Component separation for B-mode experiments

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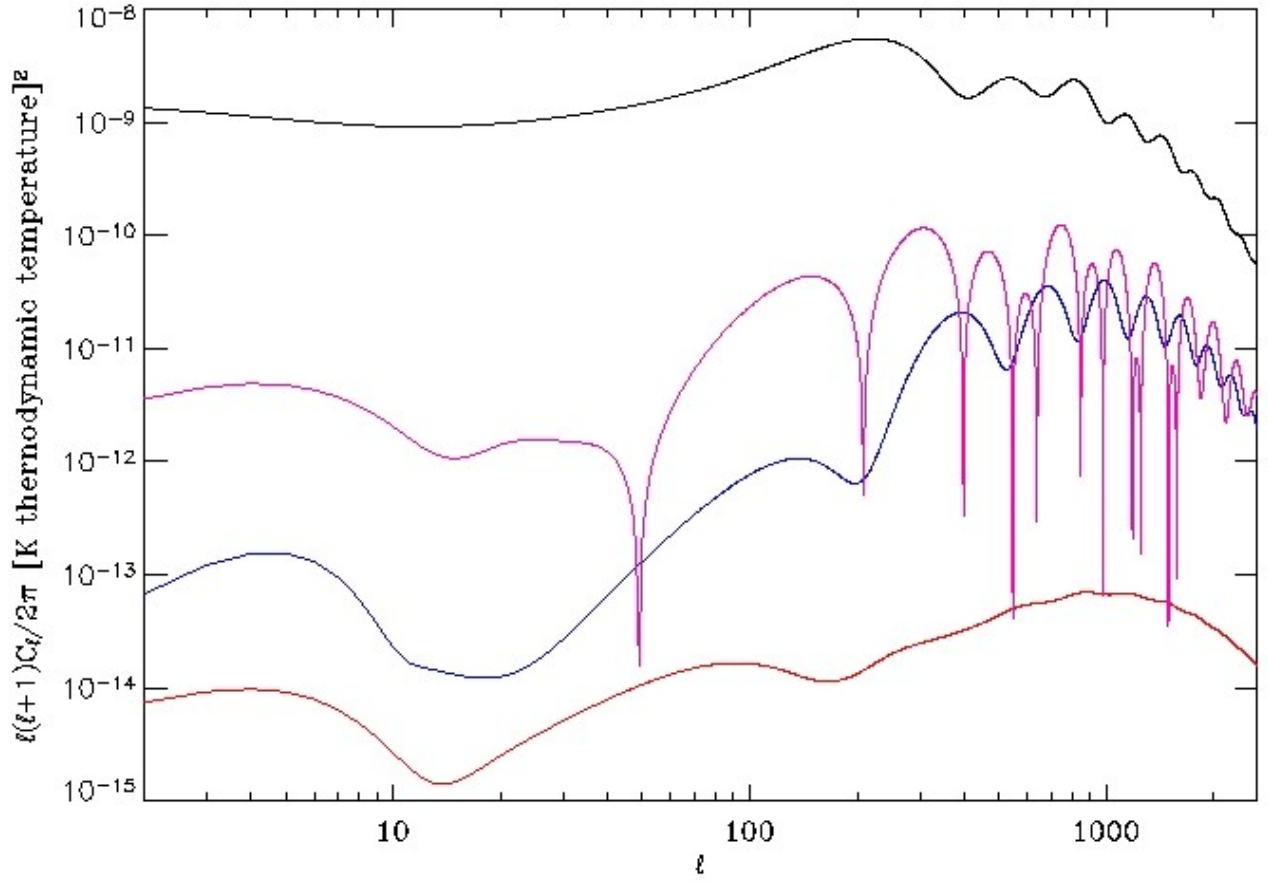
EWASS 2015

Outline

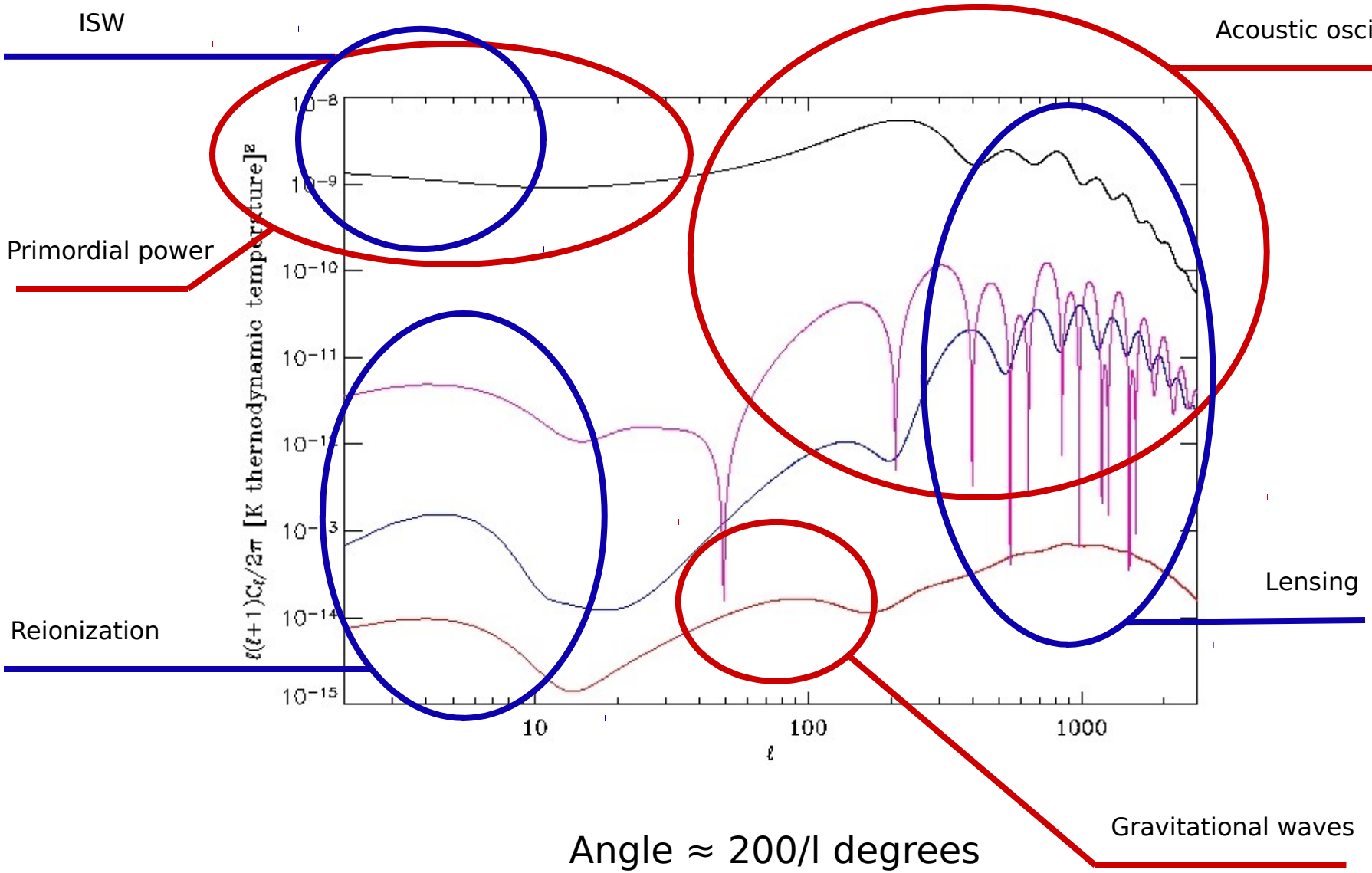
- Galactic foreground contamination to cosmological B-modes
- Status of observations
- Component separation
- Concluding remarks

CMB angular power spectrum



Angle ≈ 200/l degrees

CMB angular power spectrum



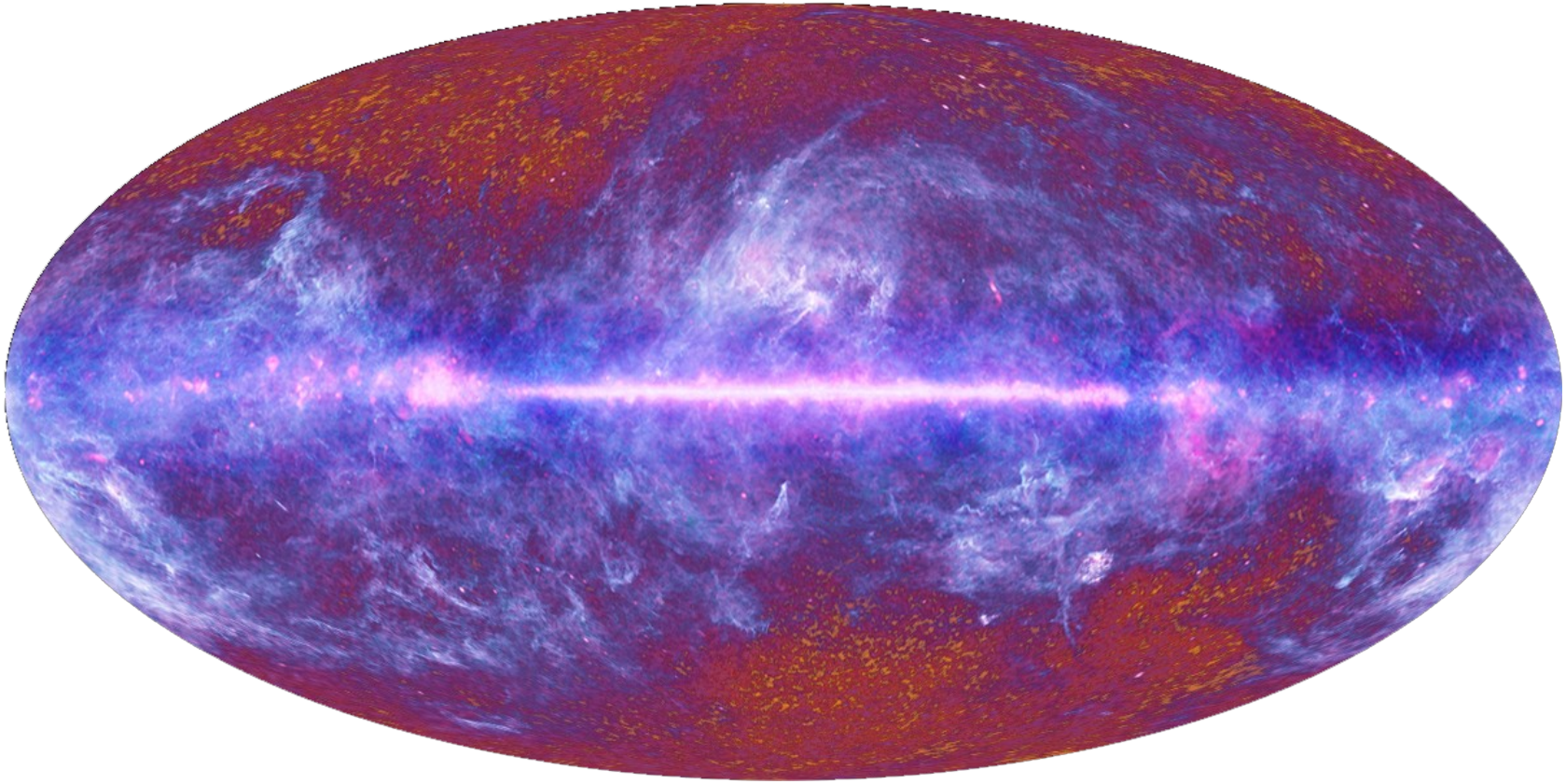
Angle ≈ 200/l degrees

Galactic foreground Contamination to cosmological B-modes

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

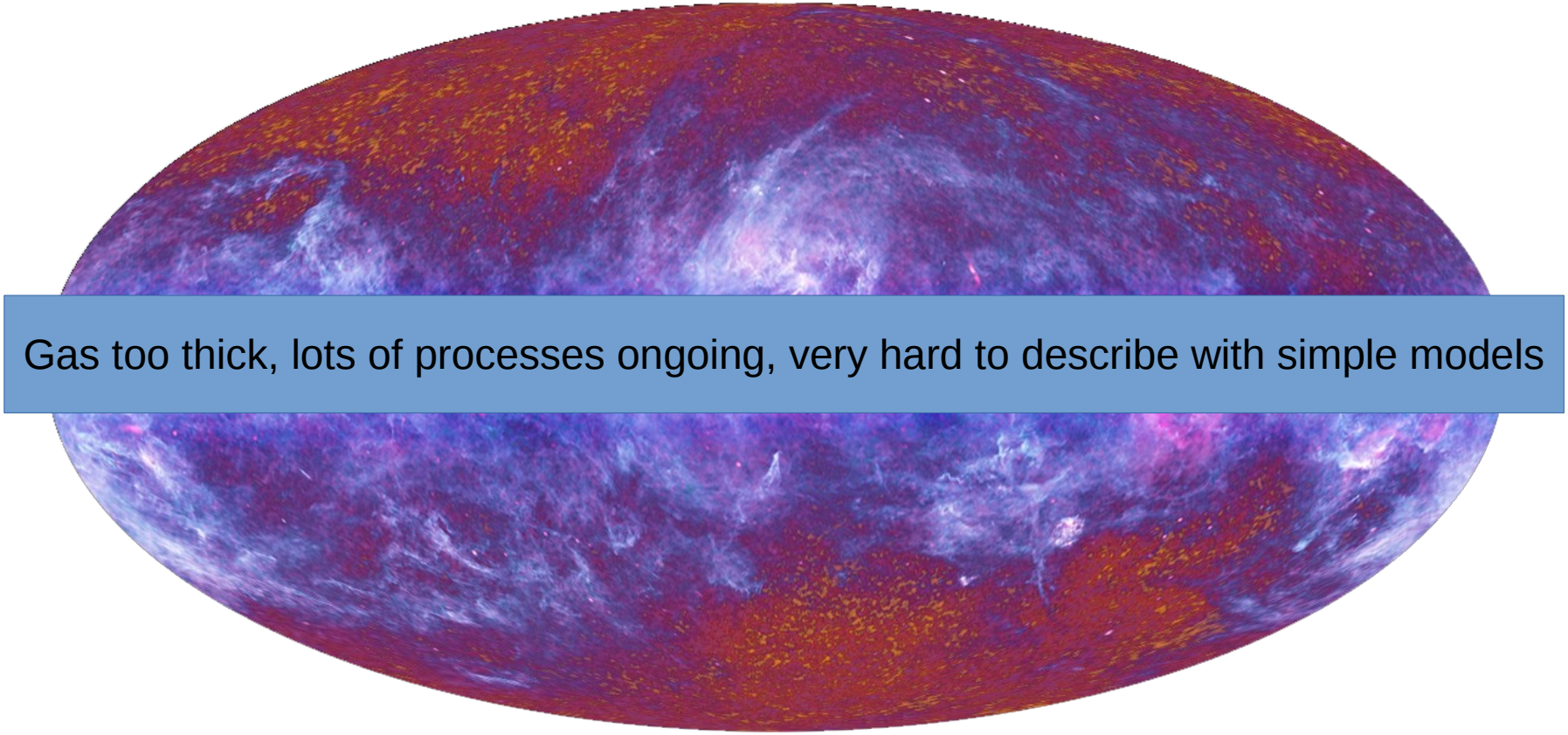
Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific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

F=A (sky direction) × F(frequency)



Planck 2013

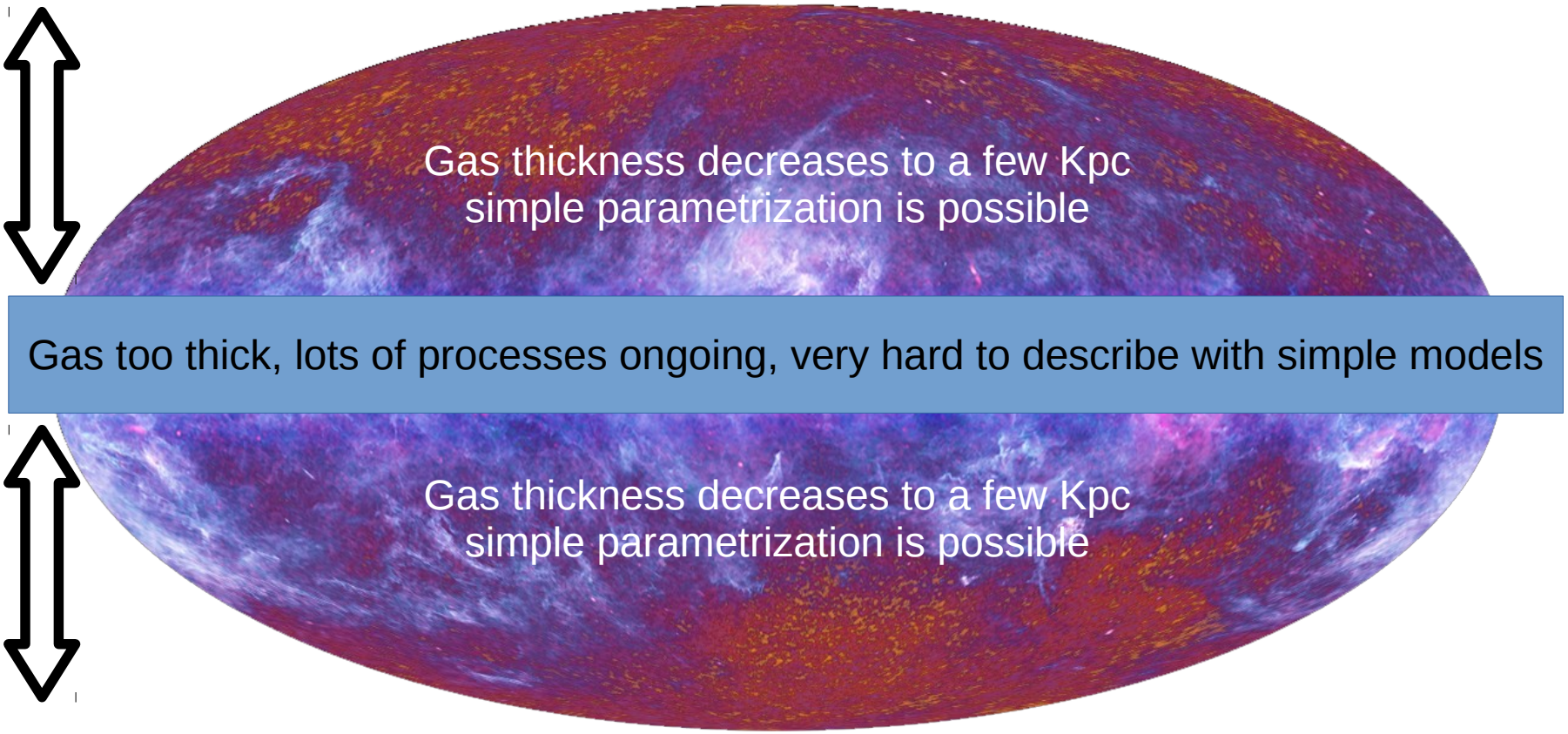
F=A (sky direction) × F(frequency)



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

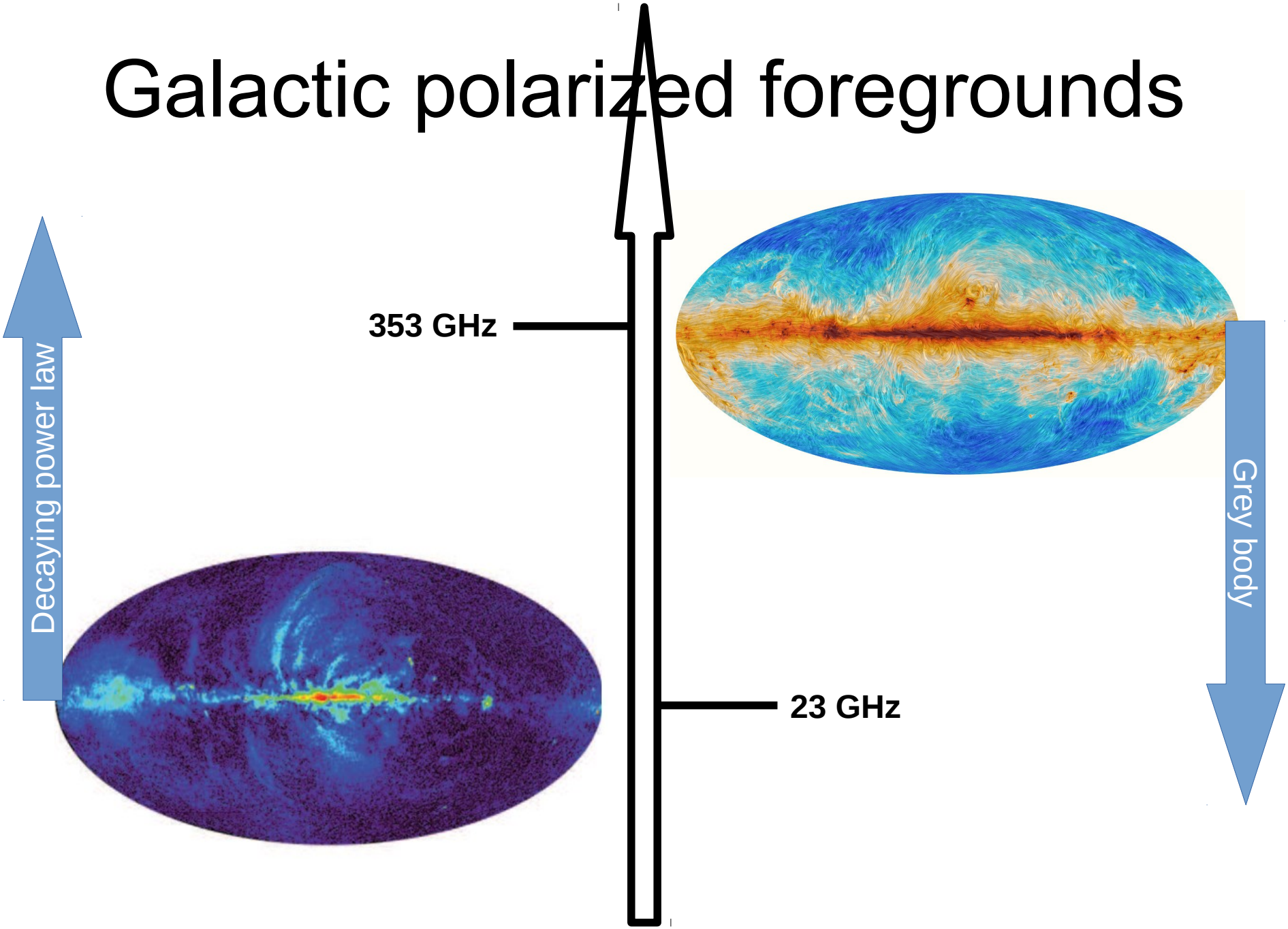
Planck 2013

F=A (sky direction) × F(frequency)

