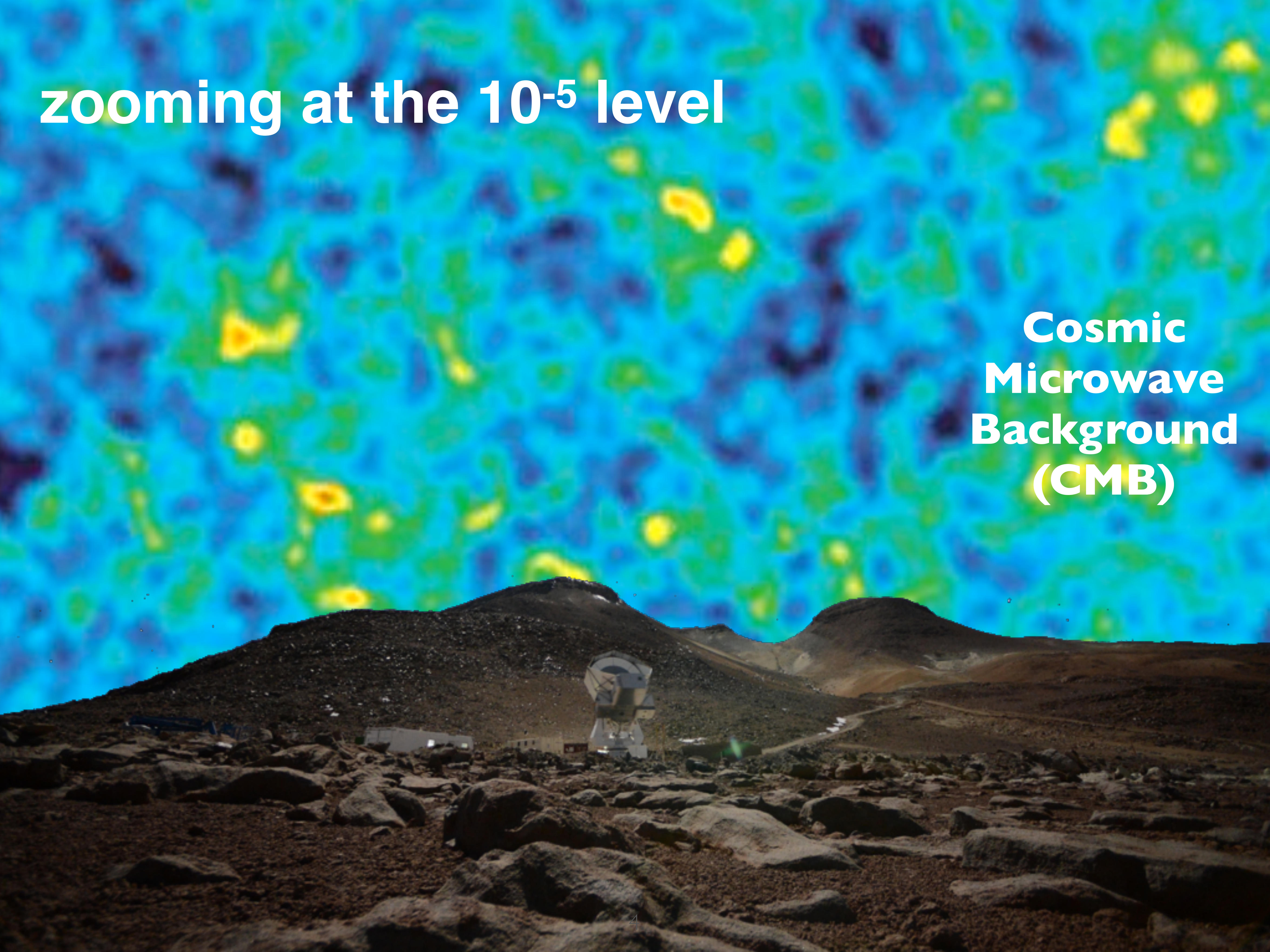
Measuring r

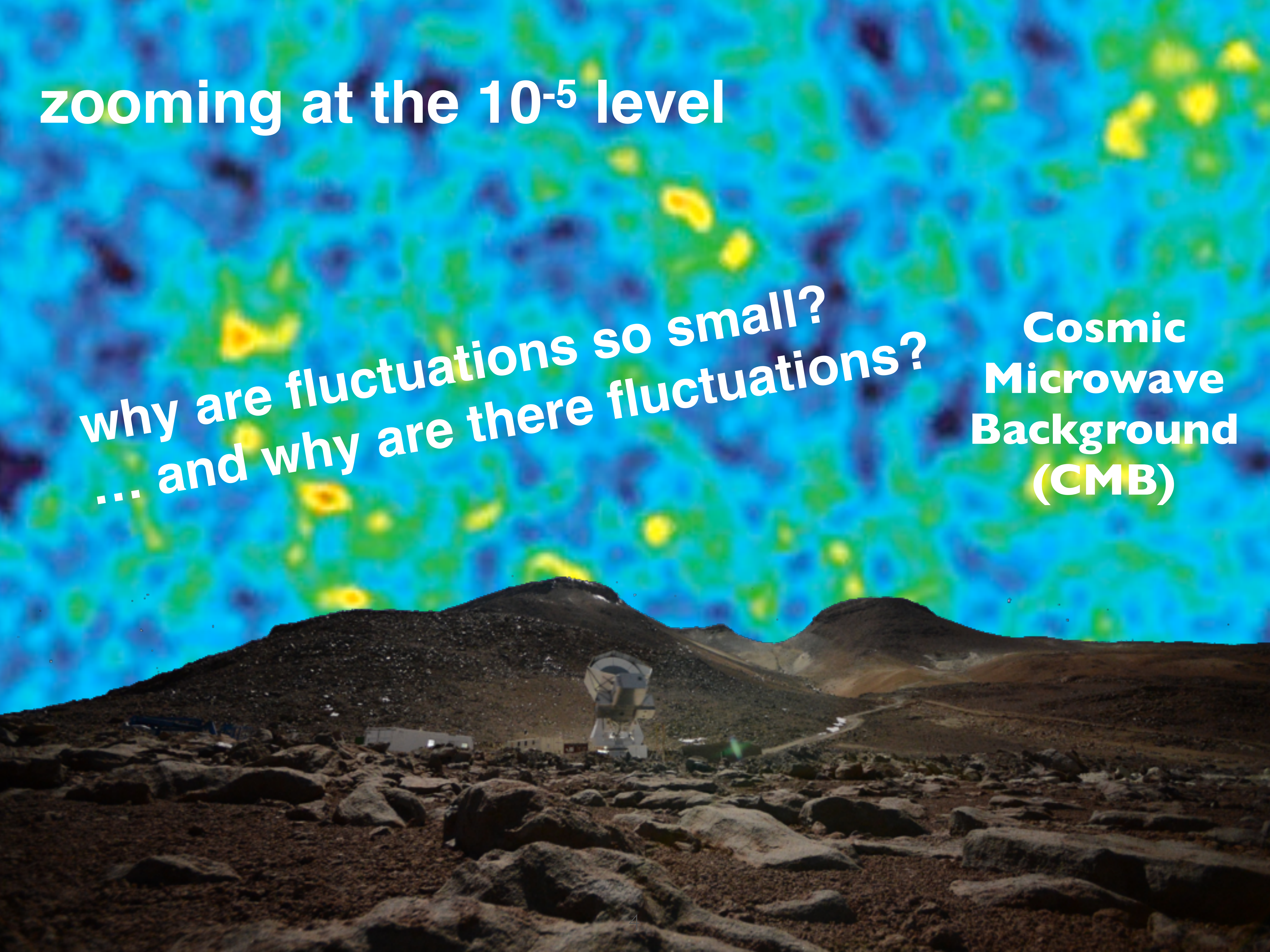
Josquin ERRARD

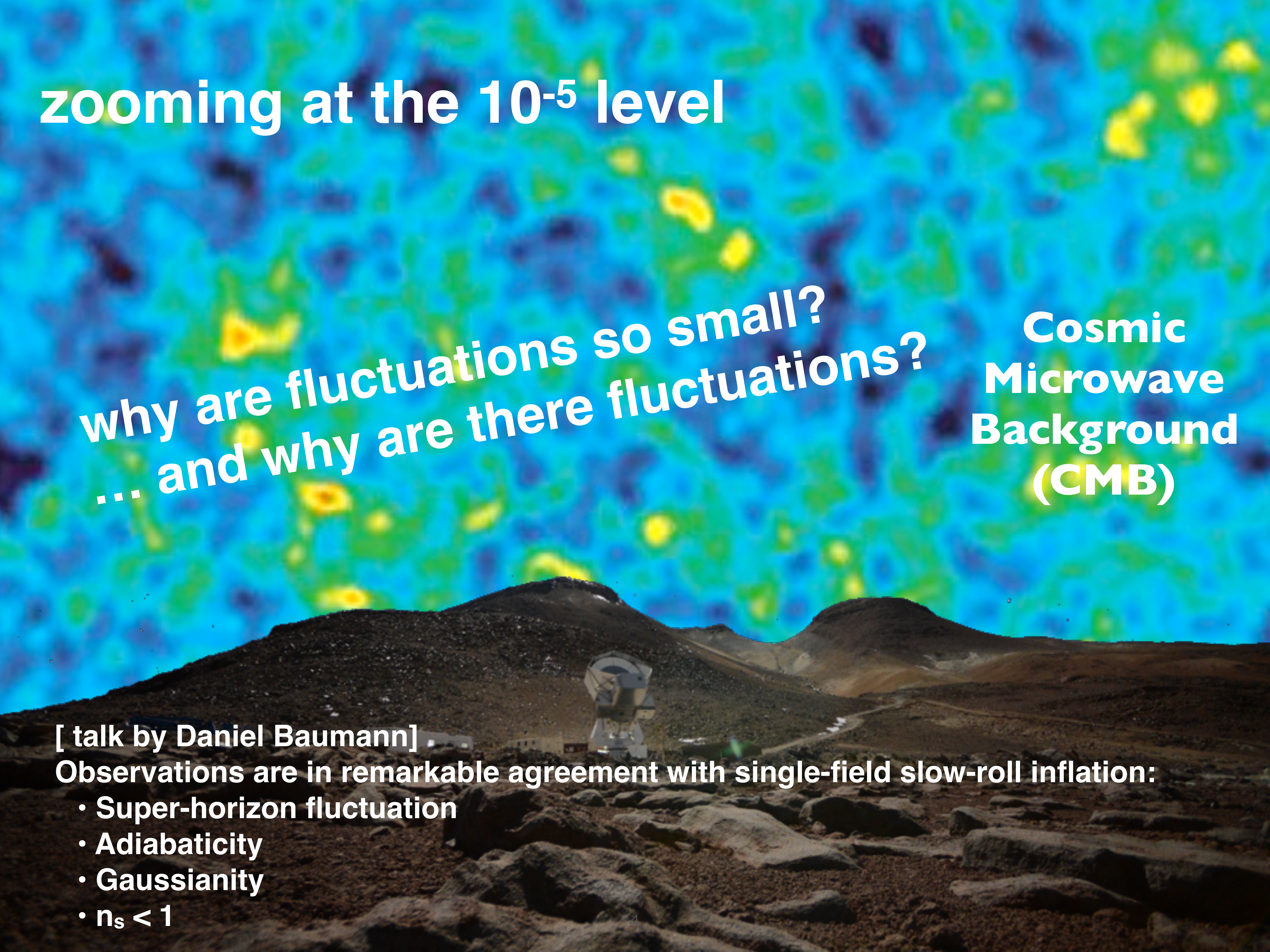
Firenze — Sep 5, 2017


POLARBEAR telescope
5,200m, Atacama desert, Chile
see talk “CMB in Chile” tomorrow


Cosmic Microwave Background (CMB)
POLARBEAR telescope
5,200m, Atacama desert, Chile


zooming at the 10^{-5} level
Cosmic Microwave Background (CMB)


zooming at the 10-5 level
why are fluctuations so small?
… and why are there fluctuations?
Cosmic Microwave Background (CMB)

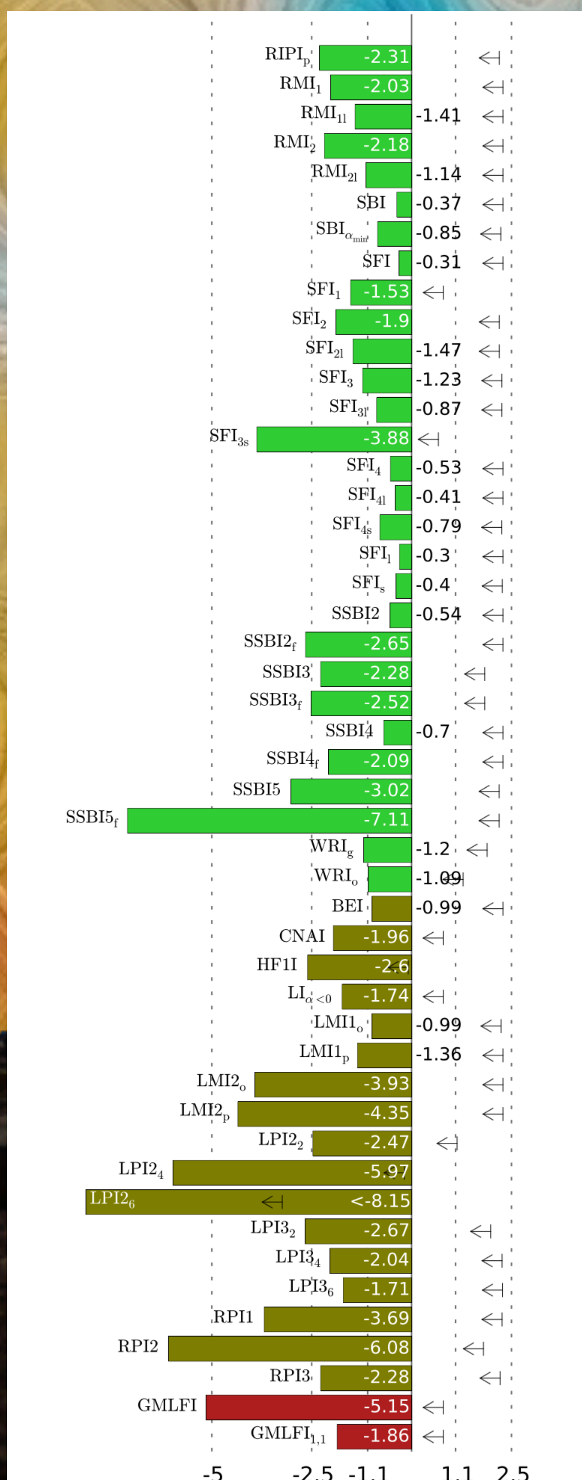


zooming at the 10^{-5} level
why are fluctuations so small?
… and why are there fluctuations?
Cosmic Microwave Background (CMB)
[talk by Daniel Baumann]
Observations are in remarkable agreement with single-field slow-roll inflation:
• Super-horizon fluctuation
• Adiabaticity
• Gaussianity
• $n_s < 1$

zooming at the 10^{-7} level

zooming at the 10^{-7} level

➤ but we want gravitational waves in addition!

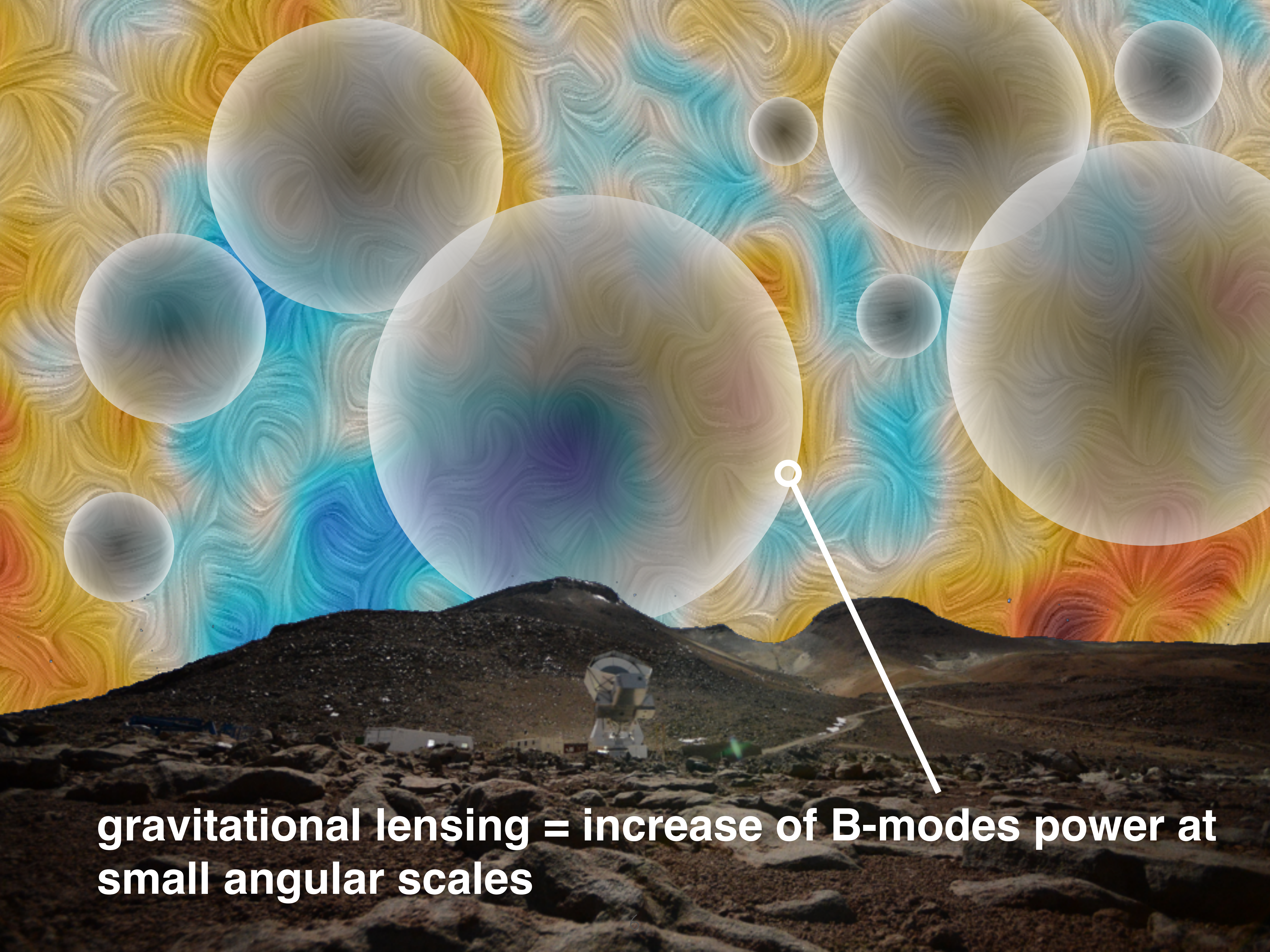


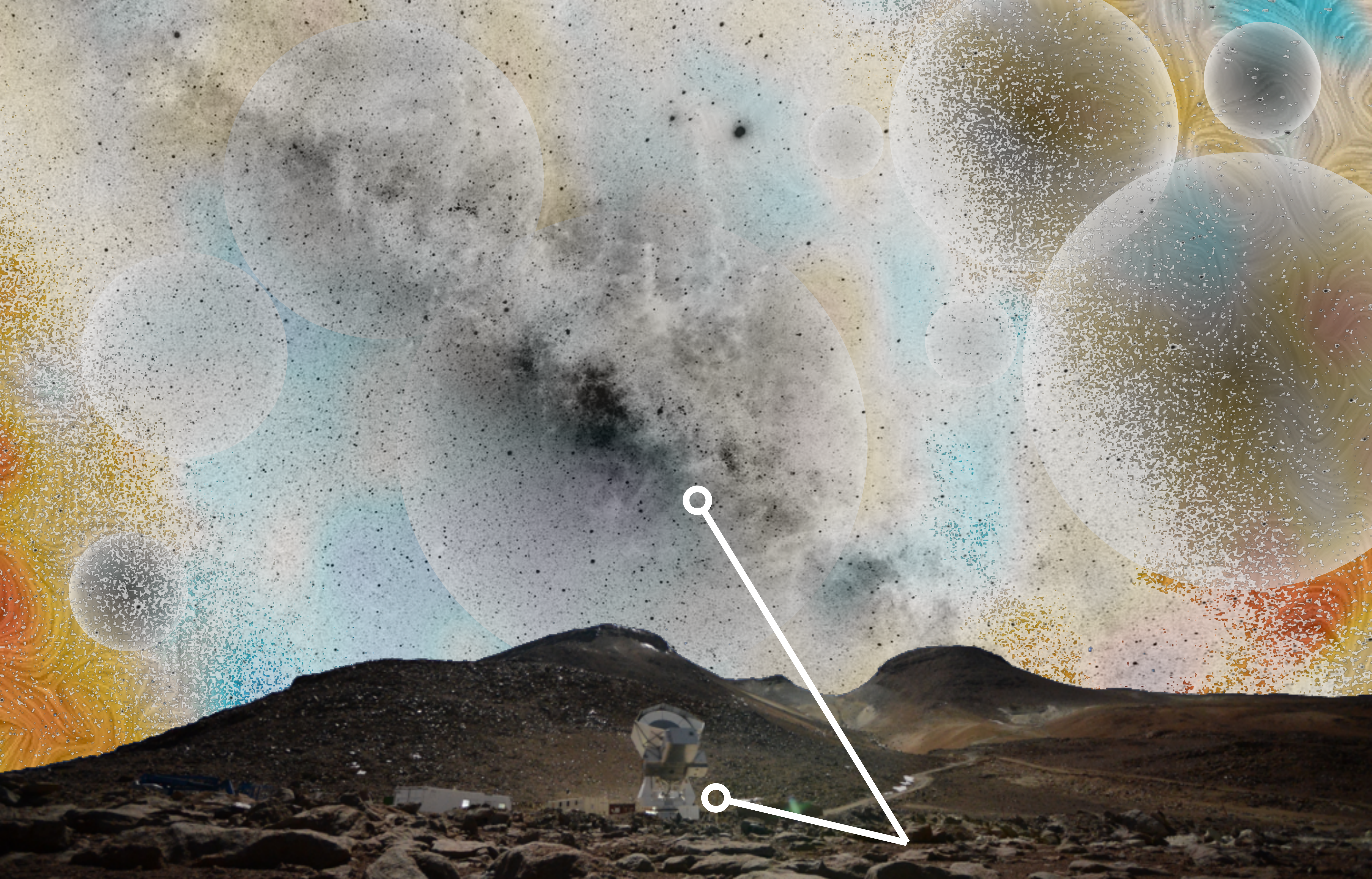
The Best Inflationary Models After Planck
J. Martin, C. Ringeval, R. Trotta, V. Vennin, JCAP, 2014

Parameter	Meaning	Physical Origin	Current Status
A_s	Scalar amplitude	H, $\dot{H}$, c_s	$(2.13 \pm 0.05) \times 10^{-9}$
n_s	Scalar tilt	$\dot{H}$, $\ddot{H}$, $\dot{c}_s$	0.965 ± 0.005
$dn_s/d\ln k$	Scalar running	$\dddot{H}$, $\ddot{c}_s$	only upper limits
A_t	Tensor amplitude	H	only upper limits
n_t	Tensor tilt	$\dot{H}$	only upper limits
r	Tensor-to-scalar ratio	$\dot{H}$, c_s	only upper limits
Ω_k	Curvature	Initial conditions	only upper limits
f_{NL}	Non-Gaussianity	Extra fields, sound speed, $\cdots$	only upper limits
S	Isocurvature	Extra fields	only upper limits
$G\mu$	Topological defects	End of inflation	only upper limits

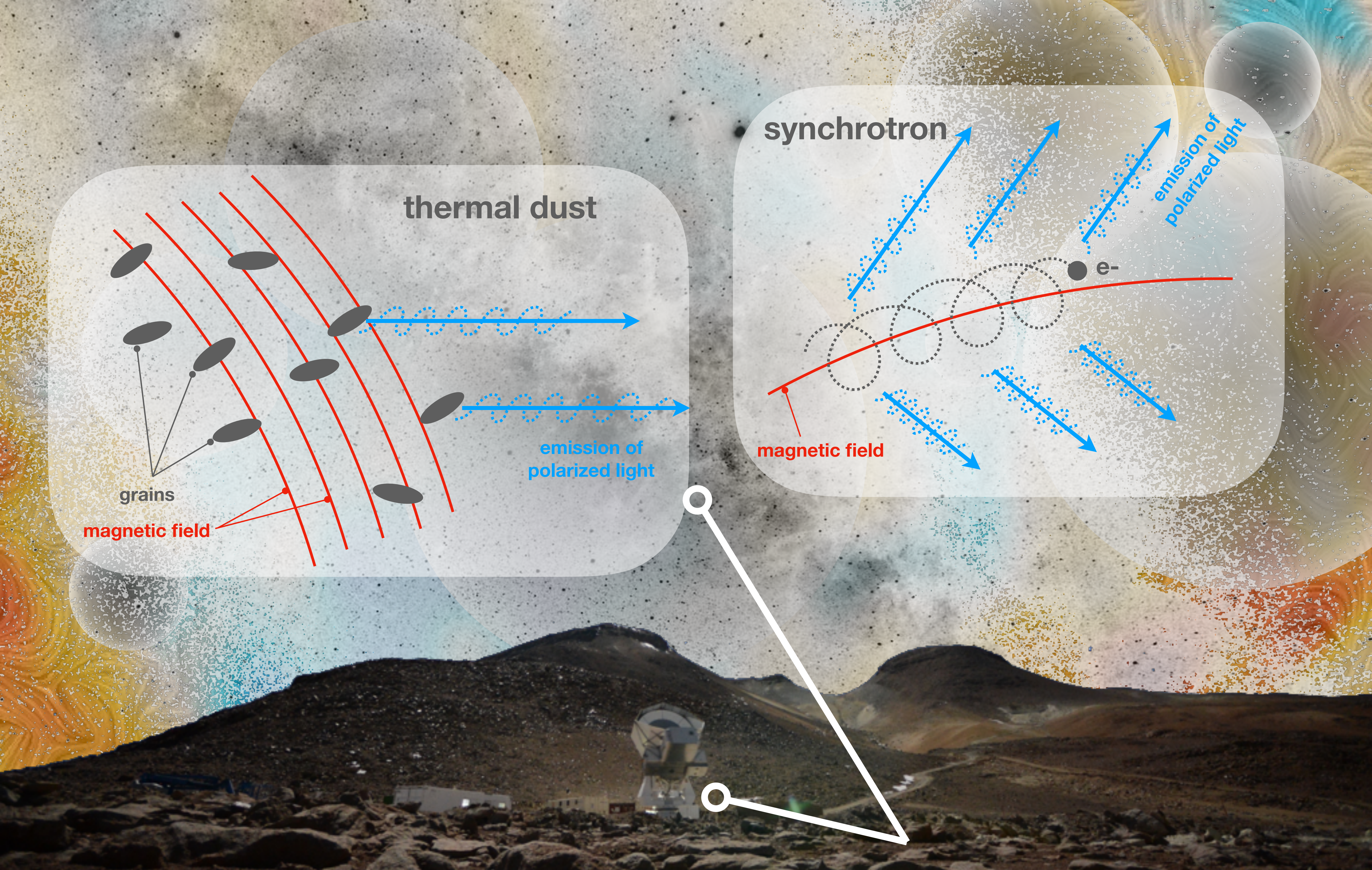
Table 1: Summary of key parameters in inflationary cosmology, together with their likely physical origins and current observational constraints. At present, only upper limits exist for all parameters except A_s and n_s [5].

Exploring Cosmic Origins with CORE: Inflation
F. Finelli, M. Bucher et al., JCAP, 2017


gravitational lensing = increase of B-modes power at small angular scales



astrophysical and instrumental systematics: the biggest challenges for the new generation CMB projects



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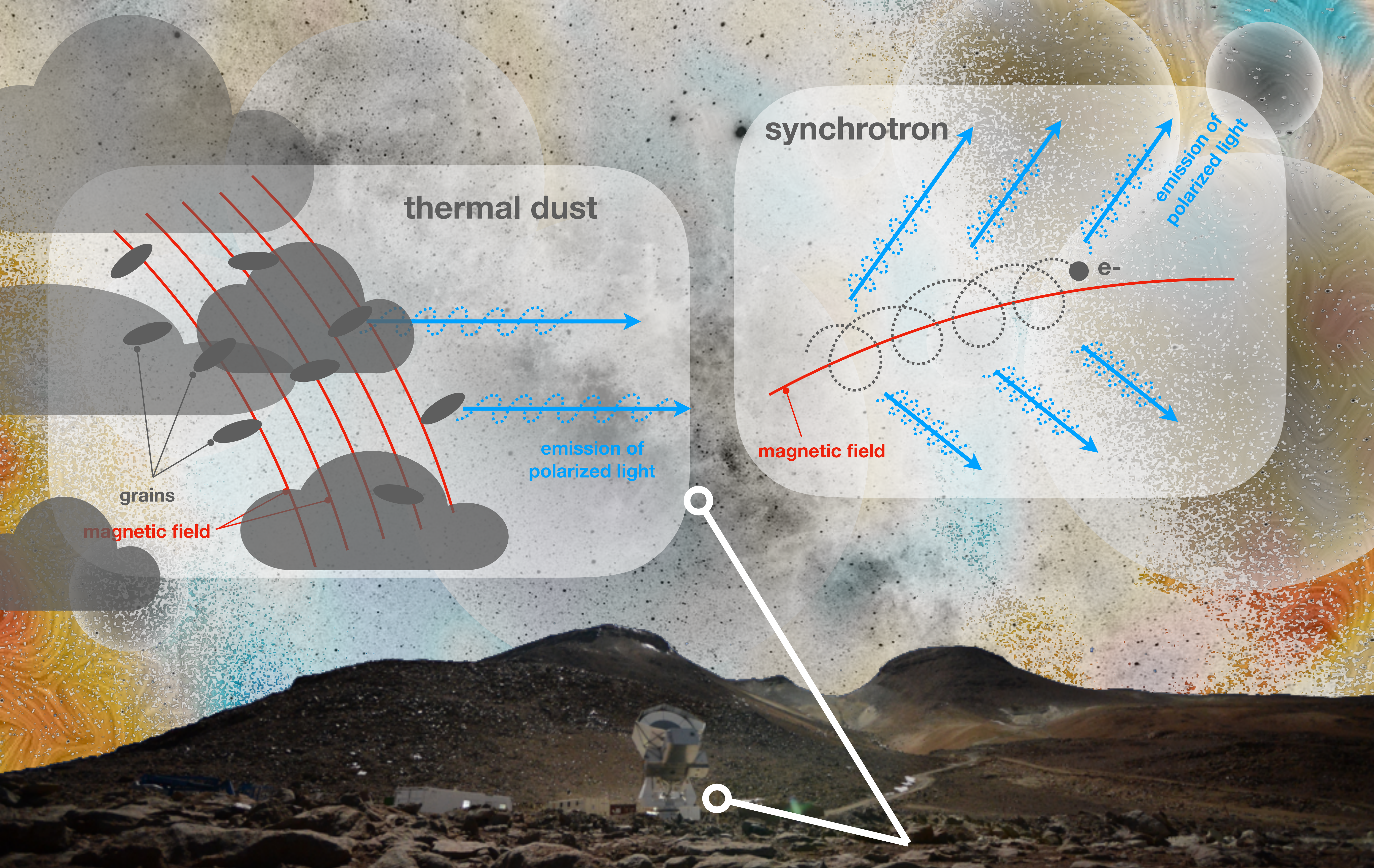
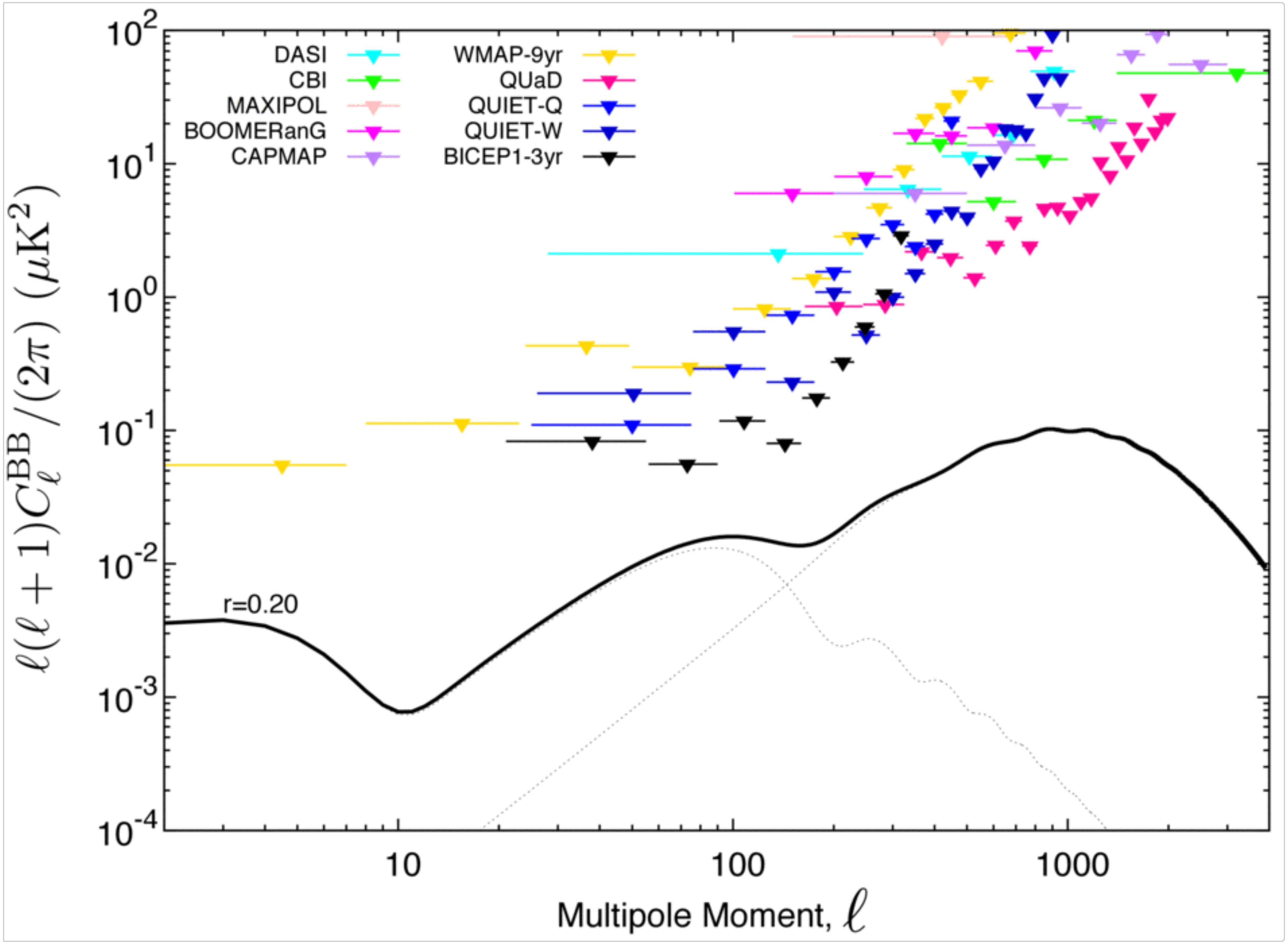


astrophysical and instrumental systematics: the biggest challenges for the new generation CMB projects

