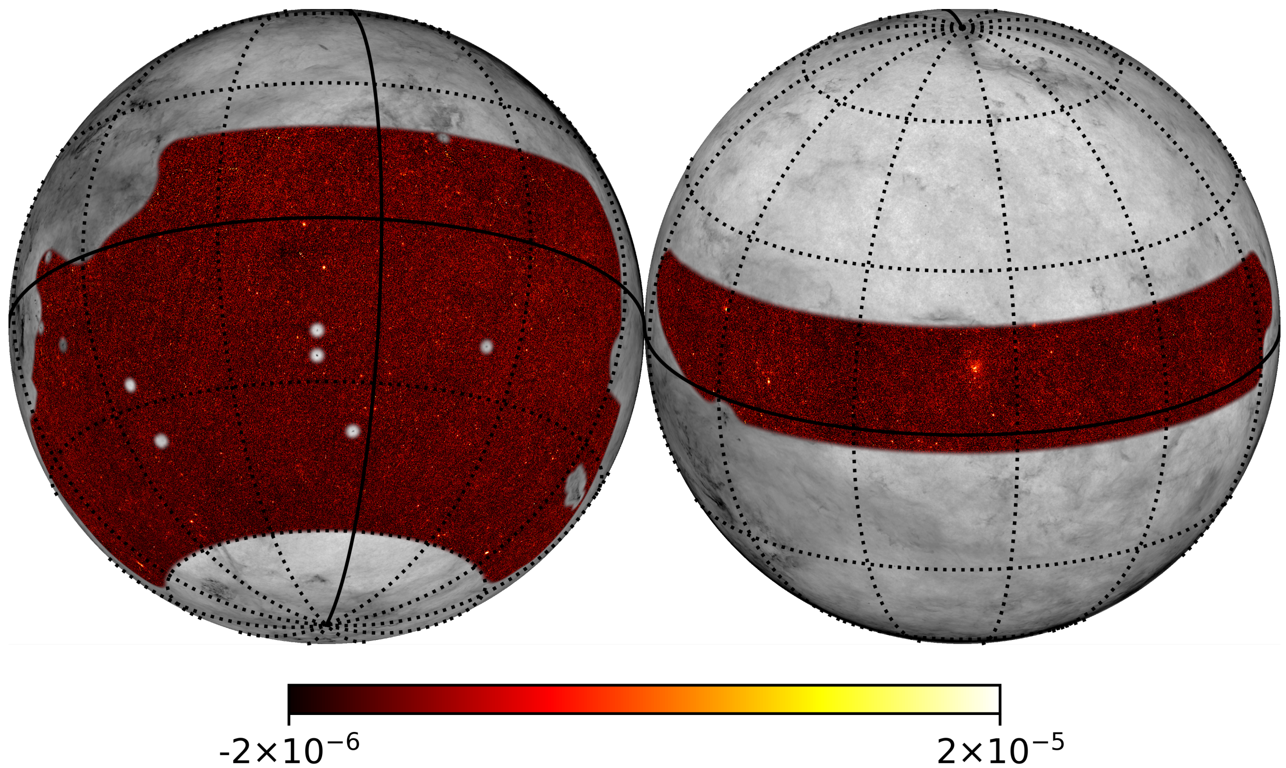
# The "Cosmological Wu Experiment"