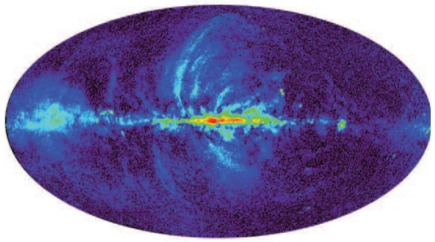


Planck 2013

Galactic polarized foregrounds

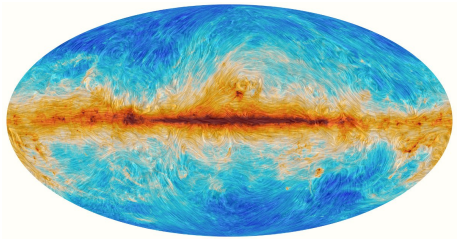


Polarized synchrotron



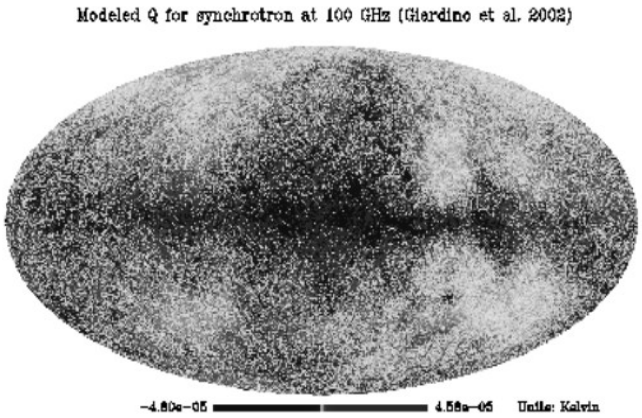
- Amplitude: cosmic ray electrons spilarizing around the Galactic magnetic field
- Frequency scaling: approximate decaying power law frequency scaling ($F_{RJ} \sim f^{-3}$), determined by the electron distribution in energy
- Data: total intensity and polarization, several surveys at radio frequencies,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

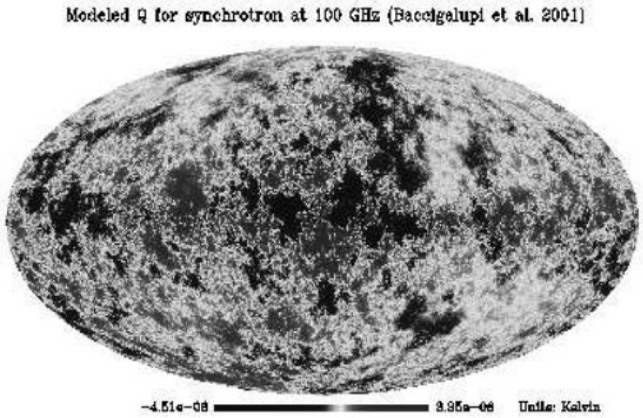
Polarized dust

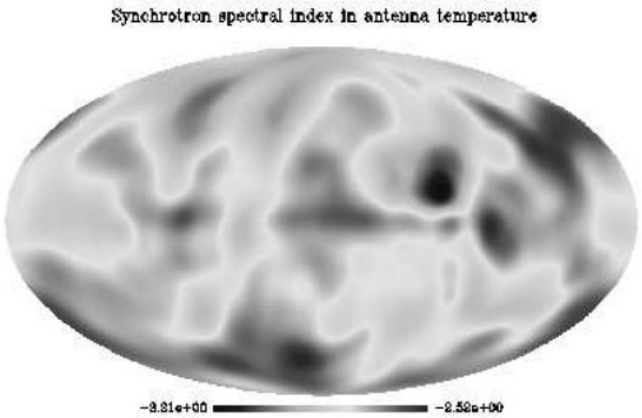


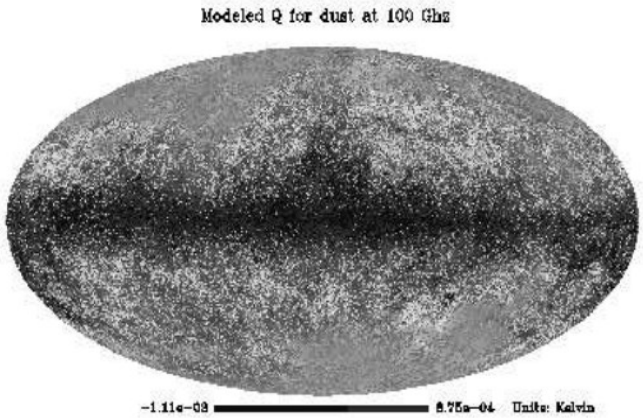
- Amplitude: magnetized dust grains emitting almost thermally, linearly polarized via local alignment with the Galactic magnetic field
- Frequency scaling: grey body $F_{RJ} \sim BB(f) \times f^{1.5}$
- Total intensity data: high resolution (few arcminutes) and sensitivity (IRAS and Planck) at 3000, 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