Recent history of direct BB detection



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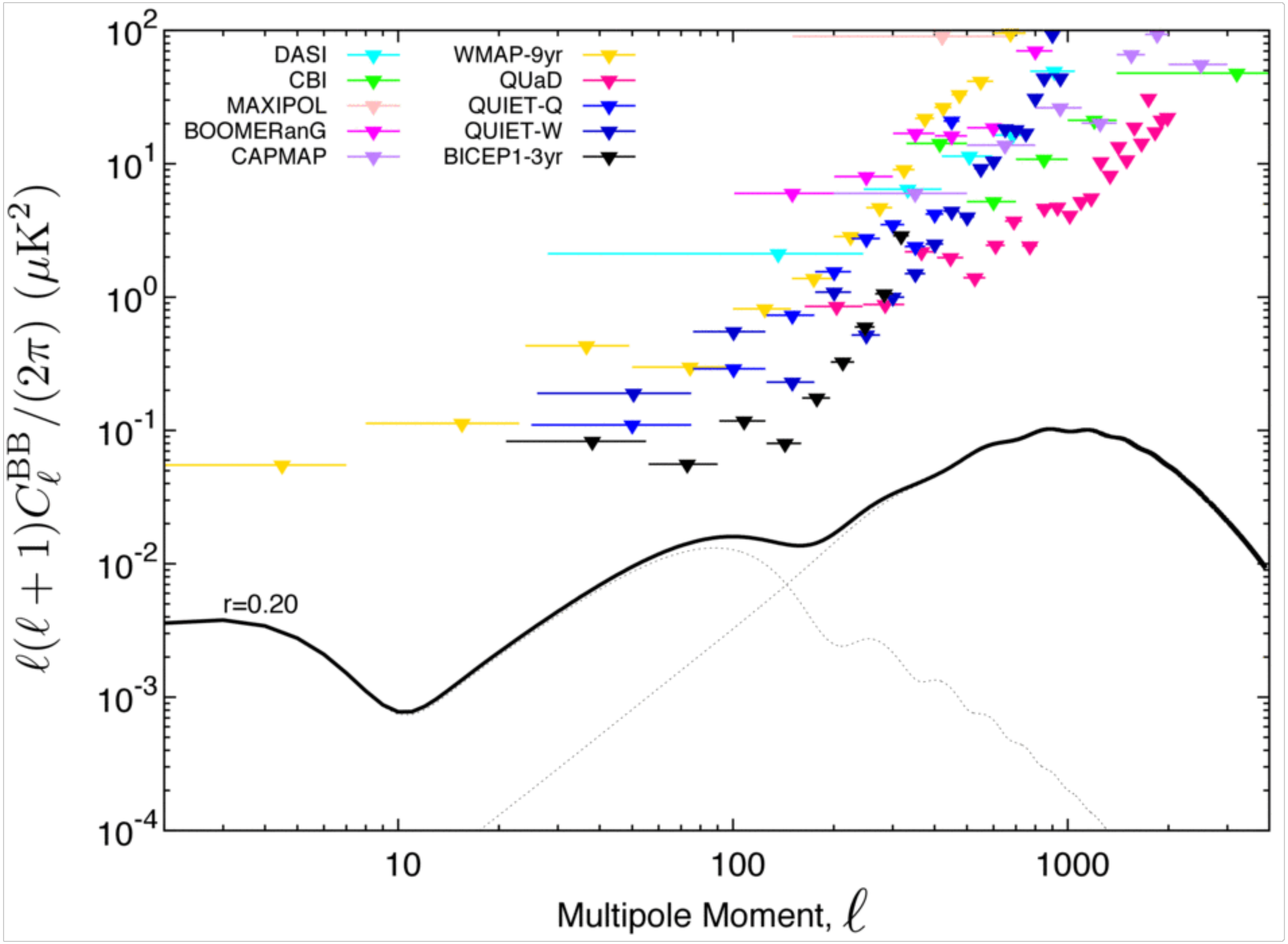

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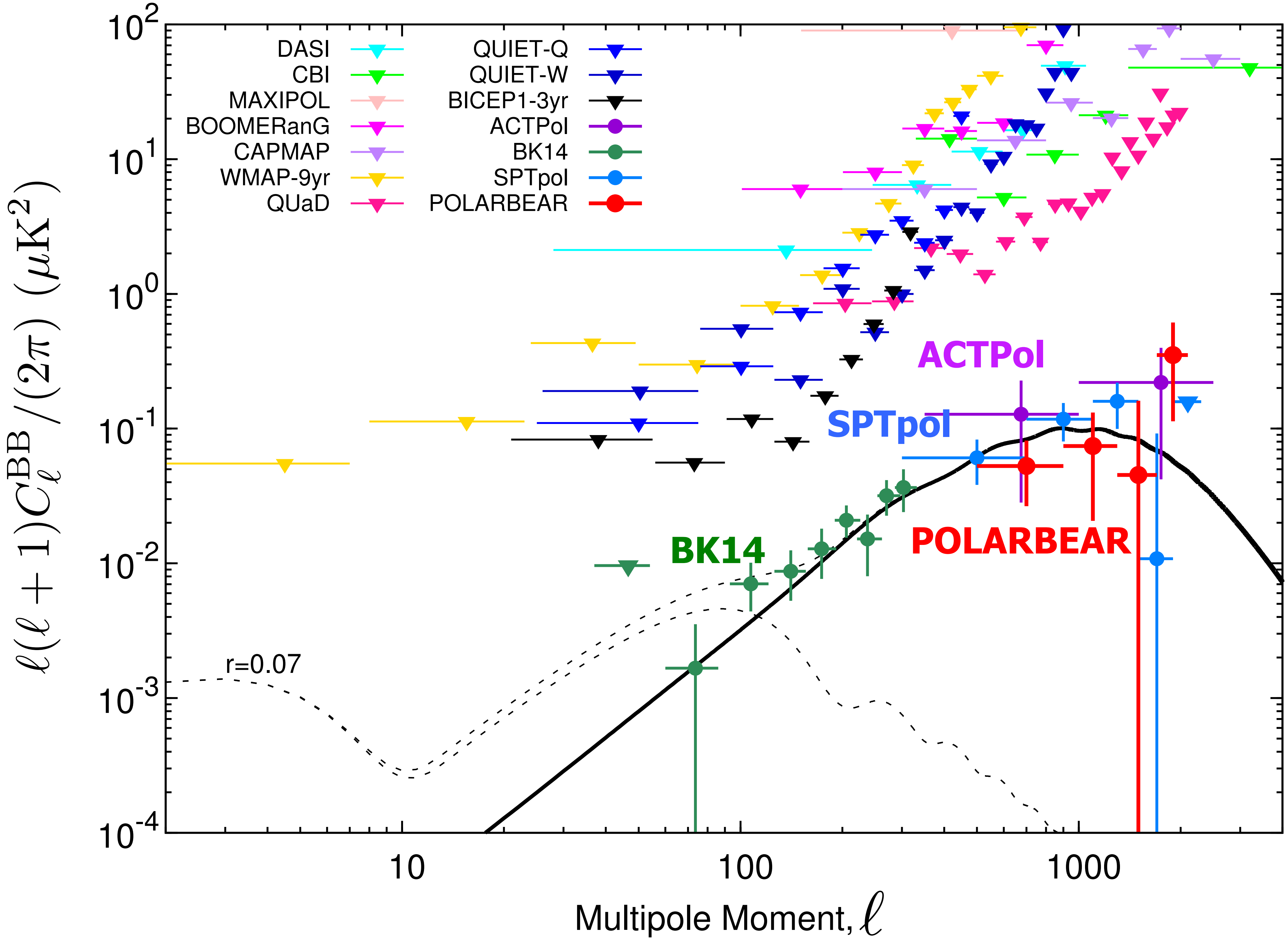
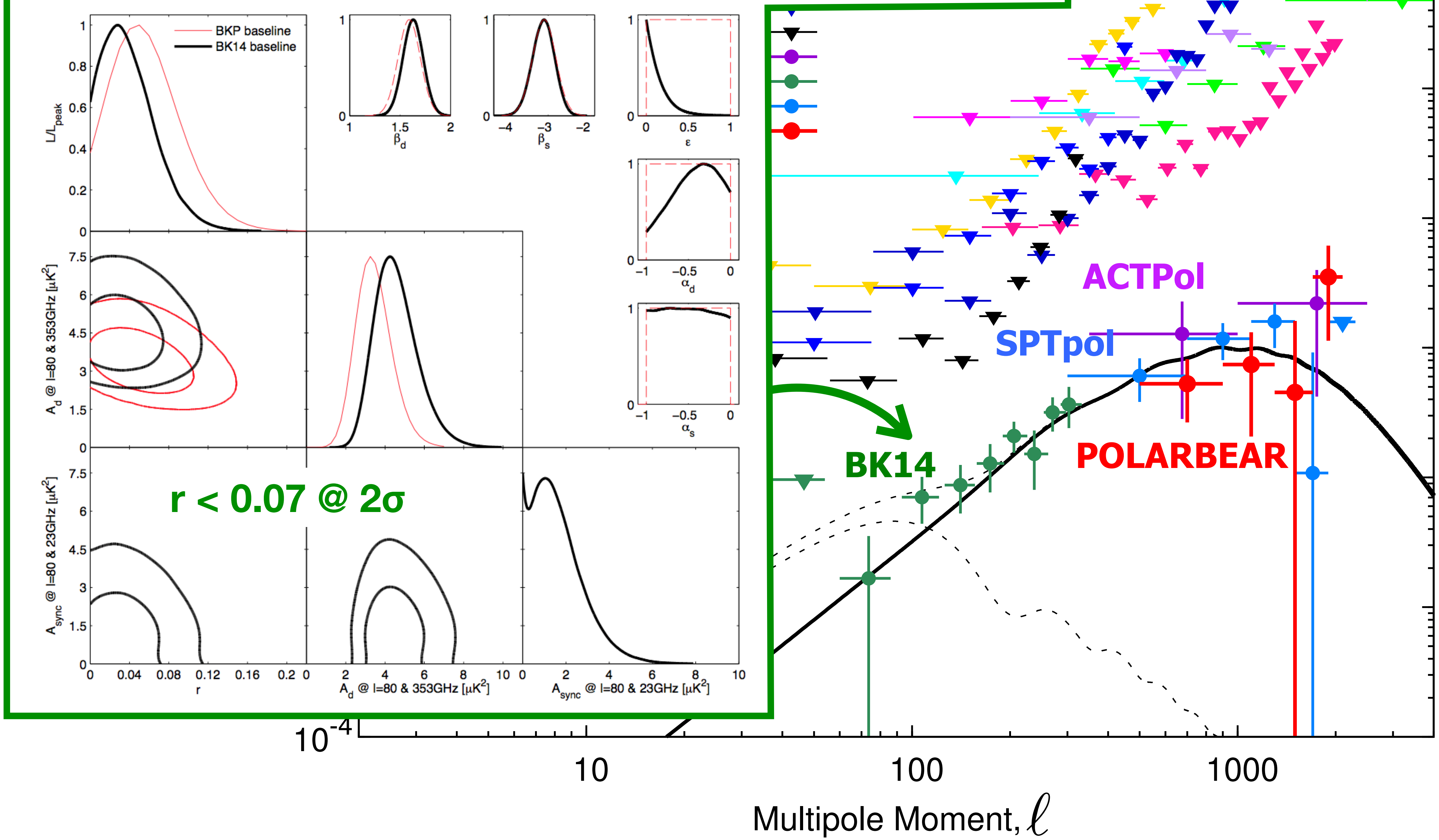


Recent history of direct BB detection

BICEP2 / Keck Array VI: Improved Constraints On Cosmology and Foregrounds When Adding 95 GHz Data From Keck Array
Keck Array and BICEP2 Collaborations



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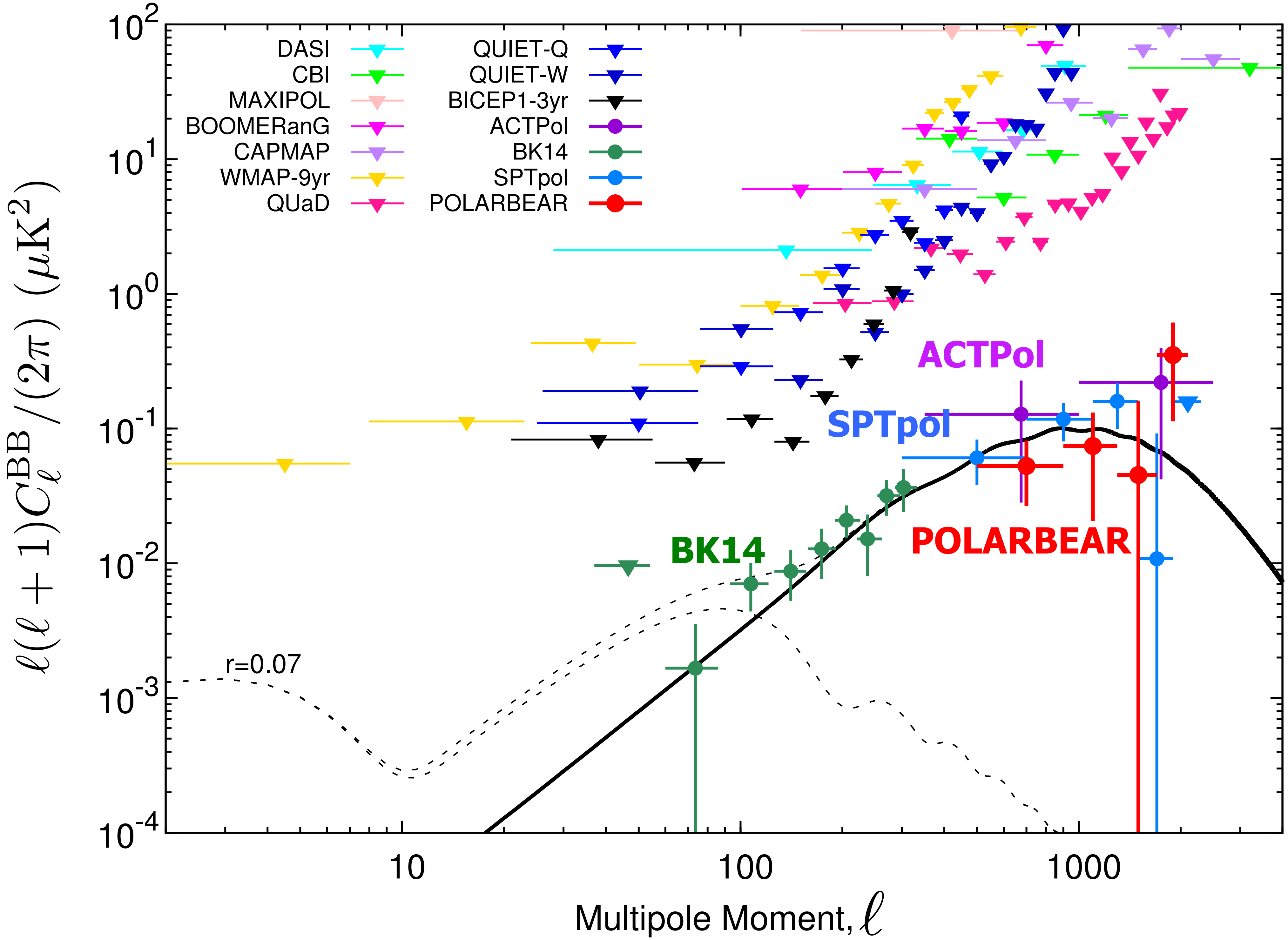

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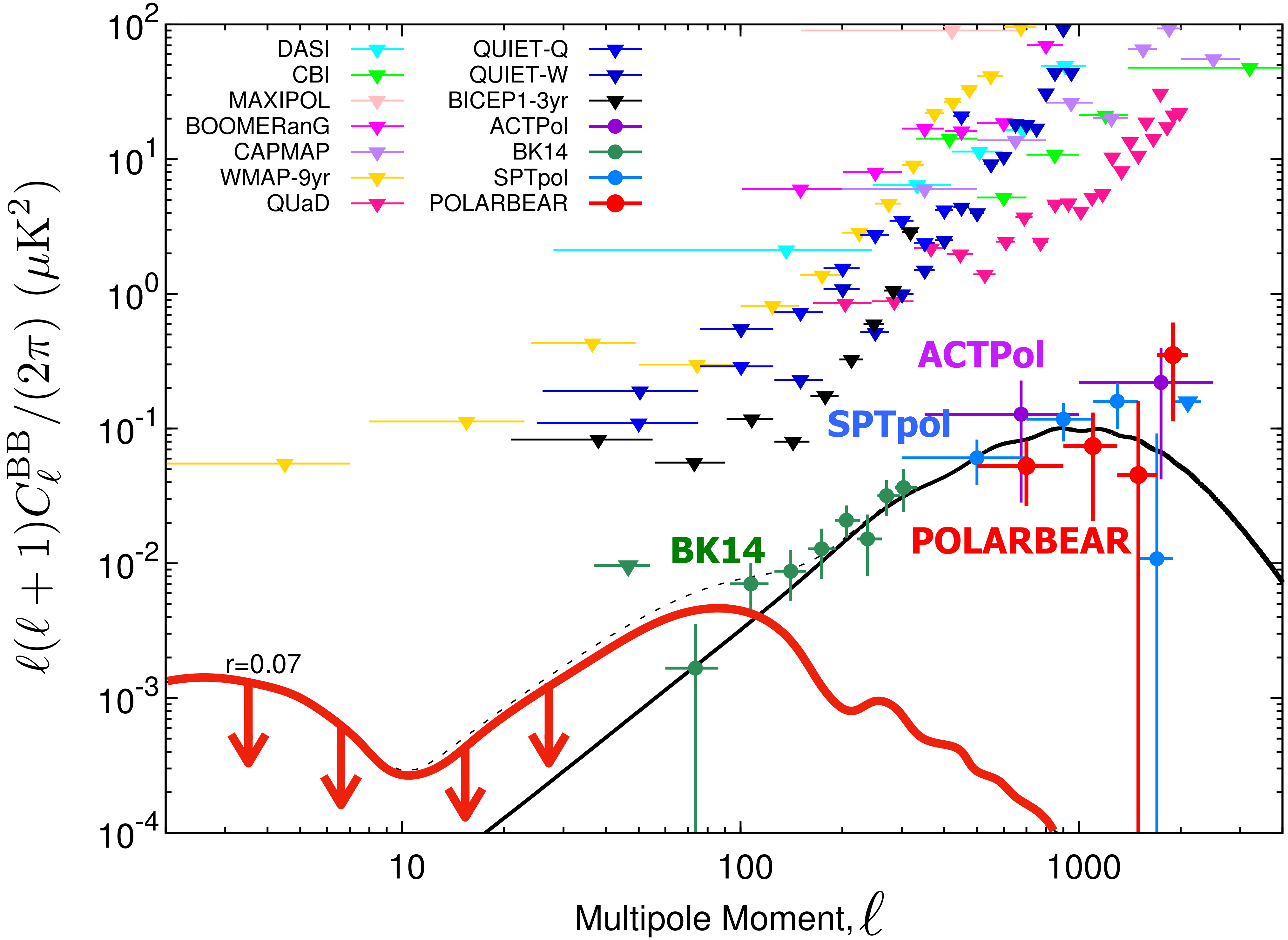

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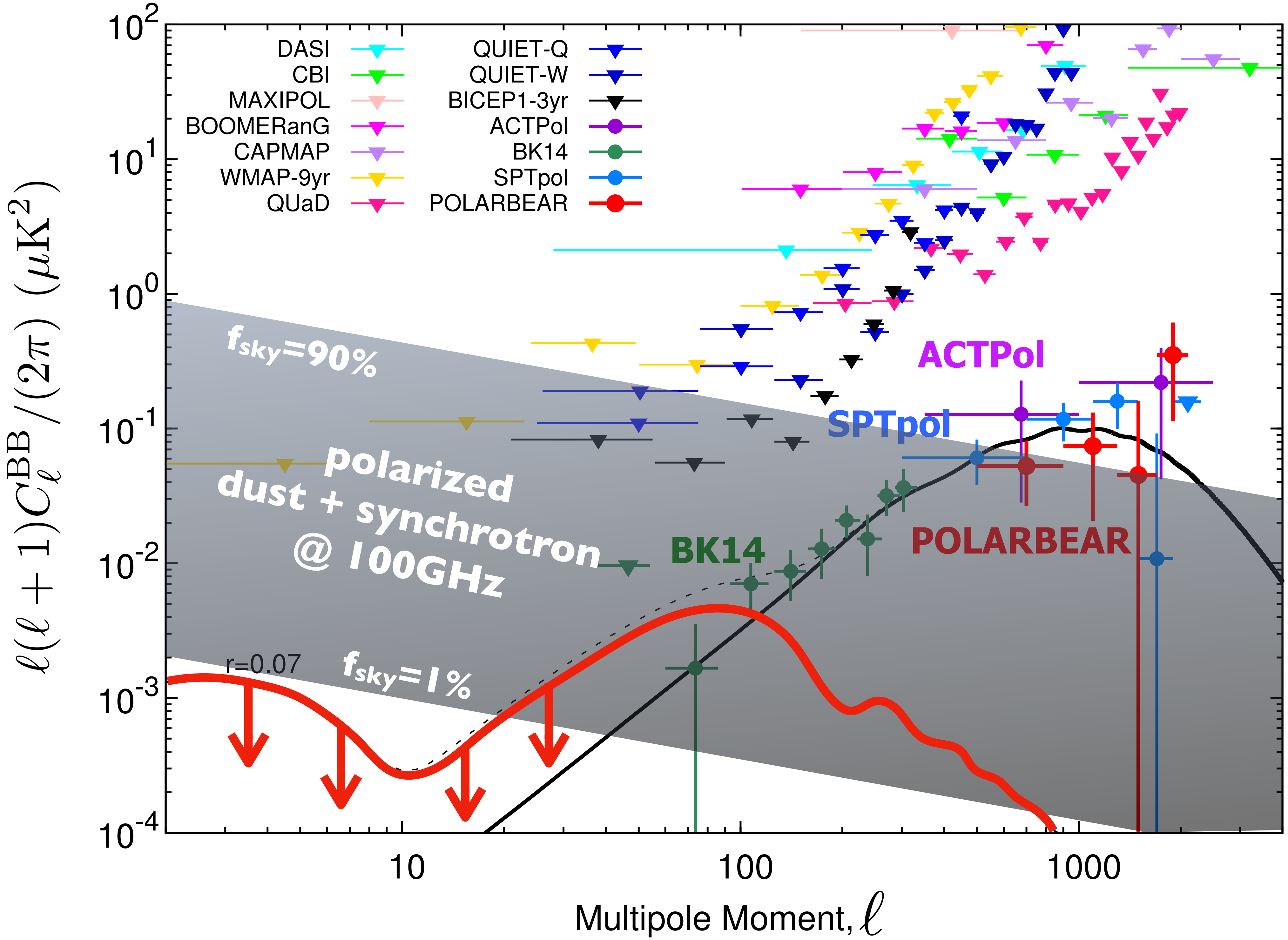

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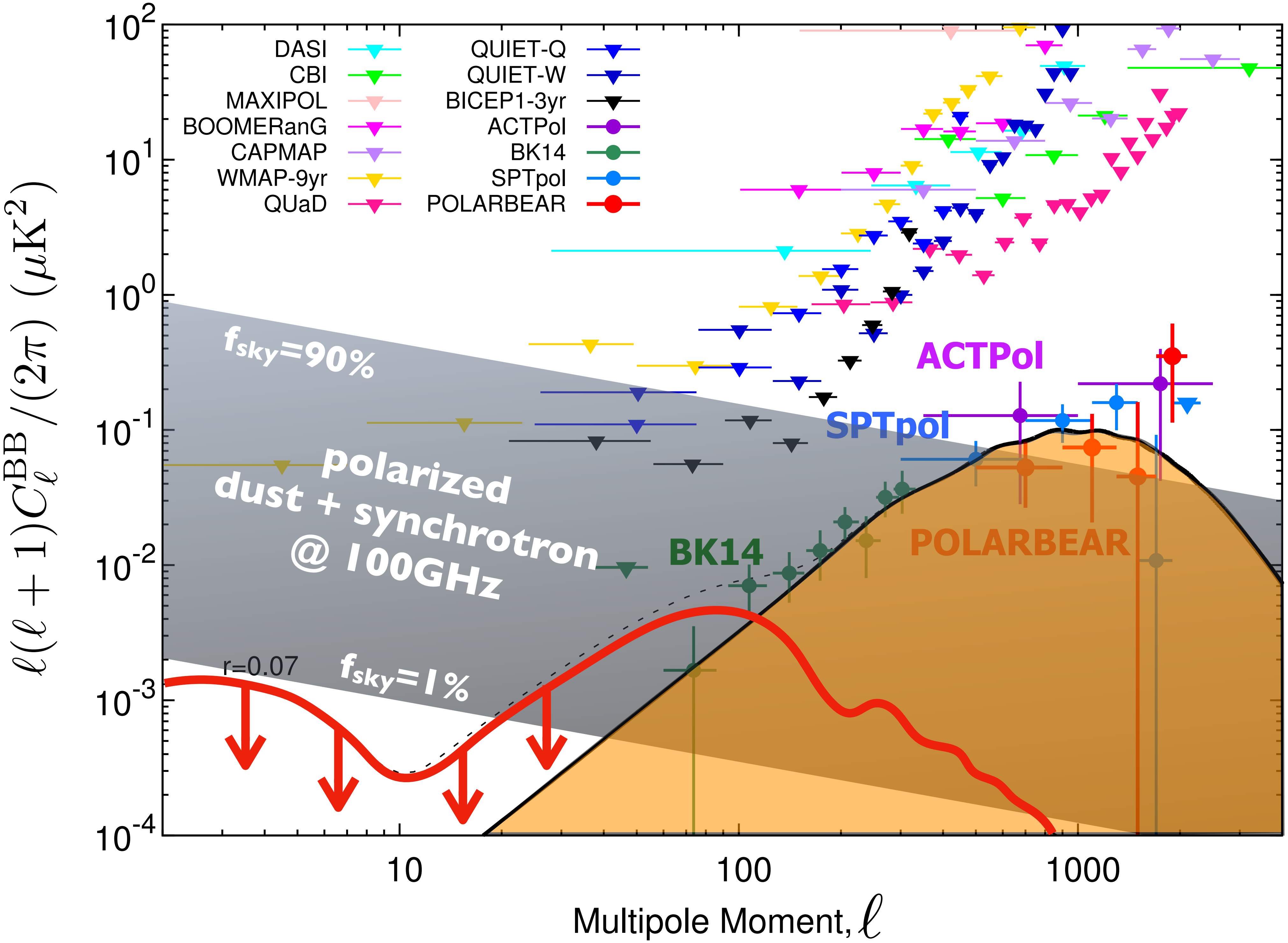

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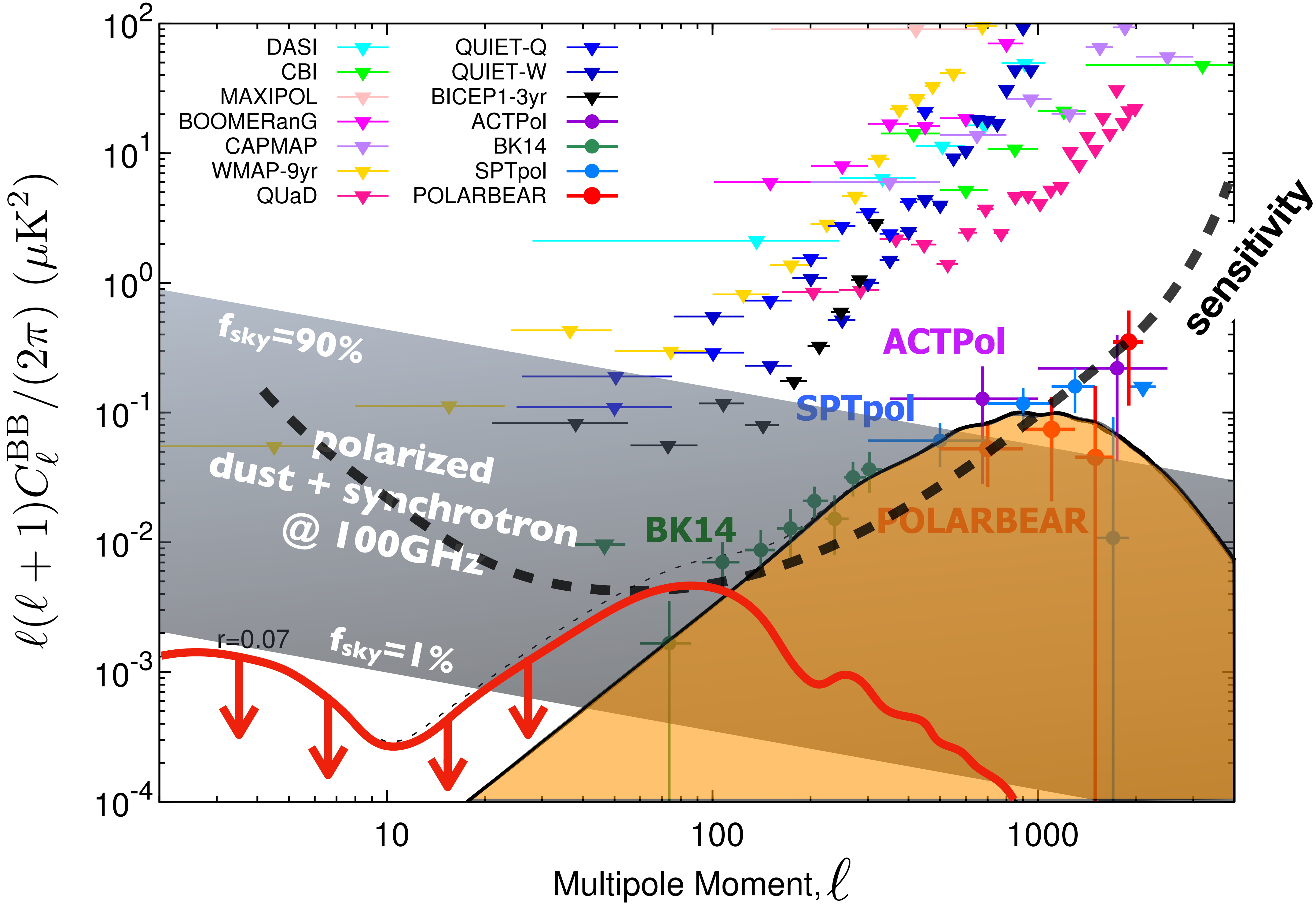

