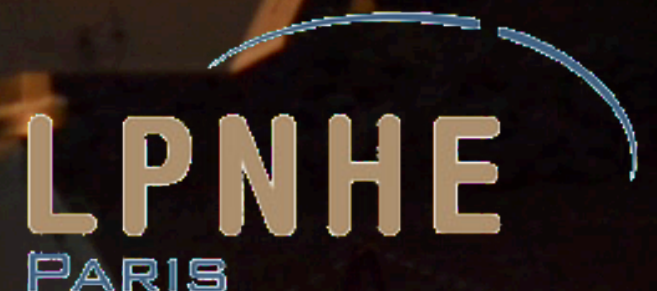


Measuring the foreground- obscured, gravitationally- lensed Cosmic Microwave Background polarization

JOSQUIN ERRARD
Institut Lagrange Paris (ILP)
LPNHE

Seminar @ LPSC,
19/01/2016

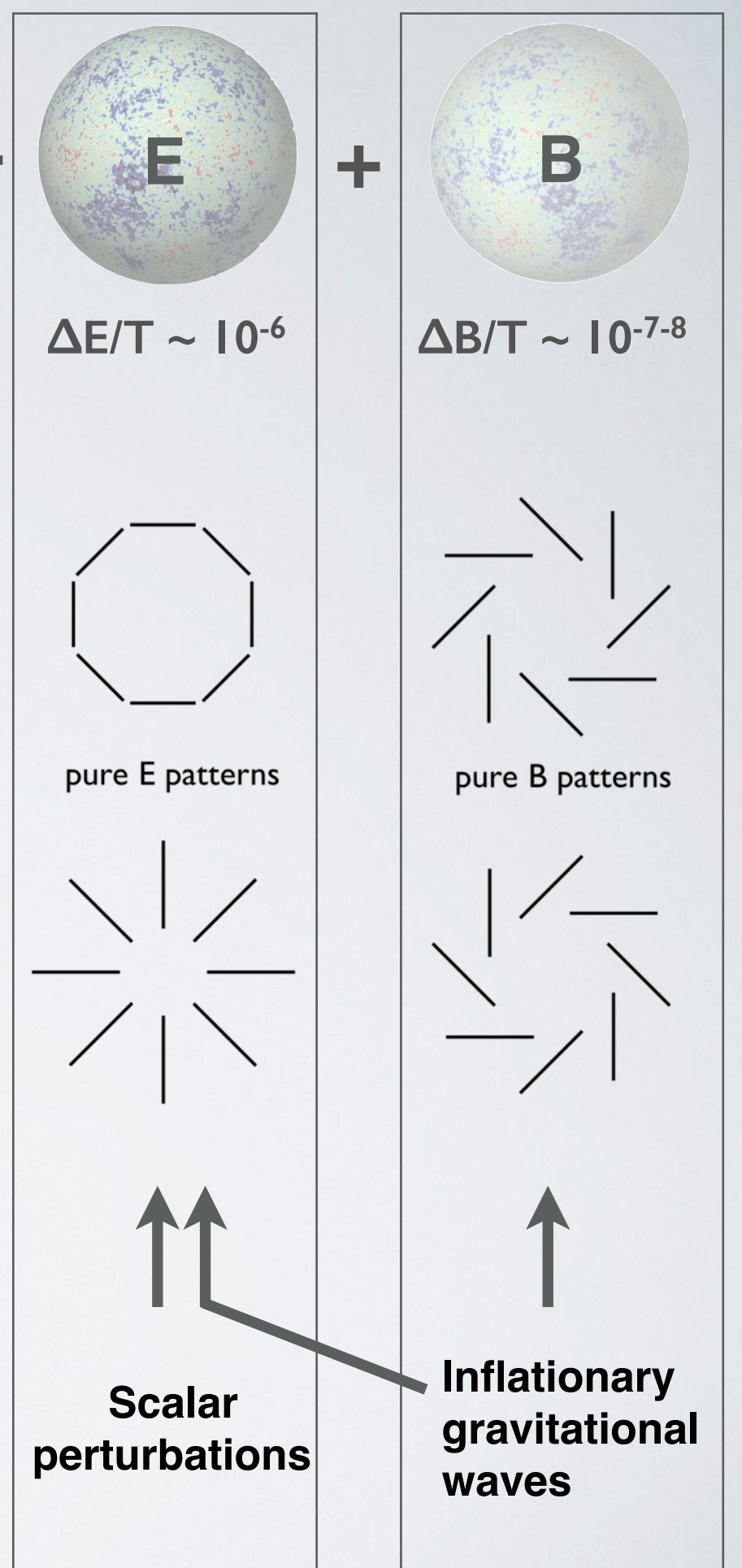
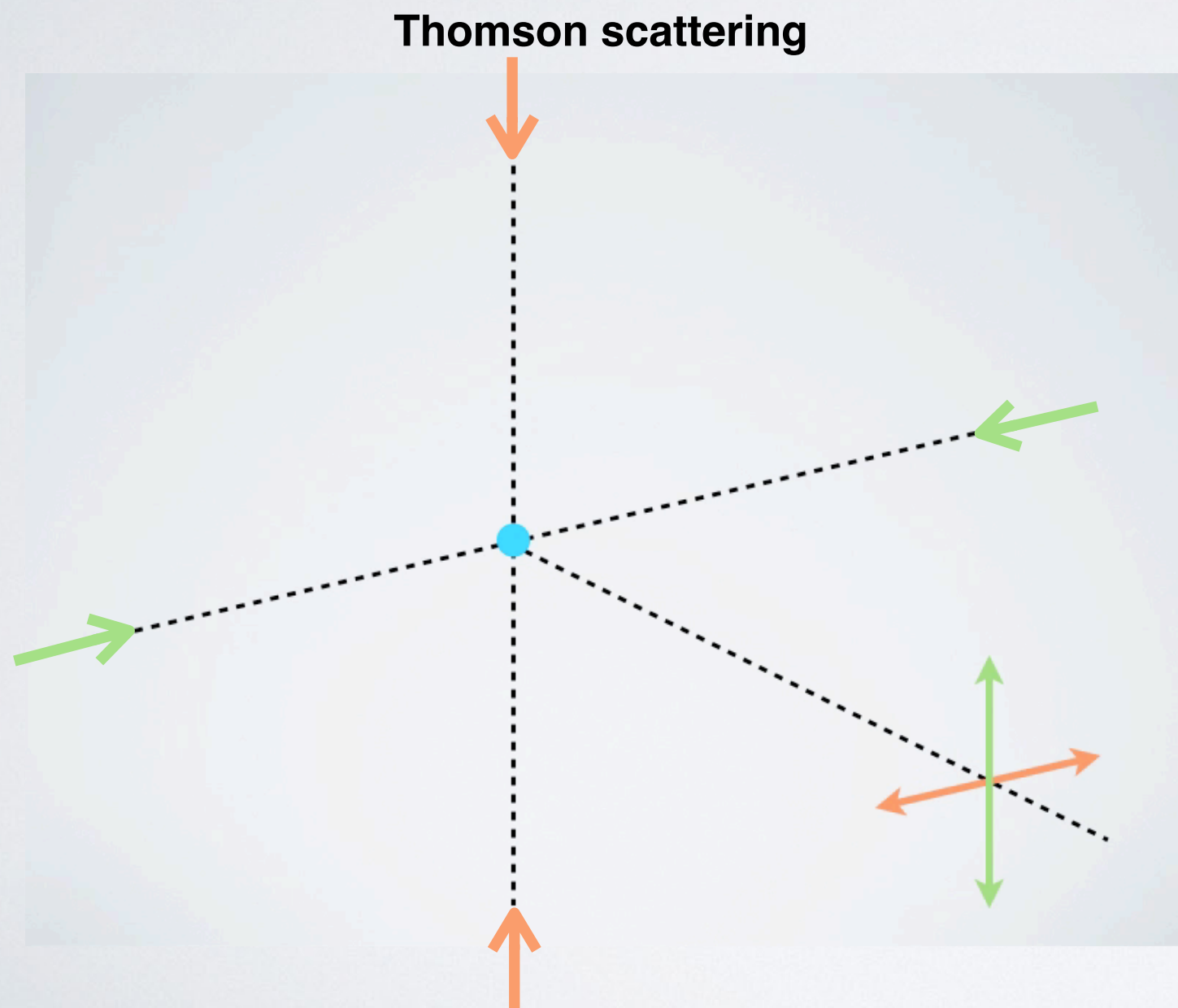
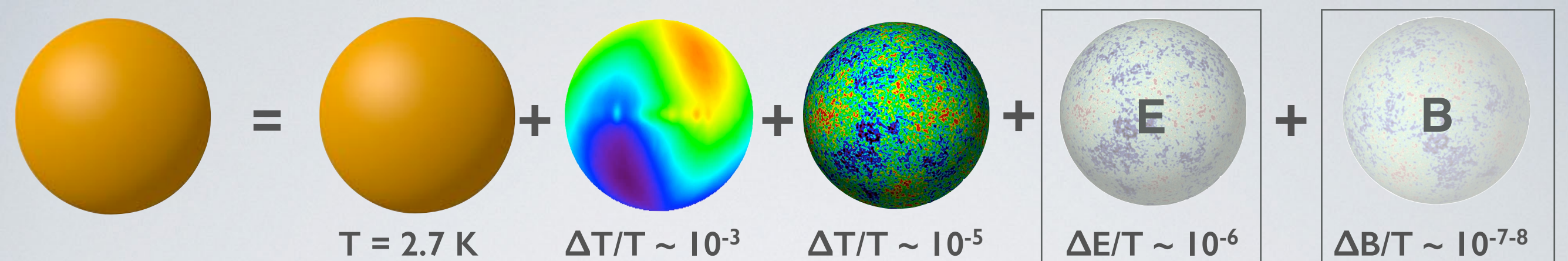


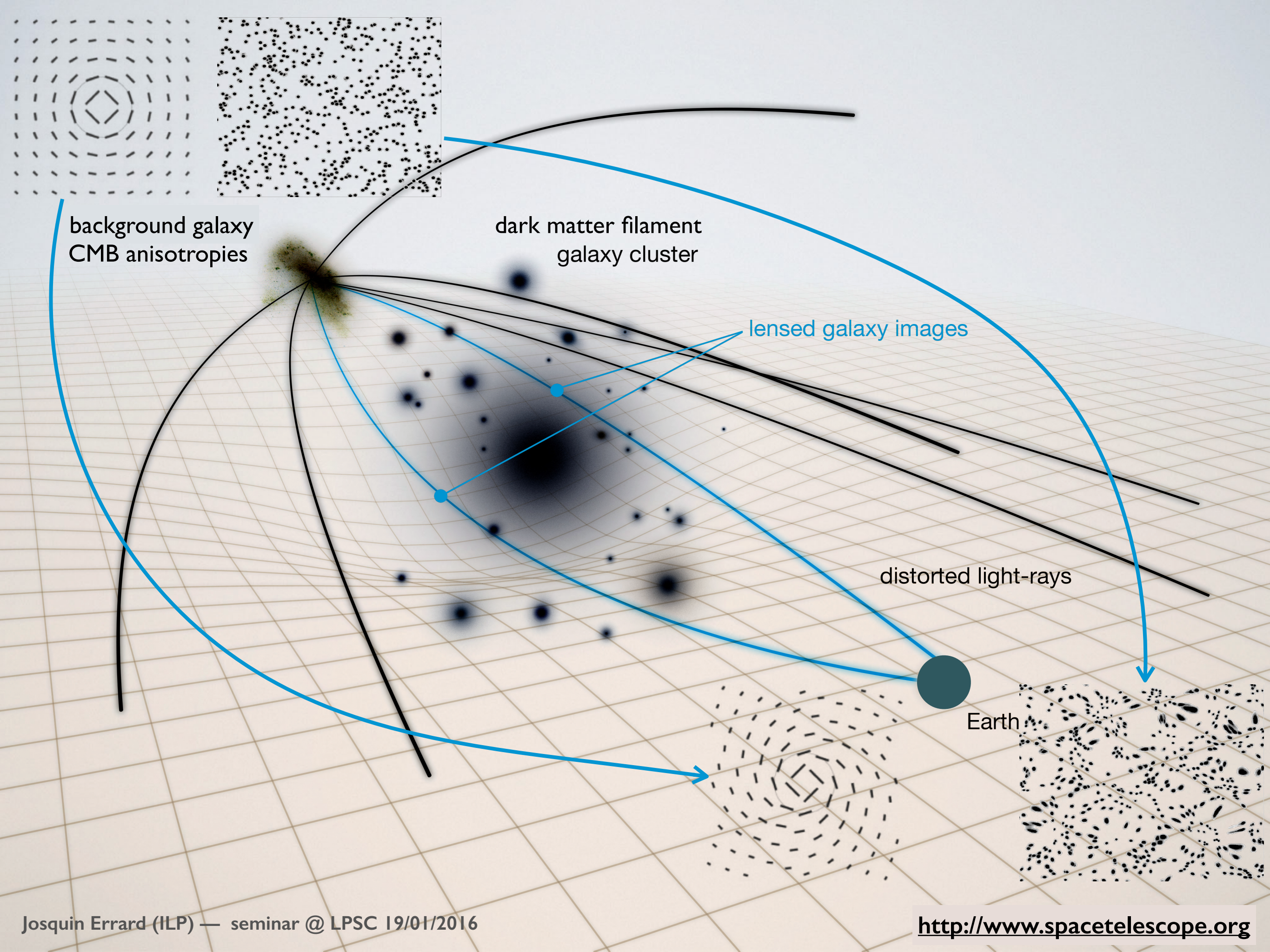
OUTLINE

- 1 - CMB polarization and constraints on B-modes
- 2 - Designing new projects in the presence of foregrounds and gravitational lensing
- 3- POLARBEAR-II, Simons Array, Stage-IV and LiteBIRD
- 4 - Extension: combining CMB with LSST weak lensing!

