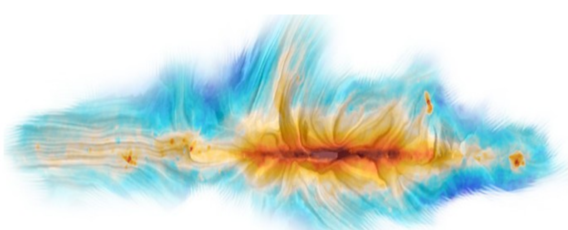
CMB Synergy with European Experiments

Carlo Baccigalupi
SISSA
Villa Finaly, Florence, September 21st, 2018



Outline

- CMB Synergy: Large Scale Structure
- CMB Synergy: Multi-Probe, Multi-Frequency Dataset Combinations

Outline

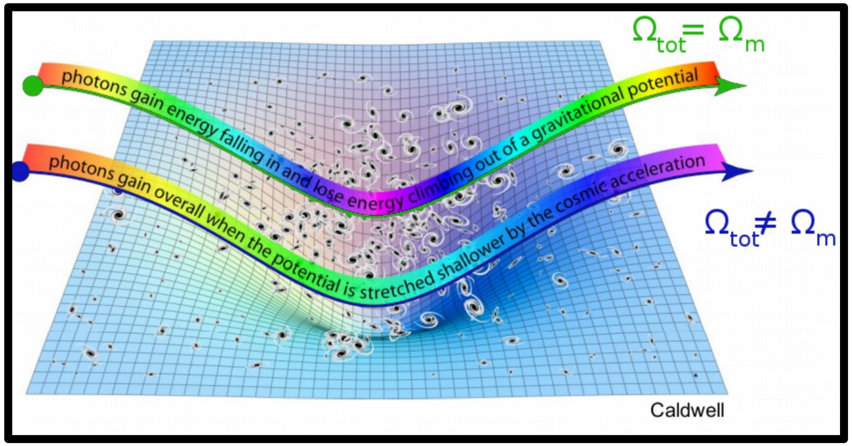
- **CMB Synergy: Large Scale Structure**
  - Observables
  - Forecasts from Euclid, eROSITA, S4
  - Synergies with LSS & the CMB Roadmap
- **CMB Synergy: Multi-Probe, Multi-Frequency Dataset Combinations**
  - B-modes from Diffuse Polarized Foregrounds
  - Low Frequencies: Combination of S-PASS and Planck
  - Conclusions and link to next talks

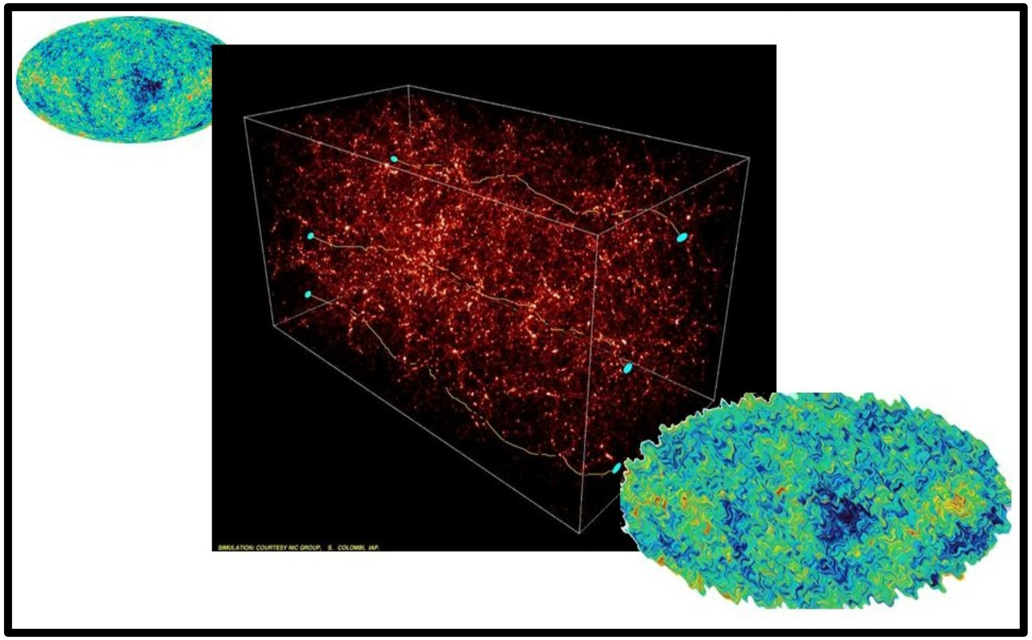
CMB Synergy: Large Scale Structure

Material from
Euclid Consortium & Redbook, arxiv 1110.3193
Nabila Aghanim for the CMBXC Working Group
eROSITA Science Book, arxiv 1209.3114
Simons Observatory Paper, arxiv 1808.07445
CMB-S4 Science Book, arxiv 1610.02743

CMBXC observables

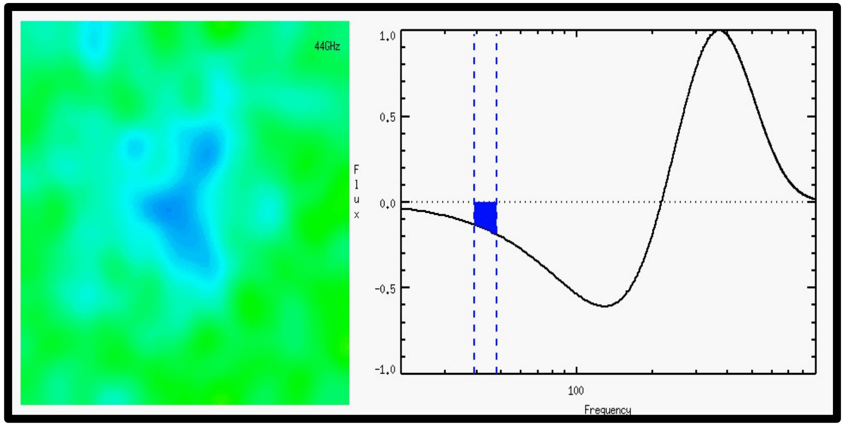
Large Scales (degree & super-degree):
Integrated Sachs-Wolfe (iSW) CMB temperature changes while crossing evolving structures





Intermediate Scales (arcminute-degree):
CMB Lensing deflection by cosmological structures
Sunyaev-Zel'dovich (tSZ) by hot gas in LSS and Doppler (kSZ)
Cosmic Infrared Background (CIB) from high-z galaxies

Planck detection of tSZ effect A2318

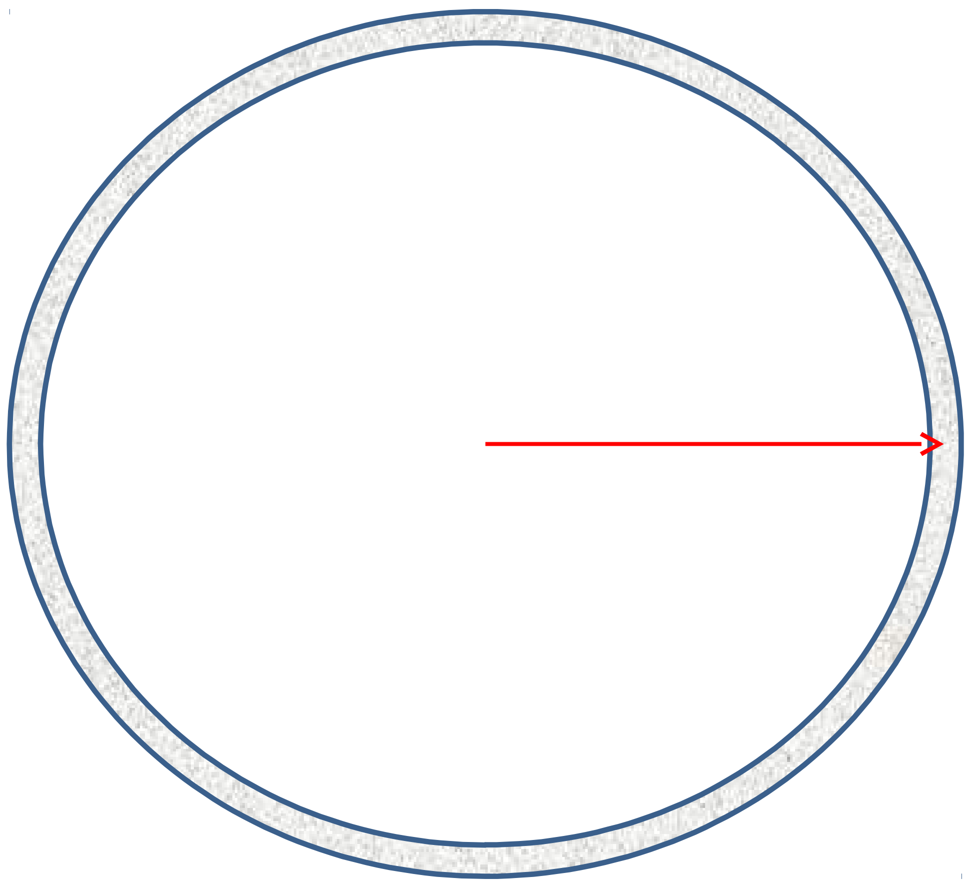


Expansion and clustering histories

$$D = H_0^{-1}\int_0^z \frac{dz}{[\Sigma_i \Omega_i (1+z)^{3(1+w_i)}]^{1/2}}$$

$$k^2(\Phi+\Psi) = -8\pi G a^2 \rho \Pi$$

$$k^2\Phi = 4\pi G a^2 \rho \delta$$



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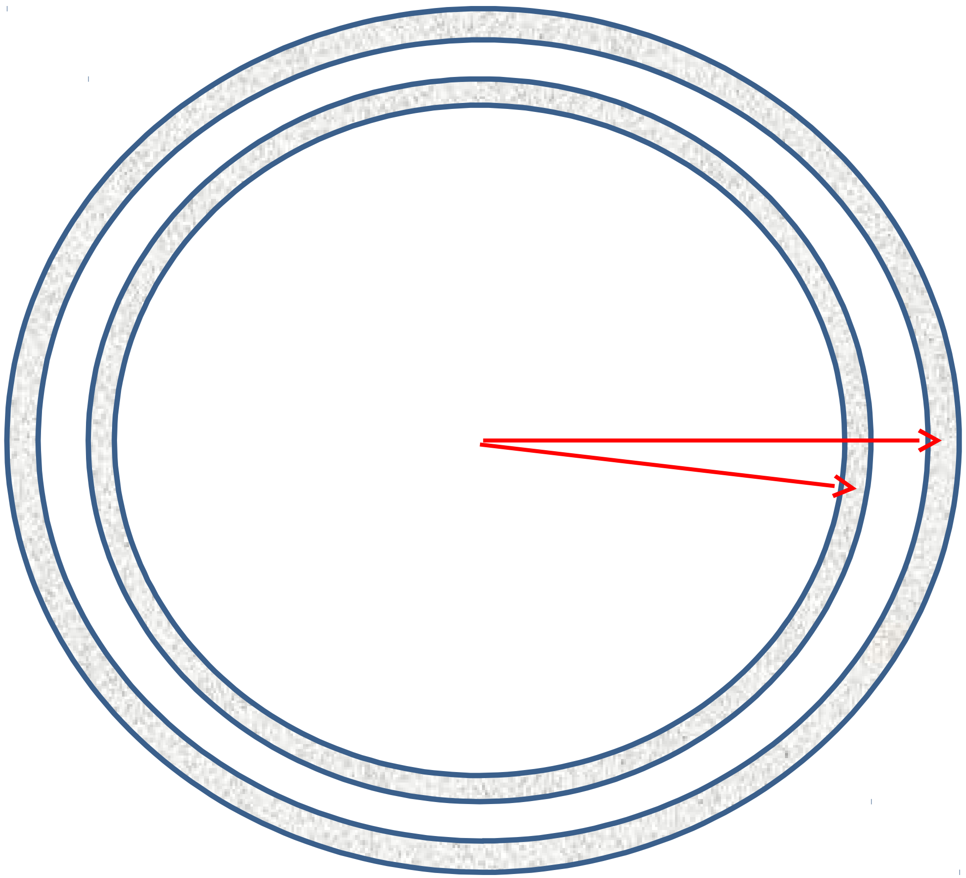

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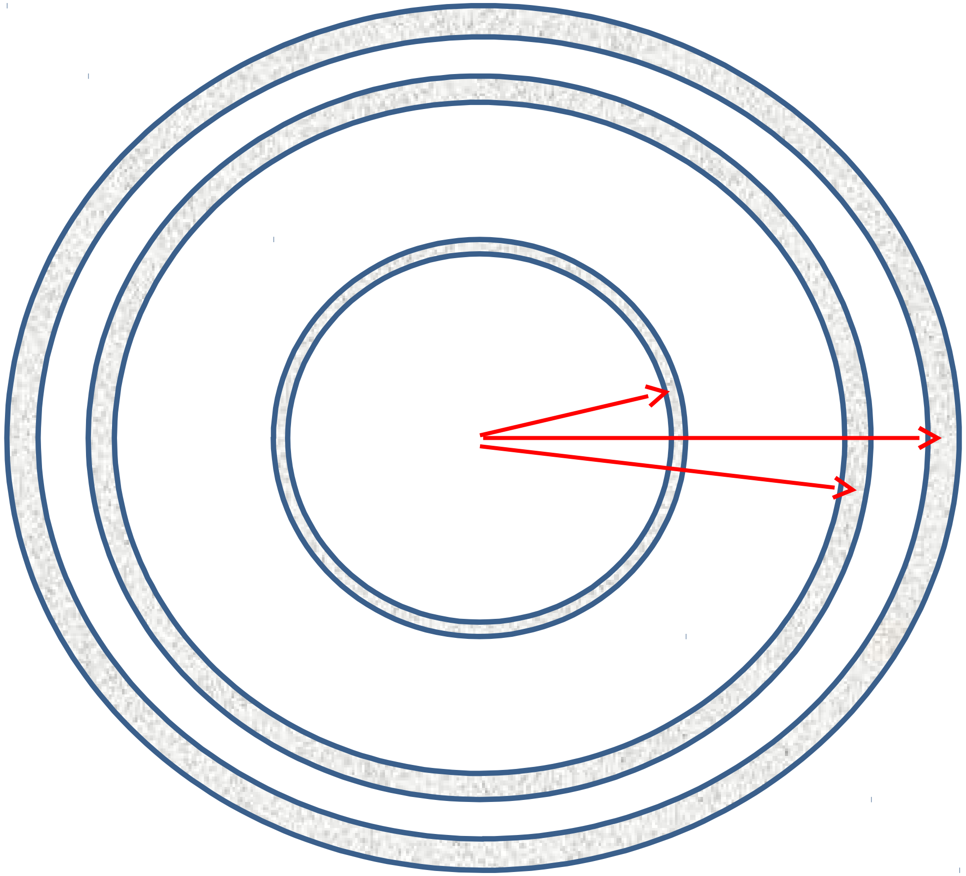
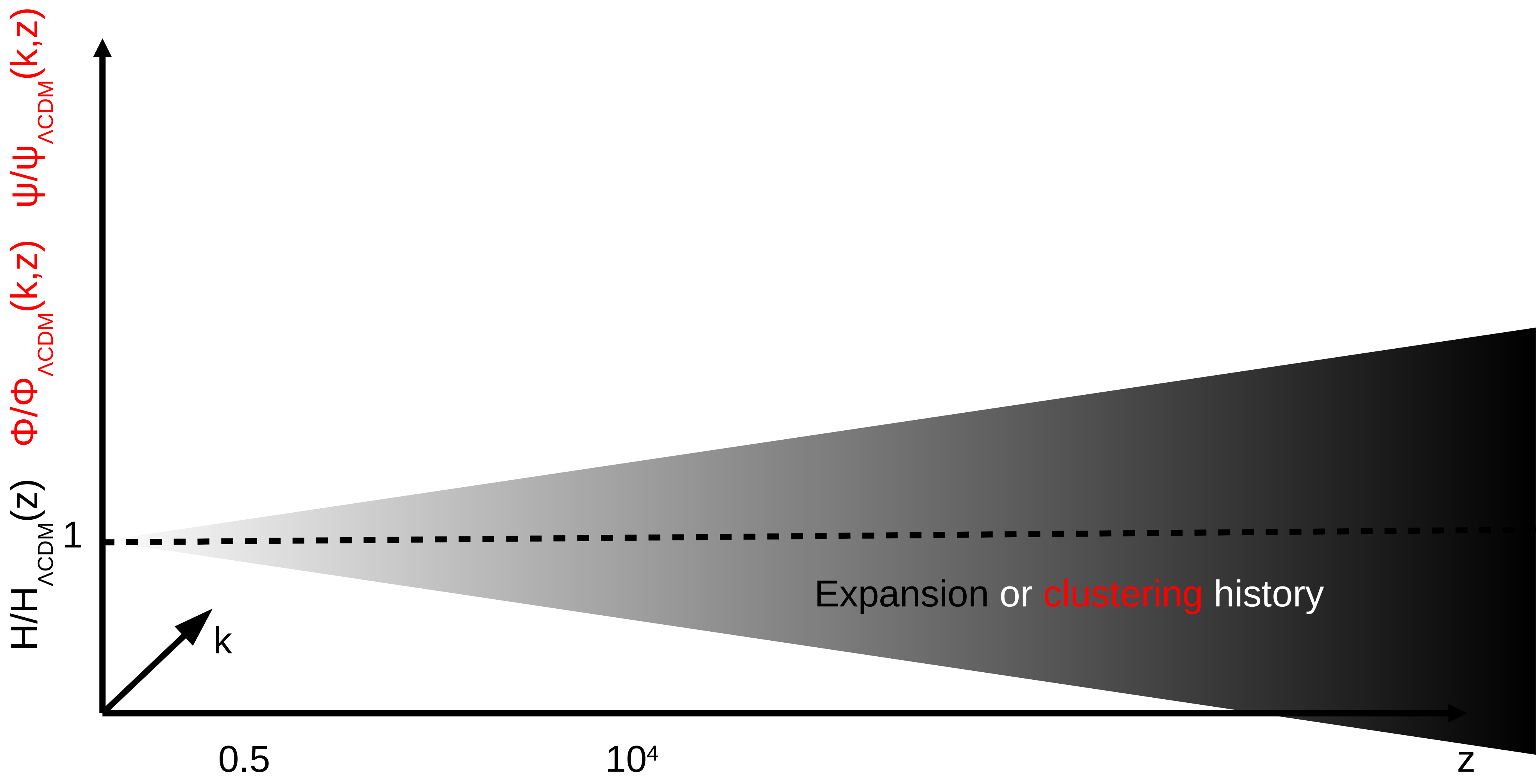
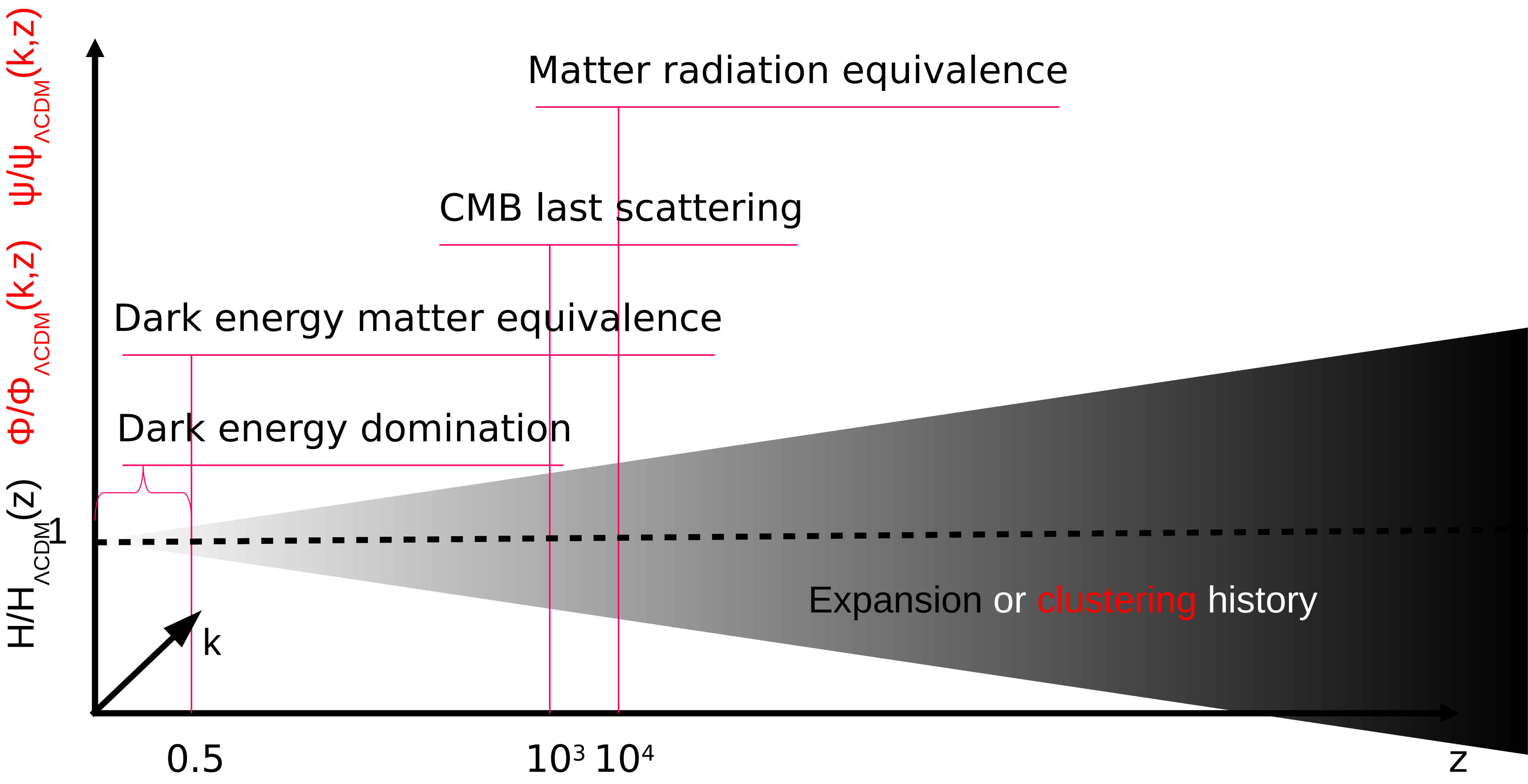


