CMB component separation intution and GreenPol

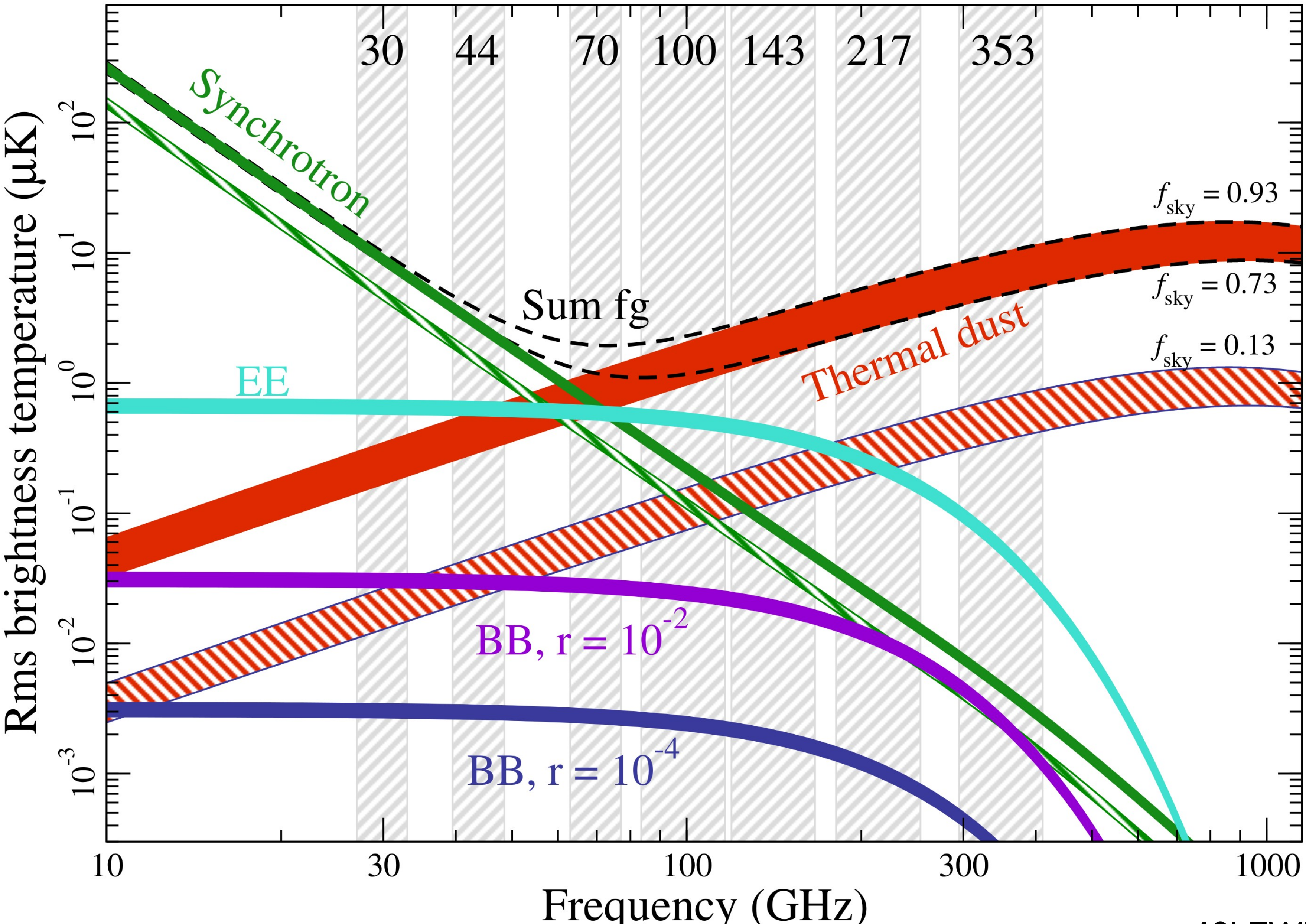
Hans Kristian Eriksen

University of Oslo

Nordita, Stockholm July 2017

in collaboration with Unni Fuskeland, Ari Kaplan, Ingunn Wehus, Hao Liu, Phil Lubin, Peter Meinhold, Pavel Naselsky and Andrea Zonca

The Challenge



40' FWHM

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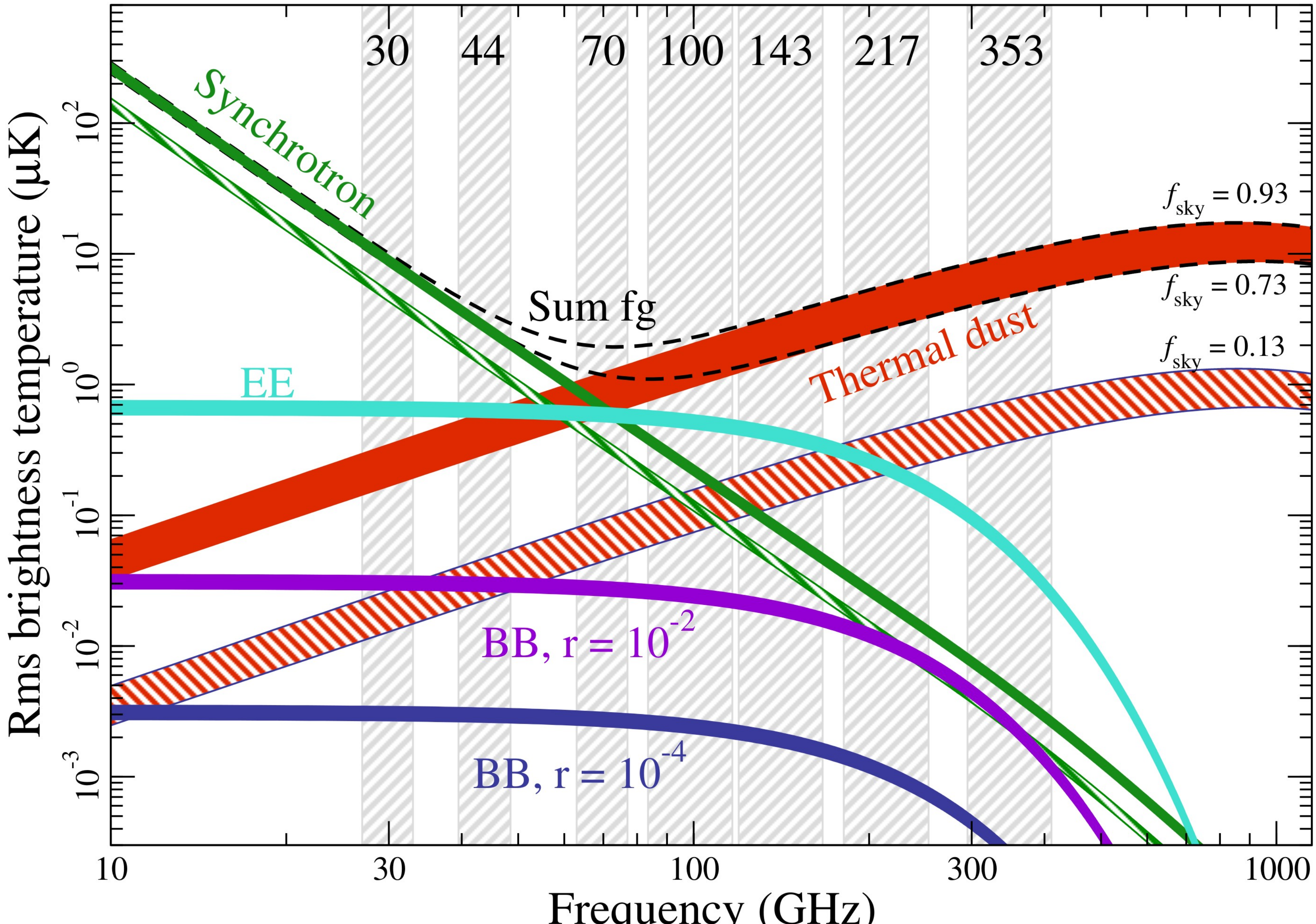

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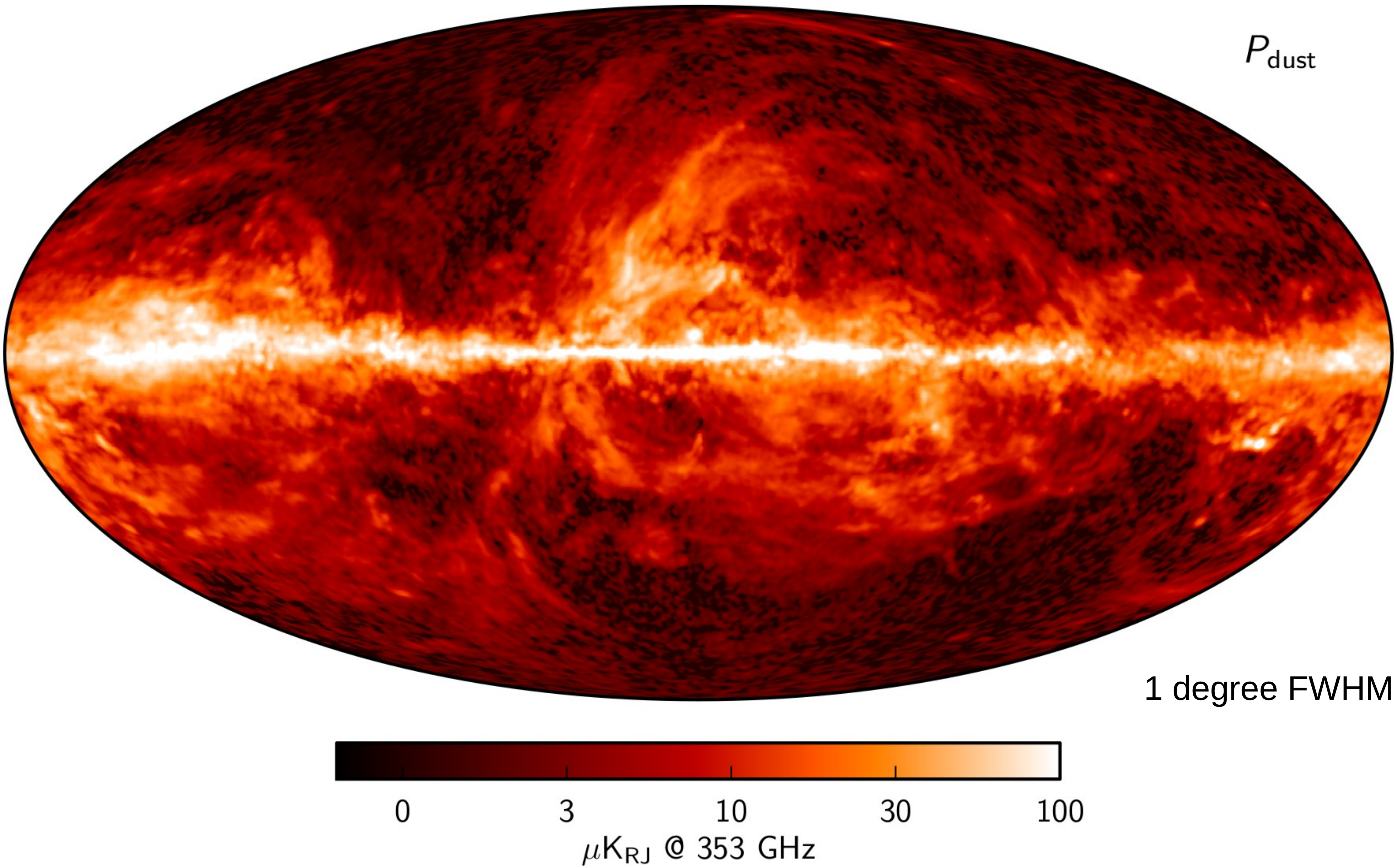

1 degree FWHM

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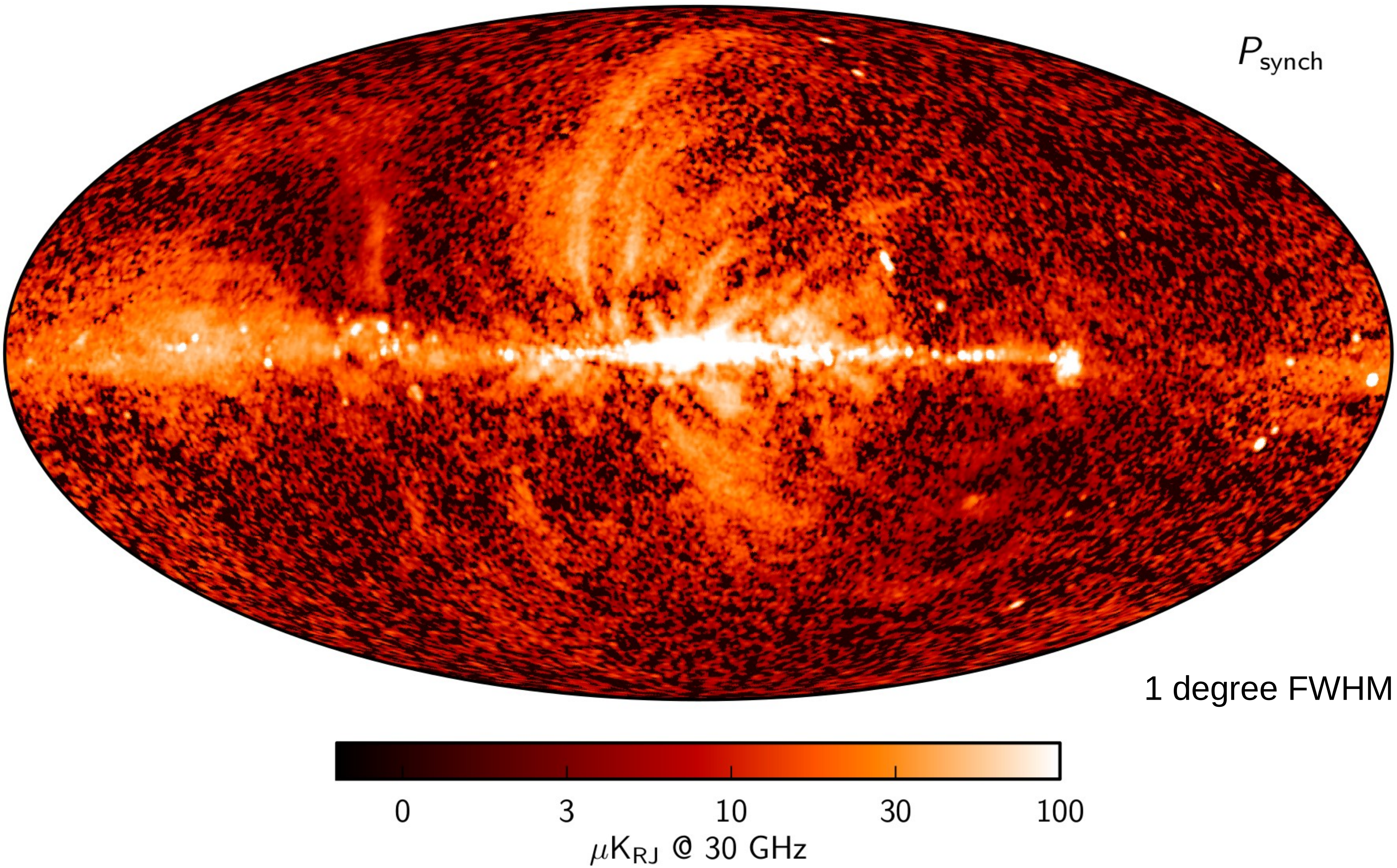

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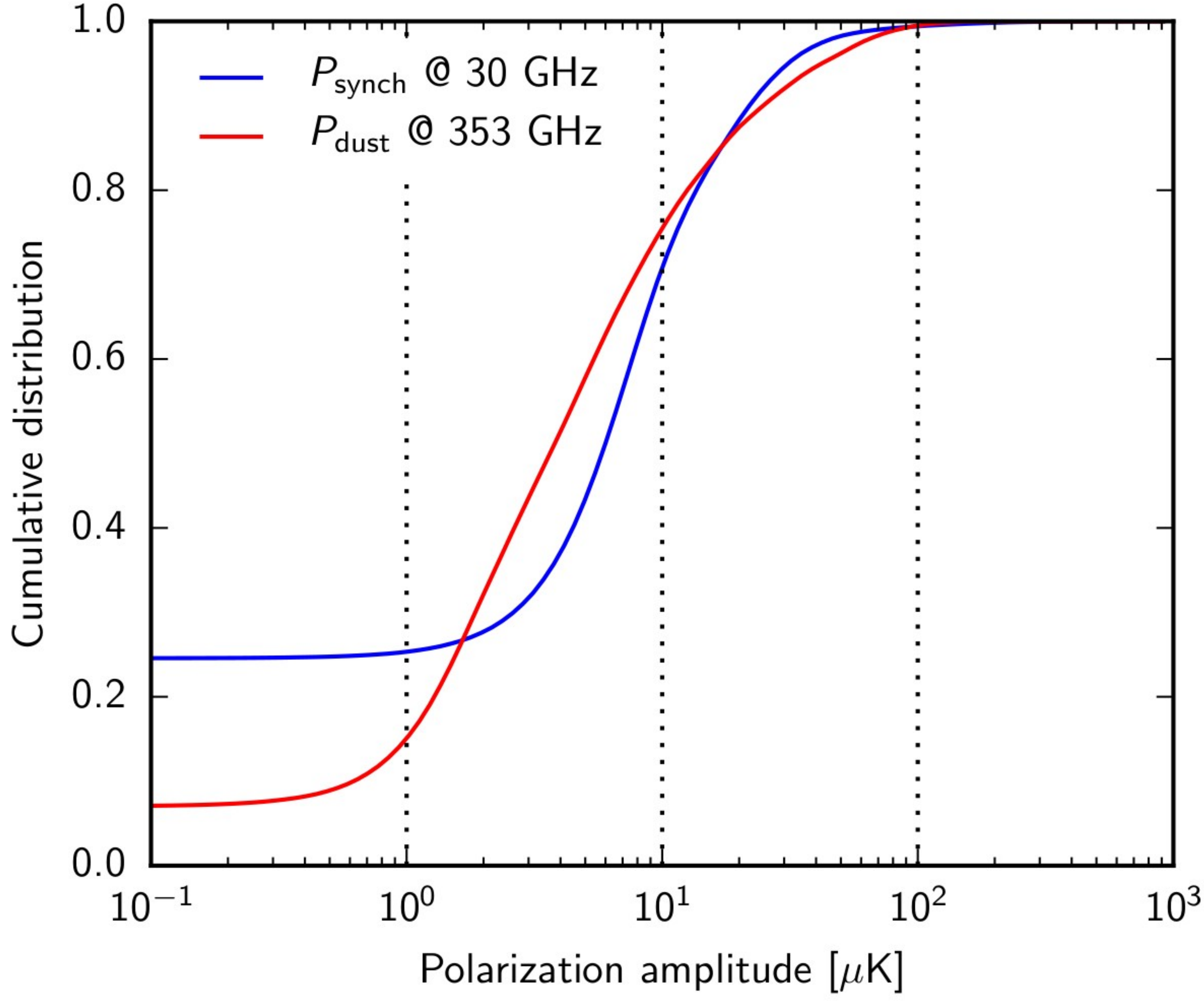

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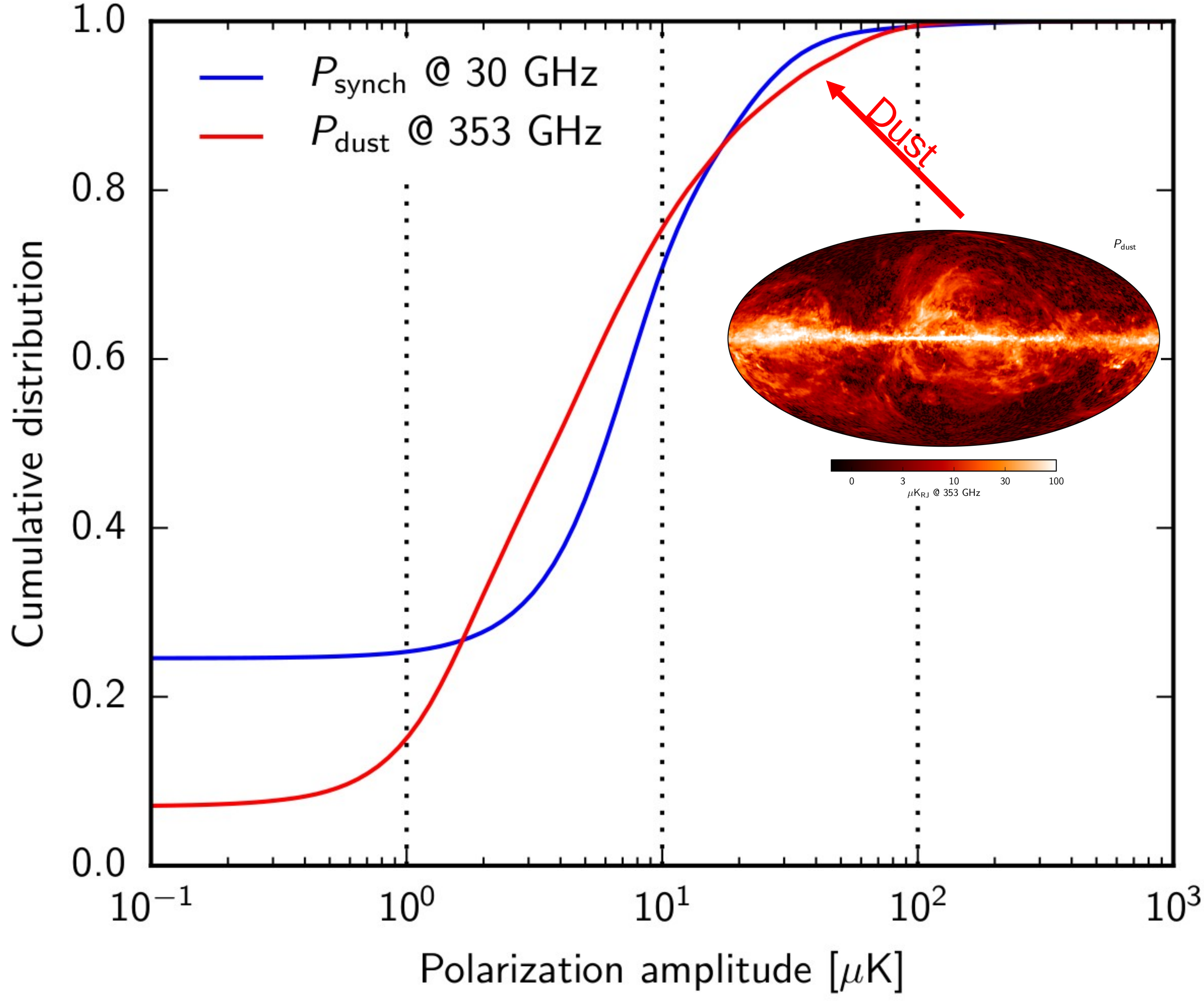

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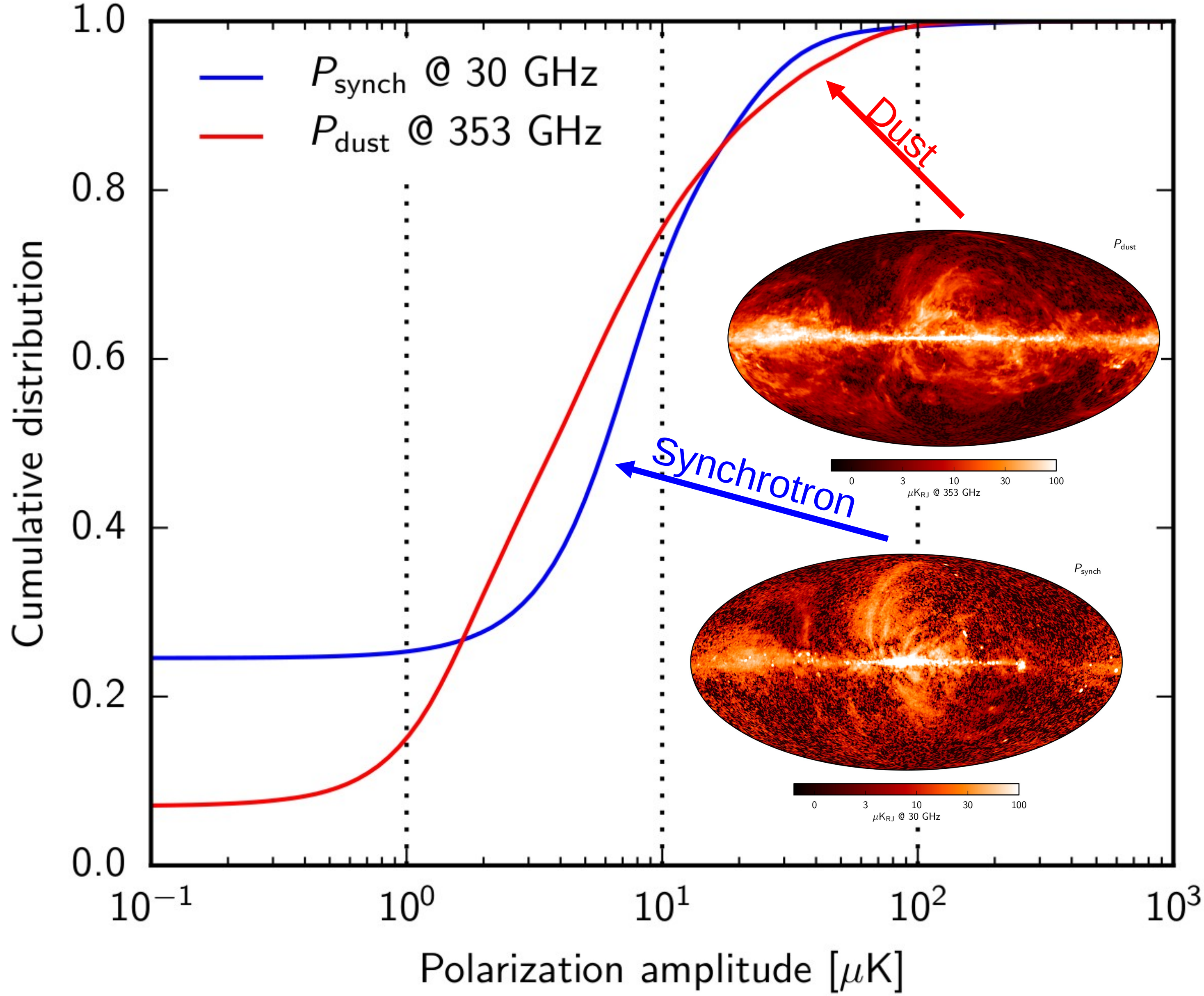