Foreground model building: the early days

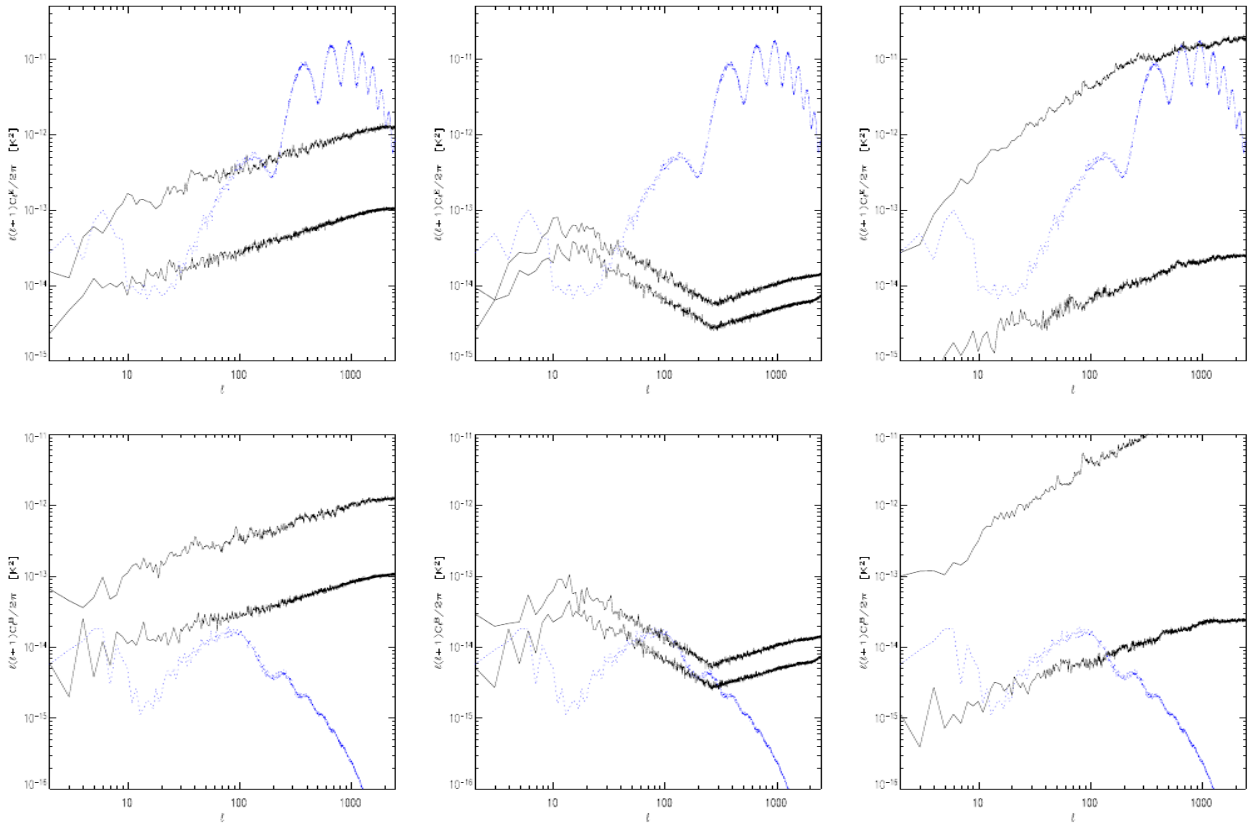






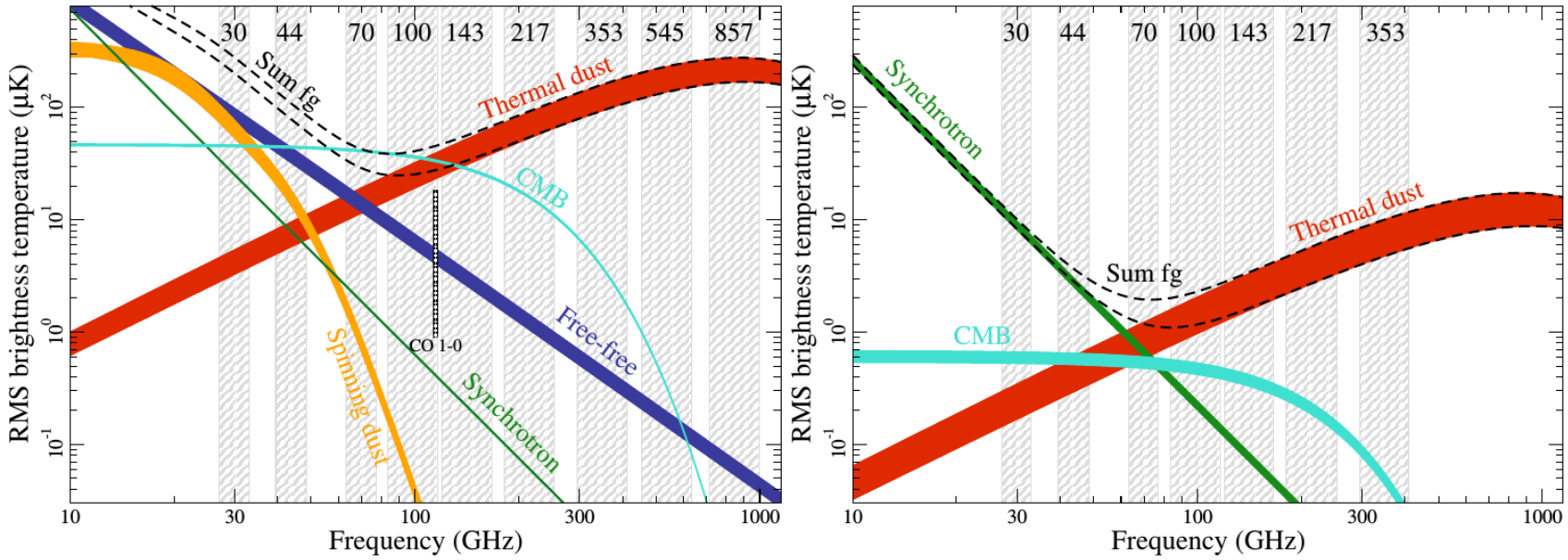


Foreground model building: the early days



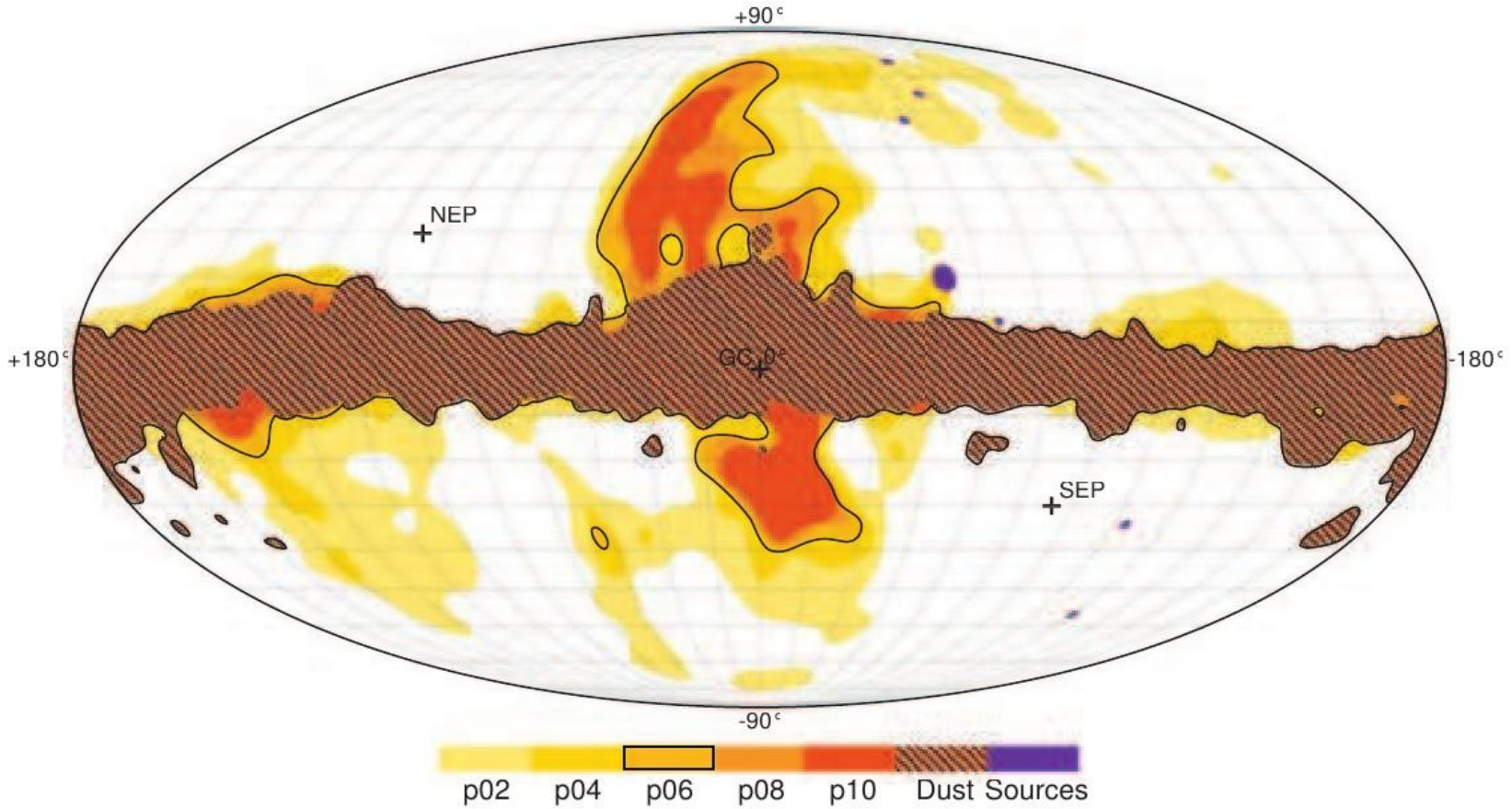
B03

Foregrounds and frequency



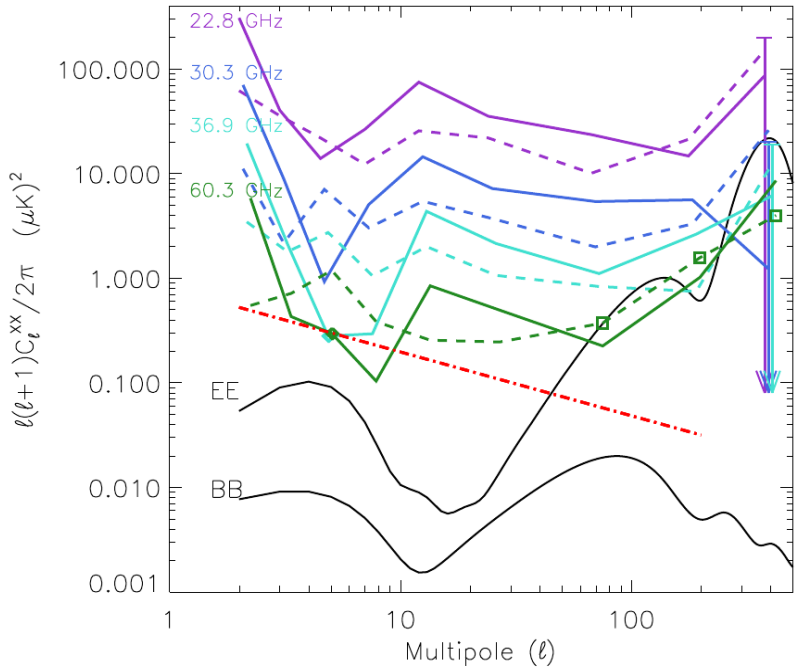
Planck 2015

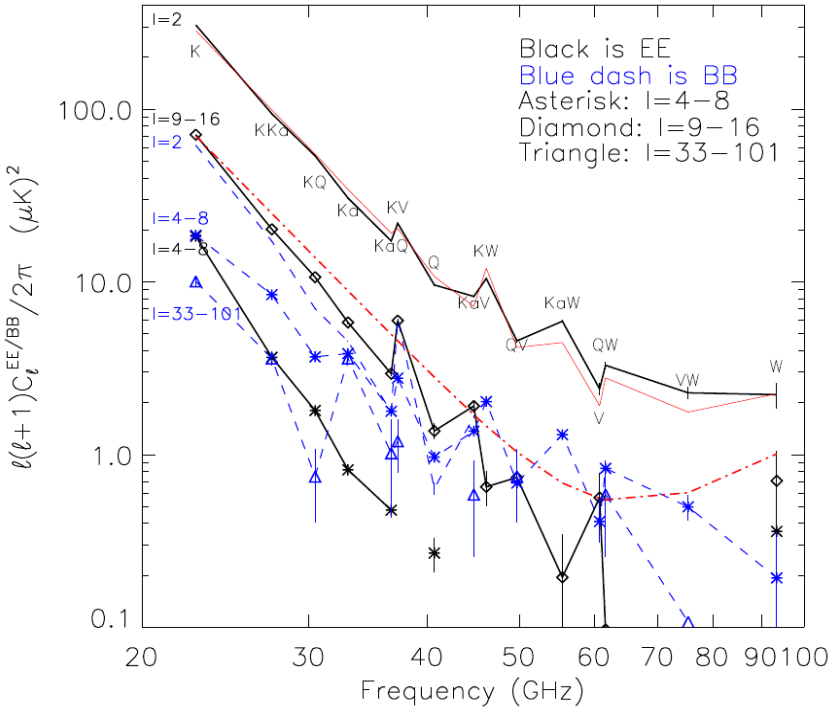
Observations: WMAP



Page et al. 2007 for WMAP

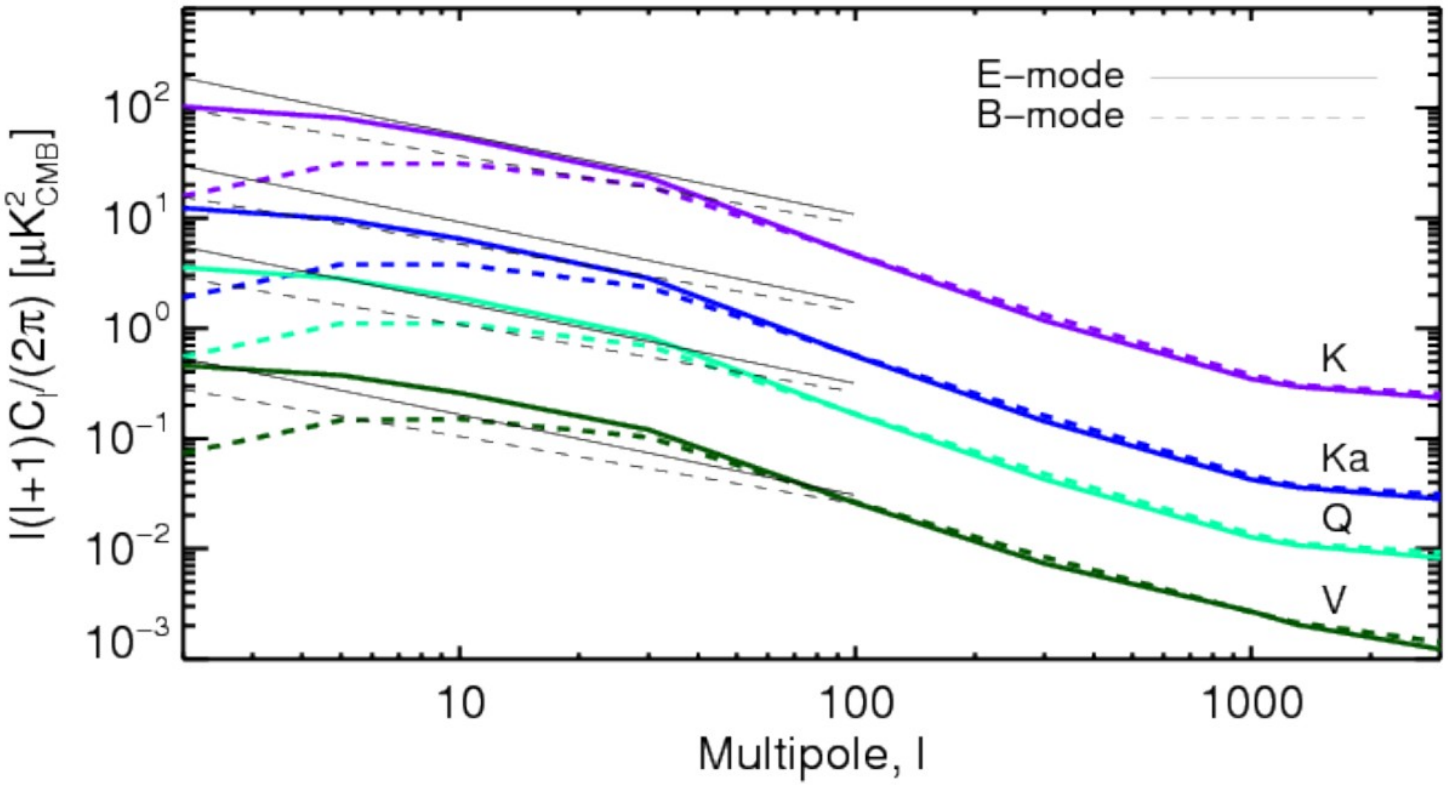
WMAP polarised foregrounds





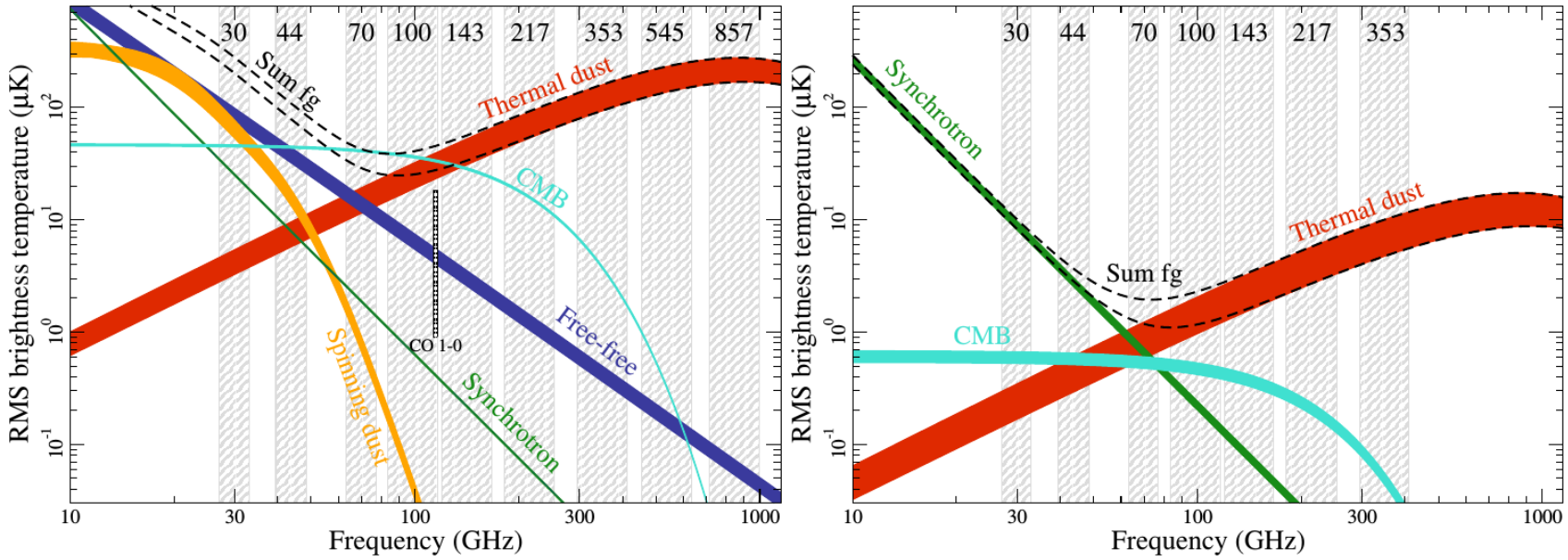
Page et al. 2007 for WMAP

The (WMAP matching) Planck sky model



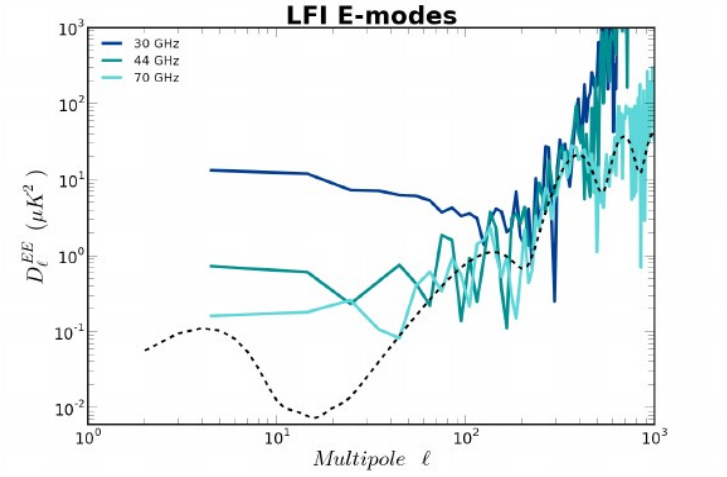
Delabrouille et al. 2012

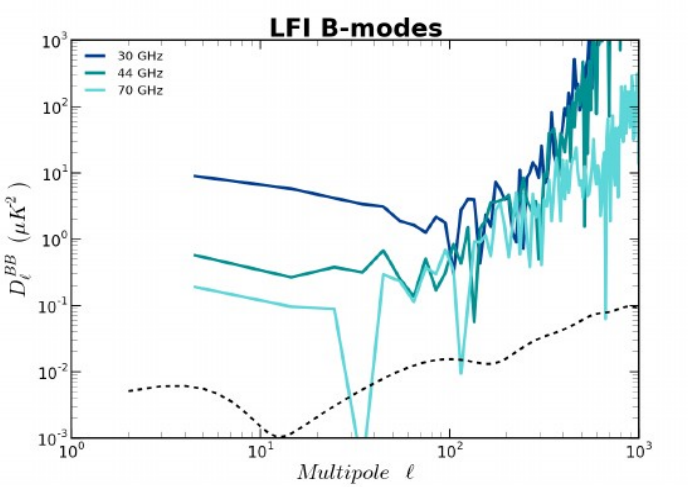
Foregrounds and frequency

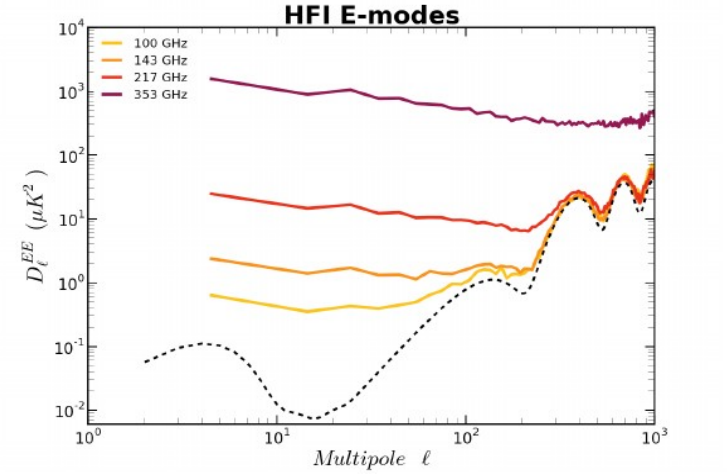


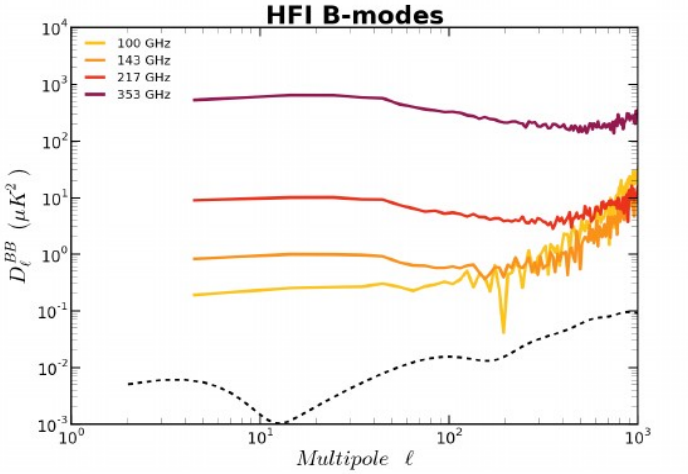
Planck 2015

Planck foregrounds across multipoles with P06 masking





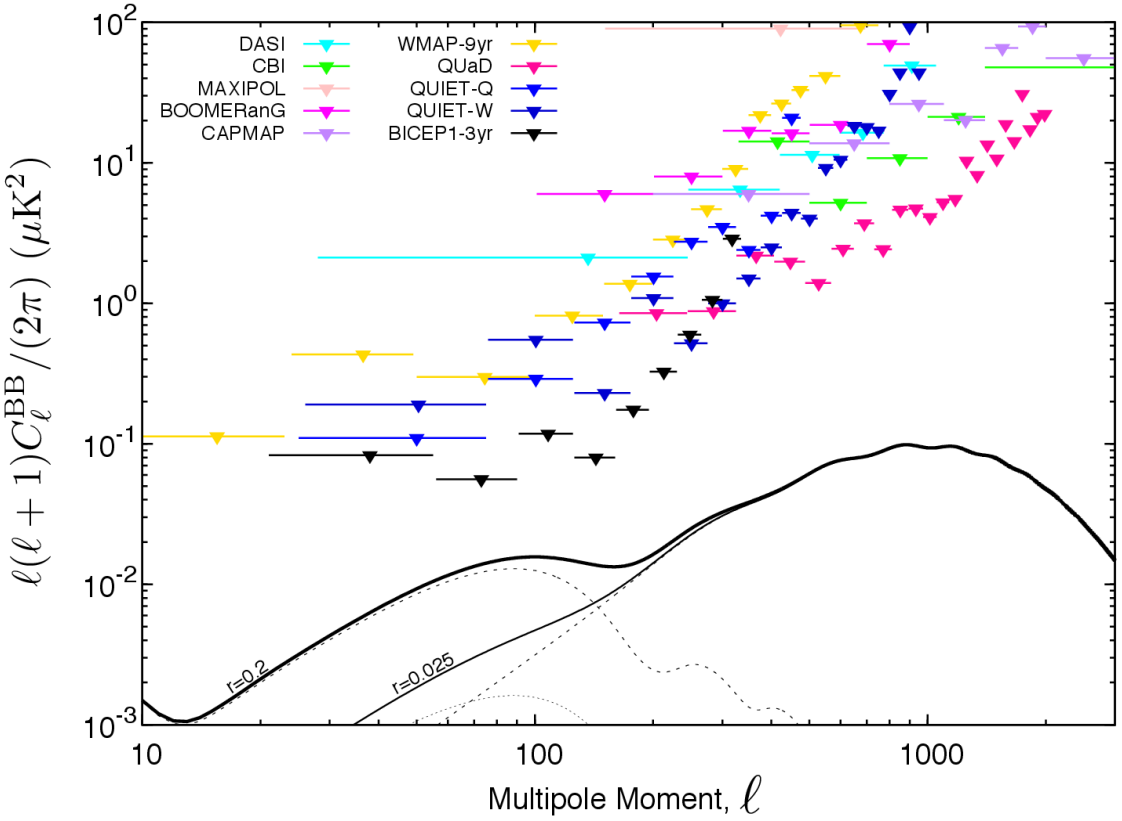




Planck 2015, plot by Krachmanicoff

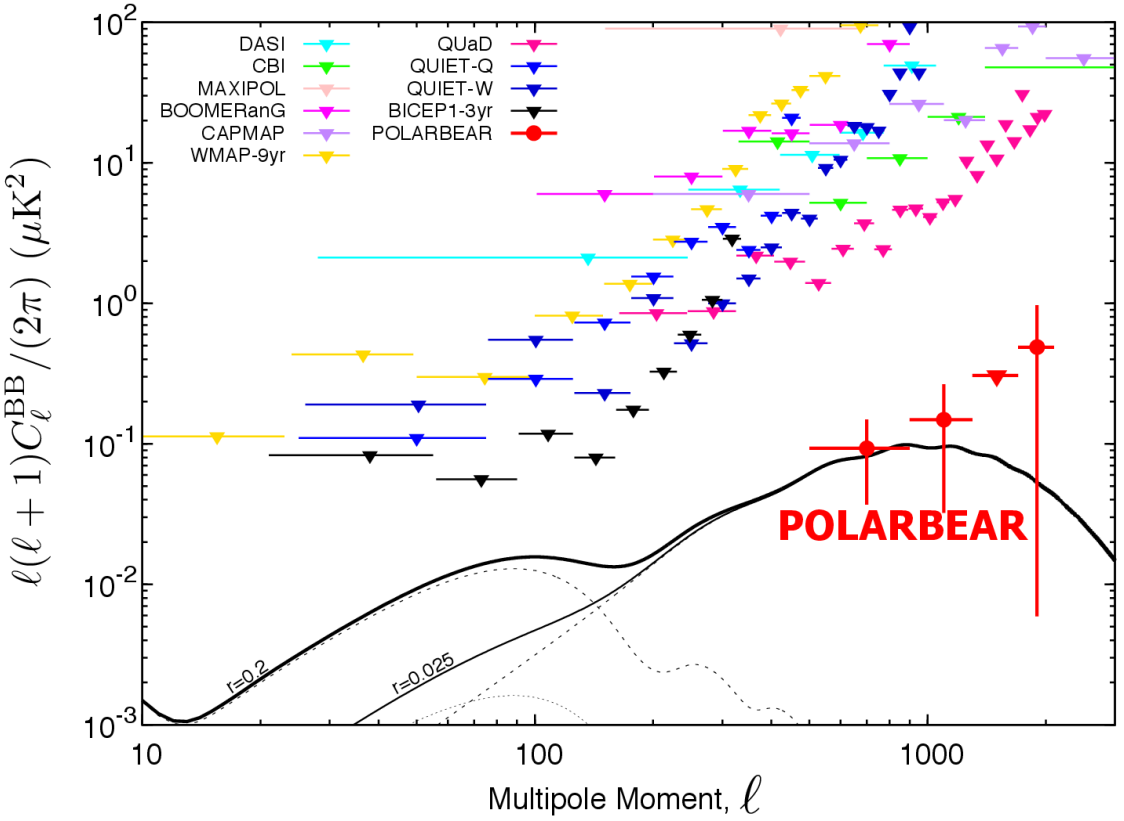
Status of observations

Early 2014



Plots by Chinone

March 2014



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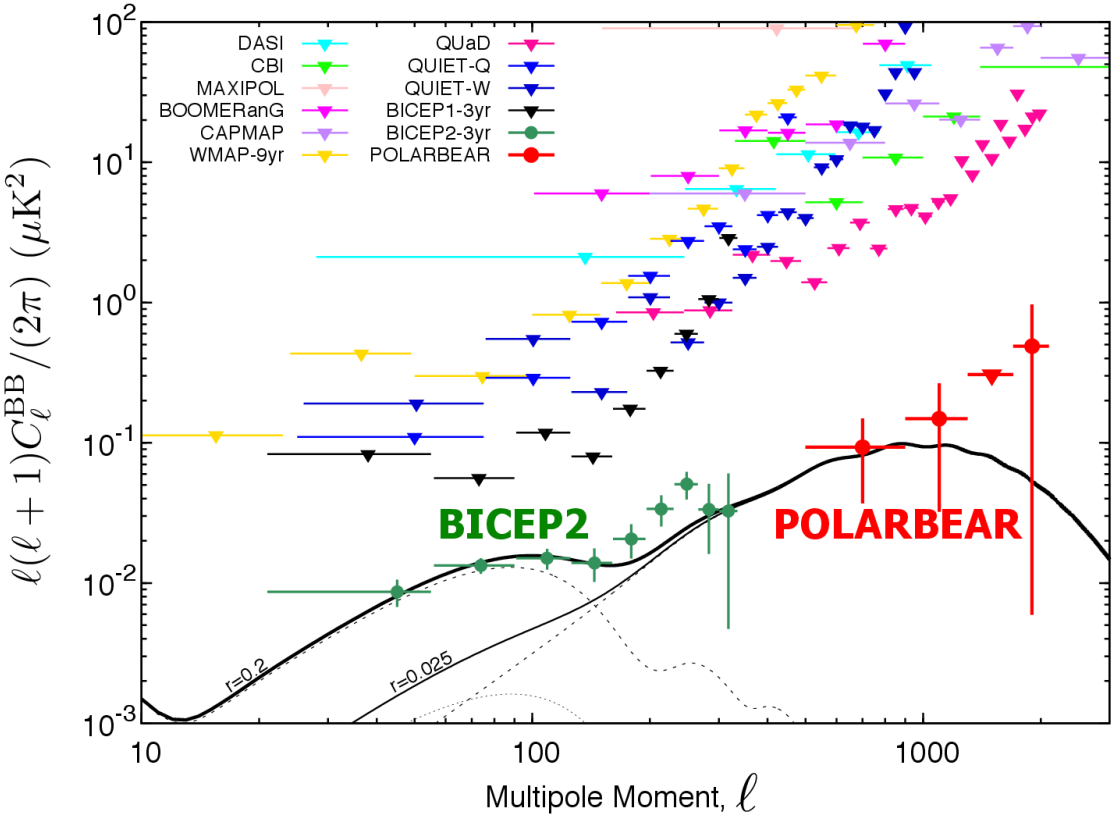
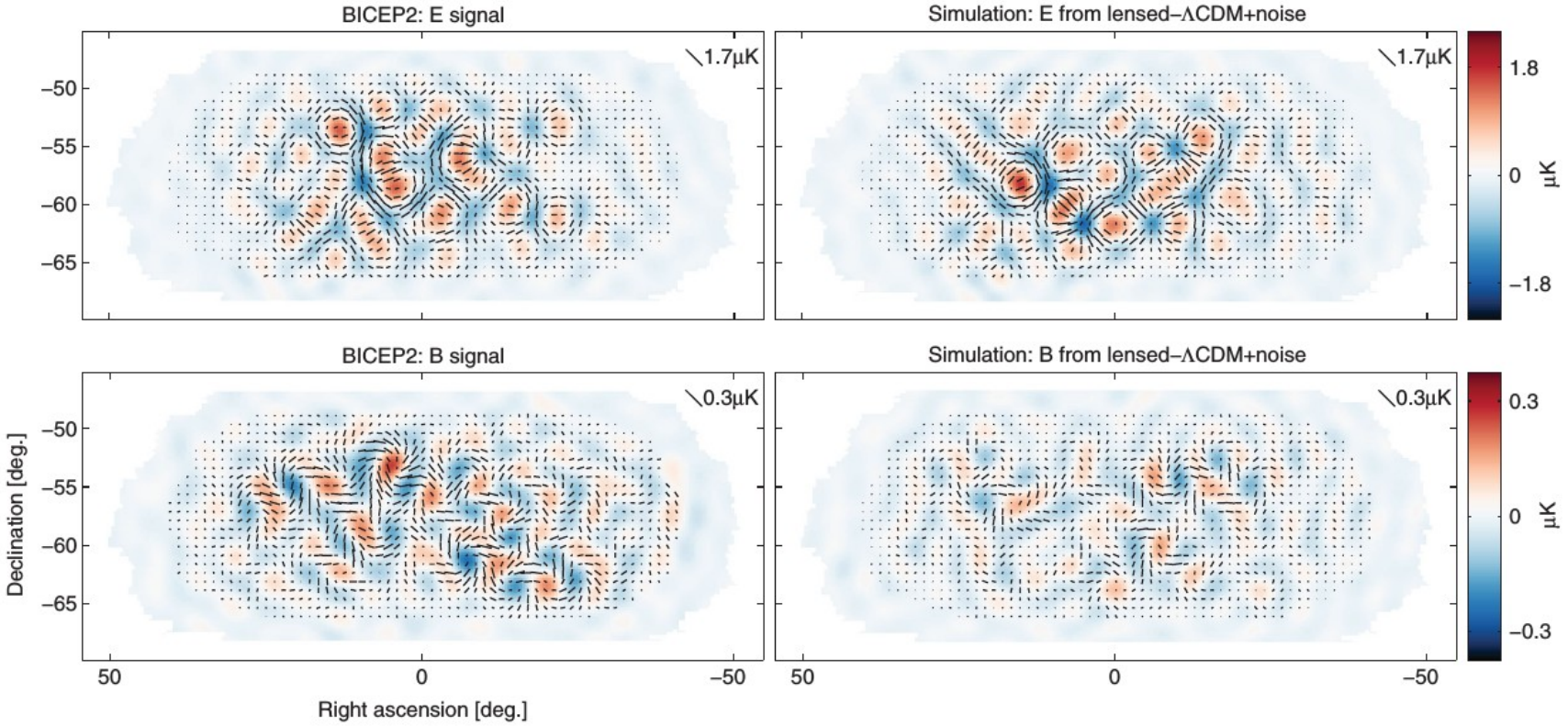
March 2014