The promise of CMB lensing



The promise of CMB lensing



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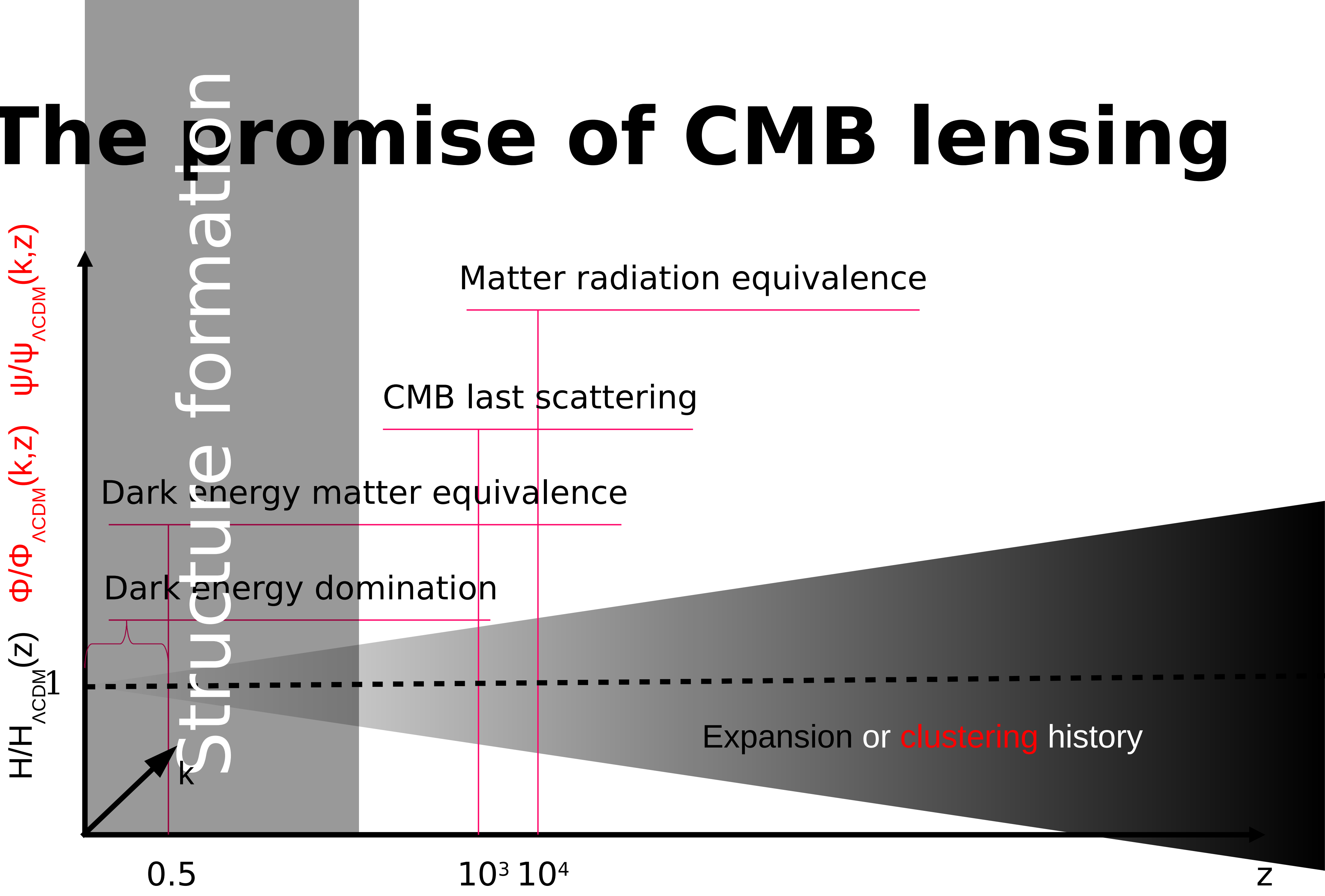
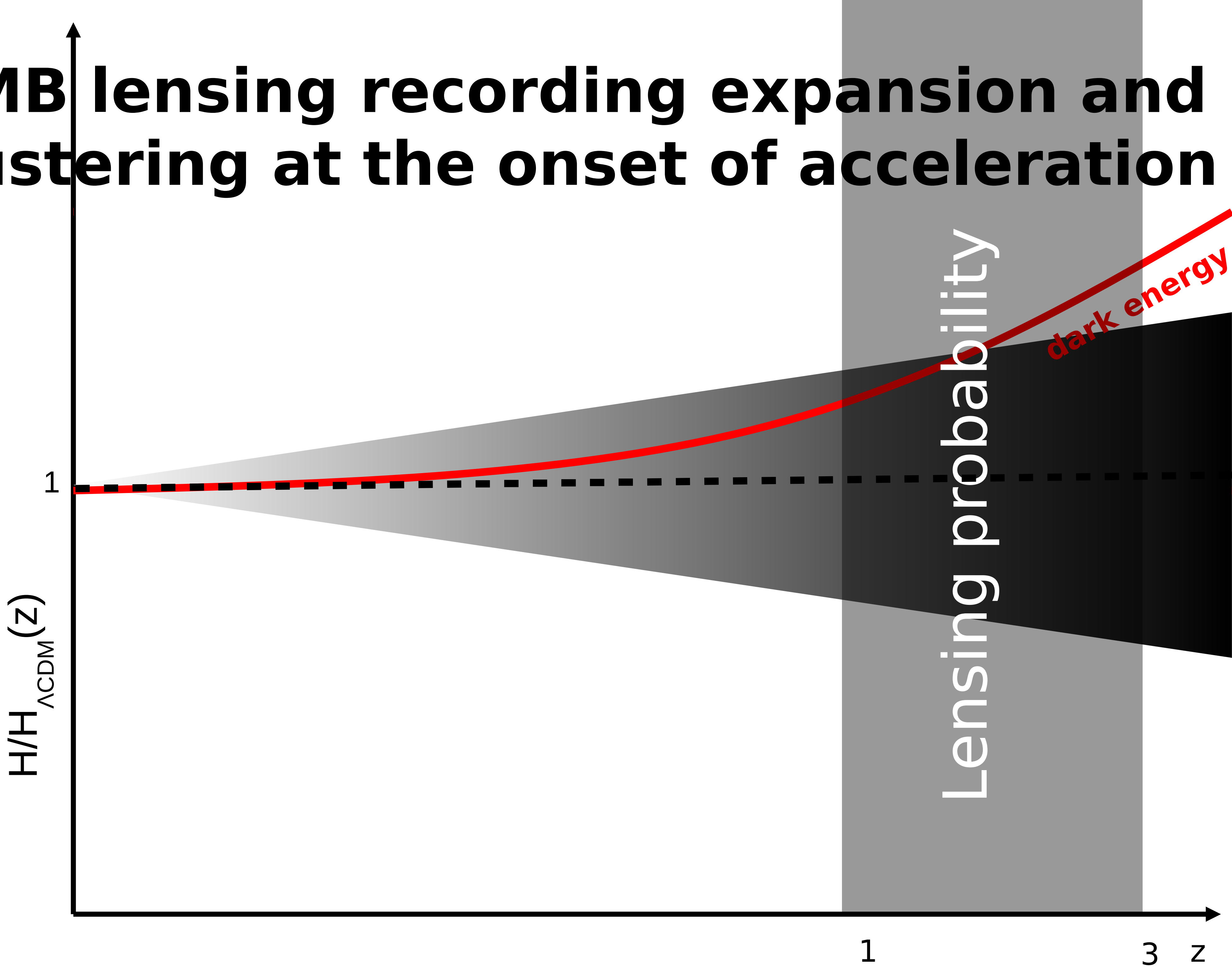
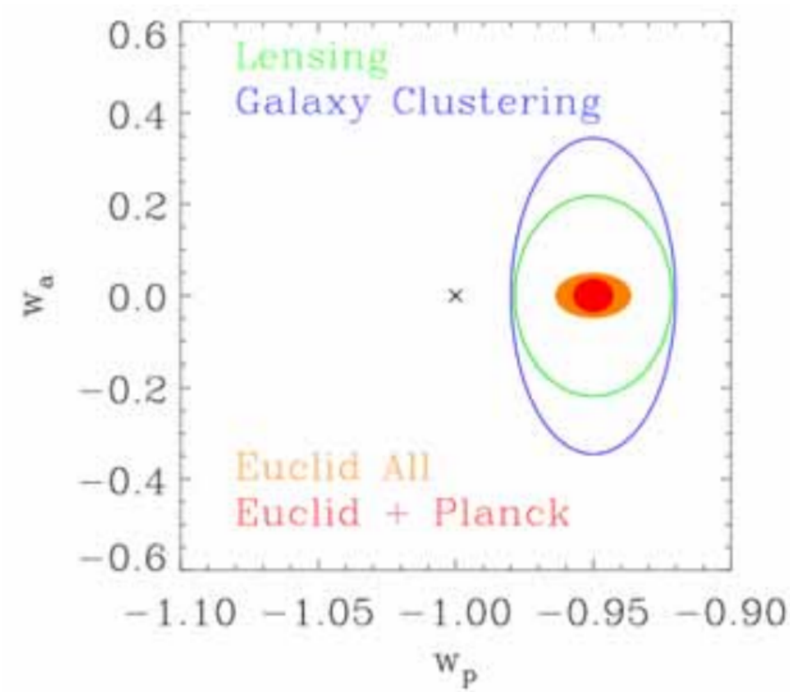
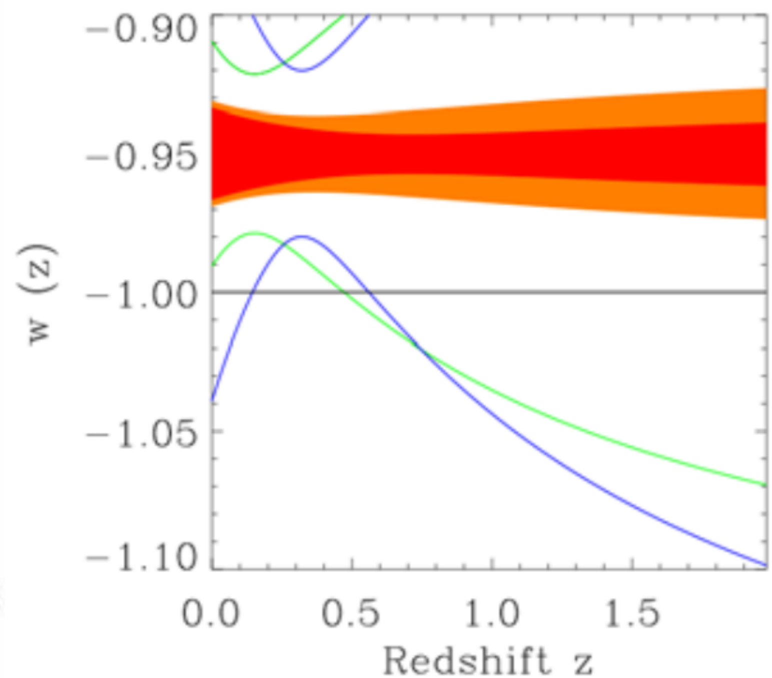


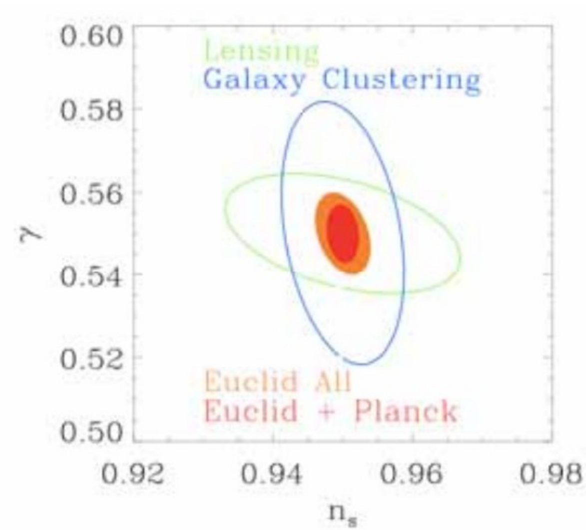
CMB lensing recording expansion and clustering at the onset of acceleration



Forecasts on Euclid Planck combination: dark energy equation of state and modified gravity

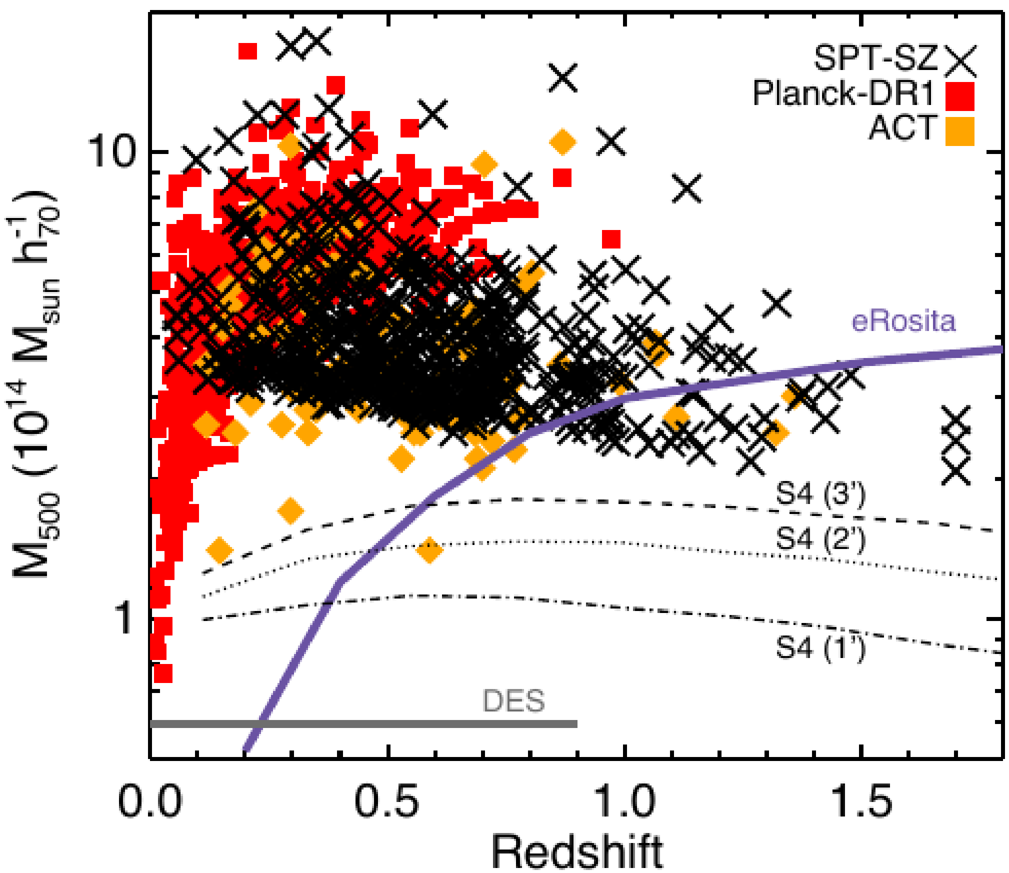


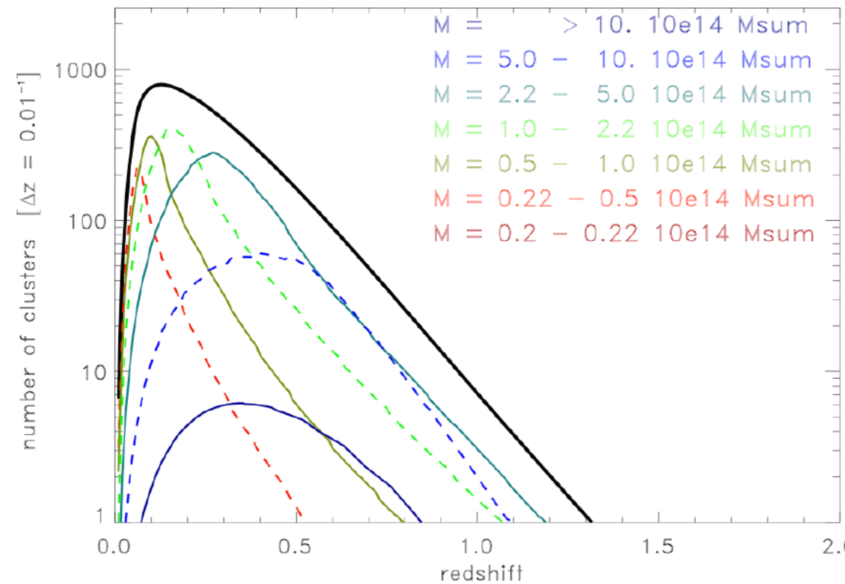


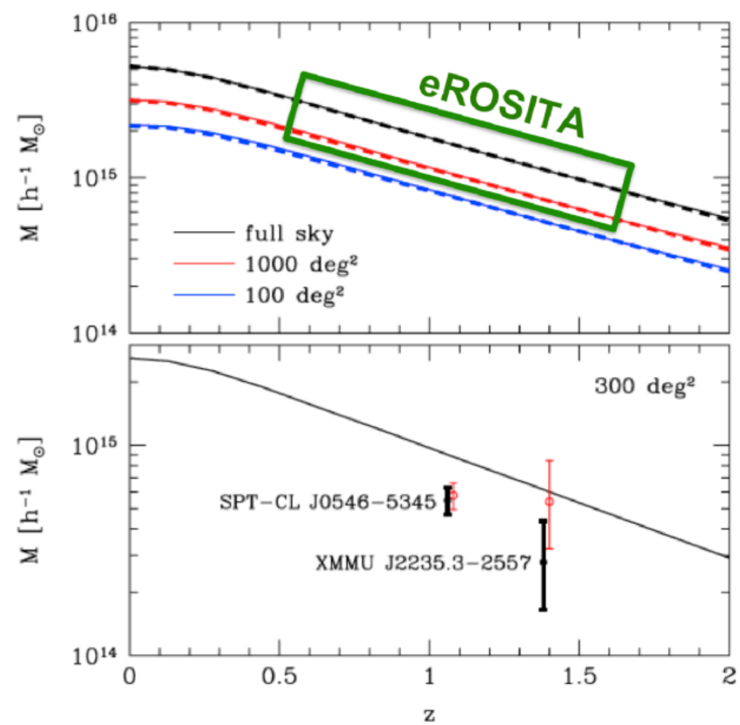


Euclid Red Book

X-rays & CMB



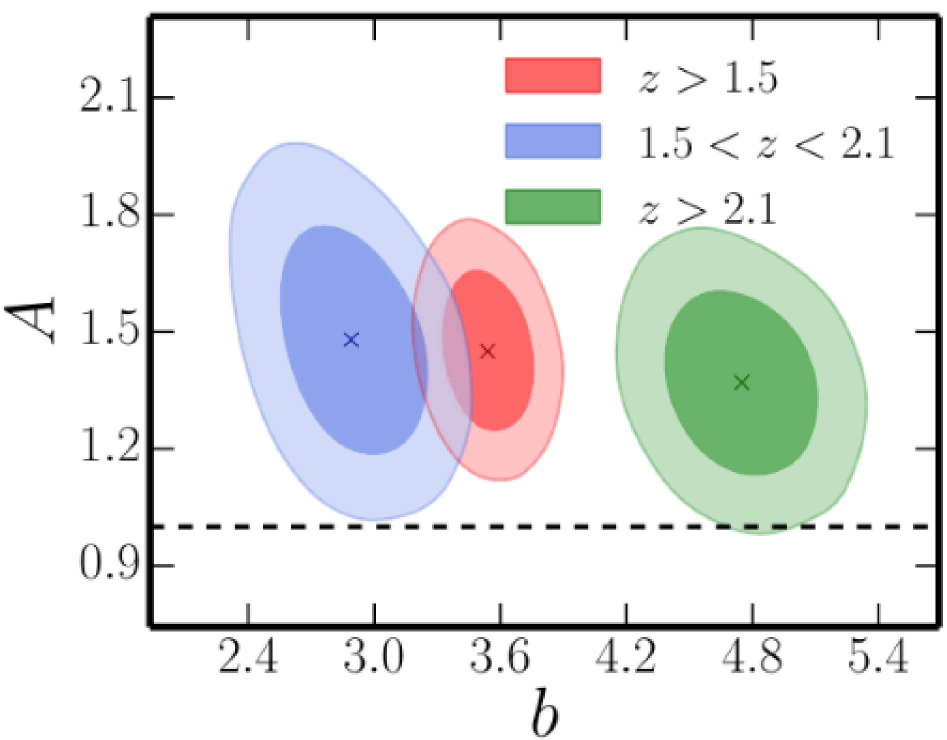


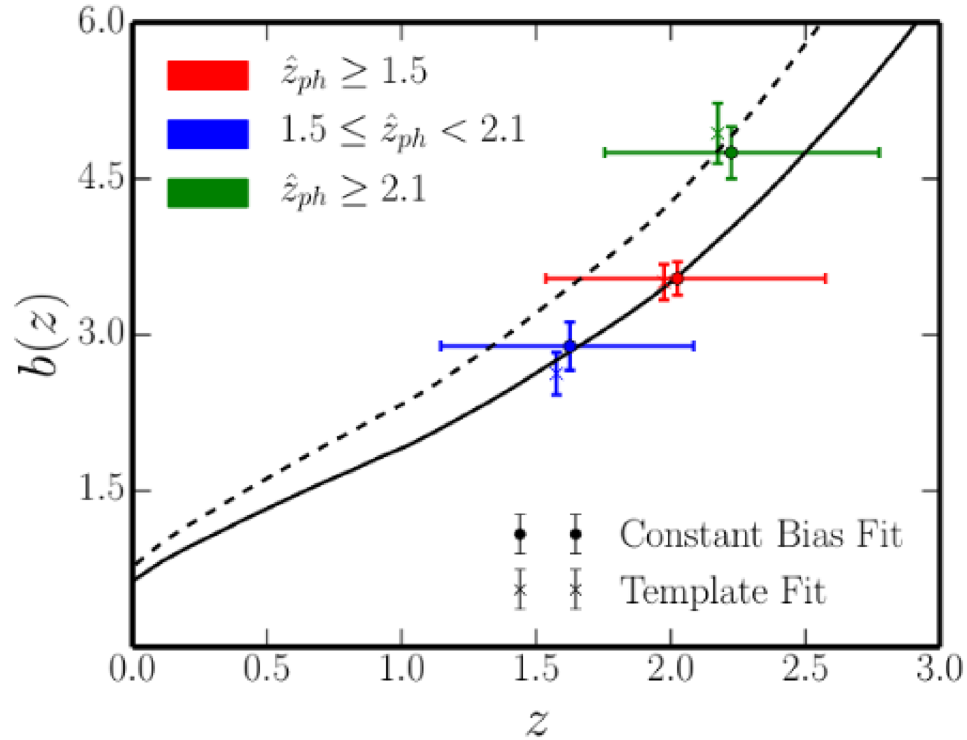


eROSITA, CMB-S4 Science Books

Planck x Herschel

Tomography and Bias evolution



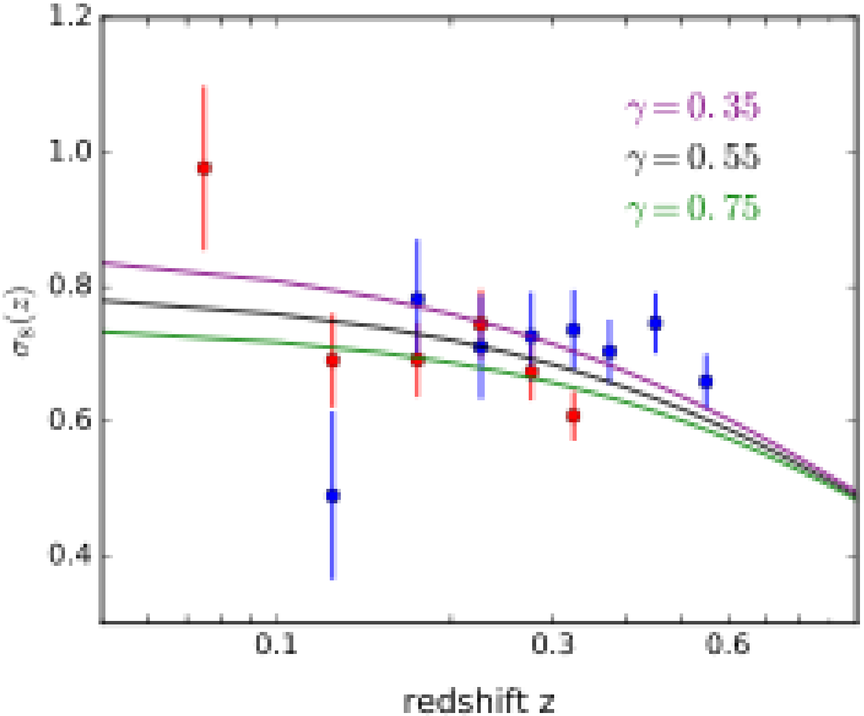


Bianchini et al., 2015, 2016

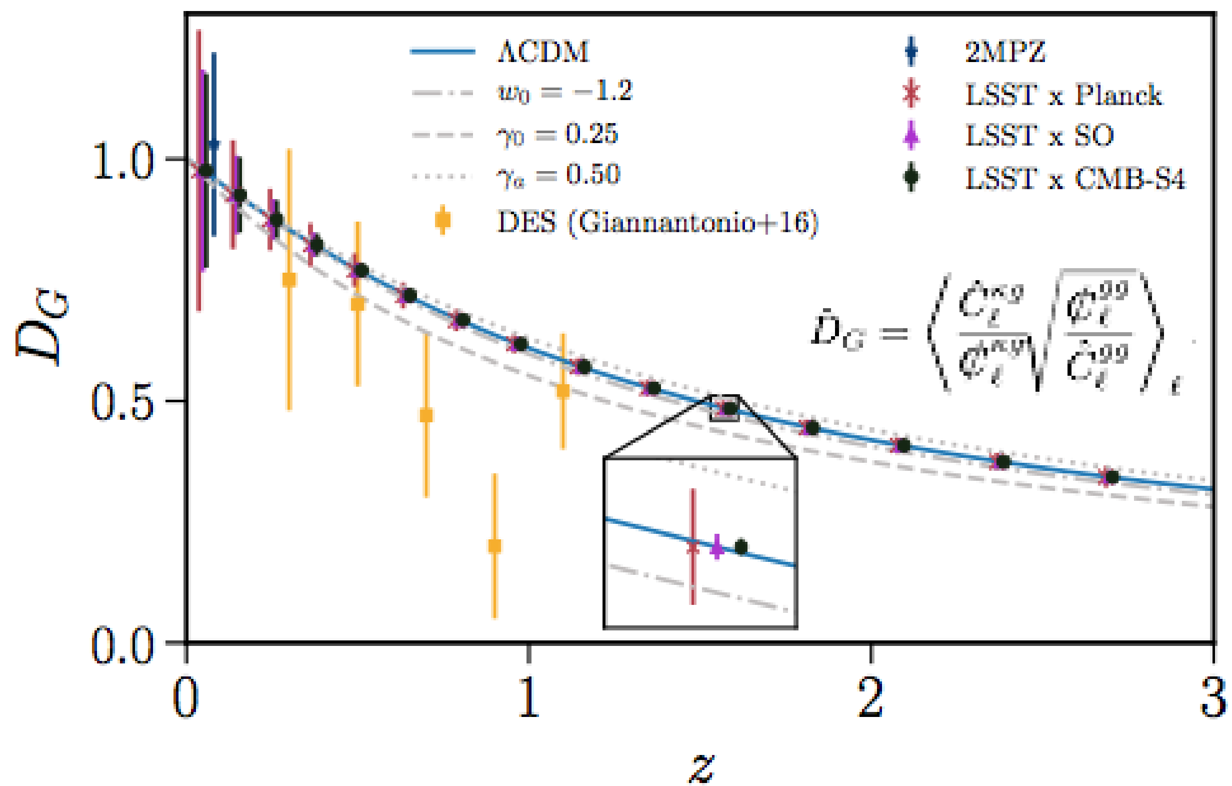
Detections & Forecasts on Cross-Correlation

