Records from Primordial Gravitational Waves and Cosmic Acceleration in CMB polarization

Carlo Baccigalupi
SISSA, Trieste

VI Challenges of New Physics in Space,
Campos de Jordao, Brazil, May 25-29, 2015

Records from Primordial Gravitational Waves and Cosmic Acceleration in CMB polarization

Part I: physical processes and cosmological relevance
Part II: status of observations

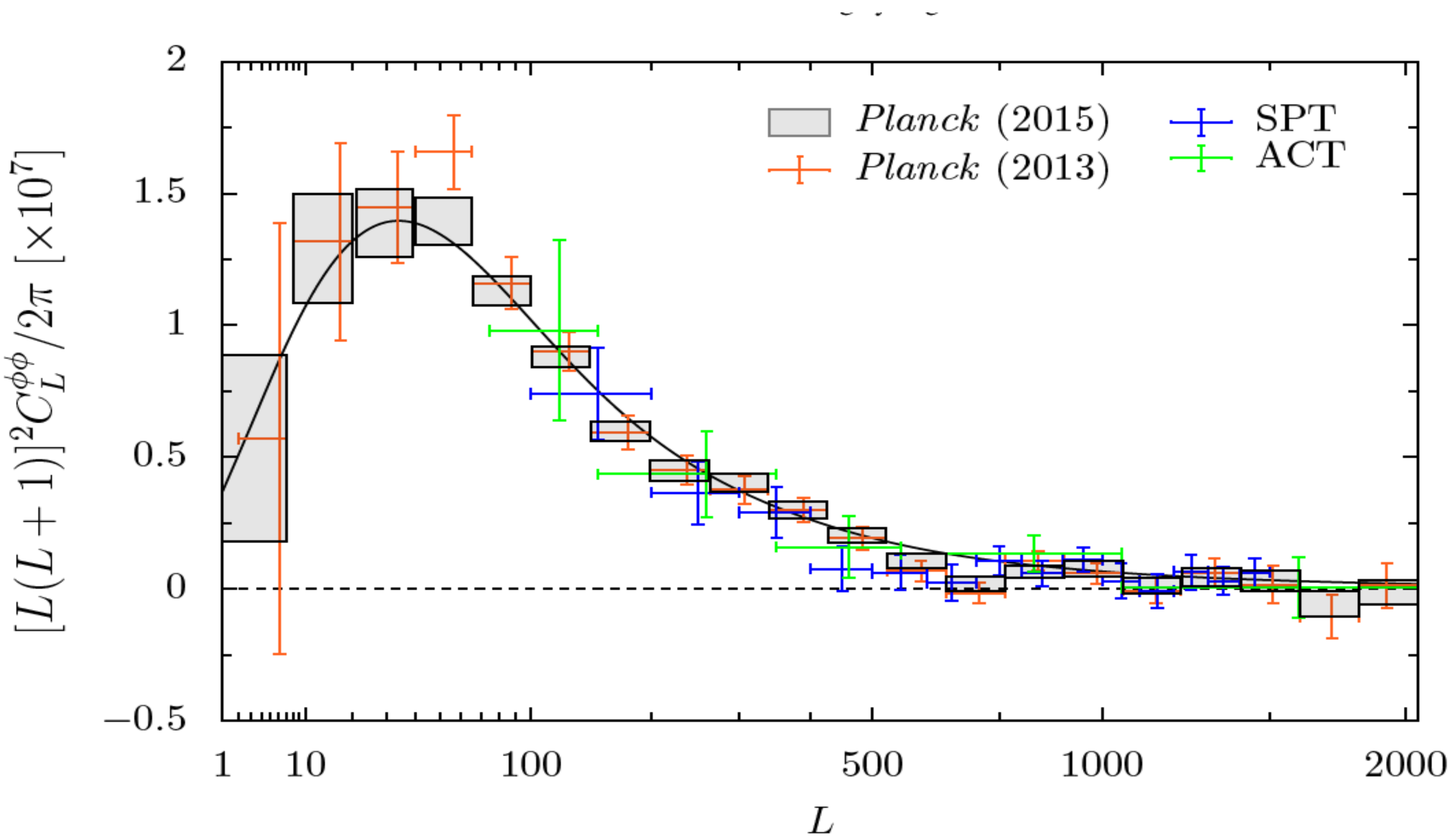
Carlo Baccigalupi
SISSA, Trieste

VI Challenges of New Physics in Space,
Campos de Jordao, Brazil, May 25-29, 2015

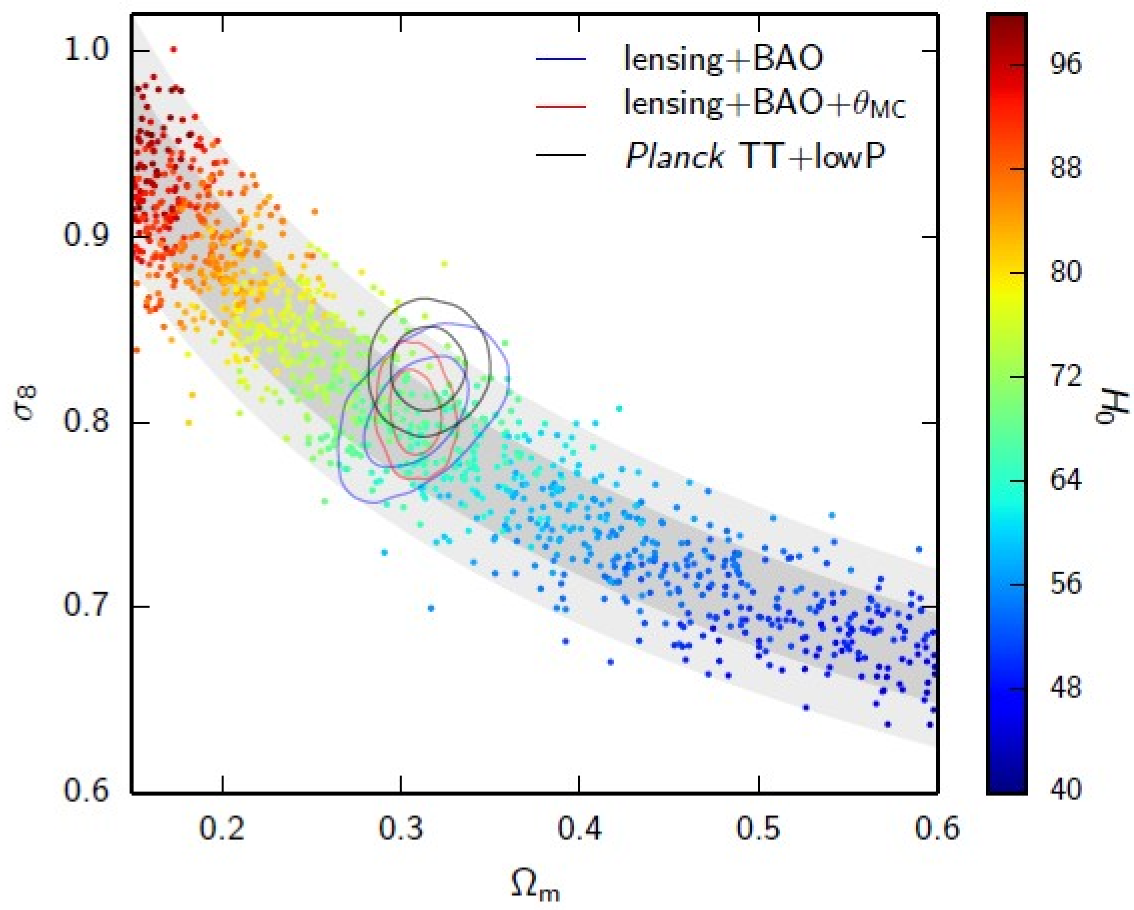
Outline

- Remaining topics from tuesday
- Galactic foreground contamination to cosmological B-modes
- Status of observations:
  - PolarBear
  - Planck
  - Planck × Bicep2 × KEcK
- Component separation: dealing with foregrounds within data reduction
- Concluding remarks

Planck lensing 2015



Planck lensing 2015



Lensing-LSS Cross-Correlations

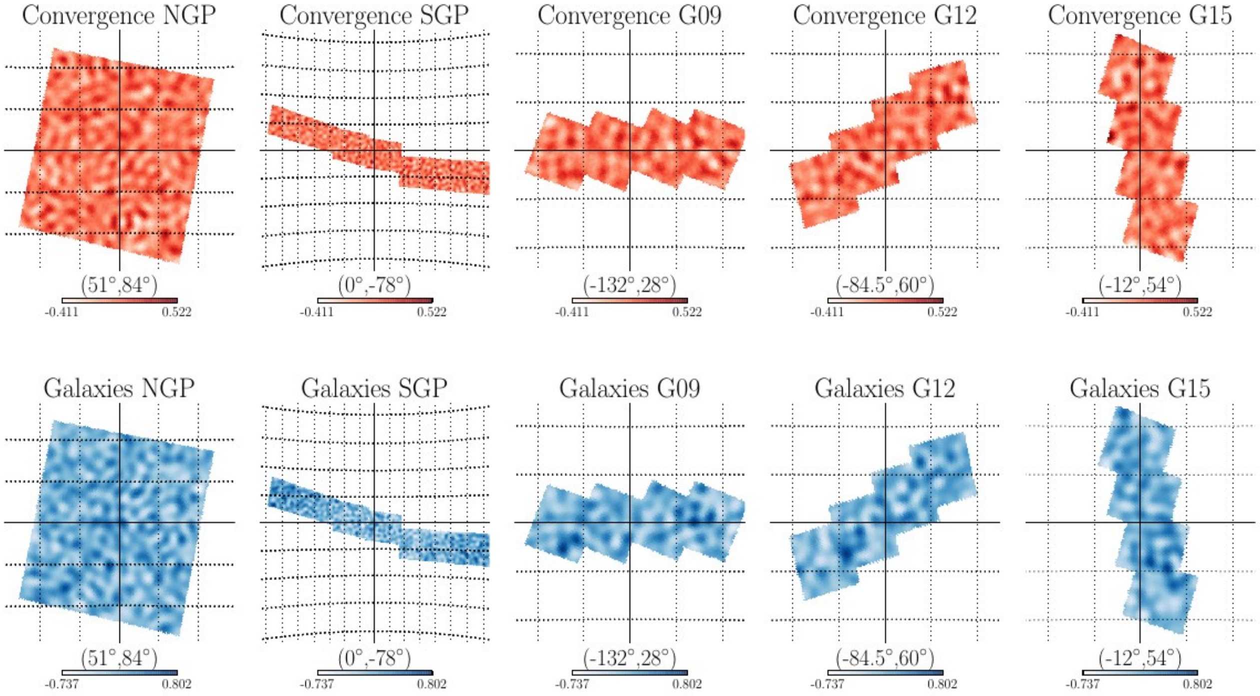


Fig. 5.— Convergence maps (upper row) and galaxy overdensity maps (lower row) in the H-ATLAS fields: noise-dominated multipoles $\ell > 400$ have been filtered out. Galactic longitude and latitude (l, b) of patches centers are provided in brackets. The grid overlay has spacing of 3° in each box.

Bianchini et al. 2014, 2015 in preparation

Lensing-LSS Cross-Correlations

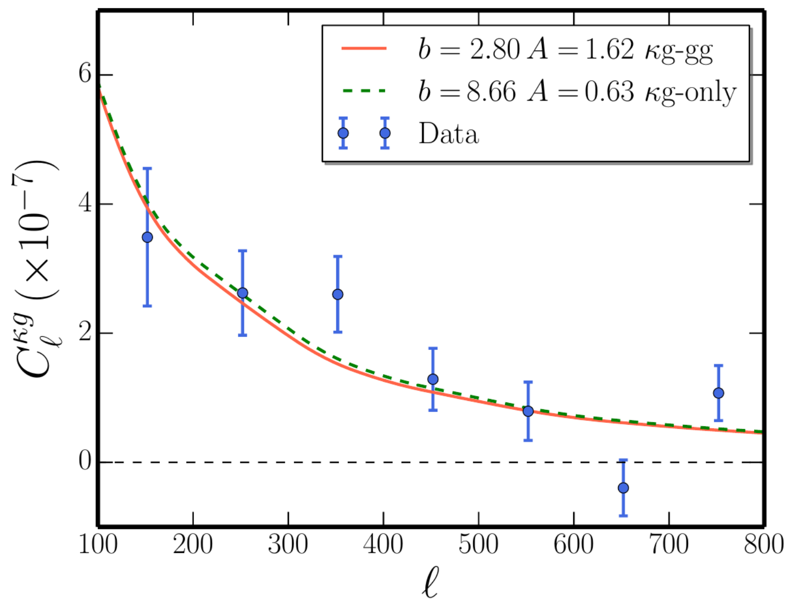
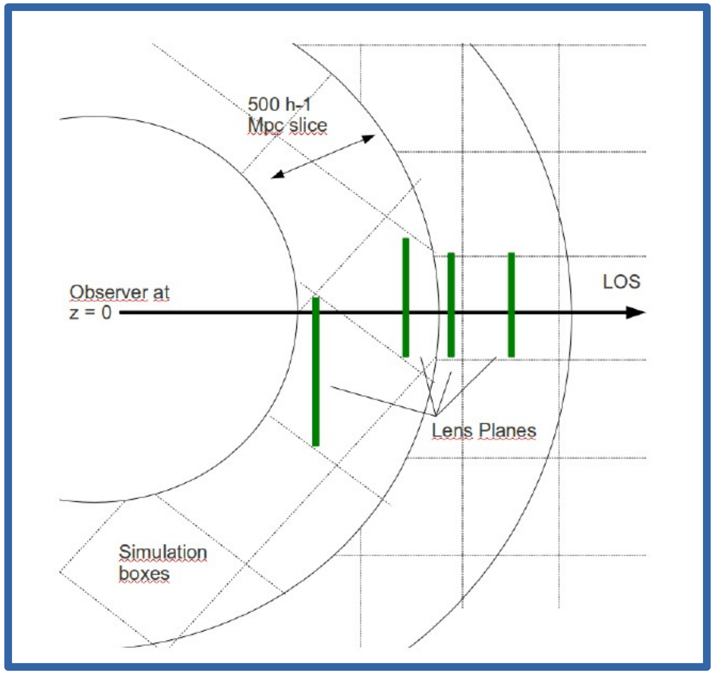
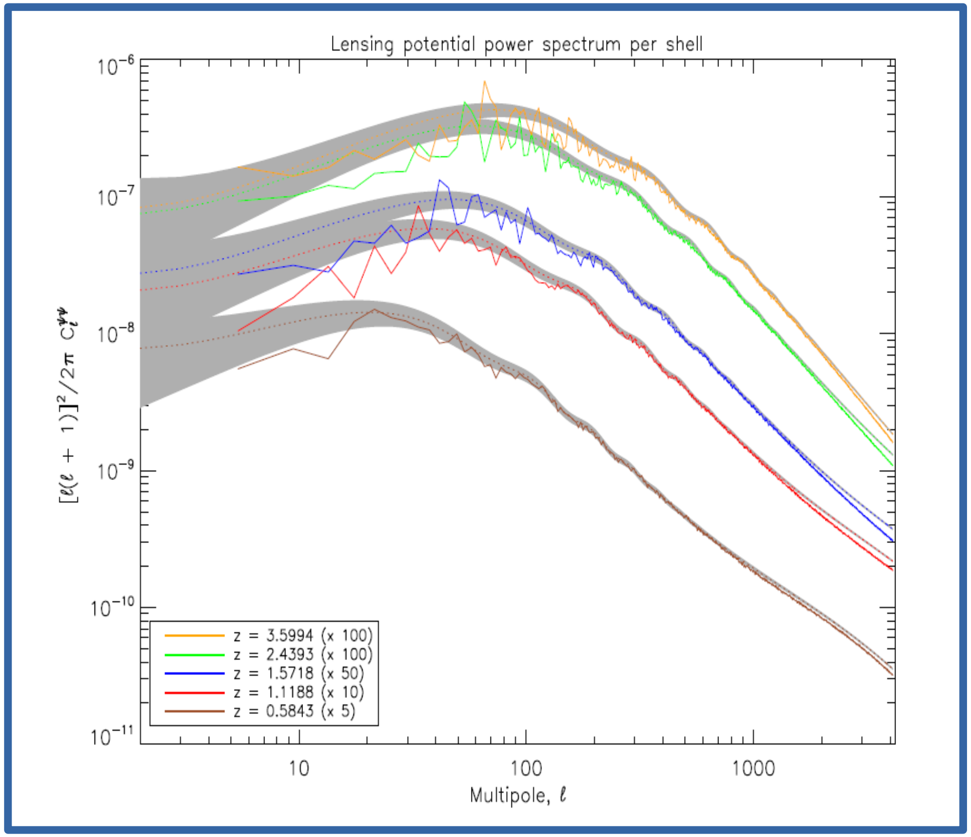


Fig. 9.— The CMB convergence - galaxy density cross-spectrum as measured from *Planck* and *Herschel* data. The data points are shown in blue, with error bars computed using the full covariance matrix obtained from Monte Carlo realizations of convergence maps. The theoretical spectra calculated with the bias values inferred from the likelihood analysis (as described in text) using the cross-correlation data only (solid red line) and the cross-correlation together with the galaxy auto-correlation data (dot-dashed green line) are also shown; we fix $\alpha = 3$ in this analysis. The null (no correlation) hypothesis is rejected at the $20\,\sigma$ level.

Bianchini et al. 2014, 2015 in preparation

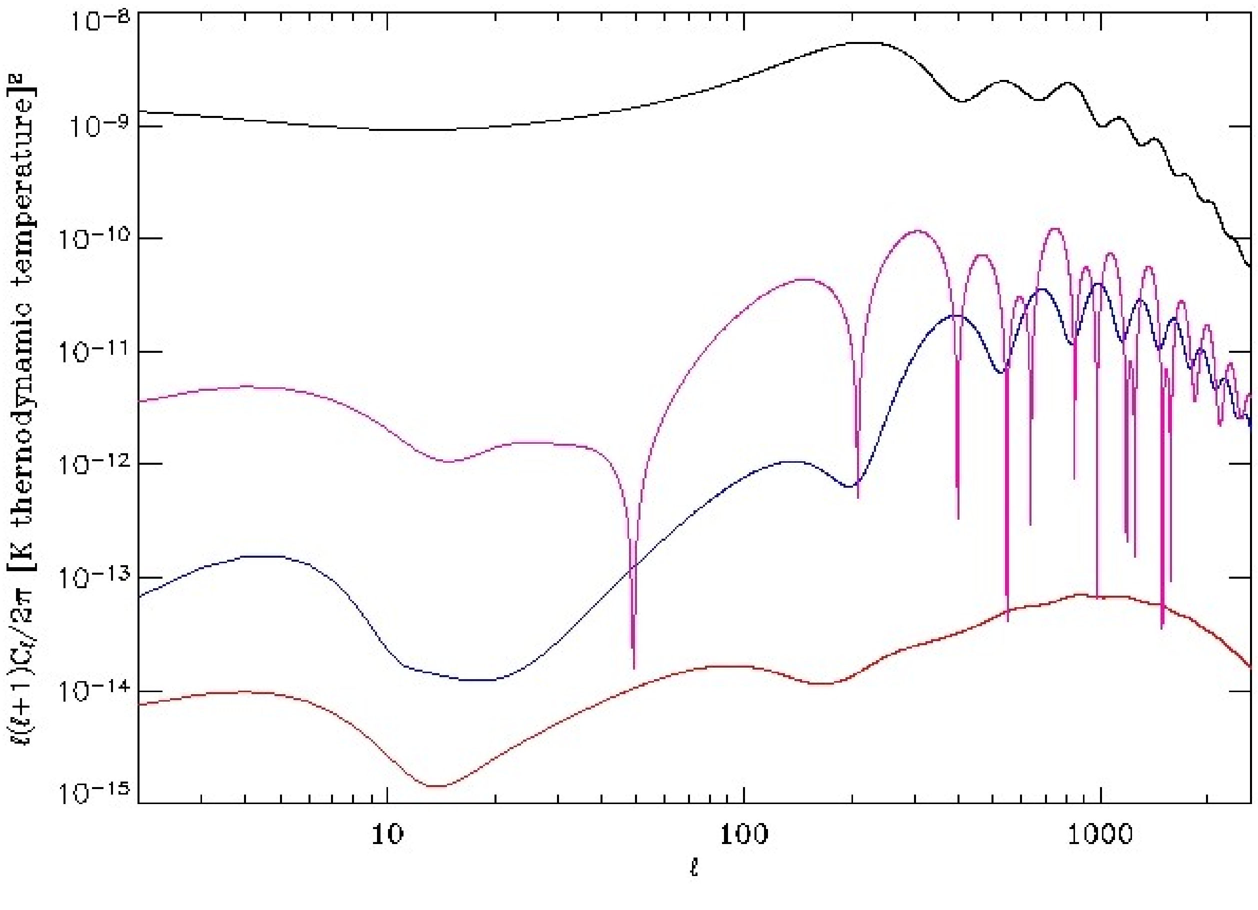
CMB-N-body Lensing





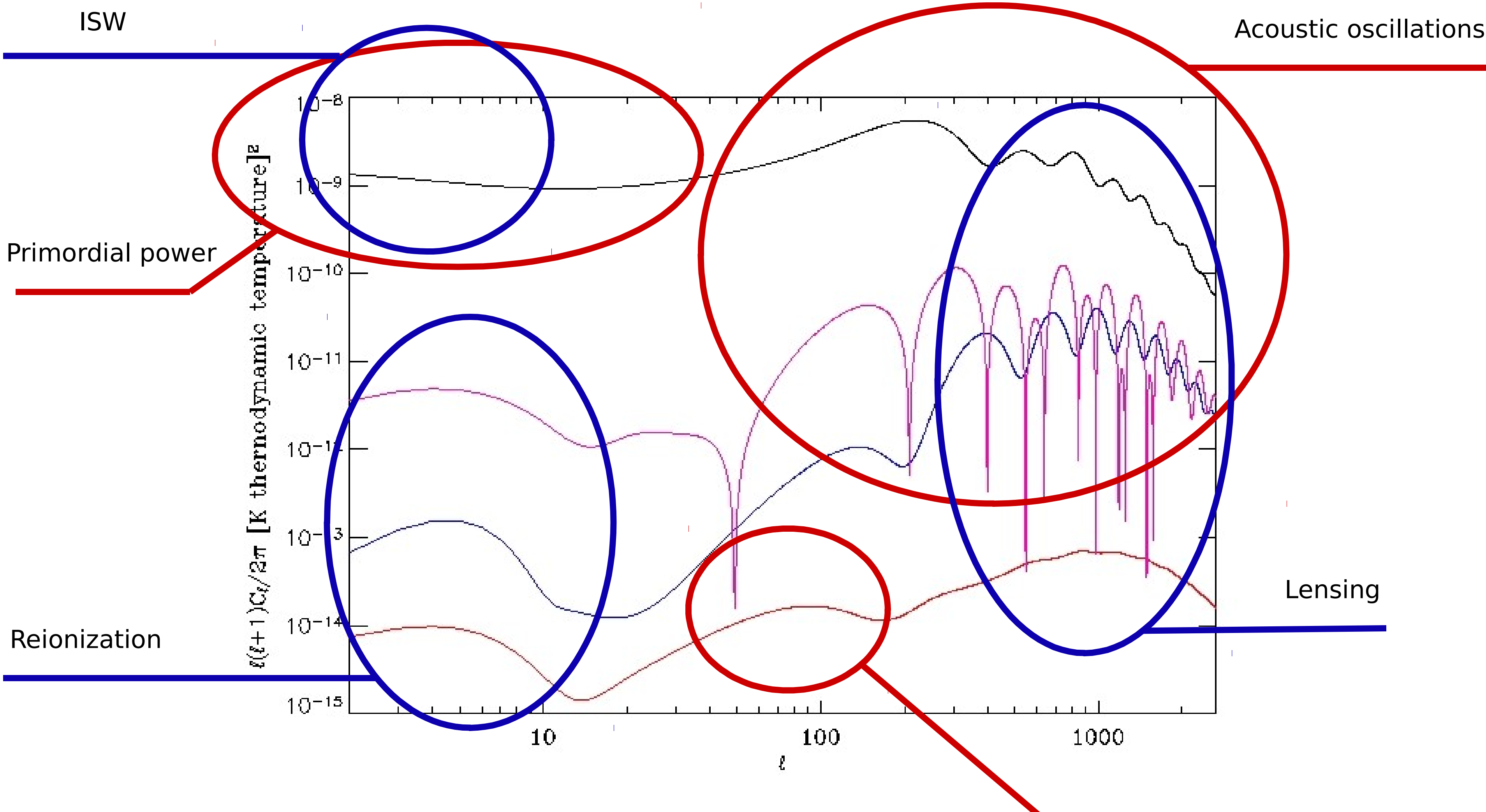
Calabrese et al. 2014, 2015 in preparation

