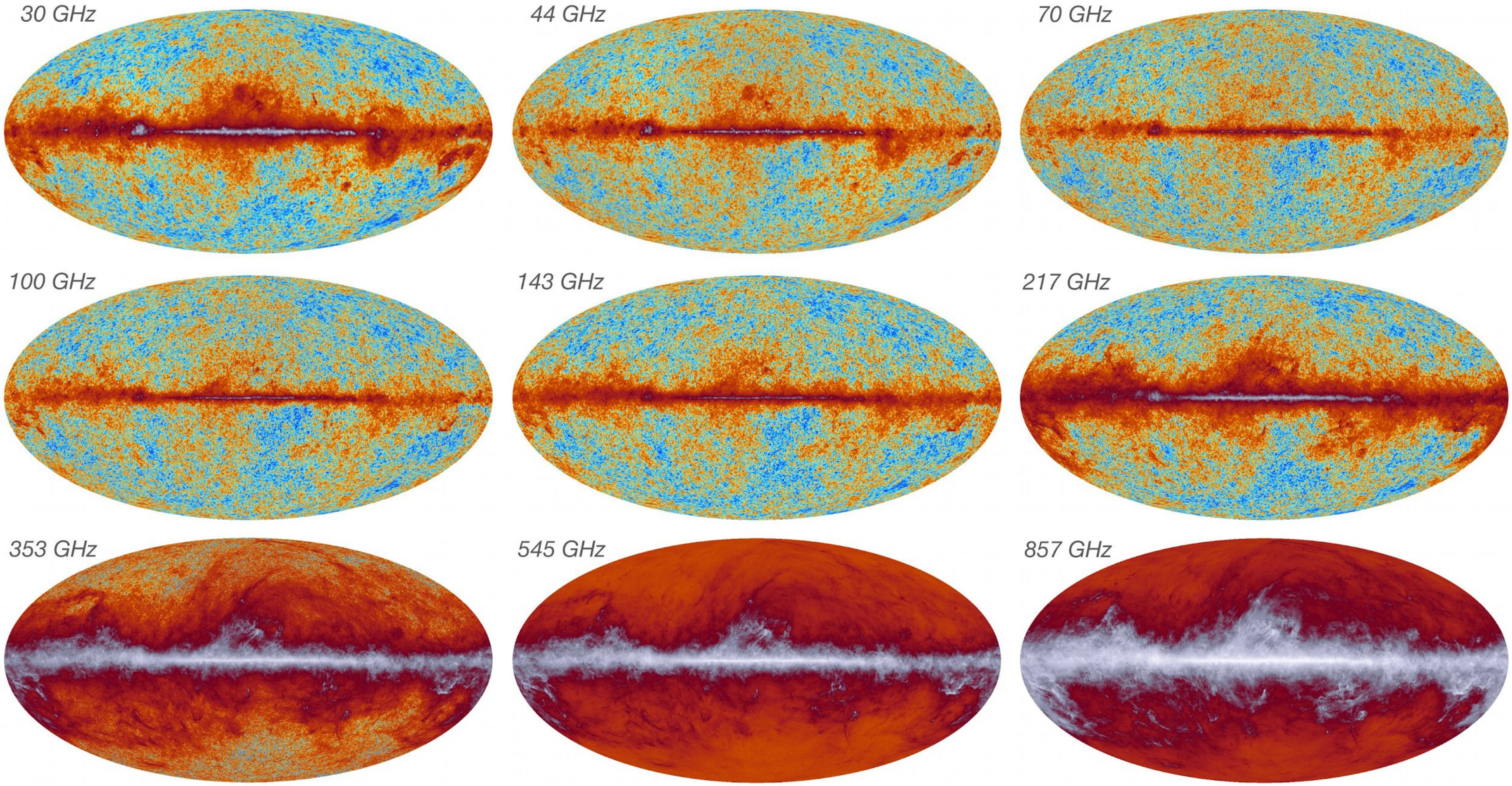
Discovery from Millimeter-Wave Surveys in the Next Five Years

Zack Li, Princeton



Planck Collaboration, 2018

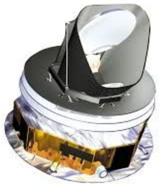
A new era:

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

2018

Planck

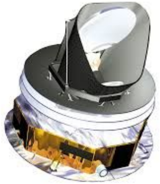
70% of the sky, 5-10 arcmin resolution



2018

Planck

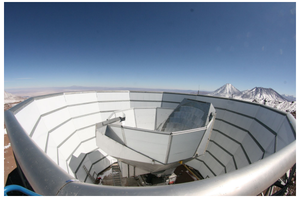
70% of the sky, 5-10 arcmin resolution



2020

ACT (DR4)

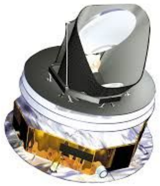
30% of the sky, 1-2 arcmin resolution



2018

Planck

70% of the sky, 5-10 arcmin resolution

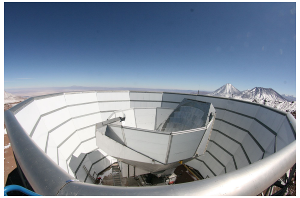


2020

2021

ACT (2008-2021)

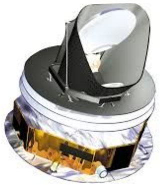
30% of the sky, 1-2 arcmin resolution



2018

Planck

70% of the sky, 5-10 arcmin resolution

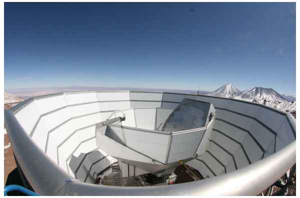


2020

ACT

2021

30% of the sky, 1-2 arcmin resolution

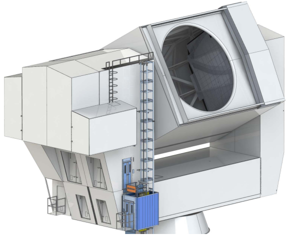


2023

Simons Observatory

40% of the sky, 1-2 arcmin resolution

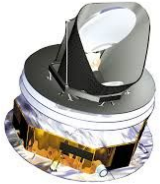
2028



2018

Planck

70% of the sky, 5-10 arcmin resolution

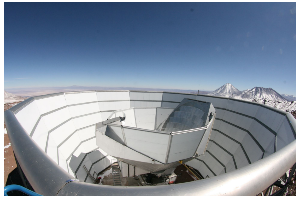


2020

ACT

2021

30% of the sky, 1-2 arcmin resolution

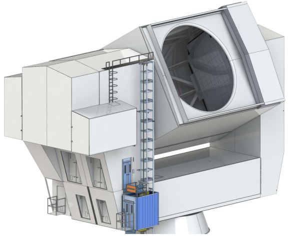


2023

Simons Observatory

40% of the sky, 1-2 arcmin resolution

2028



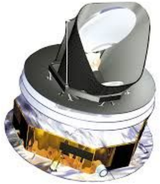
Lots of other great instruments out there!

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

2018

Planck

70% of the sky, 5-10 arcmin resolution

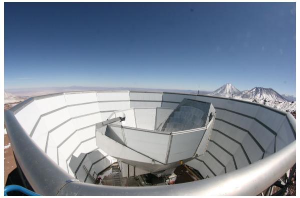


2020

ACT

30% of the sky, 1-2 arcmin resolution

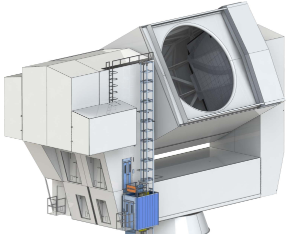
2021



2023

Simons Observatory

40% of the sky, 1-2 arcmin resolution



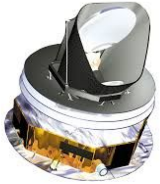
2028

3x lower noise

2018

Planck

70% of the sky, 5-10 arcmin resolution

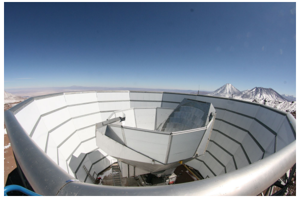


2020

ACT

30% of the sky, 1-2 arcmin resolution

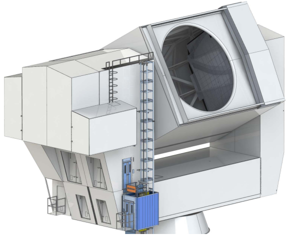
2021



2023

Simons Observatory

40% of the sky, 1-2 arcmin resolution



2028

3x *lower noise*

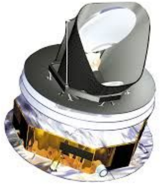
3x *lower noise*

2018

Planck

70% of the sky, 5-10 arcmin resolution

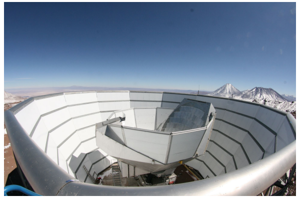
9 bands, 30 - 857 GHz



2020

ACT

30% of the sky, 1-2 arcmin resolution

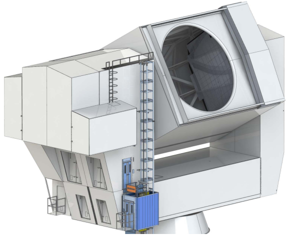


2021

2023

Simons Observatory

40% of the sky, 1-2 arcmin resolution

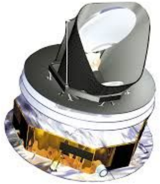


2028

2018

Planck

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

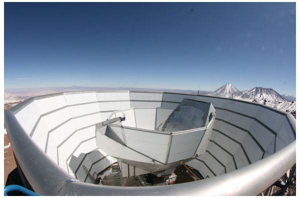


2020

ACT

2021

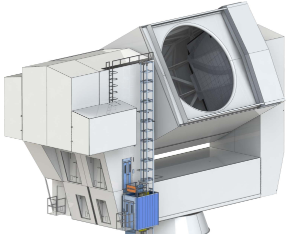
30% of the sky, 1-2 arcmin resolution
98, 150, 226 GHz bands,
30, 40 GHz coming soon!