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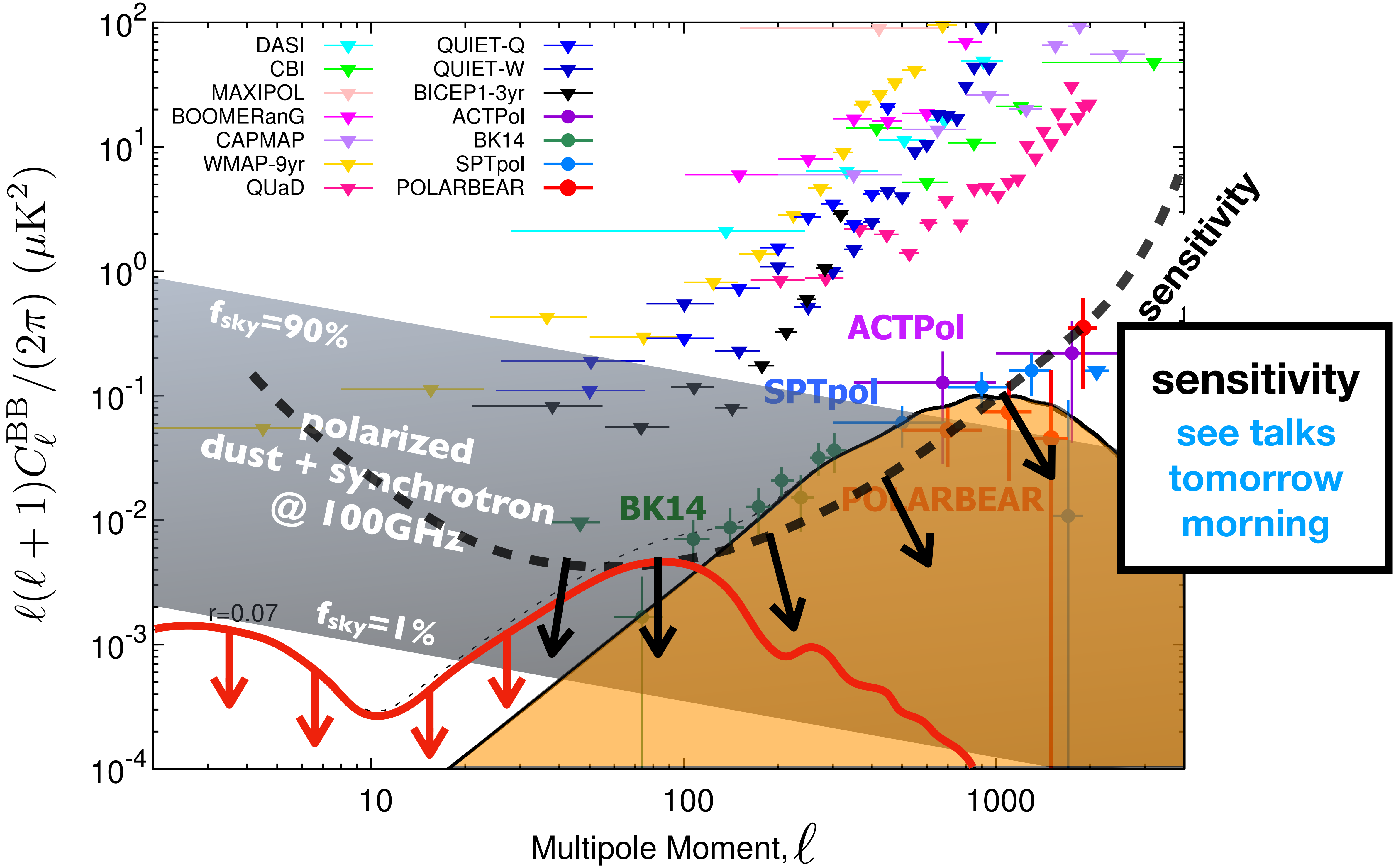

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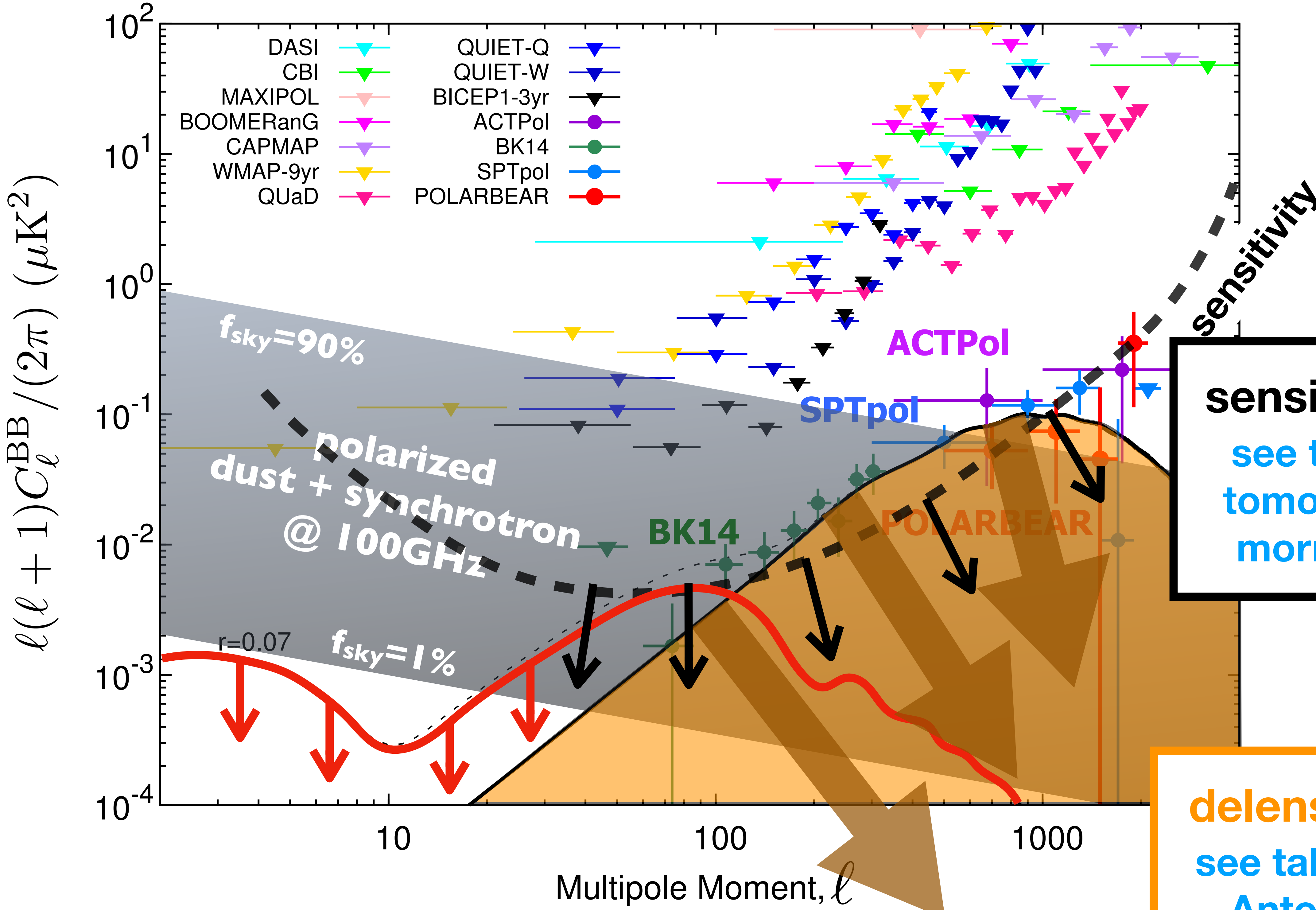
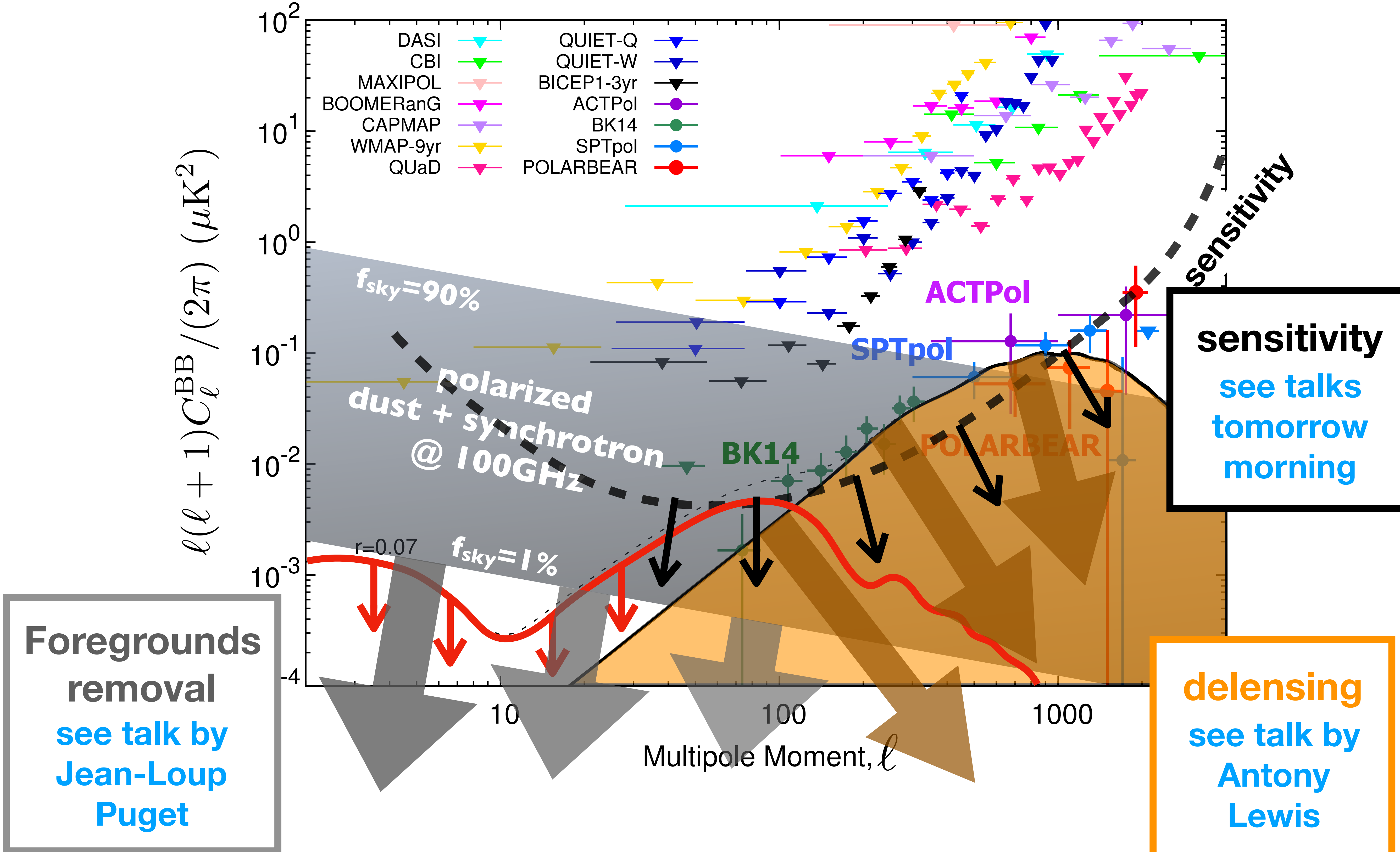
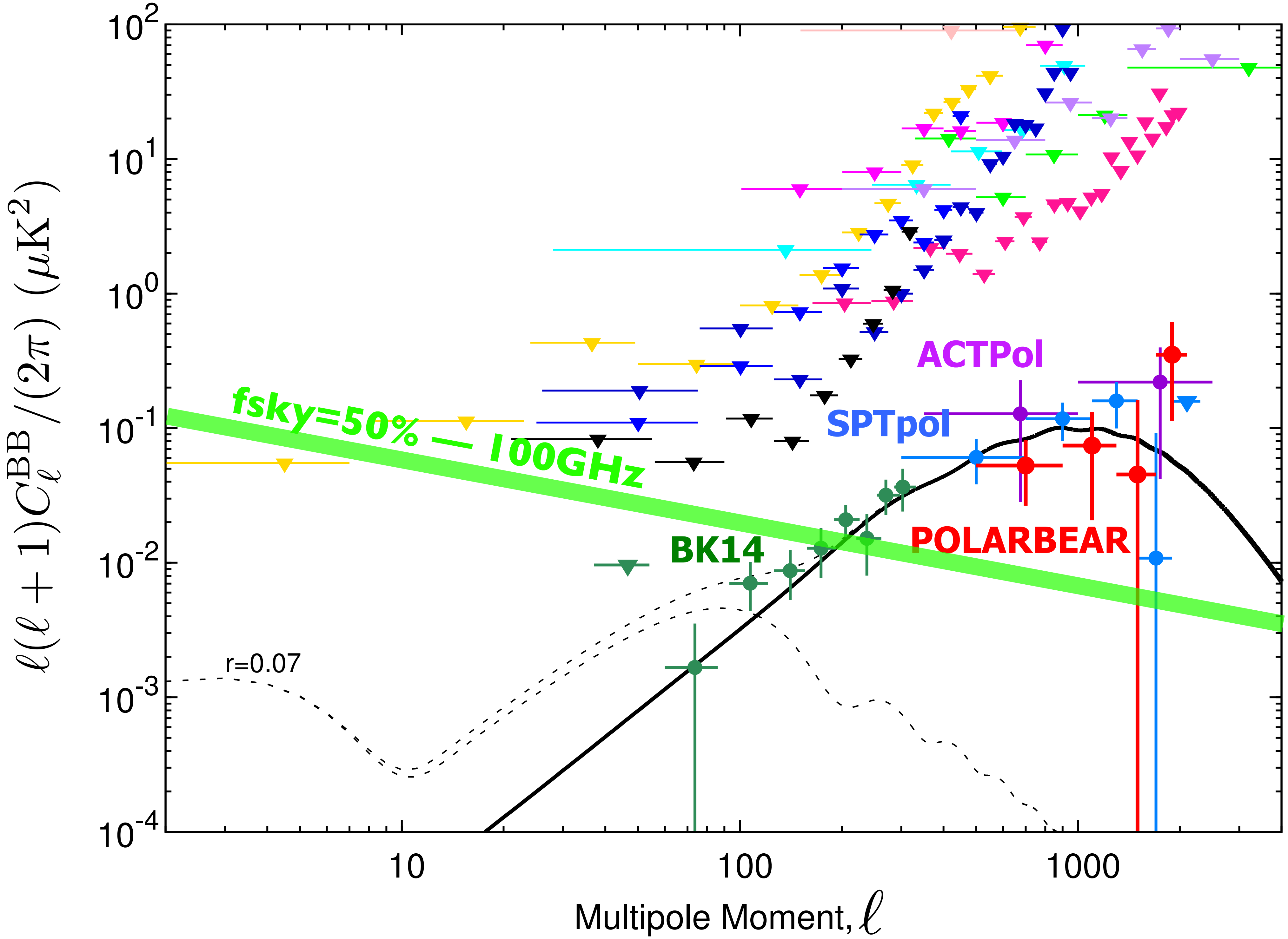


sensitivity
see talks tomorrow morning

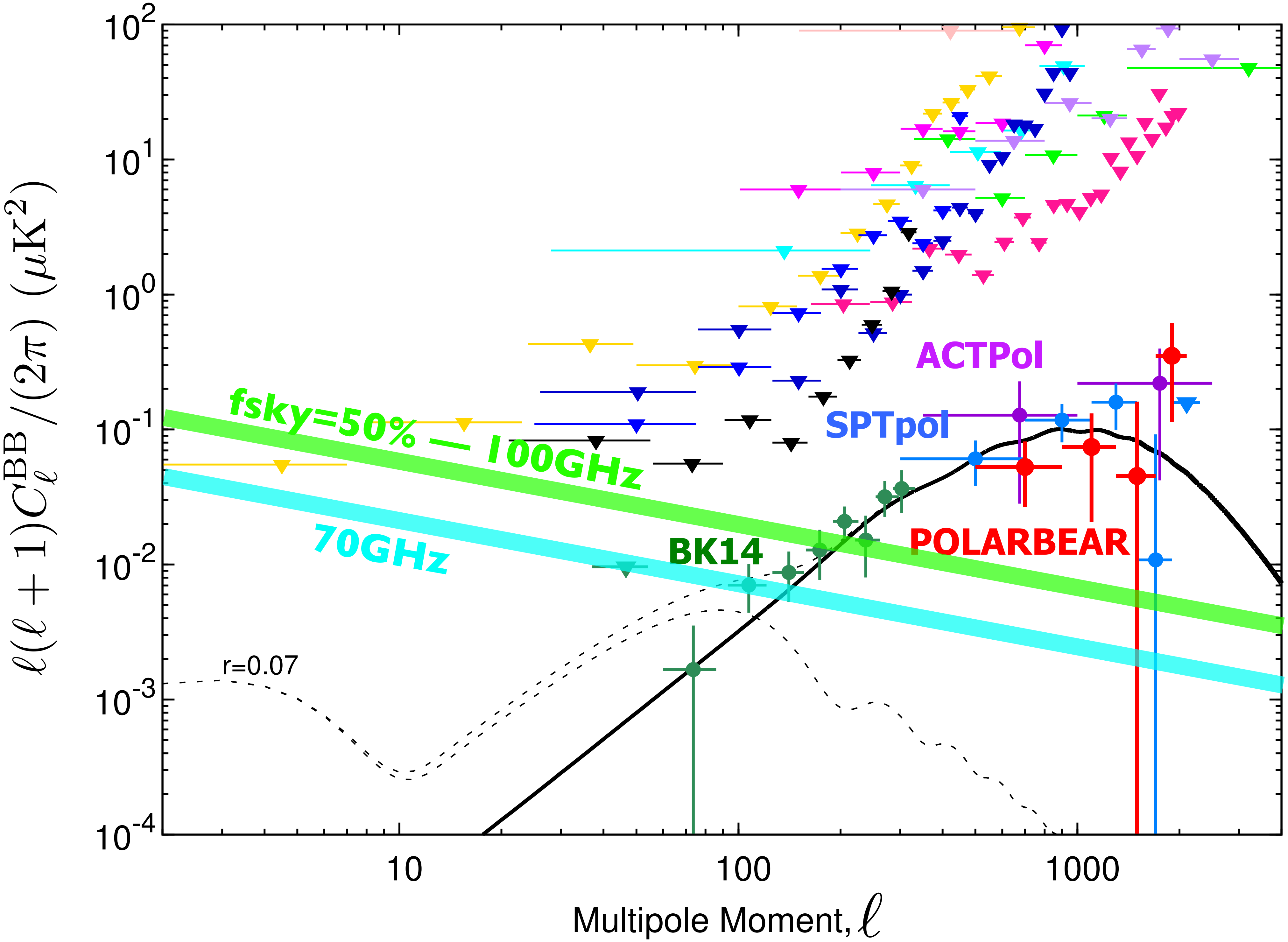
delensing
see talk by Antony Lewis

Recent history of direct BB detection

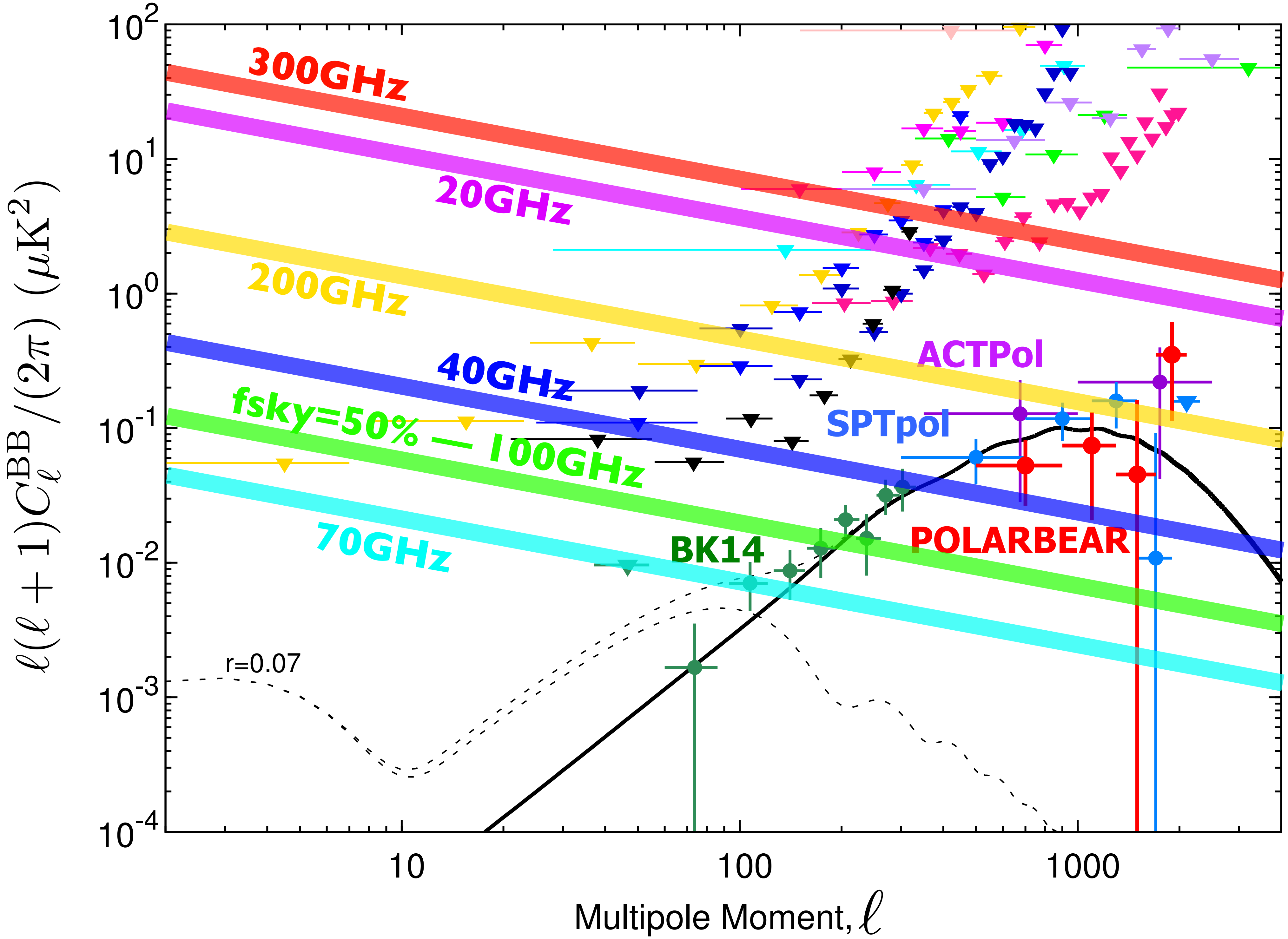




$\ell(\ell+1)C_\ell^{\mathrm{BB}}/(2\pi)$ $(\mu\mathrm{K}^2)$
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10
100
1000
Multipole Moment, ℓ
fsky=50% — 100GHz
ACTPol
SPTpol
POLARBEAR
BK14
r=0.07

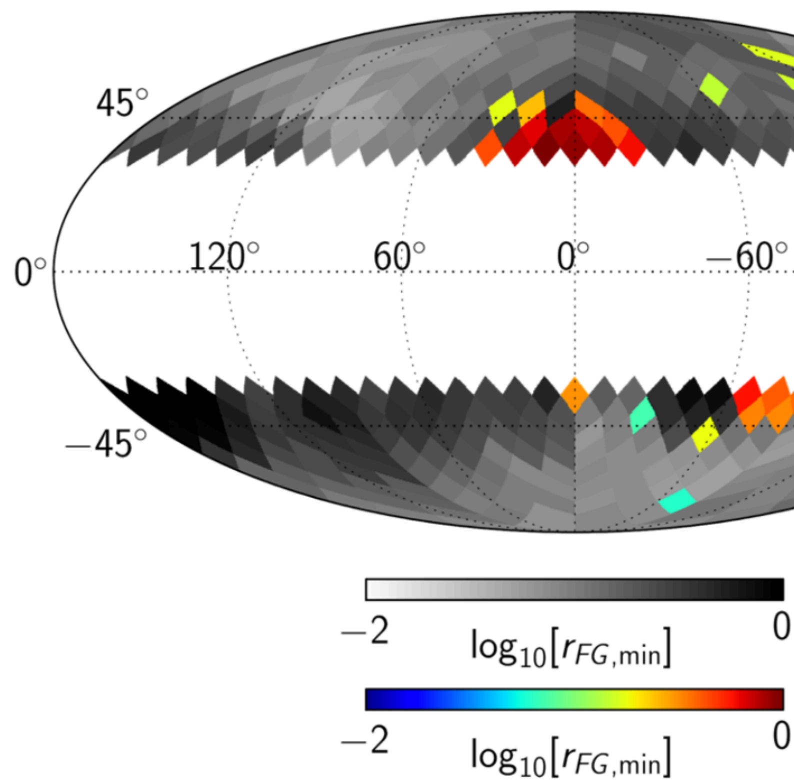


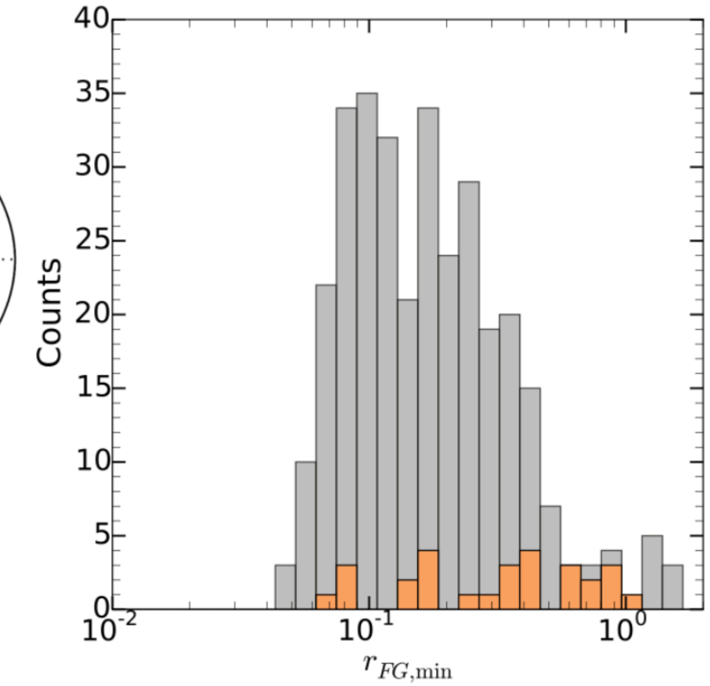
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$\ell(\ell+1)C_\ell^{\mathrm{BB}}/(2\pi)\ (\mu\mathrm{K}^2)$
10
100
1000
Multipole Moment, ℓ
ACTPol
SPTpol
POLARBEAR
BK14
fsky=50% — 100GHz
70GHz
r=0.07


300GHz
20GHz
200GHz
40GHz
fsky=50% — 100GHz
70GHz
ACTPol
SPTpol
POLARBEAR
BK14
r=0.07
$\ell(\ell+1)C_\ell^{\mathrm{BB}}/(2\pi)$ (μK^2)
Multipole Moment, ℓ
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10
100
1000

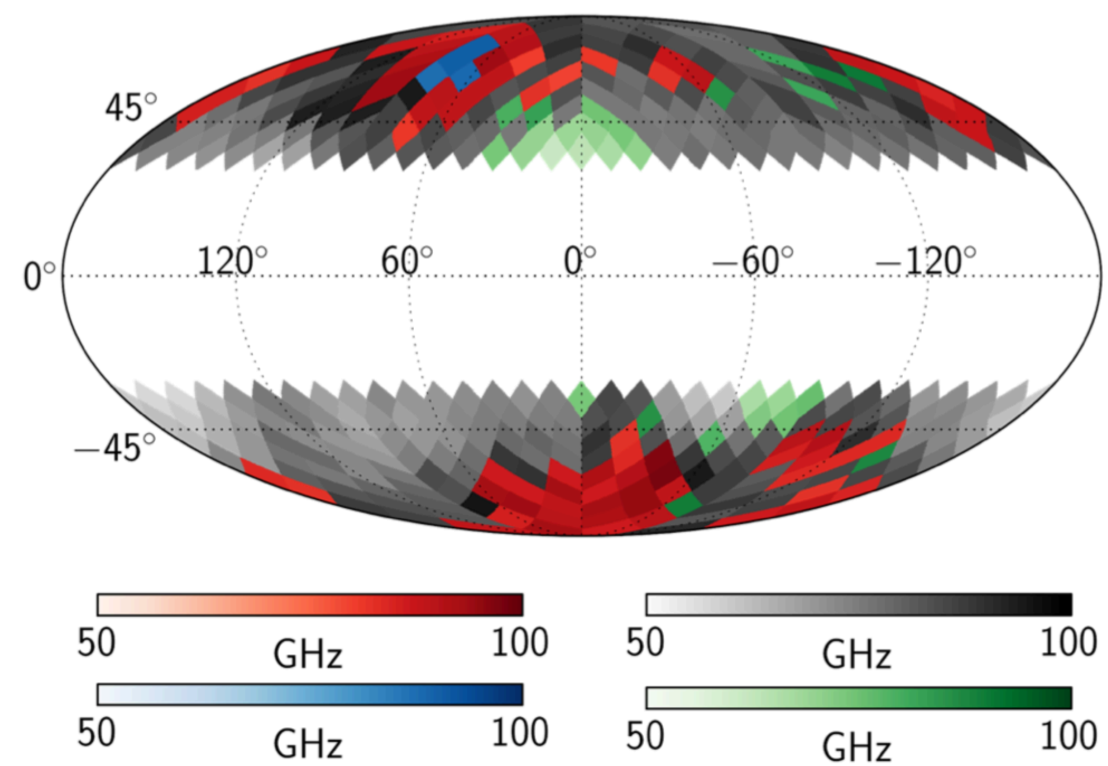
Foregrounds cleaning, option #1 : avoid them?