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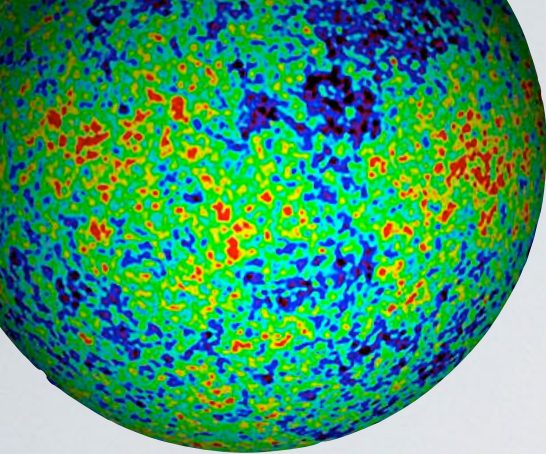
background galaxy
CMB anisotropies

dark matter filament
galaxy cluster

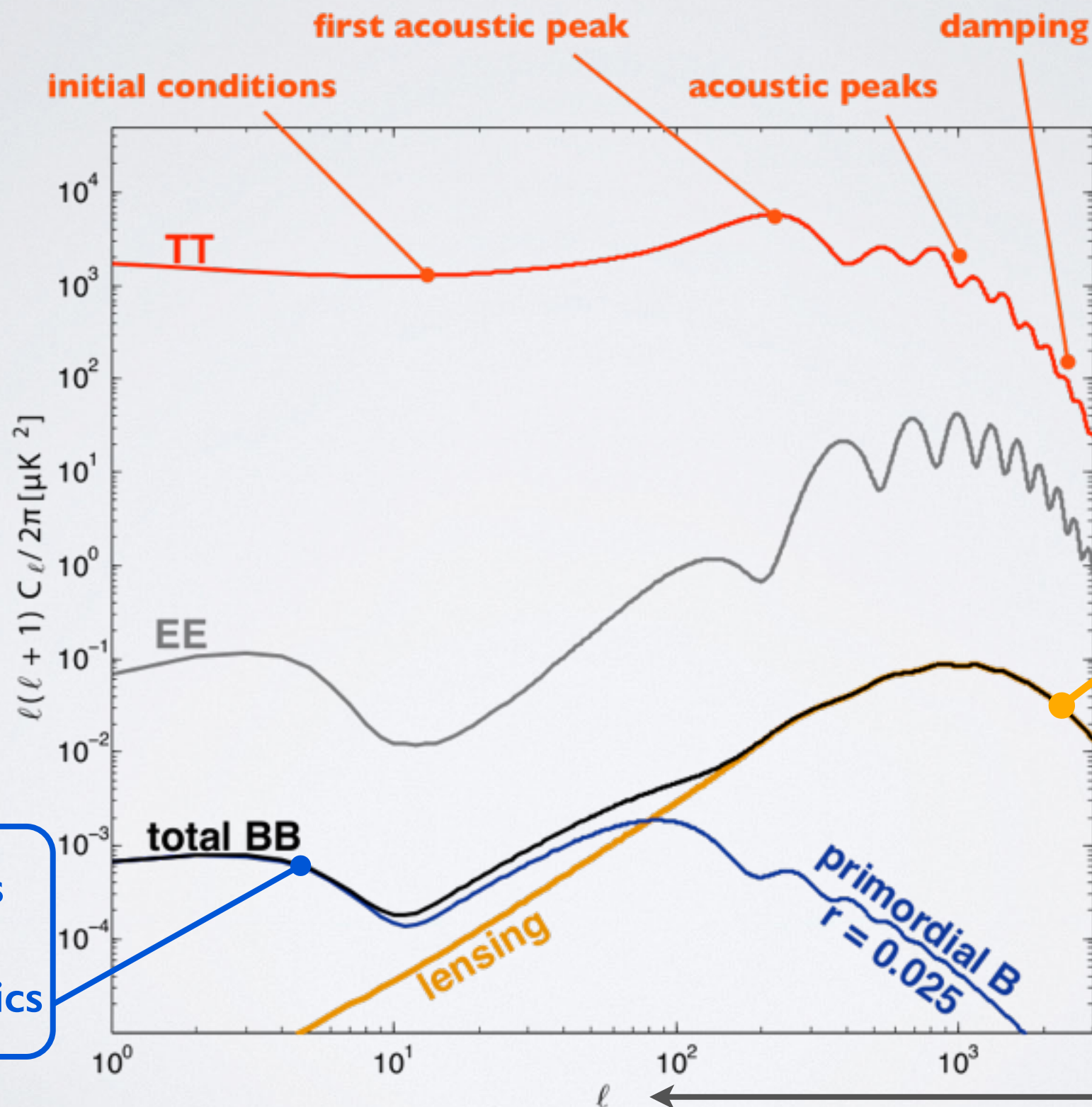
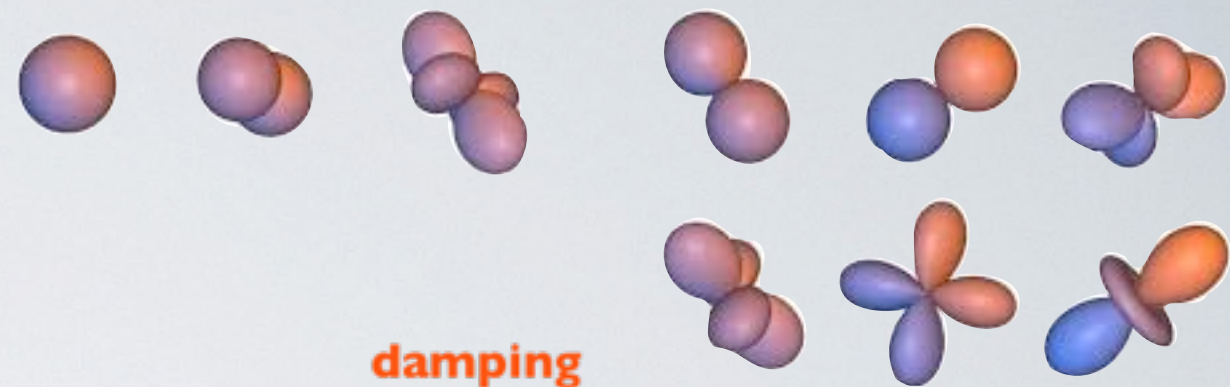
lensed galaxy images

distorted light-rays

Earth



$$= \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m}^T Y_{\ell}^m(\theta, \phi)$$

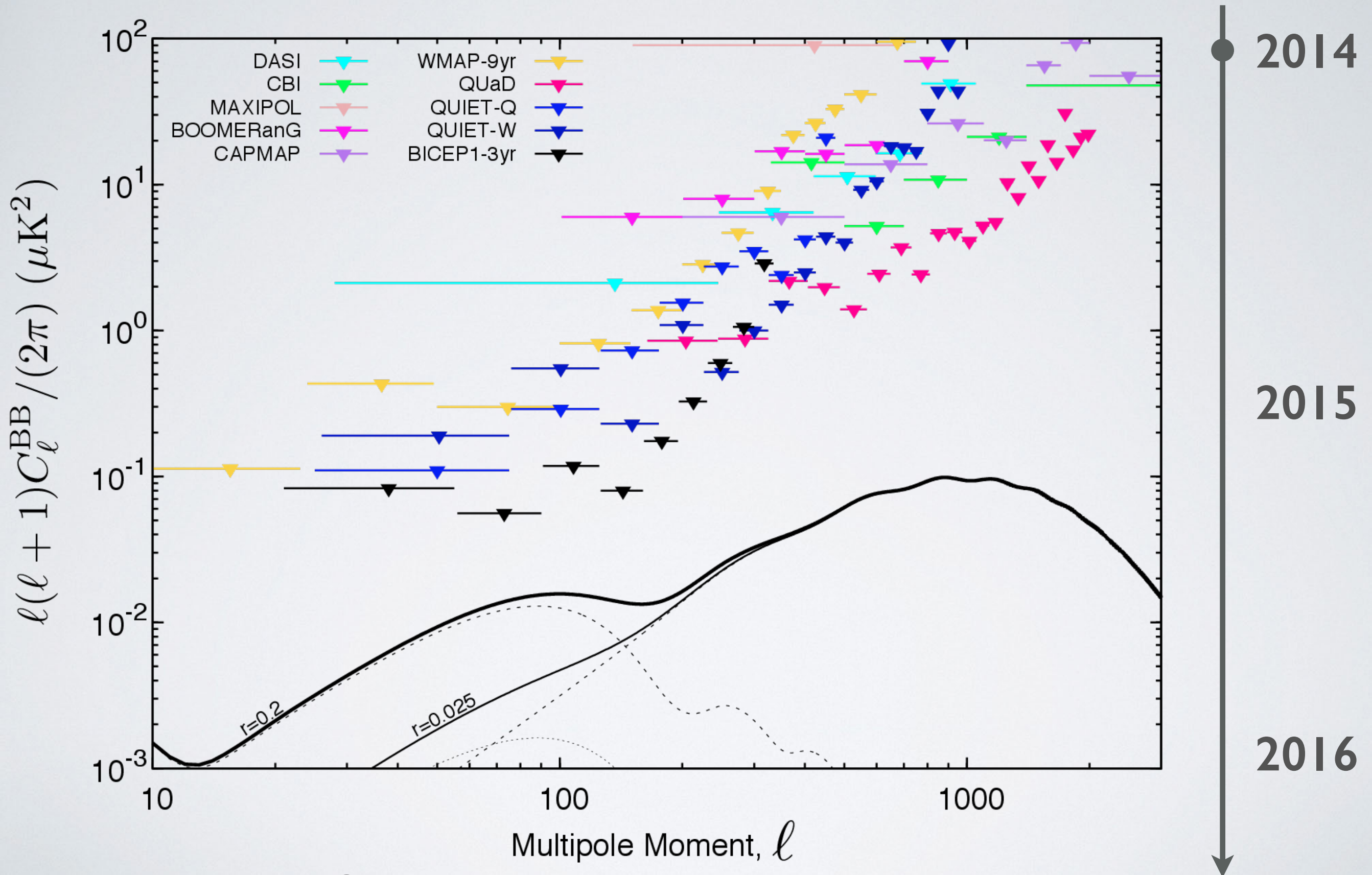


Large scale
structures
 $\Sigma m_\nu, w, N_{\text{eff}}, \dots$

inflation and its
energy
high energy physics

$\sim 1/\theta$

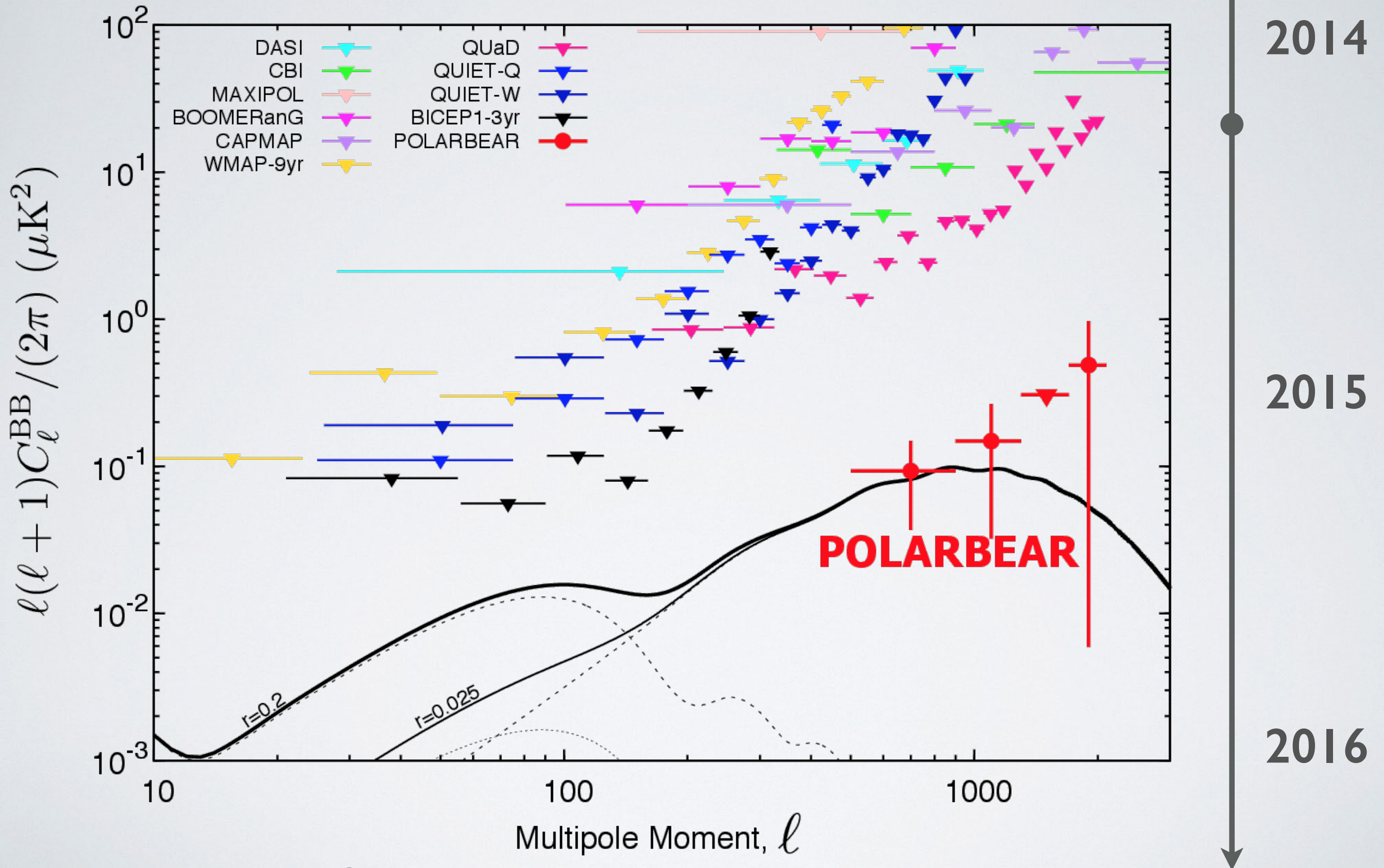
direct measurements of B-modes in the past 2 years ...



