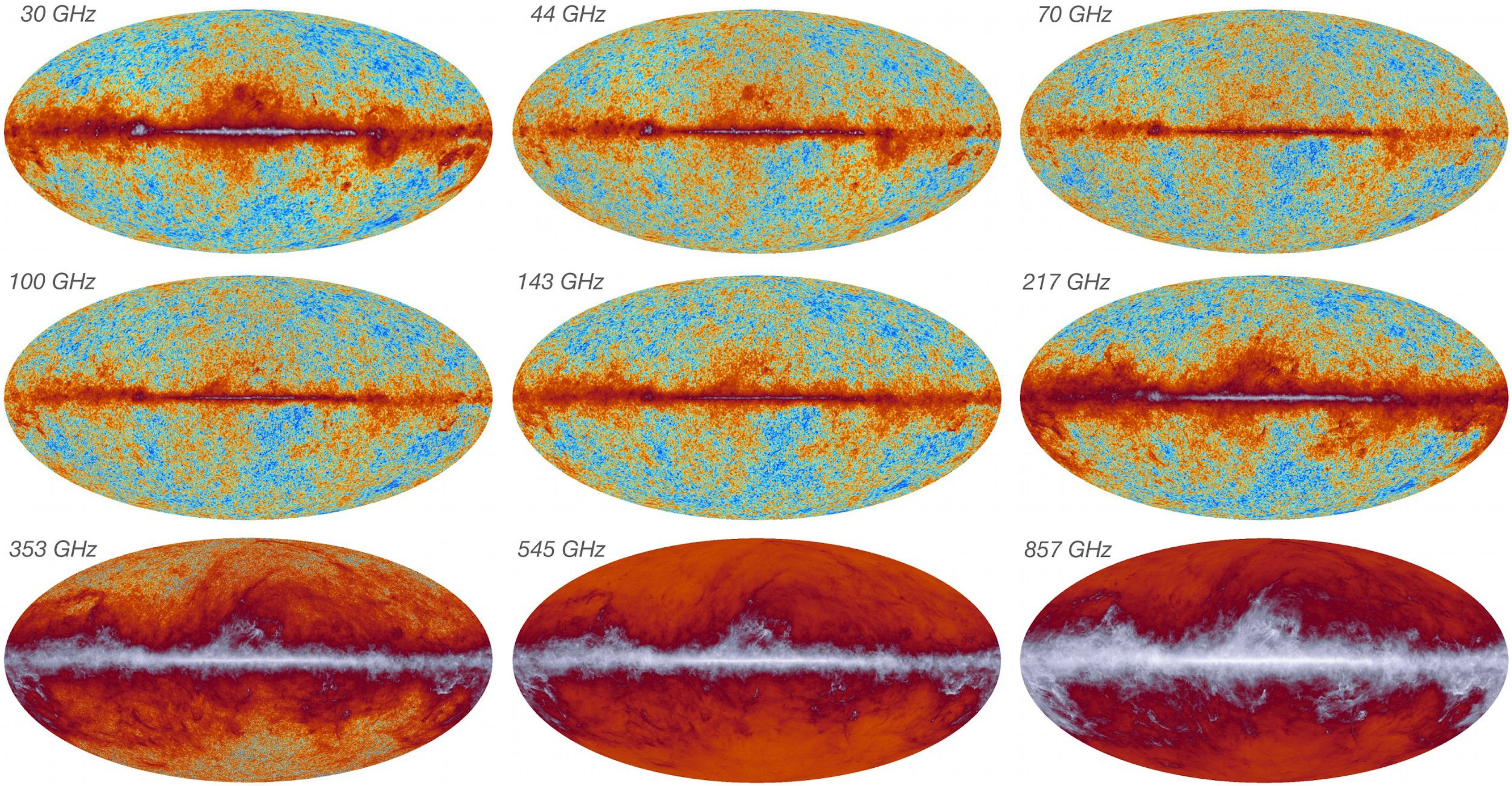
Enabling New Views of the Early Universe from the Atacama

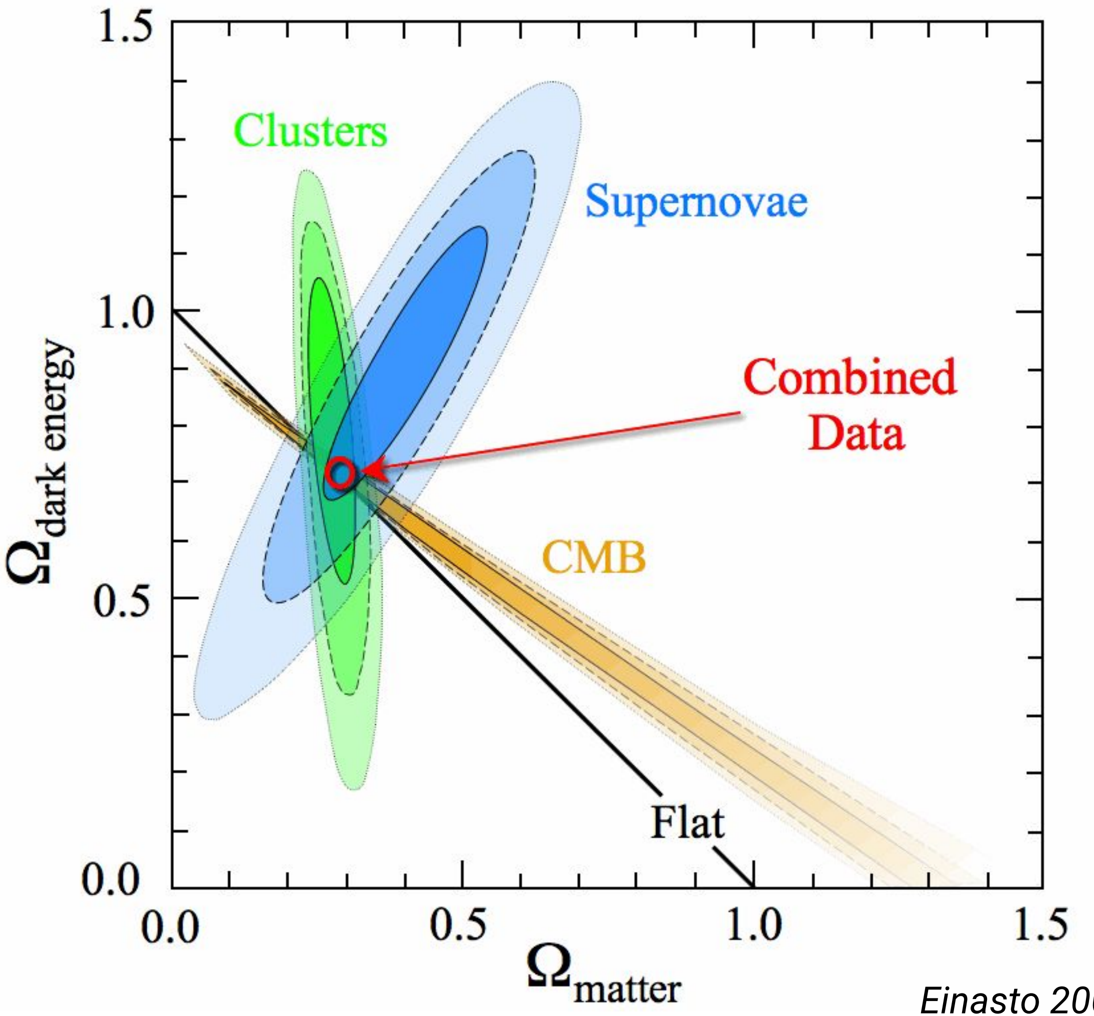
(in the Next Five Years)

Zack Li, Princeton



Planck Collaboration, 2018

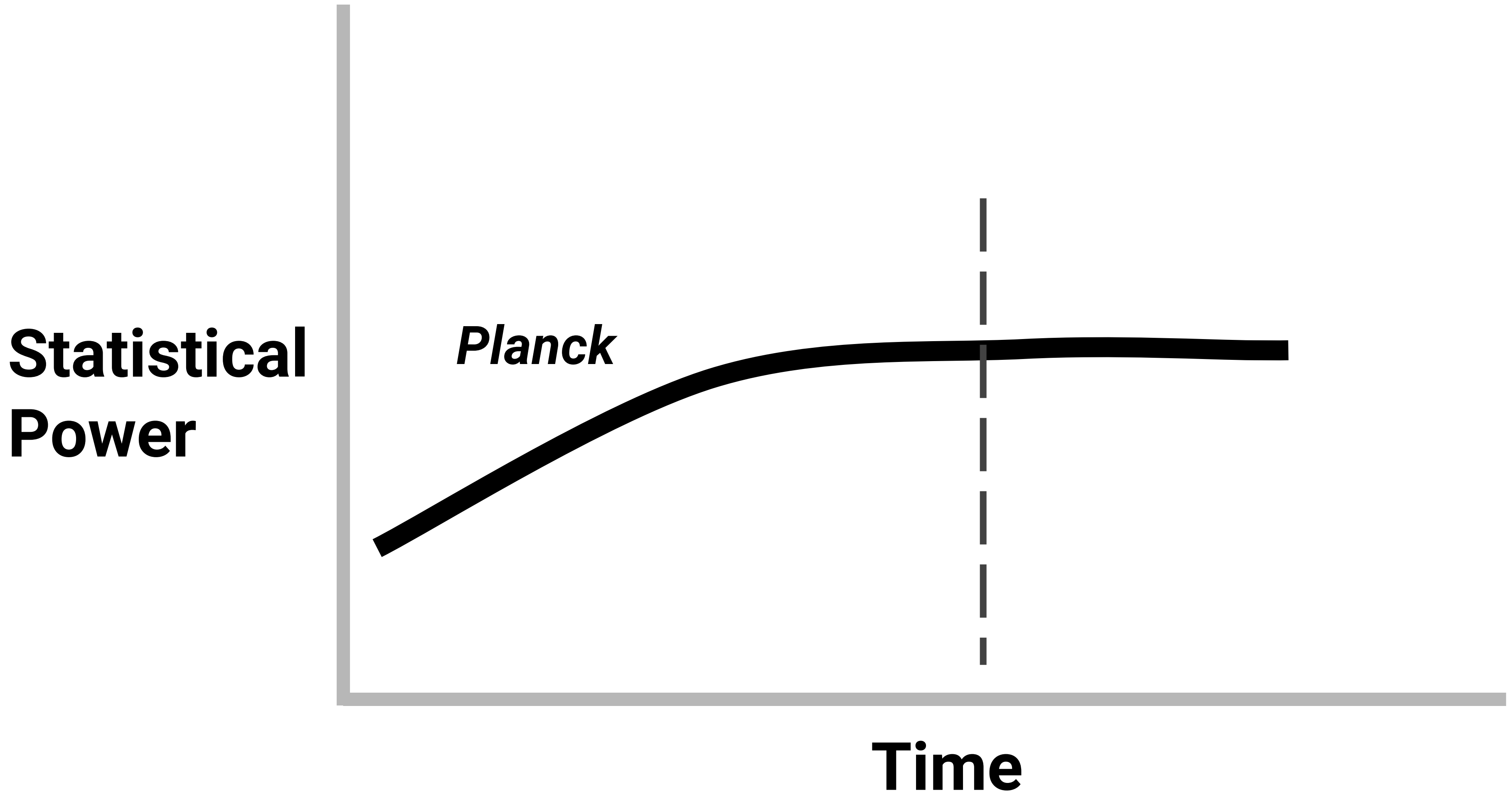
The ***Planck*** era has helped build a consistent, precisely measured **Standard Model of Cosmology.**



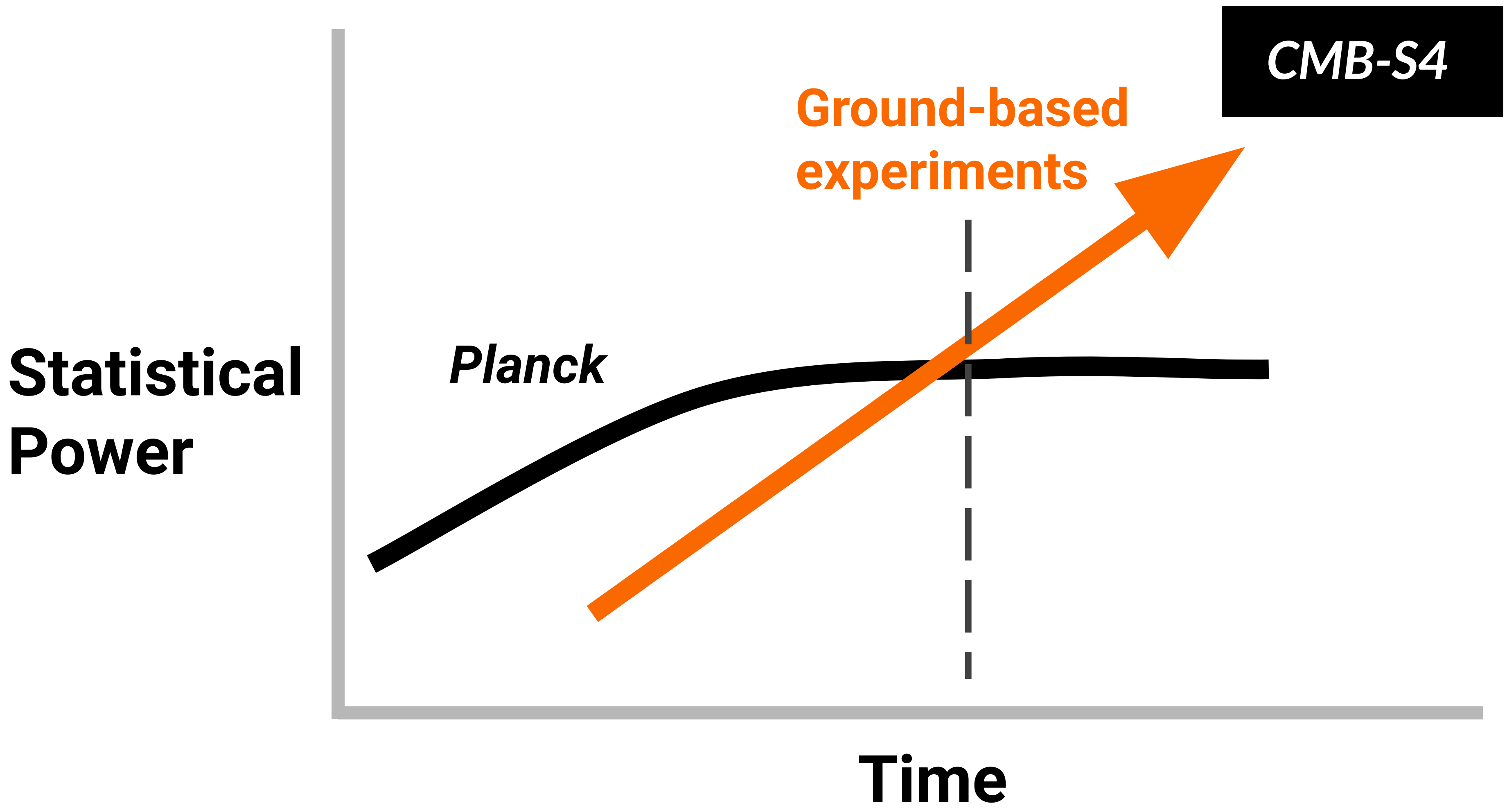
Einasto 2009

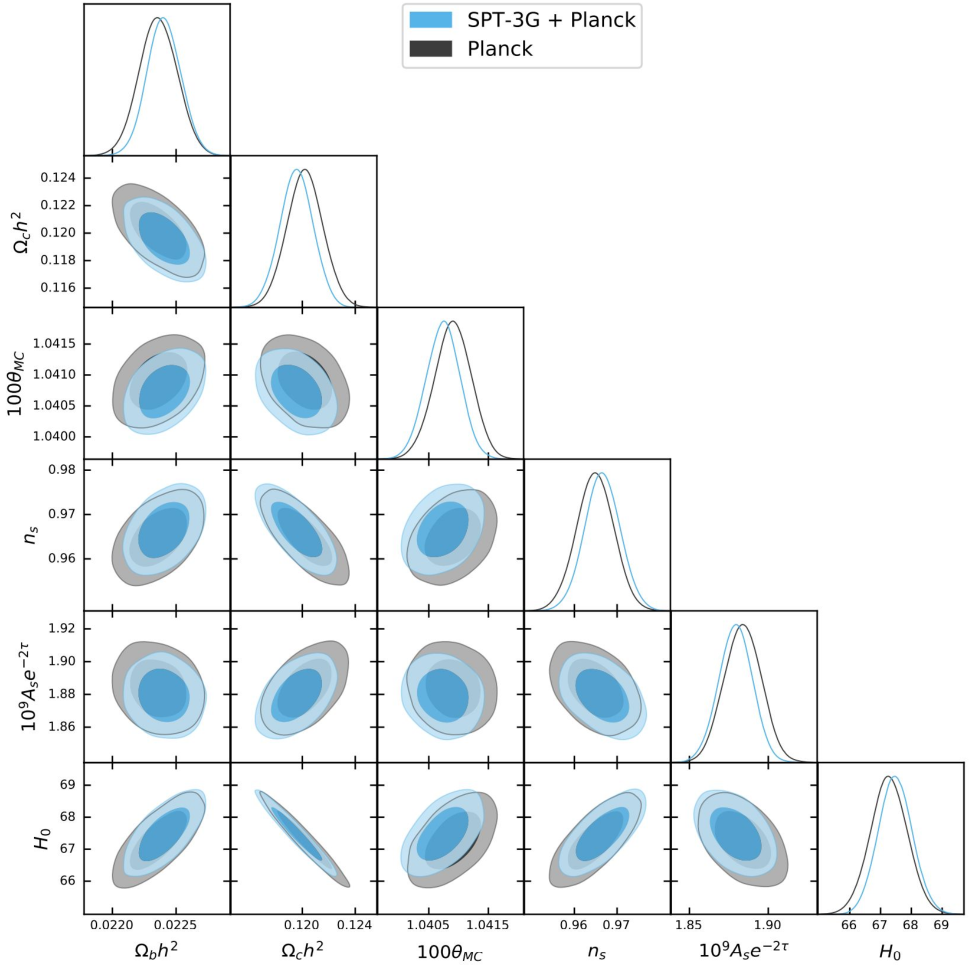
A new era:

Ground-based,
high-resolution polarization,
over half the sky.

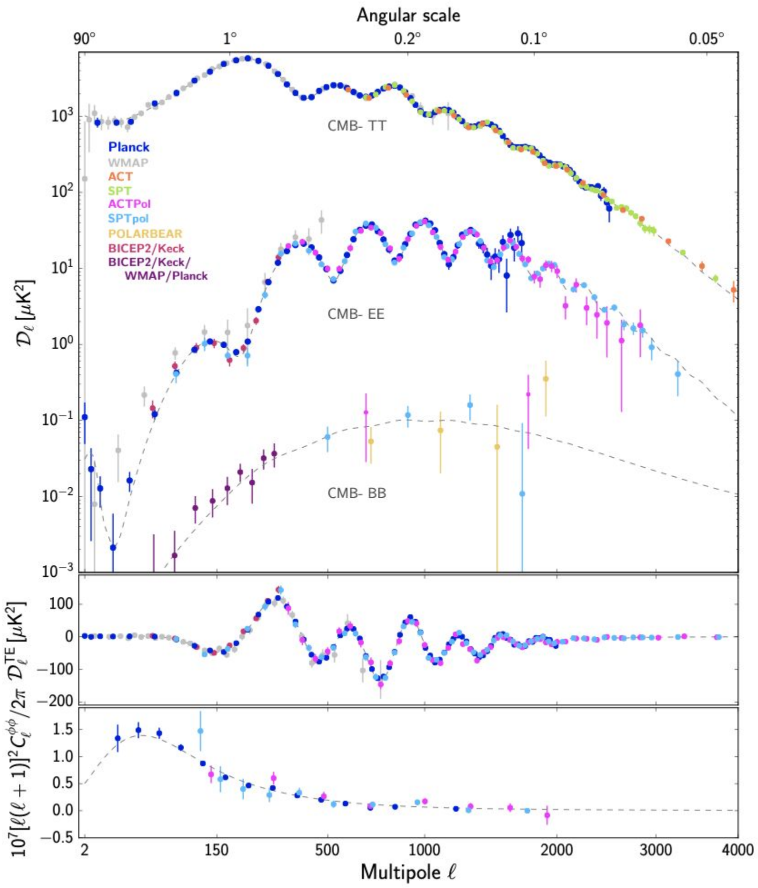


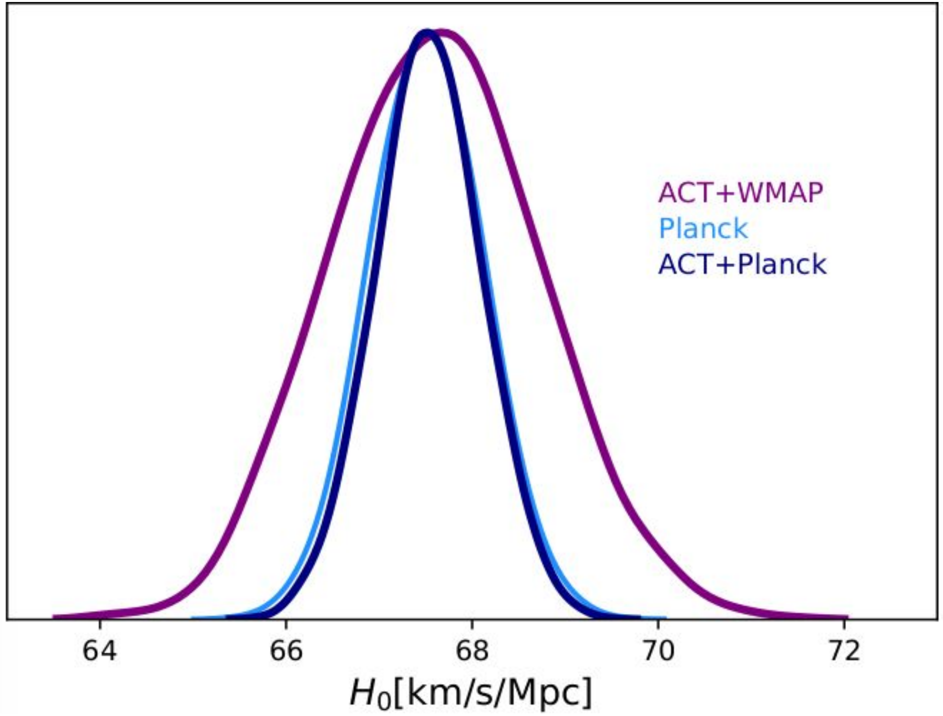
Statistical Power
Planck
Time


CMB-S4
Ground-based
experiments
Planck
Statistical
Power
Time



Dutcher et al. 2021



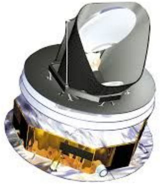


Choi et al 2020, Aiola et al 2020

2018

Planck

70% of the sky, 5-10 arcmin resolution

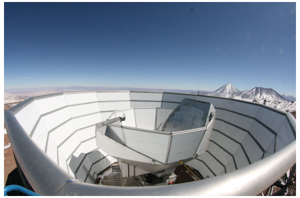


2020

ACT

2021

30% of the sky, 1-2 arcmin resolution



Lots of other great instruments out there!