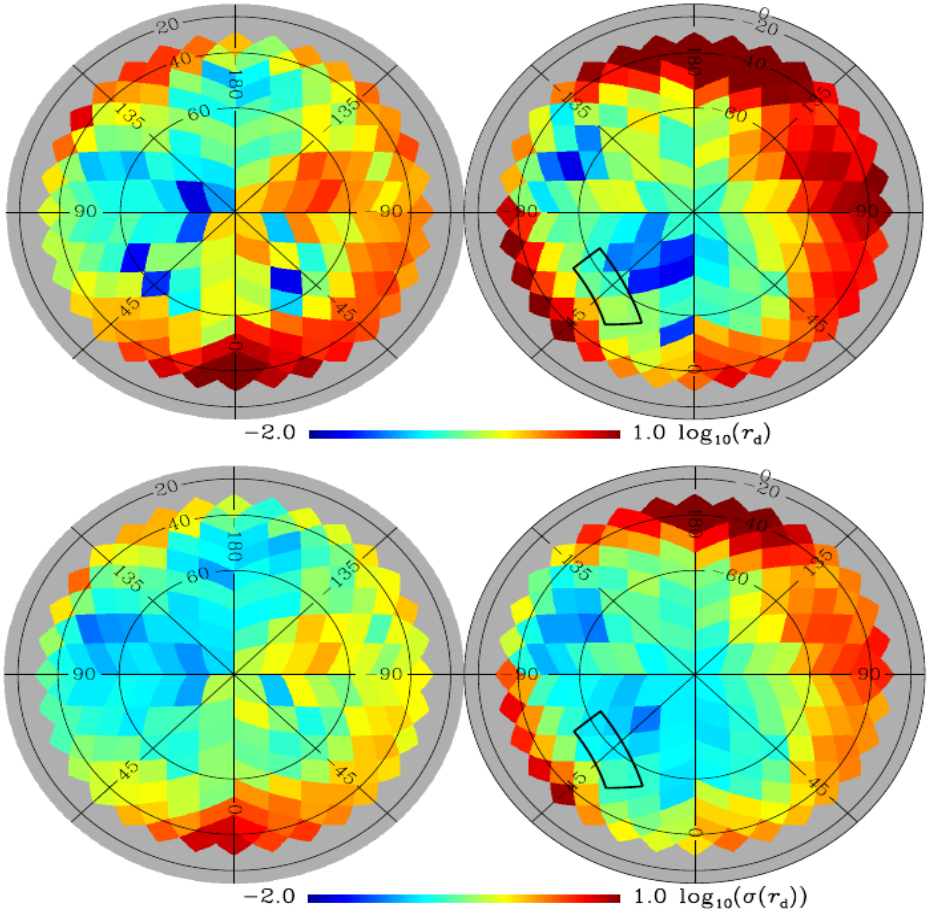
Plots by Chinone

The B-modes at degree scale



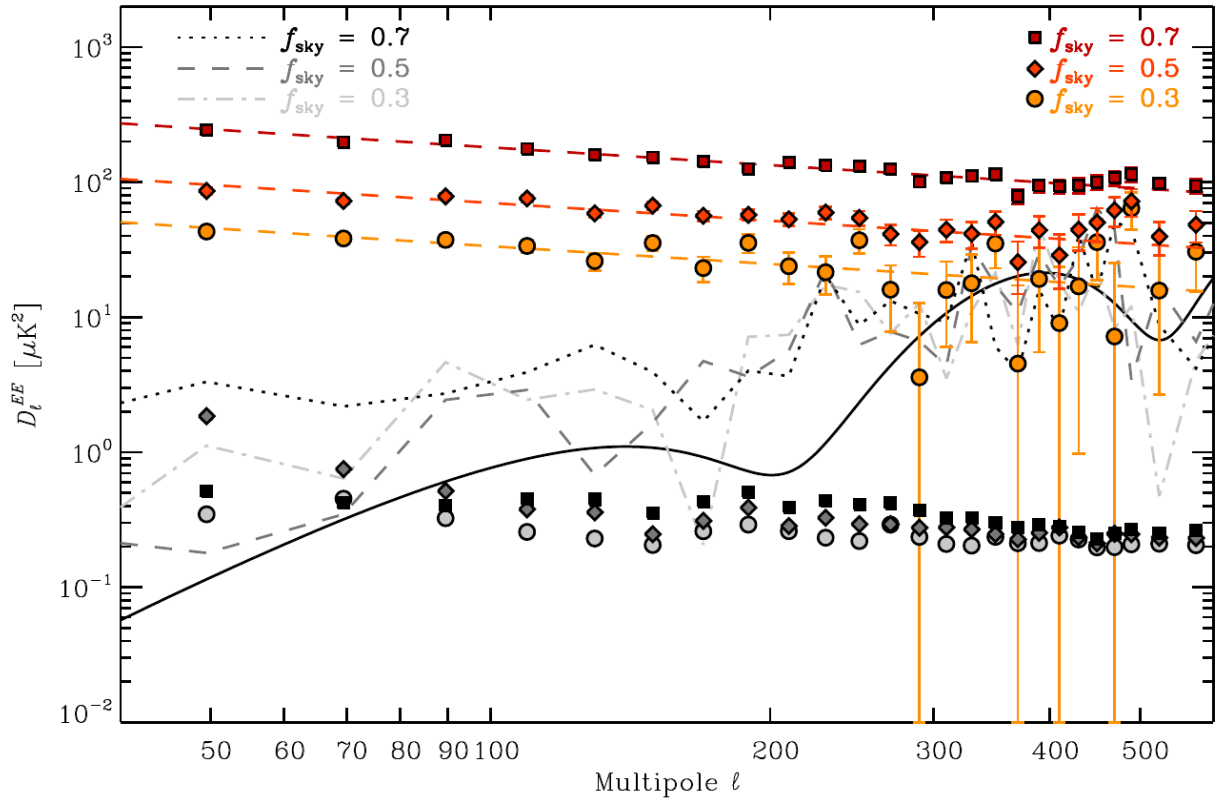
BICEP2 2014

Planck observed dust polarization at high latitudes



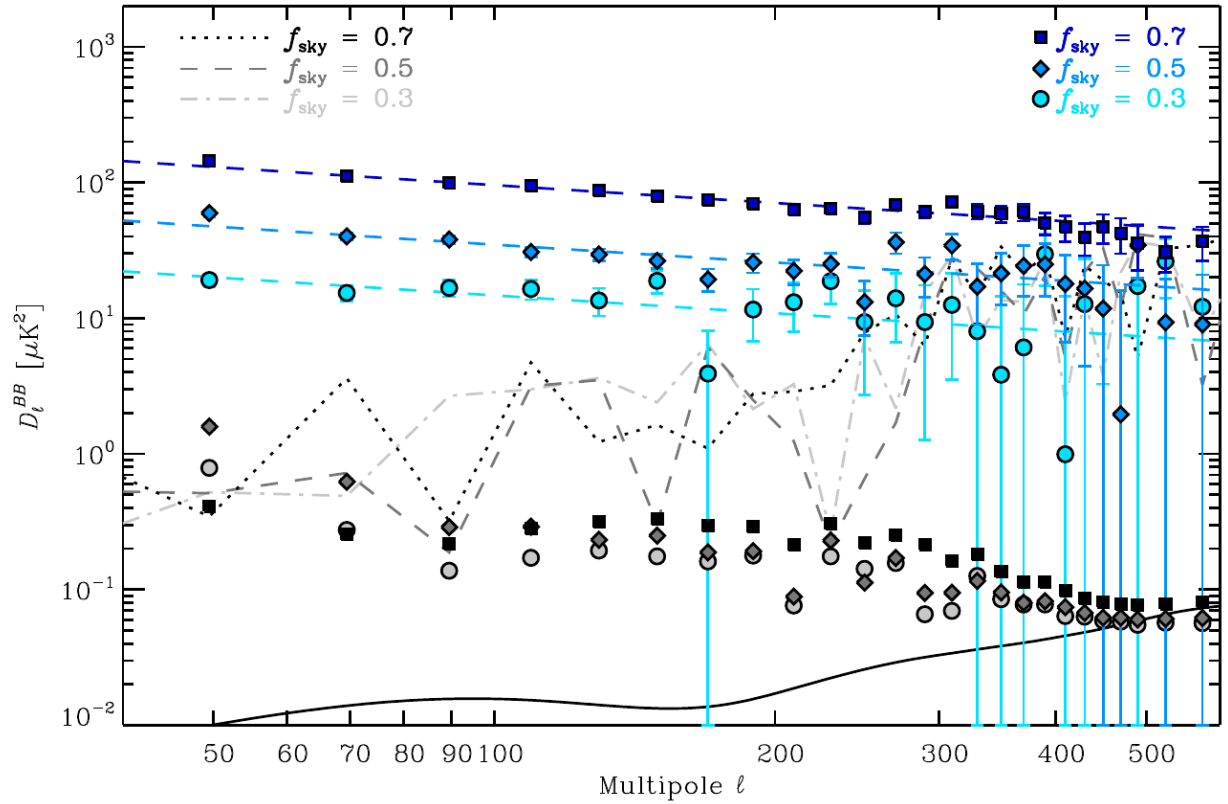
Planck 2014

Planck observed dust polarization at high latitudes



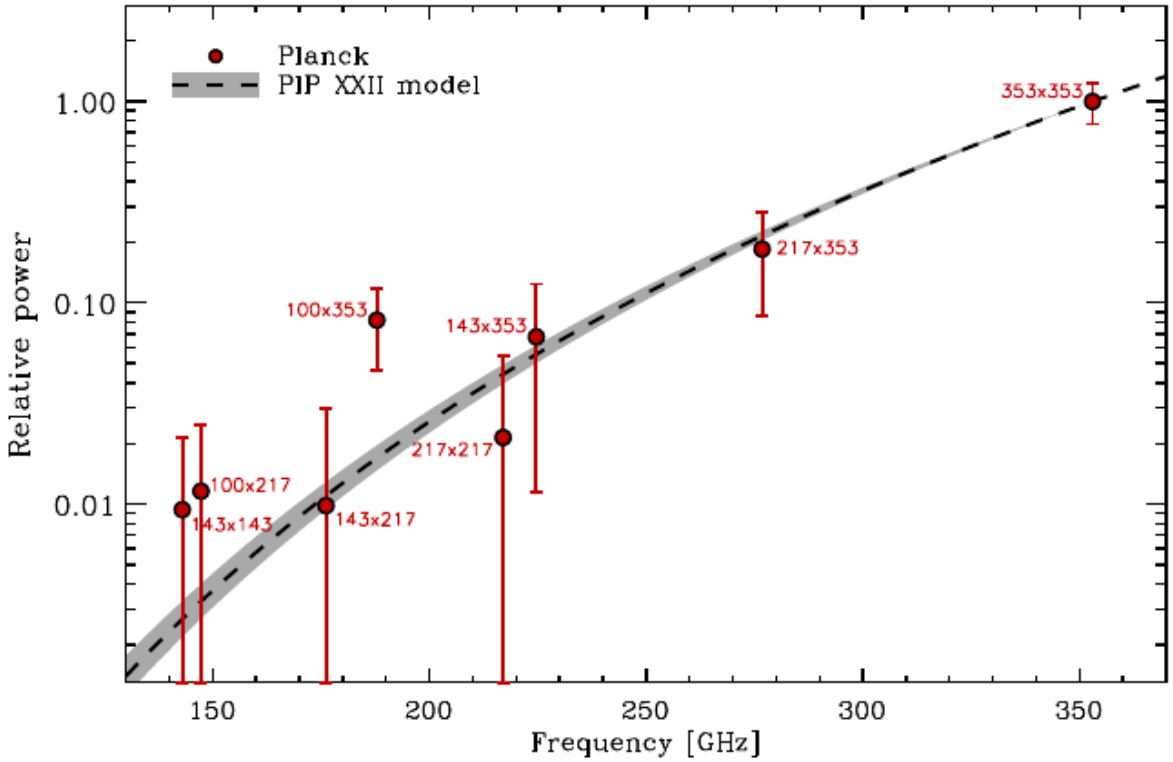
Planck 2014

Planck observed dust polarization at high latitudes



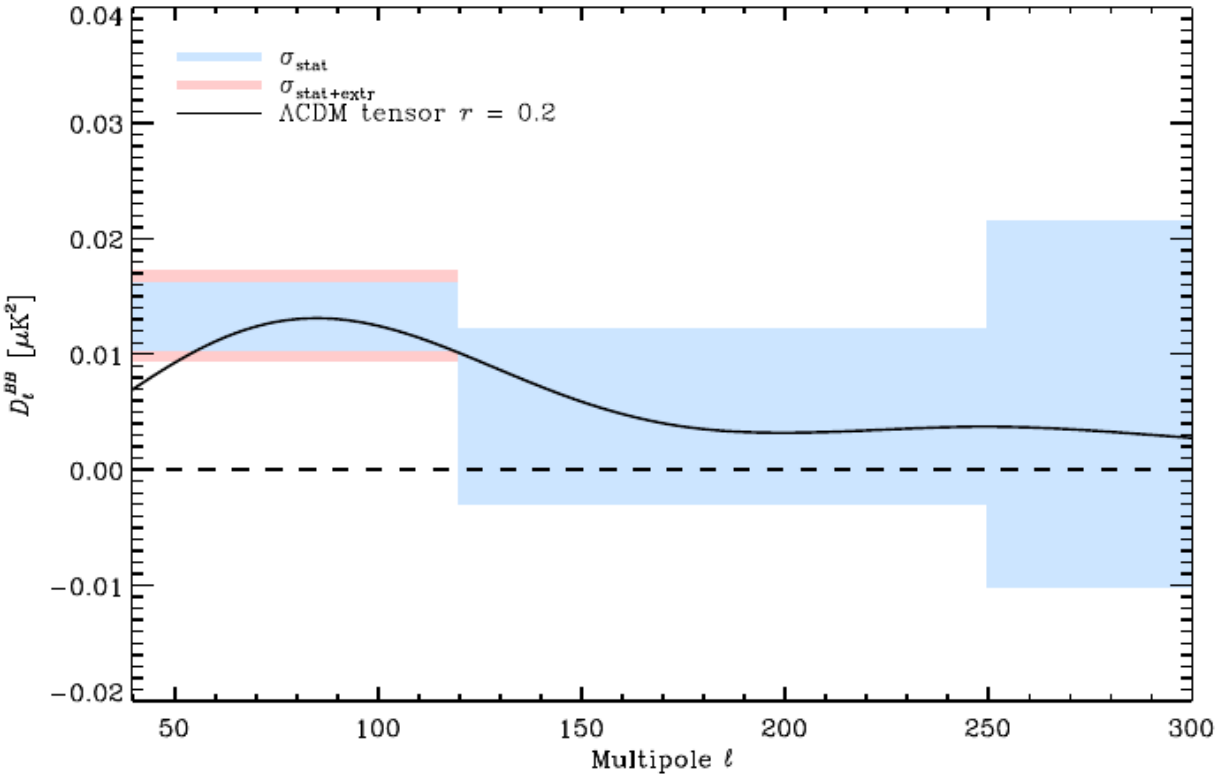
Planck 2014

Planck observed dust polarization in the BICEP2 area



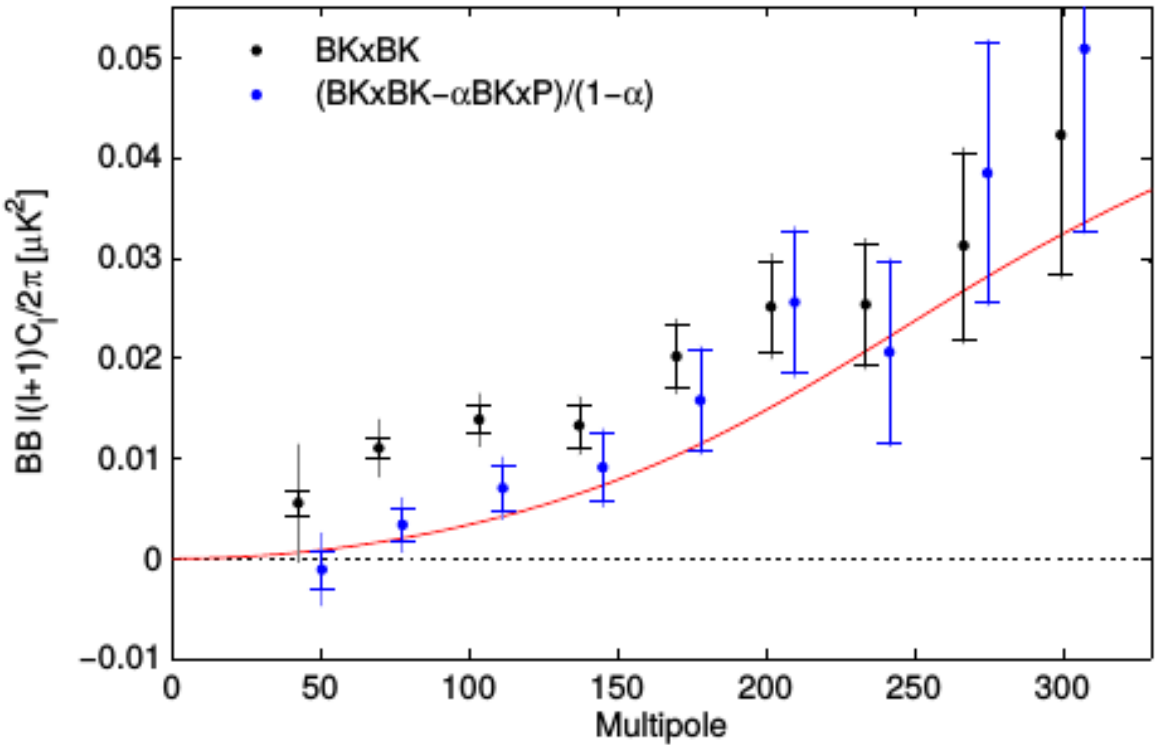
Planck 2014

Planck observed dust polarization in the BICEP2 area



Planck 2014

Planck × Bicep2 × KEcK



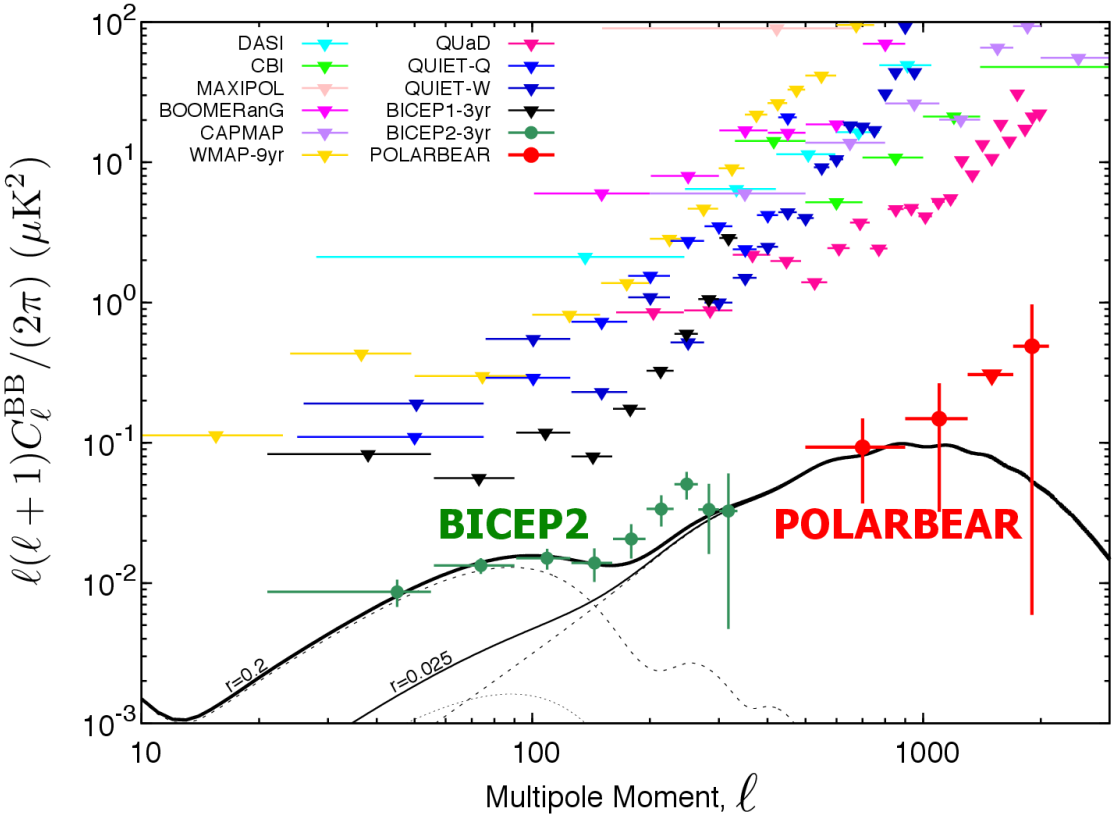
BKP 2015

Planck × Bicep2 × KEcK

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

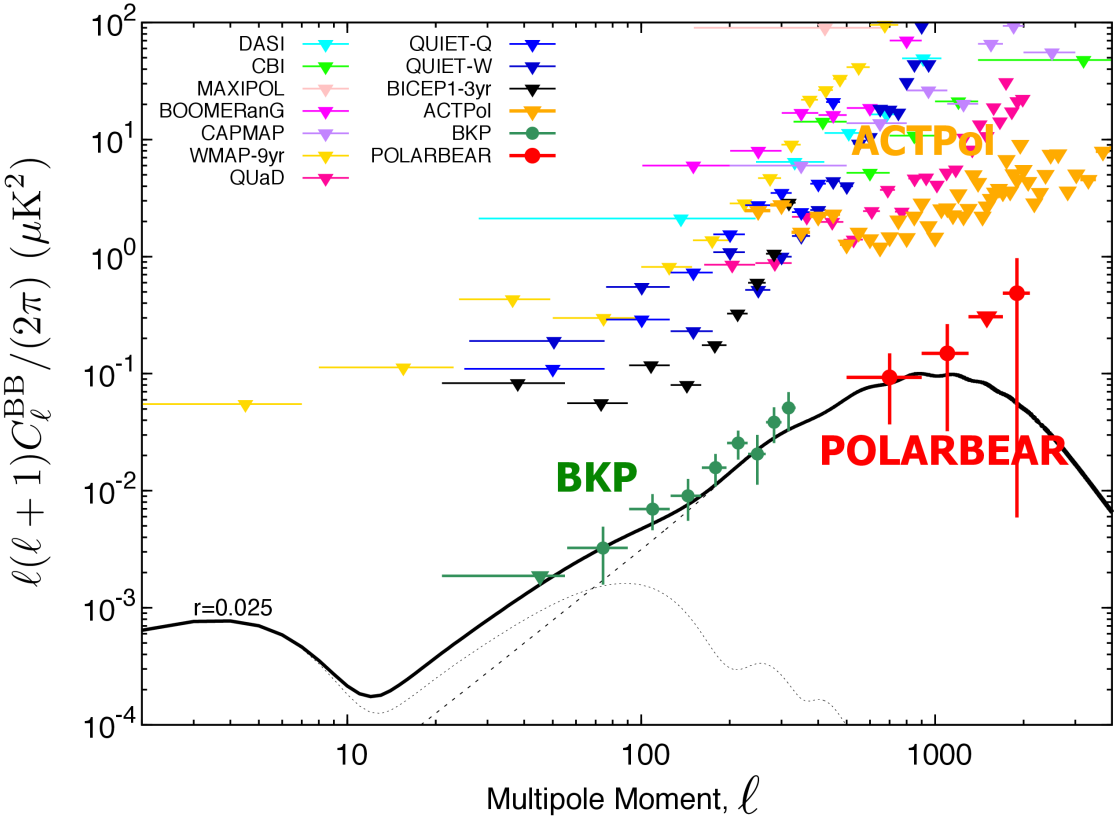
BKP 2015

March 2014



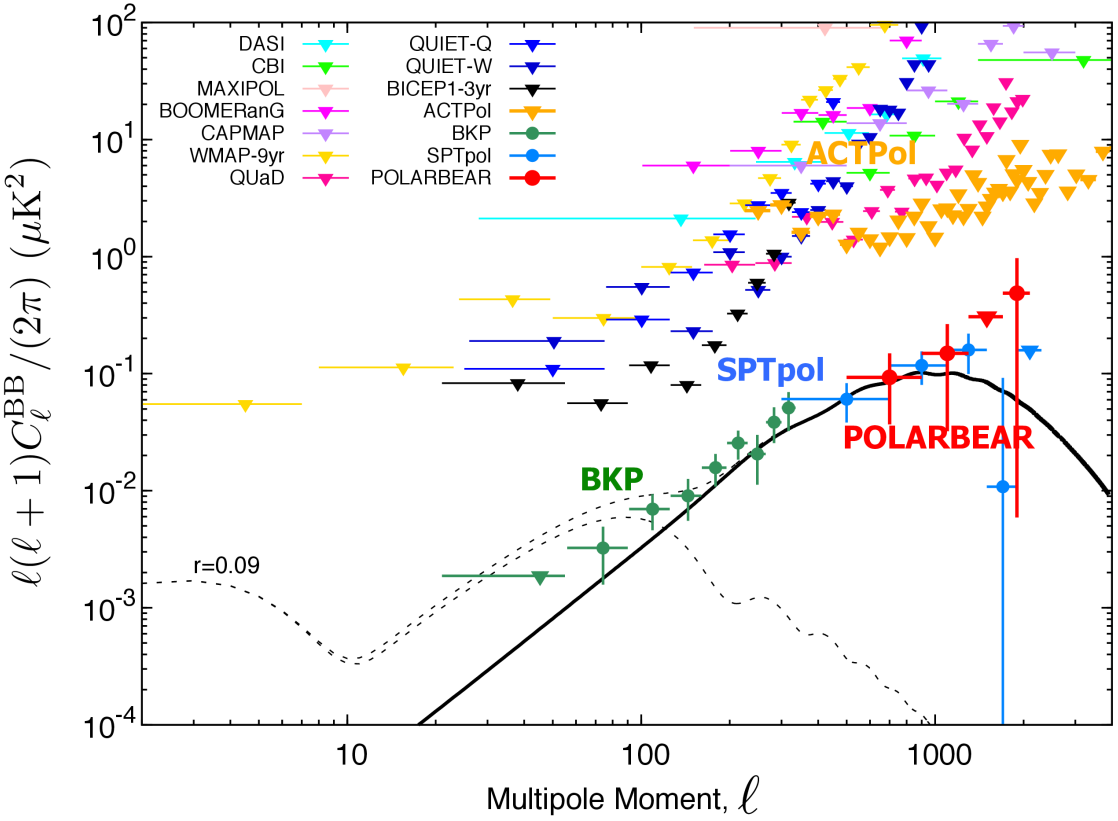
Plots by Chinone

Now



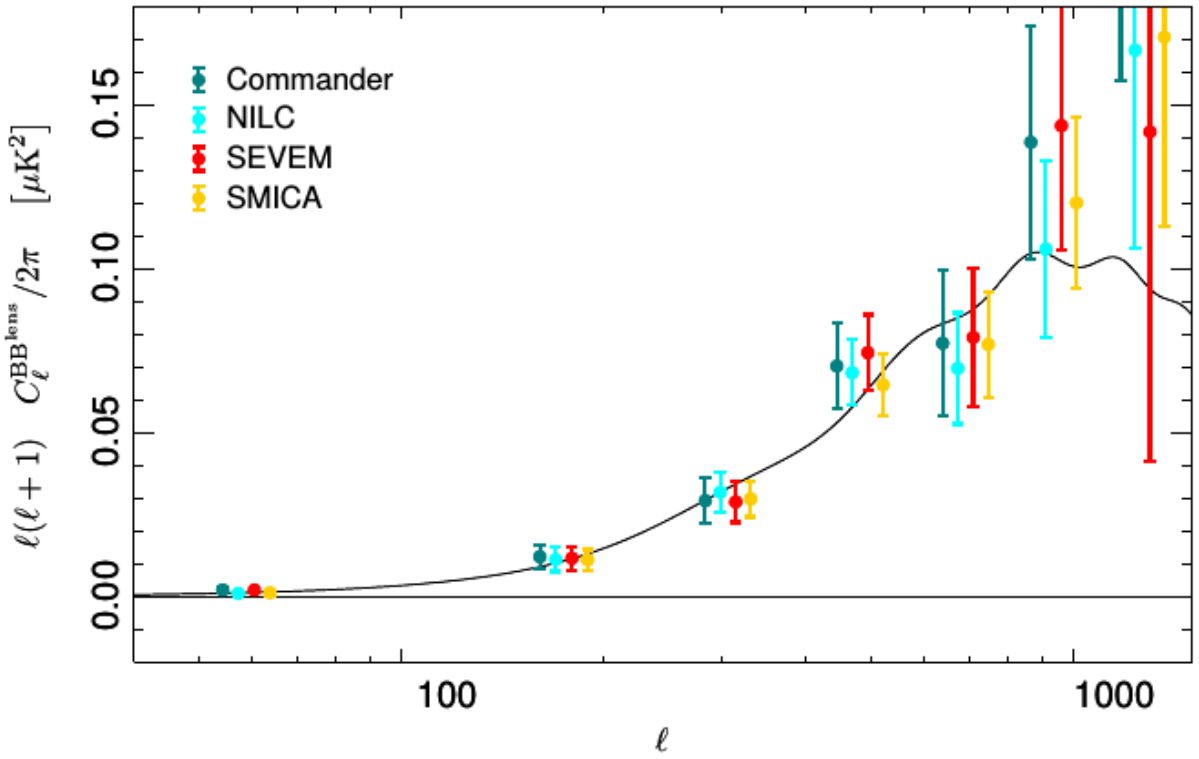
Plots by Chinone

Now



Plots by Chinone

Now



Planck 2015

Remarks

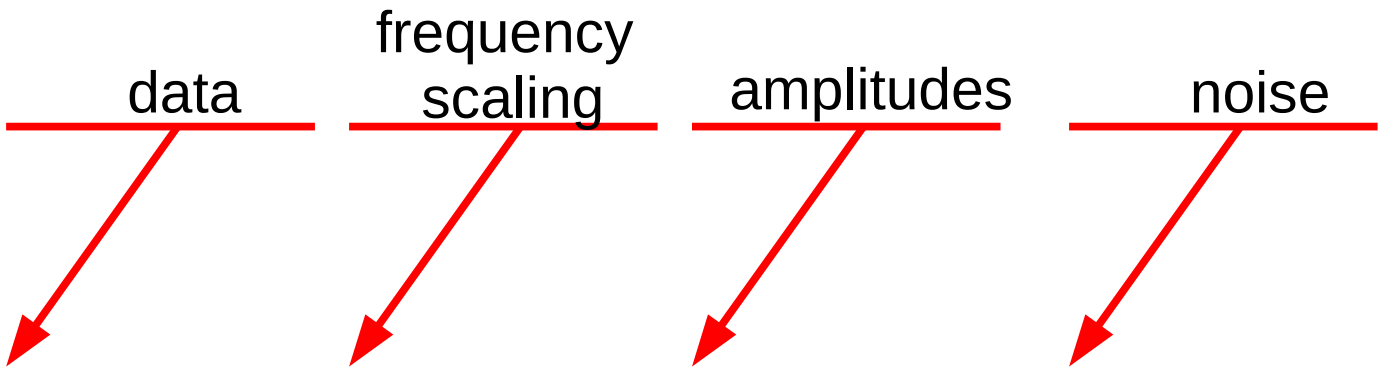
- The issue with diffuse foreground being comparable or dominant with respect to cosmologically interesting B-modes was guessed about a decade ago, and now confirmed by experiments
- Not only data, but data analysis progressed substantially to be able to include foreground cleaning into the data analysis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

Component separation

Component separation

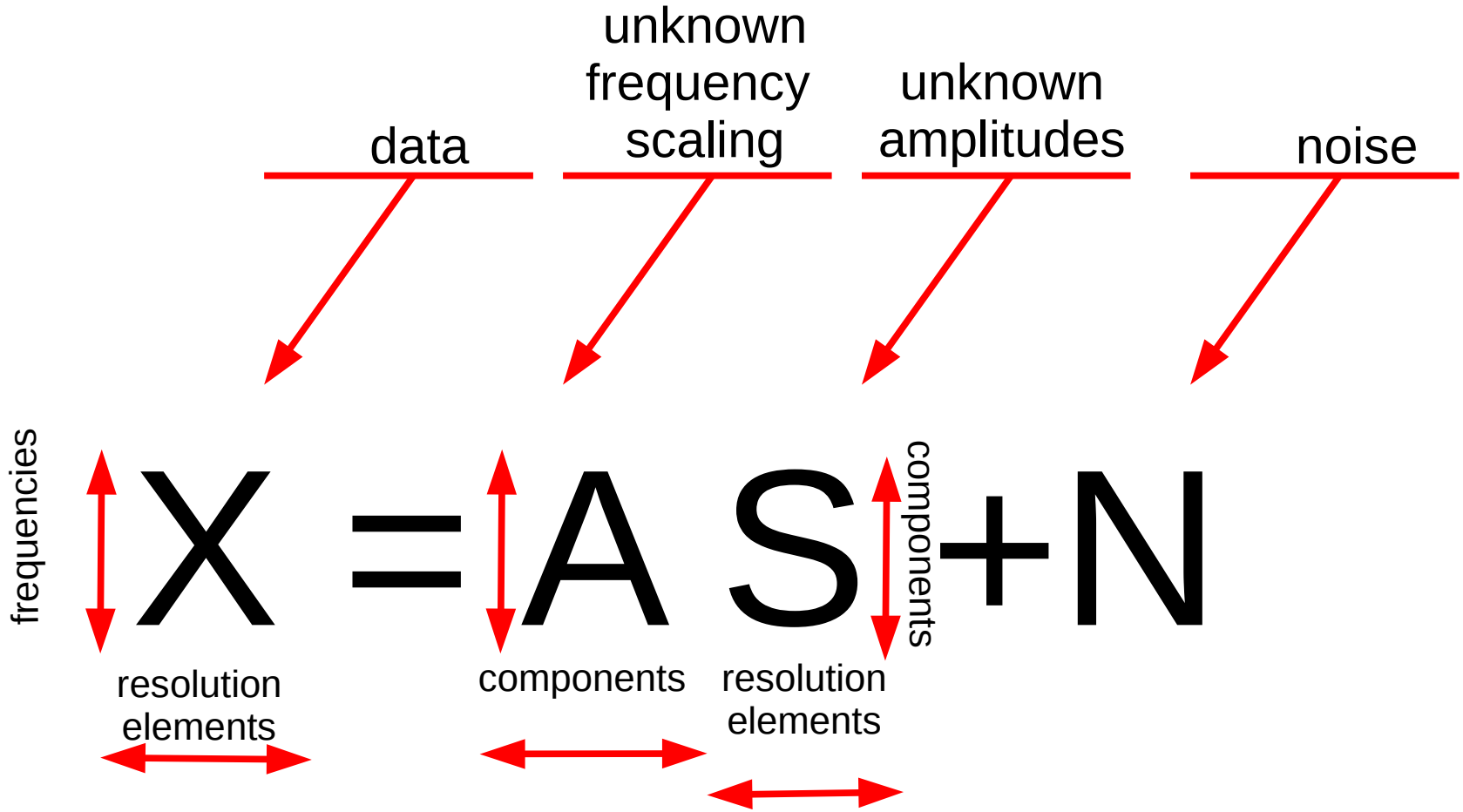
$$X = AS + N$$

Component separation



$$X = A S + N$$

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

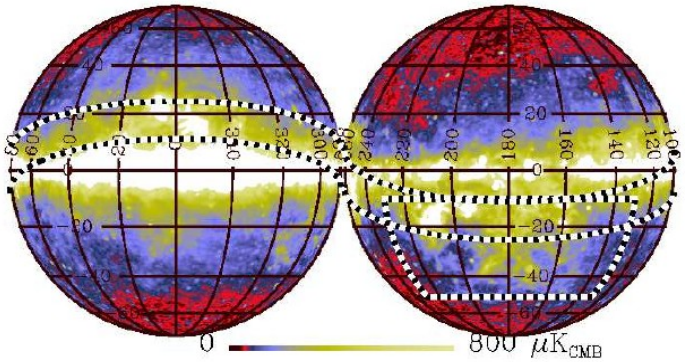
Component separation

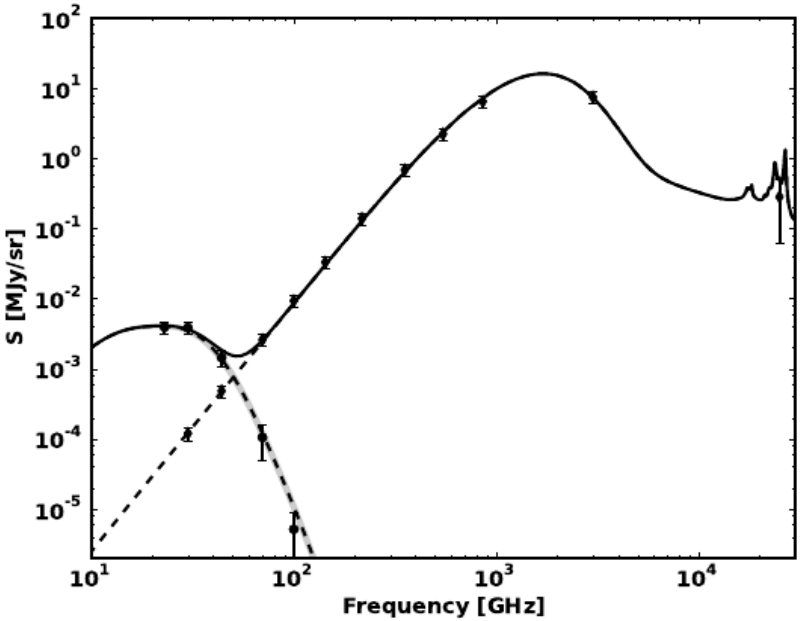
- If you know nothing, you
  - Look for minimum variance internal linear combination, constrained to scale as a black body:

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

Component separation

- If you know something, you
  - model and fit