2023

Simons Observatory

40% of the sky, 1-2 arcmin resolution

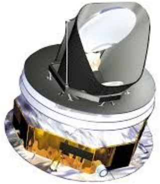


2028

2018

Planck

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

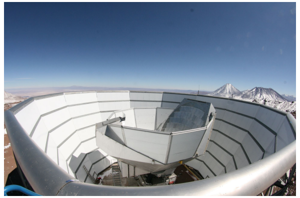


2020

ACT

2021

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

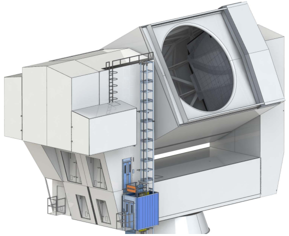


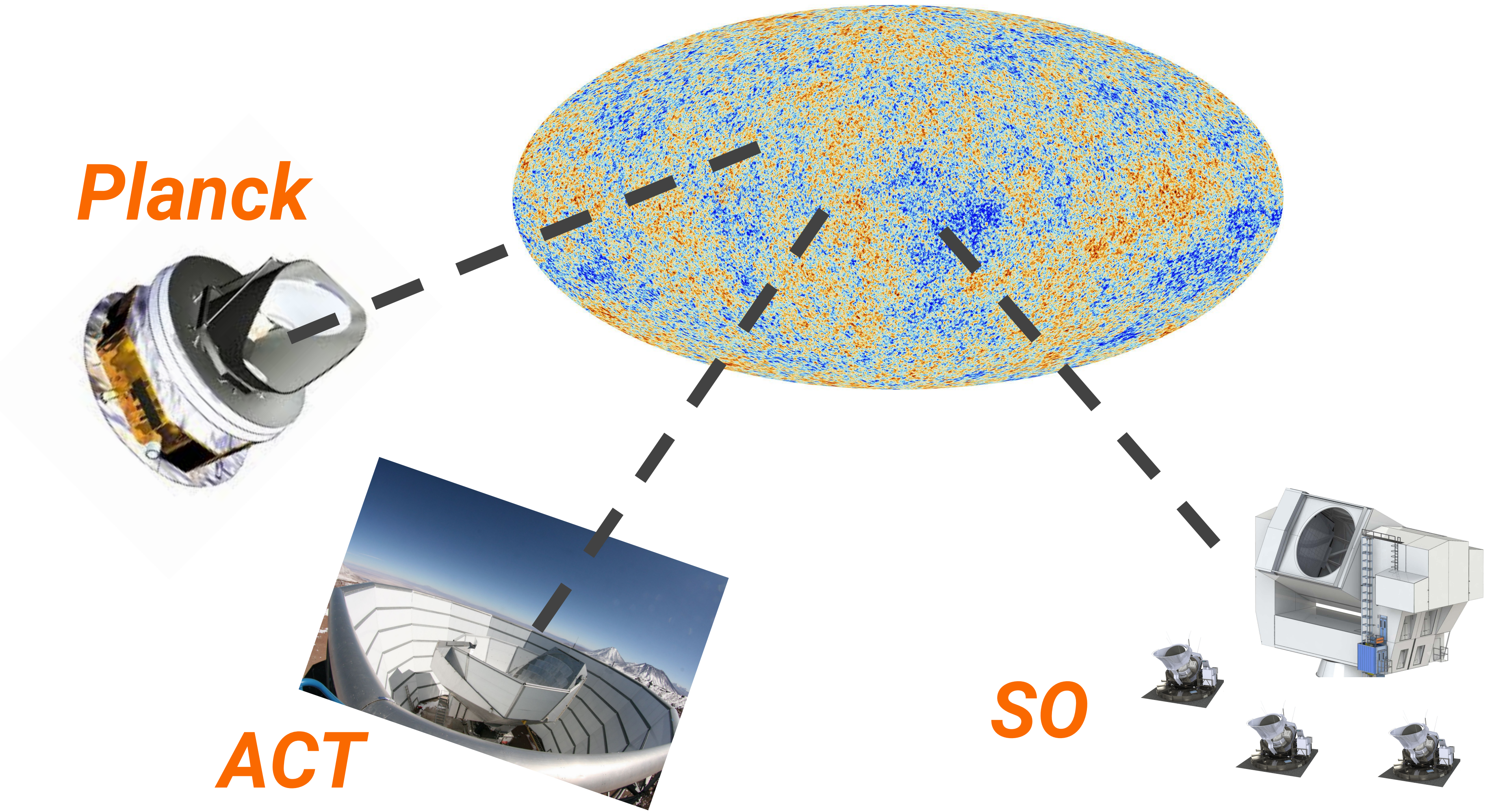
2023

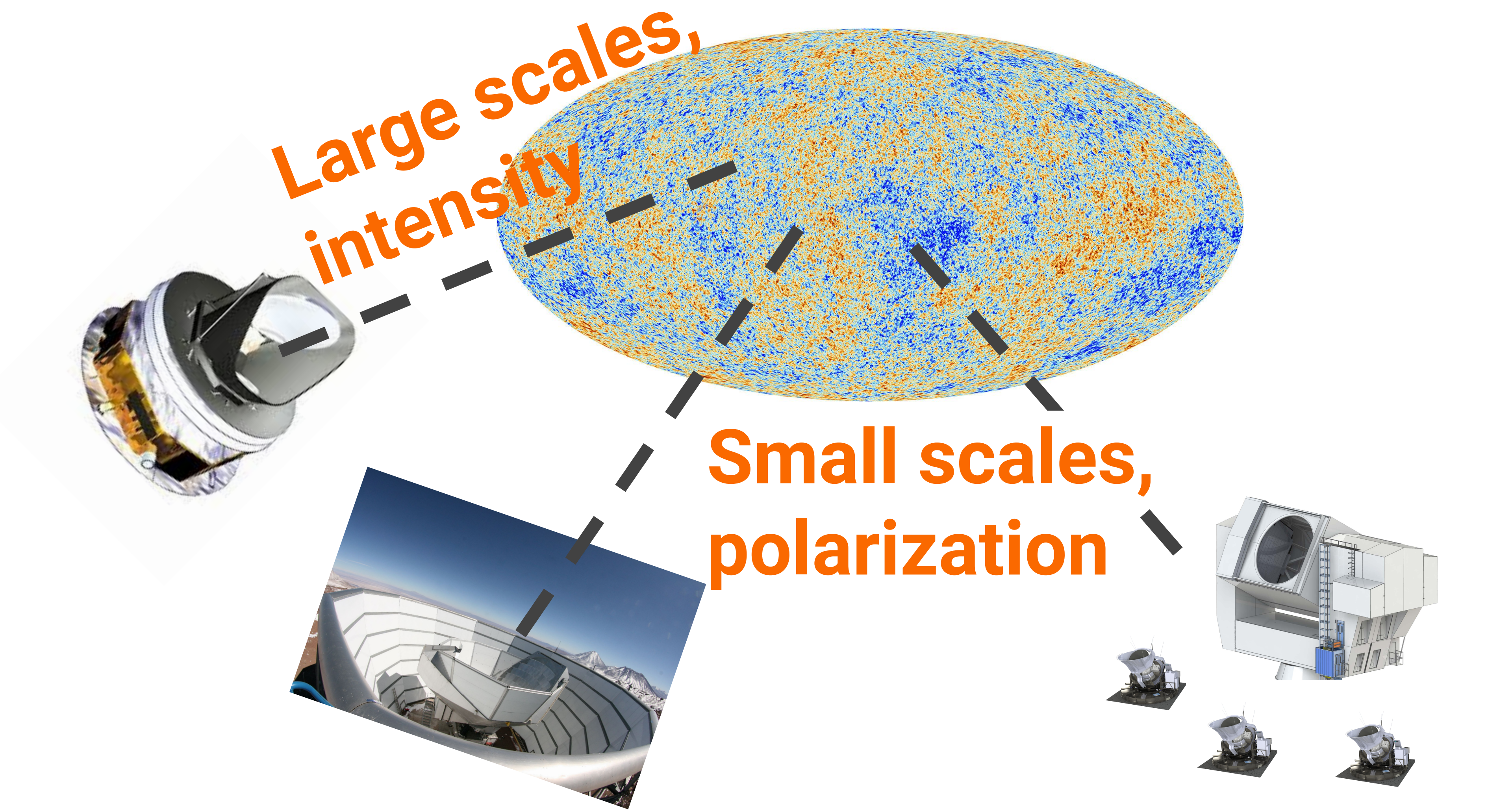
Simons Observatory

40% of the sky, 1-2 arcmin resolution
6 bands from 30 - 270 GHz

2028

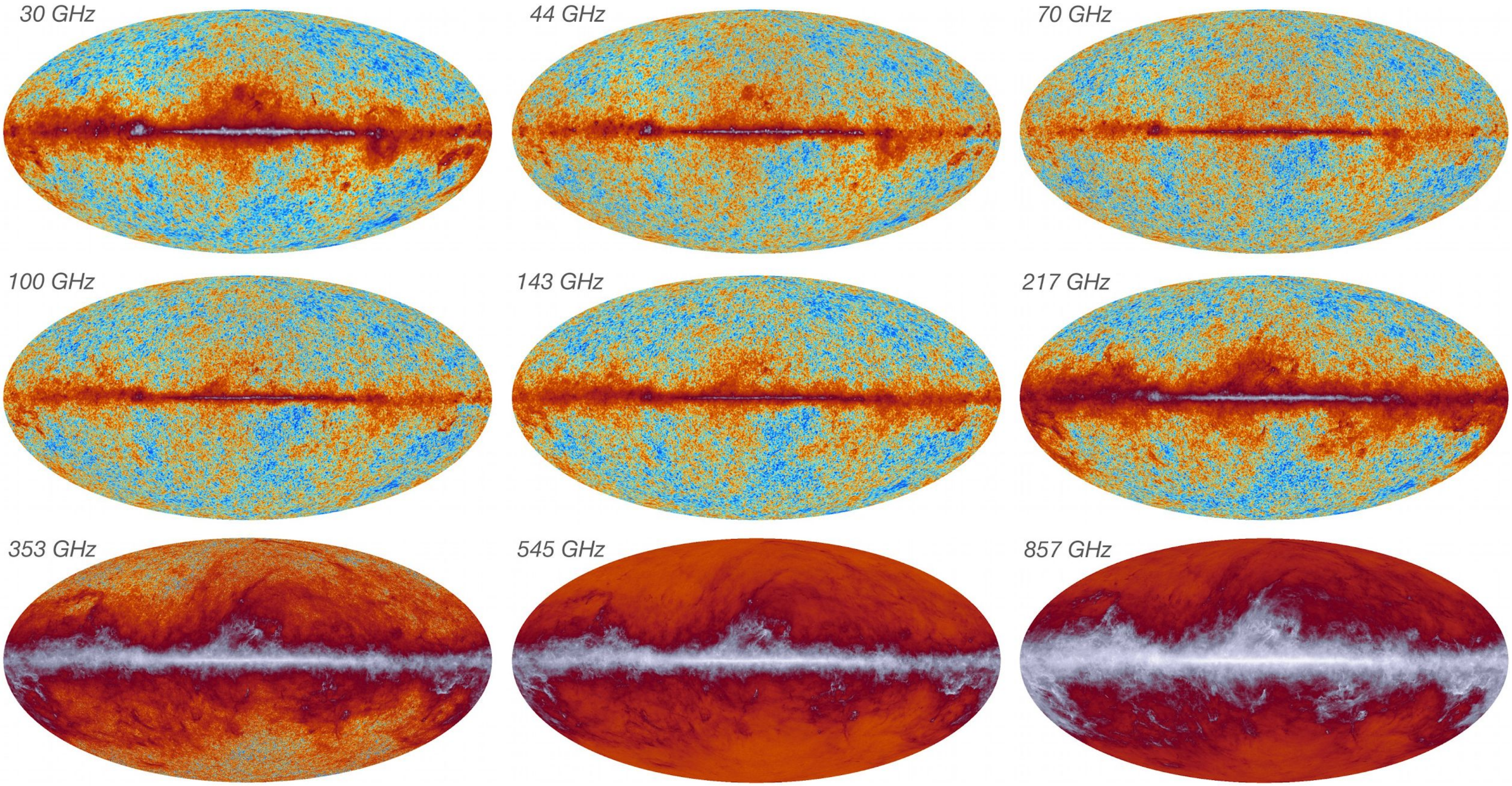



Planck
ACT
SO

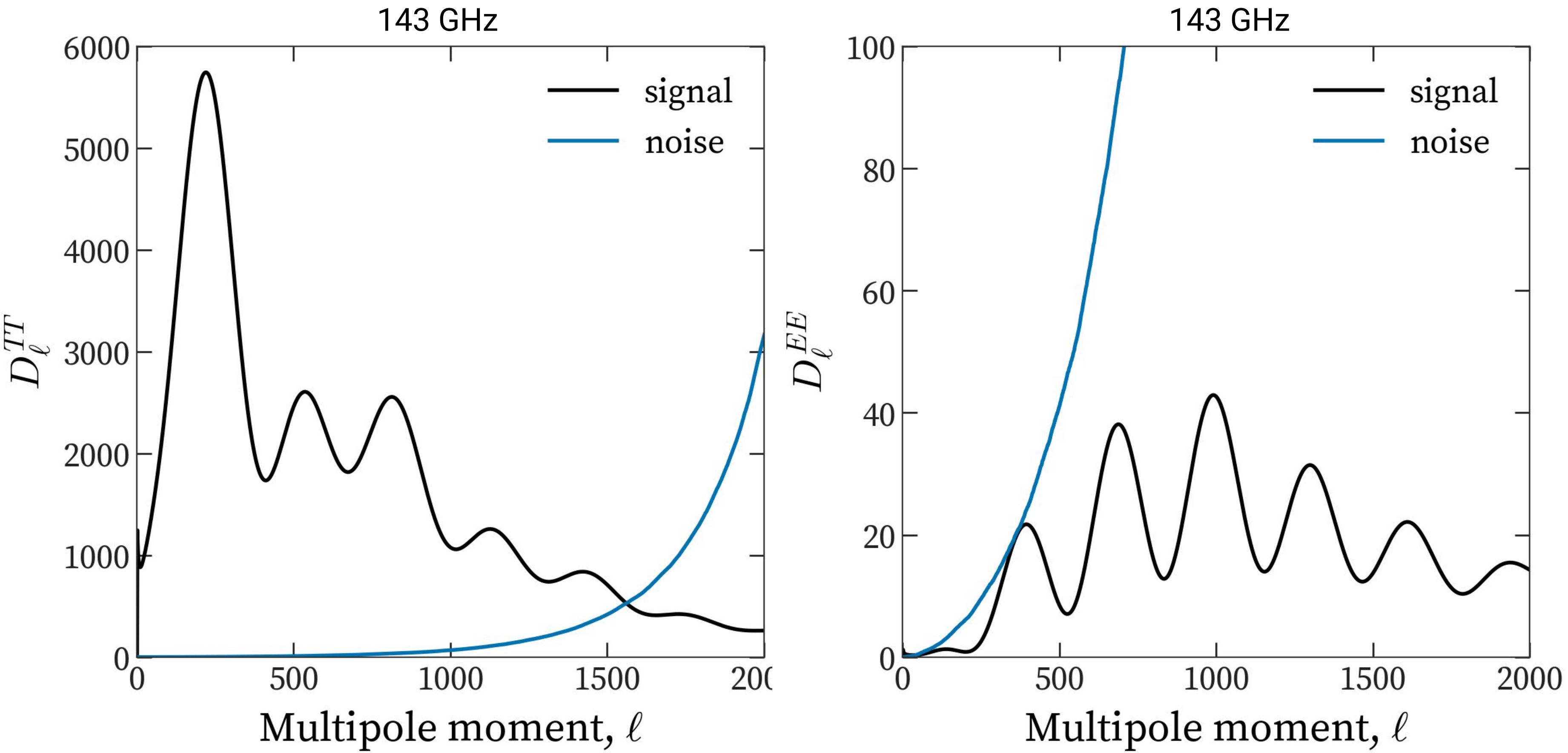

Large scales,
intensity
Small scales,
polarization

Planck

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

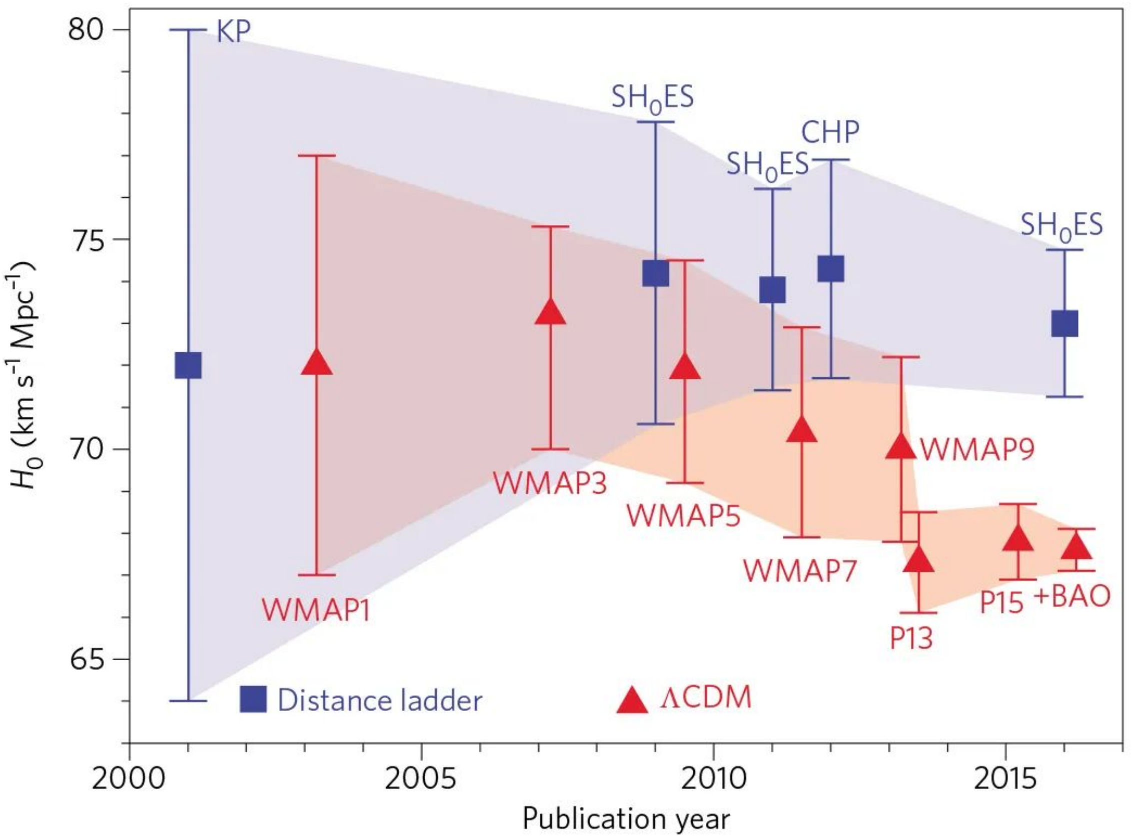


Planck Collaboration, 2018



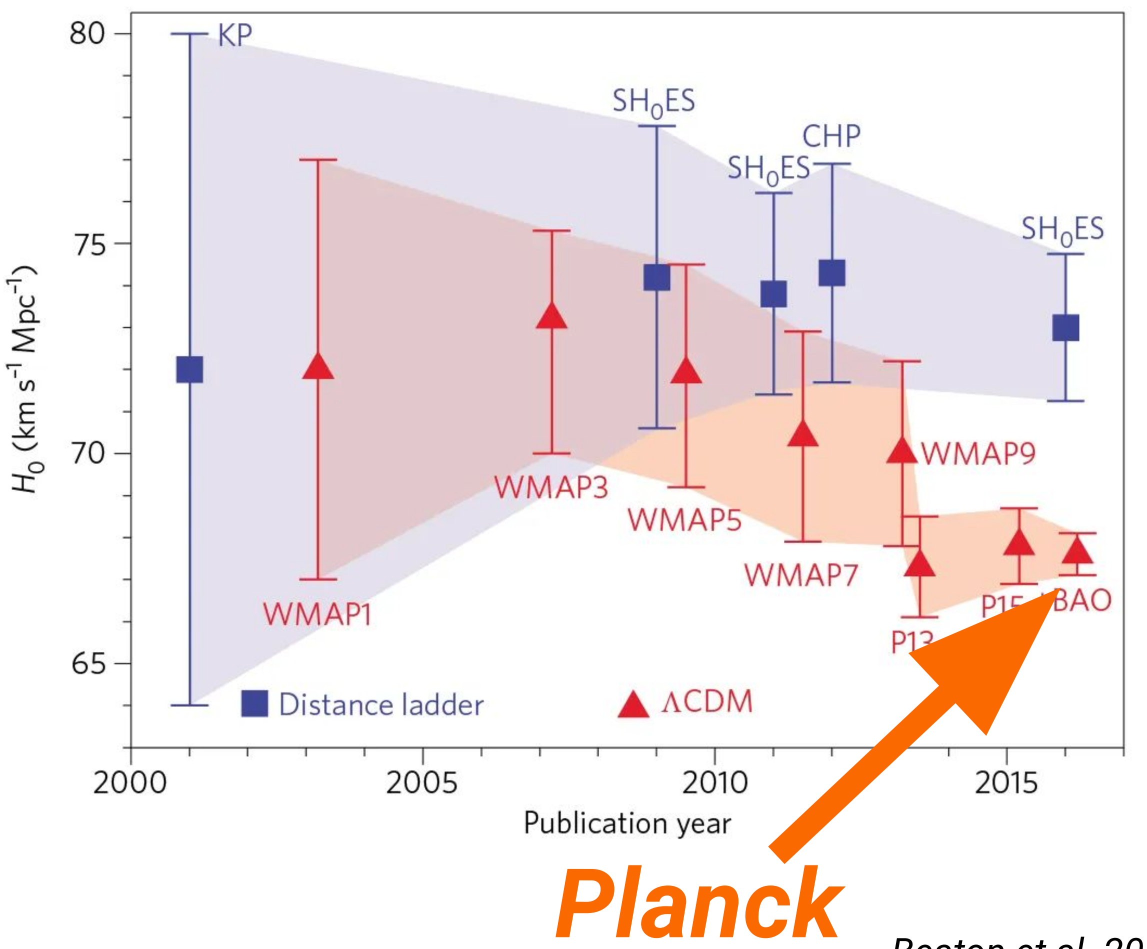
Planck has **full sky** temperature (CV-limited to ℓ~1800).

~4σ Hubble Tension



Beaton et al. 2016

~4σ Hubble Tension

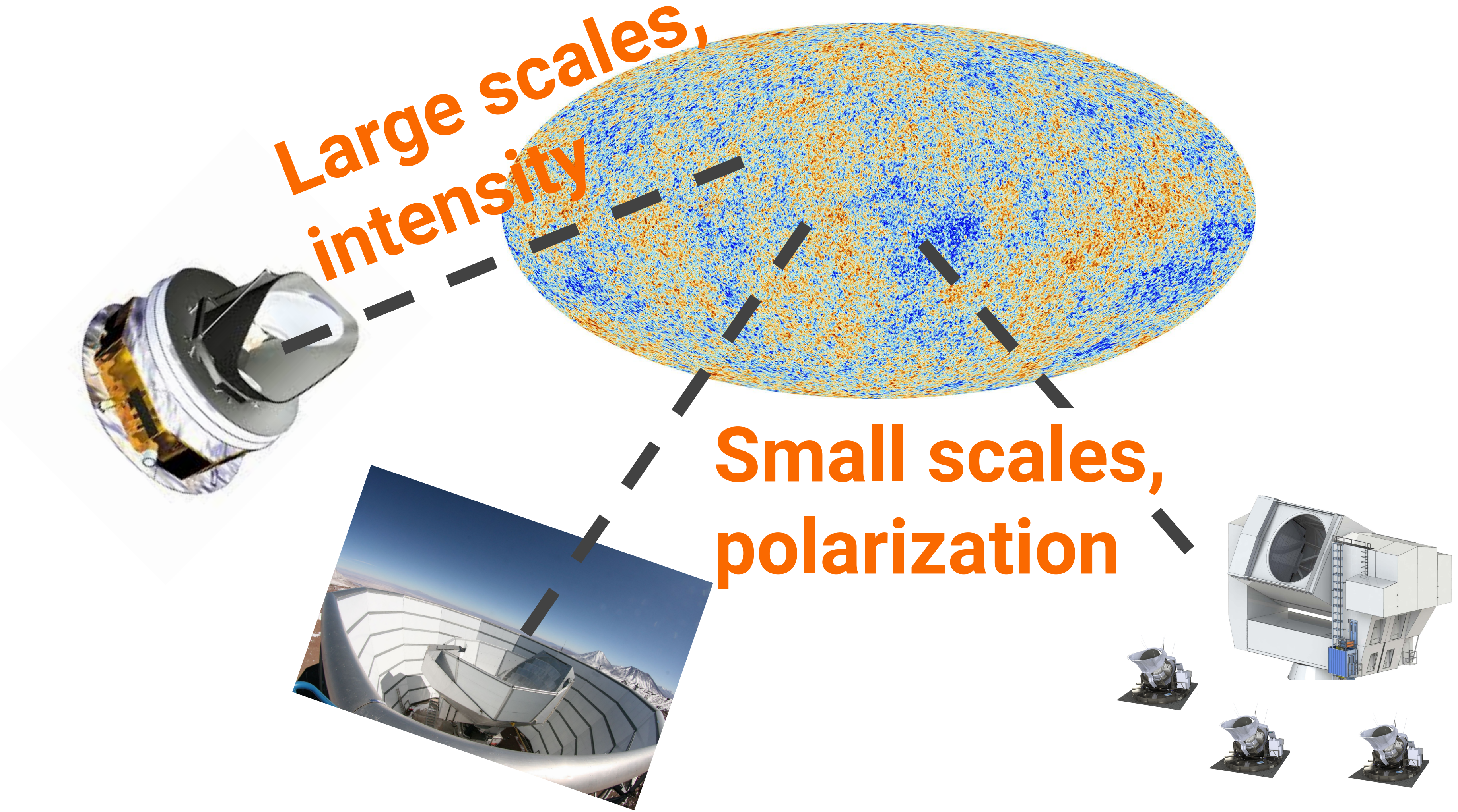


Beaton et al. 2016

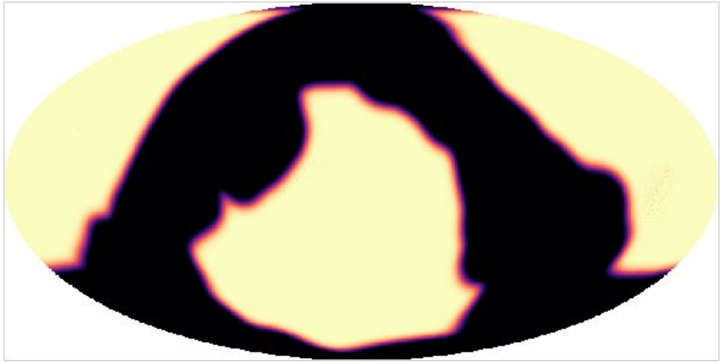
Planck maps are also useful for finding ground-based **systematics**.


ACT

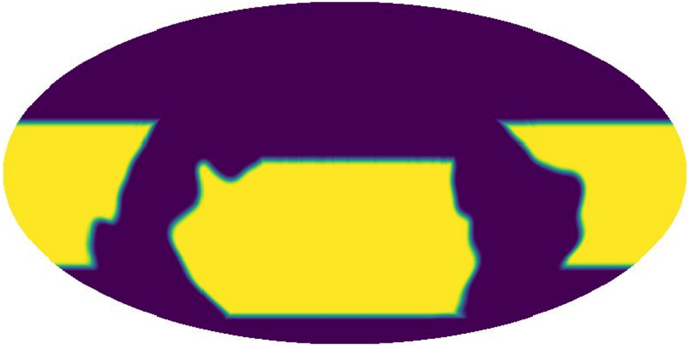
Ground
Pickup
PWV
ACT


Large scales,
intensity
Small scales,
polarization

Problem:
We share the same sky.

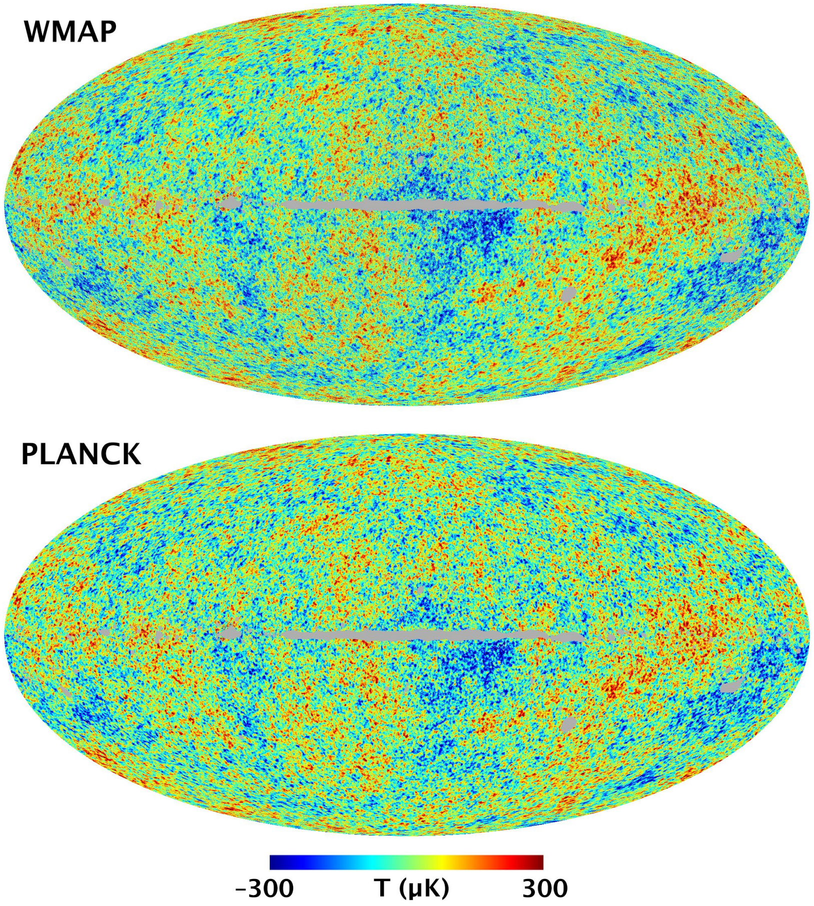


Planck



Simons Observatory

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



WMAP Science Team

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

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

We need to make sure this doesn't confuse us.

The Simons Observatory
Power Spectrum Pipeline (PSPipe)

Two pipelines wrapped in Python

1. *pspy* (Fortran) based on ACT code
2. *NaMaster* (C) used by LSST DESC

pspy (Thibaut Louis) and *NaMaster* (David Alonso) are both
pseudo-Cl codes (i.e. the “MASTER” algorithm, Hivon et al. 2002).

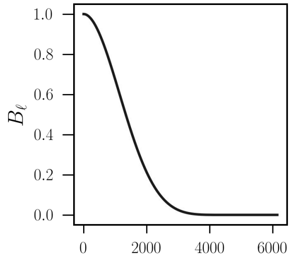
Li et al. + SO Collaboration, in prep.

We ***need*** the Planck data.
Our work ensures we'll be able to use it with ACT and SO.

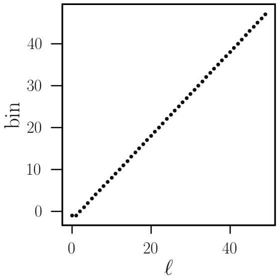
Reanalysis of *Planck* 2018

* Bandpower binning
* Noise spectra
* Missing pixels
* Polarization efficiency magic numbers

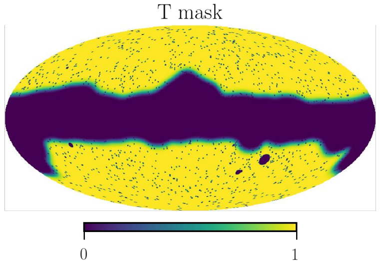
Data Inputs



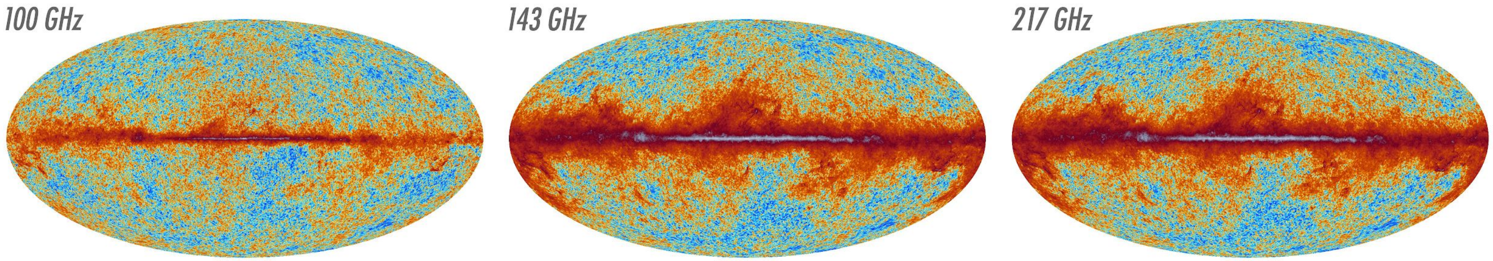
1.0
0.8
0.6
0.4
0.2
0.0
B_ℓ
0
2000
4000
6000