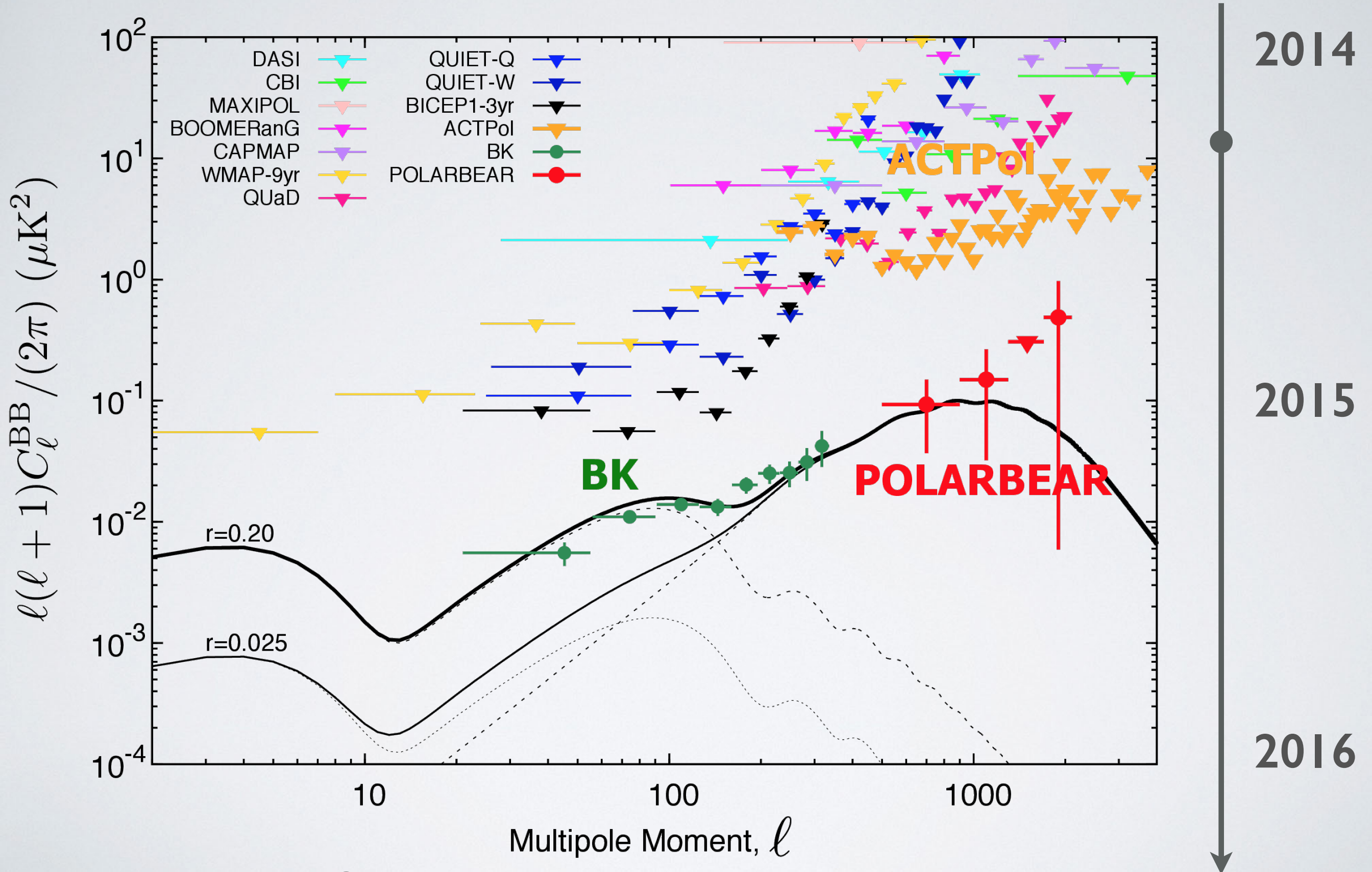
A Measurement of the Cosmic Microwave Background B-Mode Polarization Power Spectrum at Sub-degree Scales with POLARBEAR

The POLARBEAR Collaboration

The Astrophysical Journal, Volume 794, 171 (2014)



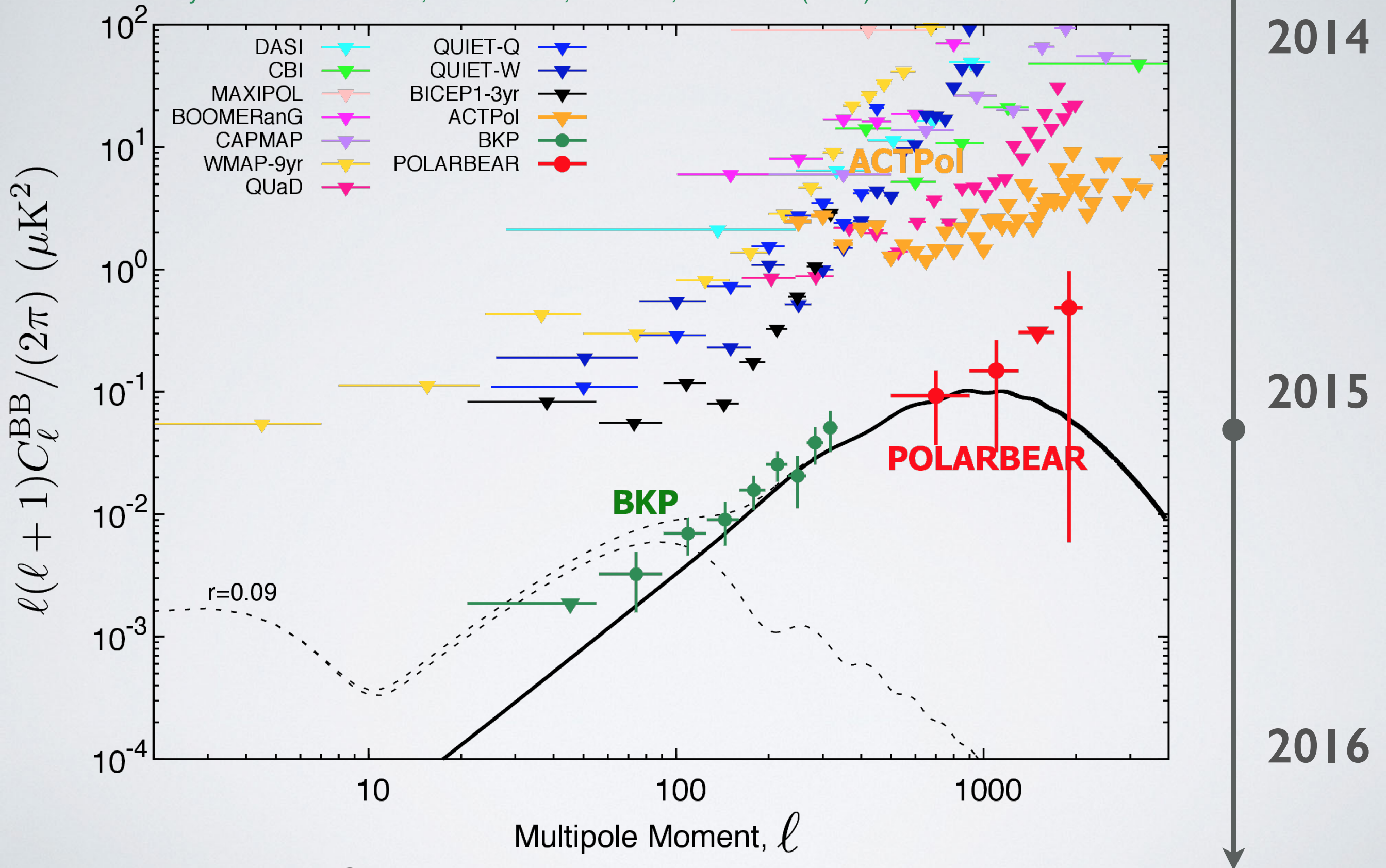
BK-V: Measurements of B-mode Polarization at Degree Angular Scales and 150 GHz by Keck Array
 The Keck Array and BICEP2 Collaborations, ApJ 811, 126, 2015



Joint Analysis of BICEP 2 / Keck Array and Planck Data

P. Ade et al.

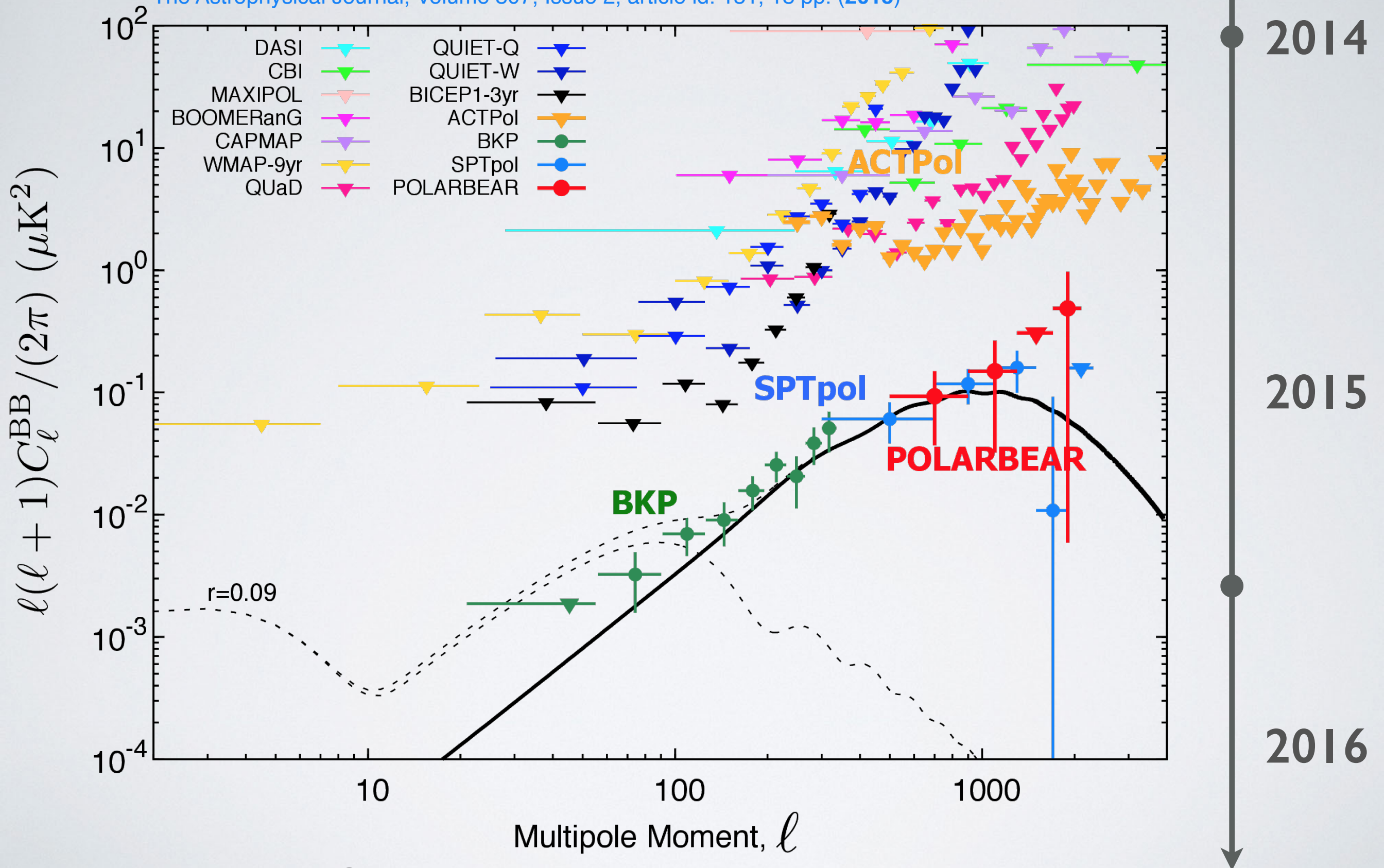
Physical Review Letters, Volume 114, Issue 10, id.101301 (2015)



Measurements of Sub-degree B-mode Polarization in the Cosmic Microwave Background from 100 Square Degrees of SPTpol Data