Planck 2012

Component separation

- 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

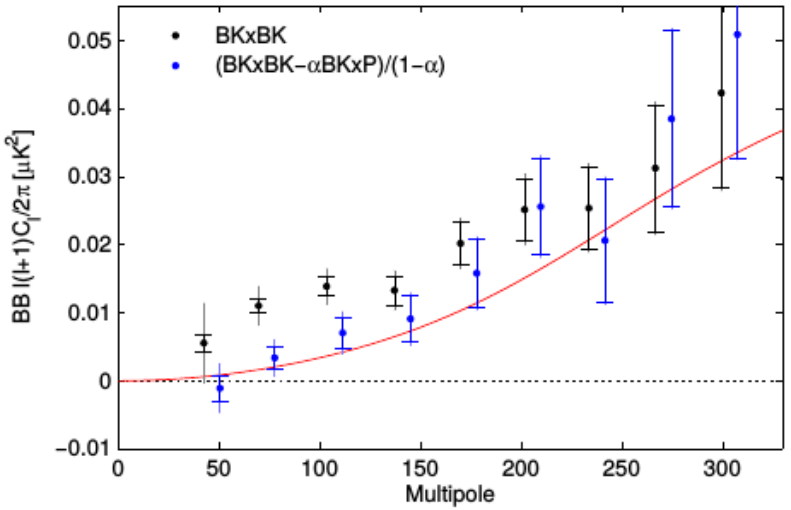
Component separation

- 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 B-mode experiments

- Existing studies on simulations mostly based on parametric fitting
- Largely based on simulations till BKP15, which implements a template fitting in the harmonic domain
- Main driver for configurations of modern and future experiments aiming at the B-modes

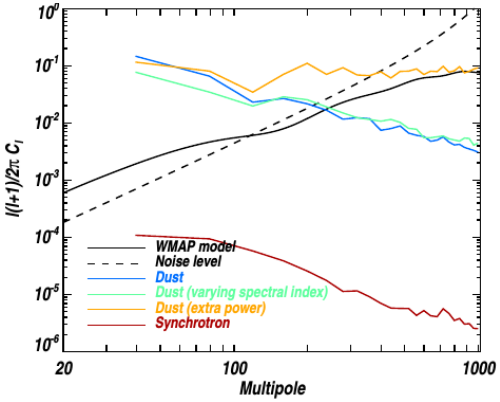


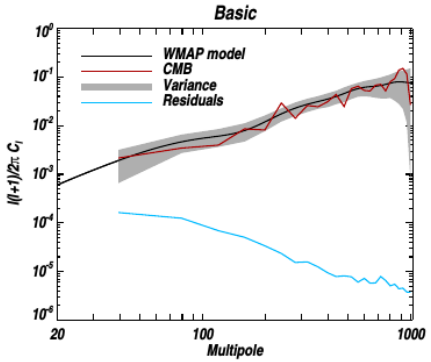
Component separation for B-mode experimens

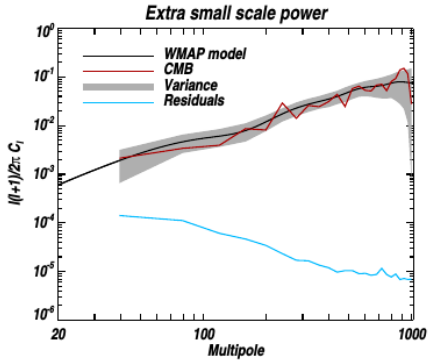
- Casting in a maximum likelihood framework (Brandt et al. 1994, Eriksen et al. 2006, Stompor et al. 2009)
- Application to sub-orbital designs (Stivoli et al. 2010)
- Propagation to cosmological parameter estimation (Fantaye et al. 2011)
- Optimization scheme for sub-orbital designs proposed (Errard et al. 2011)
- Linearization and Fisher matrix for Quick Look Analysis (Errard & Stompor 2012)
- Check for effects on lensing reconstruction (Fantaye et al. 2012)

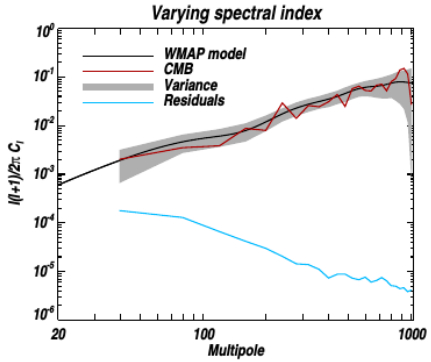
Baloon and ground-based setup analysis for B-foreground cleaning

- Considered designs: EBEX (150, 250, 410 GHz), PolarBear (90, 150, 220 Ghz), targeting BICEP-like regions
- Dust removal successful for r of order percent for EBEX, possible bias for PolarBear due to unresolved residual synchrotron at 90 GHz





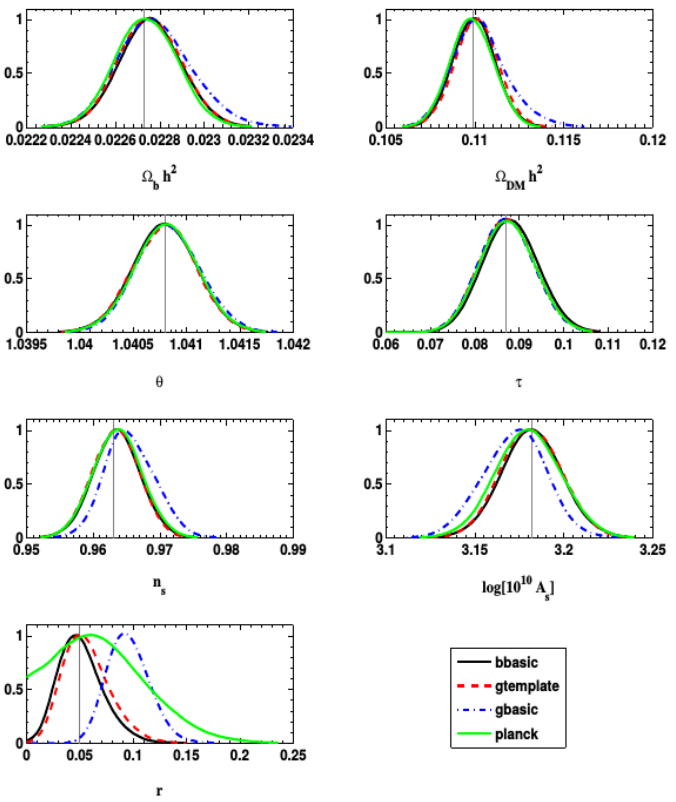




Stivoli et al. 2010

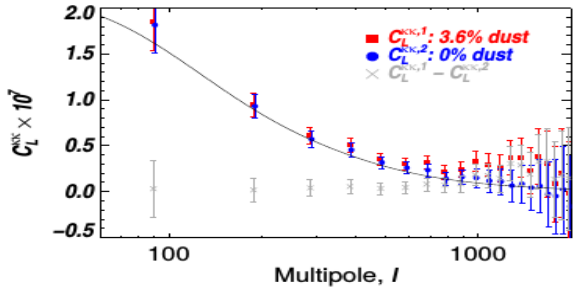
Baloon and ground-based setup analysis for B-foreground cleaning

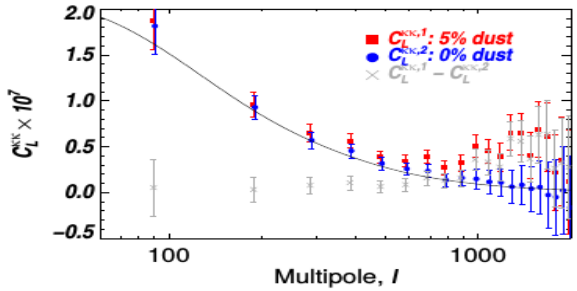
- Map-r end2end (no systematics) simulation responses:
  - no bias for 150, 250, 410 Ghz setups, robust foreground monitor (EBEX, bbasic)
  - Possible bias from residual synchrotron in the foreground minimum (90 GHz) for ground measurements, alleviated if templates are available (PolarBear, gbasic)