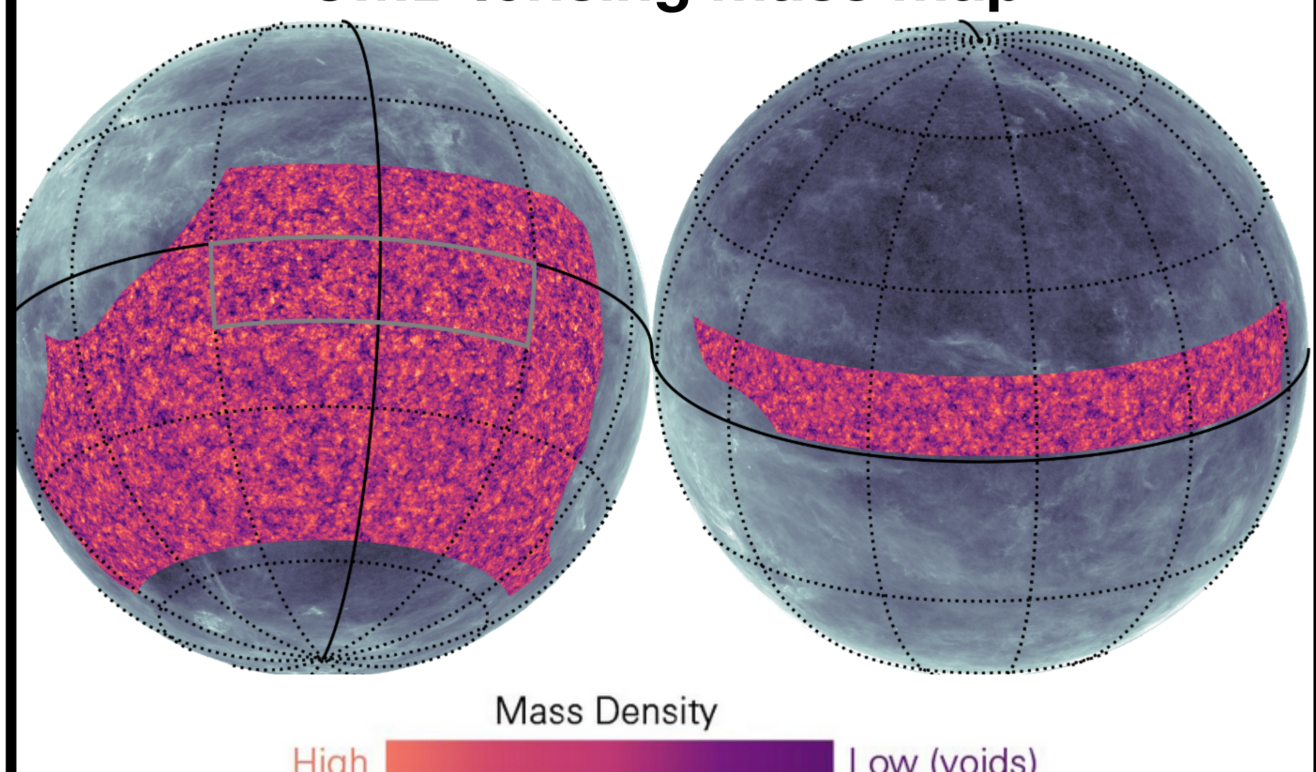

**Coulton, Philcox and Villaescusa-Navarro (2023)**

# Conclusions

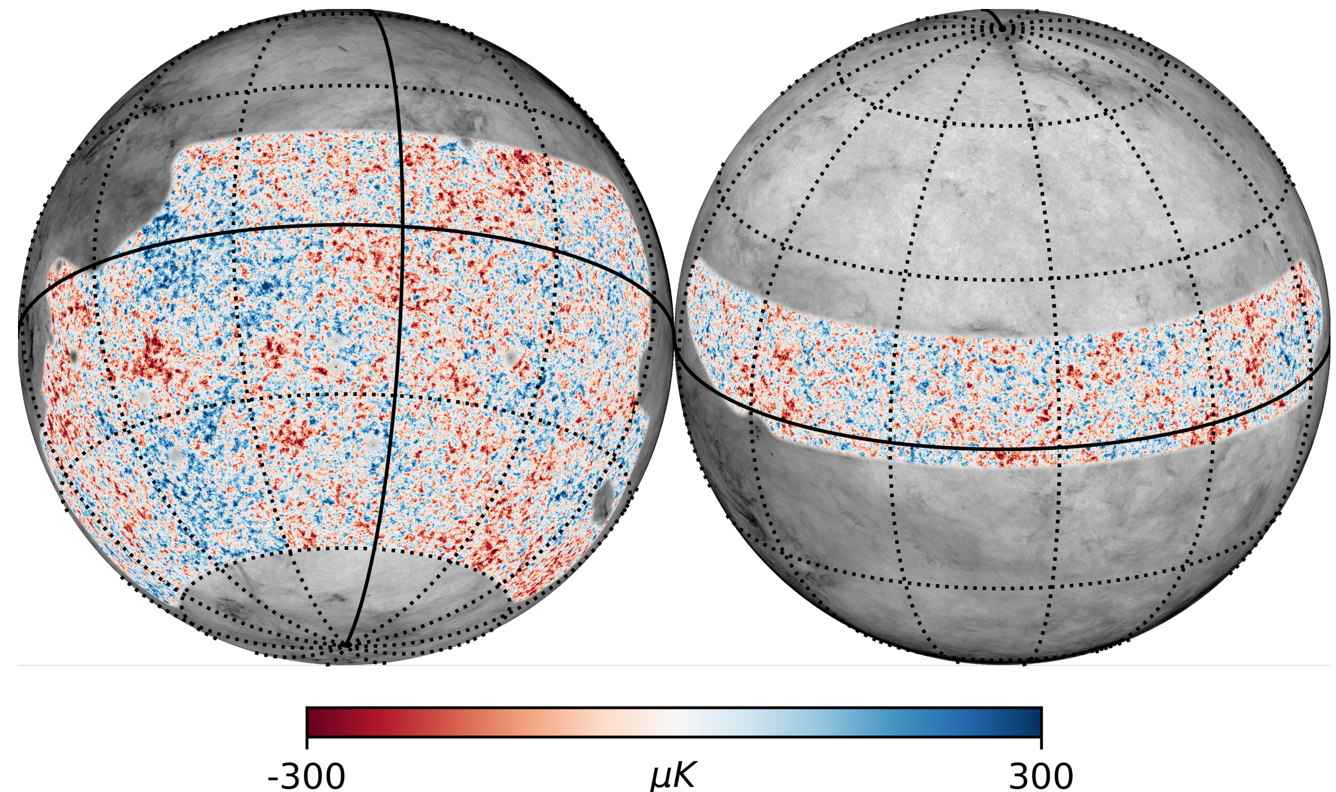
