Are foregrounds a fundamental limit to the characterization of primordial B-modes ?

Josquin ERRARD

COSMO-17 — Paris — Aug 29, 2017

1. Introduction
2. Galactic foregrounds
3. Get a clean CMB map
4. Forecasts

1. **Introduction**
2. Galactic foregrounds
3. Get a clean CMB map
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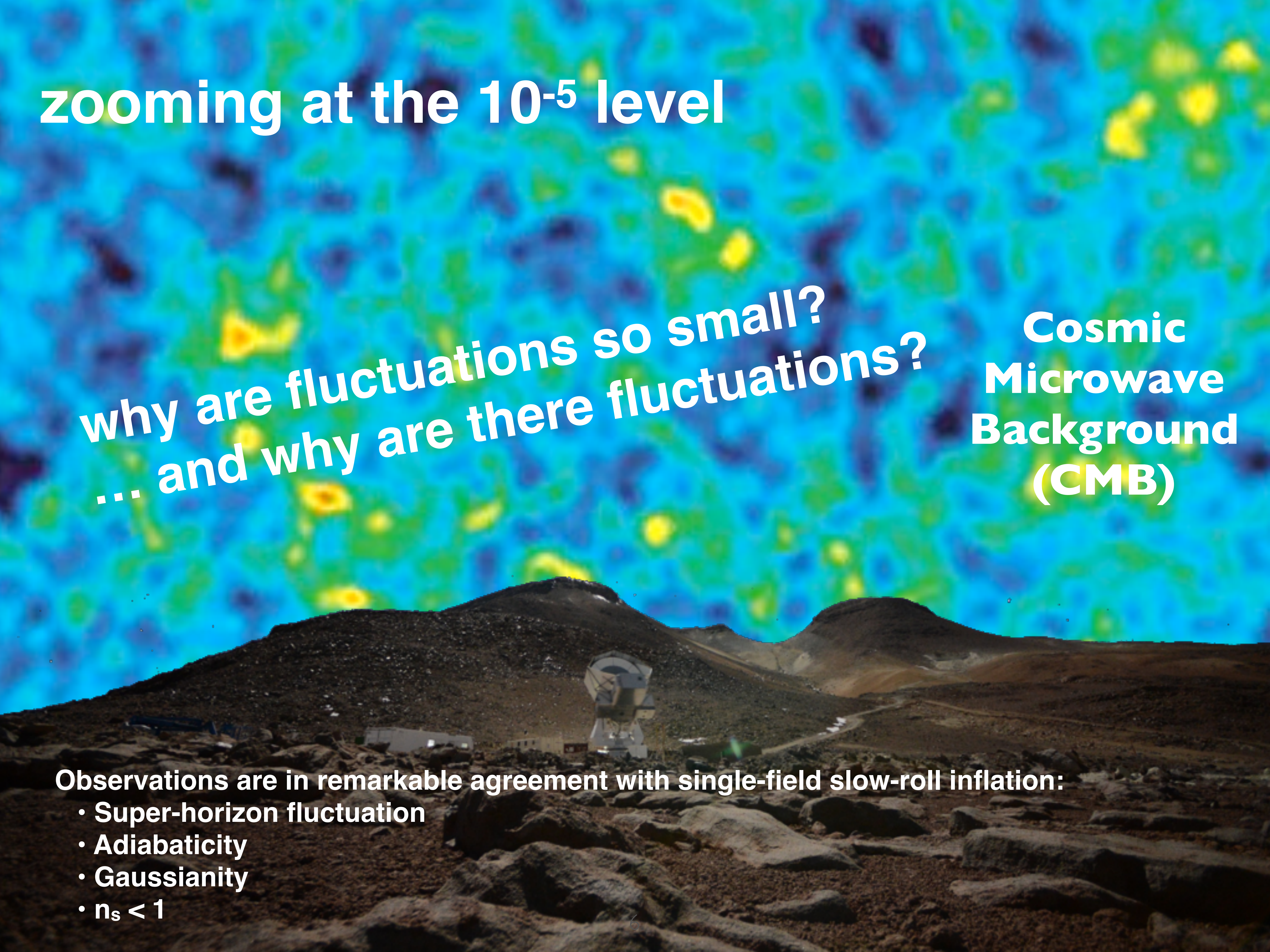
POLARBEAR telescope
5,200m, Atacama desert, Chile
[see Julien Peloton’s talk]


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

zooming at the 10^{-5} level



why are fluctuations so small?

… and why are there fluctuations?

Cosmic Microwave Background (CMB)

Observations are in remarkable agreement with single-field slow-roll inflation:

- Super-horizon fluctuation
- Adiabaticity
- Gaussianity
- $n_s < 1$

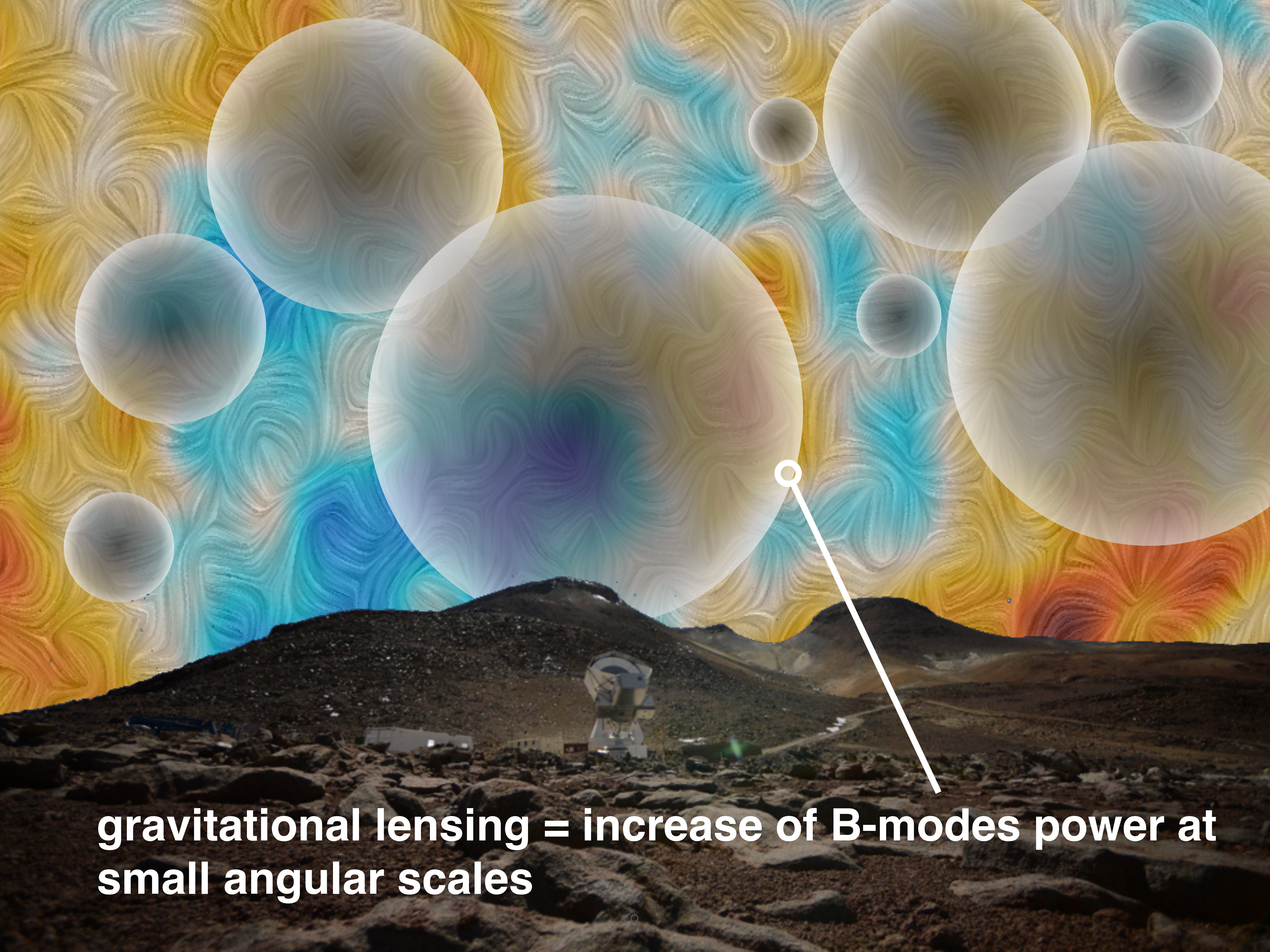
zooming at the 10^{-7} level

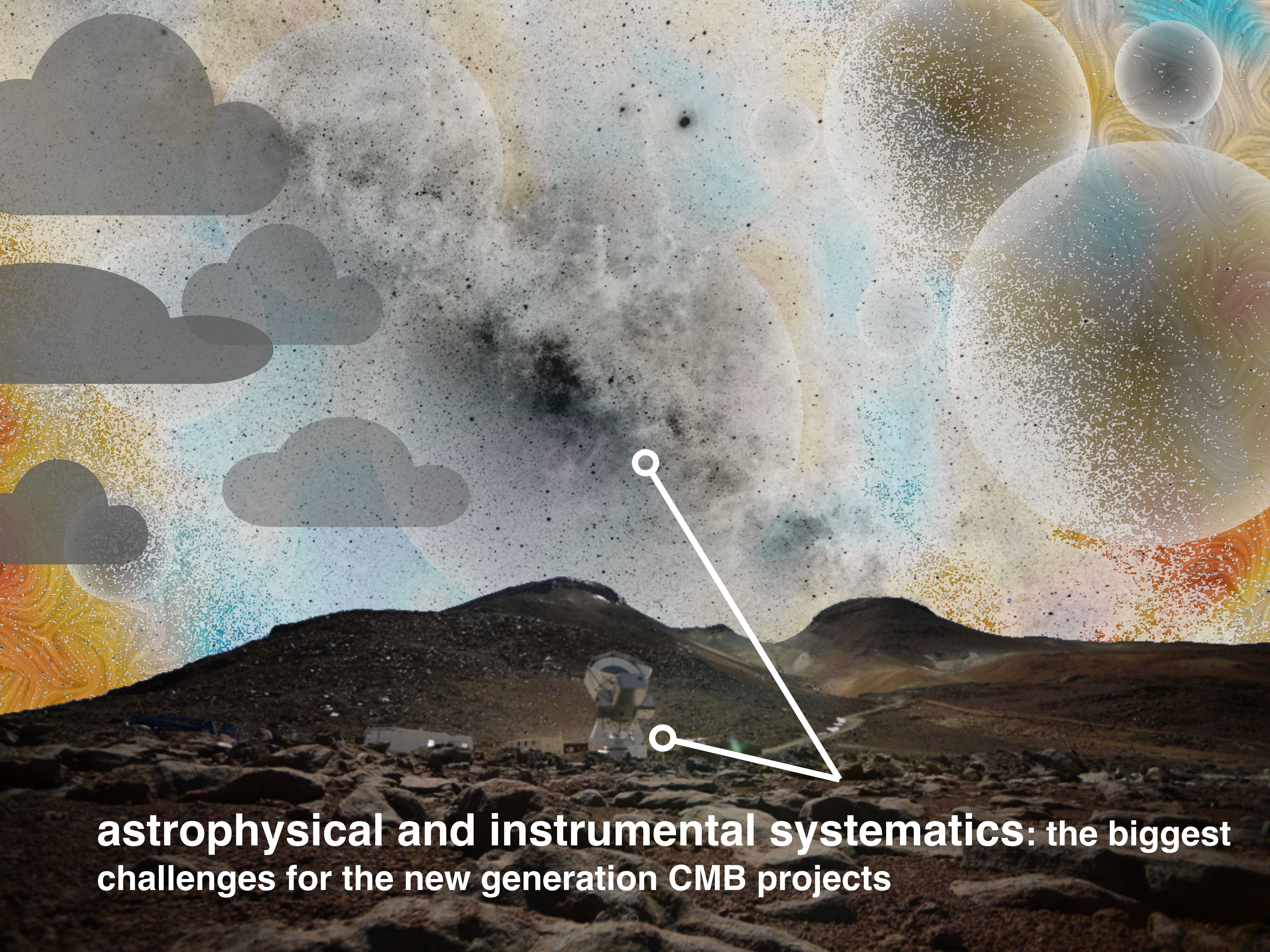
- ➤ but we want gravitational waves in addition!

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
$\mathrm{d}n_s/\mathrm{d}\ln k$	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

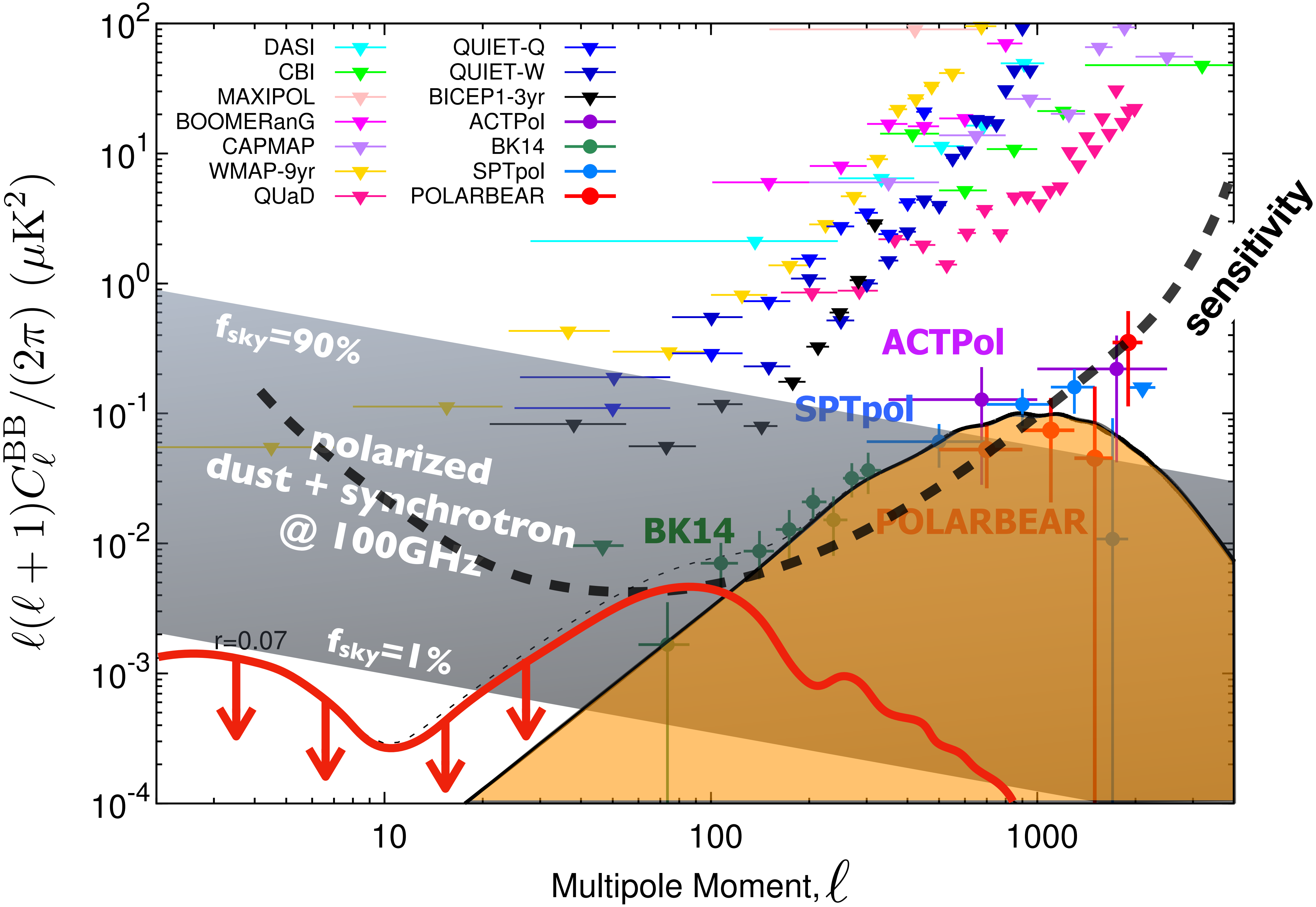
Table 1: Summary of key parameters in inflationary cosmology, together with their likely physical origins and current observational constraints. At present, only upper limits exist for all parameters except A_s and n_s [5].

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

Recent history of direct BB detection



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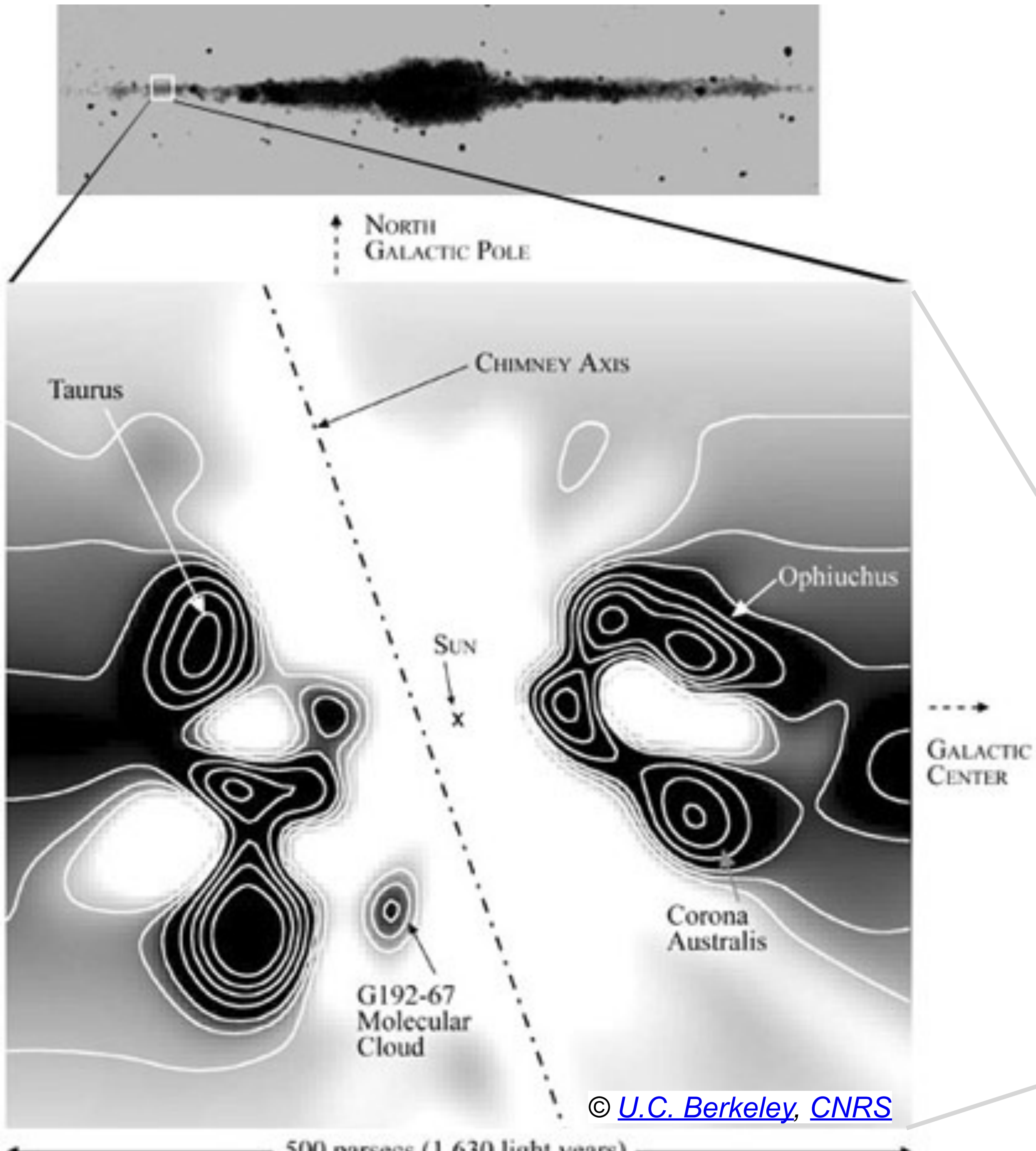
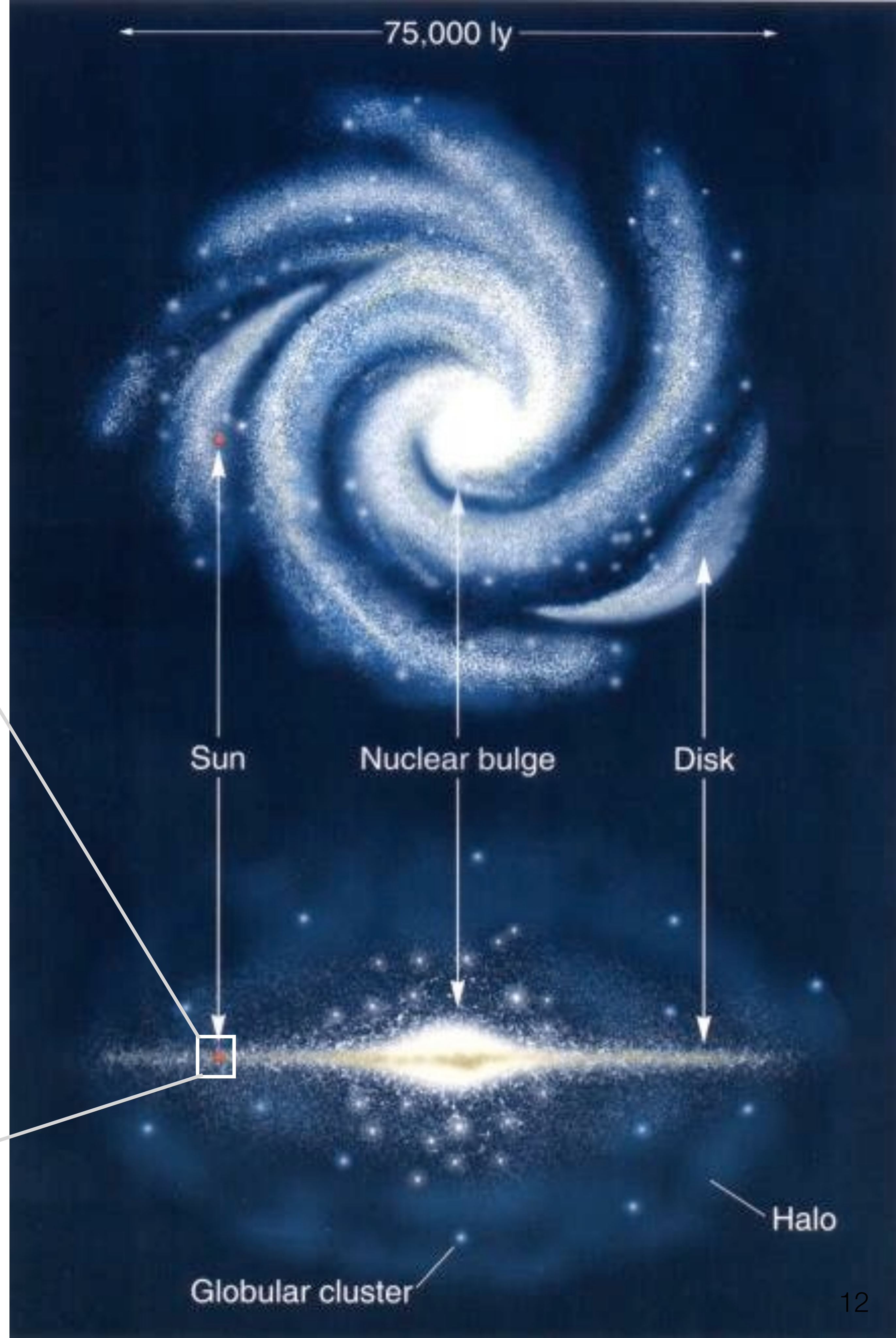
"Over the last 5 to 10 million years, the Solar System has been moving through the lower density region of interstellar gas of the Local Bubble. As a result, Earth and its lifeforms have avoided dangerous flows of cosmic radiation and gas." — http://www.solstation.com/