CMB angular power spectrum



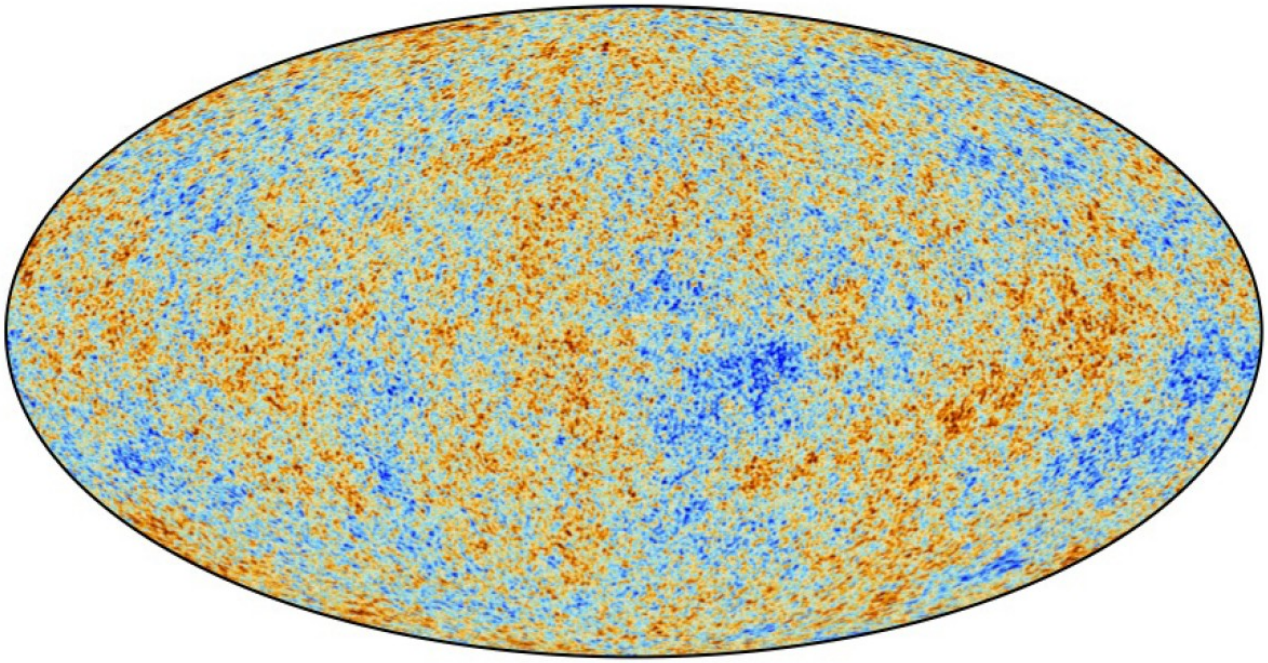
Angle ≈ 200/l degrees

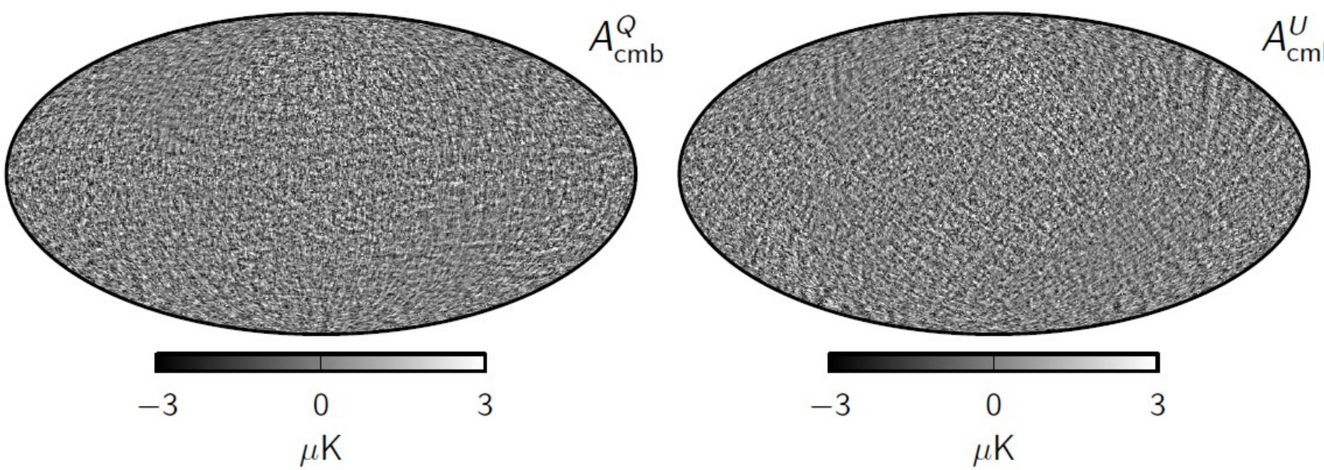
CMB angular power spectrum



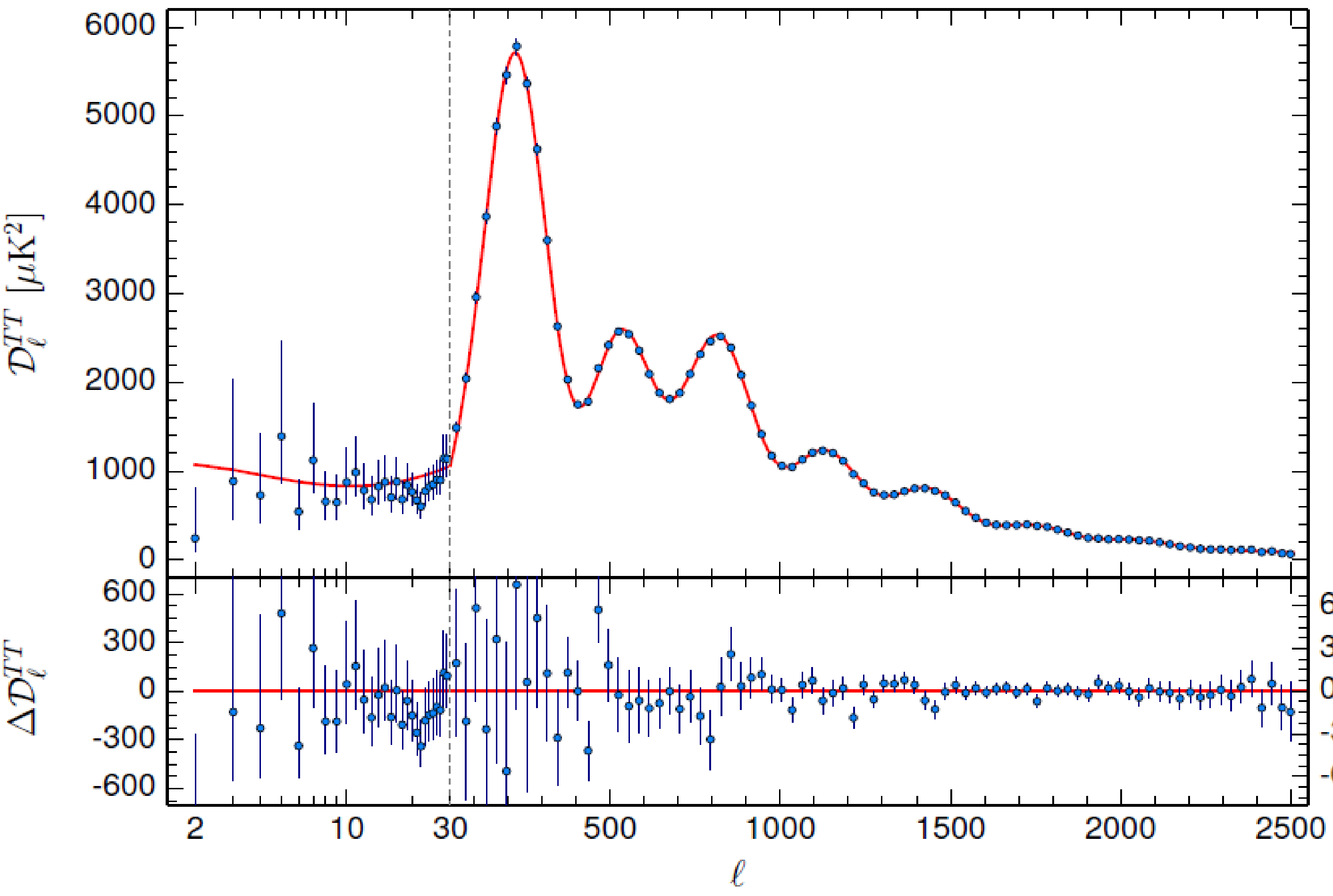
Angle ≈ 200/l degrees

Planck 2015 CMB

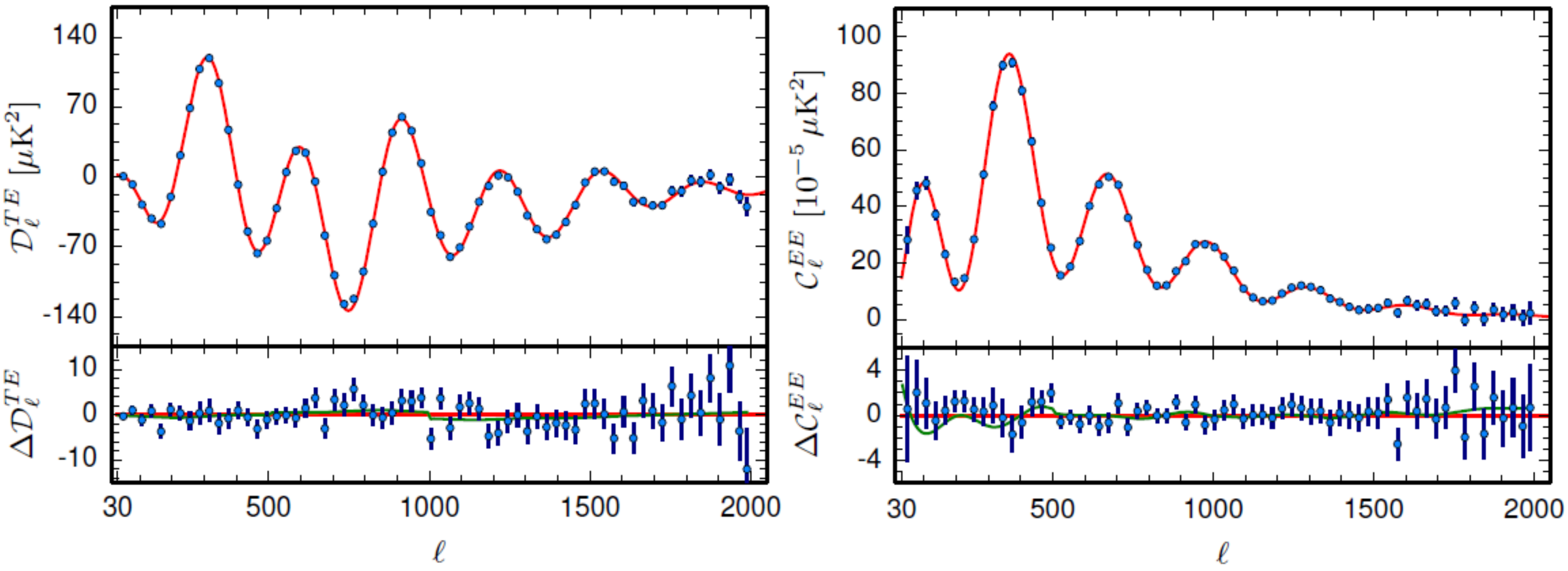




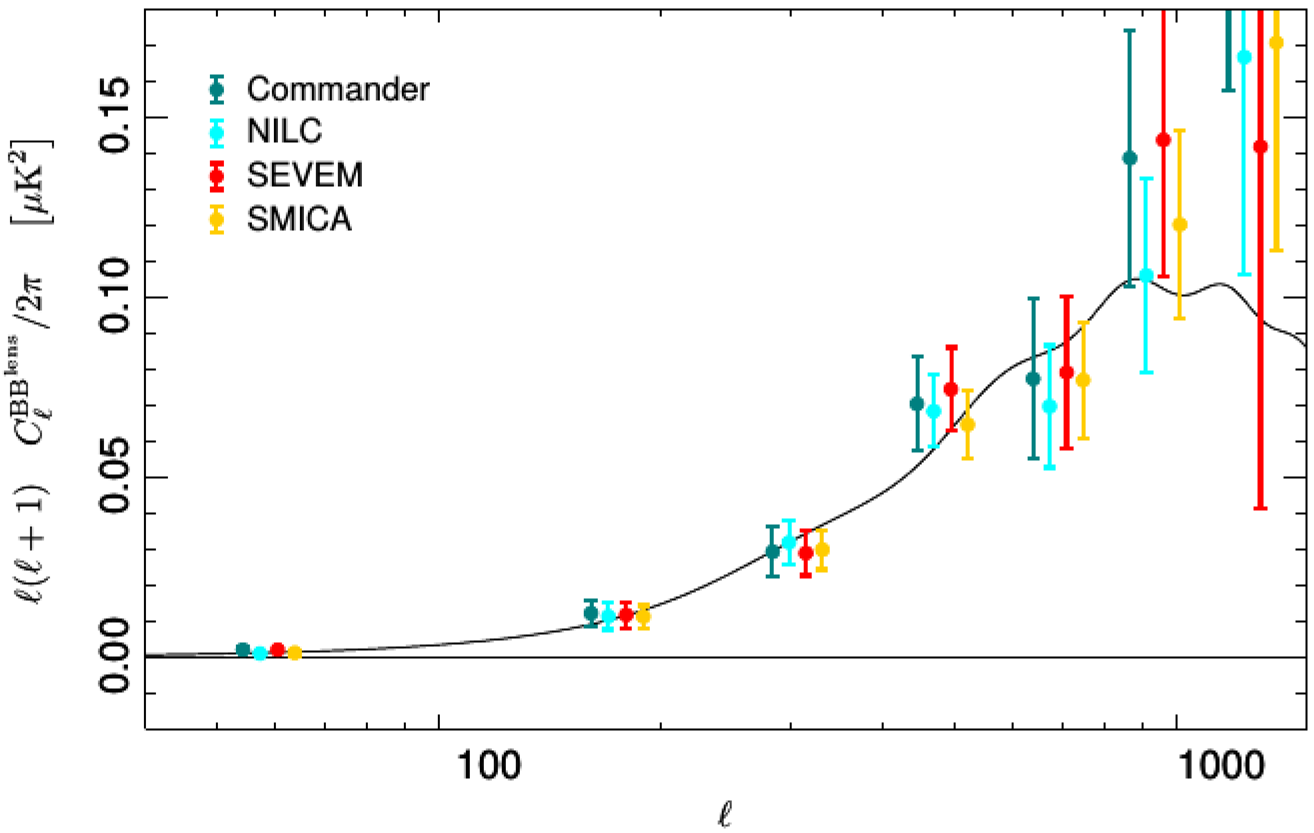
Planck 2015 TT power spectrum



Planck 2015
TE and EE power spectra



Planck 2015 BB power spectra



Concluding remarks, I

- Effects from the Early Universe and Large Scale Structure affect large parts of CMB anisotropies, and directly compete for detection, for example in the B-modes
- Measurements of the abundance of primordial Gravitational Waves, and constraints on the Dark Energy dynamics must proceed jointly in the analysis of data from operating and future high resolution and sensitivity probes, LSS surveys
- Cross-correlation studies gathering relevance, large scale simulations CMB LSS experiments being implemented
- ...

Galactic foreground Contamination to cosmological B-modes

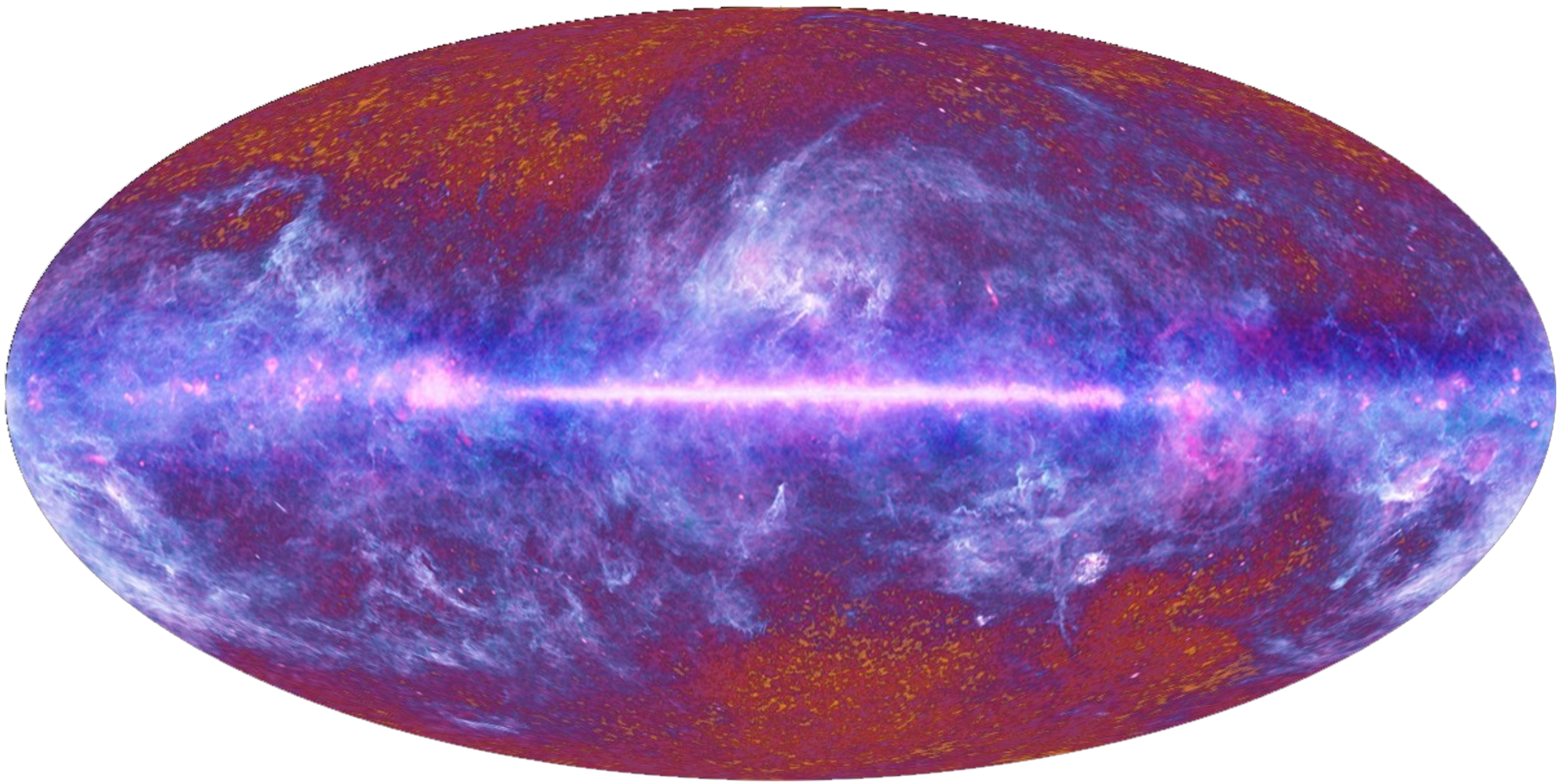
The (ongoing) Planck 2015 paper and data release

- Still ongoing, likely to extend for several more weeks: see www.cosmos.esa.int/web/planck/publications
- Mission and data processing: out
- Main Cosmology (Parameters, early Universe, Dark Energy and Modified Gravity, Geometry and topology, ISW, lensing, clusters, ...): out
- Isotropy and statistics: days
- General foregrounds from component separation: out
- Cluster catalogue: out
- CMB from component separation: out
- Focused study on low frequency foregrounds: weeks
- Likelihood and power spectra: days
- Simulations: days
- Point sources: days
- ...

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

F=A (sky direction) × F(frequency)



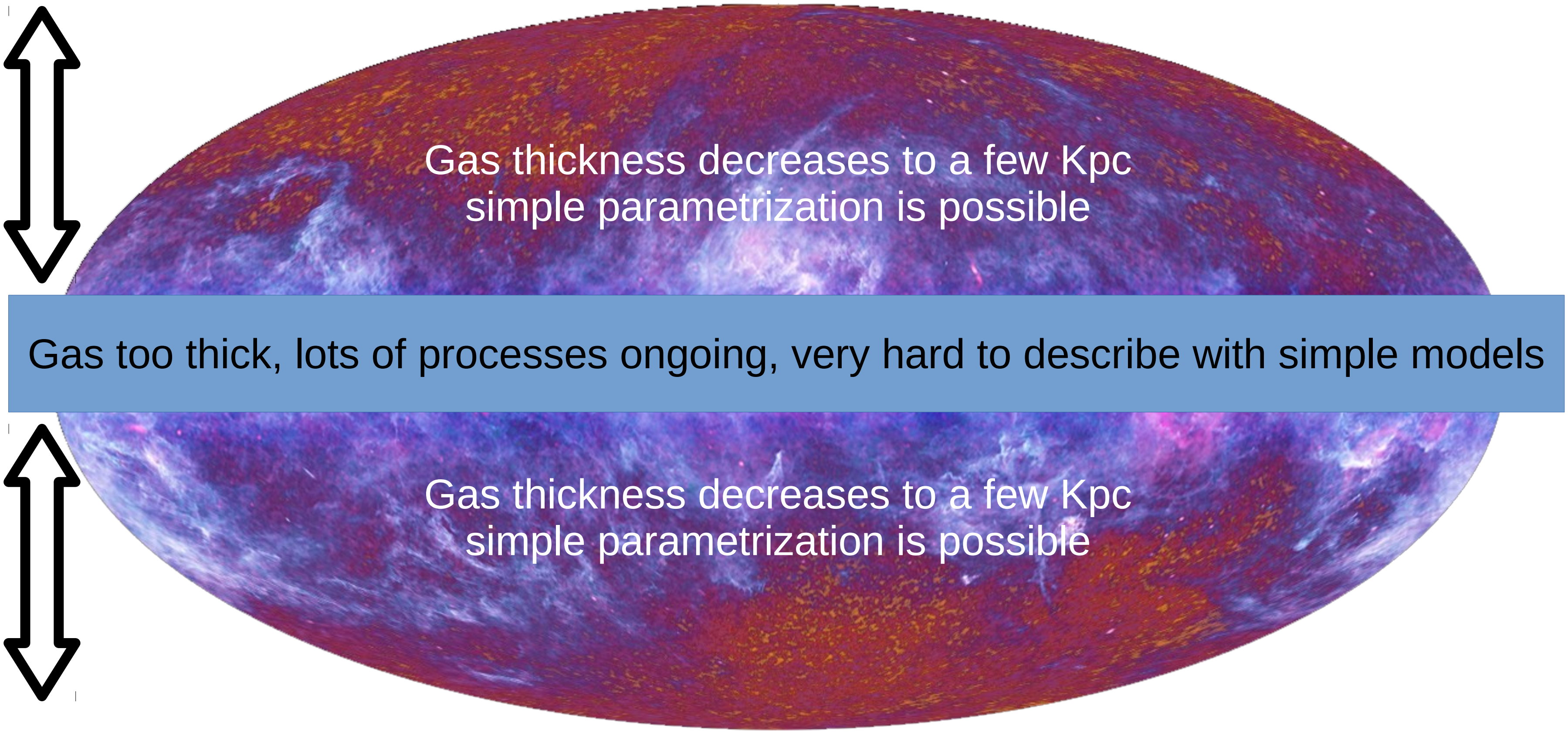
Planck 2013

F=A (sky direction) × F(frequency)

Gas too thick, lots of processes ongoing, very hard to describe with simple models