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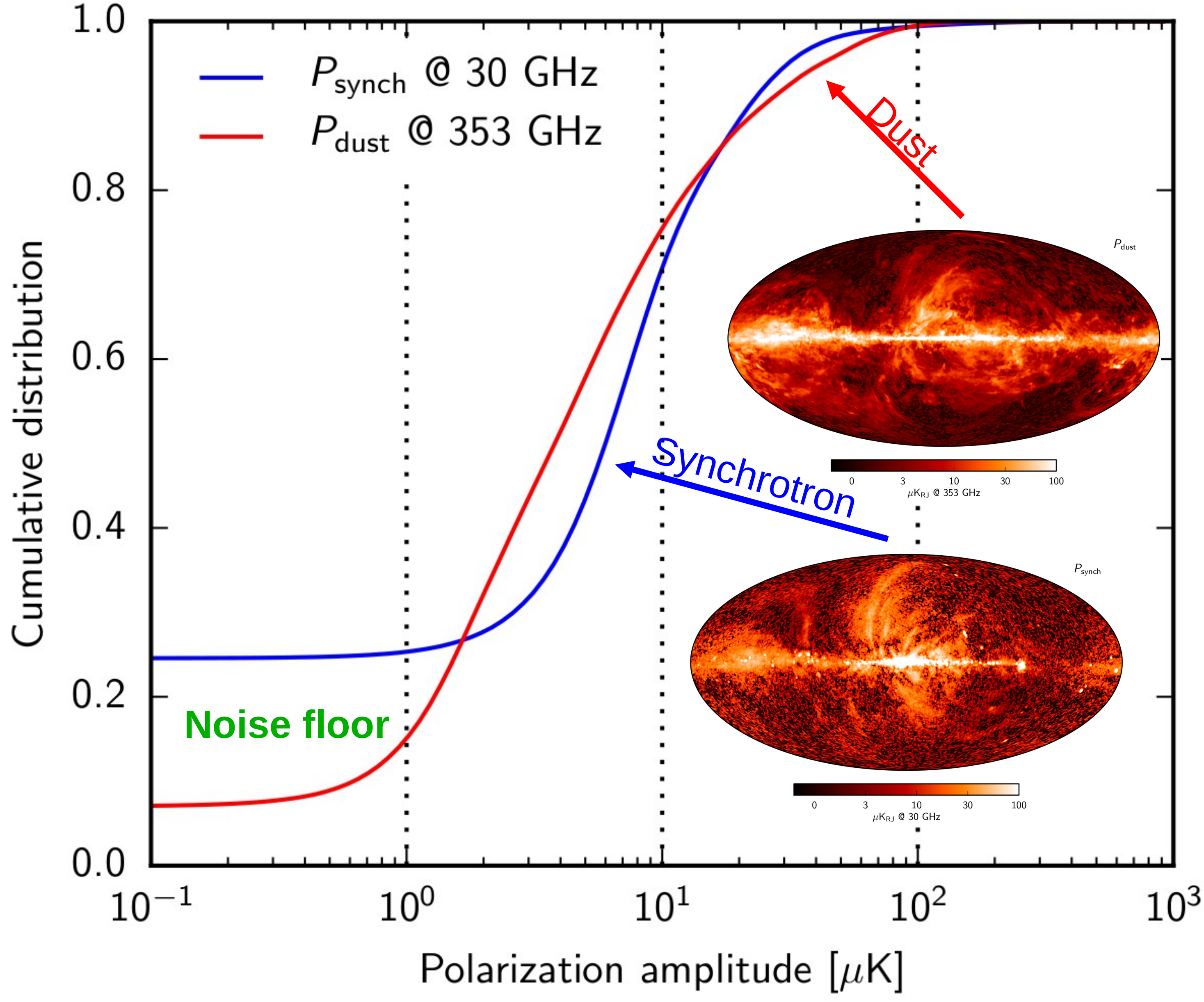

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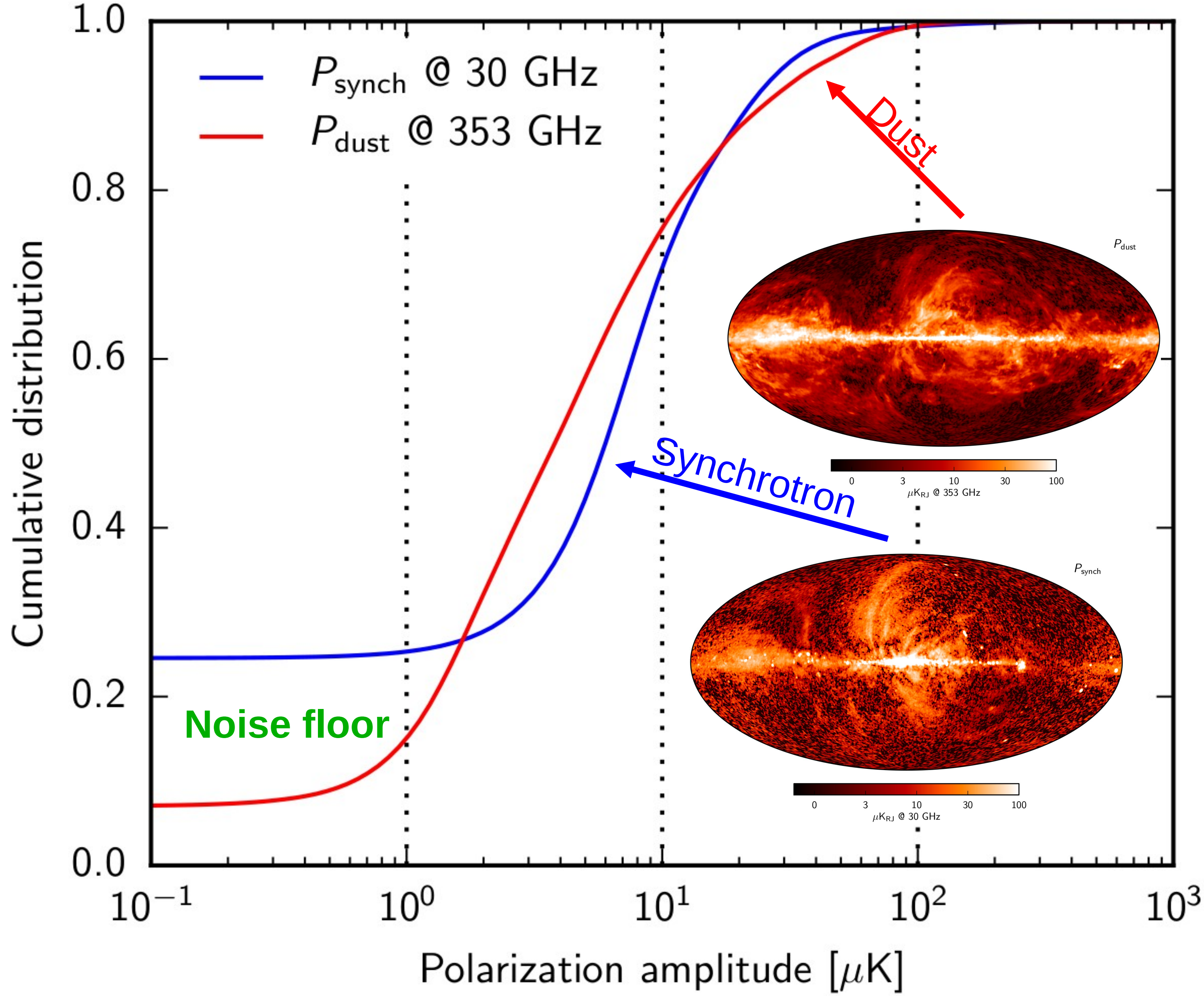

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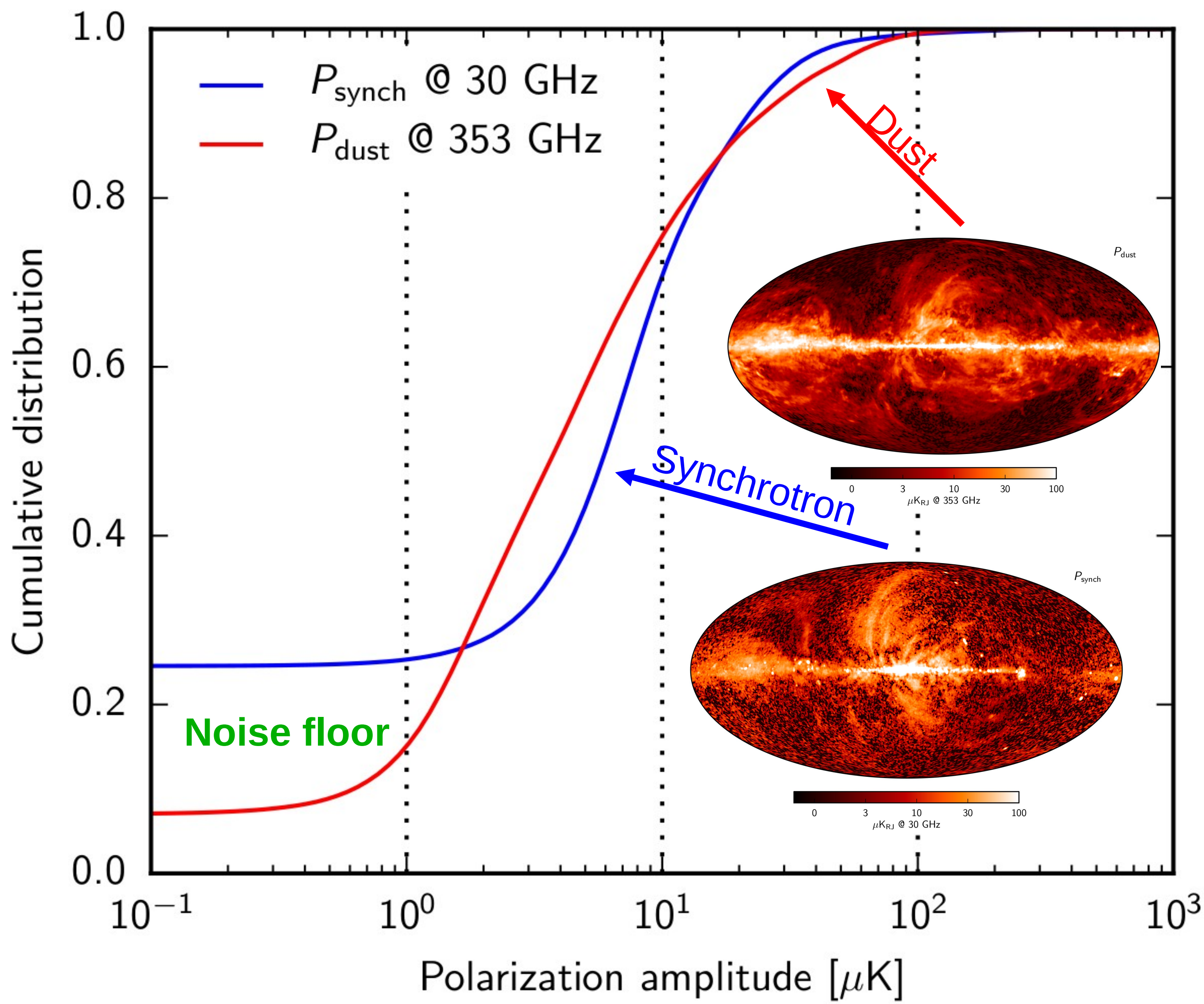
$A_{fg} < 1\mu K$ at $f_{sky} \sim 0.1$



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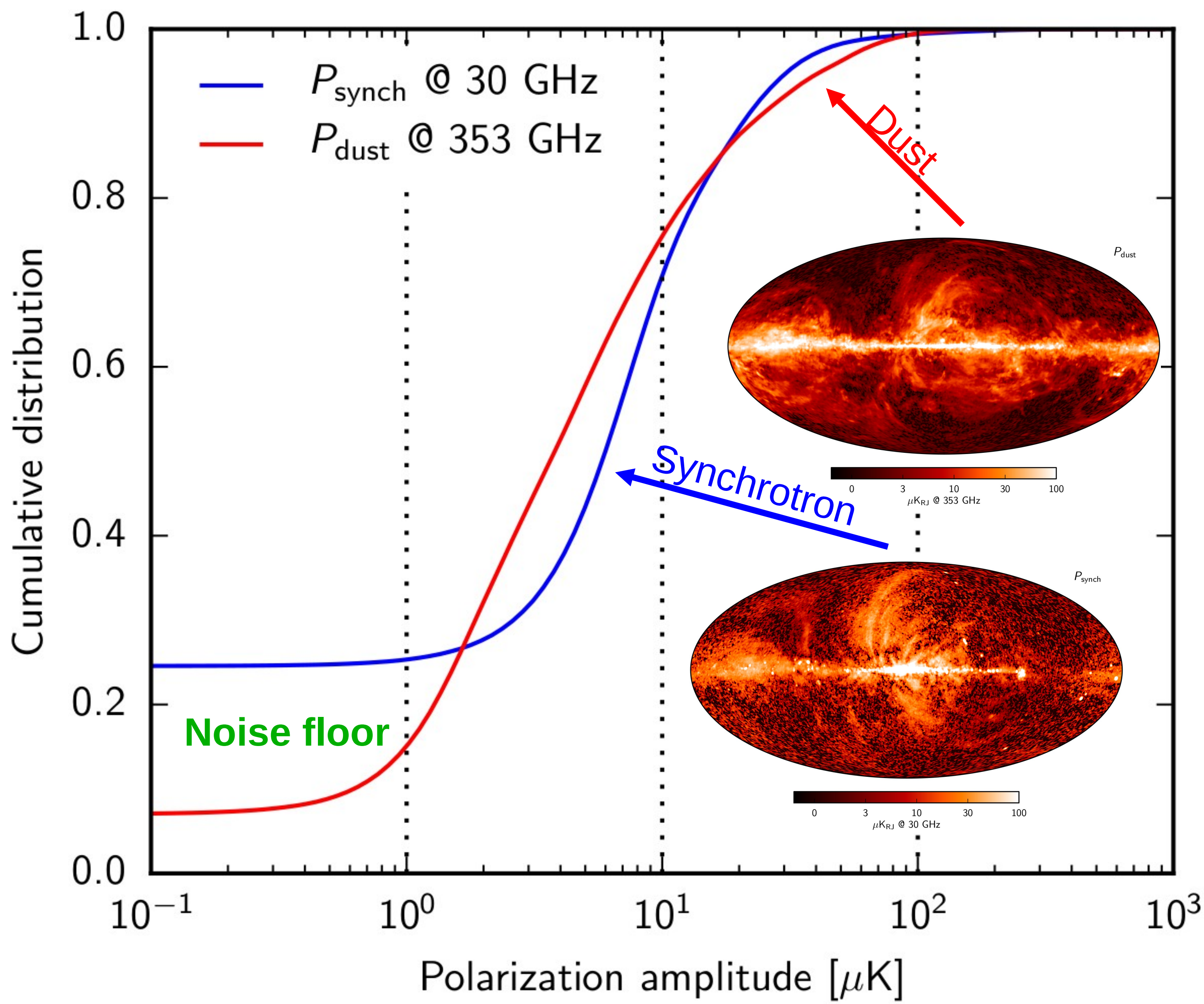

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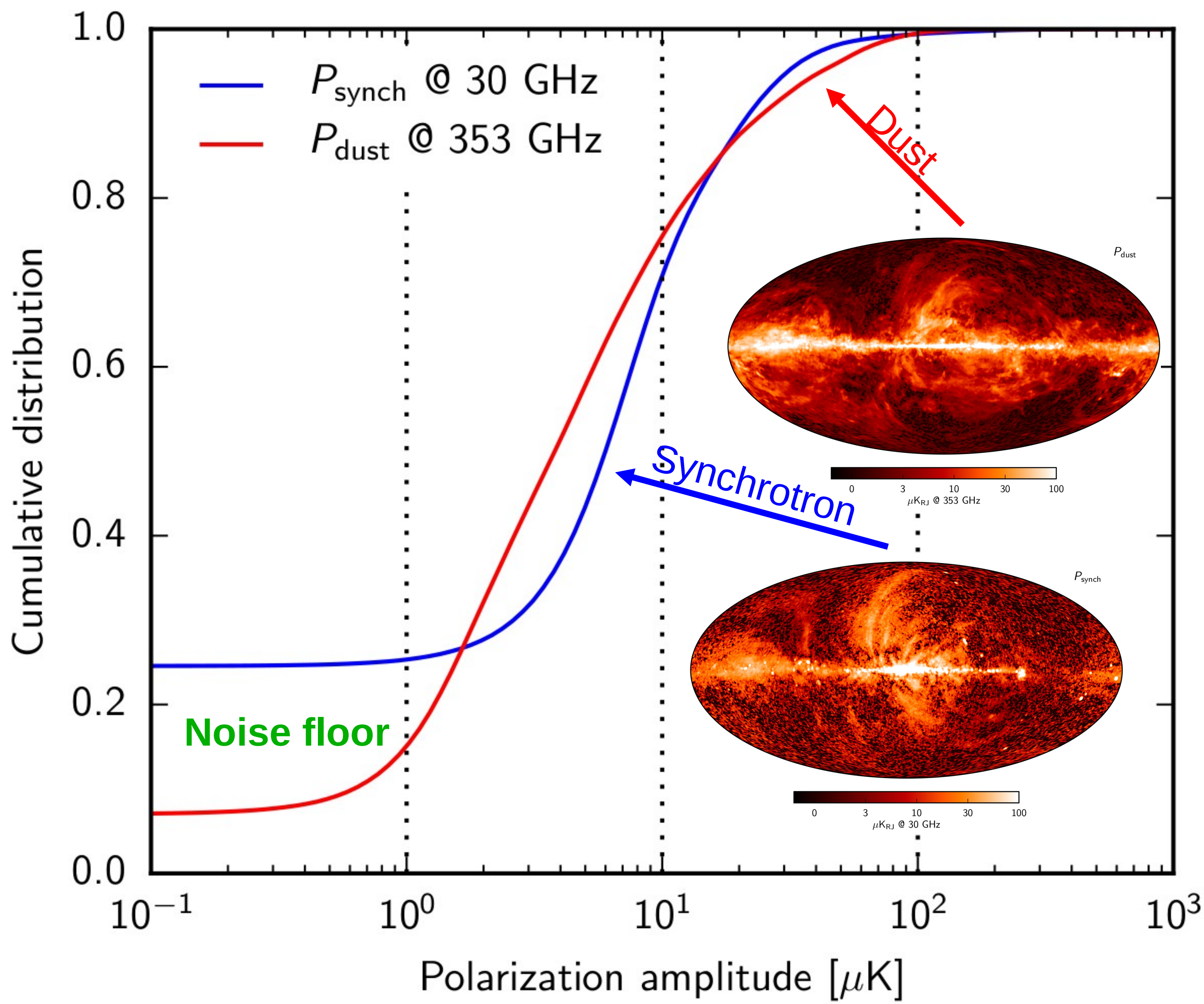
for

$\nu_0^{synch} = 30$ GHz
$\nu_0^{dust} = 353$ Ghz



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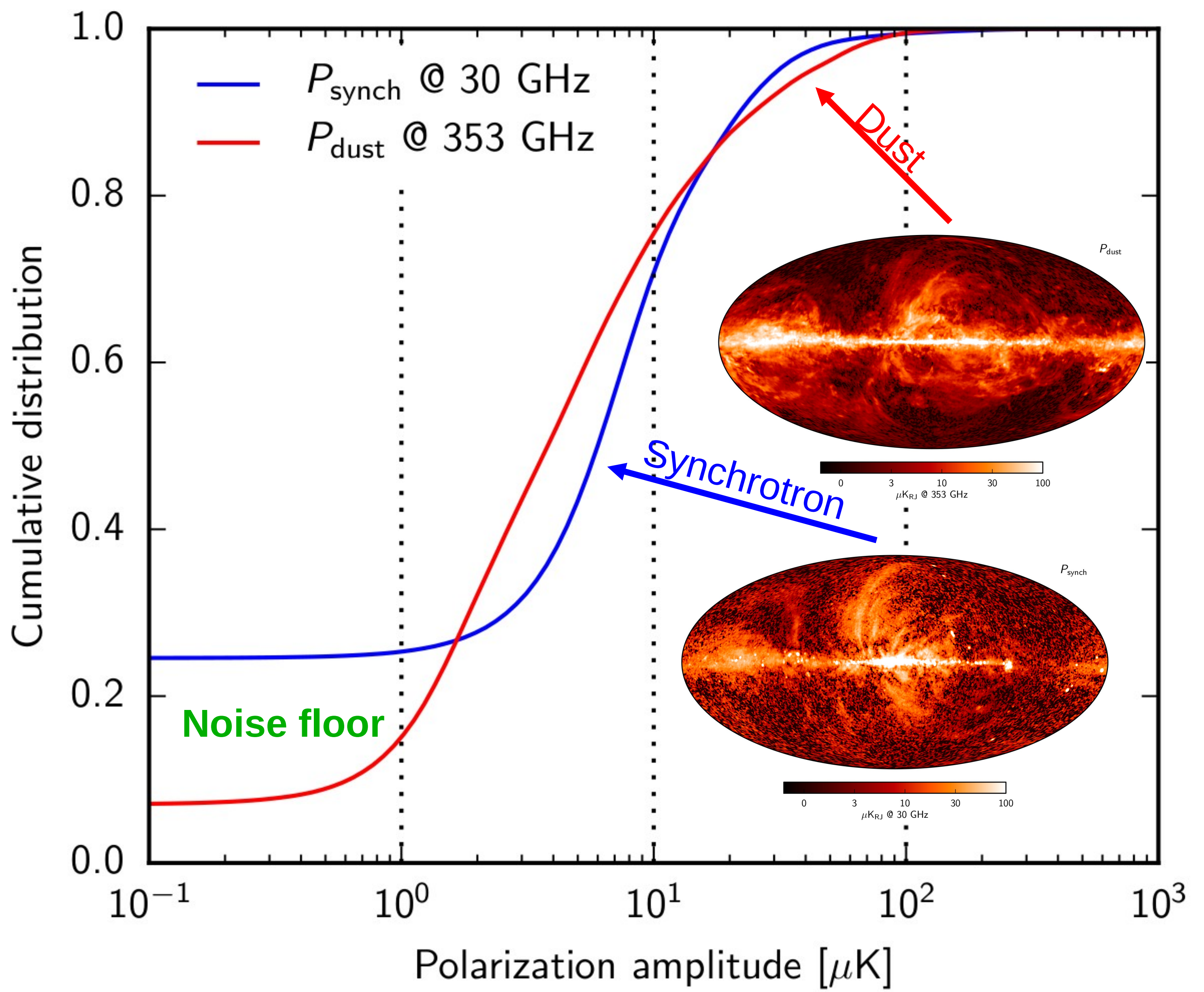
For comparison, the RMS of a pure B-mode signal (l=25-150 at 1 deg FWHM) with a given value of *r* is

~35 nK for r = 10^{-2}
~3.5 nK for r = 10^{-4}



Tensor-to-scalar ratio foreground floor

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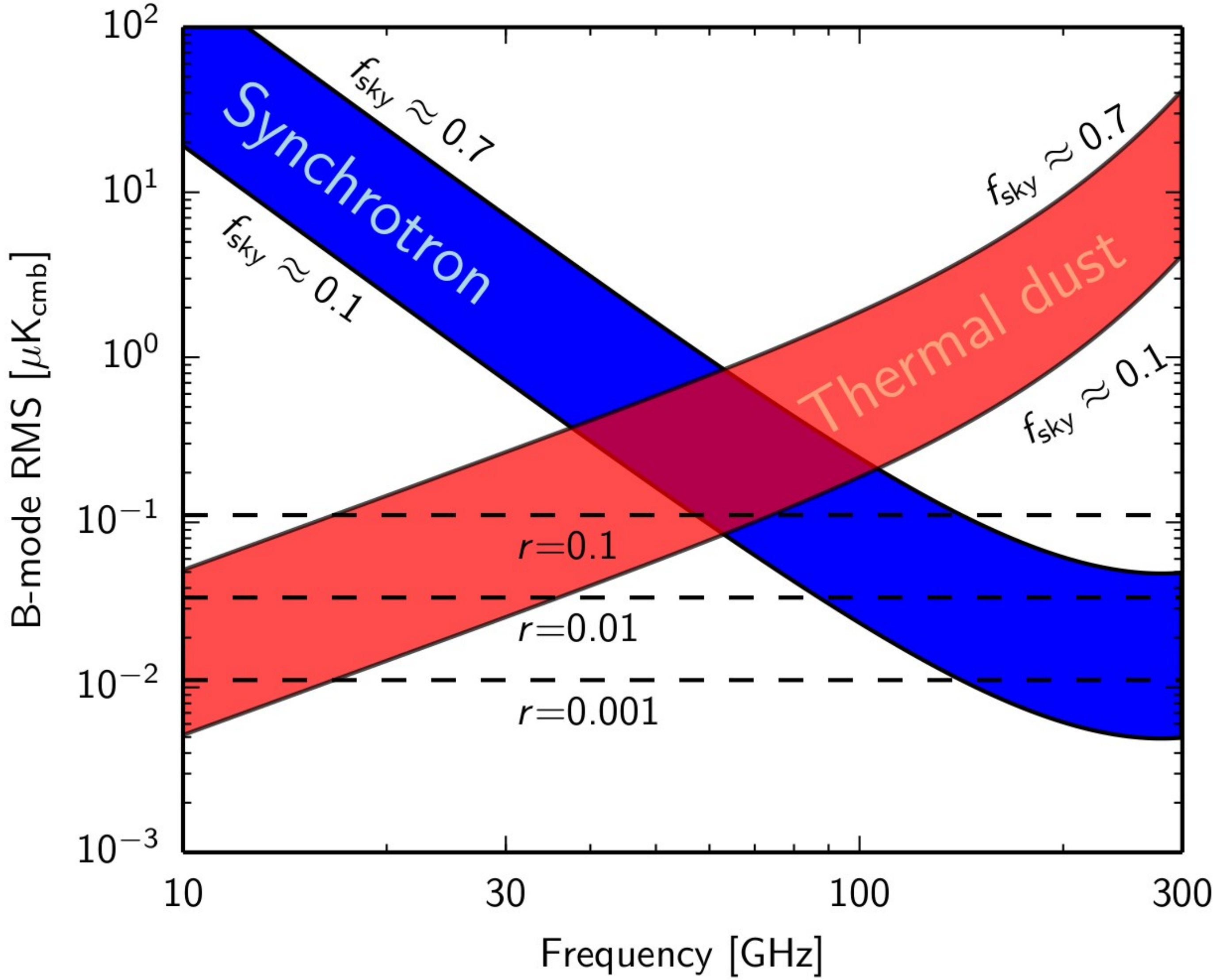

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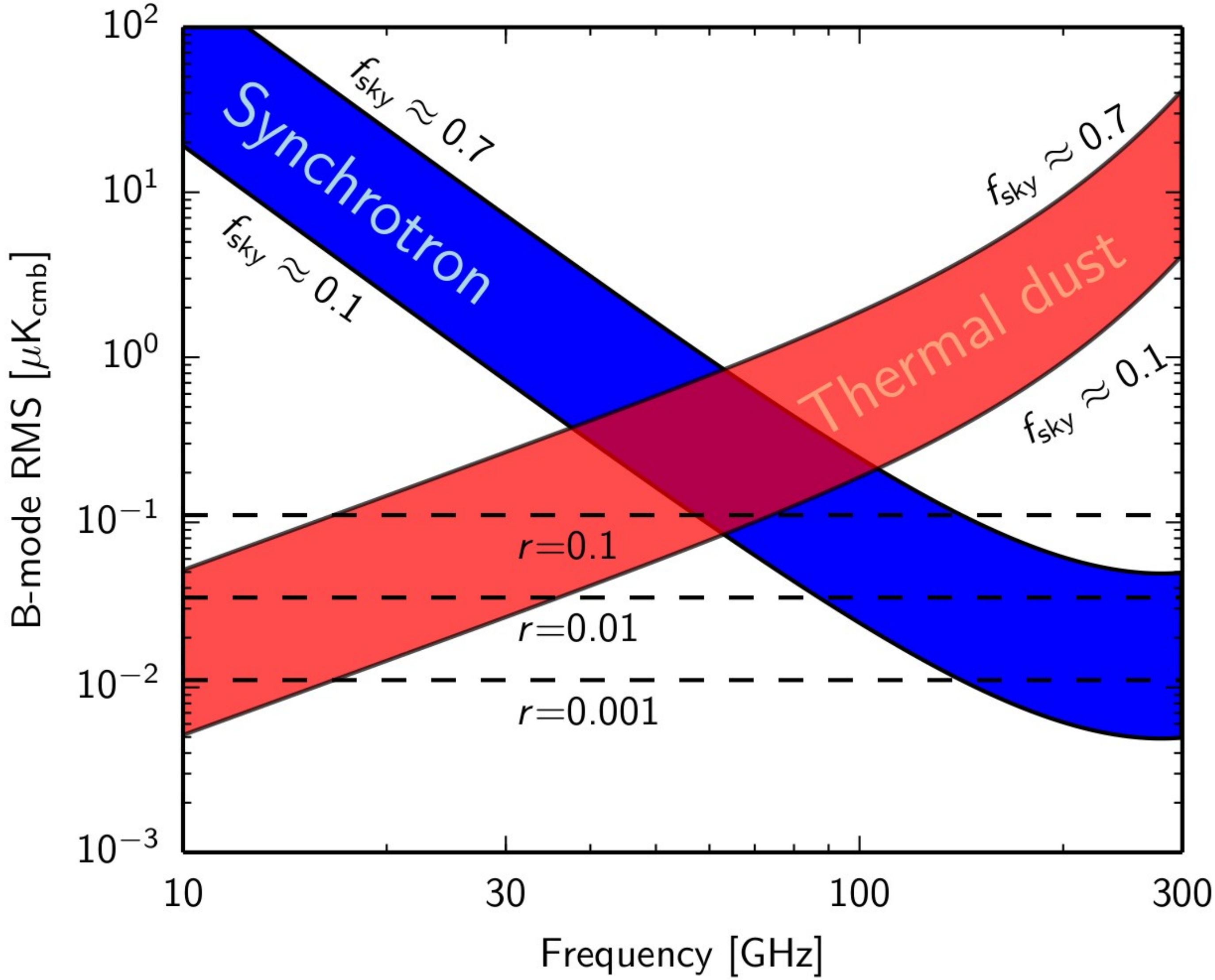

NB! Only intended to provide a rough order-of-magnitude estimate!
Precise values depend of course sensitively on sky location and angular scales

What is the ideal frequency coverage for a typical CMB + synchrotron + thermal dust model space?