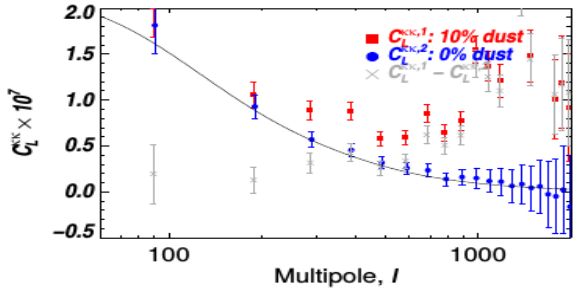


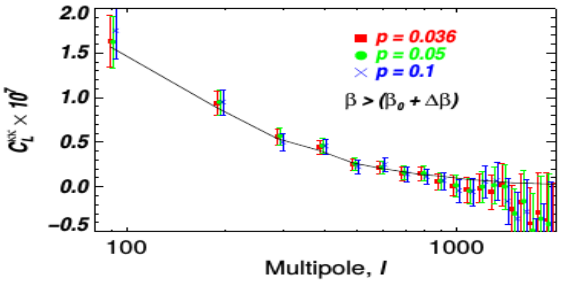
Fantaye et al. 2011

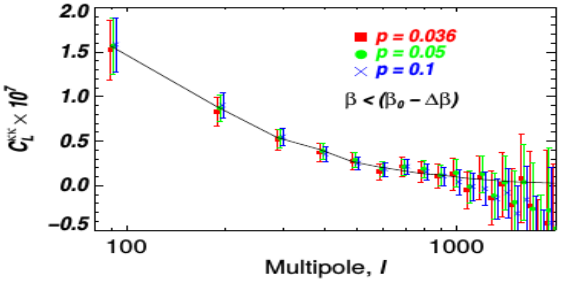
Dust residuals on lensing extraction

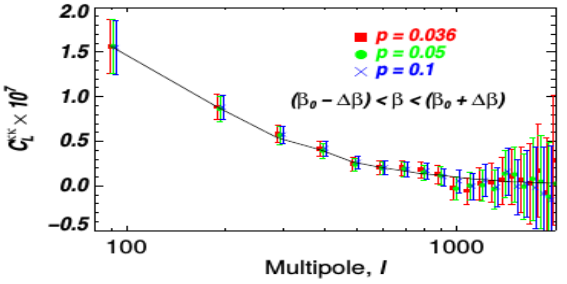






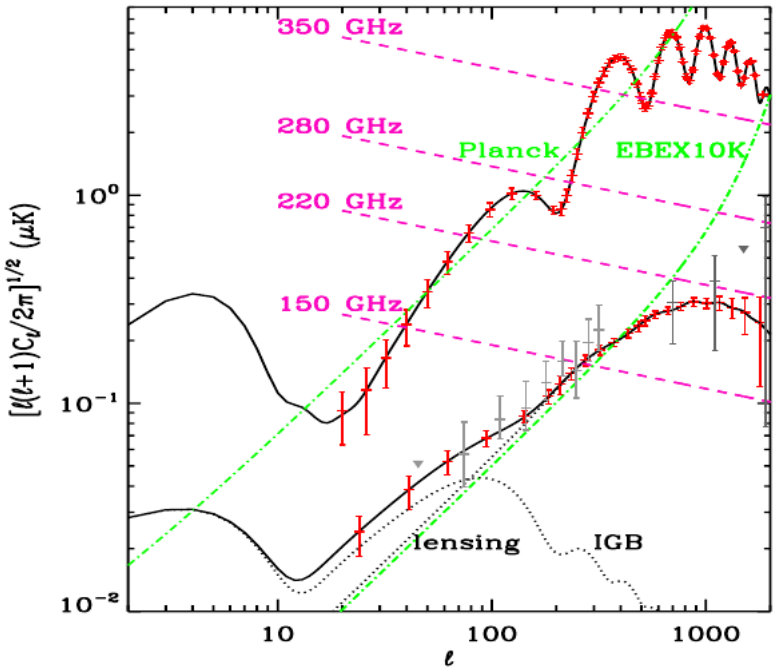


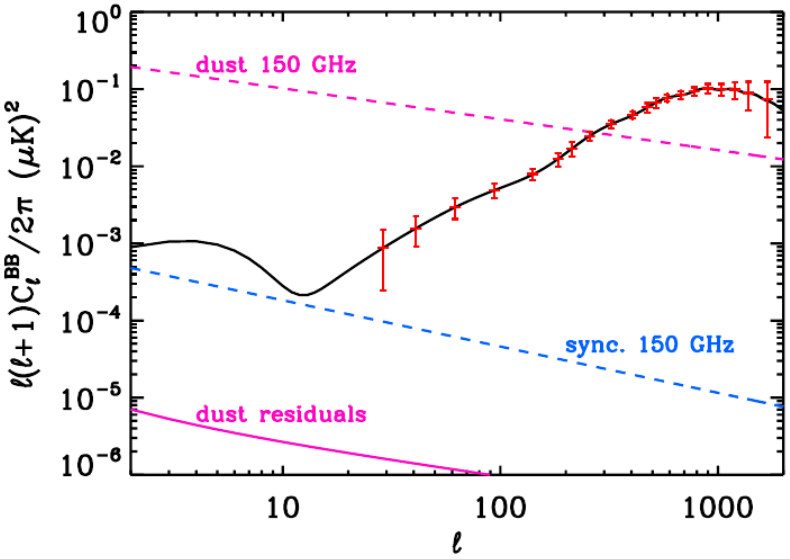




Fantaye et al. 2013

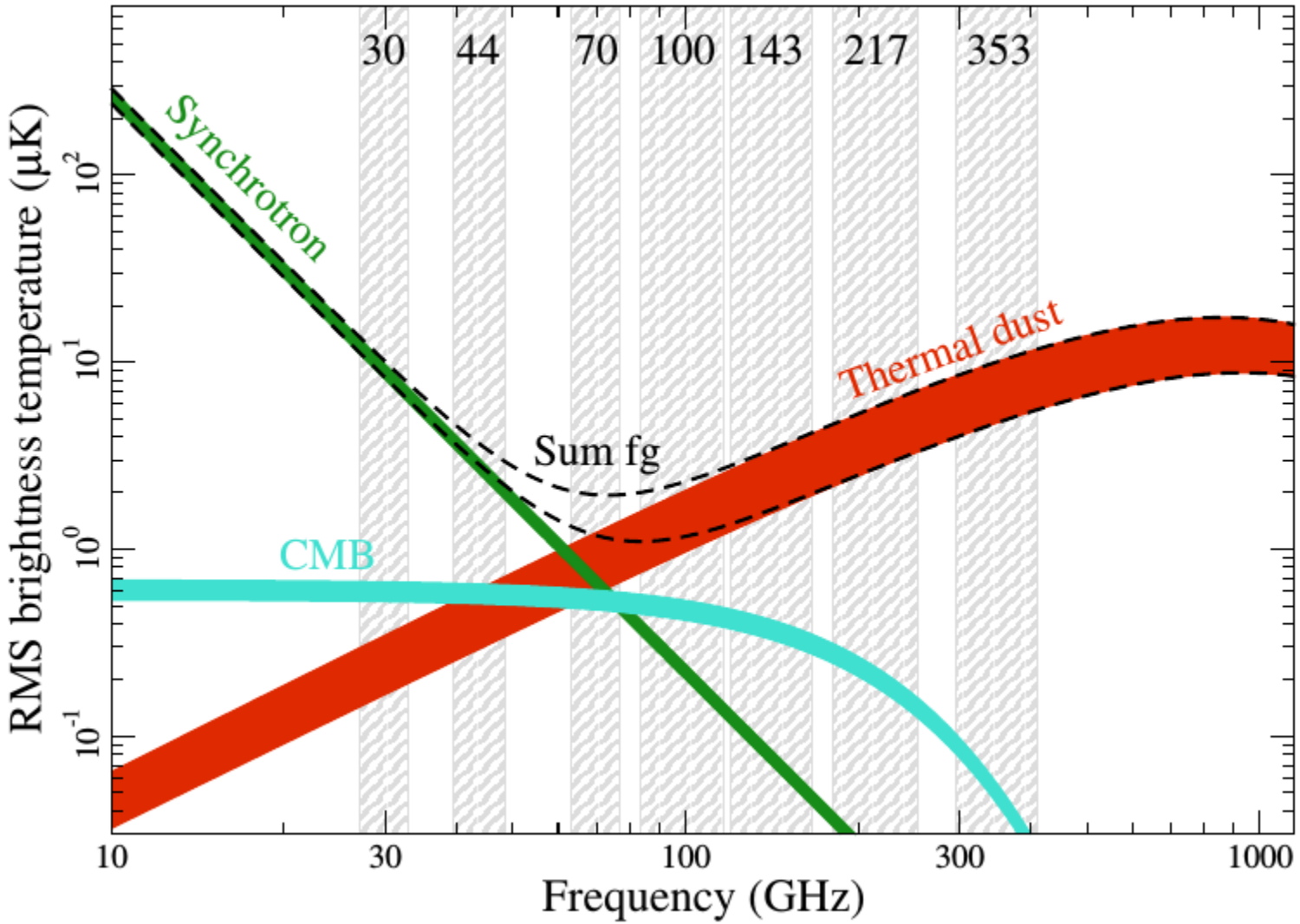
B-foreground cleaning driving experimental setups

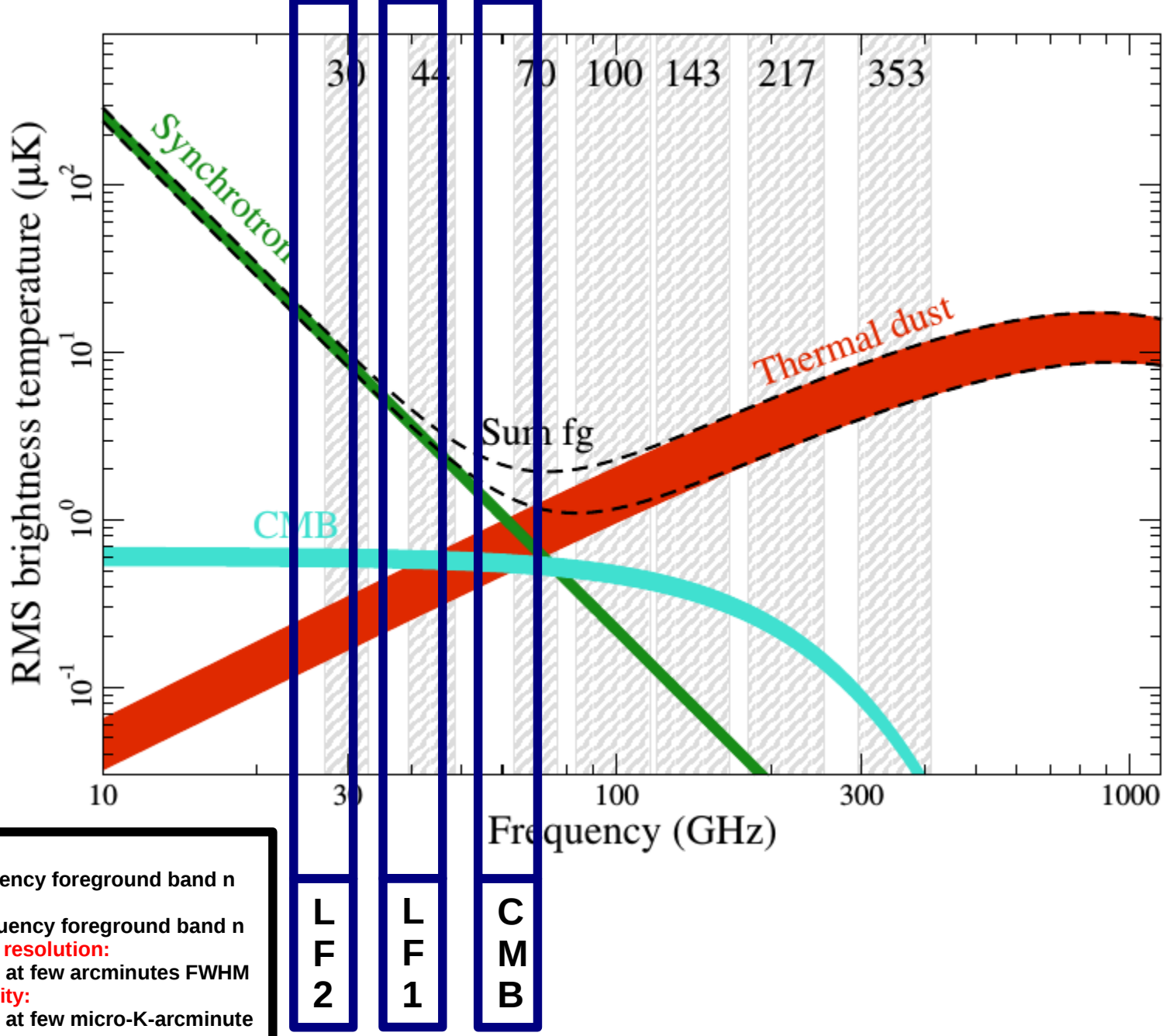




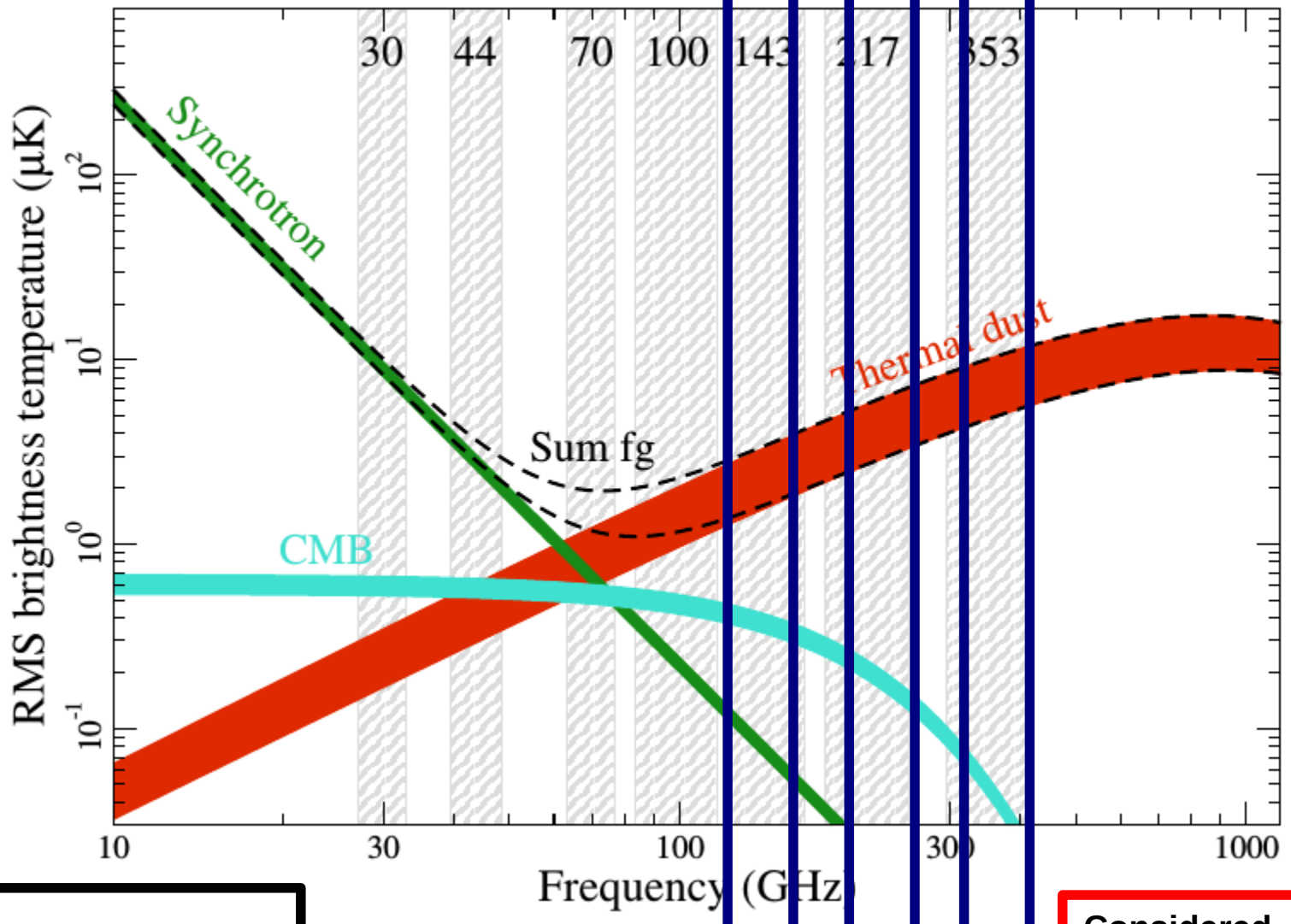
Errard 2015, courtesy of the EBEX collaboration

Concluding remarks


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

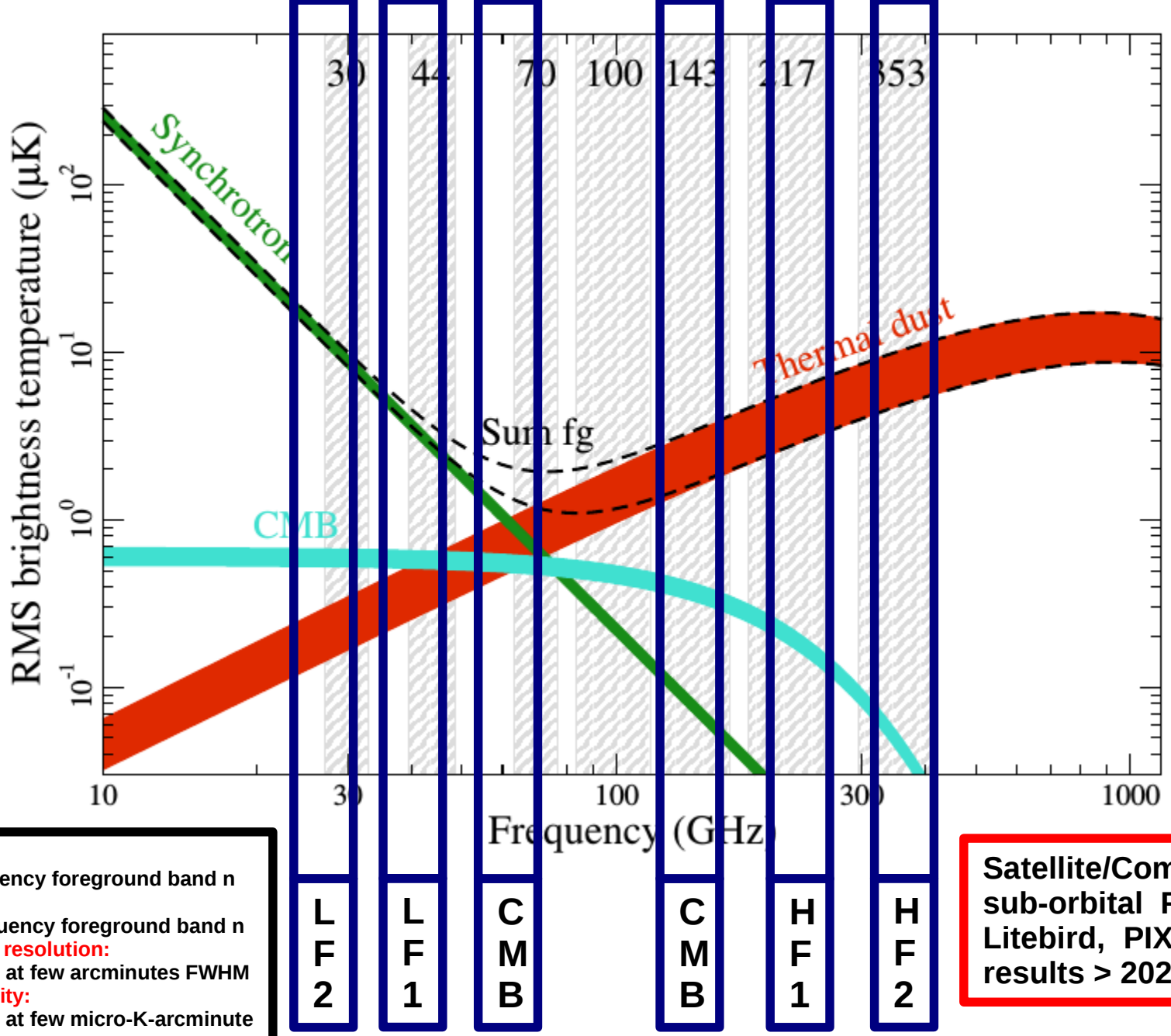


*** LFn:**
low frequency foreground band n
*** HFn:**
high frequency foreground band n
*** Angular resolution:**
All bands at few arcminutes FWHM
*** Sensitivity:**
All bands at few micro-K-arcminute



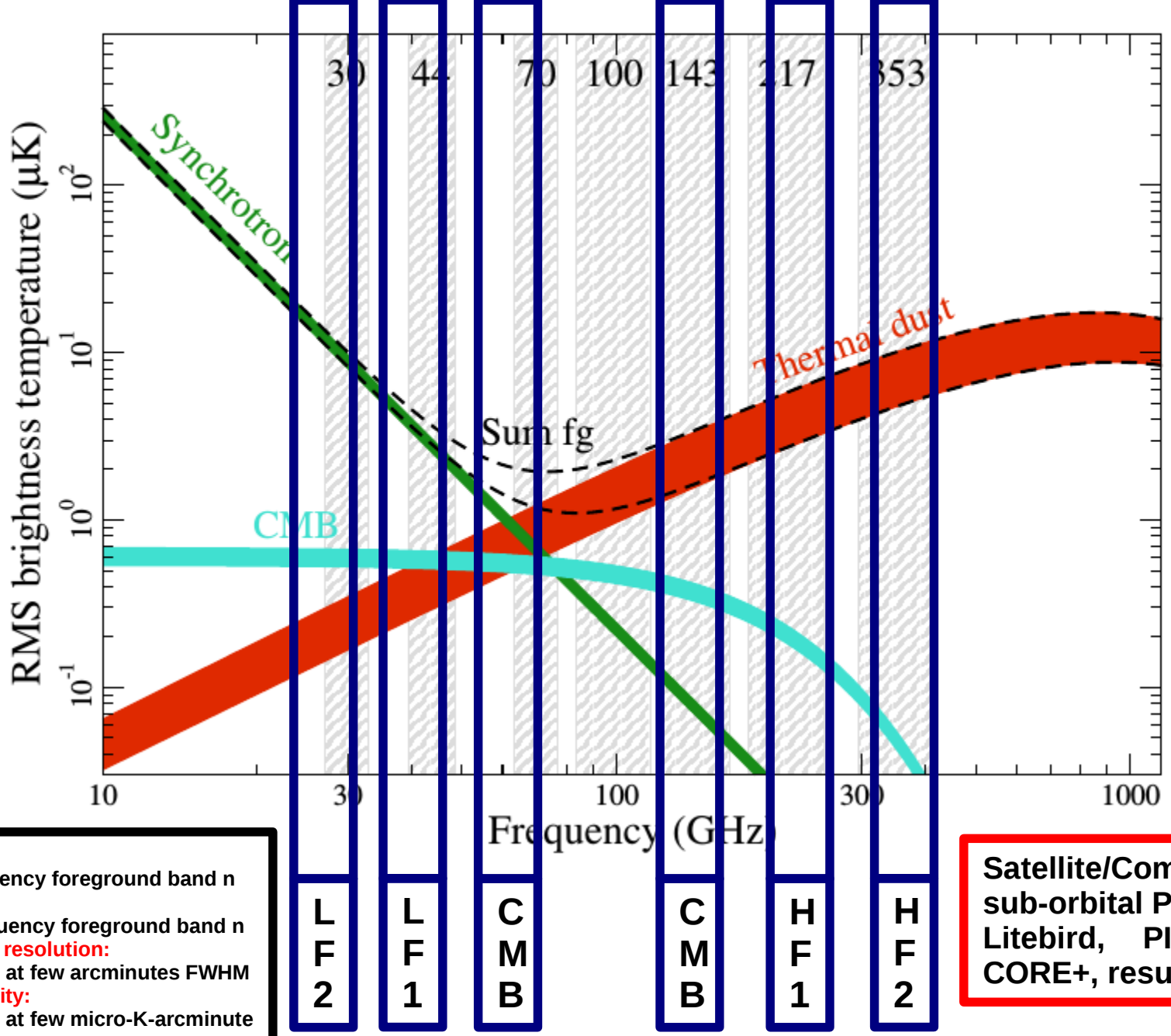
*** LFn:**
low frequency foreground band n
*** HFn:**
high frequency foreground band n
*** Angular resolution:**
All bands at few arcminutes FWHM
*** Sensitivity:**
All bands at few micro-K-arcminute

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

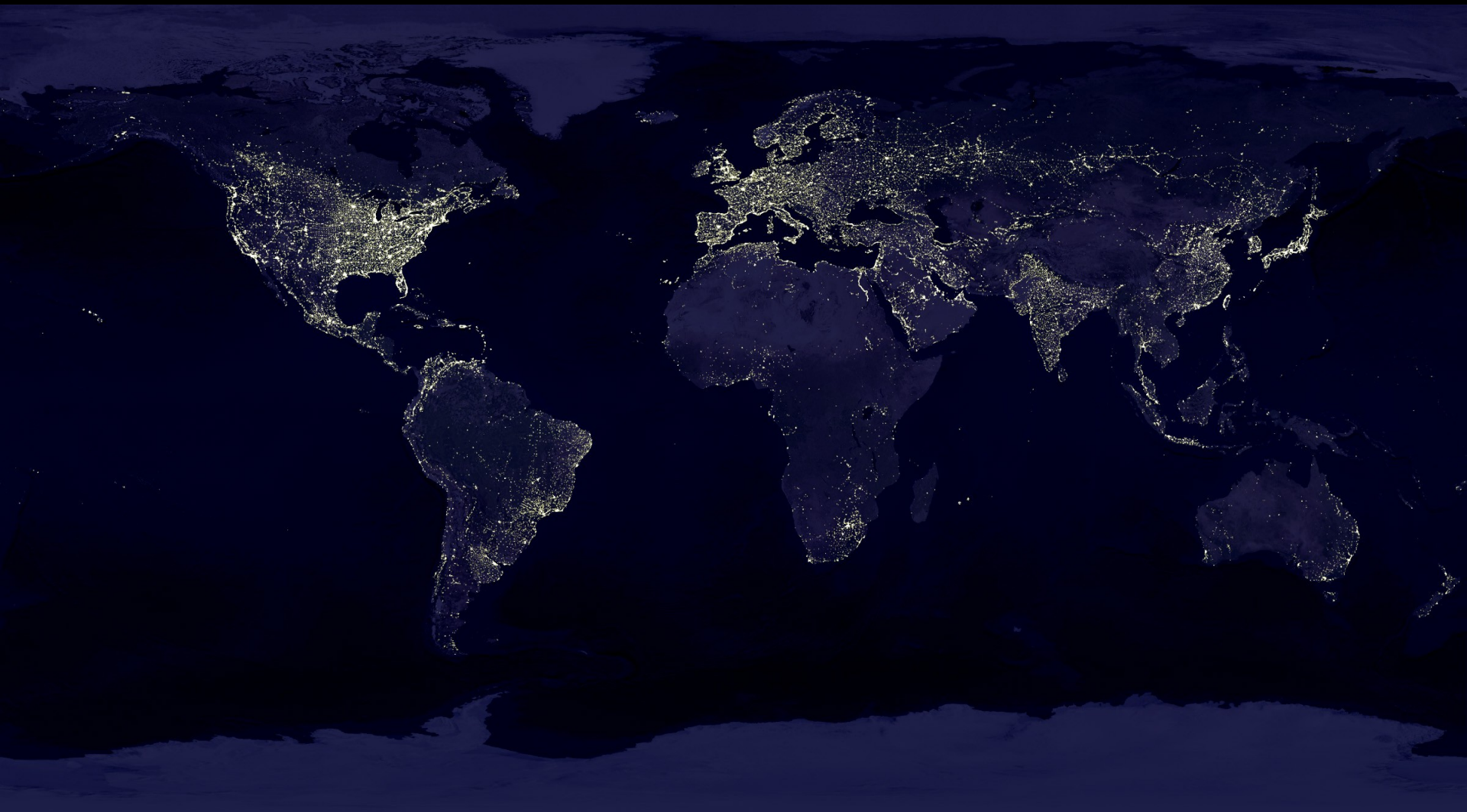
Satellite/Combined sub-orbital Probes: Litebird, PIXIE, S4, results > 2020