## Compton-y Anisotropies



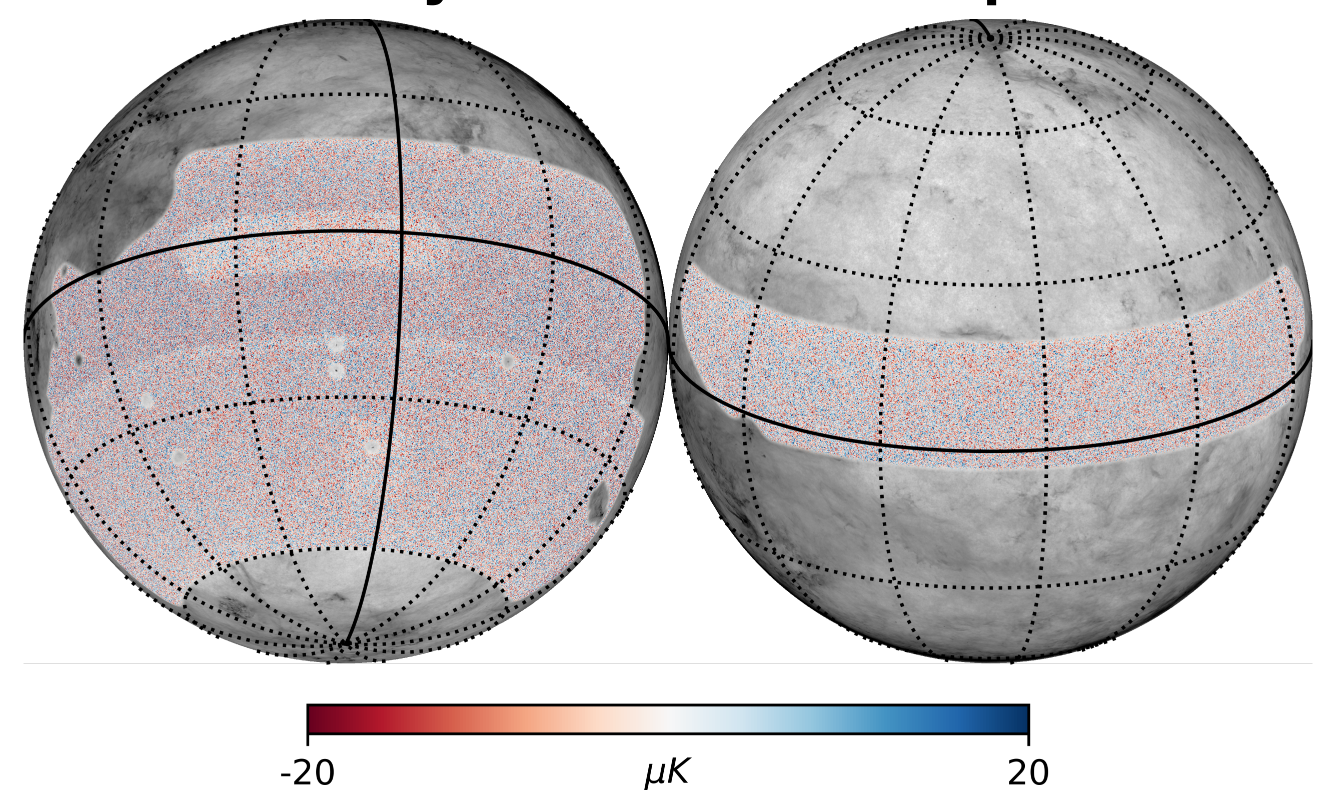

## CMB lensing mass map




## Blackbody Temperature Anisotropies




## Blackbody E-mode anisotropies



Thanks!