- Bias independent measurements of the growth-rate
- Constraints on e.g. modified gravity

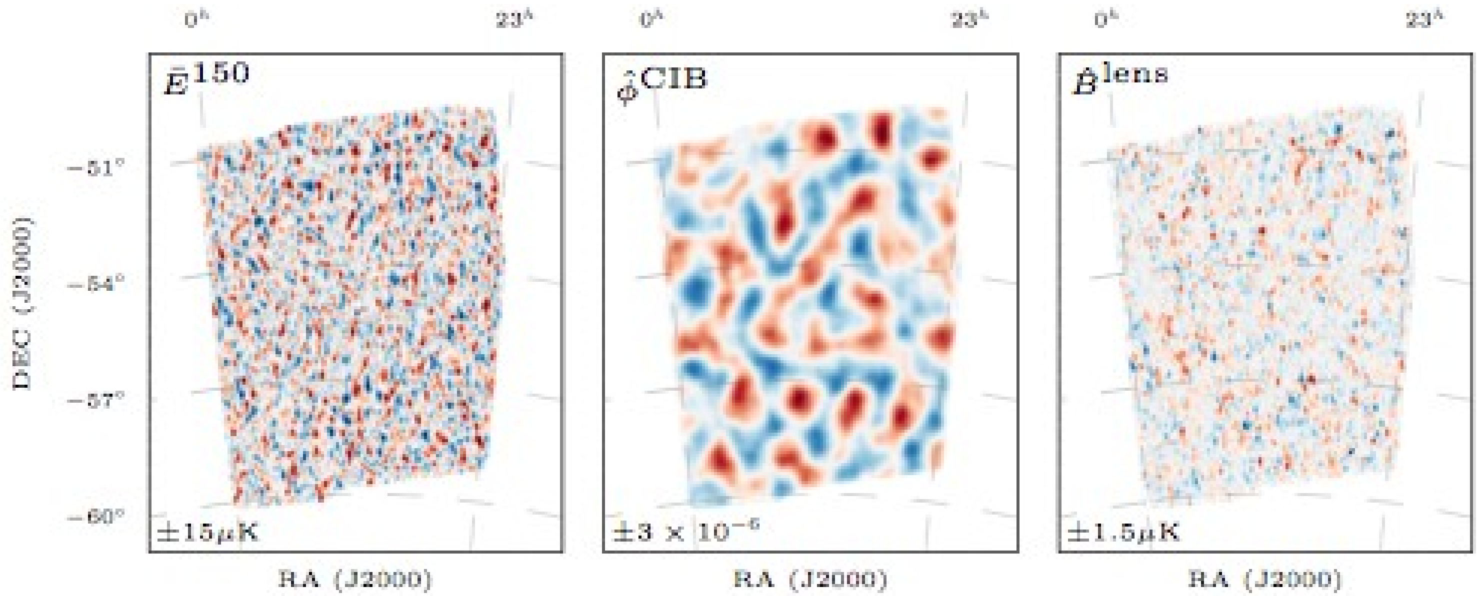
Peackock & Bilicki (2018)

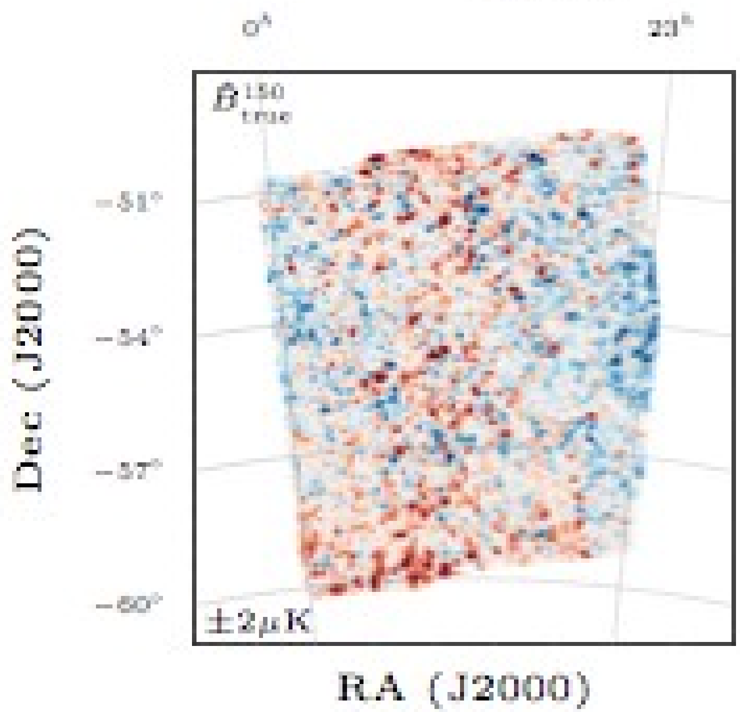


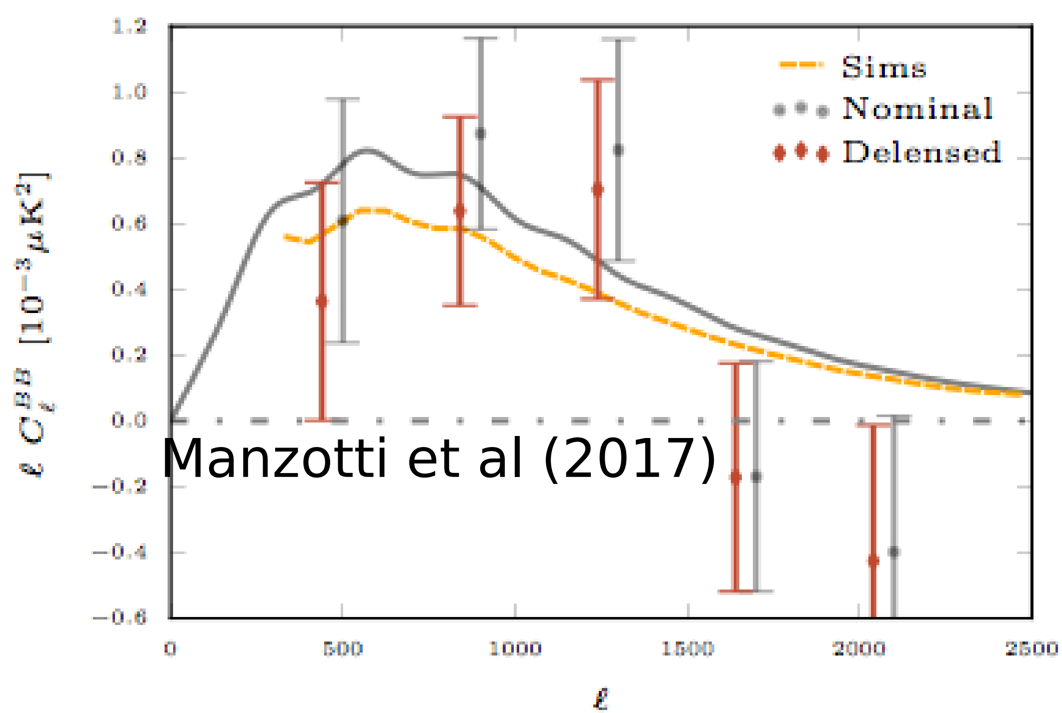
Bianchini & Reichardt (2018)



B-modes external delensing







Manzotti et al (2017)

CMBXC in the Euclid Consortium

Euclid Lead & Board

8 Science Working Groups

Operational Units

CMBXC Working Group
Nabila Aghanim, CB
About 60 members
6 WPs including
Theory and Forecasts
N-body Simulations
Methods and Likelihood

--- 7 years of data analysis

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--- 2019 – Launch in early 2020s: make contact and agreements with CMB Probes

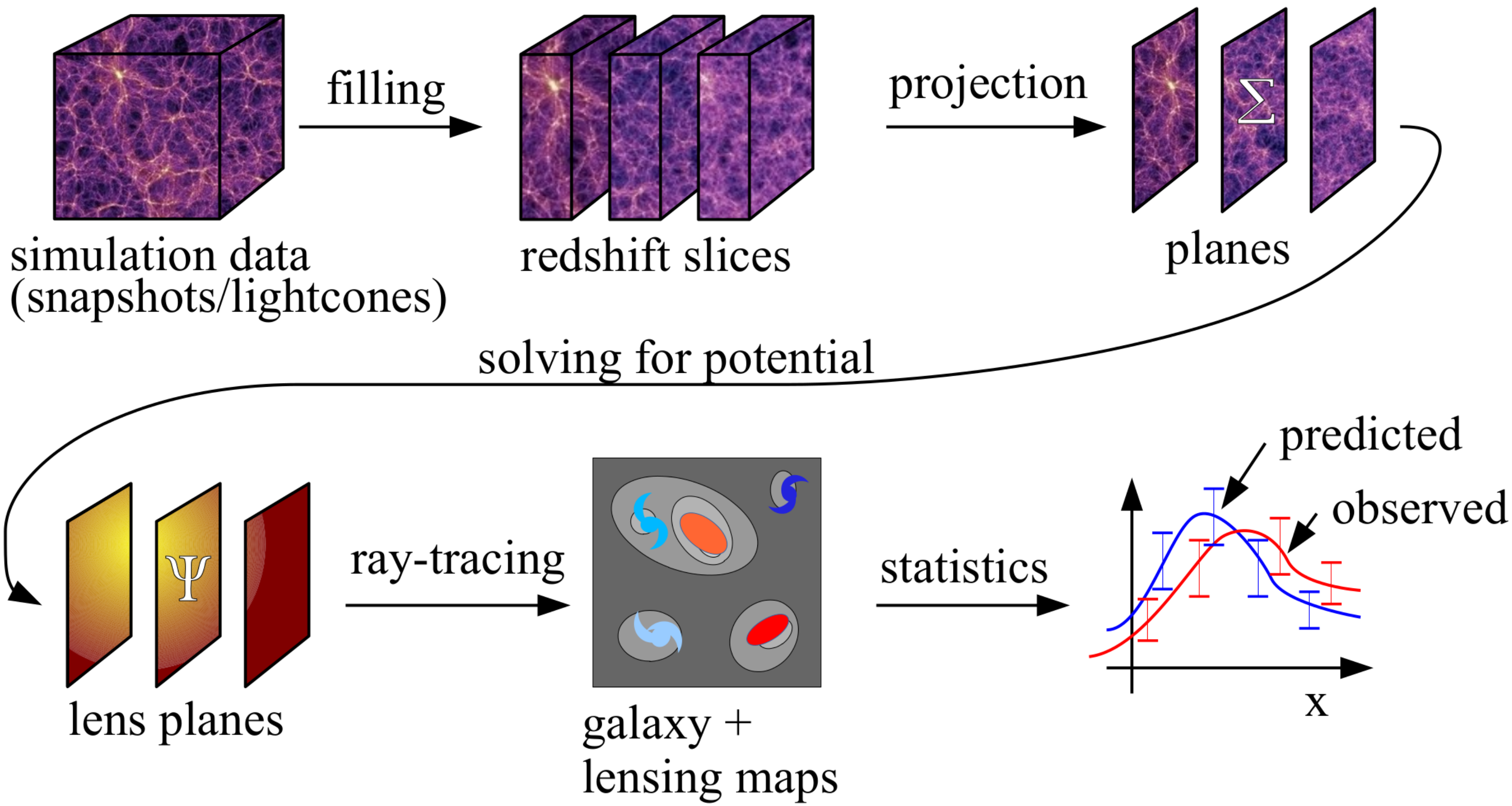
--- Within 2018: Contribution to the Key Paper Projects Definition of Additional Science

--- Now: Working at first Forecast Paper

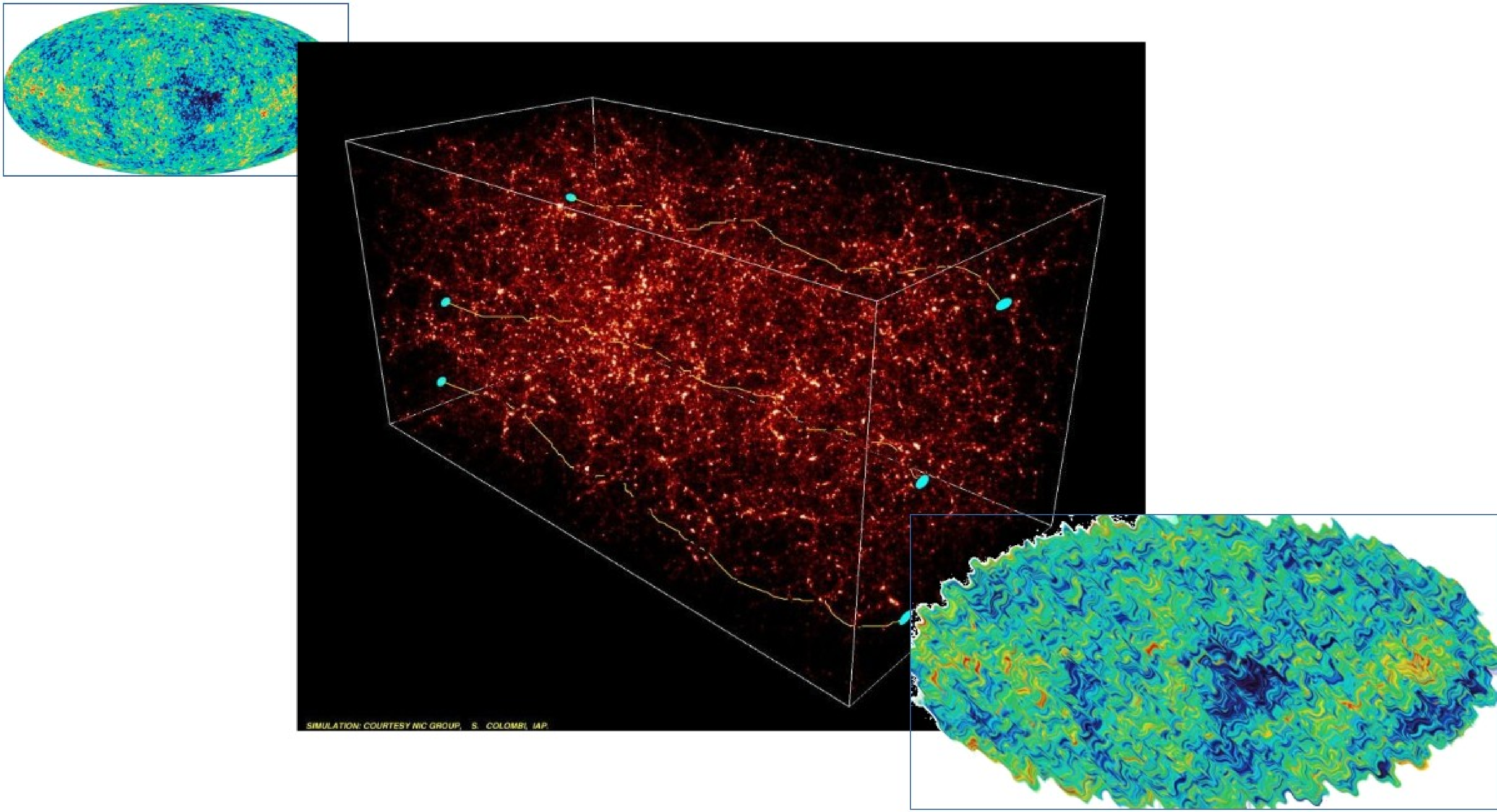
Euclid consortium

Simulations for CMBXC

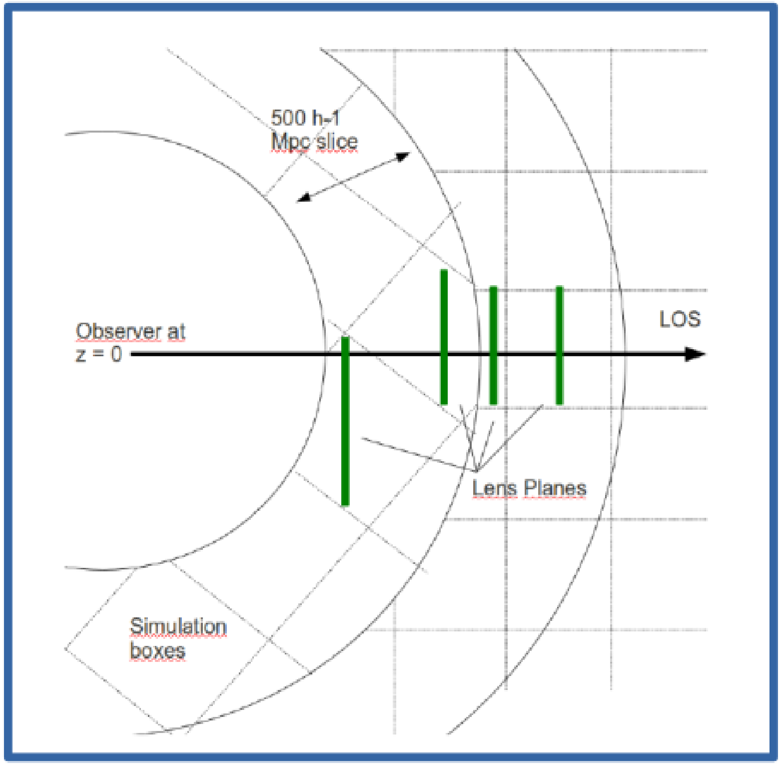
Courtesy S. Hilbert

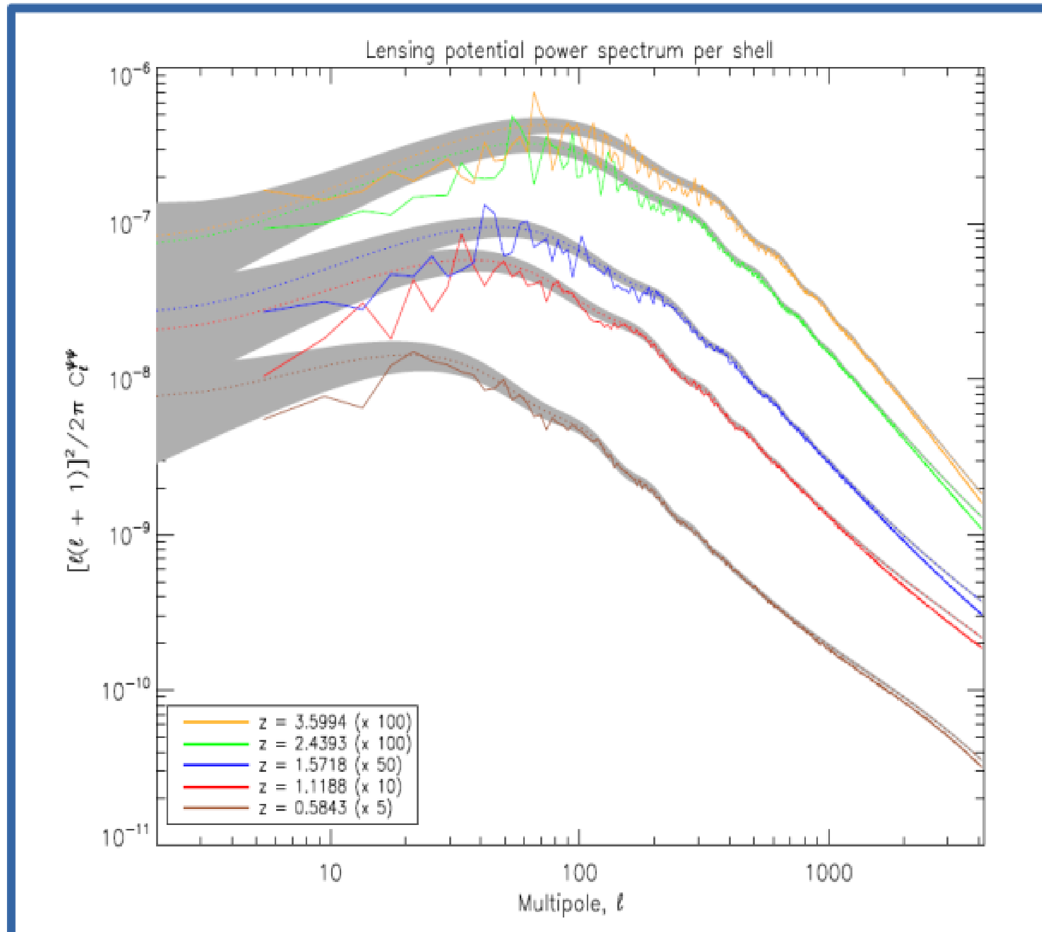


CMB-N-Body Lensing



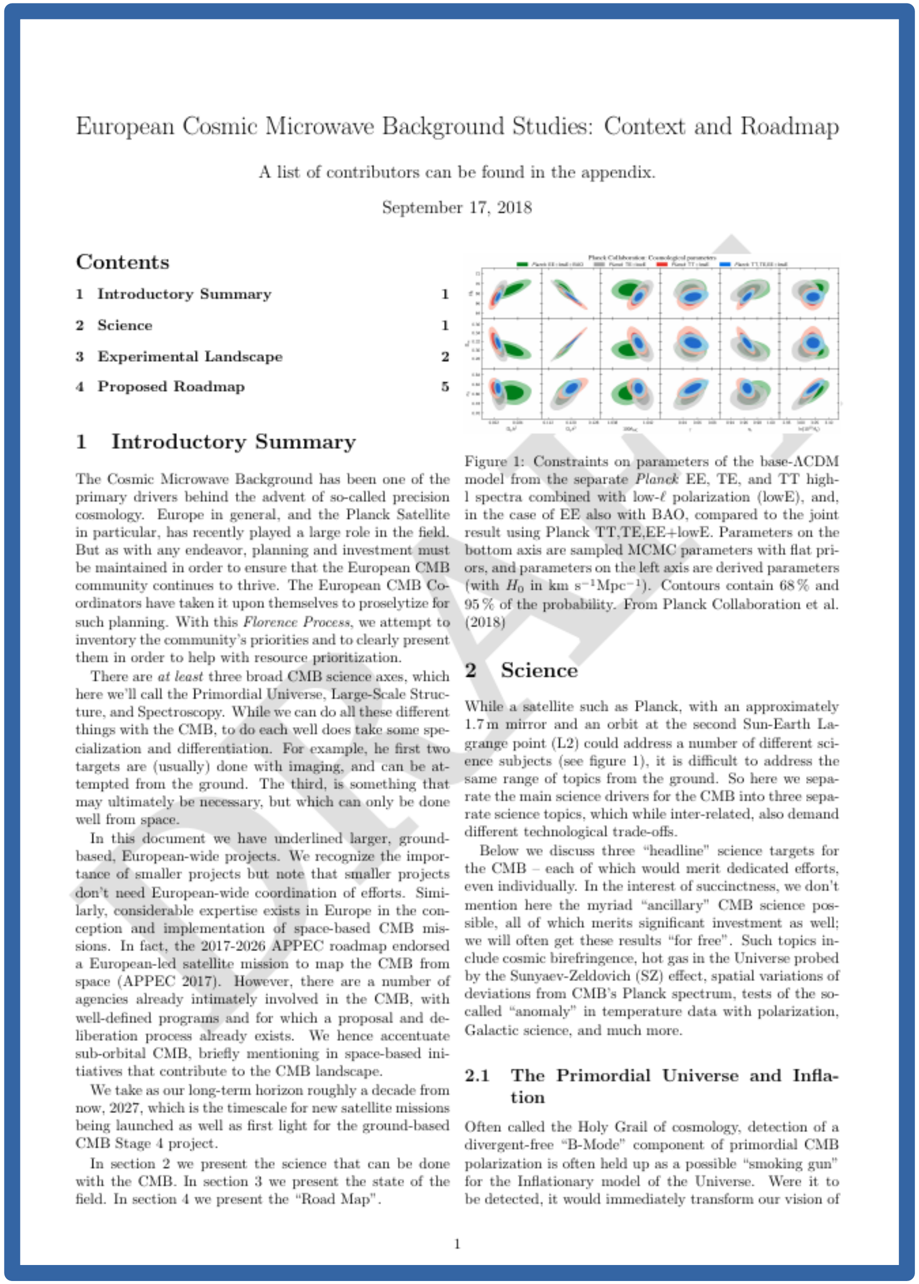
CMB-N-Body Lensing





Hilbert et al. 2009, Carbone et al. 2009, Calabrese et al. 2015, Fabbian et al. 2018

CMB-LSS Synergies in the Roadmap



European Cosmic Microwave Background Studies: Context and Roadmap

A list of contributors can be found in the appendix.

September 17, 2018

Contents

1 Introductory Summary

The Cosmic Microwave Background has been one of the primary drivers behind the advent of so-called precision cosmology. Europe in general, and the Planck Satellite in particular, has recently played a large role in the field. But as with any endeavor, planning and investment must be maintained in order to ensure that the European CMB community continues to thrive. The European CMB Co-ordinators have taken it upon themselves to proselytize for such planning. With this *Florence Process*, we attempt to inventory the community's priorities and to clearly present them in order to help with resource prioritization.

There are *at least* three broad CMB science axes, which here we'll call the Primordial Universe, Large-Scale Structure, and Spectroscopy. While we can do all these different things with the CMB, to do each well does take some specialization and differentiation. For example, he first two targets are (usually) done with imaging, and can be attempted from the ground. The third, is something that may ultimately be necessary, but which can only be done well from space.