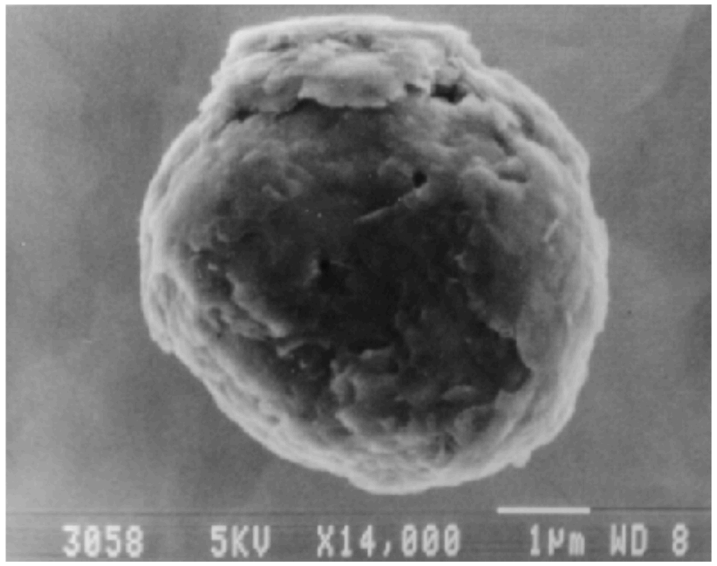


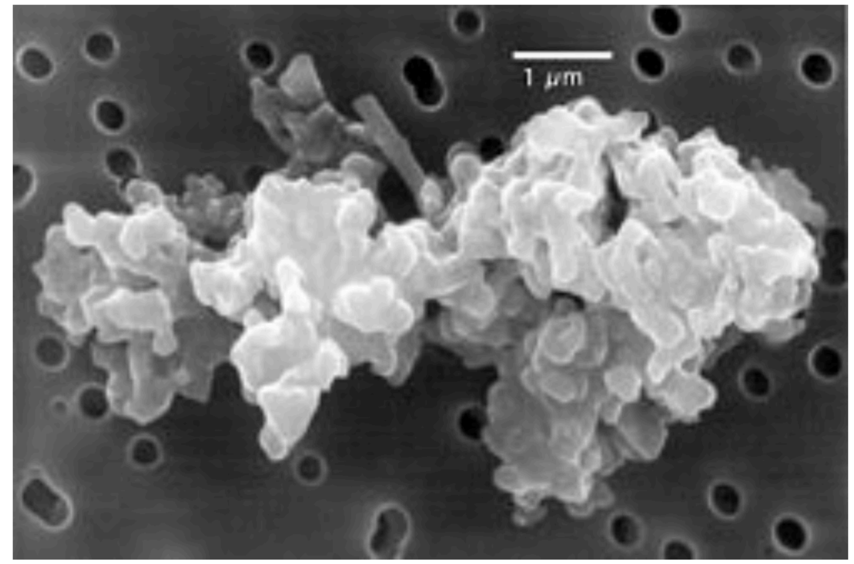
from Marc-Antoine Miville-Deschênes

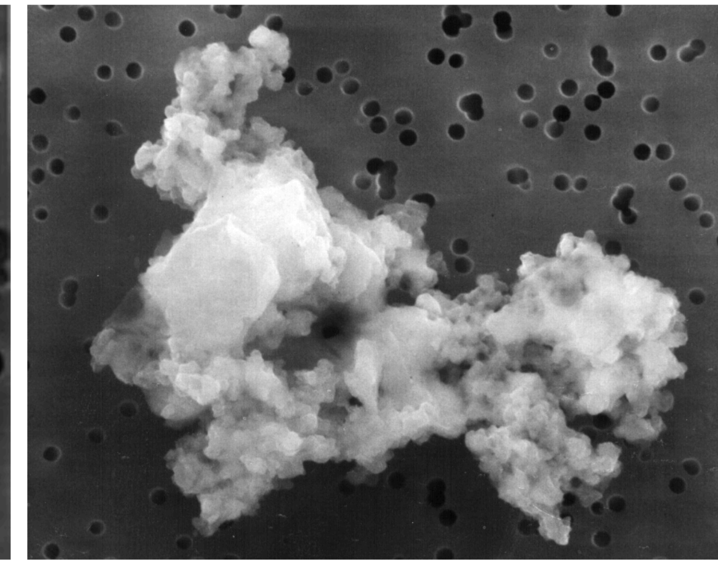


Interstellar medium

thermal dust

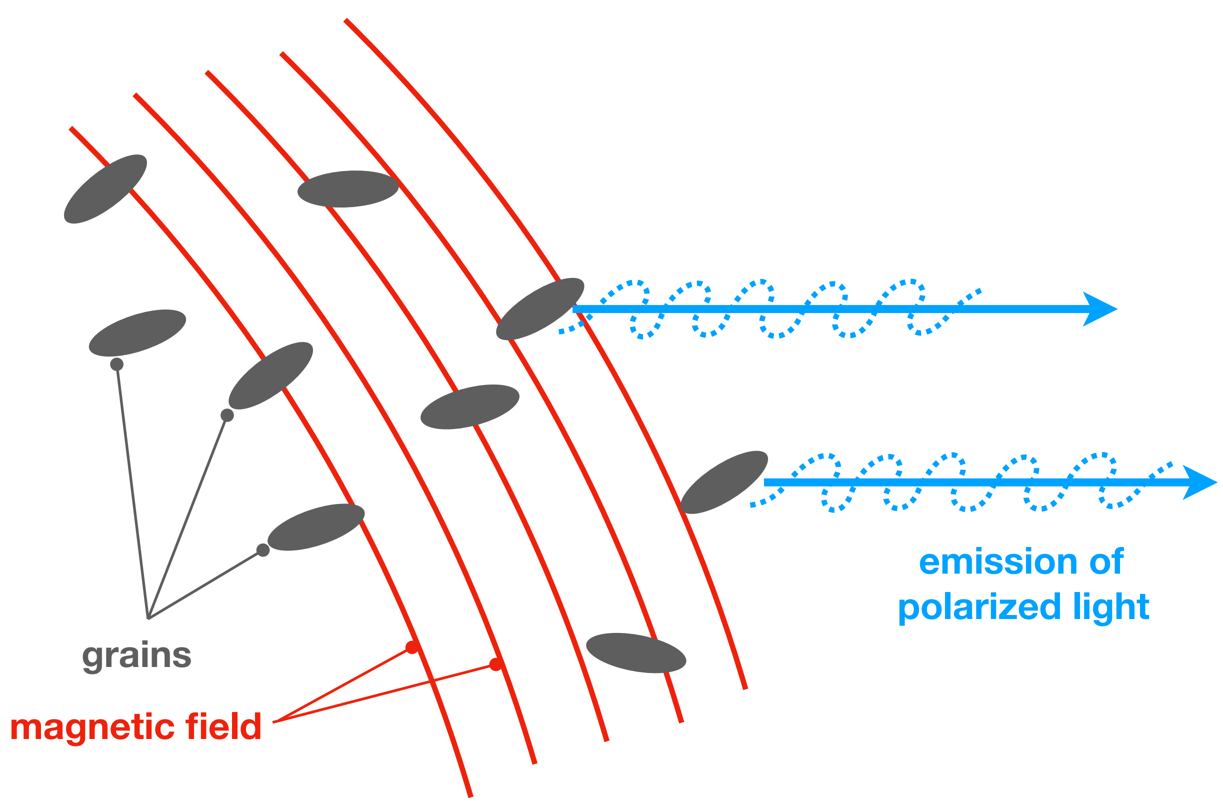




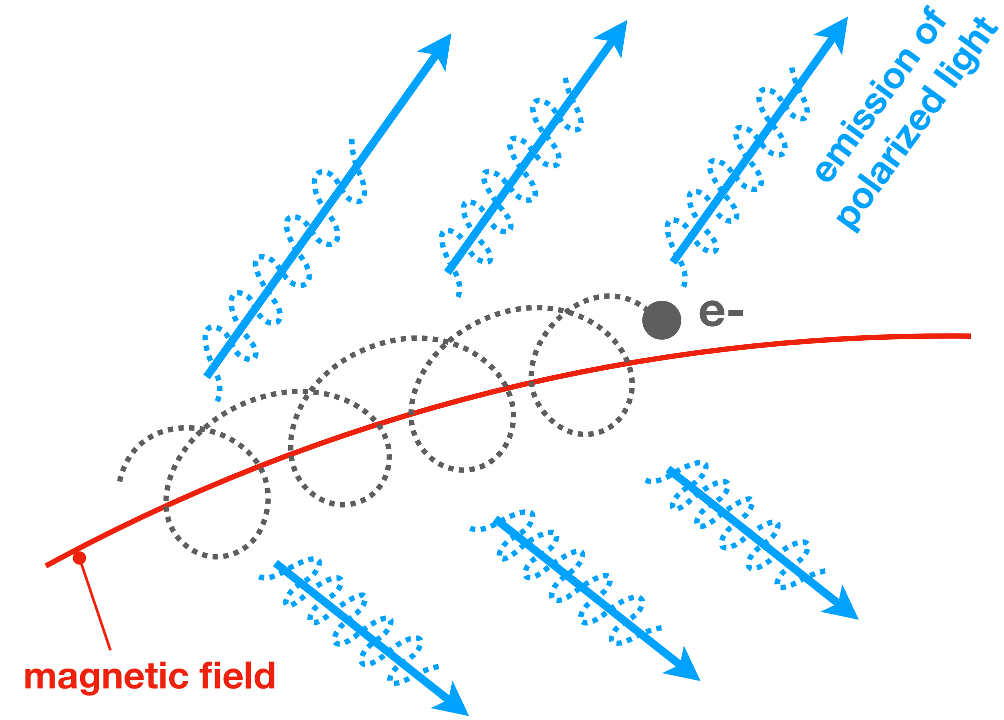


smooth and compact?

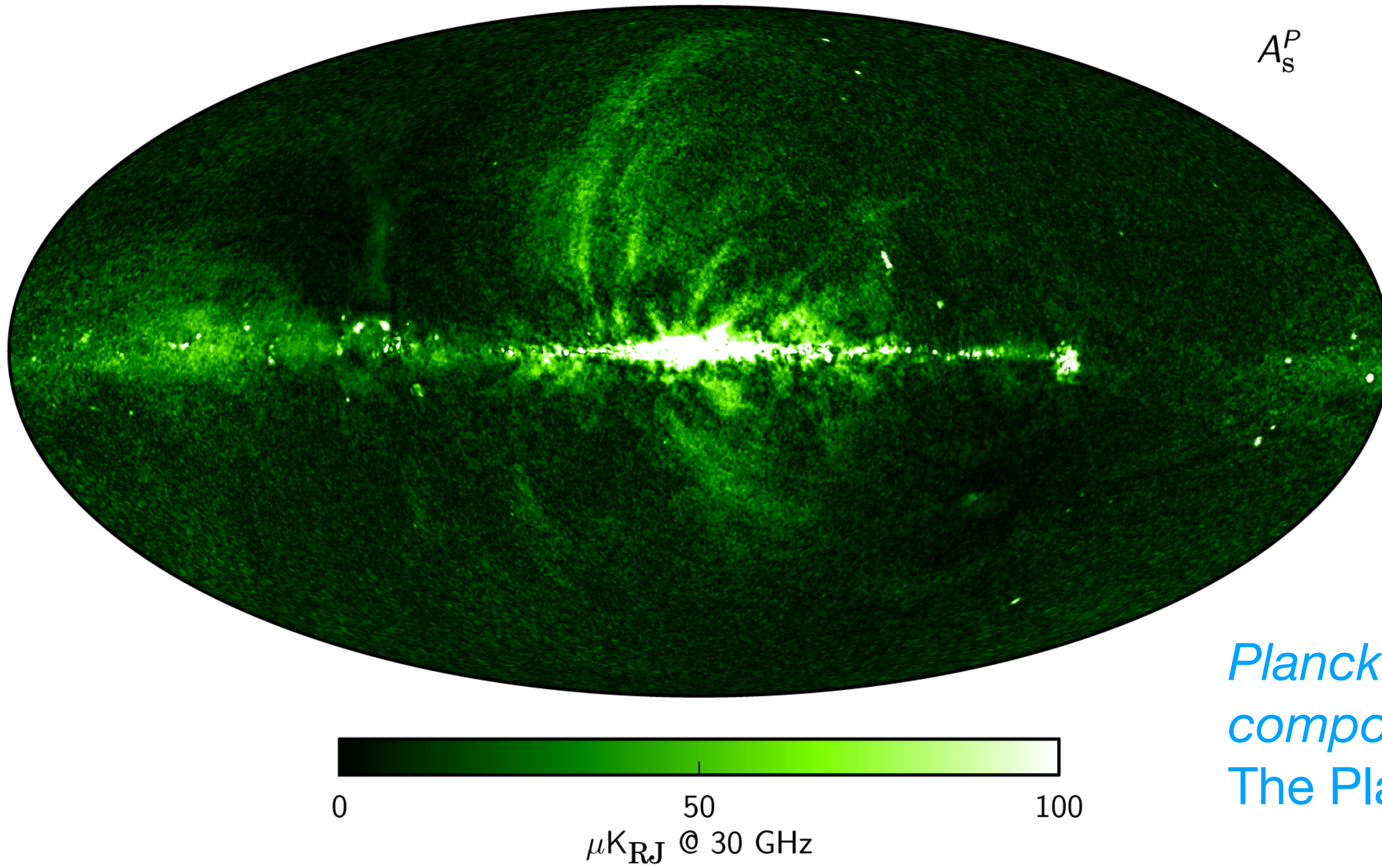
loose aggregates of smaller particles?



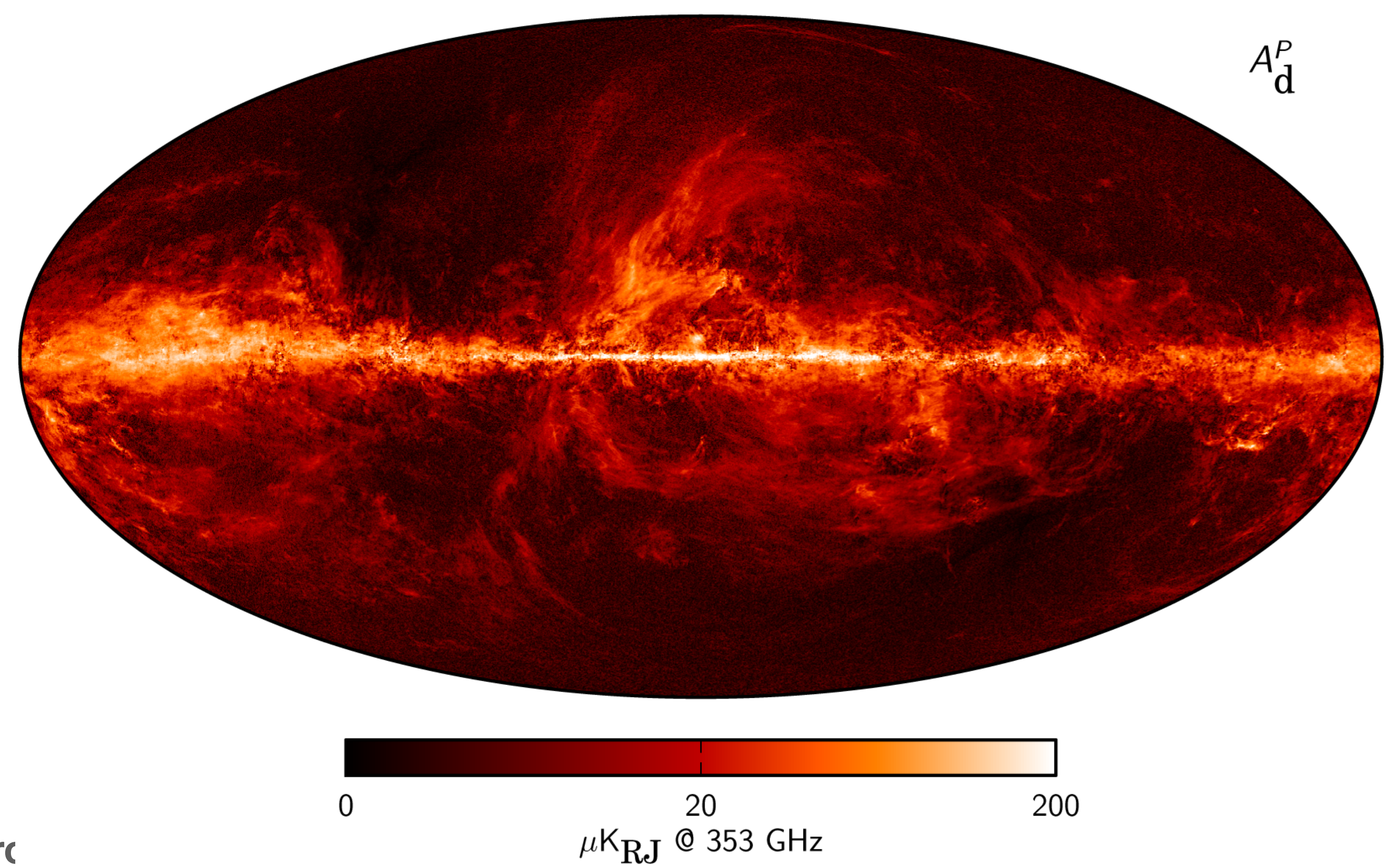
synchrotron



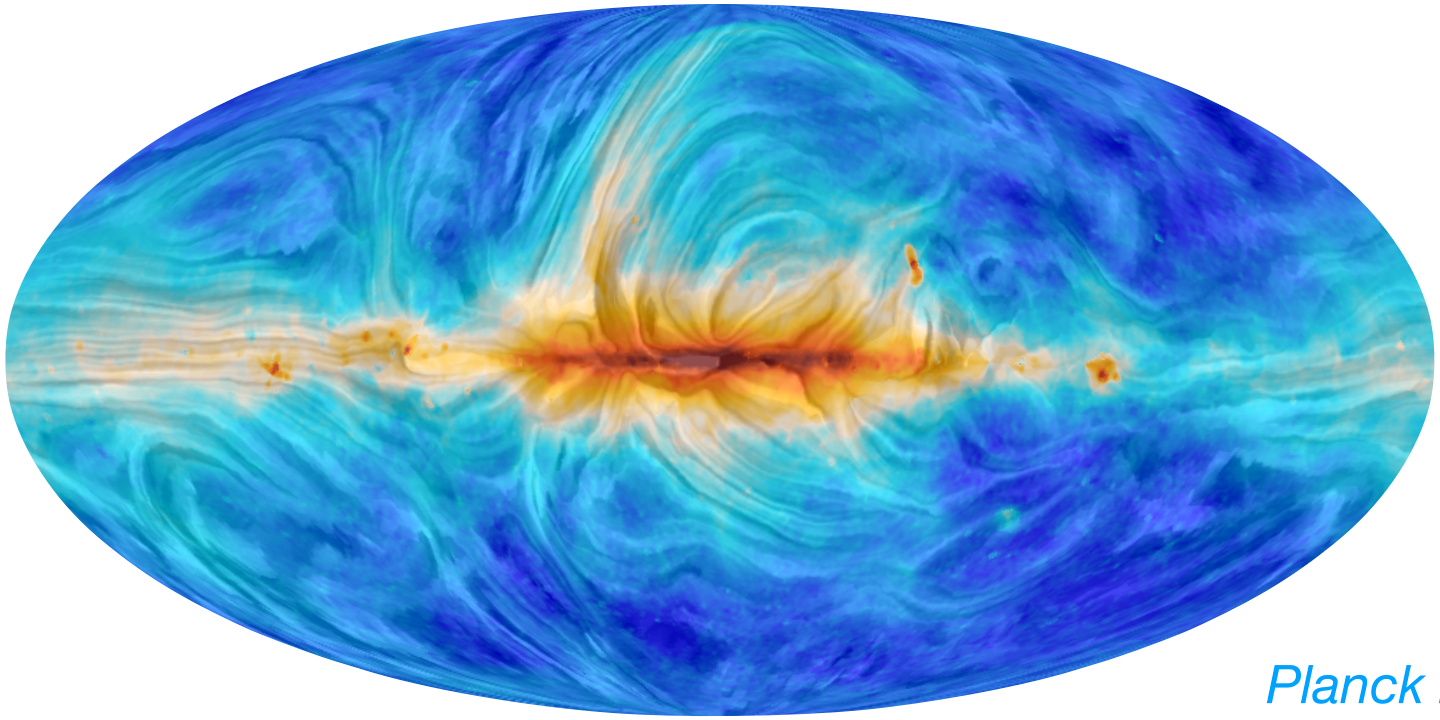
synchrotron and dust polarized emissions follow the galactic magnetic field