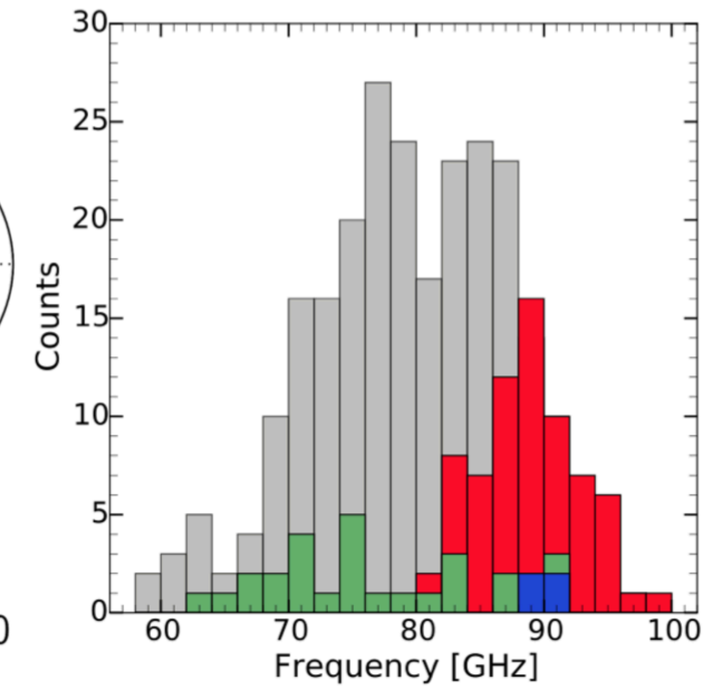
Characterization of foreground emission at degree angular scale for CMB B-modes observations
N. Krachmalnicoff, C. Baccigalupi et al (2016)

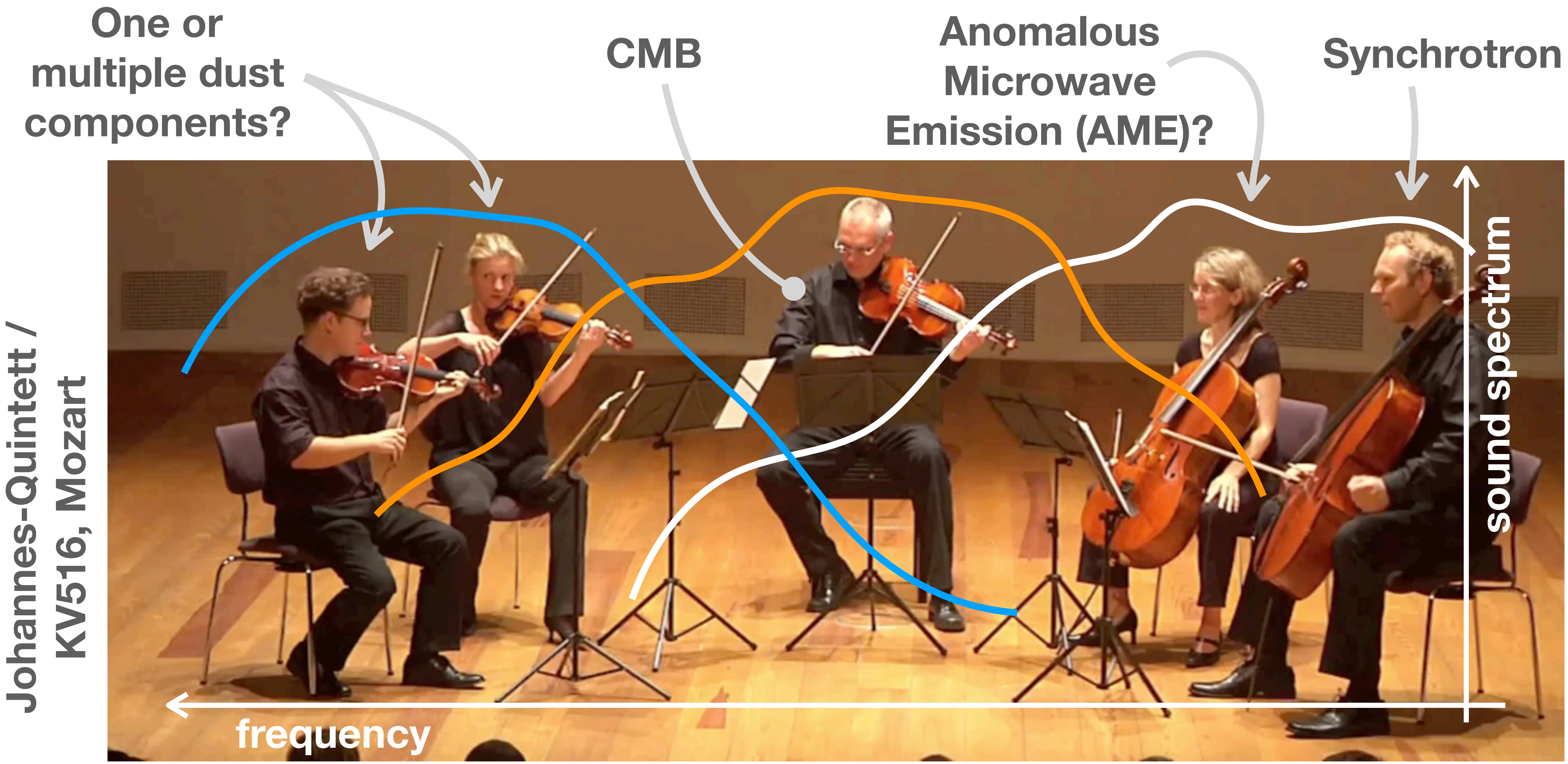


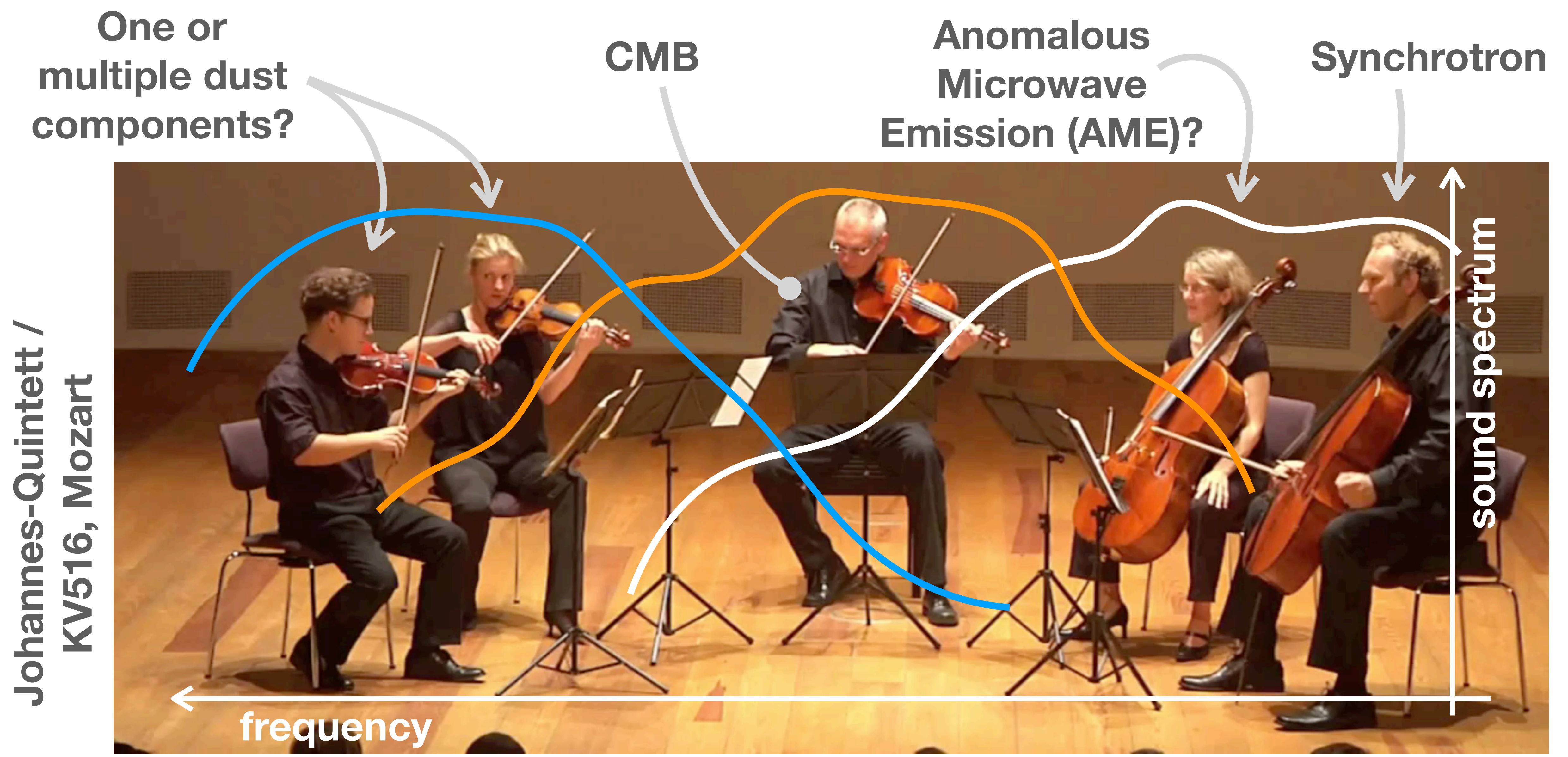


+ Polarized galactic synchrotron and dust emission and their correlation
S. K. Choi, L. A. Page (2015)






One or multiple dust components?
CMB
Anomalous Microwave Emission (AME)?
Synchrotron
Johannes-Quintett / KV516, Mozart
sound spectrum
frequency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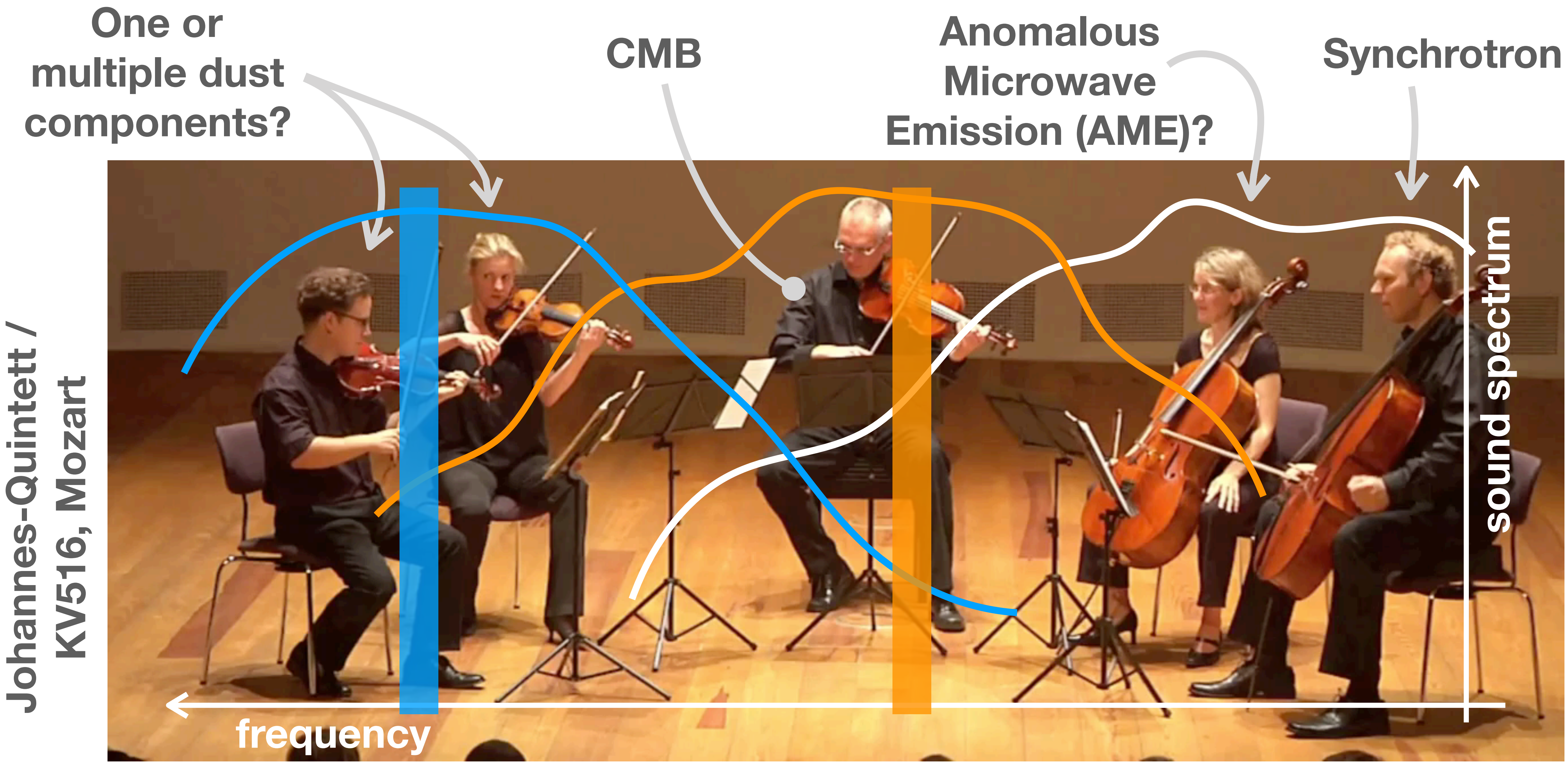
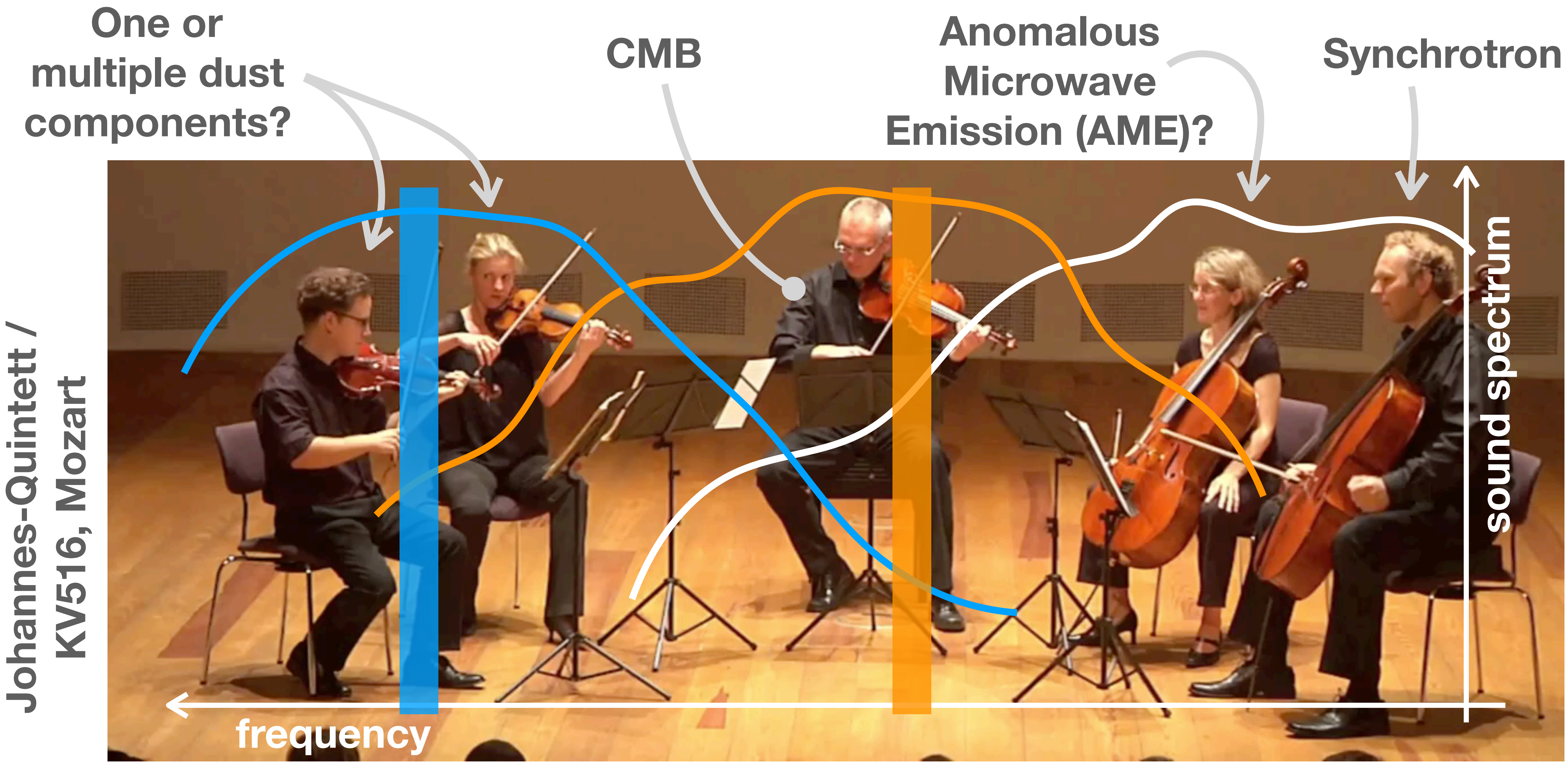


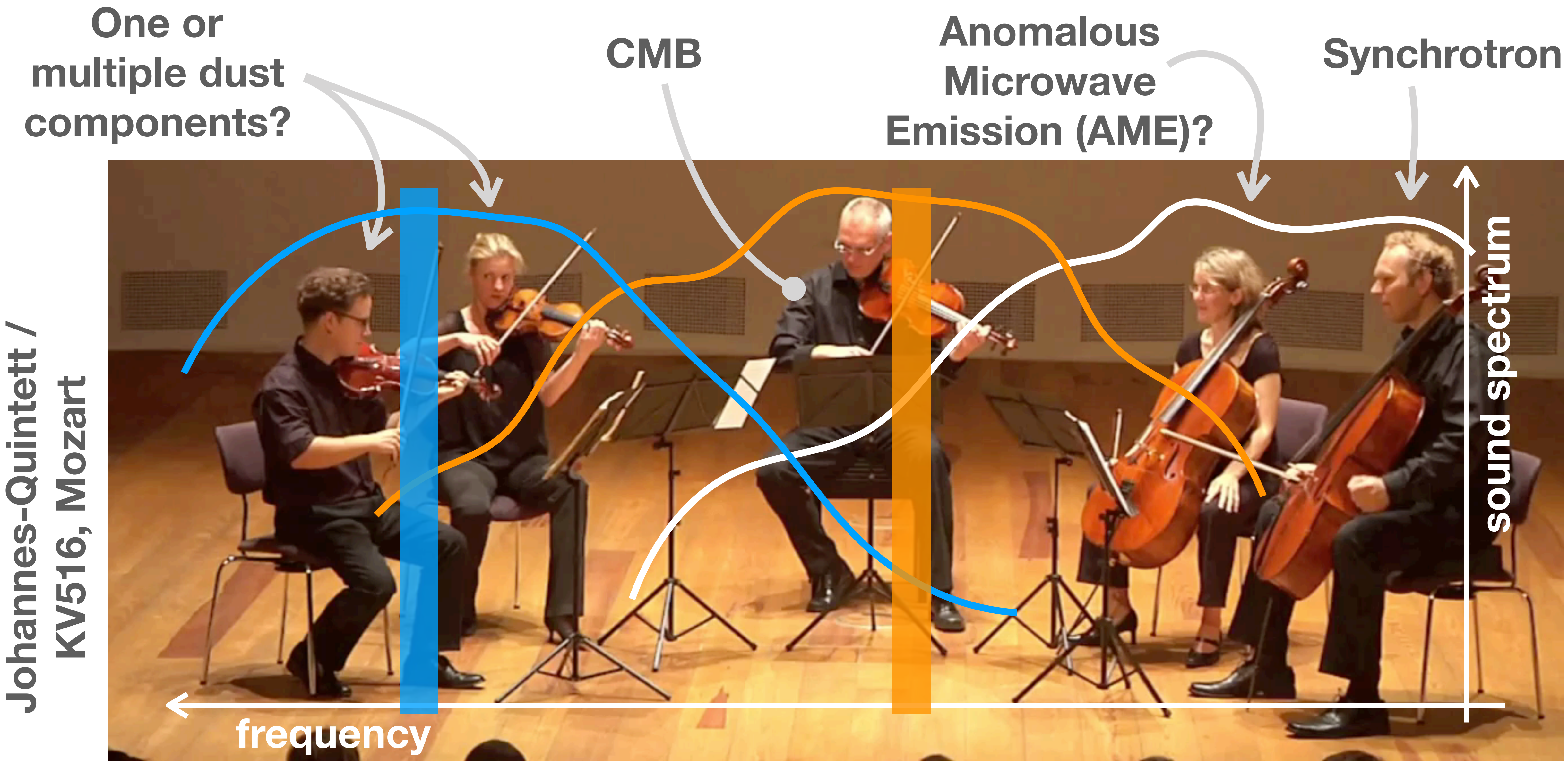
$$d_{\nu_0} = a_0\,\mathrm{CMB} + b_0\,\mathrm{dust} + n_{\nu_0}$$

$$d_{\nu_1} = a_1\,\mathrm{CMB} + b_1\,\mathrm{dust} + n_{\nu_1}$$



$$d_{\nu_0} = a_0\,\mathrm{CMB} + b_0\,\mathrm{dust} + n_{\nu_0}$$
$$d_{\nu_1} = a_1\,\mathrm{CMB} + b_1\,\mathrm{dust} + n_{\nu_1}$$

$$\longrightarrow\; d_{\nu_0} b_1 - d_{\nu_1} b_0 = CMB\,(b_1 a_0 - b_0 a_1) + n_{\nu_0} b_1 - n_{\nu_1} b_0$$



$$d_{\nu_0} = a_0\,\mathrm{CMB} + b_0\,\mathrm{dust} + n_{\nu_0}$$
$$d_{\nu_1} = a_1\,\mathrm{CMB} + b_1\,\mathrm{dust} + n_{\nu_1}$$
$$\longrightarrow \quad d_{\nu_0} b_1 - d_{\nu_1} b_0 = CMB\,(b_1 a_0 - b_0 a_1) + n_{\nu_0} b_1 - n_{\nu_1} b_0$$

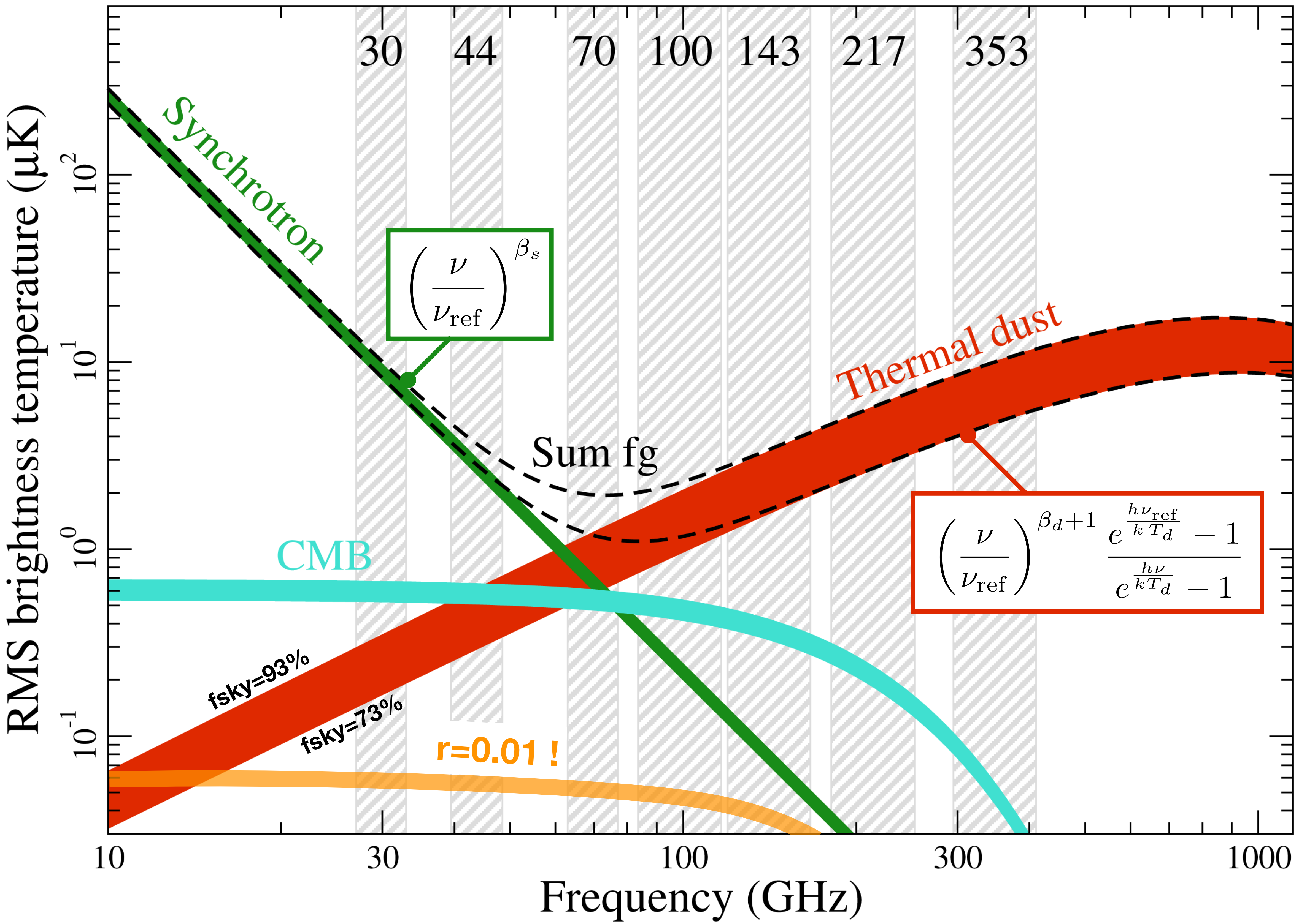
boosted variance in recovered CMB

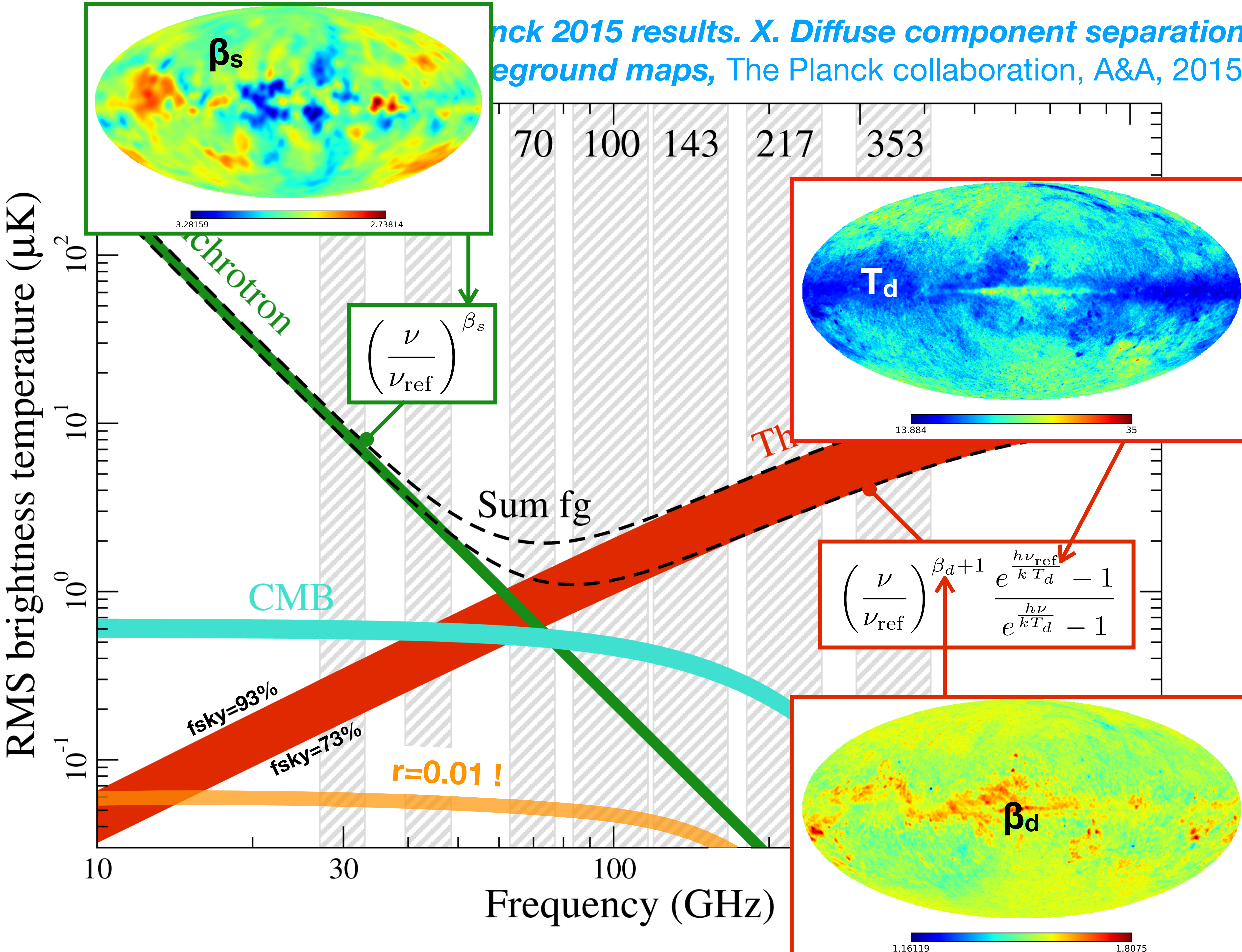
$$\sigma^2_{\mathrm{CMB}} = \frac{\sigma^2_{\nu_0} b_1^2 + \sigma^2_{\nu_1} b_0^2}{(b_1 a_0 - b_0 a_1)^2}$$

statistical/systematic residuals in the cleaned signal

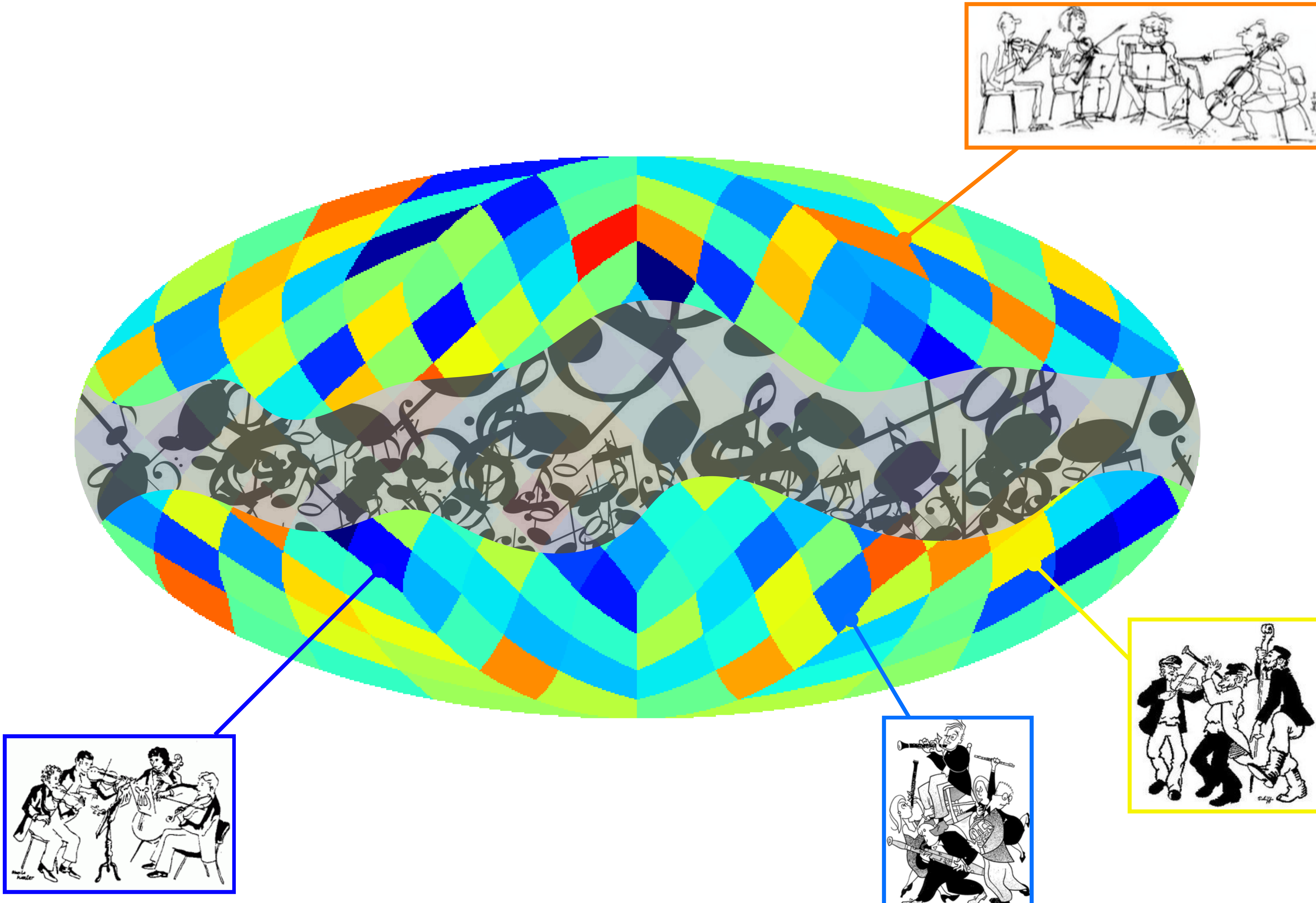
$$\delta\mathrm{CMB} \propto \delta b_1\,(\alpha\, d_{\nu_0} + \beta\, d_{\nu_1})$$

Planck 2015 results. X. Diffuse component separation: Foreground maps, The Planck collaboration, A&A, 2015

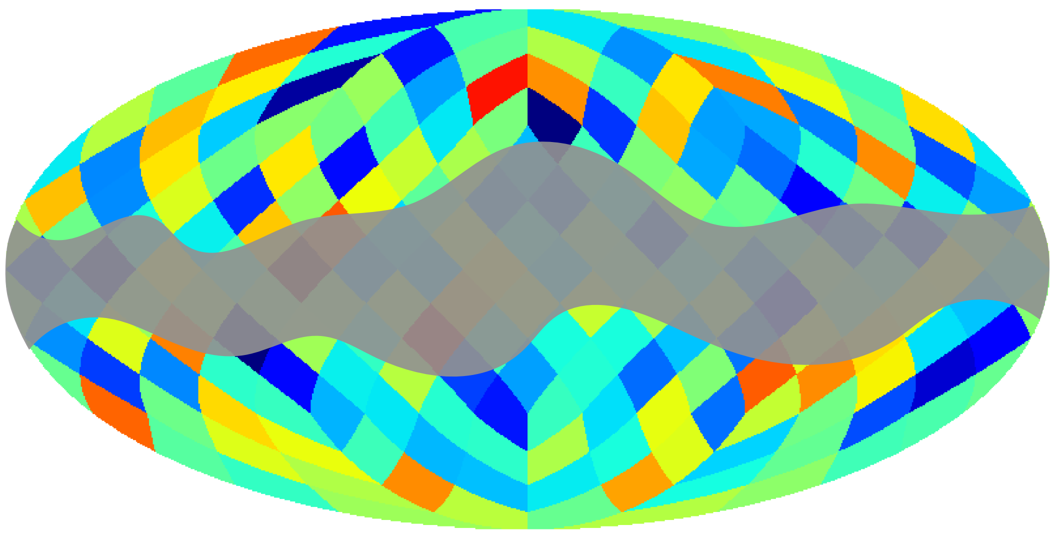




nck 2015 results. X. Diffuse component separation:
eground maps, The Planck collaboration, A&A, 2015
βs
-3.28159
-2.73814
70
100
143
217
353
chrotron
$\left(\frac{\nu}{\nu_{\rm ref}}\right)^{\beta_s}$
Sum fg
CMB
Th
Td
13.884
35
$\left(\frac{\nu}{\nu_{\rm ref}}\right)^{\beta_d+1} \frac{e^{\frac{h\nu_{\rm ref}}{k\,T_d}}-1}{e^{\frac{h\nu}{kT_d}}-1}$
fsky=93%
fsky=73%
r=0.01 !
βd
1.16119
1.8075
RMS brightness temperature (μK)
10^2
10^1
10^0
10^{-1}
10
30
100
Frequency (GHz)