Method: Posterior mapping

- Assume following typical model for a single pixel on the sky:

$$s_\nu = A_{cmb} + A_s\, g(\nu) \left(\frac{\nu}{\nu_0^s}\right)^{\beta_s} + A_d\, g(\nu) \left(\frac{\nu}{\nu_0^d}\right)^{\beta_d + 1} \frac{e^{\frac{h\nu_0^d}{kT_d}} - 1}{e^{\frac{h\nu_0}{kT_d}} - 1}$$

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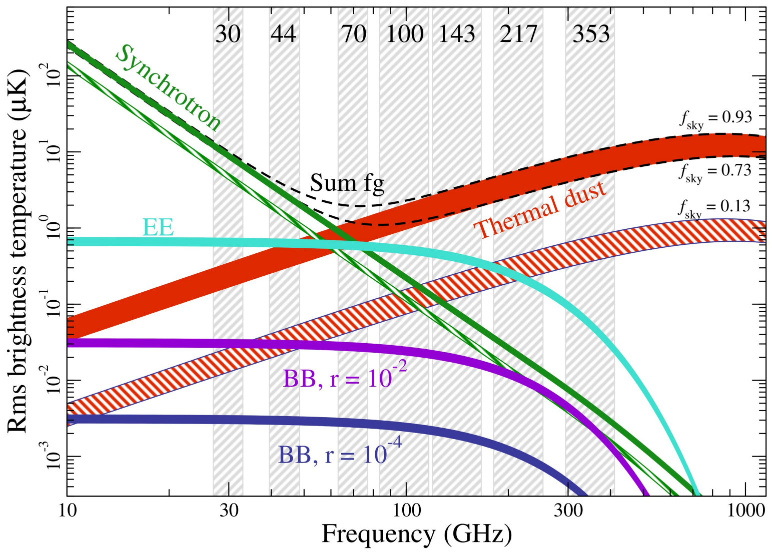

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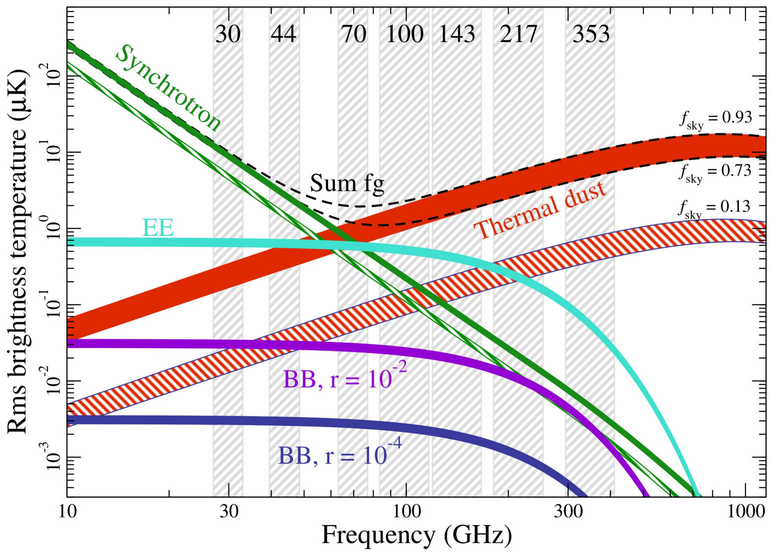

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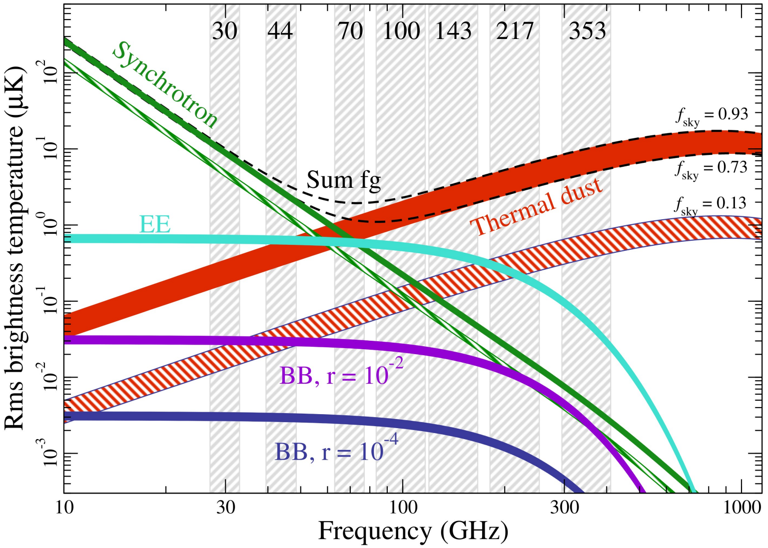

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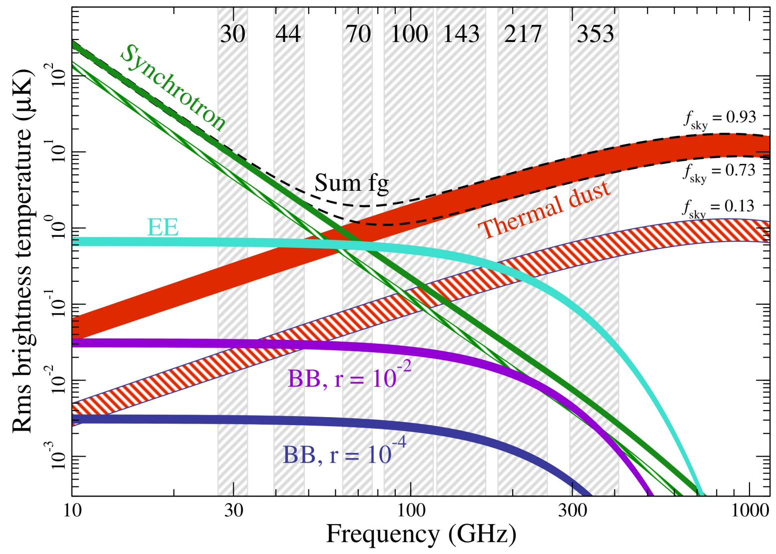

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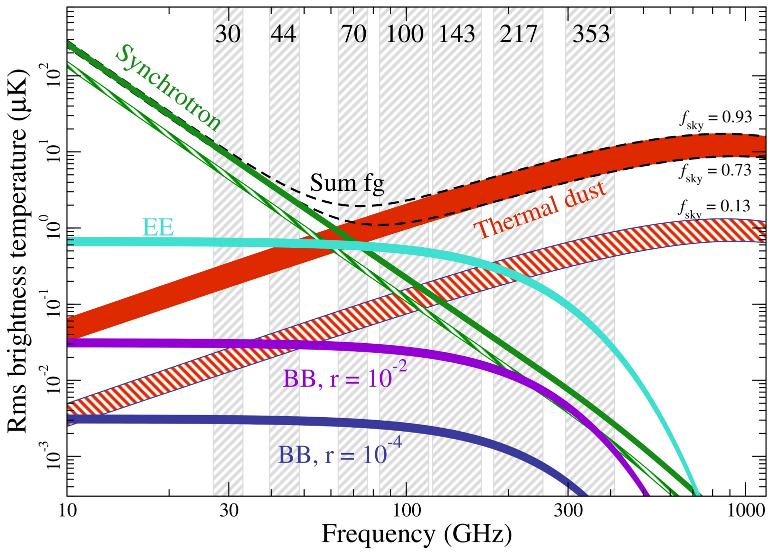

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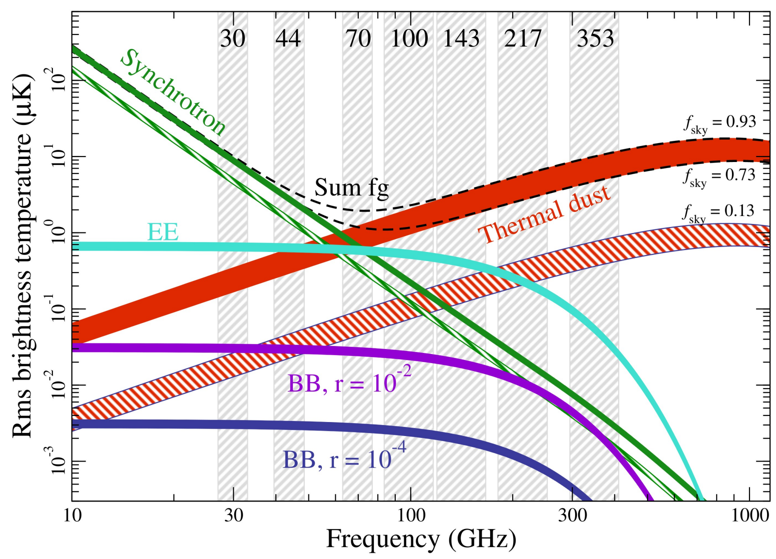
  - T_{d}: Effective thermal dust temperature



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- Given a set of observed frequencies with associated instrumental noise RMS's, the posterior distribution for this model reads

$$P(\theta) \sim L(\theta)\,P(\theta) = e^{-\frac{1}{2}\sum\left(\frac{d_\nu - s_\nu}{\sigma_\nu}\right)^2} P(\beta_s, \beta_d, T_d)$$

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  - Note: This is essentially a special case of the Planck 2015 analysis, reducing *Commander* to a single pixel, and including only CMB, synchrotron and thermal dust in the model

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$$\sigma = \frac{T_{sys}}{\sqrt{\Delta\nu}} = \frac{\left(T_{cmb} + T_{inst} + T_{sidelobe} + \cdots\right) + T_{atmos}}{\sqrt{\Delta\nu}} \sim \frac{\sigma_0 + \sigma_{atm}(\nu)}{\sqrt{\nu}}$$

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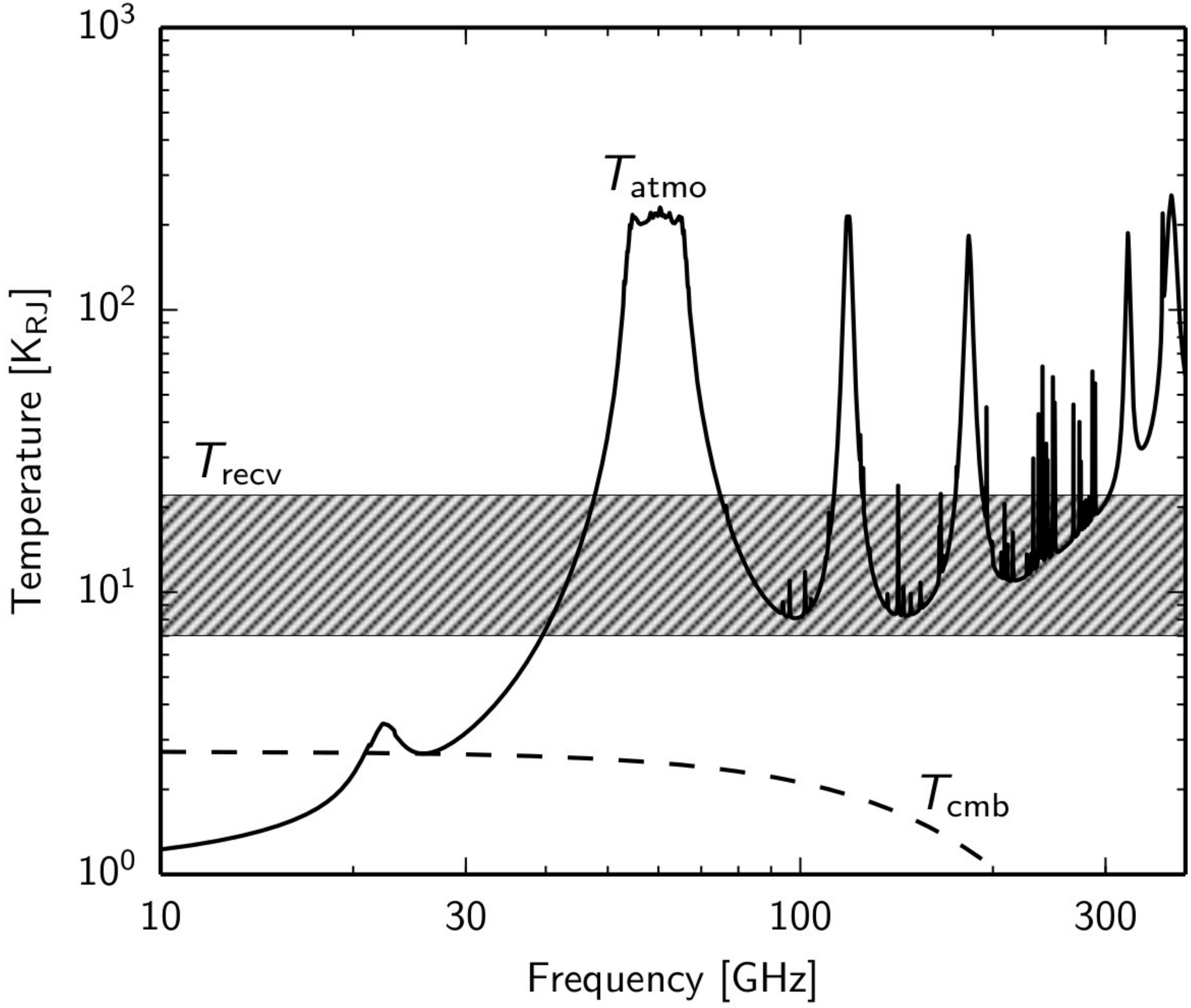
- Distribute channels according to total signal-to-noise in the following cases

The atmosphere



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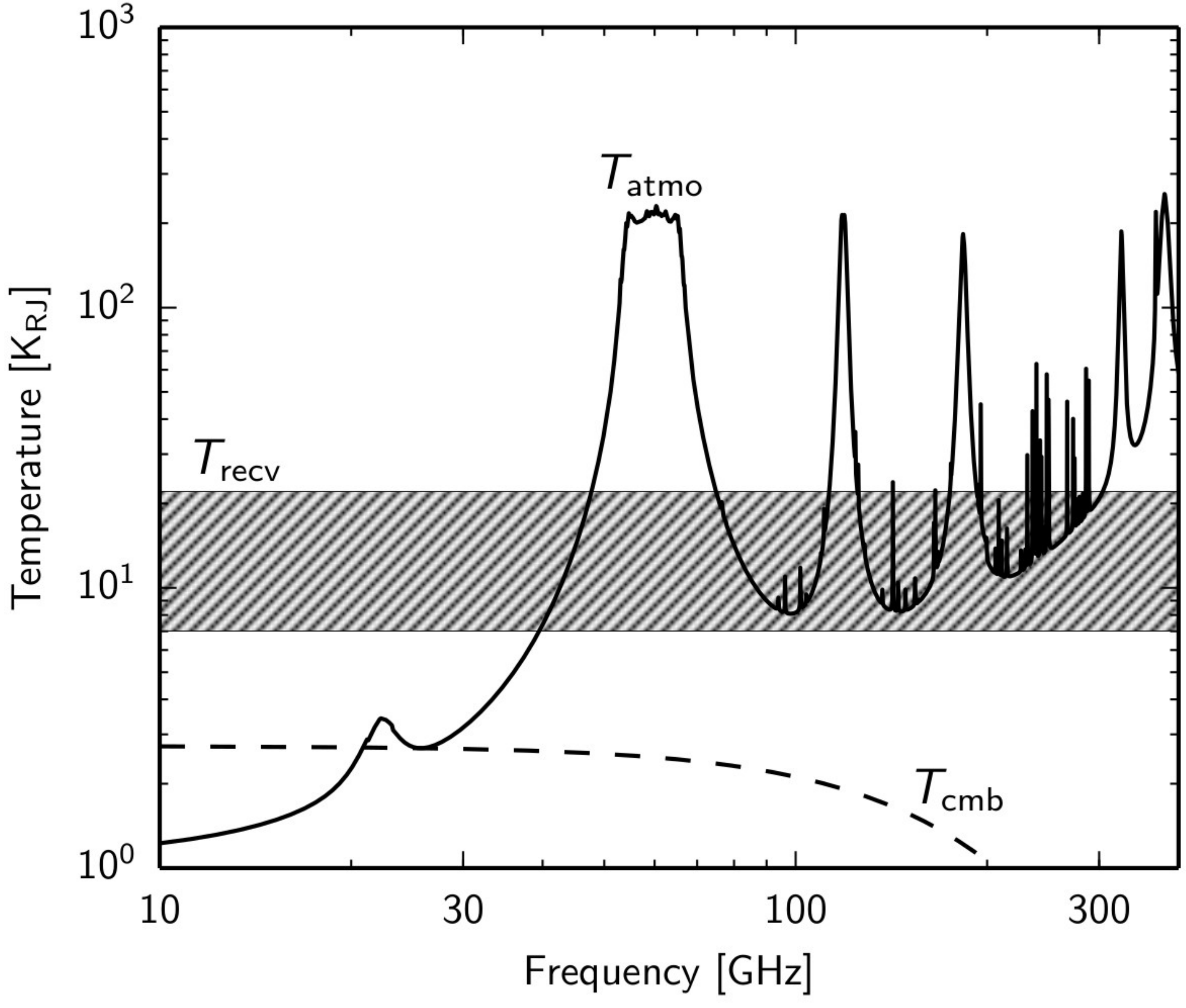
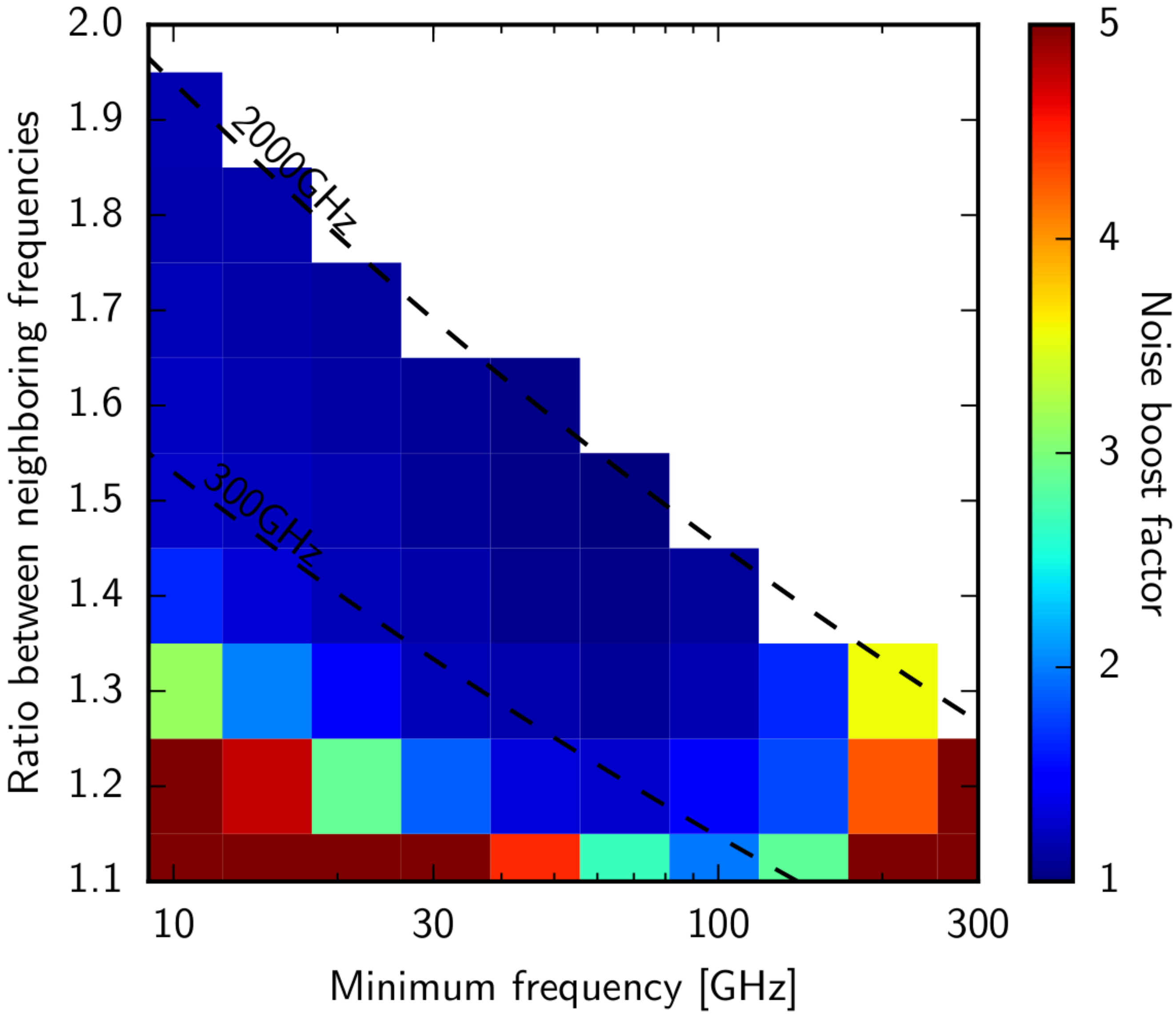


Case 1: Low foreground, high-latitude sky

$N_{\mathrm{band}} = 9$

$A_{\mathrm{fg}} = 1\ \mu\mathrm{K}$



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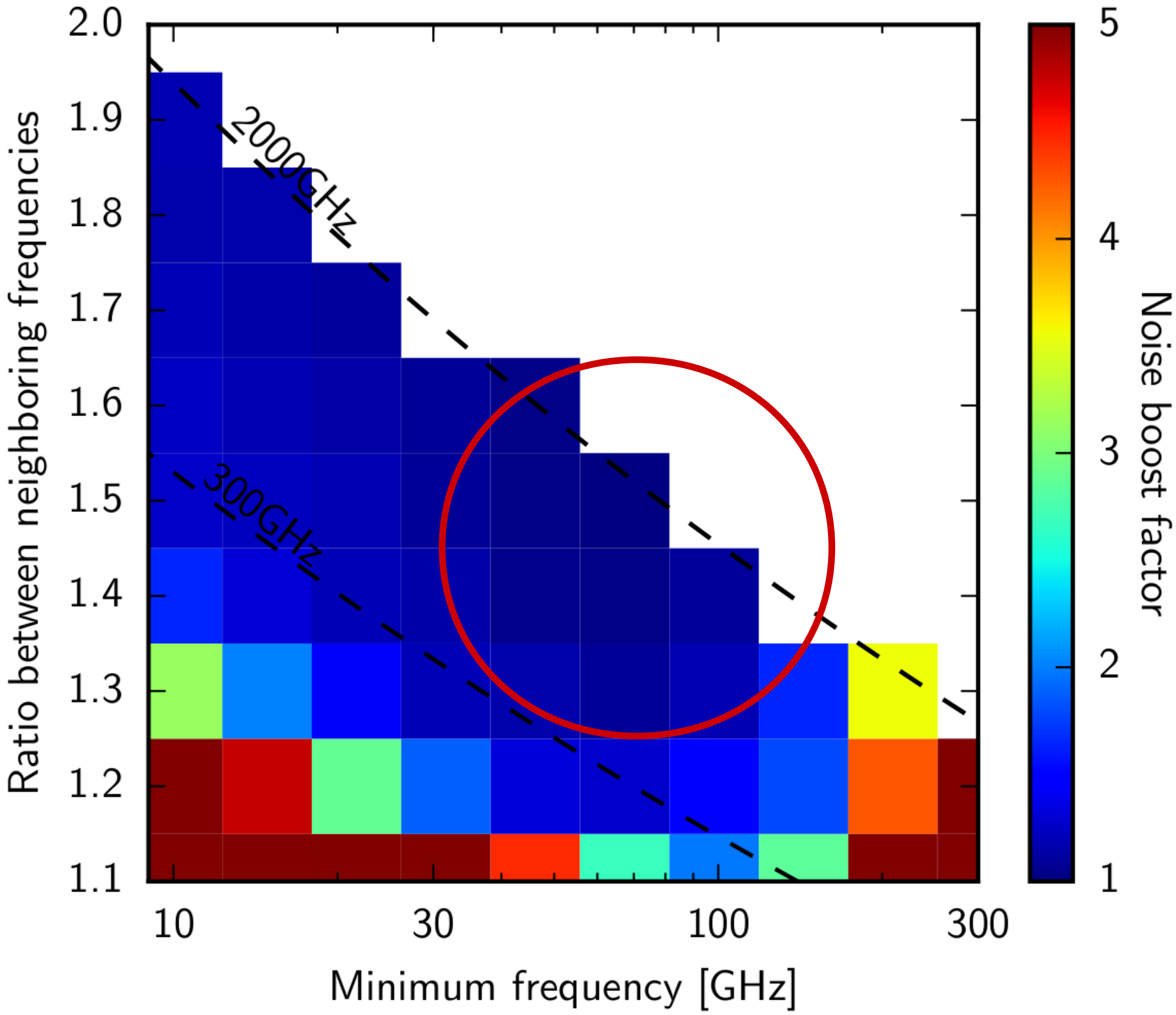

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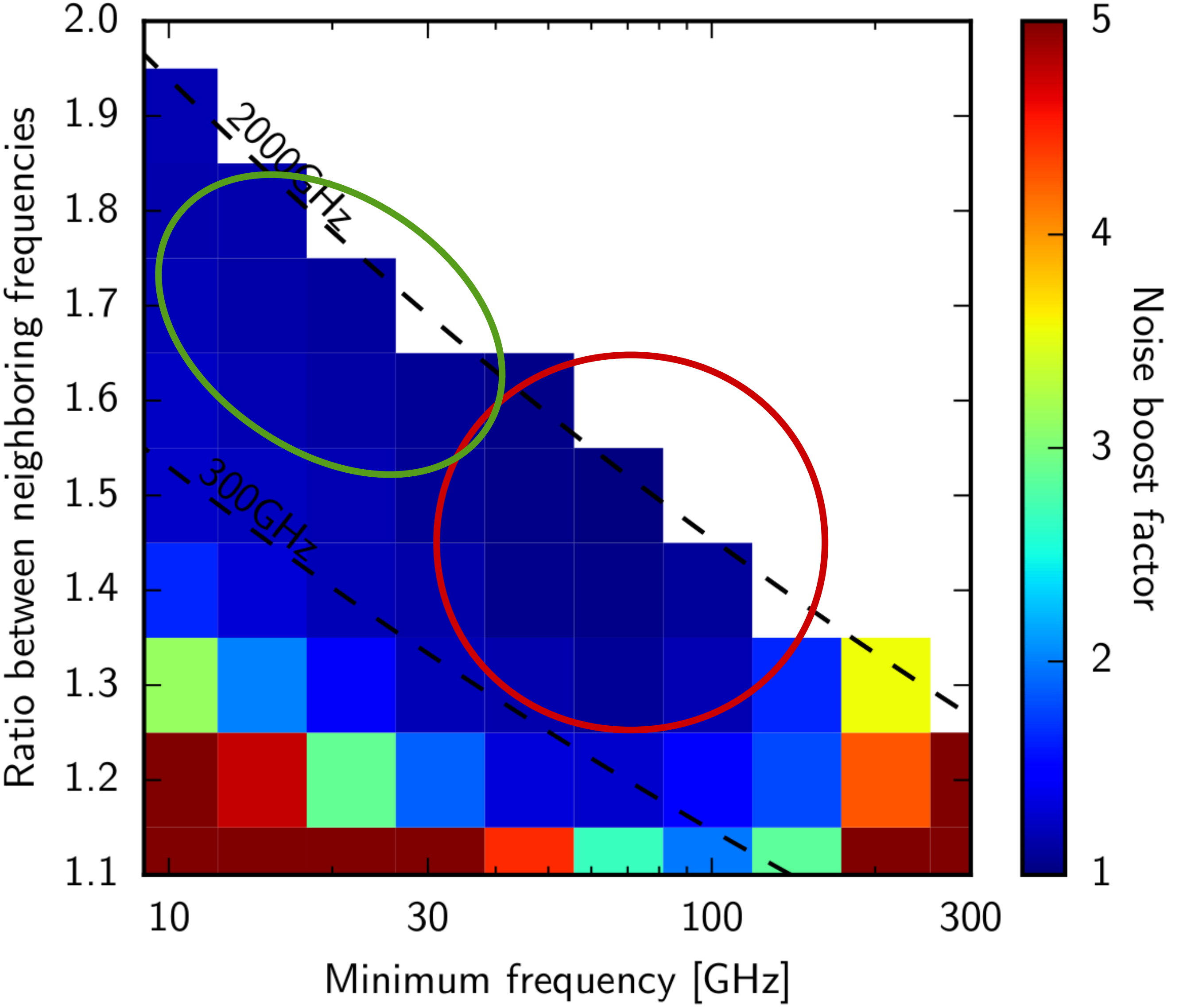

1) For low-foreground regions, the optimal solution is ~60 – 600 Ghz (ie., COrE+ - like)
2) However, extending to lower frequencies carries a very low cost in sensitivity, ***even when accounting for focal plane area.*** Critical point: $S \sim \nu^{-3}$, while $N \sim \nu^{-3/2}$.