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

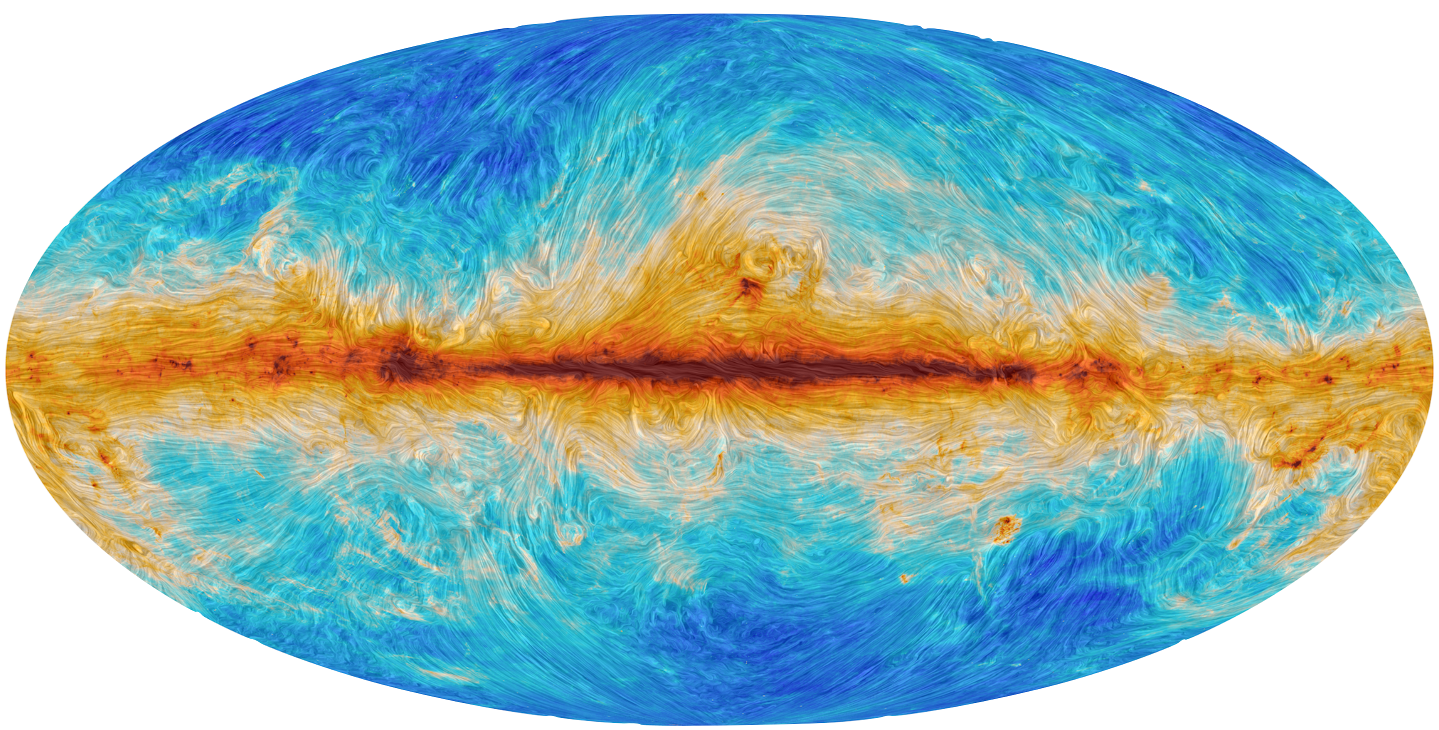


synchrotron and dust polarized emissions follow the galactic magnetic field

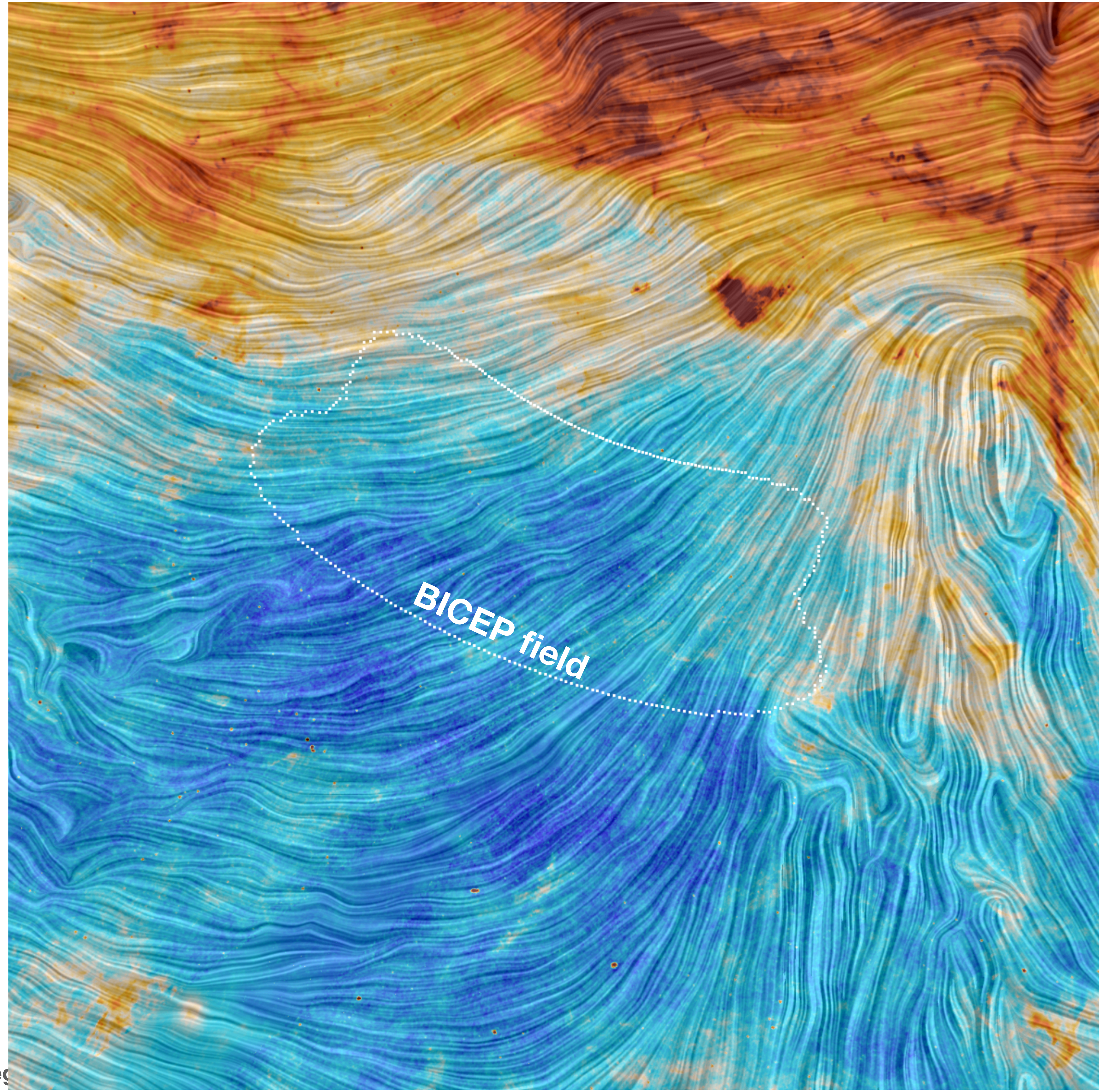


intensity @ 30GHz
+ B-field from polarization

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



intensity @ 353GHz
+ B-field from polarization


BICEP field

dust intensity and polarization

$$I(\nu) = \int S(\nu) \left[1 - p_0 \left(\cos^2\gamma - \frac{2}{3}\right)\right] \mathrm{d}\tau_\nu$$

$$Q(\nu) = \int p_0\, S(\nu)\, \cos(2\phi) \cos^2\gamma\, \mathrm{d}\tau_\nu$$

$$U(\nu) = \int p_0\, S(\nu)\, \sin(2\phi) \cos^2\gamma\, \mathrm{d}\tau_\nu$$

parameter related to dust polarization properties (the grain cross sections and the degree of alignment with the magnetic field)

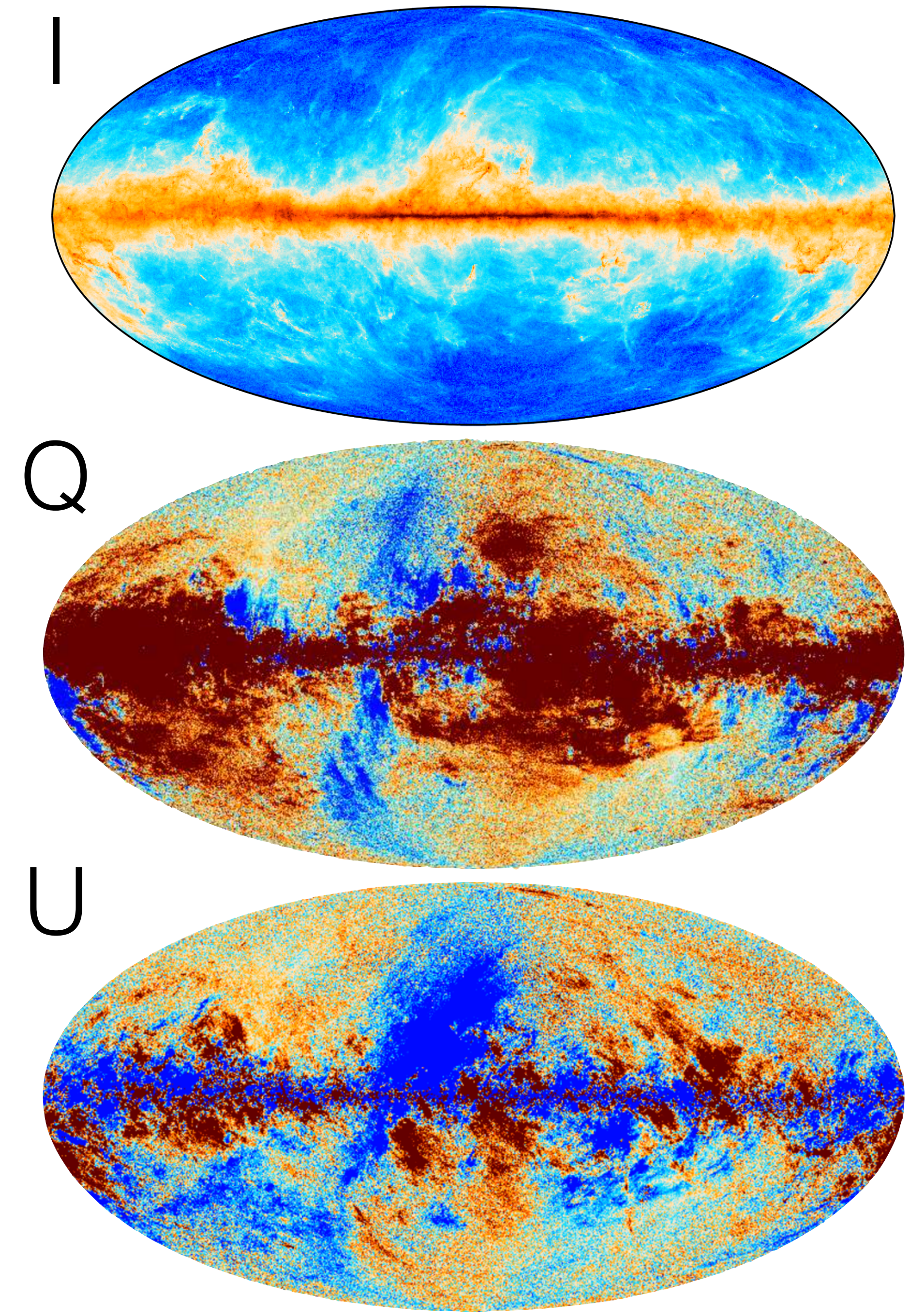
source function

local polarization angle

angle between local magnetic field and the plane of the sky

optical depth

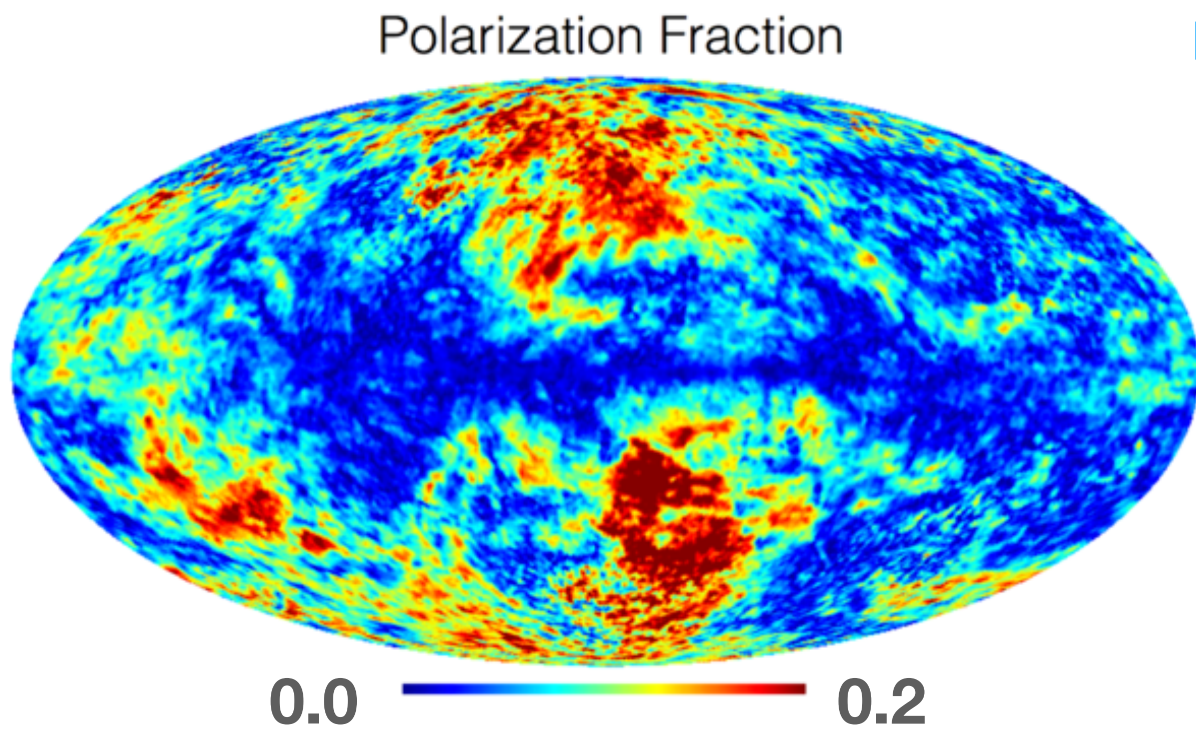
Planck Collaboration Int. XX (2015)
Vansyngel , Boulanger et al. A&A (2017)



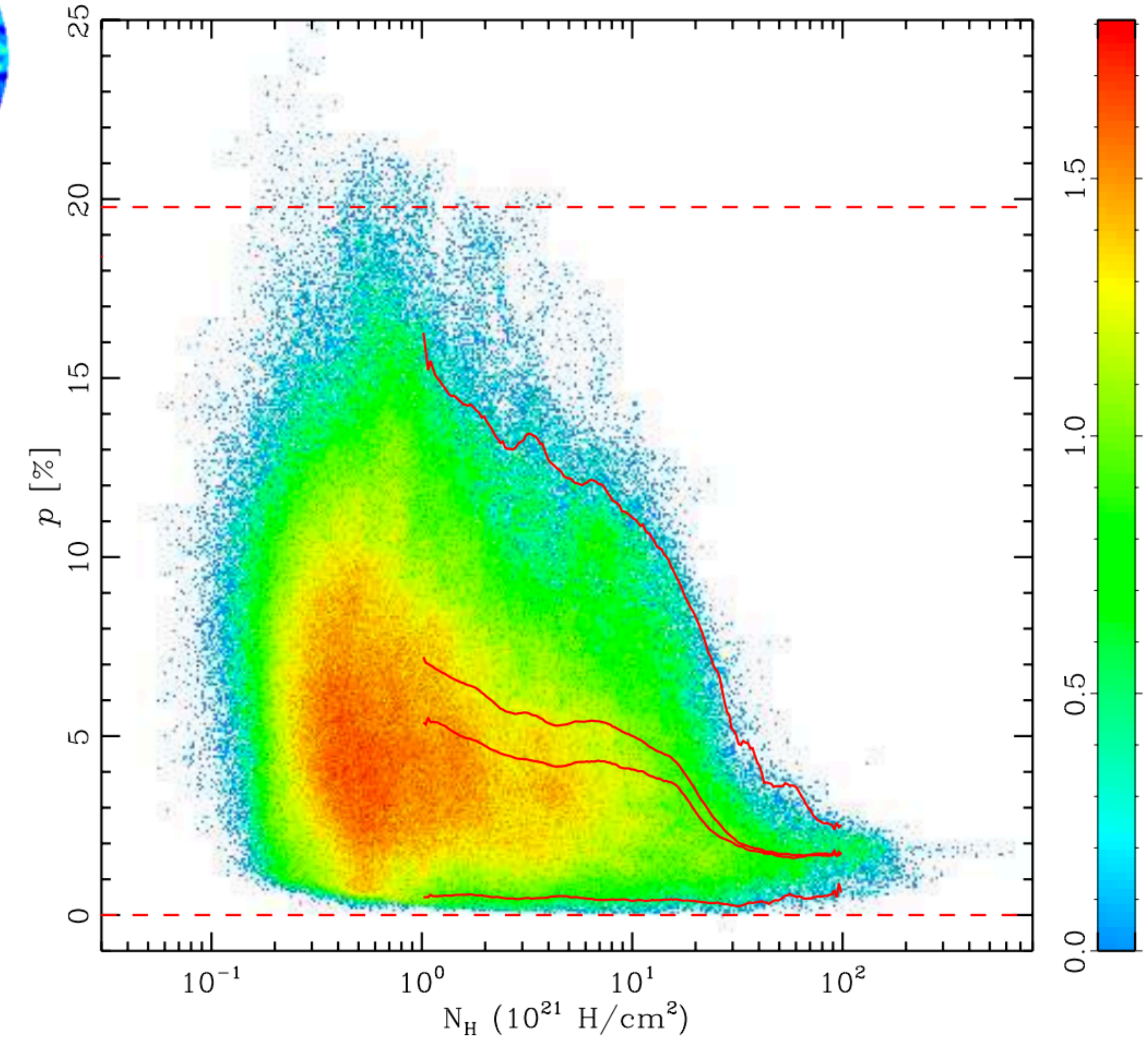
353 GHz

- fluctuations in I are dominated by column density
- fluctuations in Q and U trace column density and magnetic field orientation variations
- the large scale in Q and U are modulated by a simple geometrical effect, not present in I, due to the magnetic field of the local spiral arm

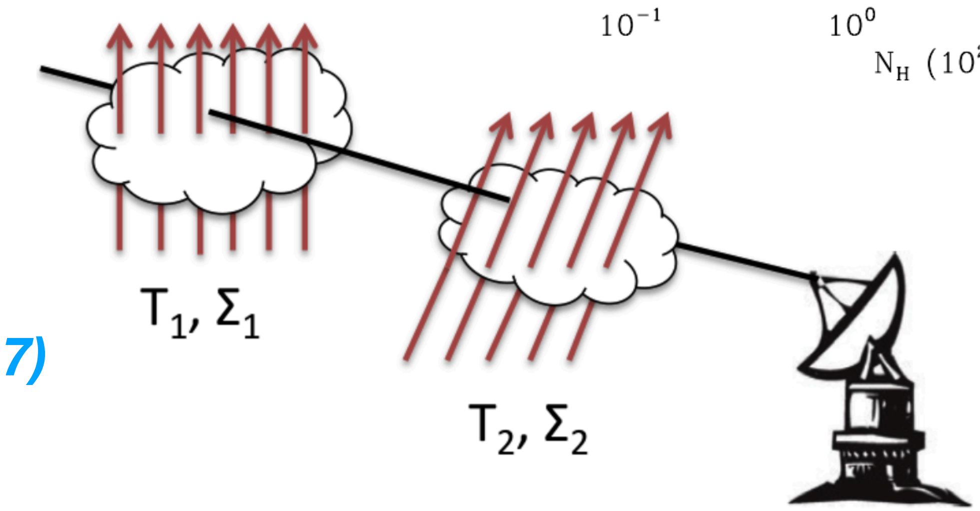
Planck intermediate results, XIX, 2014
Planck intermediate results, L, 2017



$$p \equiv \frac{\sqrt{Q^2 + U^2}}{I}$$



- Polarization fraction up to 20%.
- Large dispersion of p at all N_H, tracing changes in B-field orientation and depolarization associated with interstellar turbulence
- Rapid decrease of $p > 10^{22}$ H/cm^2 — interpreted by a loss of grain alignment in the shielded interiors of clouds and depolarization inside the galactic plane.



Tassis & Pavlidou (2015)
Vansyngel, Boulanger et al (2017)
Gosh et al (2017)

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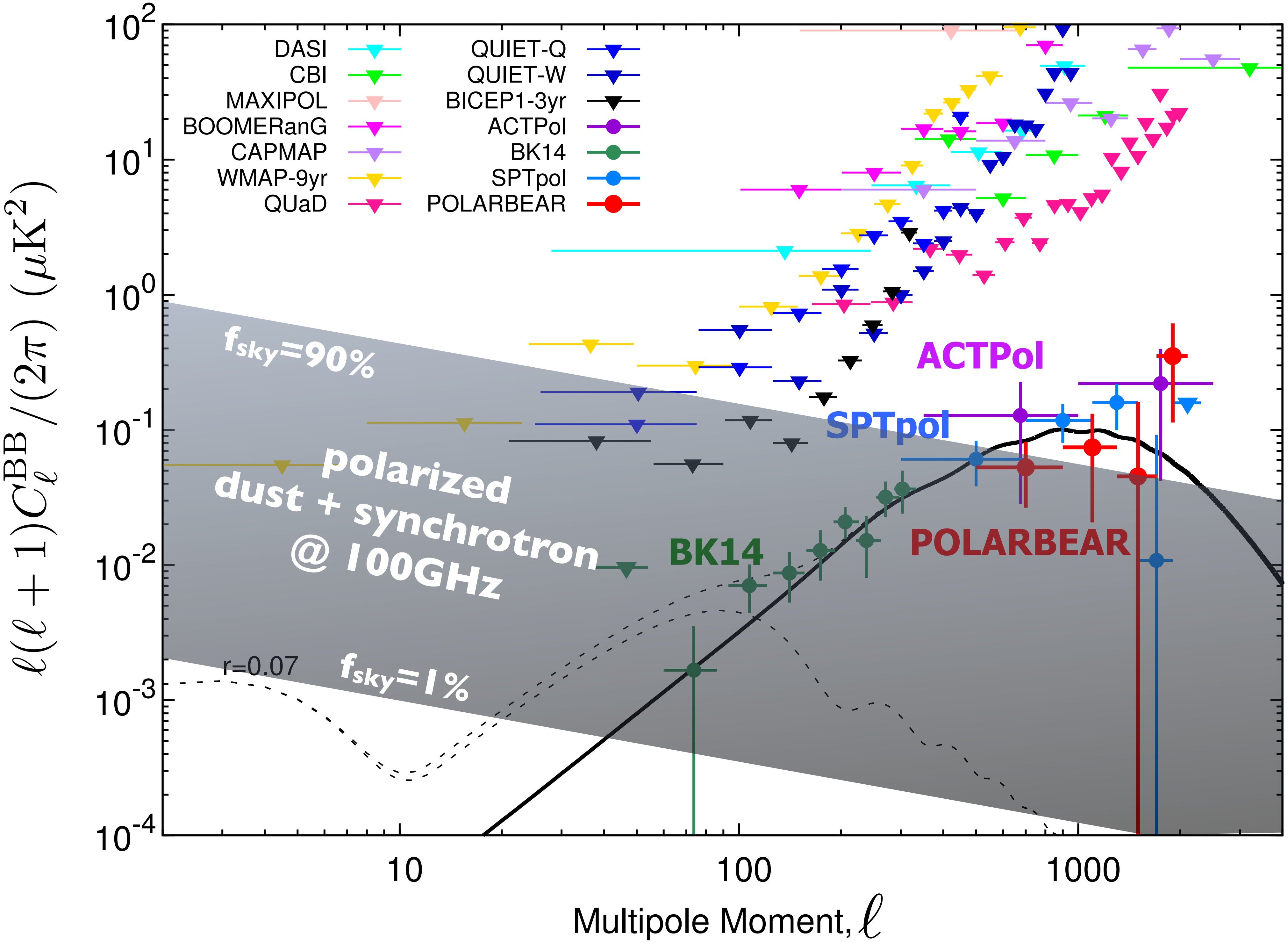
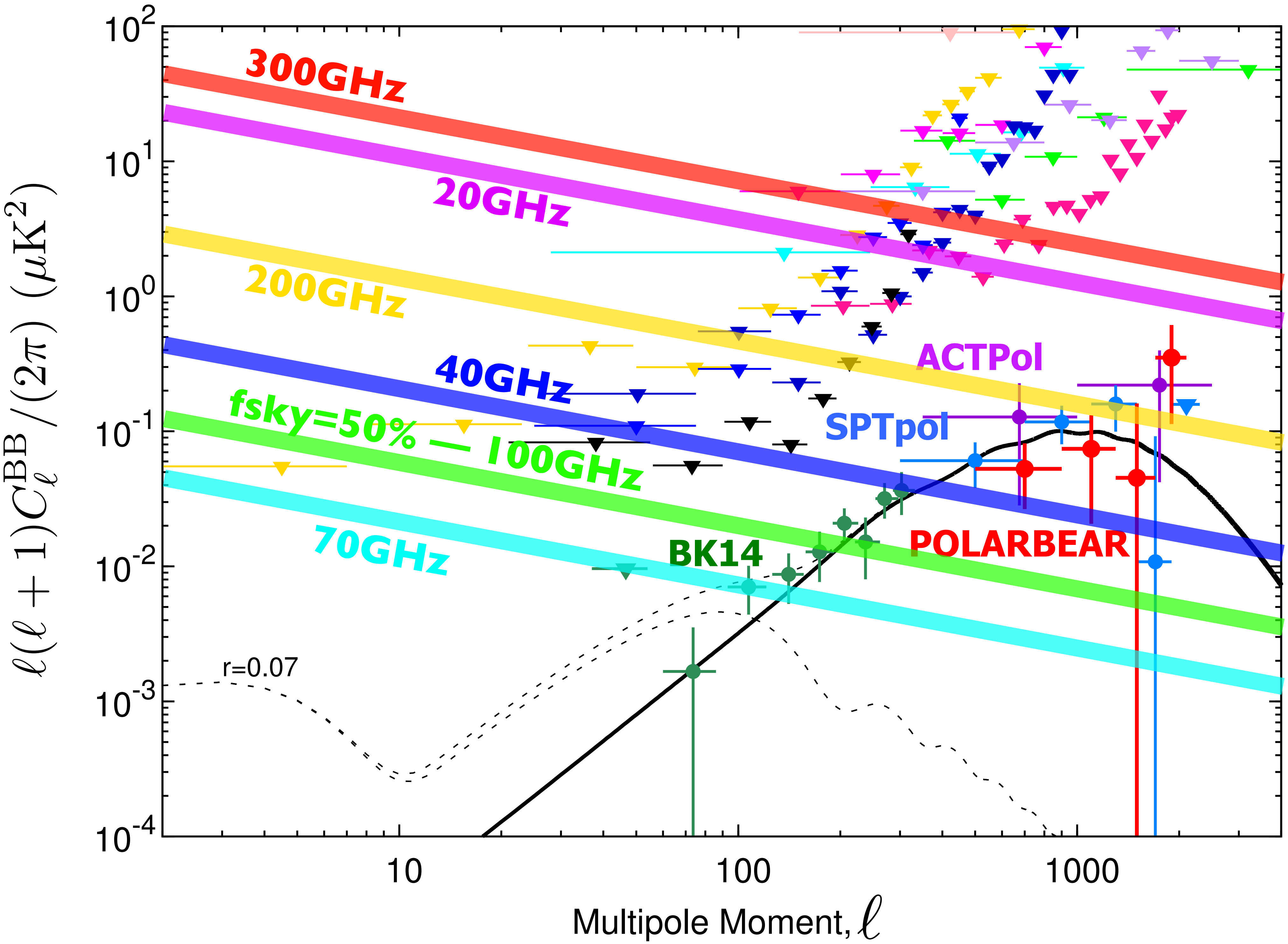
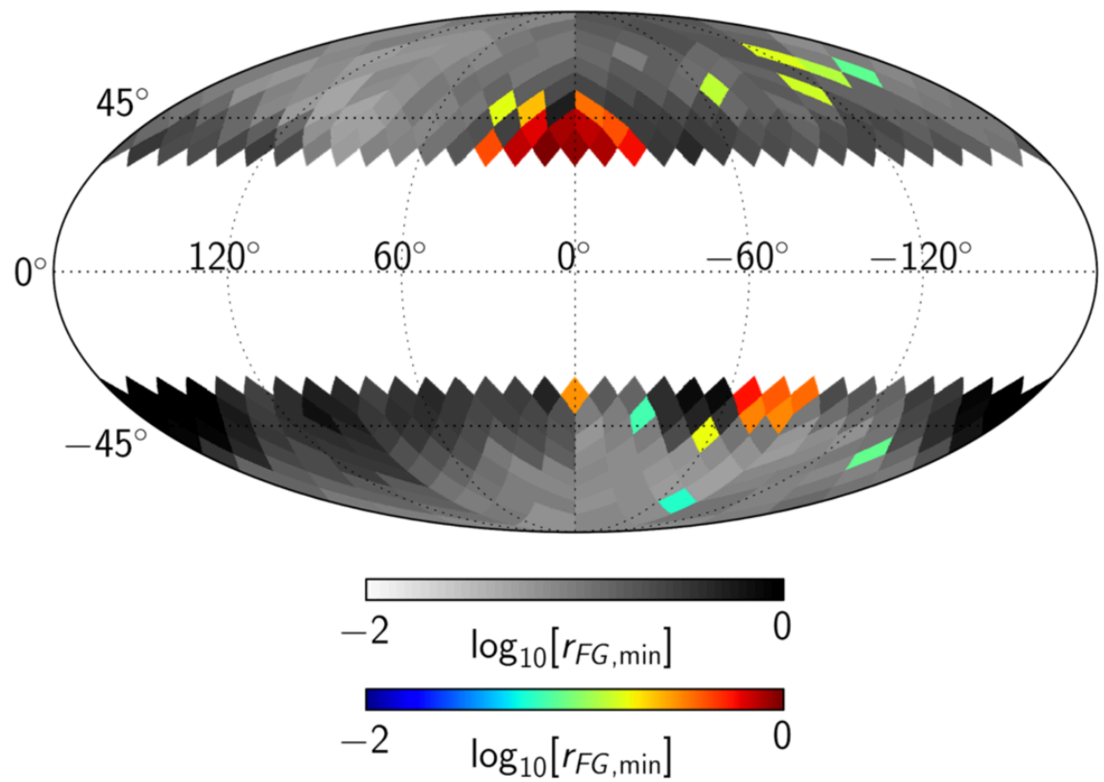