40
30
20
10
0
bin
0
20
40
ℓ



T mask
0
1

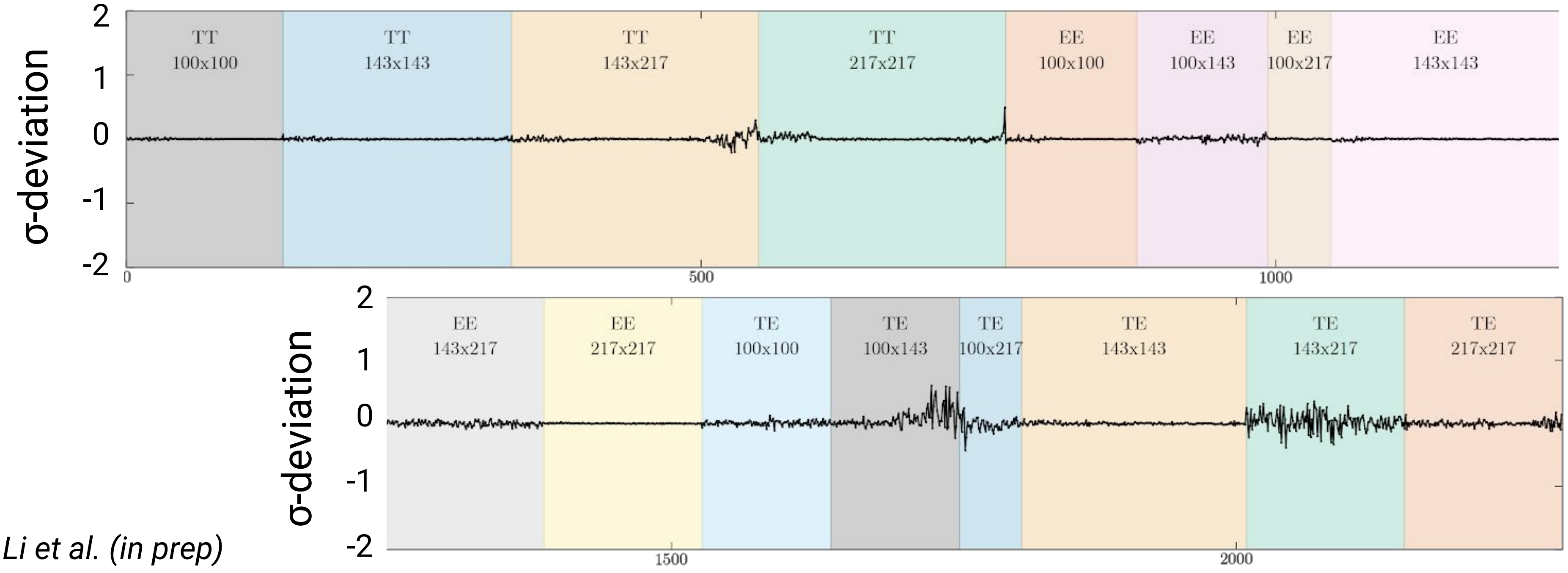


100 GHz
143 GHz
217 GHz

1. Check their analysis.
2. Validate our pipeline.

Agreement

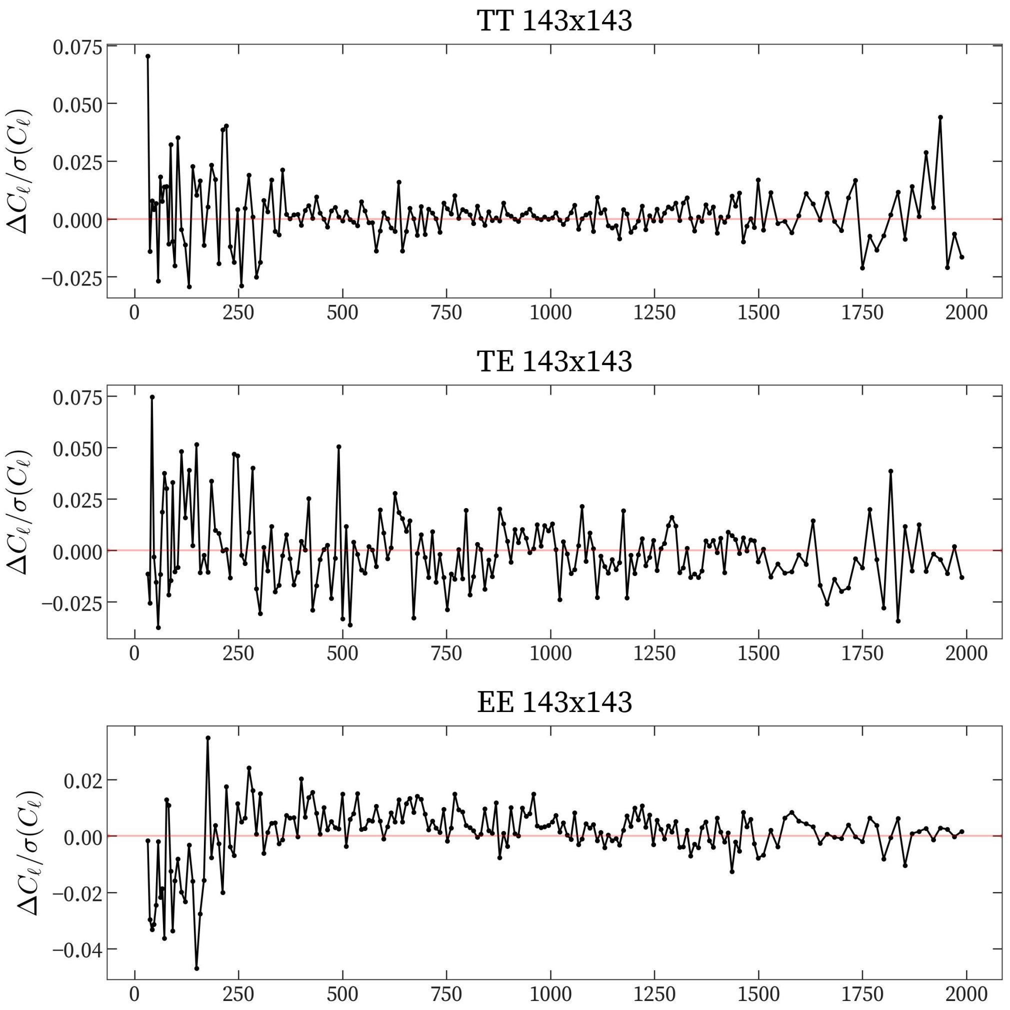
0.1σ in all frequencies and cross-spectra



Li et al. (in prep)

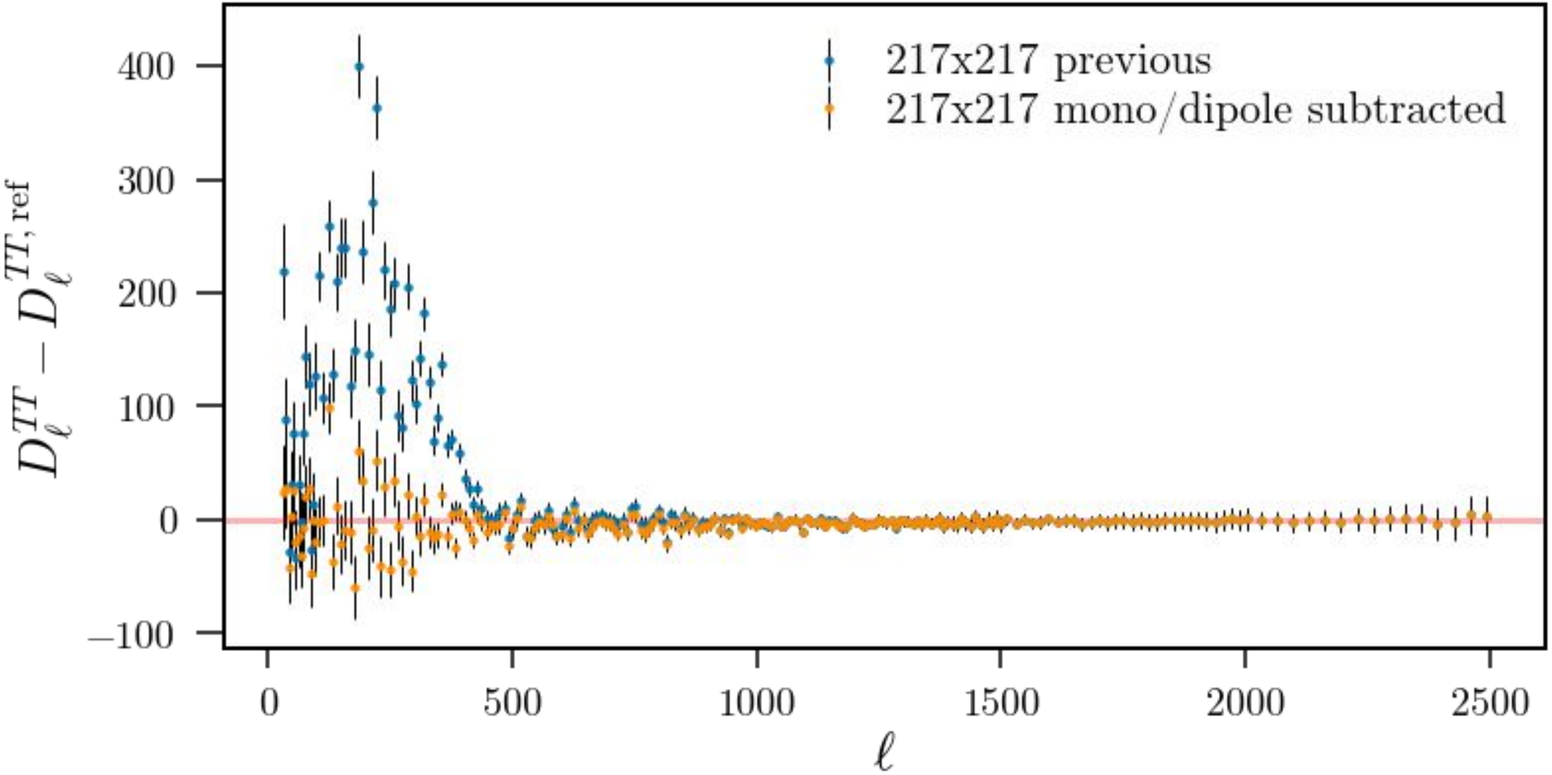
143 GHz

Residuals due to use of PolSpice



Li et al. (in prep)

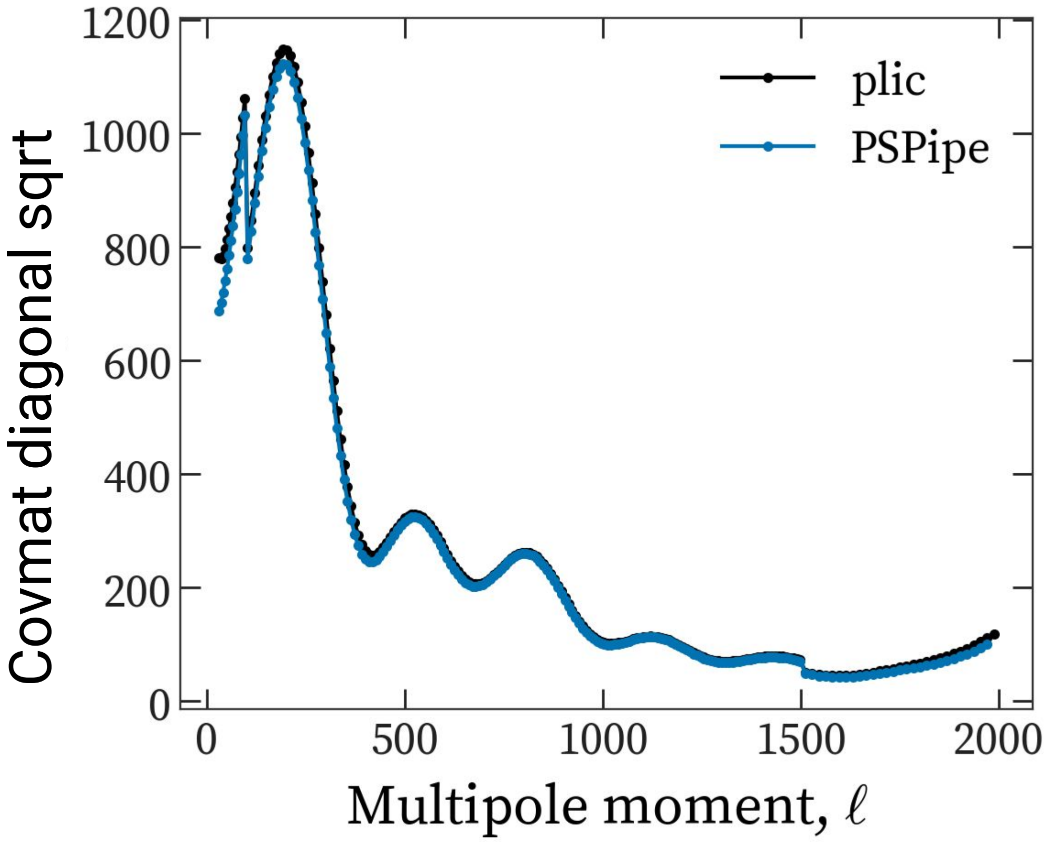
Example of what can go wrong



Li et al. (in prep)

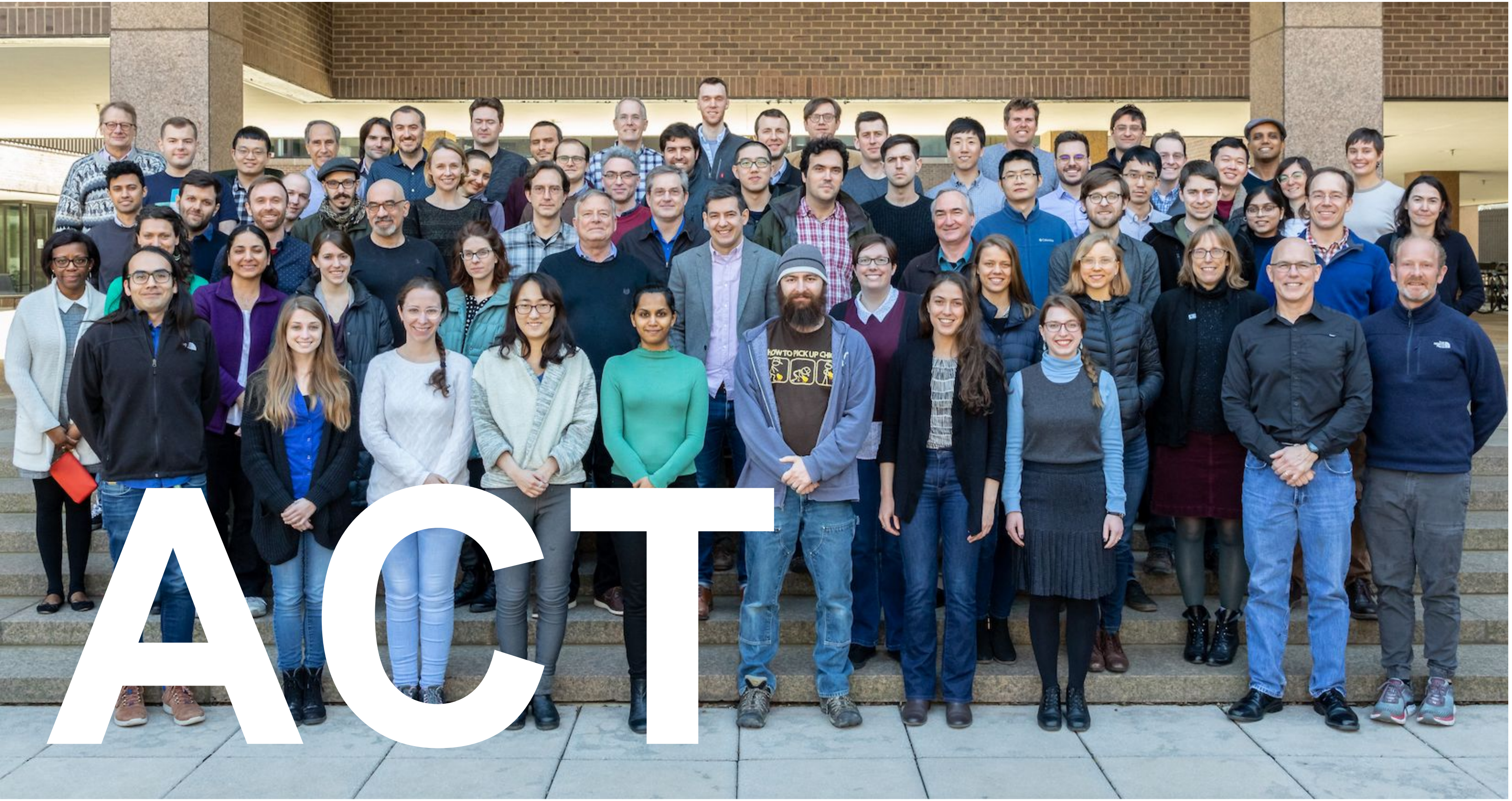
Covariance

Re-estimating the Planck covariance matrices



Li et al. (in prep)


ACT
Image credit: Debra Kellner



CONICYT
Ministerio de Educación
Gobierno de Chile

DR4:

ACT data
through 2016

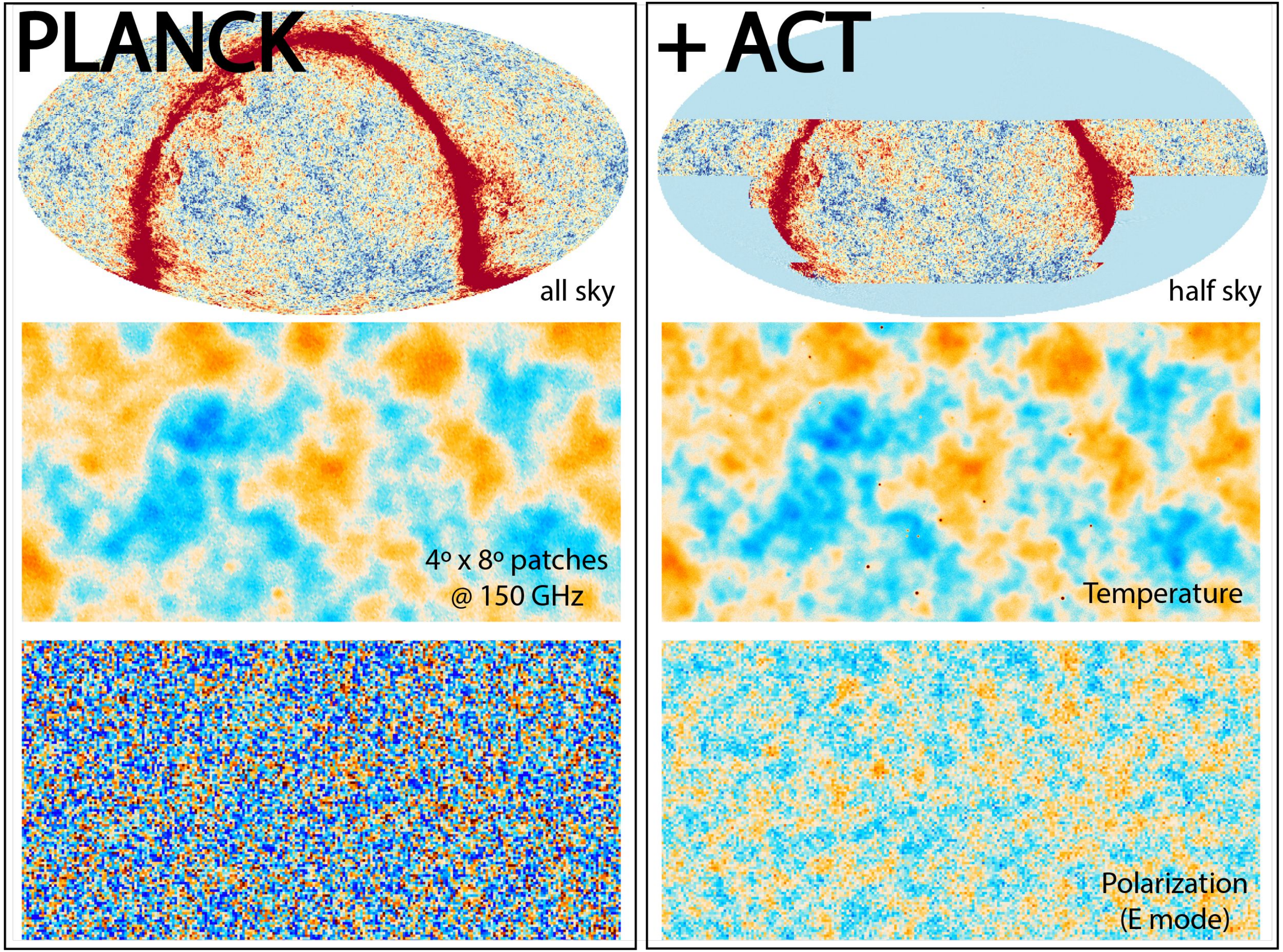
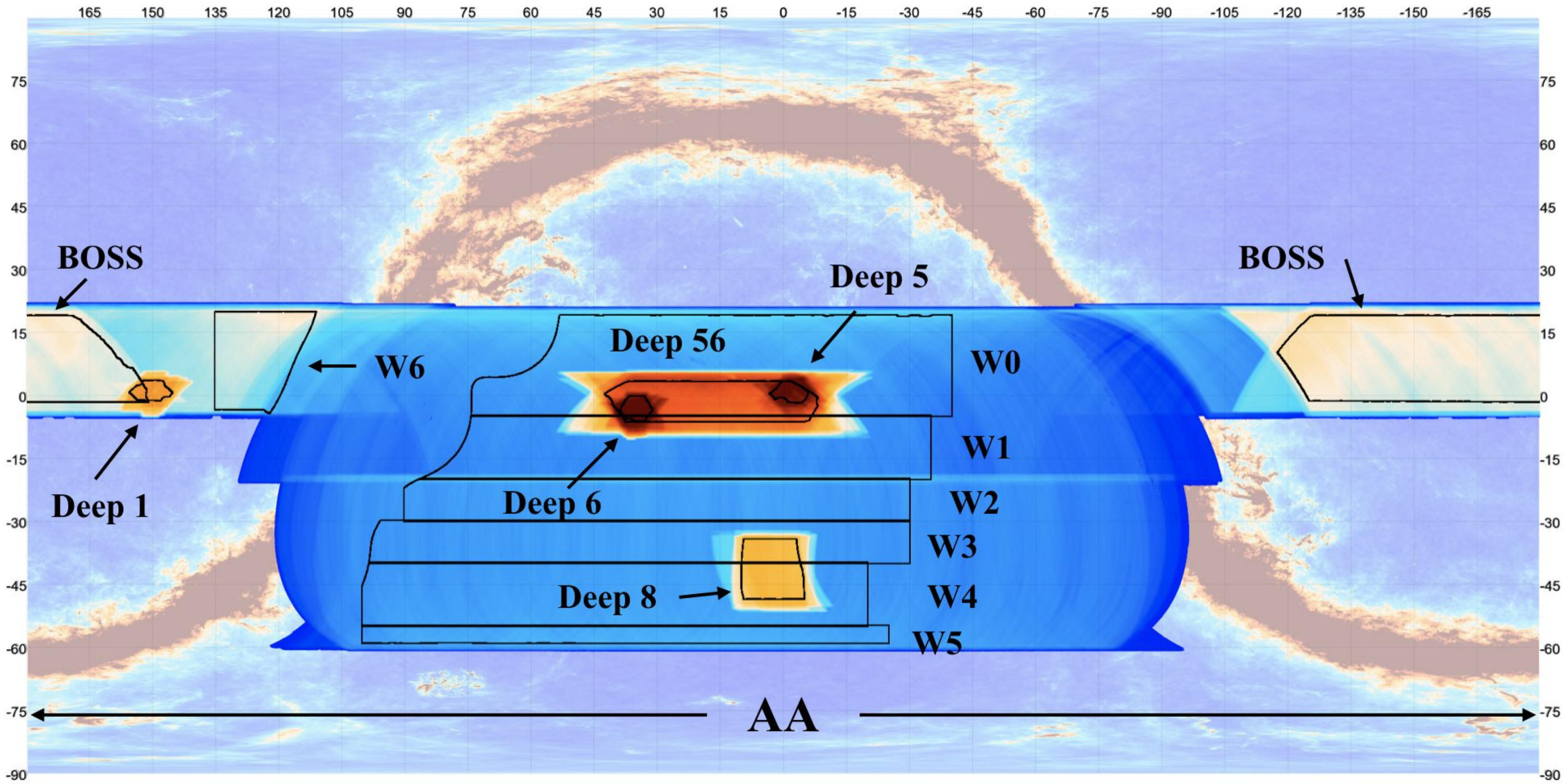
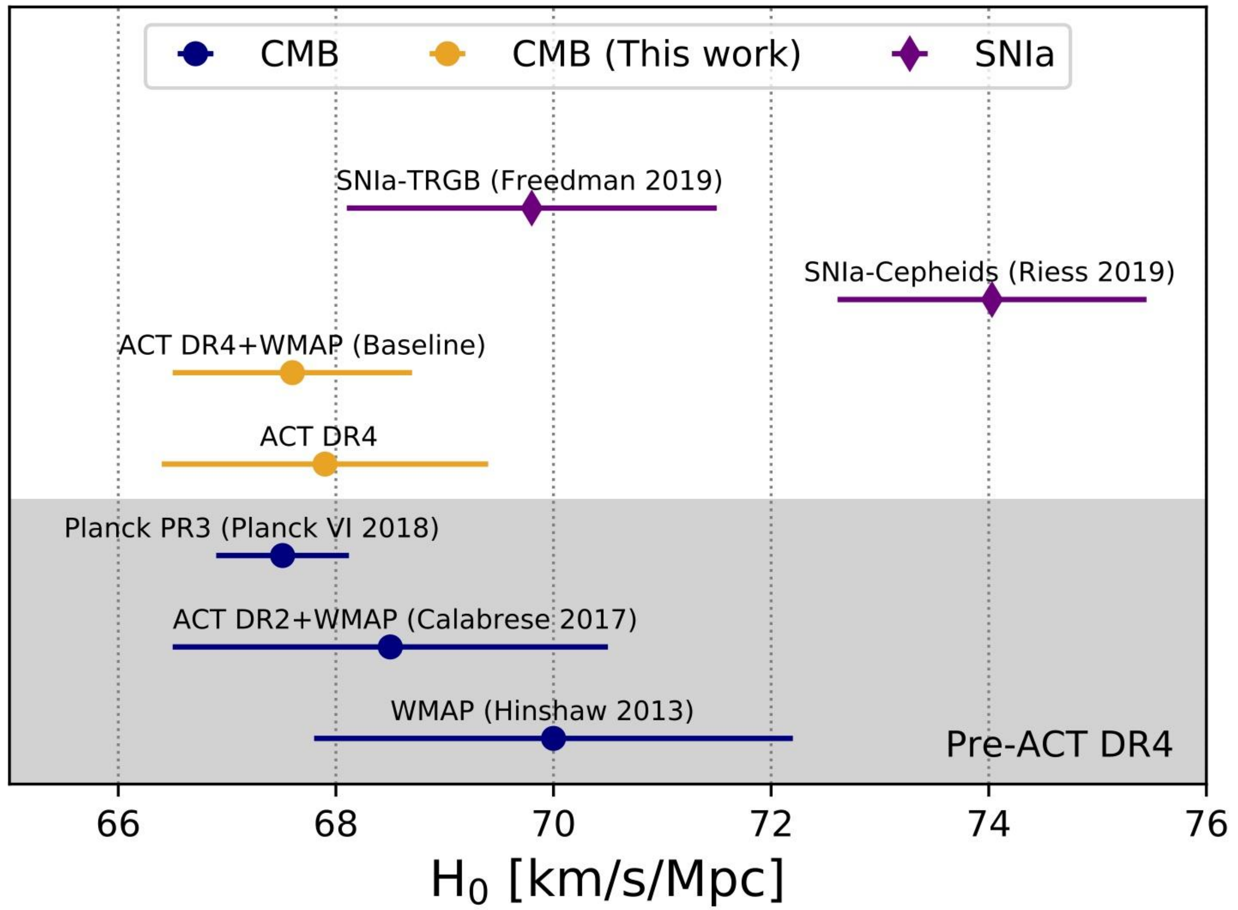