In this document we have underlined larger, ground-based, European-wide projects. We recognize the importance of smaller projects but note that smaller projects don't need European-wide coordination of efforts. Similarly, considerable expertise exists in Europe in the conception and implementation of space-based CMB missions. In fact, the 2017-2026 APPEC roadmap endorsed a European-led satellite mission to map the CMB from space (APPEC 2017). However, there are a number of agencies already intimately involved in the CMB, with well-defined programs and for which a proposal and deliberation process already exists. We hence accentuate sub-orbital CMB, briefly mentioning in space-based initiatives that contribute to the CMB landscape.

We take as our long-term horizon roughly a decade from now, 2027, which is the timescale for new satellite missions being launched as well as first light for the ground-based CMB Stage 4 project.

In section 2 we present the science that can be done with the CMB. In section 3 we present the state of the field. In section 4 we present the "Road Map".

Figure 1: Constraints on parameters of the base-ΛCDM model from the separate *Planck* EE, TE, and TT high-l spectra combined with low-ℓ polarization (lowE), and, in the case of EE also with BAO, compared to the joint result using Planck TT,TE,EE+lowE. Parameters on the bottom axis are sampled MCMC parameters with flat priors, and parameters on the left axis are derived parameters (with H_0 in km $s^{-1}Mpc^{-1}$). Contours contain 68 % and 95 % of the probability. From Planck Collaboration et al. (2018)

2 Science

While a satellite such as Planck, with an approximately 1.7 m mirror and an orbit at the second Sun-Earth Lagrange point (L2) could address a number of different science subjects (see figure 1), it is difficult to address the same range of topics from the ground. So here we separate the main science drivers for the CMB into three separate science topics, which while inter-related, also demand different technological trade-offs.

Below we discuss three "headline" science targets for the CMB – each of which would merit dedicated efforts, even individually. In the interest of succinctness, we don't mention here the myriad "ancillary" CMB science possible, all of which merits significant investment as well; we will often get these results "for free". Such topics include cosmic birefringence, hot gas in the Universe probed by the Sunyaev-Zeldovich (SZ) effect, spatial variations of deviations from CMB's Planck spectrum, tests of the so-called "anomaly" in temperature data with polarization, Galactic science, and much more.

2.1 The Primordial Universe and Inflation

Often called the Holy Grail of cosmology, detection of a divergent-free "B-Mode" component of primordial CMB polarization is often held up as a possible "smoking gun" for the Inflationary model of the Universe. Were it to be detected, it would immediately transform our vision of

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--- 7 years of data analysis

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--- 2019 – Launch in early 2020s: make contact and agreements with CMB Probes

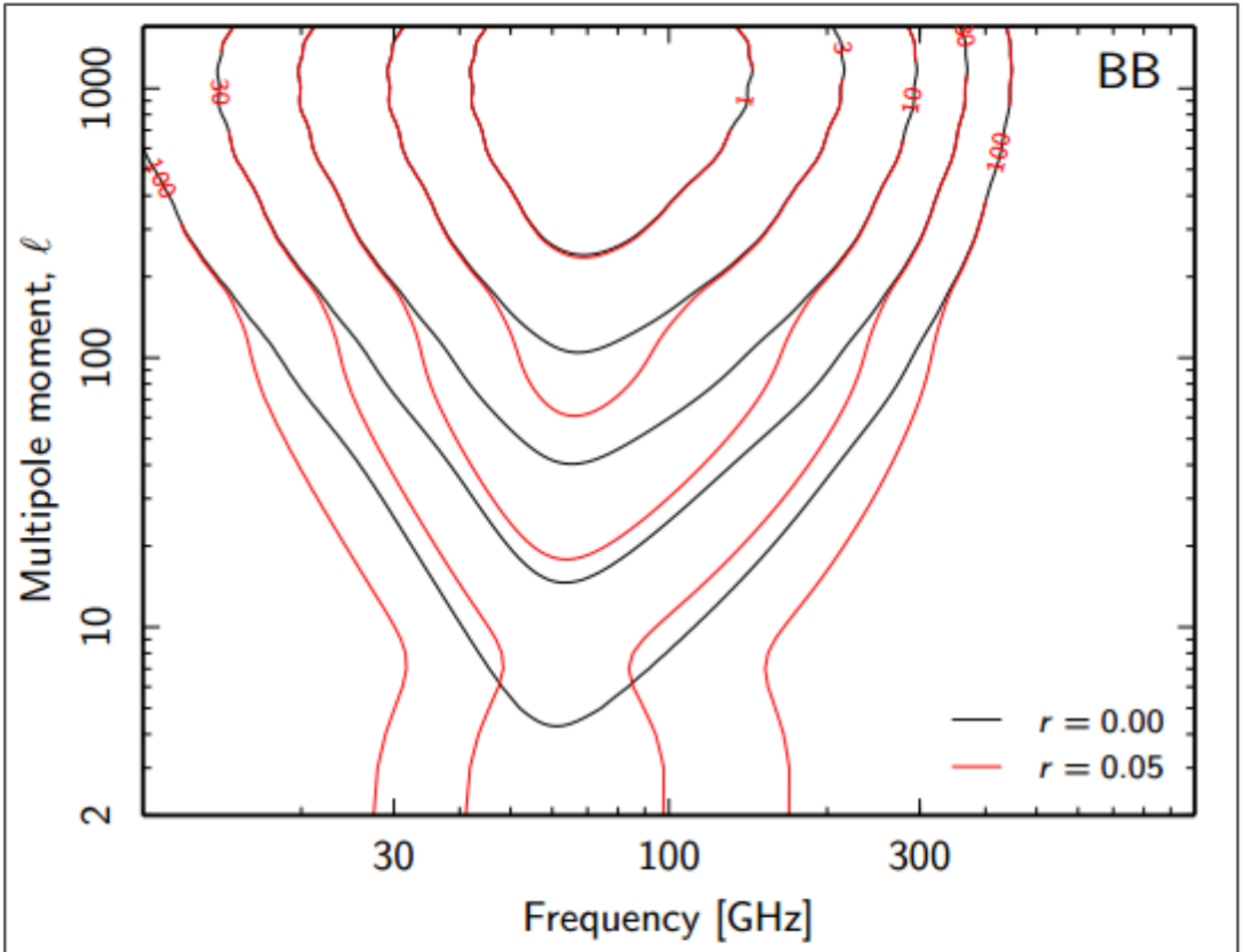
--- Within 2018: Contribution to the Key Paper Projects Definition of Additional Science

--- Now: Working at first Forecast Paper

CMB Synergy: Multi-Probe, Multi-Frequency Dataset Combinations

Based on
Krachmalnicoff et al. 2016,arxiv 1511.00532
Planck 2018 results, XI, arxiv 1801.04945
Krachmalnicoff et al. 2018, arxiv 1802.01145
Planck 2018 results IV, arxiv 1807.06208

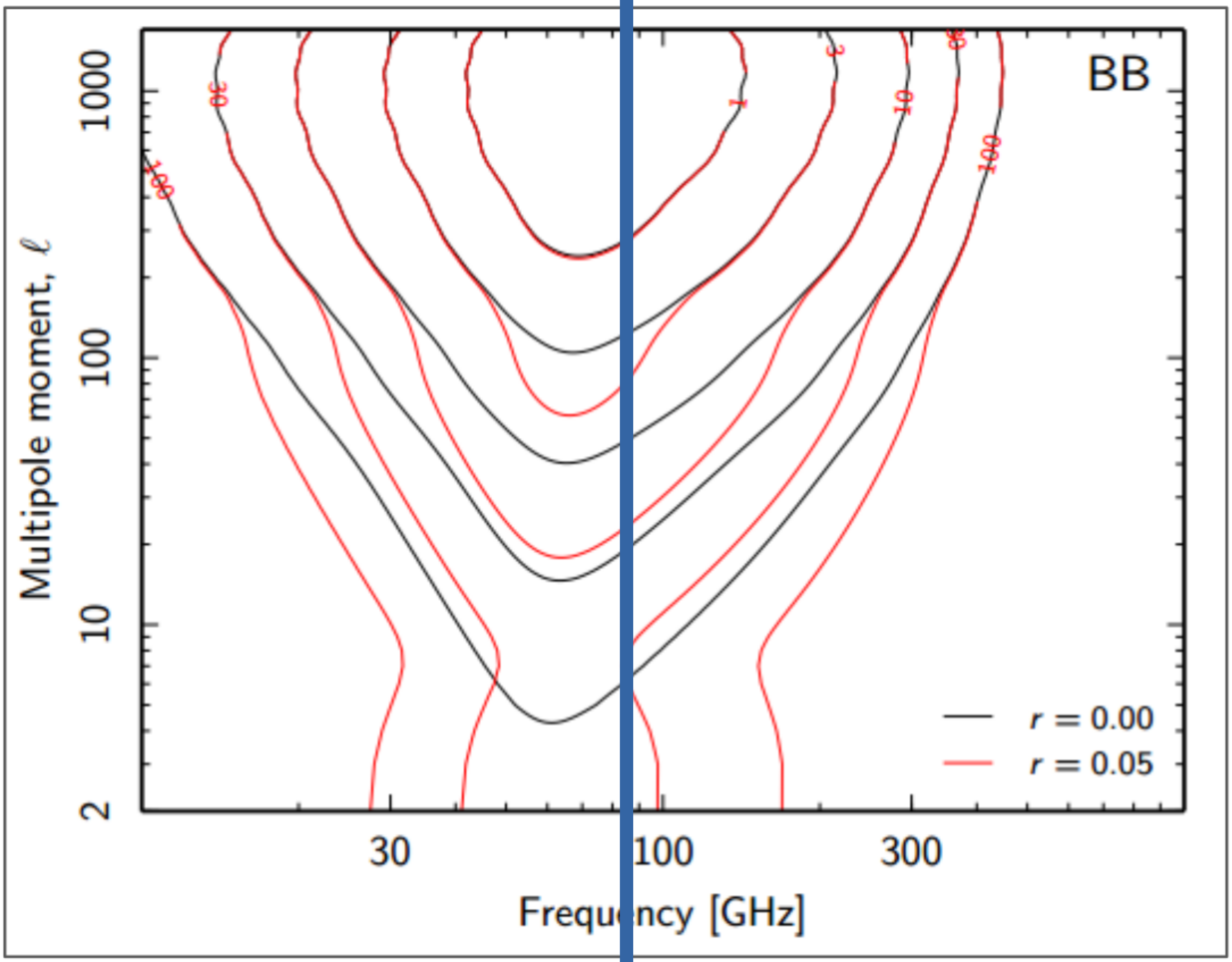
Diffuse foregrounds and CMB B-modes



$$f(\ell, \nu) = [C_\ell^{\mathrm{fg}}(\nu)/C_\ell^{\mathrm{CMB}}]^{1/2}$$

Planck 2015, 2018

Diffuse foregrounds and CMB B-modes



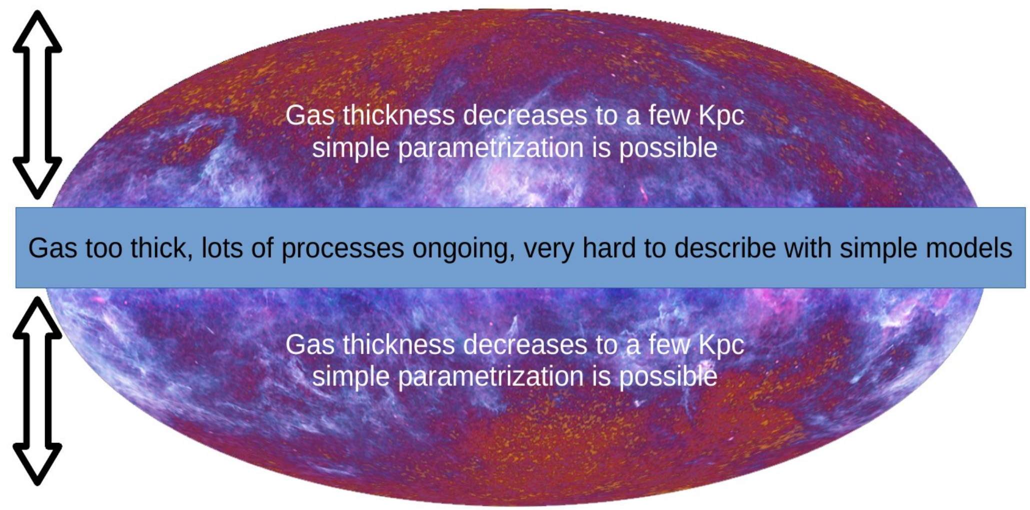
$$f(\ell, \nu) = [C_\ell^{\mathrm{fg}}(\nu)/C_\ell^{\mathrm{CMB}}]^{1/2}$$

Planck 2015, 2018

Polarized Galactic Synchrotron at intermediate and high latitudes

- **Spatial distribution of amplitudes:**
  - **super-degree**
  - **degree**
  - **sub-degree**
- **SED in poilarization**
- **Contamination to CMB B-modes**
- **SED break**
- **Dust Correlation:**
  - **Super-degree**
  - **degree**
  - **Sub-degree**
- **de-Correlation**

F=A (sky direction) × F(frequency)



Polarized Galactic Synchrotron at intermediate and high latitudes

- Spatial distribution of amplitudes:
  - super-degree (Planck & WMAP)
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  - sub-degree
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- Contamination to CMB B-modes (Planck & WMAP):
  - 0.05<rFG<0.1
  - 60 GHz < minimum frequency < 90 GHz
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- de-Correlation

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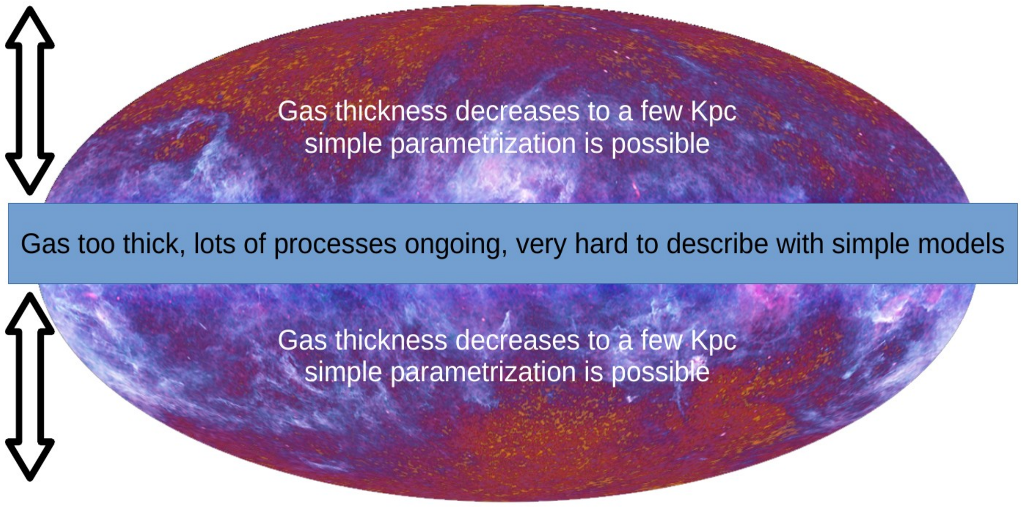

Unknown
Some information
Measures

Polarized Galactic Synchrotron at intermediate and high latitudes

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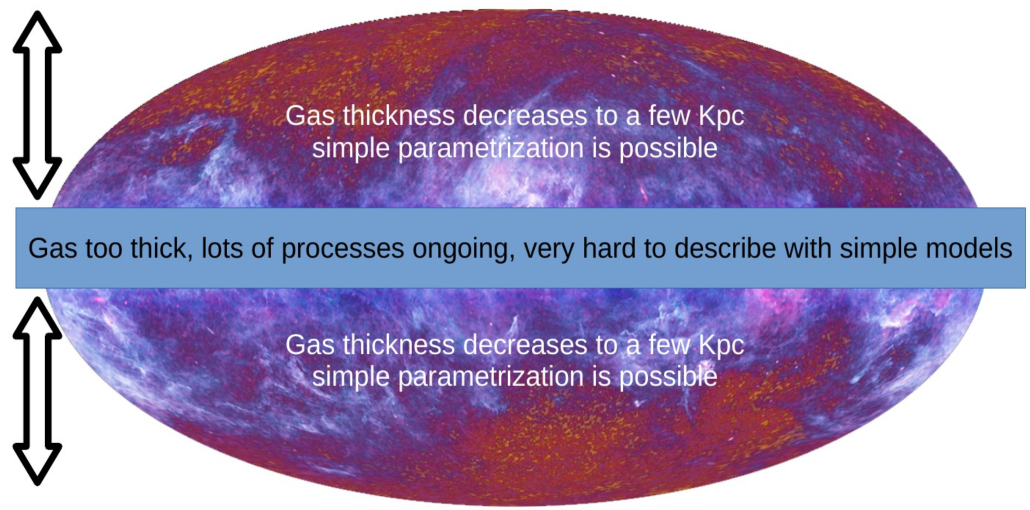

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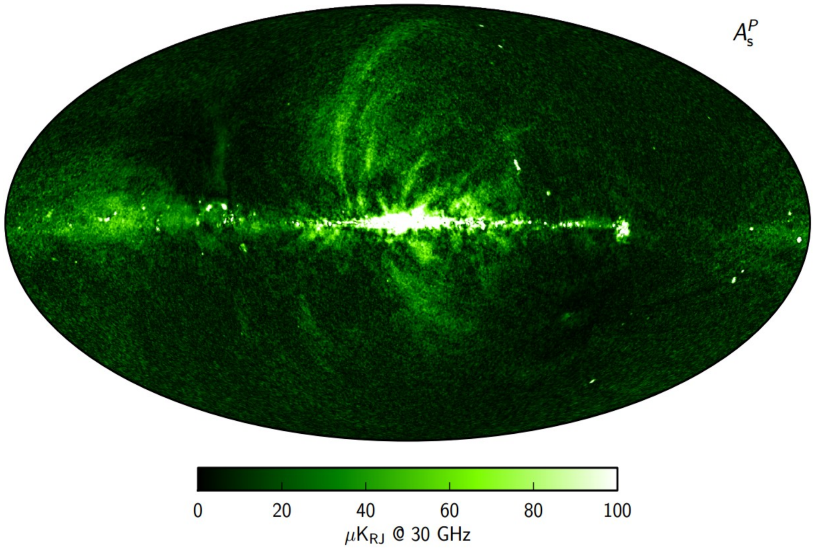
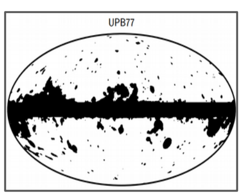
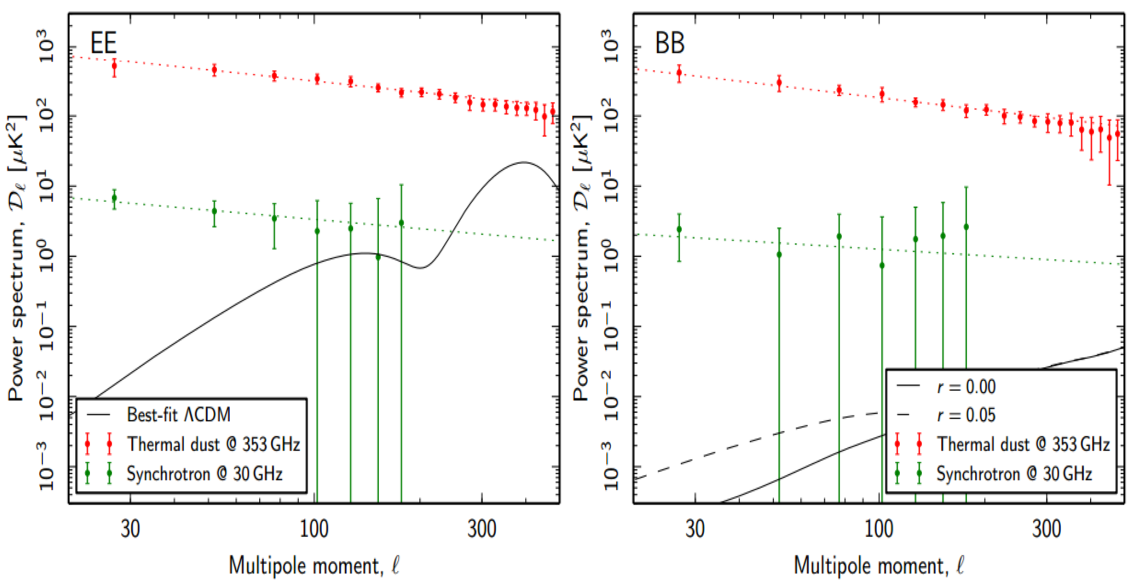
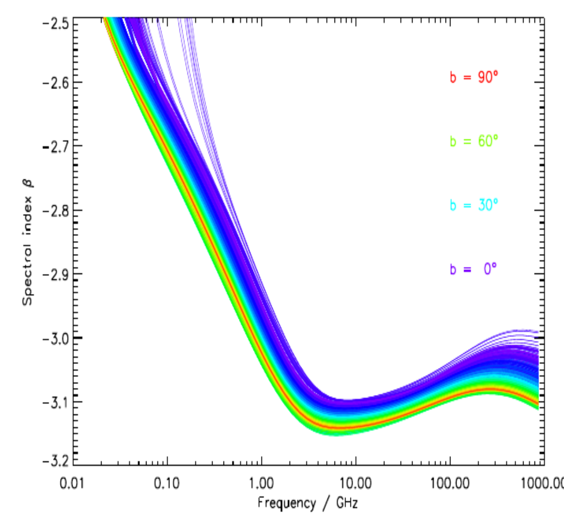
Planck & WMAP Synchrotron



- Fitting Q and U Synchrotron using spectral index from intensity
- Neglected components:
  - anomalous dust emission, expected to be less than 1% (Rubino-Martın et al., 2012)
  - polarized COs (Puglisi et al. 2016)