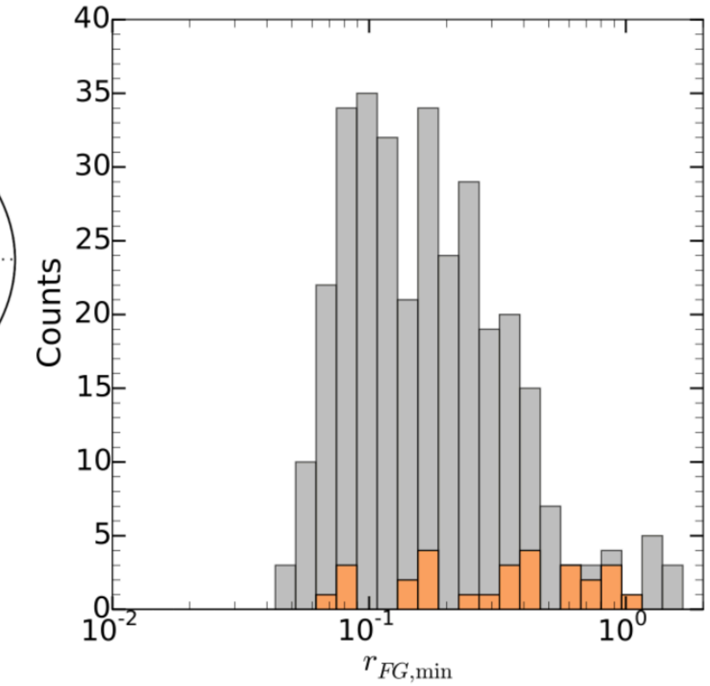
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10
100
1000
$\ell(\ell+1)C_\ell^{\rm BB}/(2\pi)\ (\mu{\rm K}^2)$
Multipole Moment, ℓ
DASI
CBI
MAXIPOL
BOOMERanG
CAPMAP
WMAP-9yr
QUaD
QUIET-Q
QUIET-W
BICEP1-3yr
ACTPol
BK14
SPTpol
POLARBEAR
f_{sky}=90%
polarized
dust + synchrotron
@ 100GHz
f_{sky}=1%
r=0.07
BK14
ACTPol
SPTpol
POLARBEAR



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

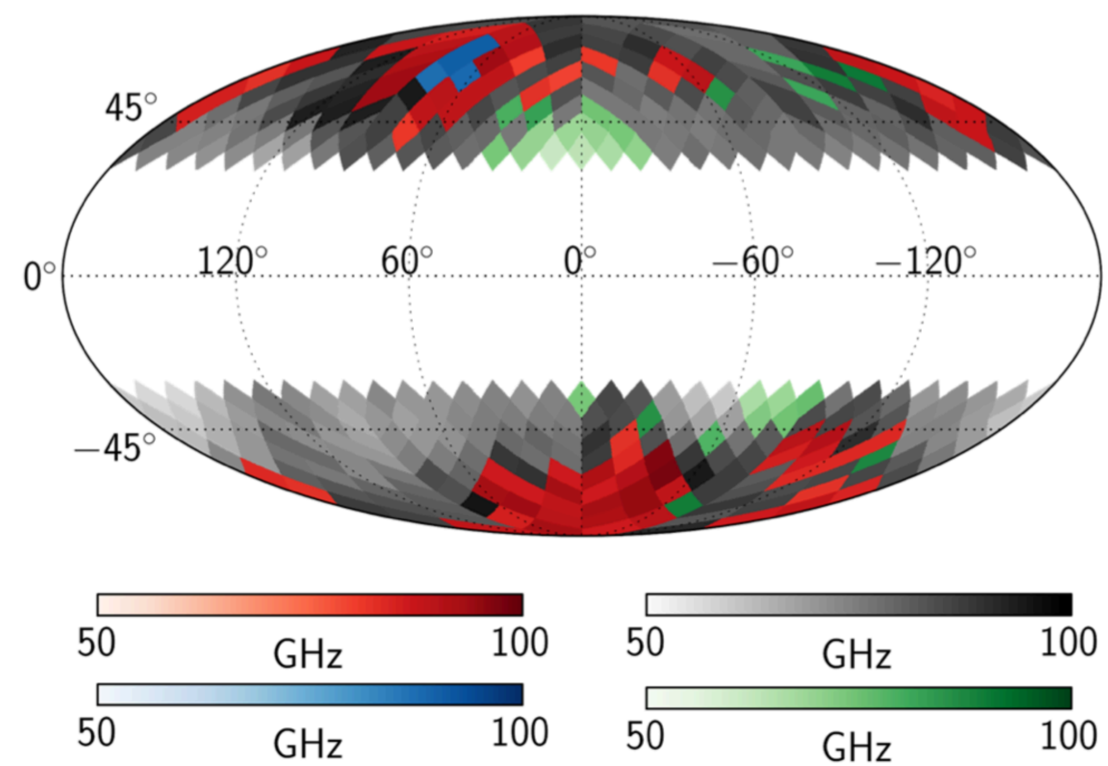
Foregrounds cleaning, option #1 : avoid them?

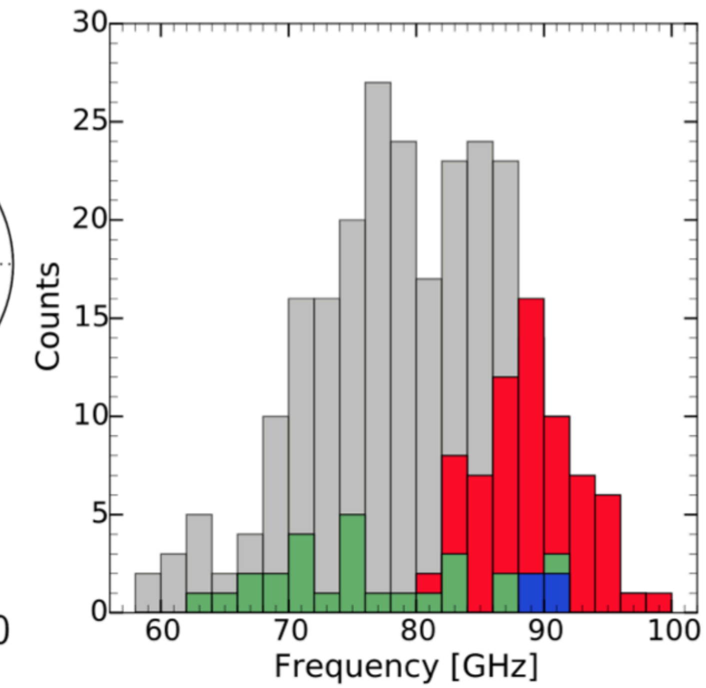




Characterization of foreground emission at degree angular scale for CMB B-modes observations
N. Krachmalnicoff, C. Baccigalupi et al (2016)

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





Foregrounds cleaning, option #2 : remove them

analogy interlude

Foregrounds cleaning, option #2 : remove them

analogy interlude

One or multiple dust components?

CMB

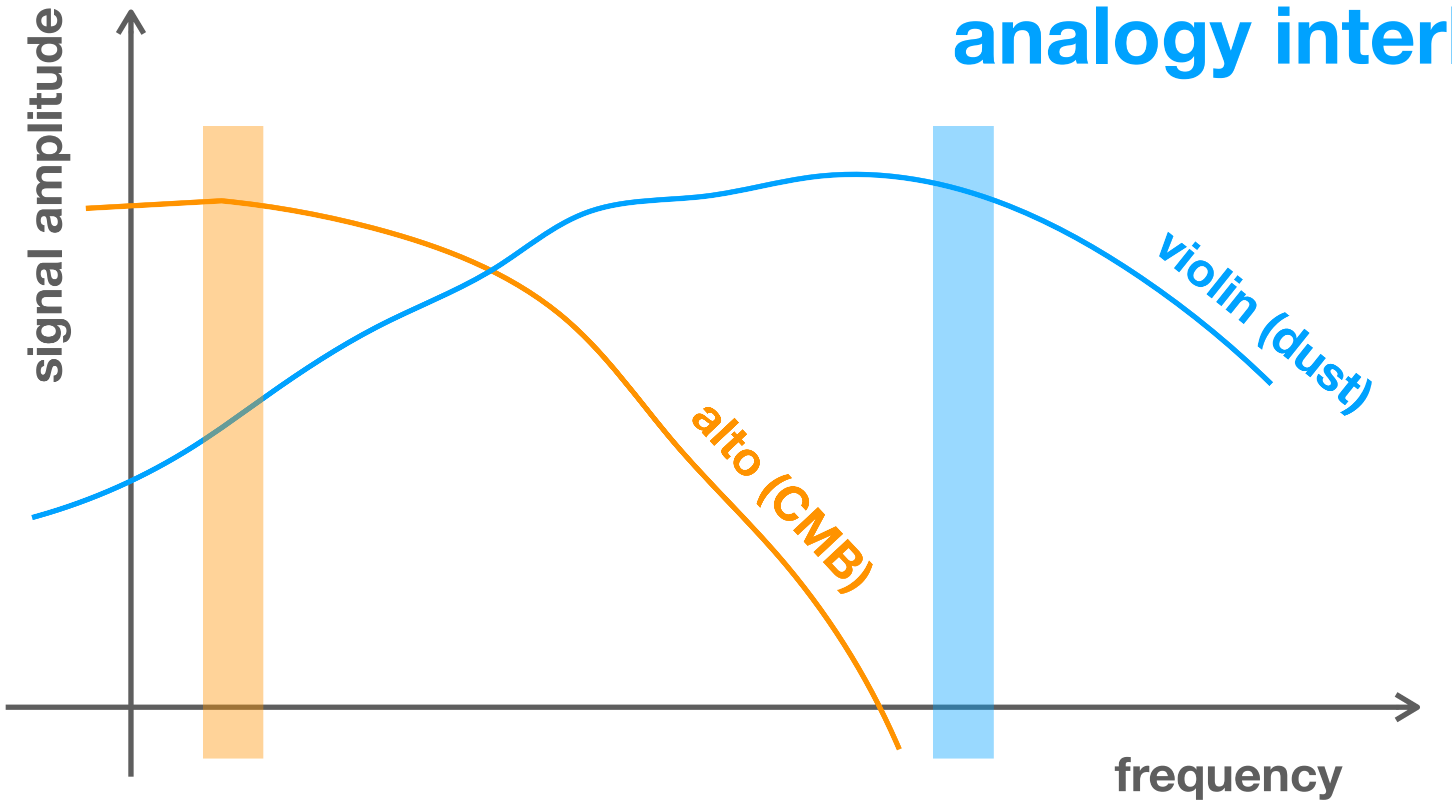
Anomalous Microwave Emission (AME)?

Synchrotron

(black body)

Foregrounds cleaning, option #2 : remove them

analogy interlude



- removing one or several components increase the noise variance in the final "clean" component
- misestimating a spectrum leaks components to the "clean" component (can be statistical or systematic misestimation)

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

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

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

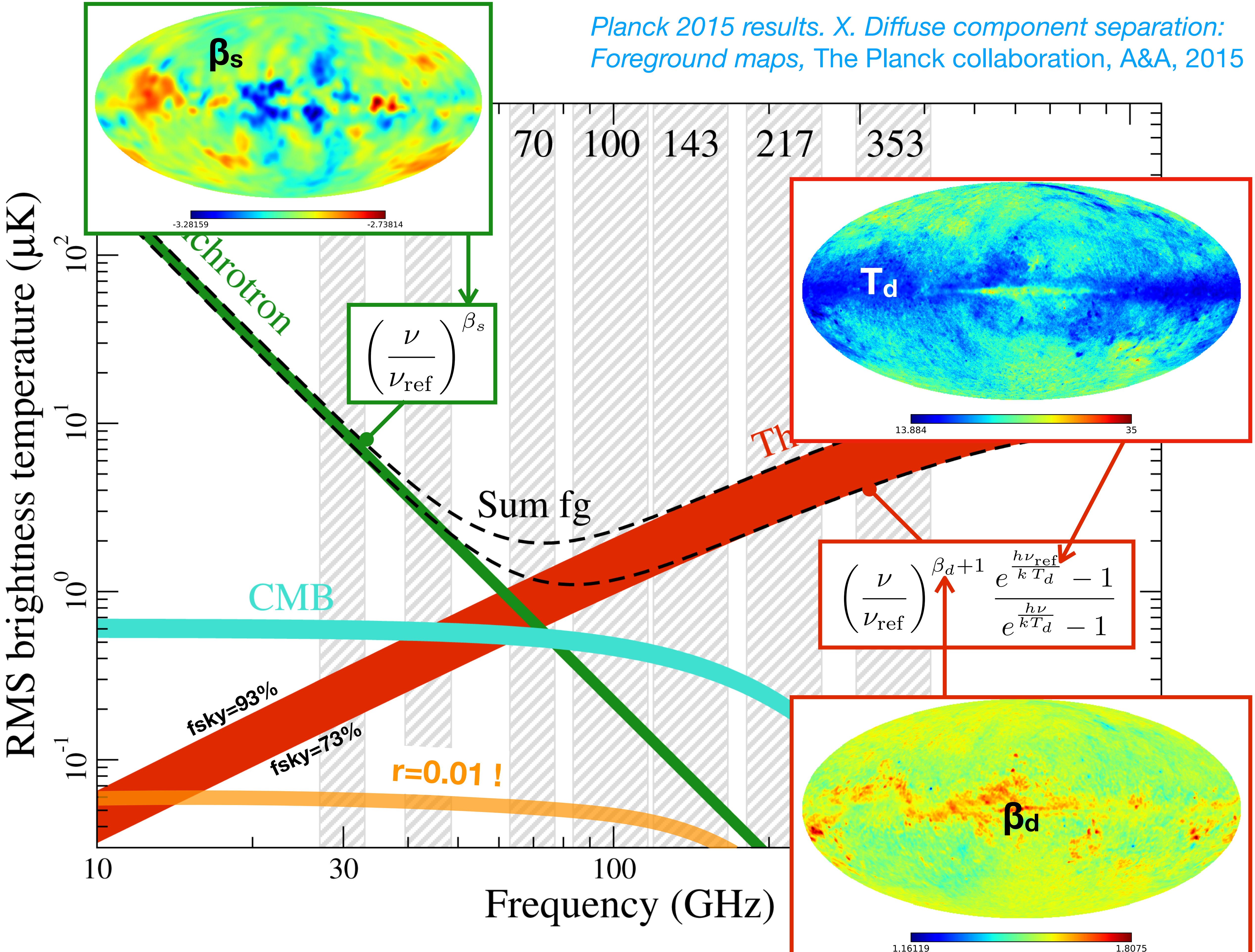
boosted variance

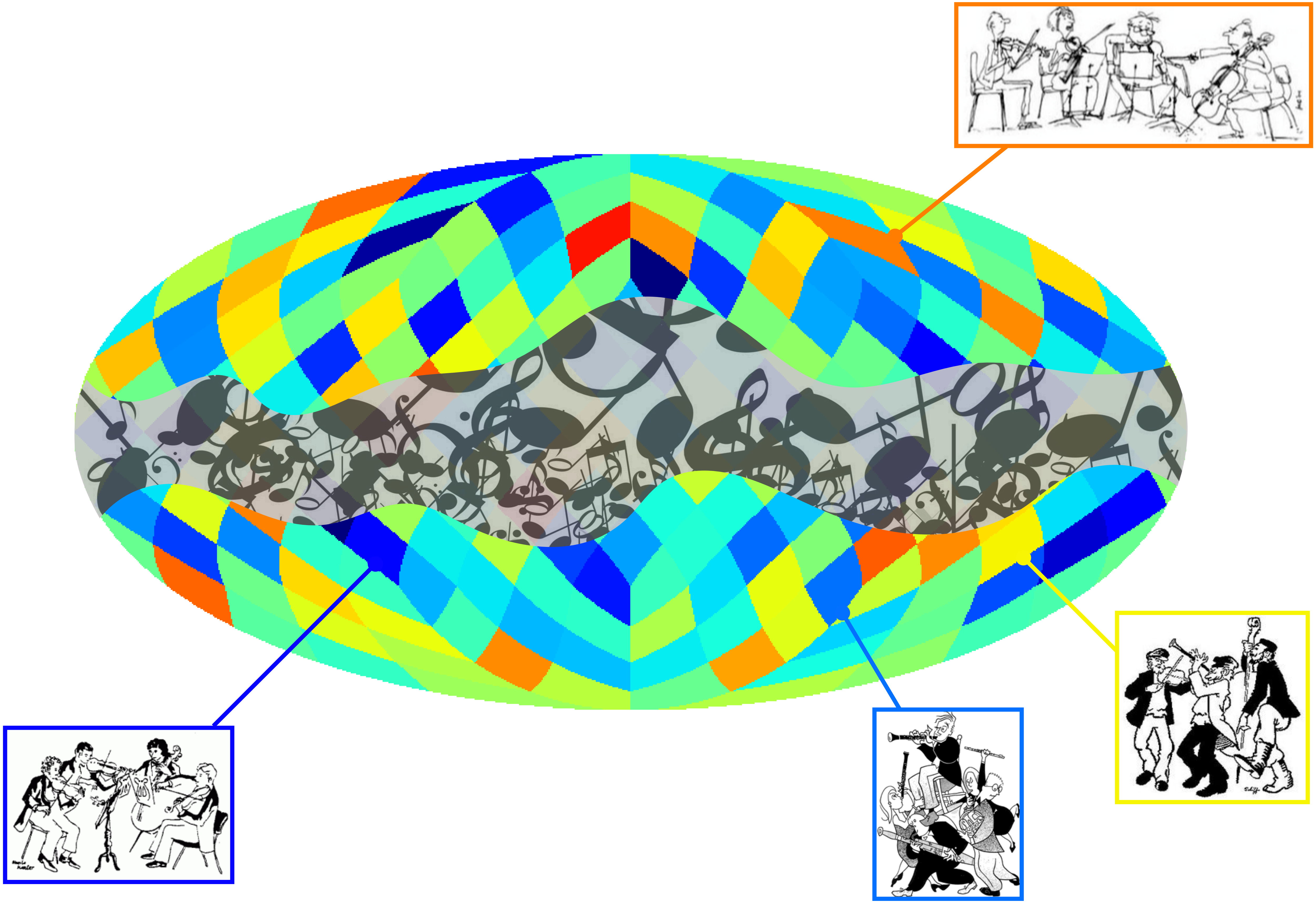
$$\sigma^2_{\mathrm{CMB}} = \frac{\sigma^2_{\nu_0} b_1^2 + \sigma^2_{\nu_1} b_0^2}{\left(b_1 a_0 - b_0 a_1\right)^2}$$

statistical/systematic residuals in the cleaned signal

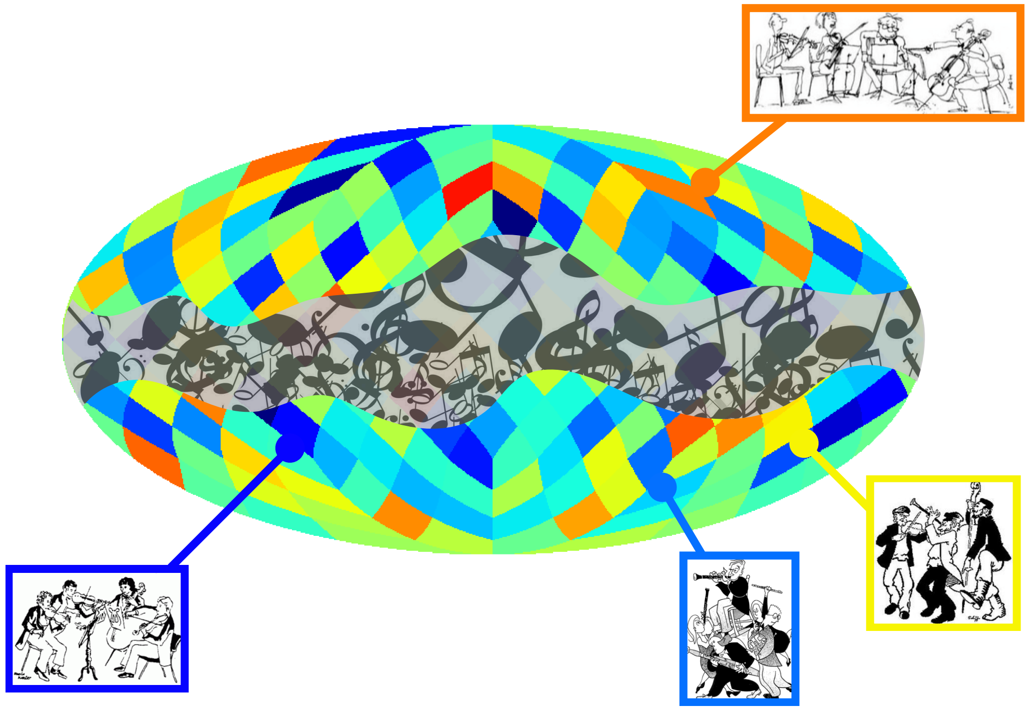
$$\delta\mathrm{CMB} \propto \delta b_1 \left(\alpha\, d_{\nu_0} + \beta\, d_{\nu_1}\right)$$