Image credit: ACT Collaboration



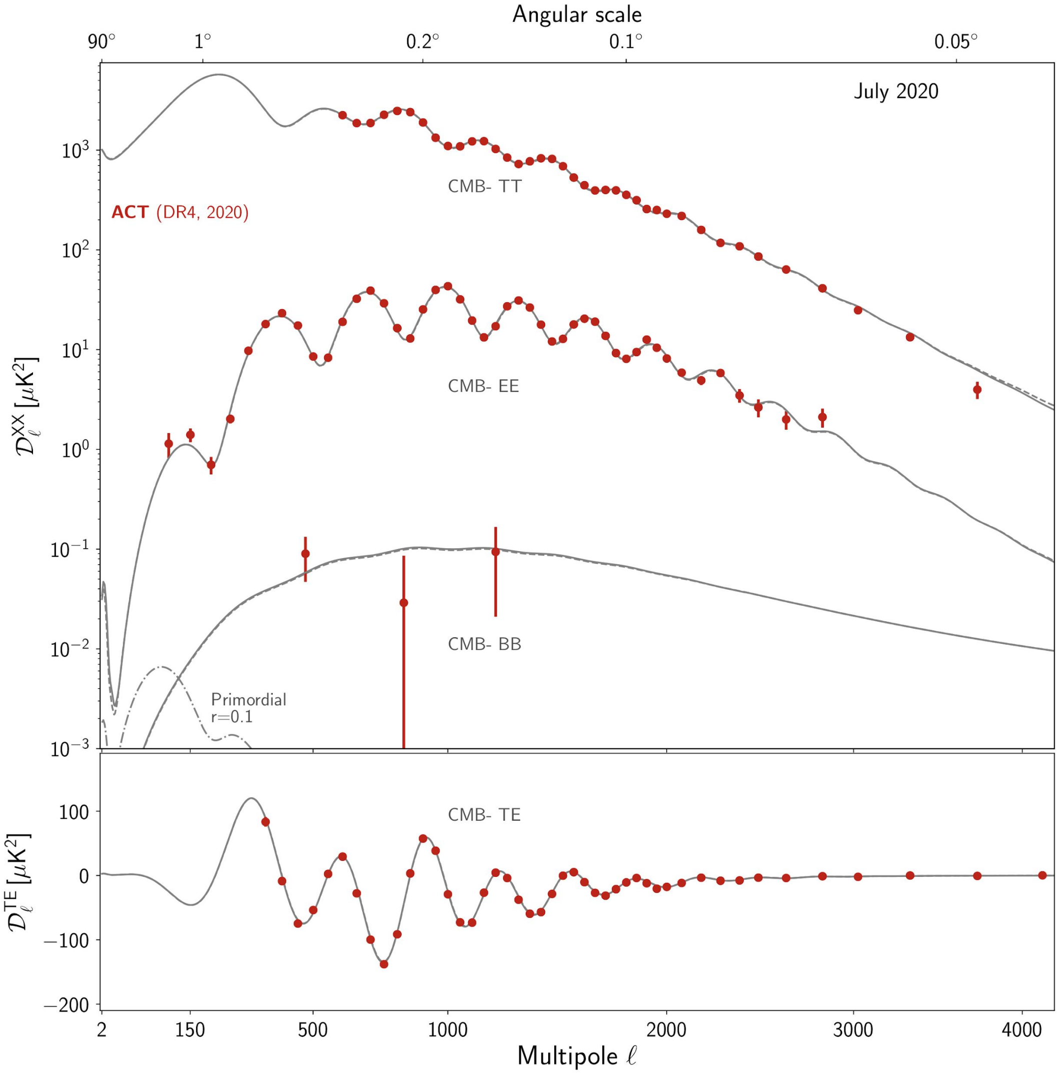
Notes: In the final spectra, we do not include D8, W2, W6

Choi et al 2020



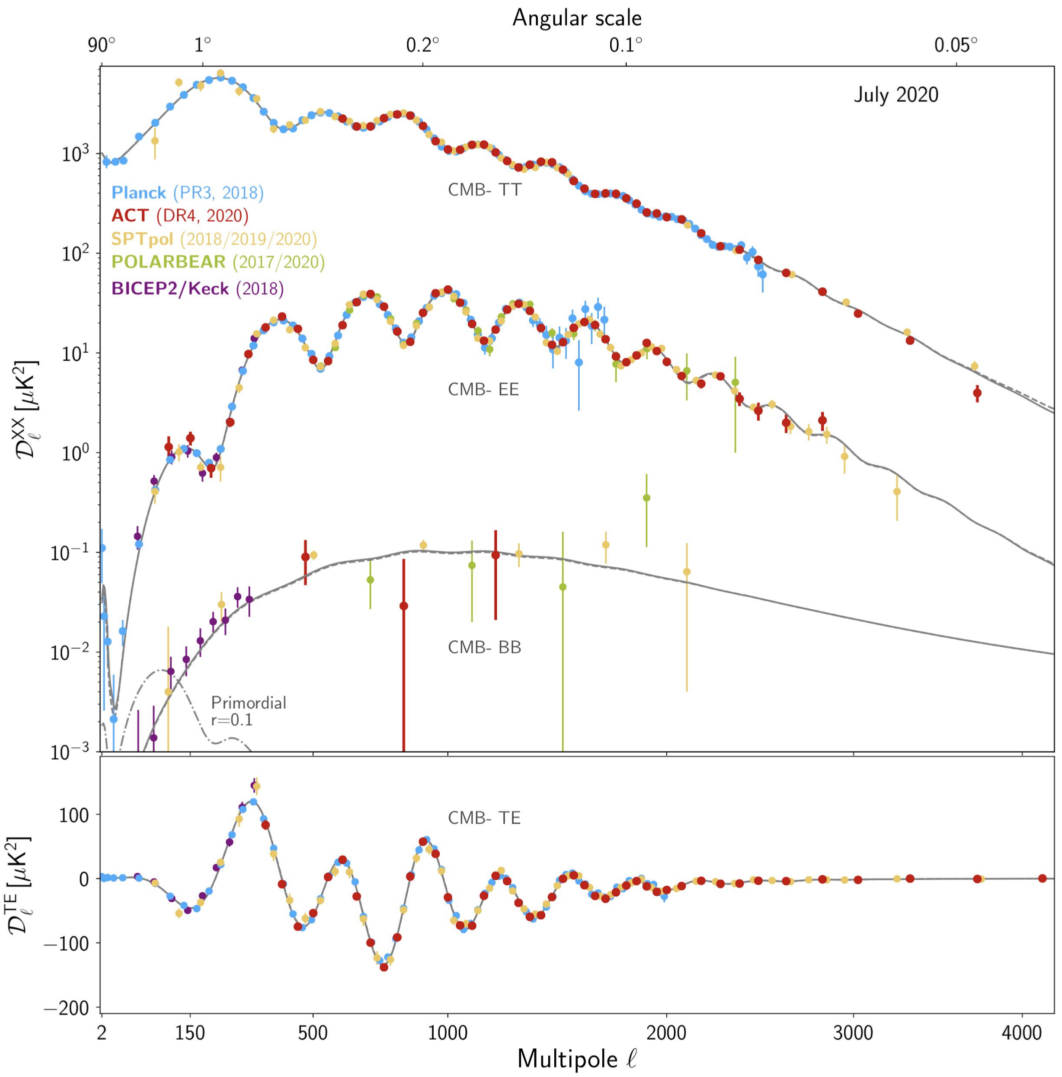
Aiola et al. 2020

DR4 spectra

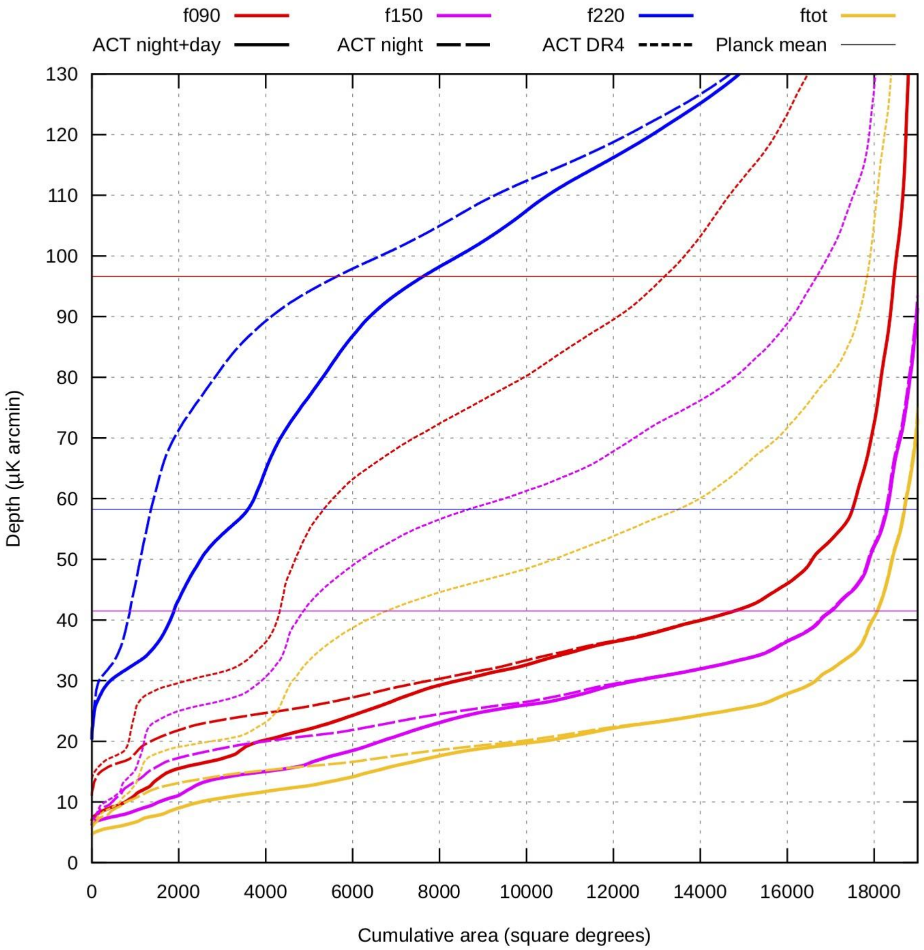


Choi et al 2020

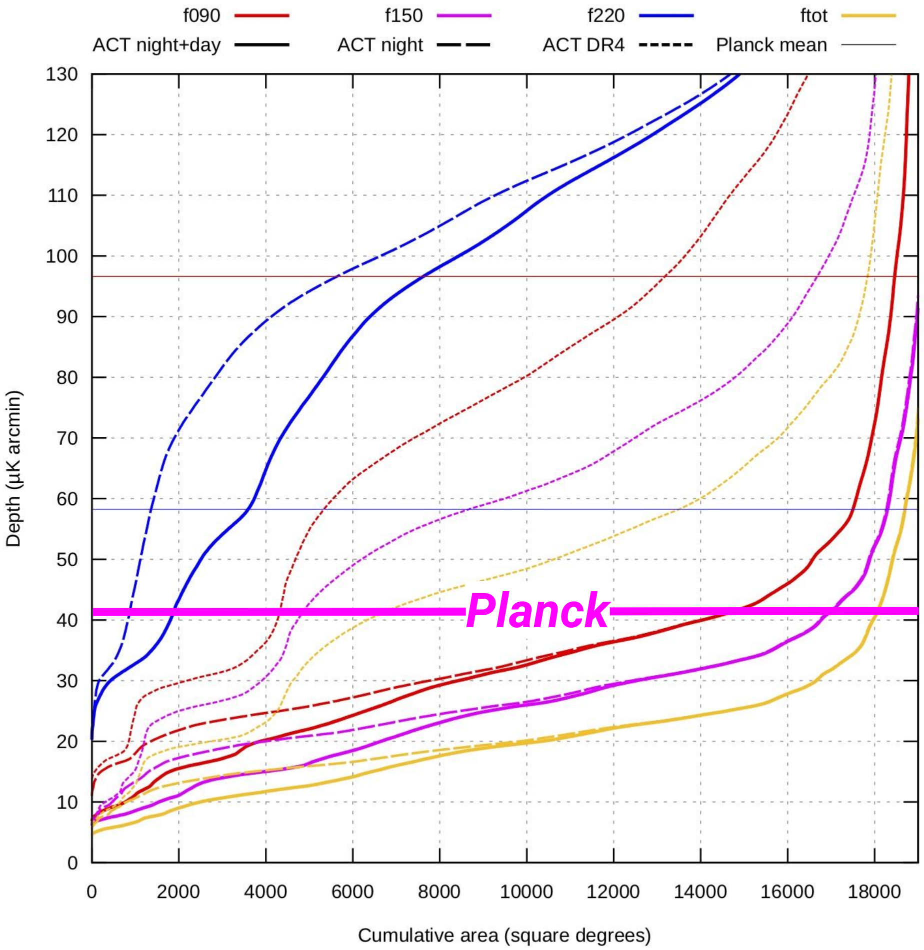
DR4 spectra



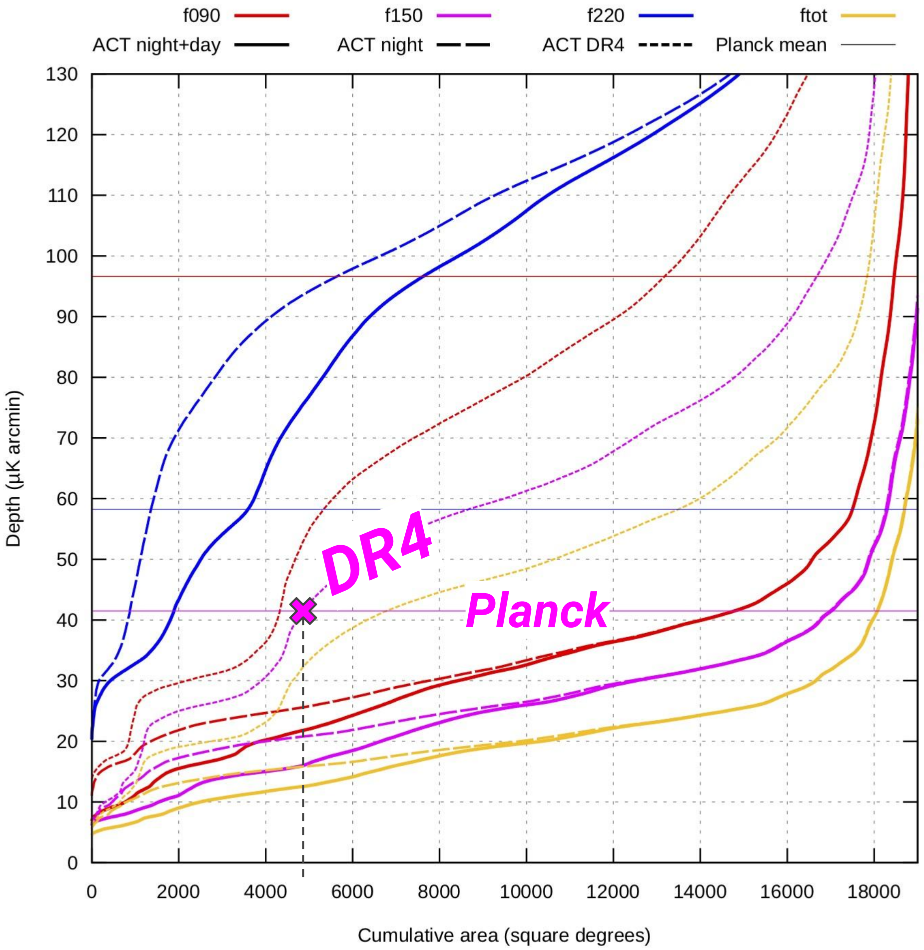
Choi et al 2020



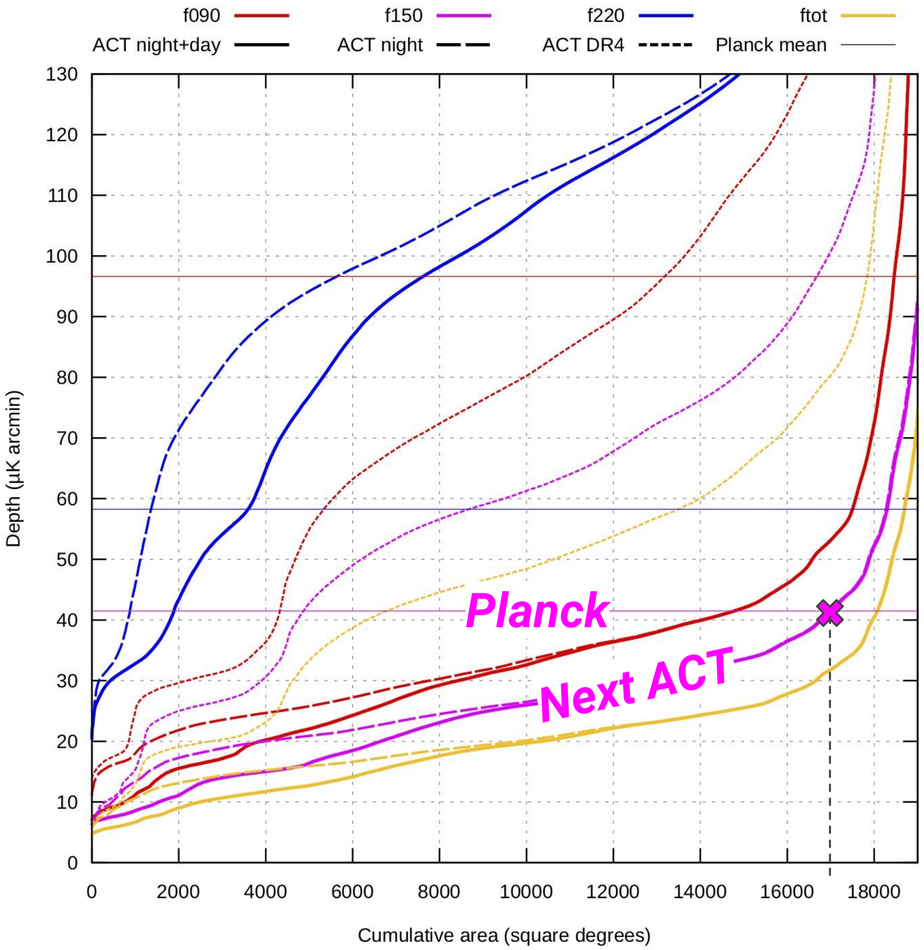
Naess et al. 2020



Naess et al. 2020



Naess et al. 2020



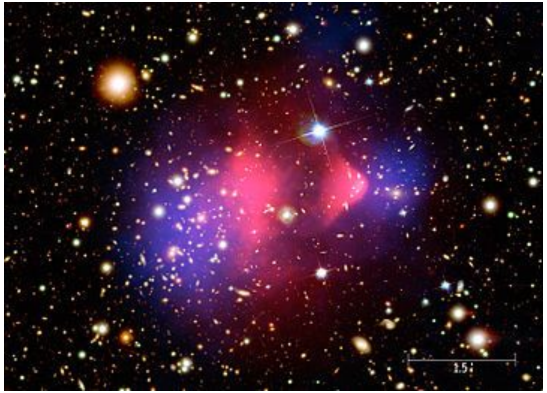
Naess et al. 2020

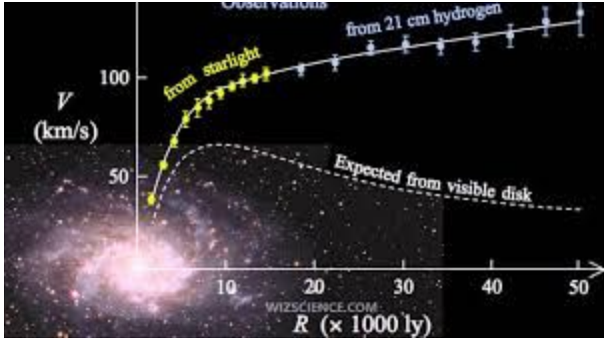
- damping tail physics
- lensing
- secondaries like tSZ, kSZ
- constraints on reionization
- cluster cosmology
- bispectra
- Galactic dust physics!