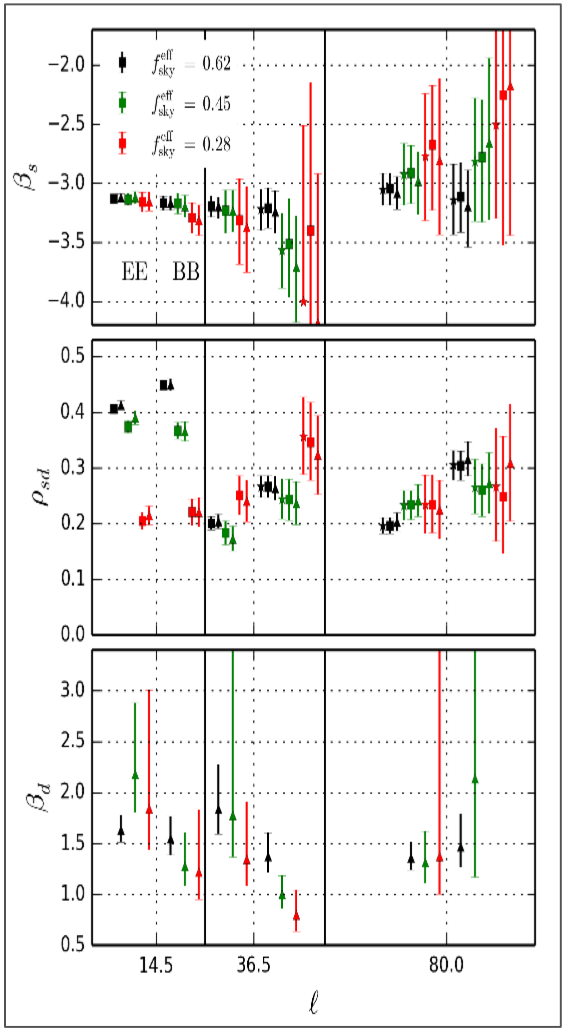


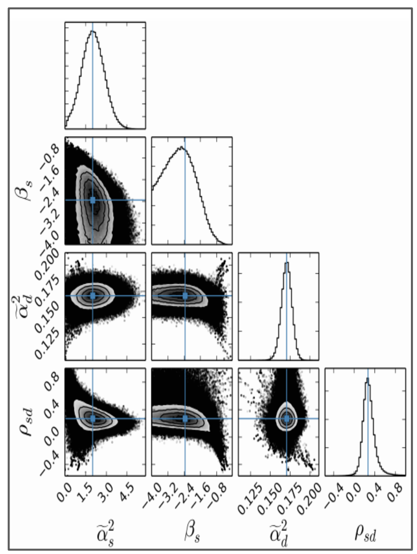


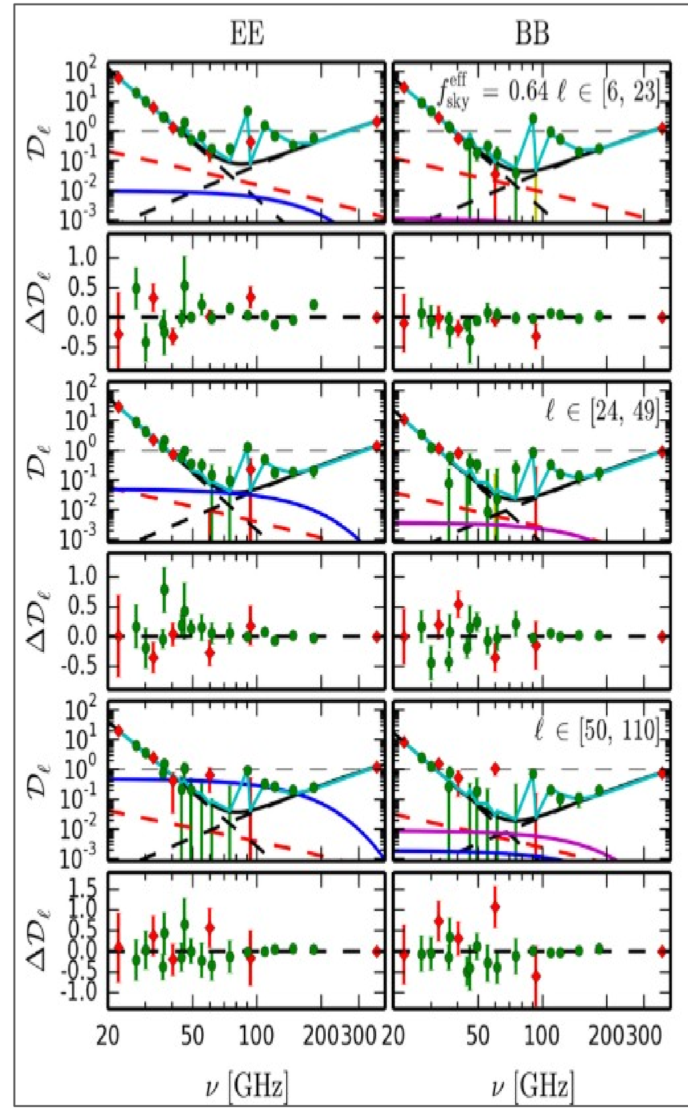


Planck 2015, 2018

Planck & WMAP Synchrotron: dust cross-correlation







Choi & Page 2016, Planck 2018

THE SPASS SURVEY

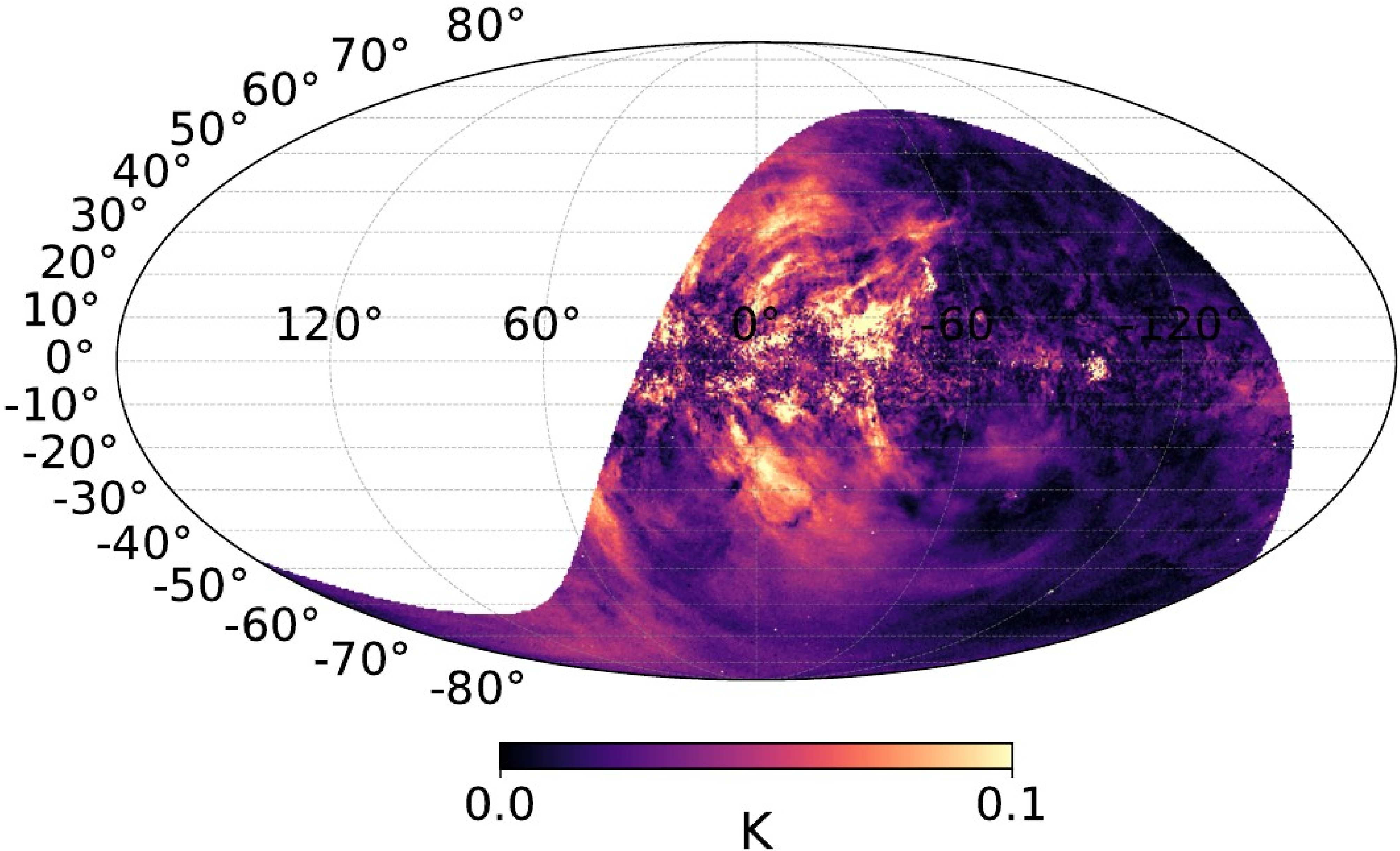
Carretti et al. 2013
Carretti et al. 2017 in preparation

PARKES radio telescope: 64 m
Frequency: **2.3 GHz** (224 MHz BW)
Sky coverage ~ 50% (South Emisphere)
Angular resolution **~ 9 arcmin**

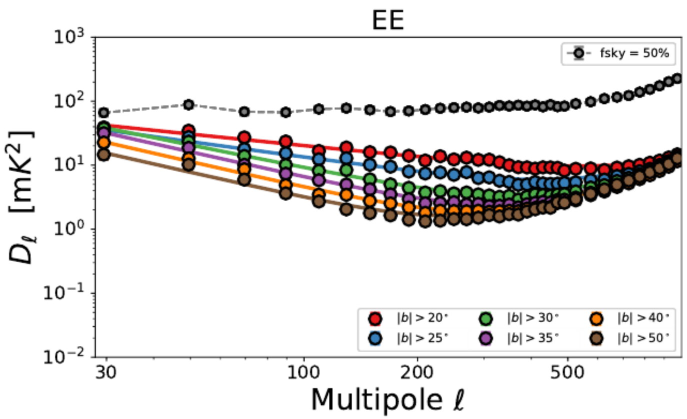
SPASS science:

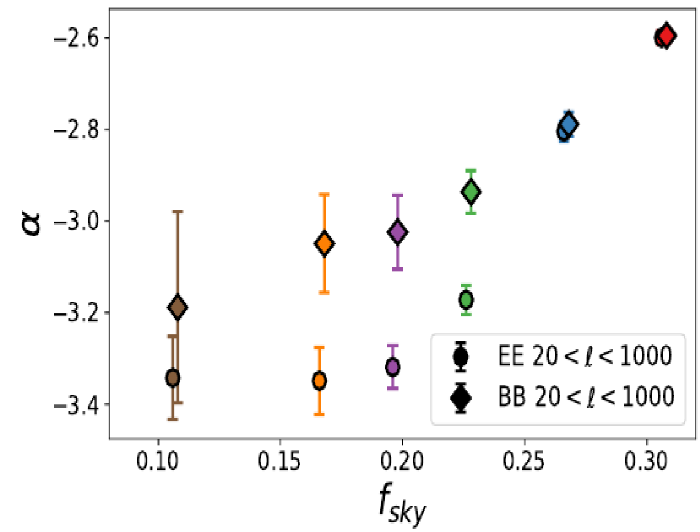
- Galactic Magnetic field
- Fermi Bubbles and Galactic structure
- ISM turbulence
- Gum Nebula
- ICM of galaxy clusters
- Extragalactic source properties
- Synchrotron Cosmic Web
- RM catalogue
- **CMB foregrounds**
- ...

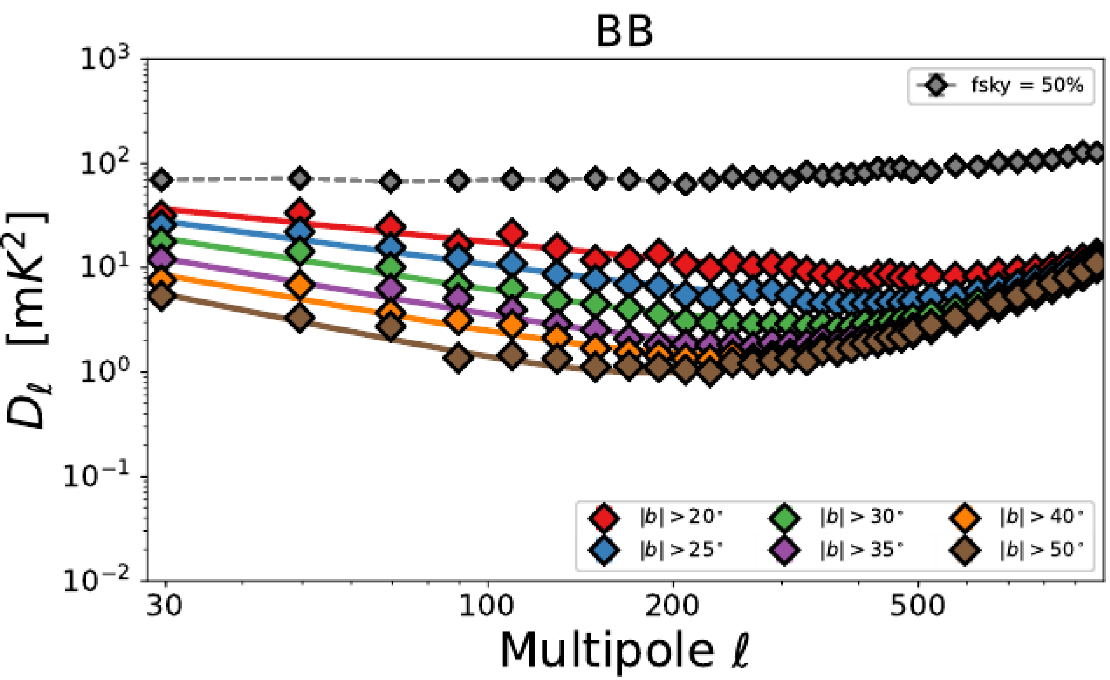
Radio-Microwave Synergy: S-PASS x WMAP x Planck

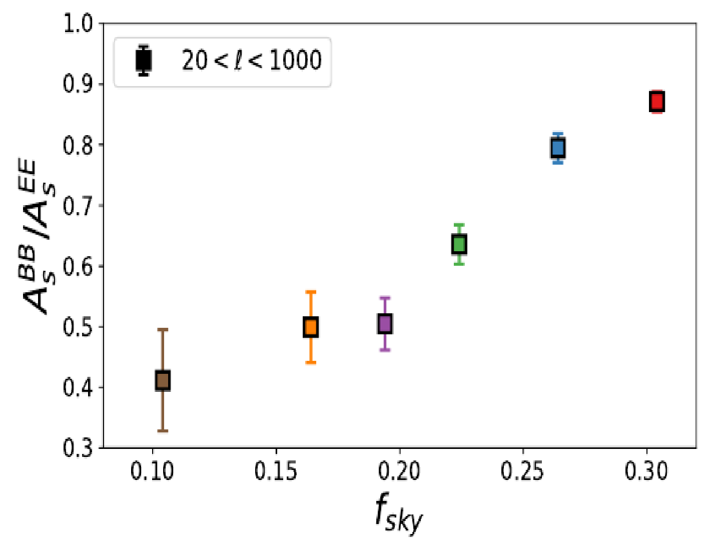


S-PASS Angular Power Spectra



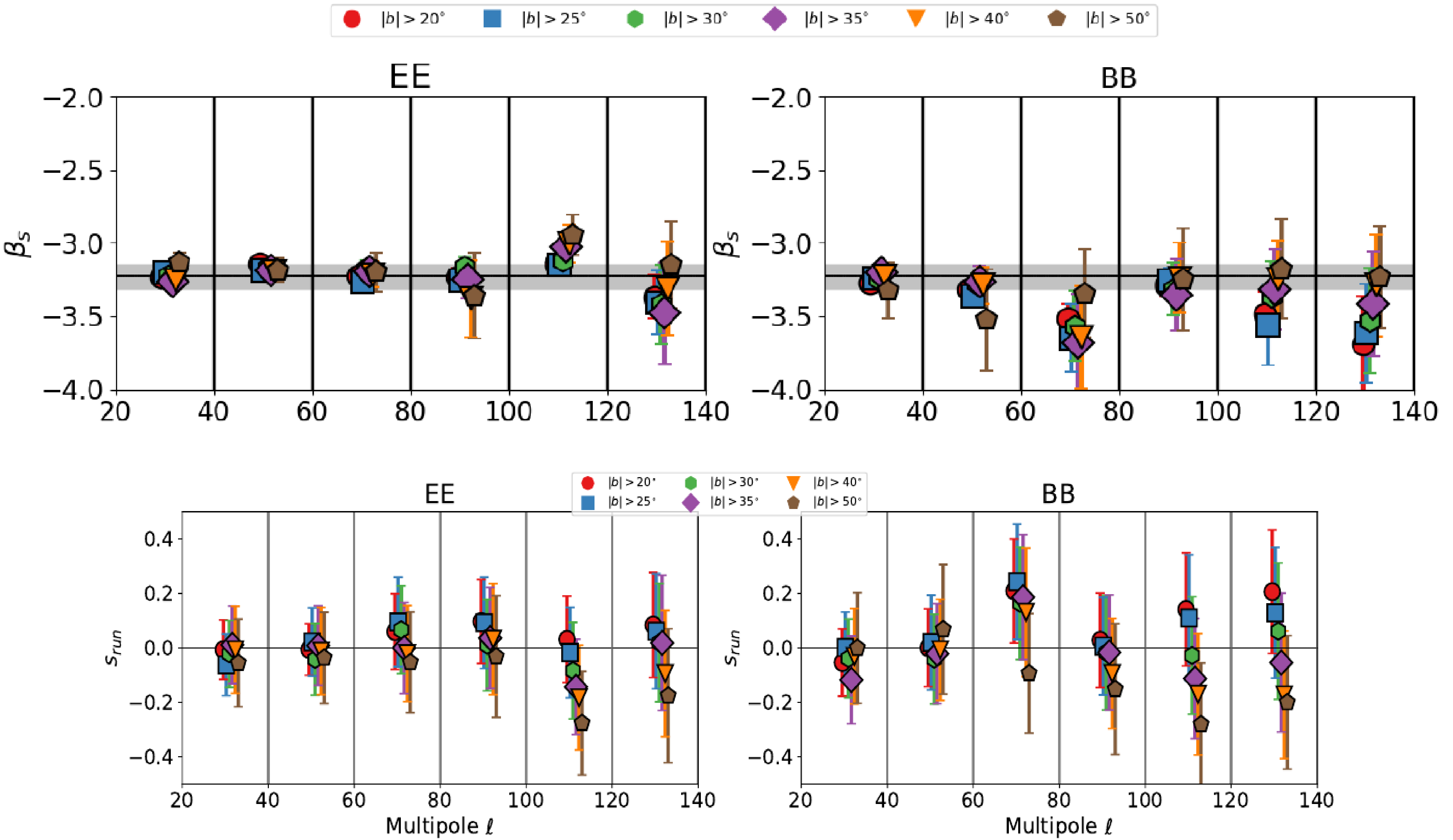






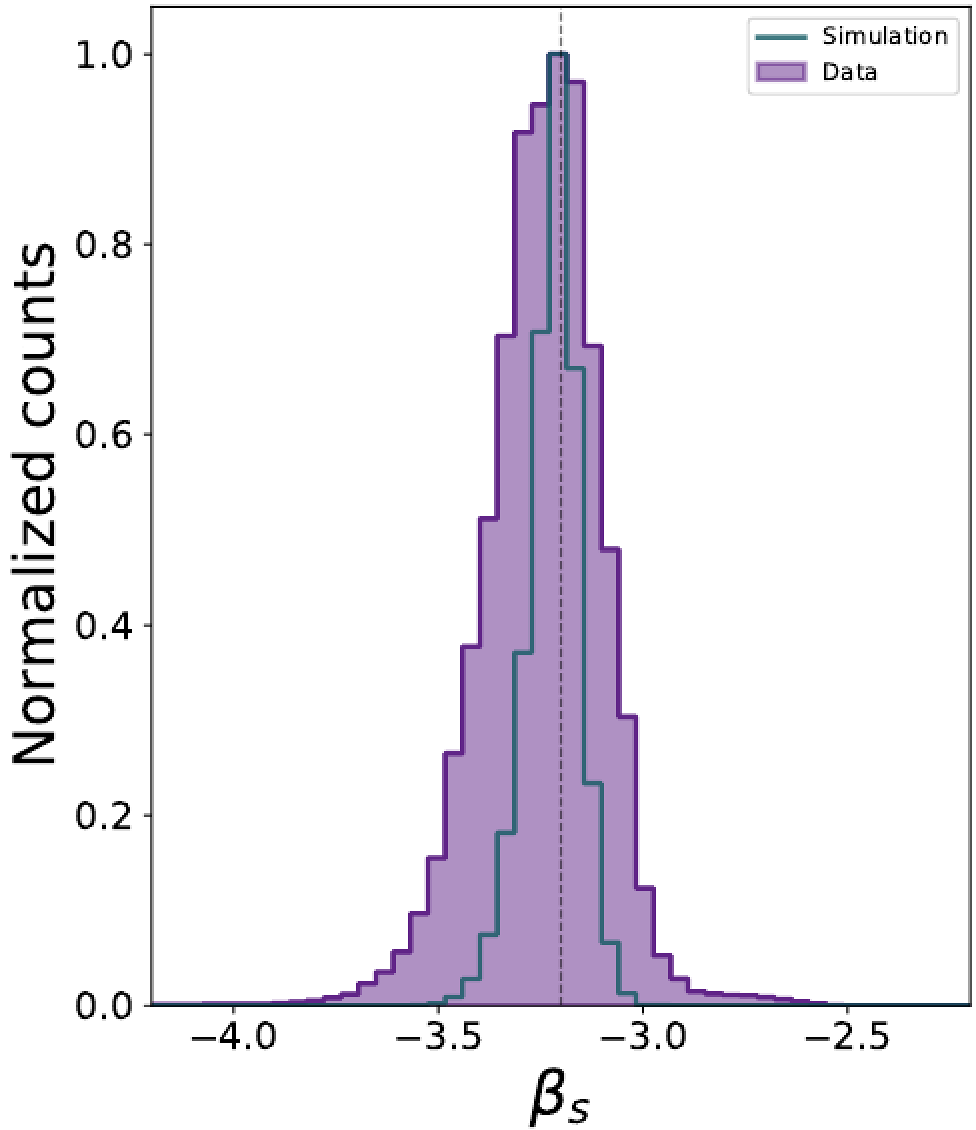
Krachmalnicoff et al. 2018

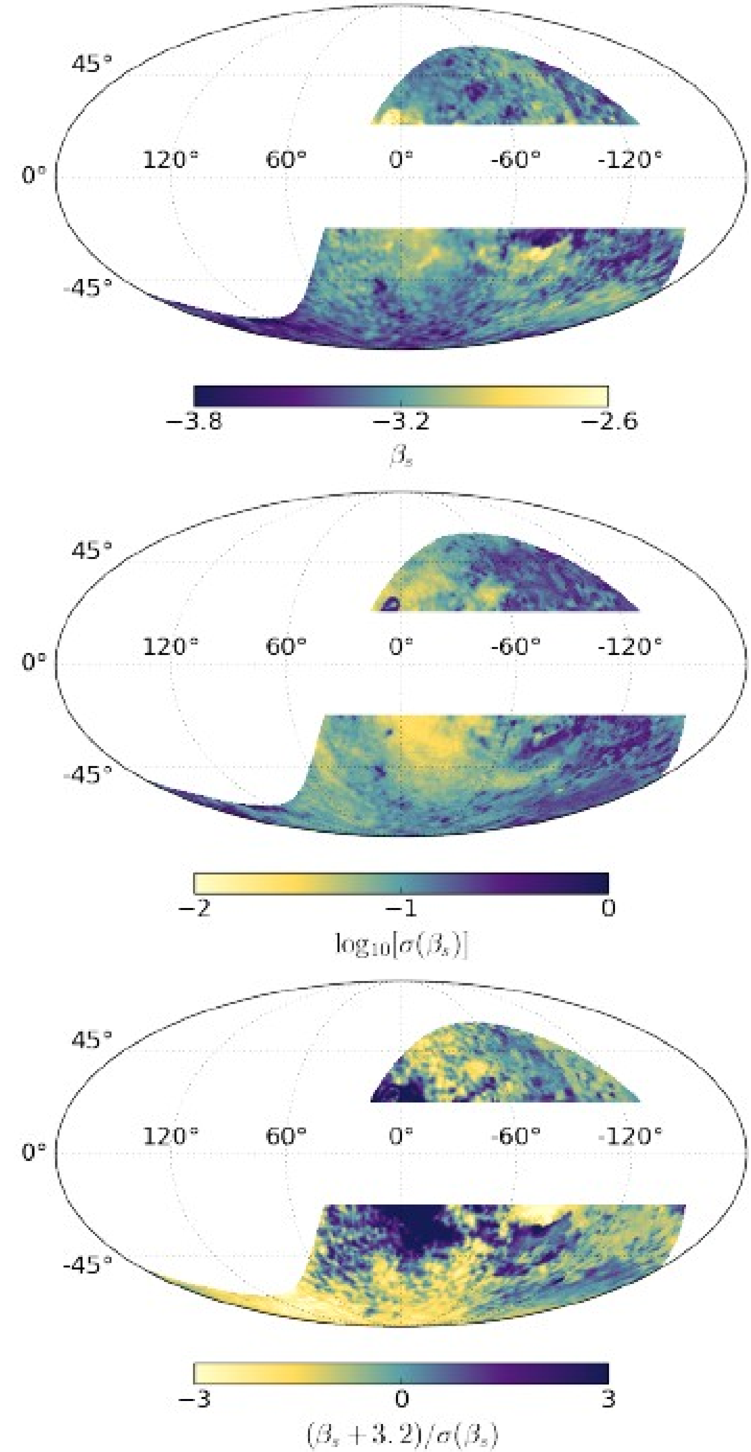
Radio-Microwave Synergy: S-PASS x WMAP x Planck