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



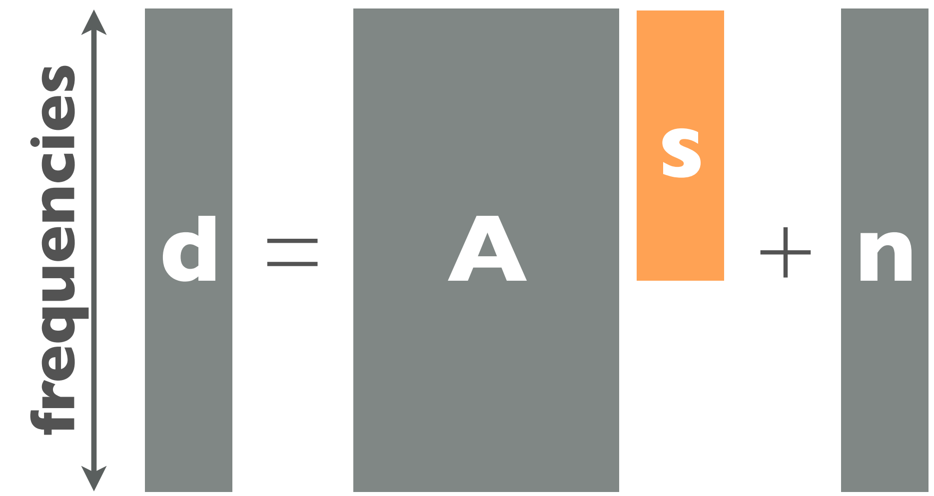


Rendition of parametric max-likelihood component separation



data modeling
for each sky pixel:

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



1. estimation of the mixing matrix A

e.g. Stompor et al. (2009)

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

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

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

not perfect recovery of input spectral parameters ➤ foregrounds residuals

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

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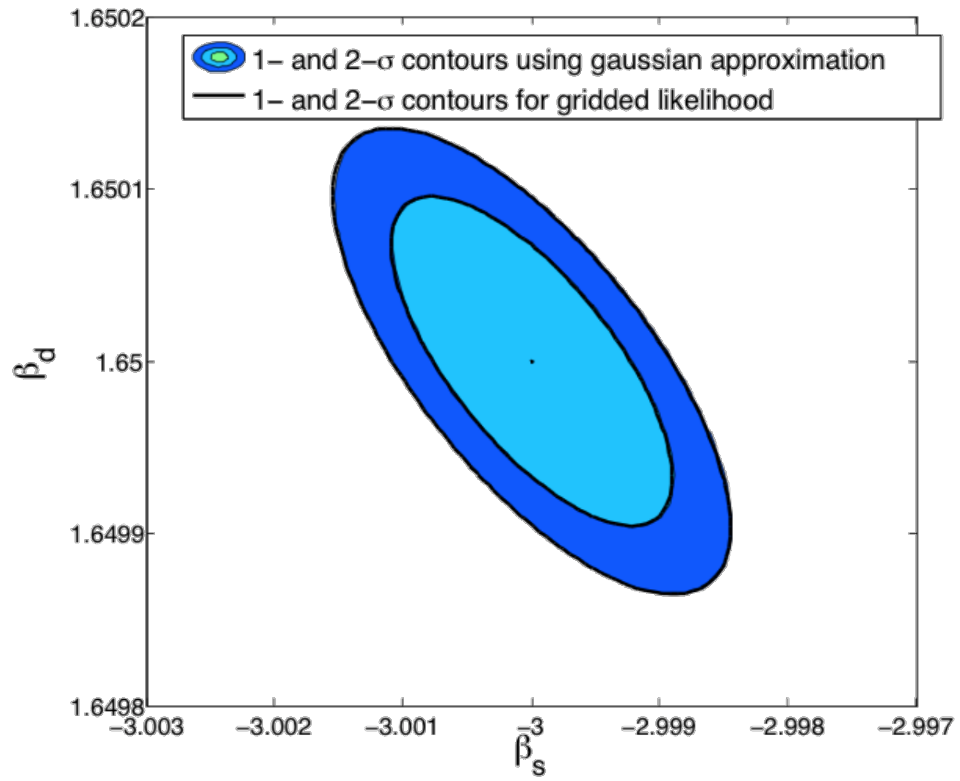
Rendition of parametric max-likelihood component separation

Statistical error bars on spectral parameters:



Errard, Stivoli and Stompor (PRD, 2011)

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

➔ averaged error bars for parametric methods like COMMANDER

Amplitude of statistical foregrounds residuals:

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

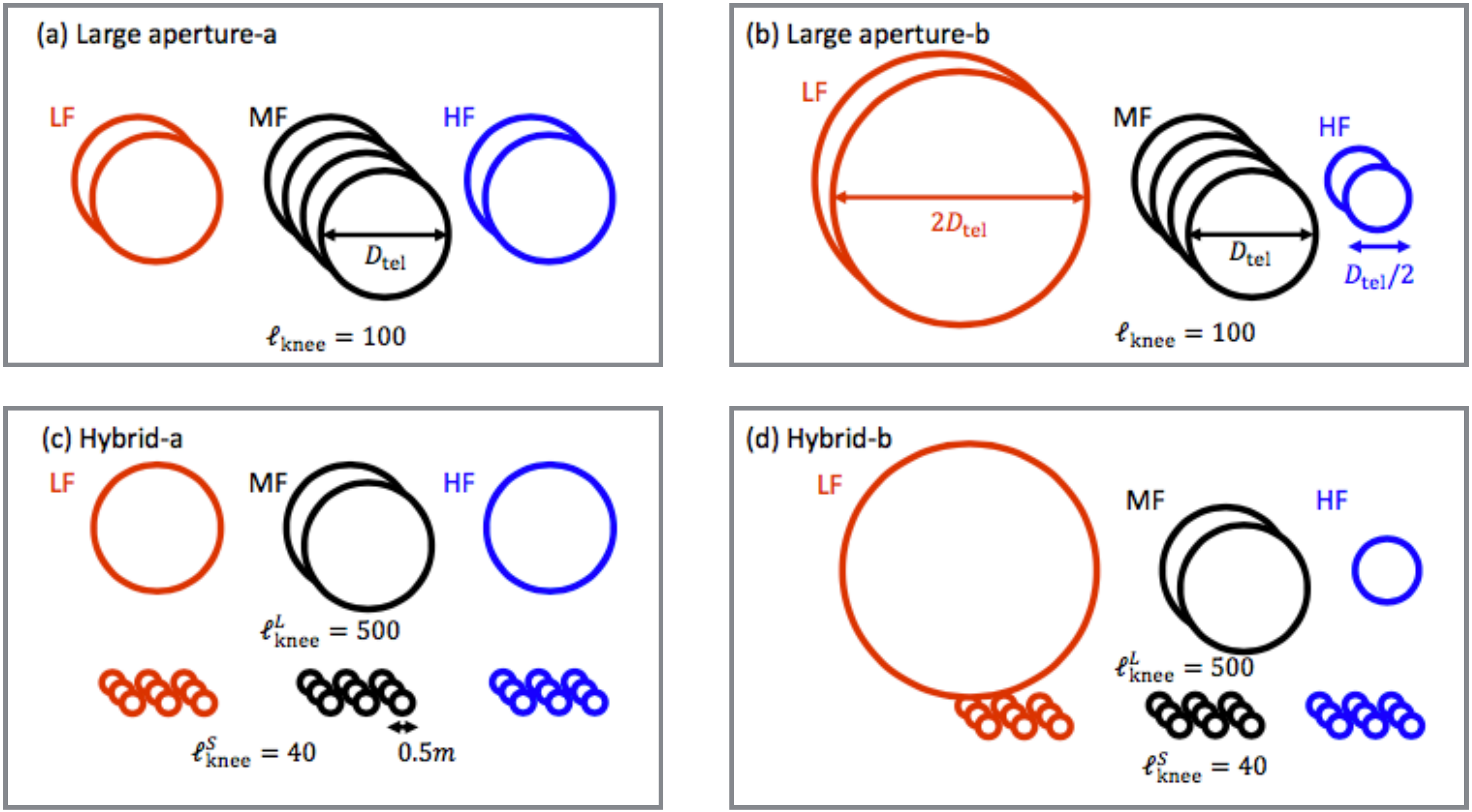
Stivoli, Grain, Leach, Tristram, Baccigalupi, Stompor (MNRAS, 2010)

Combination with delensing and cosmological parameters estimation:

CMB4CAST GROUNDS

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

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



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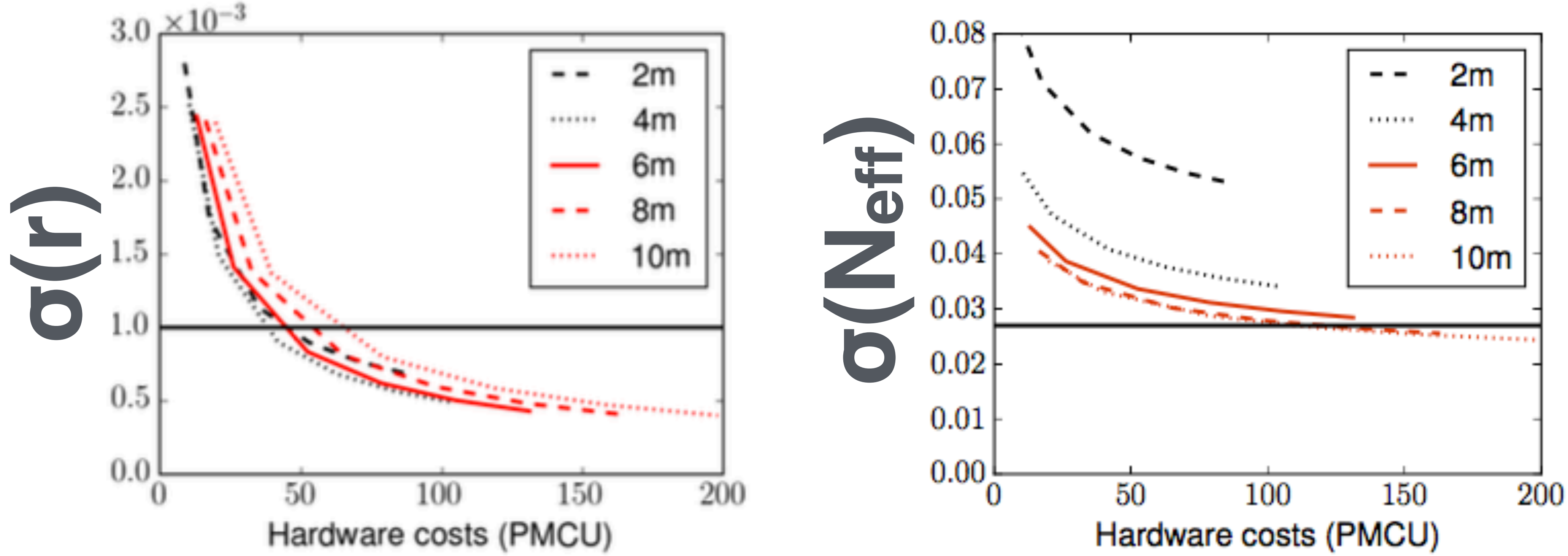


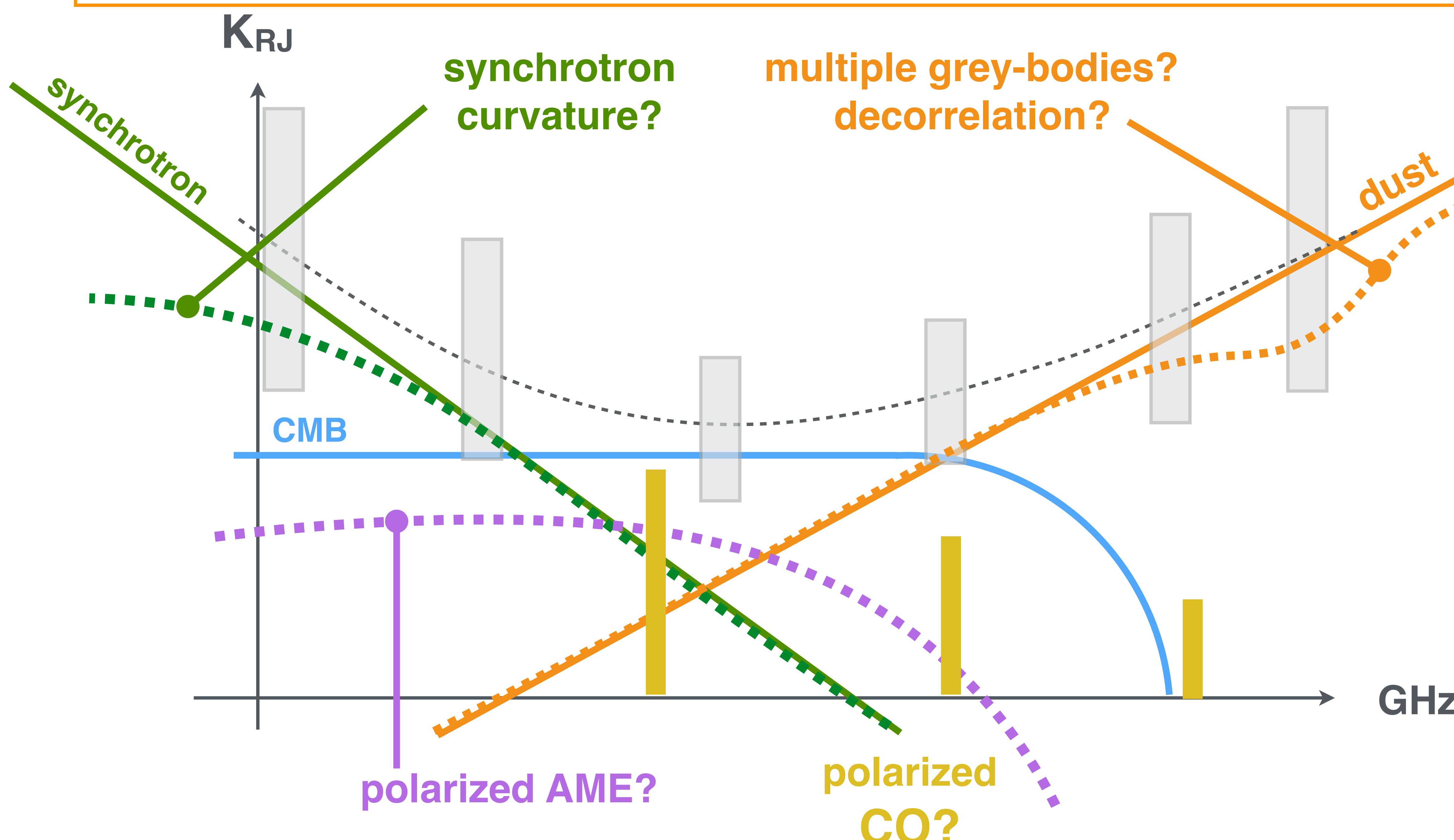
Figure 12 Constraint on r with $f_{\rm sky} = 0.05$ (left) and $N_{\rm eff}$ with $f_{\rm sky} = 0.5$ (right) for different apertures, as a function of the total cost of the project. Both are for the large aperture telescope array with fixed aperture sizes (*Large aperture-a*). For both, the improvement 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

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

xForecast [Stompor, Errard, Poletti (PRL, 2016)]



xForecast

simul... (+ ...atics)

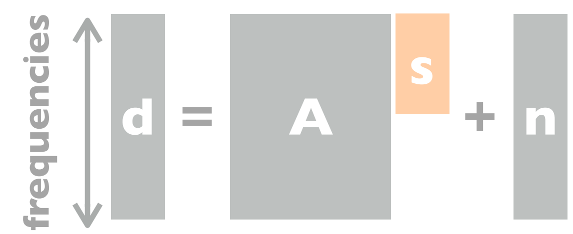
CMB (r=0) + PySM dust and synchrotron

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

toy designs

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

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



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

estimation of statistical and systematic foregrounds residuals

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

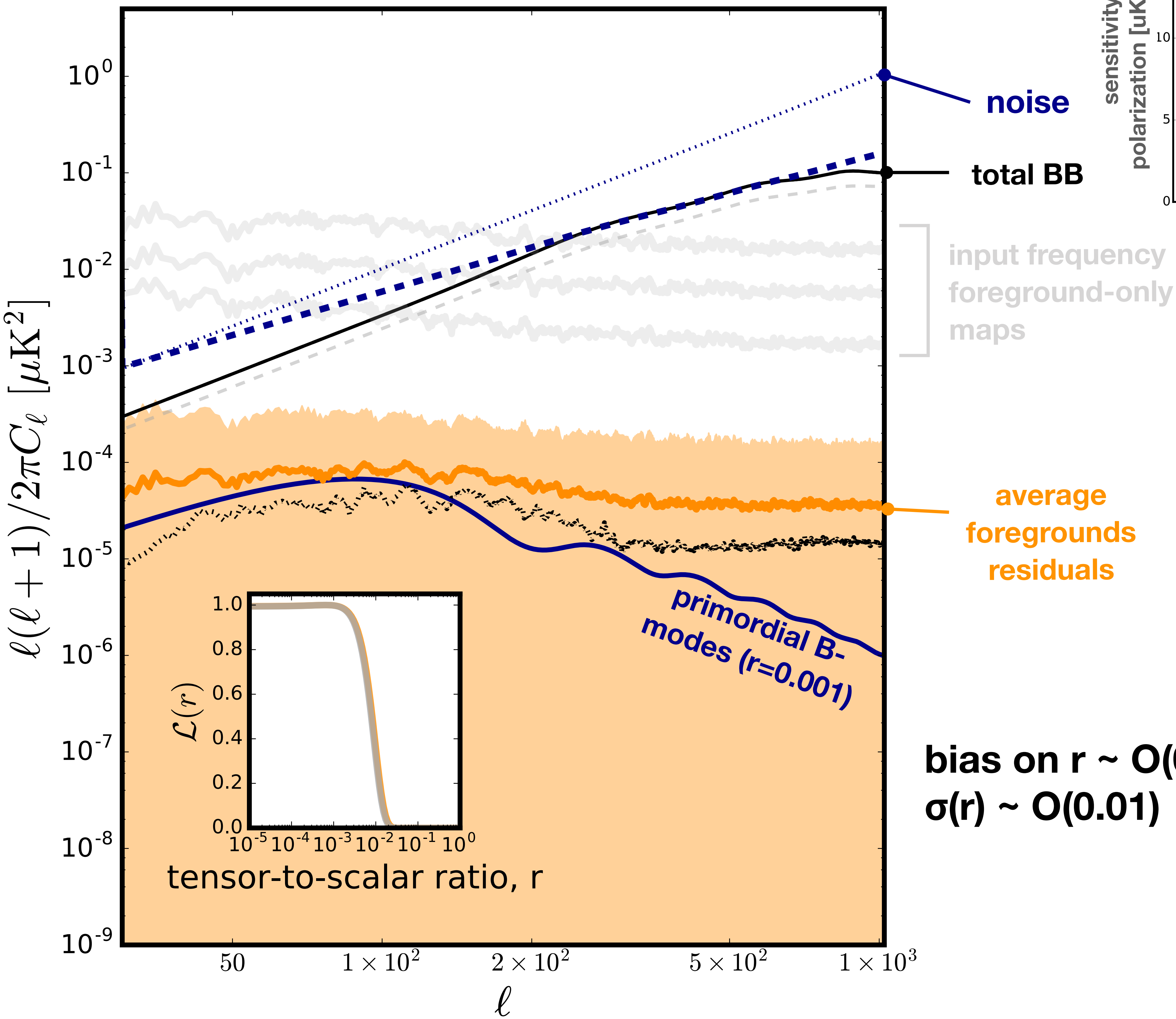
propagation of these to the estimation of tensor-to-scalar ratio *r*

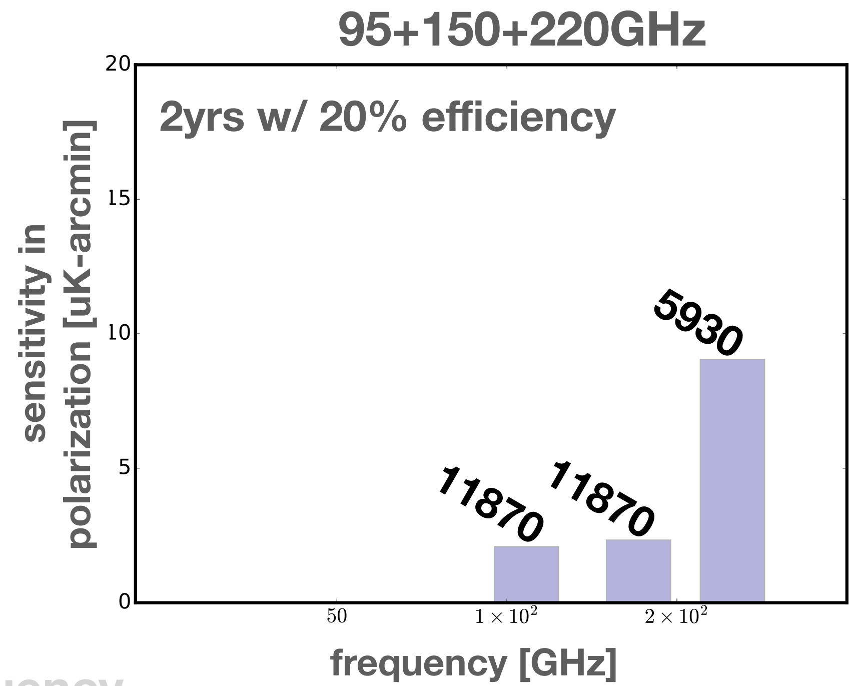
$$\langle \mathcal{S}^{par} \rangle = \mathrm{tr}\, \mathbf{C}^{-1}\mathbf{E} + \ln \det \mathbf{C}$$