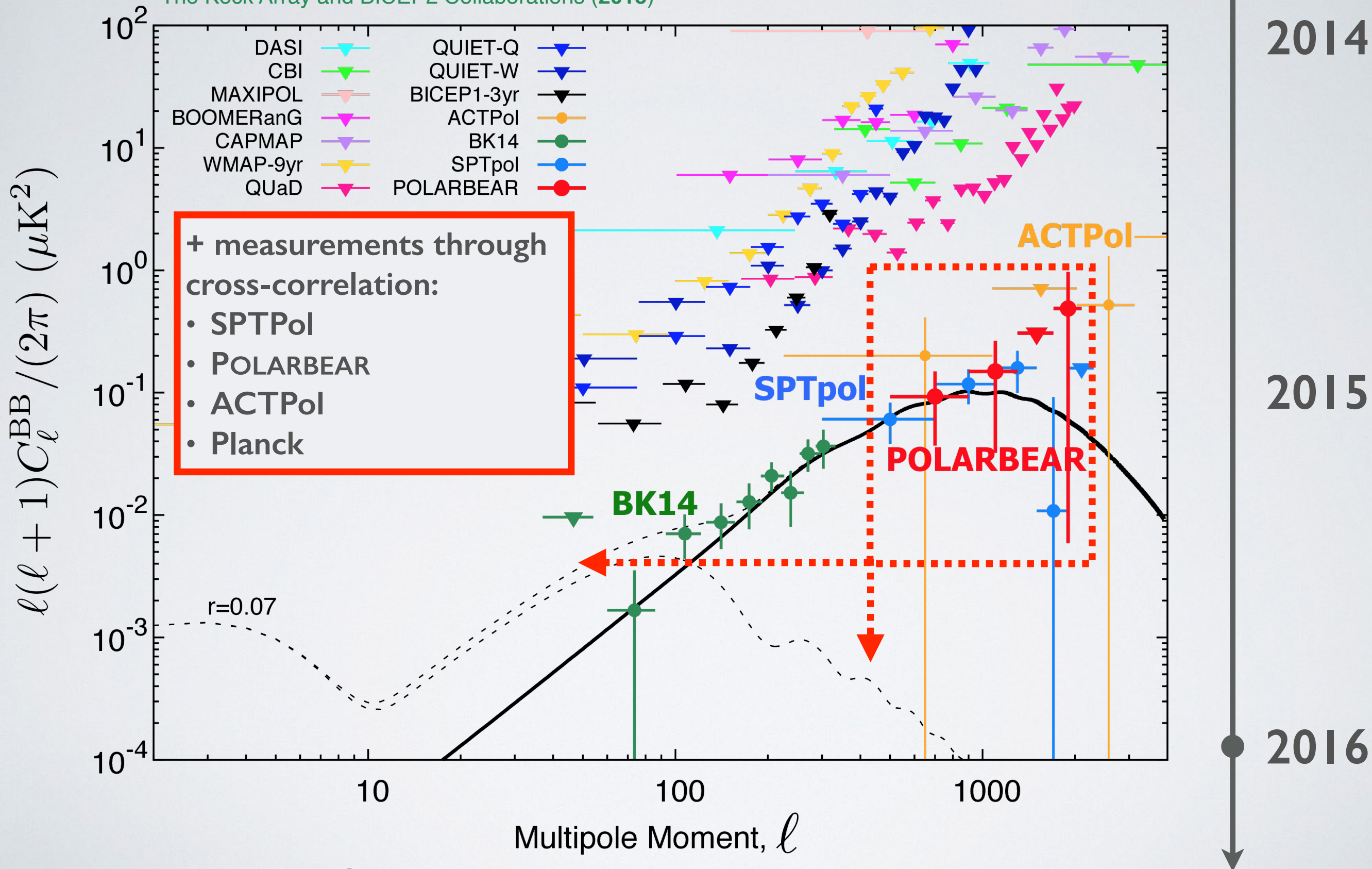
R. Keisler et al.

The Astrophysical Journal, Volume 807, Issue 2, article id. 151, 18 pp. (2015)



BK-VI: Improved Constraints On Cosmology and Foregrounds When Adding 95 GHz Data From Keck Array

The Keck Array and BICEP2 Collaborations (2015)



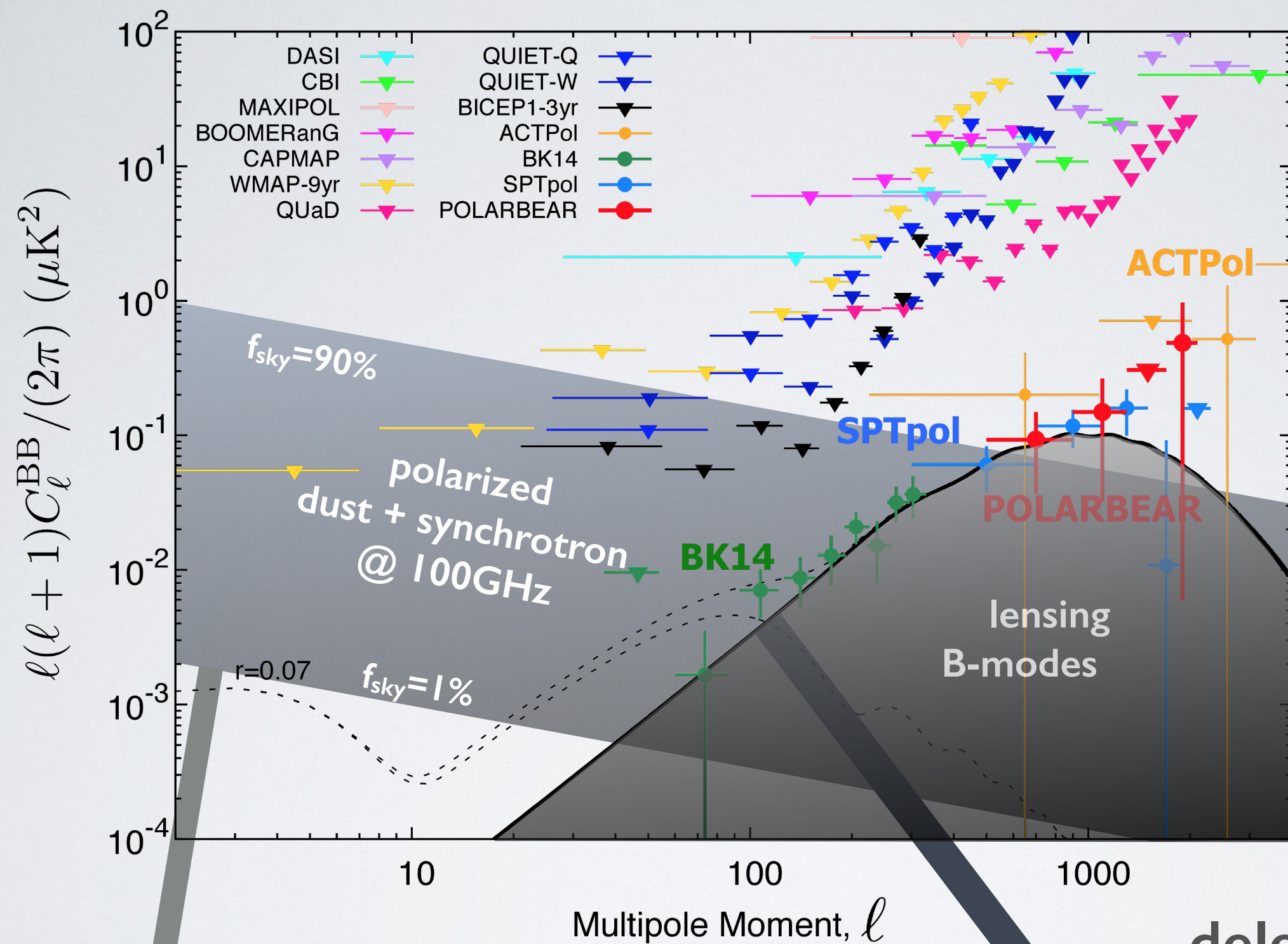
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Robust forecasts on fundamental physics from the foreground-obscured, gravitationally- lensed CMB polarization

JE, Feeney, S. M., Peiris, H.V. and Jaffe, A. H. (2015)

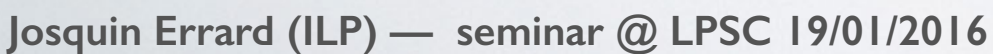
arXiv: 1509.06770



delensing

[Seljak & Hirata (2004),
Smith et al (2012),
Sherwin & Schmidtfull (2015)]

$f_{\text{sky}} = 50\%$



Instrument specification
frequencies, number of detectors,
FWHM, T_{obs}

Observation strategy
fsky, patch location

Astrophysical foreground
maps and power spectra

$\mu\text{K-arcmin}$ computation per
frequency channel

1.

Astrophysical foreground
rejection: σ_{CMB} , Δ , $C_{\ell}^{\text{fg res}}$, r_{eff}

2.

Delensing: $C_{\ell}^{\text{BB, del}}$, α

3.

Fisher forecasts on
cosmological parameters

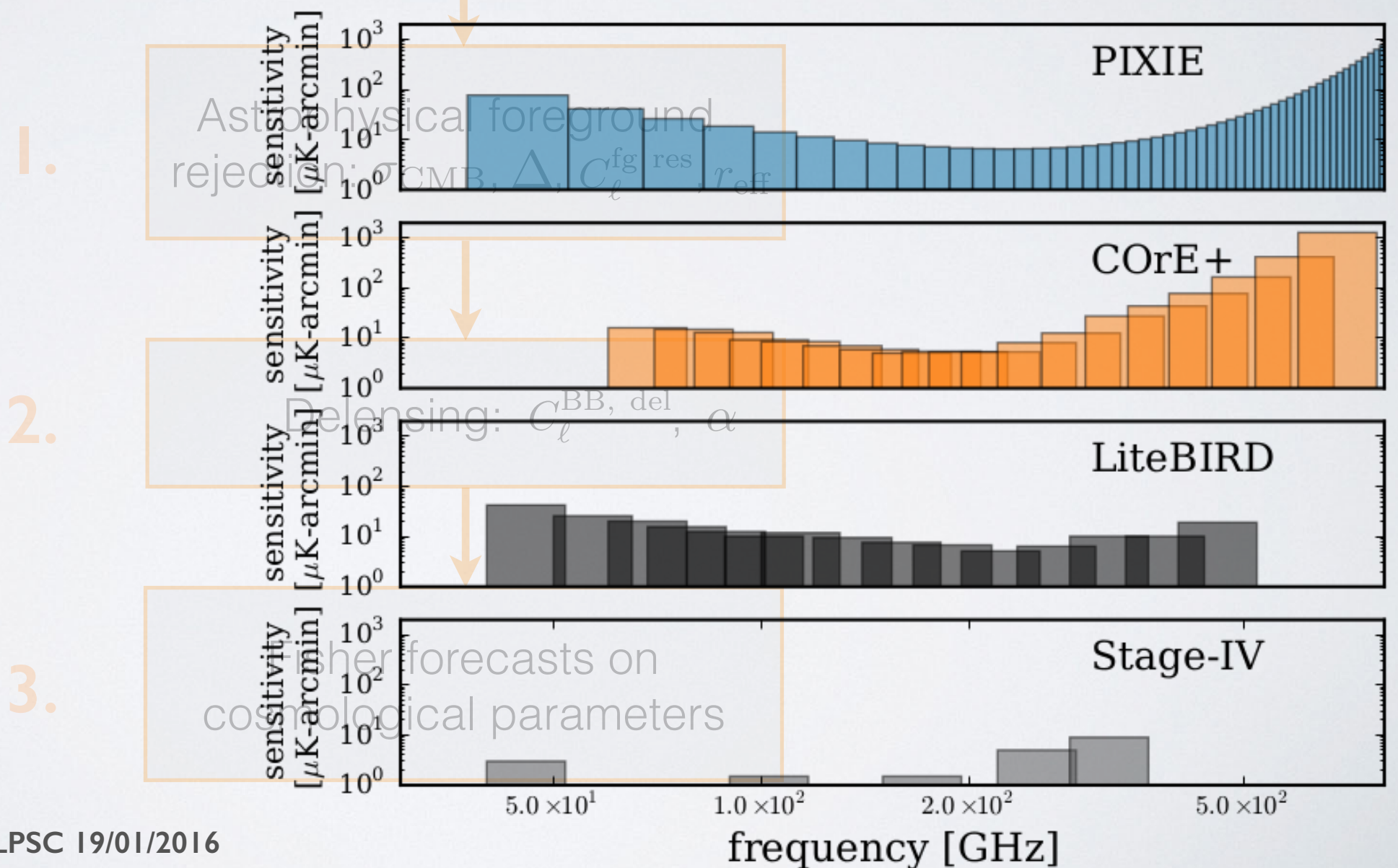
Robust forecasts on
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from the foreground-
obscured,
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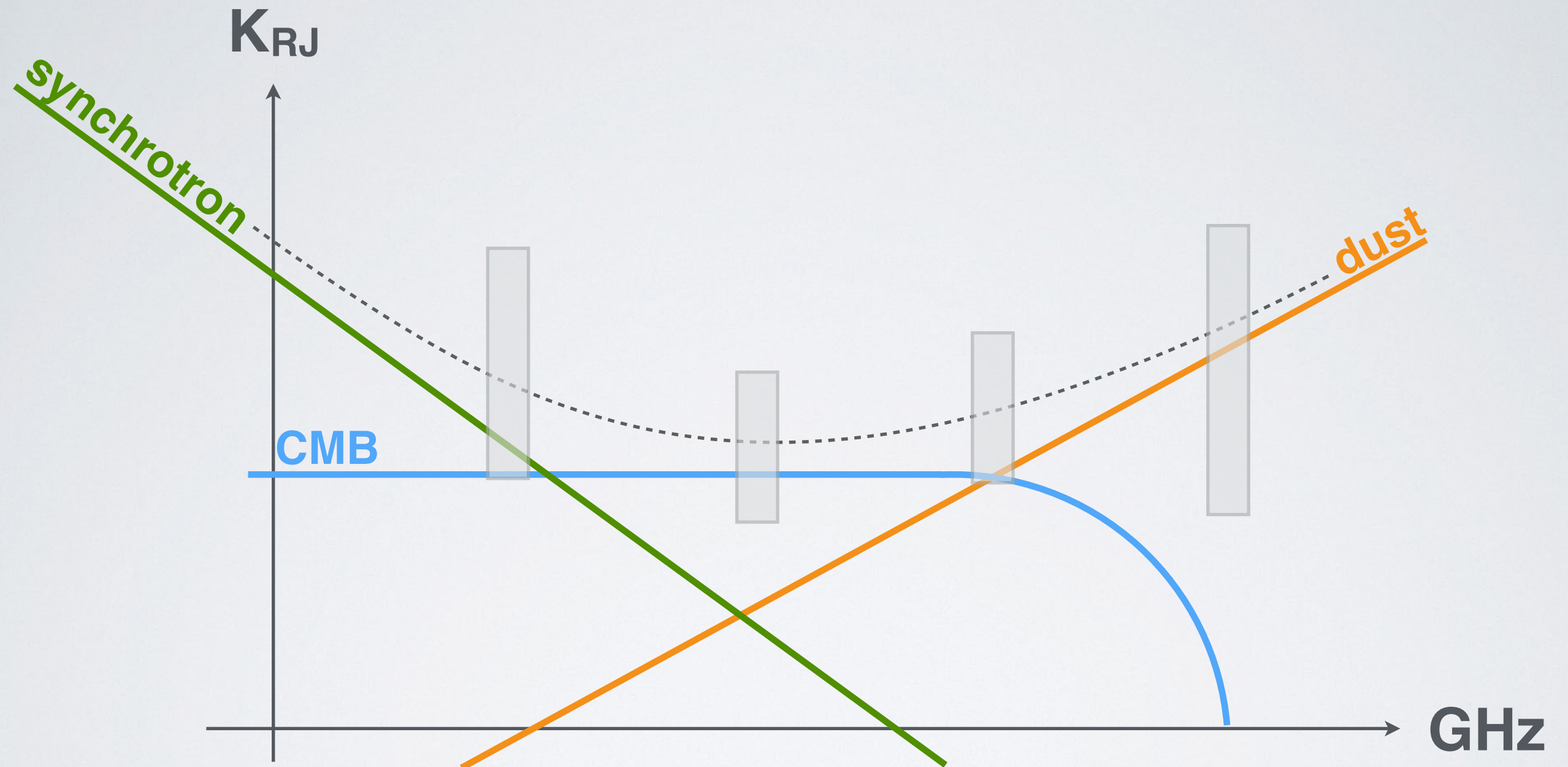
2.