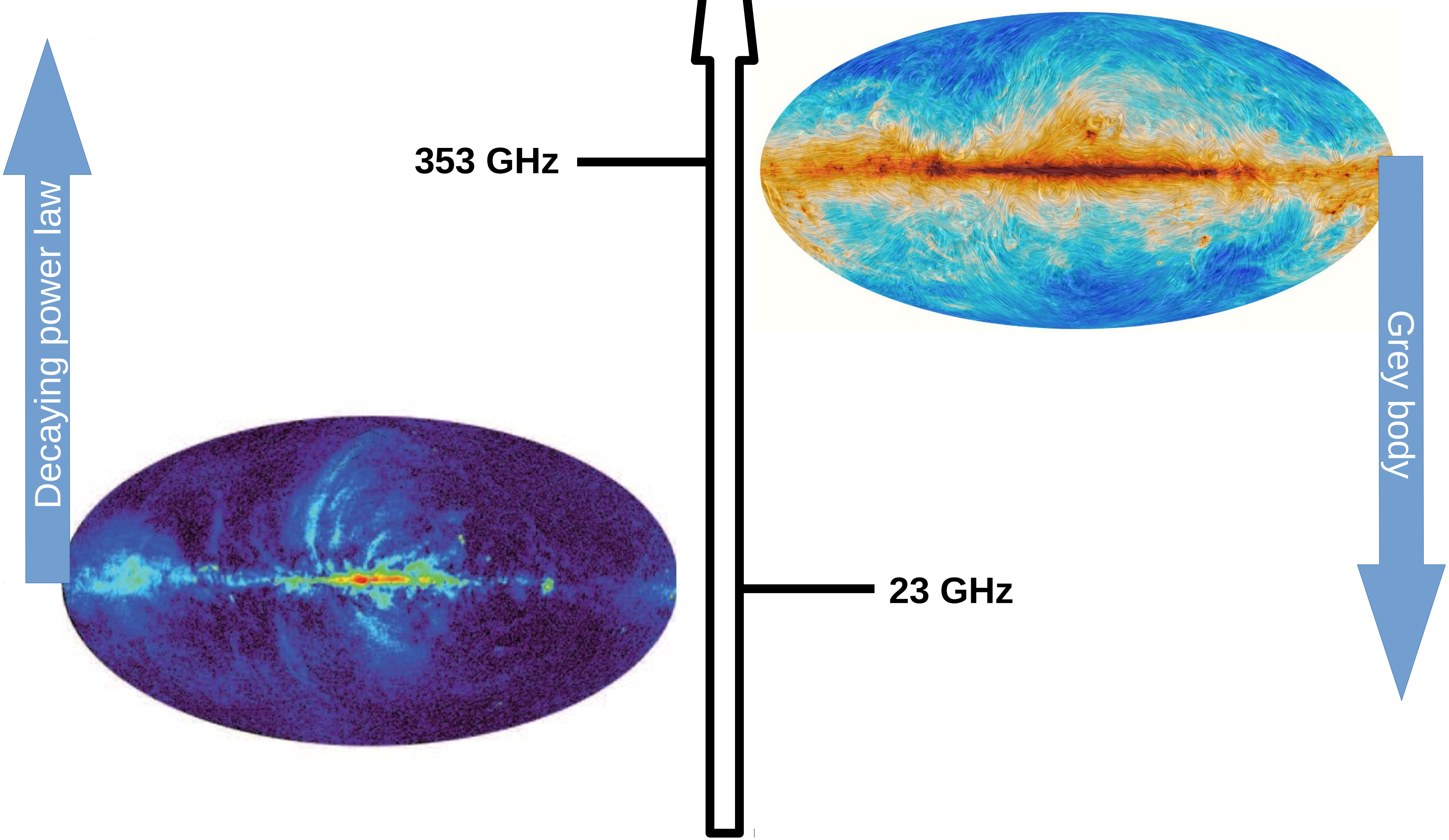
Planck 2013

F=A (sky direction) × F(frequency)

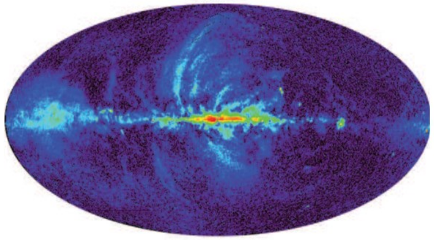


Planck 2013

Galactic polarized foregrounds

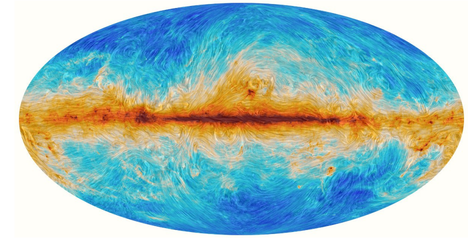


Polarized synchrotron



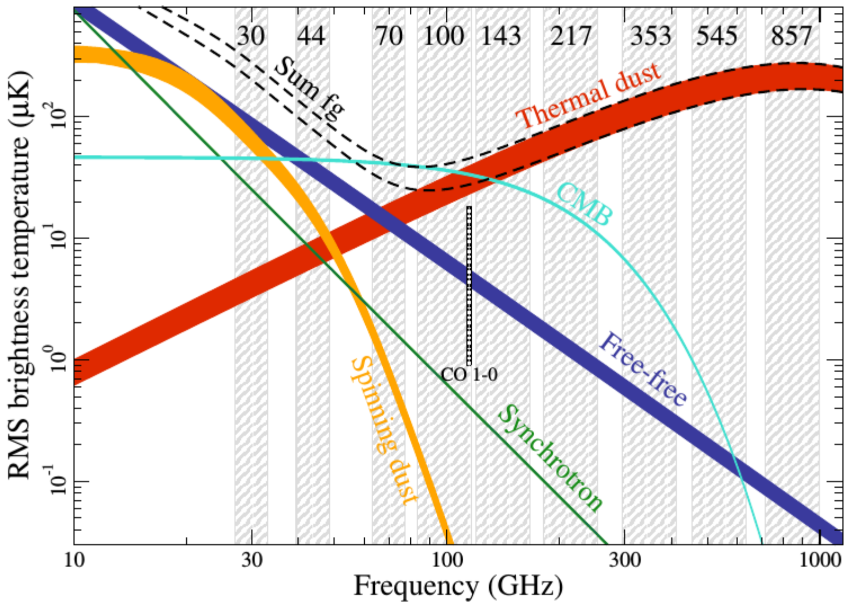
- Amplitude: cosmic ray electrons spilarizing around the Galactic magnetic field
- Frequency scaling: approximate decaying power law frequency scaling (F_{RJ}~f^{-3}), determined by the electron distribution in energy
- Data: total intensity and polarization, several surveys at radio frequencies, WMAP and Planck at microwave frequencies
- Data at the required quality for B-mode cleaning: none

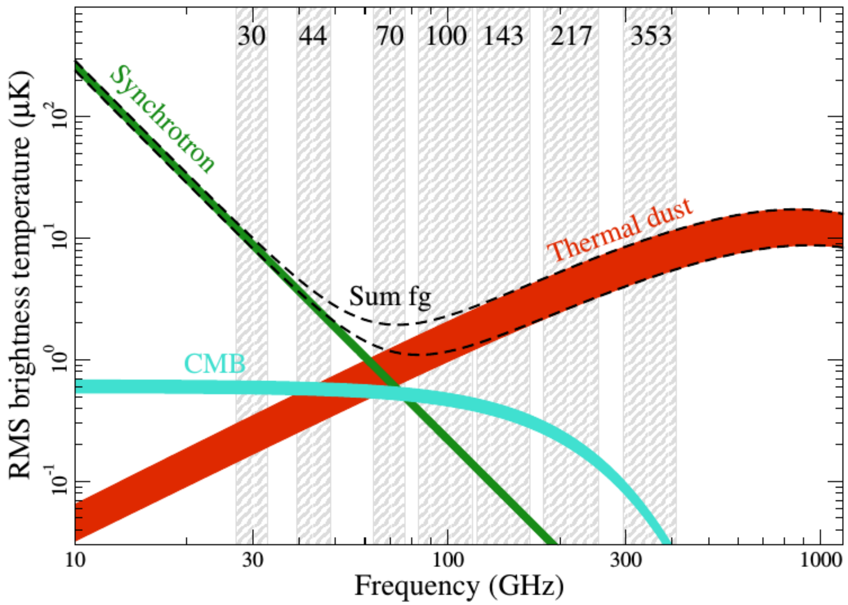
Polarized dust



- Amplitude: magnetized dust grains emitting almost thermally, linearly polarized via local alignment with the Galactic magnetic field
- Frequency scaling: grey body F_{RJ}~BB(f)×f $^{1.5}$
- Total intensity data: high resolution (few arcminutes) and sensitivity (IRAS and Planck) at 3000, 857, 545, 353 GHz for total intensity, degree scale mapping of temperature and emissivity
- Polarization data: Planck 2015 at 353 GHz
- Data at the required quality for B-mode cleaning: none