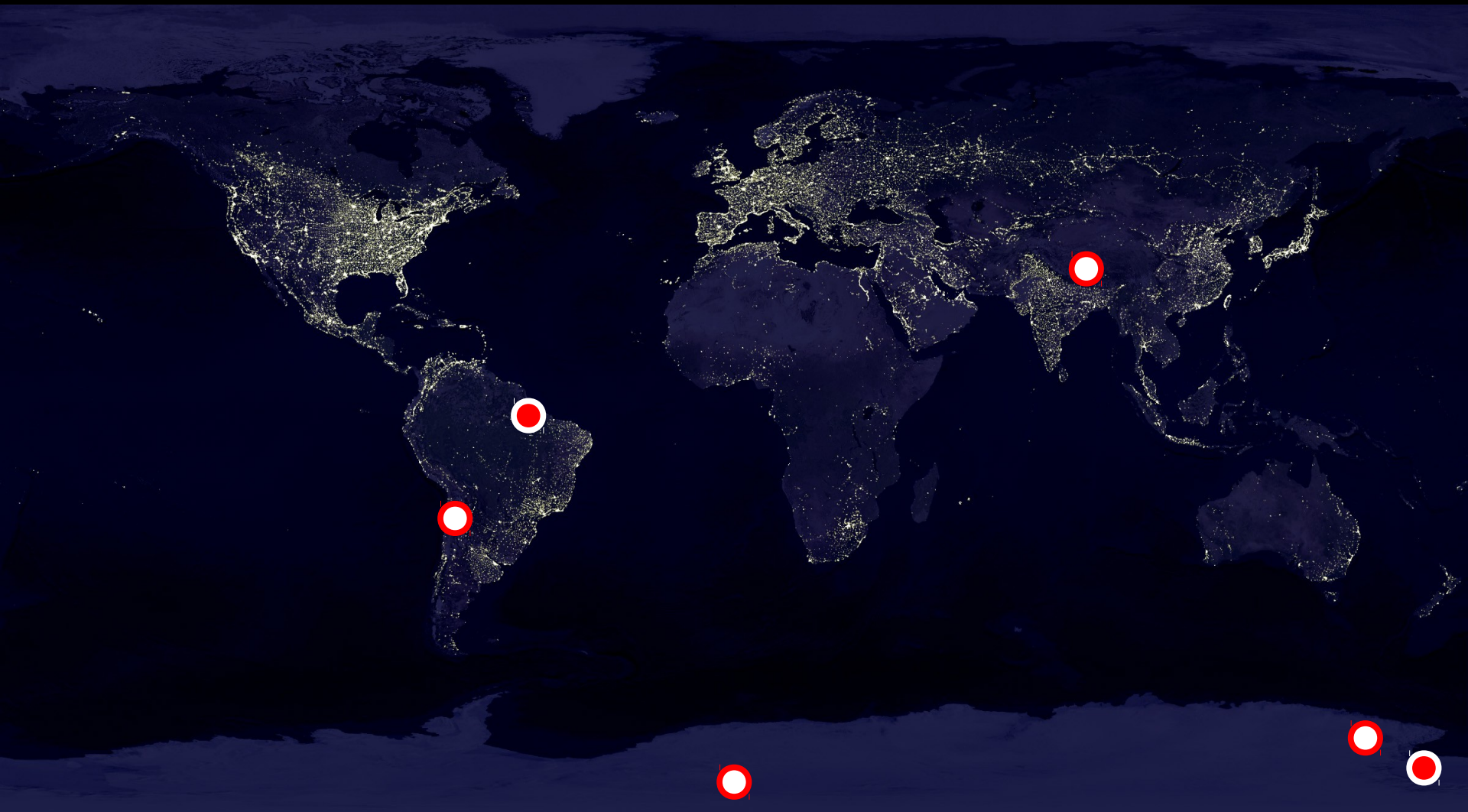


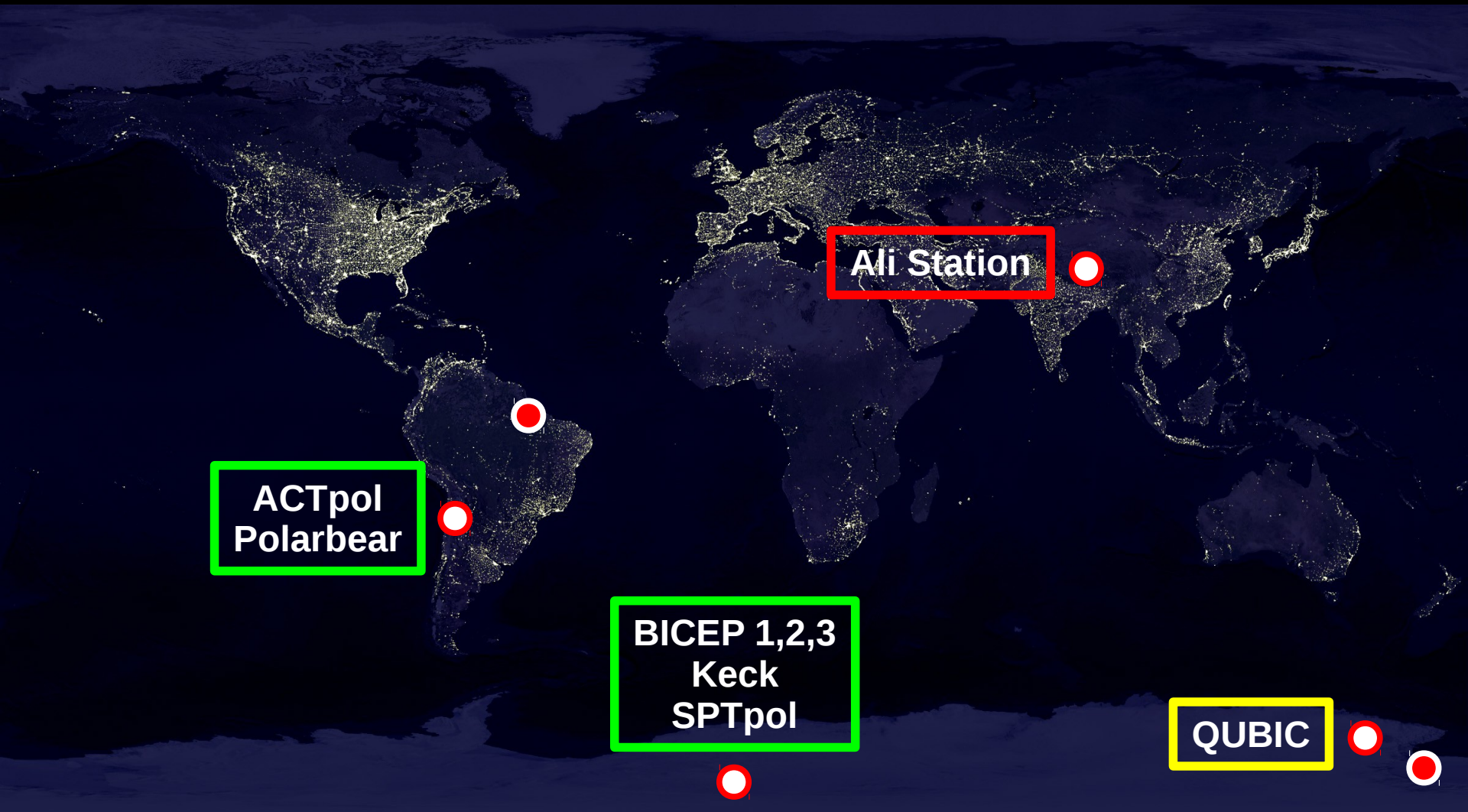
*** LFn:**
low frequency foreground band n
*** HFn:**
high frequency foreground band n
*** Angular resolution:**
All bands at few arcminutes FWHM
*** Sensitivity:**
All bands at few micro-K-arcminute

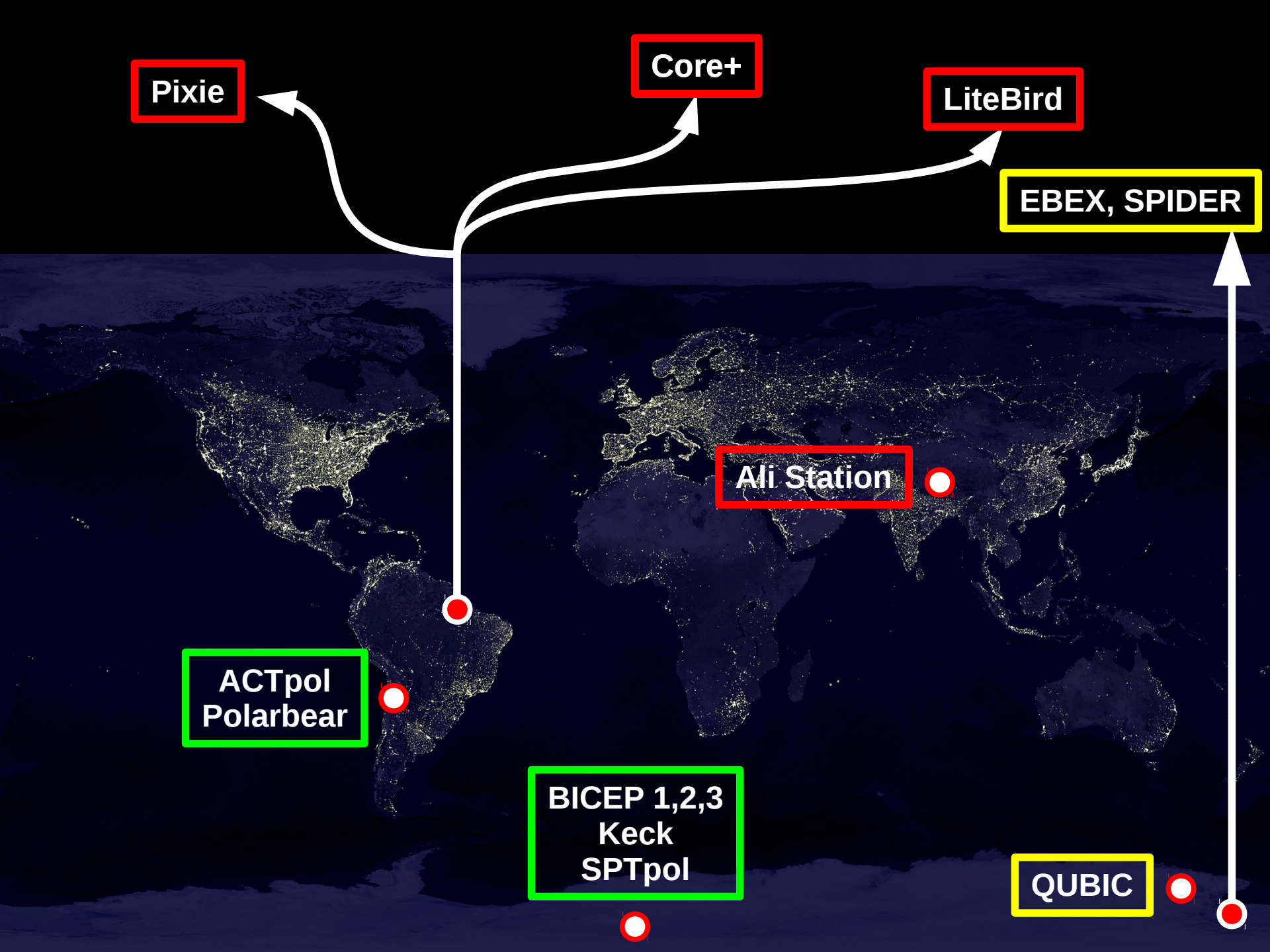
Satellite/Combined sub-orbital Probes: Litebird, PIXIE, S4, CORE+, results > 2020

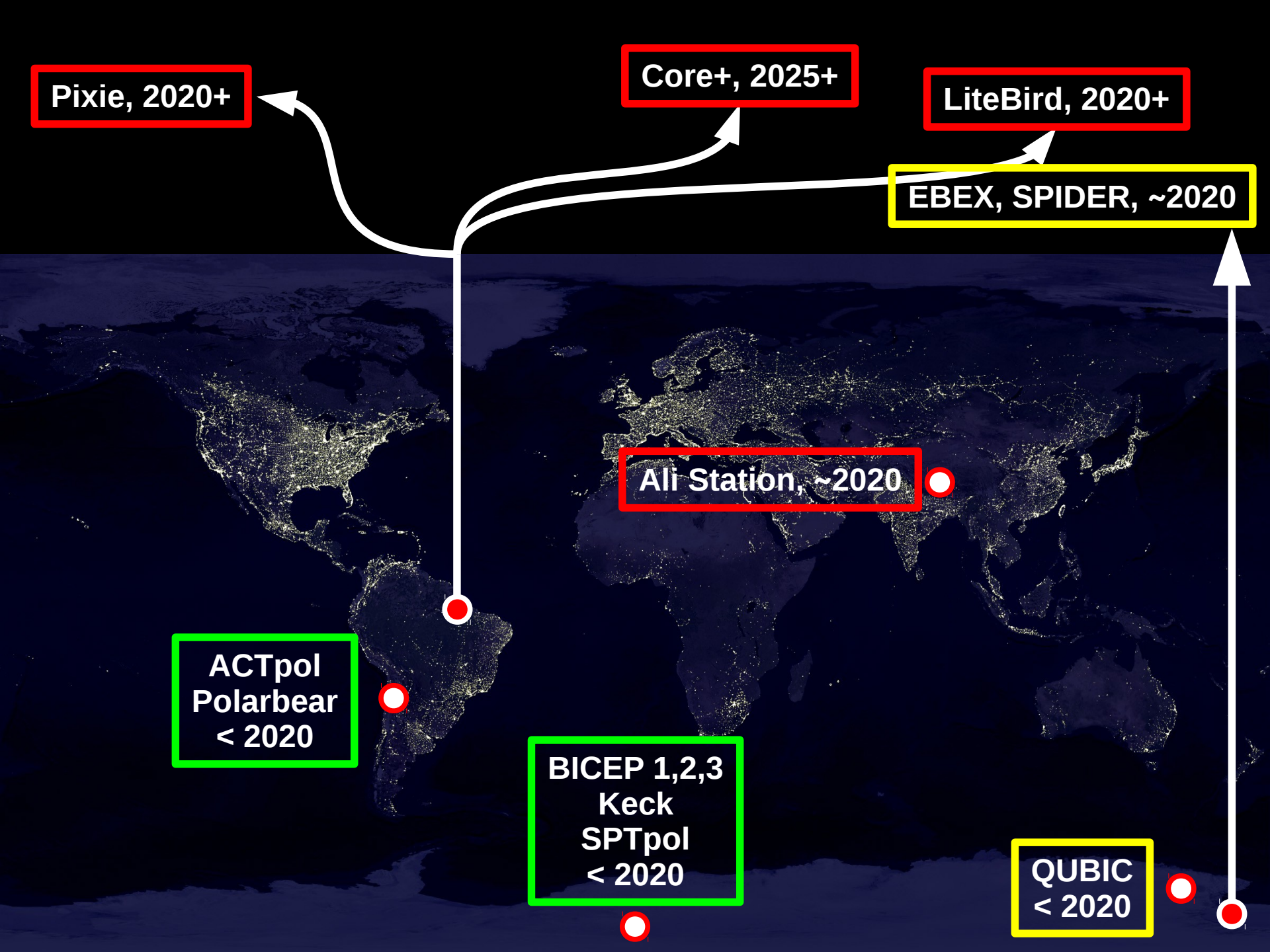
Minimum detectable r: few × 10^{-3}






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	$N_{\rm det}$	ΔT μK.arcmin	ΔP μK.arcmin	ΔI kJy/sr.arcmin	$\Delta y \times 10^6$ $y_{\rm SZ}$.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

LiteBird configuration

Band GHz	Beam† [arcmin]	NET $[\mu K\sqrt{s}]$	Pixel # per wafer	Wafer #	Bolometer #	NETarr $[\mu K\sqrt{s}]$	Sensitivity $[\mu K\text{arcmin}]$
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

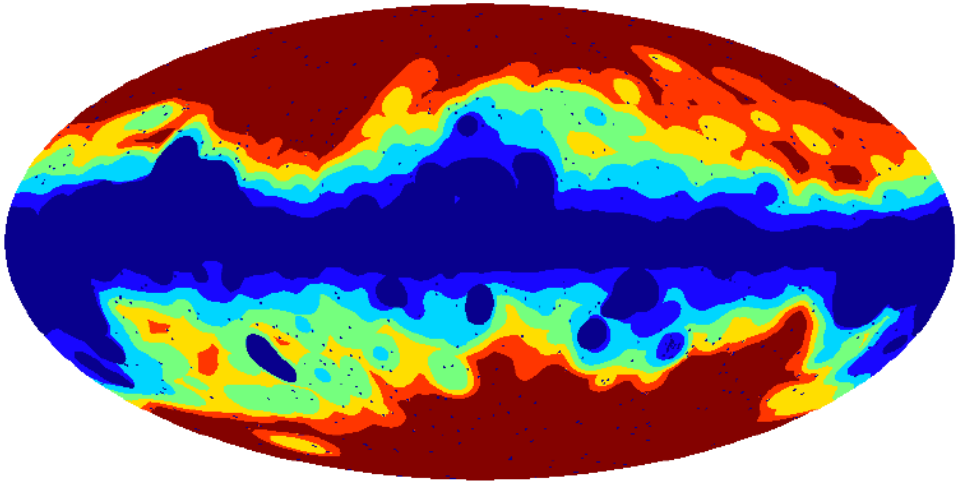


Fig. 1: Masks and complementary selected large regions that retain fractional coverage of the sky $f_{\rm sky}$ from 0.8 to 0.3 (see details in Sect. 3.3.1). The darkest blue is the CO mask, whose complement is a selected region with $f_{\rm sky} = 0.8$. In increments of $f_{\rm sky} = 0.1$, the retained 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 2015

Planck observed dust polarization in the BICEP2 area

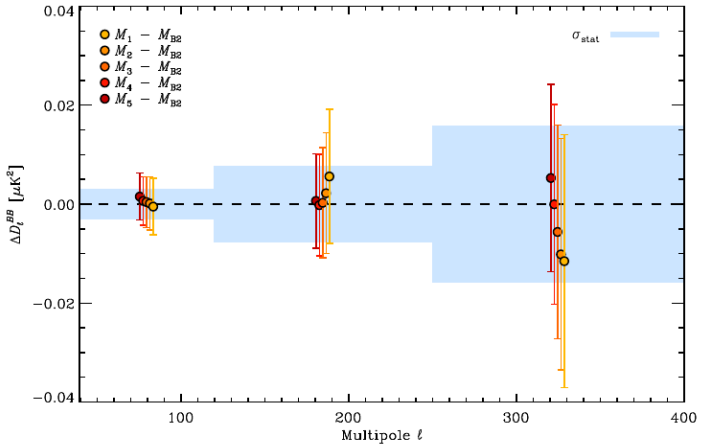


Fig. C.2: *Planck* 353 GHz $\mathcal{D}_\ell^{BB}$ angular power spectrum differences extrapolated to 150 GHz, determined from the spectra computed on the M_{1-5} regions presented in Appendix C.2 and the spectrum computed on M_{B2}. $\mathcal{D}_\ell^{BB}$ difference values for the five regions are 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.

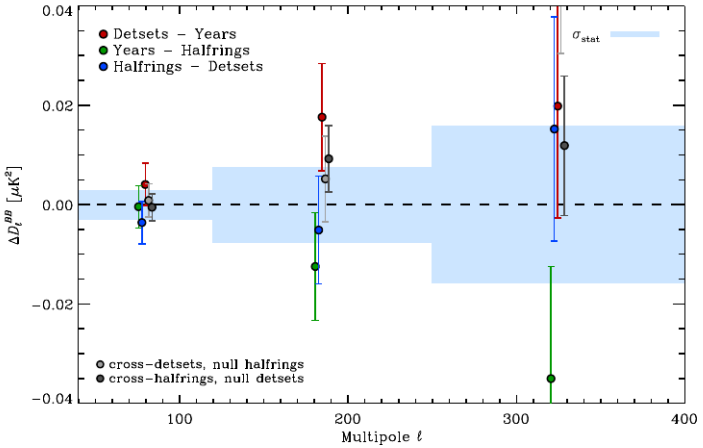


Fig. C.3: *Planck* 353 GHz $\mathcal{D}_\ell^{BB}$ angular power spectrum differences extrapolated to 150 GHz, computed from the following cross-spectra differences: DetSets minus Years (red circles); Years minus HalfRings (green circles); and HalfRings minus DetSets (blue circles). We also show the 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

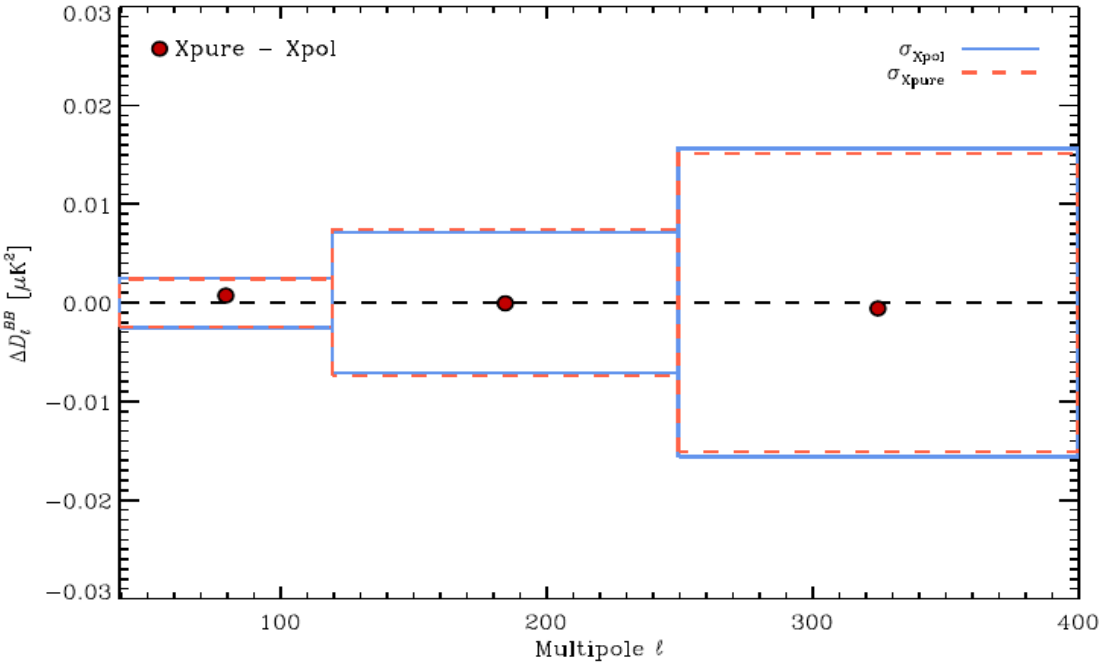


Fig. C.1: `Xpol` minus `Xpure` *Planck* 353 GHz $\mathcal{D}_\ell^{BB}$ angular power spectrum differences extrapolated to 150 GHz, computed from the cross-DetSets on $M_{\rm B2}$ (red circles). The blue boxes represent the $\pm1\,\sigma$ errors computed using `Xpol` from the data on $M_{\rm B2}$, while the dashed-orange boxes are the `Xpure` $\pm1\,\sigma$ errors coming from Monte Carlo simulations of *Planck* noise.