Delensing: $C_{\ell}^{\text{BB, del}}$, α

3.

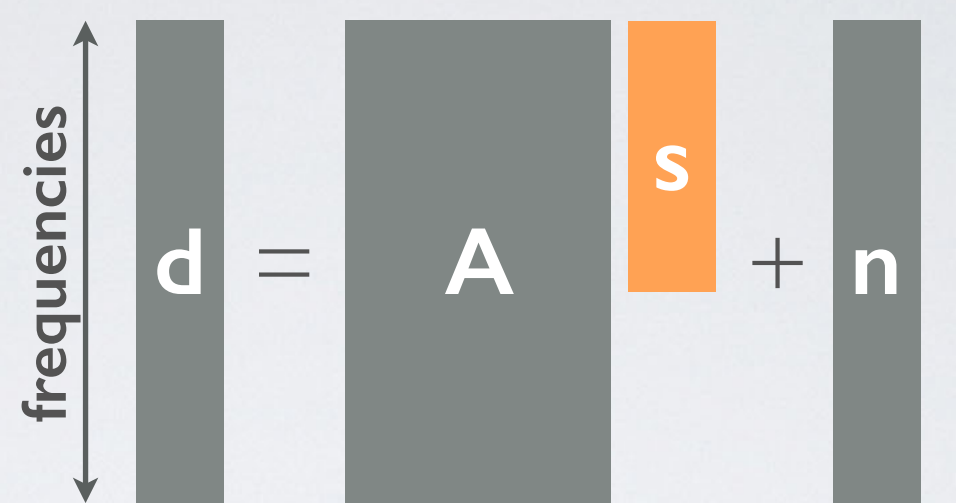
Fisher forecasts on
cosmological parameters

Component separation: idea



Component separation: rendition of parametric max-L 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**

$$A_{\text{sync}}^{\text{raw}}(\nu, \nu_{\text{ref}}) \equiv \left(\frac{\nu}{\nu_{\text{ref}}} \right)^{\beta_s}$$

$$A_{\text{dust}}^{\text{raw}}(\nu, \nu_{\text{ref}}) \equiv \left(\frac{\nu}{\nu_{\text{ref}}} \right)^{\beta_d+1} \frac{e^{\frac{h\nu_{\text{ref}}}{kT_d}} - 1}{e^{\frac{h\nu}{kT_d}} - 1}$$

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

not perfect recovery
of input spectral
parameters ➤
foregrounds
residuals

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

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

linear combination of
various frequency maps
➤ **boosted noise**

Component separation: rendition of parametric max-L component separation

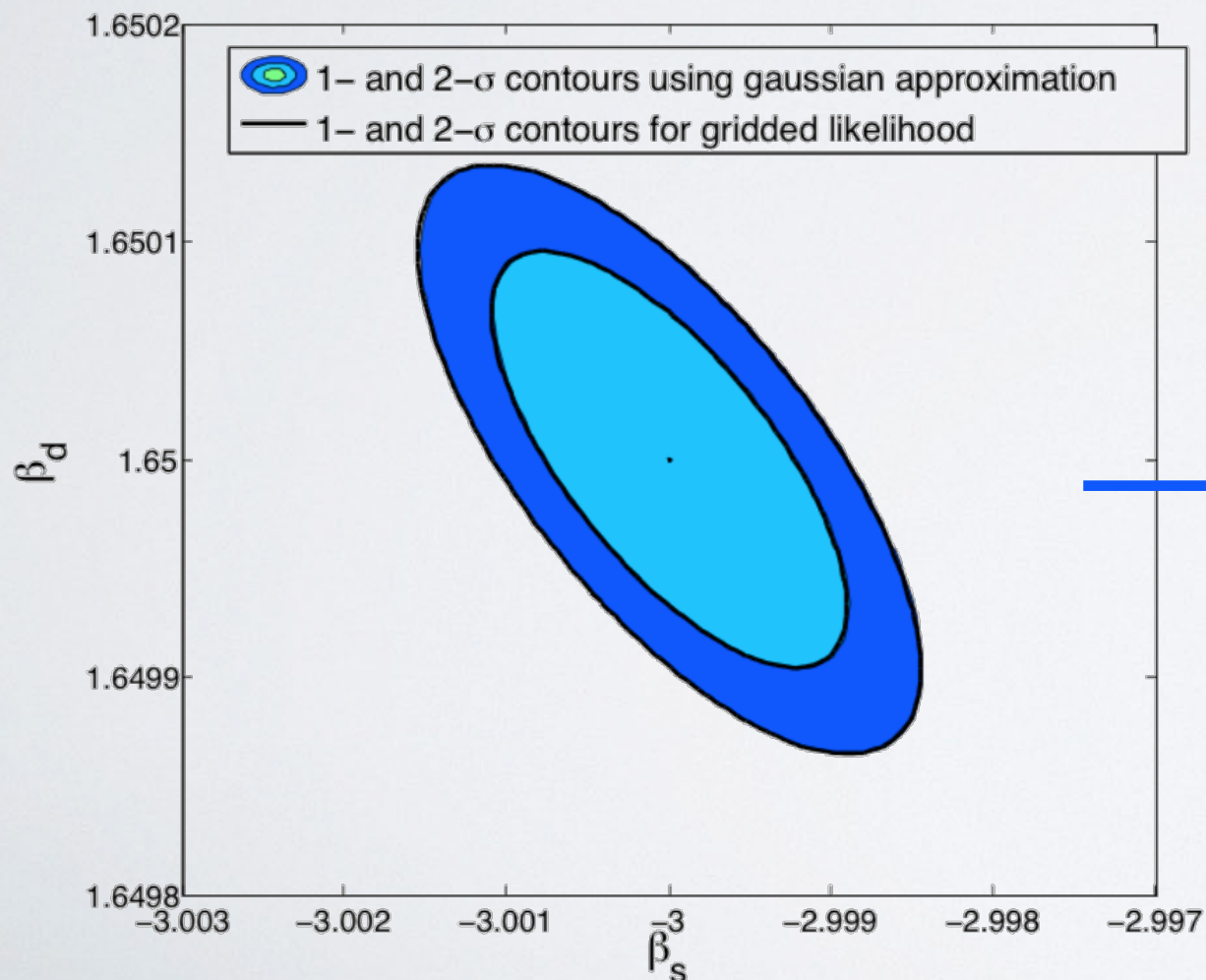
[Brandt et al. (1994), Ericksen et al. (2006), Stompor et al. (2009)]

$$\longrightarrow -2 \log \mathcal{L}(\mathbf{s}, \beta) = \text{constant} + \sum_p (d_p - \mathbf{A}_p \mathbf{s}_p)^T \mathbf{N}_p^{-1} (d_p - \mathbf{A}_p \mathbf{s}_p)$$

$$-2 \log \mathcal{L}_{\text{marg}}(\beta) = -2 \log \int d\mathbf{s} \exp \left[-\frac{1}{2} (\mathbf{d} - \mathbf{A}\mathbf{s})^T \mathbf{N}^{-1} (\mathbf{d} - \mathbf{A}\mathbf{s}) \right]$$

$$= \text{constant} - (\mathbf{A}^T \mathbf{N}^{-1} \mathbf{d})^T (\mathbf{A}^T \mathbf{N}^{-1} \mathbf{A})^{-1} (\mathbf{A}^T \mathbf{N}^{-1} \mathbf{d}) + \log |(\mathbf{A}^T \mathbf{N}^{-1} \mathbf{A})^{-1}|$$

$$-2 \log \mathcal{L}_{\text{spec}}(\beta)$$



[J.E., F. Stivoli and R. Stompor (2011)]

$-2 \log \mathcal{L}_{\text{spec}}(\beta)$ turns out to be **often** well-approximated by a Gaussian at its peak

Component separation: rendition of parametric max-L component separation

$$\Sigma^{-1} \simeq - \left\langle \frac{\partial^2 \mathcal{L}}{\partial \beta \partial \beta'} \right\rangle_{\text{noise}} \Big|_{\text{true } \beta} \quad \text{[JE. et al (2011)]}$$
$$= - \text{tr} \left\{ \left[\frac{\partial \mathbf{A}^T}{\partial \beta} \mathbf{N}^{-1} \mathbf{A} \left(\mathbf{A}^T \mathbf{N}^{-1} \mathbf{A} \right)^{-1} \mathbf{A}^T \mathbf{N}^{-1} \frac{\partial \mathbf{A}}{\partial \beta'} - \frac{\partial \mathbf{A}^T}{\partial \beta} \mathbf{N}^{-1} \frac{\partial \mathbf{A}}{\partial \beta'} \right] \sum_p \mathbf{s}(p) \mathbf{s}^T(p) \right\}$$

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

noise in the reconstructed maps [Stivoli et al (2010)]

information about sky components

↳ prediction of error bars for parametric methods like COMMANDER

not perfect recovery of input spectral parameters ➤ foregrounds residuals

$$\sum_{\ell=20}^{200} C_\ell^{BB, \text{prim.}}(r_{eff}) = \sum_{\ell=20}^{200} C_\ell^{\text{fg, res}},$$

linear combination of various frequency maps ➤ boosted noise

$$\Delta \equiv \left(\frac{\sigma_{\text{CMB}}}{\sigma_{\text{quad}}} \right)^2 \geq 1$$