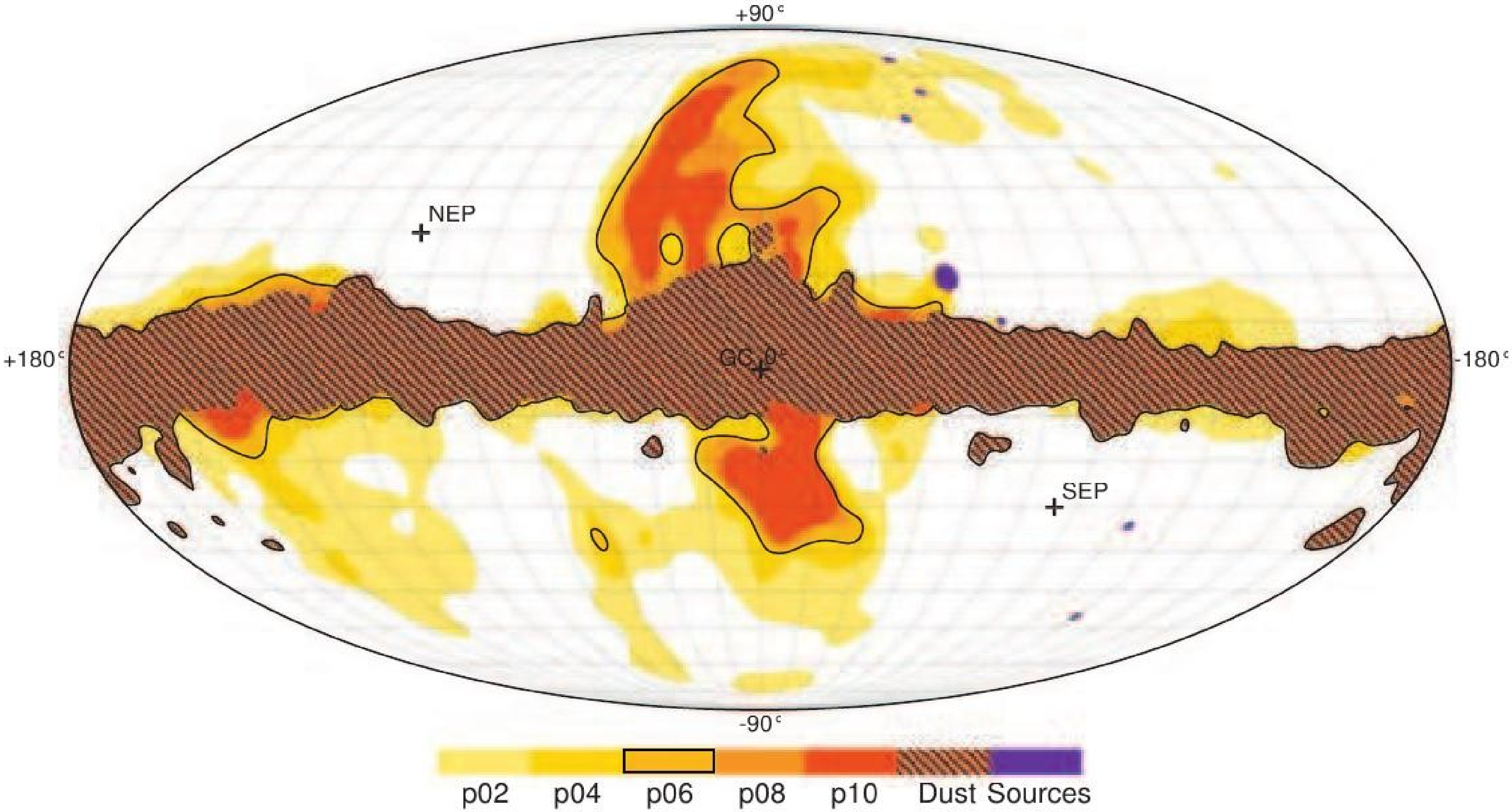
Foregrounds and frequency





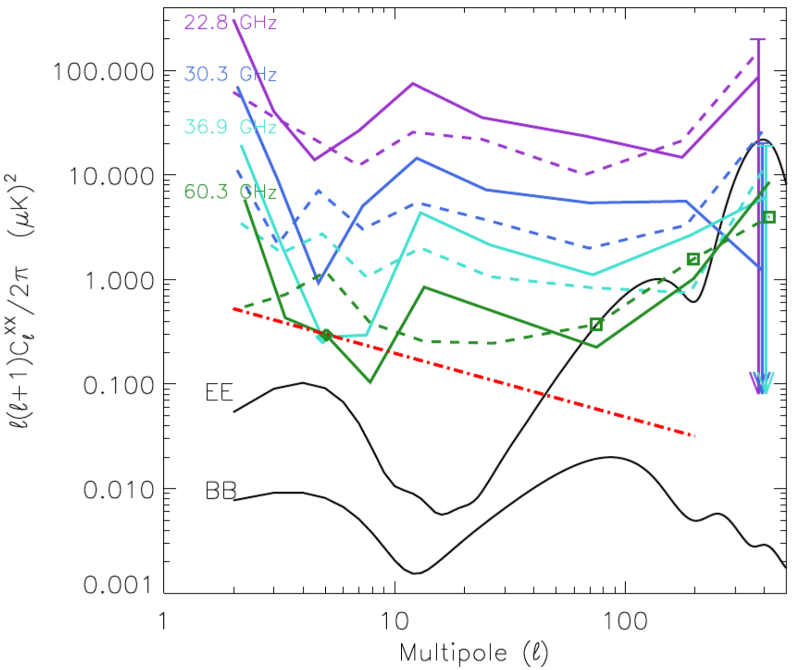
Planck 2015

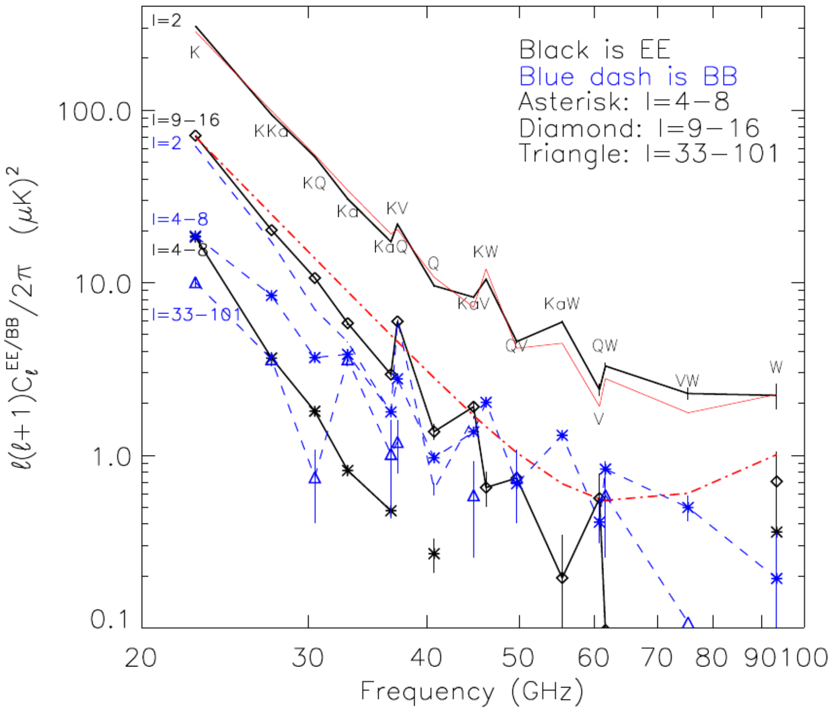
Observations: WMAP



Page et al. 2007 for WMAP

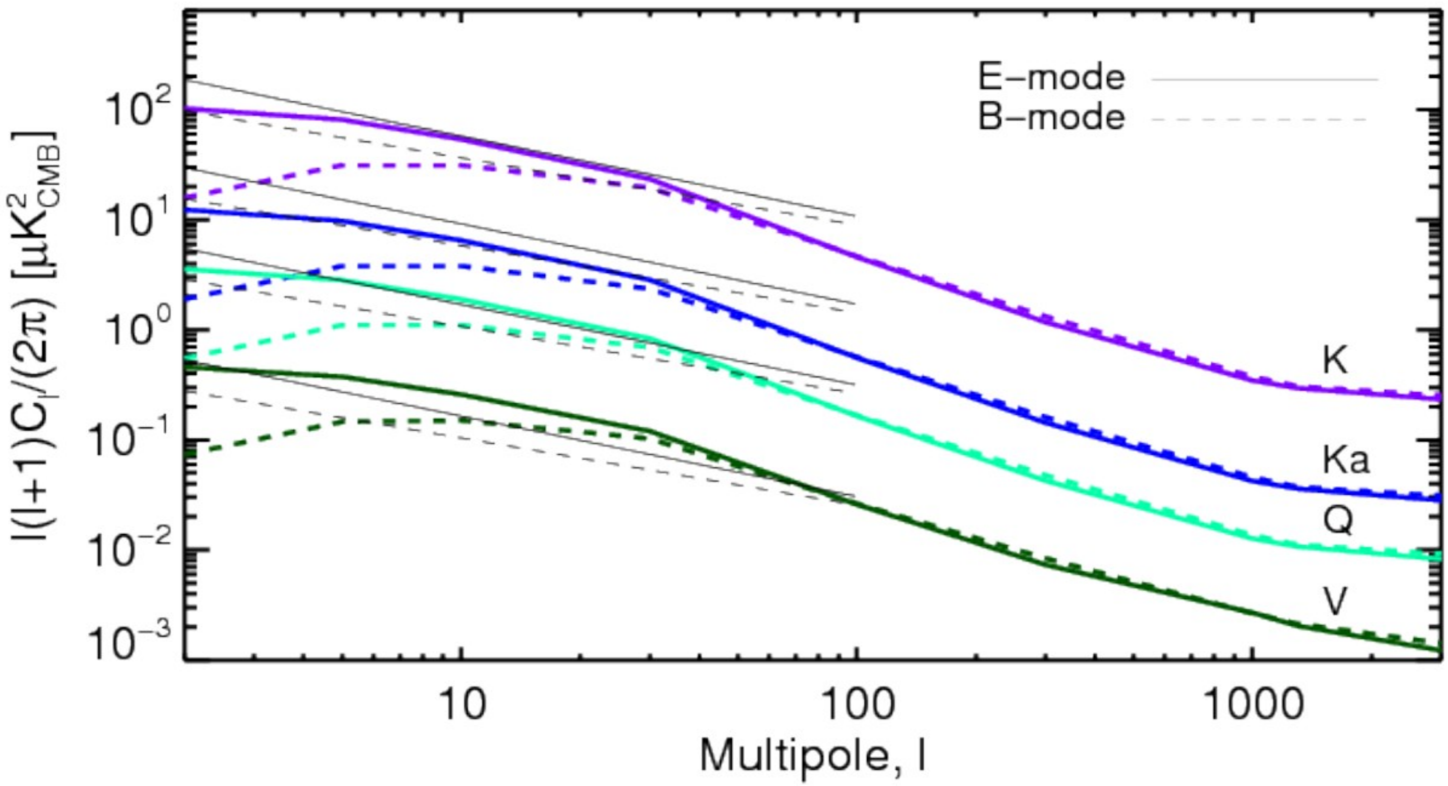
WMAP polarised foregrounds





Page et al. 2007 for WMAP

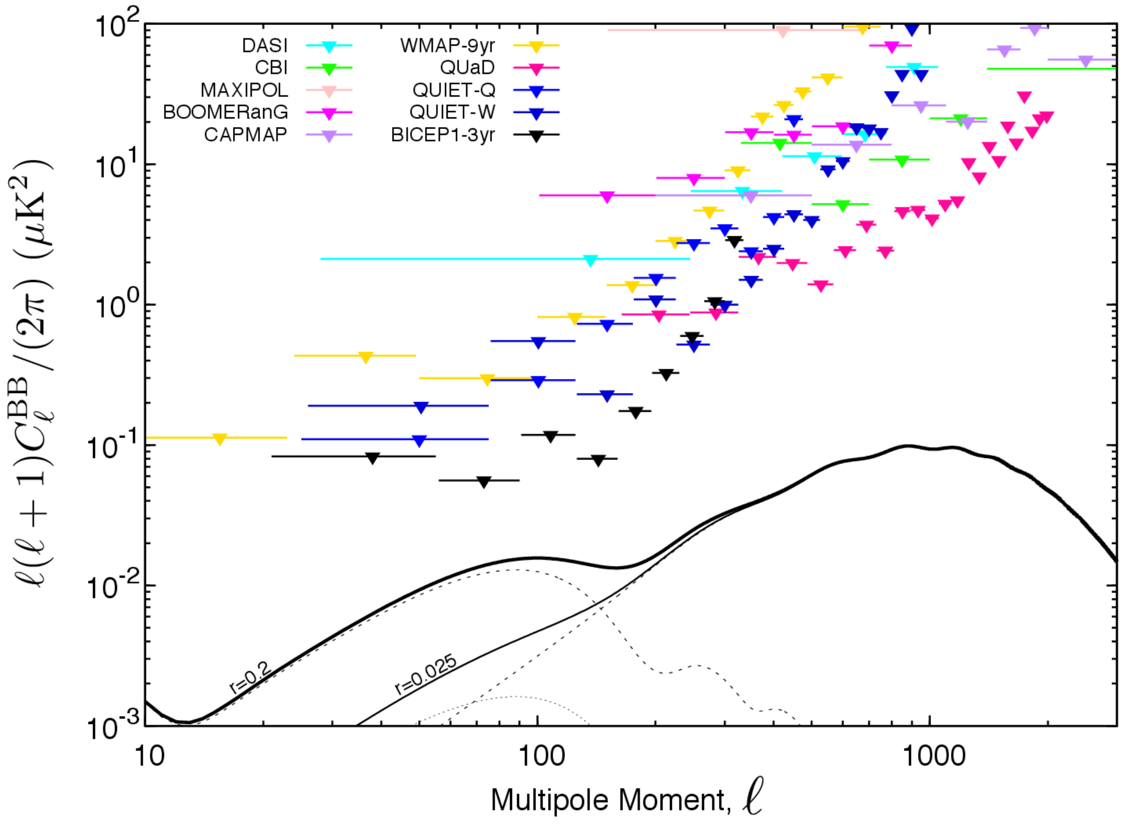
The (WMAP matching) Planck sky model



Delabrouille et al. 2012

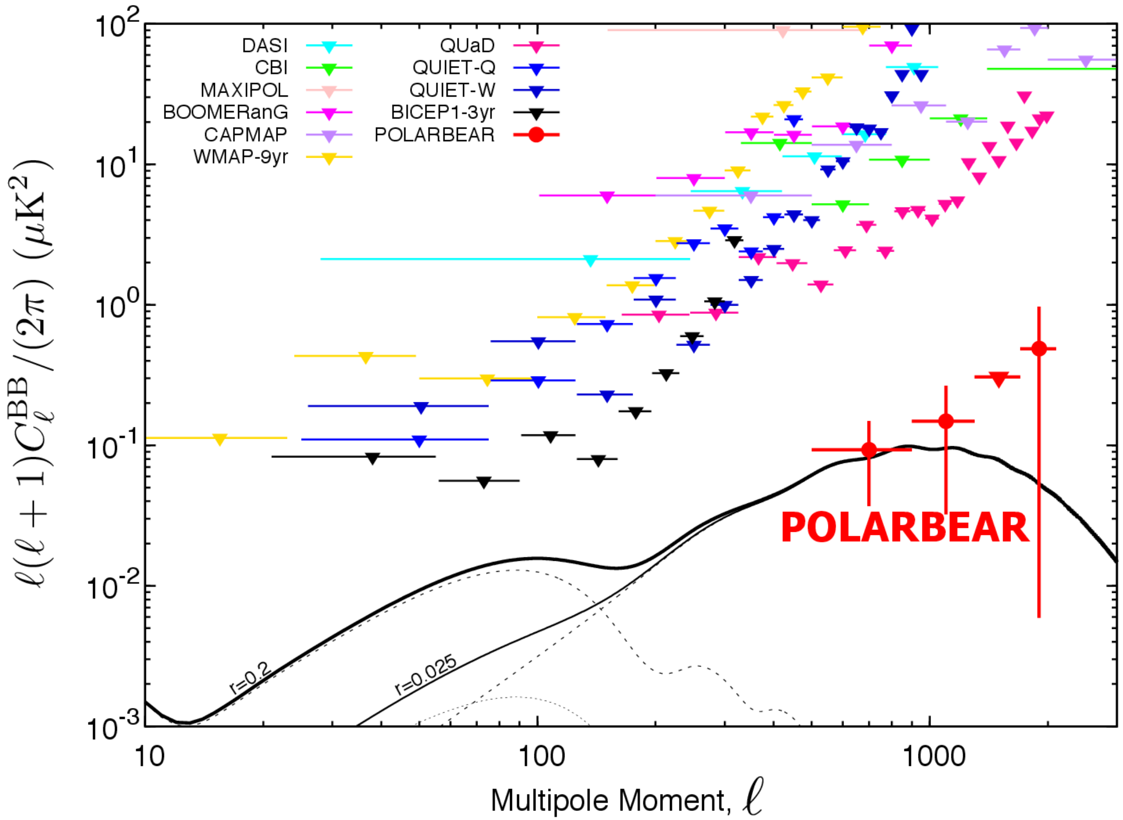
Status of observations

Early 2014



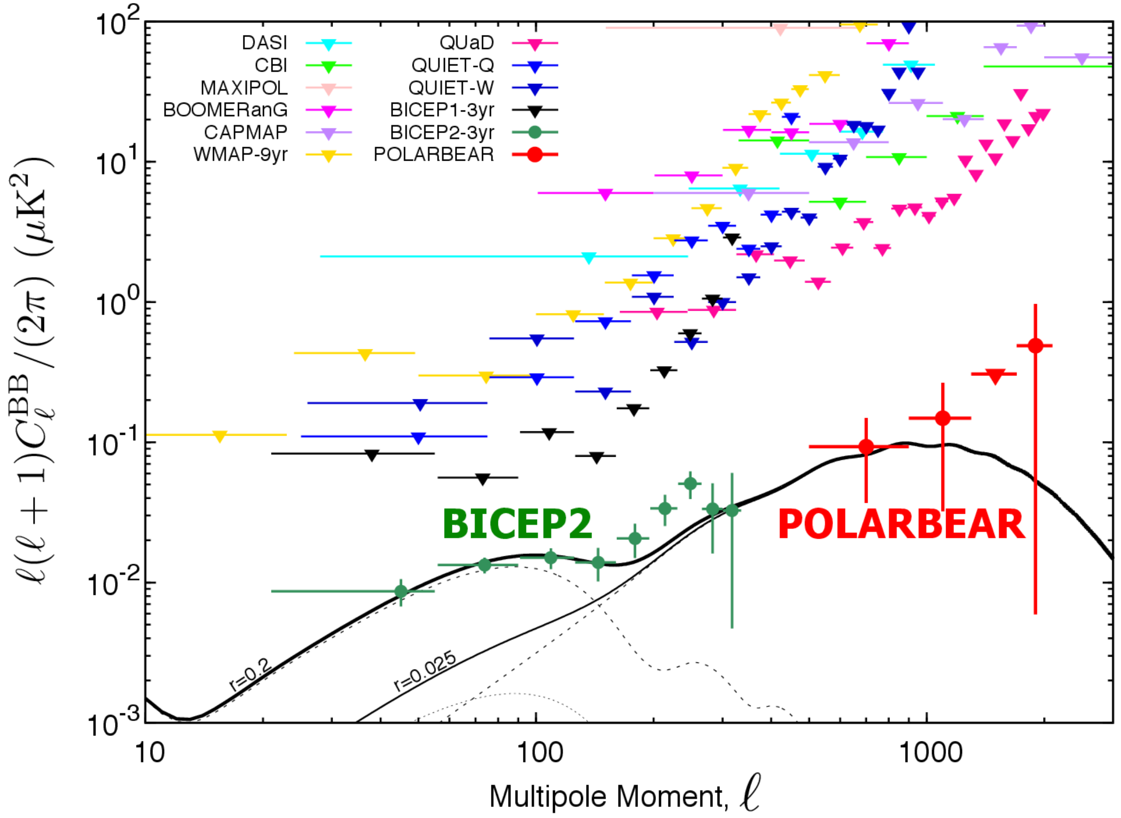
Plots by Chinone for PB

March 2014



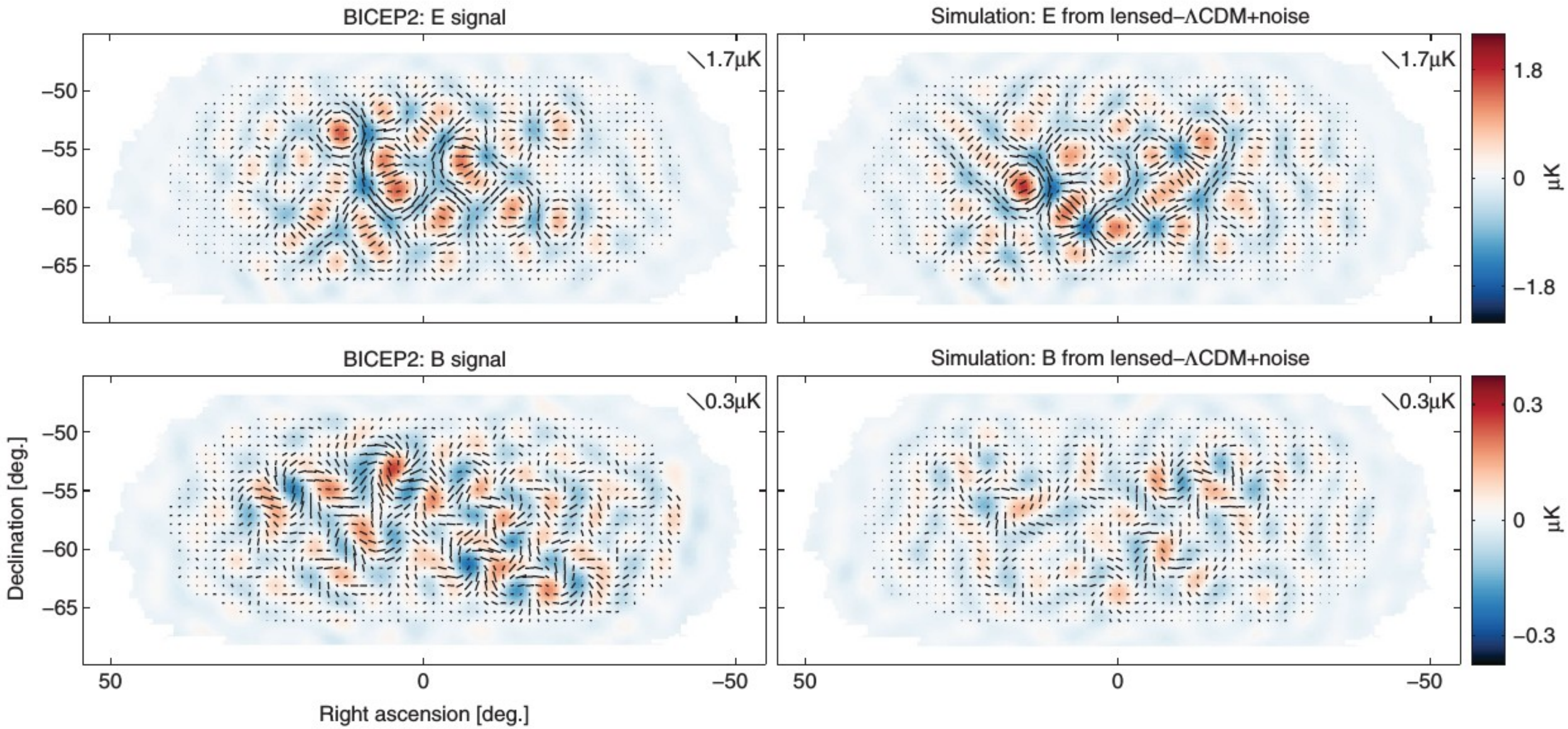
Plots by Chinone for PB

March 2014



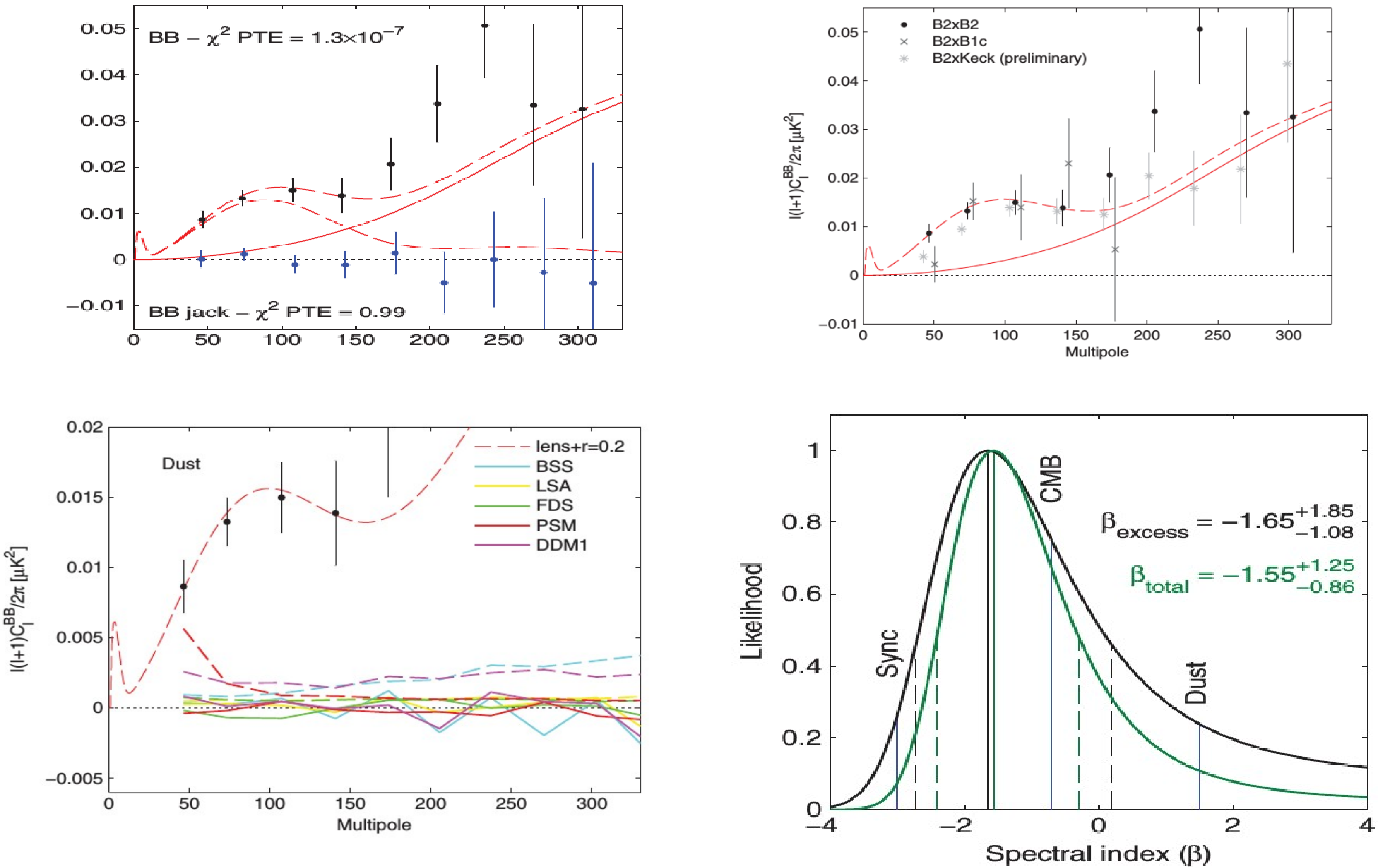
Plots by Chinone for PB

The B-modes at degree scale



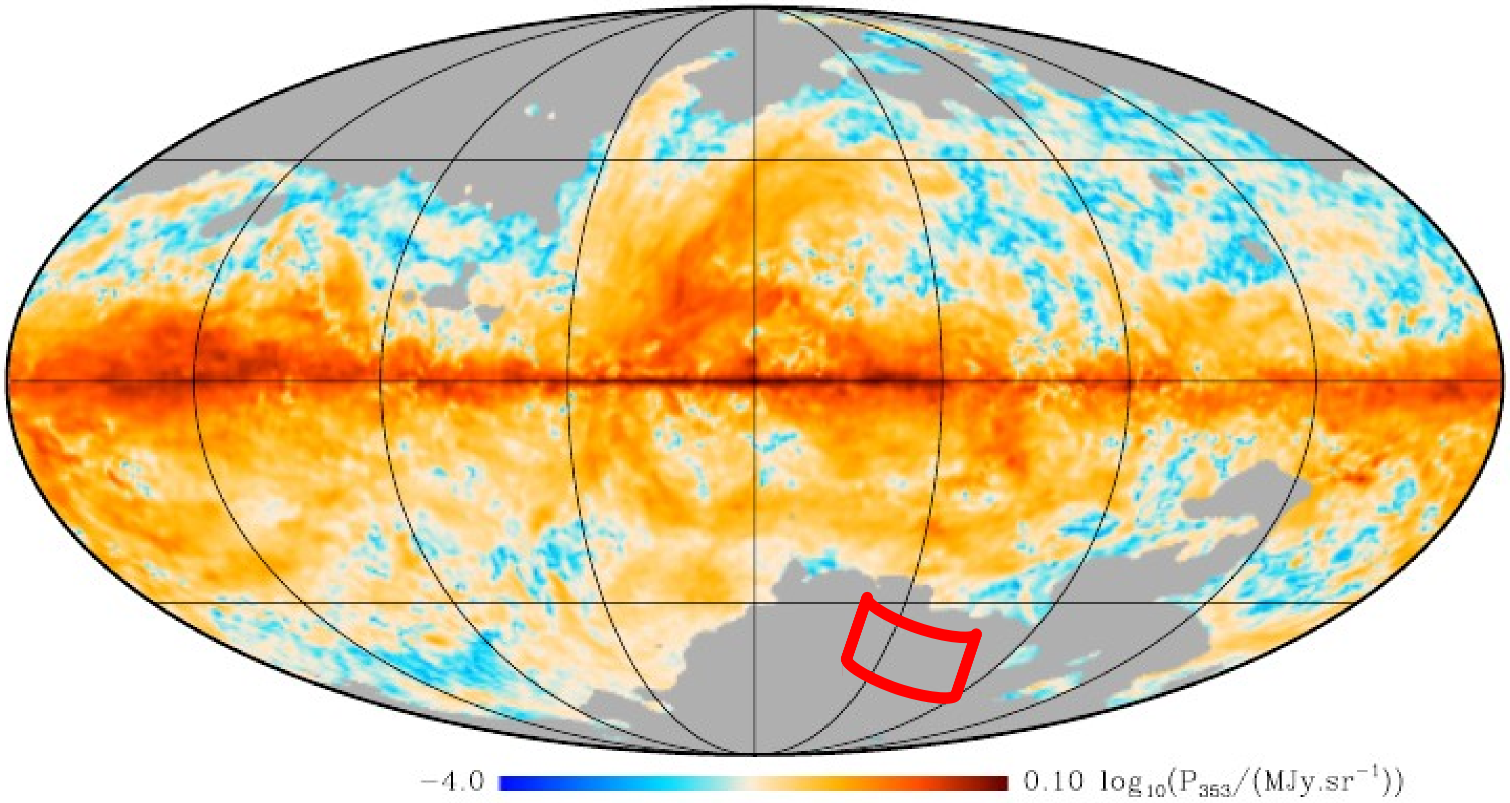
BICEP2 2014

The B modes at degree angular scale



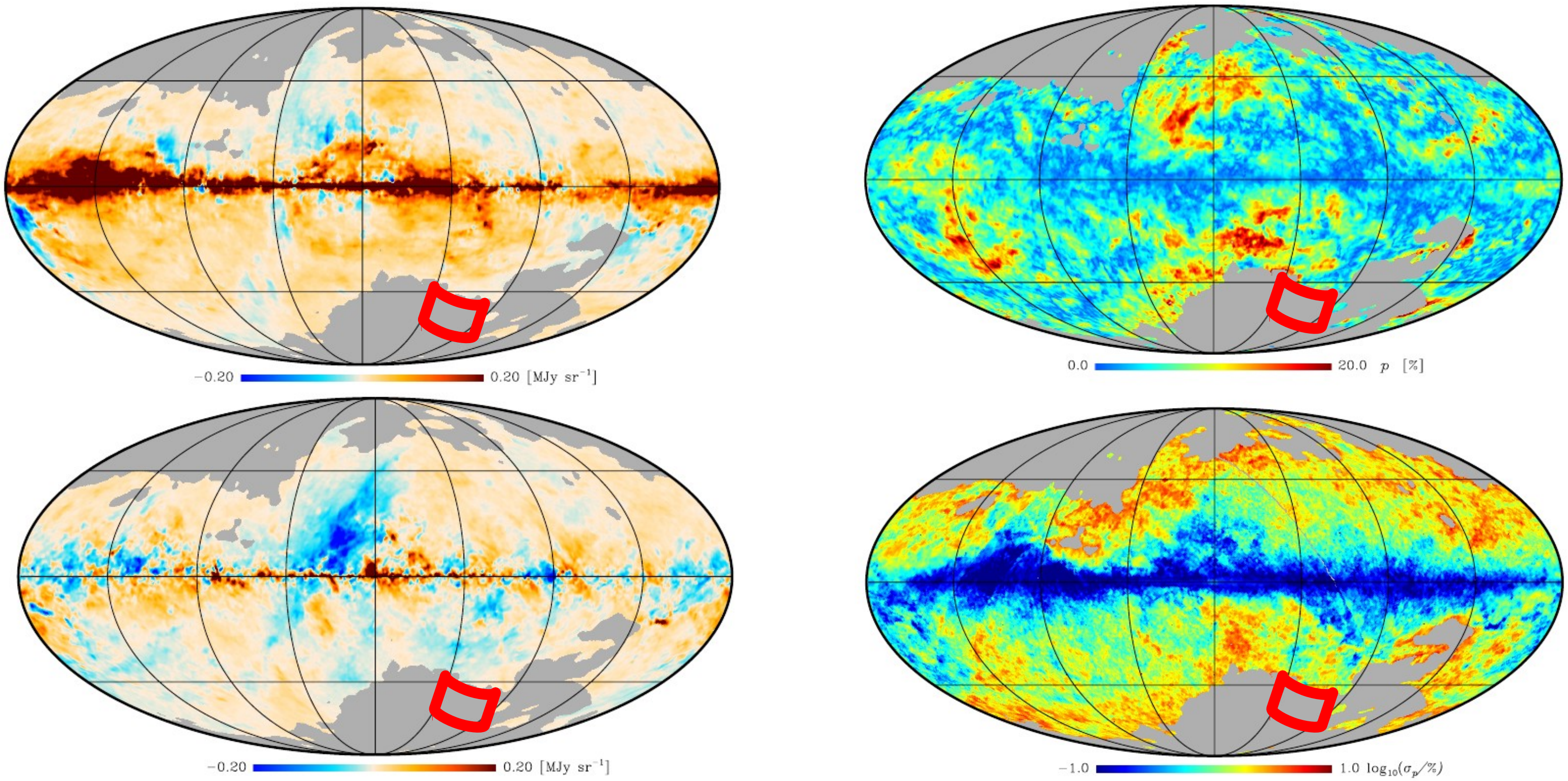
BICEP2 2014

Planck observed dust polarization at intermediate latitudes



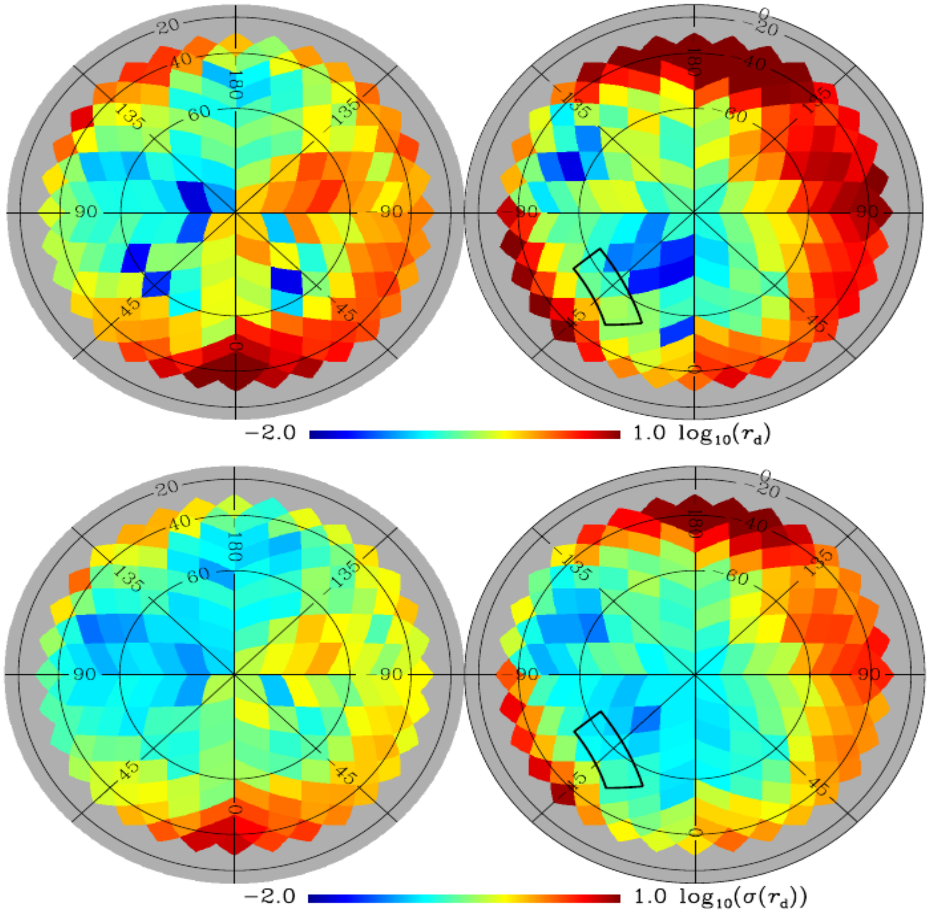