Case 2: Intermediate latitude sky

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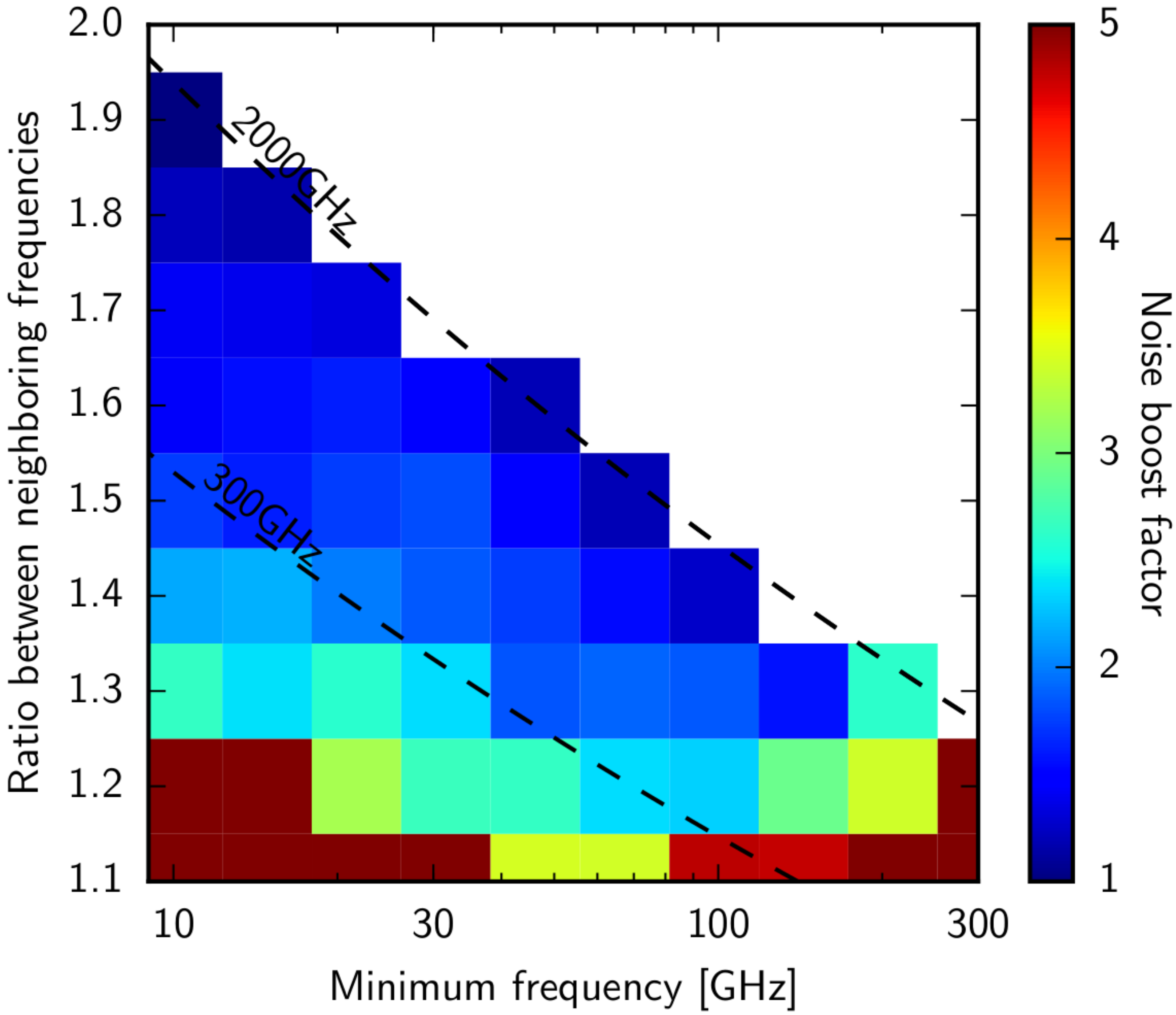

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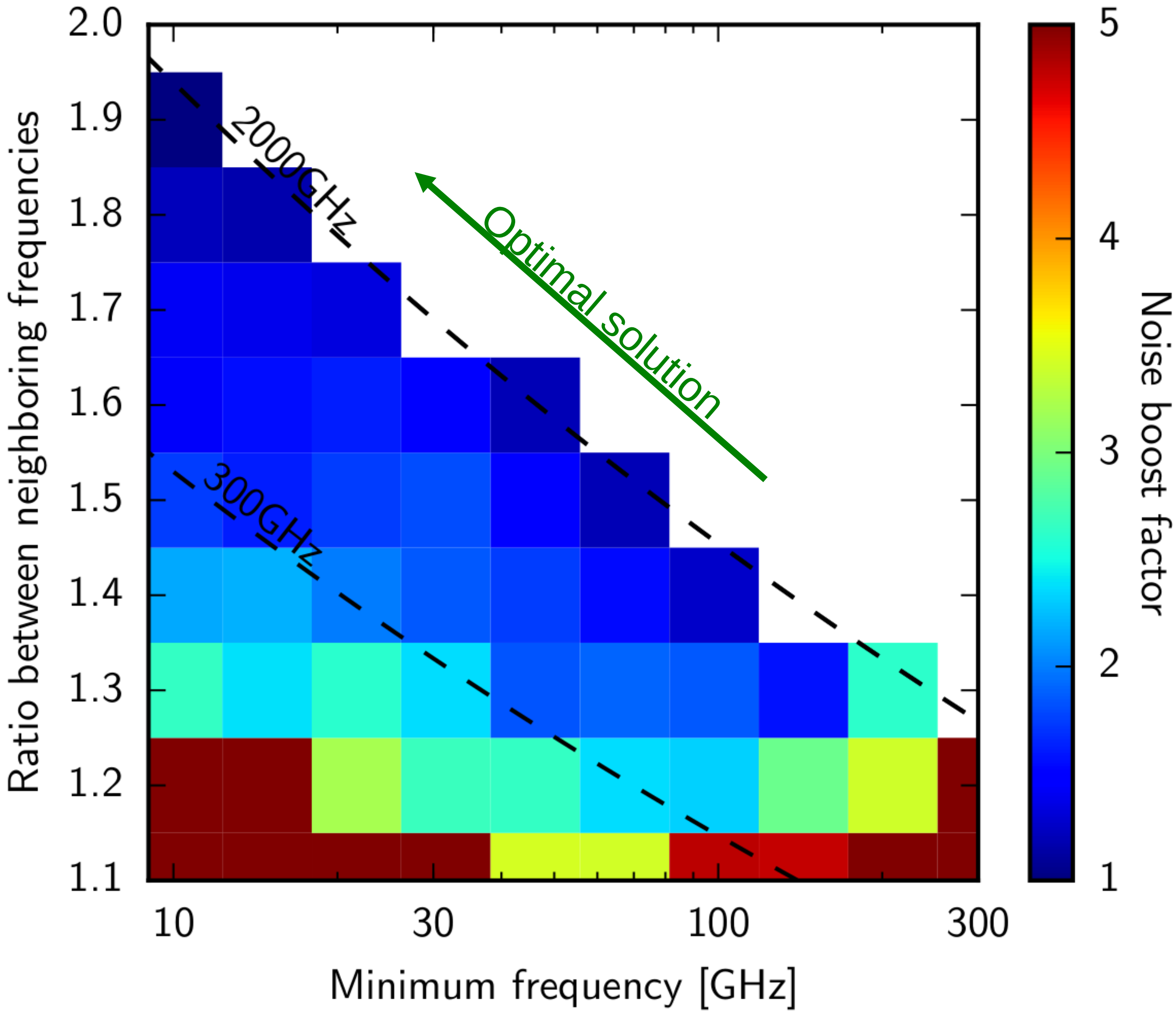

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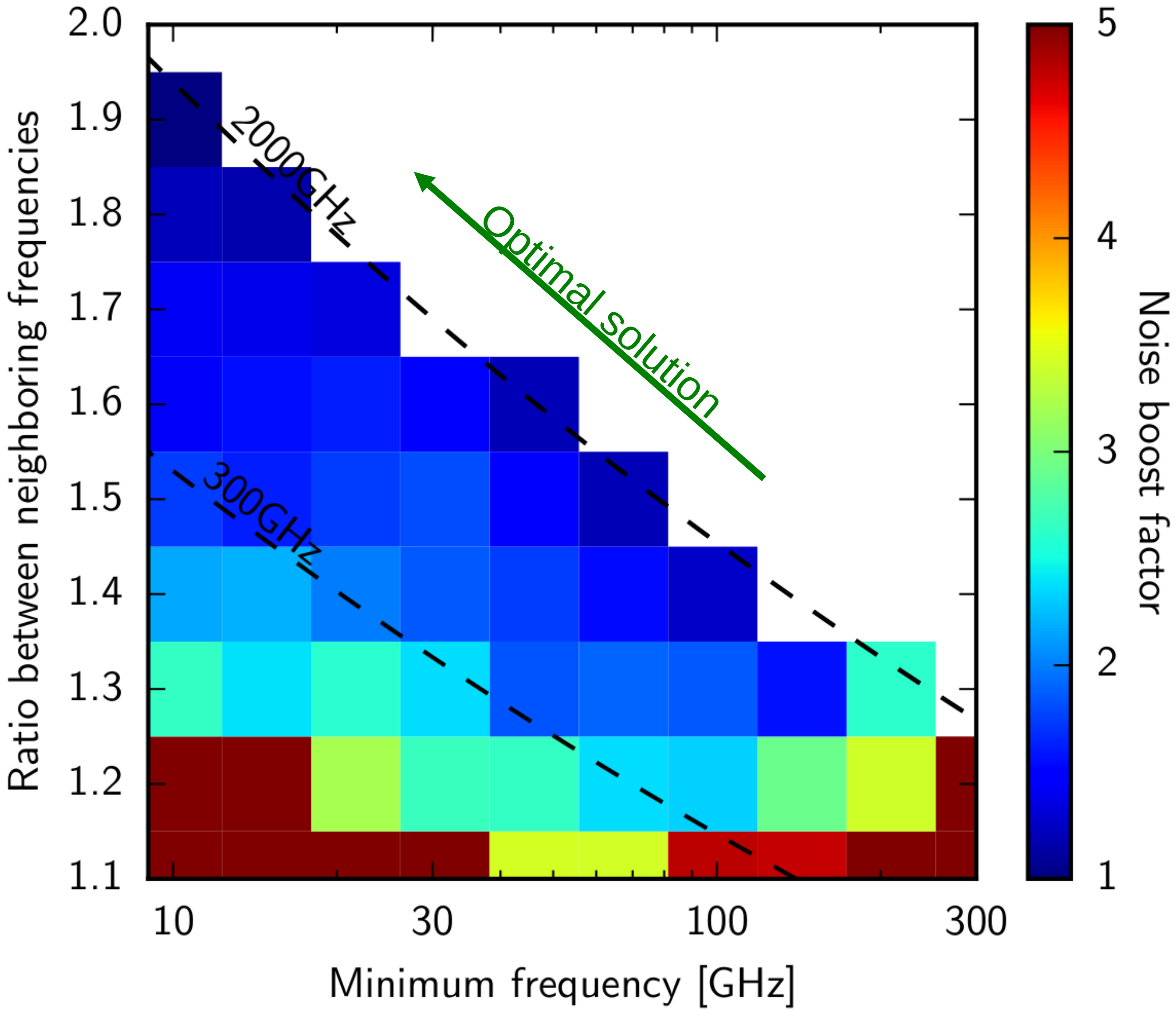

1) As foregrounds become brighter, the optimal solution moves to lower frequencies.

Case 2b: Intermediate latitude sky, no focal plane penalty

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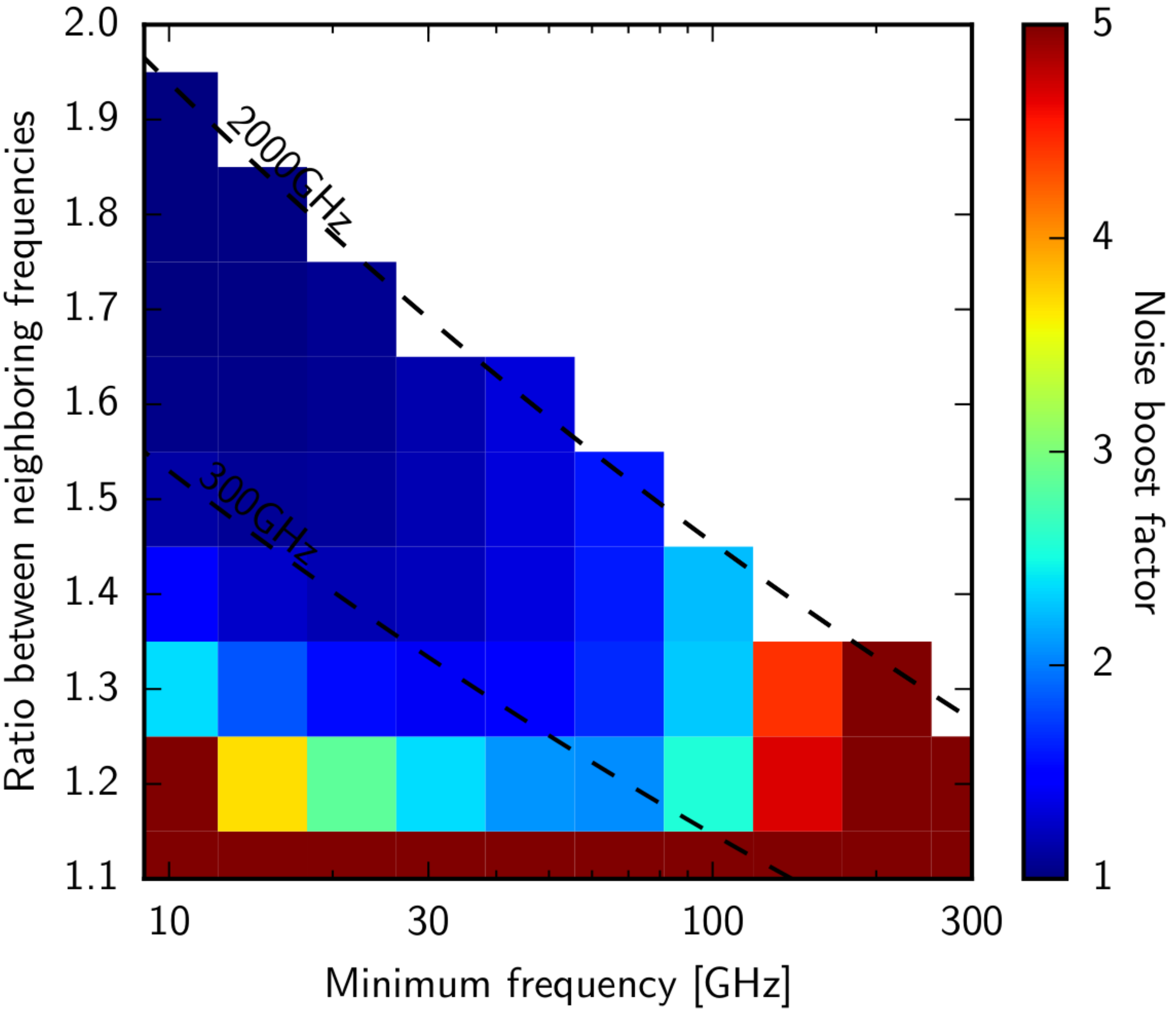
Assume all detectors require the same amount of focal plane area



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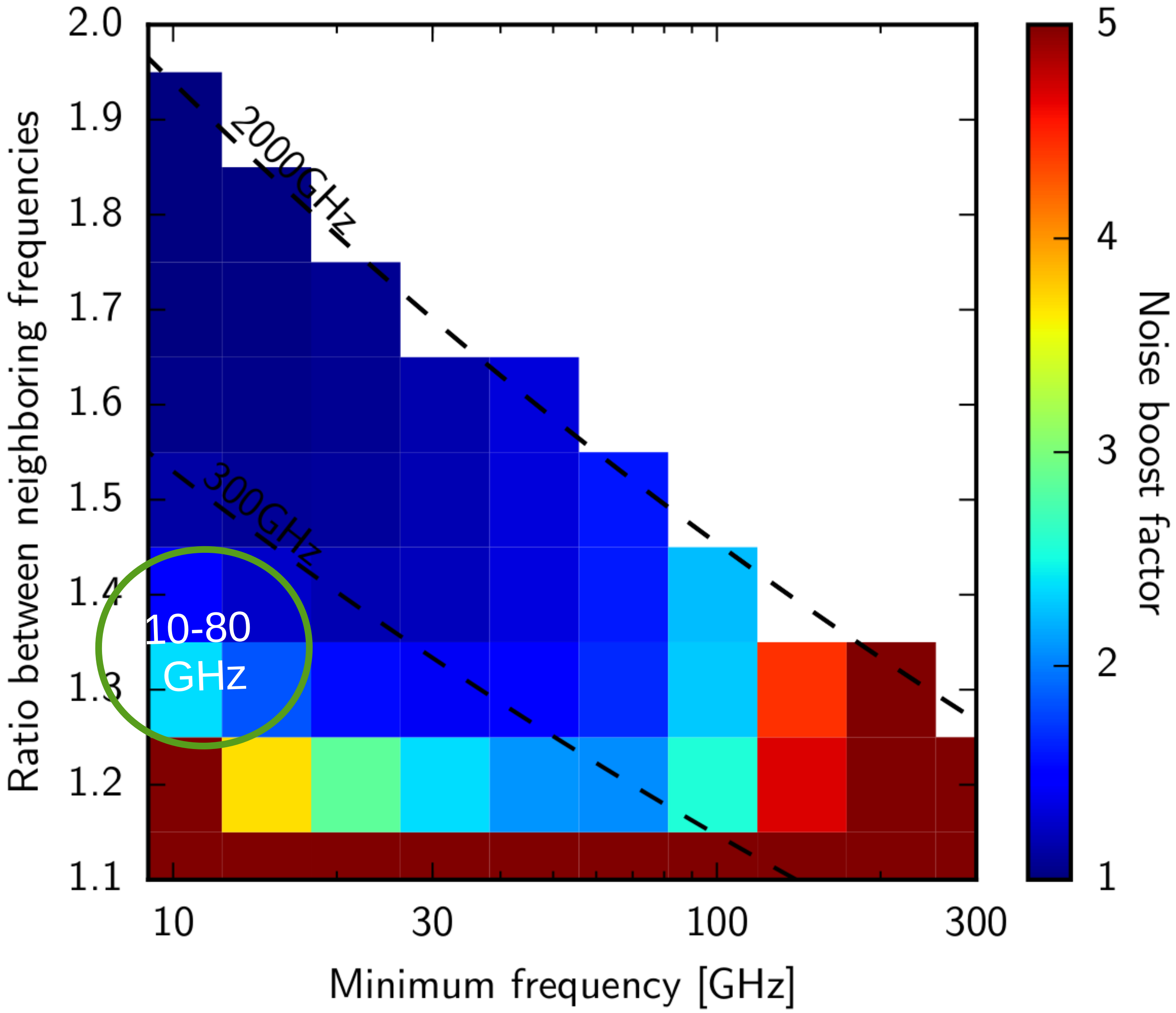

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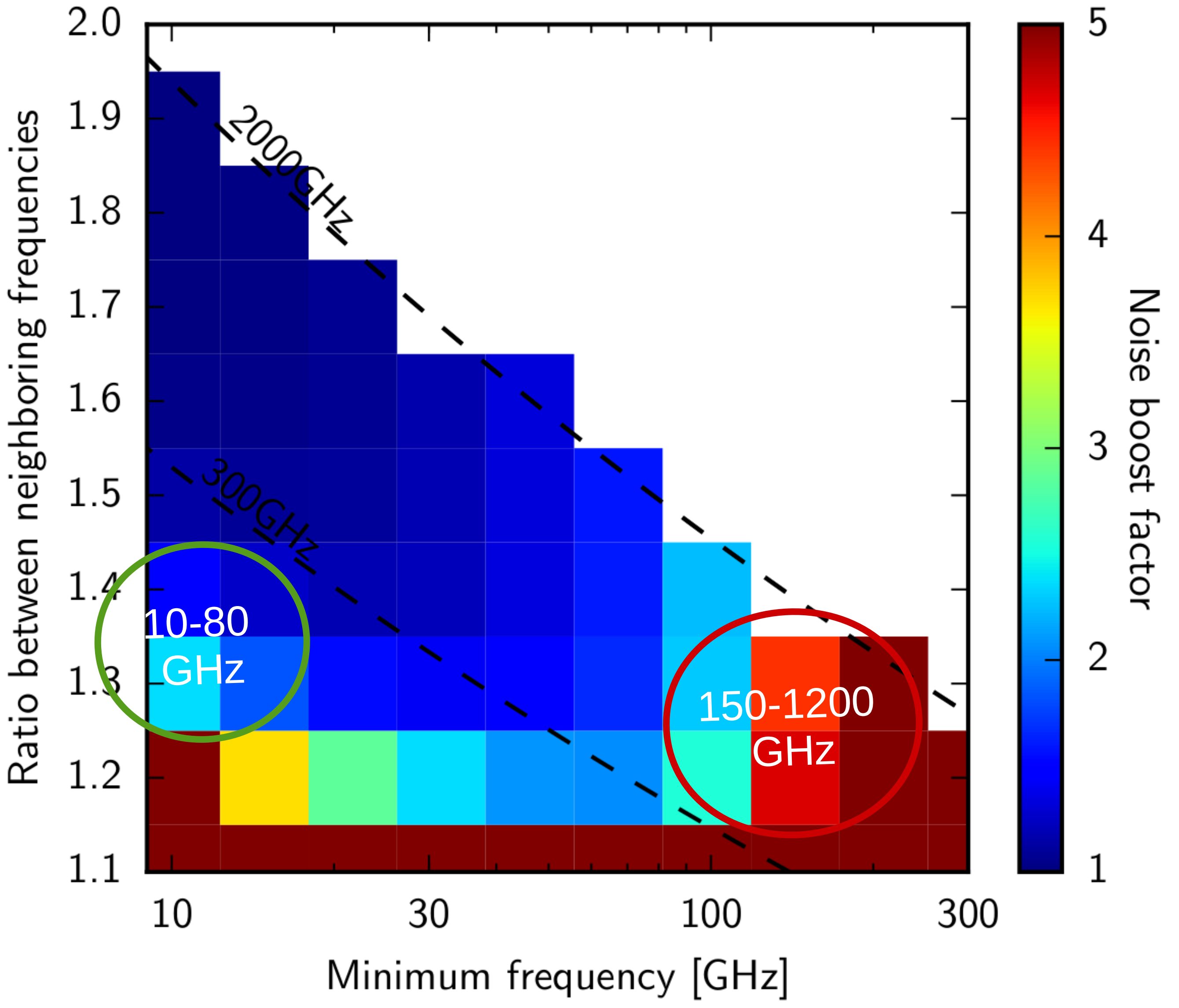

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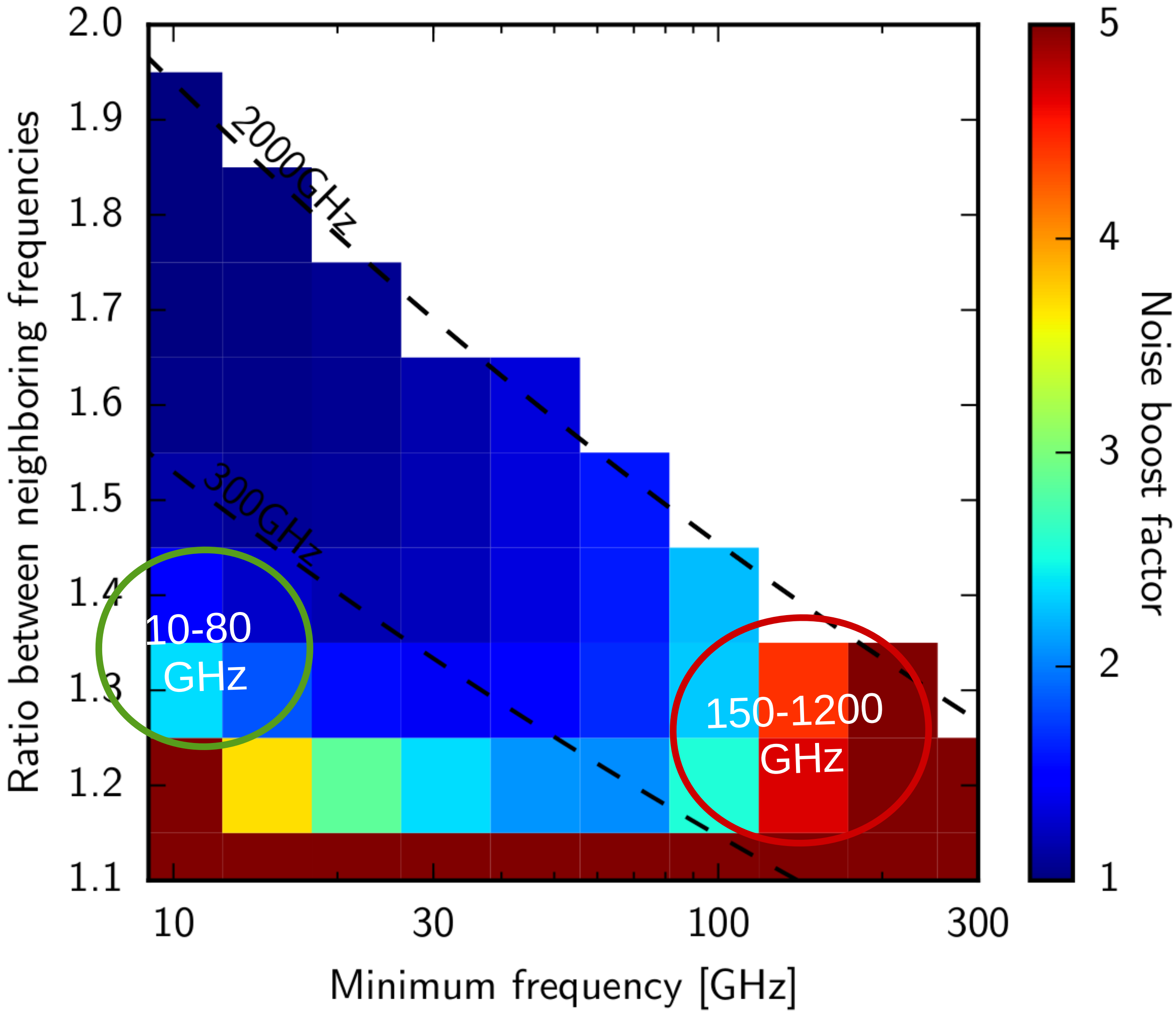