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%

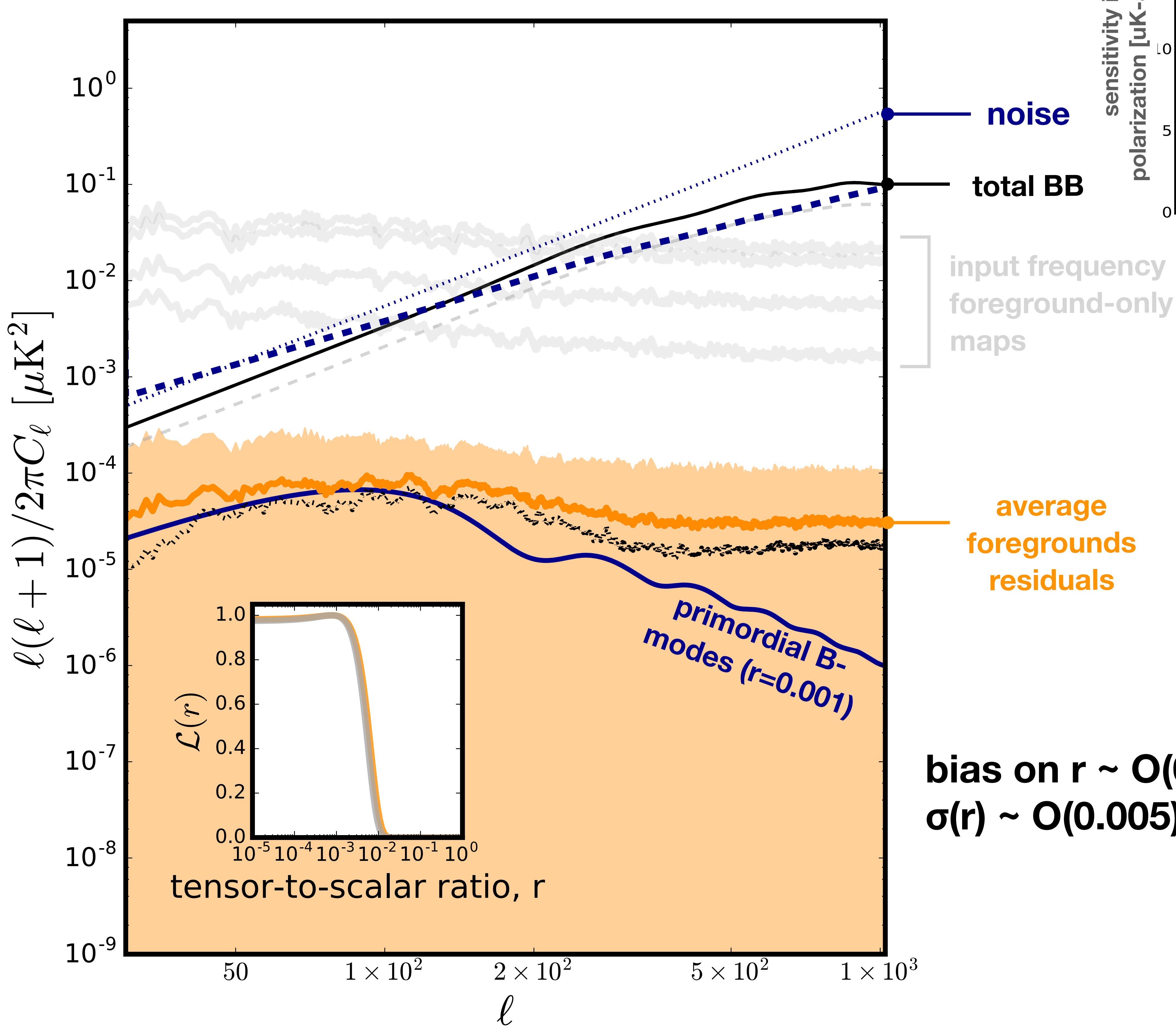


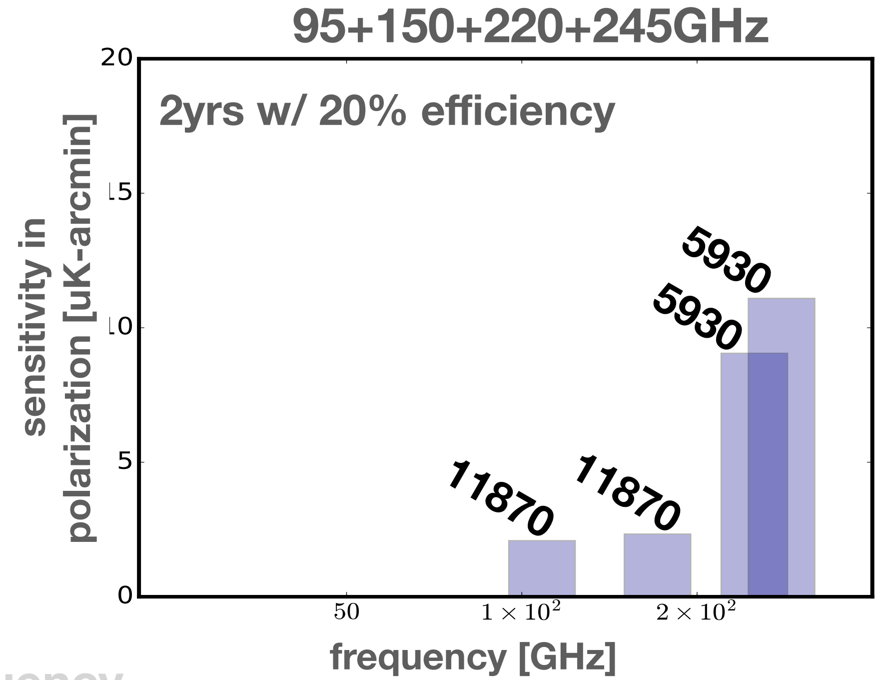


bias on r ~ O(0.001-0.01)
σ(r) ~ O(0.01)

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%

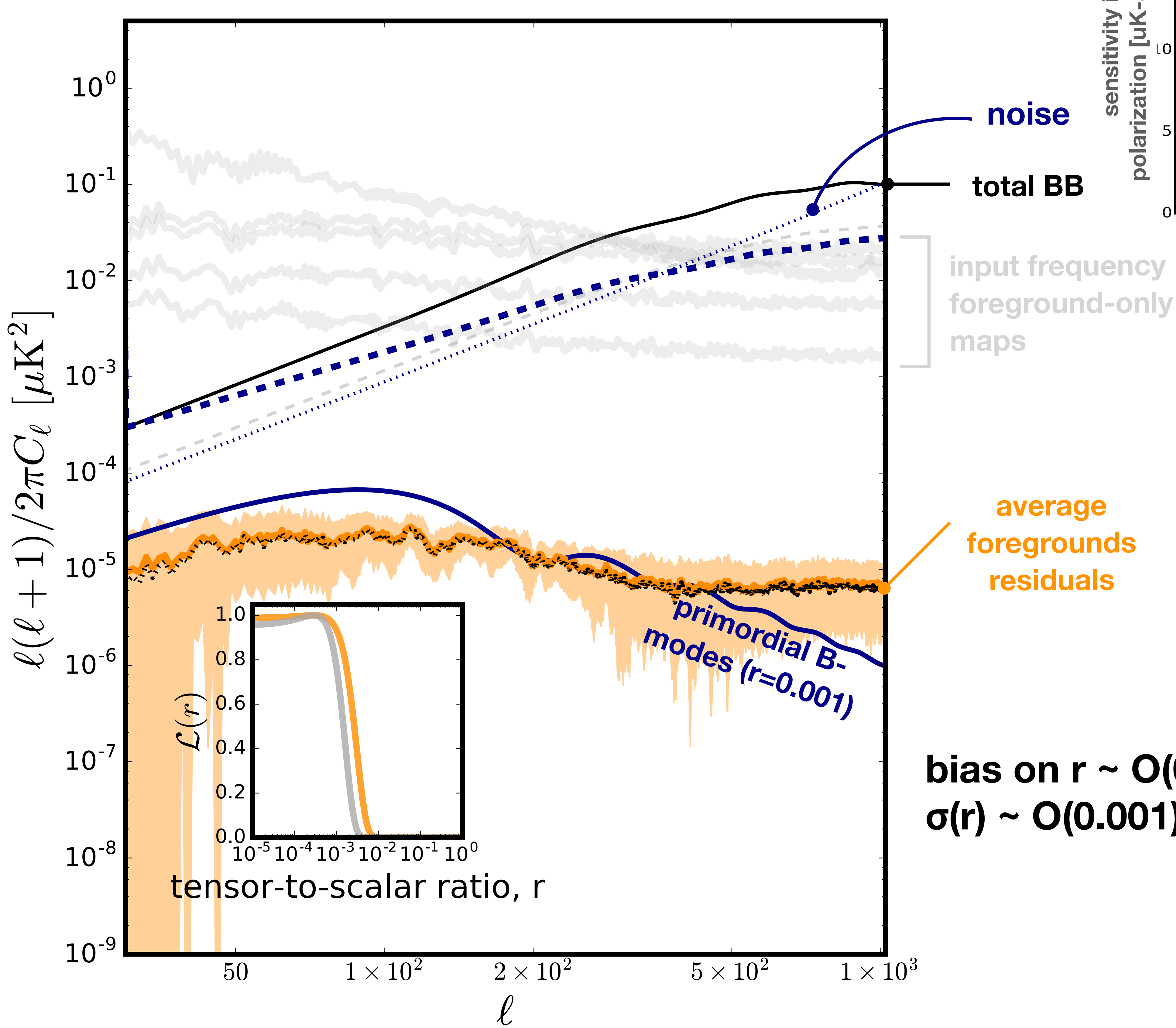


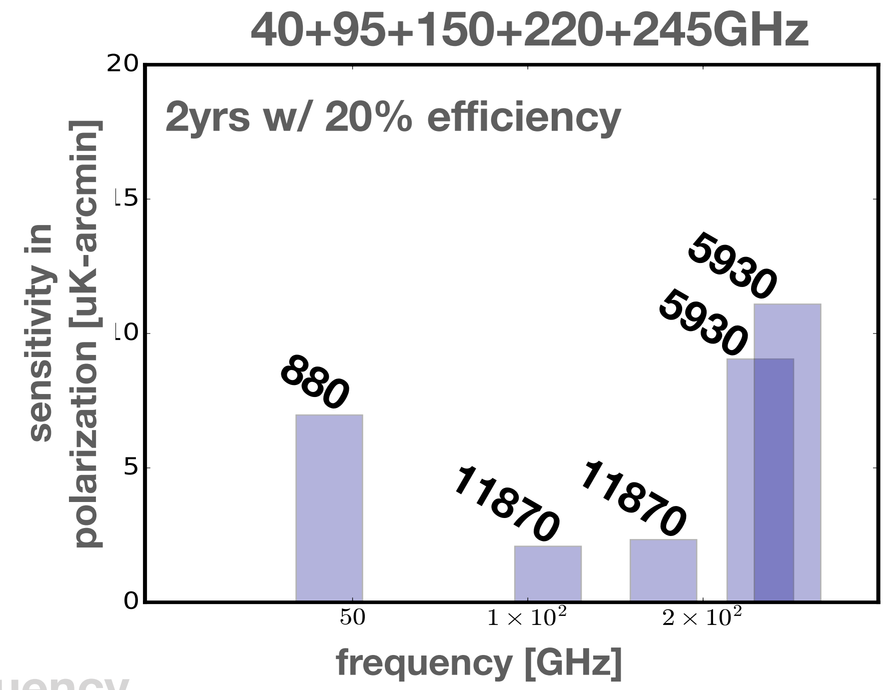


bias on r ~ O(0.001-0.005)
σ(r) ~ O(0.005)

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%

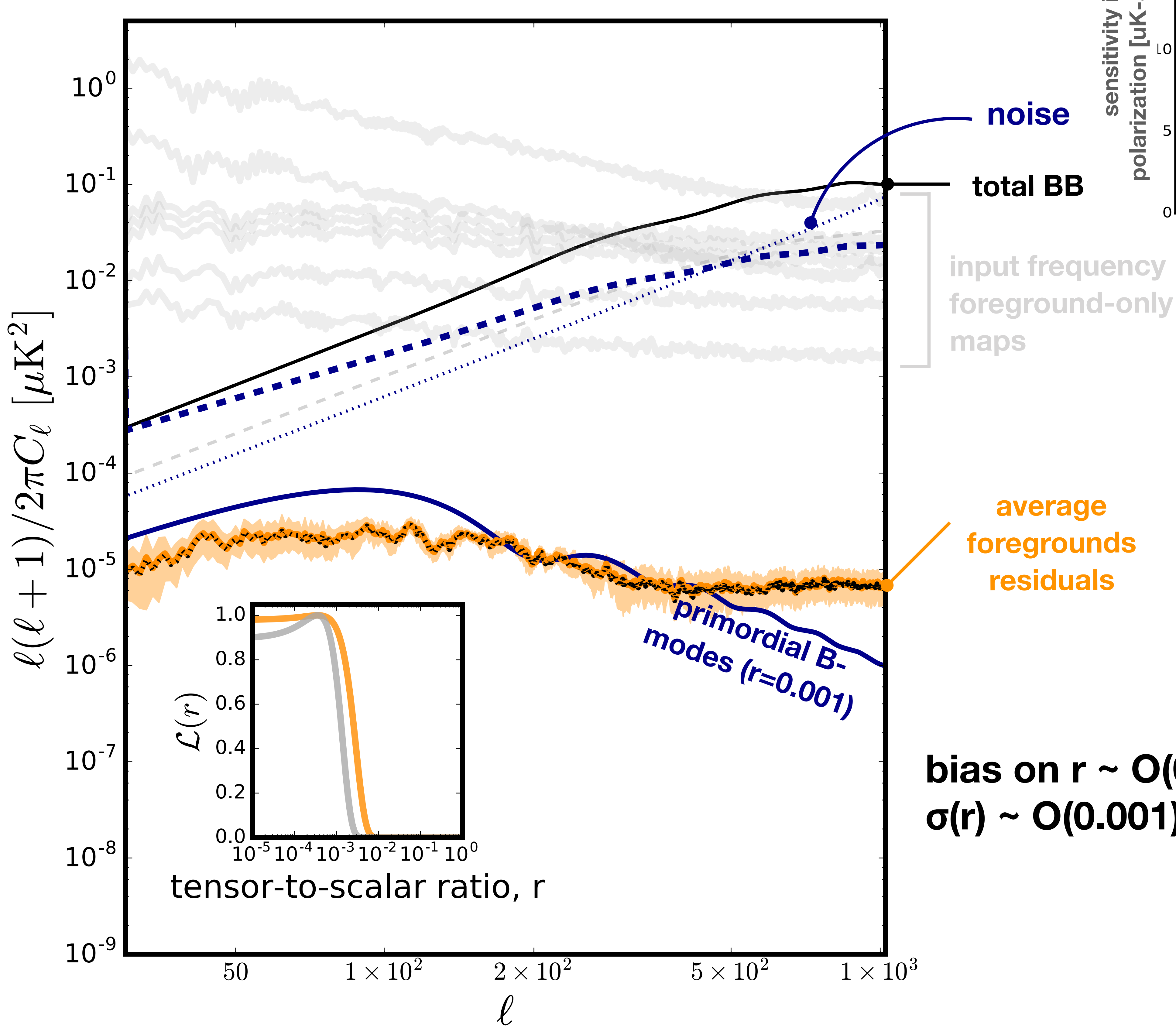


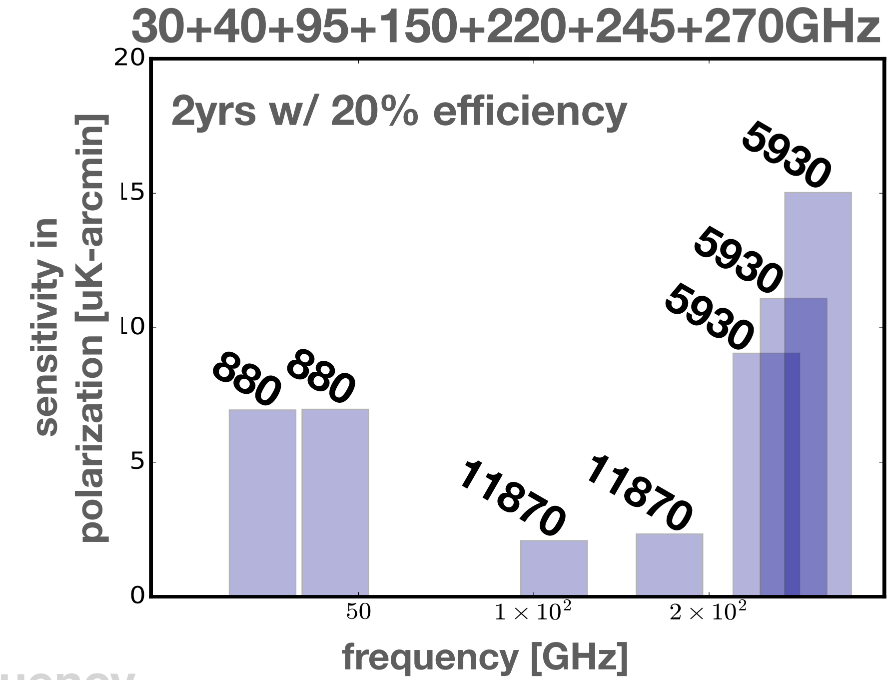


bias on r ~ O(0.0005)
σ(r) ~ O(0.001)

toy example

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

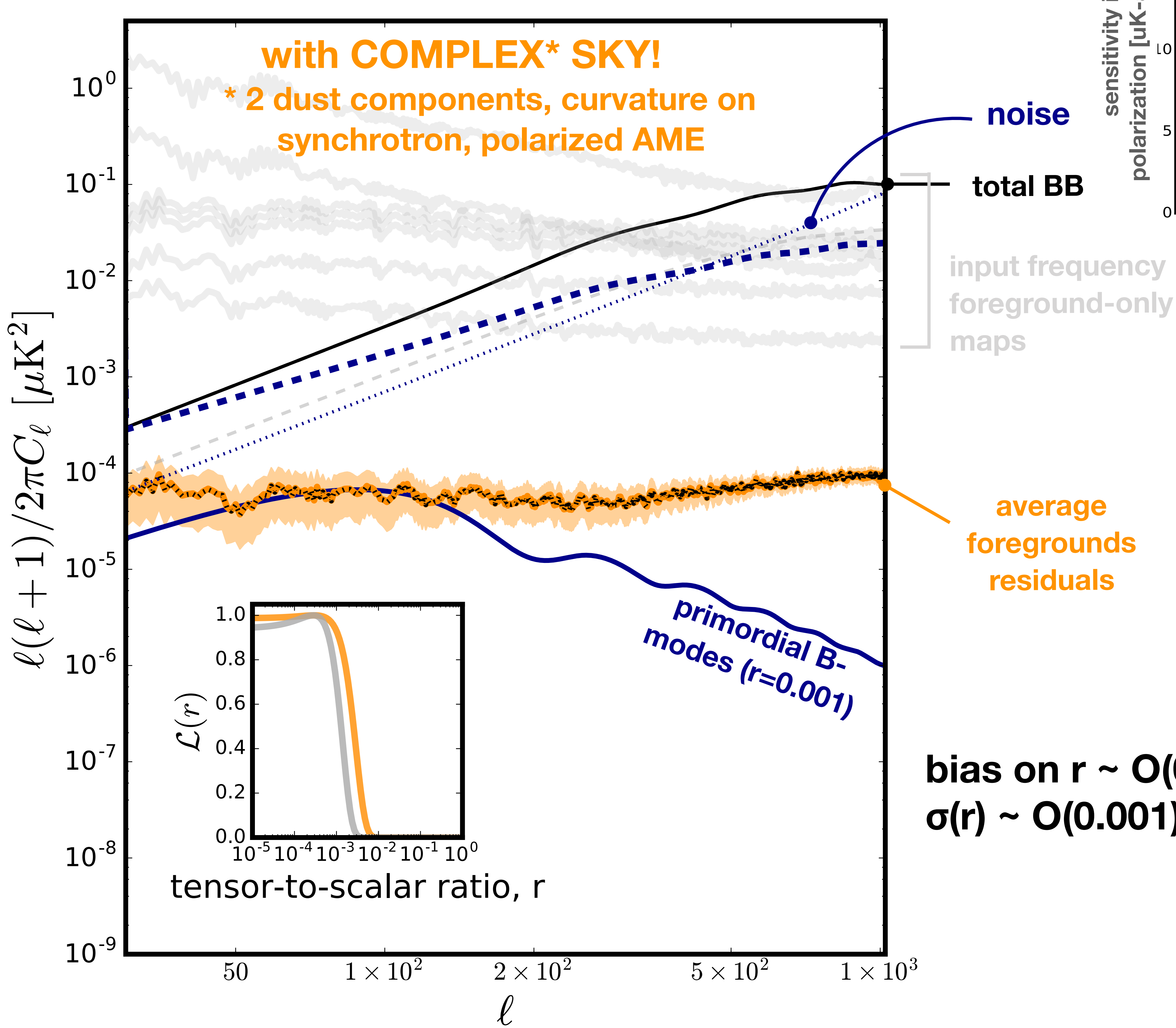


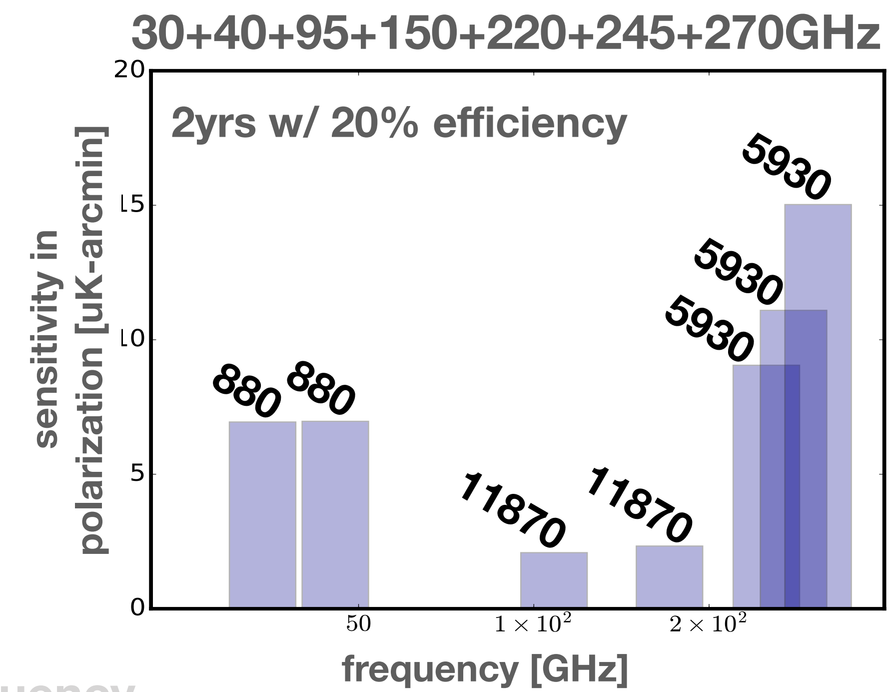


bias on r ~ O(0.0005)
σ(r) ~ O(0.001)