i.e. BICEP, SPT, CLASS, Simons Array

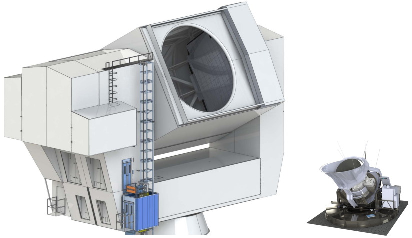
2023

Simons Observatory

2028

40% of the sky, 1-2 arcmin resolution

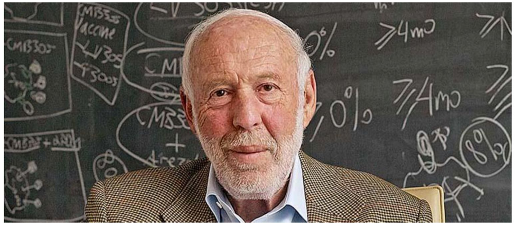
Stepping stone towards CMB-S4



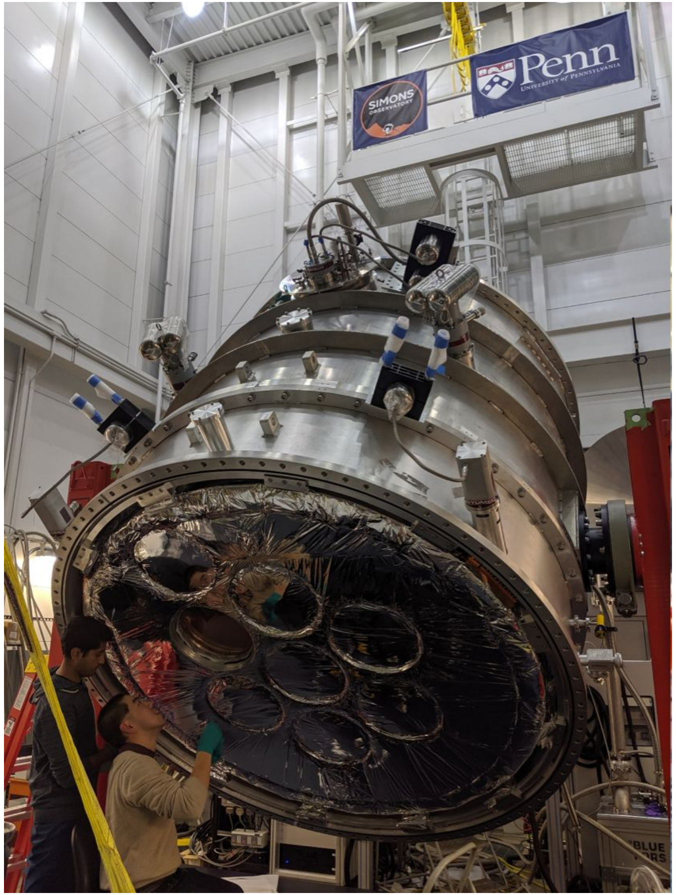
Simons Observatory (SO)

SIMONS FOUNDATION

HEISING-SIMONS FOUNDATION



Construction of nominal project is funded privately and has already begun. >200 collaborators



LAT

Large Aperture Telescope

New 6-meter-primary telescope

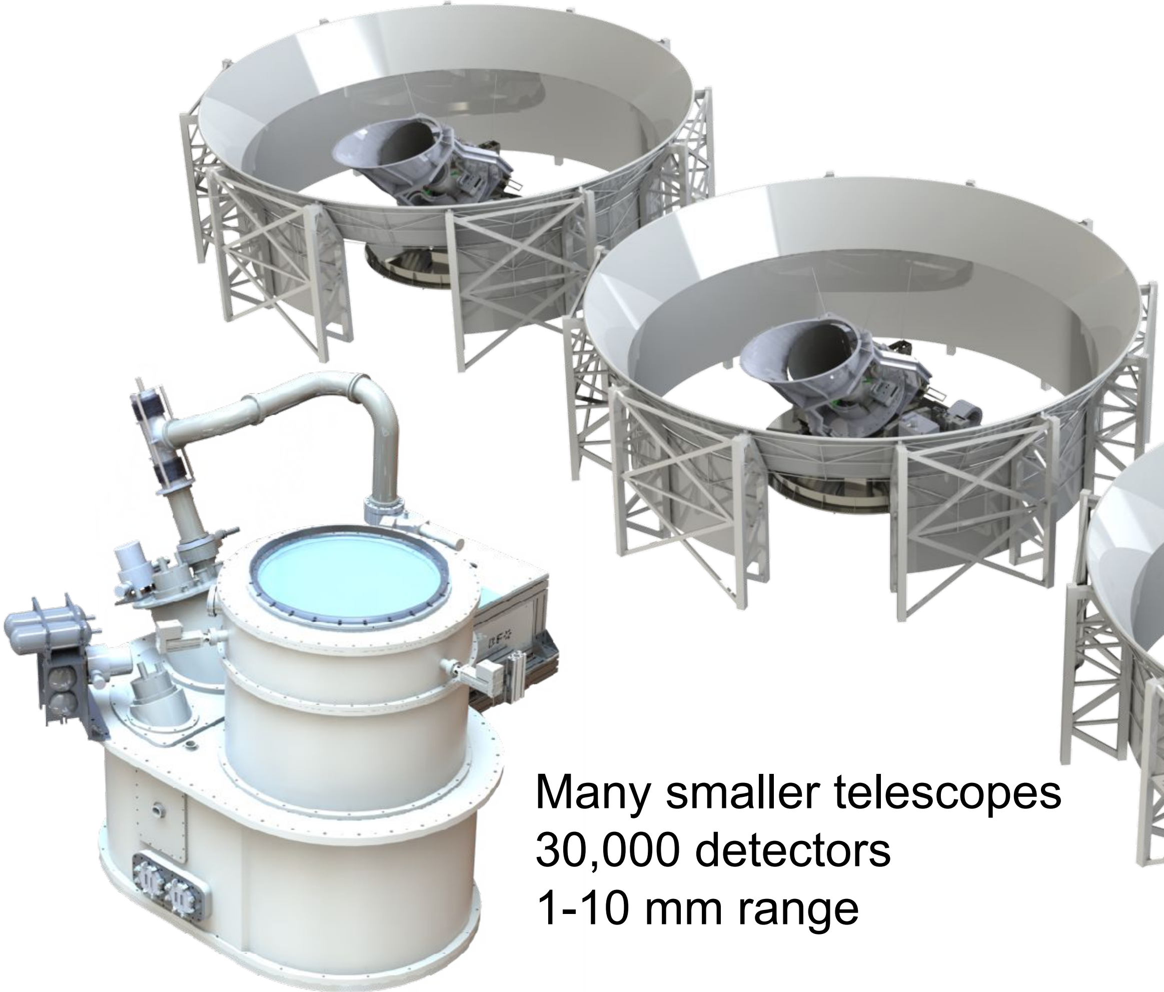
Detectors measure 6 wavelength bands:

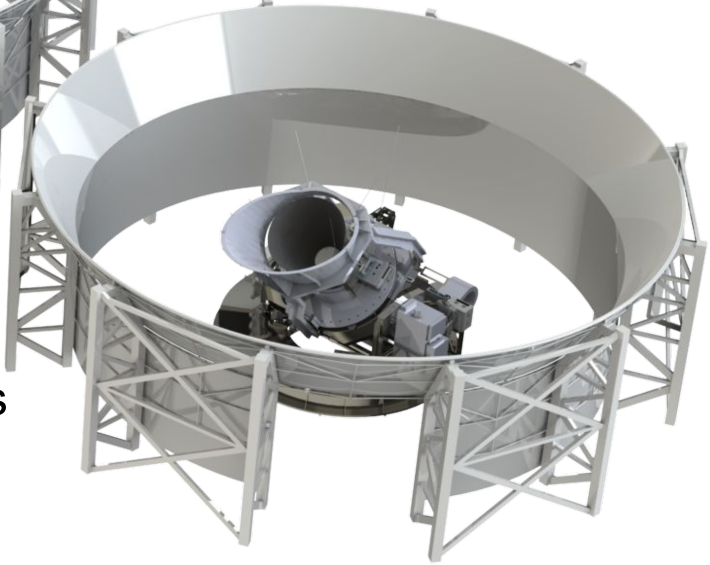
1-10 mm (30-280 GHz)

>30,000 Transition Edge Sensor detectors

SAT

Small Aperture Telescopes





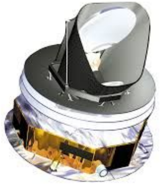
Many smaller telescopes
30,000 detectors
1-10 mm range

2018

Planck

70% of the sky, 5-10 arcmin resolution

9 bands, 30 - 857 GHz



2020

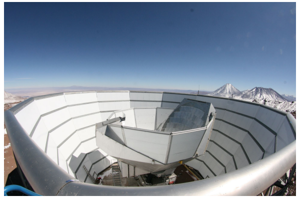
ACT

2021

30% of the sky, 1-2 arcmin resolution

98, 150, 226 GHz bands,

30, 40 GHz coming soon!



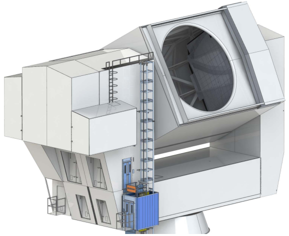
2023

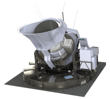
Simons Observatory

40% of the sky, 1-2 arcmin resolution

6 bands from 30 - 270 GHz

2028

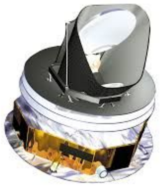




2018

Planck

70% of the sky, 5-10 arcmin resolution

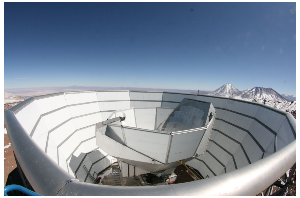


2020

ACT

2021

30% of the sky, 1-2 arcmin resolution

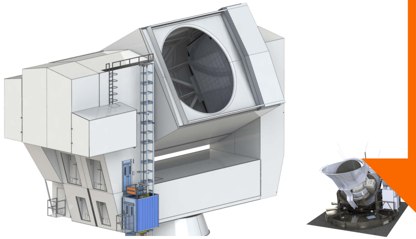


3x lower noise

2023

Simons Observatory

40% of the sky, 1-2 arcmin resolution



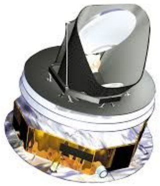
3x lower noise

2028

2018

Planck

70% of the sky, 5-10 arcmin resolution
9 bands, 30 - 857 GHz

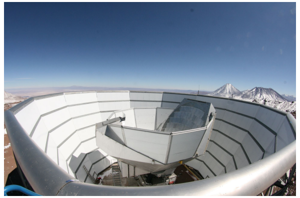


2020

ACT

2021

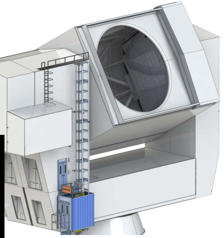
30% of the sky, 1-2 arcmin resolution
98, 150, 226 GHz bands,
30, 40 GHz coming soon!



2023

Simons Observatory

40% of the s
6 bands fro



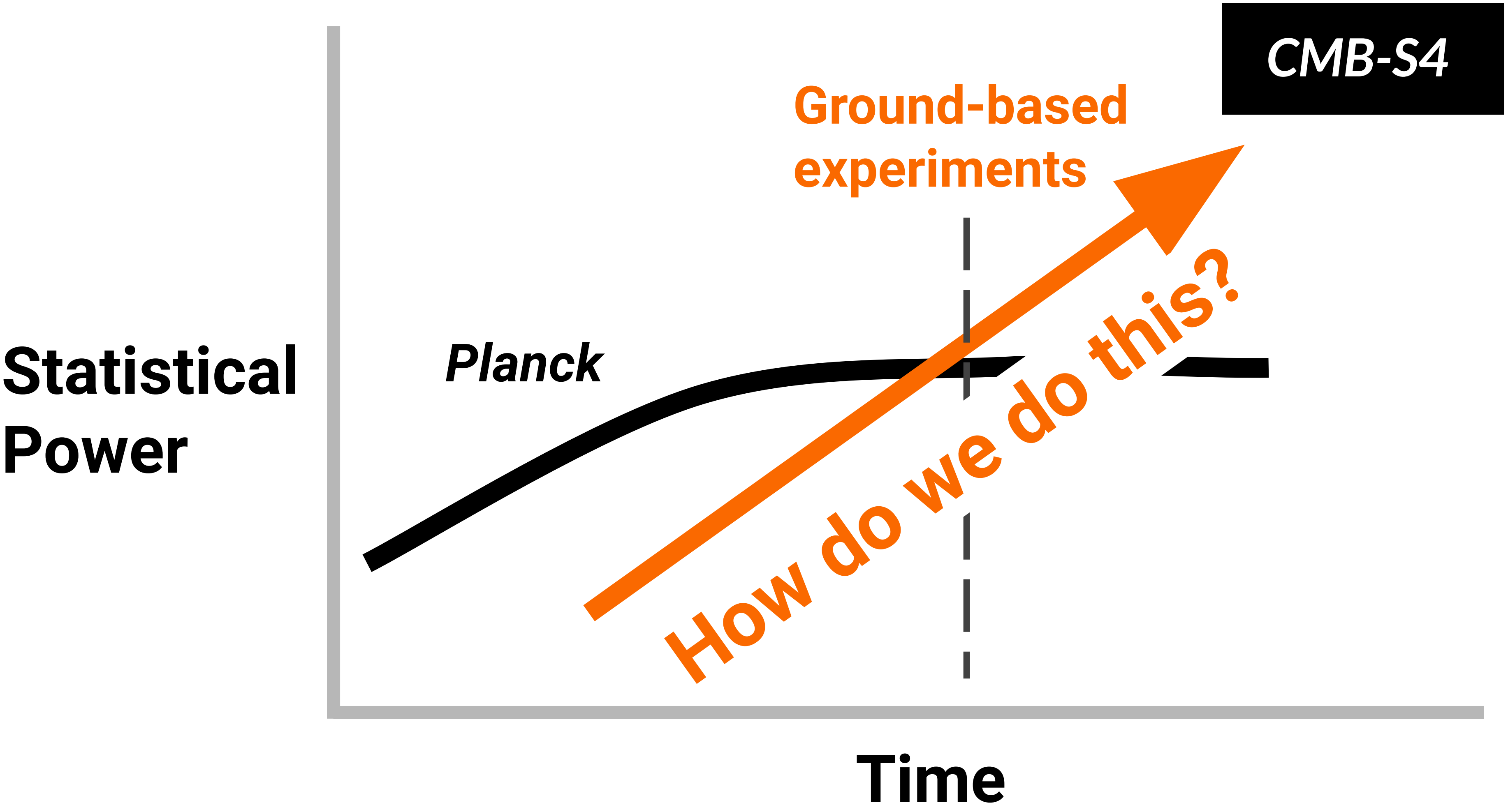
2028

CMB-S4

~10x

sensitivity over Stage-3

2029


CMB-S4
Ground-based experiments
Statistical Power
Planck
How do we do this?
Time

The Simons Observatory LAT

Power Spectrum Pipeline (PSPipe)

Science from just the CMB Primary:

- Measure the **cosmic neutrino background** at early times ($N_{\rm eff}$), other light relics
- Search for **dark matter** interactions, isocurvature
- Test models which resolve the Hubble tension, like **Early Dark Energy**

Science from Secondaries (Joint Estimation)

- Sum of the **neutrino masses** from lensing, clusters
- **Non-gaussianity** and galaxy evolution from kSZ, clusters/tSZ
- High redshift **dark energy** from lensing

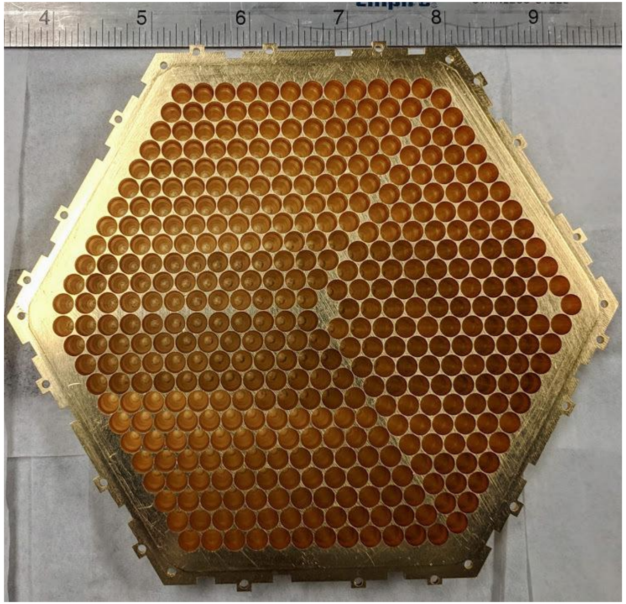
$$N_{\mathrm{eff}} = 3.046 \pm \sigma$$

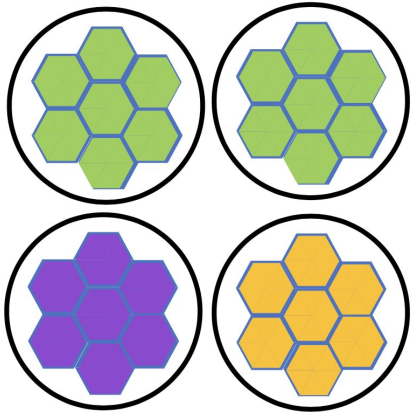
Planck σ	~ 0.2
ACT forecast σ	~ 0.1
SO σ	~ 0.05

What will it take to **double** our sensitivity to N_{eff}?

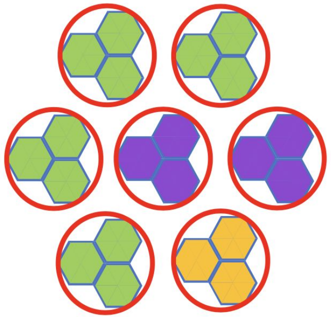
What will it take to **quadruple** our sensitivity to N_{eff}?