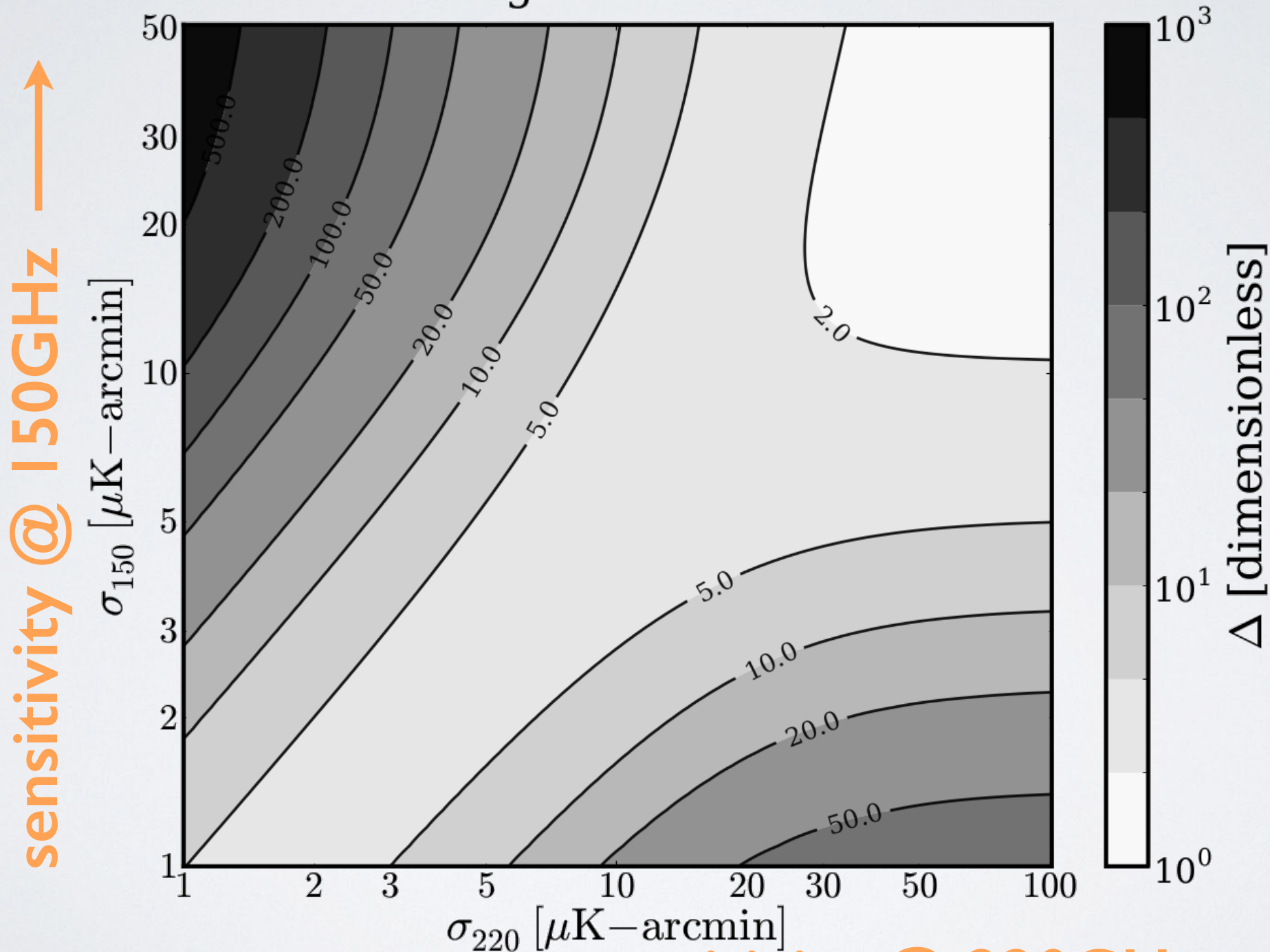
post component separation noise

simple quadratic combination of sensitivities in all channels

3 frequency channels: 150 + 220 + Planck's 353GHz @ 200 μK -arcmin

CMB + dust only

Noise degradation factor Δ



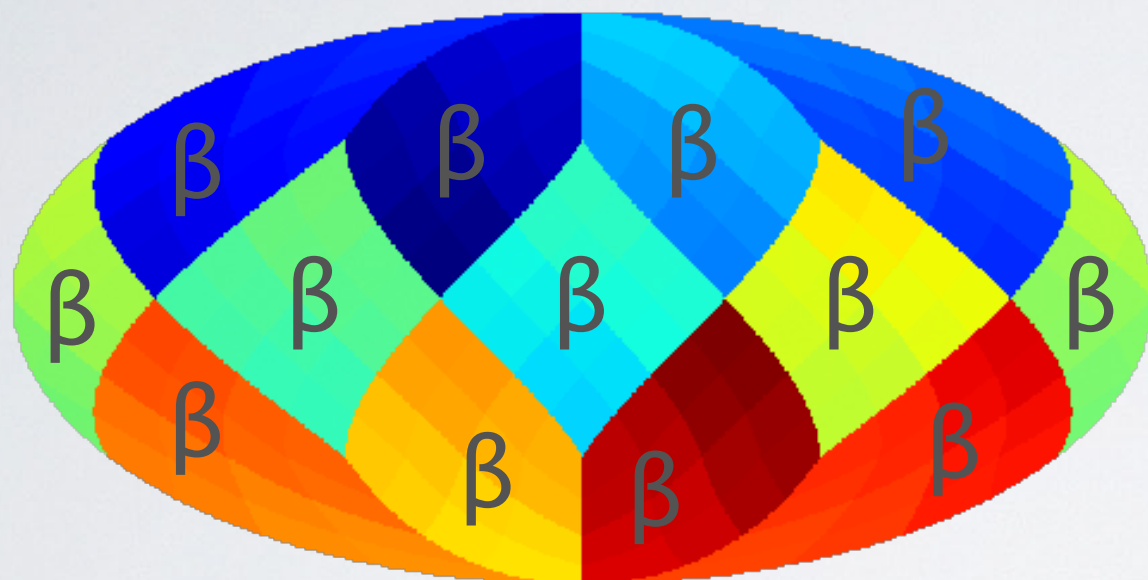
sensitivity @ 150GHz $\uparrow$

sensitivity @ 220GHz $\rightarrow$

Component separation: spatial variation of spectral indices



“ n_p -approach”



$$n_p \equiv \lfloor 12 \times f_{sky} \times 4^2 \rfloor$$

$$\sigma(\beta) \propto \sqrt{n_p} \Leftrightarrow C_{\ell}^{\text{fg, res}} \propto n_p$$

“A-expansion approach”

[e.g. Stolyarov et al (2005)]

$$\mathbf{A}(\beta) \approx \mathbf{A}(\hat{\beta}) + \delta\beta(p) \left. \frac{\partial \mathbf{A}}{\partial \beta} \right|_{\hat{\beta}} + \mathcal{O}(\delta\beta(p)^2)$$

$$\mathbf{A} = \left[\mathbf{A}_{\text{cmb}}, \mathbf{A}_{\text{dust}}, \frac{\partial \mathbf{A}_{\text{dust}}}{\partial \beta_d}, \mathbf{A}_{\text{sync}}, \frac{\partial \mathbf{A}_{\text{sync}}}{\partial \beta_s} \right]$$

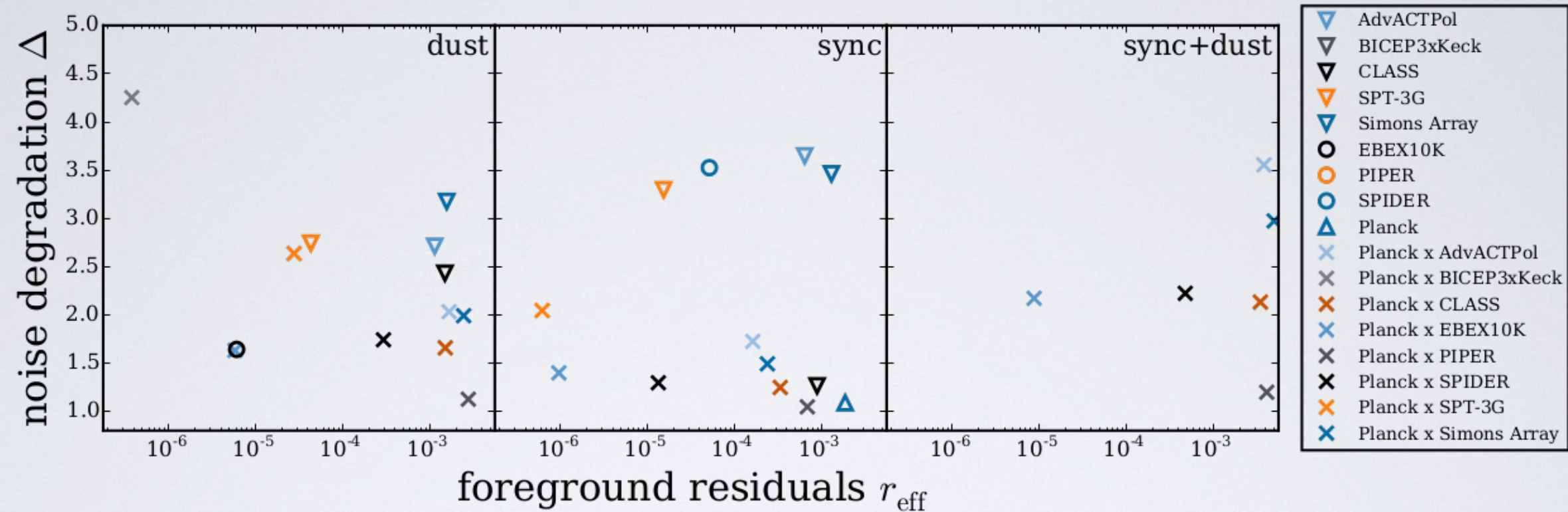
compared to the “ n_p -approach”:

higher boosted noise, $\Delta \nearrow$

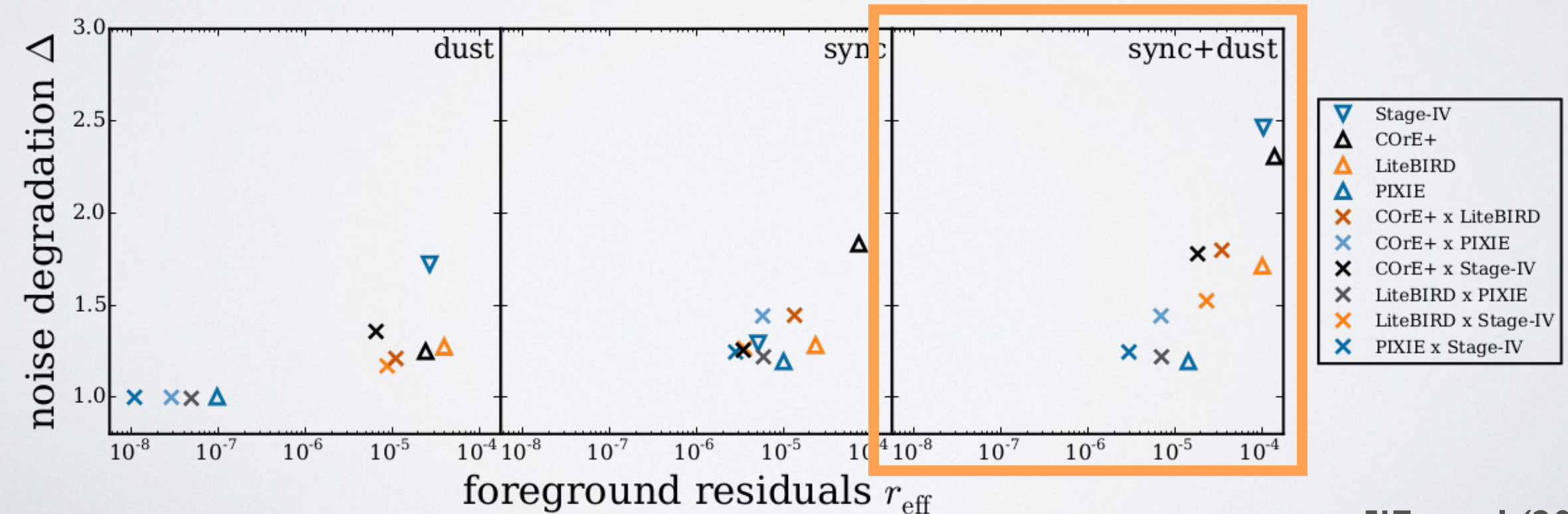
lower foregrounds residuals, $r_{\text{eff}} \searrow$