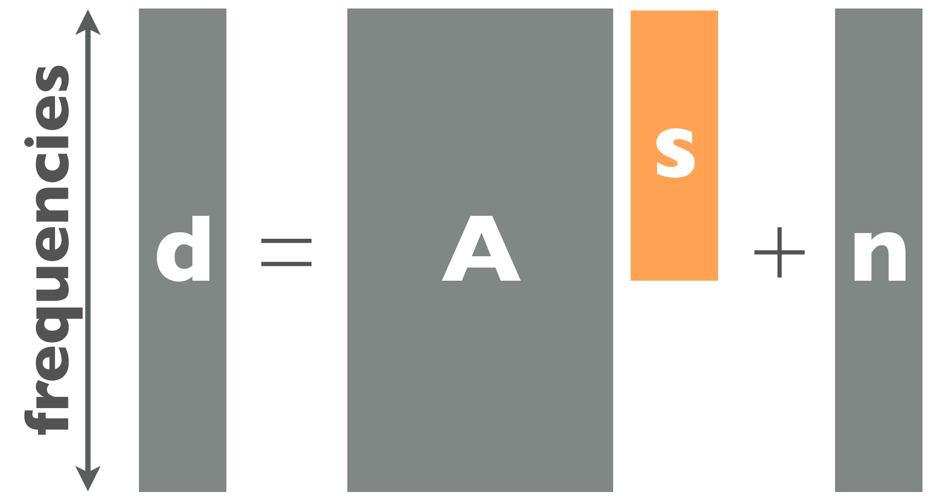


Rendition of parametric max-likelihood component separation



data modeling
for each sky pixel:

$$d_i(p) = A_{ij}\, s_j(p) + n_i(p)$$



see talk by Jean-Loup Puget this afternoon

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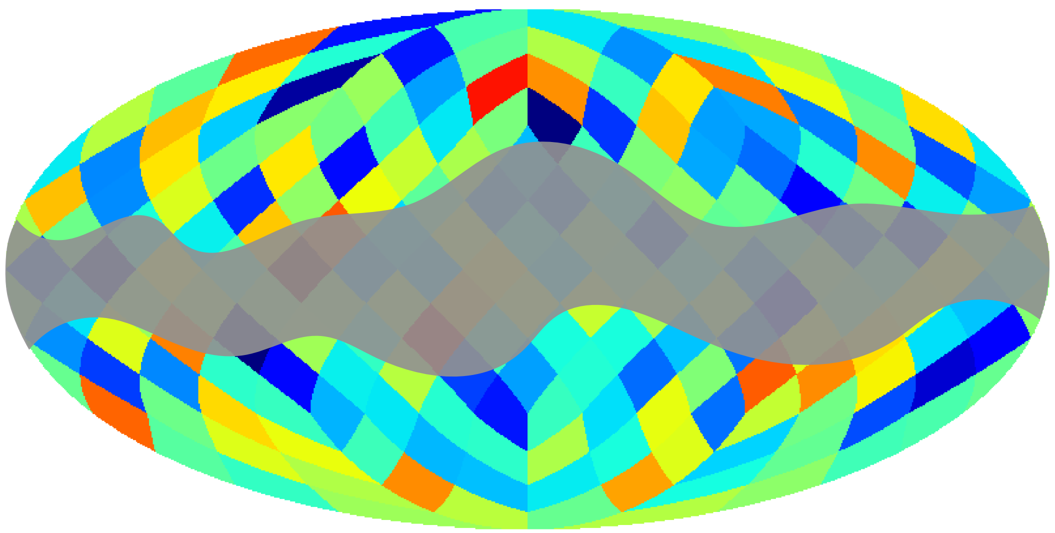

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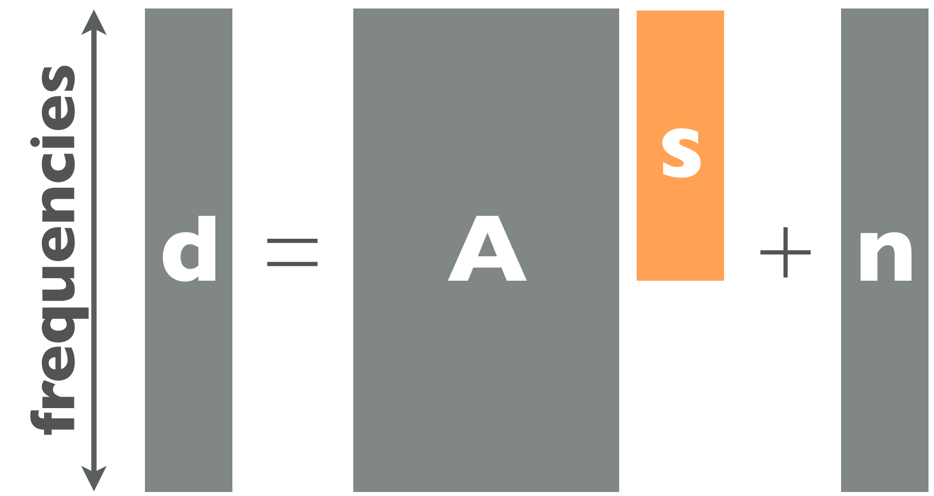

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1. estimation of the mixing matrix A

e.g. **Stompor et al. (2009)**

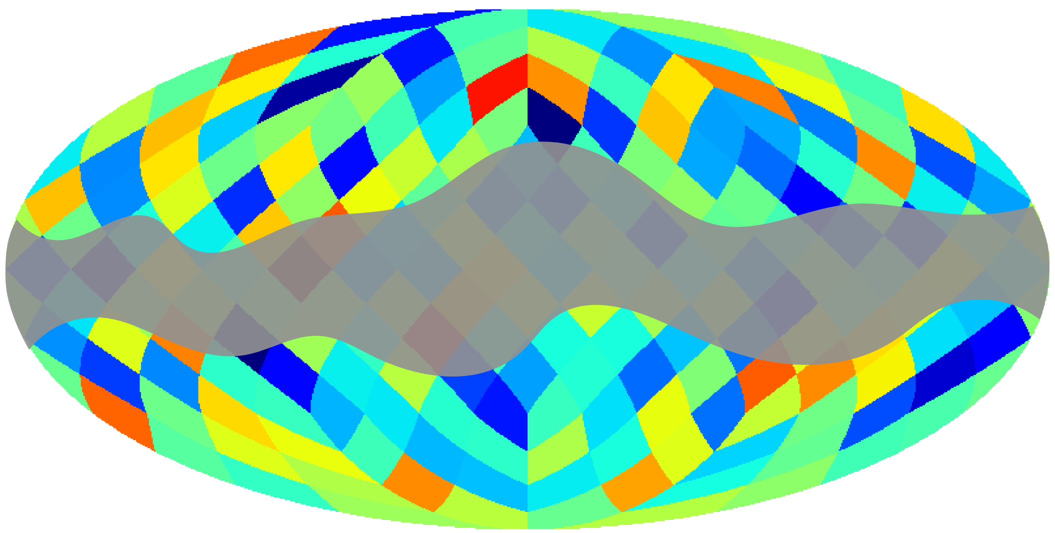
$$A^{\mathrm{raw}}_{\mathrm{sync}}(\nu, \nu_{\mathrm{ref}}) \equiv \left(\frac{\nu}{\nu_{\mathrm{ref}}}\right)^{\beta_s}$$

$$A^{\mathrm{raw}}_{\mathrm{dust}}(\nu, \nu_{\mathrm{ref}}) \equiv \left(\frac{\nu}{\nu_{\mathrm{ref}}}\right)^{\beta_d+1} \frac{e^{\frac{h\nu_{\mathrm{ref}}}{k\,T_d}} - 1}{e^{\frac{h\nu}{kT_d}} - 1}$$

$$\mathbf{A} \equiv \mathbf{A}(\beta = \beta_d, \beta_s, \ldots) \longrightarrow \max\left(\mathcal{L}(\beta)\right)$$

not perfect recovery of input spectral parameters ➤ foregrounds residuals

Rendition of parametric max-likelihood component separation



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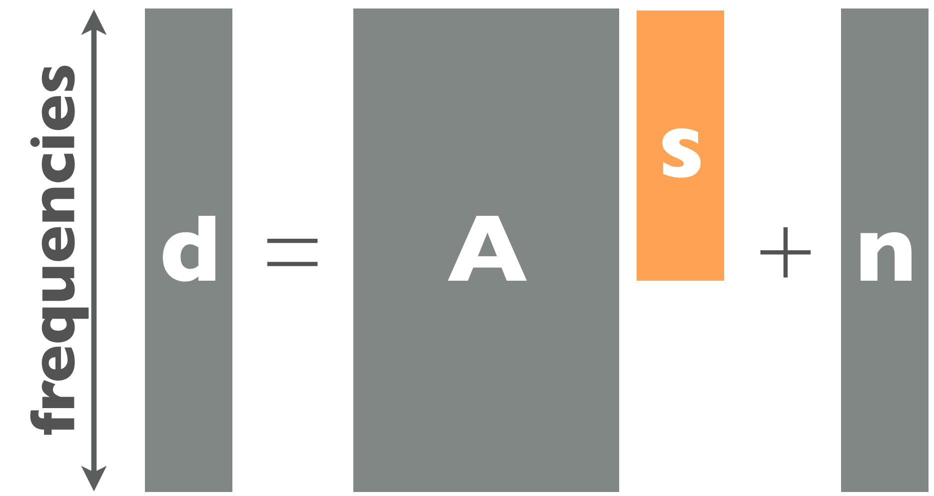

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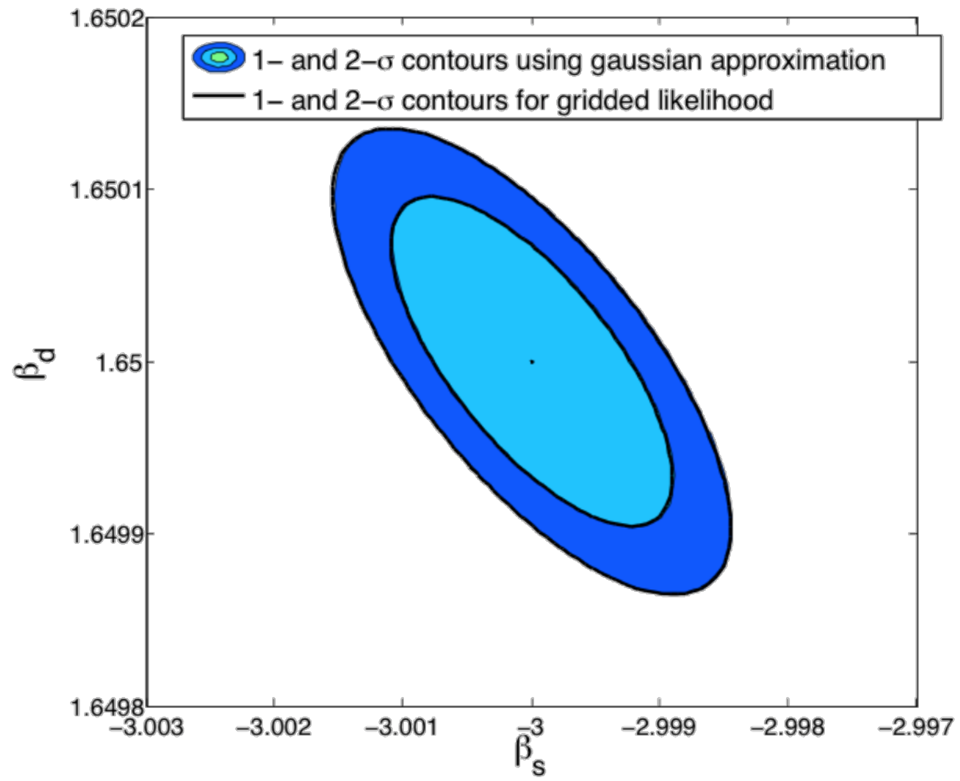
not perfect recovery of input spectral parameters ➤ foregrounds residuals

2. solve for s [rather general to any comp sep method]

$$\mathbf{s} = \left(\mathbf{A}^T\mathbf{N}^{-1}\mathbf{A}\right)^{-1}\mathbf{A}^T\mathbf{N}^{-1}\mathbf{d}$$

linear combination of various frequency maps ➤ boosted noise

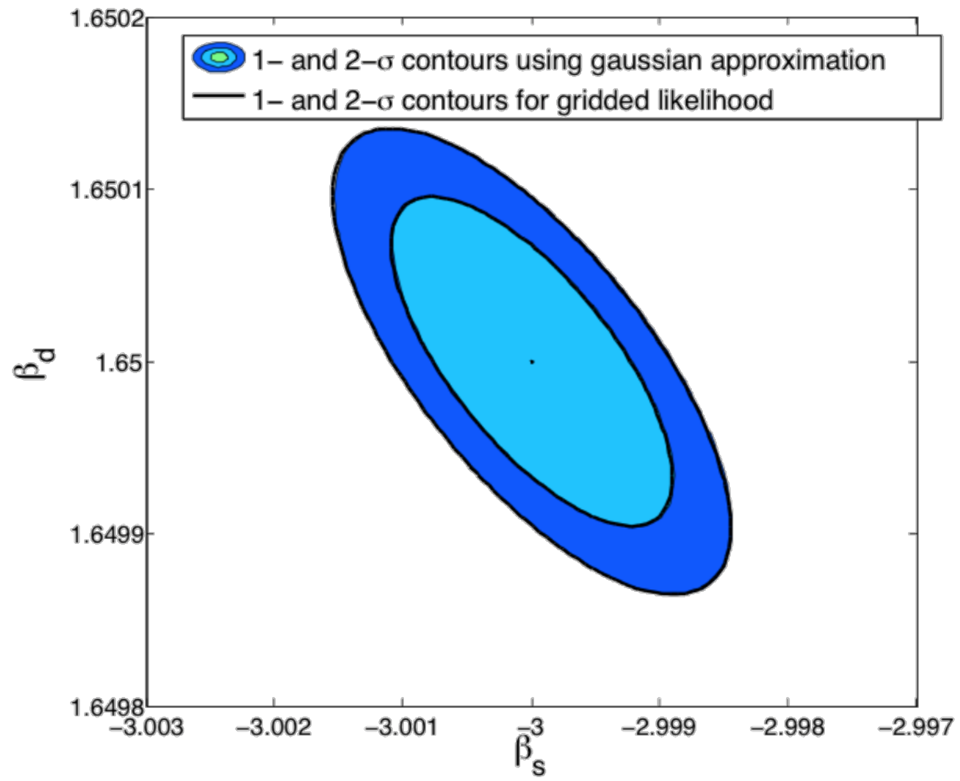
Statistical error bars on spectral parameters:



Errard, Stivoli and Stompor (PRD, 2011)

$$\mathbf{\Sigma}^{-1} \simeq \quad - \left\langle \frac{\partial^2 \mathcal{L}}{\partial\beta\partial\beta'} \right\rangle_{\rm noise} \Big|_{\rm true\ \beta}$$

Statistical error bars on spectral parameters:



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→ averaged error bars for parametric methods like COMMANDER

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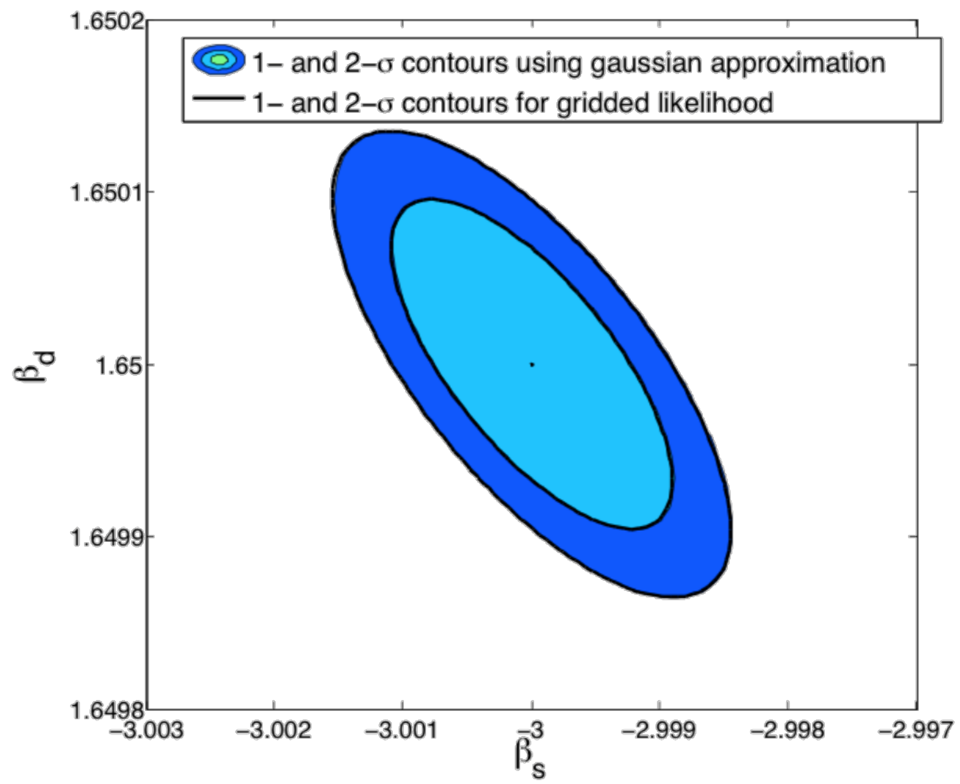

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$$\mathbf{\Sigma}^{-1} \simeq \quad -\left\langle \frac{\partial^2 \mathcal{L}}{\partial\beta\partial\beta'} \right\rangle_{\rm noise} \Bigg|_{\rm true\ \beta}$$

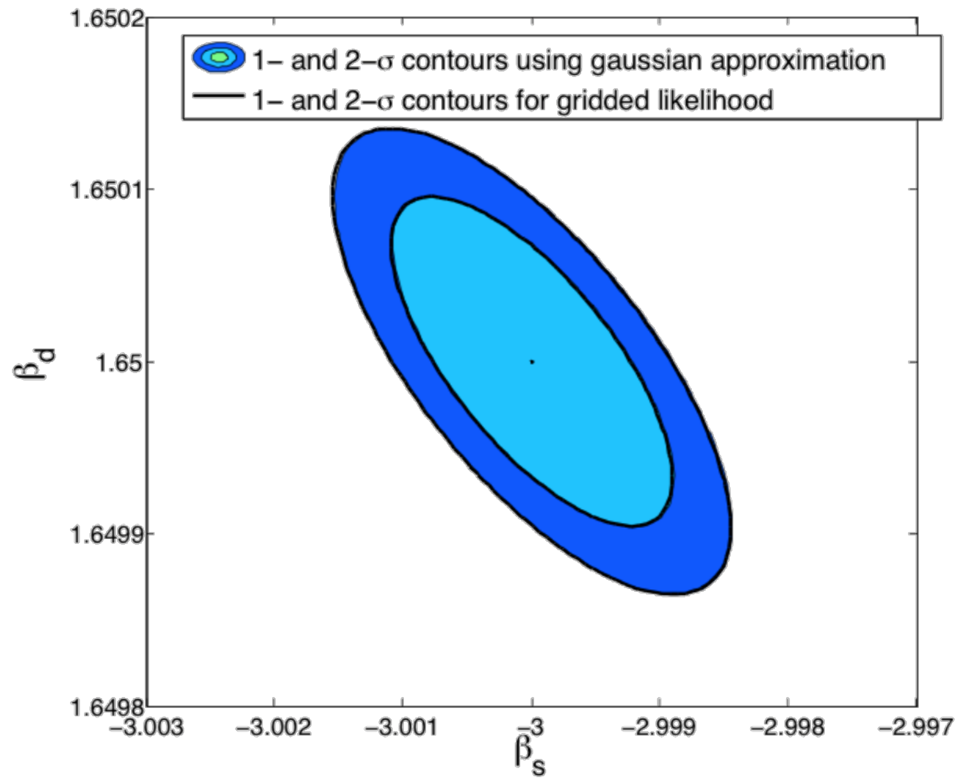
→ **averaged error bars for parametric methods like COMMANDER**

Amplitude of statistical foregrounds residuals:

$$C_\ell^{\rm fg\ res} \equiv \sum_{k,k'} \sum_{j,j'} \Sigma_{kk'}\, \kappa_{kk'}^{jj'} C_\ell^{jj'}$$

Stivoli, Grain, Leach, Tristram, Baccigalupi, Stompor (MNRAS, 2010)

Statistical error bars on spectral parameters:



Errard, Stivoli and Stompor (PRD, 2011)

$$\boldsymbol{\Sigma}^{-1} \simeq - \left\langle \frac{\partial^2 \mathcal{L}}{\partial \beta \partial \beta'} \right\rangle_{\rm noise} \bigg|_{\rm true\ \beta}$$

➔ averaged error bars for parametric methods like COMMANDER

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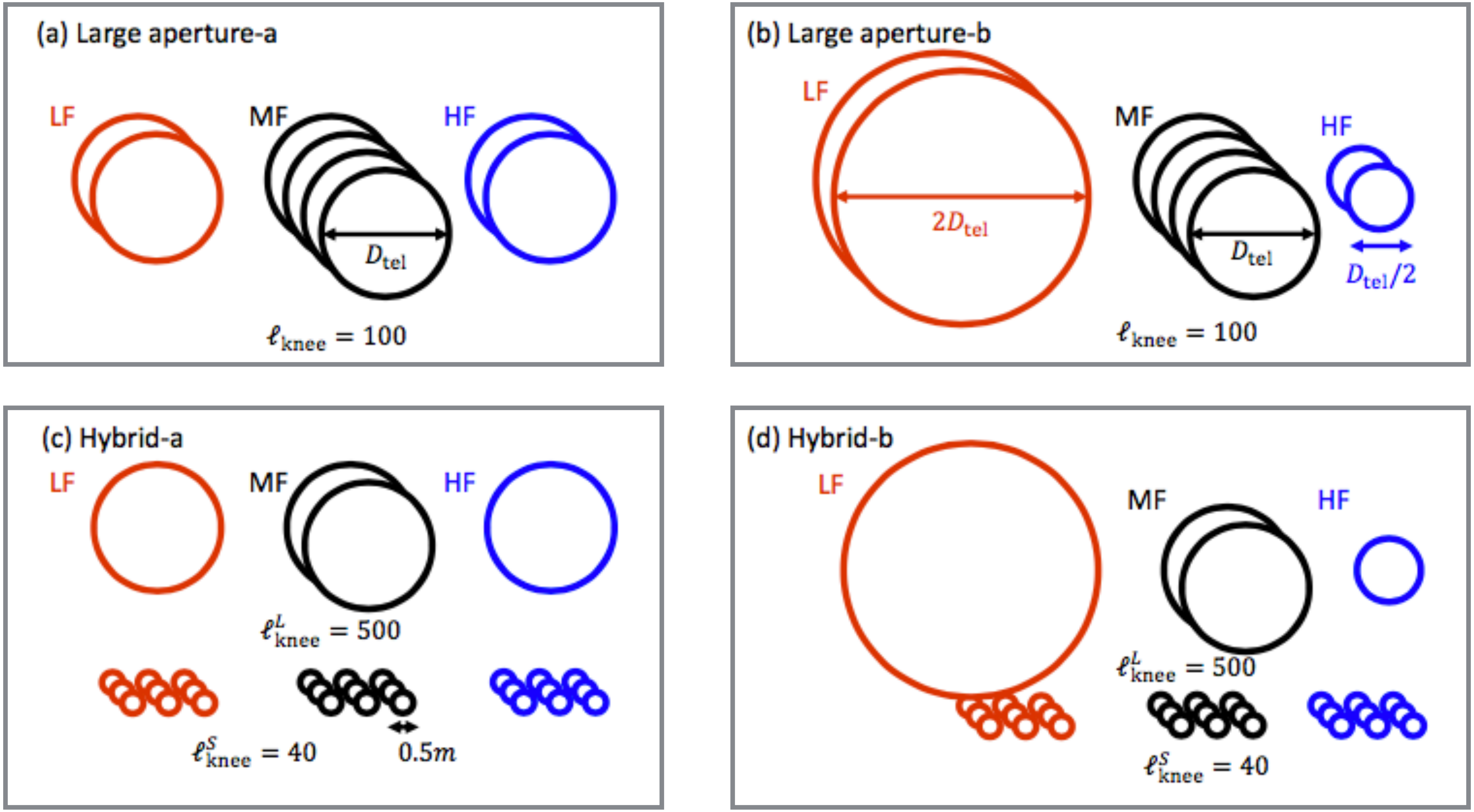
Stivoli, Grain, Leach, Tristram, Baccigalupi, Stompor (MNRAS, 2010)

Combination with delensing and cosmological parameters estimation:

CMB4CAST GROUNDS

JE, Feeney, Peiris and Jaffe (JCAP, 2016)

Optimization Study for the Experimental Configuration of CMB-S4
D. Barron et al., arXiv:1702.07467



Optimization Study for the Experimental Configuration of CMB-S4

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CMB4CAST GROUNDS

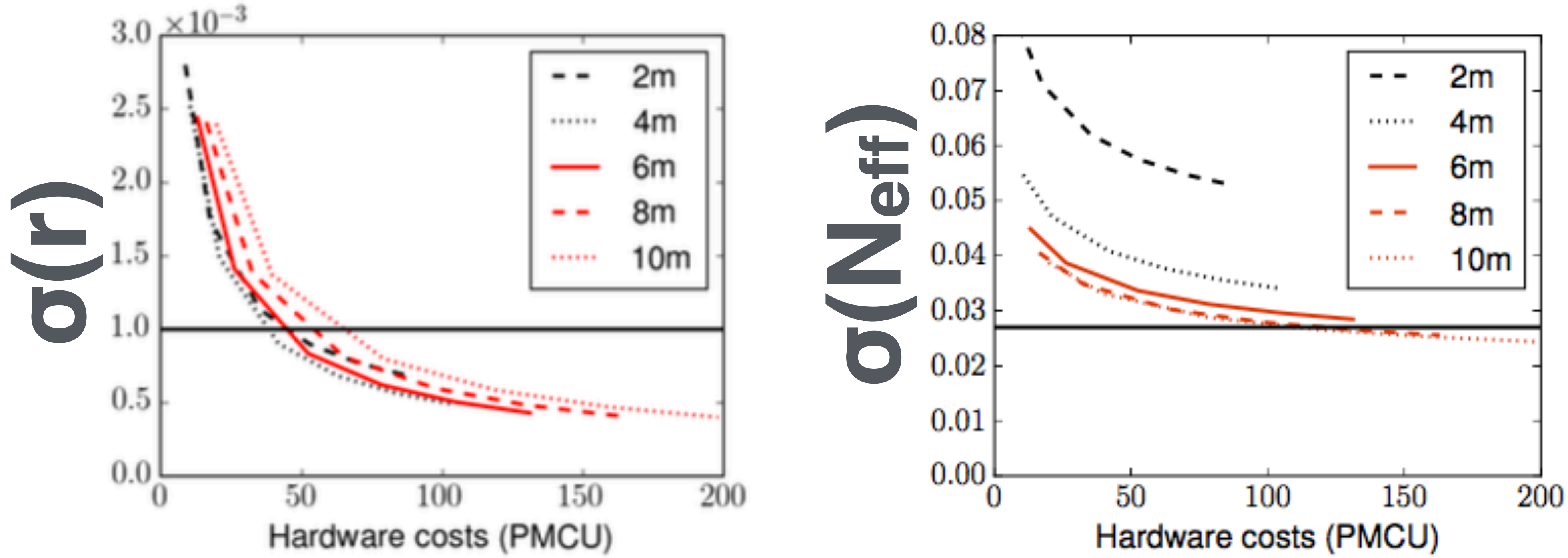
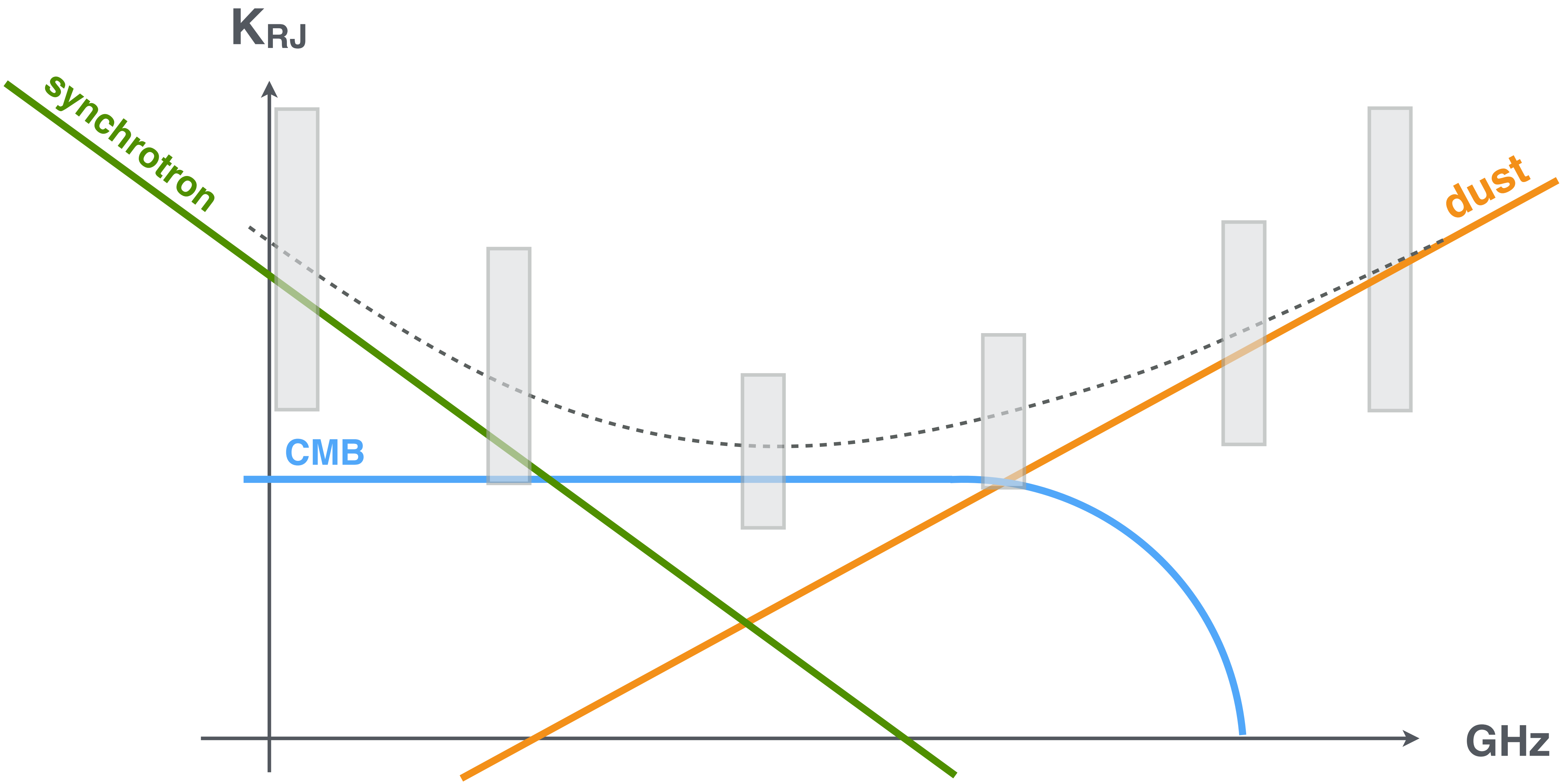


Figure 12 Constraint on r with $f_{\rm sky} = 0.05$ (left) and $N_{\rm eff}$ with $f_{\rm sky} = 0.5$ (right) for different apertures, as a function of the total cost of the project. Both are for the large aperture telescope array with fixed aperture sizes (*Large aperture-a*). For both, the improvement saturates approximately at a total hardware cost of 50 PCU. The improvement of r is not linear with the total cost, or with the total number of detectors, because the de-lensing noise levels do not improve as fast as the map depth.

- Framework to optimize overall instrumental configurations
- Connection of science and instrumental configurations
- Optimum is broad, and aperture size of 4-6m is a good number.
- Iteration over the model needed.
    - ⋆ What's expensive? Which part of the costing has large uncertainty?
    - ⋆ Which part of the instrumental configuration requires more thoughts? (e.g., LF instruments)
- Foreground complication to be included, e.g. polarized AME, synchrotron curvature, etc.