toy example

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

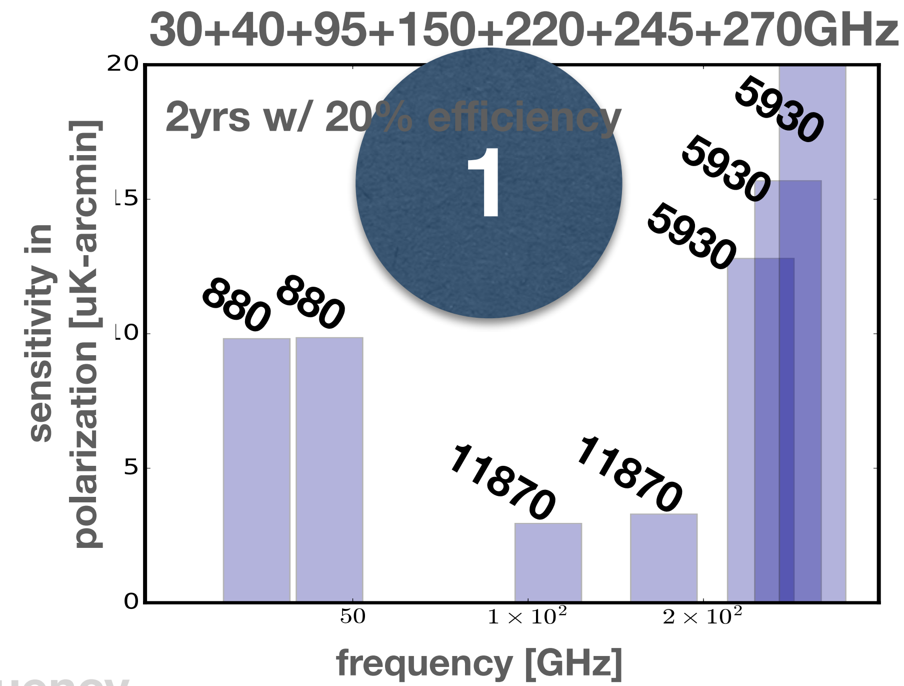


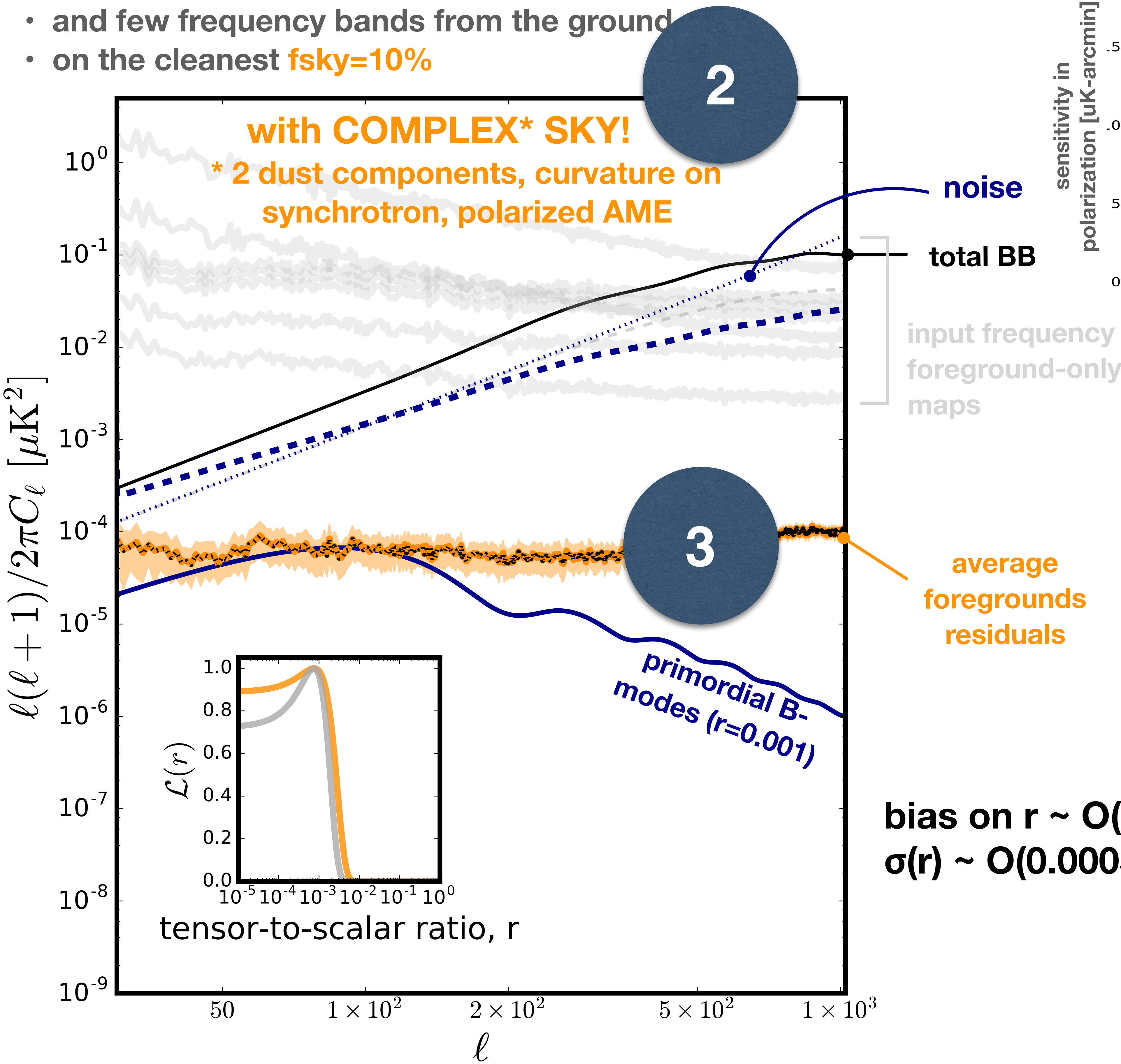


bias on r ~ O(0.001)
σ(r) ~ O(0.001)

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%



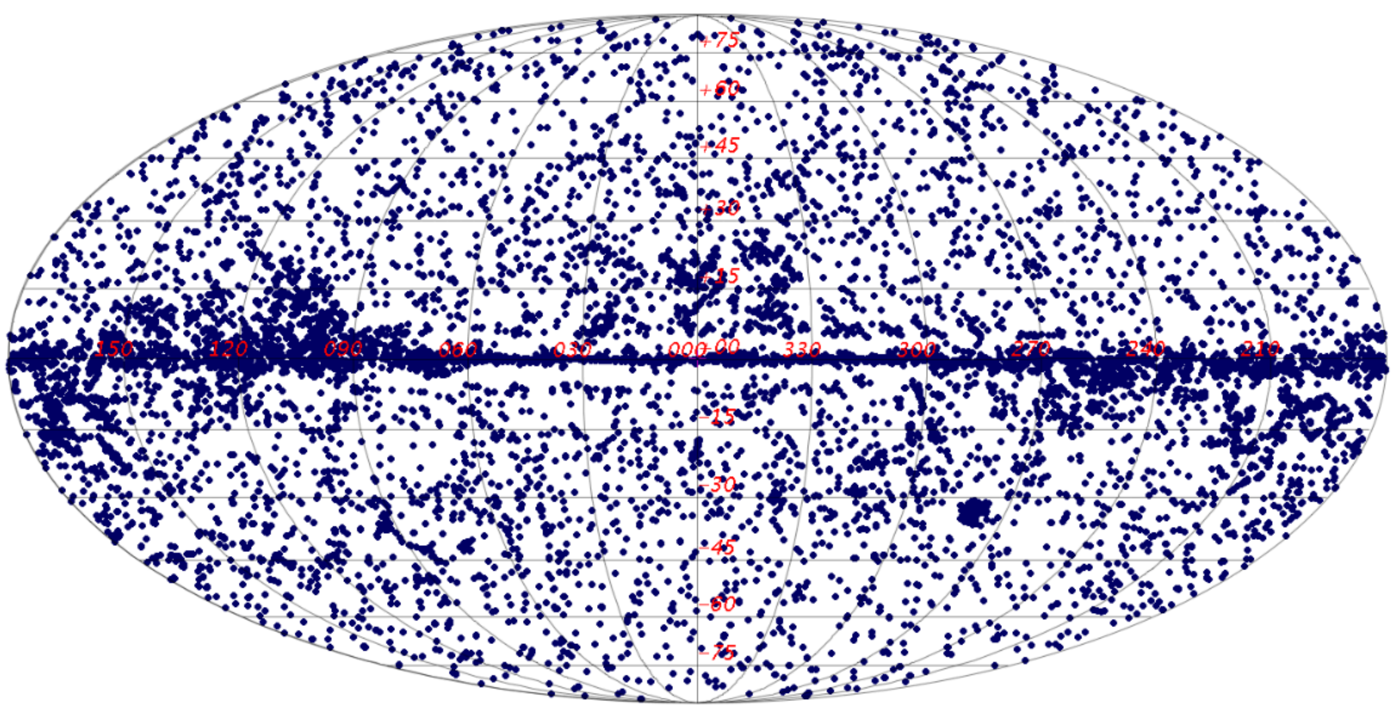


bias on r ~ O(0.001)
σ(r) ~ O(0.0005)

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).



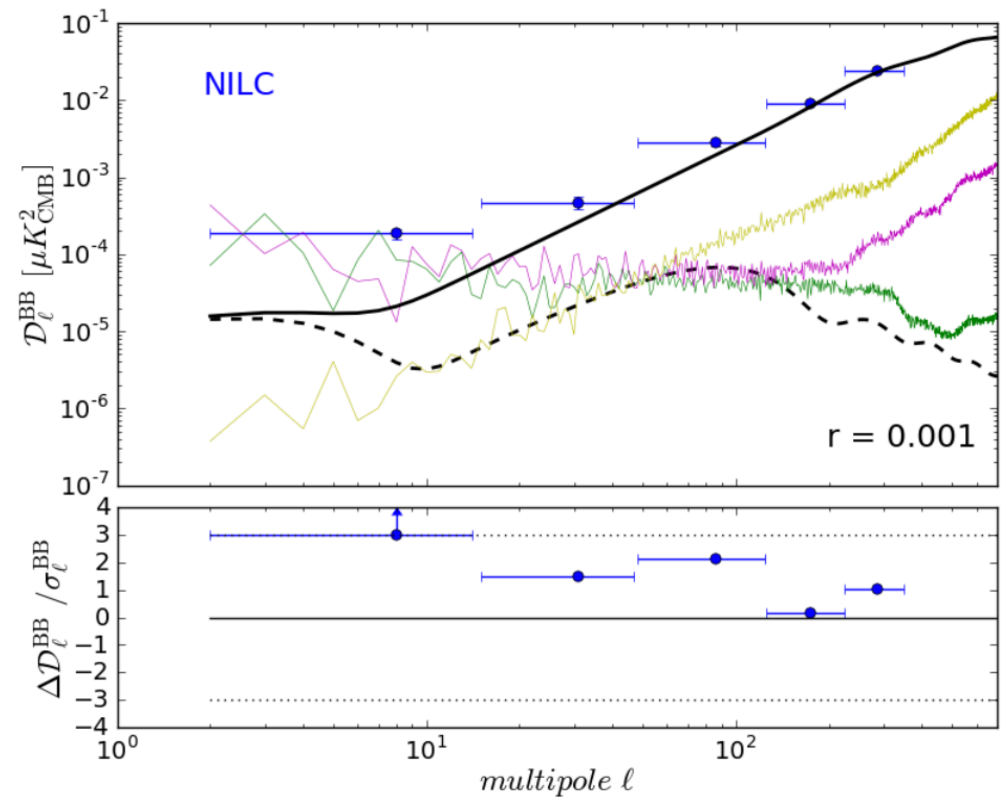
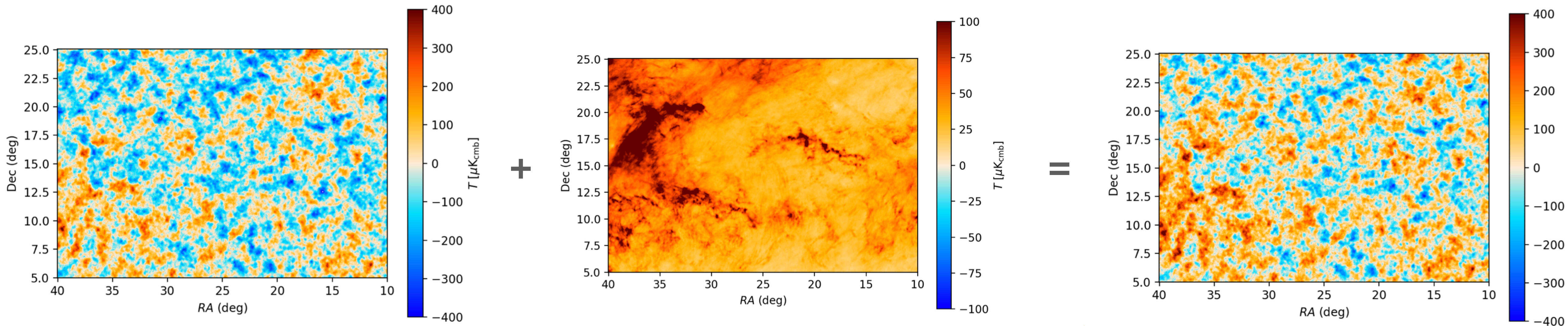


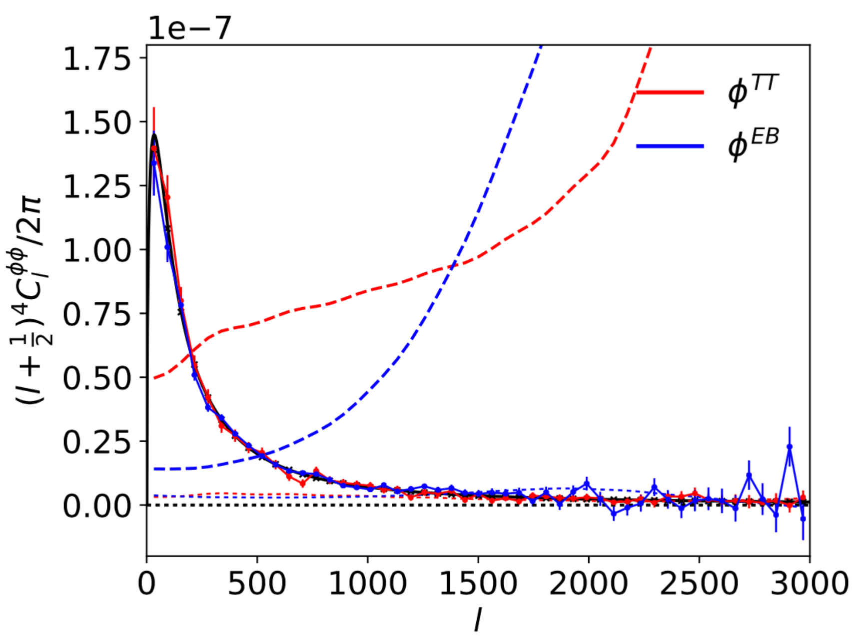
Figure 4. Union of 60 to 600 GHz polarization masks used in the analysis for mitigating the contamination from polarized compact sources. Individual polarized sources are detected in each frequency band of *CORE*.

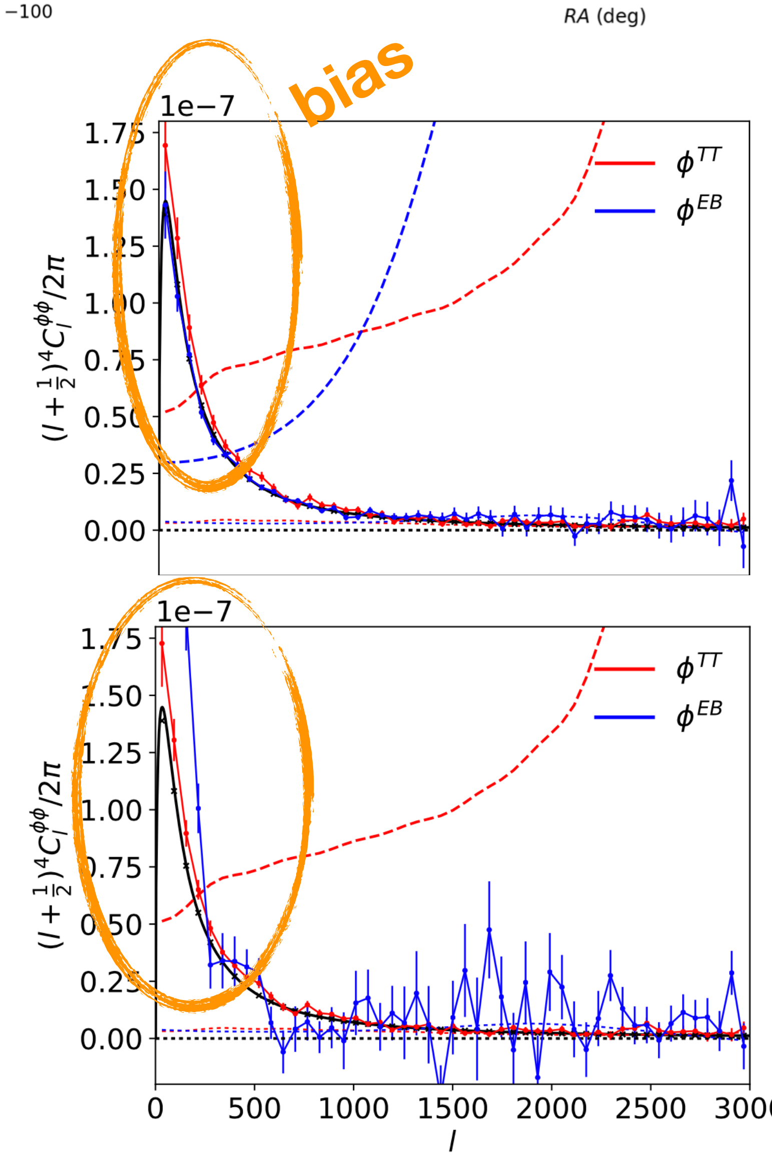
- "careful treatment is required for CMB B-mode polarization observations if the tensor-to-scalar ratio, r, is ≪ 10^{-2}"

Effect of foregrounds on lensing reconstruction and delensing

Exploring cosmic origins with CORE: gravitational lensing of the CMB
A. Challinor et al, JCAP, 2017







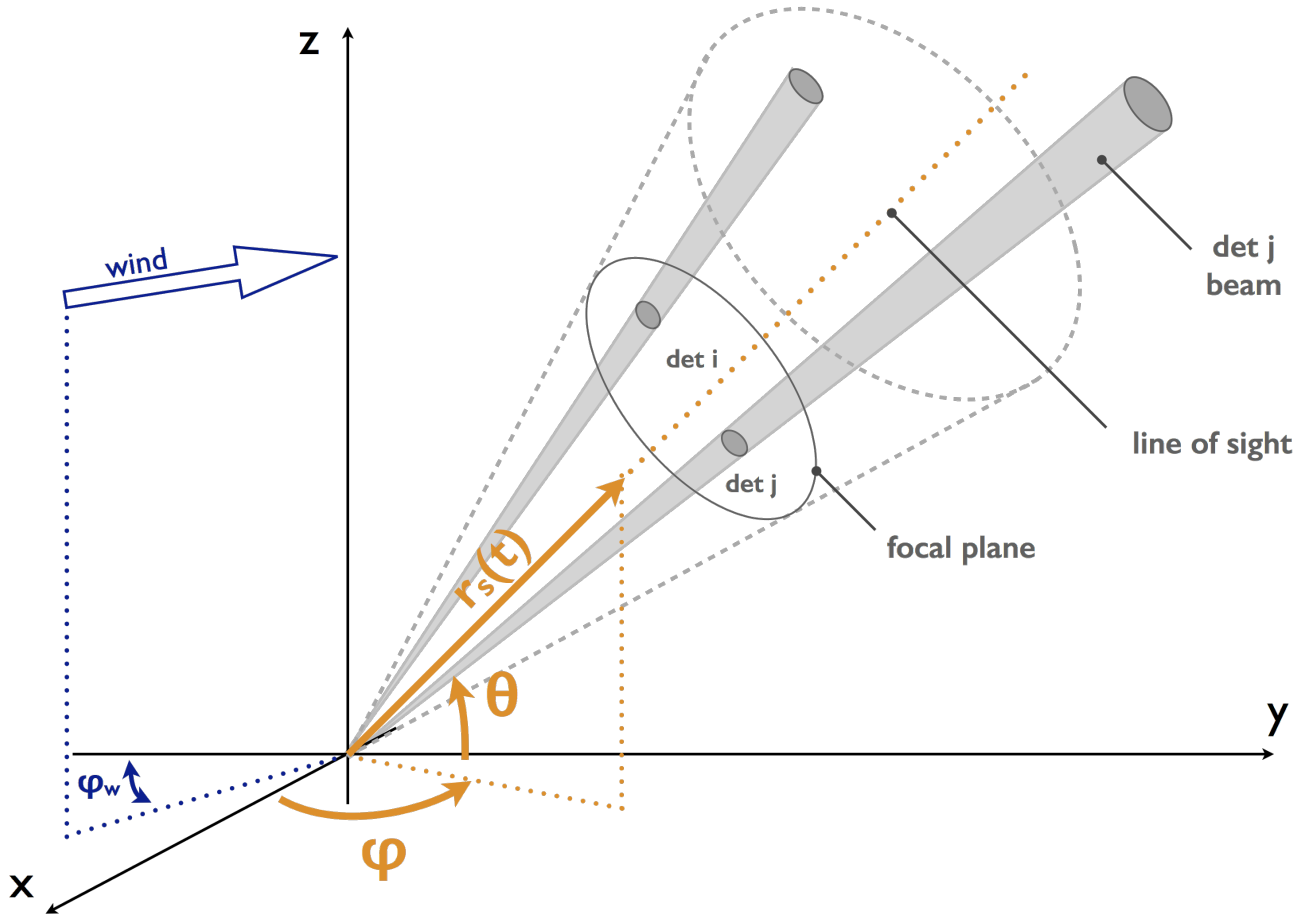
1. Introduction
2. Galactic foregrounds
3. Get a clean CMB map
4. Forecasts

    ➤ few words on another foreground: atmosphere

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



Sarah Church, **Predicting residual levels of atmospheric sky noise in ground-based observations of the cosmic background radiation**, MNRAS, **272**, 551-569 (1995)

The contribution dT_{ant} to the antenna temperature of a small element dV of atmosphere located at a distance r is proportional to the effective area of the telescope beam as seen from that point, i.e.

$$dT_{ant}(\mathbf{r}) = \frac{1}{\lambda^2} B(\hat{\mathbf{r}}_\mathbf{s}, \mathbf{r})\, \alpha(\mathbf{r}, \lambda)\, T_{phys}(\mathbf{r})\, \frac{dV}{r^2}$$