Planck 2014

Planck observed dust polarization at intermediate latitudes



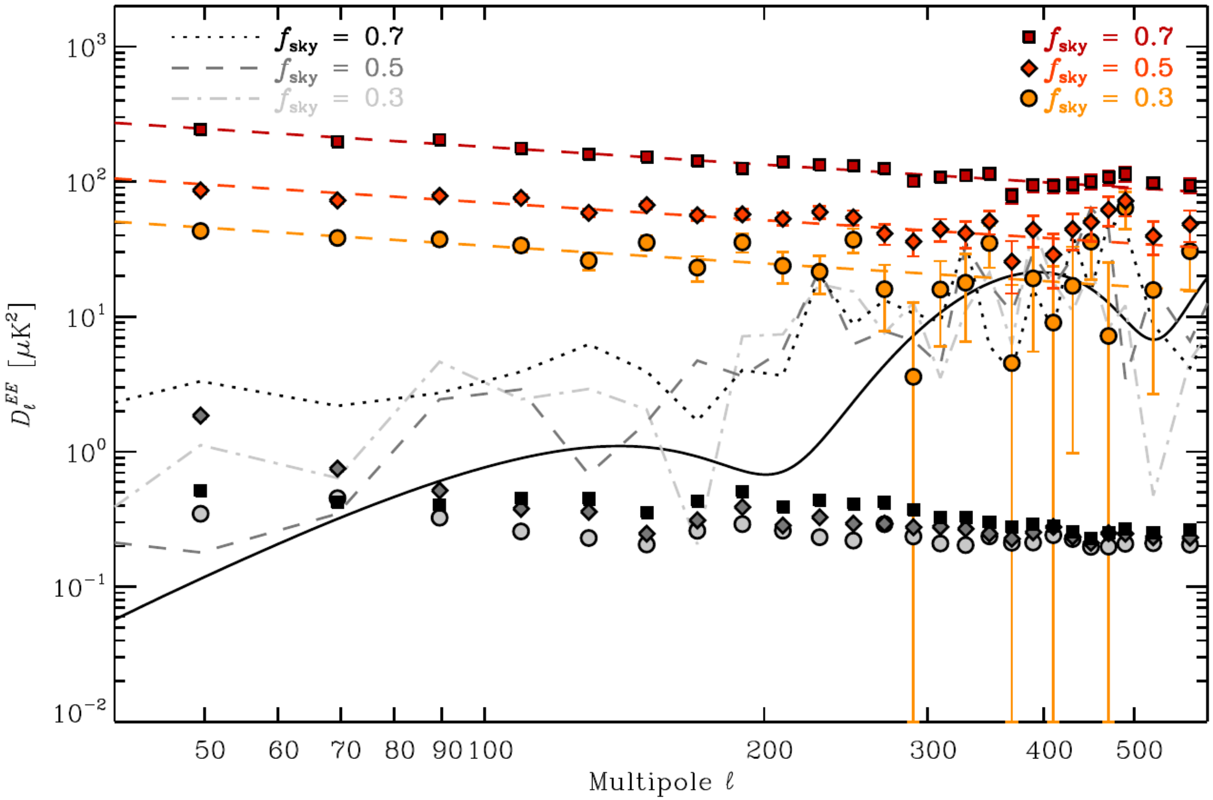
Planck 2014

Planck observed dust polarization at high latitudes



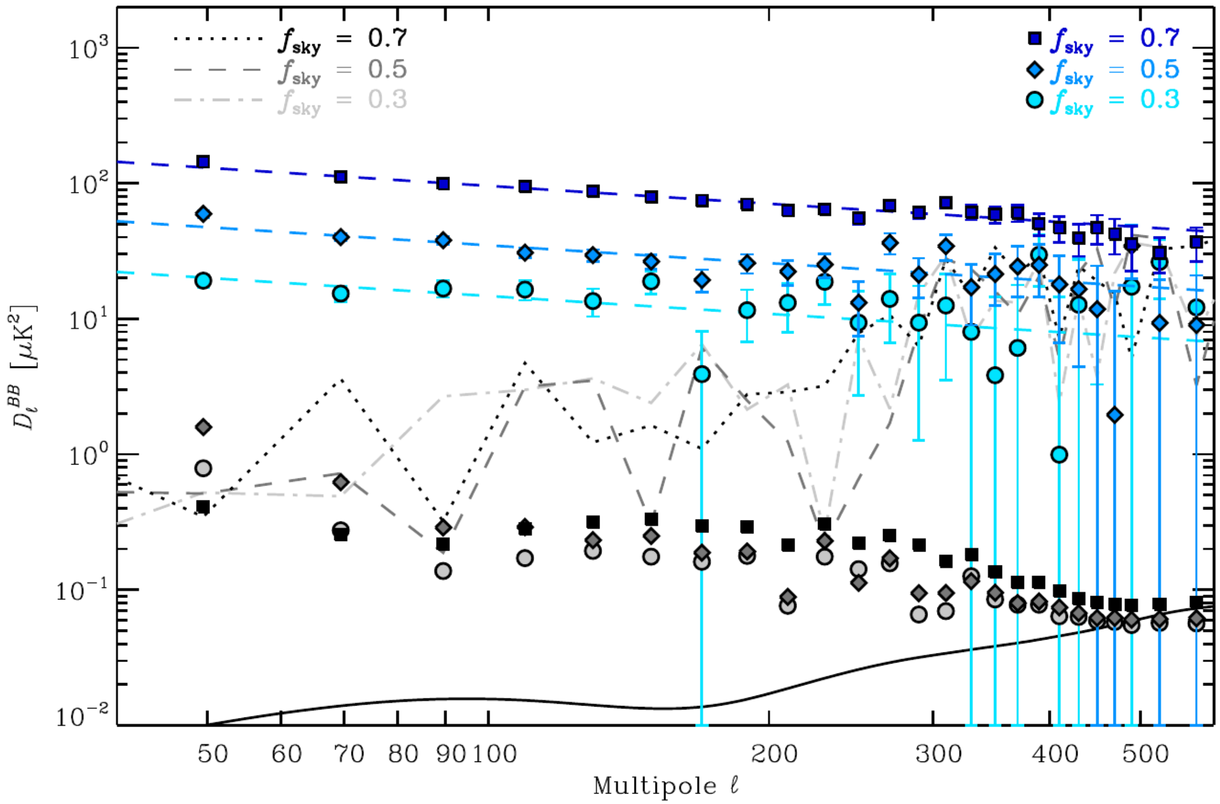
Planck 2014

Planck observed dust polarization at high latitudes



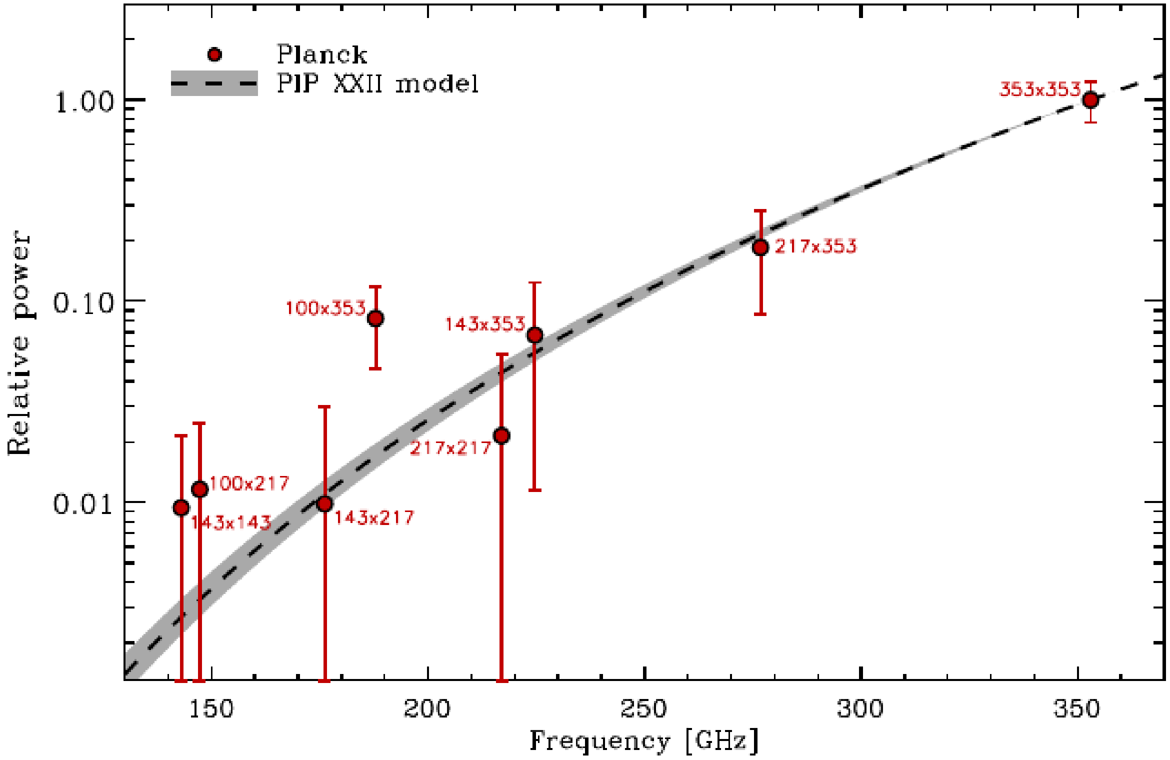
Planck 2014

Planck observed dust polarization at high latitudes



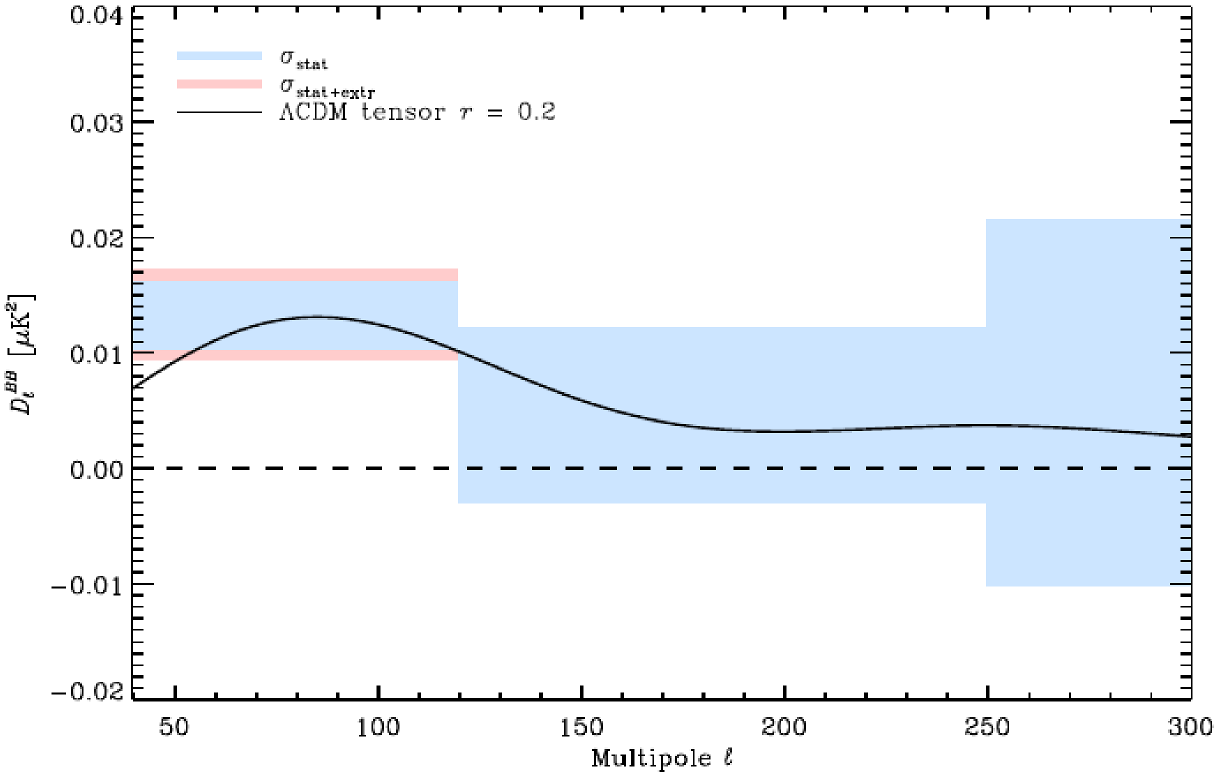
Planck 2014

Planck observed dust polarization in the BICEP2 area



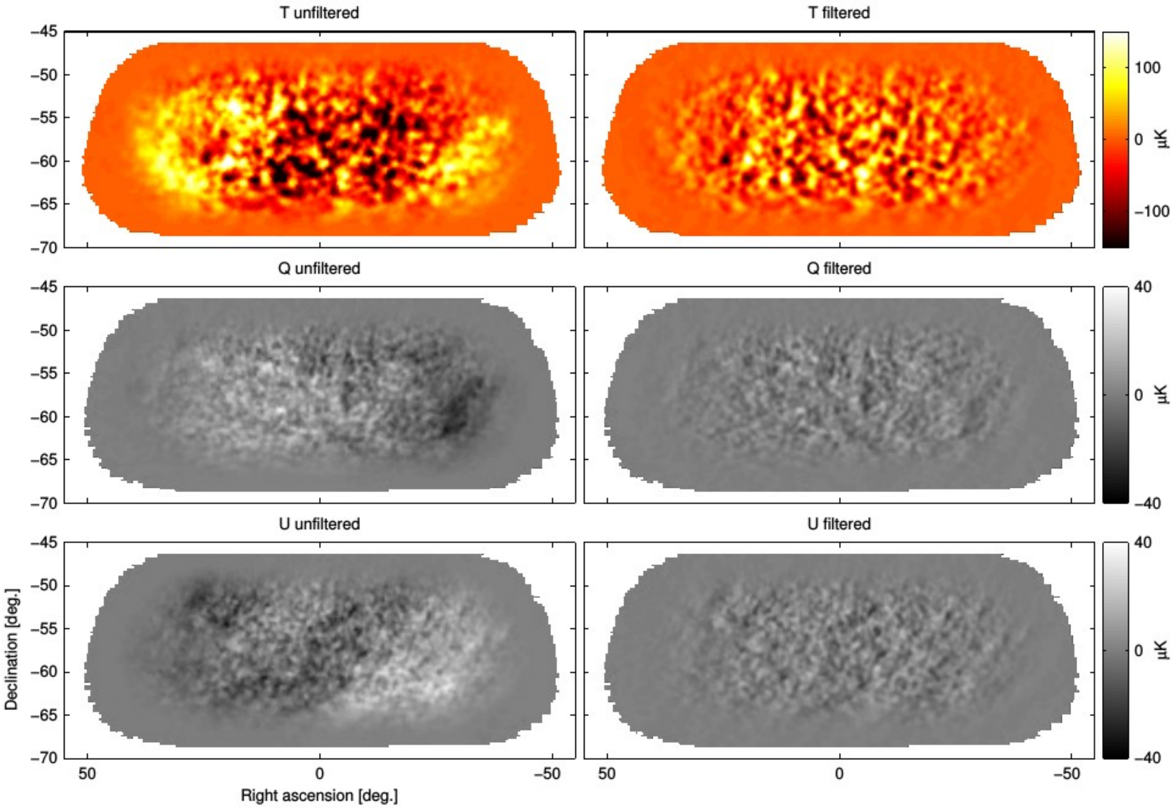
Planck 2014

Planck observed dust polarization in the BICEP2 area



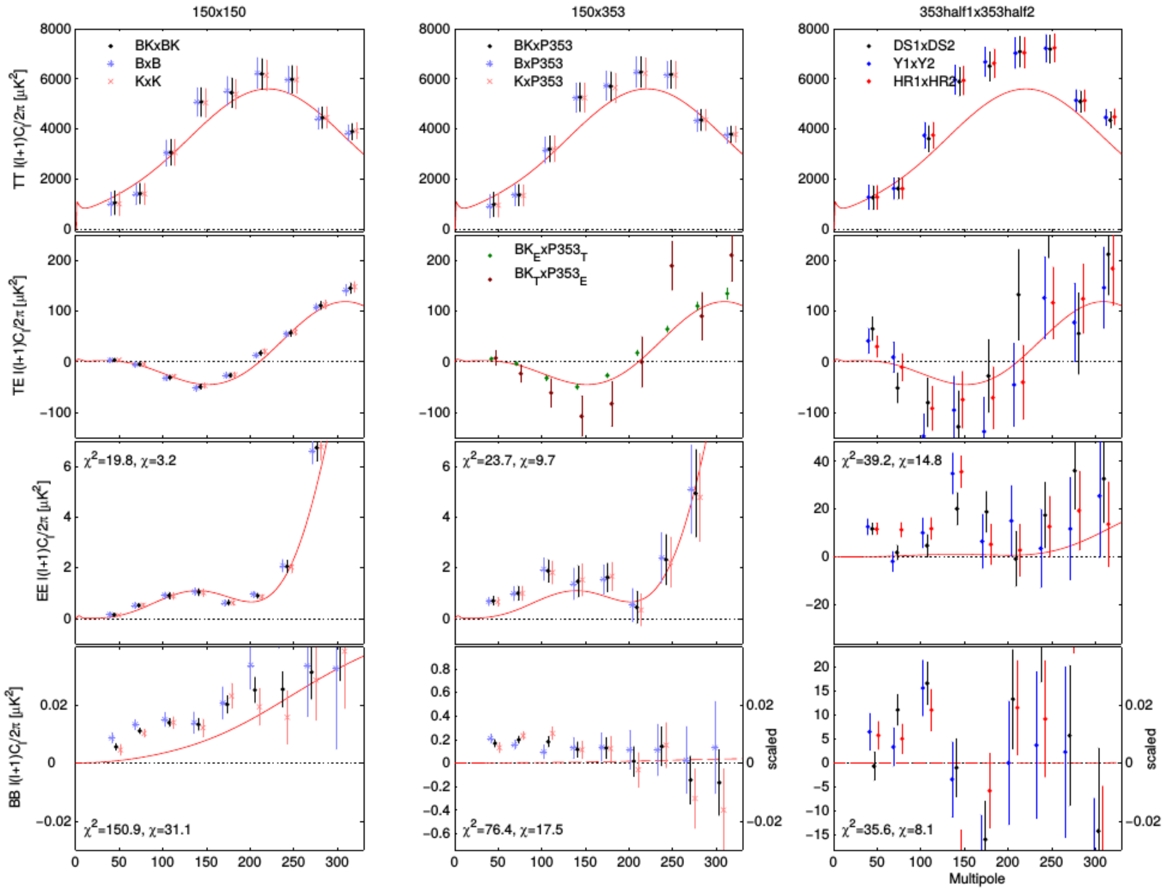
Planck 2014

Planck × Bicep2 × KEcK



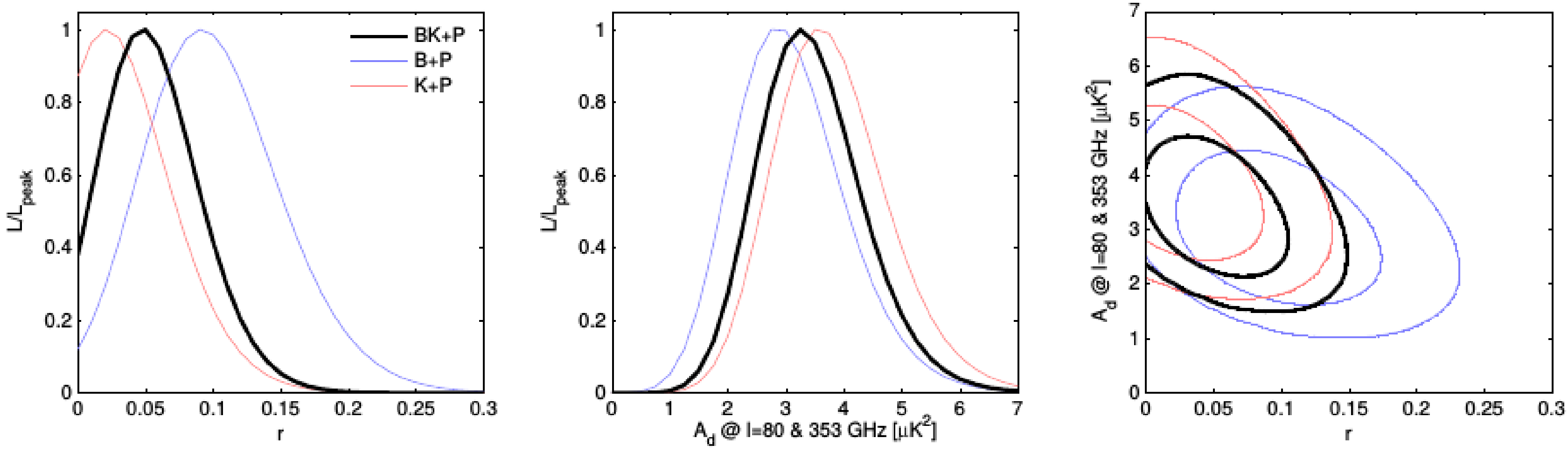
BKP 2015

Planck × Bicep2 × KEcK



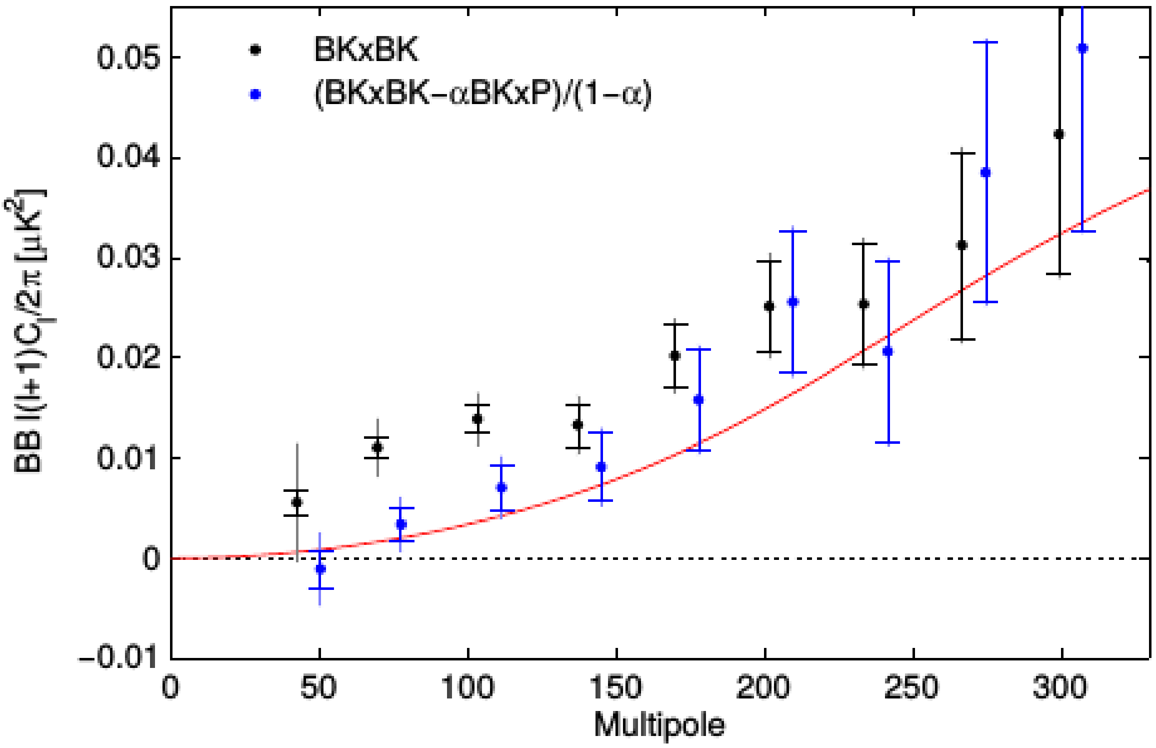
BKP 2015

Planck × Bicep2 × KEcK



BKP 2015

Planck × Bicep2 × KEcK



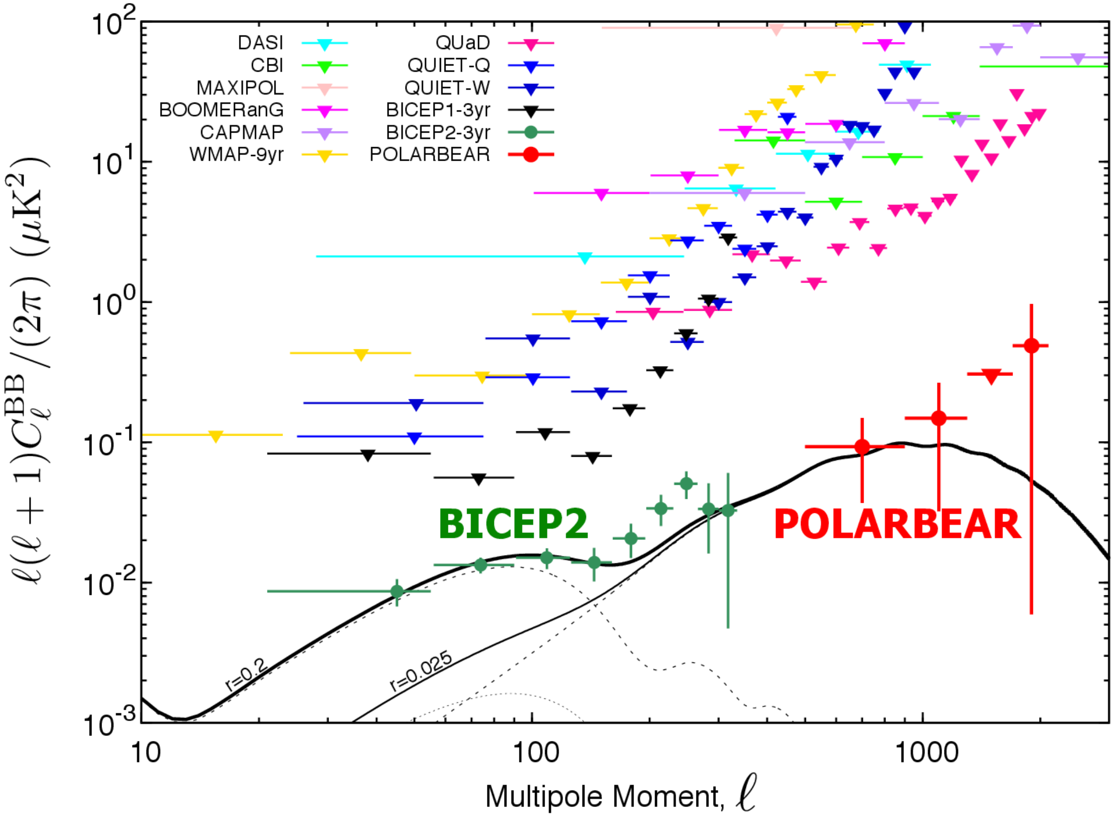
BKP 2015

Planck × Bicep2 × KEcK

$r < 0.12$ at 95% C.L.