CMB4CAST GROUNDS

JE, Feeney, Peiris and Jaffe (JCAP, 2016)



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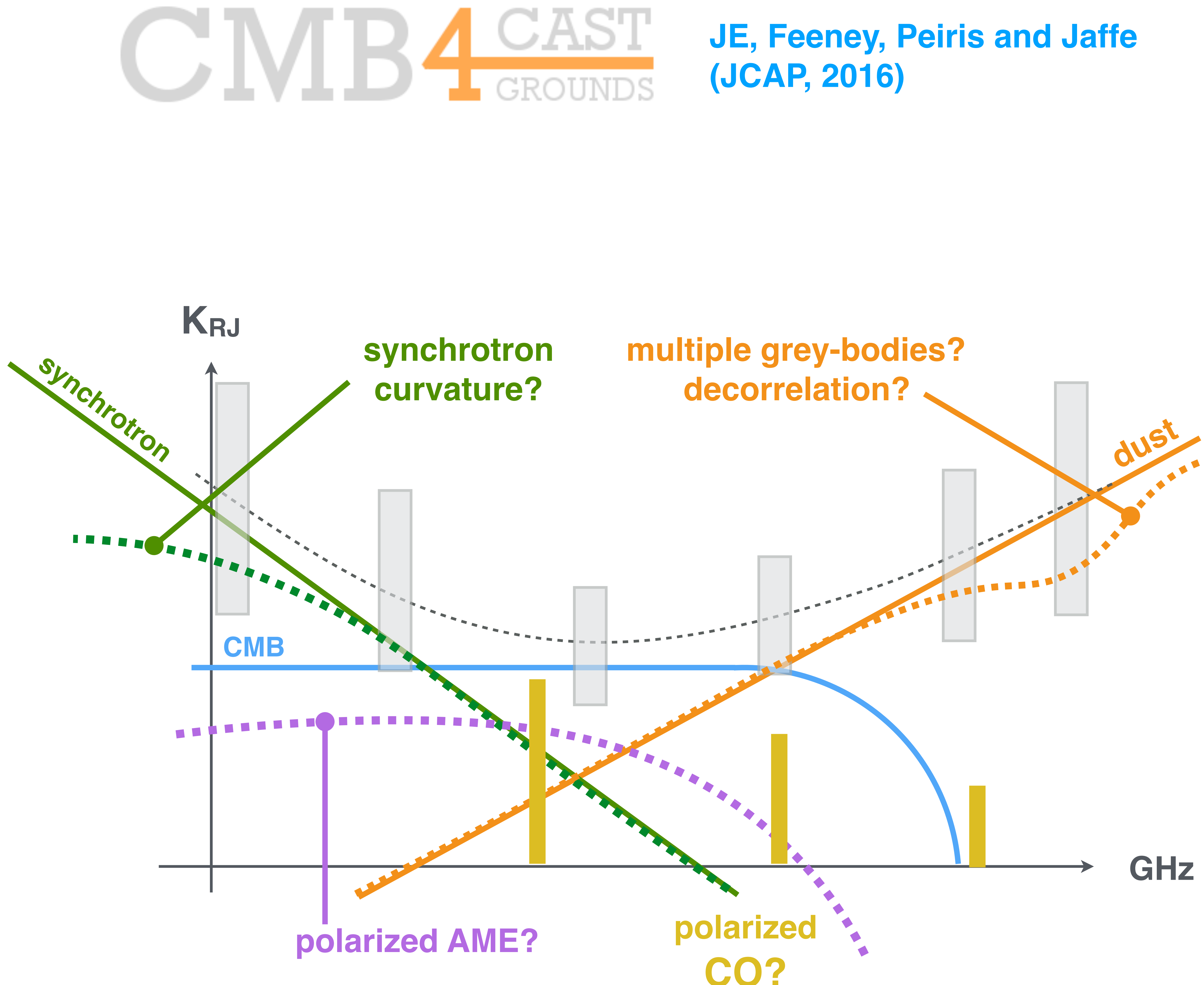
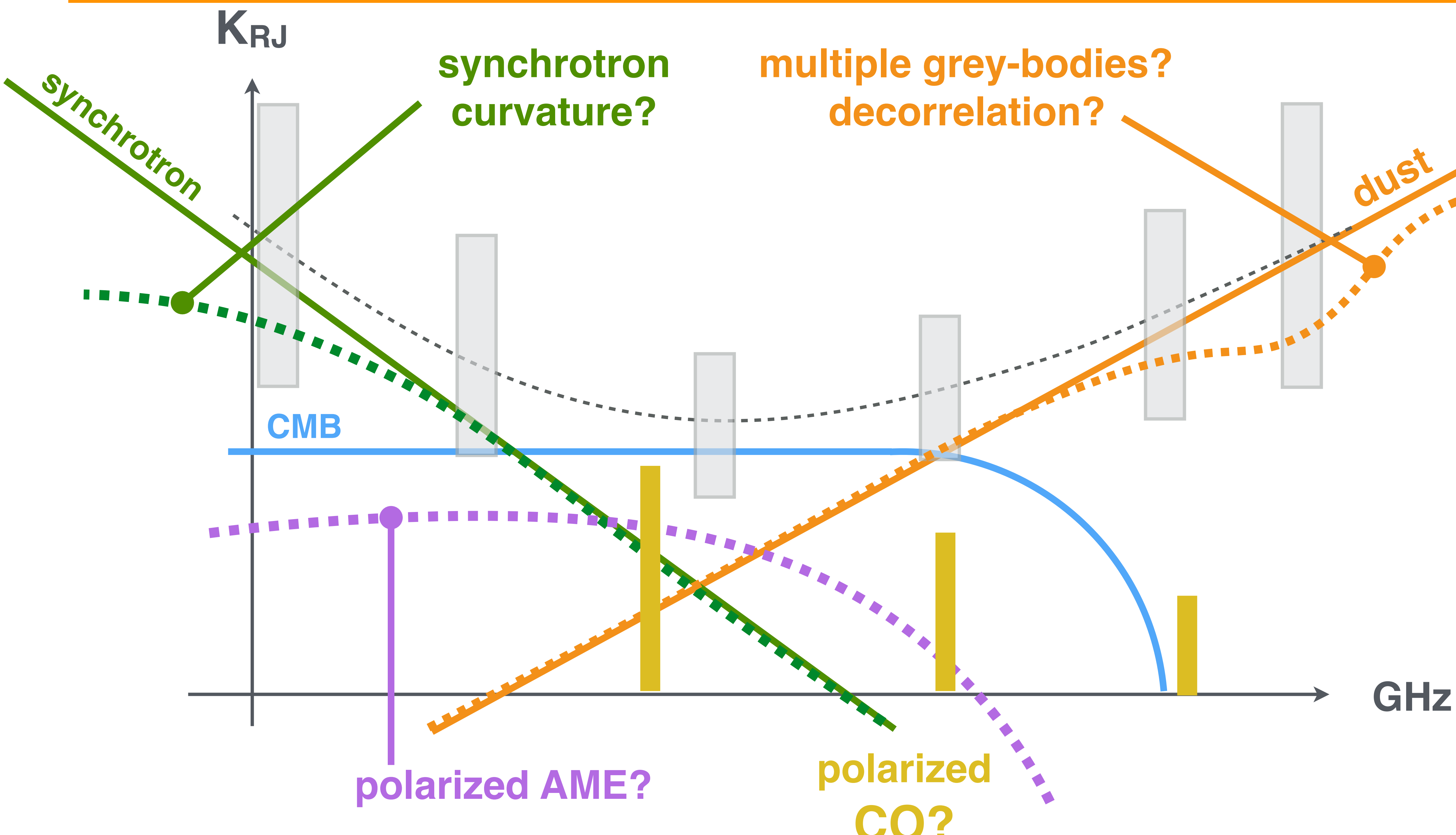


CMB4 CAST GROUNDS

JE, Feeney, Peiris and Jaffe (JCAP, 2016)

xForecast Stompor, JE, Poletti (PRL, 2016)



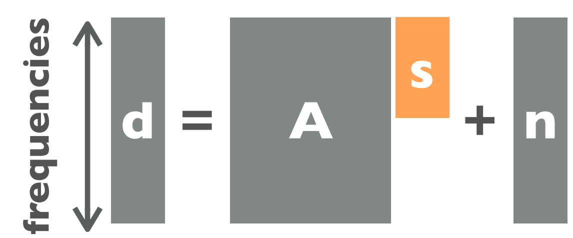
xForecast

simulation of observation with CMB + foregrounds (+systematics)

instrument design (frequencies, sensitivities, FWHM, etc.)

spectral analysis using simple scaling laws (e.g. power-law synchrotron and gray body dust)

$$\mathbf{d}_p = \hat{\mathbf{A}}_p \, \hat{\mathbf{s}}_p + \mathbf{n}_p$$



$$\langle \mathcal{S}_{spec} \rangle = -\mathrm{tr} \sum_p \left\{ (\mathbf{N}_p^{-1} - \mathbf{P}_p) \left(\hat{\mathbf{d}}_p \hat{\mathbf{d}}_p^t + \mathbf{N}_p \right) \right\}$$

estimation of statistical and systematic foregrounds residuals

$$C_\ell^{\mathrm{res}} \simeq \otimes_\ell(\tilde{\mathbf{y}}, \tilde{\mathbf{y}}) + \otimes_\ell(\tilde{\mathbf{y}}, \tilde{\mathbf{z}}) + \otimes_\ell(\tilde{\mathbf{z}}, \tilde{\mathbf{y}}) + \mathrm{tr}\left[\mathbf{\Sigma} \otimes_\ell(\tilde{\mathbf{Y}}^{(1)}, \tilde{\mathbf{Y}}^{(1)}) \right]$$

propagation of these to the estimation of tensor-to-scalar ratio *r*

$$\langle \mathcal{S}^{par} \rangle = \mathrm{tr}\, \mathbf{C}^{-1} \mathbf{E} + \ln \det \mathbf{C}$$

R. Stompor, JE and D. Poletti (PRD 2016, 1609.03807)

xForecast

simulation of observation with CMB + foregrounds (+systematics)

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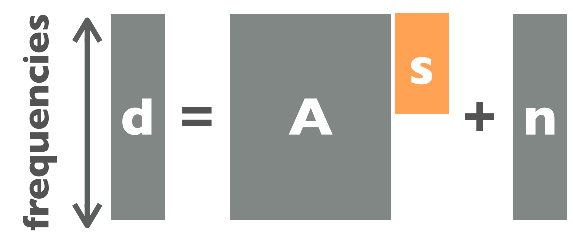

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optimization under technical/ hardware constraints

R. Stompor, JE and D. Poletti (PRD 2016, 1609.03807)

xForecast

simulation of observation with CMB + foregrounds (+systematics)

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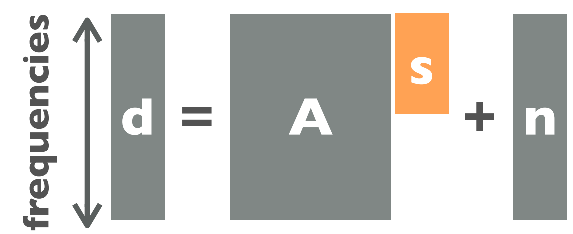


$$\langle \mathcal{S}_{spec}\rangle = -\mathrm{tr}\sum_p \left\{(\mathbf{N}_p^{-1} - \mathbf{P}_p)\left(\hat{\mathbf{d}}_p\hat{\mathbf{d}}_p^t + \mathbf{N}_p\right)\right\}$$

estimation of statistical and systematic foregrounds residuals

$$C_\ell^{\rm res} \simeq \otimes_\ell(\tilde{\mathbf{y}},\tilde{\mathbf{y}}) + \otimes_\ell(\tilde{\mathbf{y}},\tilde{\mathbf{z}}) + \otimes_\ell(\tilde{\mathbf{z}},\tilde{\mathbf{y}}) + \mathrm{tr}\left[\mathbf{\Sigma}\otimes_\ell(\tilde{\mathbf{Y}}^{(1)},\tilde{\mathbf{Y}}^{(1)})\right]$$

iterative delensing

propagation of these to the estimation of tensor-to-scalar ratio *r*

$$\langle\mathcal{S}^{par}\rangle = \mathrm{tr}\,\mathbf{C}^{-1}\mathbf{E} + \ln\det\mathbf{C}$$

optimization under technical/ hardware constraints

R. Stompor, JE and D. Poletti (PRD 2016, 1609.03807)

xForecast

simul...

CMB (r=0) + PySM dust and synchrotron

(+ ...atics)

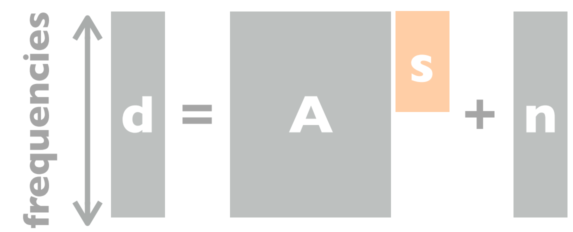
instrument design (freq..., ...ivities, FWHM, etc.)

toy designs

↓

spectral analysis using simple scaling laws (e.g. power-law synchrotron and gray body dust)

$$\mathbf{d}_p = \hat{\mathbf{A}}_p \, \hat{\mathbf{s}}_p + \mathbf{n}_p$$



$$\langle \mathcal{S}_{spec} \rangle = -\mathrm{tr} \sum_p \left\{ (\mathbf{N}_p^{-1} - \mathbf{P}_p) \left(\hat{\mathbf{d}}_p \hat{\mathbf{d}}_p^t + \mathbf{N}_p \right) \right\}$$

↓

estimation of statistical and systematic foregrounds residuals

$$C_\ell^{\mathrm{res}} \simeq \otimes_\ell(\tilde{\mathbf{y}}, \tilde{\mathbf{y}}) + \otimes_\ell(\tilde{\mathbf{y}}, \tilde{\mathbf{z}}) + \otimes_\ell(\tilde{\mathbf{z}}, \tilde{\mathbf{y}}) + \mathrm{tr}\left[\mathbf{\Sigma} \otimes_\ell(\tilde{\mathbf{Y}}^{(1)}, \tilde{\mathbf{Y}}^{(1)}) \right]$$

↓ — **iterative delensing**

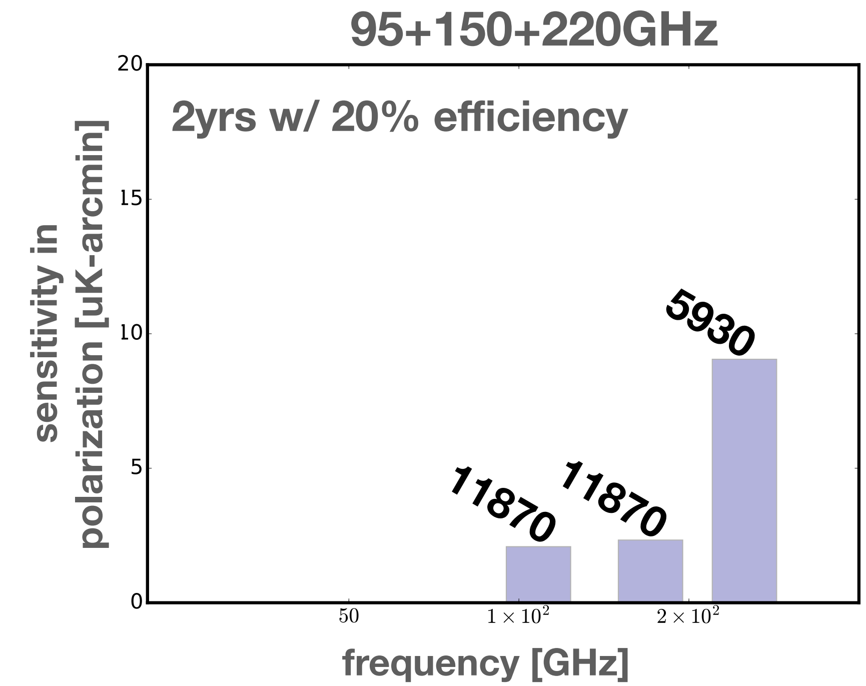
propagation of these to the estimation of tensor-to-scalar ratio *r*

$$\langle \mathcal{S}^{par} \rangle = \mathrm{tr}\, \mathbf{C}^{-1} \mathbf{E} + \ln \det \mathbf{C}$$

optimization under technical/ hardware constraints

toy example

- with priors from Planck on β, fit for single {βd,βs} only
- and few frequency bands from the ground
- on the cleanest fsky=5%



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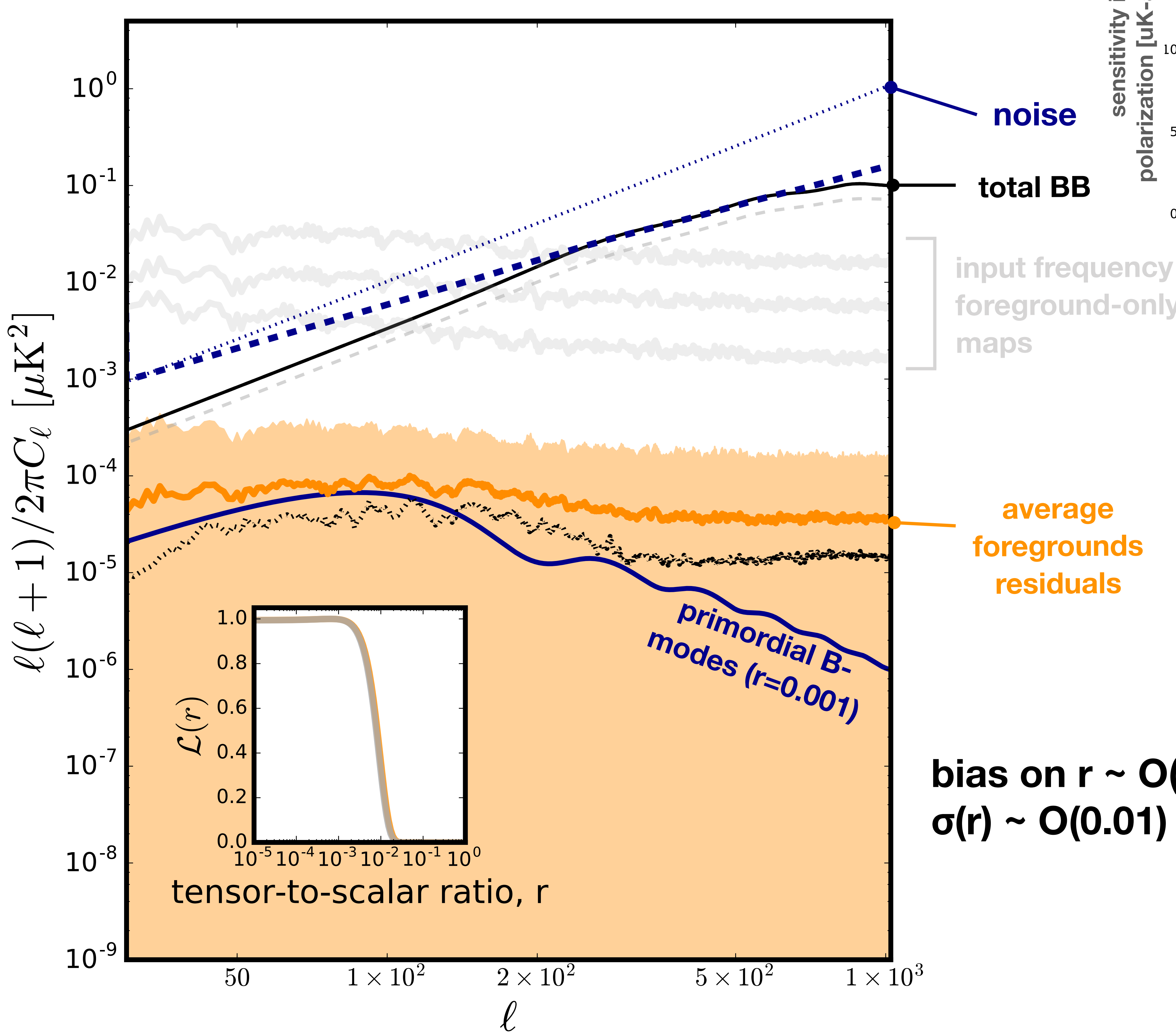

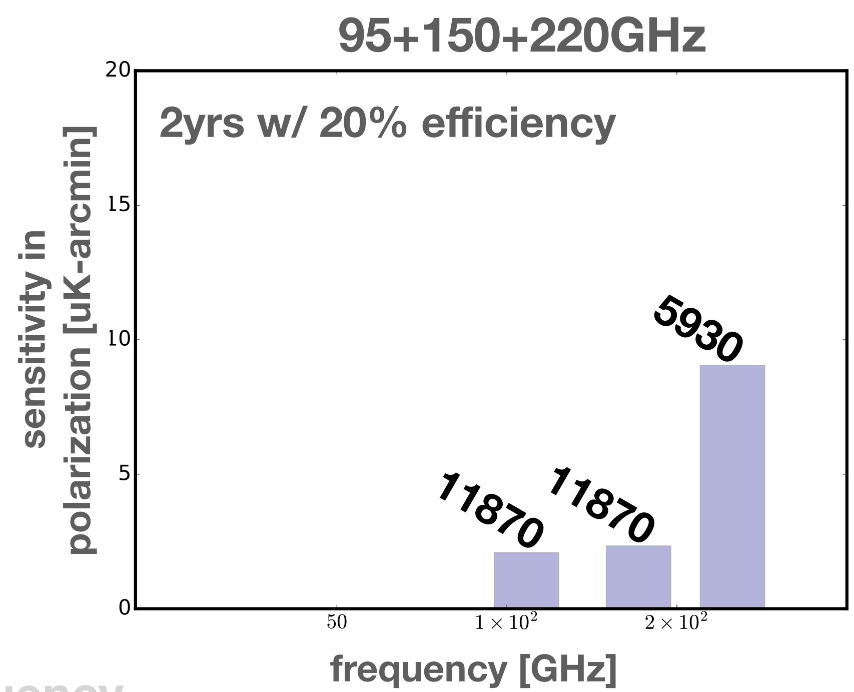

bias on r ~ O(0.001-0.01)
σ(r) ~ O(0.01)

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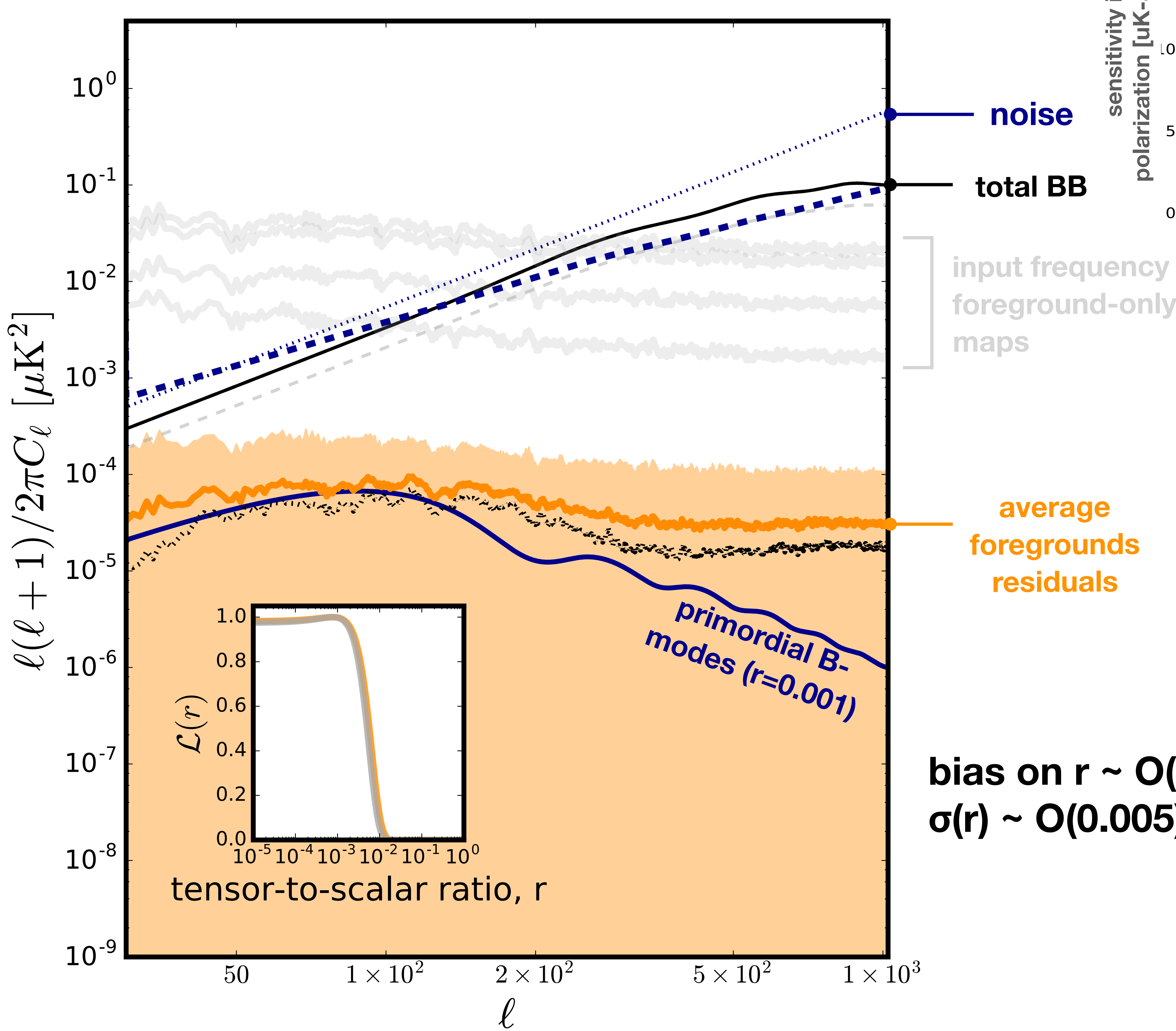
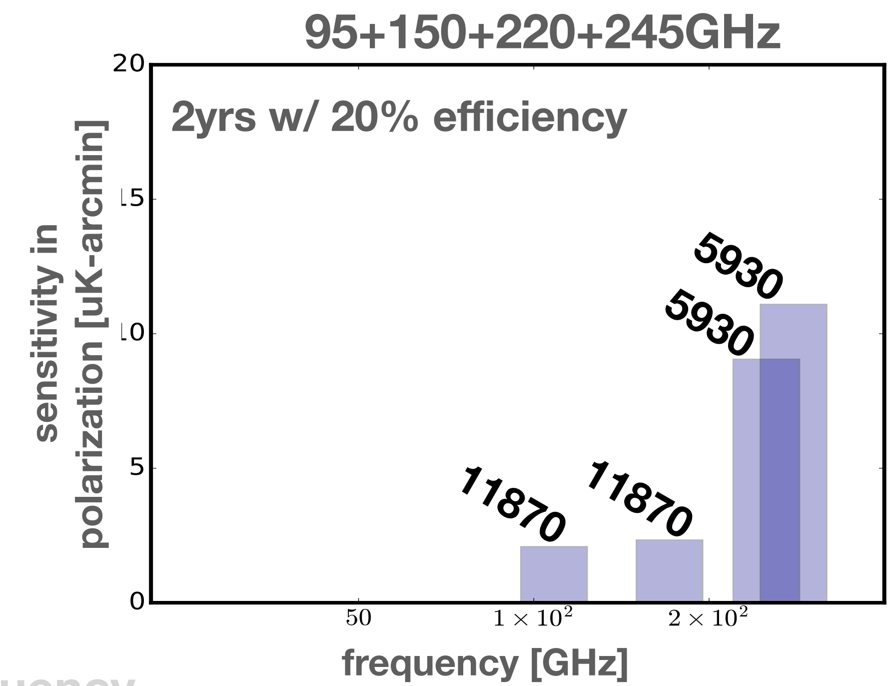
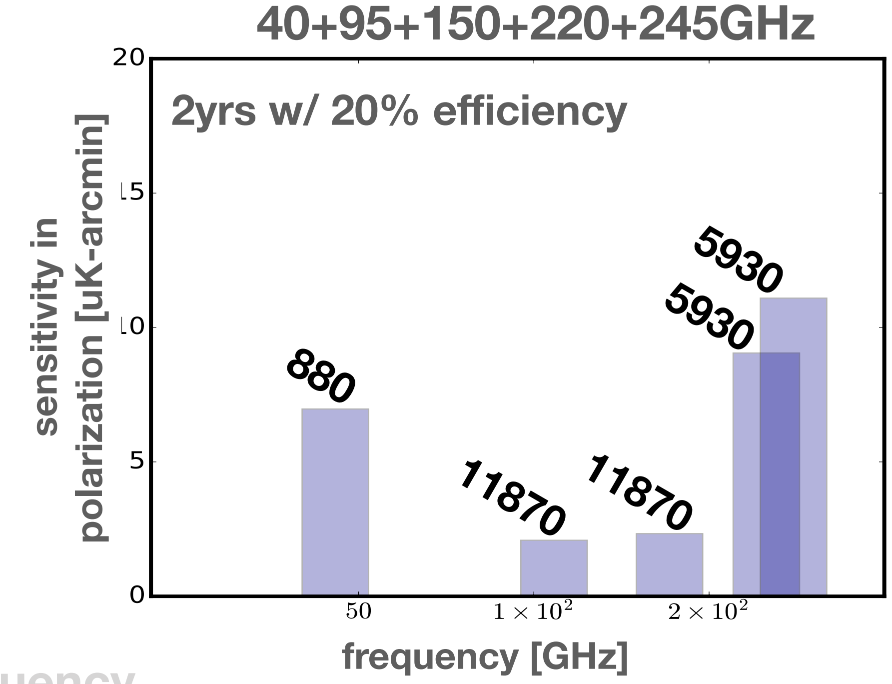


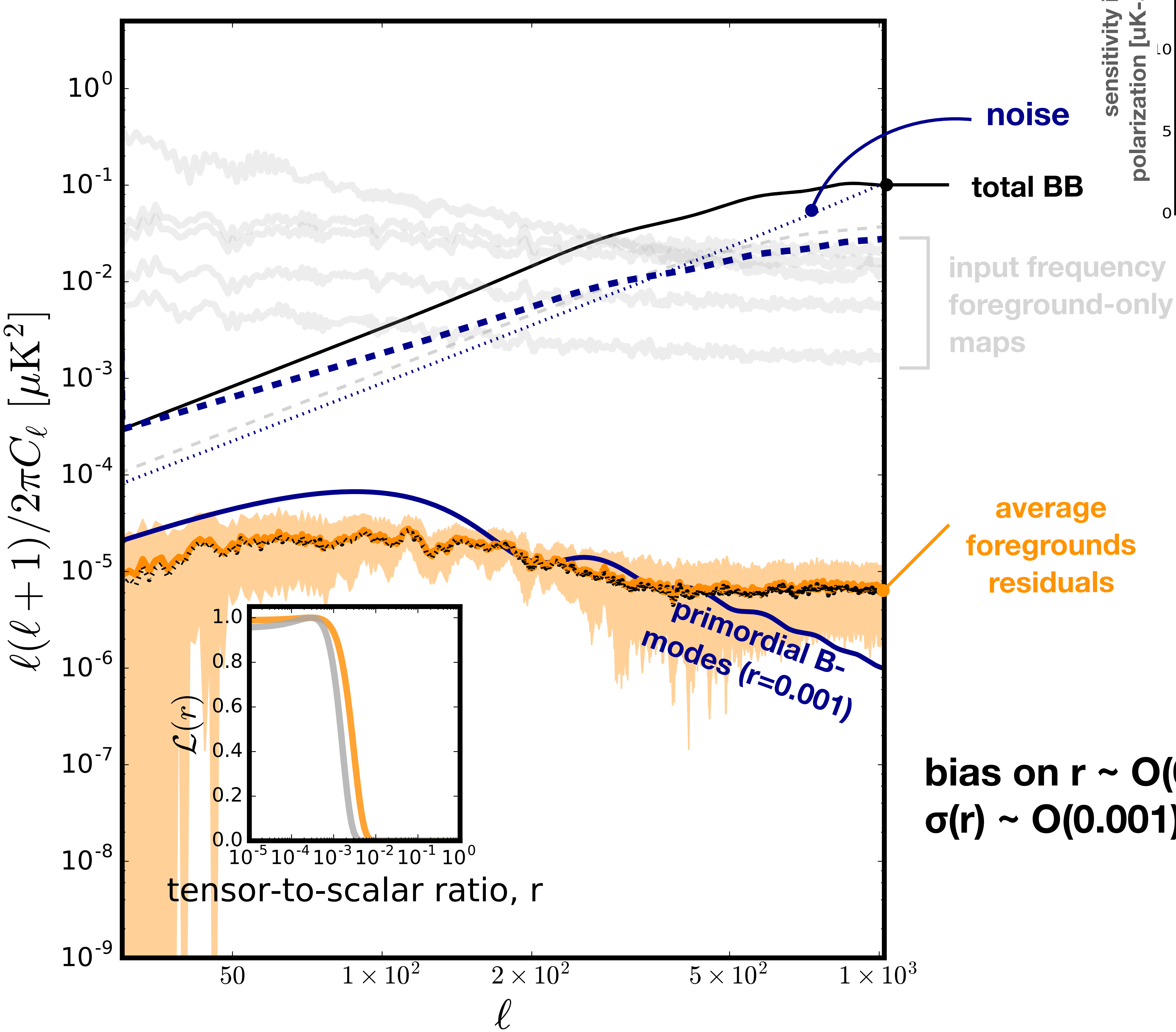


bias on r ~ O(0.001-0.005)
σ(r) ~ O(0.005)

toy example

- with priors from Planck on β, fit for single {βd,βs} only
- and few frequency bands from the ground
- on the cleanest fsky=5%





bias on r ~ O(0.0005)
σ(r) ~ O(0.001)