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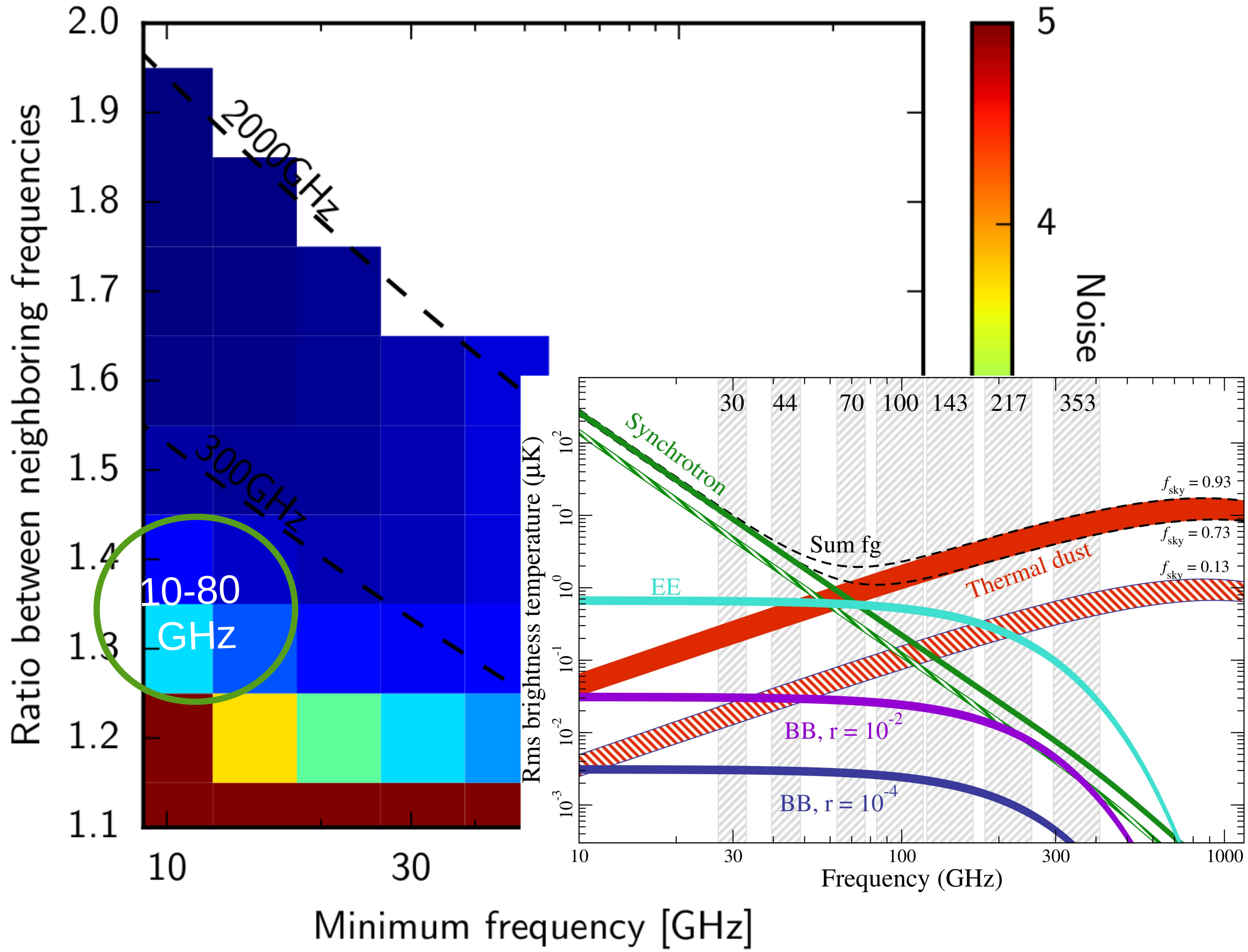

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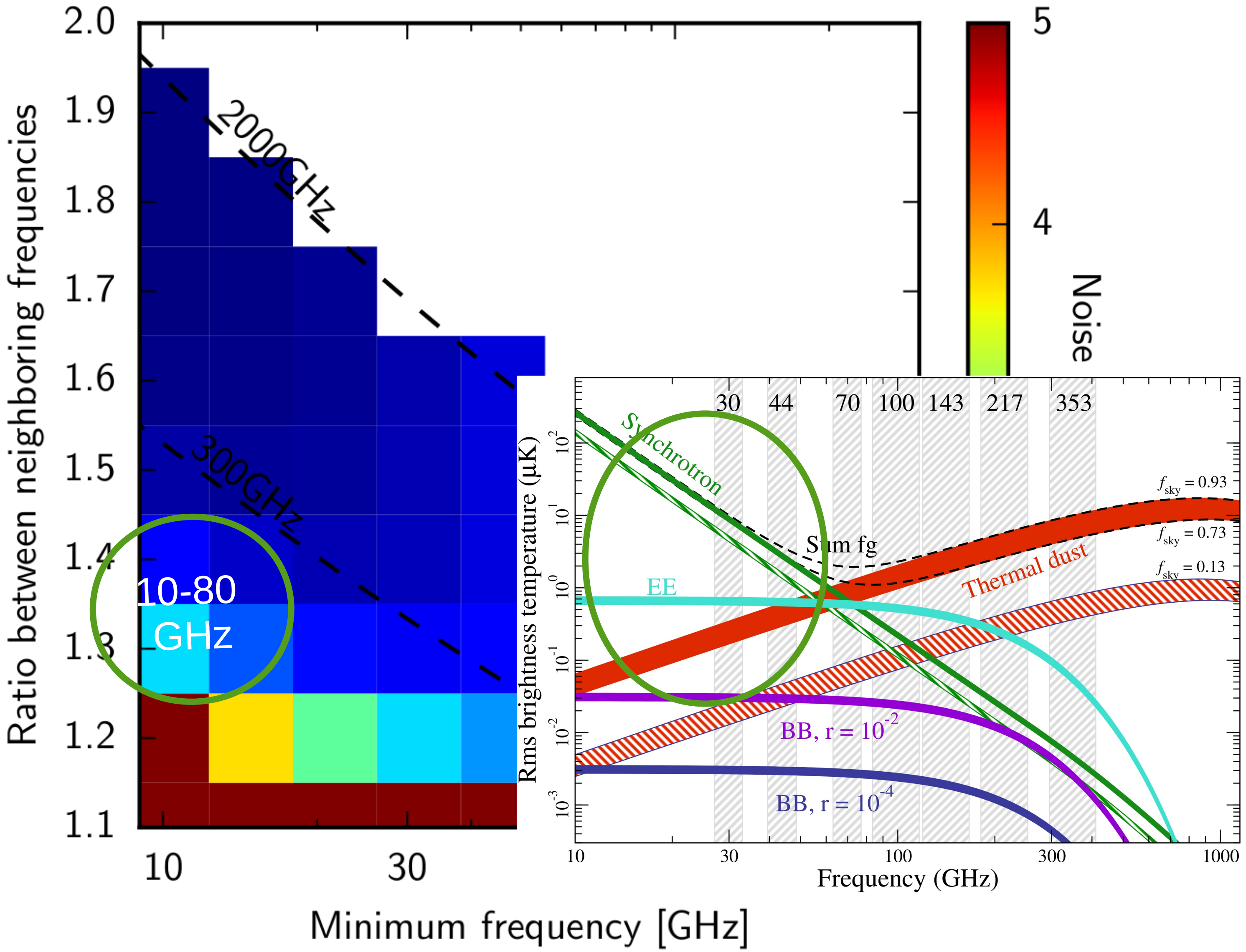

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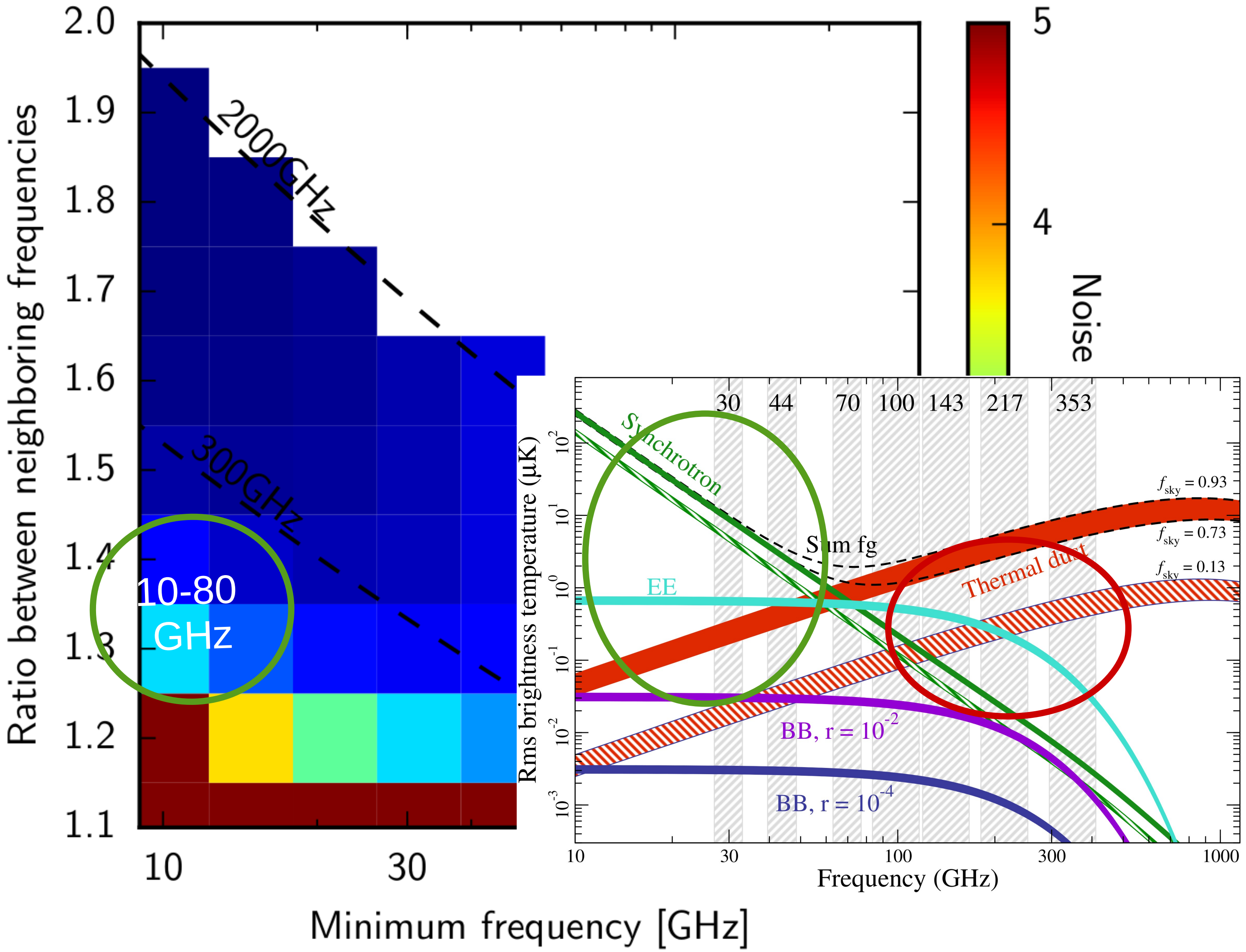
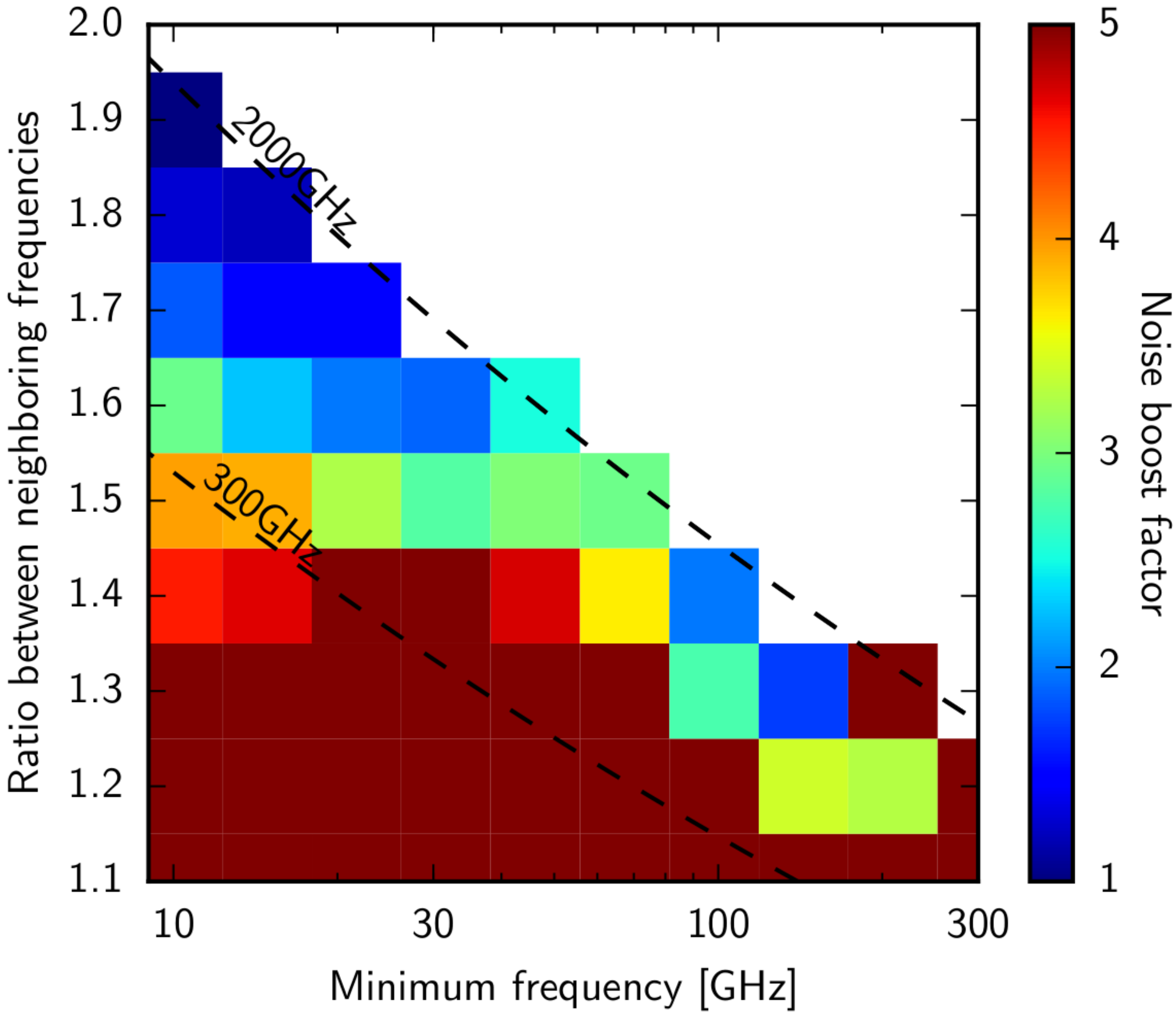


- Without the focal plane penalty, a pure low-frequency experiment would perform *better* than a pure high-frequency experiment
  - This is because the CMB is more orthogonal to synchrotron ($S \sim \nu^{-3}$) than to thermal dust ($T \sim \nu^{1.5}$) over relevant frequencies

Case 3: Galactic plane

$N_{\mathrm{band}} = 9$

$A_{\mathrm{fg}} = 100\ \mu\mathrm{K}$



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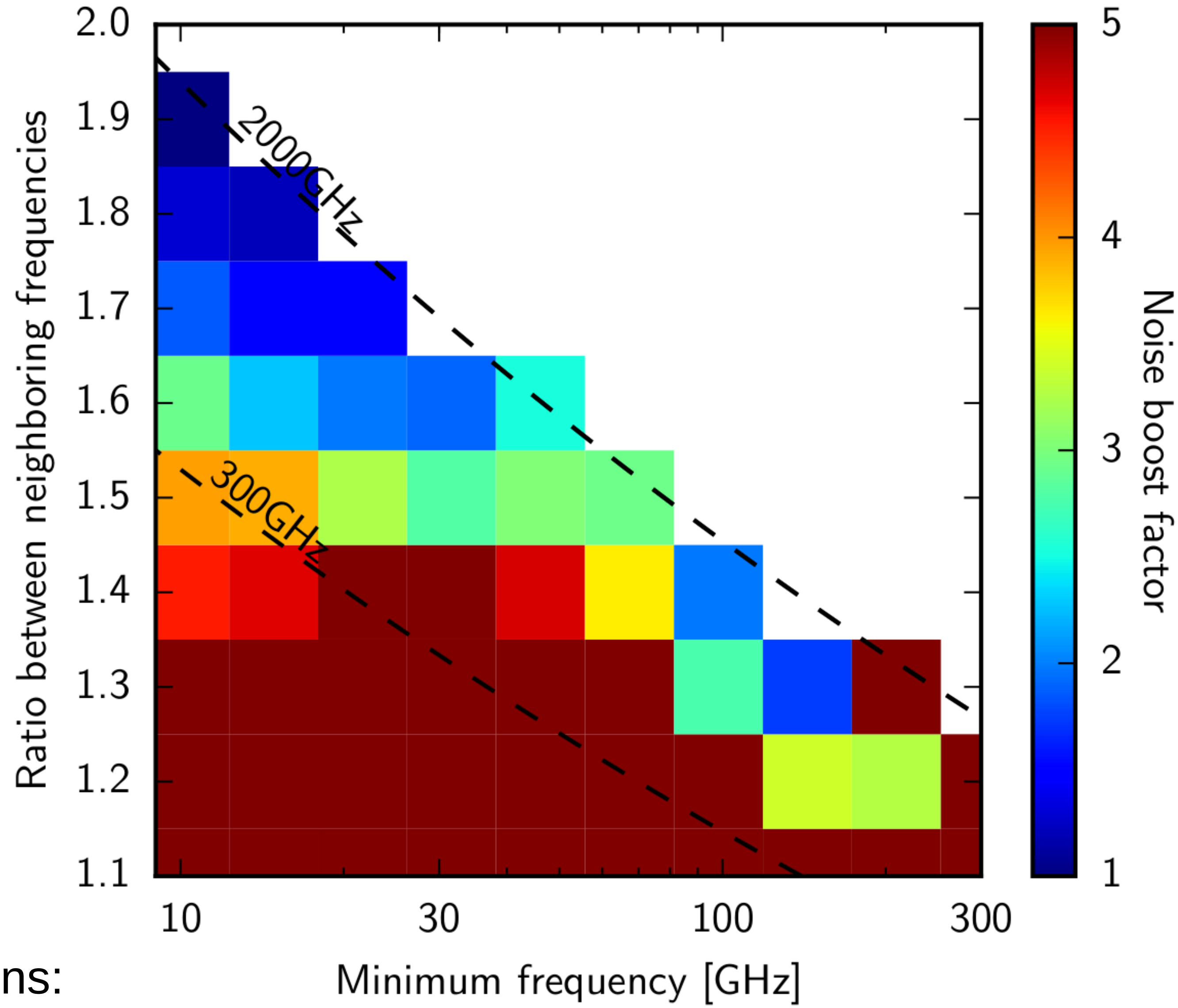

General conclusions:

1) If foregrounds are negligible, minimum CMB RMS is obtained by focussing all detectors around the foreground minimum, covering ~60-300 GHz

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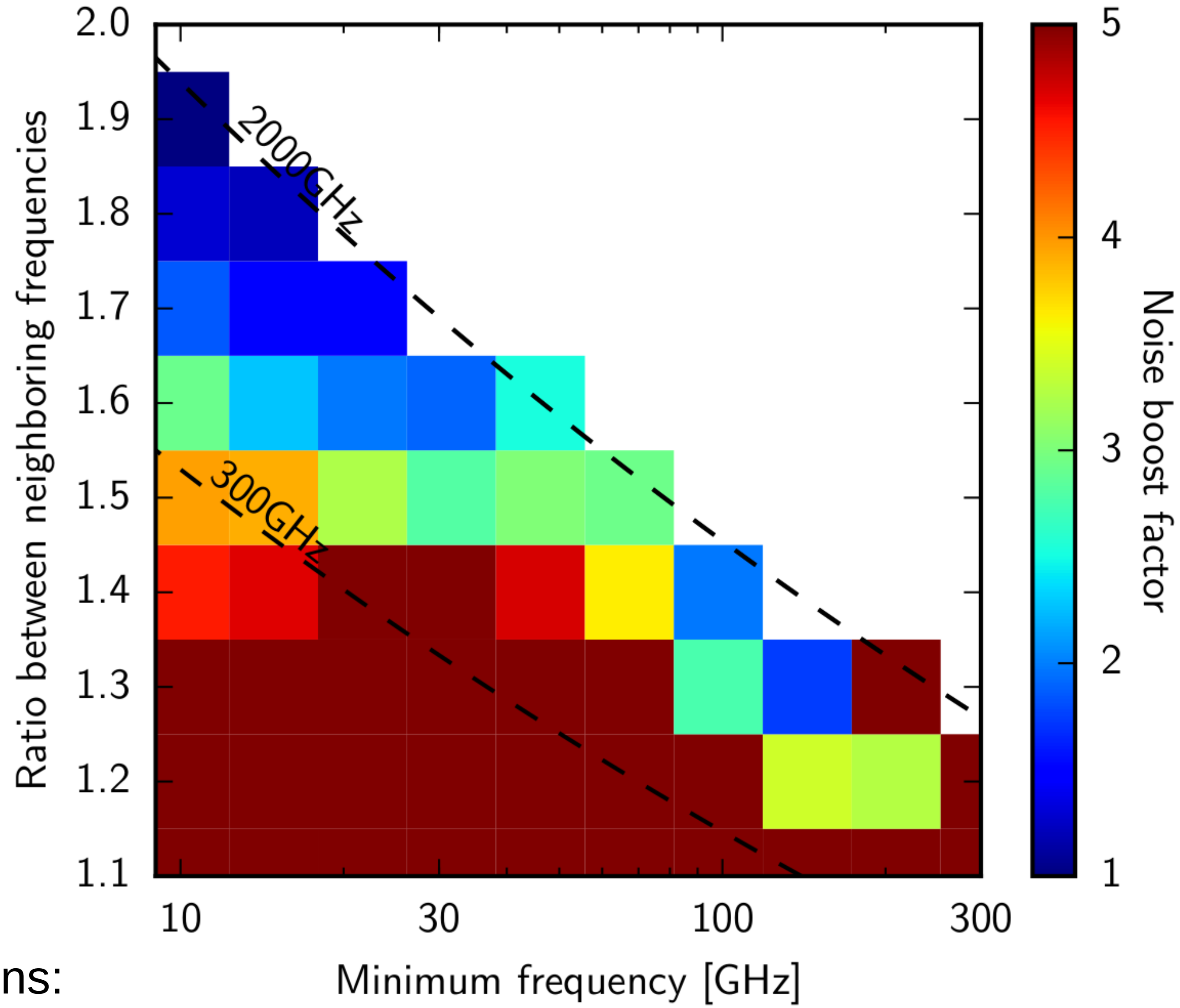

General conclusions:

1) If foregrounds are negligible, minimum CMB RMS is obtained by focussing all detectors around the foreground minimum, covering ~60-300 GHz

2) But if foregrounds are non-negligible, ***extend the frequency range as much*** as possible until the model breaks down, ***even when accounting for focal plane area!***

Spectral index constraining power

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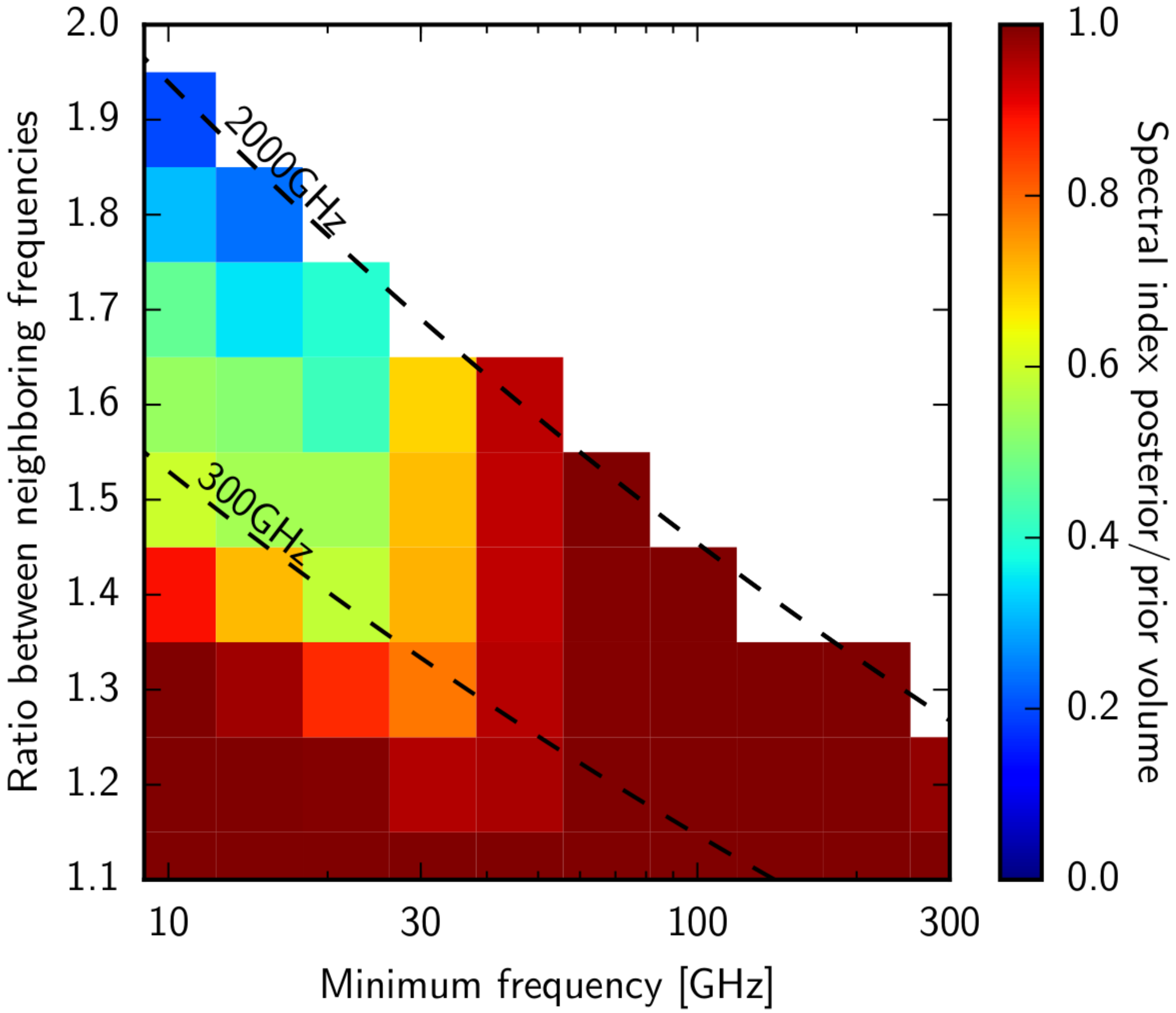