Prerequisite:
Fill up the focal plane with detector arrays

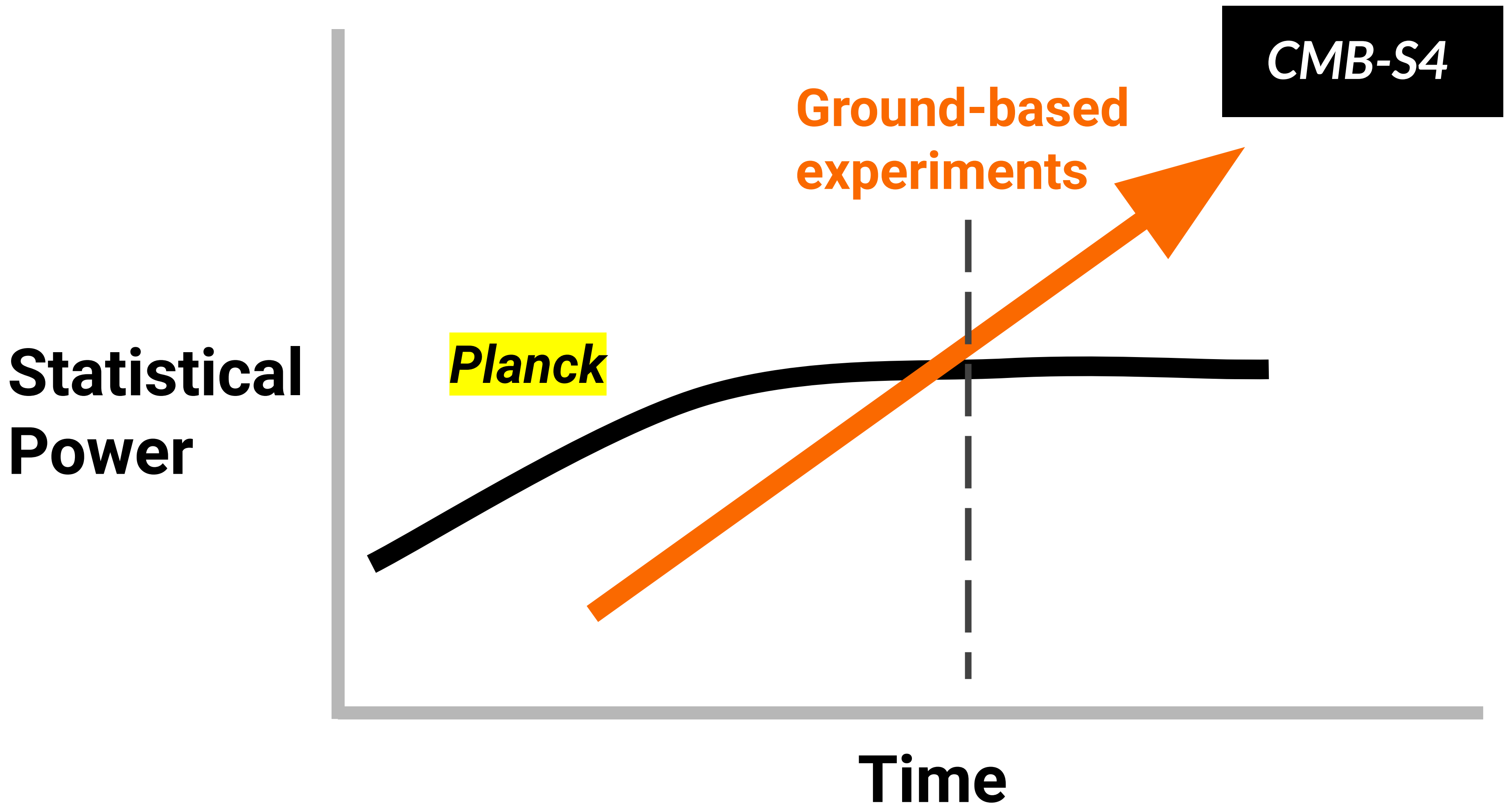




4 SAT focal planes



6m (LAT) inner focal plane


CMB-S4
Ground-based
experiments
Planck
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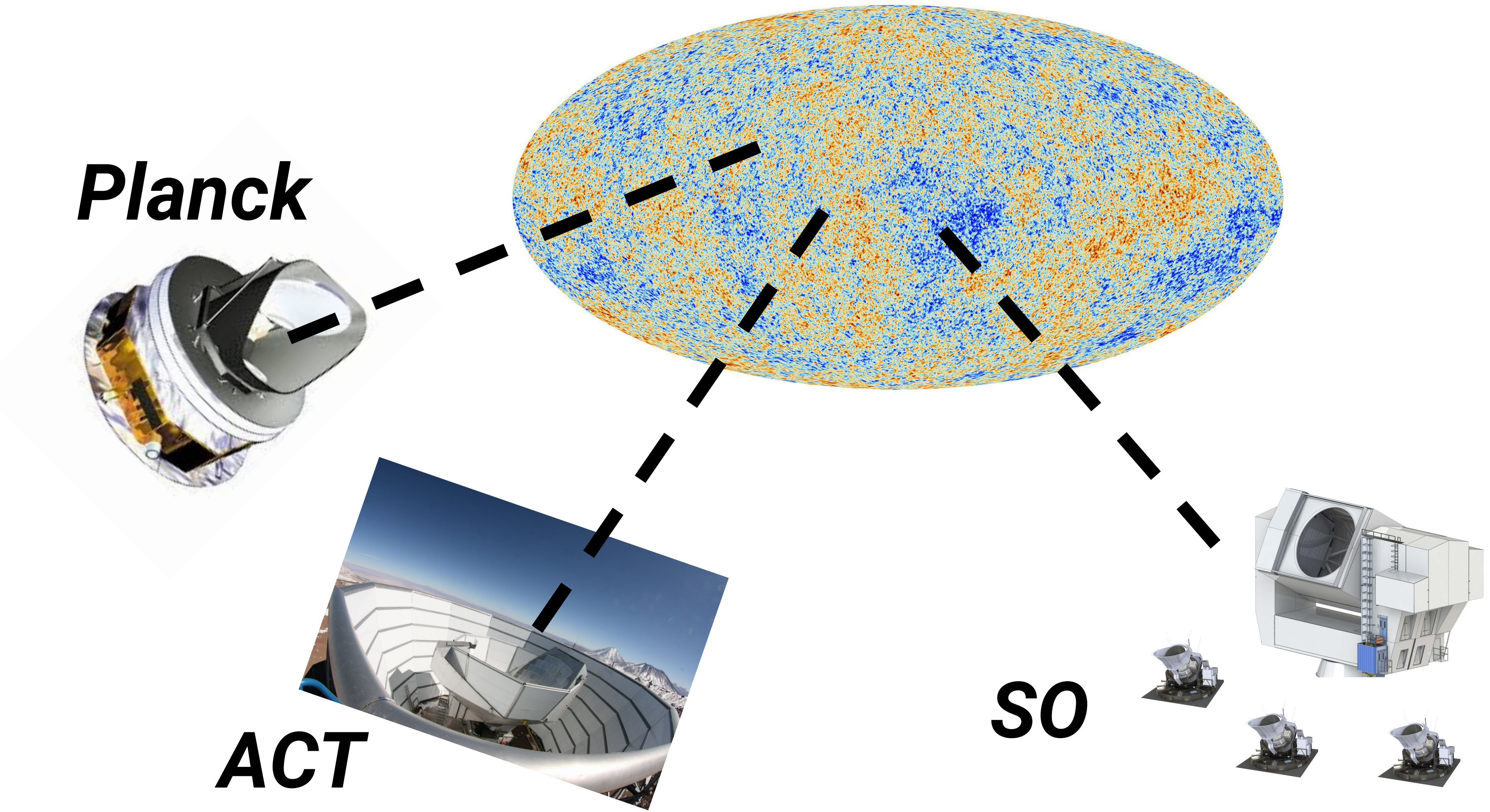
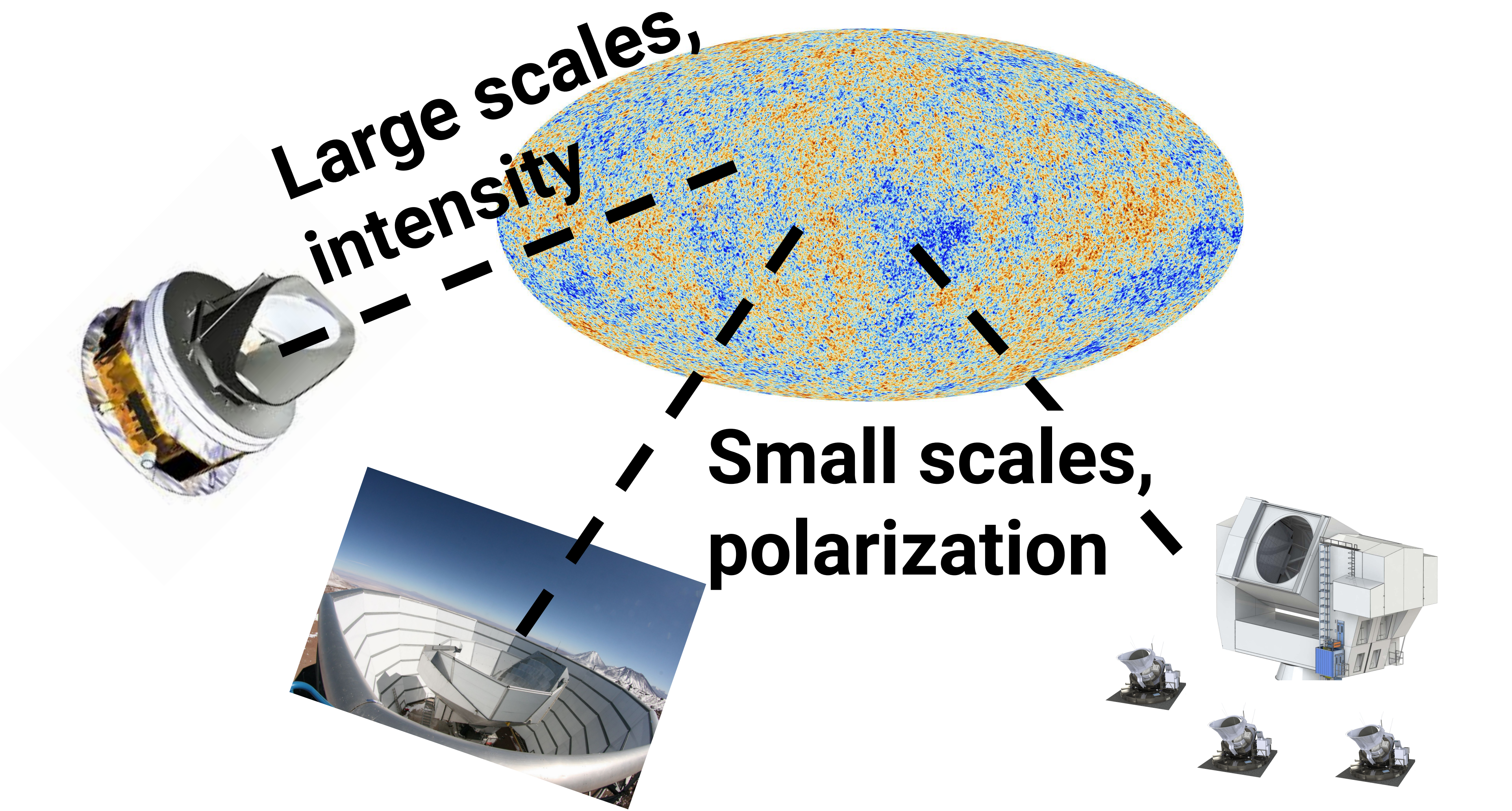
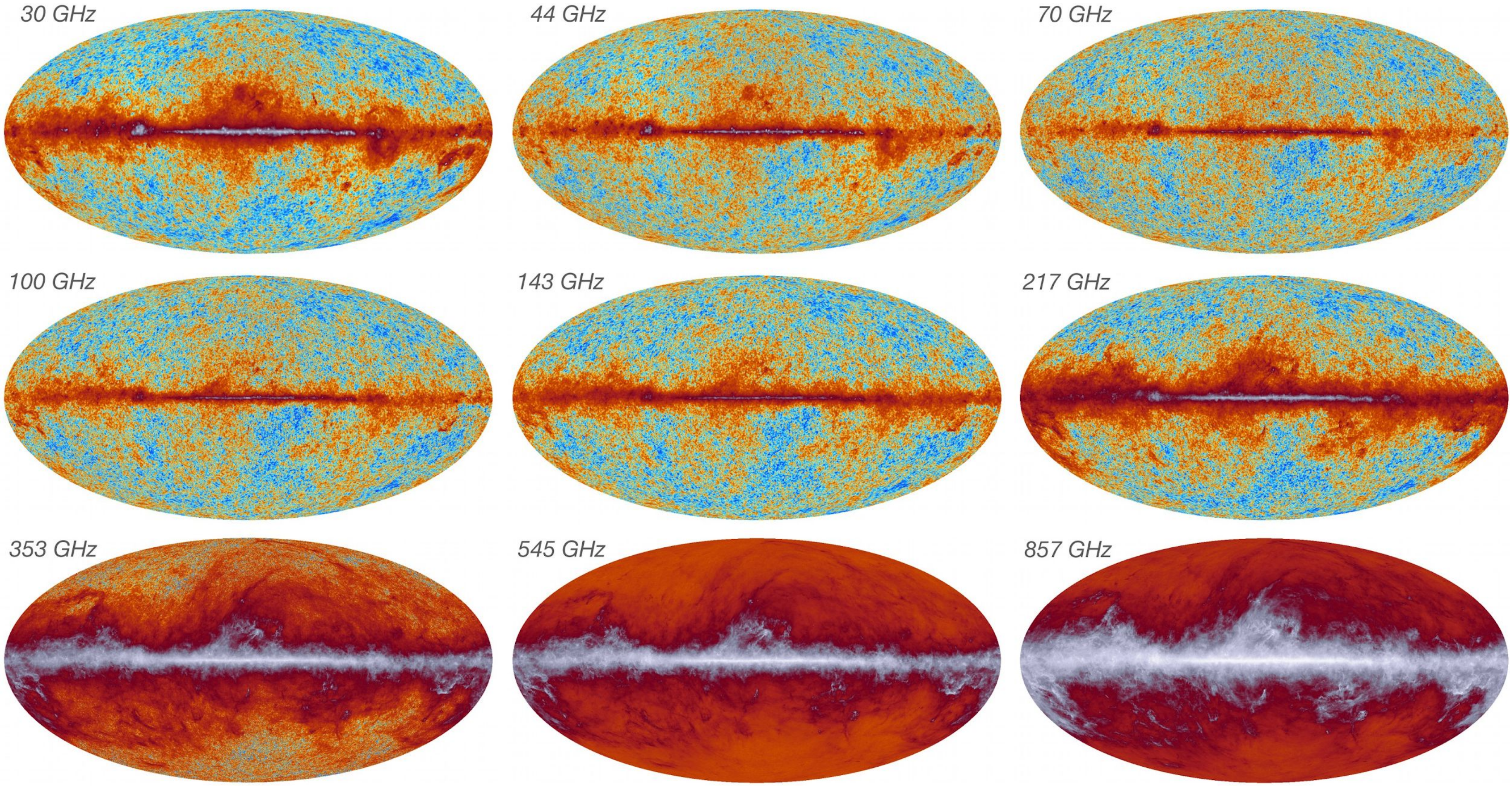
Power
Time


Planck
ACT
SO


Large scales,
intensity
Small scales,
polarization

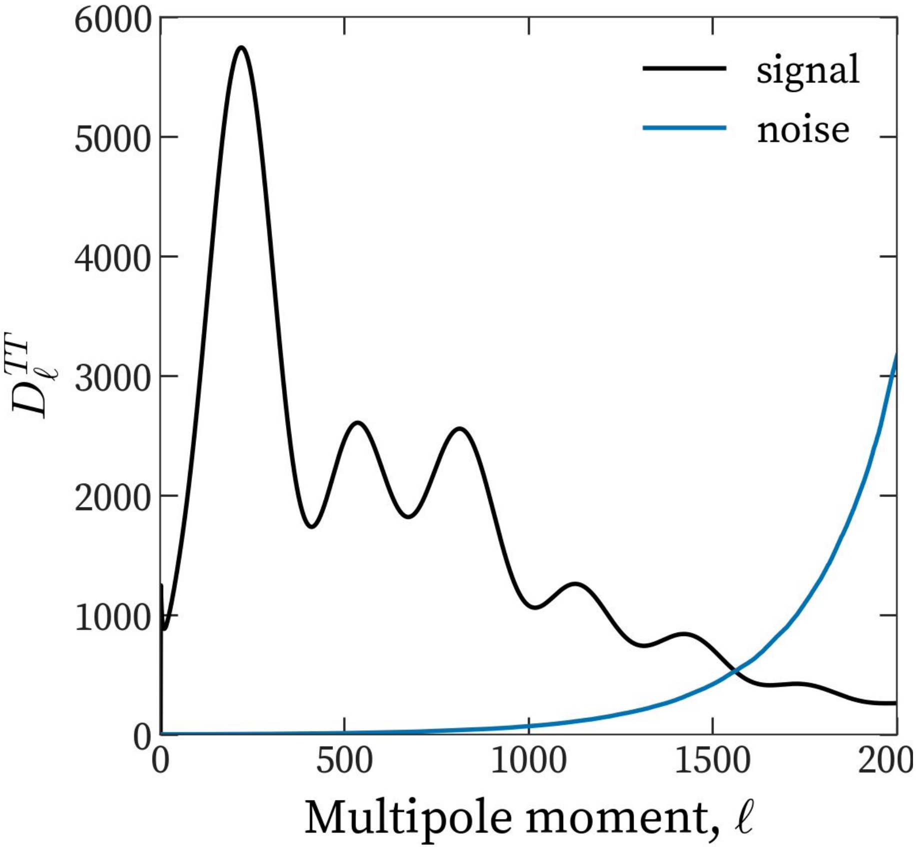
Planck

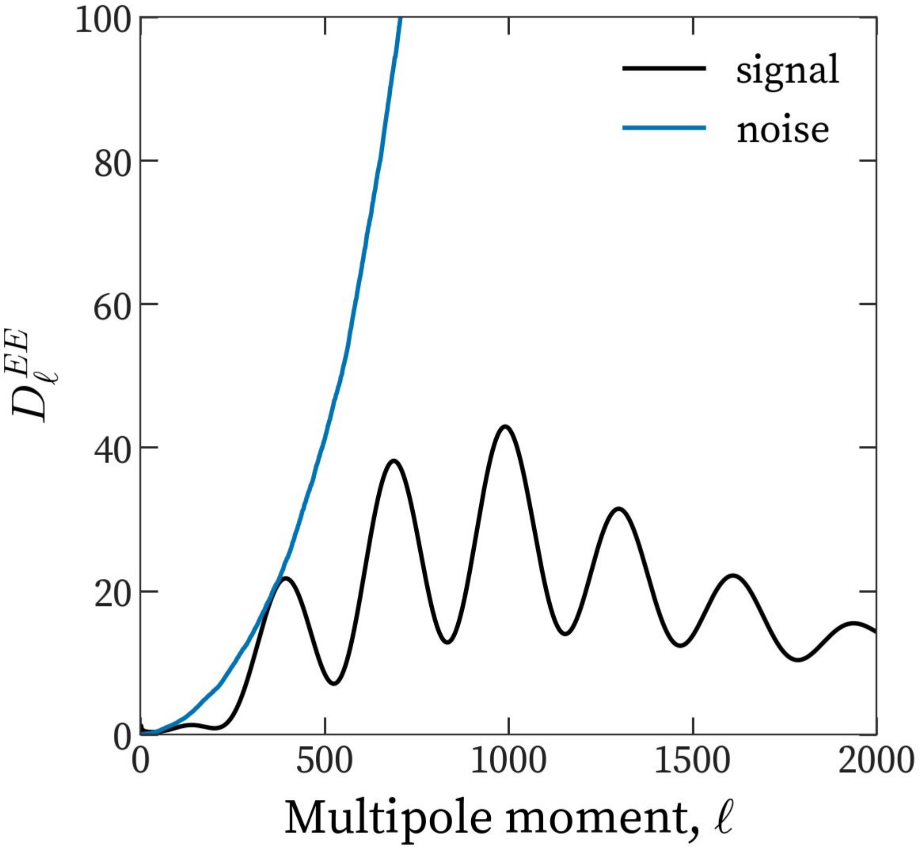
We’ll be using its data well into the next decade!



Planck Collaboration, 2018

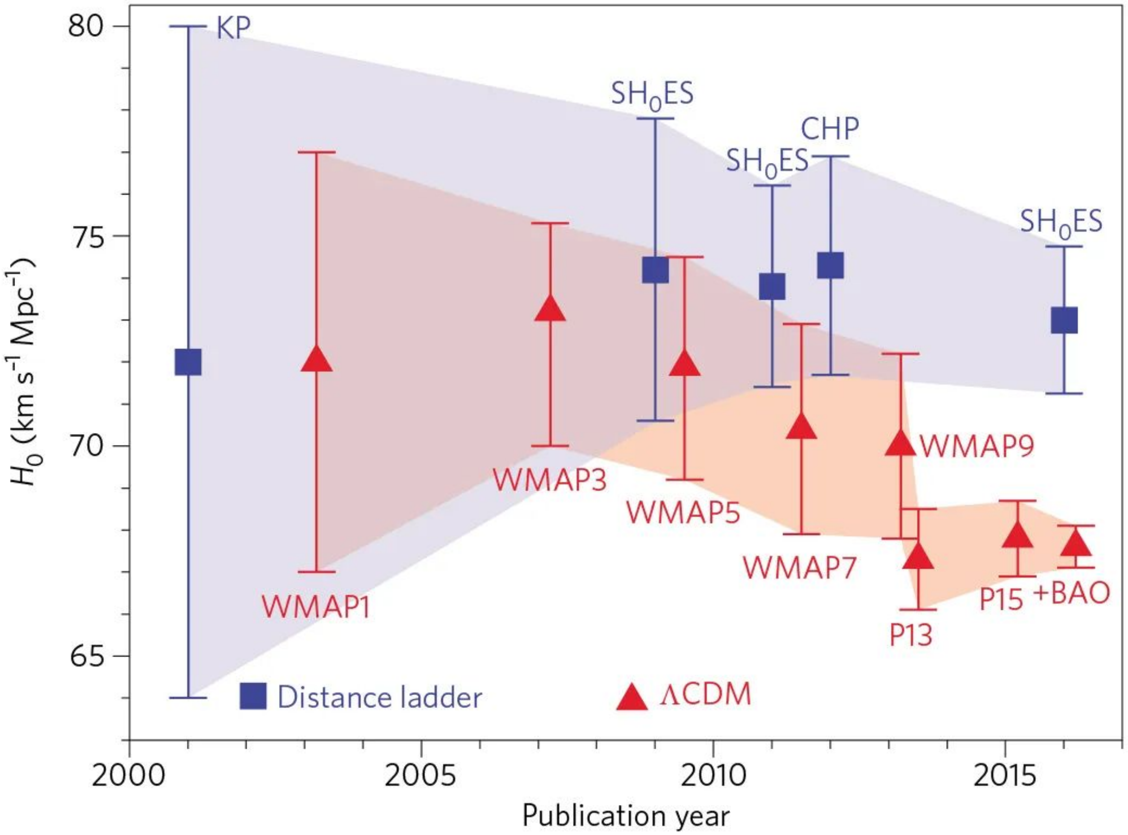
Planck has **full sky** temperature (CV-limited to ℓ~1800).





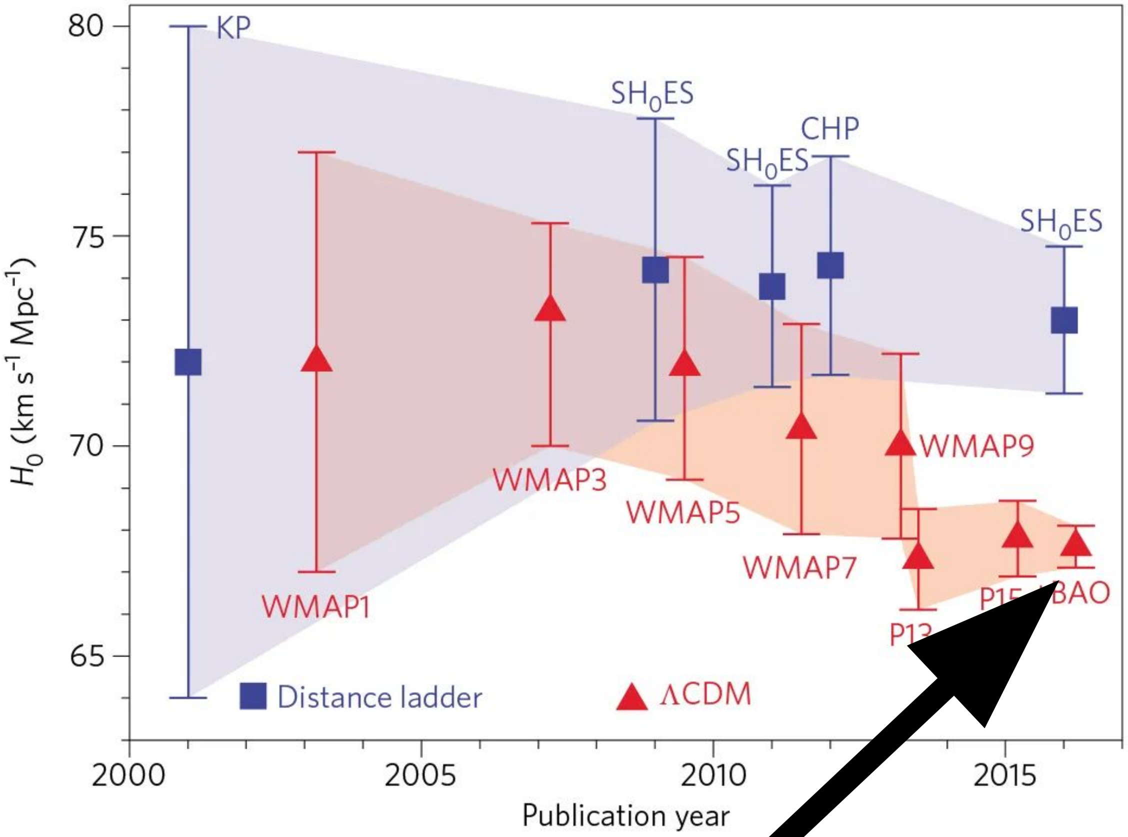
Planck 143 GHz

~4σ Hubble Tension



Beaton et al. 2016

~4σ Hubble Tension

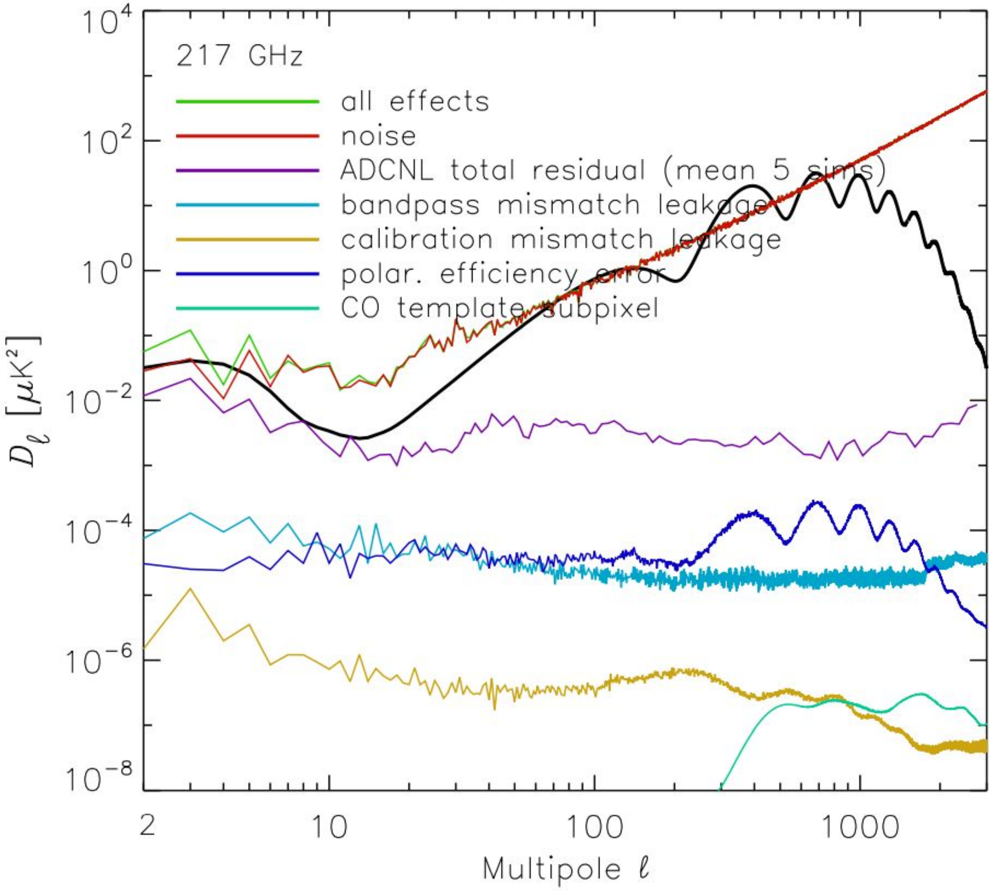


Planck

Beaton et al. 2016

Space is ***really great.***

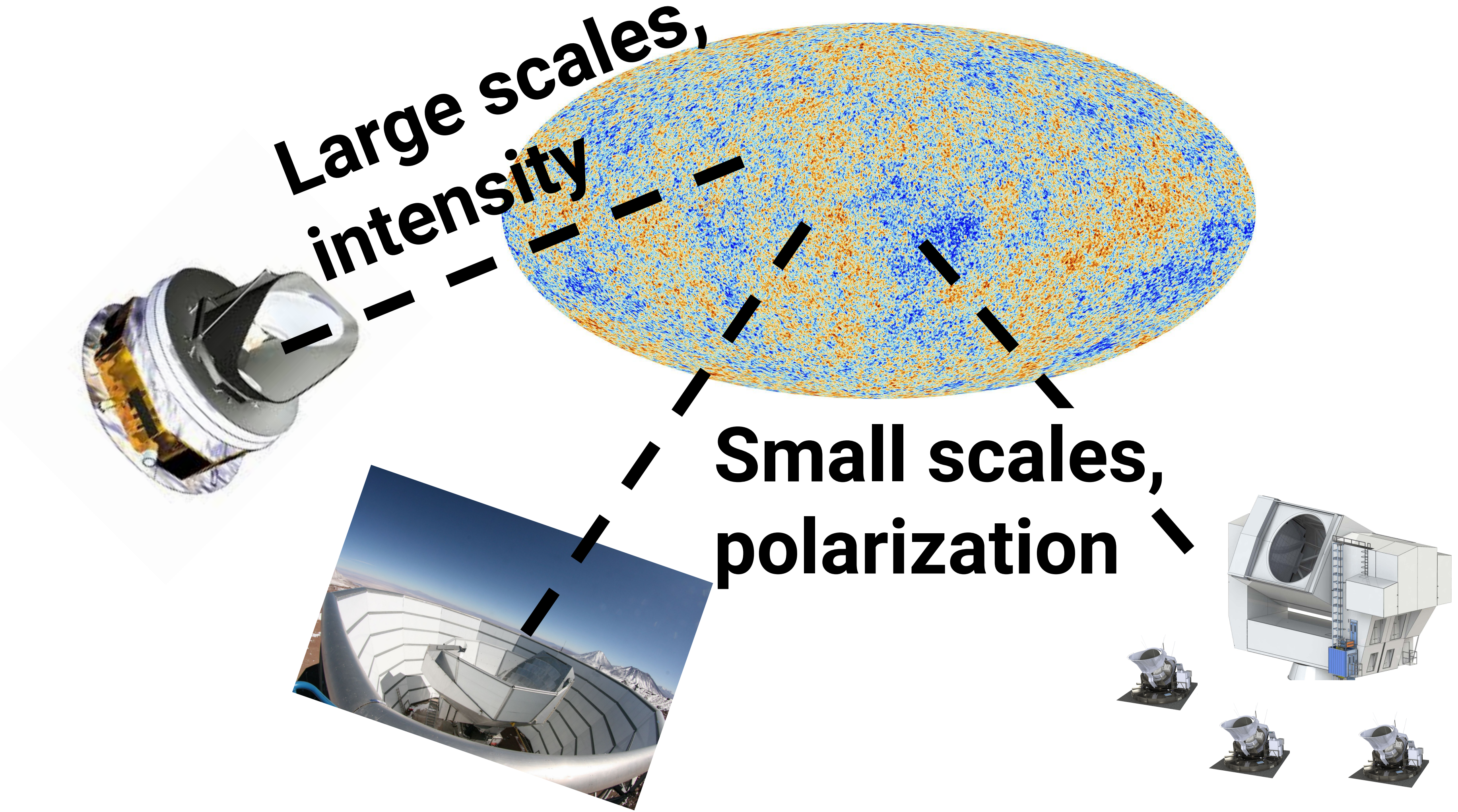
Planck had ***exquisite*** systematics control.