toy example

- with priors from Planck on β, fit for single {βd,βs} only
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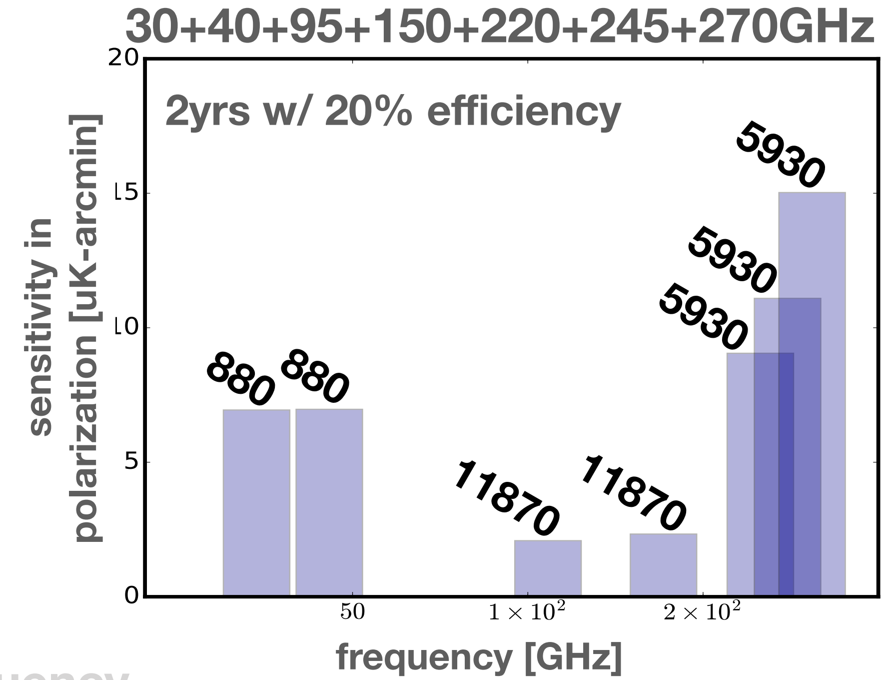
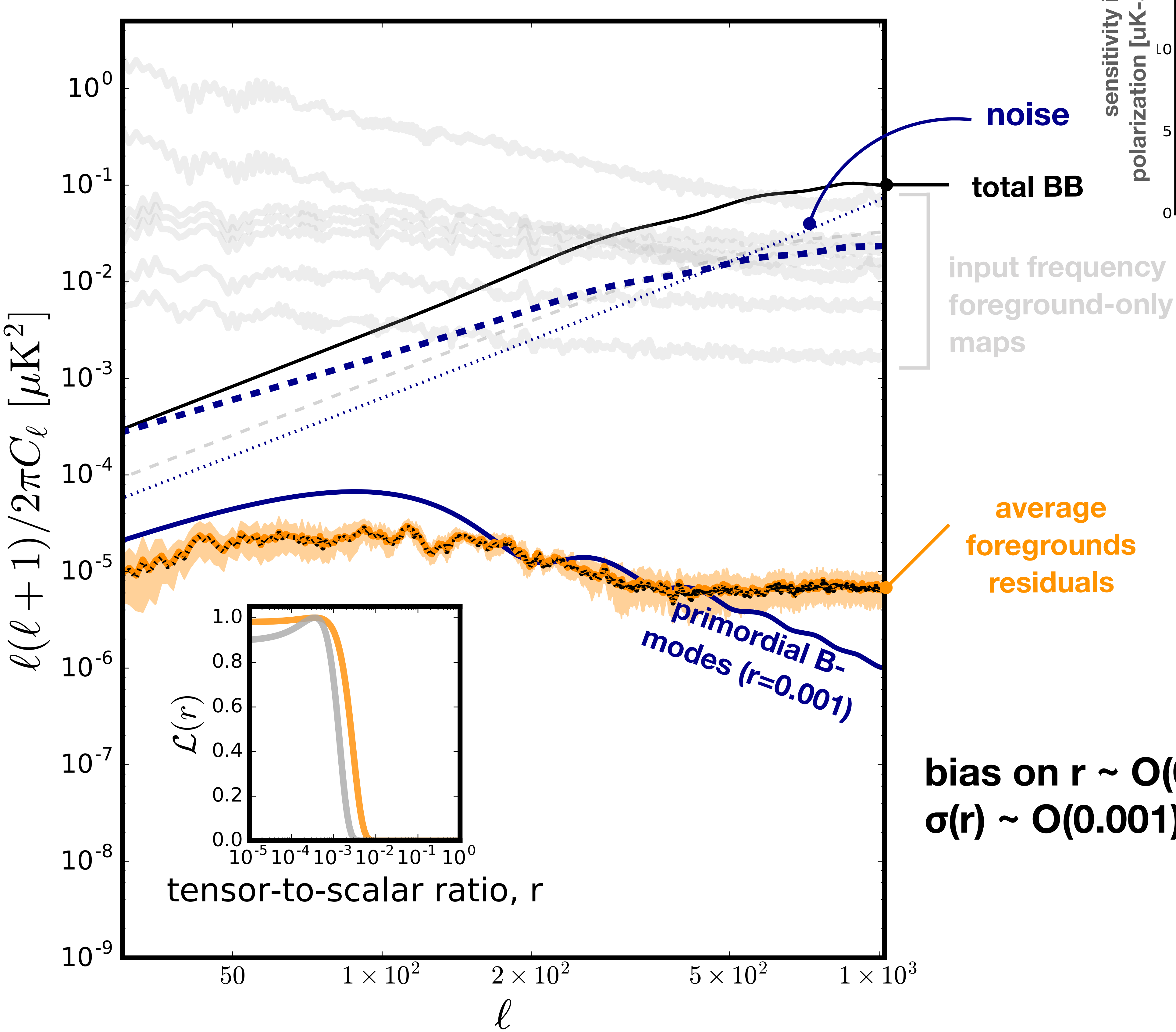
- on the cleanest fsky=5%





bias on r ~ O(0.0005)
σ(r) ~ O(0.001)

toy example

- with priors from Planck on β, fit for single {βd,βs} only
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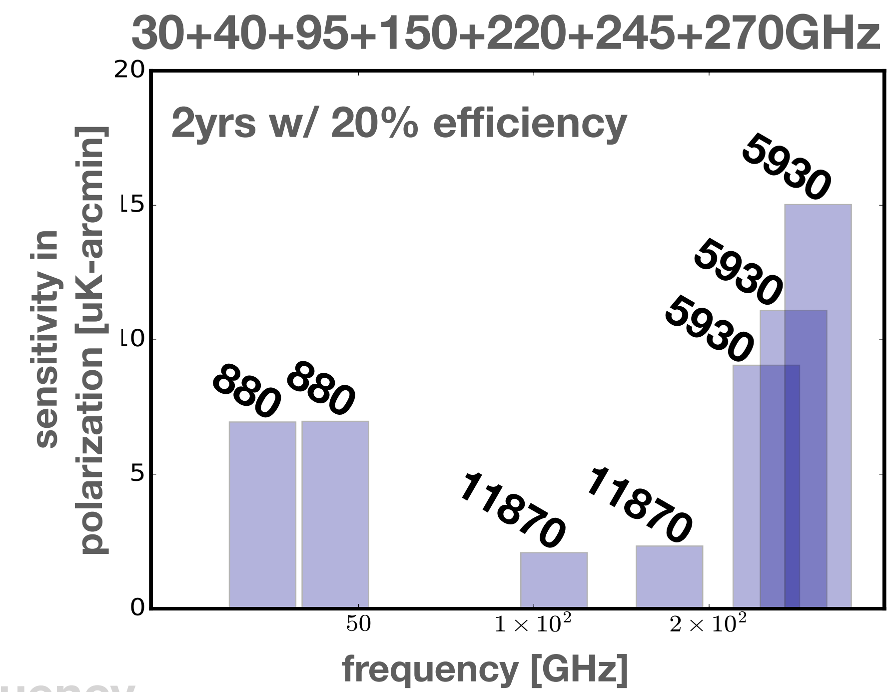

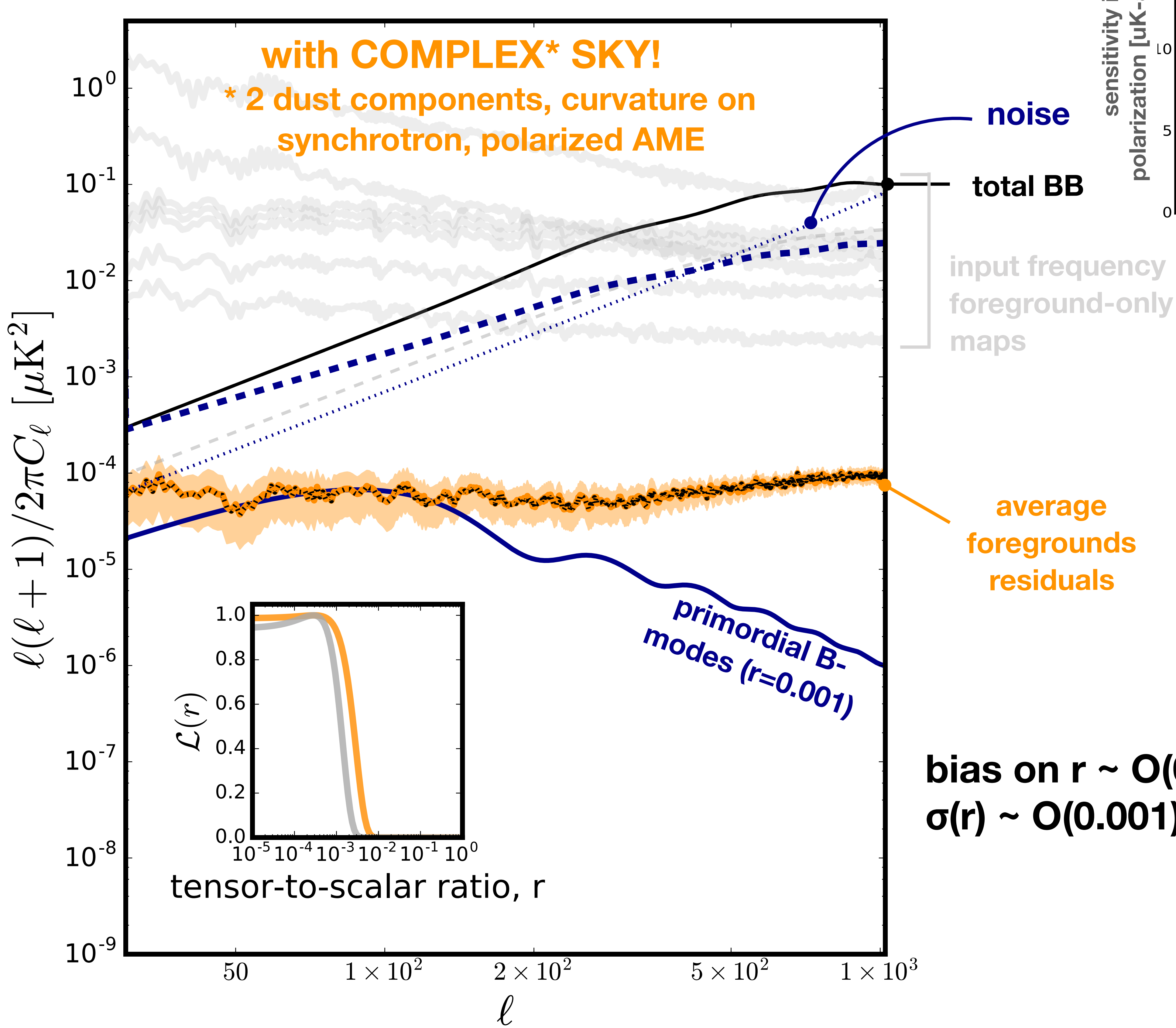

bias on r ~ O(0.001)
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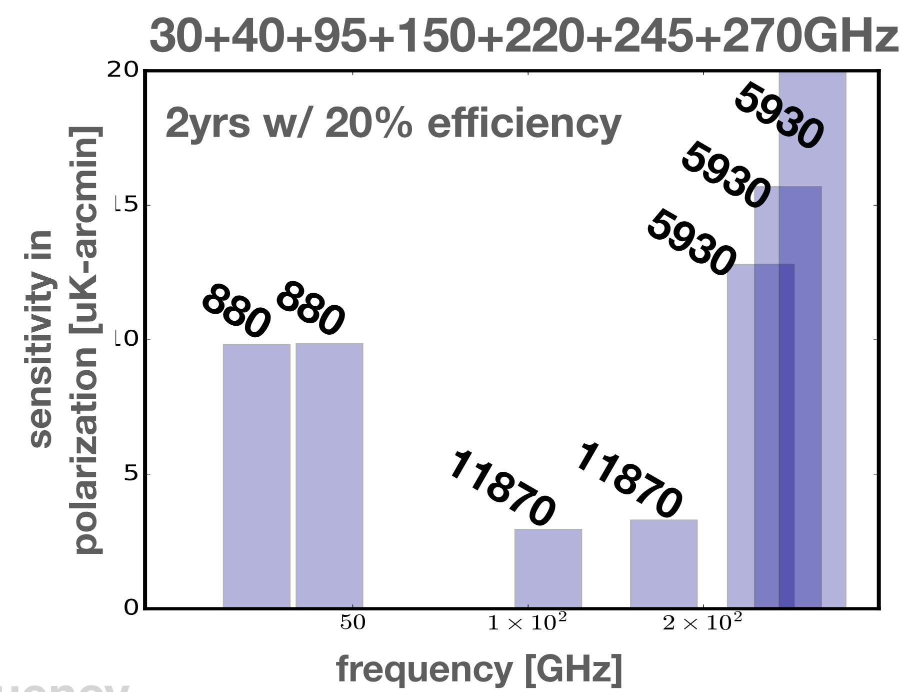
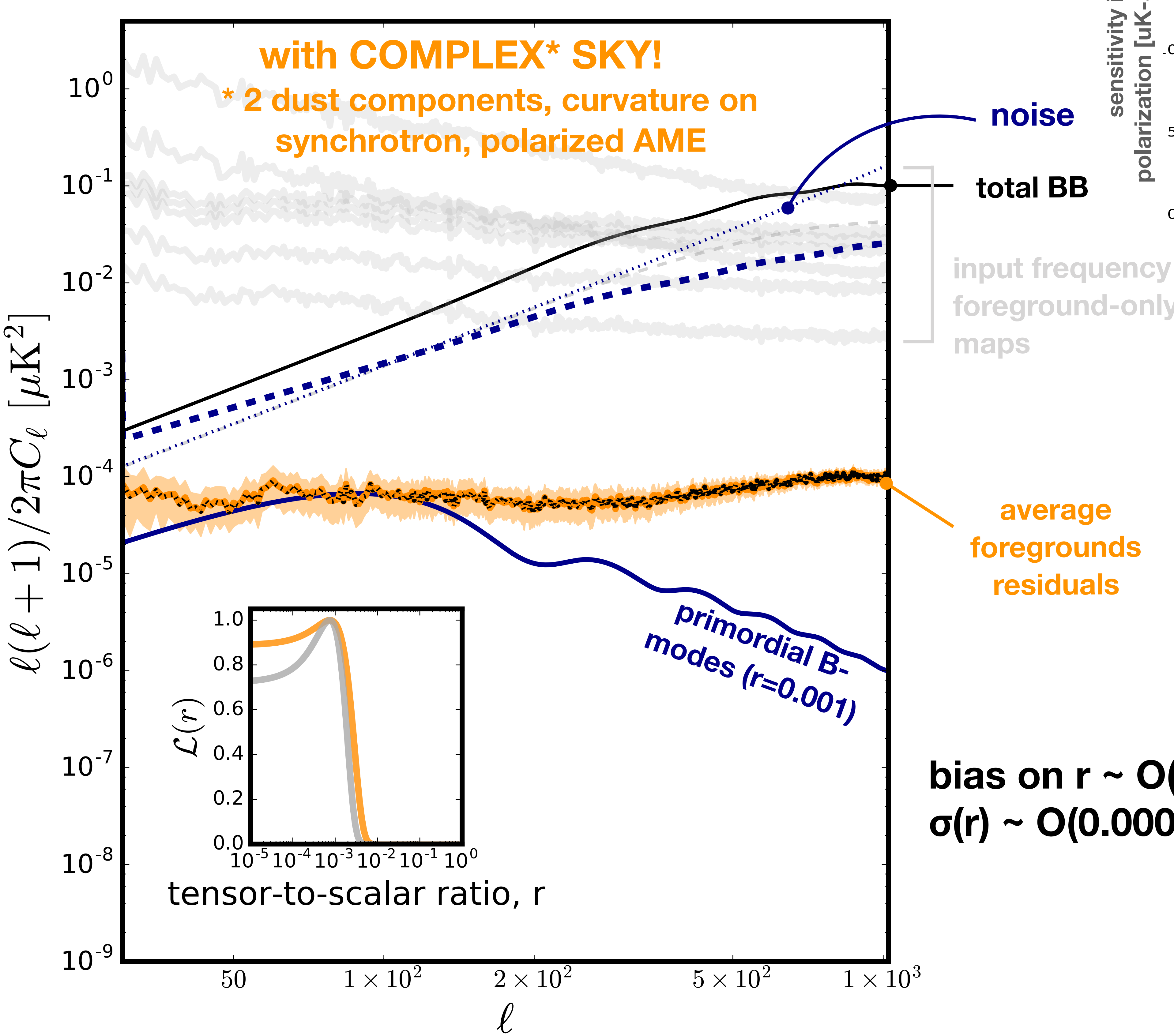
toy example

- with priors from Planck on β, fit for single {βd,βs} only
- and few frequency bands from the ground
- on the cleanest fsky=10%





bias on r ~ O(0.001)
σ(r) ~ O(0.0005)

toy example

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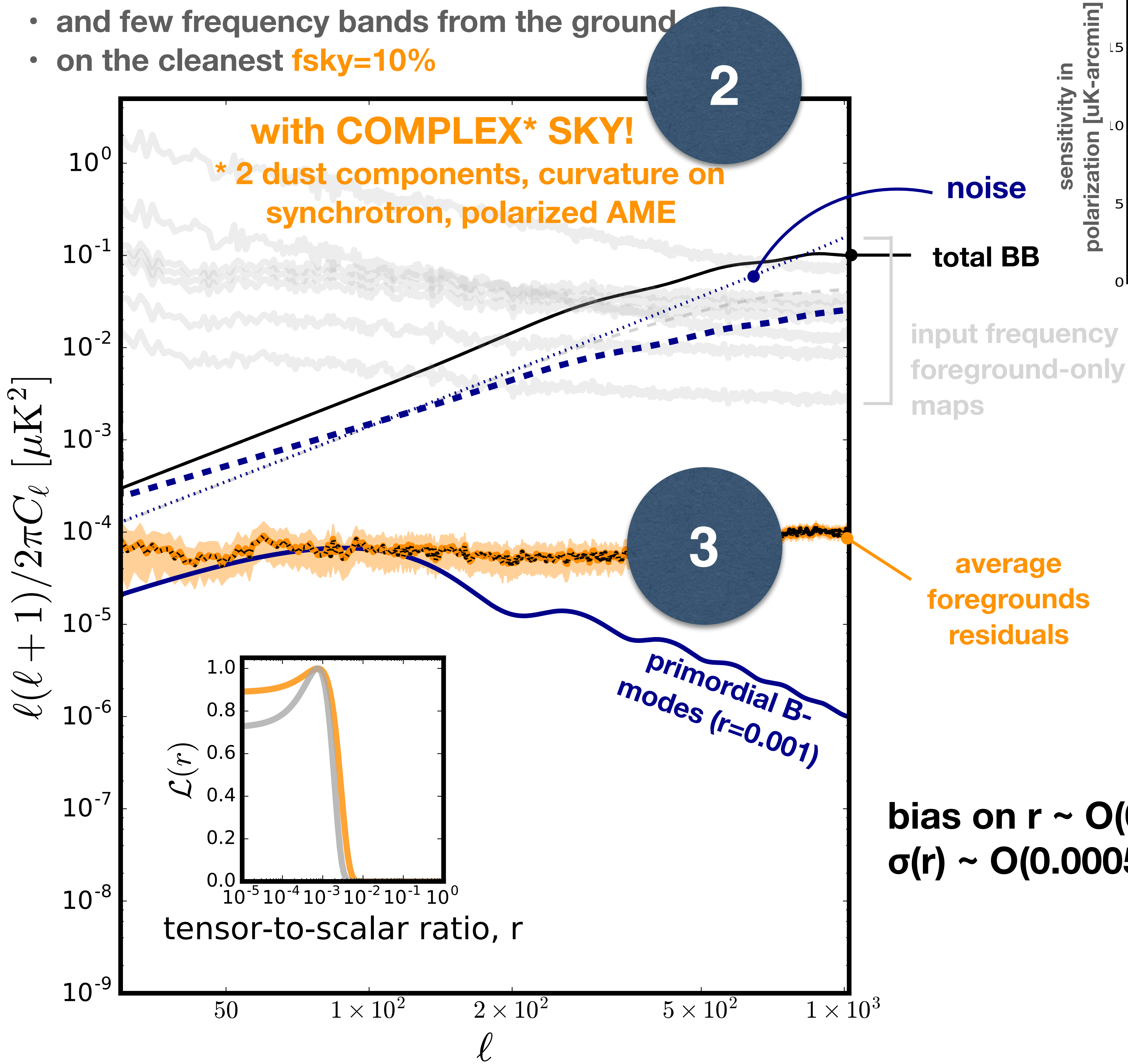
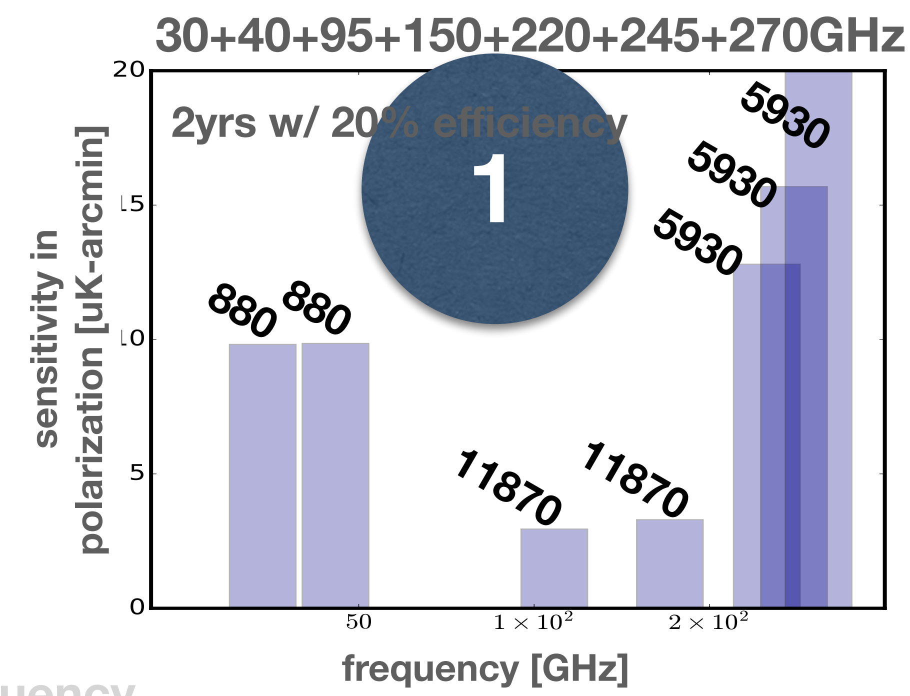


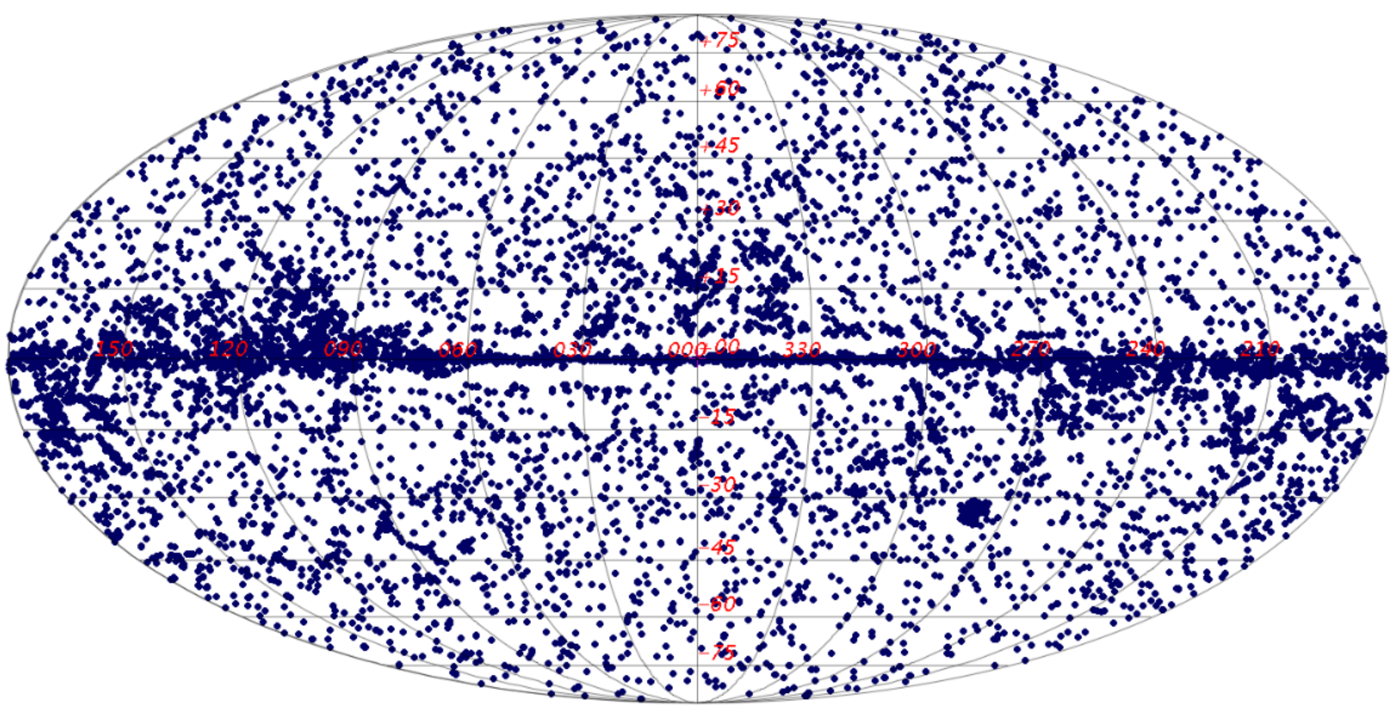


bias on r ~ O(0.001)
σ(r) ~ O(0.0005)

One should not forget about point sources!

Exploring Cosmic Origins with CORE: B-mode Component Separation
M. Remazeilles et al, JCAP, 2017

- In general, the compact source contribution does not impact the large angular scales (near the reionization peak), but can play an important role on intermediate and small angular scales where the lensing-induced B-mode signal is present (Curto et al. 2013).



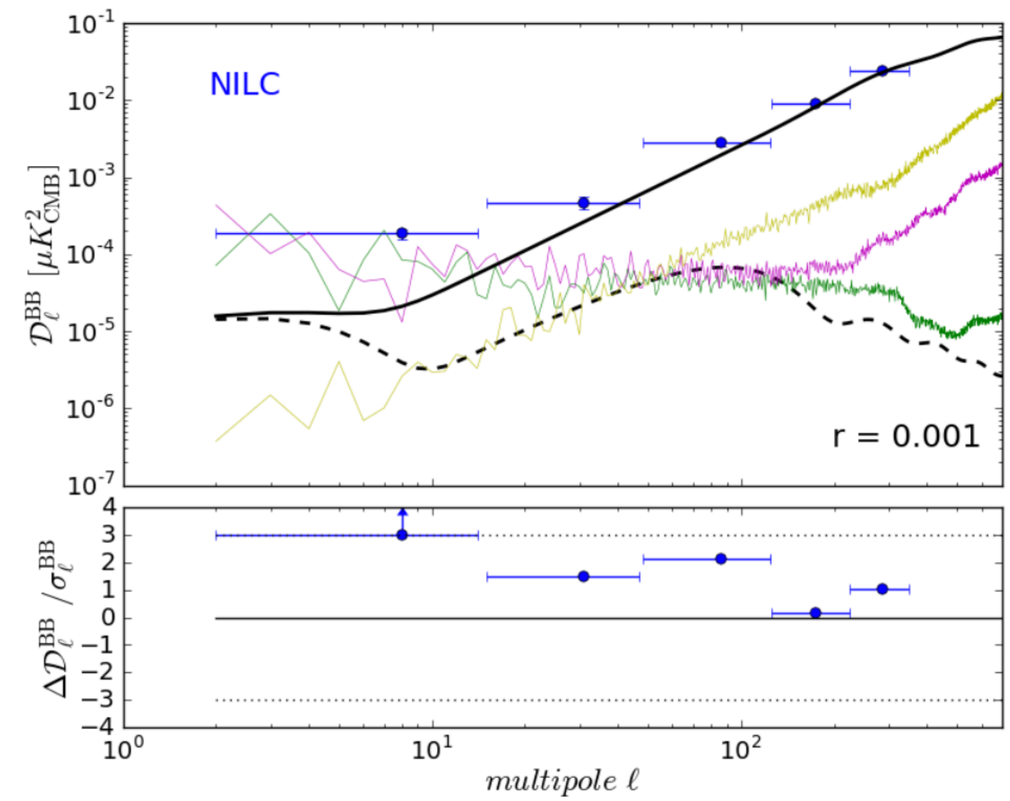


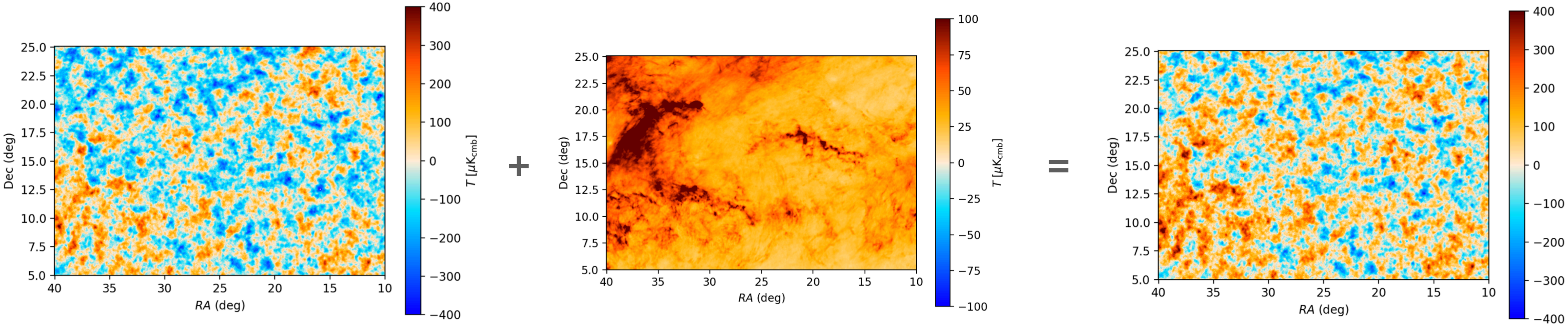
Figure 4. Union of 60 to 600 GHz polarization masks used in the analysis for mitigating the contamination from polarized compact sources. Individual polarized sources are detected in each frequency band of *CORE*.