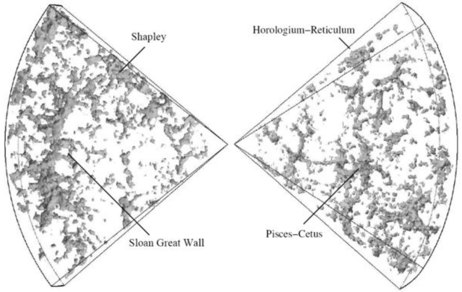
Science Case:

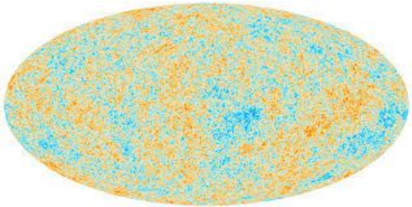
Dark Matter Physics

Standard dark matter:
no interactions with the standard model





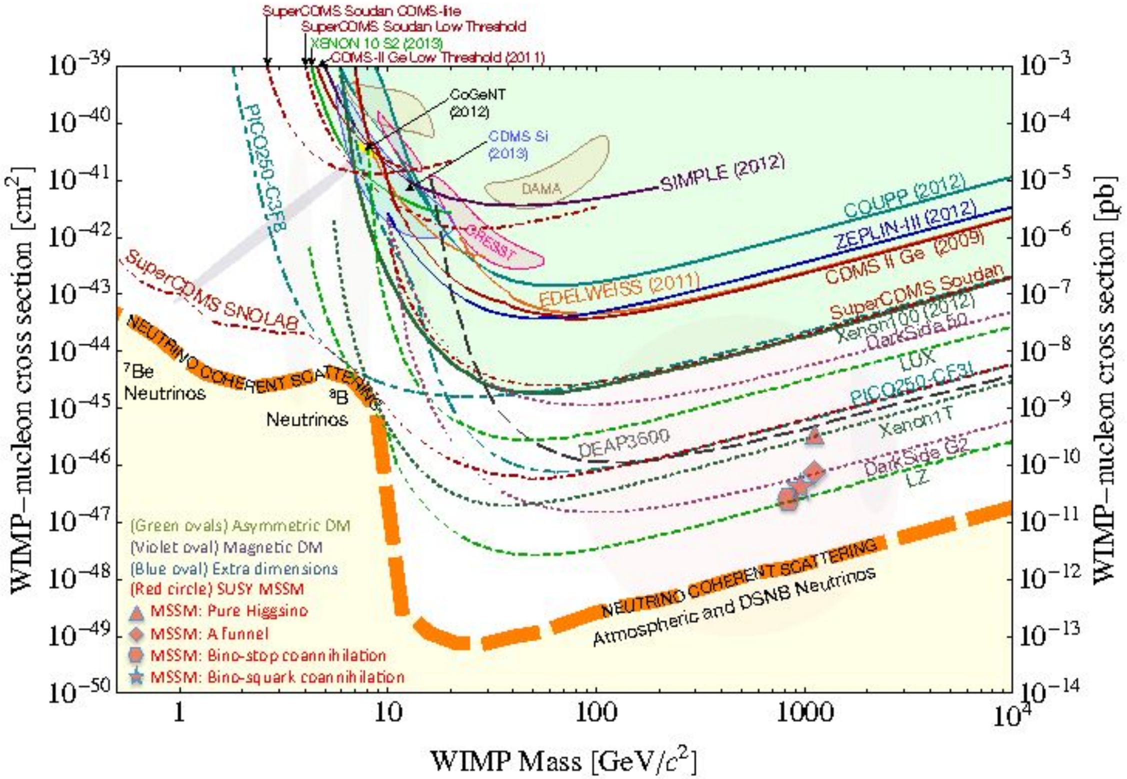




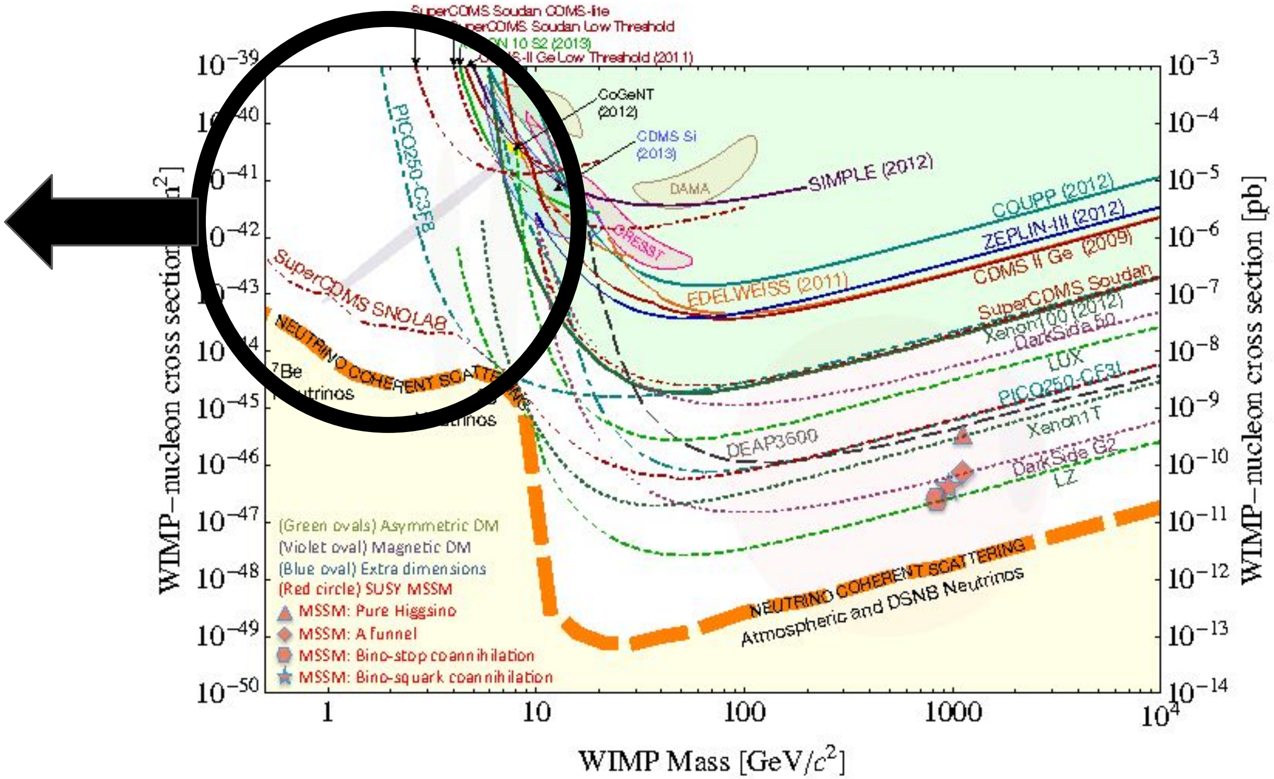
Direct detection experiments:
It would be nice if there was some small, nonzero coupling between dark matter and baryons.

XENON1T, LUX

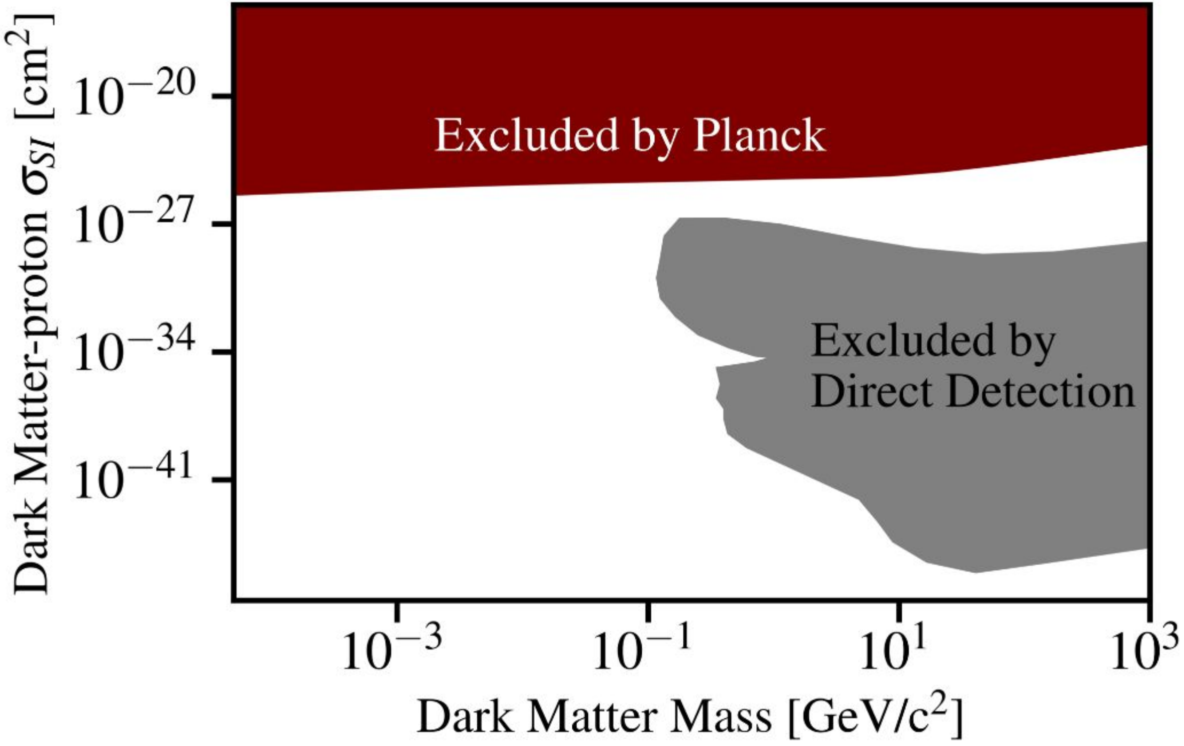
Massive tanks of Xenon



Massive tanks of Xenon

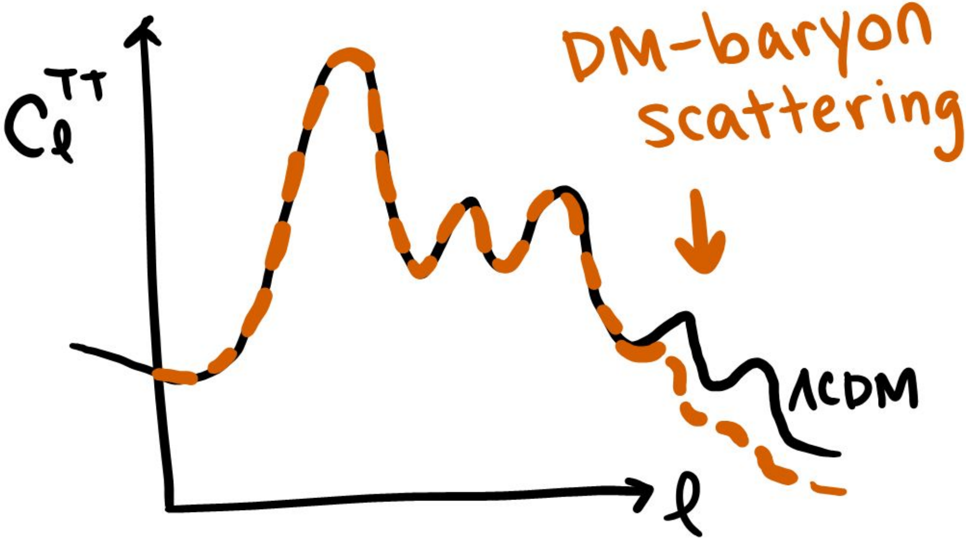


The CMB is competitive at **low masses**.

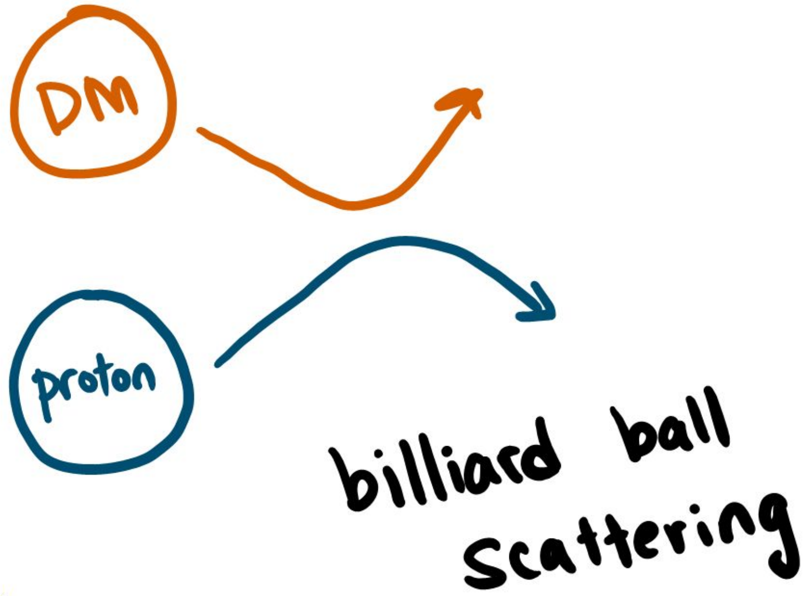


VG and Boddy 2018

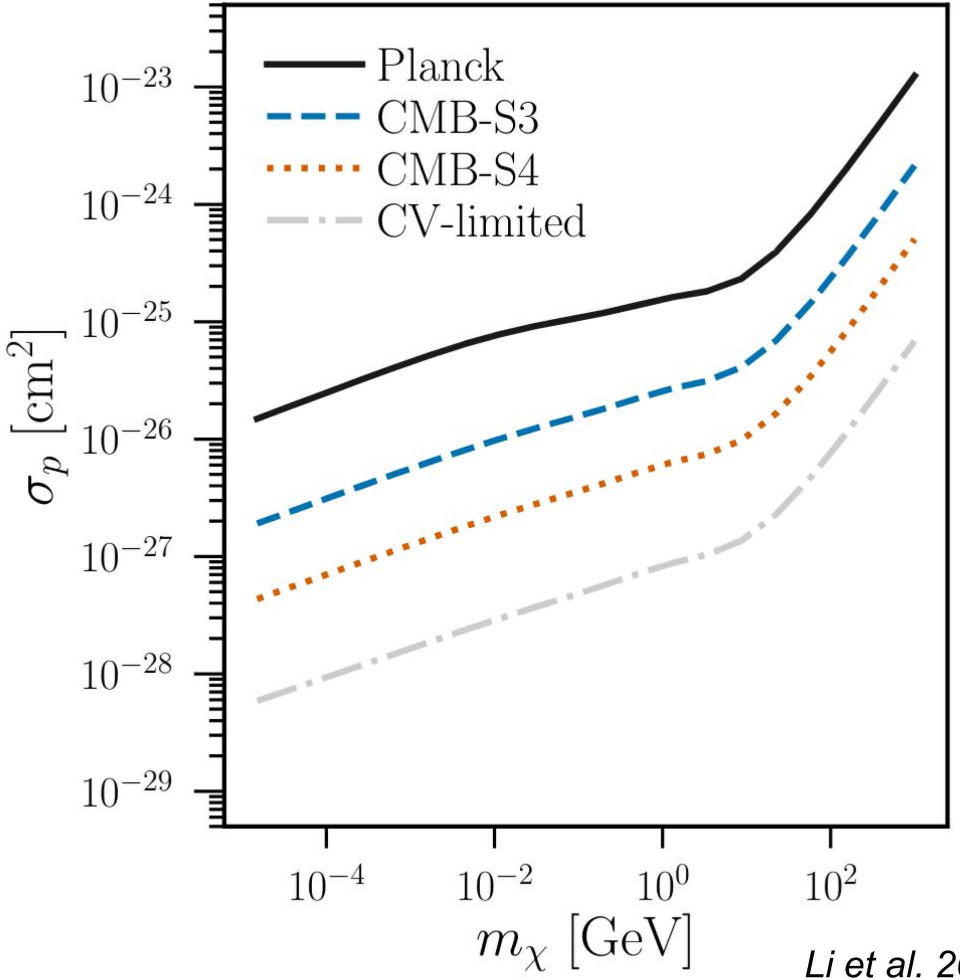
Scattering appears in the CMB as **suppressed structure on small scales**