Krachmalnicoff et al. 2018

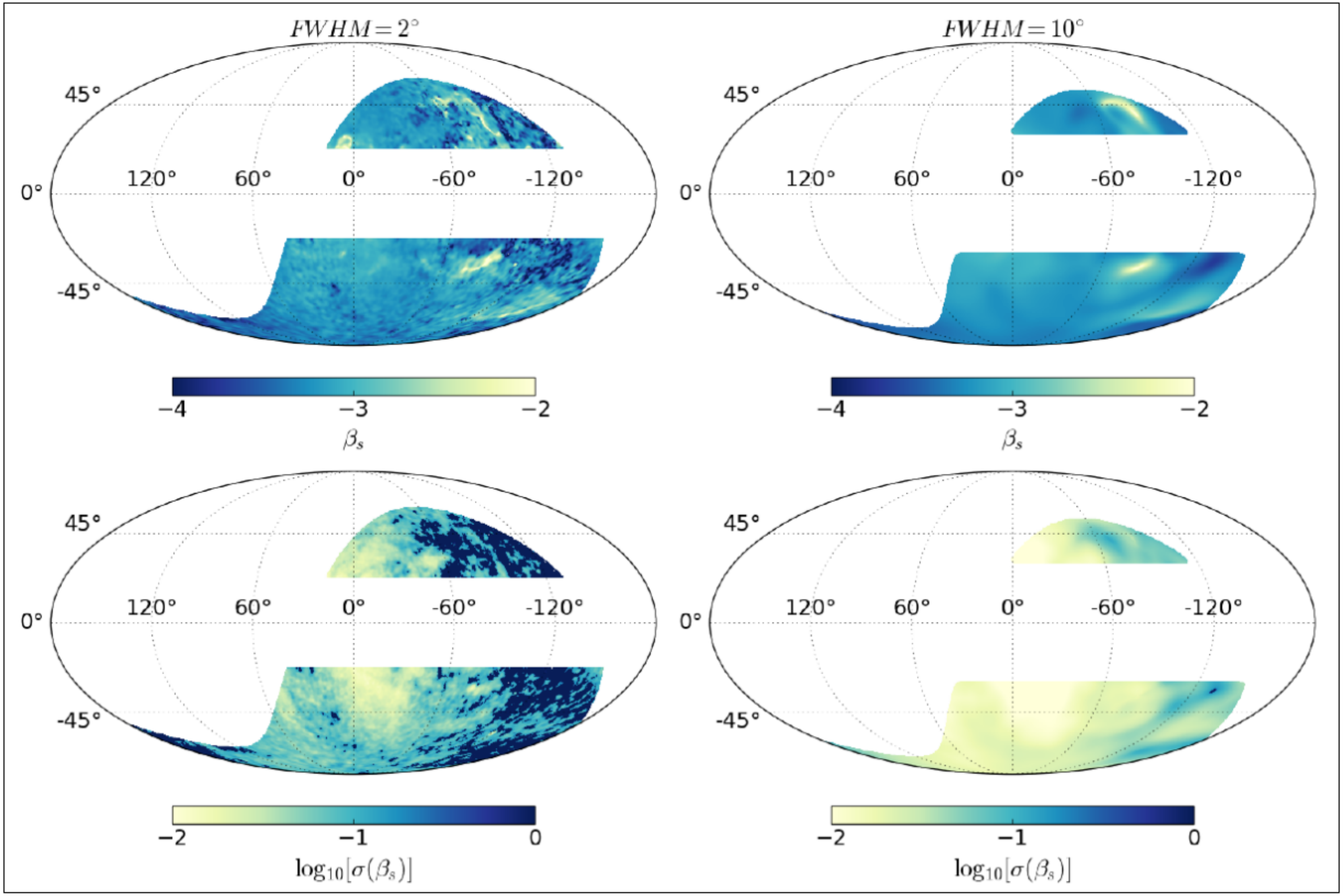
Synchrotron SED





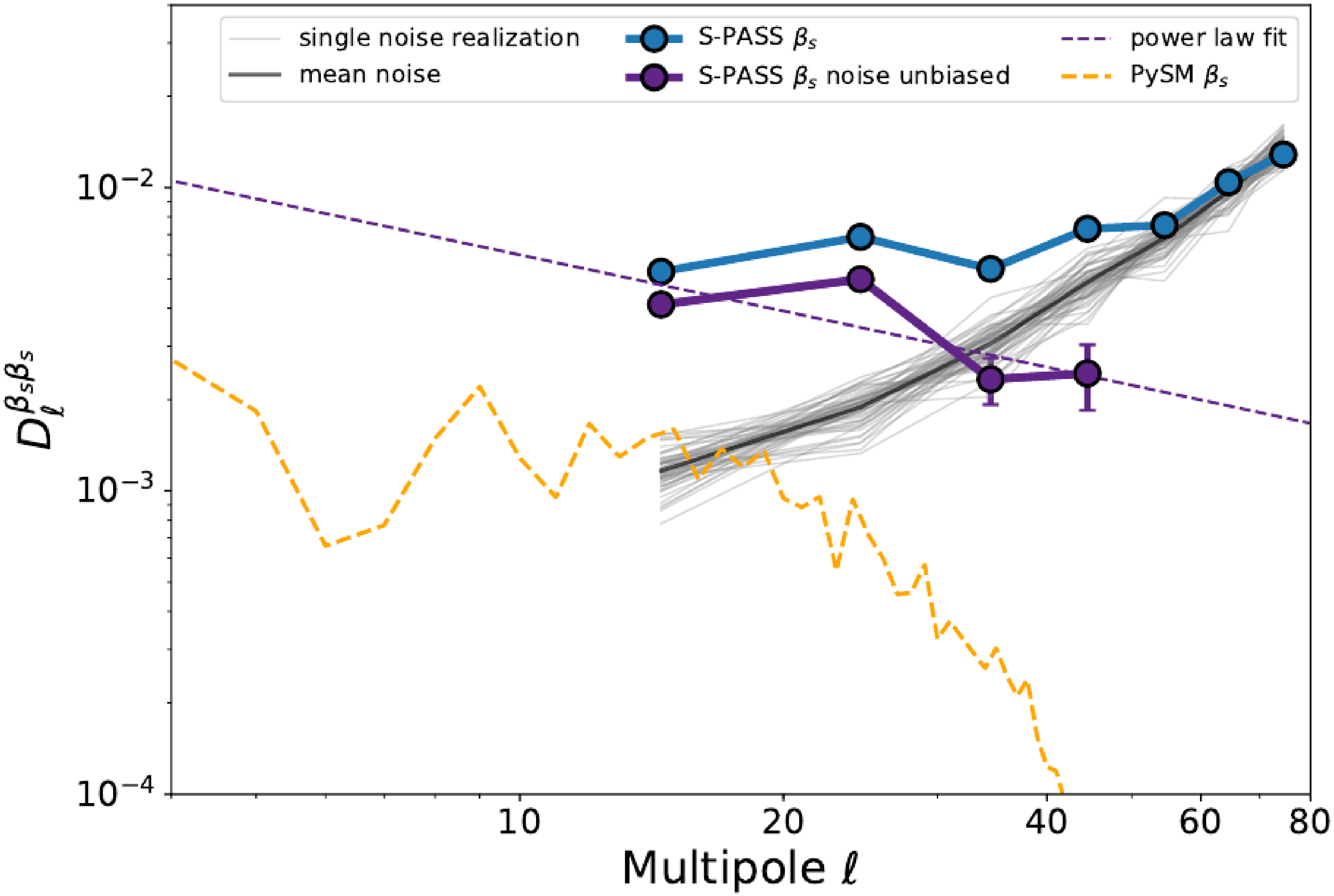
Krachmalnicoff et al. 2018

Synchrotron SED



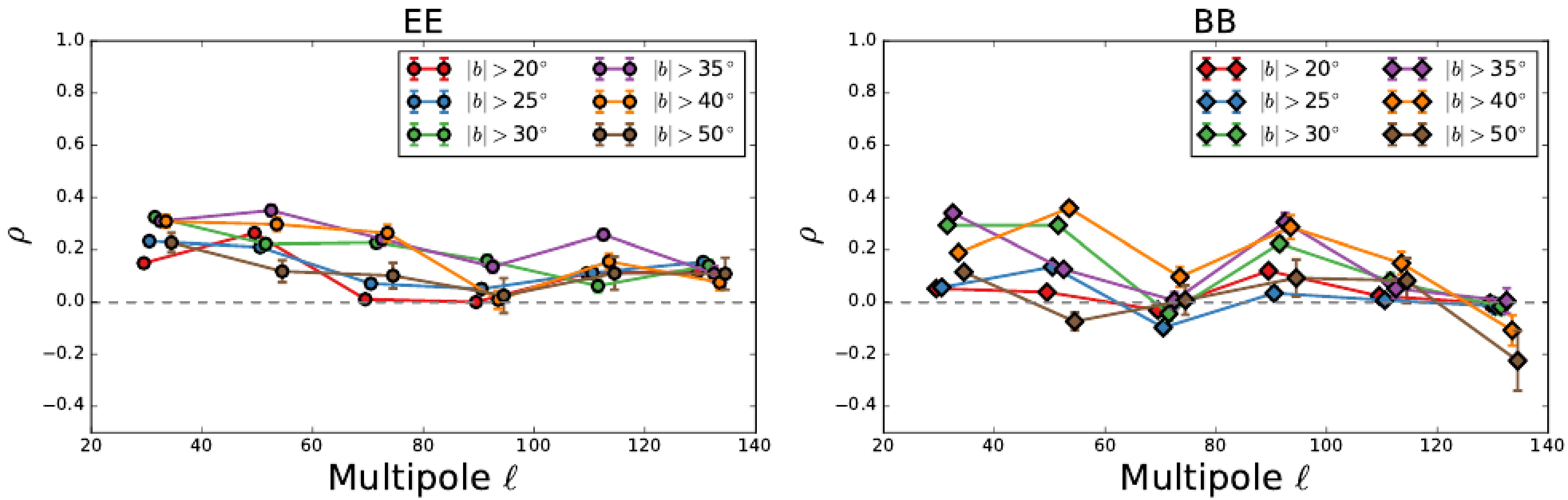
Krachmalnicoff et al. 2018

Synchrotron SED angular power spectrum



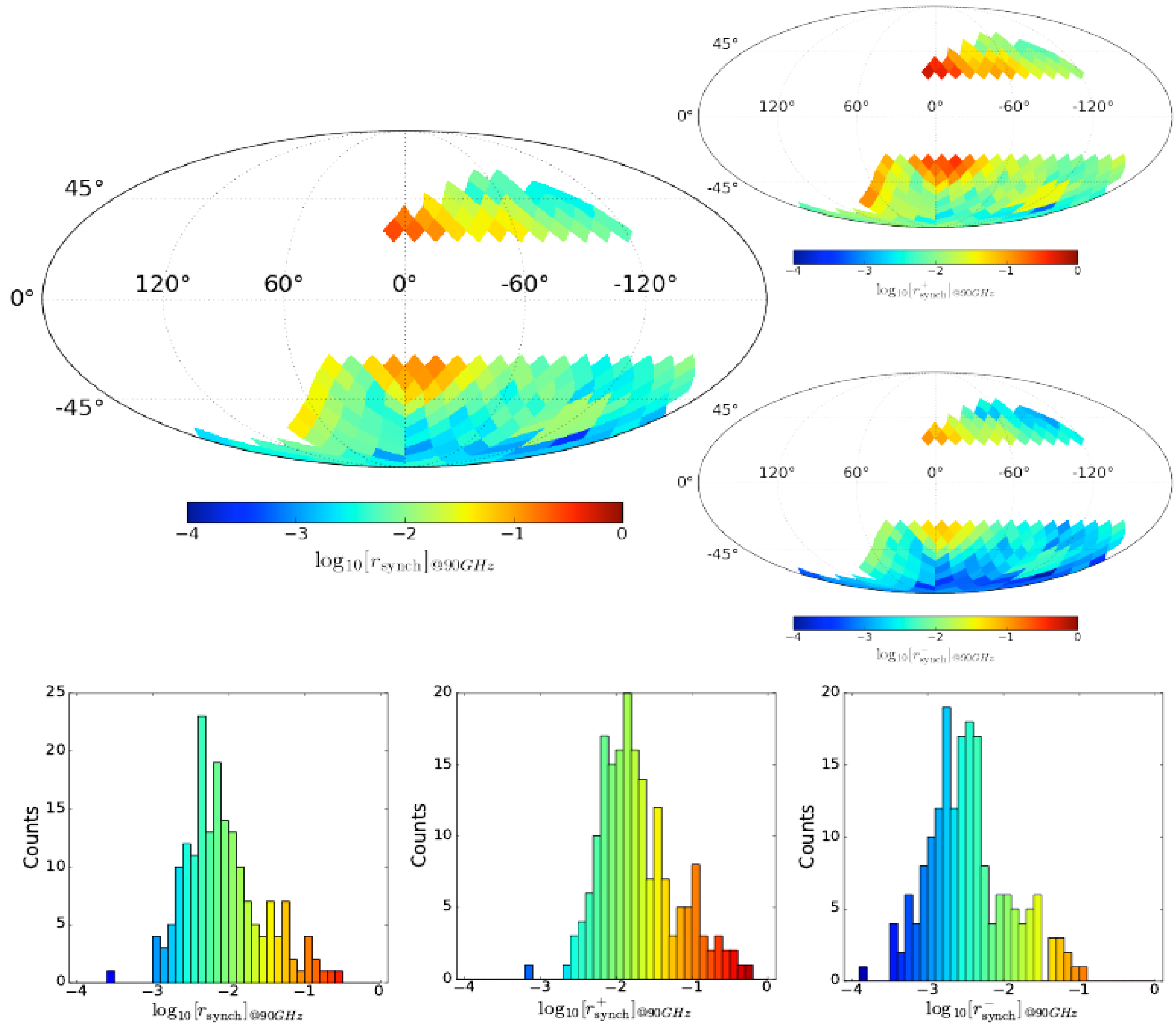
Krachmalnicoff et al. 2018

S-PASS x Planck 353 GHz



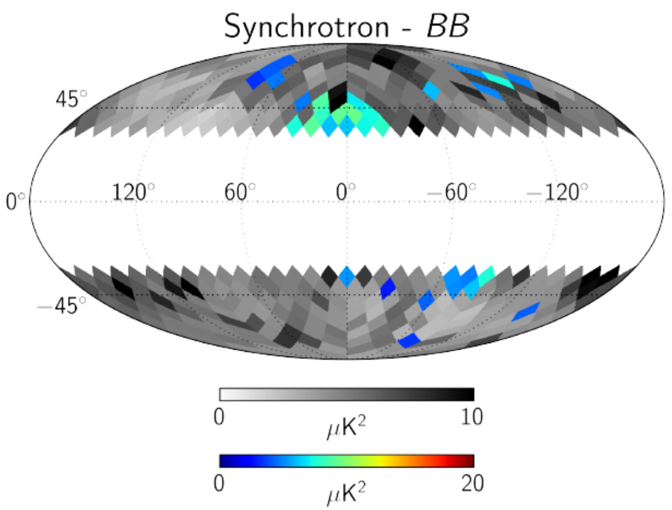
Krachmalnicoff et al. 2018

$r_{\text{synch at l=80}}$ at 90 GHz

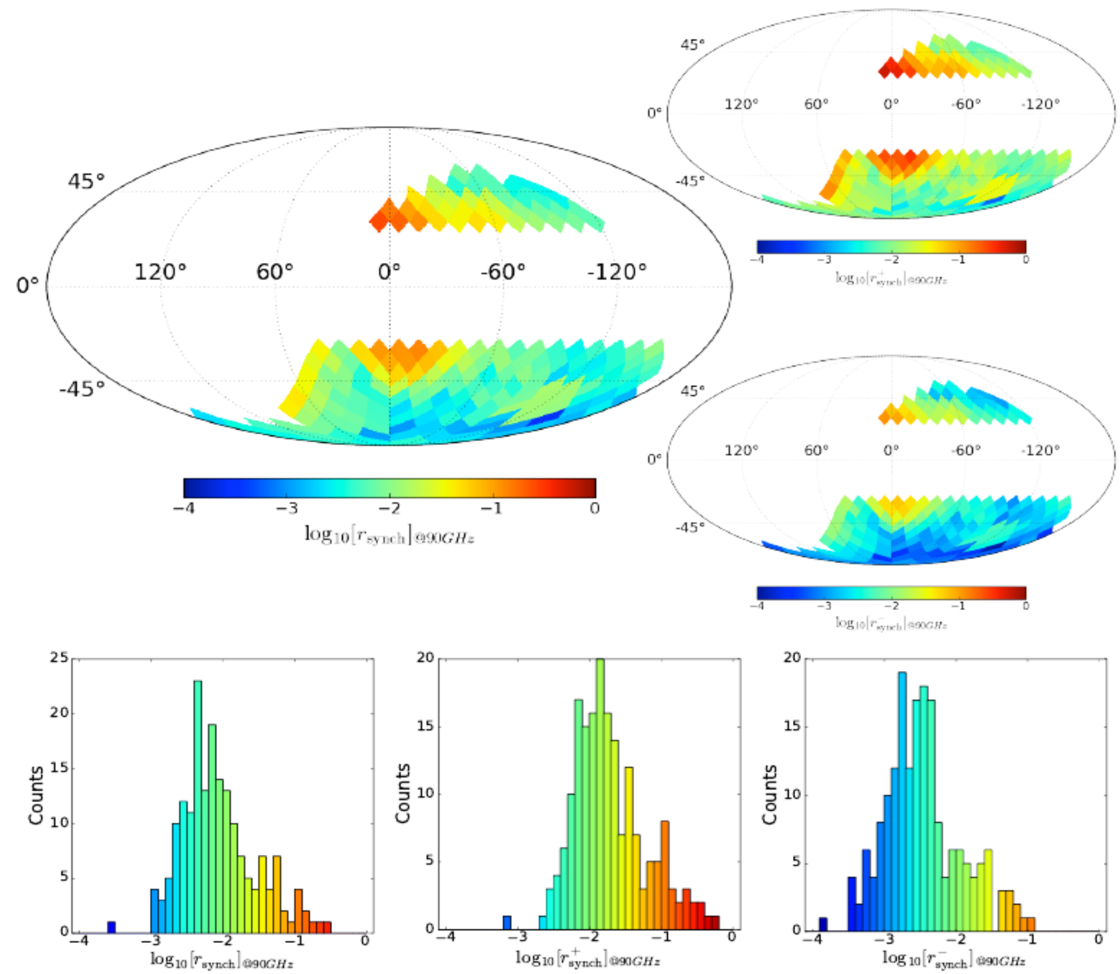


Krachmalnicoff et al. 2018

$r_{\mathrm{synch\ at\ l=80}}$ at 90 GHz



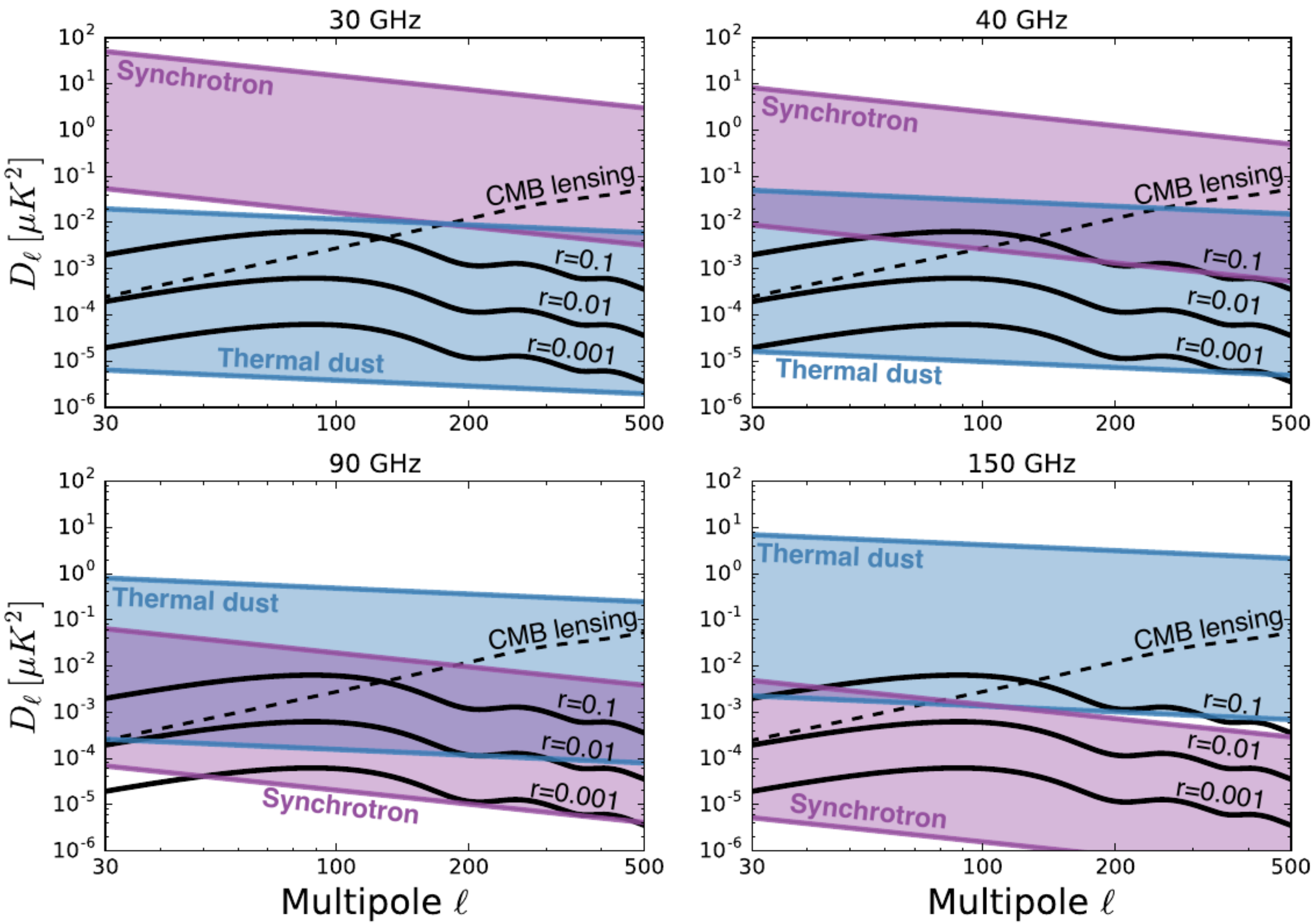
Planck & WMAP only, 2016



With S-PASS, 2018

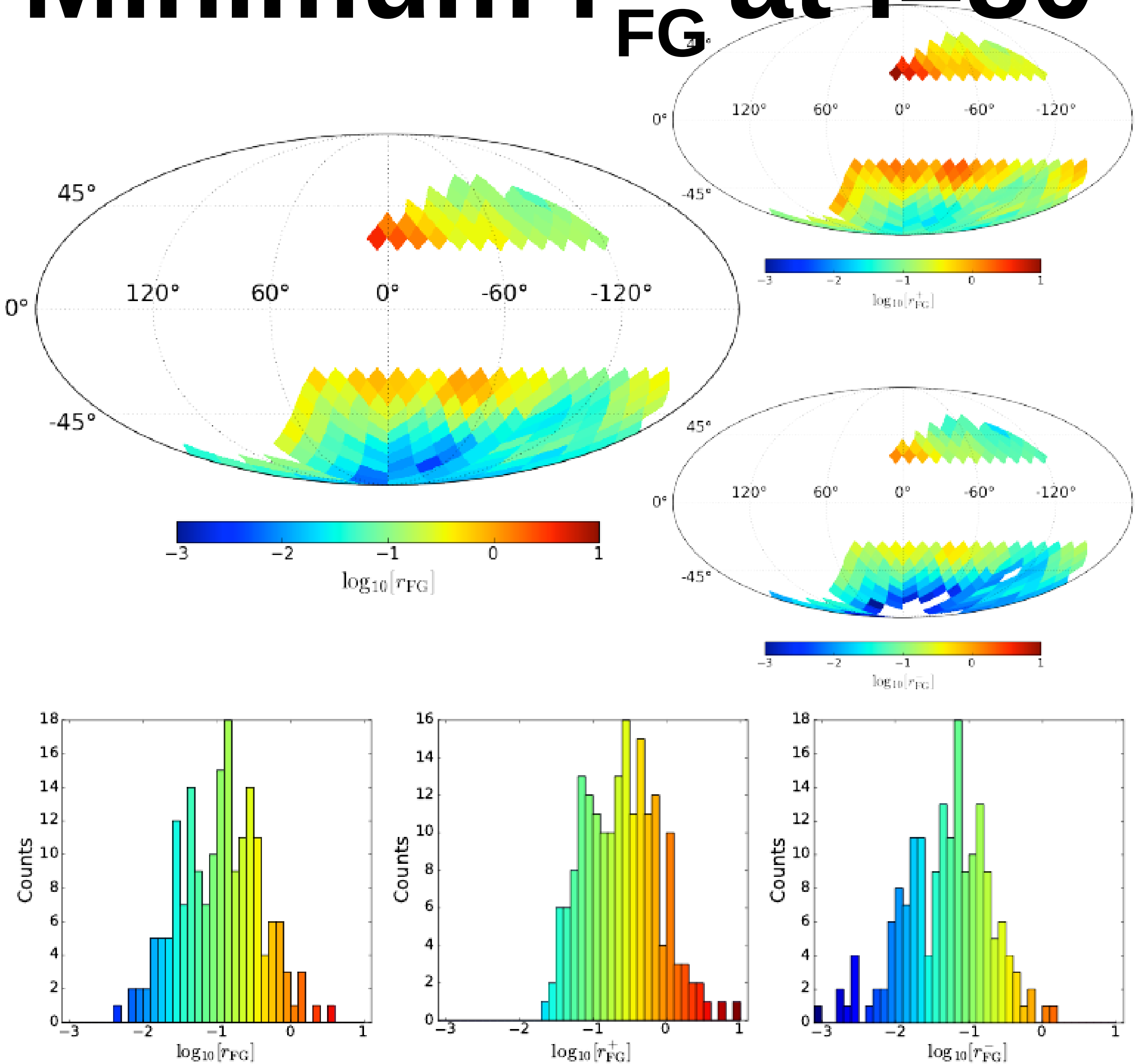
Krachmalnicoff et al. 2016, 2018

S-PASS x WMAP x Planck: Synchrotron Contamination across Frequencies



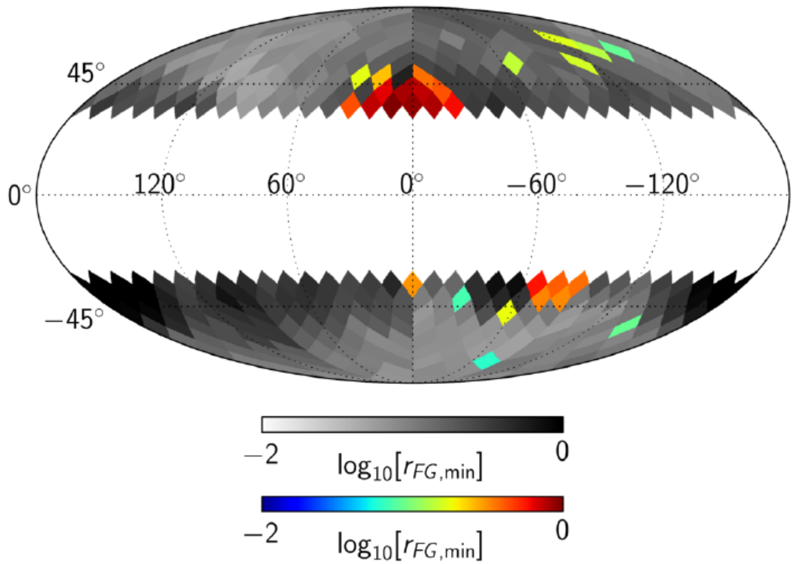
Krachmalnicoff et al. 2018

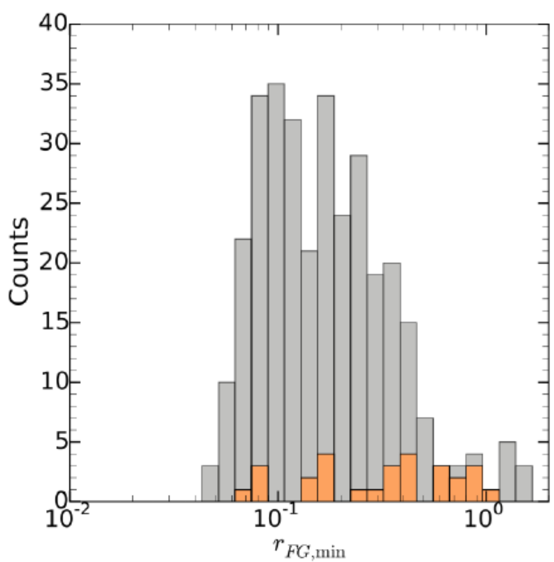
Minimum r_{FG} at l=80



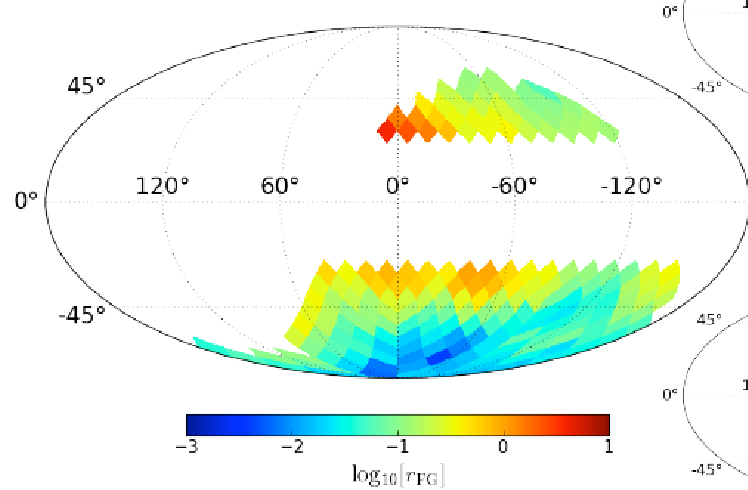
Krachmalnicoff et al. 2018

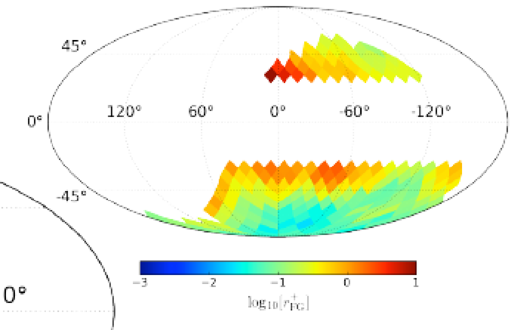
Minimum r_{FG} at l=80

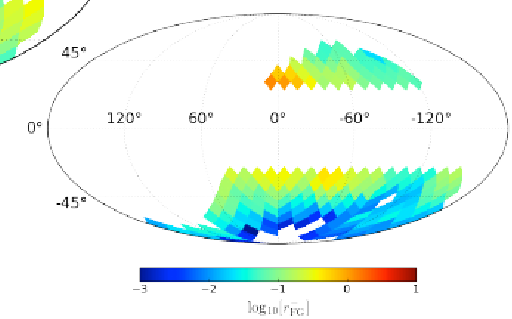


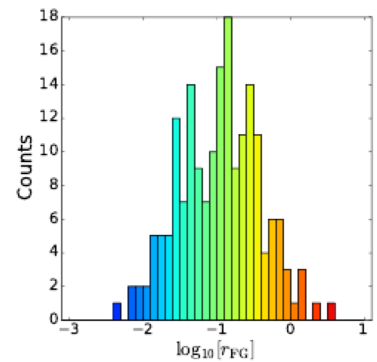


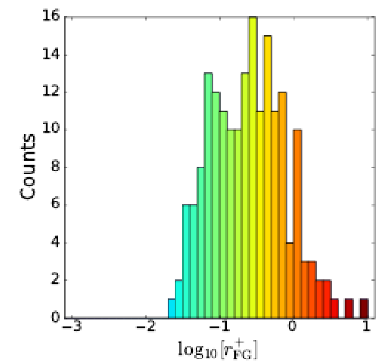
Planck & WMAP only, 2016

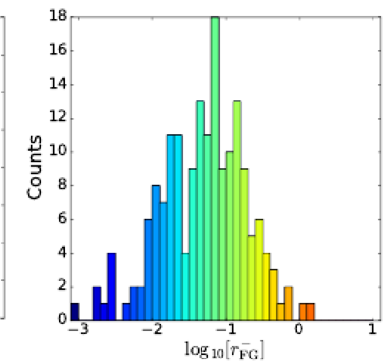








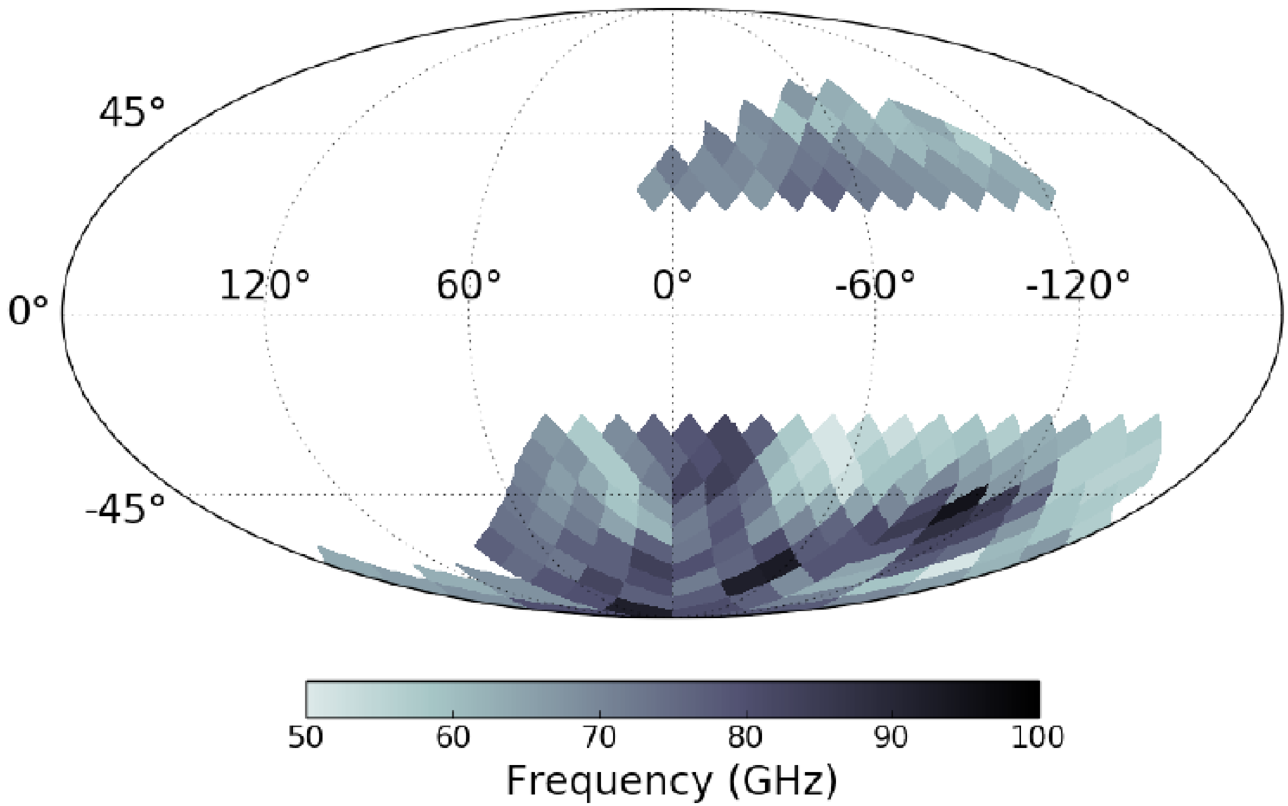


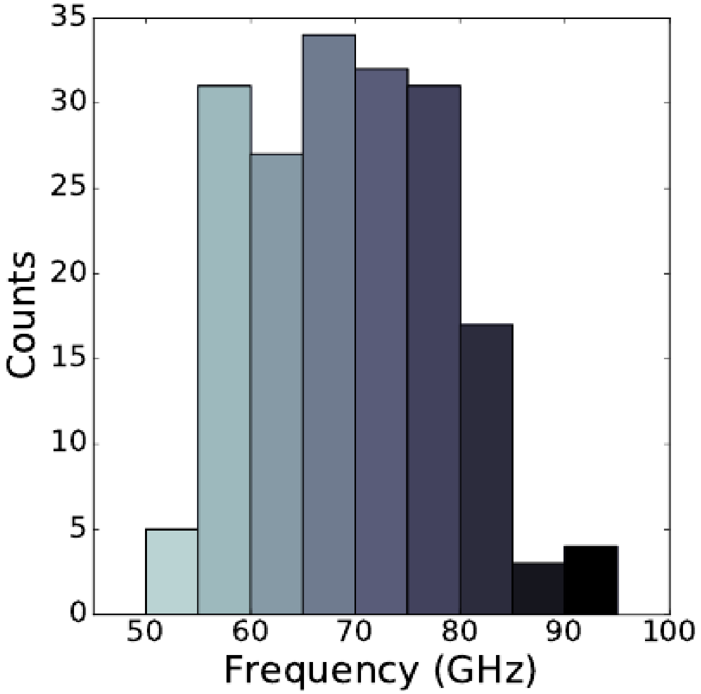


With S-PASS, 2018

Krachmalnicoff et al. 2016, 2018

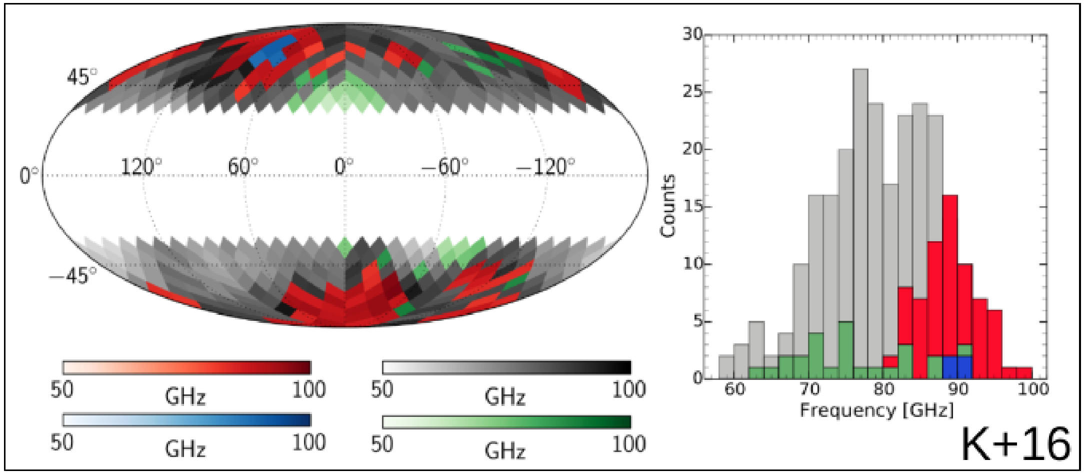
S-PASS x WMAP x Planck: emerging spatial and frequency distribution of degree scale B-mode power of Synchrotron

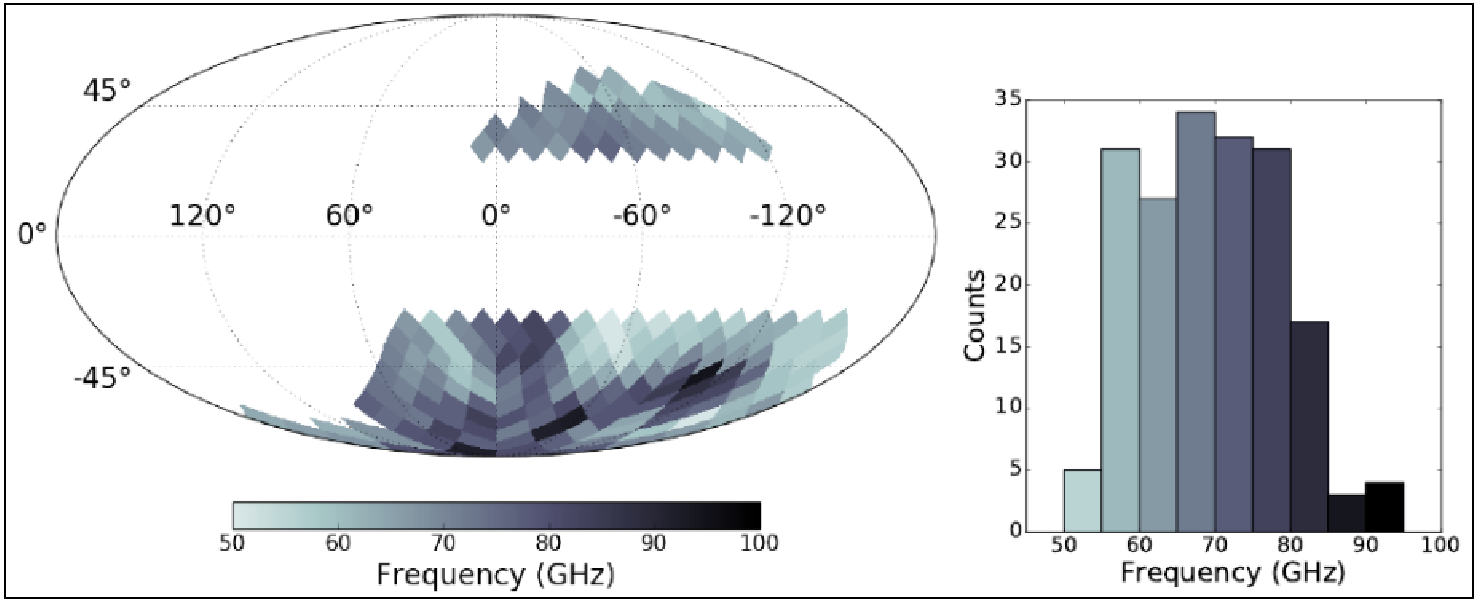




Krachmalnicoff et al. 2018