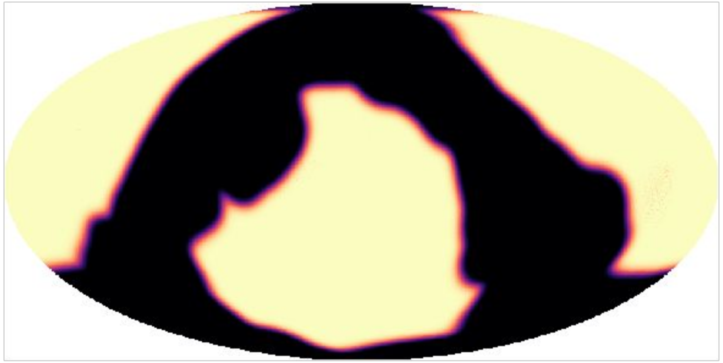
Planck 2018 III. HFI DPC


ACT

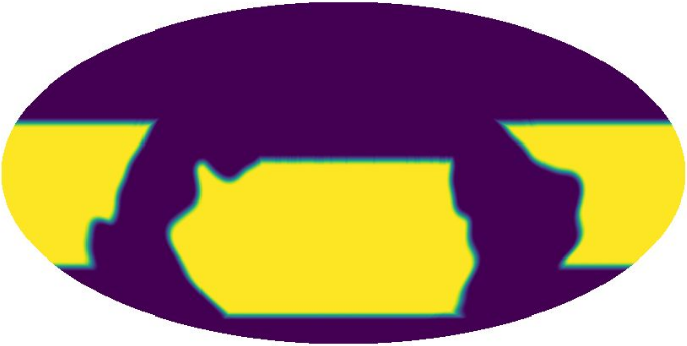

Ground
Pickup
PWV
ACT


Large scales,
intensity
Small scales,
polarization

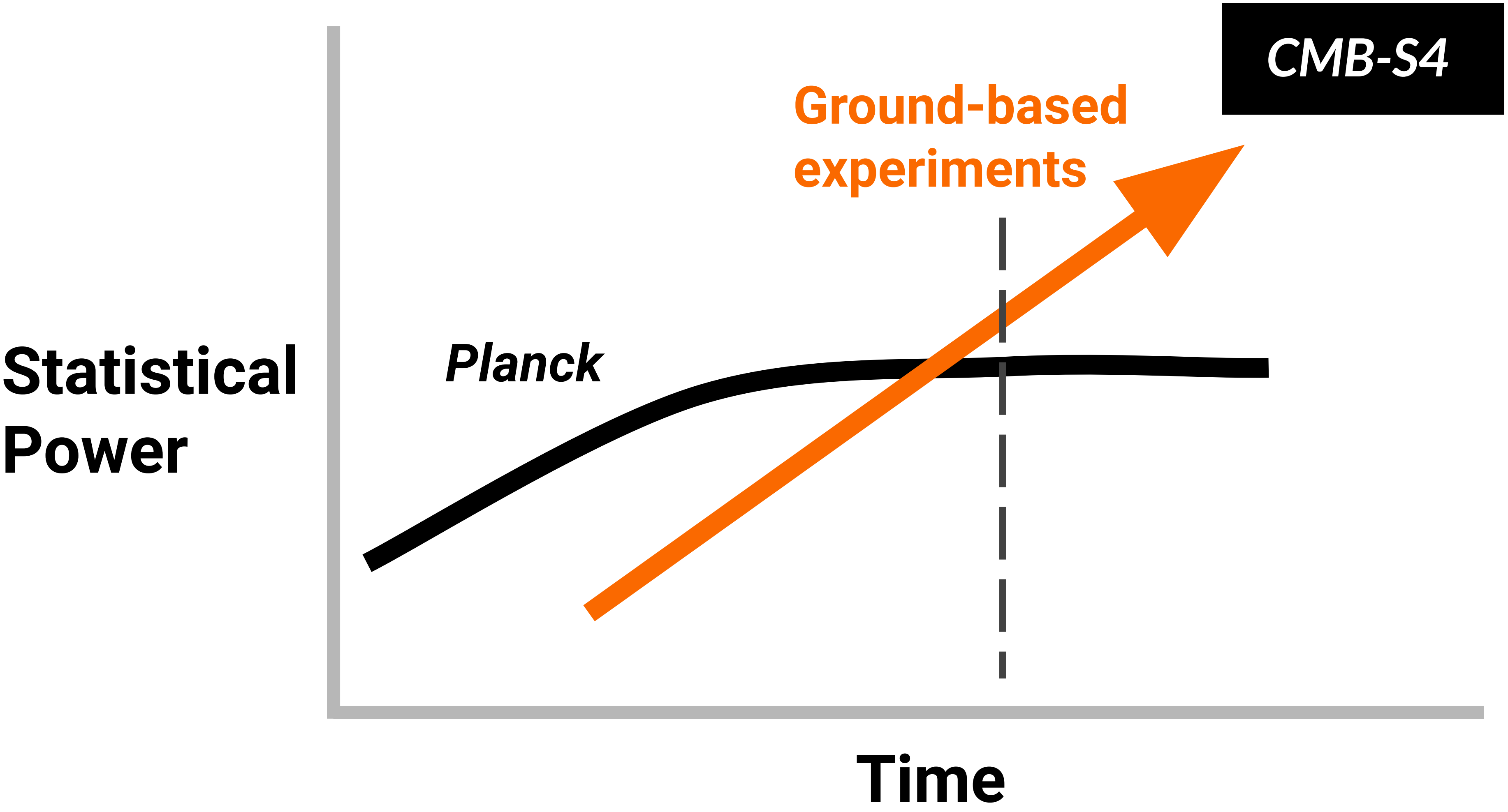
We observe the same sky.



Planck

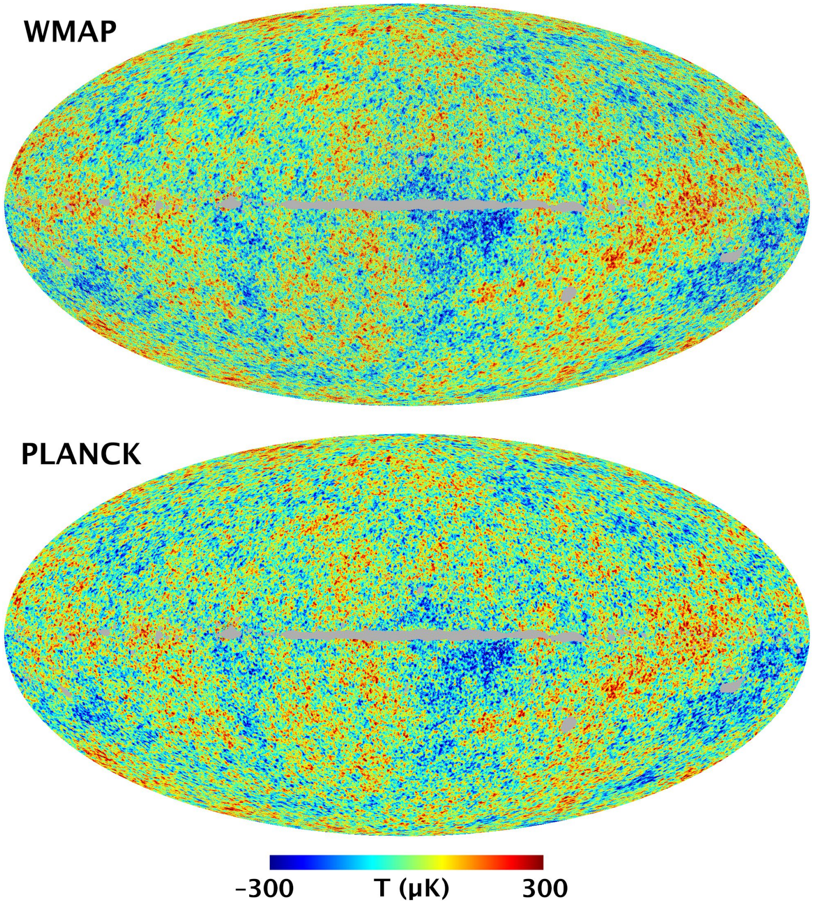


Simons Observatory



CMB-S4
Ground-based experiments
Planck
Statistical Power
Time

To extract cosmology, we need to know the covariance **between surveys.**

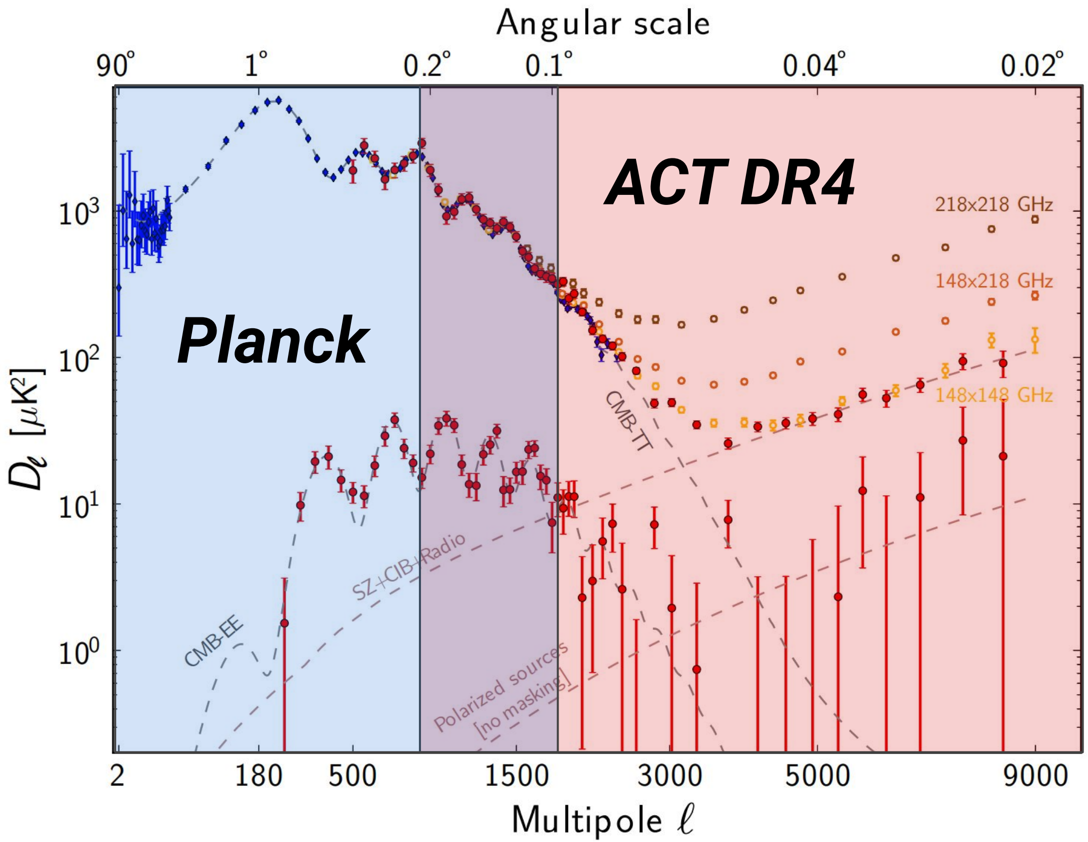


WMAP Science Team

Data analysis is **complicated**, and the data scale is rapidly increasing.

Planck made a set of analysis choices. Current and future experiments like *ACT* and *SO* will make choices...

Planck and the ground dominate at **different regimes**, so making different choices between instruments is dangerous.



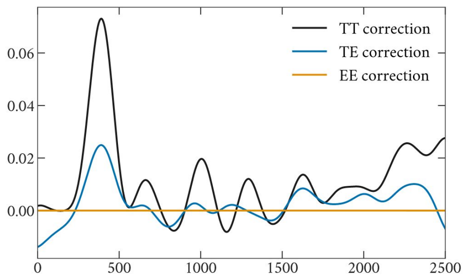
Modified from Choi et al. 2020

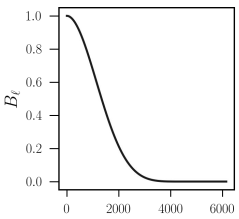
Li et al. + SO Collaboration, in prep.

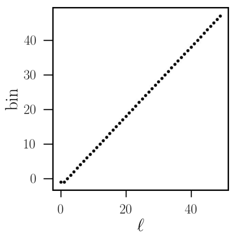
This detailed re-analysis of *Planck* will be used in **every** future ACT and SO power spectrum analysis.

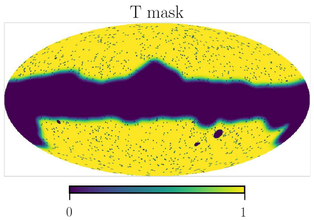
A **cosmology-grade** power spectrum analysis of the legacy Planck maps.

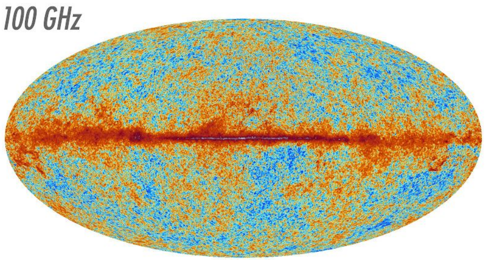
Signal and Noise

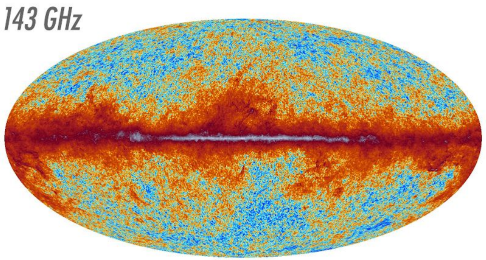


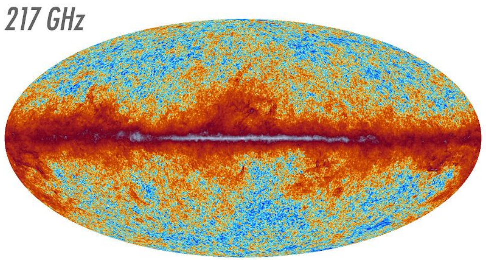








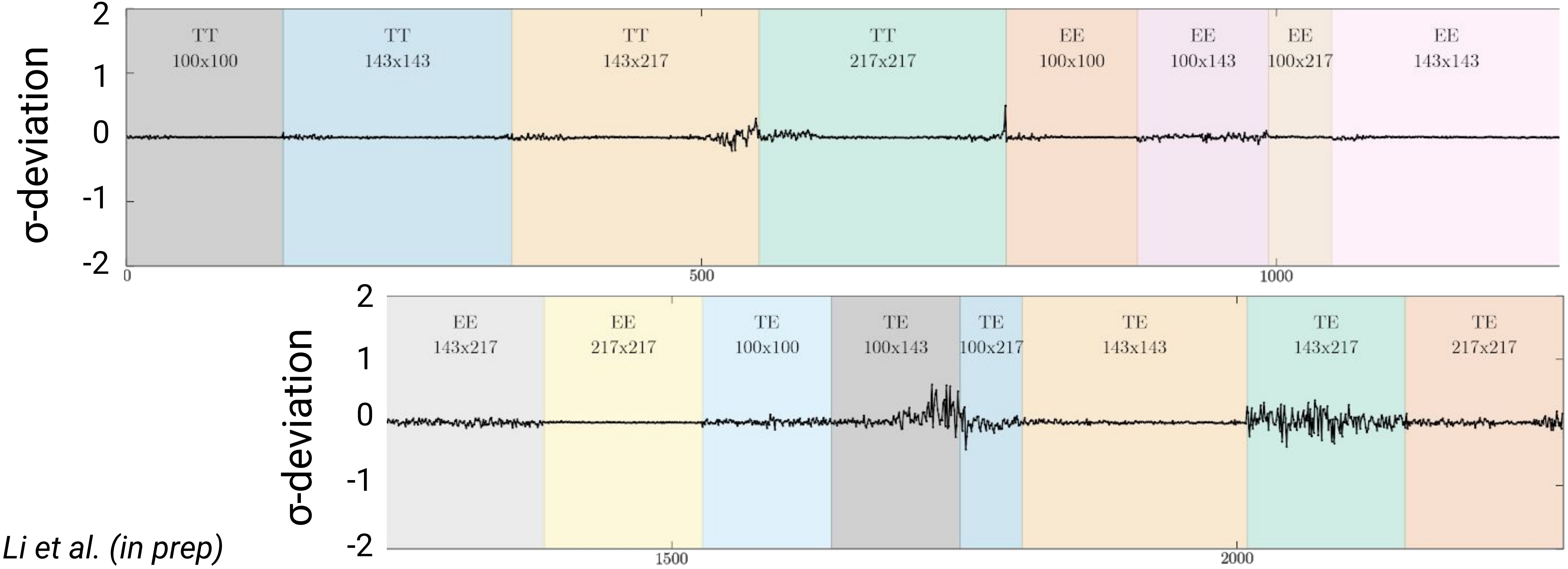




1. Check their analysis.
2. Build the SO pipeline.

Agreement

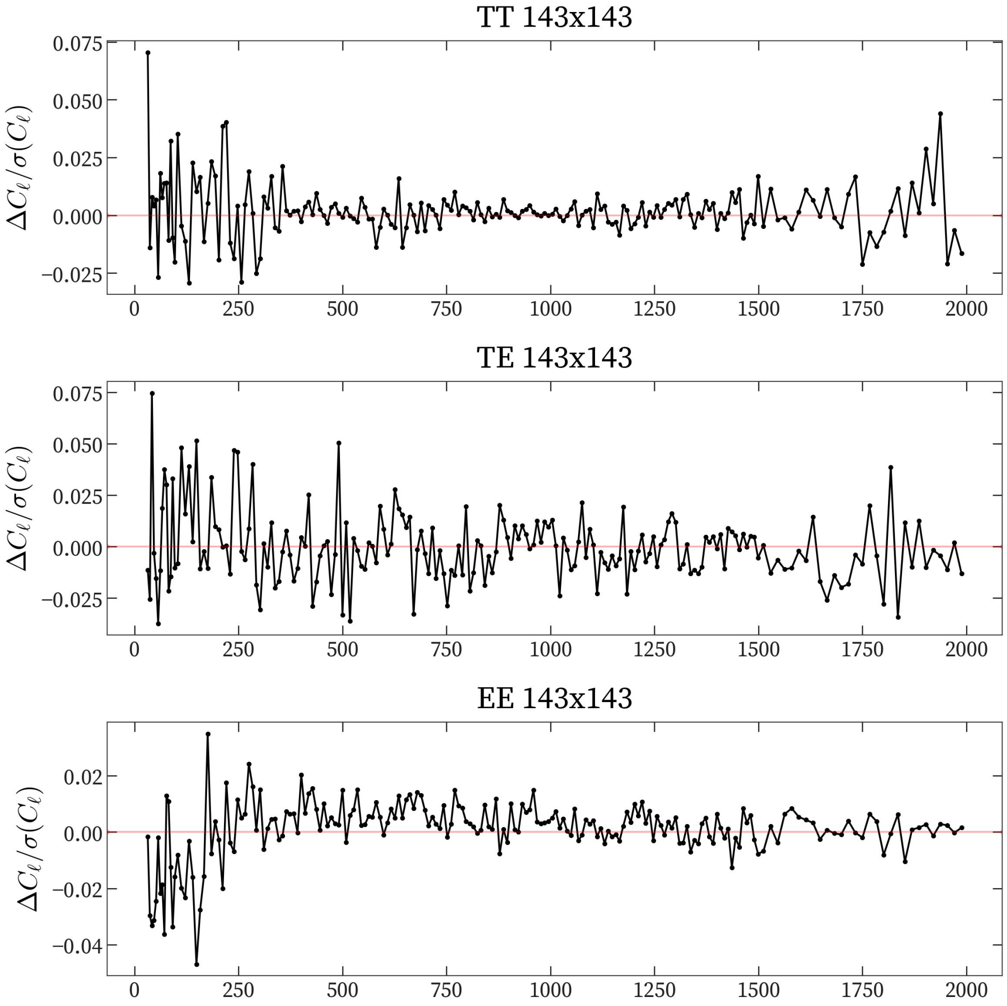
0.1σ in all frequencies and cross-spectra



Li et al. (in prep)

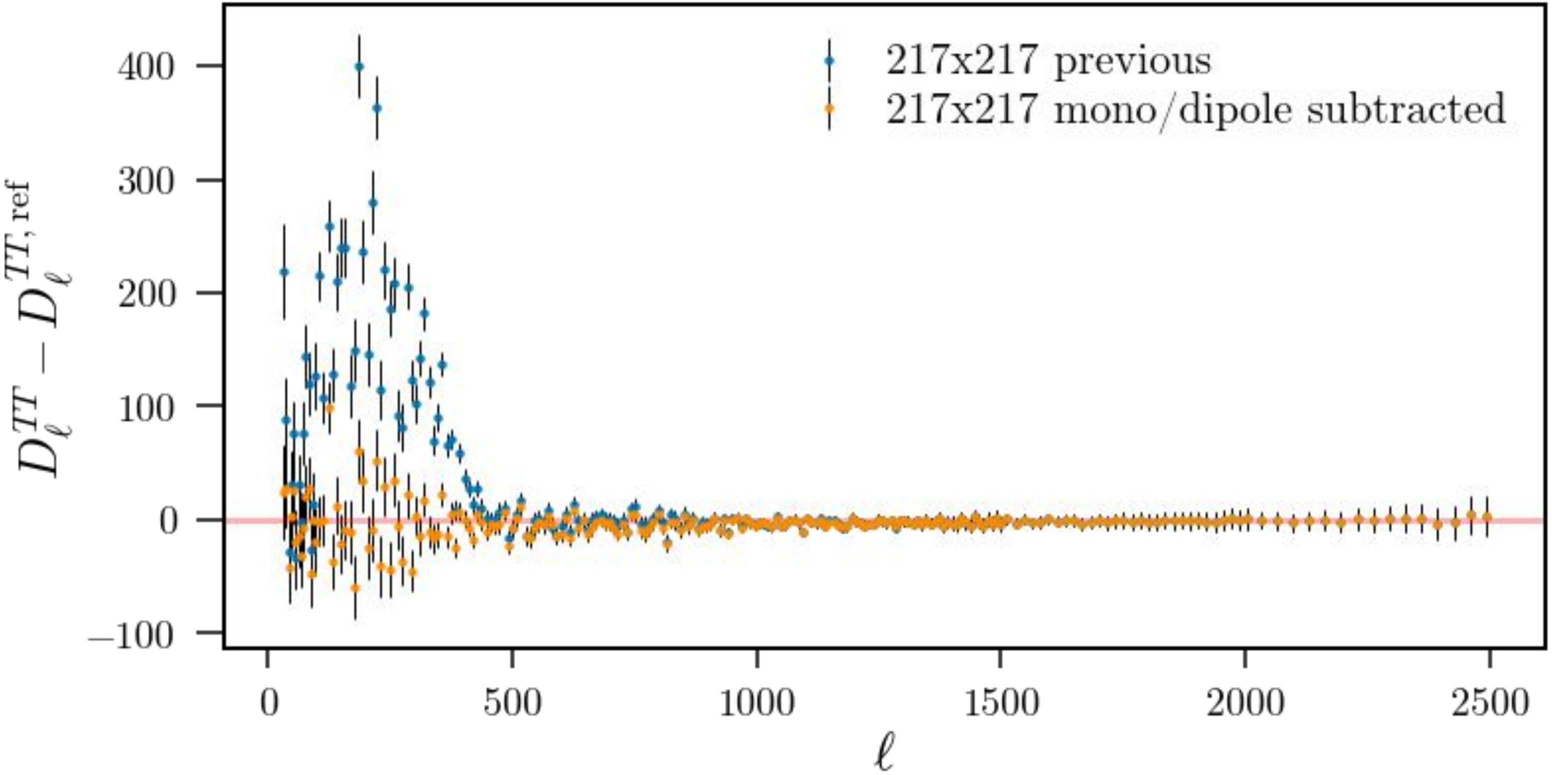
143 GHz

Residuals due to use of PolSpice



Li et al. (in prep)

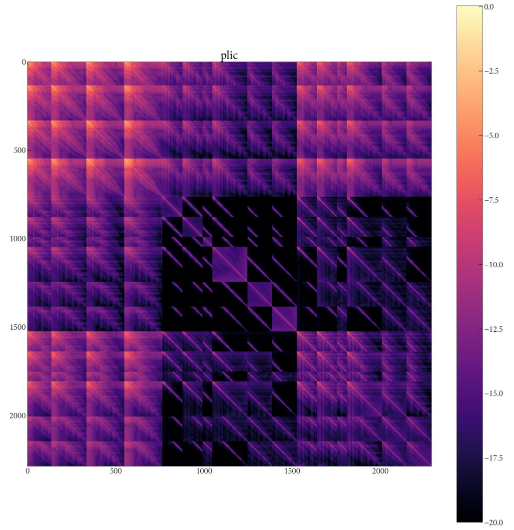
Example of what can go wrong

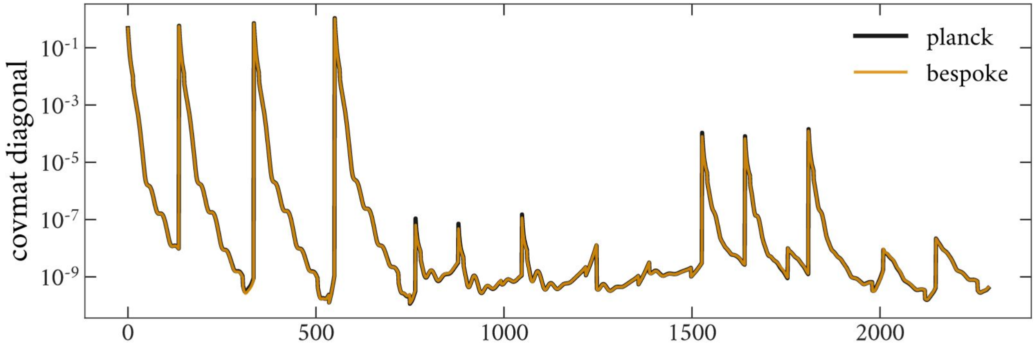


Li et al. (in prep)

Covariance

We re-estimate the Planck covariance matrices, using the same treatment of inhomogeneous noise.