Component separation: results for the independent patch approach

n_p approach, pre-2020

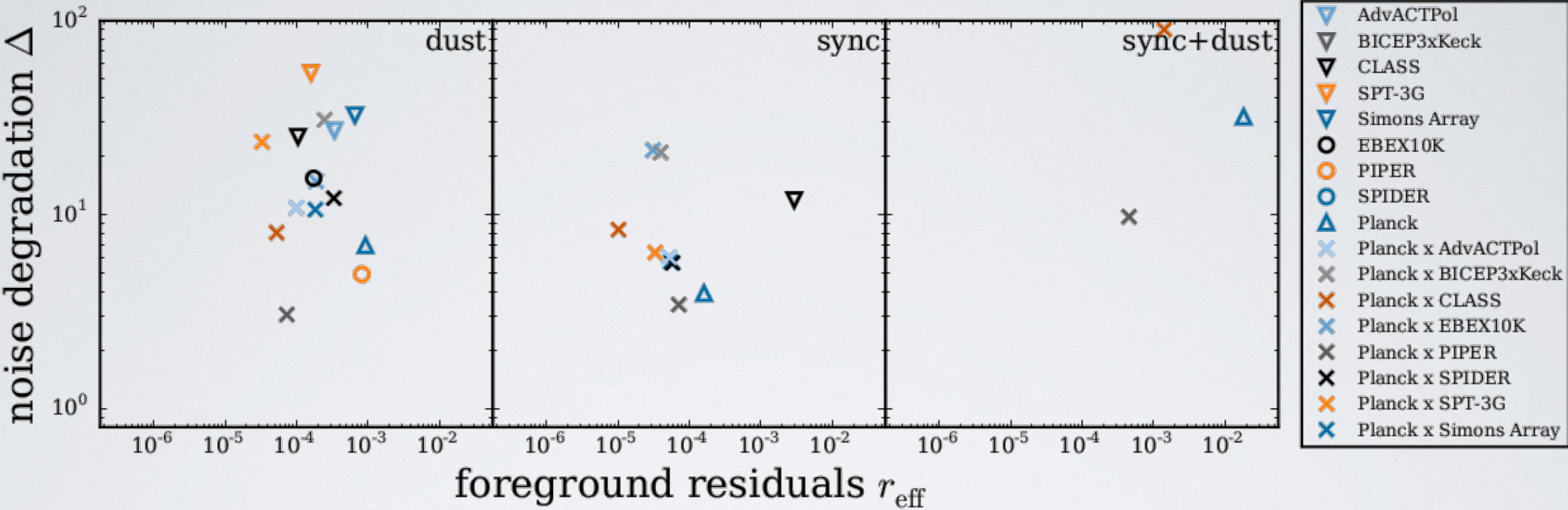


n_p approach, post-2020

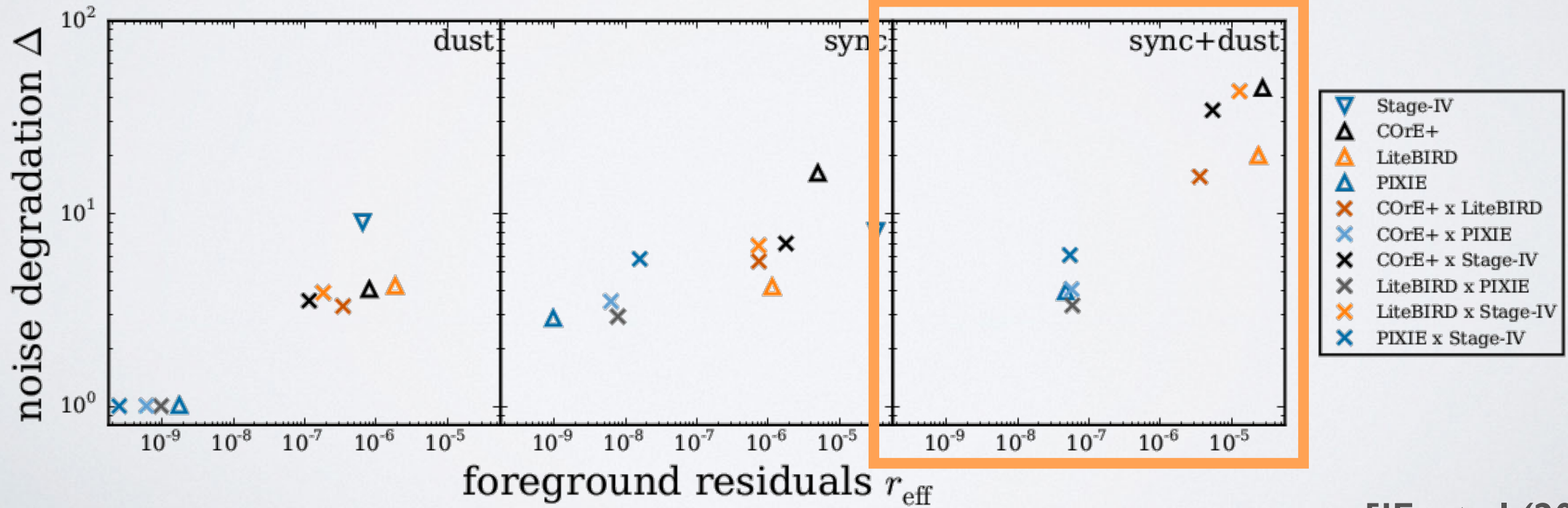


Component separation: results for the A-expansion approach

A-expansion approach, pre-2020

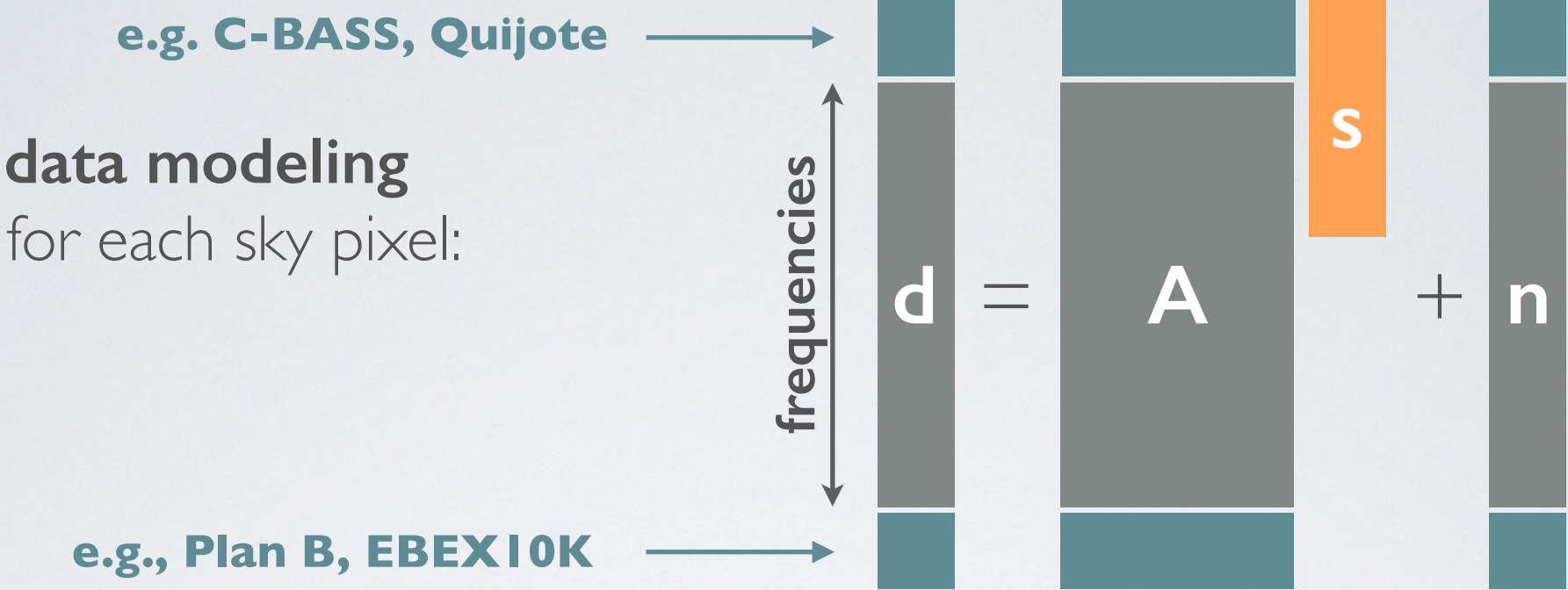


A-expansion approach, post-2020



Component separation: external tracers for extra components?