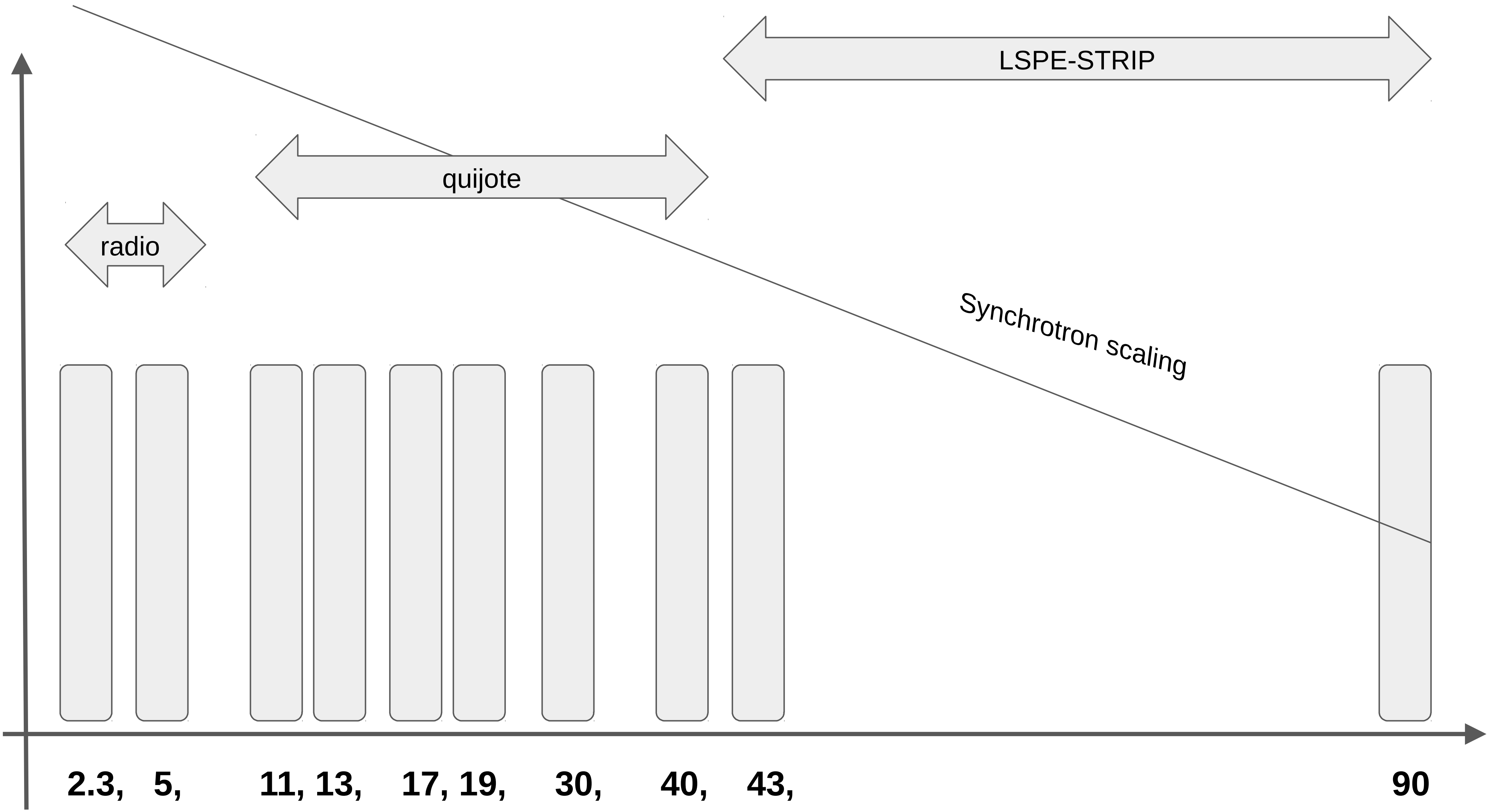
S-PASS x WMAP x Planck: emerging spatial and frequency distribution of degree scale B-mode power of Synchrotron





Krachmalnicoff et al. 2016, 2018

Ongoing EU Synergies at low frequencies: Next Talks



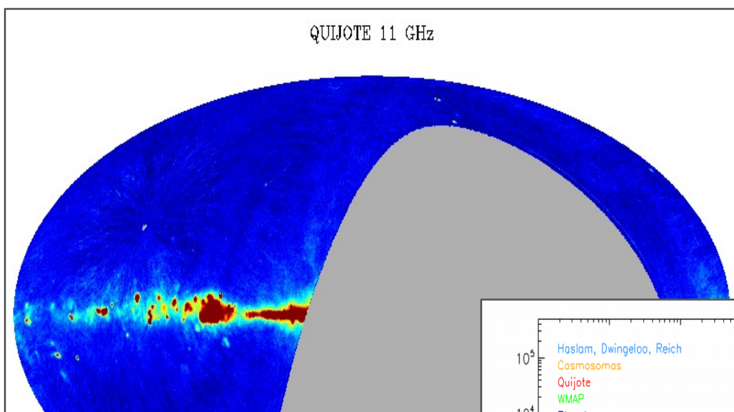
Conclusions

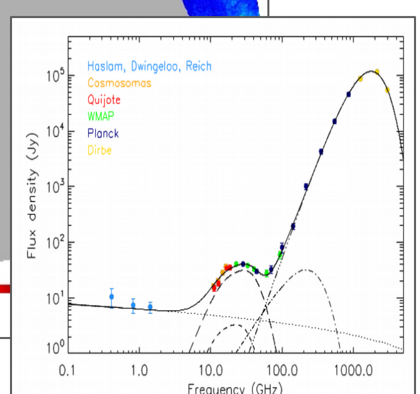
- The B-modes from Synchrotron are poorly known on degree and sub-degree scales:
- Concerning the SED distribution in polarization, S-PASS x WMAP x Planck allows to have a first look at that:
  - Indicatations exists of granularity of the spectral index on degree scales
  - the angular power spectrum appears to be about 10 times larger than in simulations
- De-correlation is unknown
- Correlation with dust polarization is known to be macroscopic on large angular scales
- On the degree scale, the observed B-modes from Synchrotron is comparable to dust at:
  - $0.05 < r_{FG} < 0.1$
  - 60<frequency<90 GHz
- More low frequency observations (C-BASS, LSPE-STRIP, QUIJOTE) being analyzed/taking data and bringing more information
- Planning needed ahead for facilities designed to solve the Synchrotron diffuse foreground problem for B-mode CMB experiments
- To the Roadmap!

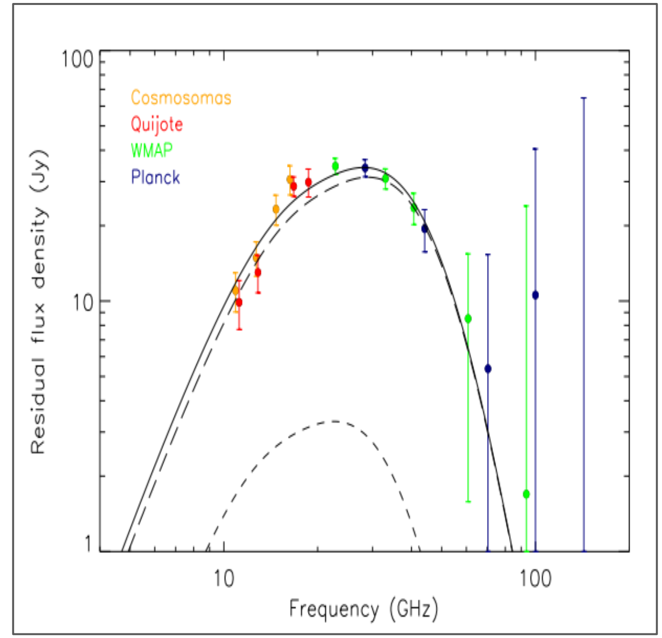
BACKUPS

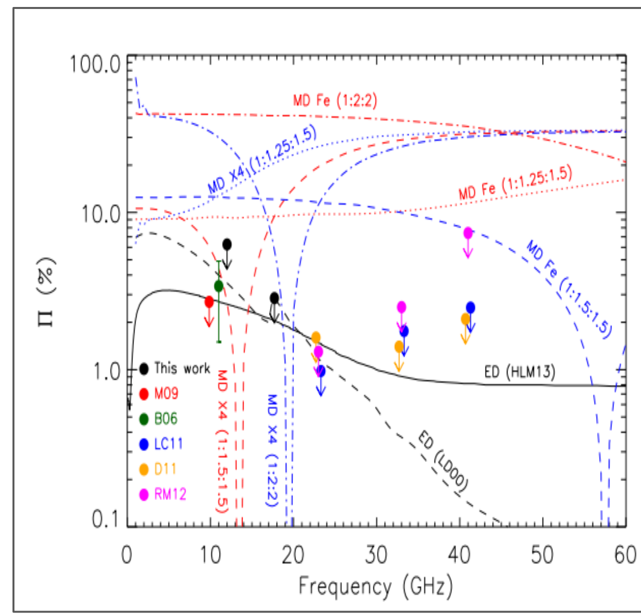
QUIJOTE @ Tenerife

	MFI				TGI	FGI
Frequency [GHz]	11.0	13.0	17.0	19.0	31.0	41.0
Bandwidth [GHz]	2.0	2.0	2.0	2.0	10.0	12.0
Number of horns	2	2	2	2	31	31
Channels per horn	4	4	4	4	4	4
Tsys [K]	25.0	25.0	25.0	25.0	35.0	45.0
Beam FWHM [deg]	0.92	0.92	0.60	0.60	0.37	0.28
NET [μK s^1/2]	280	280	280	280	50	57
Sensitivity per beam [Jy s^1/2]	0.30	0.42	0.31	0.38	0.06	0.08