Example model:
velocity-independent cross sections

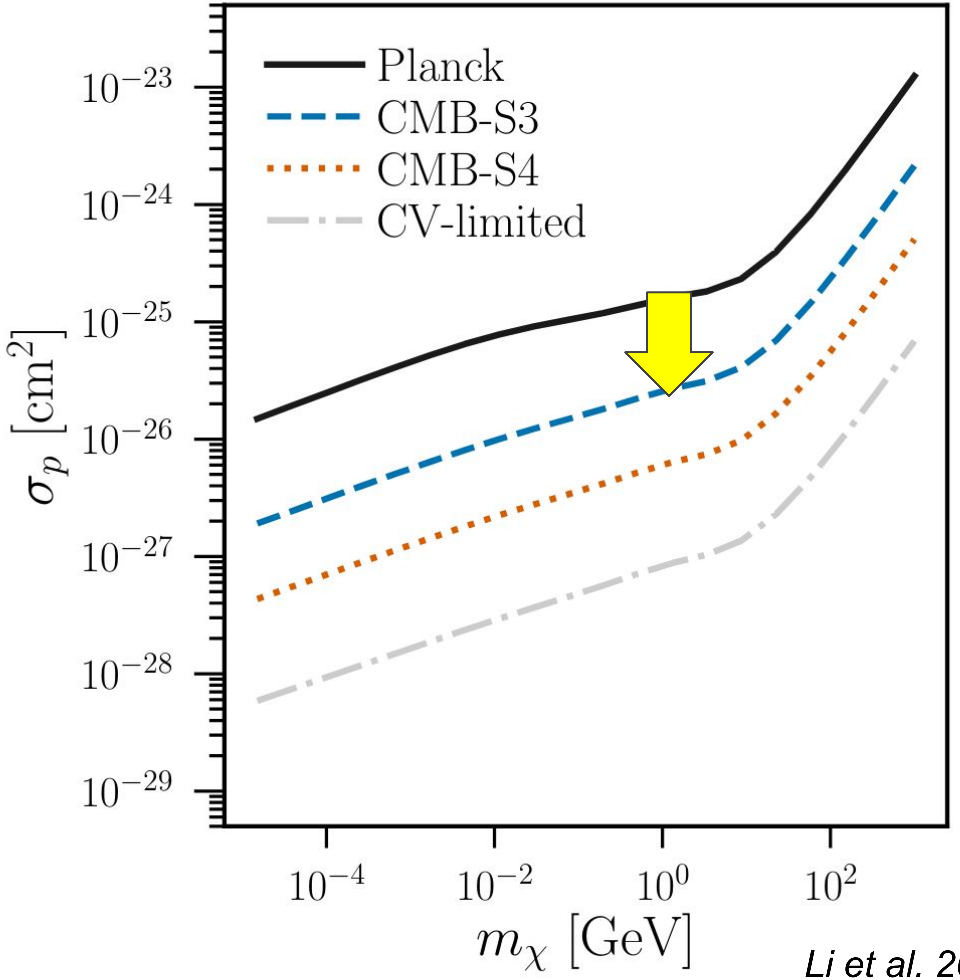


Forecasted **exclusion curves** on the DM-baryon interaction cross-section



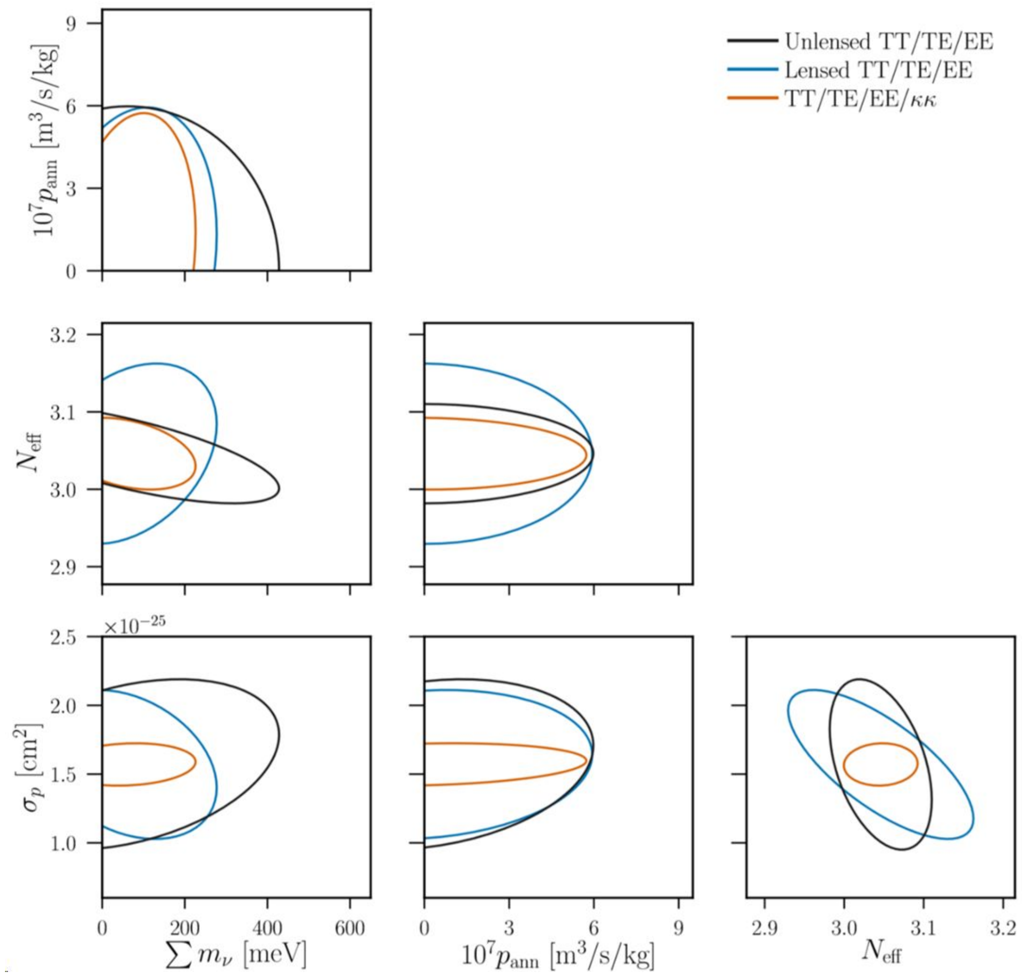
Li et al. 2018

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

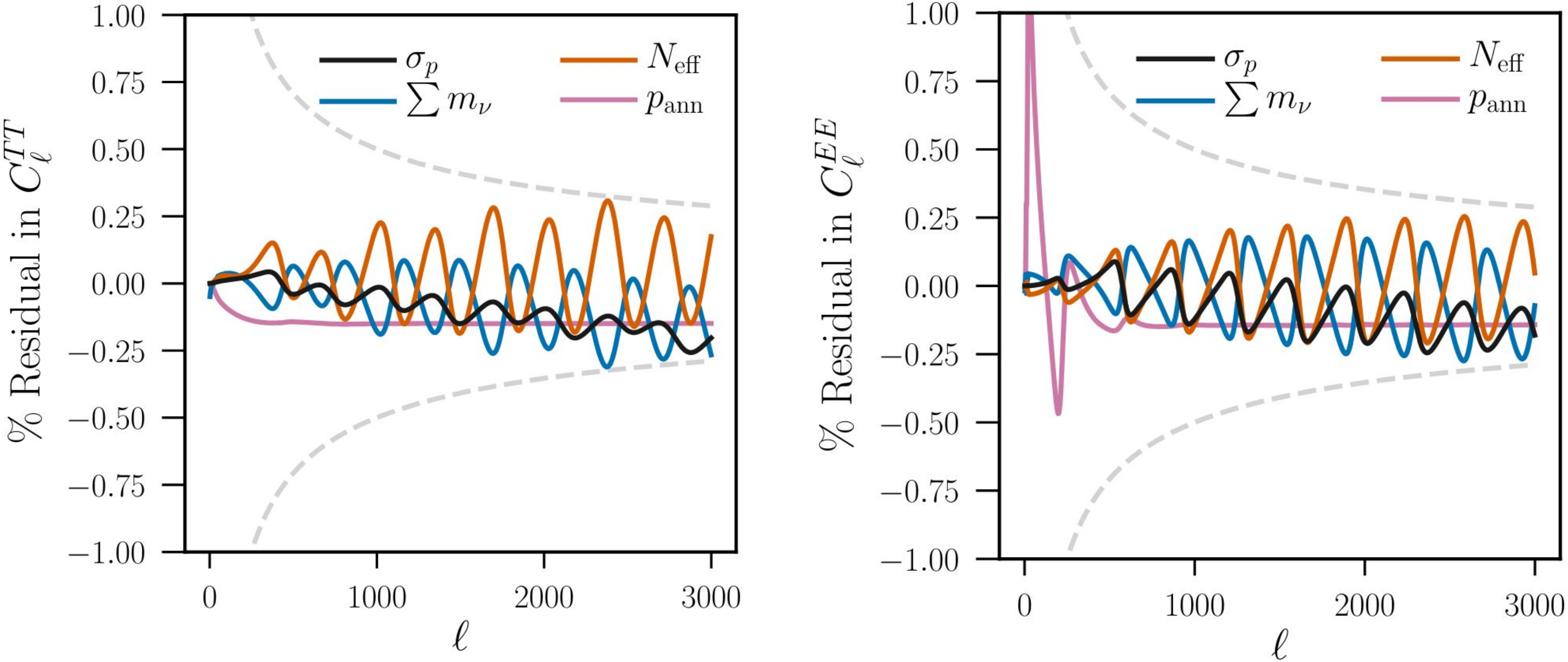


Li et al. 2018

The signal is distinguishable from other LCDM extension physics.

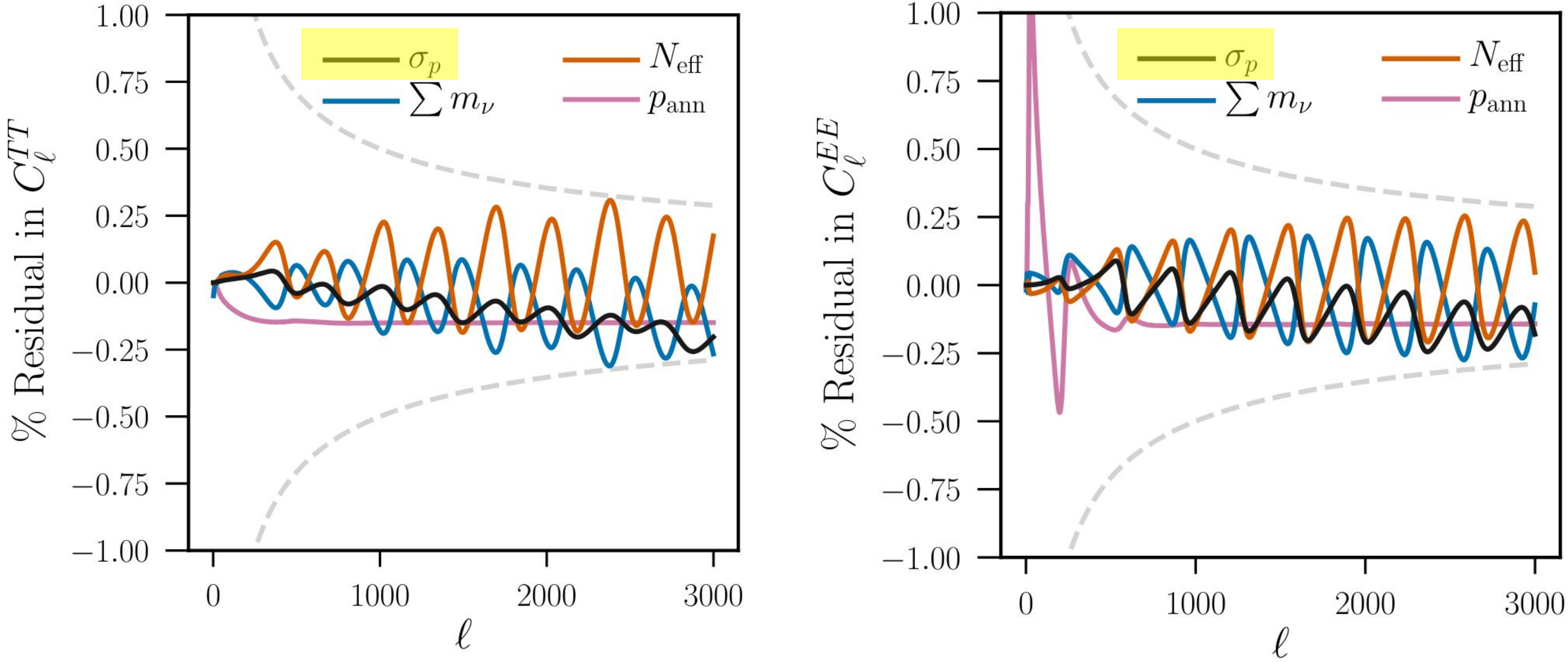


Li et al. 2018



σ_p
$N_{\rm eff}$
$\sum m_\nu$
$p_{\rm ann}$
% Residual in C_ℓ^{TT}
% 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

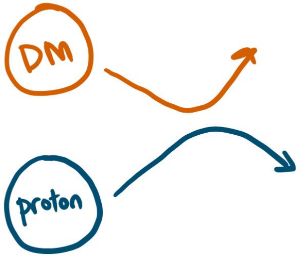


σ_p
$N_{\rm eff}$
$\sum m_\nu$
$p_{\rm ann}$
% Residual in C_ℓ^{TT}
% Residual in C_ℓ^{EE}
ℓ

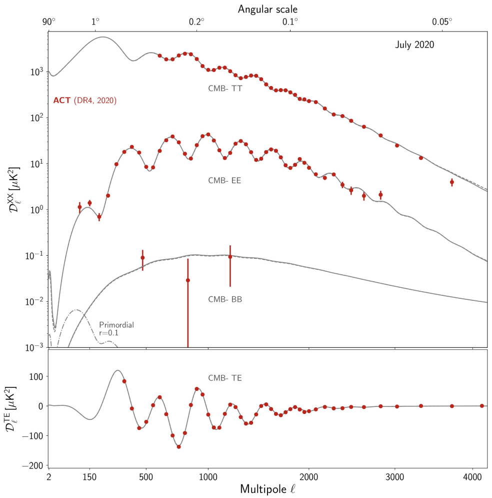
Li et al. 2018

In prep: Li et al. + ACT

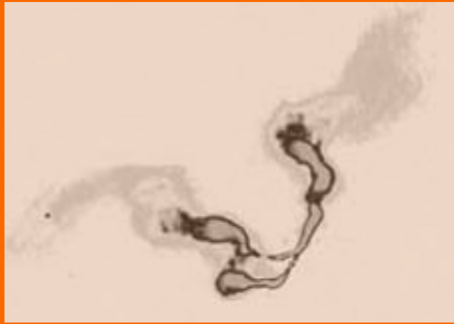
Dark matter interaction constraints from DR4 spectra

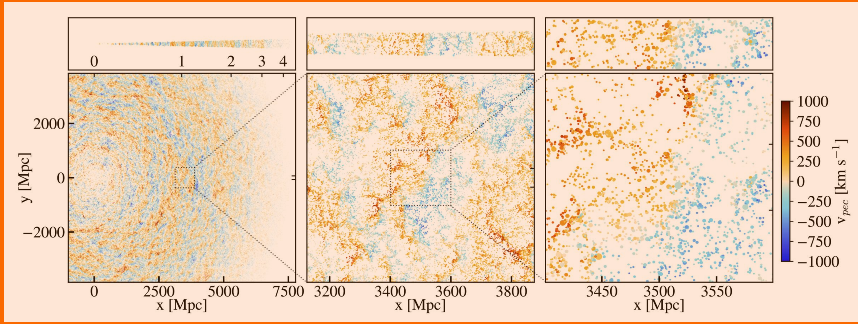


+



Choi et al 2020



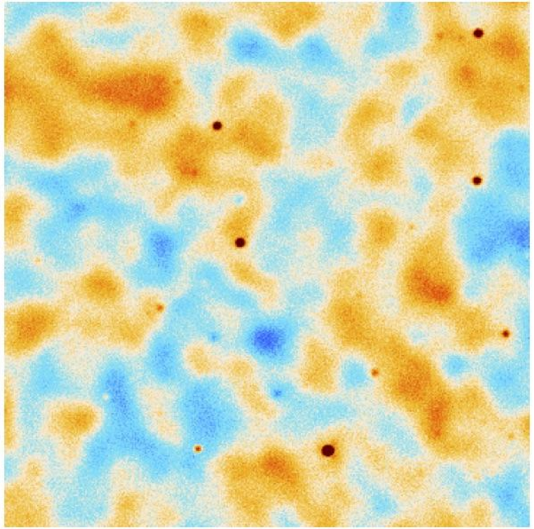


Science Case: Radio Sources

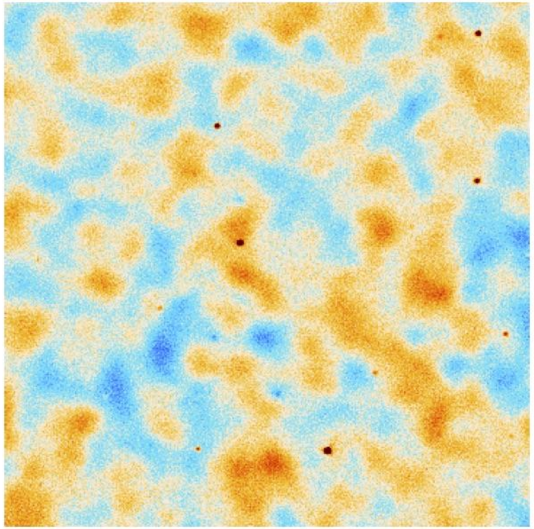
Collaborators:
Marcelo Alvarez, Mat Madhavacheril, Giuseppe Puglisi

Bright radio galaxies are **everywhere** in our maps.

ACT f90

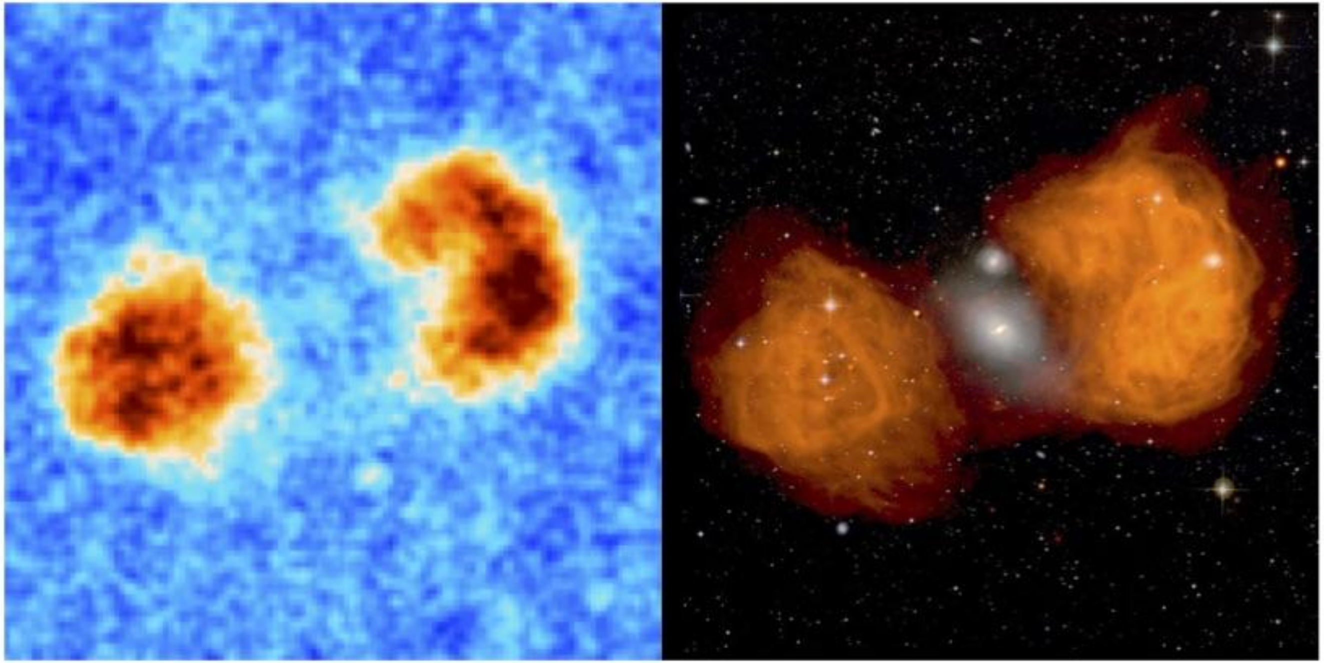


ACT f150



Naess et al. 2020.

Fornax A



ACT+Planck f090 - f150   Radio+Optical

Naess et al. 2020.

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

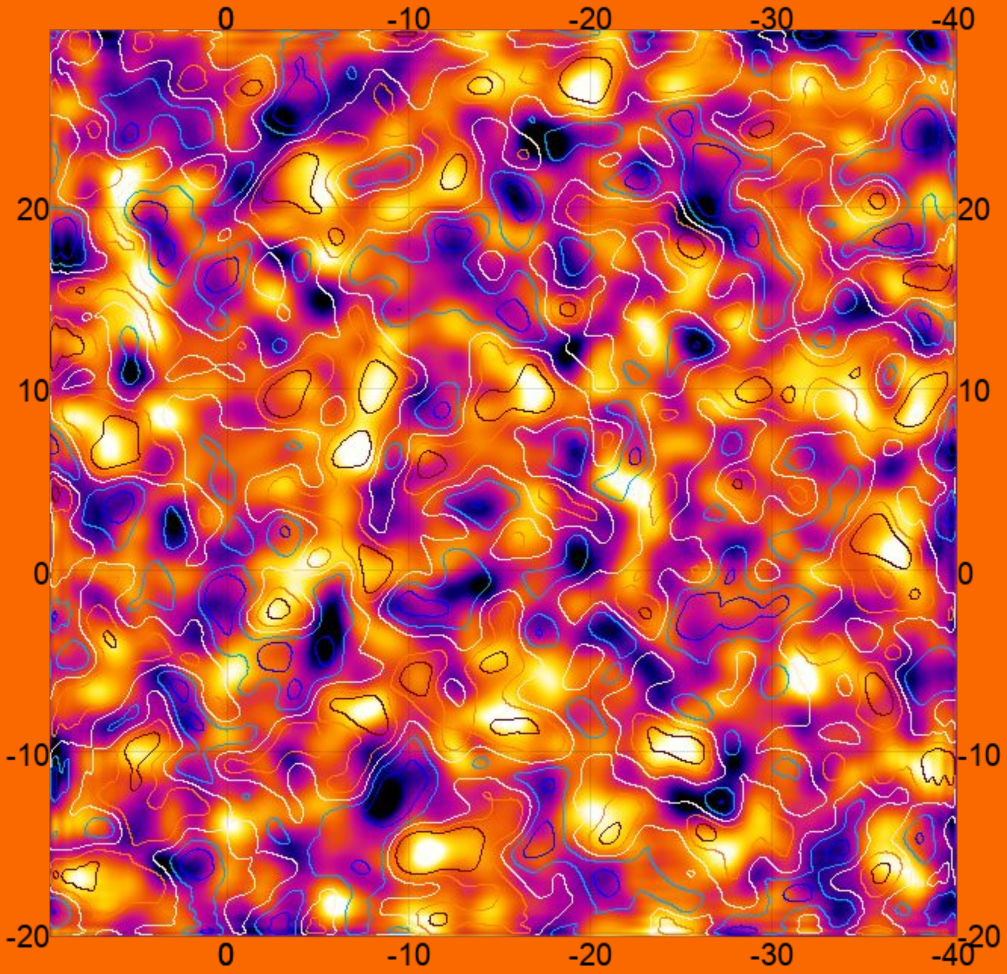
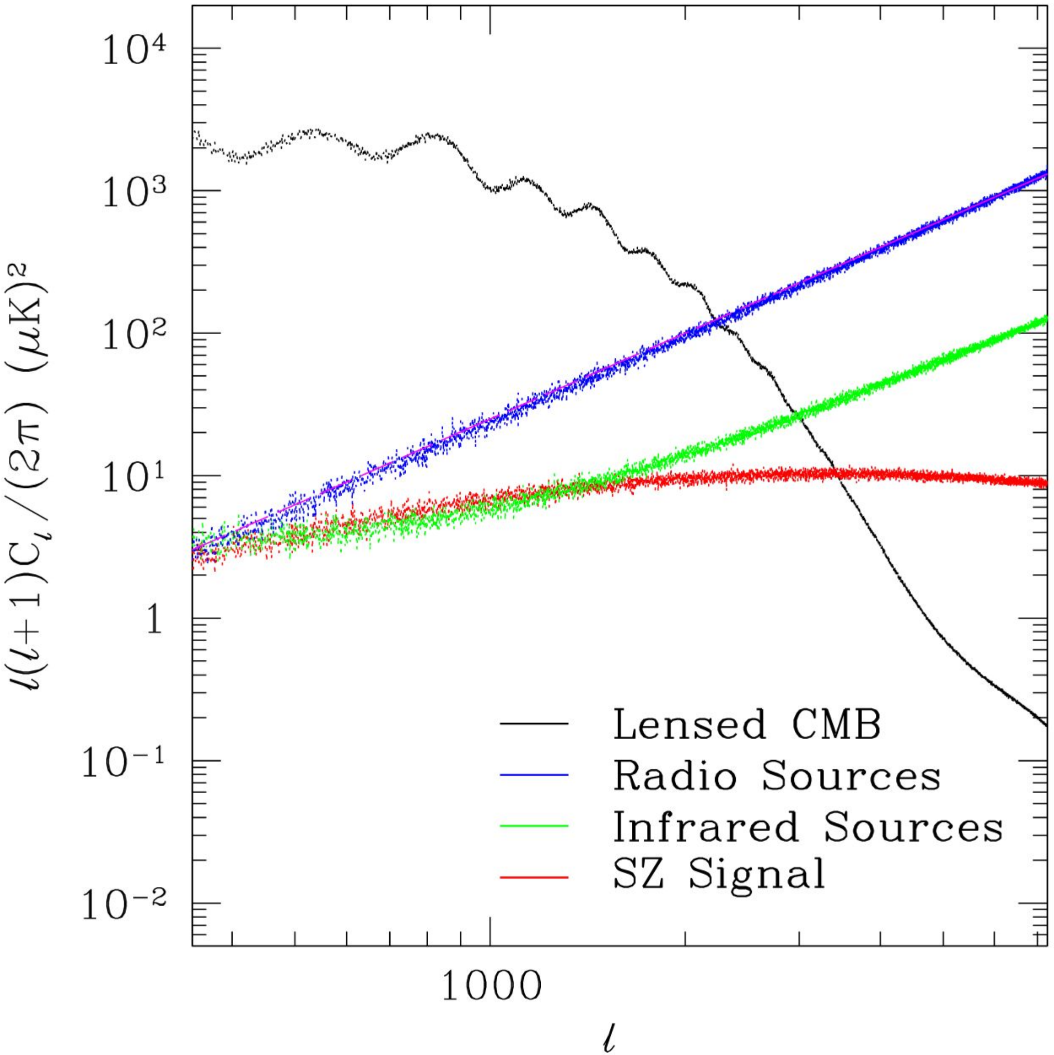