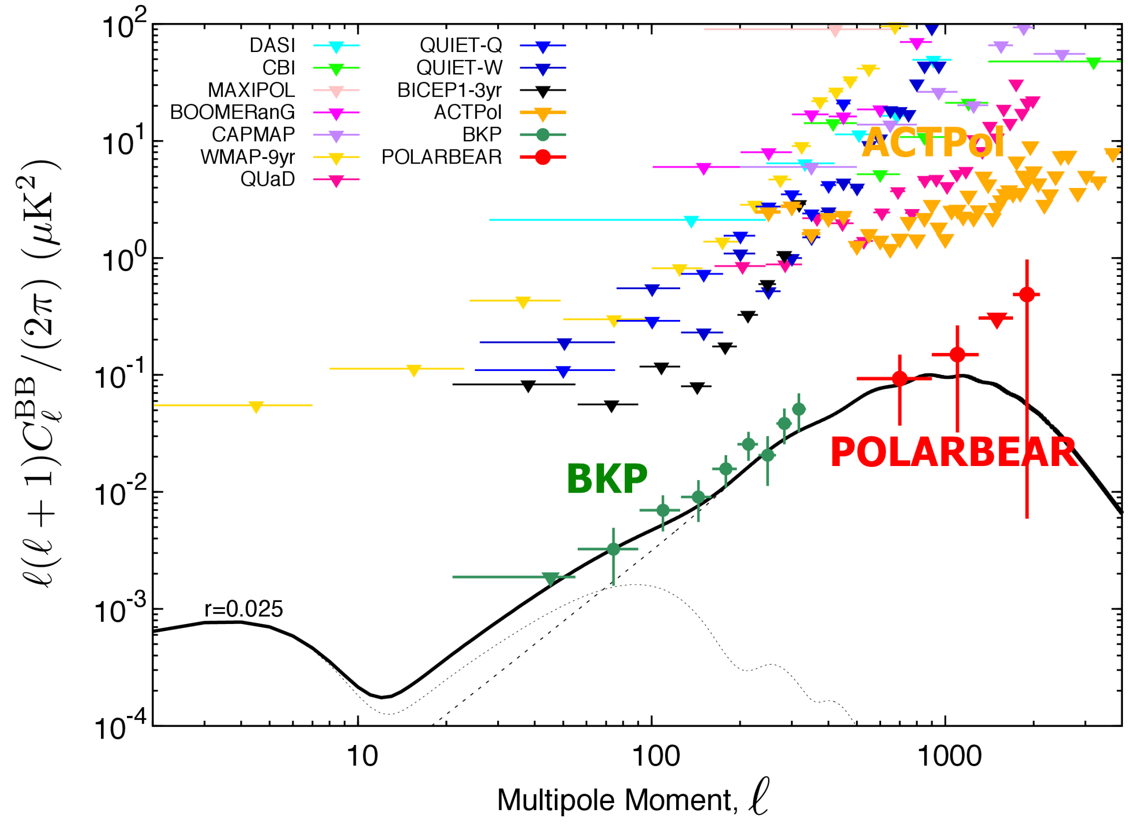
BKP 2015

March 2014



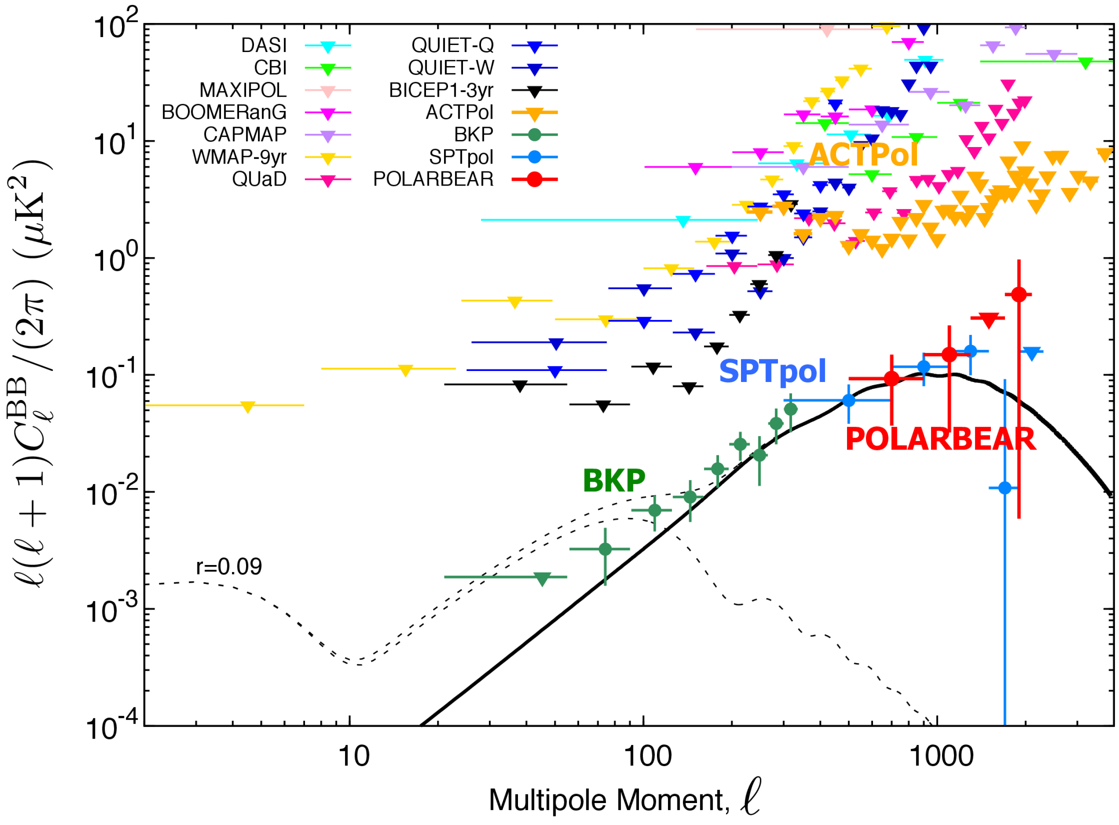
Plots by Chinone for PB

February 2015



Plots by Chinone for PB

May 2015



Plots by Chinone for PB

Remarks

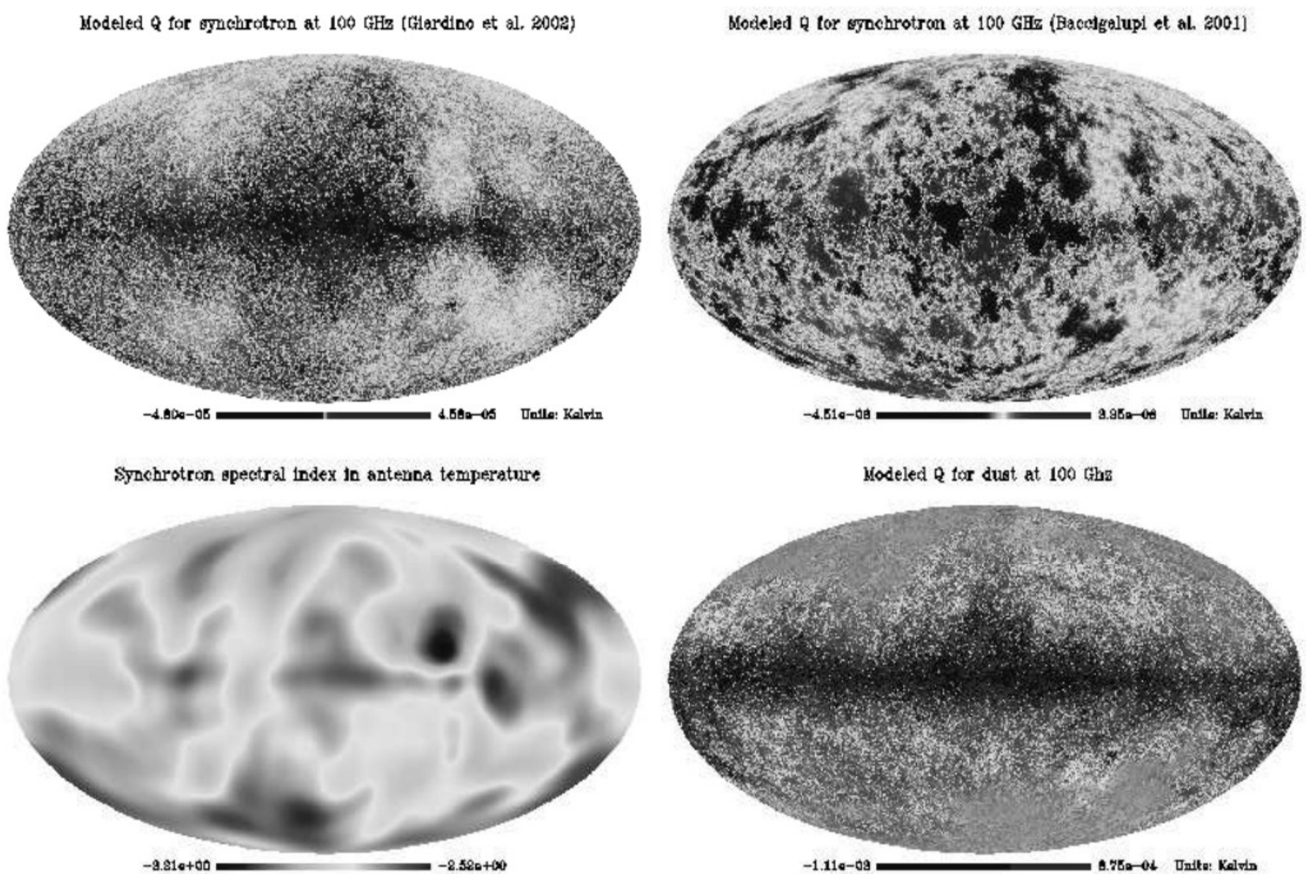
- The issue with diffuse foreground being comparable or dominant with respect to cosmologically interesting B-modes was guessed about a decade ago, and now confirmed by experiments
- Not only data, but data analysis progressed substantially to be able to include foreground cleaning into the data analysis pipeline
- The indication for operating experiments is clear: in addition to **at least one CMB band**, we need **at least two bands per foreground**, with **same angular resolution and sensitivity**, in order to fit and marginalize foregrounds out

Component separation

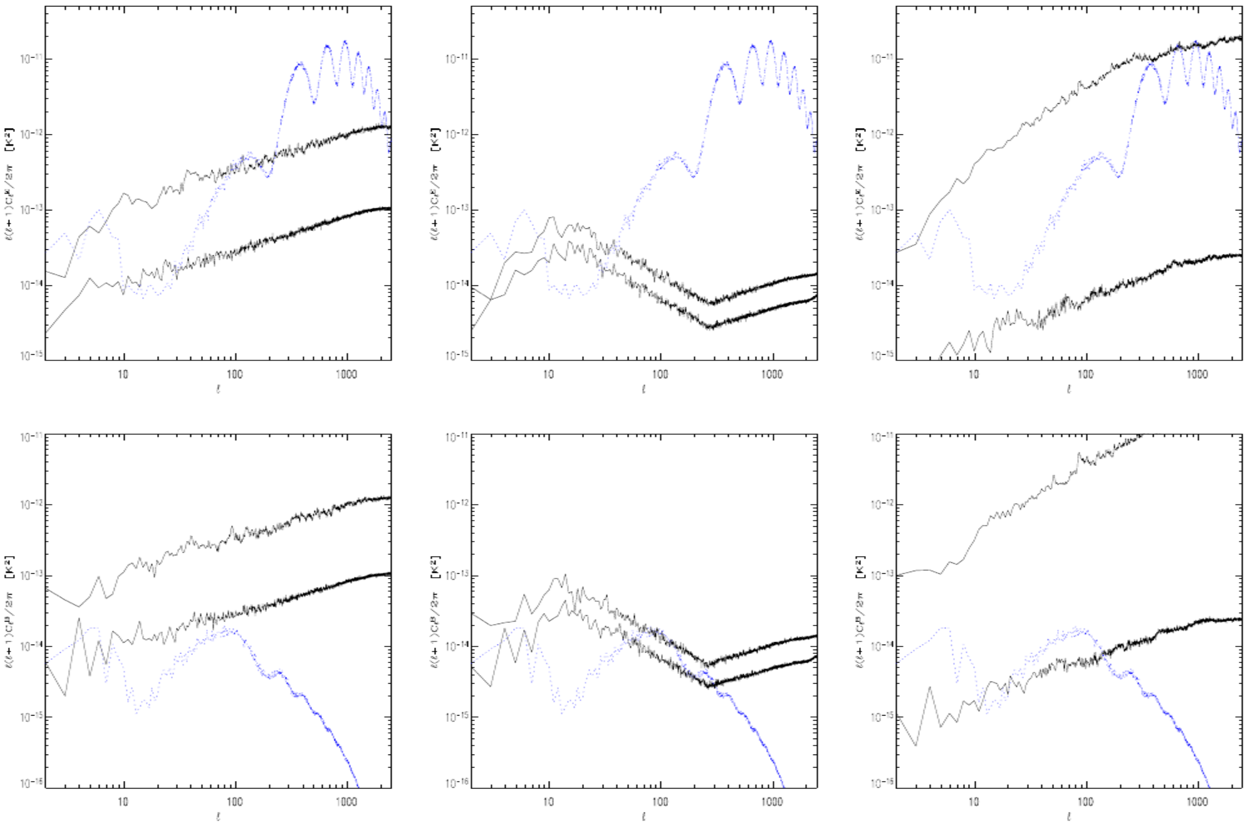
Foreground model building

- Start from total intensity measurements, if available
- Get polarized intensity by imposing a constant polarization fraction
- Construct a pattern for the polarization angle, starting from large scale measurements, adding by hand small scale power according to various recipes
- Assume the same spectral variation for total intensity and polarization
- Check everything with observations when available

The early days



The early days



B03

Component separation

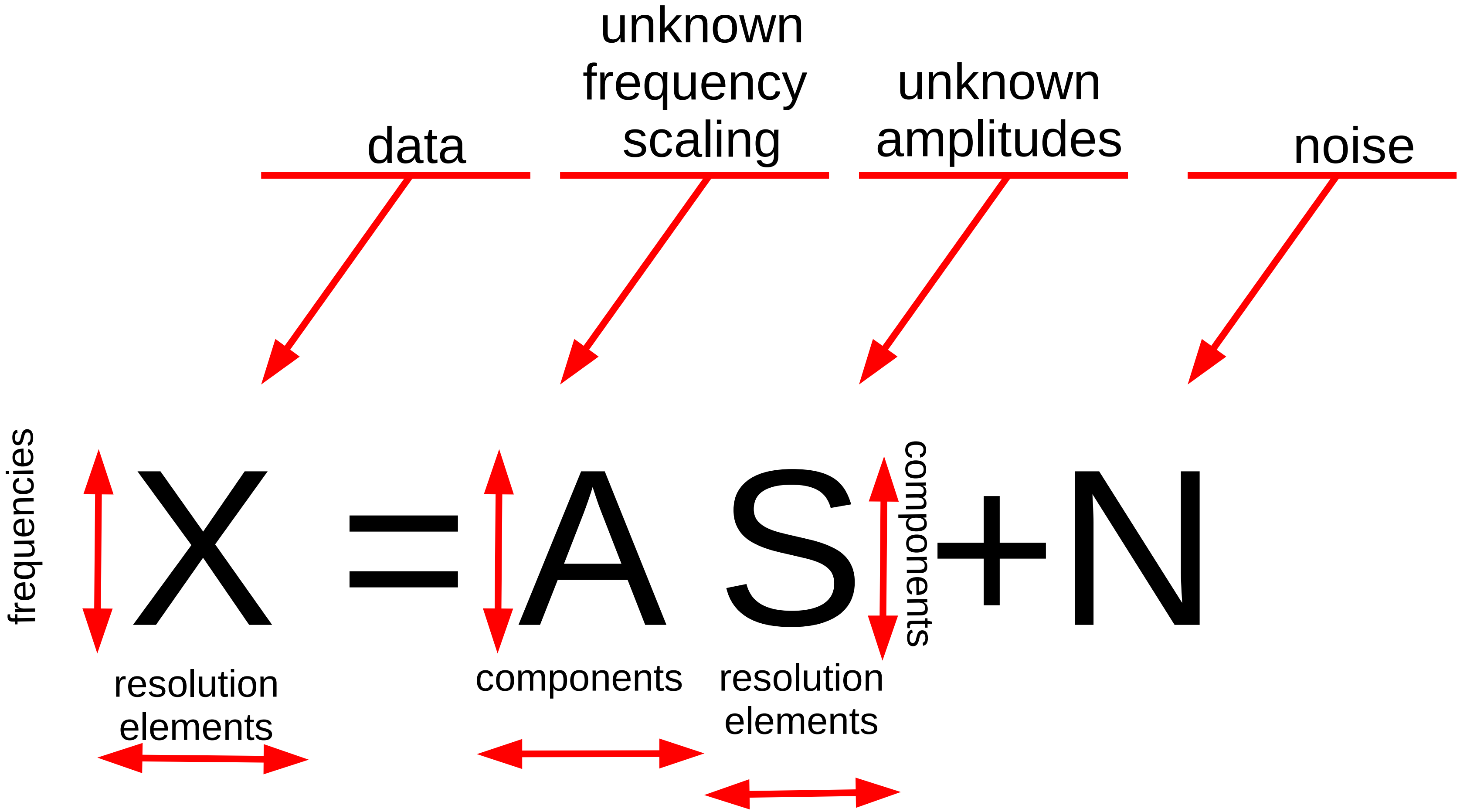
$$X = A\,S + N$$

Component separation

data | frequency scaling | amplitudes | noise

$$X = A\,S + N$$

Component separation



Component separation

- On foregrounds you...
  - Know nothing
  - Know something

Component separation

- Thus if you...
  - Know nothing, you
    - Look for minimum variance internal linear combination
  - Know something, you
    - Model foreground unknowns and fit

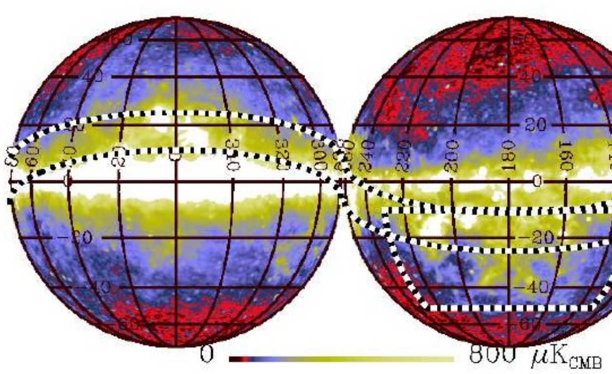
Component separation

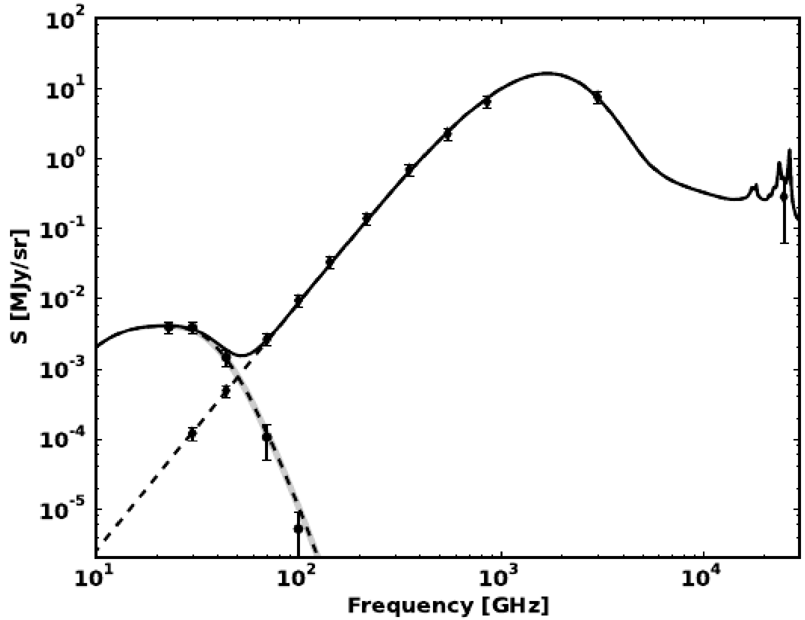
- If you know nothing, you
  - Look for minimum variance internal linear combination, constrained to scale as a black body:

$$\sum_i w_i X_i \qquad \sum_i w_i = 1$$

Component separation

- If you know something, you
  - model and fit

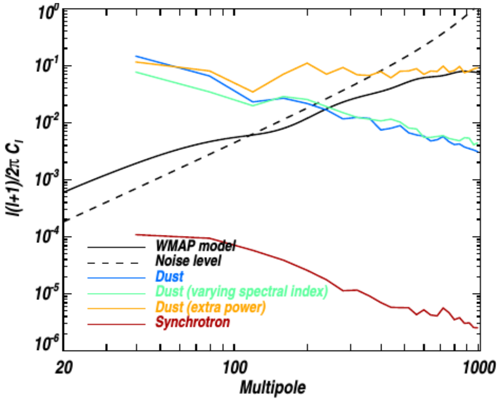


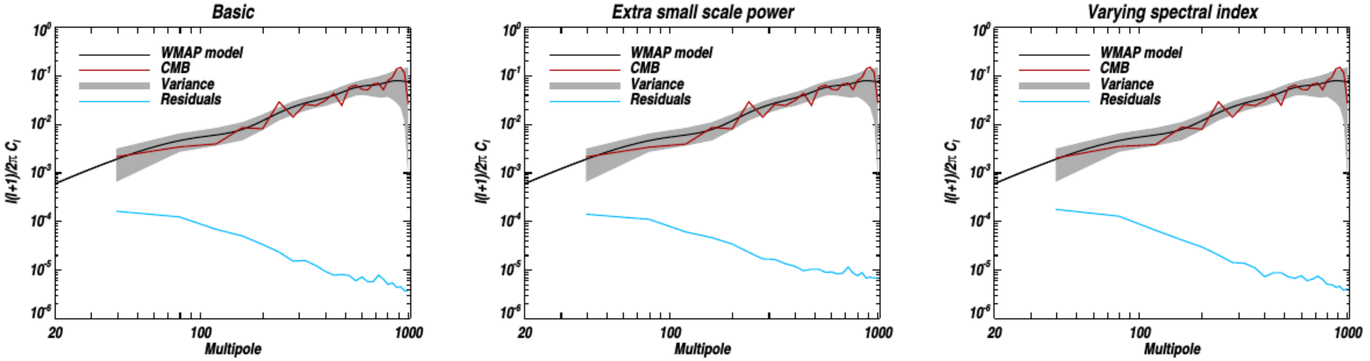


Planck 2012

Component separation

- If you know something, you
  - model and fit





Stivoli et al. 2010

Component separation

- Opearting domains: you can choose to cast your minimum variance search, or your fit, in
  - Pixel domain
  - Harmonic domain
  - Intermediate (needlets, wavelets) domain

Component separation

- Thus if you...
  - Know nothing, you
    - Look for minimum variance internal linear combination
      - In the pixel domain
      - In the needlet domain
  - Know something, you
    - Model foreground unknowns and fit
      - In the pixel domain
      - In the needlet domain

Planck 2013, XII, 2015, IX

Component separation

- Thus if you...
  - Know nothing, you
    - Look for minimum variance internal linear combination
      - In the pixel domain – SEVEM
      - In the needlet domain – NILC
  - Know something, you
    - Model foreground unknowns and fit
      - In the pixel domain – COMMANDER
      - In the needlet domain – SMICA

Planck 2013, XII, 2015, IX

Component separation

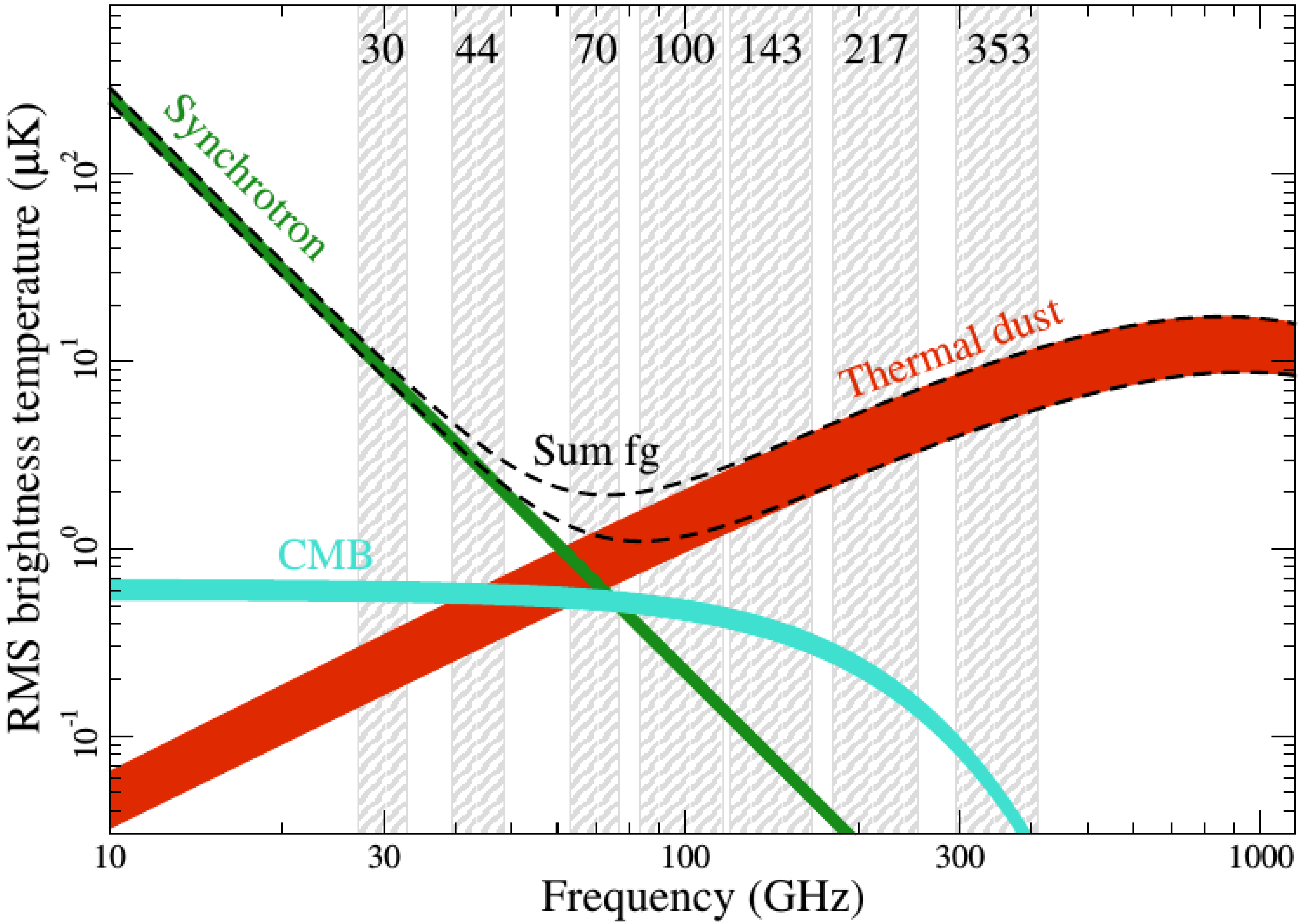
- Thus if you...
  - Know nothing, you
    - Look for minimum variance internal linear combination
      - In the pixel domain – SEVEM (CMB only)
      - In the needlet domain – NILC (CMB only)
  - Know something, you
    - Model foreground unknowns and fit
      - In the pixel domain – COMMANDER (CMB and foregrounds)
      - In the needlet domain – SMICA (CMB and foregrounds)