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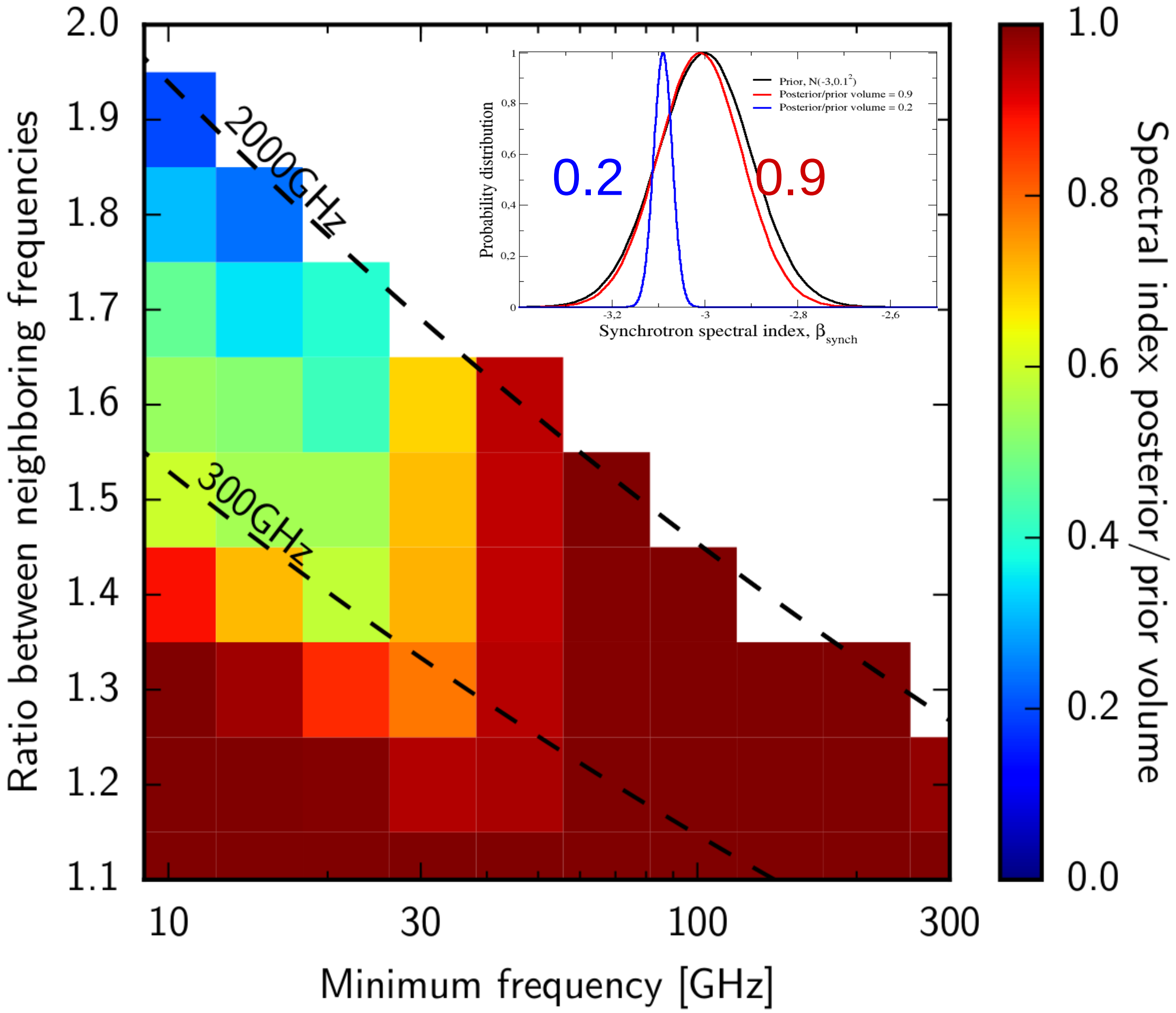

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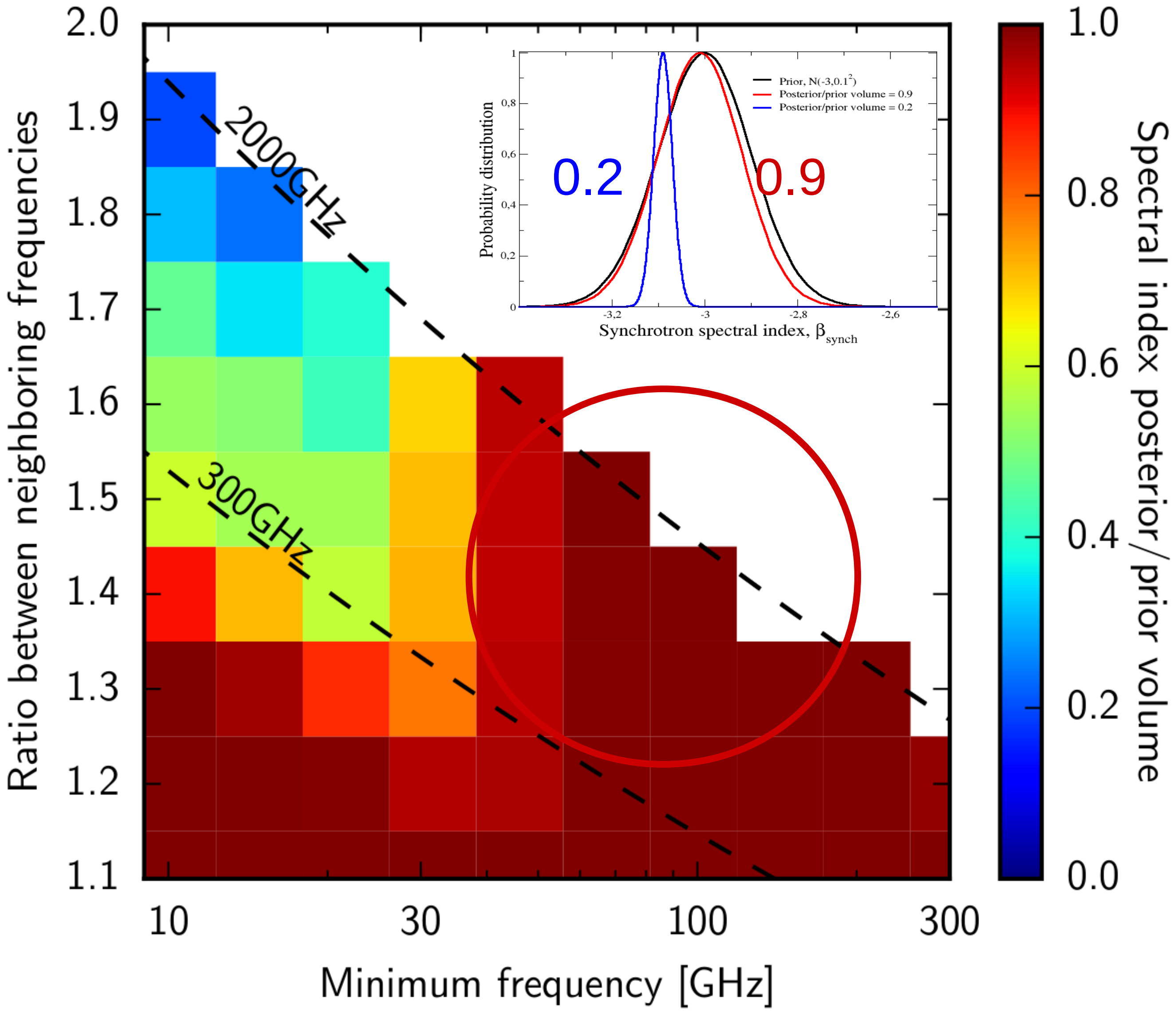

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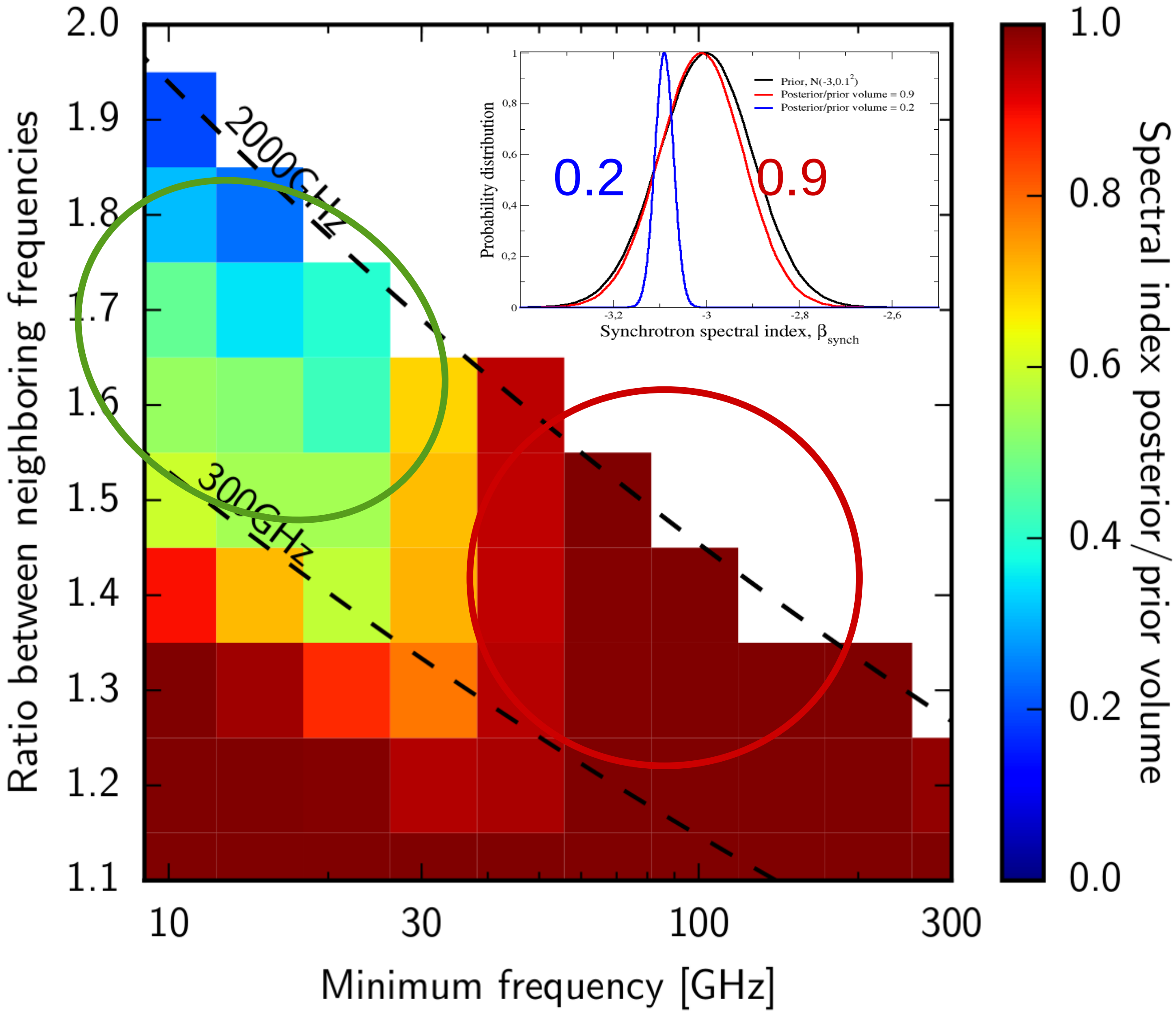


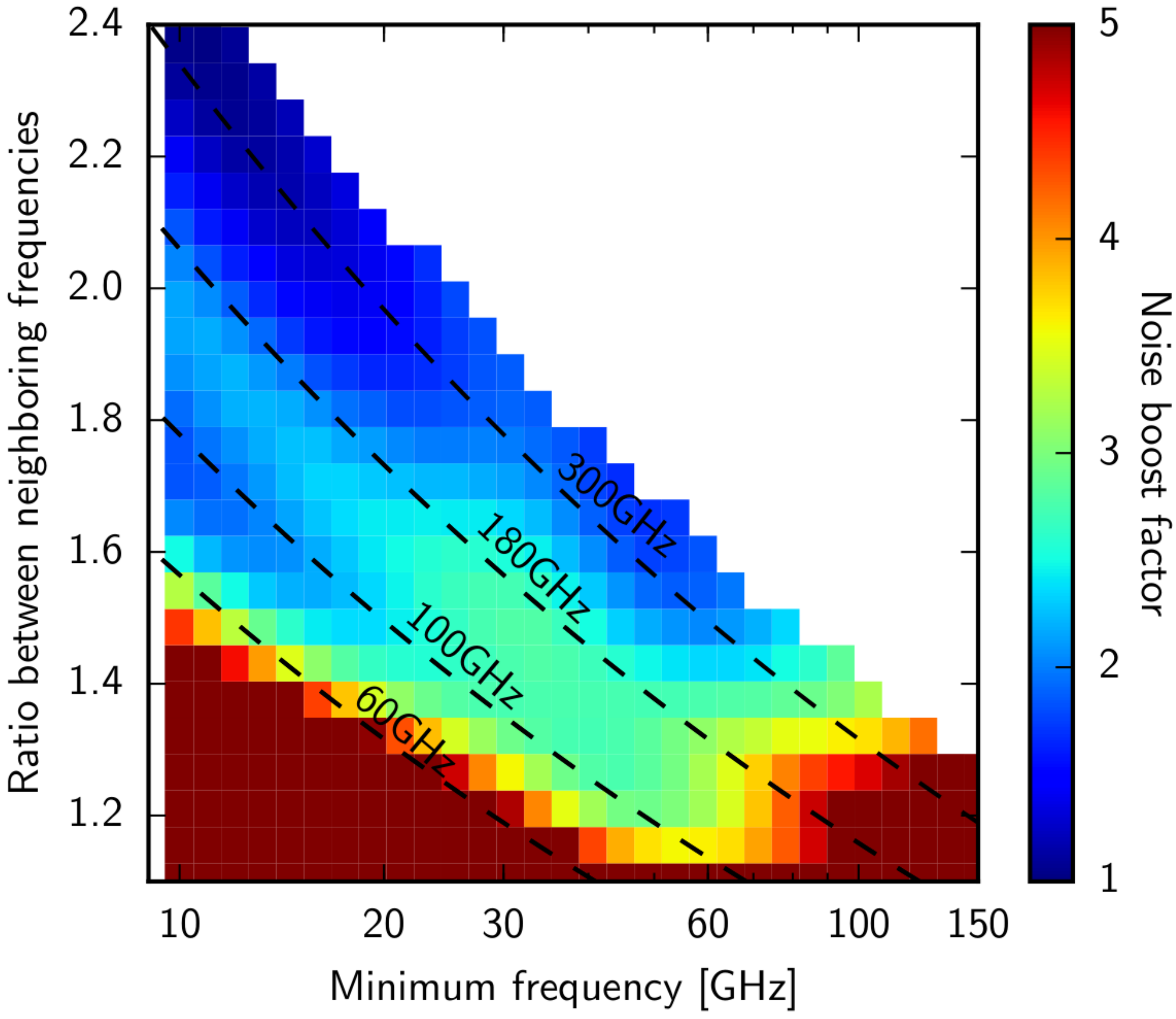
1) While a lowest frequency of ~40-60 GHz is good for optimizing CMB RMS in the low foreground case, such experiments have essentially *no handle* on β_s.

2) If at all possible, one should strive to include frequencies below 30 GHz in order to measure synchrotron properly (as opposed to gambling on being lucky)

Case 4: Ground-based, intermediate latitudes

$N_{\mathrm{band}} = 5$

$A_{\mathrm{fg}} = 10\ \mu\mathrm{K}$



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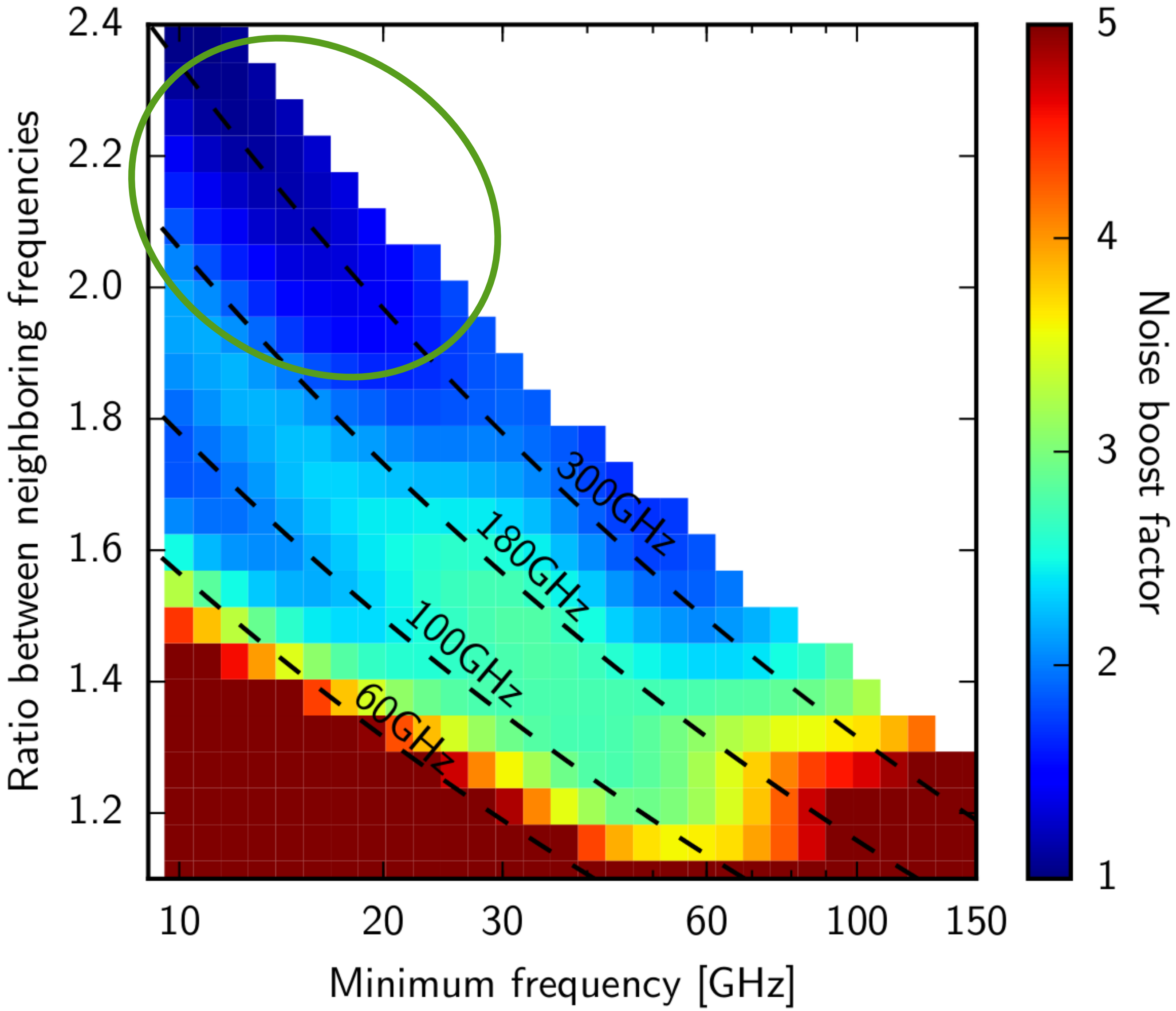

1) Best 5-band ground-based solution is 10-350 GHz (maximum leverage)

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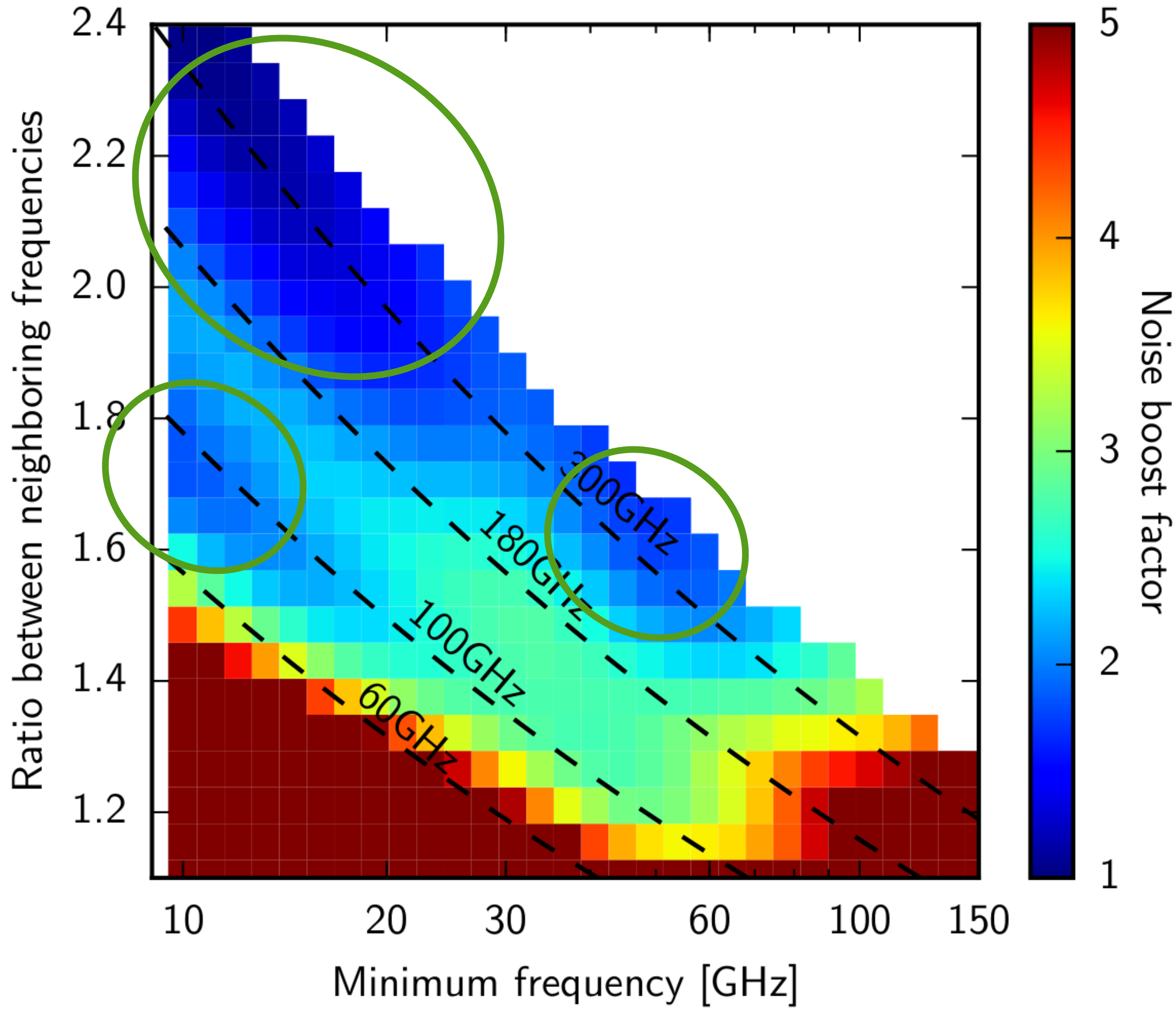

1) Best 5-band ground-based solution is 10-350 GHz (maximum leverage)

2) Two nearly equally sensitive solutions exist for 10-90 GHz and 45-350 GHz.

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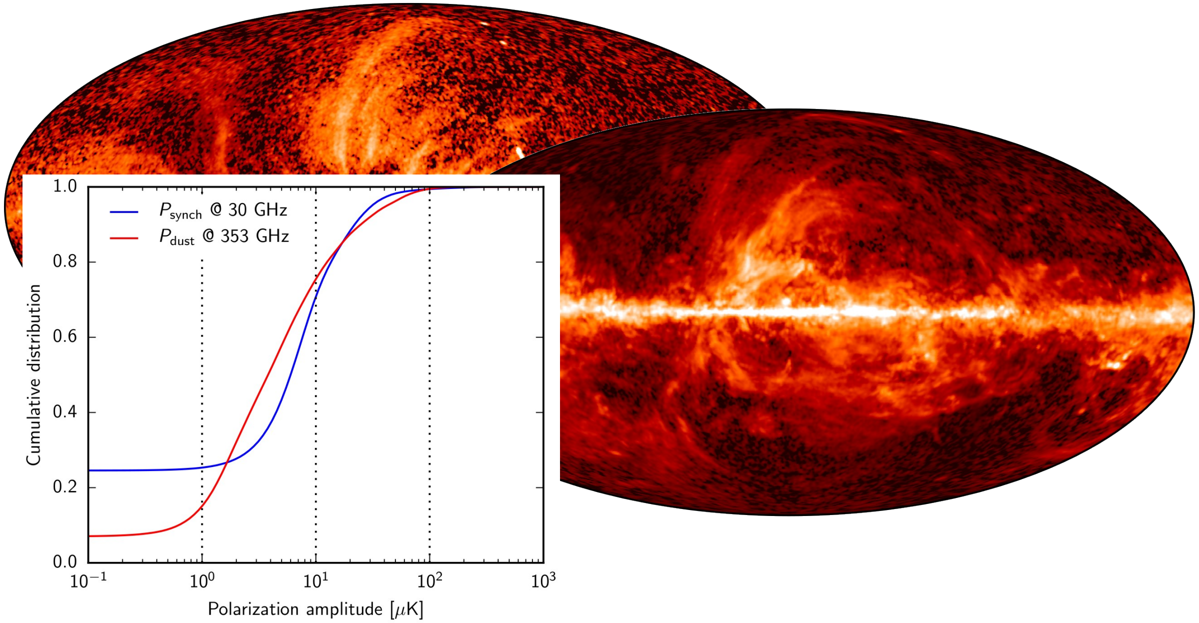

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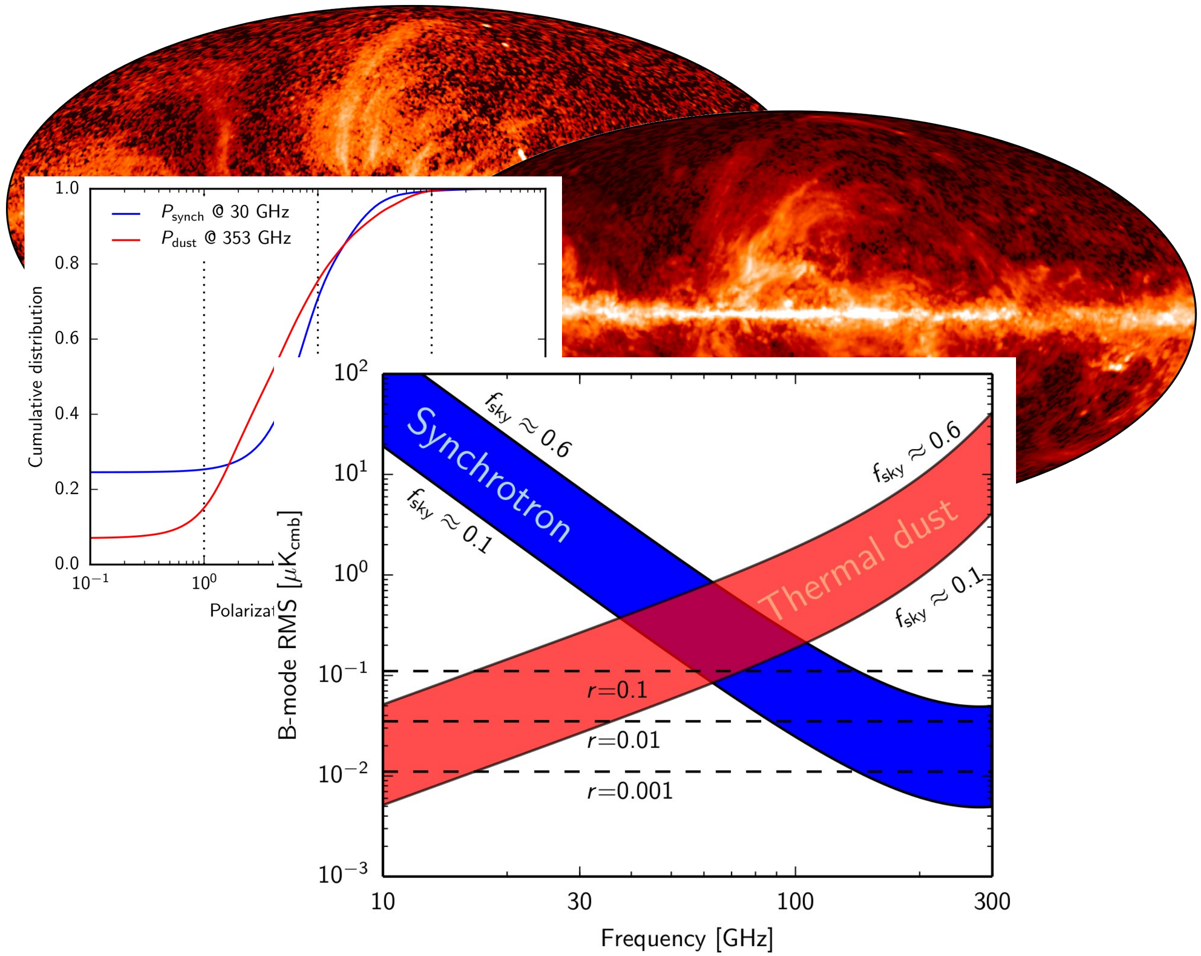