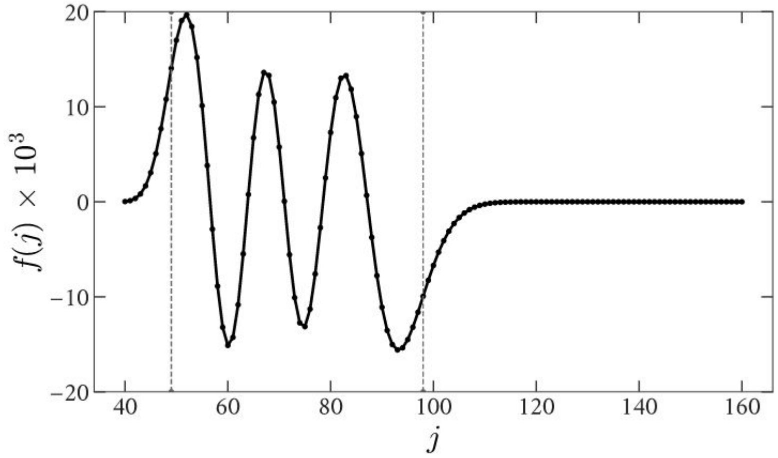


Li et al. (in prep)

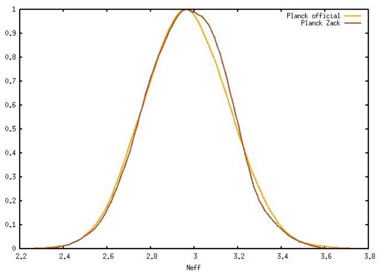
Aside: check out WignerFamilies.jl, a package that computes Wigner 3j symbols **twice as fast as SLATEC**.

I wrote it so I could develop the curved-sky mode-coupling and covariance codes used in this analysis.

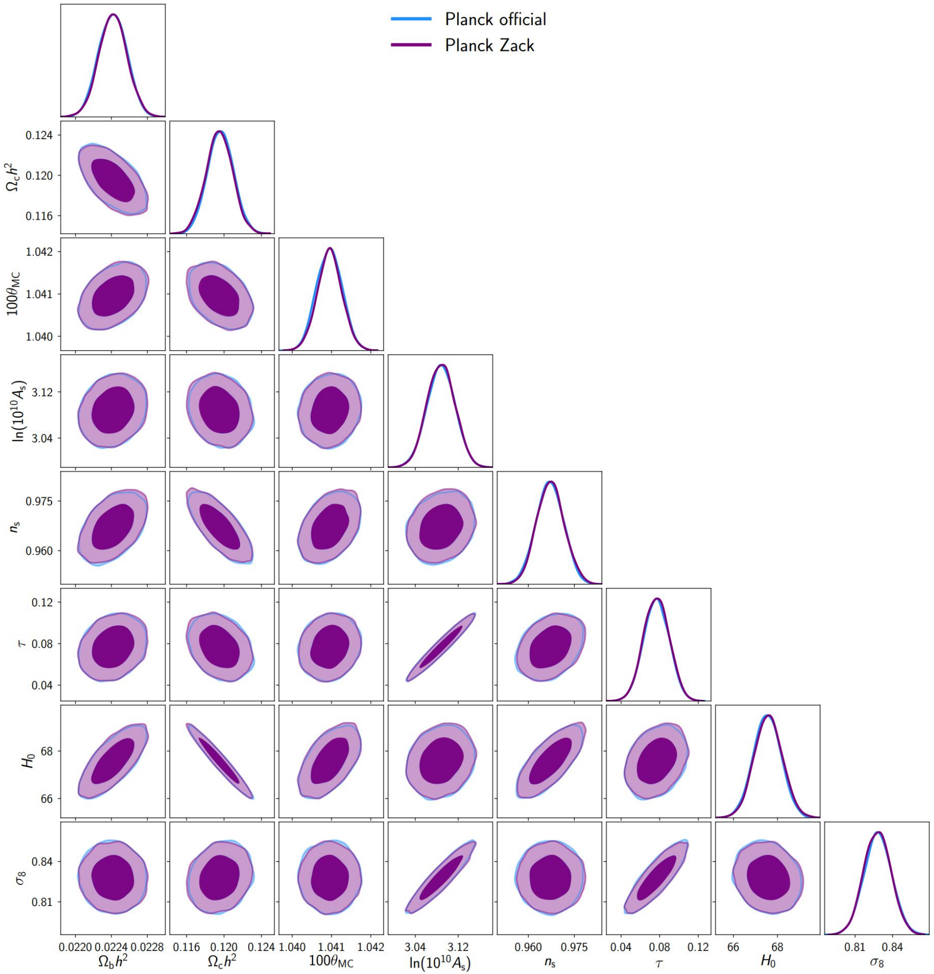
$$f(j) = \begin{pmatrix} j & j_2 & j_3 \\ -m_2 - m_3 & m_2 & m_3 \end{pmatrix}$$



Maps to power spectra to covariances to **agreement in cosmology!**

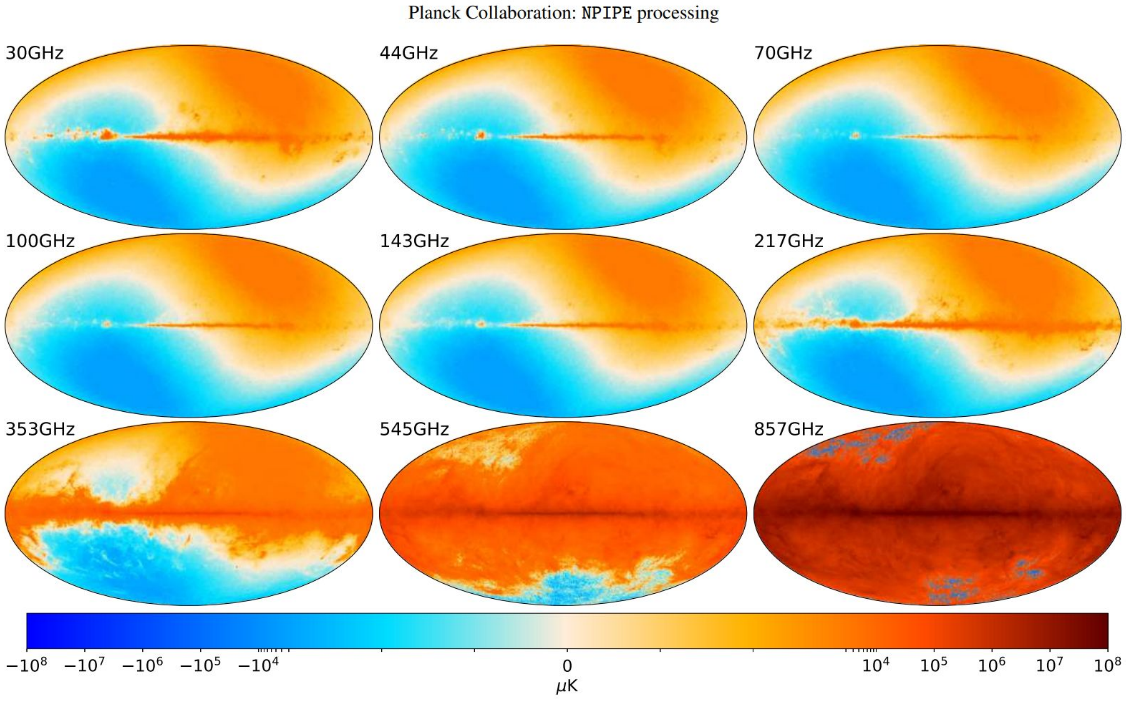


N_{eff}



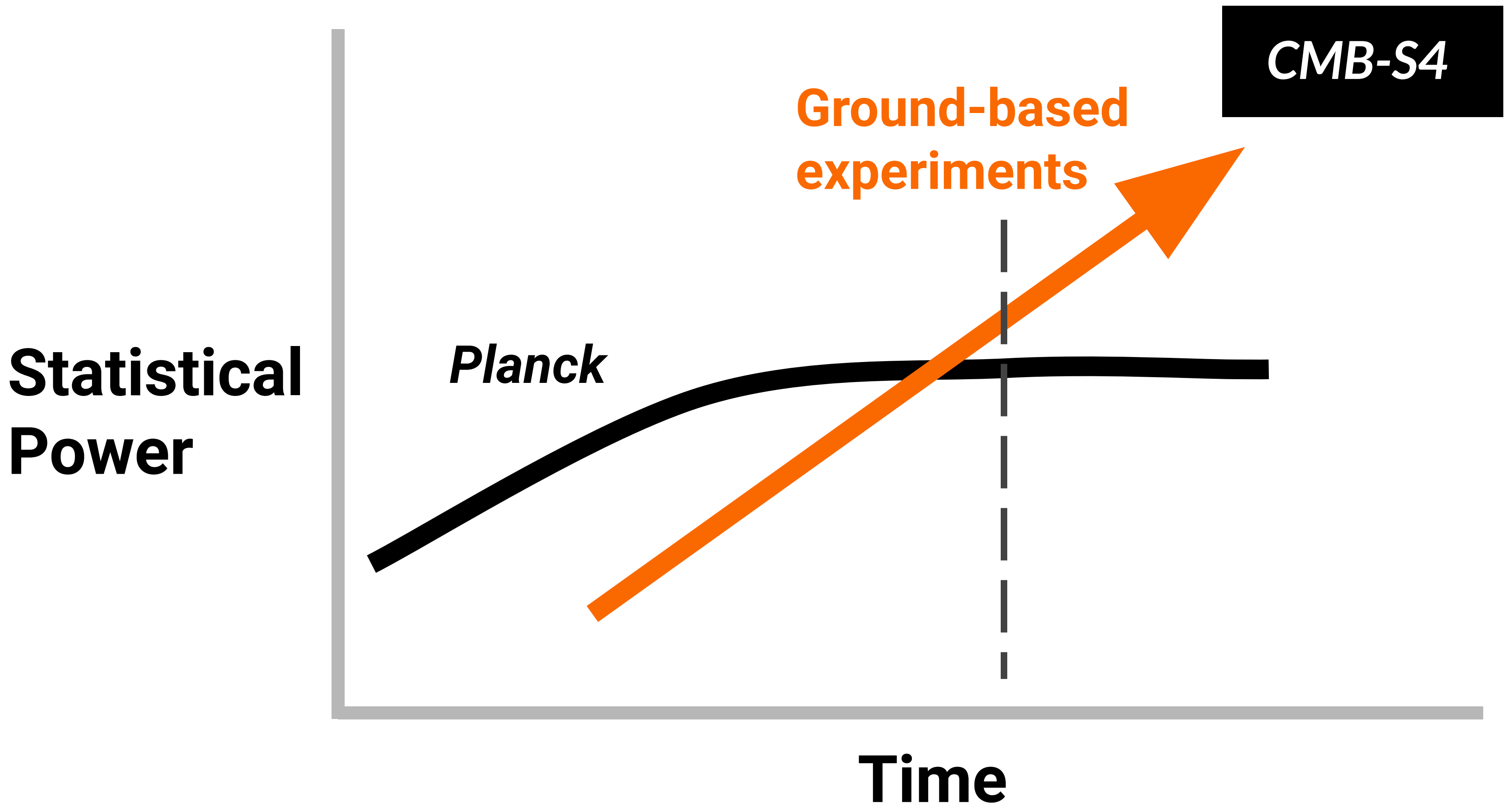
Li et al. (in prep)

NPIPE analysis is up next



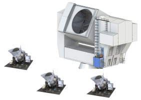
$$N_{eff} = 3.046 \pm \sigma$$

Planck σ	~ 0.2
ACT forecast σ	~ 0.1
SO σ	~ 0.05

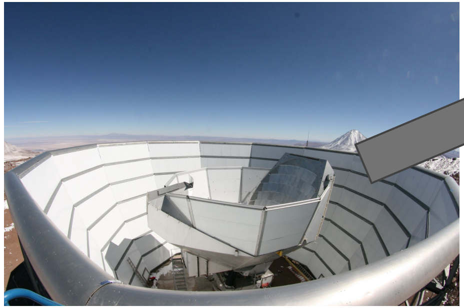

CMB-S4
Ground-based experiments
Statistical Power
Planck
Time

My next year or two:

Planck



ACT



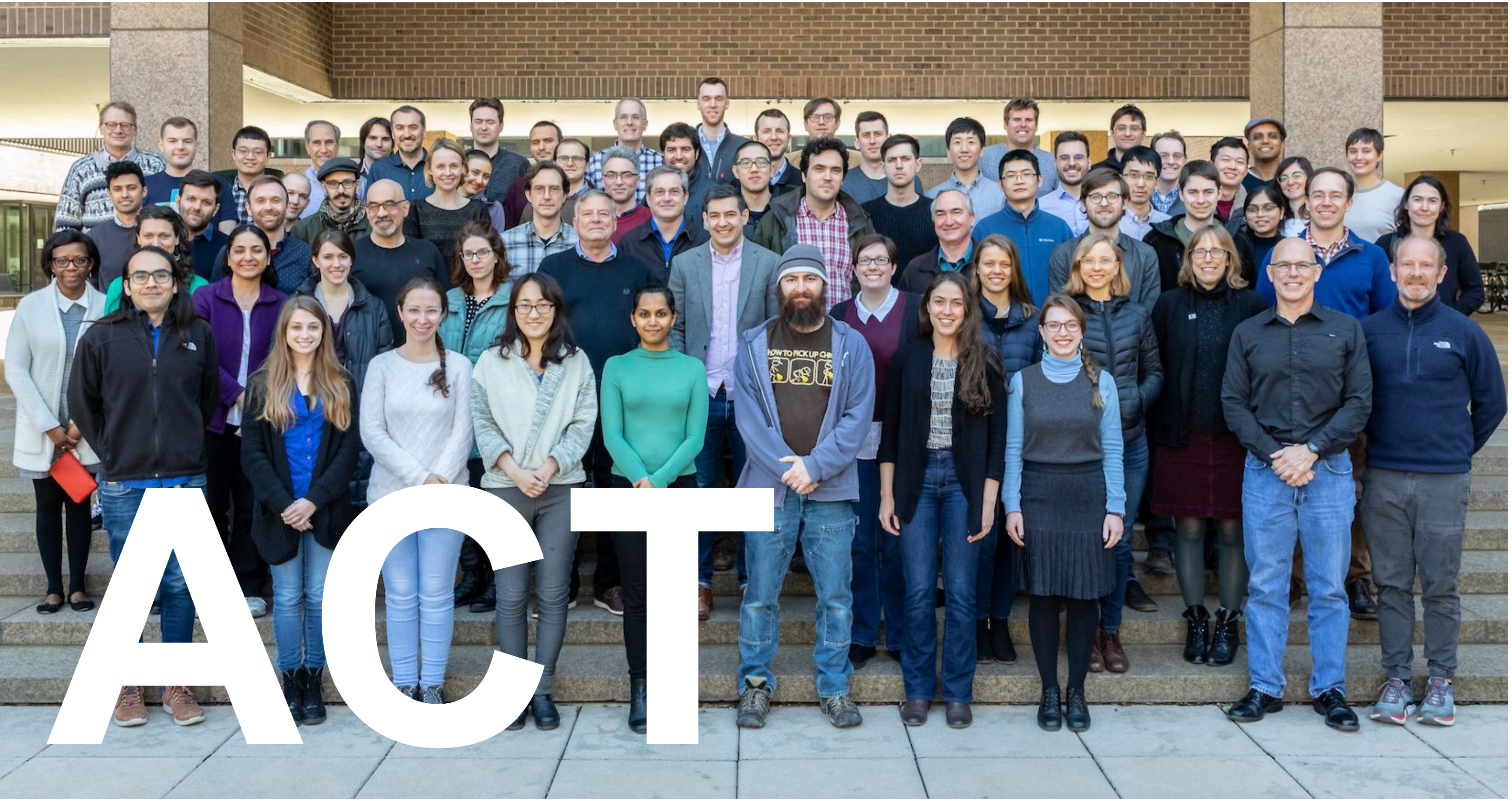
SO

SIMONS OBSERVATORY

PSPipe

Image credit: Debra Kellner

Argonne CITA ICAT HAVERFORD NIST RUTGERS SLAC Stony Brook University Penn WCU West Chester University