Planck 2014

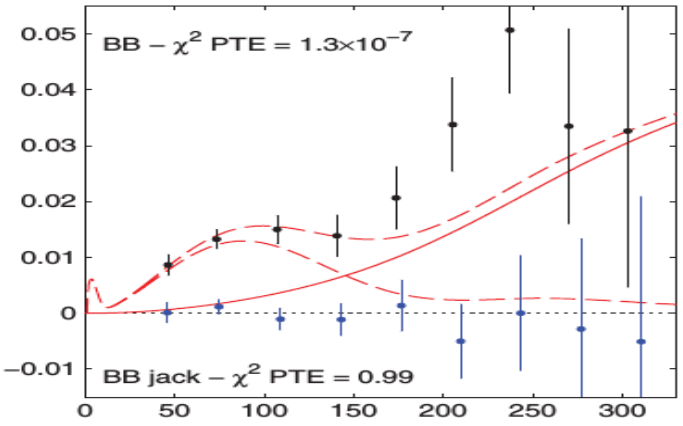
Foreground model building

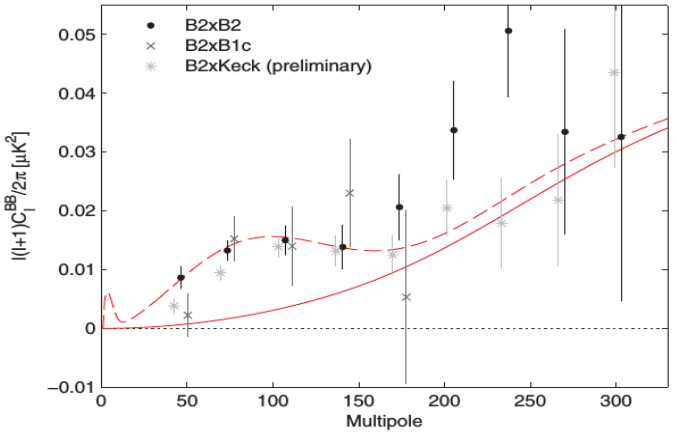
- Start from total intensity measurements, if available
- Get polarized intensity by imposing a constant polarization fraction
- Construct a pattern for the polarization angle, starting from large scale measurements, adding by hand small scale power according to various recipes
- Assume the same spectral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

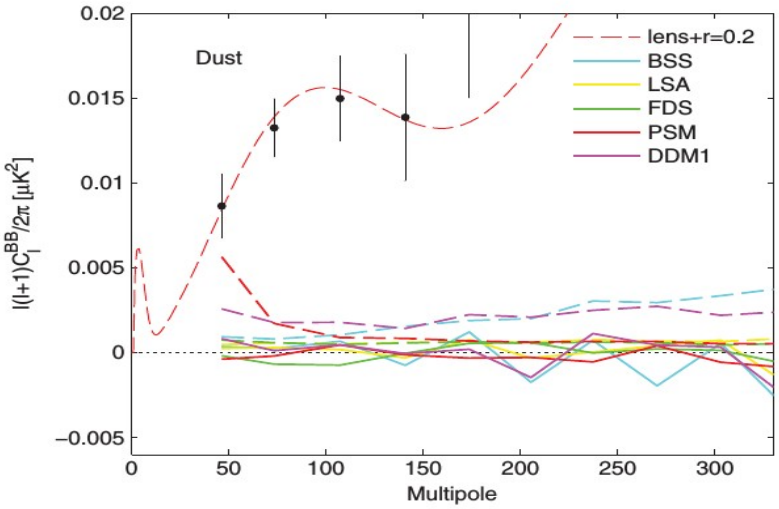
Component separation in one slide

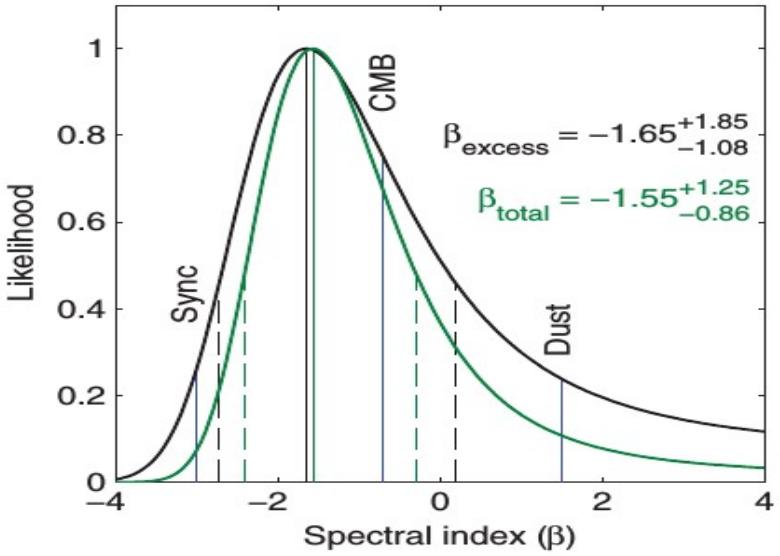
- Foreground variables are parametrized, and fitted through:
  - Minimum variance
  - Physical parametrization (amplitude, spectral parameters)
- See Planck 2013 for reviews
- Our approaches: Stompor et al. (2009, physical parametrization), B et al. 2004 (minimum variance)
- Analytic linearization available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

The B modes at degree angular scale



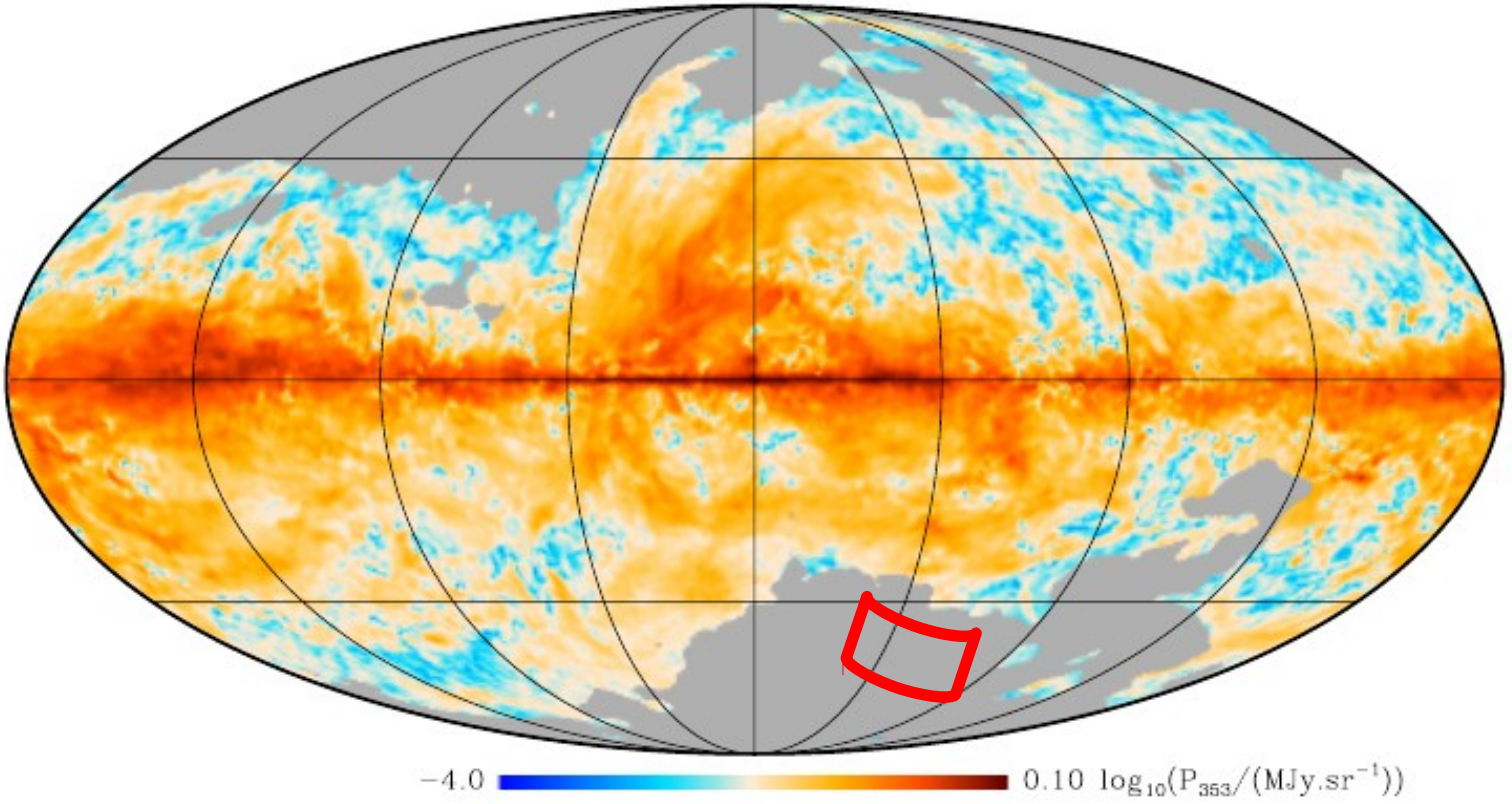






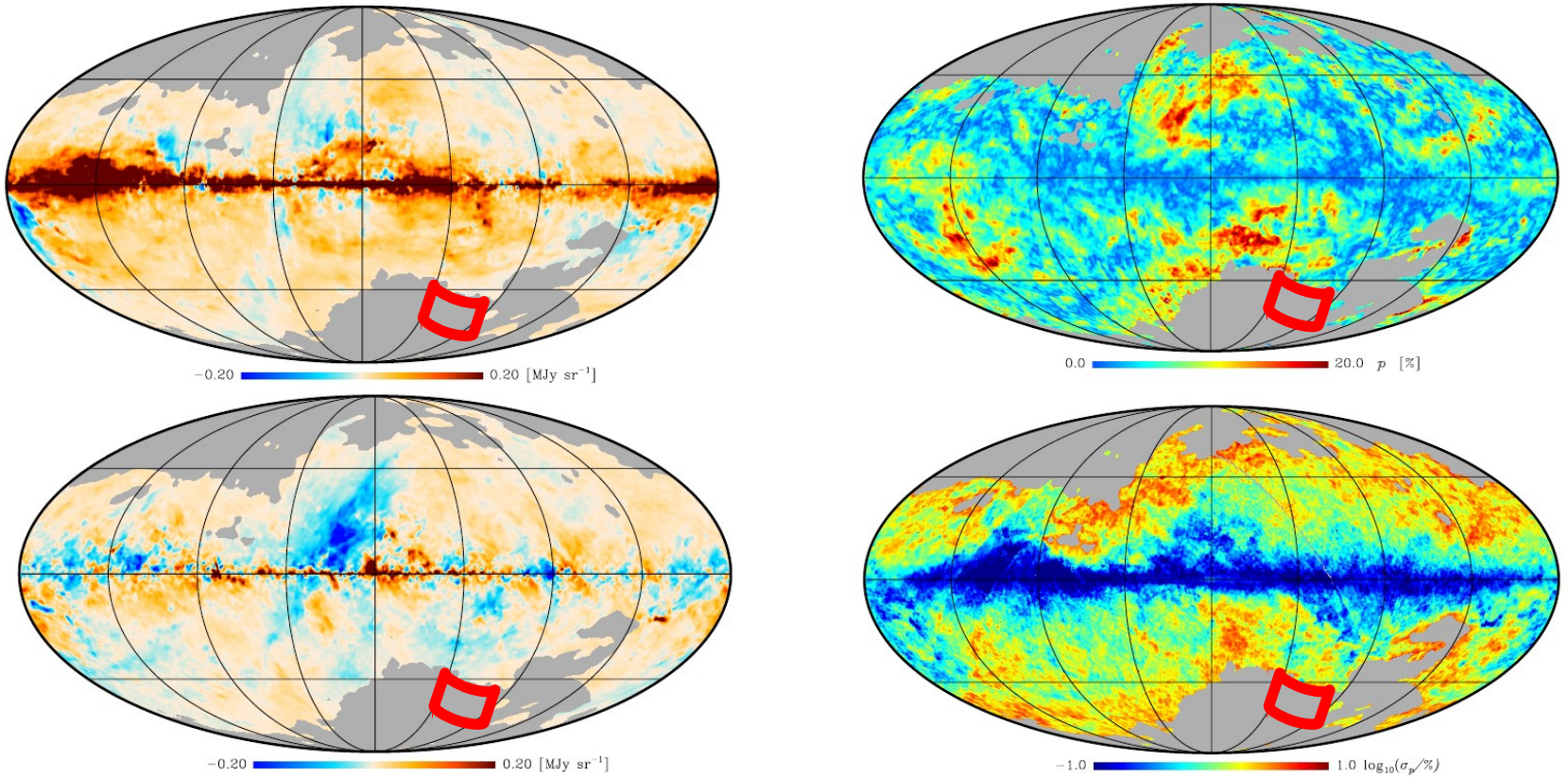
BICEP2 2014

Planck observed dust polarization at intermediate latitudes



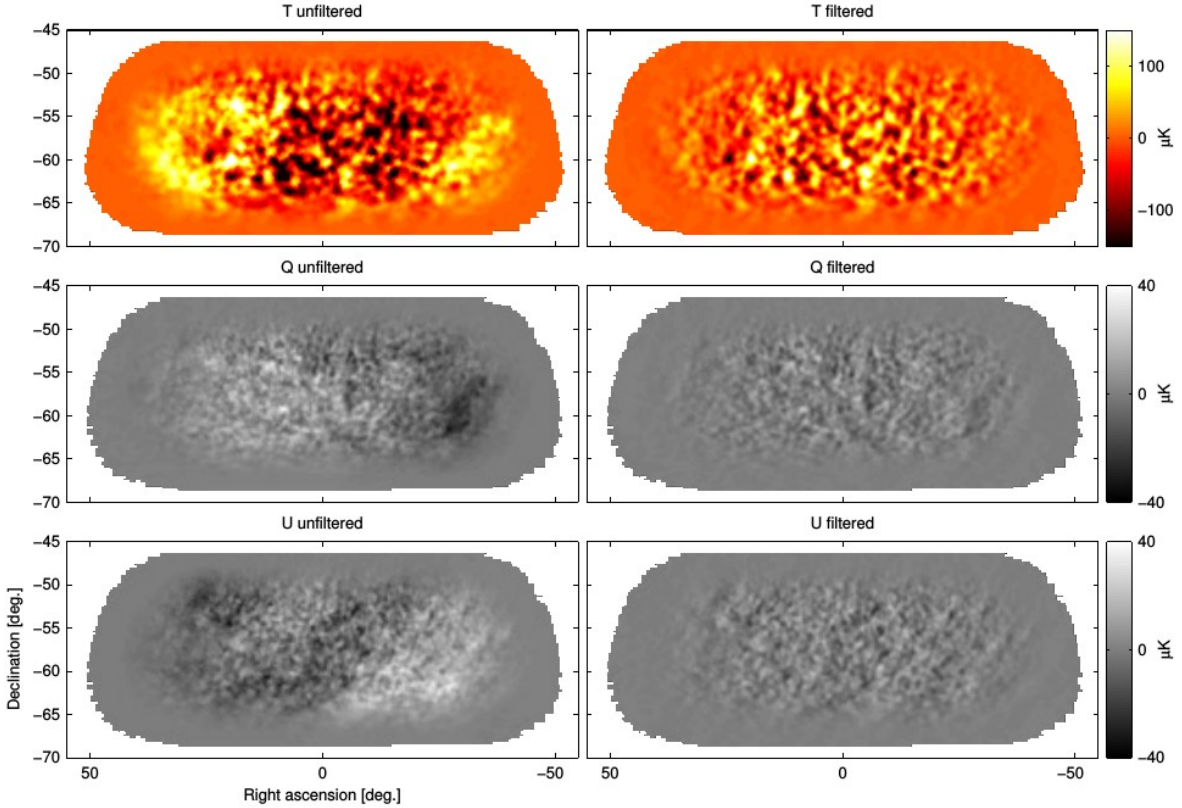
Planck 2014

Planck observed dust polarization at intermediate latitudes



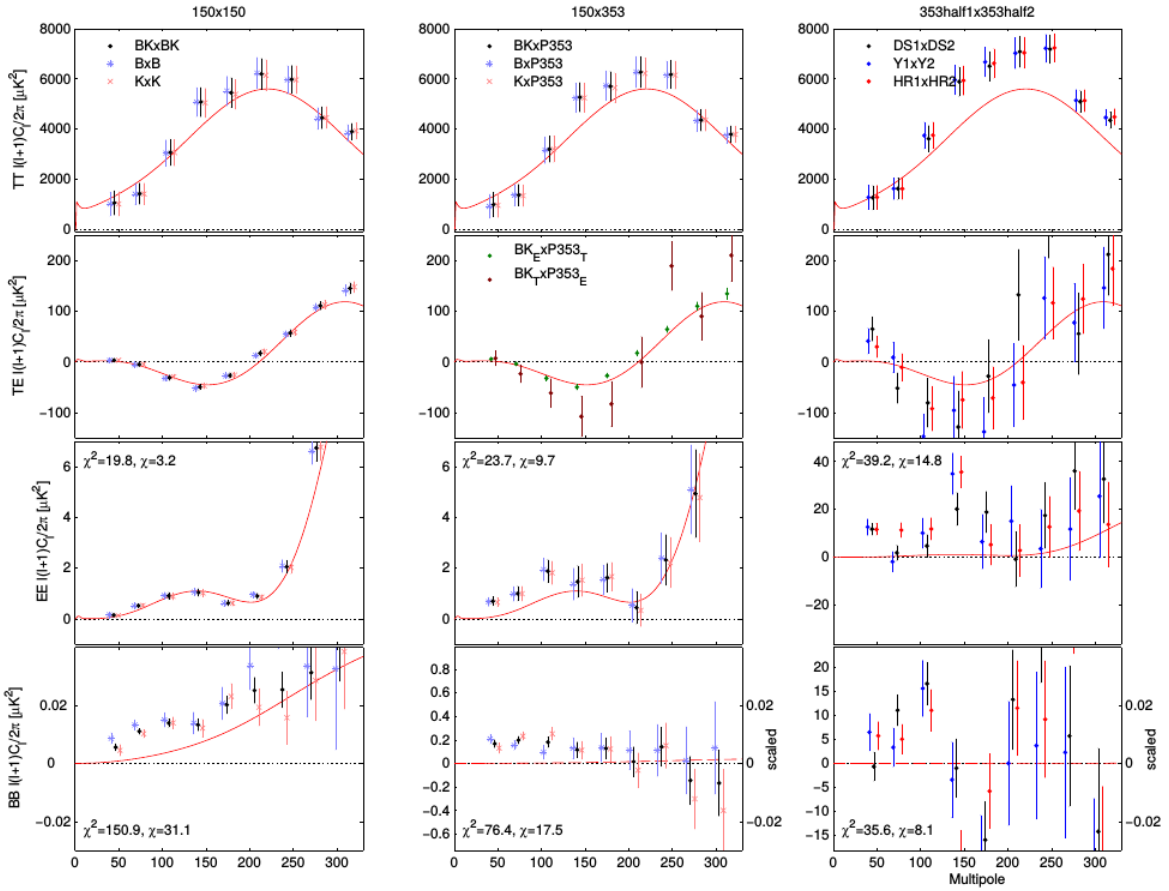
Planck 2014

Planck × Bicep2 × KEcK



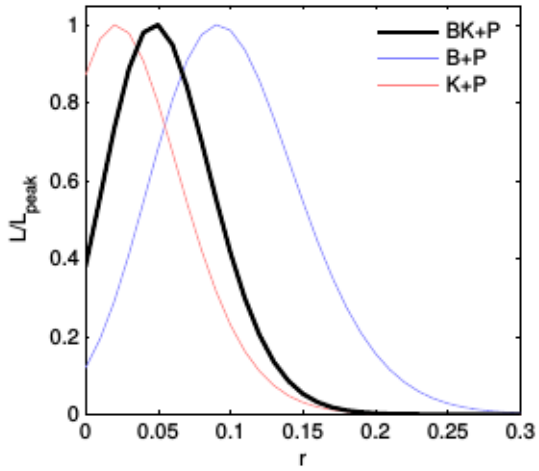
BKP 2015

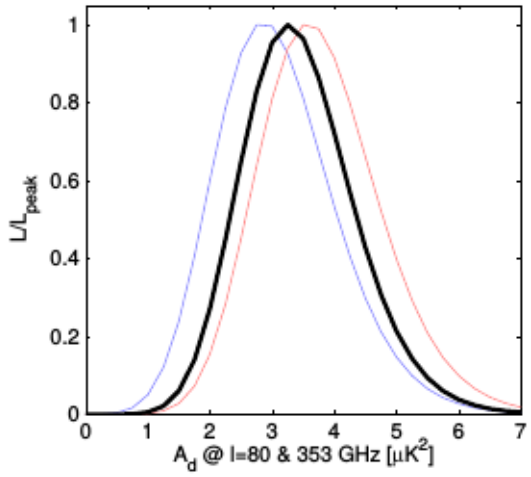
Planck × Bicep2 × KEcK

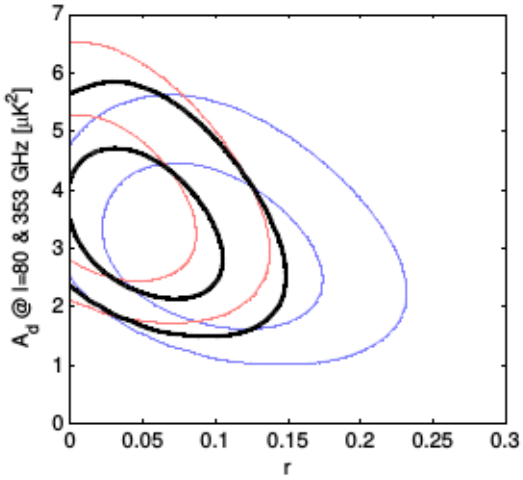


BKP 2015

Planck × Bicep2 × KEcK







BKP 2015

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