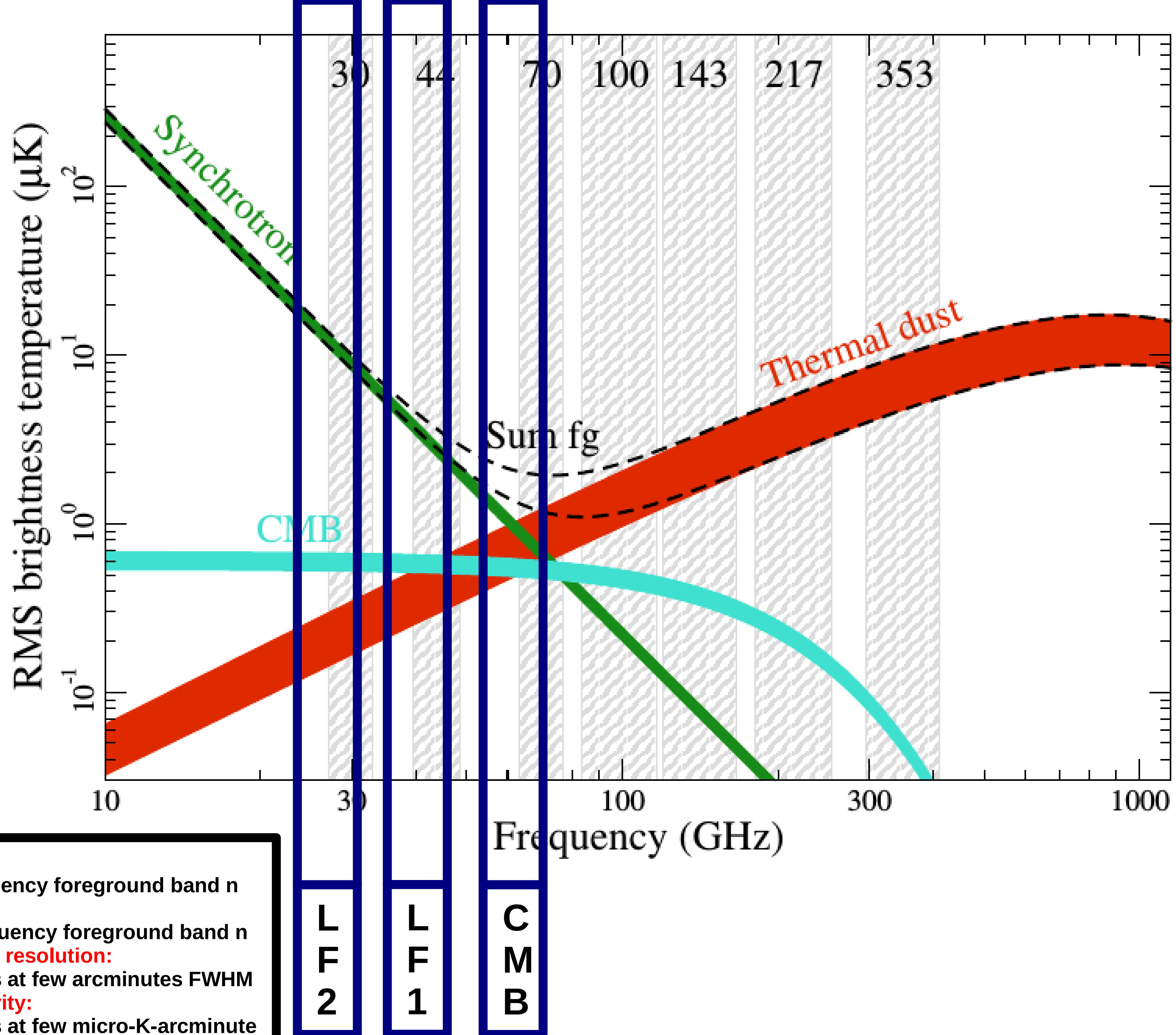
Planck 2013, XII, 2015, IX

Component separation for sub-orbital experiments

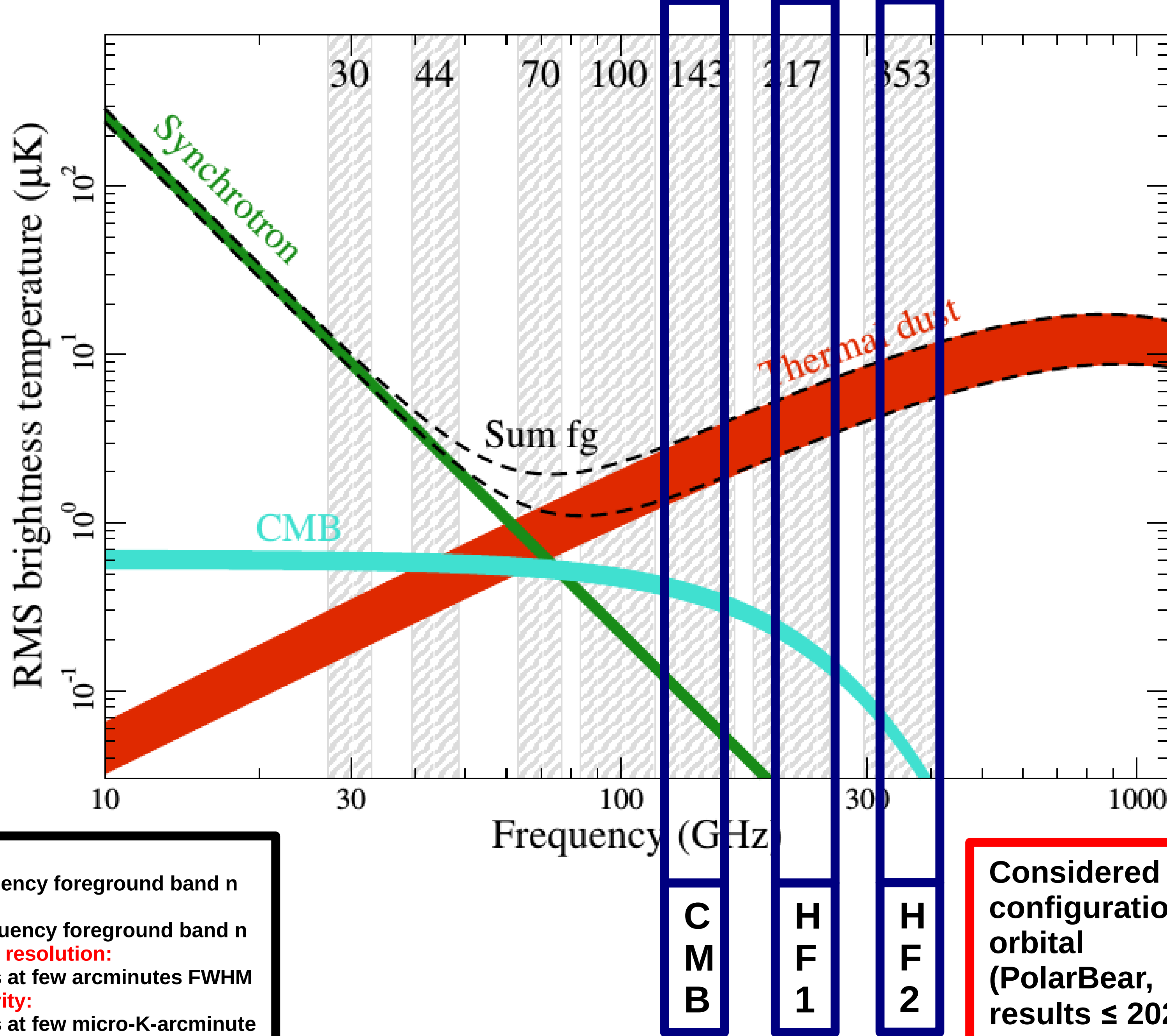
- Maximum likeihood casting, Stompor et al. 2009
- Implementation in the Miramare code, Leach e al., 2010
- Simulations of sub-orbitals, Stivoli et al. 2010
- Parameter estimation, Fantaye et al. 2011
- Power spectrum estimation through the Xpure code, Grain et al. 2012
- Foreground cleaning and lensing reconstruction, Fantaye et al. 2012
- Linearized system for forecasts, Errard and Stompor 2012

Concluding remarks


30
44
70
100
143
217
353
Synchrotron
Thermal dust
Sum fg
CMB
RMS brightness temperature (μK)
10^2
10^1
10^0
10^-1
10
30
100
300
1000
Frequency (GHz)

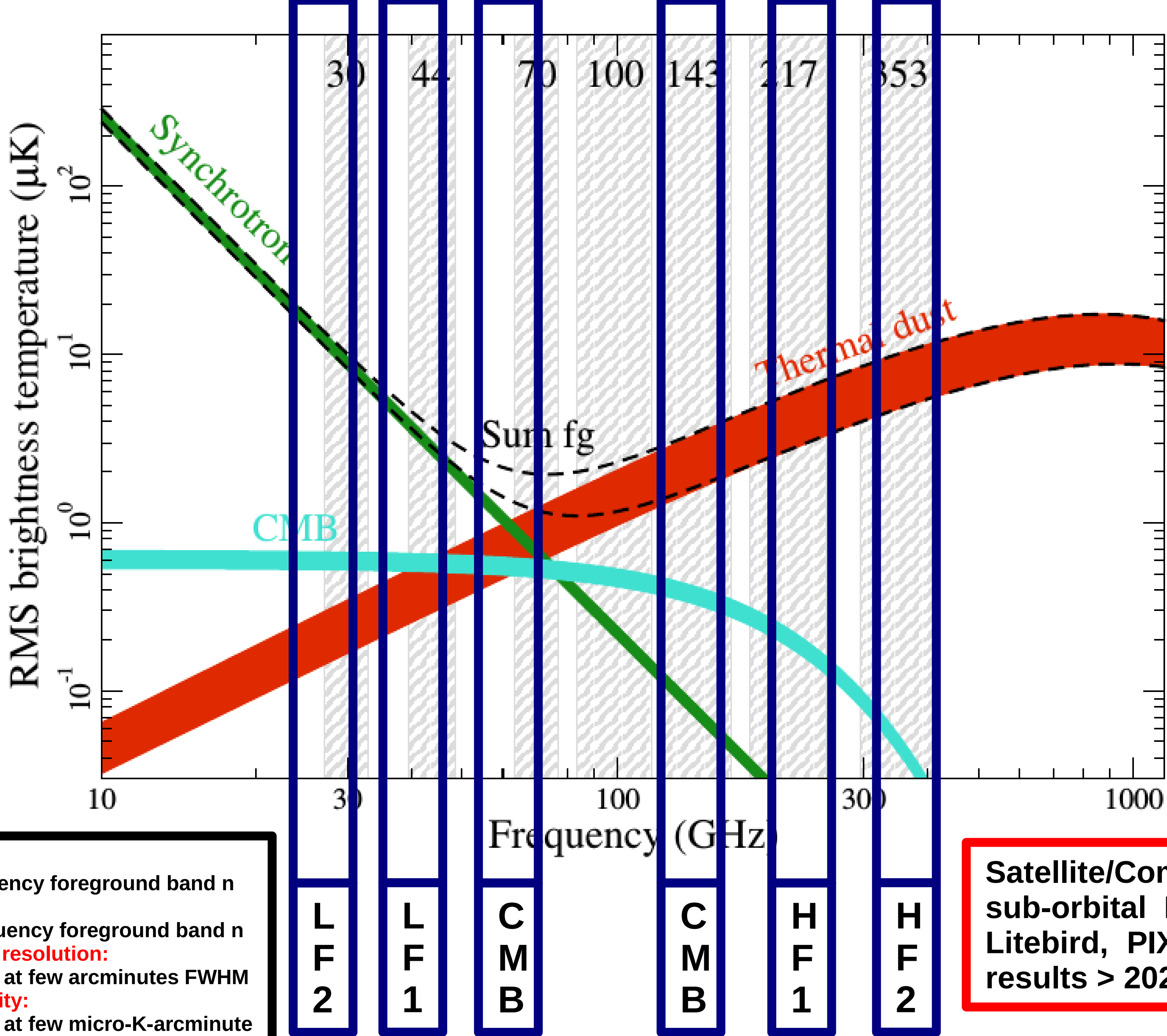


* LFn:
low frequency foreground band n
* HFn:
high frequency foreground band n
* Angular resolution:
All bands at few arcminutes FWHM
* Sensitivity:
All bands at few micro-K-arcminute



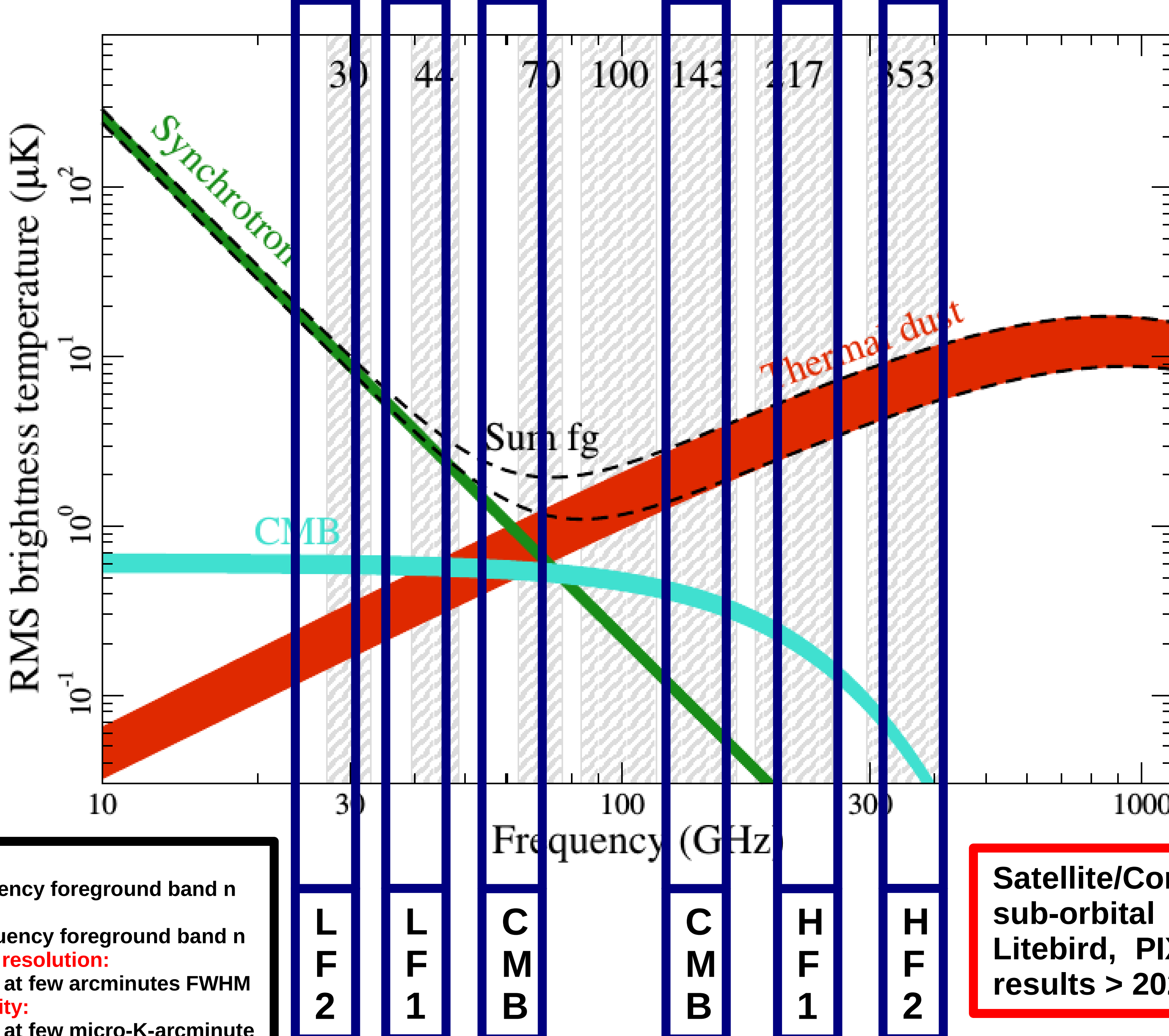
*** LFn:**
low frequency foreground band n
*** HFn:**
high frequency foreground band n
*** Angular resolution:**
All bands at few arcminutes FWHM
*** Sensitivity:**
All bands at few micro-K-arcminute

Considered for the configuration of sub-orbital probes (PolarBear, EBEX, …) results ≤ 2020



* LFn:
low frequency foreground band n
* HFn:
high frequency foreground band n
* Angular resolution:
All bands at few arcminutes FWHM
* Sensitivity:
All bands at few micro-K-arcminute

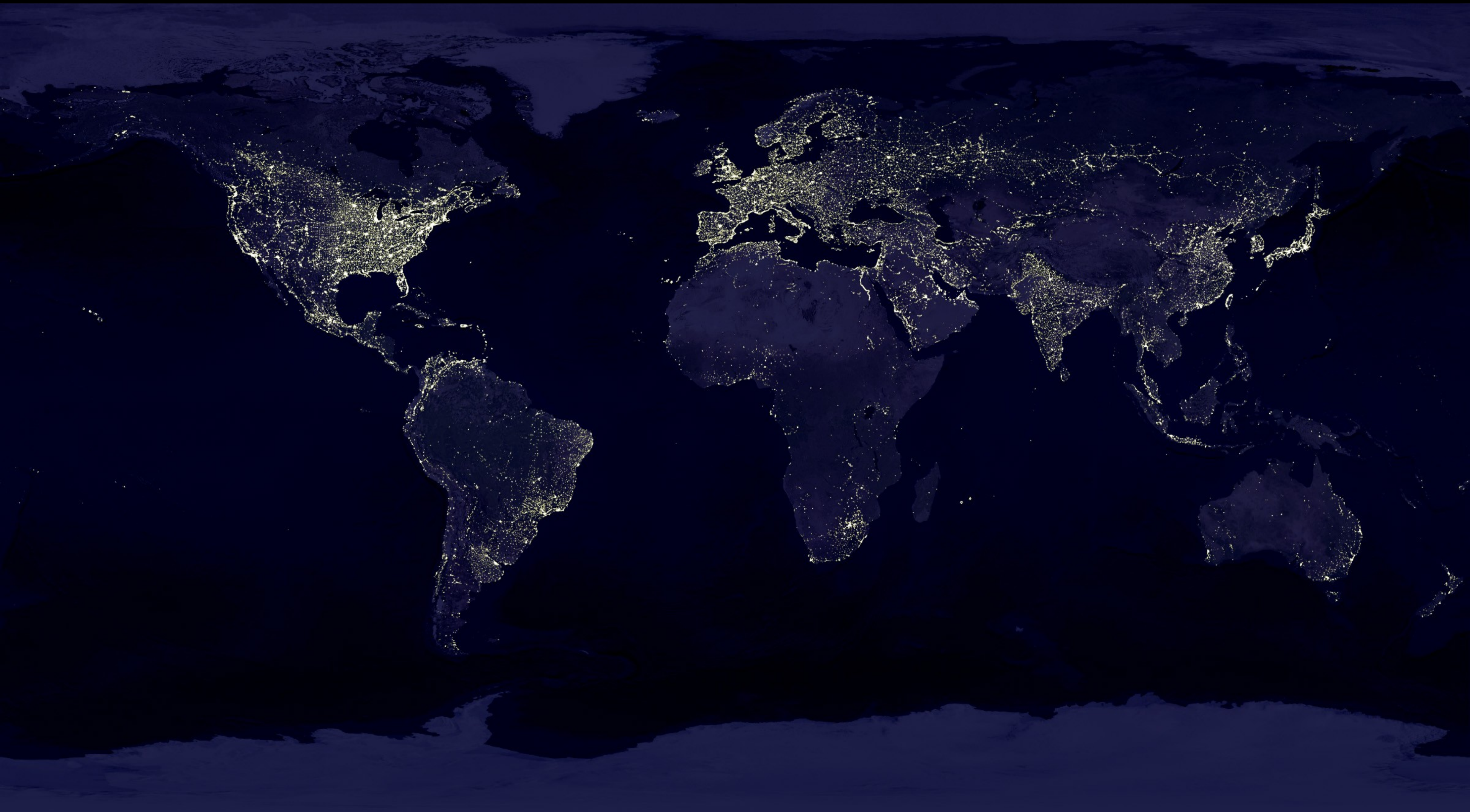
Satellite/Combined sub-orbital Probes: Litebird, PIXIE, S4, results > 2020

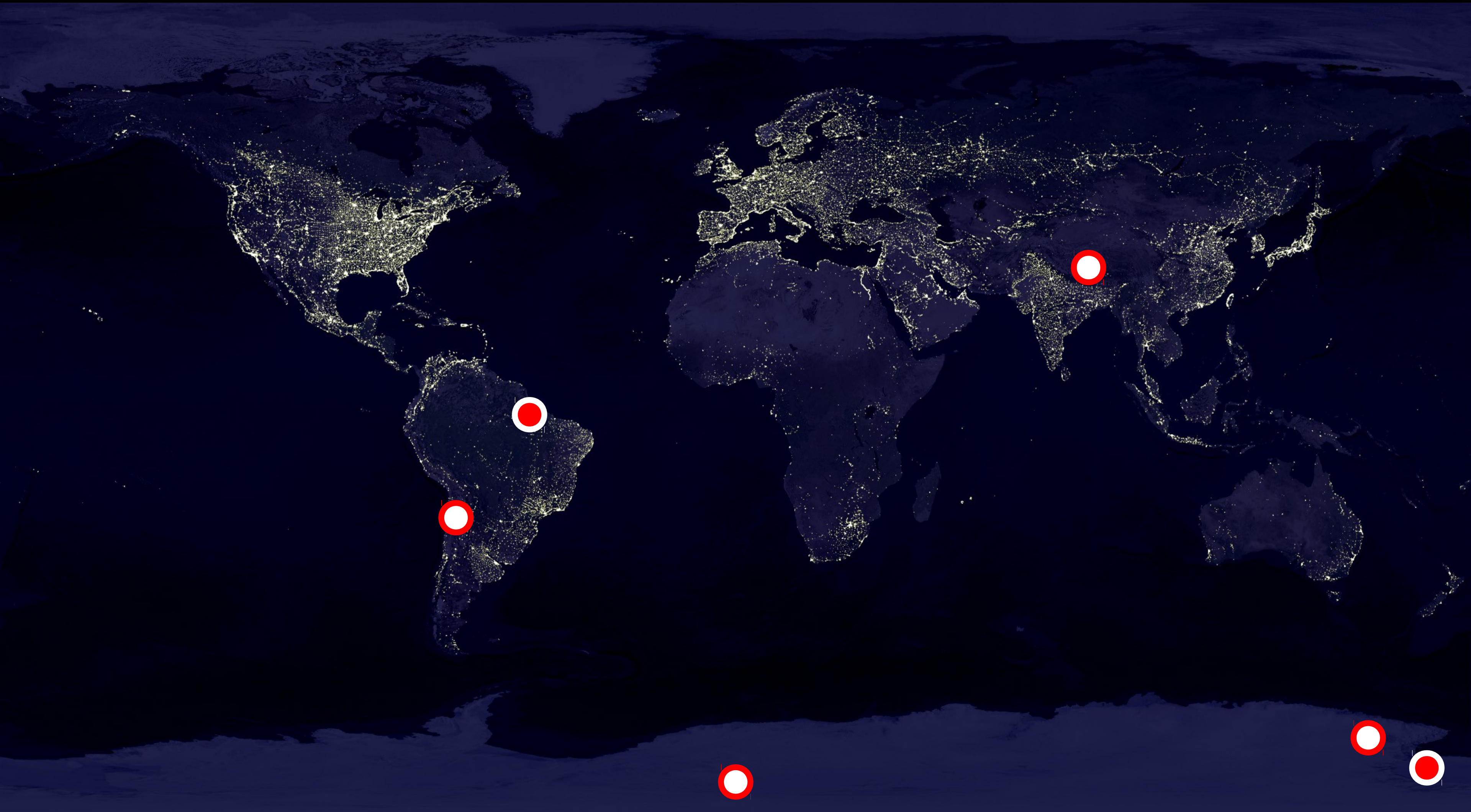


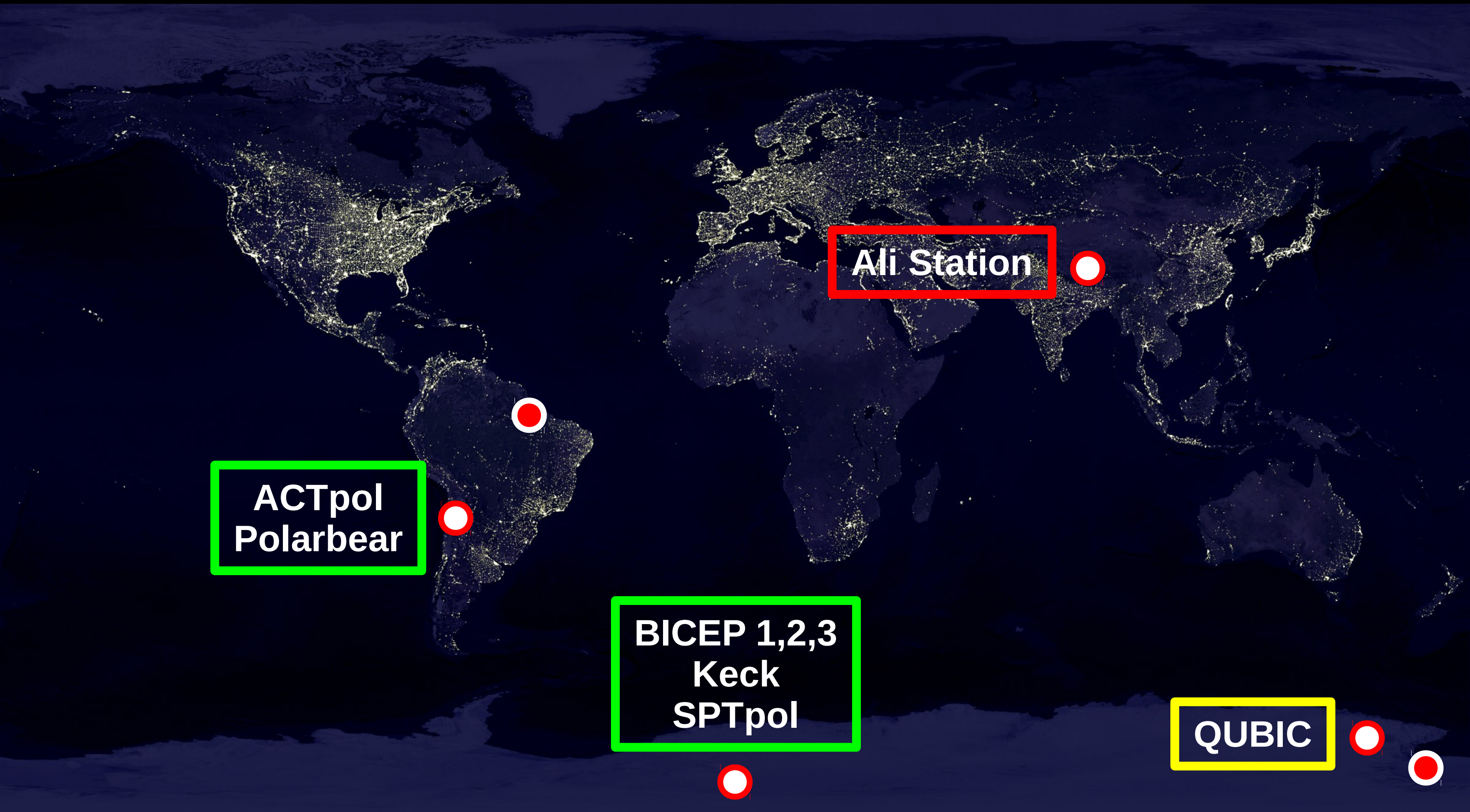
* LFn:
low frequency foreground band n
* HFn:
high frequency foreground band n
* Angular resolution:
All bands at few arcminutes FWHM
* Sensitivity:
All bands at few micro-K-arcminute