- "careful treatment is required for CMB B-mode polarization observations if the tensor-to-scalar ratio, r, is ≪ 10^{-2}"

Exploring cosmic origins with CORE: gravitational lensing of the CMB

A. Challinor et al, JCAP, 2017

+ see also Fantaye, Baccigalupi, Leach, Yadav (2012)



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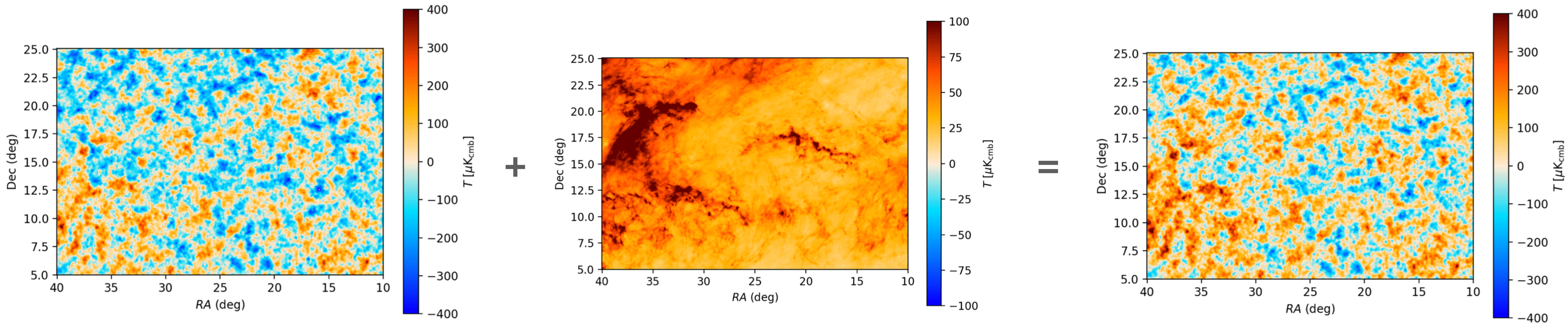

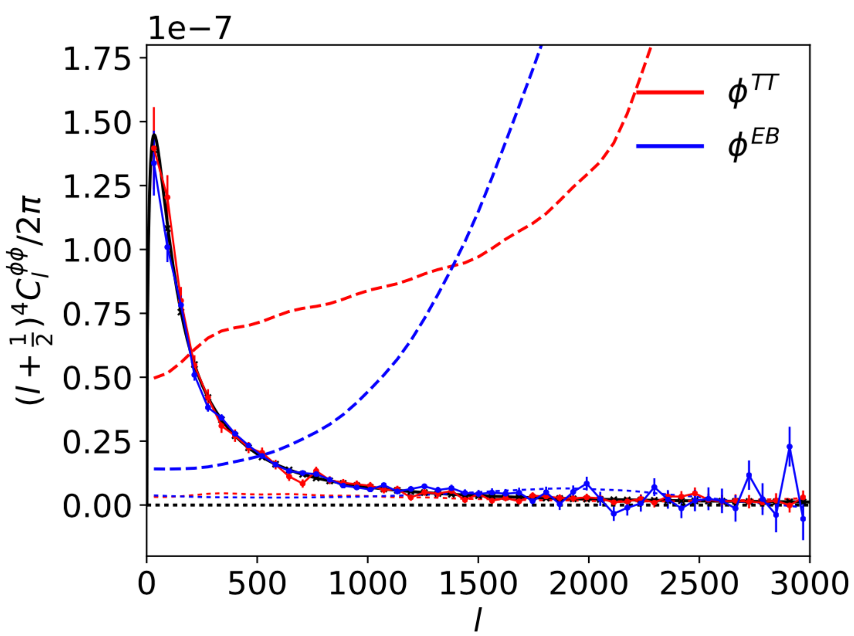

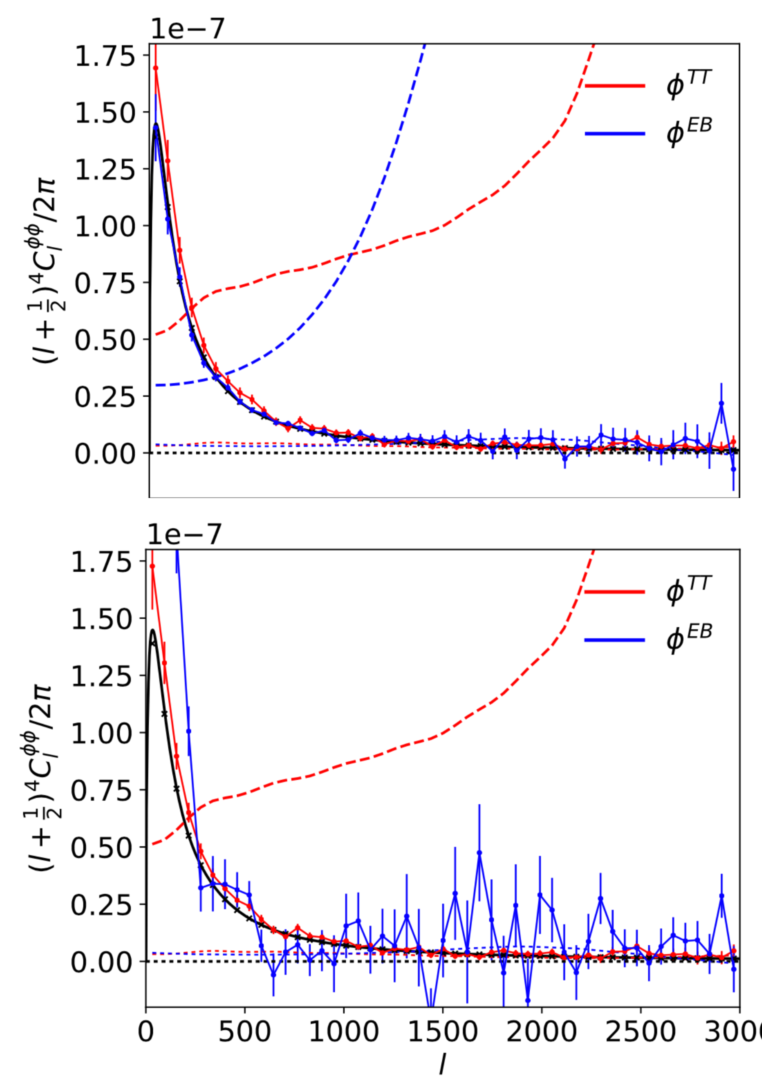

Effect of foregrounds on lensing reconstruction and delensing

Exploring cosmic origins with CORE: gravitational lensing of the CMB

A. Challinor et al, JCAP, 2017

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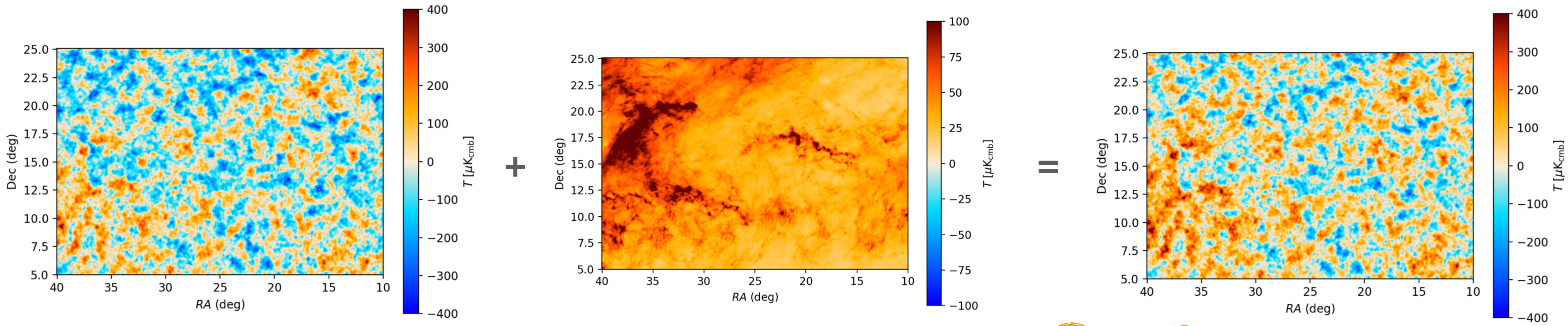
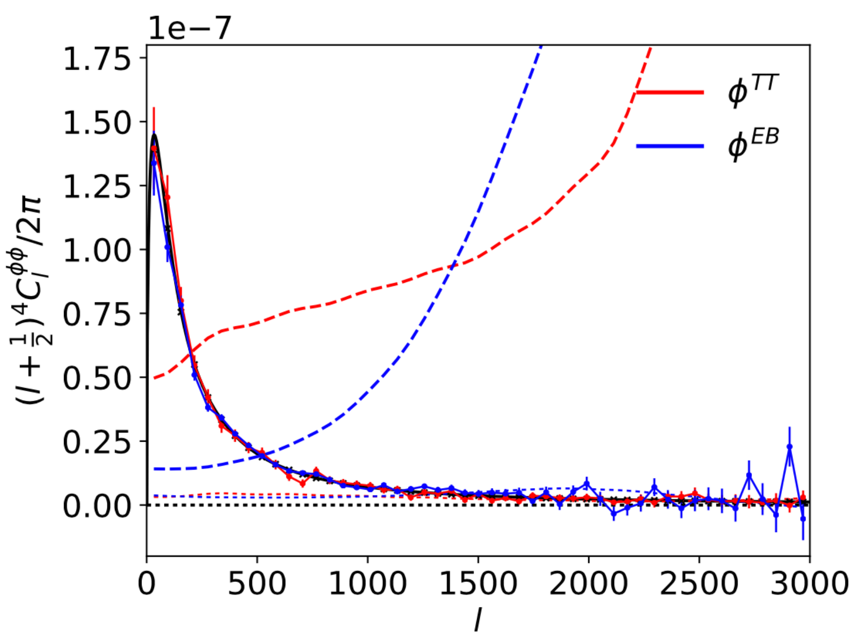
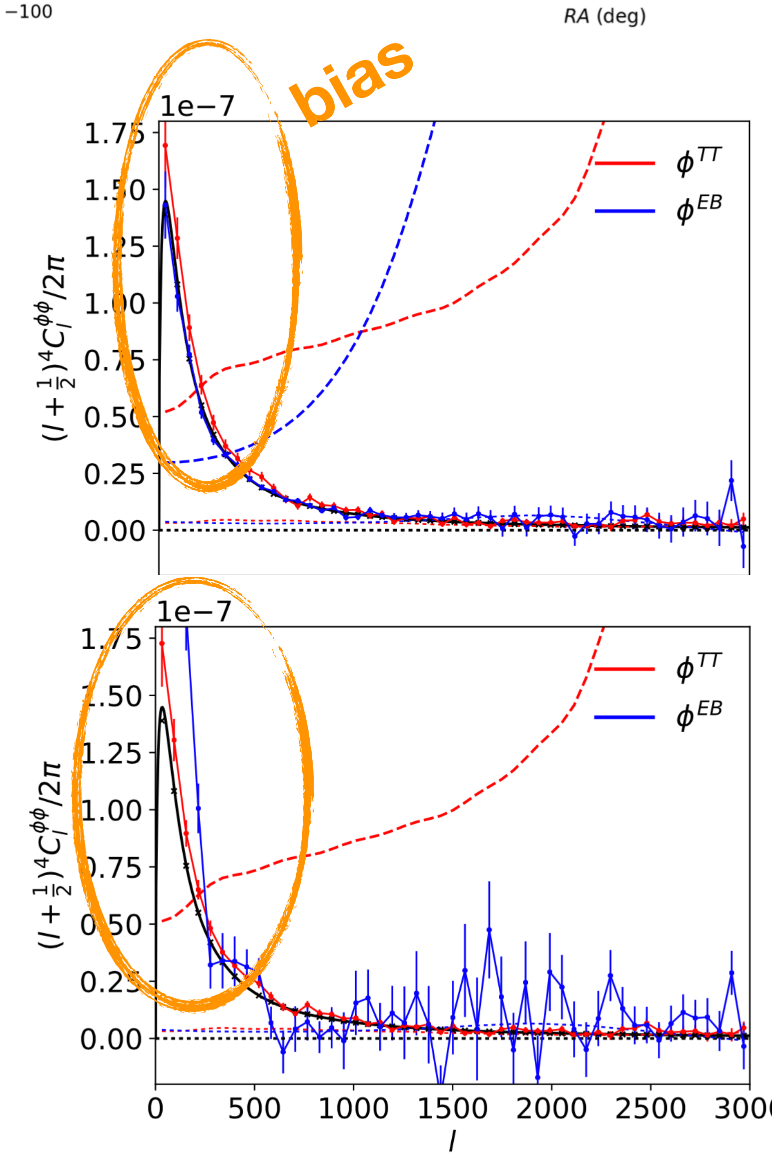
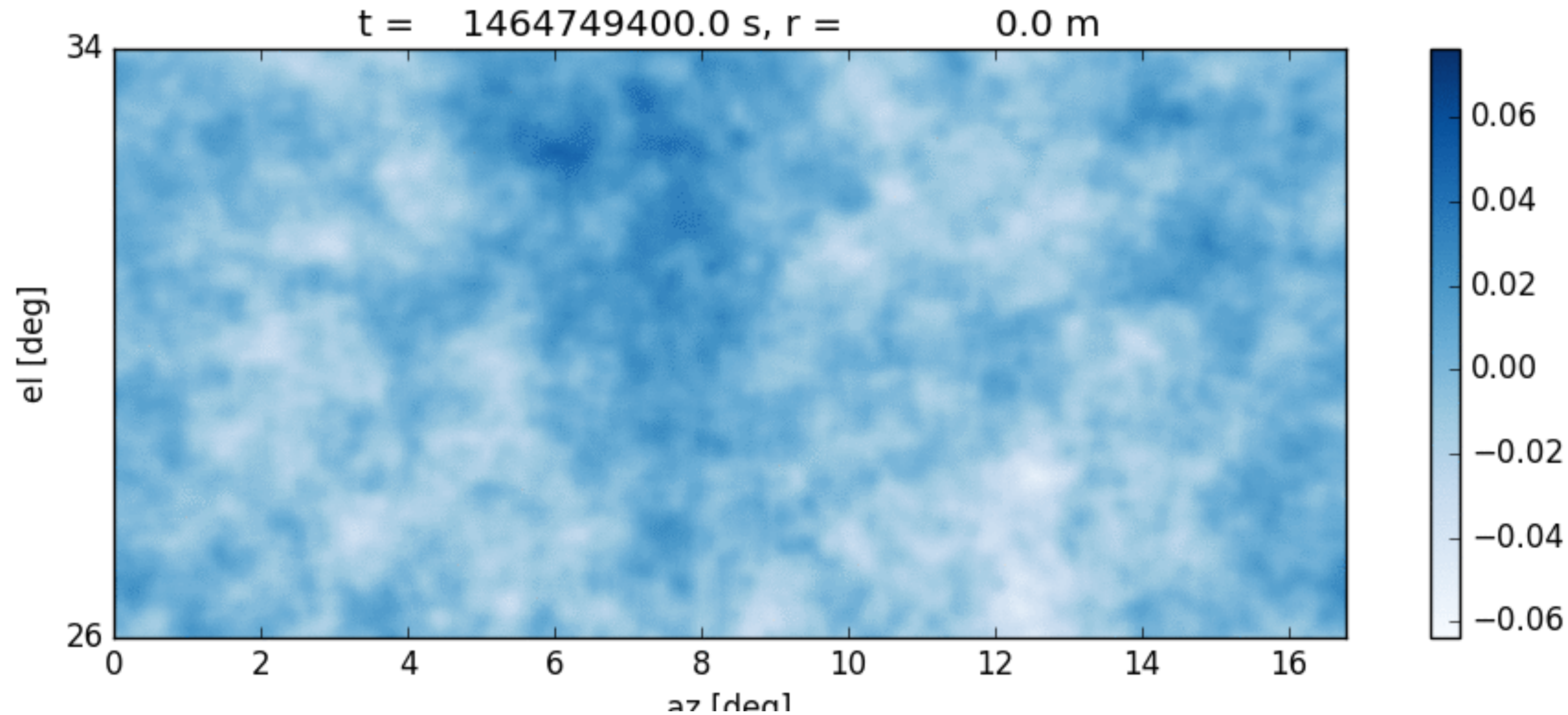






Modeling Atmospheric Emission for CMB Ground-based Observations
JE et al.
The Astrophysical Journal, Volume 809, Issue 1, article id. 63, 19 pp. (**2015**) arXiv:1501.07911

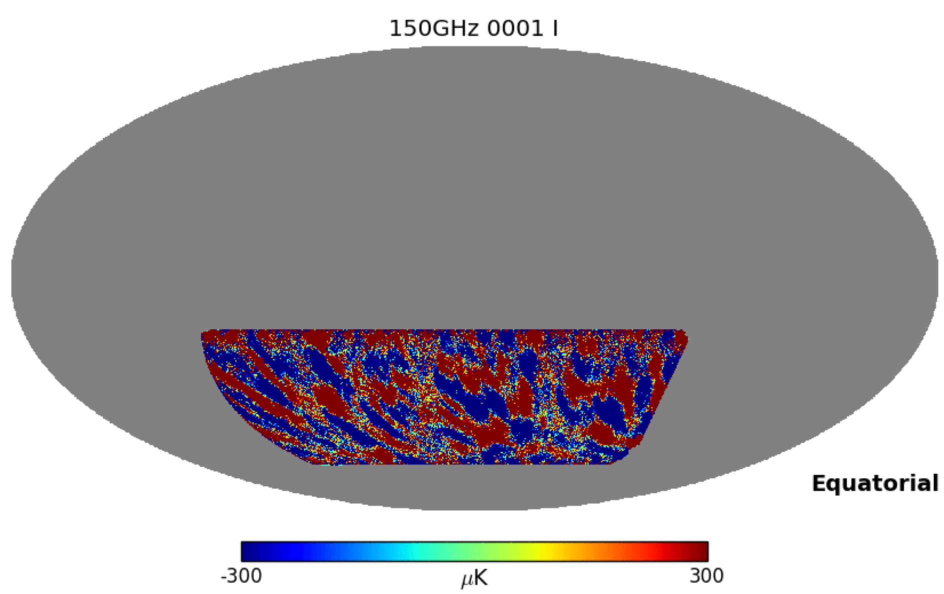
The telescope's view through one realization of turbulent, wind-blown, atmospheric water vapor.

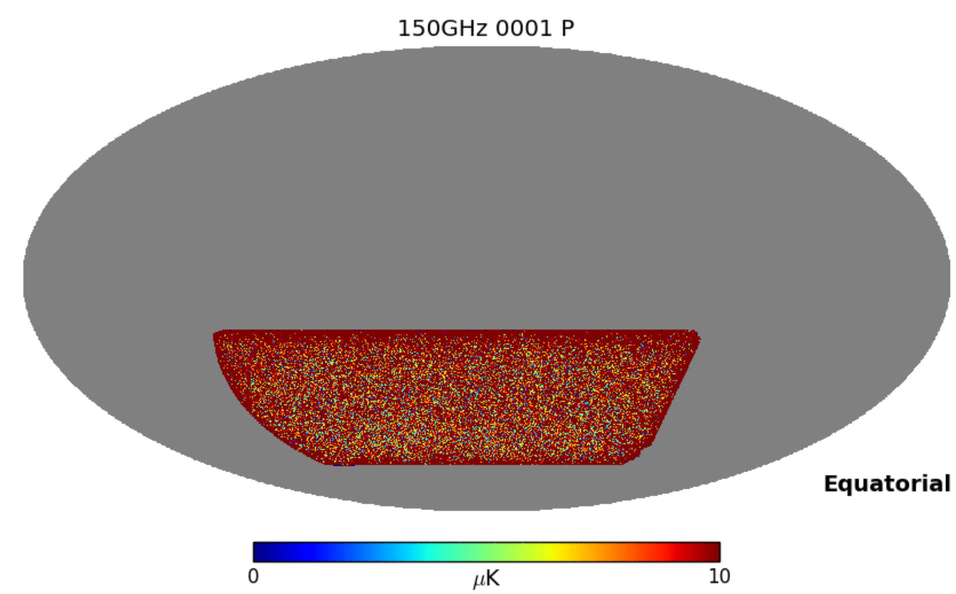


see talk by Julian Borrill

credit: C³ team @ LBNL

Cumulative daily maps of the sky temperature and polarization at each frequency showing how the atmosphere and noise integrate down over time.





https://crd.lbl.gov/departments/computational-science/c3/c3-research/cosmic-microwave-background/cmb-simulations-at-scale/

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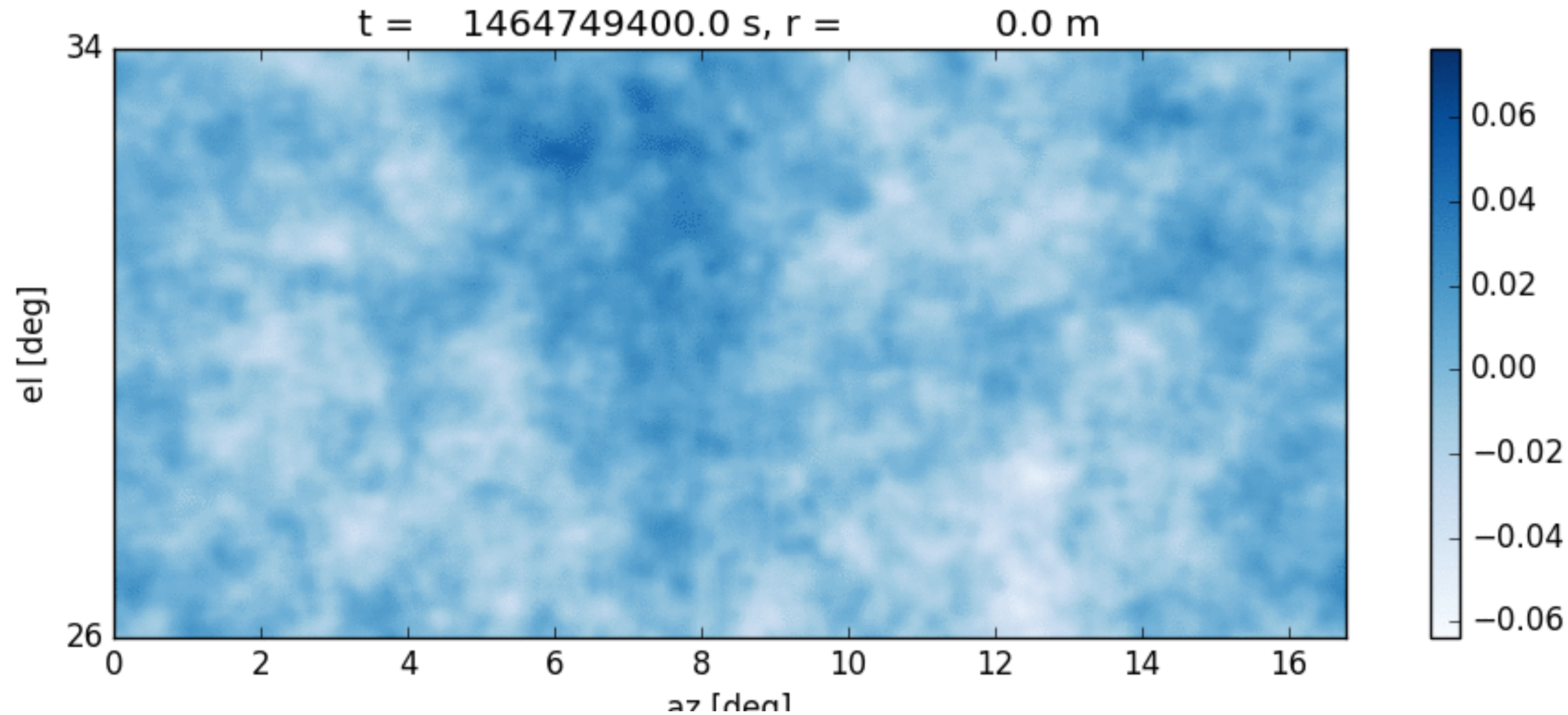

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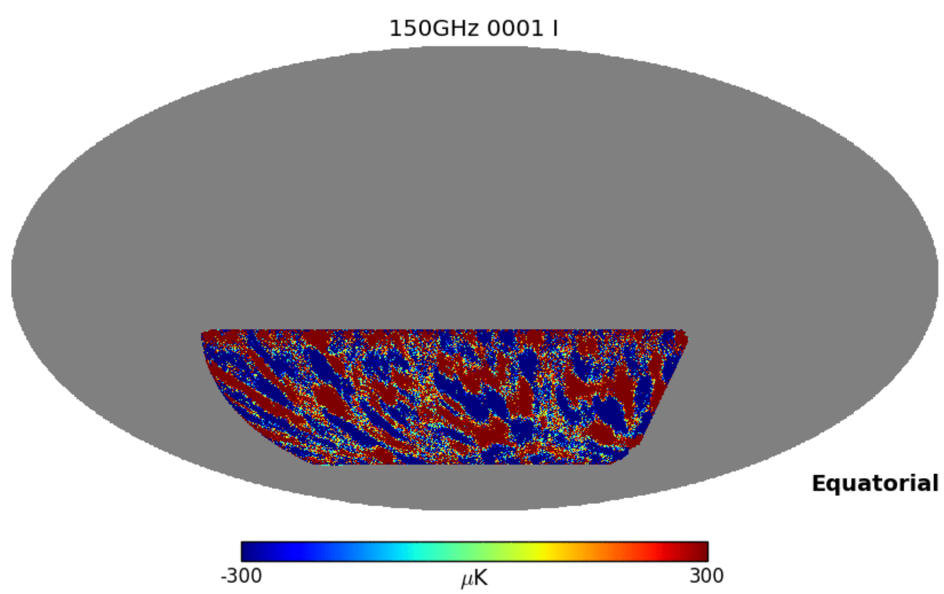
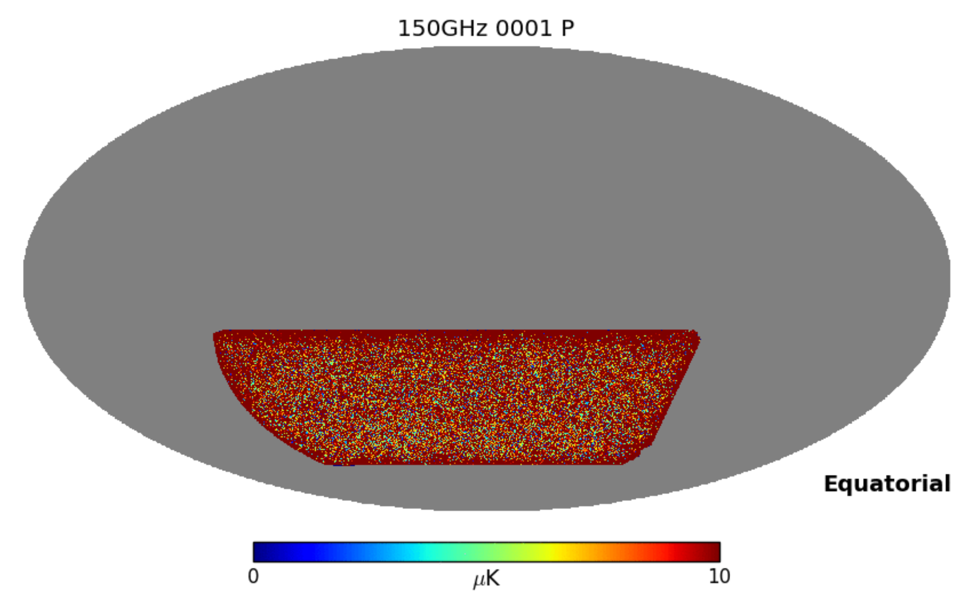
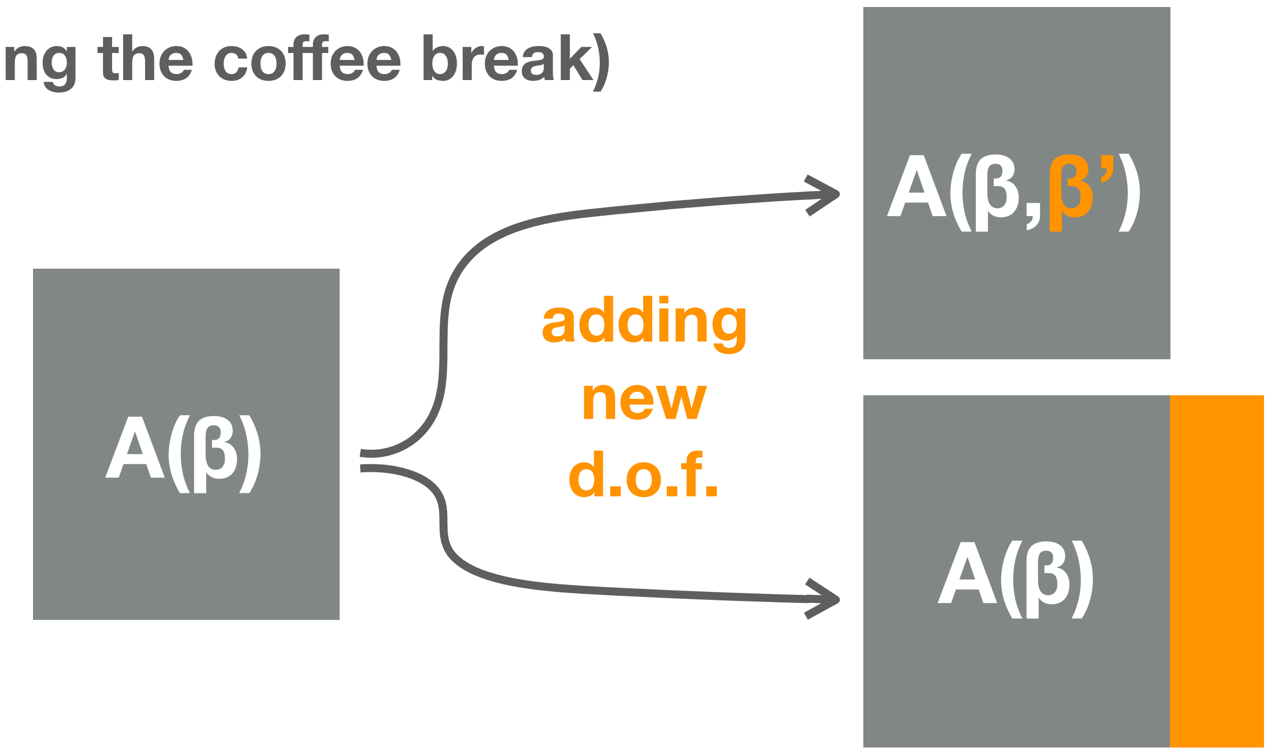




https://crd.lbl.gov/departments/computational-science/c3/c3-research/cosmic-microwave-background/cmb-simulations-at-scale/

Conclusions and (ideas for discussion during the coffee break)



- cleaning foregrounds is **unavoidable** to detect r and **one of the biggest challenges** for upcoming CMB data analysis;
- component separation is about making a **trade off** between **degrees of freedom in the modeling** and the **statistical** error budget;
- showing that one can **robustly** measure r=*O*(0.001) is very challenging given the latest foregrounds modeling;
- **lensing** (and **atmosphere**) are also foregrounds that new generation CMB projects have to deal with;

Conclusions and (ideas for discussion during the coffee break)

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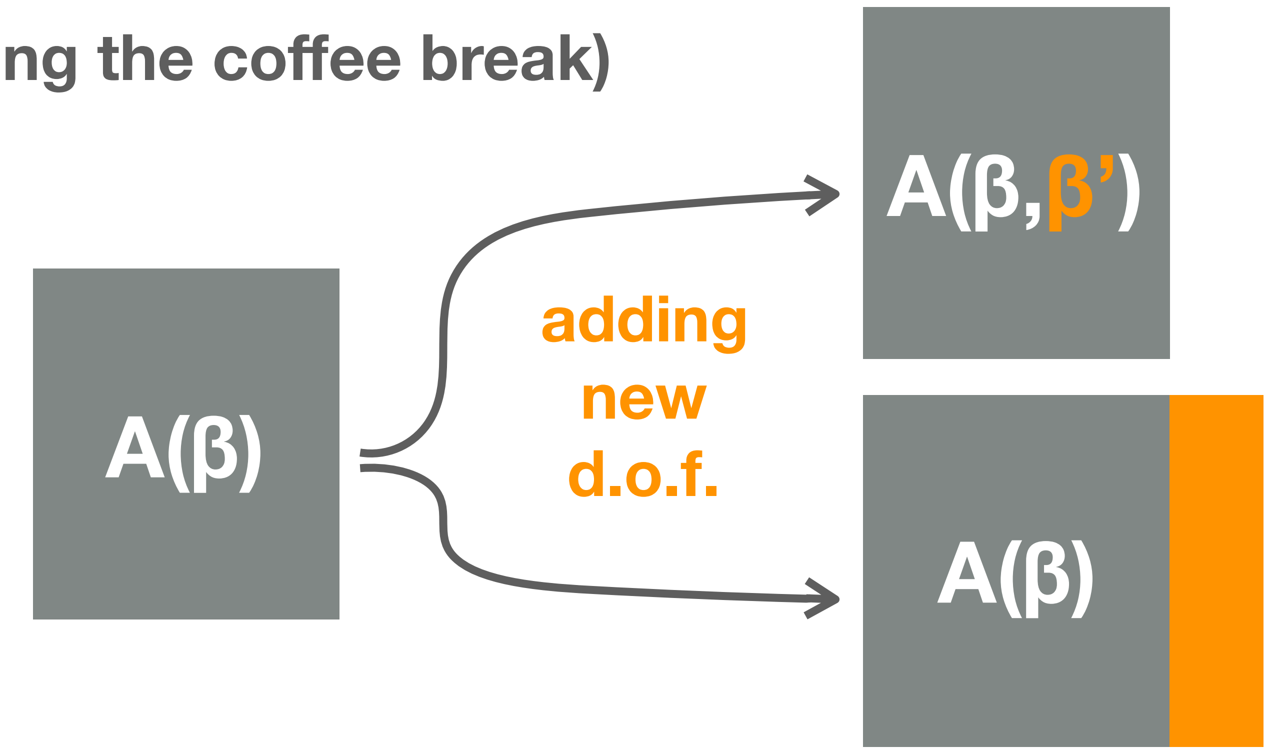

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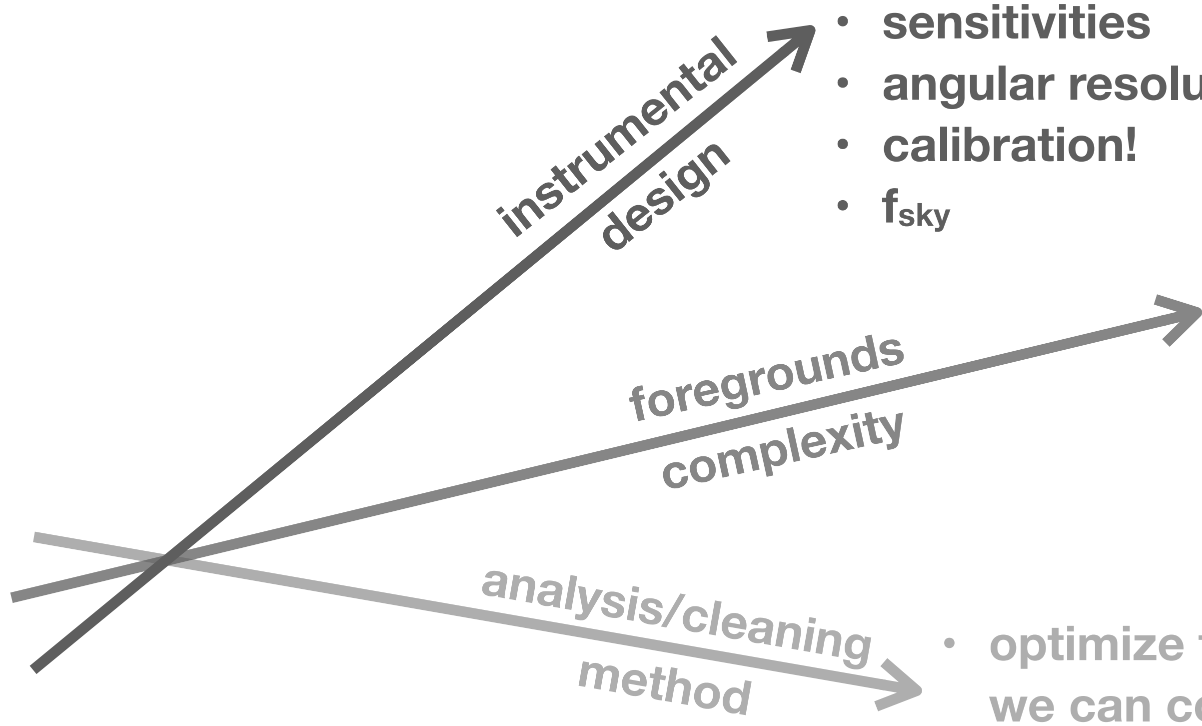

- **frequency bands**
- **sensitivities**
- **angular resolution**
- **calibration!**
- **f_{sky}**

- **include spatial variations of spectral indices**
- **decorrelation (3D structure of the galaxy)**
- **point sources**

- **optimize the trade-off between statistics (modes we can count on) and bias (degrees of freedom in the model)**