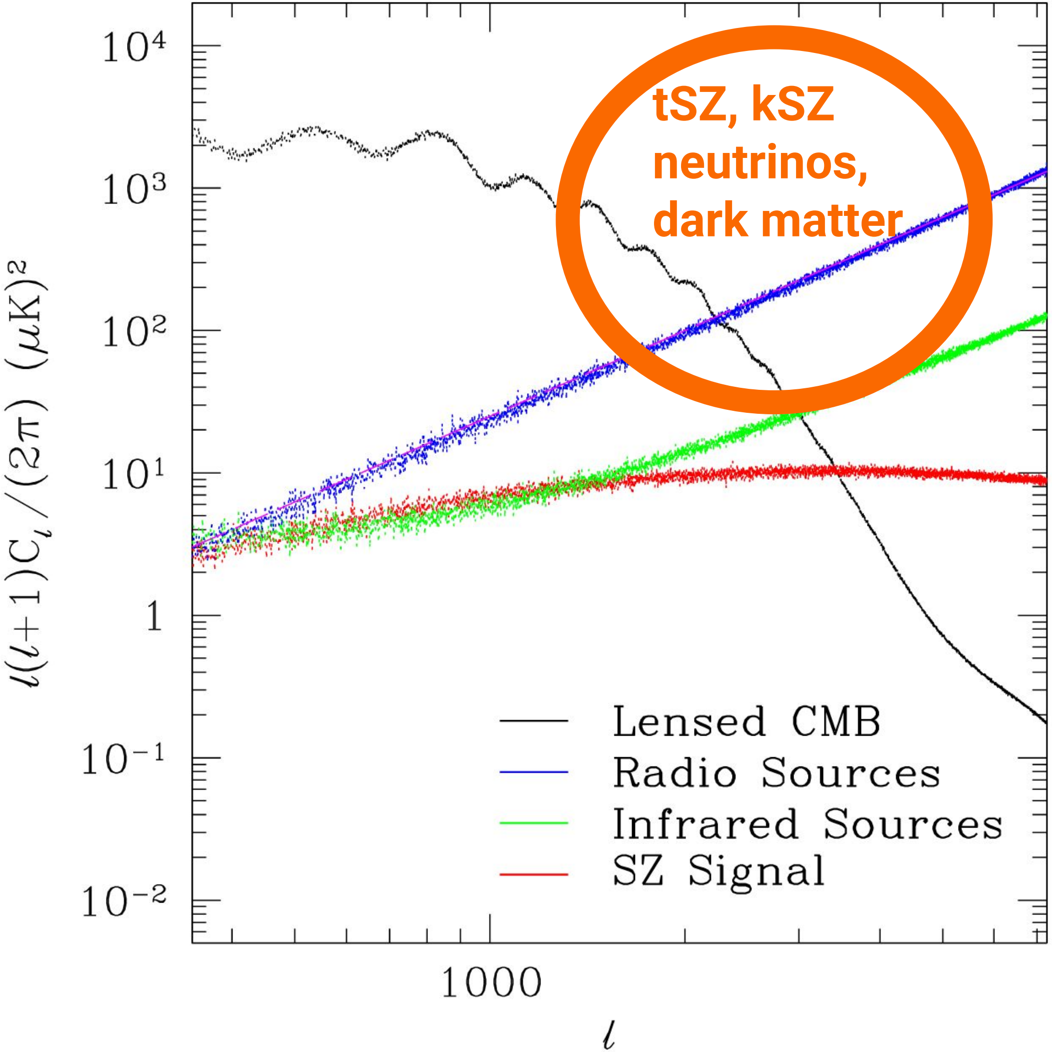
Figure: Lensing convergence contours, overlaid over simulated radio galaxies, from paper in prep

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



150 GHz plot from Sehgal et al. 2009

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

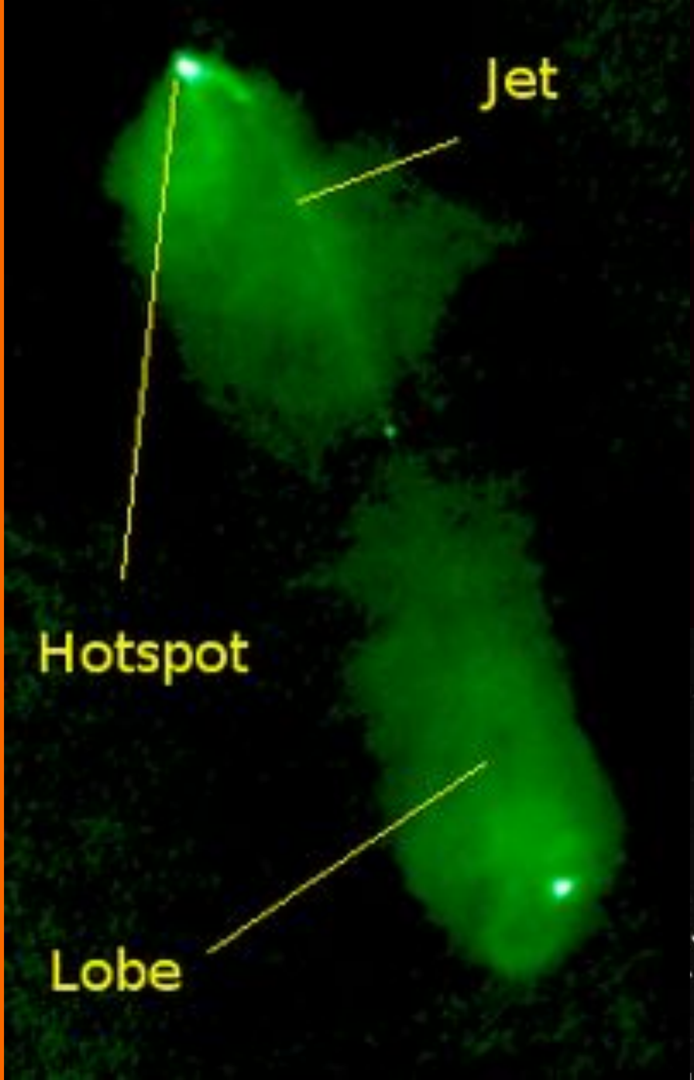


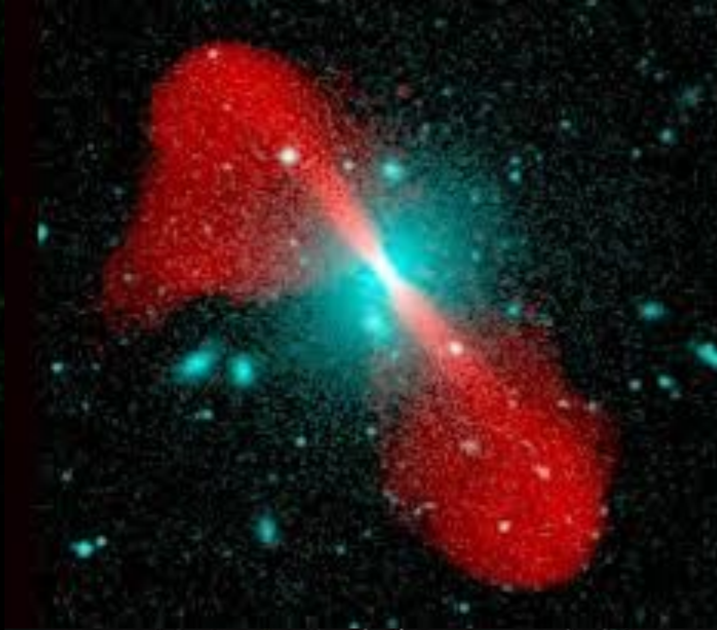
150 GHz plot from Sehgal et al. 2009

Planck didn’t have to worry about this.

But we want tSZ, ν, DM….

Jets!
Lobes!
Cores!

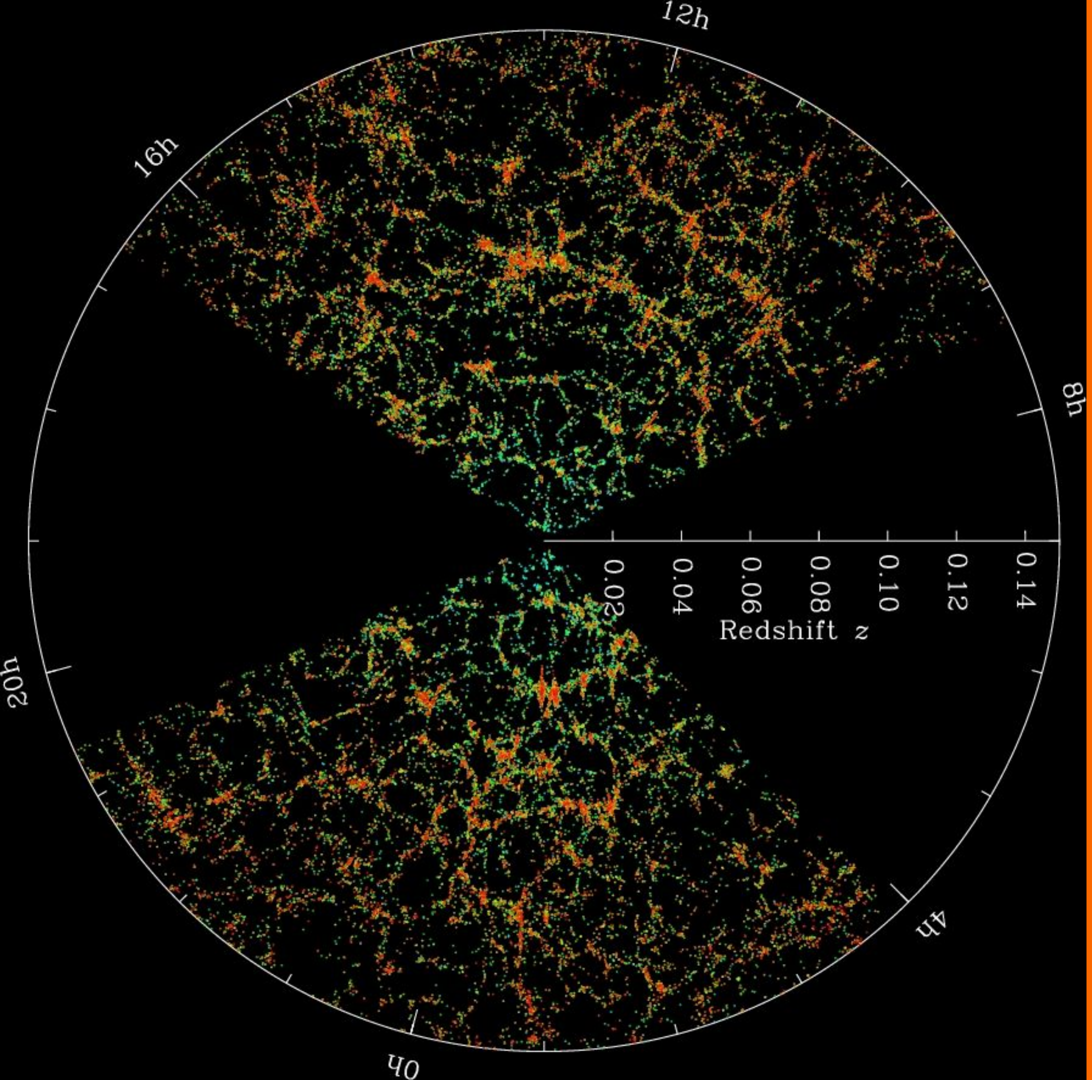


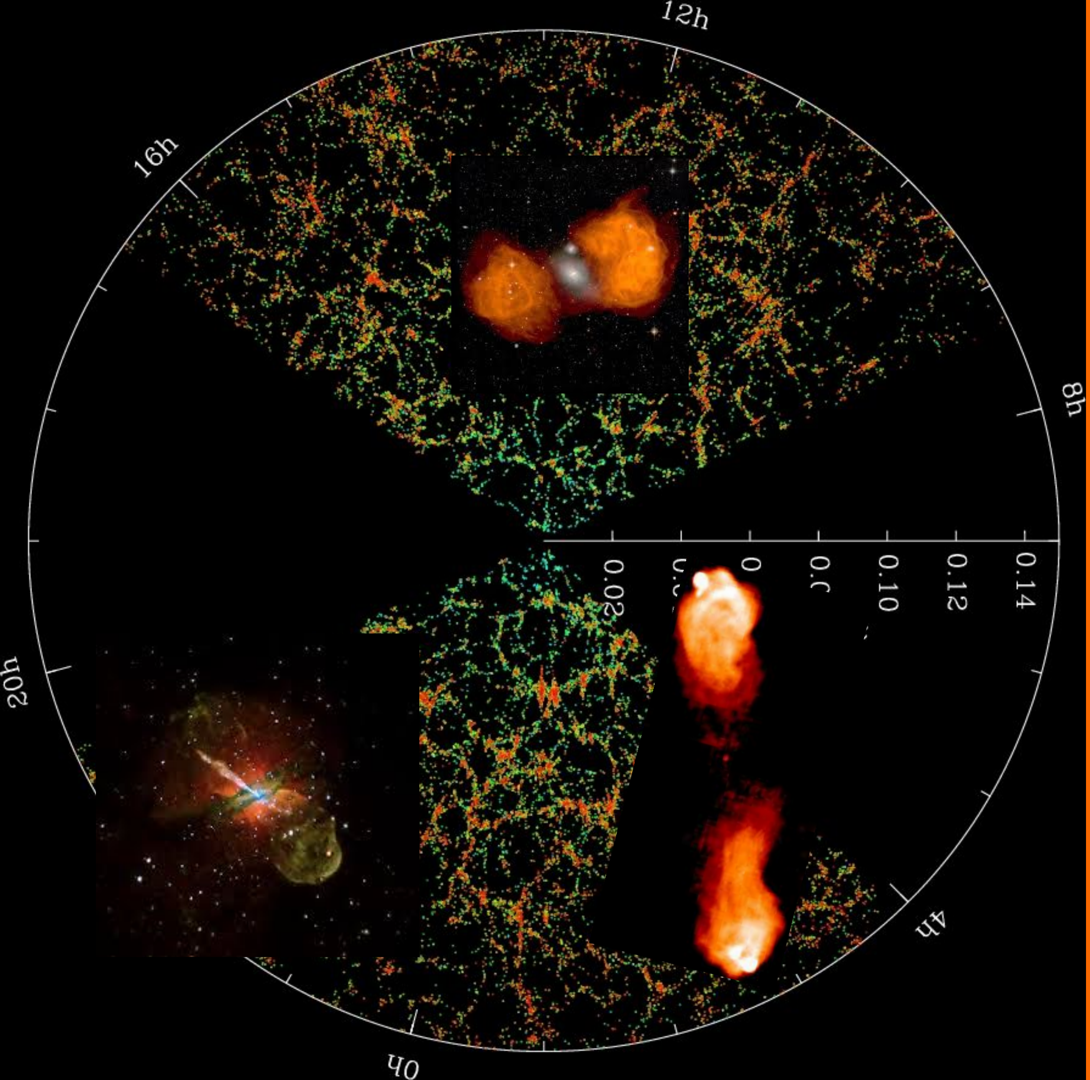


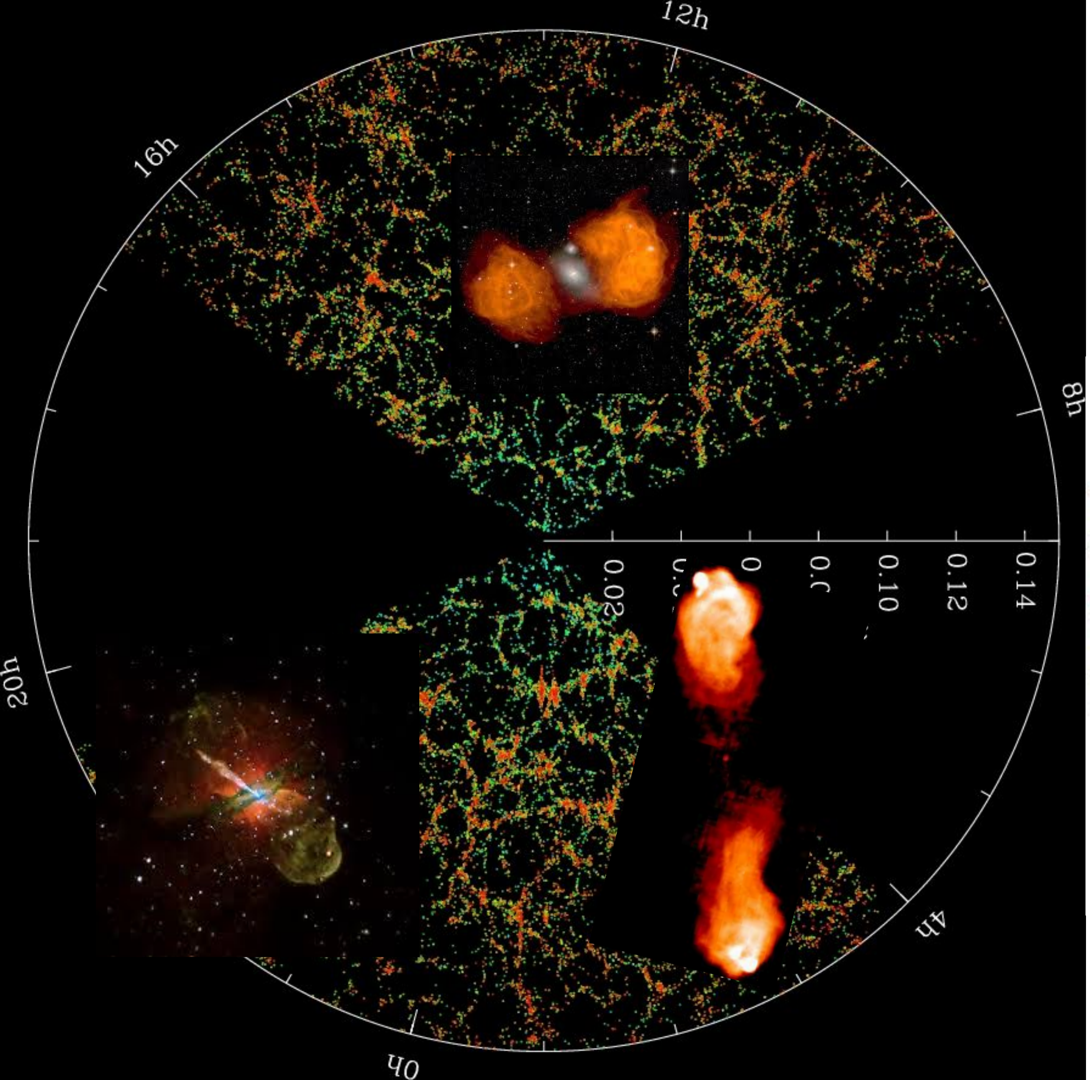
How do radio galaxies form and evolve over cosmological time?

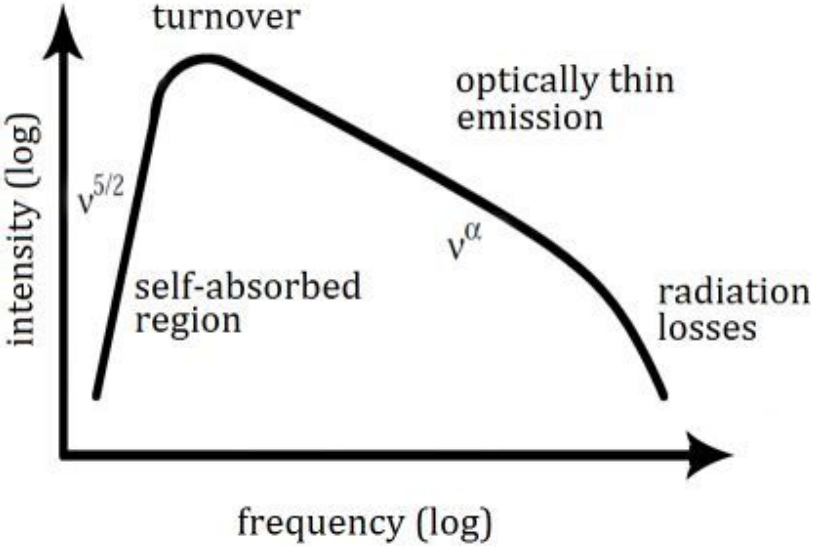
How do radio galaxies respond to their environments?

...