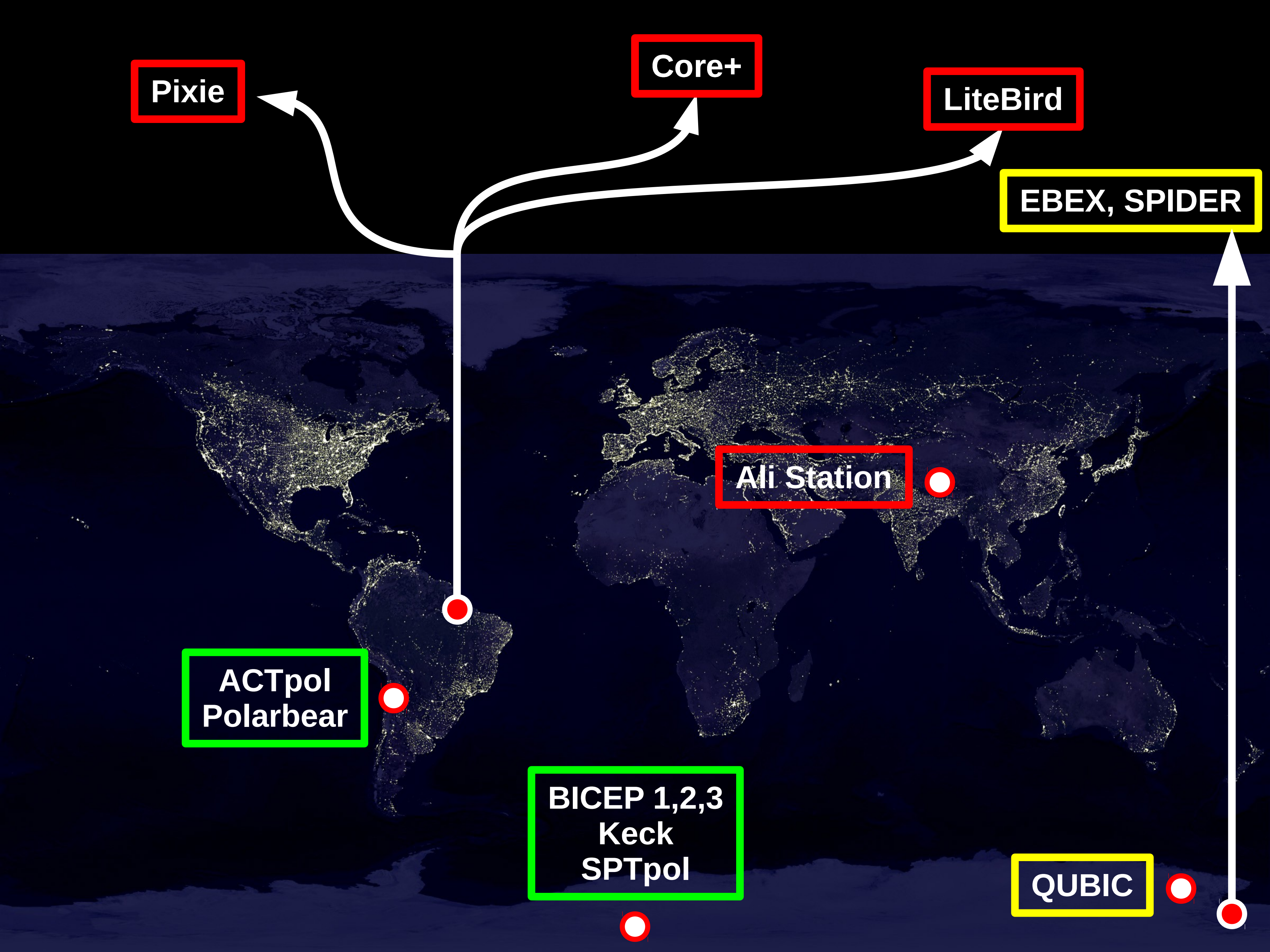
Satellite/Combined sub-orbital Probes: Litebird, PIXIE, S4, results > 2020

Minimum detectable r: few × 10^{-3}

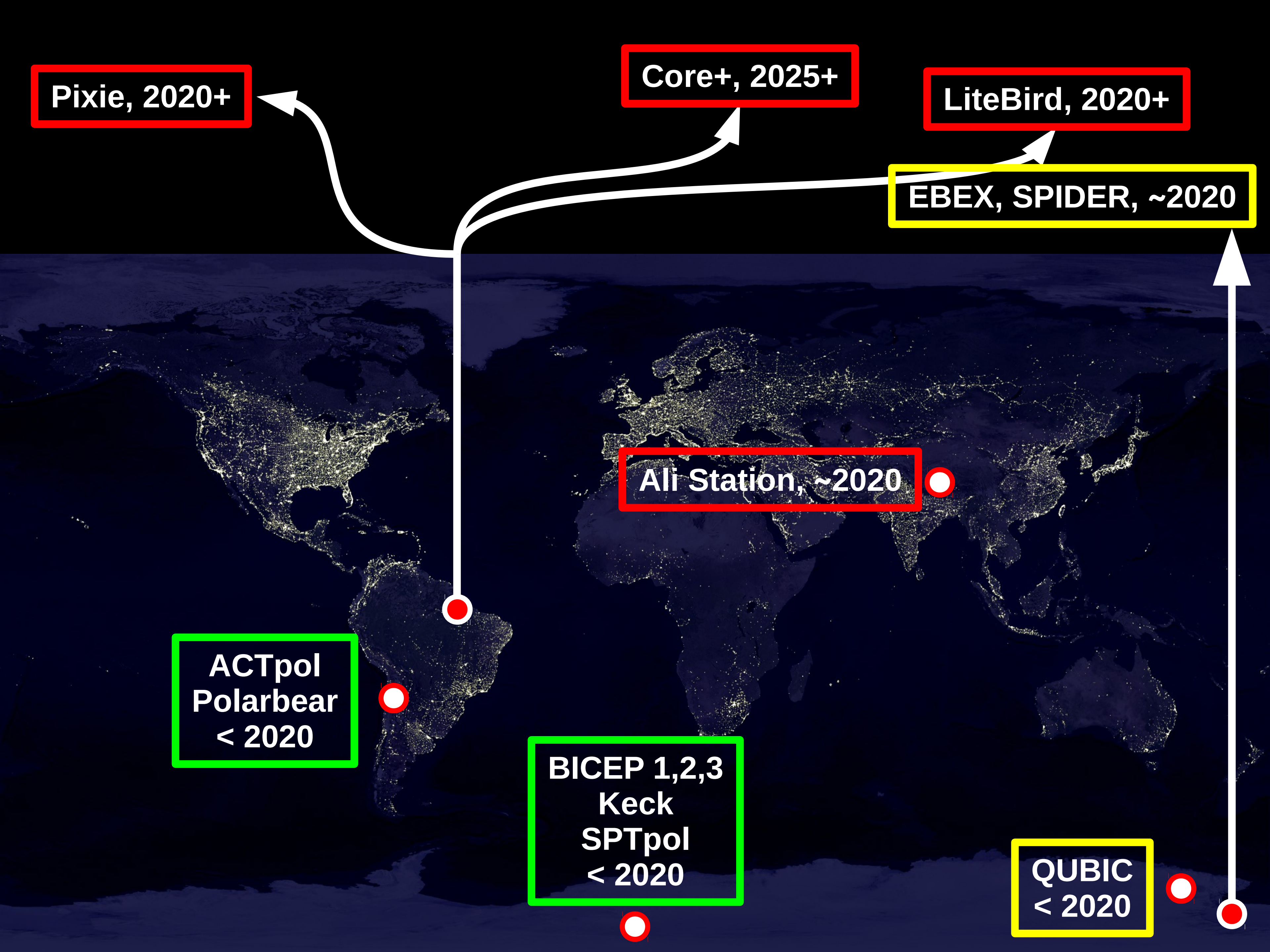





Ali Station
ACTpol
Polarbear
BICEP 1,2,3
Keck
SPTpol
QUBIC



Pixie
Core+
LiteBird
EBEX, SPIDER
Ali Station
ACTpol
Polarbear
BICEP 1,2,3
Keck
SPTpol
QUBIC


Pixie, 2020+
Core+, 2025+
LiteBird, 2020+
EBEX, SPIDER, ~2020
Ali Station, ~2020
ACTpol
Polarbear
< 2020
BICEP 1,2,3
Keck
SPTpol
< 2020
QUBIC
< 2020

Backup slides

CORE+ configuration

channel GHz	beam arcmin	N_{det}	ΔT μK.arcmin	ΔP μK.arcmin	ΔI kJy/sr.arcmin	$\Delta y \times 10^6$ y_{SZ}.arcmin	PS flux (5σ) mJy
60	14	28	11.3	16	1.14	-2.3	6
70	12	30	10.5	14.9	1.4	-2.2	6.3
80	10.5	38	9.1	12.9	1.53	-2.0	6
90	9.33	72	6.5	9.2	1.32	-1.5	4.6
100	8.4	84	6.0	8.5	1.43	-1.5	4.5
115	7.3	124	5.0	7.0	1.45	-1.3	4
130	6.46	180	4.2	5.9	1.43	-1.3	3.5
145	5.79	264	3.6	5.0	1.37	-1.3	3
160	5.25	254	3.8	5.4	1.6	-1.7	3.1
175	4.8	290	3.8	5.3	1.69	-2.2	3.0
195	4.31	346	3.8	5.3	1.79	-4.1	2.9
220	3.82	200	5.8	8.1	2.78	-	4.0
255	3.29	140	8.9	12.6	4.11	5.5	5.1
295	2.85	60	19.4	27.4	7.84	5.7	8.4
340	2.47	60	30.9	43.7	9.91	5.6	9.2
390	2.15	60	55.0	77.8	12.63	7.0	10.2
450	1.87	60	116.6	164.8	16.48	10.9	11.5
520	1.62	60	295.7	418.2	21.71	21.0	13.2
600	1.4	60	899.7	1272.4	28.61	50.3	15.0

Core+ proposal

LiteBird configuration

Band GHz	Beam[†] [arcmin]	NET [$\mu K\sqrt{s}$]	Pixel # per wafer	Wafer #	Bolometer #	NETarr [$\mu K\sqrt{s}$]	Sensitivity [μKarcmin]
60	75	99	19	8	304	5.7	10.3
78	58	62	19	8	304	3.6	6.5
100	45	45	19	8	304	2.6	4.7
140	32	40	37	5	370	2.1	3.7
195	24	33	37	5	370	1.7	3.1
280	16	40	37	5	370	2.1	3.8

Matsumura et al. ArXiv:1311.2847

Planck observed dust polarization at high latitudes

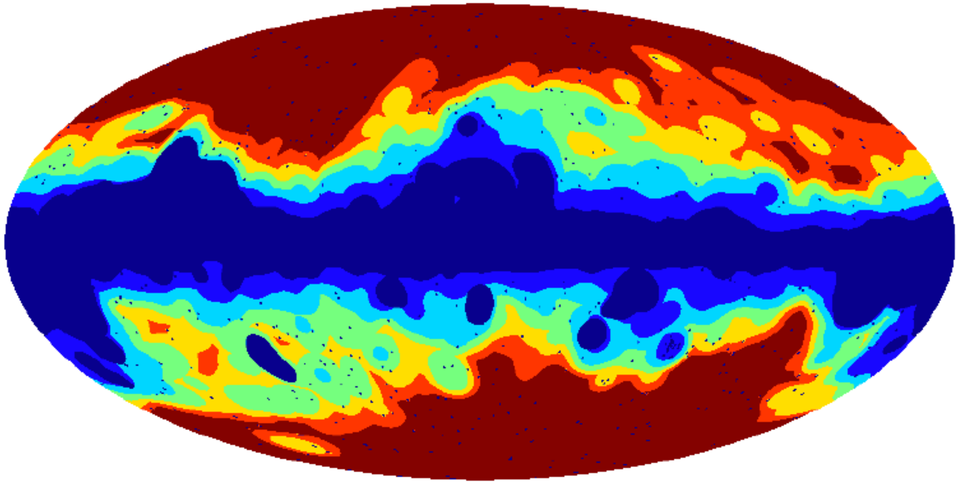


Fig. 1: Masks and complementary selected large regions that retain fractional coverage of the sky $f_{\rm sky}$ from 0.8 to 0.3 (see details in Sect. 3.3.1). The darkest blue is the CO mask, whose complement is a selected region with $f_{\rm sky} = 0.8$. In increments of $f_{\rm sky} = 0.1$, the retained regions can be identified by the colours dark red (0.3) to dark blue (0.8), inclusively. Also shown is the (unapodized) point source mask used.

Planck 2014

Planck observed dust polarization in the BICEP2 area

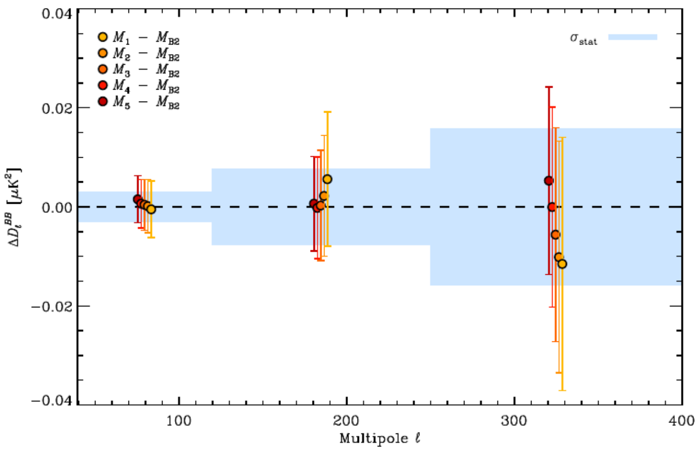


Fig. C.2: *Planck* 353 GHz $\mathcal{D}_\ell^{BB}$ angular power spectrum differences extrapolated to 150 GHz, determined from the spectra computed on the M_{1-5} regions presented in Appendix C.2 and the spectrum computed on M_{B2}. $\mathcal{D}_\ell^{BB}$ difference values for the five regions are displayed using colours from yellow (for M_1) to dark red (for M_5). As in Fig. 9, the blue boxes represent the statistical uncertainties from noise associated with the M_{B2} spectrum. They are centred on zero, since we compute spectrum differences here.

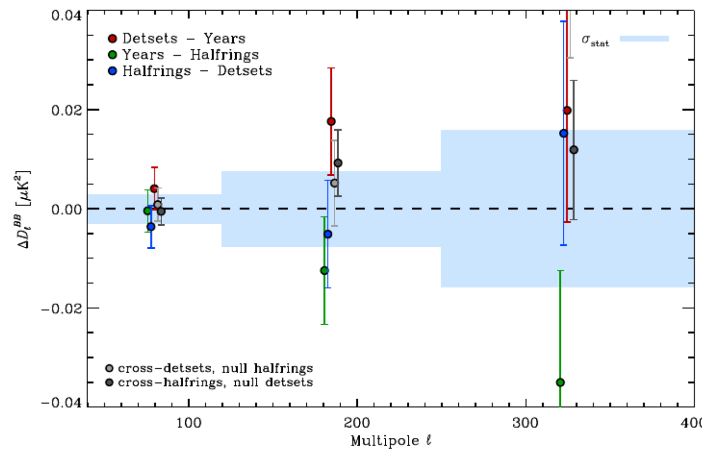


Fig. C.3: *Planck* 353 GHz $\mathcal{D}_\ell^{BB}$ angular power spectrum differences extrapolated to 150 GHz, computed from the following cross-spectra differences: DetSets minus Years (red circles); Years minus HalfRings (green circles); and HalfRings minus DetSets (blue circles). We also show the null test performed using the cross-DetSets spectra of the HalfRing half-differences (light grey circles) and the cross-HalfRings of the DetSet half-differences (dark grey circles) at 353 GHz. As in Fig. 9, the blue boxes represent the statistical uncertainties from noise; these are centred on zero, since we do not expect any signal for these null tests.

Planck 2014

The Planck polarisation at 353 GHz: the BICEP2 area

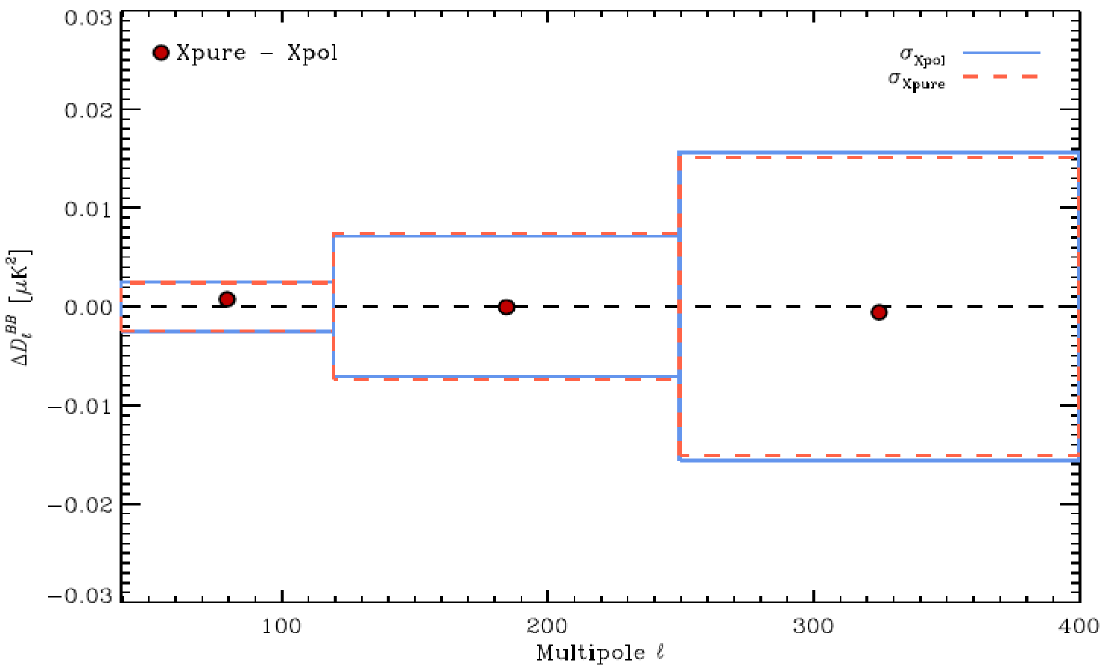
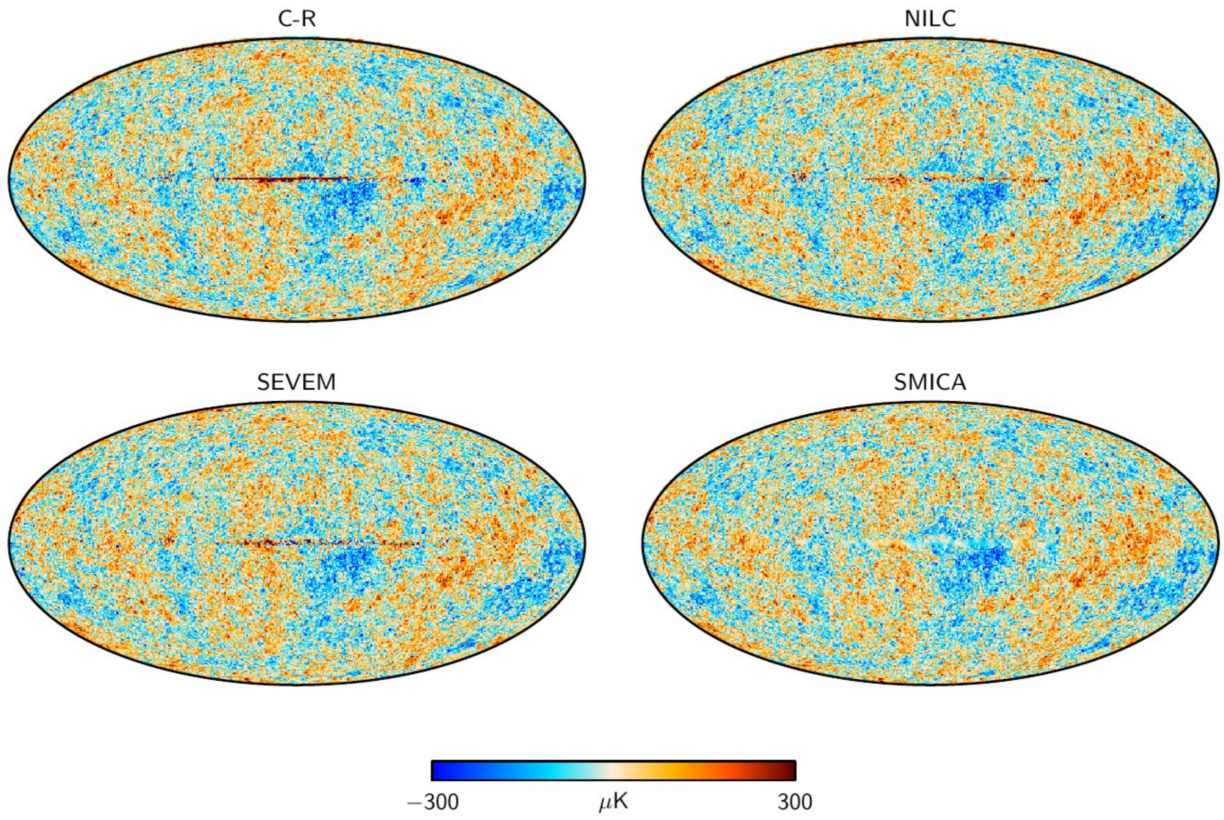


Fig. C.1: **Xpol** minus **Xpure** *Planck* 353 GHz $\mathcal{D}_\ell^{BB}$ angular power spectrum differences extrapolated to 150 GHz, computed from the cross-DetSets on M_{B2} (red circles). The blue boxes represent the $\pm 1\,\sigma$ errors computed using **Xpol** from the data on M_{B2}, while the dashed-orange boxes are the **Xpure** $\pm 1\,\sigma$ errors coming from Monte Carlo simulations of *Planck* noise.

Planck 2014

CMB



Planck 2013

Component separation in one slide

- Foreground variables are parametrized, and fitted through:
  - Minimum variance
  - Physical parametrization (amplitude, spectral parameters)
- See Planck 2013 for reviews
- Our approaches: Stompor et al. (2009, physical parametrization), B et al. 2004 (minimum variance)
- Analytic linearization available (Errard and Stompor 2012) for forecasts

Concluding remarks

- The Galactic contamination to CMB B-modes has been predicted, and confirmed, to be non-negligible
- Normalization is available for dust, while for synchrotron, despite of WMAP and Planck observations are poor for being exploited in a B-mode context
- At least two foreground monitor channels, with same sensitivity and angular resolution of CMB channels, are needed in order to fit and marginalize them out
- Likely to require a combination of near future experiments, and if successful, a post-Planck satellite