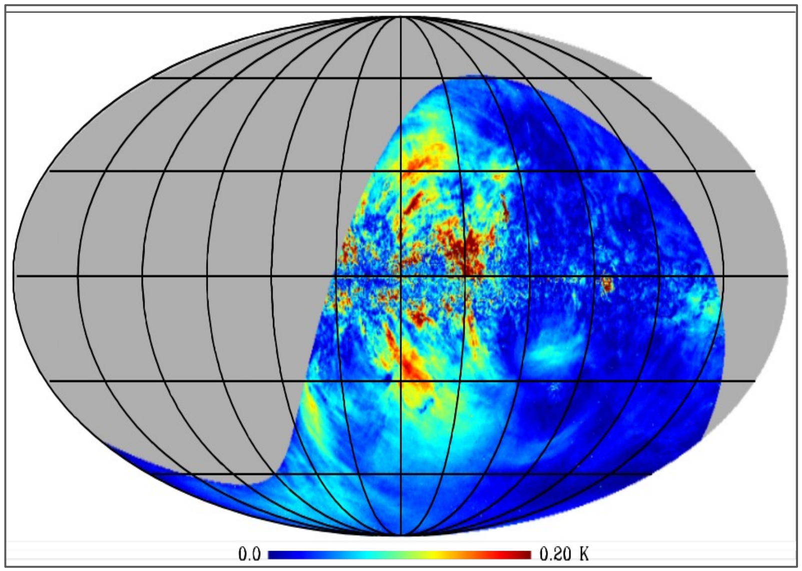




Genova-Santos et al. 2015
iac.es/proyecto/cmb/pages/en/quijote-cmb-experiment
Radioforegrounds.eu
See Flavien’s talk

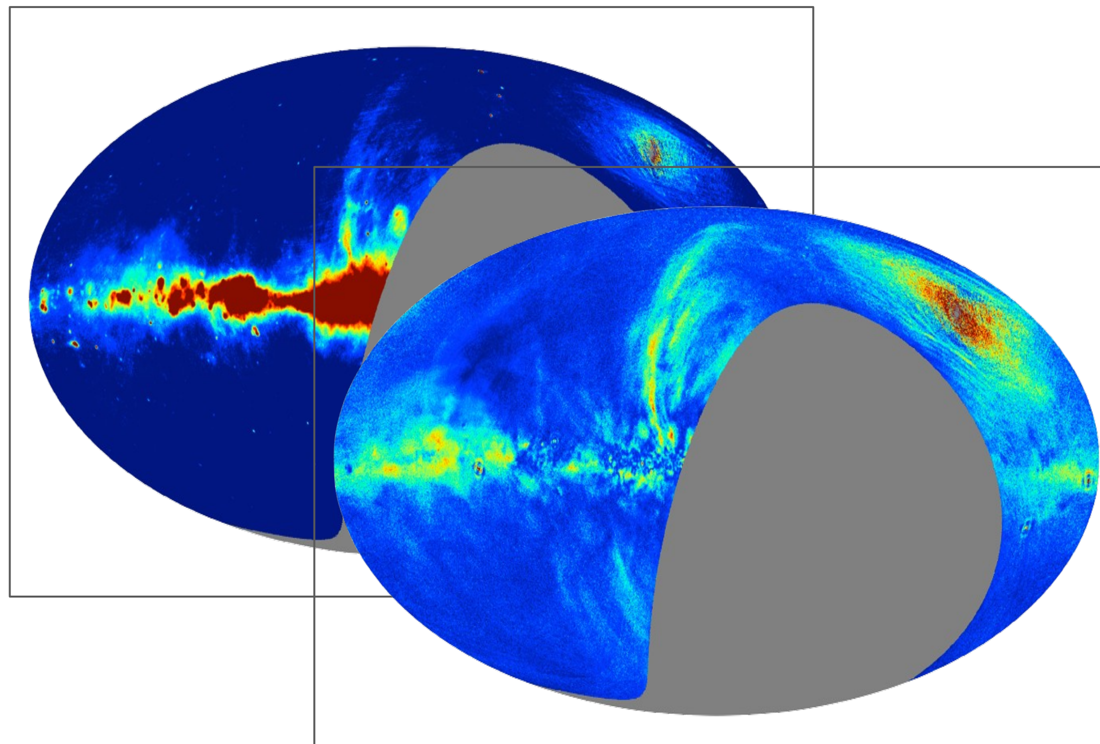
Radio Surveys: S-PASS, C-BASS

Sky-coverage:	All-sky
Angular resolution:	0.73 deg (43.8 arcmin)
Sensitivity:	<0.1 mK/beam r.m.s.
Stokes coverage:	I, Q and U
Tsys:	<20 K, including sky
Frequency/bandwidth:	1 GHz bandwidth, centered on 5.0GHz
Northern site:	OVRO, California, latitude 37.2 deg., 6.1m dish
Southern site:	meerKAT Karoo site, South Africa, latitude -30.7deg., 7.6m dish



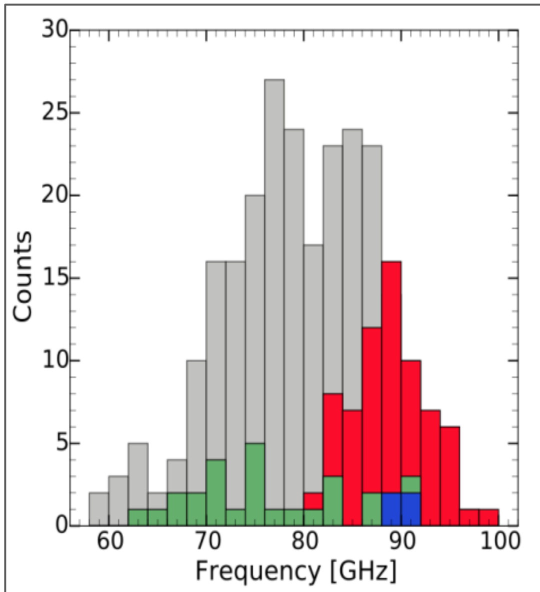
- Dec < 0° (unshaded area);
- Parkes: 2.3 GHz ;
- 224 MHz BW (100+ ch);
- FWHM = 9';
- s_{beam} < 1.0 mK;

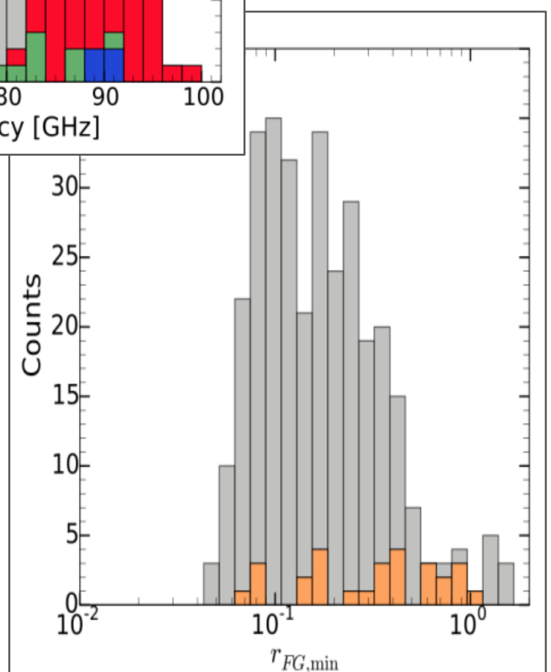
- Analysis for
  - publication of maps,
  - CMB contamination
- are ongoing,
  - Carretti et al., in preparation
  - Krachmalnicoff et al., in preparation (next talk)

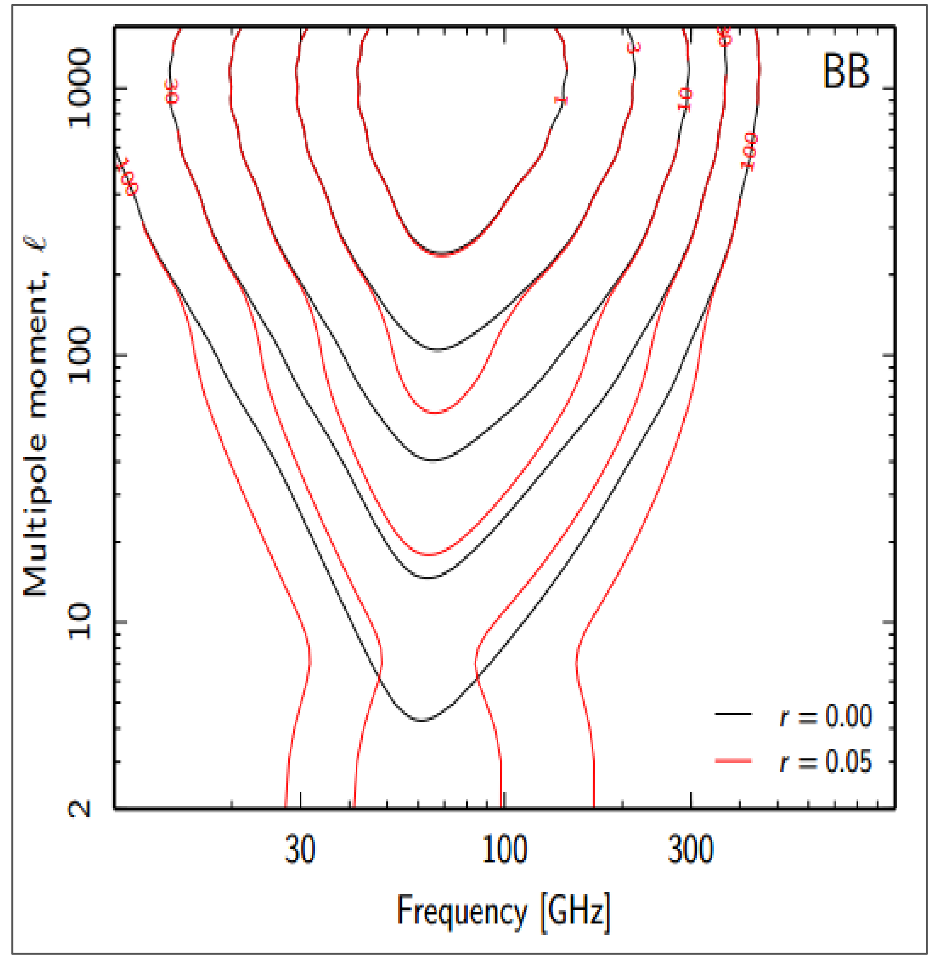


Data analysis in progress, see Jones talk
astro.caltech.edu/cbass

Contamination to CMB B-modes





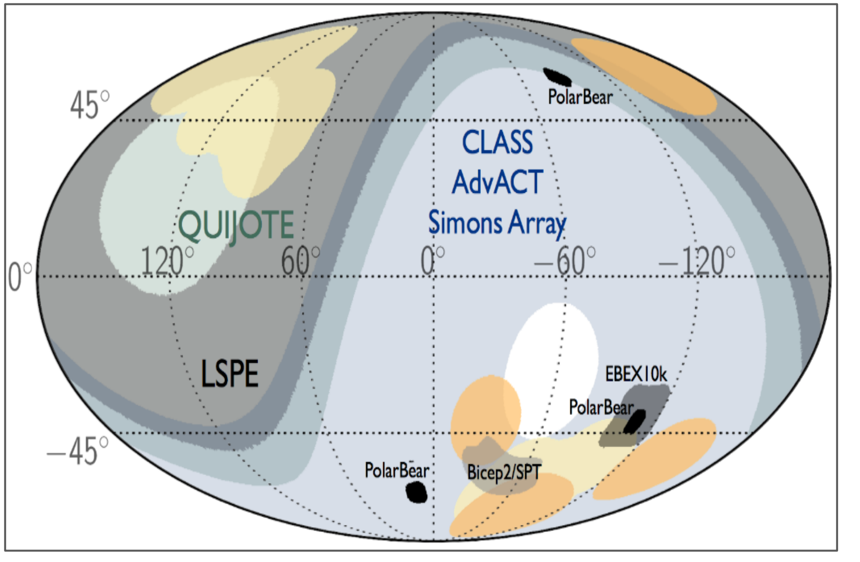


$$f(\ell, \nu) = [C_\ell^{\mathrm{fg}}(\nu)/C_\ell^{\mathrm{CMB}}]^{1/2}$$

K16, Planck 2015, X

Observations till 2020

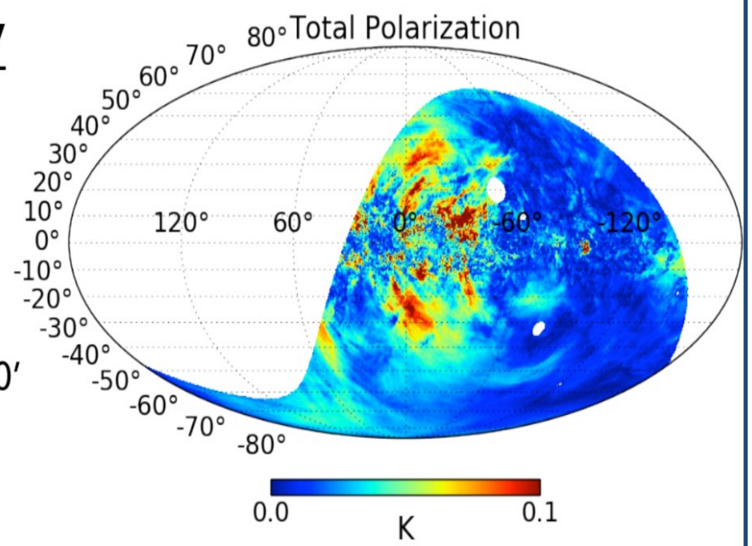
- Southern Hemisphere
  - Simlations ingesting current analyses
  - Measurements by CLASS, Simons Array, Simons Observatory
- Northern hemisphere
  - QUIJOTE polarized synchrotron maps analyzed within RadioForegrounds
  - LSPE-STRIP being deployed in Tenerife
  - Combination from Satellite and Ground measurements



Observations till 2020: southern hemisphere

SPASS survey

Carretti et al. 2013
Carretti et al. in prep



Frequency: 2.3 GHz
Angular resolution: 10′
Sky coverage: ~50%
S/N: >3 everywhere

Diffuse Synchrotron emission as CMB contaminant:
(Krachmalnicoff et al. in prep)

- Angular power spectra at different Galactic latitudes up to ell~500
- Contamination to CMB B-modes in small sky regions at high Galactic latitude
- Correlation with other data (WMAP-Planck): SED, spectral index variation, correlation with dust emission

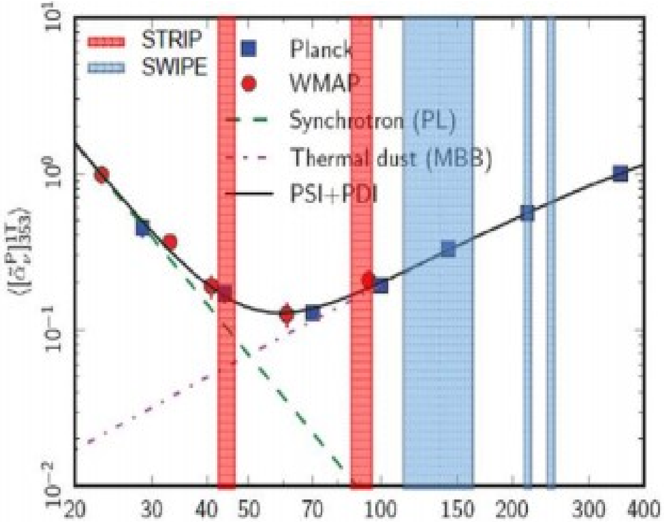
See Krachmalnocoff talk next

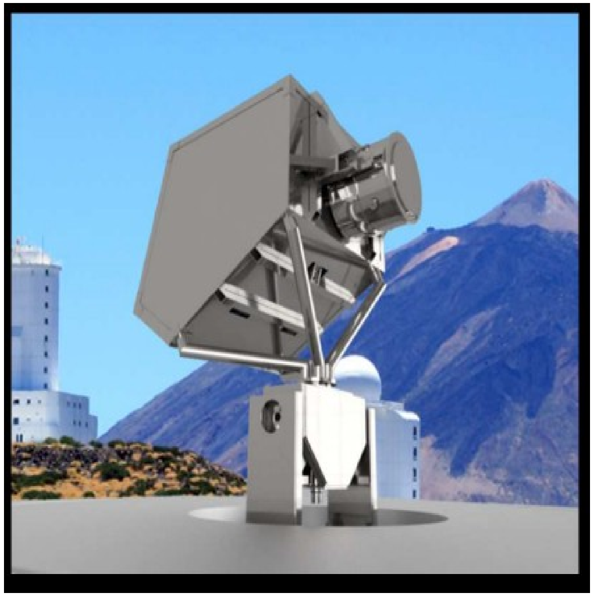
LSPE-STRIP

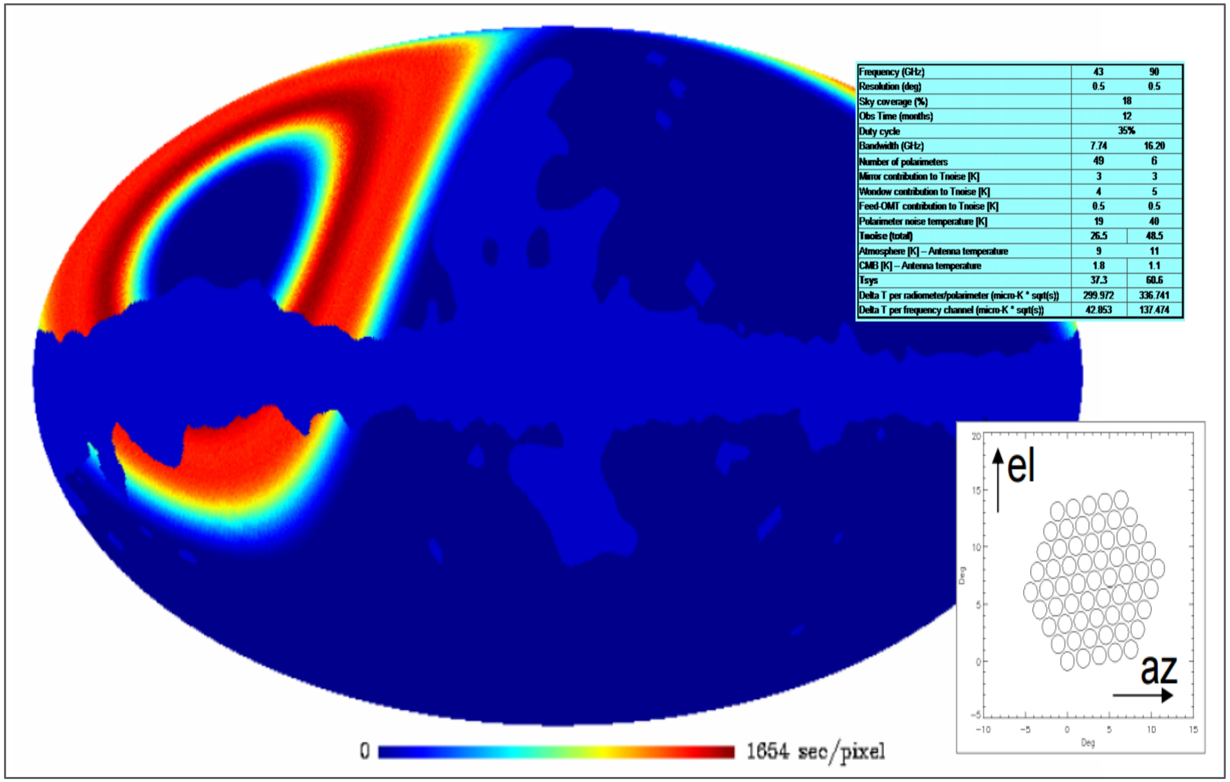
INFN Istituto Nazionale di Fisica Nucleare

agenzia spaziale italiana

COSMOS
Cosmic Orbital and Suborbital Microwave ObservationS







Frequency (GHz)	43	90
Resolution (deg)	0.5	0.5
Sky coverage (%)	18	
Obs Time (months)	12	
Duty cycle	35%	
Bandwidth (GHz)	7.74	16.20
Number of polarimeters	49	6
Mirror contribution to Tnoise [K]	3	3
Window contribution to Tnoise [K]	4	5
Feed-OMT contribution to Tnoise [K]	0.5	0.5
Polarimeter noise temperature [K]	19	40
Tnoise (total)	26.5	48.5
Atmosphere [K] – Antenna temperature	9	11
CMB [K] – Antenna temperature	1.8	1.1
Tsys	37.3	60.6
Delta T per radiometer/polarimeter (micro-K * sqrt(s))	299.972	336.741
Delta T per frequency channel (micro-K * sqrt(s))	42.853	137.474

Now deploying in Tenerife
cosmo.fisica.unimi.it/research/lspe

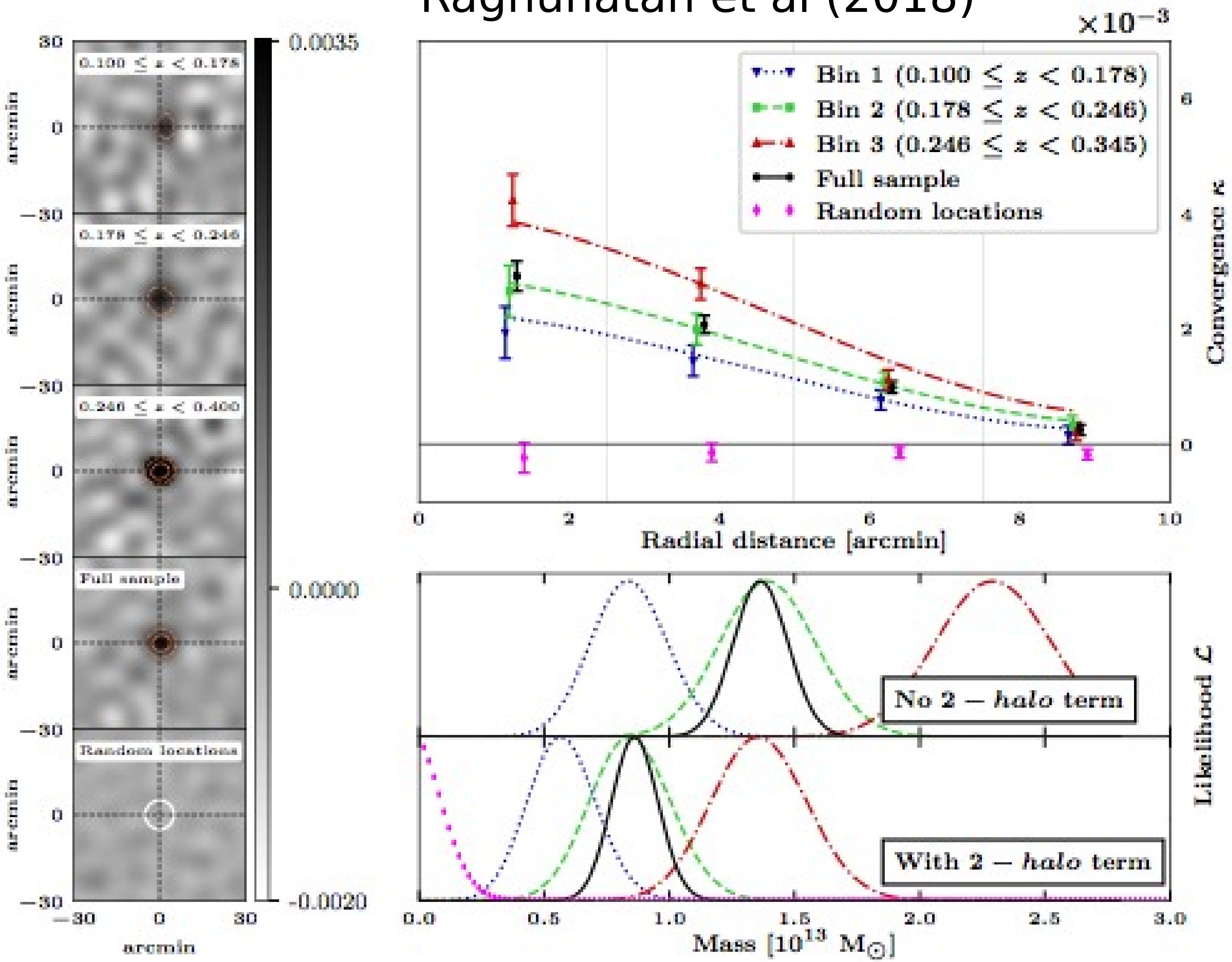
Conclusions

- The B-modes from Synchrotron are poorly known on degree and sub-degree scales
- SED in polarization is unknown
- De-correlation is unknown
- Polarization fraction of non-synchrotron components is unknown
- Correlation with dust polarization is known to be macroscopic on large angular scales
- On the degree scale, the observed B-modes from Synchrotron is comparable to dust at:
    - 0.05<rFG<0.1
    - 60<frequency<90
- Given this, 2 synchortron monitoring bands, with S/N>1 till 10 arcminute resolution are a minimum requirement for B-mode experiments
- Obervations in the Radio surveys in the southern hemisphere are being analyzed, several other observations (LSPE-STRIP, QUIJOTE) being analyzed/taking data soon in the southern hemisphere

CMB halo lensing at galaxy location

- Mass calibration of galaxies or high-z clusters with CMB lensing

Raghunatan et al (2018)



Upcoming galaxy surveys and CMB lensing

- CMB lensing entering in the high-precision era with ground based facilities
- New galaxy surveys will measure accurately the matter distribution:
  - LSST: ground-based, 20.000 deg^2, z~0.5
  - Euclid: 1.5 billion galaxies from space, z~2
- Cross-correlation : less instrumental systematics, better cosmology:
  - astrophysical systematics to be understood
  - realistic physical modeling and simulations for both observables