ACT

NSF

CONICYT
Ministerio de Educación
Gobierno de Chile

DR4:
ACT data through 2016

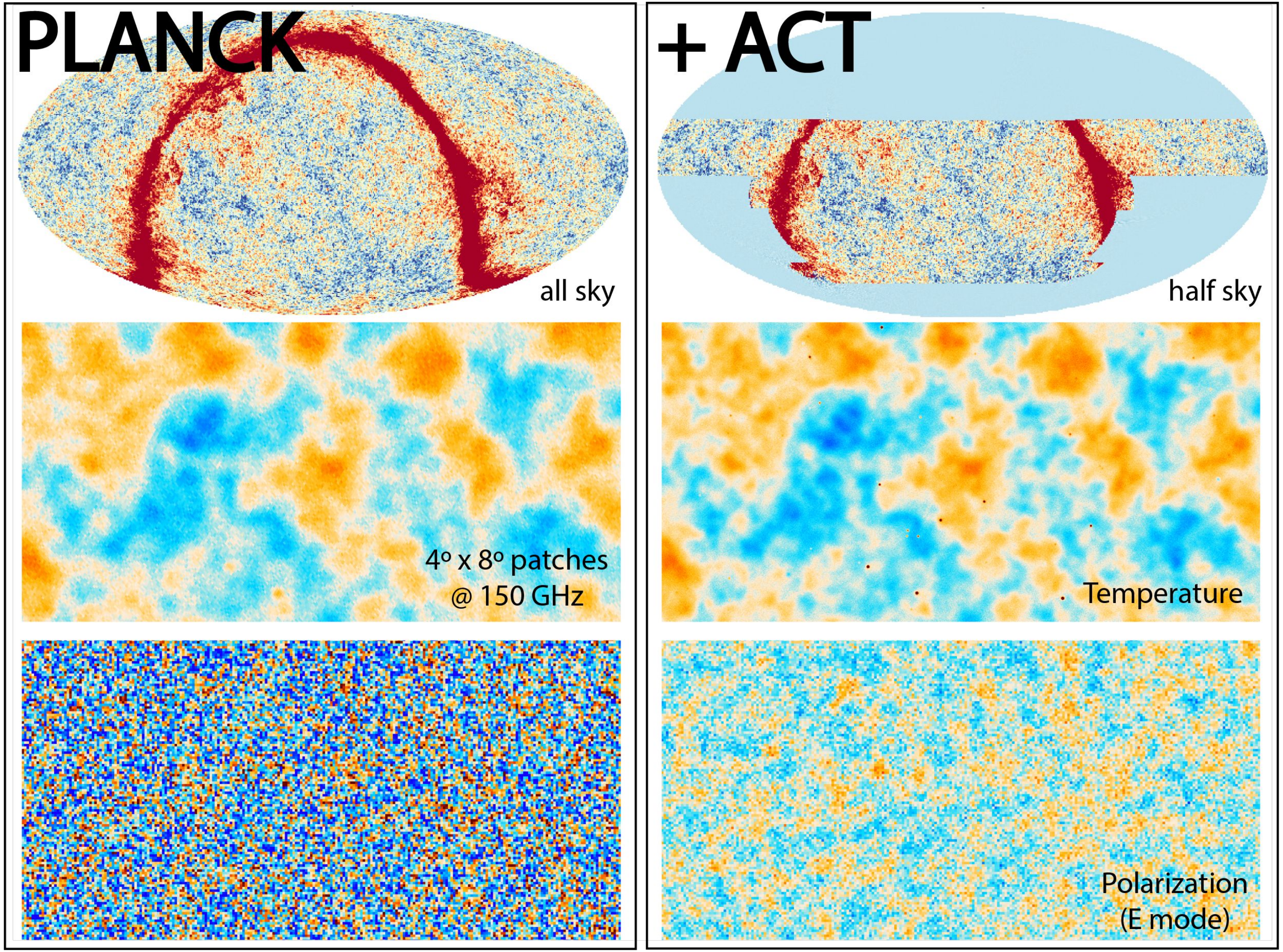
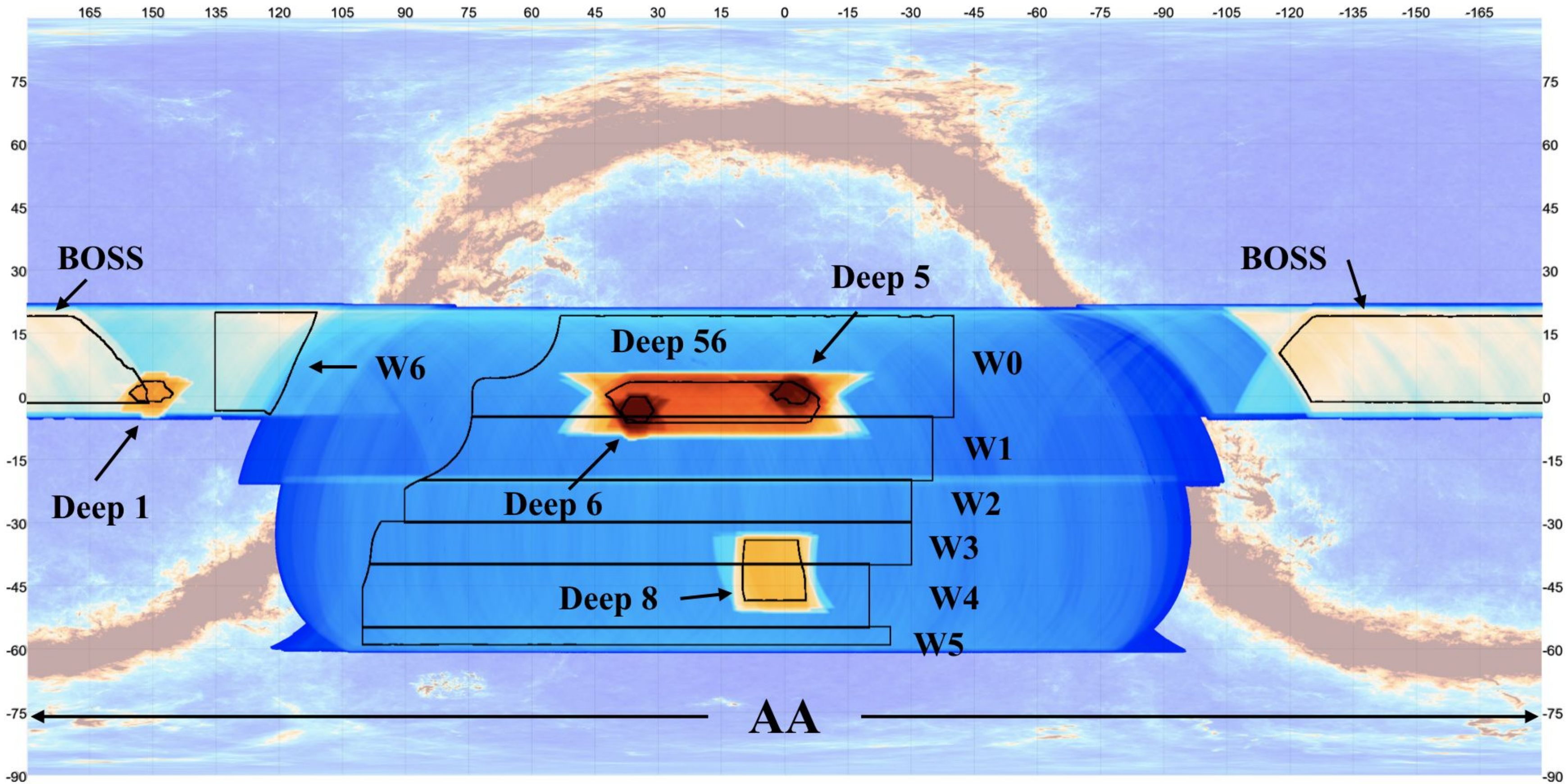
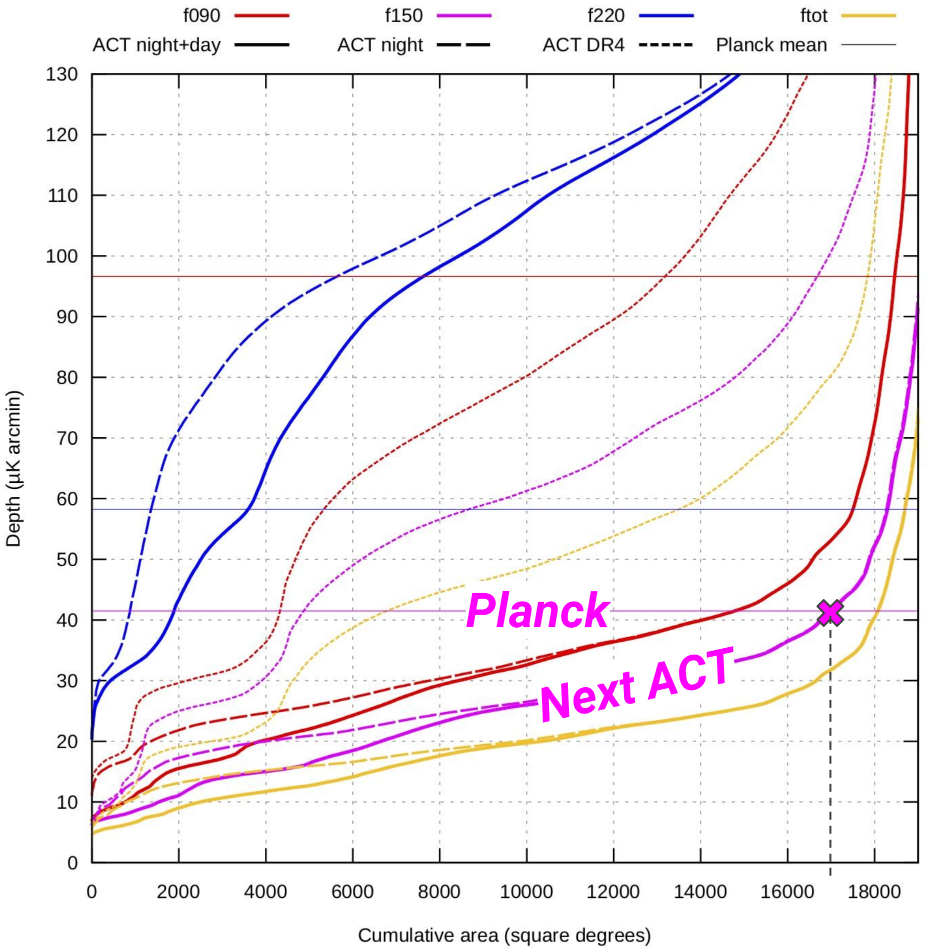


Image credit: ACT Collaboration



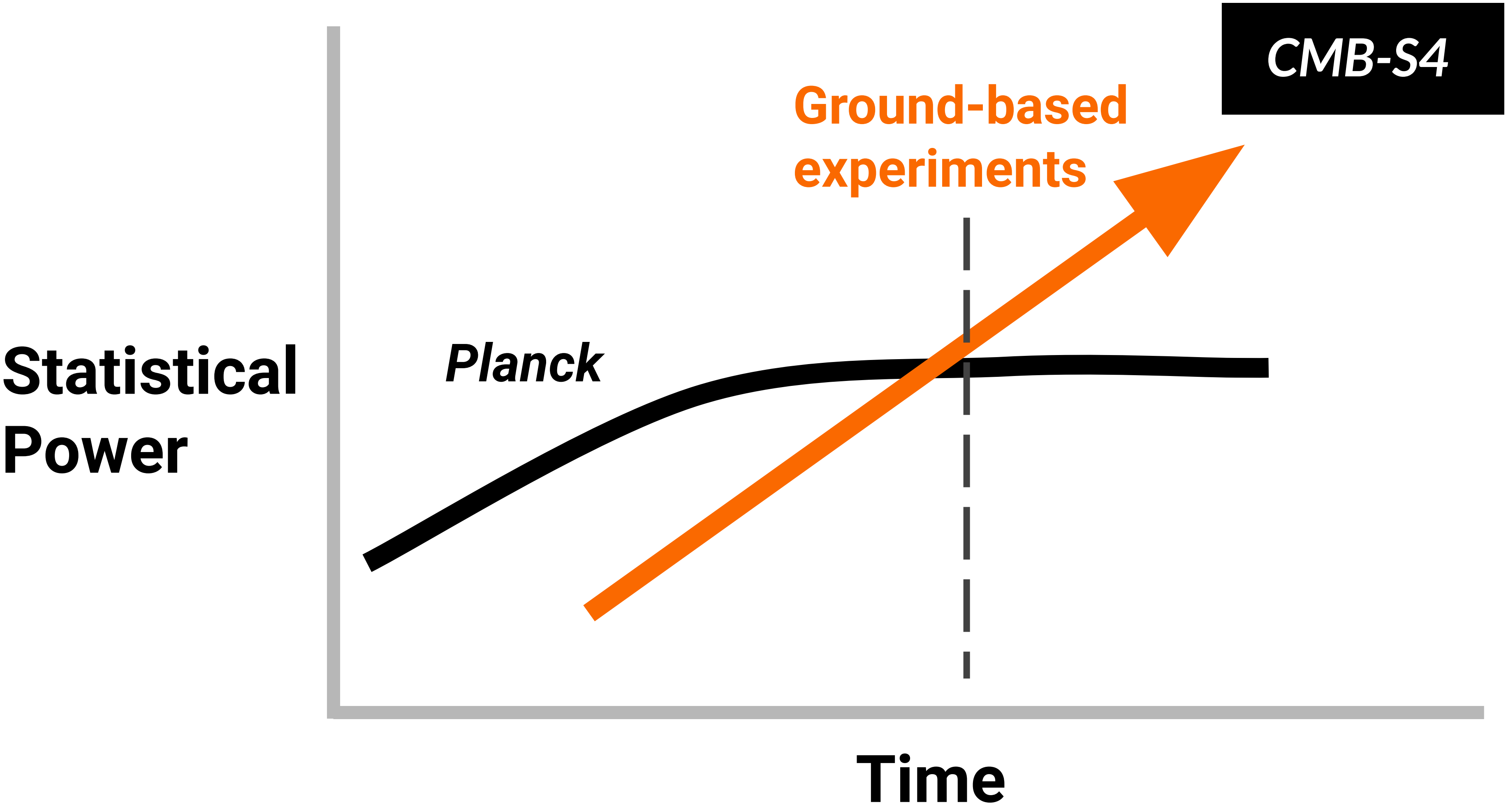
Notes: In the final spectra, we do not include D8, W2, W6

Choi et al 2020

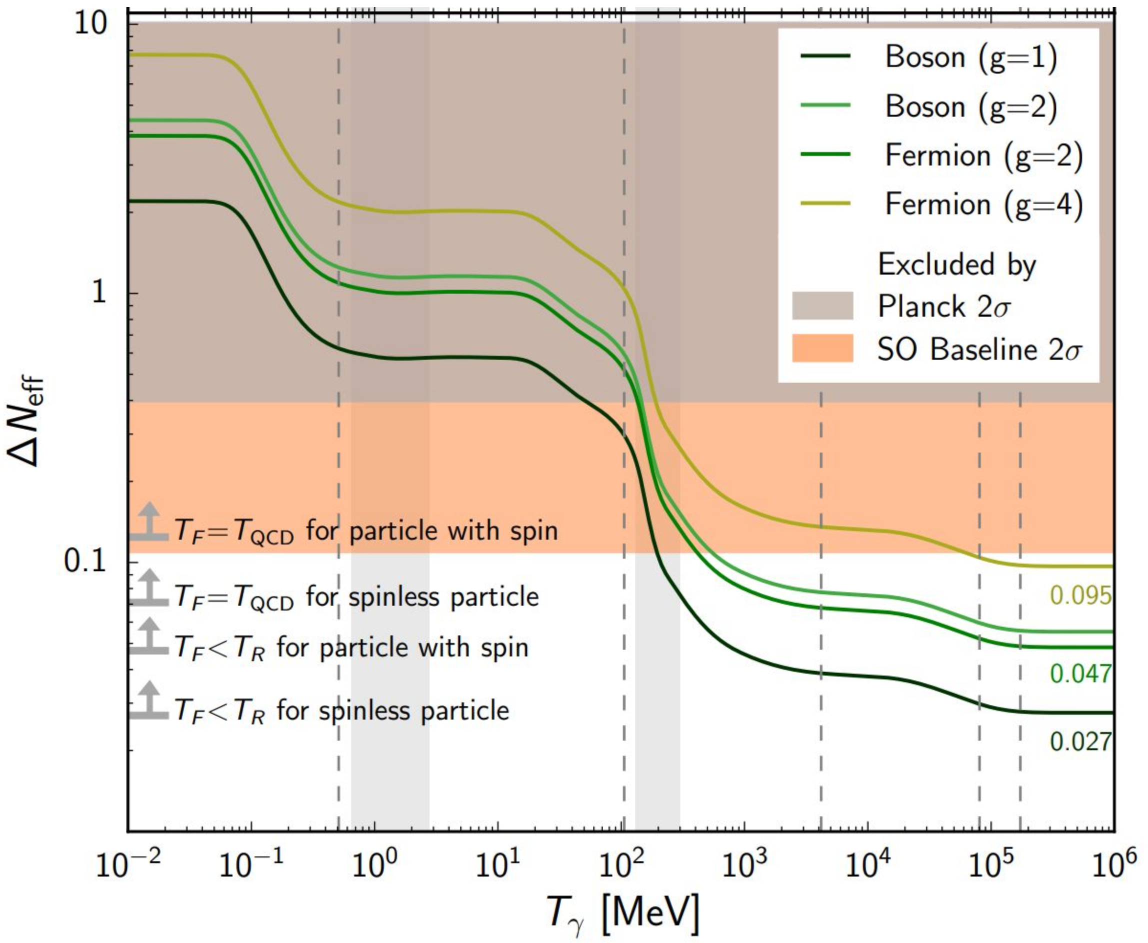


40% of the sky will be deeper than *Planck* in the next ACT release

Naess et al. 2020


CMB-S4
Ground-based experiments
Statistical Power
Planck
Time

The next ACT primary analysis, in combination with Planck, will be the **best measurement ever of** $N_{\rm eff}$.



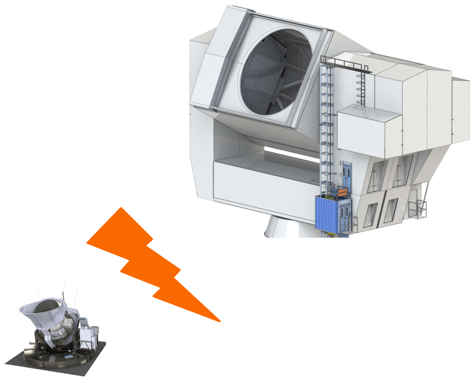
SO Science Book

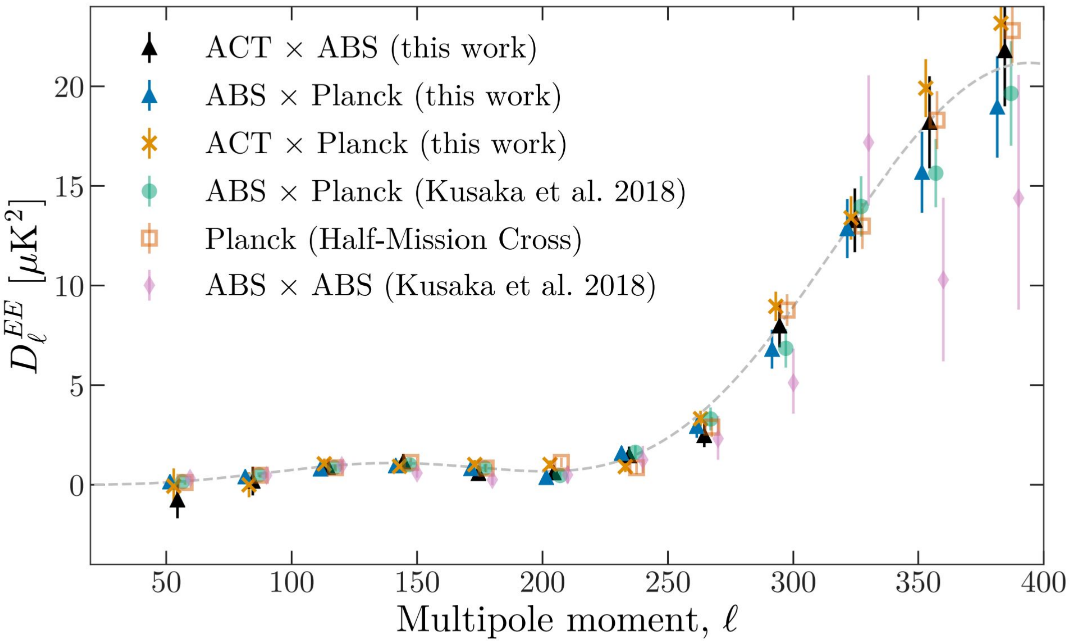
We will analyze **ACT DR6** jointly with **Planck** using the **SO power spectrum pipeline.**

- Build and test SO tools and methods by doing a cutting-edge analysis on real data.
- ACT is the closest precursor instrument to the SO LAT.
- **World-leading constraints** on cosmology, in particular N_{eff} and other BSM extensions.

- lensing
- secondaries like tSZ, kSZ
- constraints on reionization
- cluster cosmology
- bispectra
- Galactic dust physics!

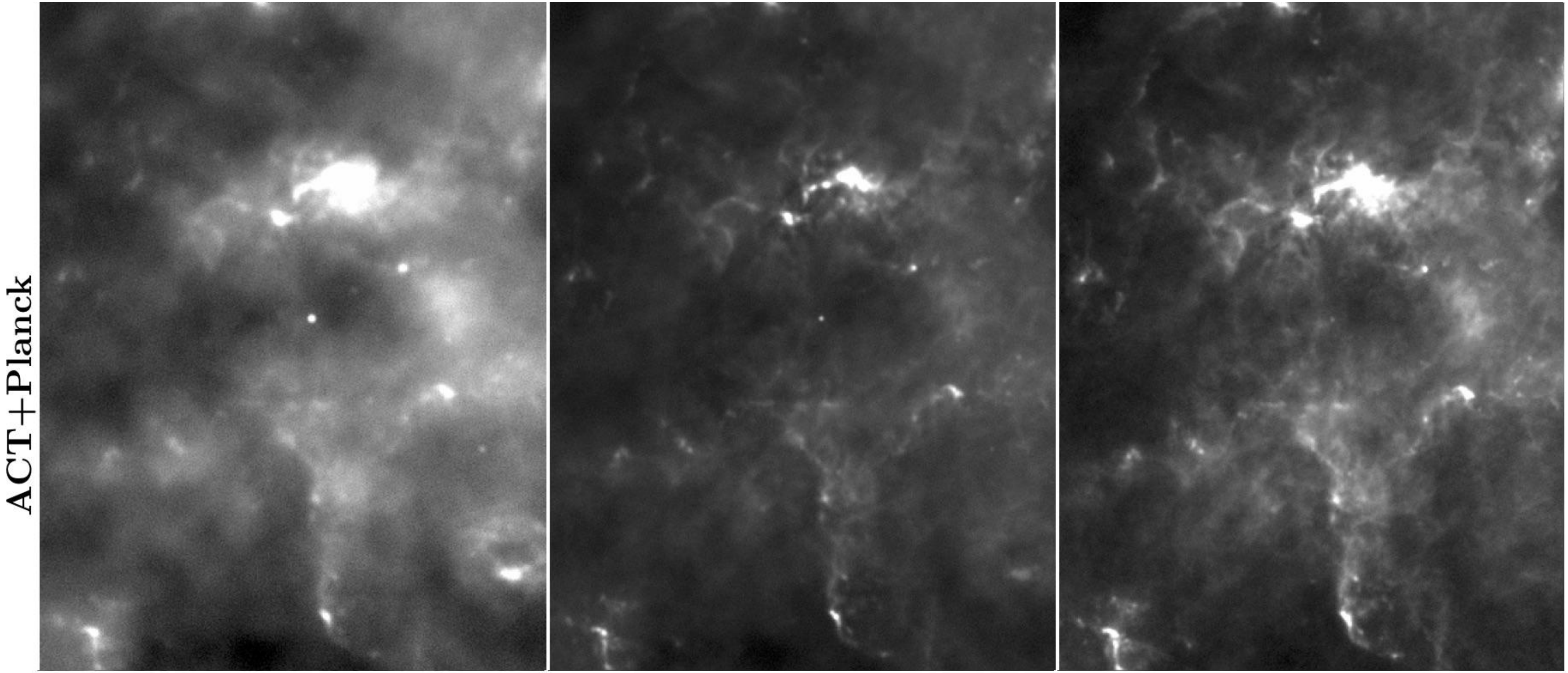
SO SAT x LAT Science





Large aperture x small aperture + HWP (shown above with ACT x ABS) can rescue low-ell signal (Li et al. 2020).

Upcoming work: power spectrum of polarized dust at small scales using ACT+Planck anticipating joint LAT x SAT foregrounds

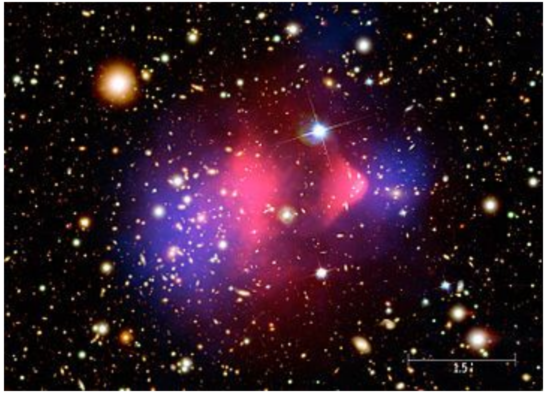


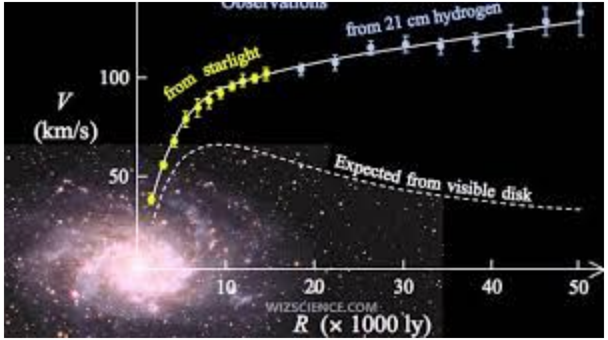
Naess et al 2020

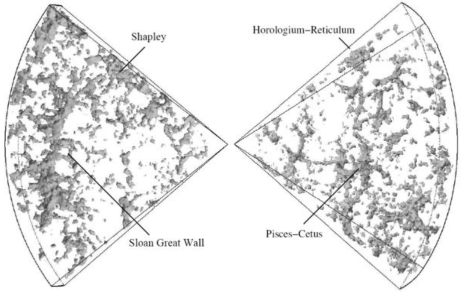
Science Case:

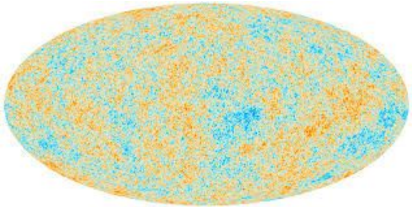
Dark Matter Physics

Standard dark matter:
no interactions with the standard model





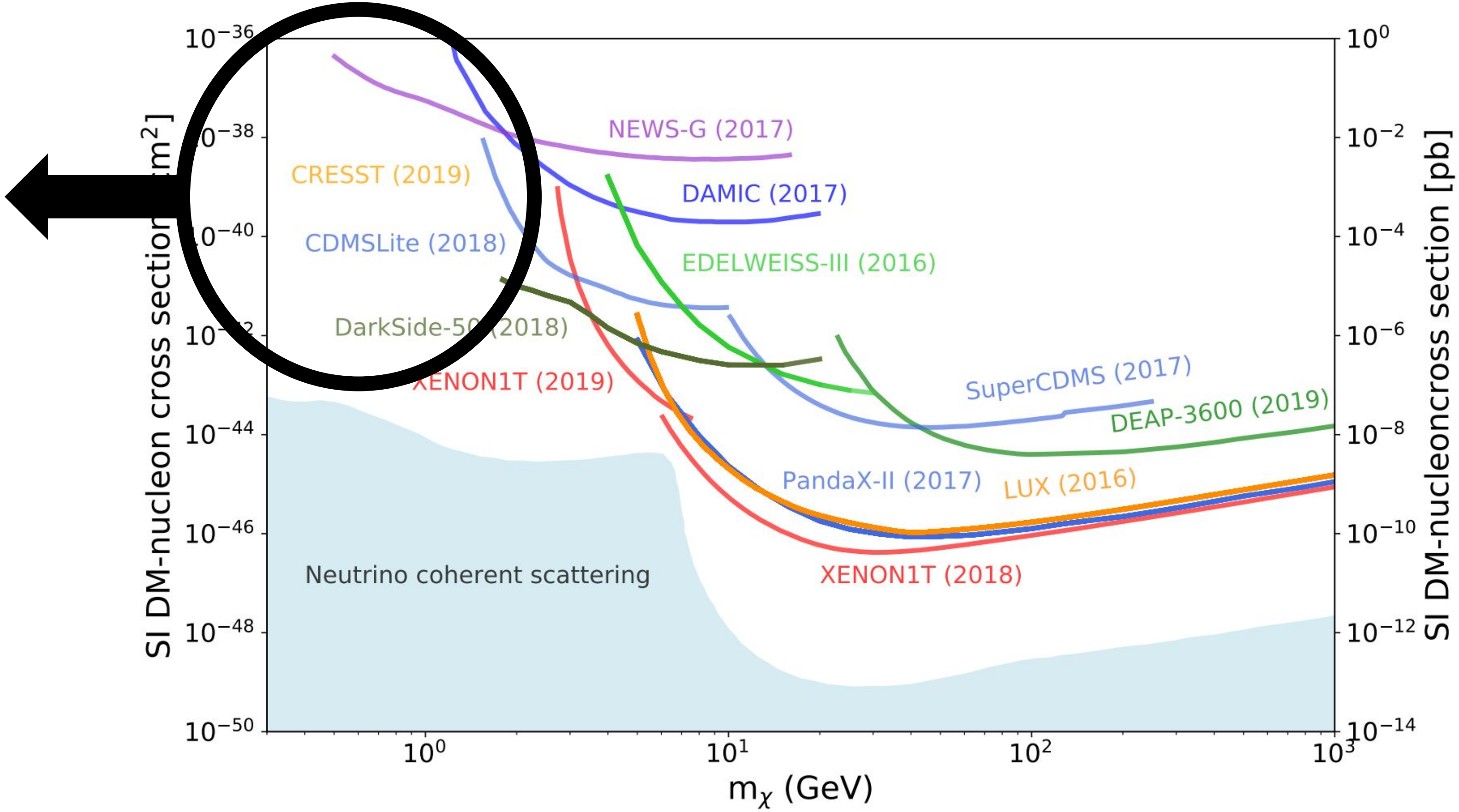




Direct detection experiments:
It would be nice if there was some small, nonzero coupling between dark matter and baryons.