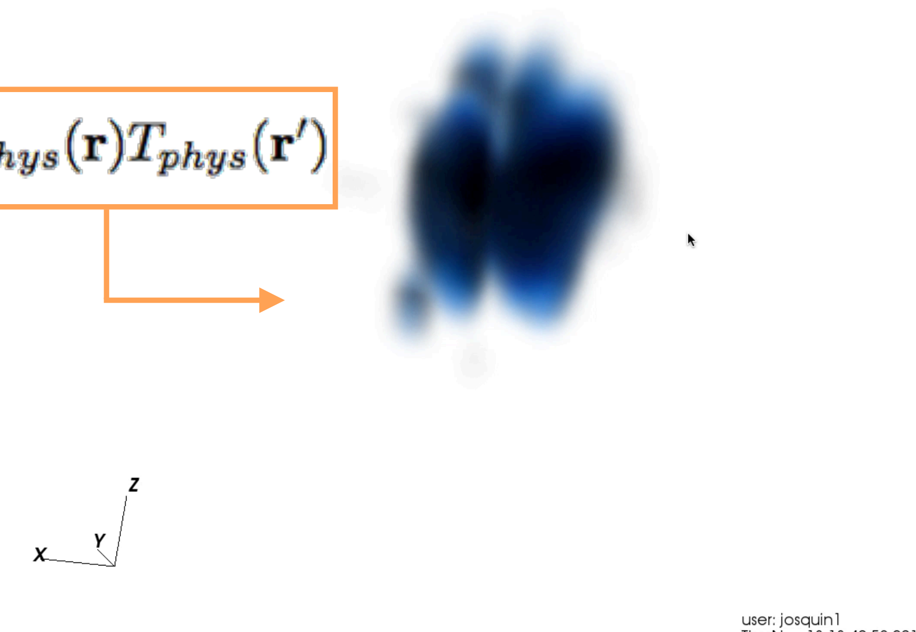
beam effective area

absorption

atmosphere temperature

$$\mathbf{C}_{ij}^{tt'} \equiv \langle T_{ant}^{\,i}(t) T_{ant}^{\,j}(t') \rangle \equiv \langle T_{ant}(\hat{\mathbf{r}}_\mathbf{s}{}^\mathbf{i}(t)) T_{ant}(\hat{\mathbf{r}}_\mathbf{s}{}^\mathbf{j}(t')) \rangle =$$

$$\frac{1}{\lambda^4} \int d\mathbf{r} \int d\mathbf{r}'\; B(\hat{\mathbf{r}}_\mathbf{s}{}^\mathbf{i}(t), \mathbf{r}) B(\hat{\mathbf{r}}_\mathbf{s}{}^\mathbf{j}(t'), \mathbf{r}') \boxed{\langle \alpha(\mathbf{r}) \alpha(\mathbf{r}') \rangle T_{phys}(\mathbf{r}) T_{phys}(\mathbf{r}')}$$



Kolmogorov turbulences
wind direction and speed
ground temperature

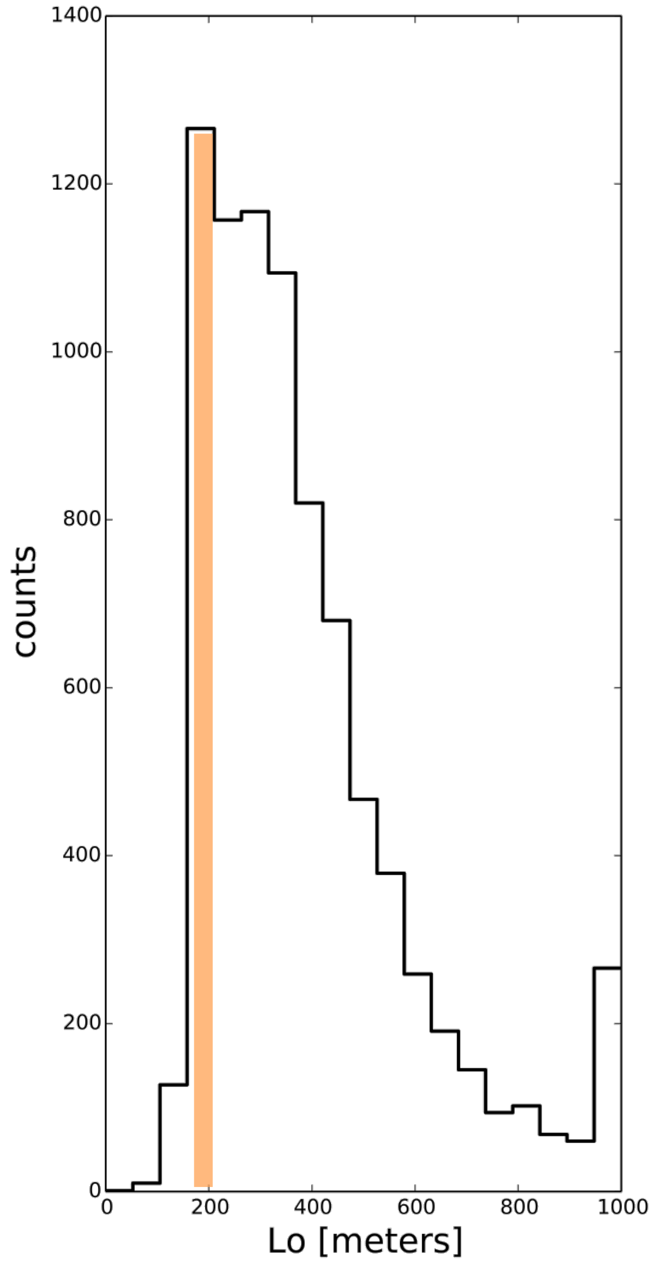
Modeling Atmospheric Emission for CMB Ground-based Observations

JE et al.

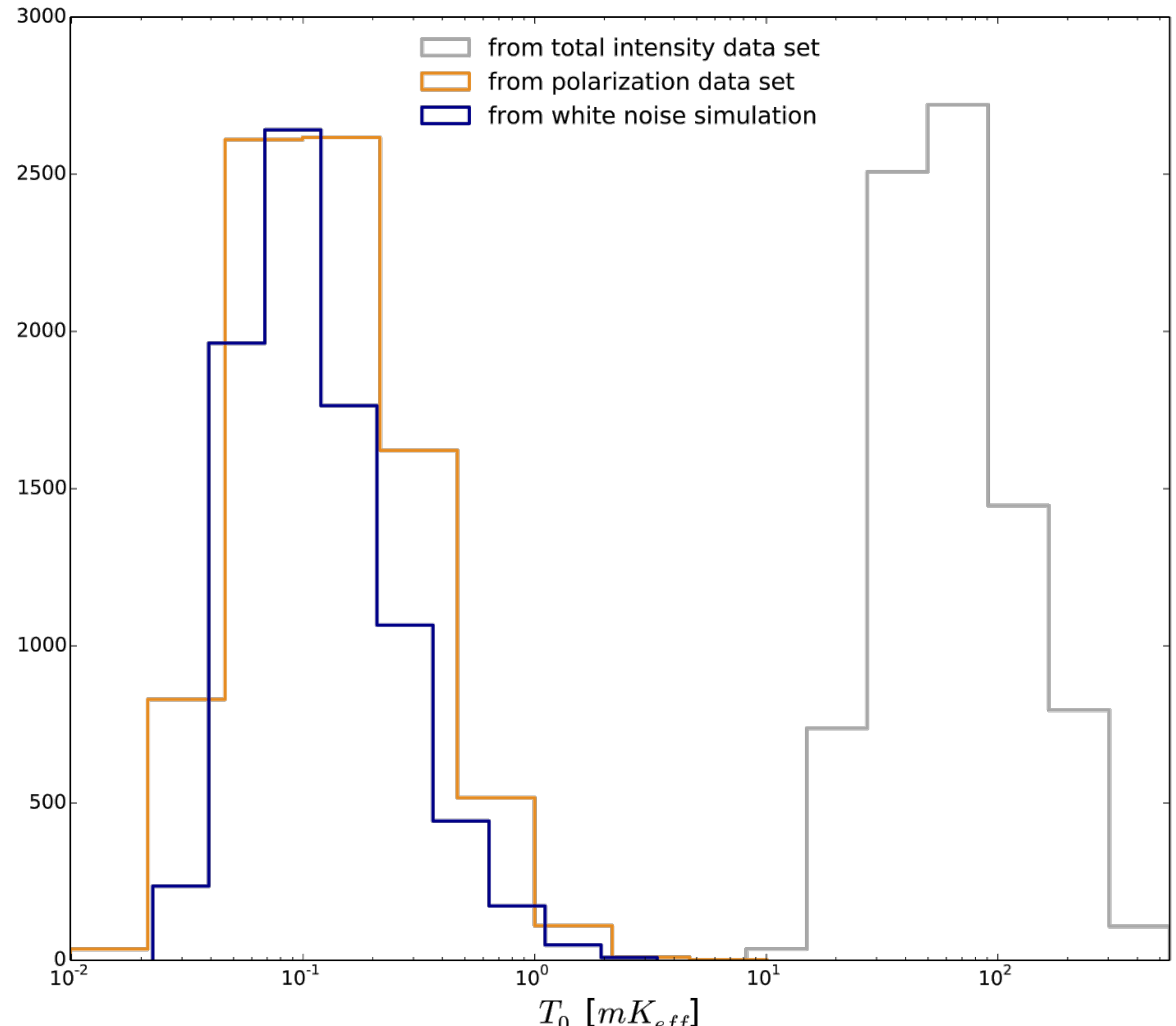
The Astrophysical Journal, Volume 809, Issue 1, article id. 63, 19 pp. (**2015**) arXiv:1501.07911

$$-2\log\left(\mathcal{L}(p)\right) \propto \sum_{t,t'}\left\{\mathrm{tr}\left[\left(\mathbf{C}_{ij}^{tt'}(p)-\mathbf{D}_{ij}^{tt'}\right)\left(\mathbf{D}_{ij}^{tt'}\right)^{-1}\left(\mathbf{C}_{ij}^{tt'}(p)-\mathbf{D}_{ij}^{tt'}\right)\left(\mathbf{D}_{ij}^{tt'}\right)^{-1}\right]\right.$$

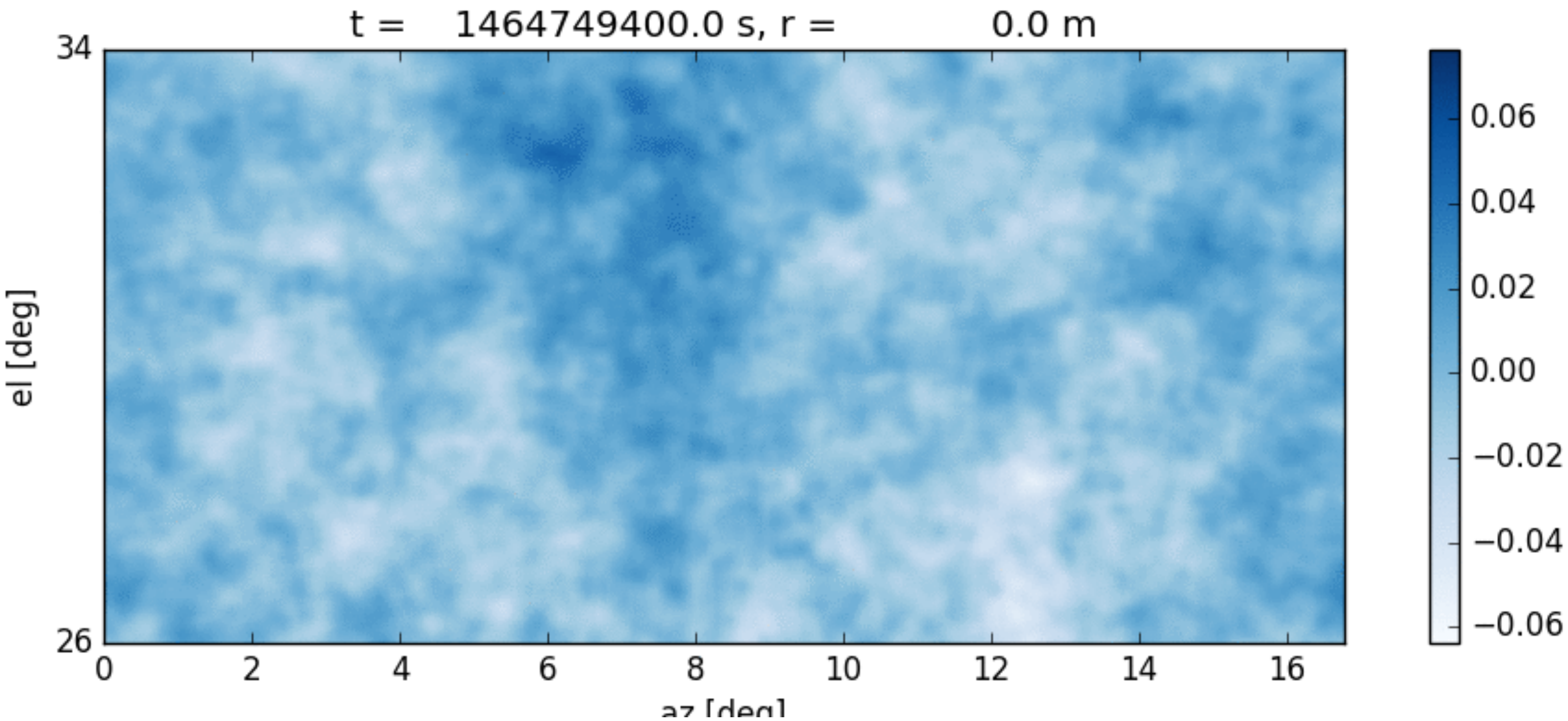
typical scale for atmospheric turbulences: Lo ~ 200m



new observational upper bound on linear polarization of the atmospheric emission: p<1%



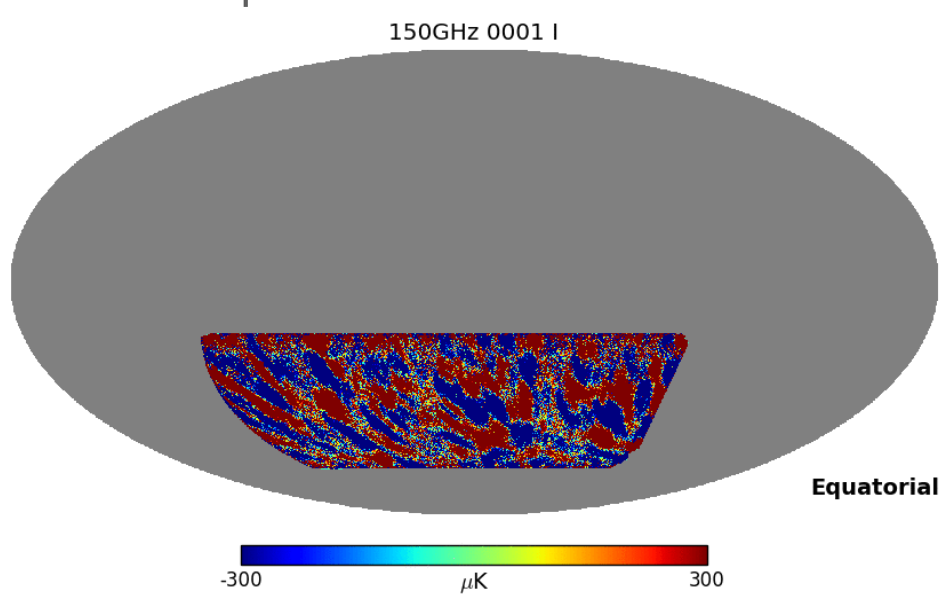
The telescope's view through one realization of turbulent, wind-blown, atmospheric water vapor. The volume of atmosphere being simulated depended on (a) the scan width and duration and (b) the wind speed and direction, both of which changed every 20 minutes. The entire observation used about 5000 such realizations.

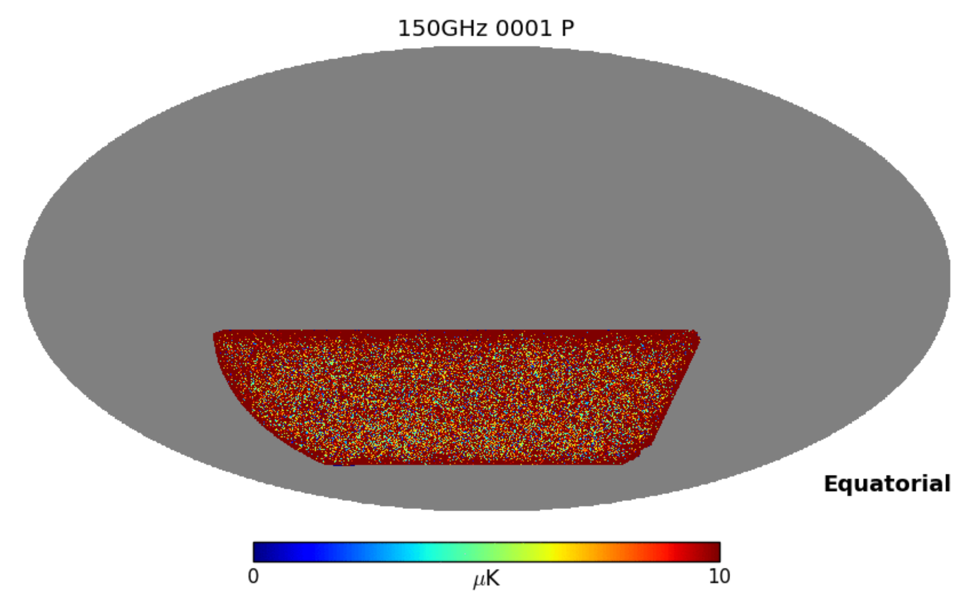


credit: R. Keskitalo and the C^3 team @ LBNL

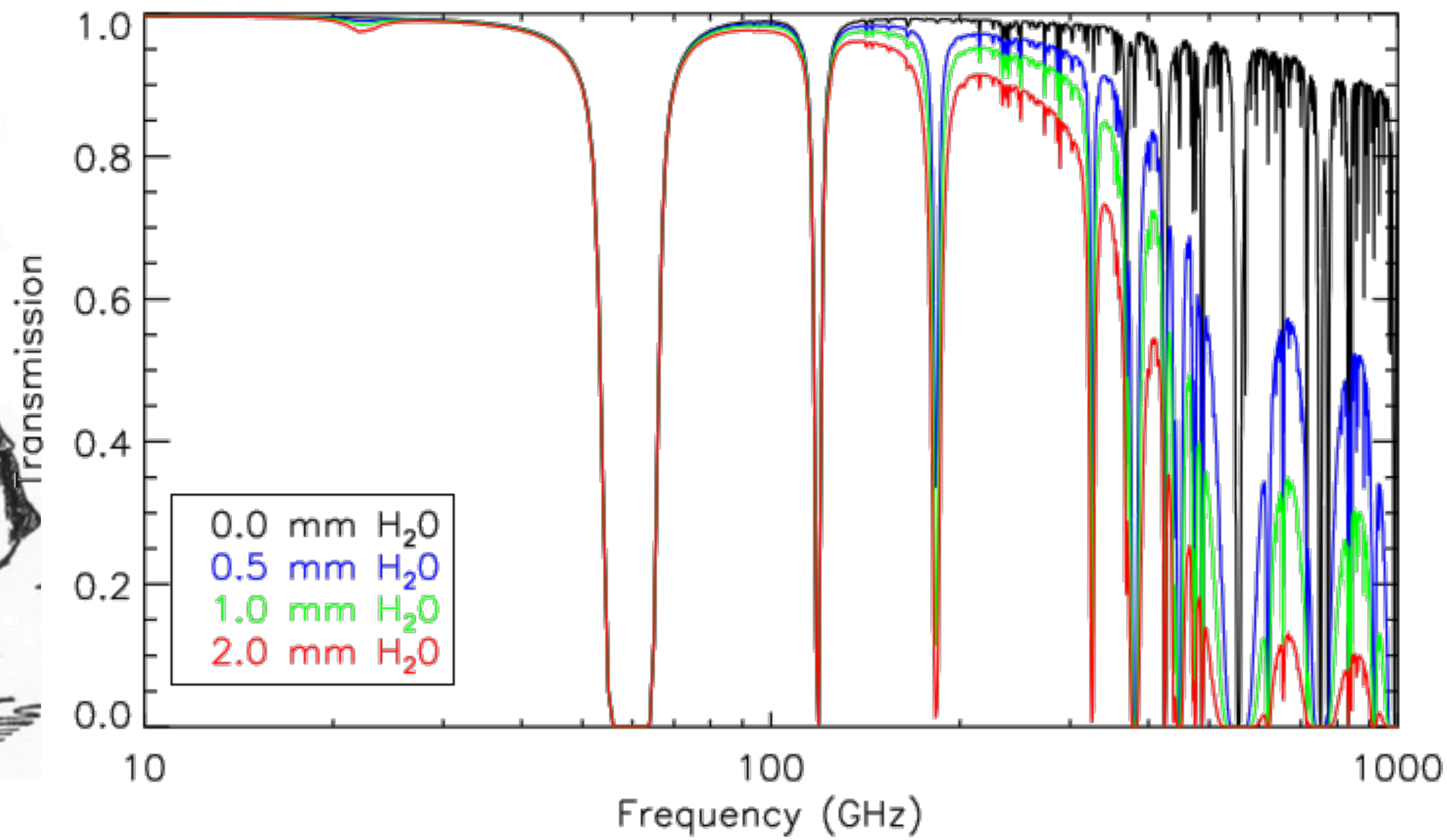
https://crd.lbl.gov/departments/computational-science/c3/c3-research/cosmic-microwave-background/cmb-simulations-at-scale/

Cumulative daily maps of the sky temperature and polarization at each frequency showing how the atmosphere and noise integrate down over time. The year-long campaign spanned 129 observation-days during which the ACTpol SS patch was available for a 13-hour constant elevation scan. To make these maps, the signal, noise, and atmosphere observations were combined (including percent level detector calibration error), filtered with a 3rd order polynomial, and binned into pixels.





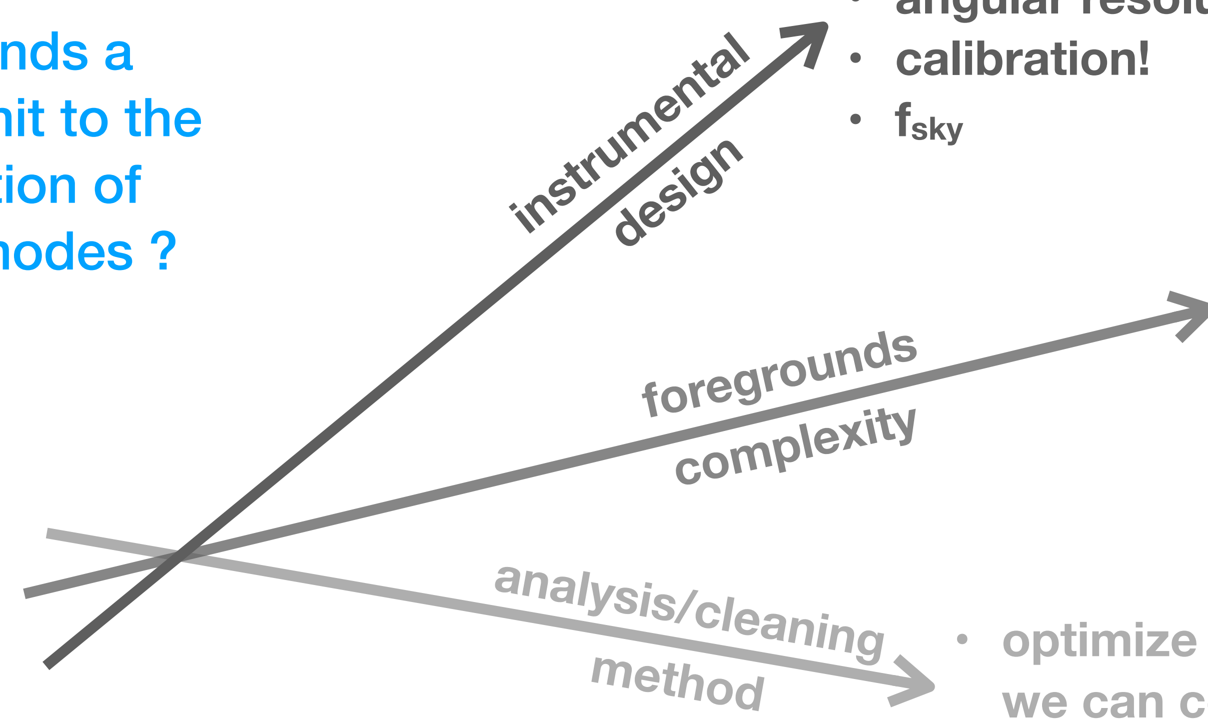
atmosphere transmission spectrum



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 the **allowed degrees of freedom in the modeling** of foregrounds emission (➔ systematic errors and bias on cosmological parameters) and the **statistical** error budget (➔ noise, statistical residuals and uncertainty on cosmological parameters);
- 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;

Are foregrounds a fundamental limit to the characterization of primordial B-modes ?



- **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)**