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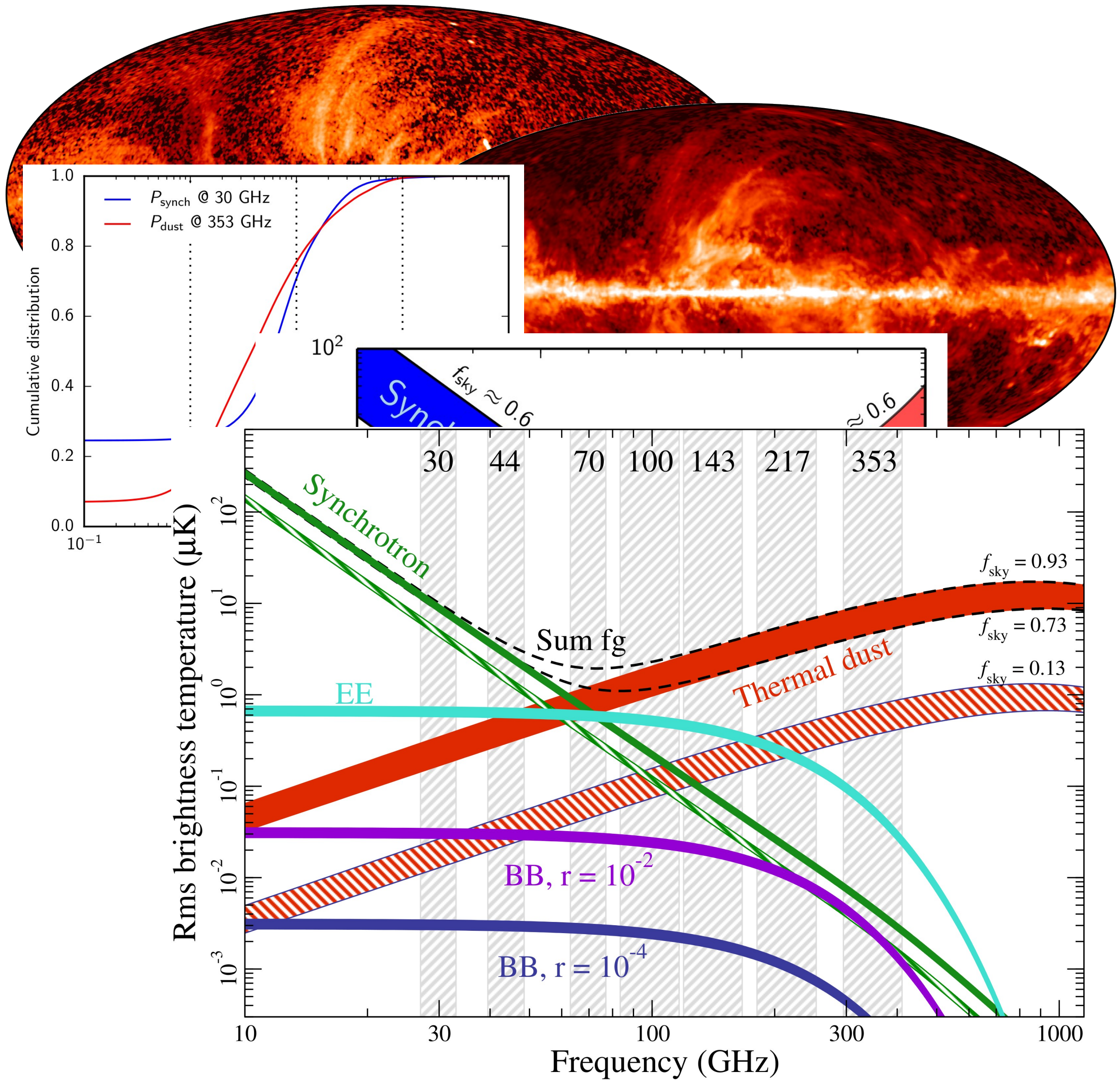

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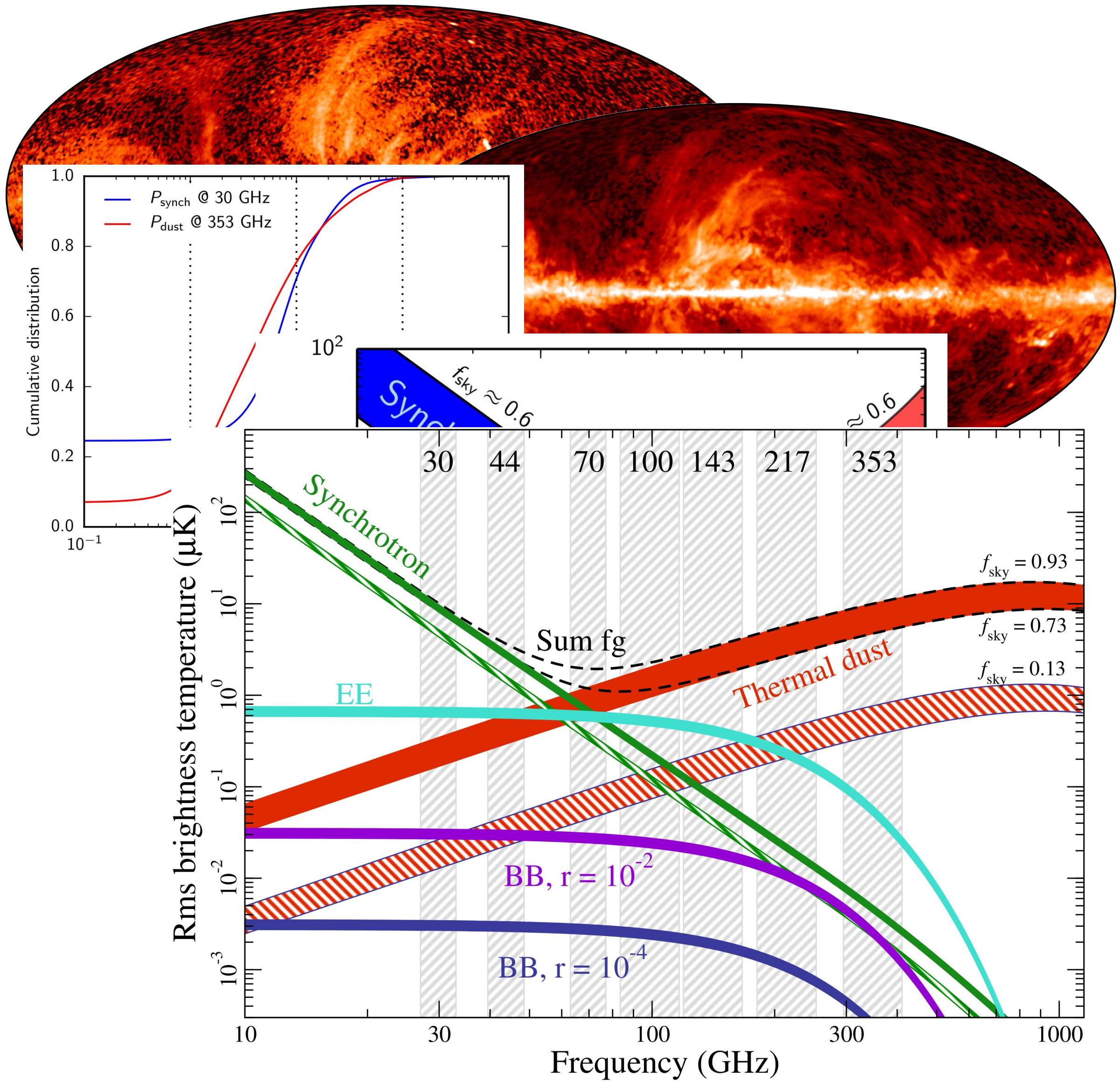

- There are no «lucky» foreground holes in which we can see B-modes below r ~ 0.01 without component separation
- There is no realistic frequency range in which either synchrotron or dust may be neglected for r < 0.01

In order to go deep (r < 0.01), we need to measure ***both low and and high*** frequencies to high precision!

«GreenPol» -- low frequencies from Greenland

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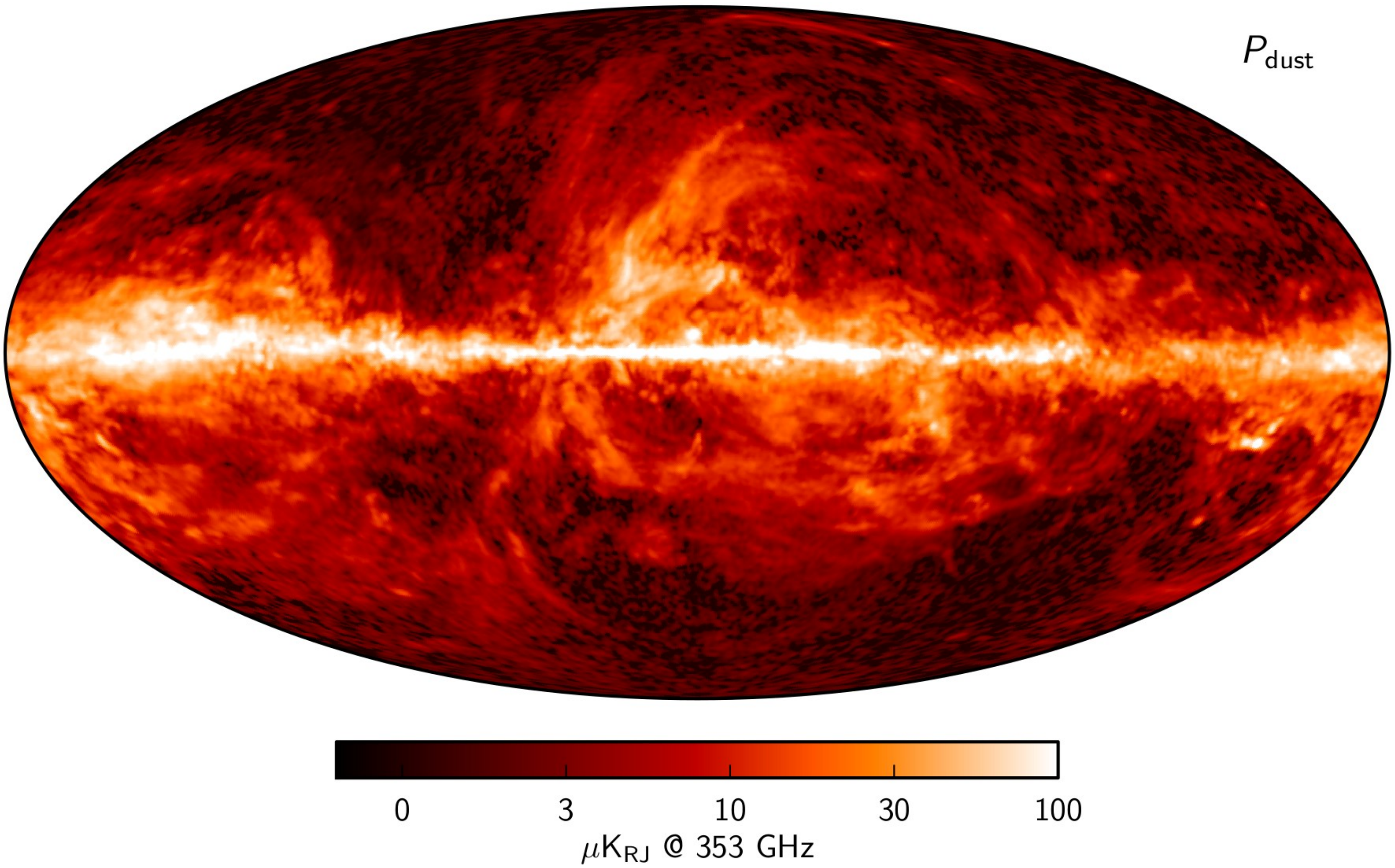

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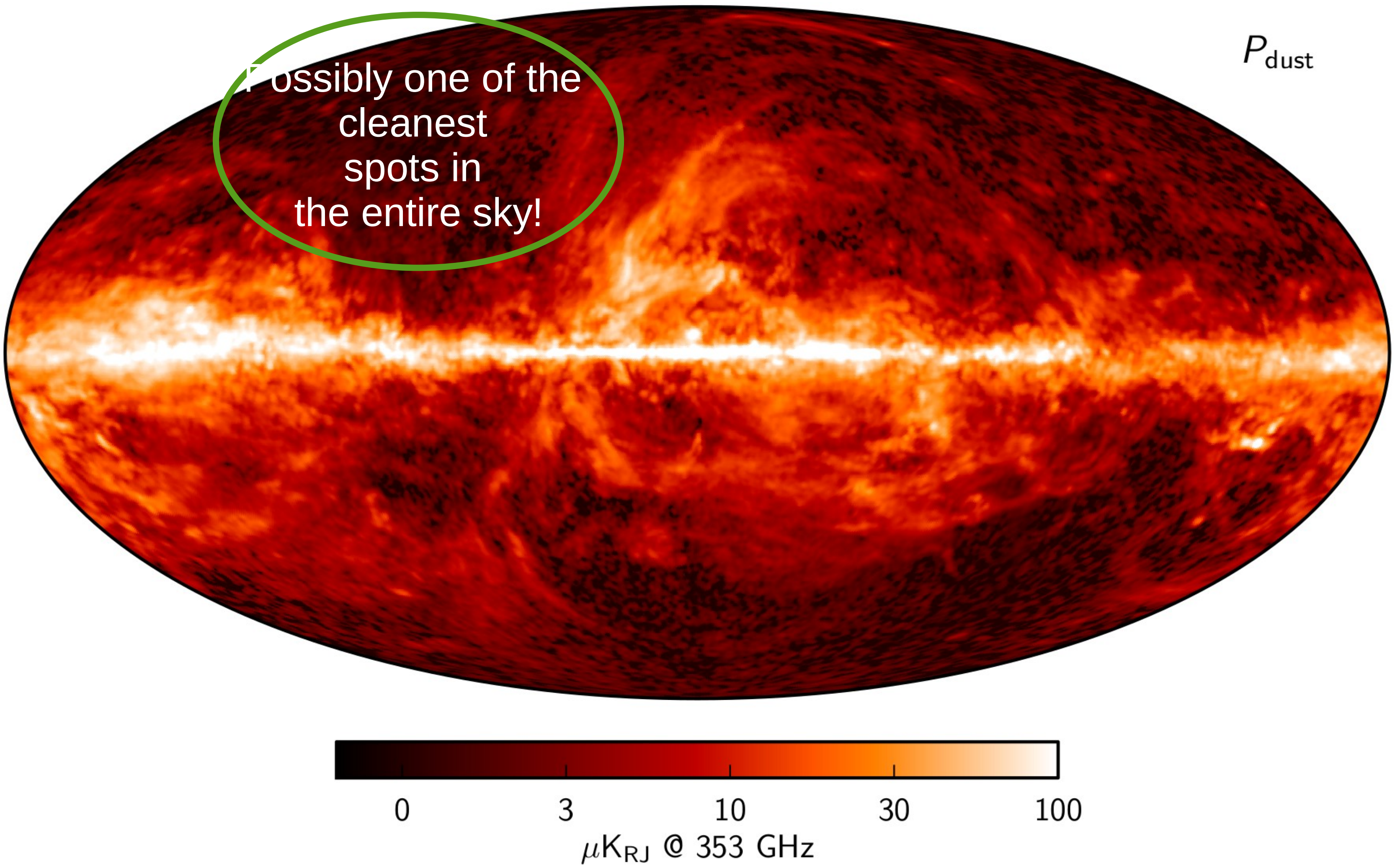

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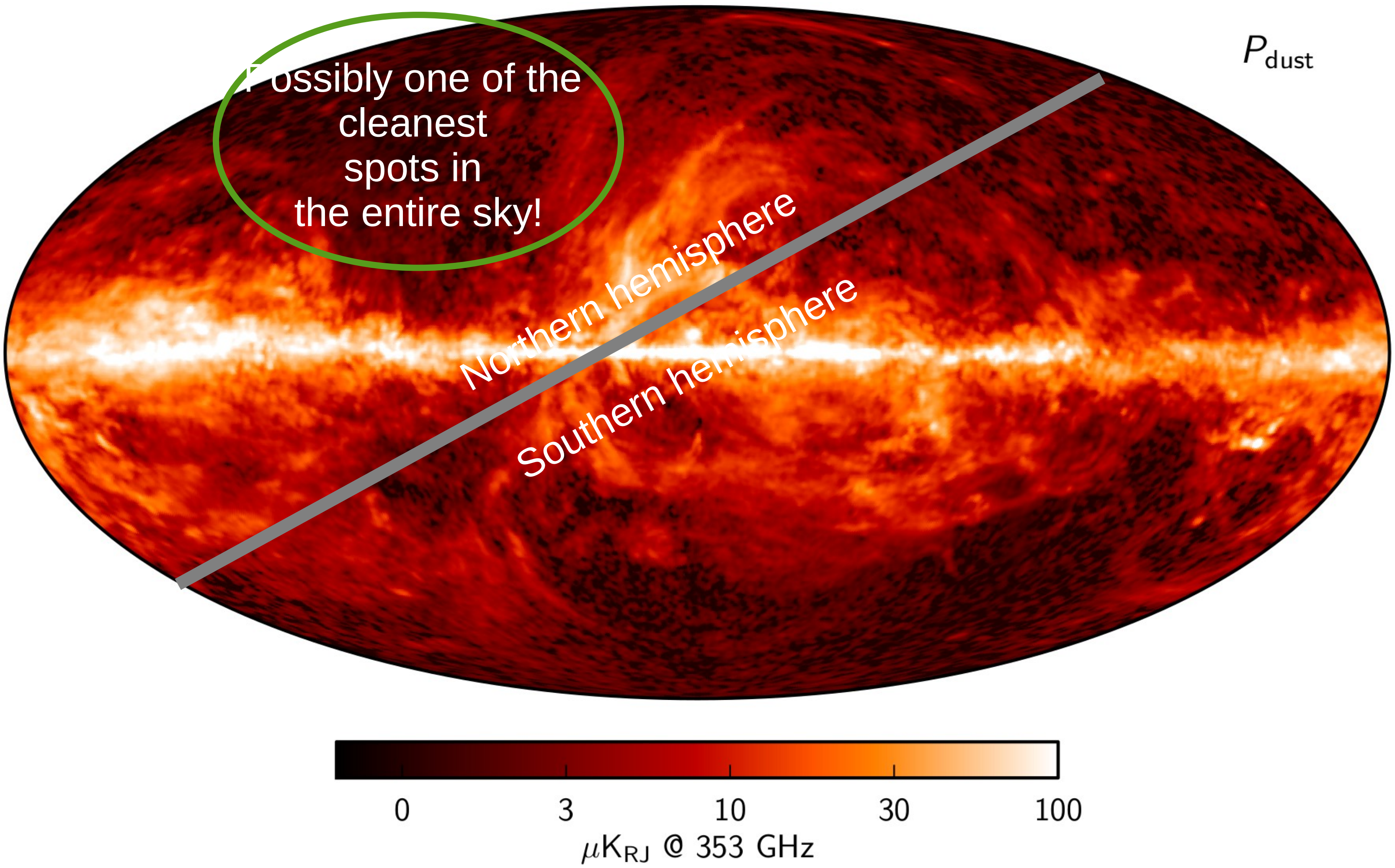

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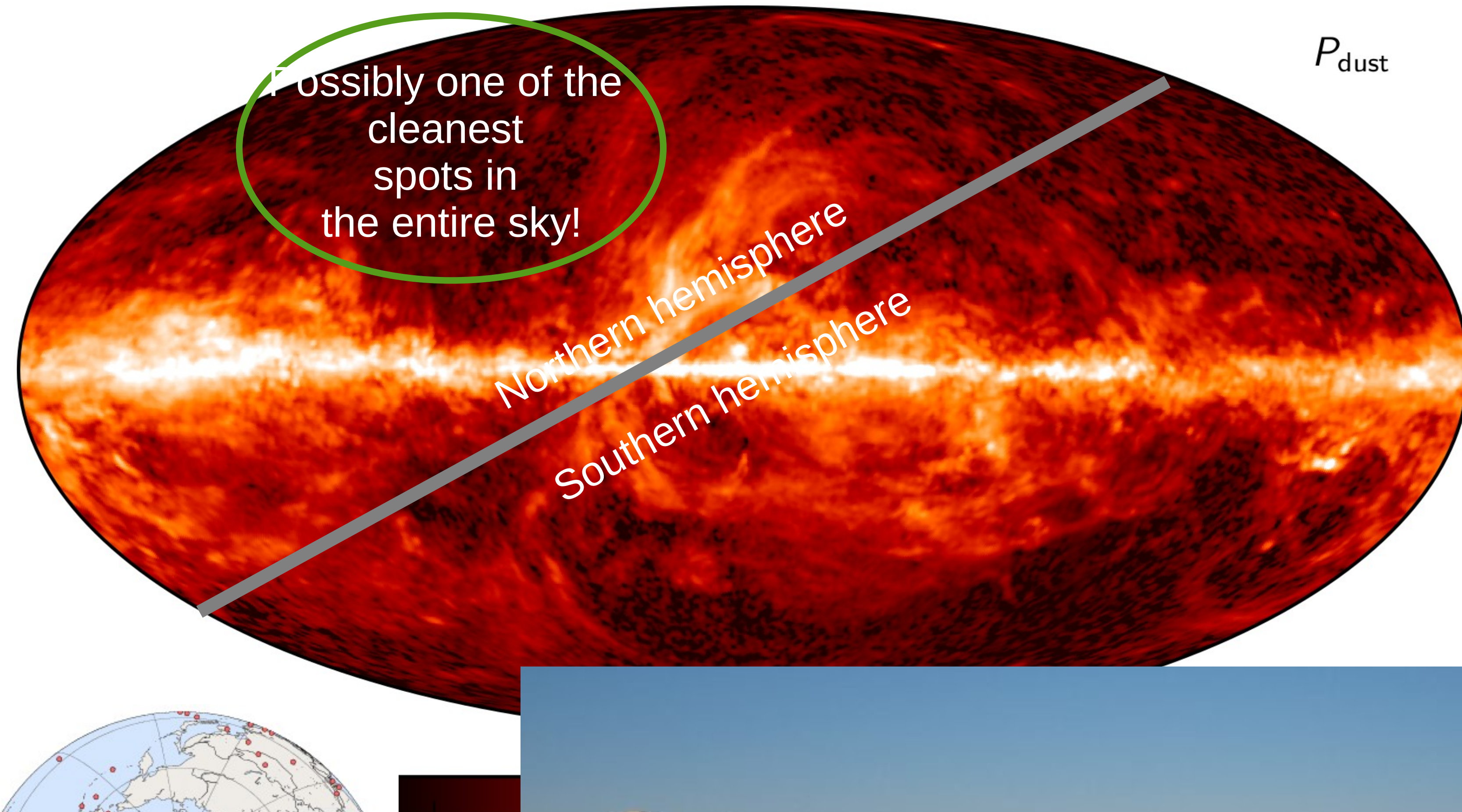
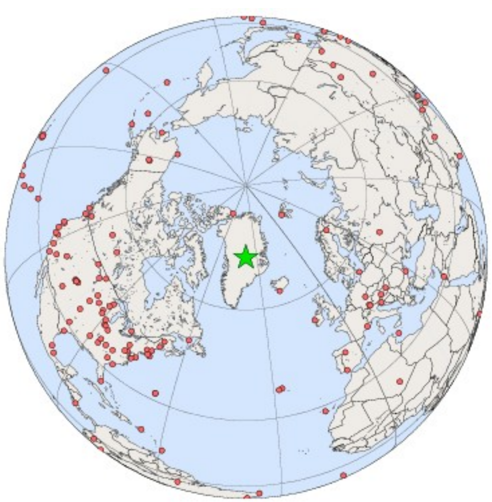
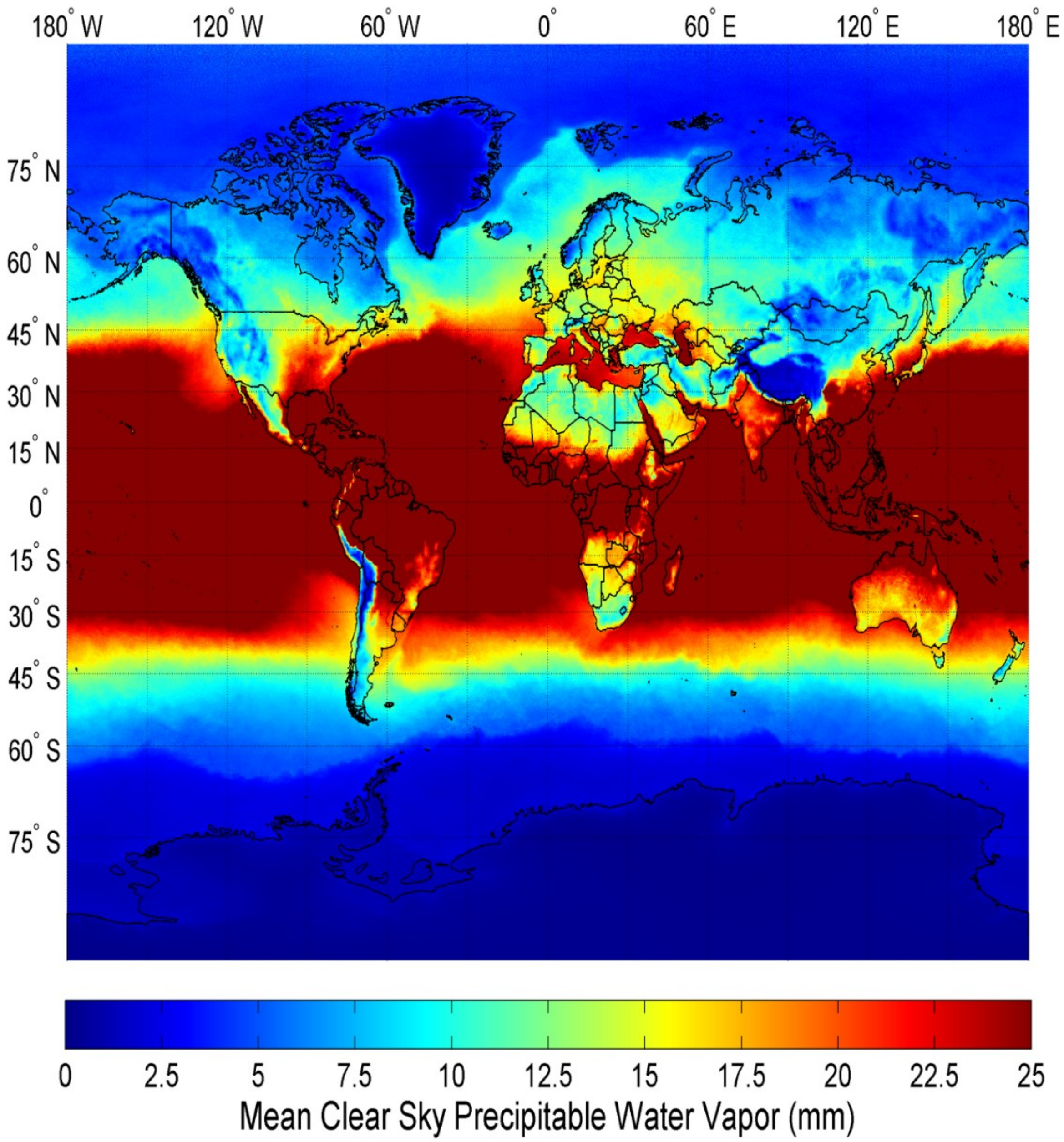