12h
8h
4h
0h
20h
16h
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Redshift z

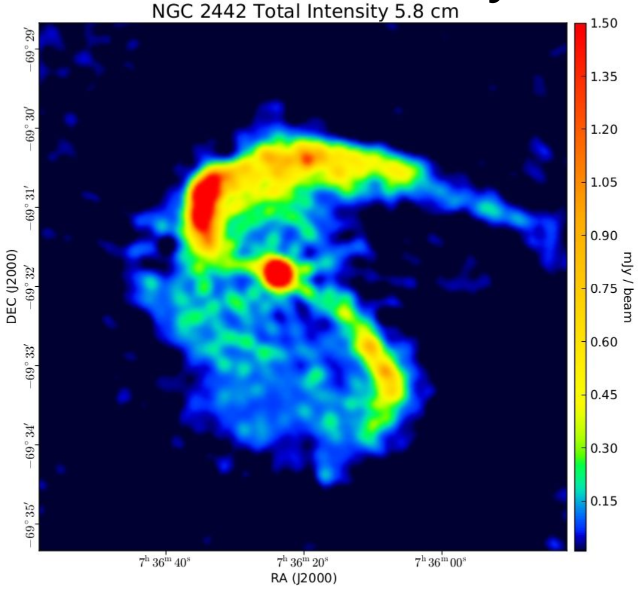

12h
16h
8h
20h
0h
4h
0.02
0.10
0.12
0.14


12h
16h
8h
20h
4h
0h
0.02
0.10
0.12
0.14

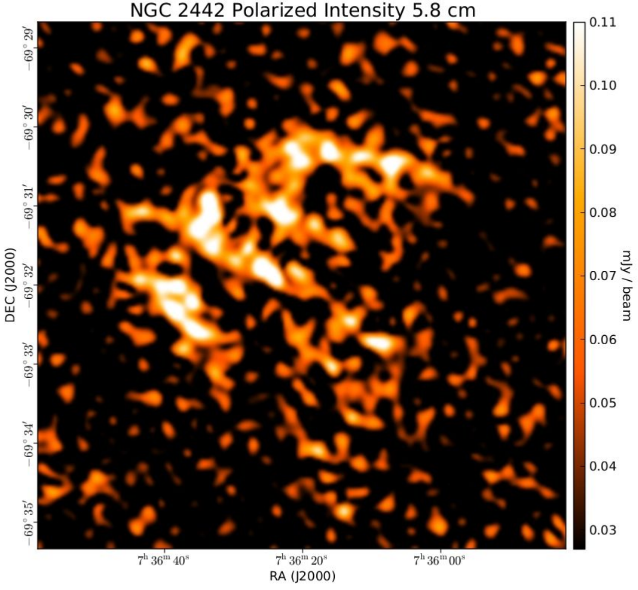

turnover
optically thin
emission
intensity (log)
$\nu^{5/2}$
ν^{α}
self-absorbed
region
radiation
losses
frequency (log)

on average, ~1% polarized

Total Intensity



Polarized Intensity

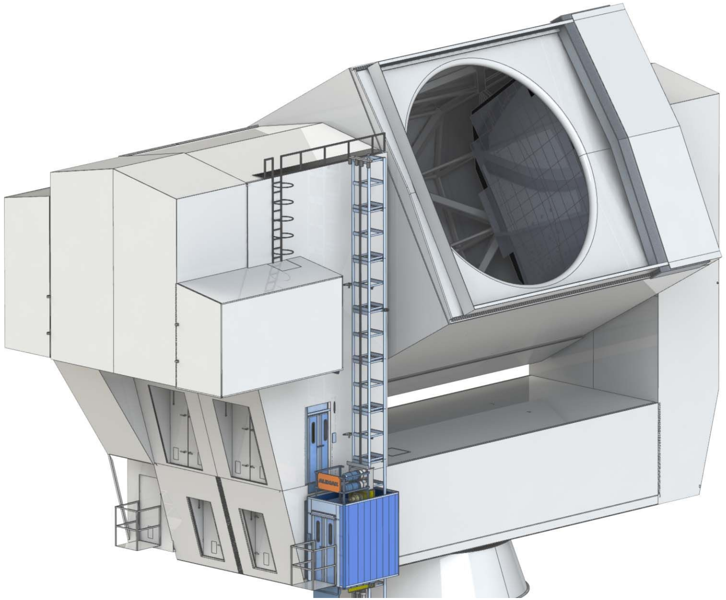


Harnett et al. 2004 (30 GHz)

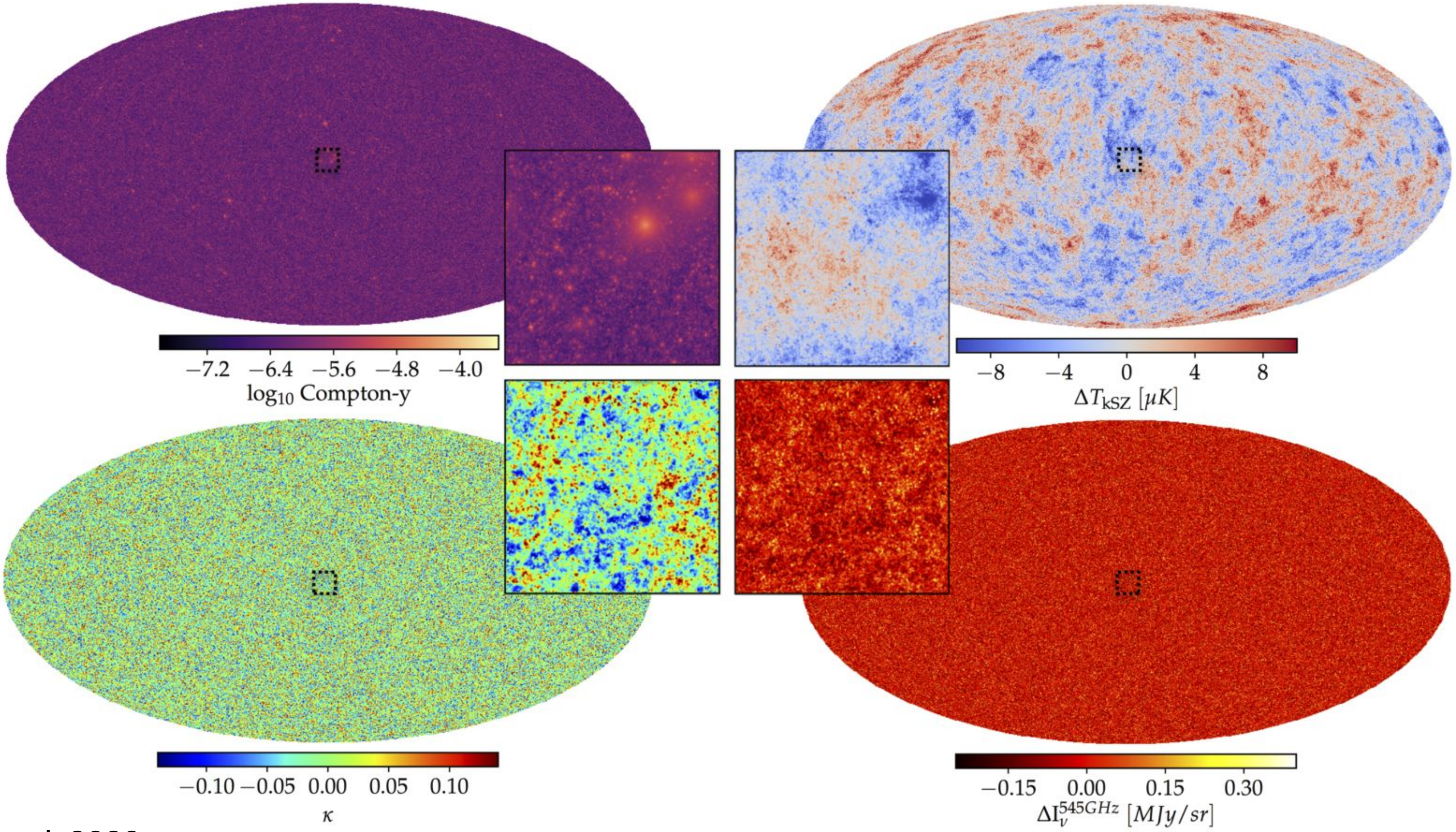
ACT and SO will double as deep ***radio source*** surveys with intensity and polarization.

Simons Observatory:

~20,000 sources



Forward simulations with Websky: full sky peak patch sims



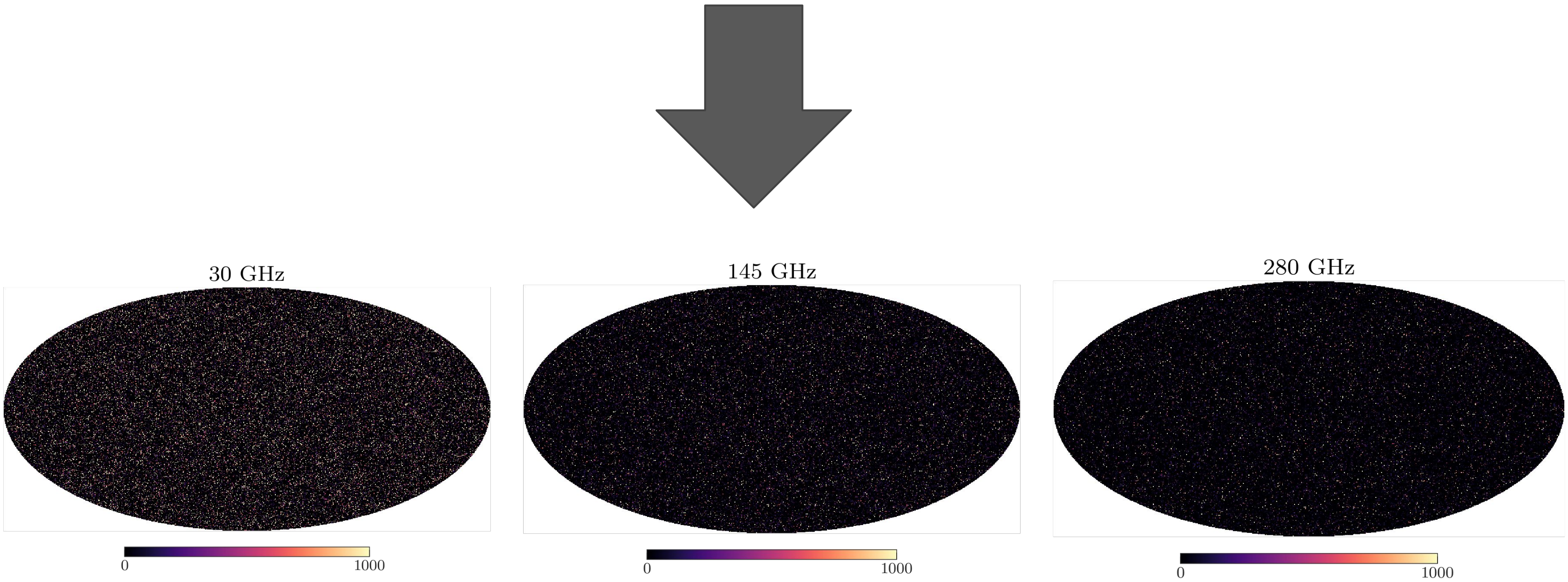
Stein et al. 2020

12288^3 particles

15.4 Gpc

Full sky extragalactic foregrounds

(Halos) + (Radio Galaxy Model)

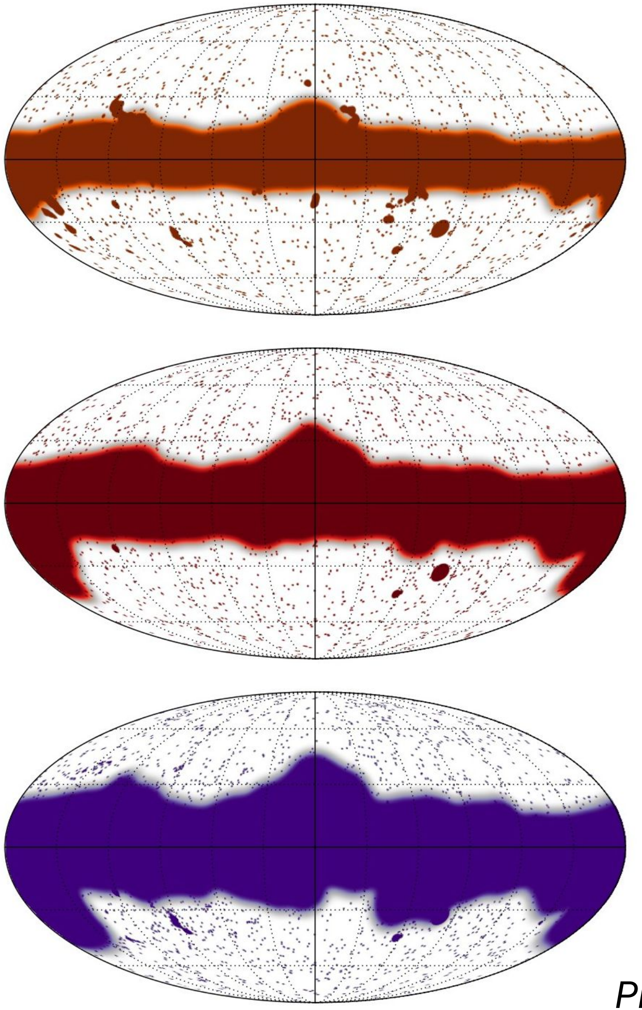


Useful for

- Compton-y sims
- Cluster finding
- Lensing reconstruction biases

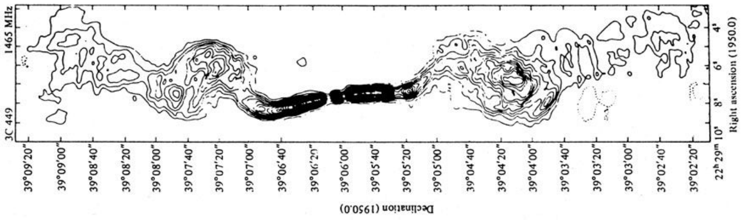
We mask the point sources!

Are we masking clusters and other secondaries?

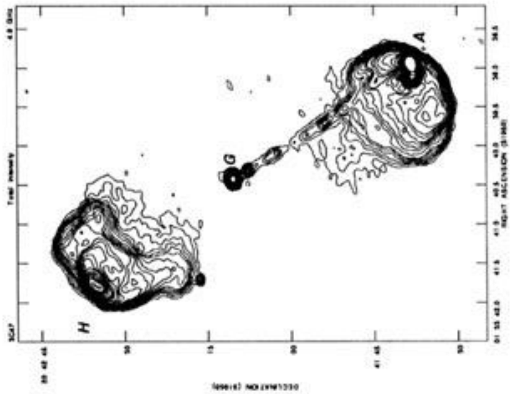


Planck 2015

Radio galaxy morphology



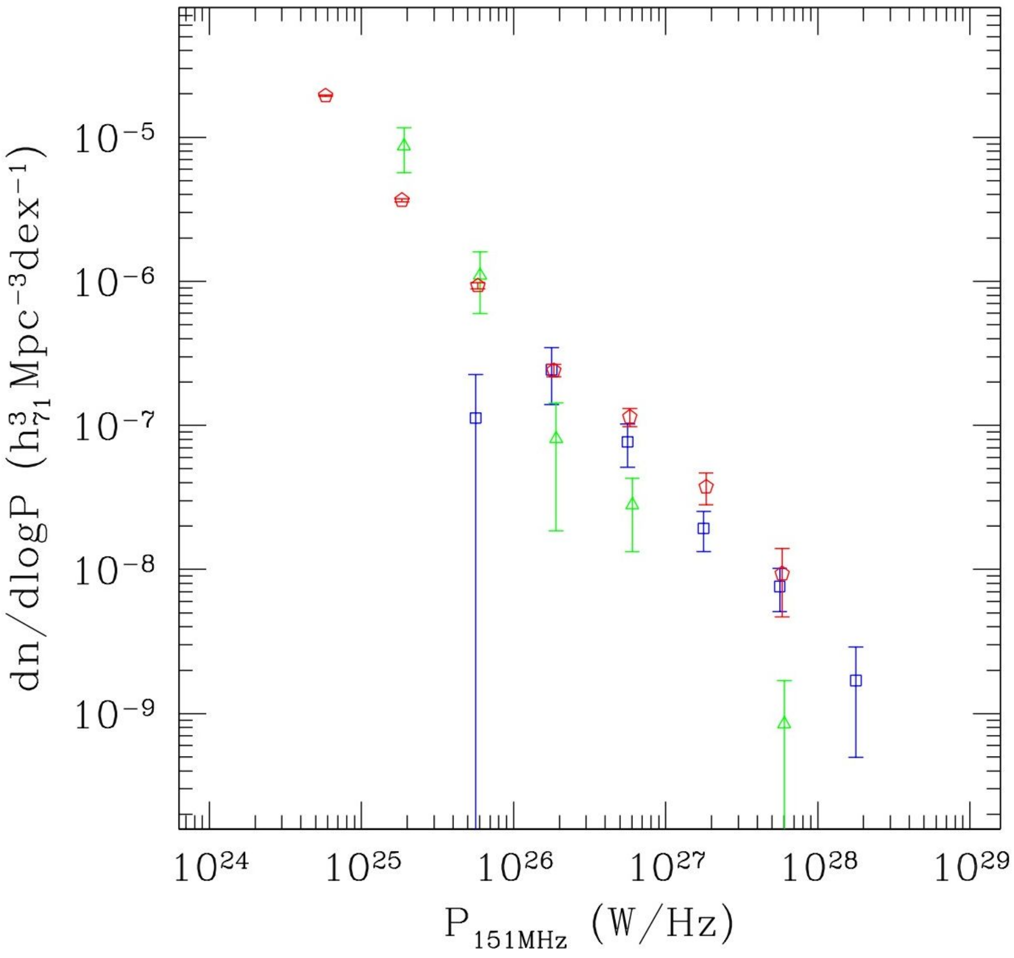
FR I



FR II

Perley, Willis and Scott (1979)

The Radio Luminosity Function at 151 MHz, at z < 0.3

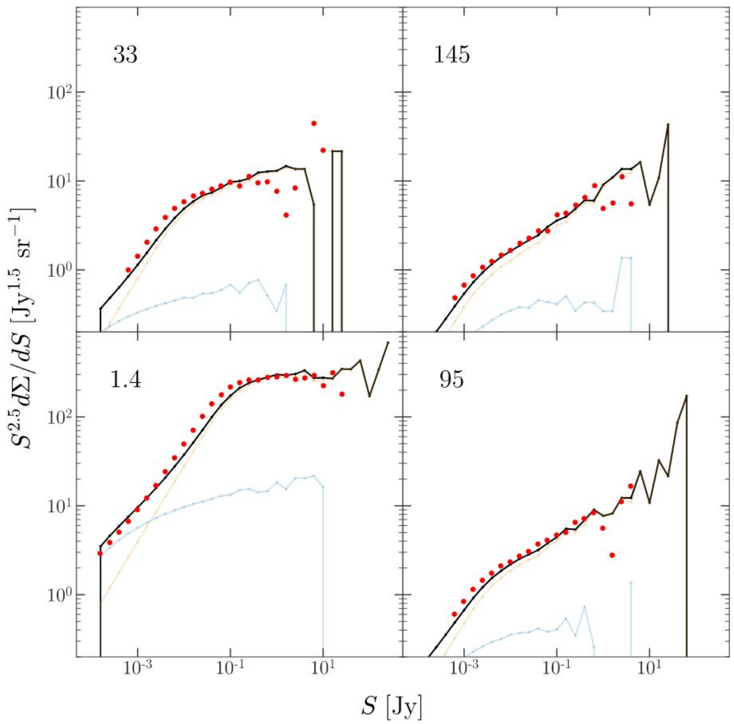


XGPaint.jl

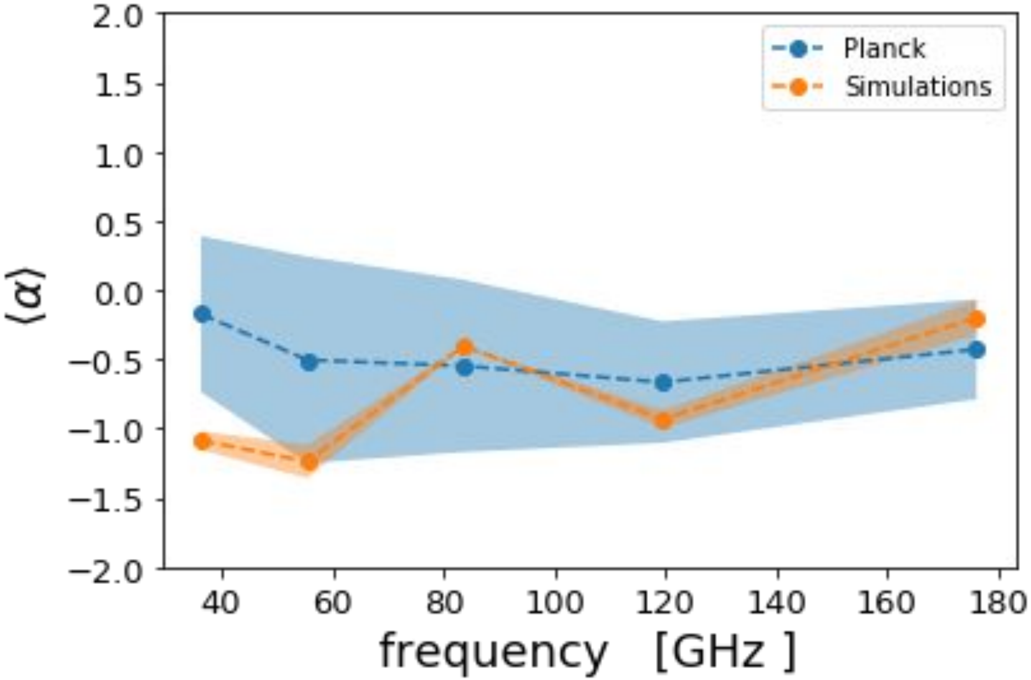
turn halo catalogs into CIB/radio maps

Parallel, fast, tested. Julia code!

We reproduce the source counts from Sehgal, with our halos from Websky.

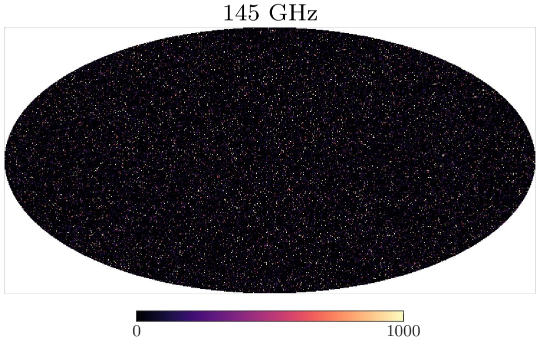


The Sehgal 2009 models don’t fully agree with new data, for example **the spectral index**.



From paper in prep, made by Giuseppe!

In prep: ***map products*** for cross-correlations, sims, etc.



Future work: ***updating*** the model with modern radio data

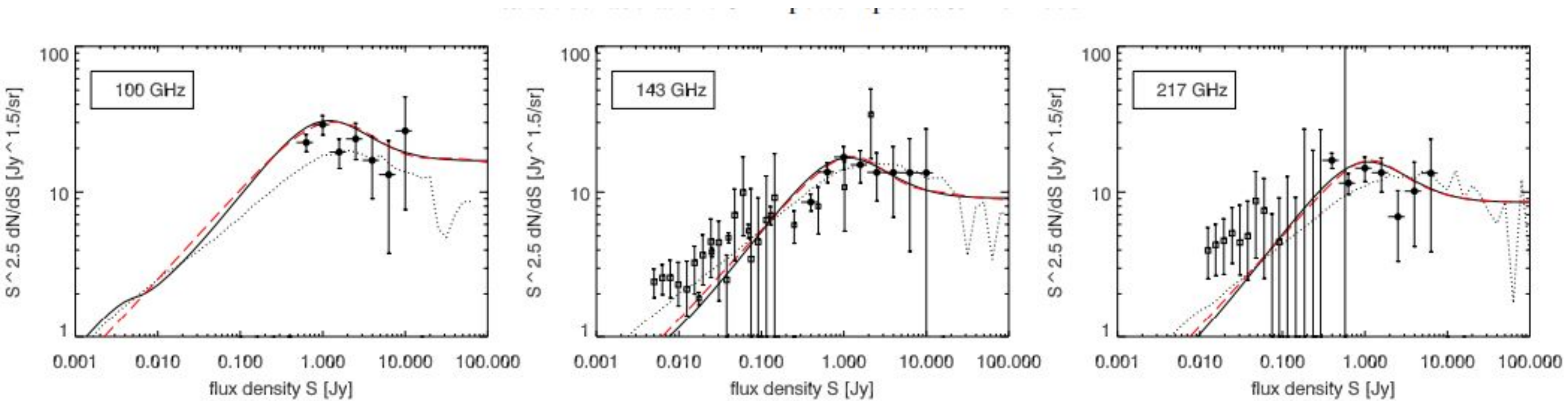


Figure 28. Number counts from *Planck* (filled circles, Planck Collaboration Int. VII 2013), ACT, and SPT (open squares) as described in the text, from 100 GHz to 217 GHz. The models from de Zotti et al. (2005, solid line) and Tucci et al. (2011, dots) are overplotted. The analytical fit from Eq. 20 and Table 7 is shown dashed, and shows a similar behaviour to the de Zotti et al. (2005) model.

The Next Five Years

- Big sky areas and polarization, from the ground! In five years, we’ll have SO data.
- Planck data will still be important.
- We will learn new things about radio galaxies (and Galactic dust, and the CIB, and clusters, and…) from these surveys.