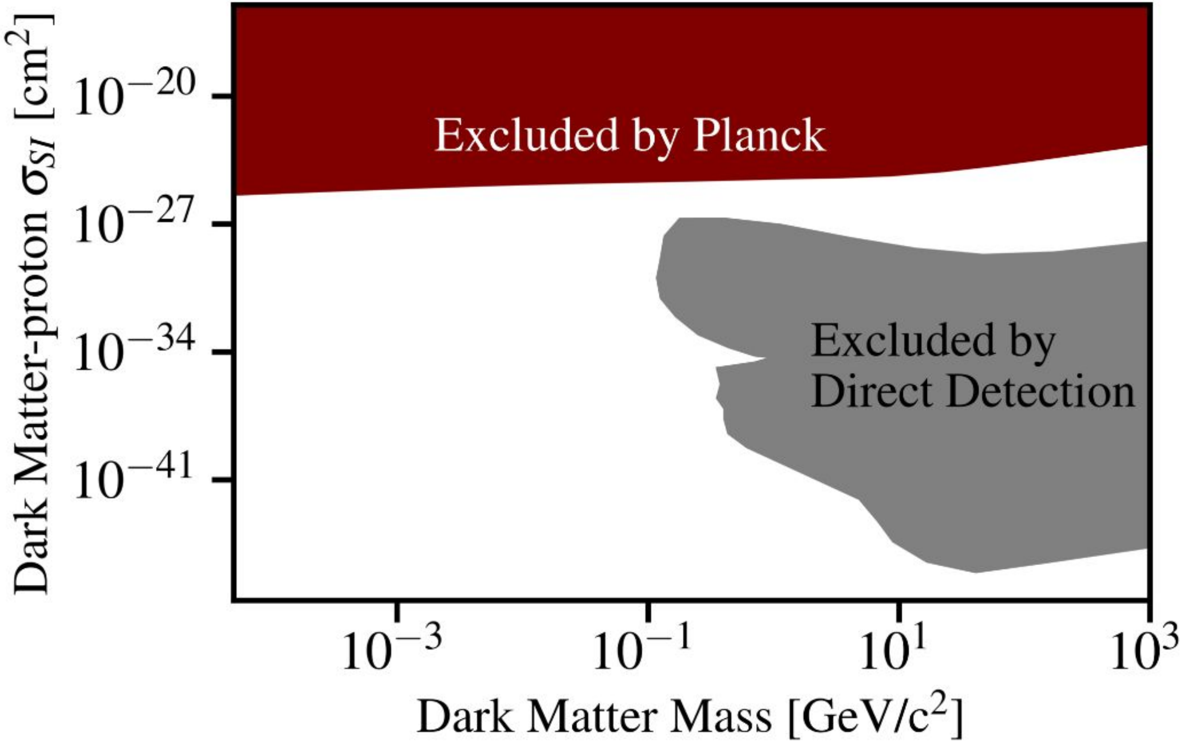
XENON1T, LUX

Direct detection with Xenon



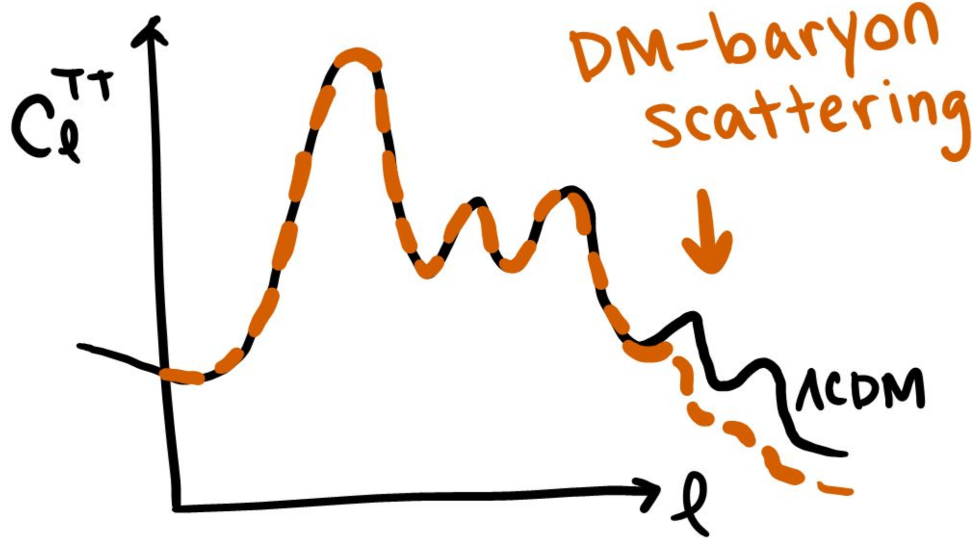
Baudis, Profumo 2020

The CMB is competitive at **low masses**.

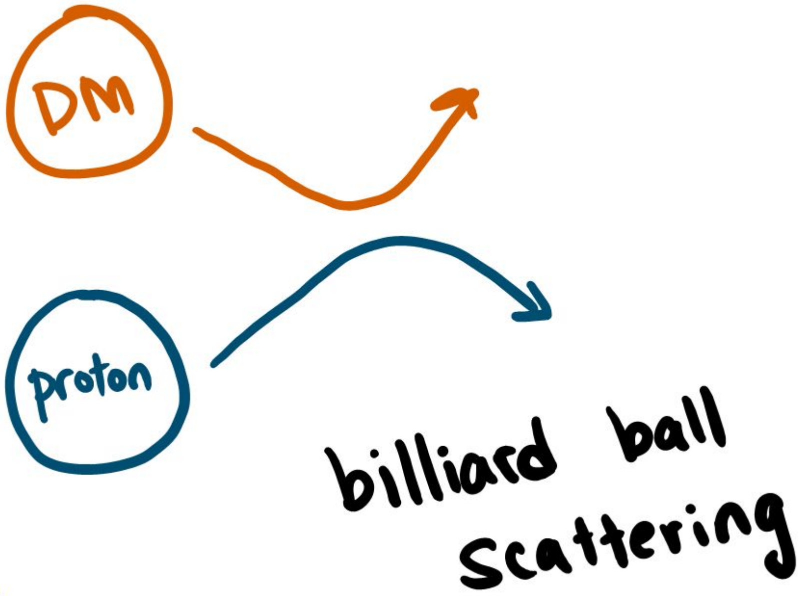


VG and Boddy 2018

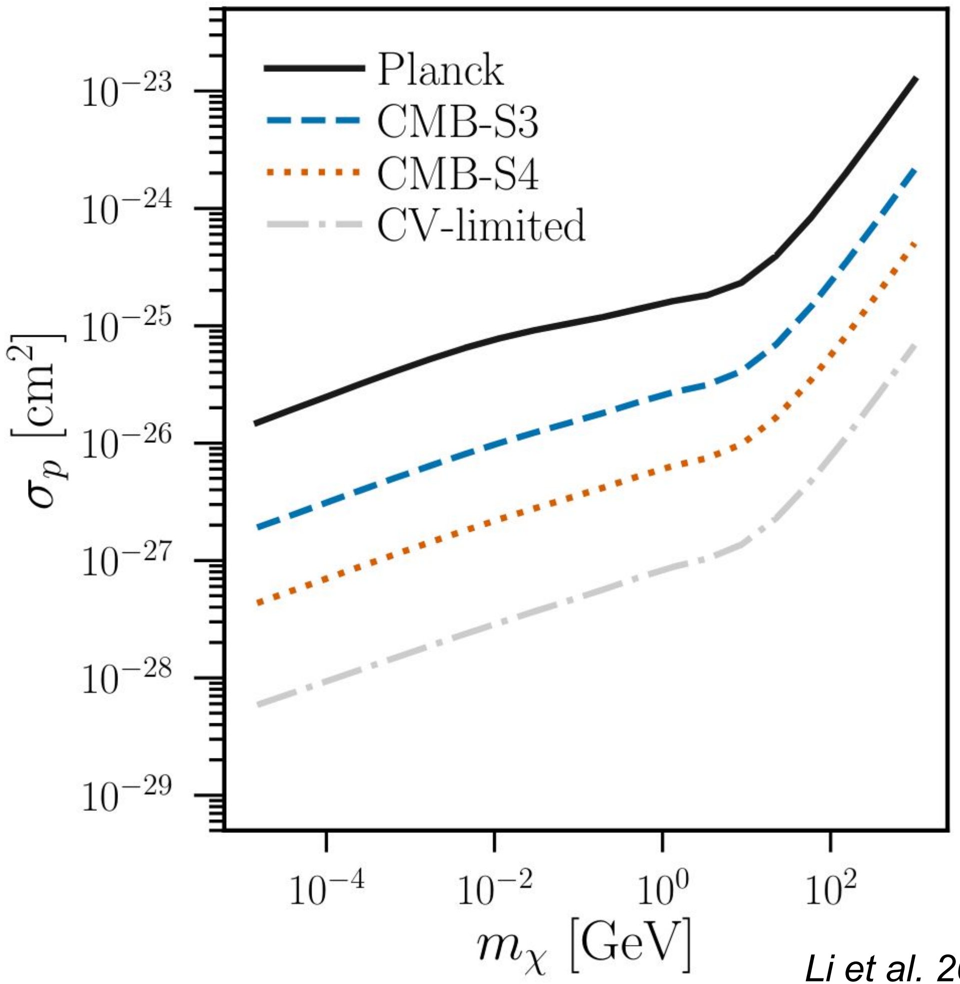
Velocity-independent scattering in the CMB is seen as **suppressed structure on small scales**



Example model:
velocity-independent cross sections

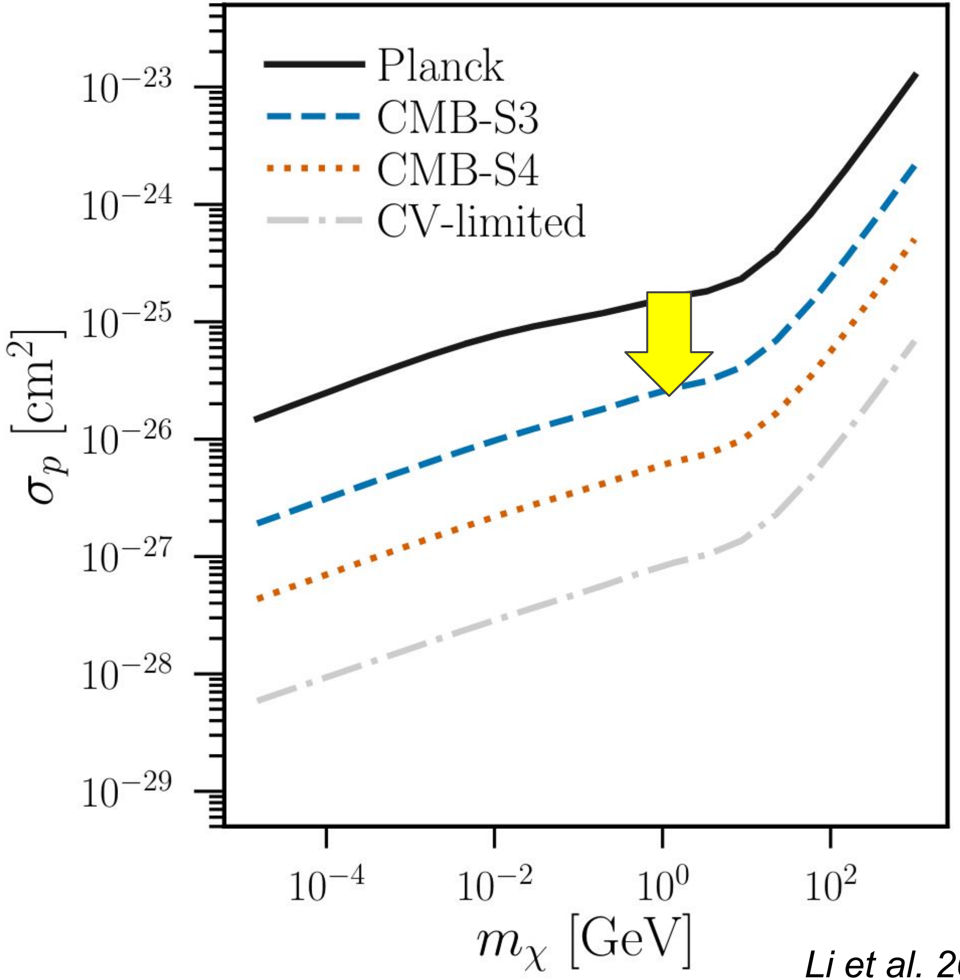


Forecasted **exclusion curves** on the DM-baryon interaction cross-section



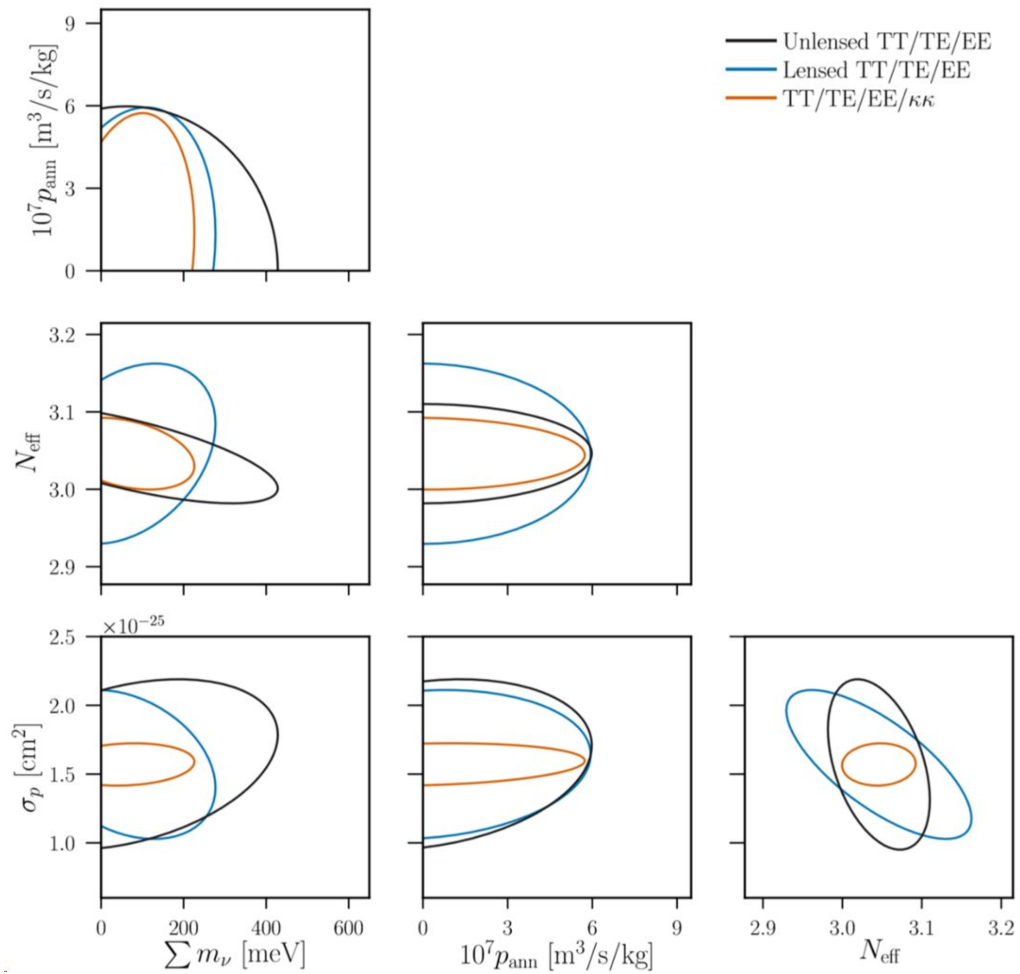
Li et al. 2018

Forecasted **exclusion curves** on the DM-baryon interaction cross-section

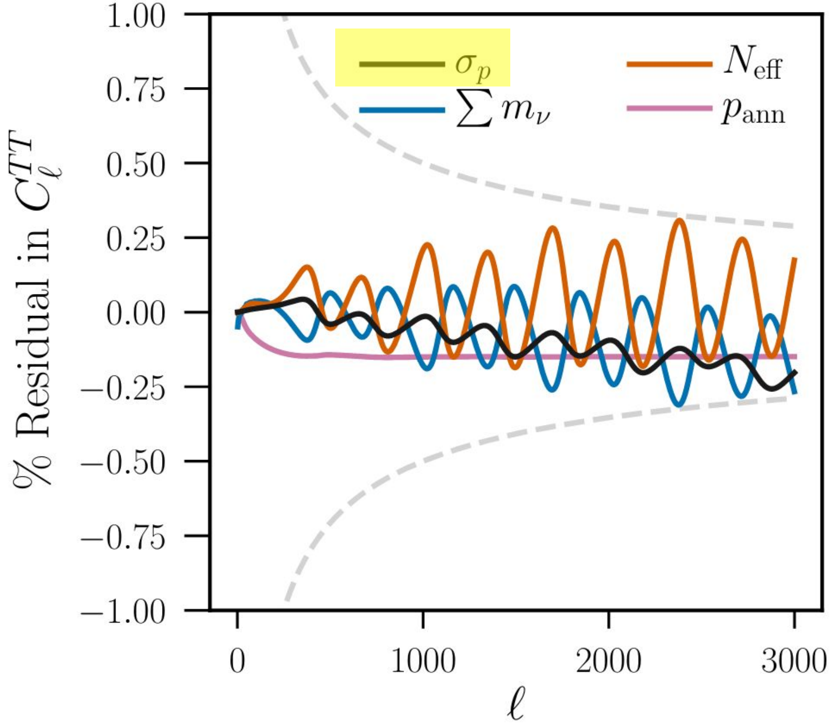


Li et al. 2018

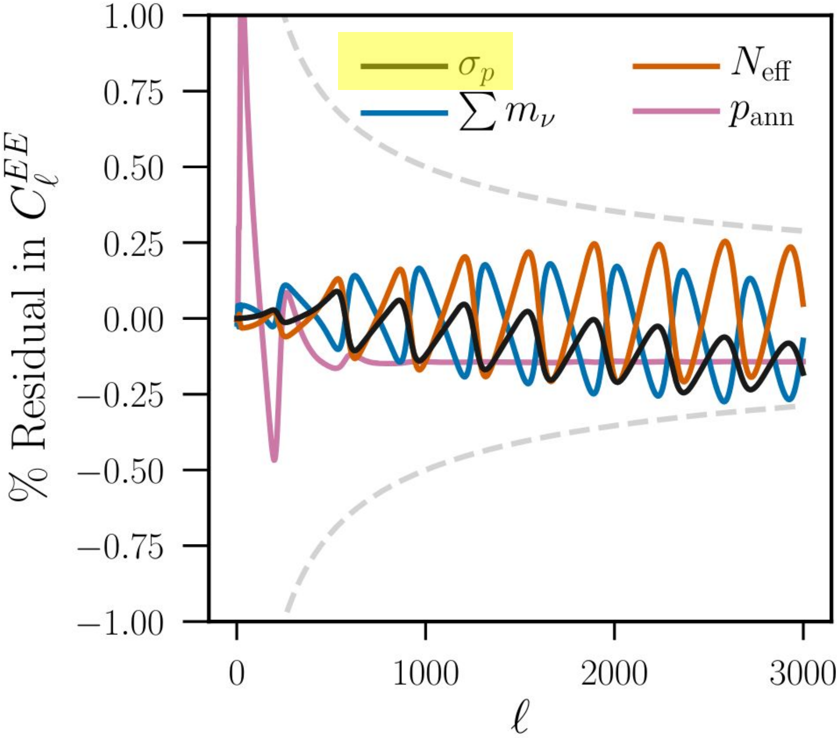
The signal is distinguishable from other LCDM extension physics!