Global water vapor distribution



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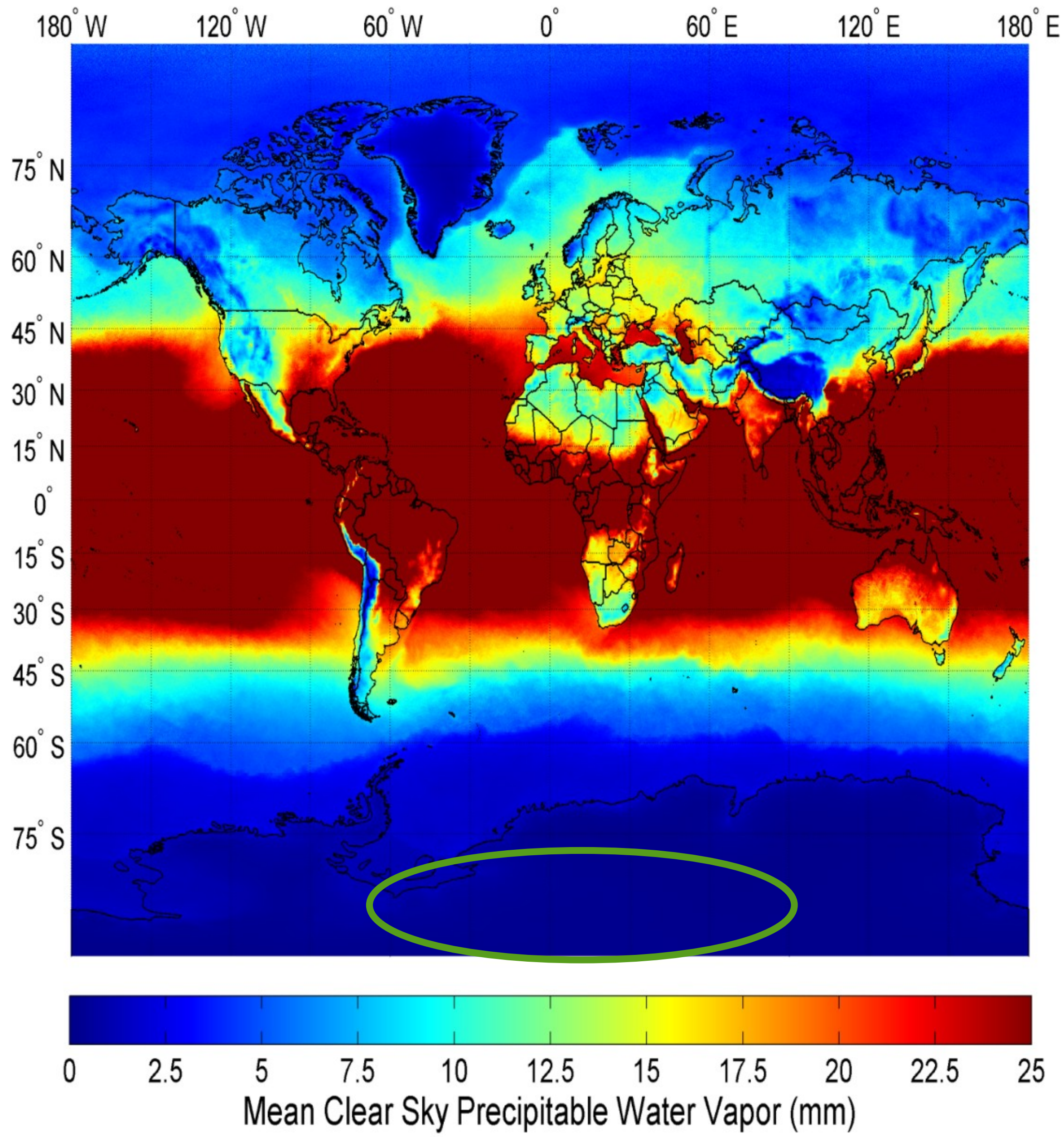

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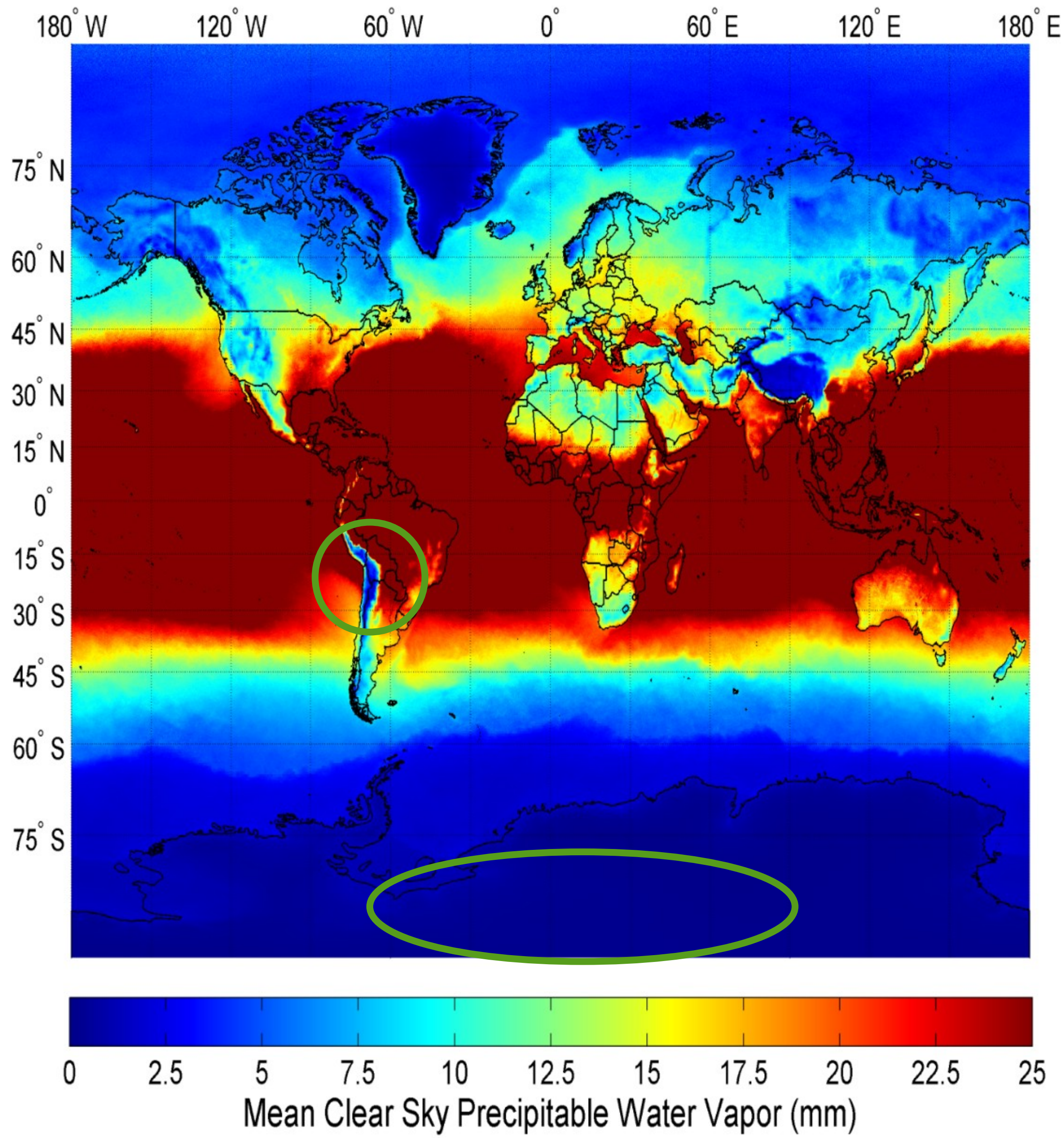

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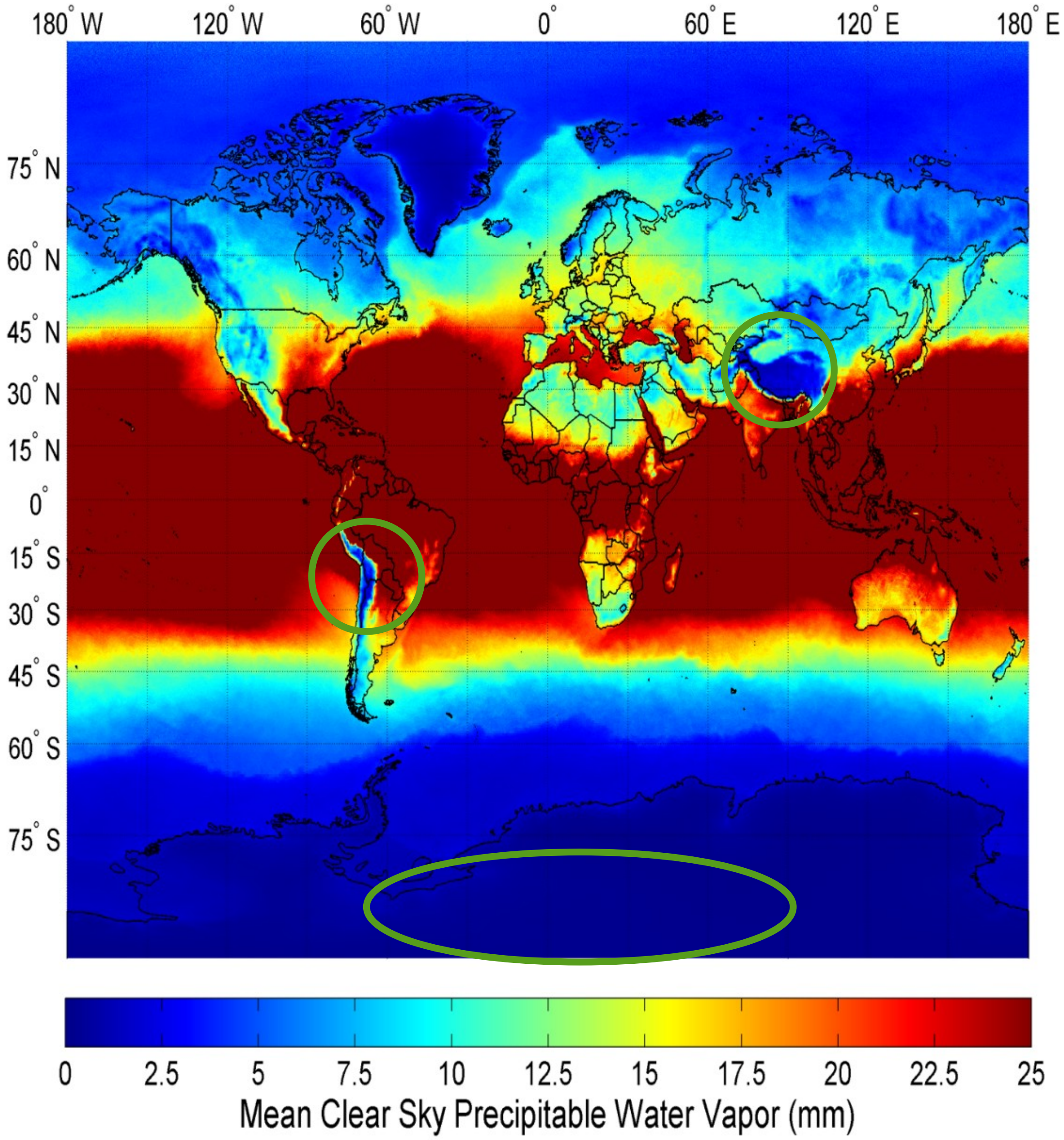

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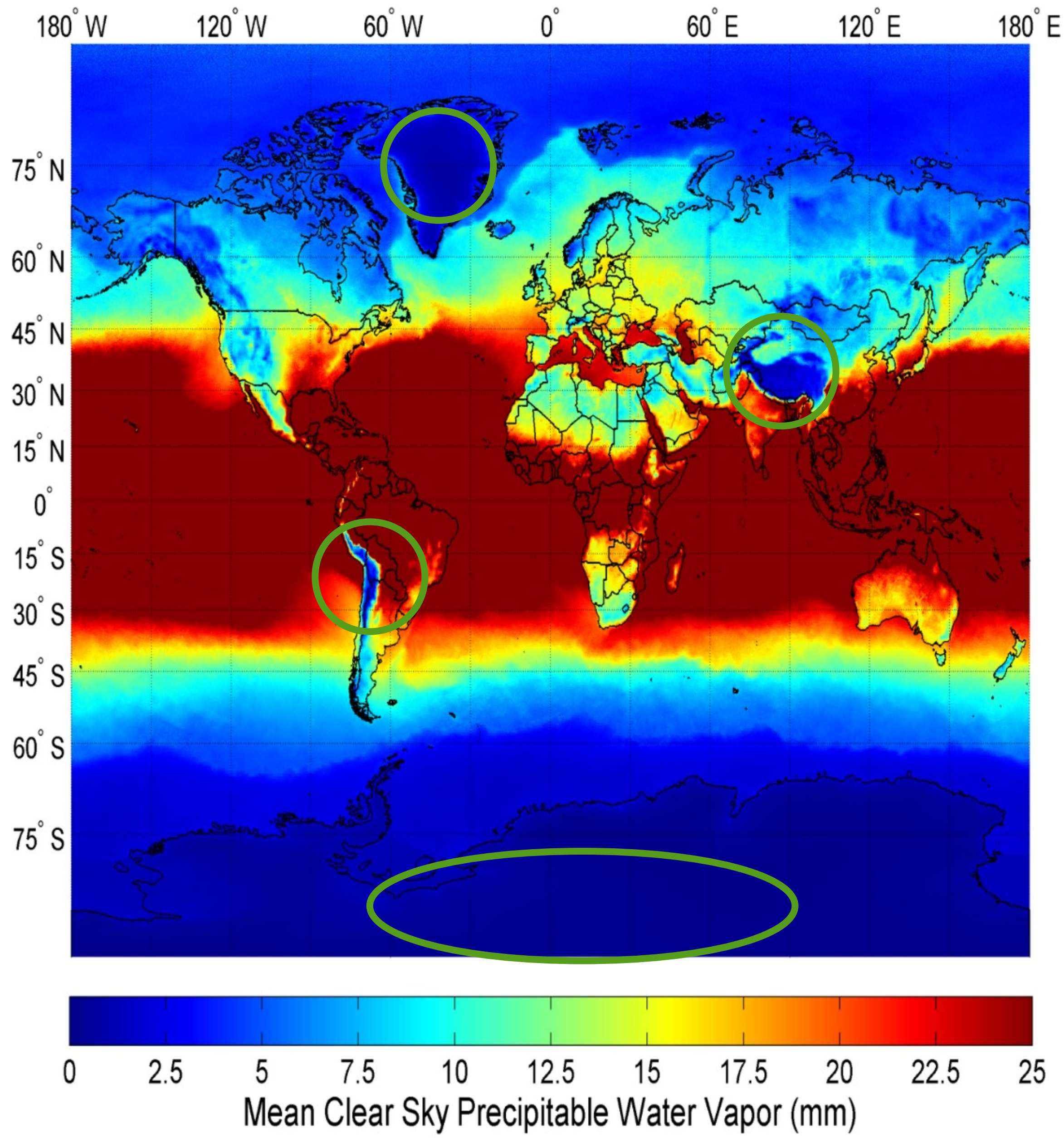
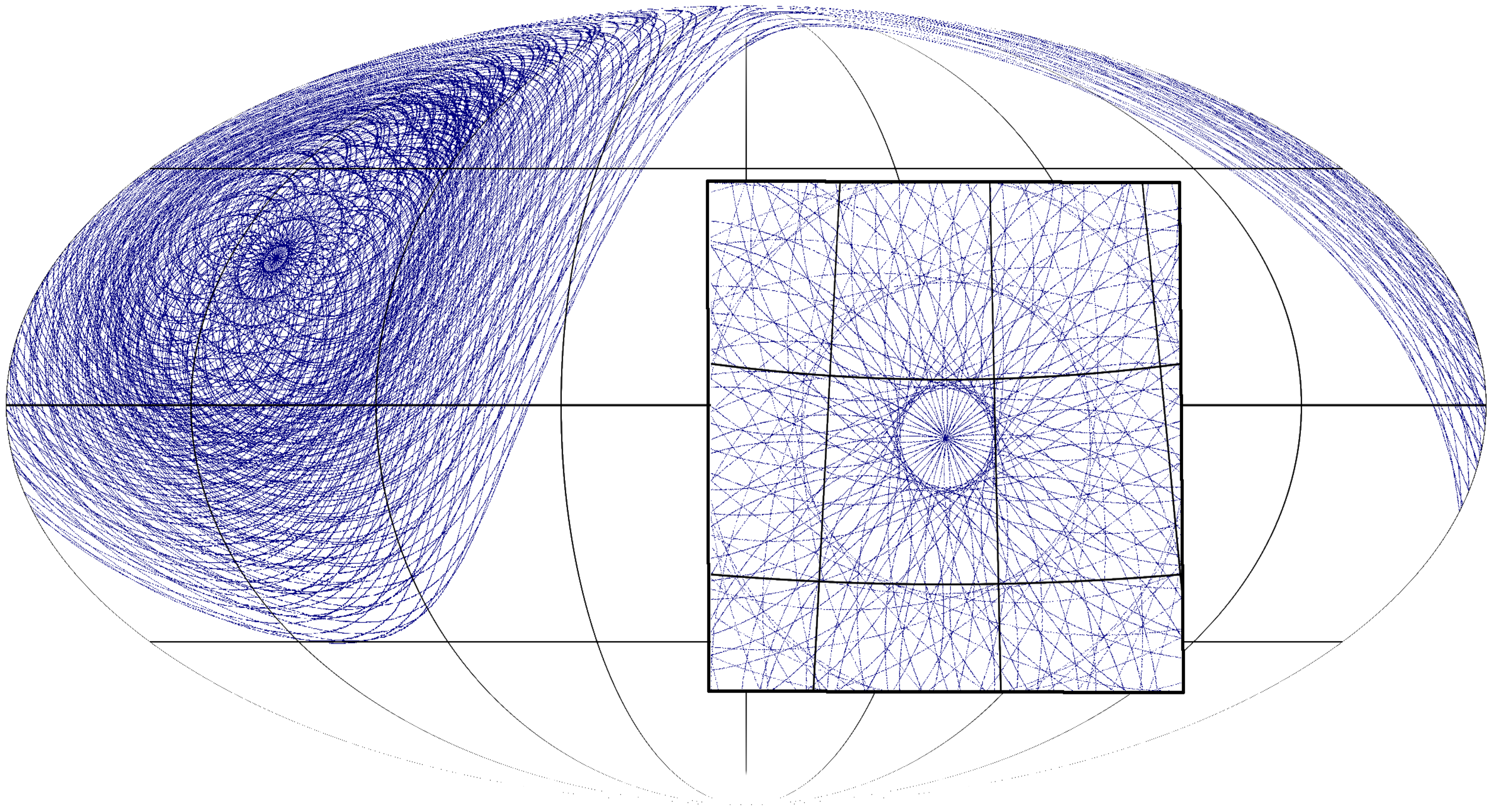


72° N supports unique cross-linking



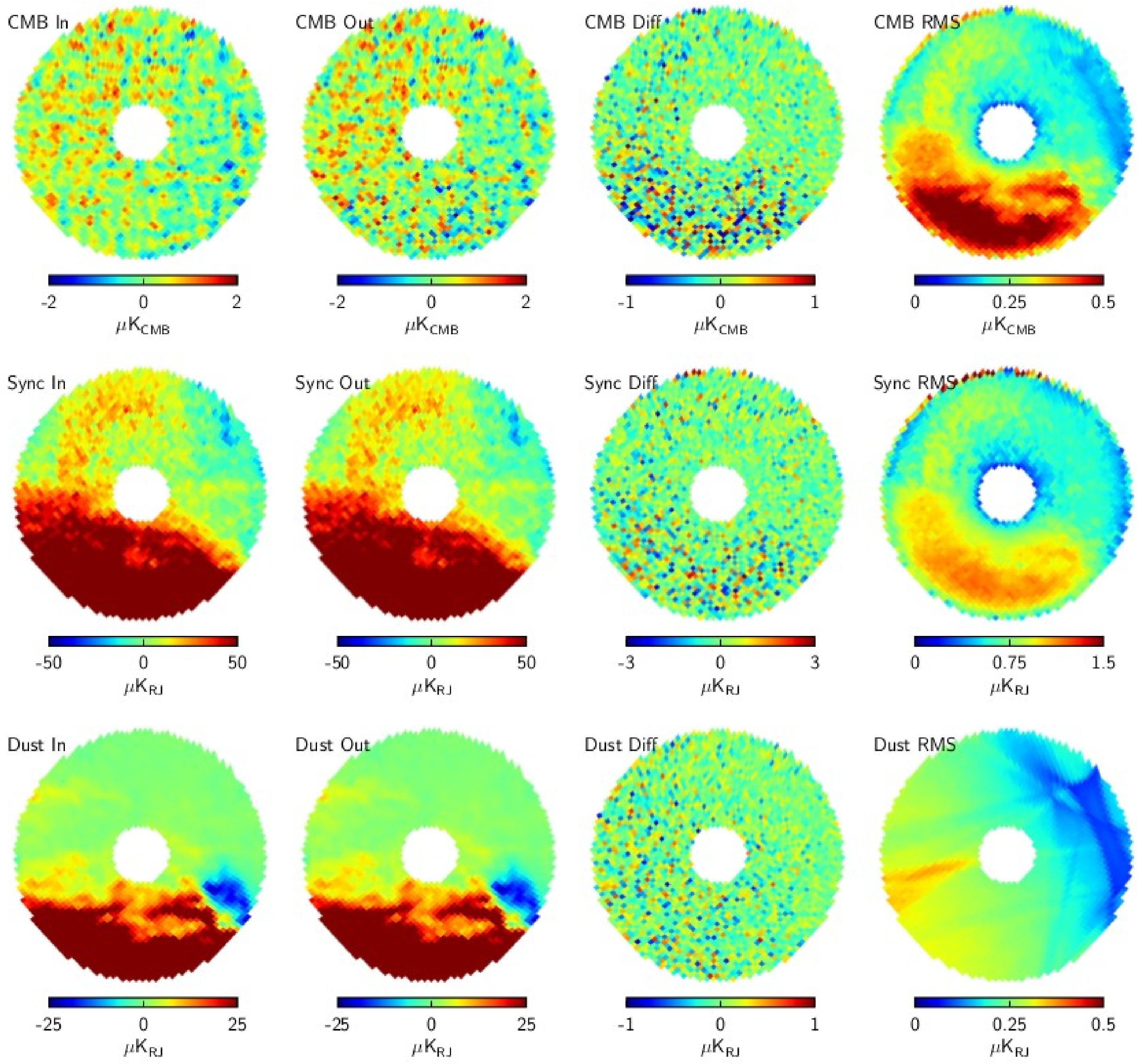
Sensitivity per focalplane

Frequency [GHz]	FWHM [Arcmin]	Bandwidth [GHz]	NET [μK*√sec]	Pixels/Telescope	Aggregate NET [μK*√sec]
10	80	4	316	7	120
15	53	4	316	13	88
20	40	4	443	19	102
30	27	6	361	25	72
45*	18	6	200	40	16

- 10-30 GHz receivers assume currently available HEMT amplifiers cooled to 20K
- 45 GHz receiver assumes an achievable bolometric detector array.

The above assumptions are for one telescope each frequency. We expect a real experiment will incorporate more than one telescope per frequency.

Commander simulations



Fuskeland et al. 2017, in prepration

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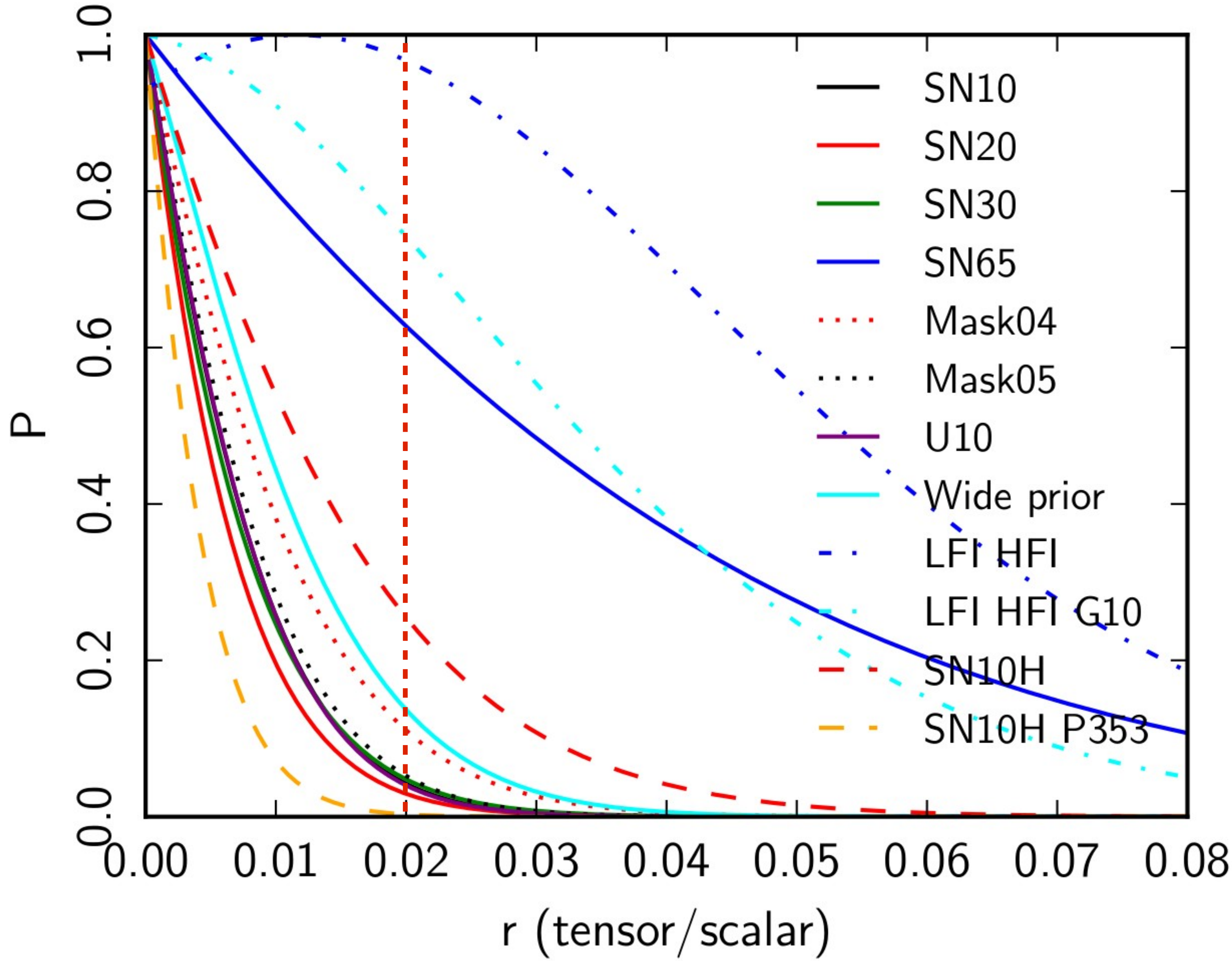

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- Strict noise optimization was a good strategy for the CMB field as a whole as long as CMB experiments were noise dominated
- That strategy ended abruptly with Planck and BICEP2
- From now on, the name of the game is component separation, not noise reduction
- In this landscape, *frequency leverage* is the key factor
- Low-frequency observations should be an integral part of any ambitious next-generation project, both for sensitivity and robustness