Li et al. 2018



σ_p
$N_{\rm eff}$
$\sum m_\nu$
$p_{\rm ann}$
% Residual in C_ℓ^{TT}
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
0
1000
2000
3000
ℓ

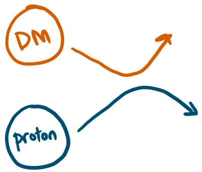


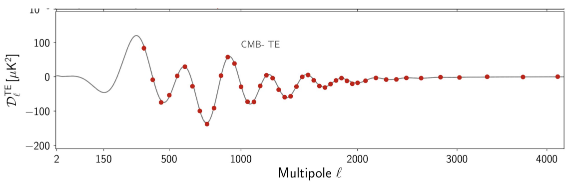
σ_p
$N_{\rm eff}$
$\sum m_\nu$
$p_{\rm ann}$
% Residual in C_ℓ^{EE}
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
0
1000
2000
3000
ℓ

Li et al. 2018

In prep: Li et al. + ACT

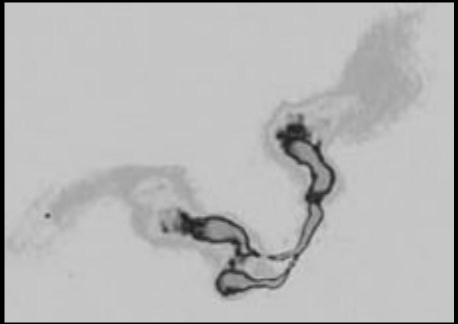
Dark matter interaction constraints from DR4 spectra

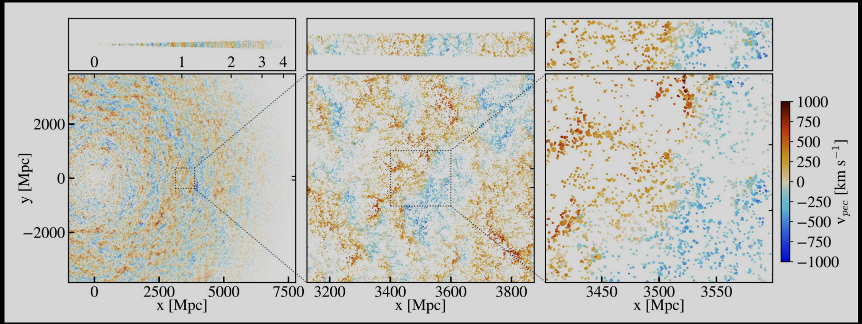




Choi et al 2020

Co-advised (with Vera Gluscevic, USC) some nice forecast work for CMB + other velocity dependence models, with student **Aizhan Akhmetzhanova** (Princeton undergrad), paper now led by Isabella Johansson (USC)

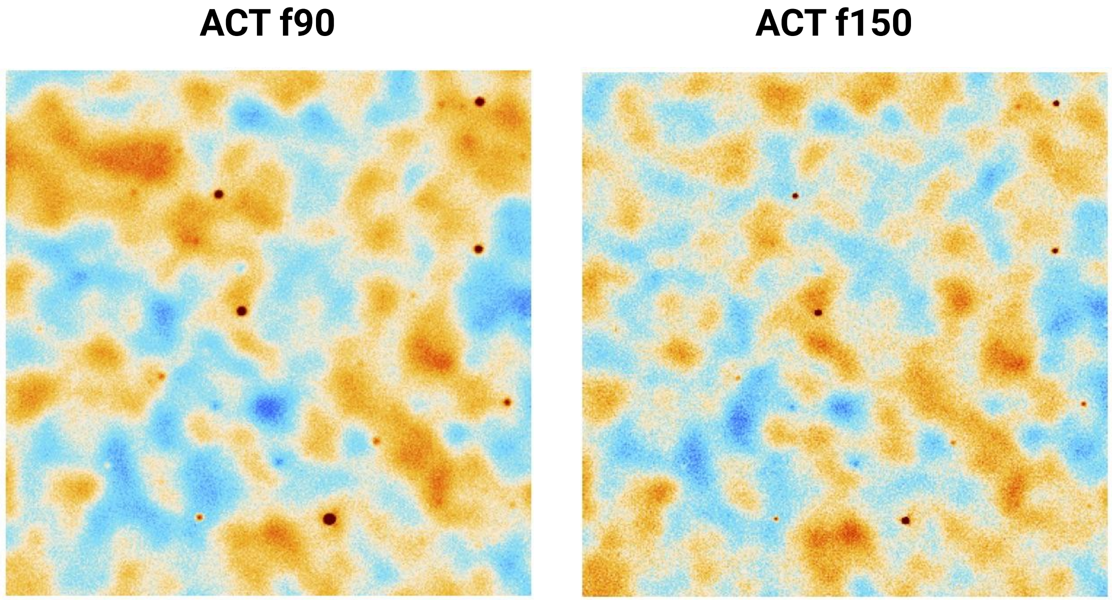




Science Case: Radio Sources

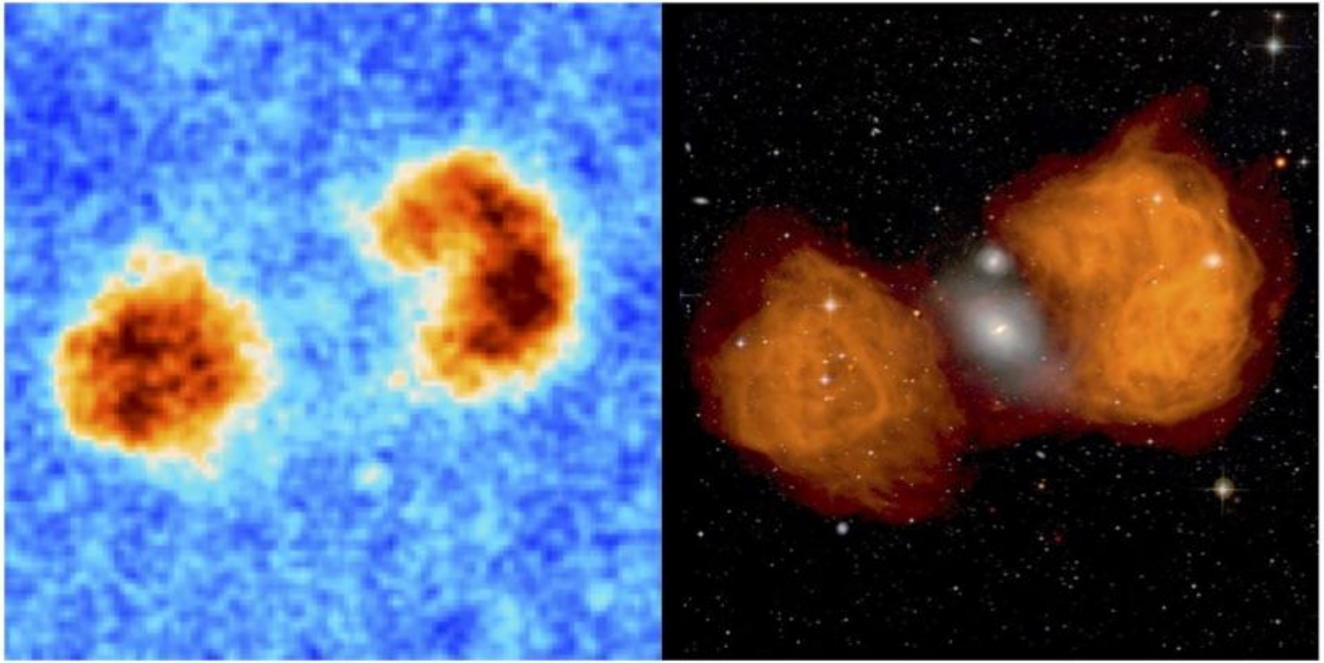
Collaborators:
Giuseppe Puglisi, Mat Madhavacheril, Marcelo Alvarez

We are going to see **a lot** of radio galaxies with SO and CMB-S4.



Naess et al. 2020.

Fornax A

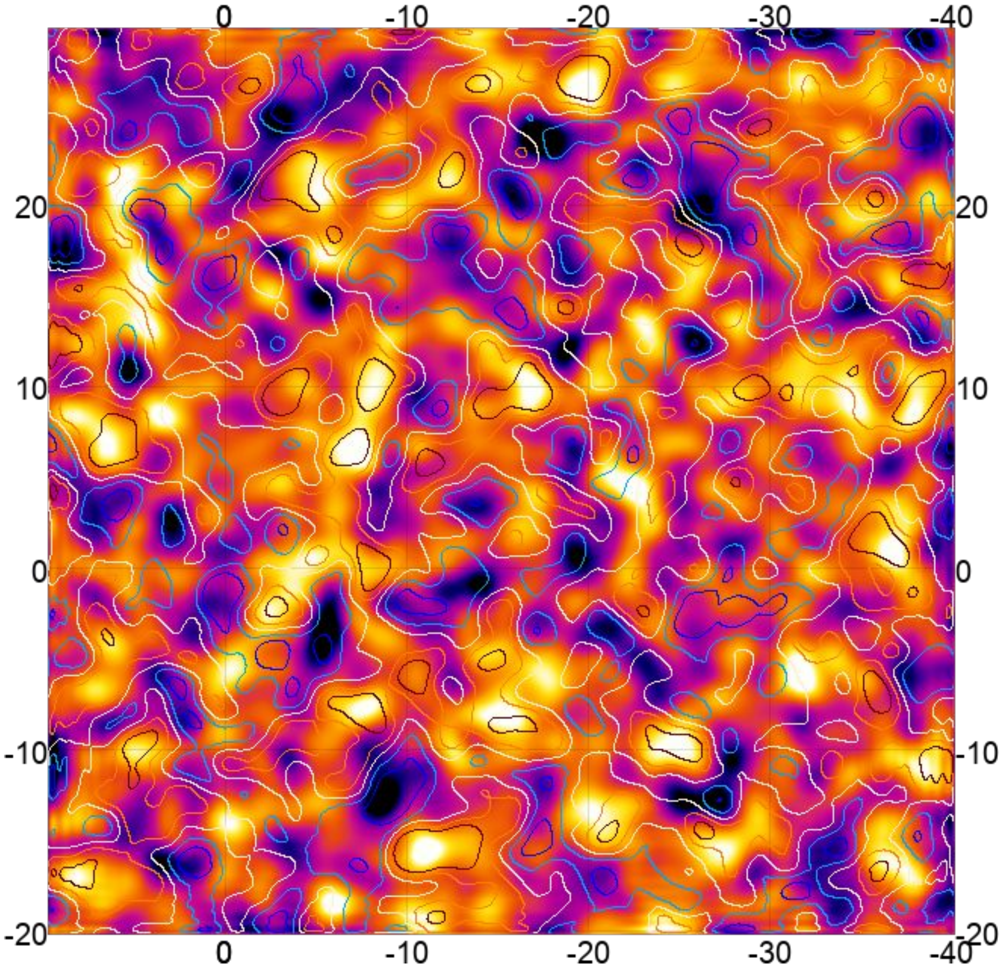


ACT+Planck f090 - f150   Radio+Optical

Naess et al. 2020.

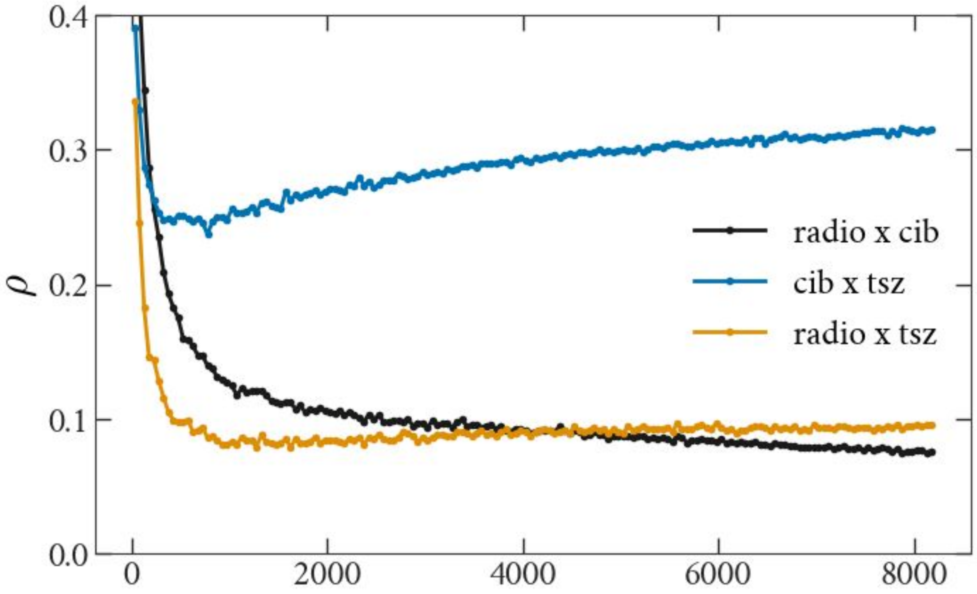
Radio sources hide ***small scale physics***.

Figure: Lensing convergence contours, overlaid over simulated radio galaxies, from paper in prep



tSZ, radio, CIB all trace the large scale structure, so they're all **correlated**.

Correlation Coeff

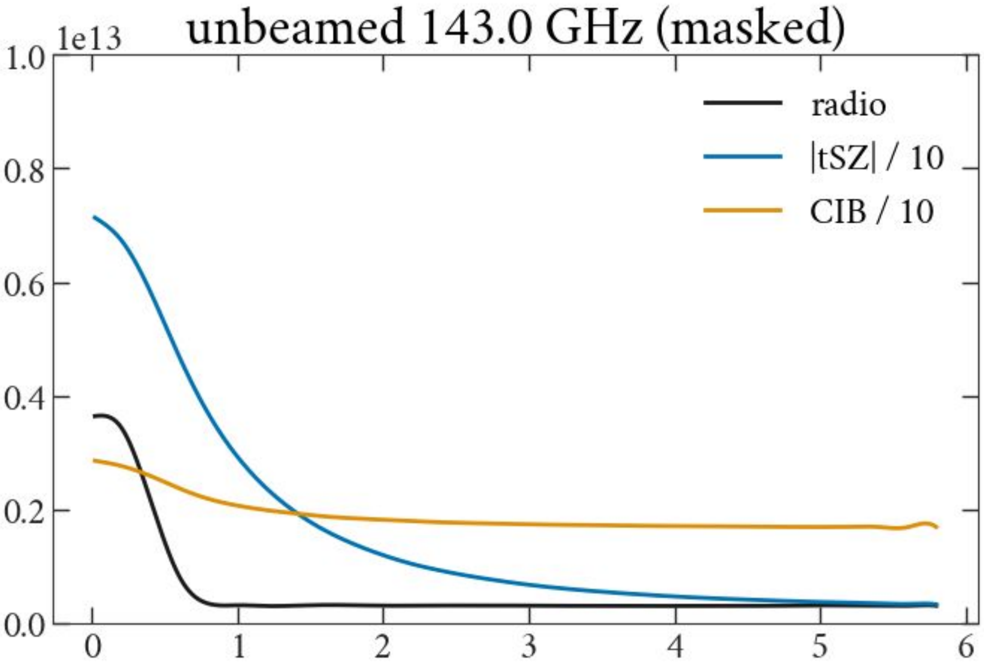


Multipole moment

Li et al (in prep)

It's known that radio galaxies are **heavily biased**, and this causes problems like cluster fill-in.

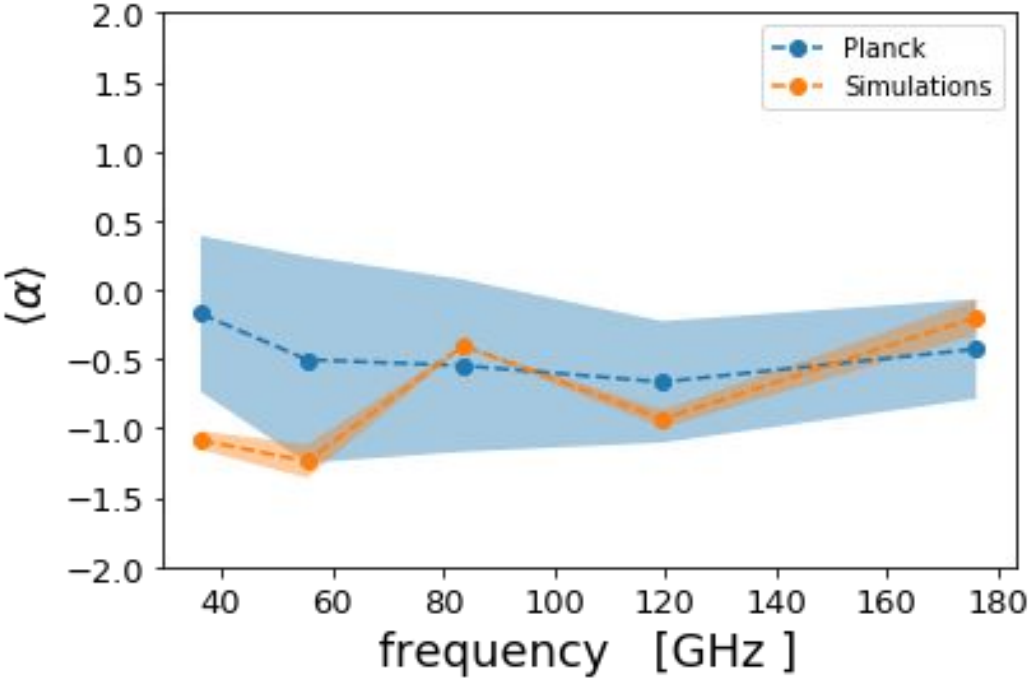
Flux profile



Angular separation from halo (arcminutes)

Li et al (in prep)

The Sehgal 2009 models don’t fully agree with new data, like **the spectral index**.



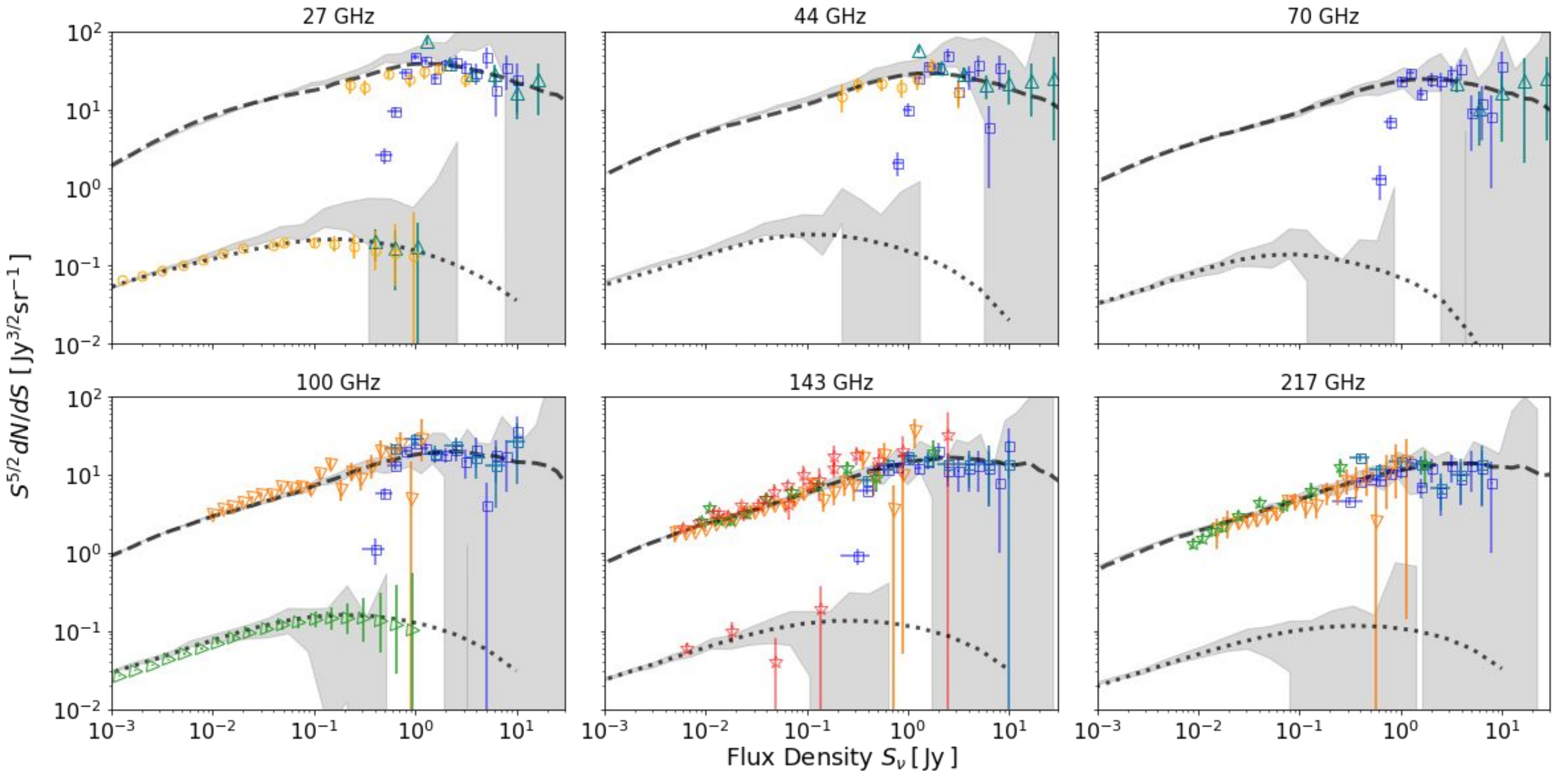
Li et al (in prep)

XGPaint.jl

An efficient, parallel Julia code for generating non-Gaussian foreground catalogs and maps with a halo model, with **CIB** from Planck+2013 and **radio sources** from Sehgal+2009.

+ Heroic resampling efforts from Giuseppe Puglisi

Cutting-edge sims: agreement with all current astrophysical data, halo-model correlations with LSS.



Li et al (in prep)

Contemporary with SO and CMB-S4:

Large Scale Structure Surveys

Exciting stuff, especially CMB secondaries x galaxies!
Would love to think more about this.

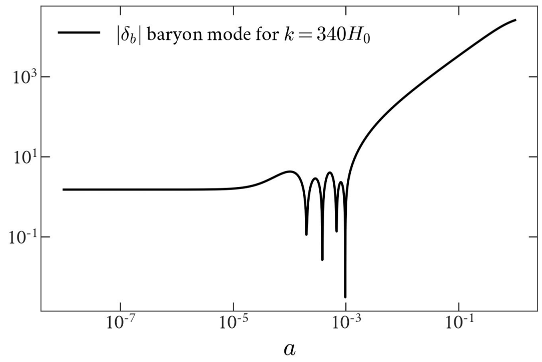
My fairly limited LSS excursions mostly been with my collaborator Jia Liu!

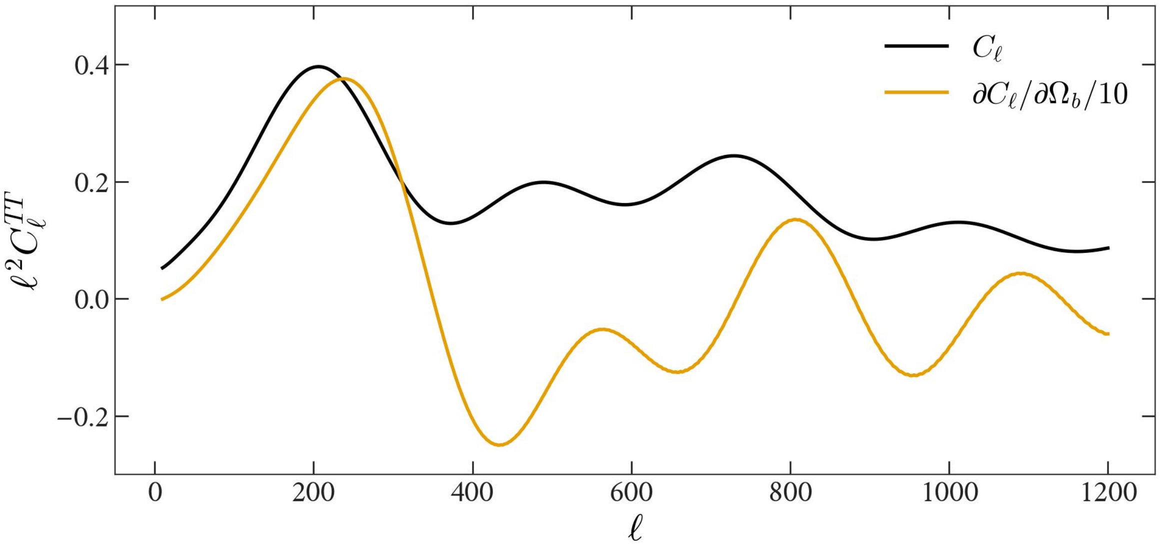
- LSST lensing **peak counts** measures the **neutrino mass** (Li et al. 2019)
- Co-advised Princeton undergraduate Gemma Zhang (now grad student) who found that the **halo mass function in voids can be sensitive to neutrino mass** (Zhang et al. 2020) (co-advisors Jia Liu, David Spergel)
- This spring, co-advising Berkeley undergrad James Sunseri on the impact of baryons on the matter power spectrum, within different morphological classifications of the large-scale structure (co-advisor Jia Liu)

VERA C. RUBIN
OBSERVATORY

Bolt

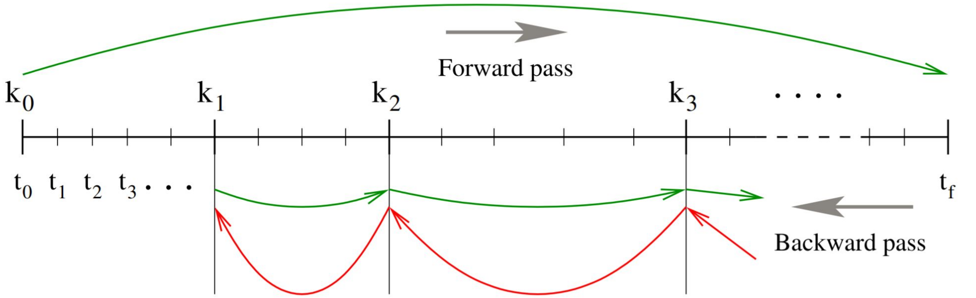
A *differentiable* Boltzmann code written in Julia





Left: The baryon perturbation evolving with time.
Right: Forward-mode **automatic differentiation** gives you cheap, accurate **gradients** of spectra with respect to cosmology, for i.e. Hamiltonian Monte Carlo.

It is possible to generate an adjoint of an ordinary differential equation.
(reverse mode autodiff for Boltzmann may be technically challenging to make efficient)



Rackauckas 2020

- Julia language means you can dream up an extension model in a Jupyter notebook and have it run at compiled-code speeds.
- Bolt is currently missing a lot of physics, it's basically CMBFAST + gradients.
- Goal: standard LCDM within a factor of ~2 of CLASS/CAMB performance

- This is the paradigm of **differentiable programming**. However, there's lots of development left before Bolt can be used for **Scientific Machine Learning.**

The Next Five Years

- Big sky areas and polarization, from the ground! Lots of analysis challenges to tackle.
- We expect great science out of the SO pipeline even before we’re on sky.
- In five years, we’ll have SO data.

- In ten years, we’ll have science from **CMB-S4**.
- A big universe left to explore!