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



C-BASS

http://www.astro.caltech.edu/cbass/posters/Dickinson_CBASS_Okinawa_June2013.pdf



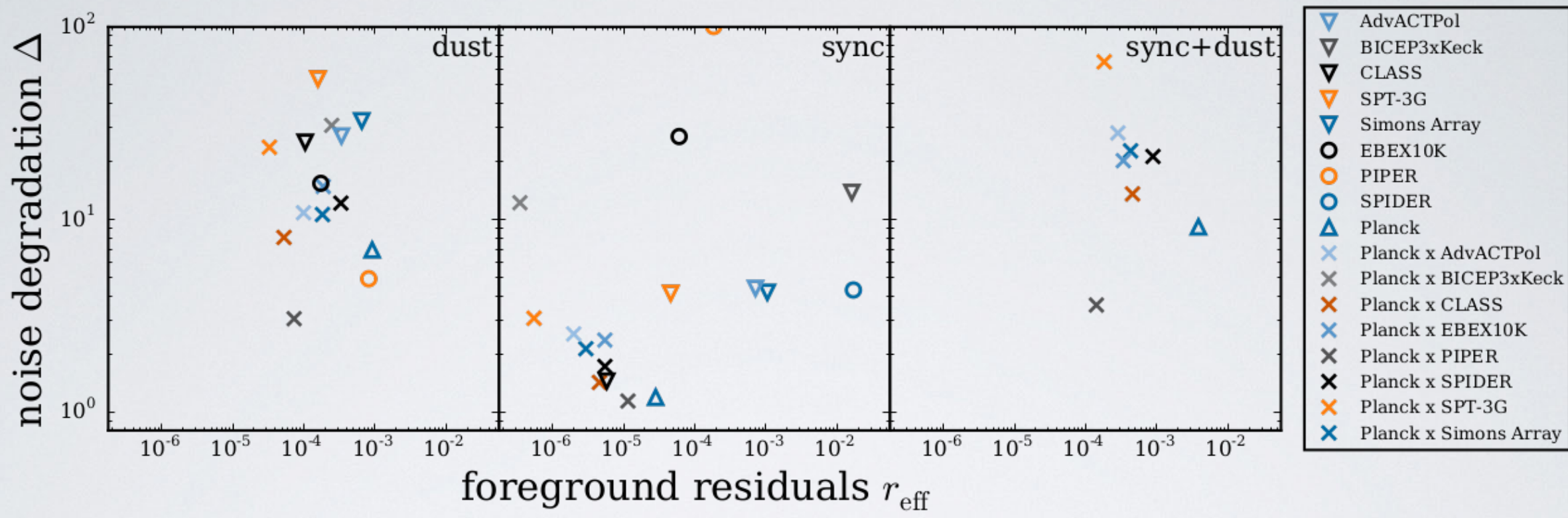
Quijote
arxiv: 1401.4690



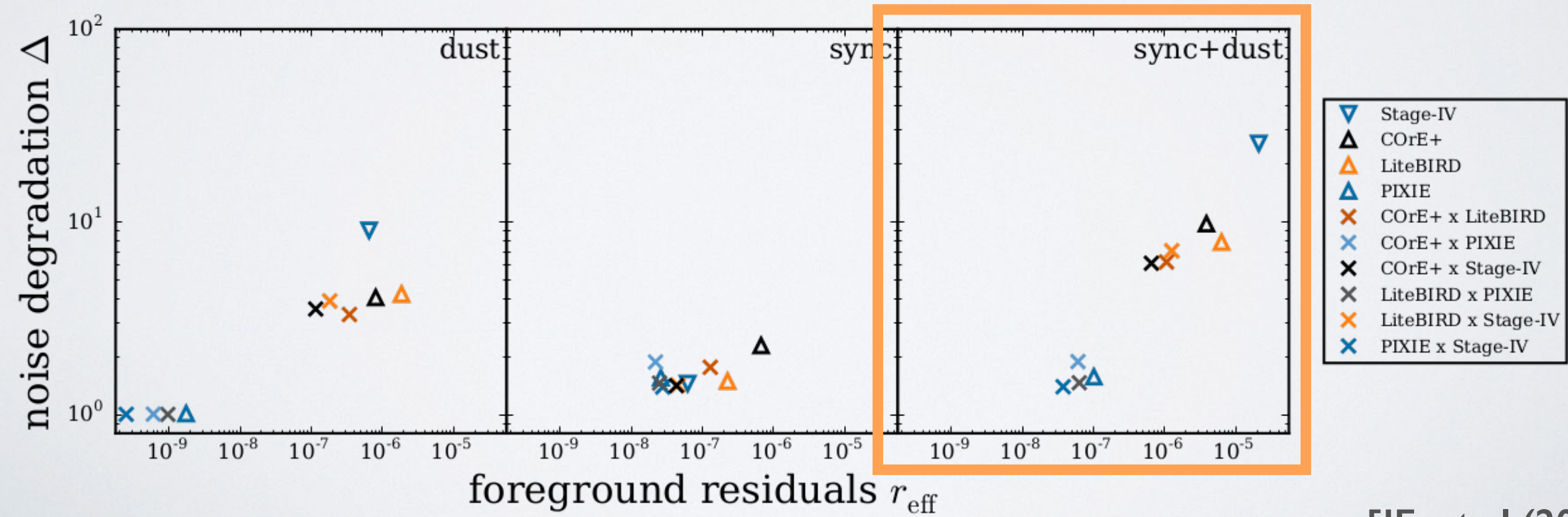
dust monitor
e.g. 1.5mK.arcmin @ 600GHz

Component separation: results for the A-expansion approach + C-BASS

A-expansion approach, pre-2020 + C-BASS

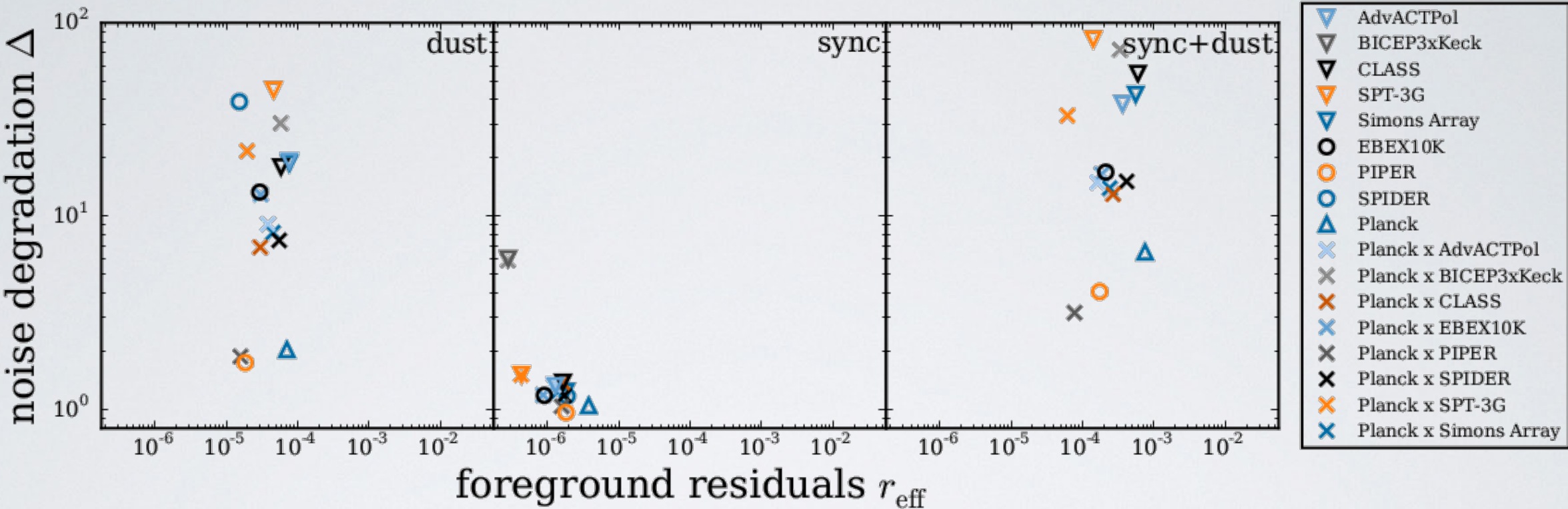


A-expansion approach, post-2020 + C-BASS

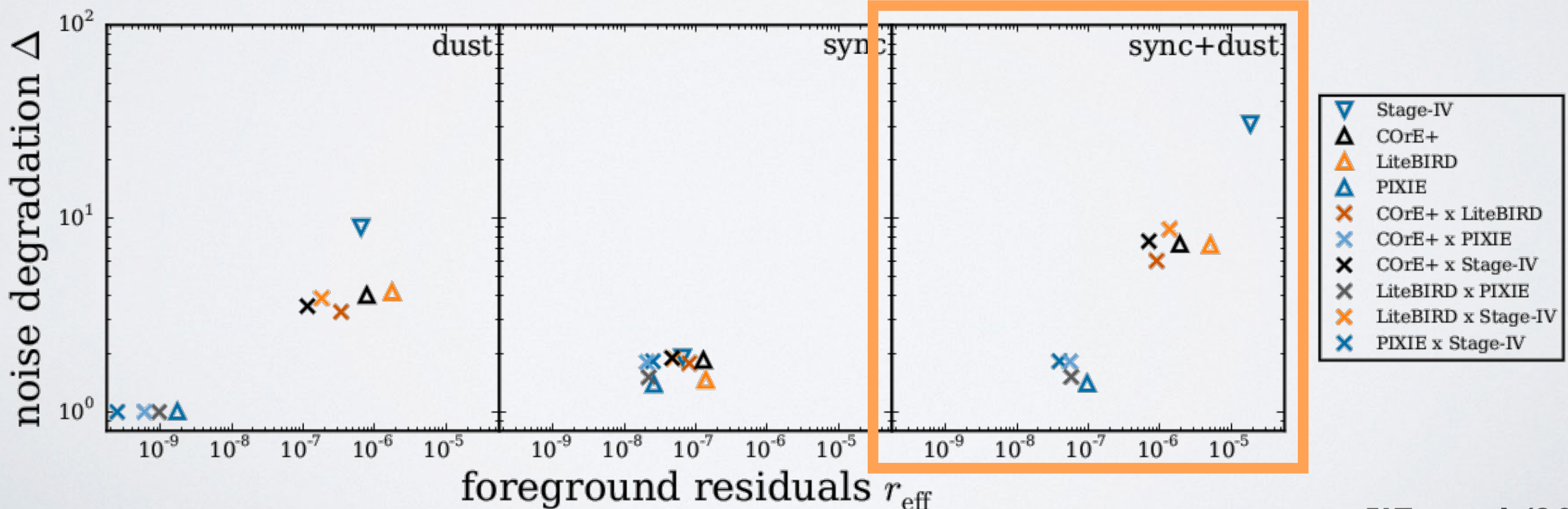


Component separation: results for the A-expansion approach + Quijote

A-expansion approach, pre-2020 + Quijote



A-expansion approach, post-2020 + Quijote



Instrument specification
frequencies, number of detectors,
FWHM, T_{obs}

Observation strategy
fsky, patch location

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maps and power spectra

μK -arcmin computation per
frequency channel

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Fisher forecasts on
cosmological parameters

CMB x CMB

[Seljak & Hirata et al (2004)]

$$C_{\ell}^{BB, \text{del}} \equiv C_{\ell}^{BB, \text{lens}} - C_{\ell}^{BB, \text{est}} \left(\ell_{\min}, \ell_{\max}, N_{\ell}^{EE}, N_{\ell}^{\phi\phi} \right)$$

[Okamoto & Hu et al (2003)]

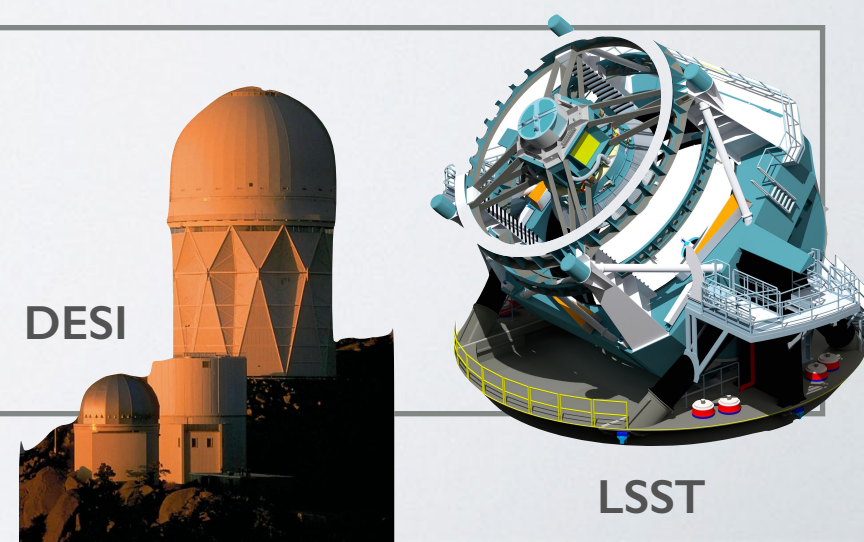
$$N_{\ell}^{\phi\phi} = \left[\frac{1}{2\ell + 1} \sum_{\ell_1 \ell_2} |f_{\ell_1 \ell_2 \ell}^{EB}|^2 \left(\frac{1}{C_{\ell_1}^{BB} + N_{\ell_1}^{BB}} \right) \times \left(\frac{(C_{\ell_2}^{EE})^2}{C_{\ell_2}^{EE} + N_{\ell_2}^{EE}} \right) \right]^{-1}$$

CMB x CIB

$$C_{\ell}^{\phi\phi} + N_{\ell}^{\phi\phi} \rightarrow C_{\ell}^{\phi\phi} / \rho_{\ell}^2 \quad [\text{Sherwin \& Schmittfull (2015)}]$$

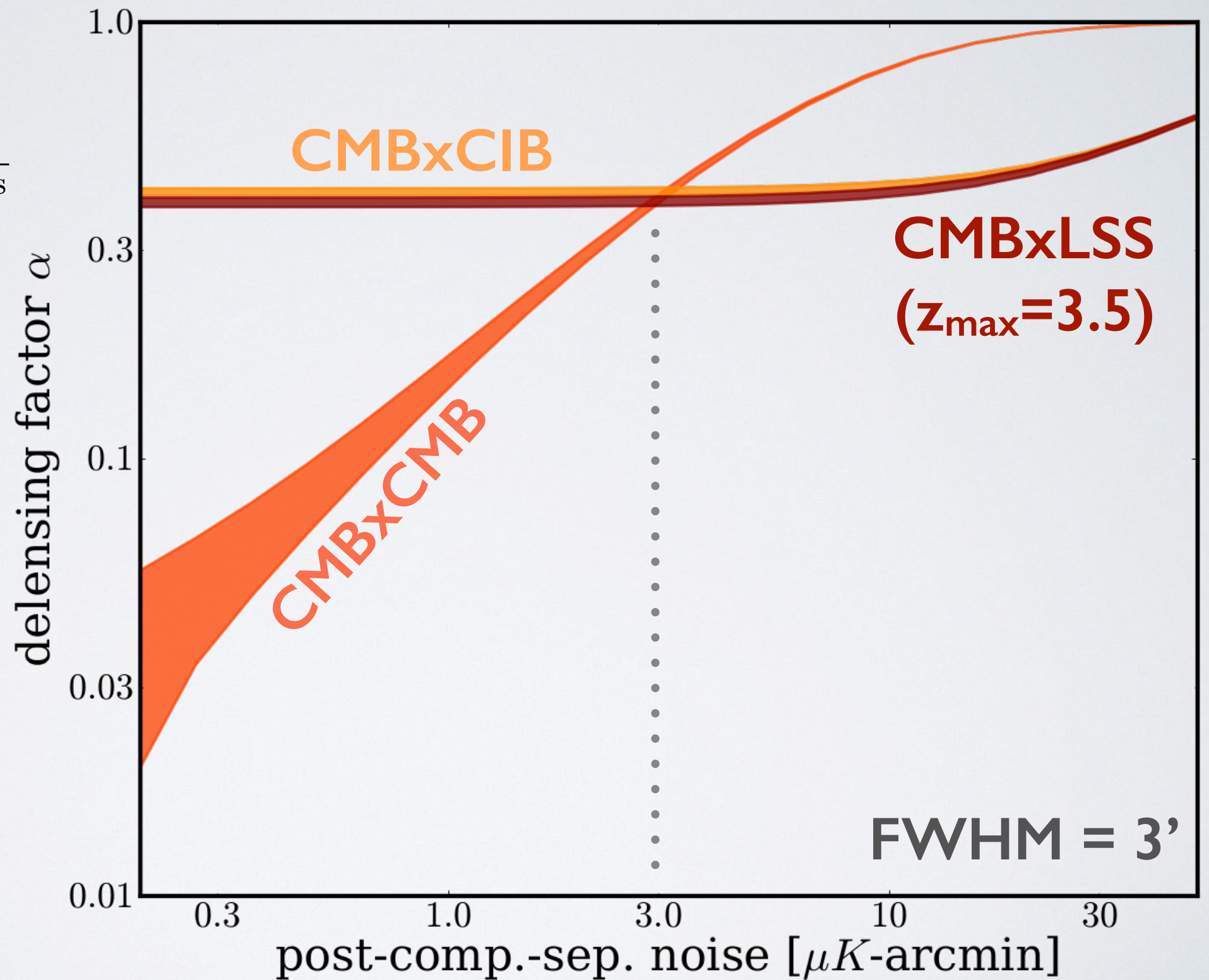
CMB x LSS

$$\frac{(C_{\ell}^{\phi\phi})^2}{C_{\ell}^{\phi\phi} + N_{\ell}^{\phi\phi}} \rightarrow C_{\ell}^{\phi\phi, z_{\max}} \quad [\text{Smith et al (2012)}]$$



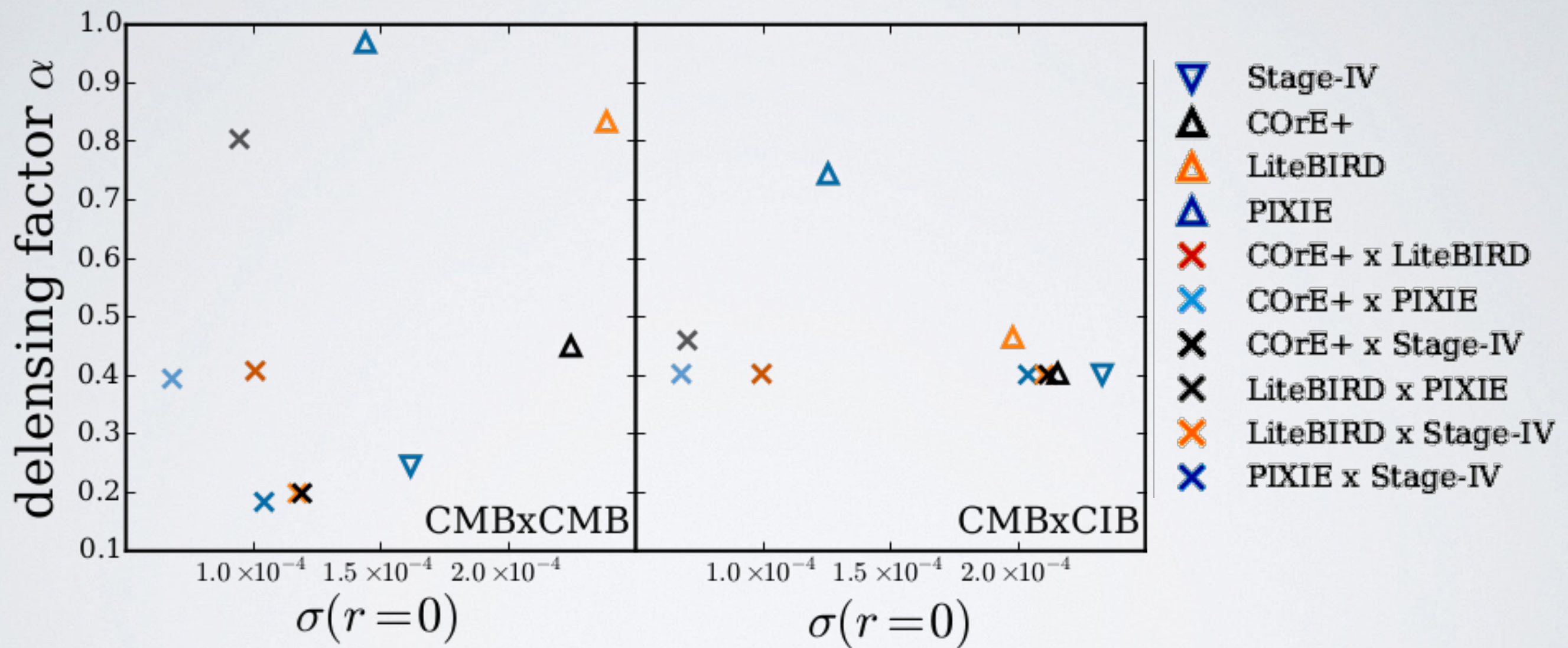
Iterative delensing

$$\alpha \equiv \frac{\sum_{\ell=20}^{200} C_{\ell}^{BB, \text{del}}}{\sum_{\ell=20}^{200} C_{\ell}^{BB, \text{lens}}}$$



n_p approach, post-2020

sync+dust



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Fisher forecasts on
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Constraints on cosmological parameters: formalism

$$F_{ij} = \sum_{\ell=\ell_m^{in}}^{\ell_m^{ax}} \frac{2\ell+1}{2} f_{sky} \text{tr} \left(\mathbf{C}_\ell^{-1} \frac{\partial \mathbf{C}_\ell}{\partial \theta_i} \mathbf{C}_\ell^{-1} \frac{\partial \mathbf{C}_\ell}{\partial \theta_j} \right),$$

$\{T, E, B, d\}$

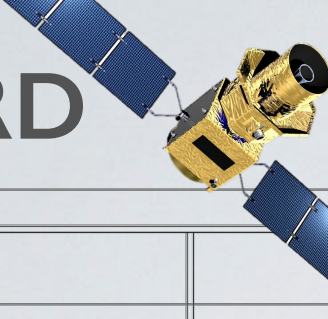


inclusion of delensing, foregrounds residuals and post component separation noise

$$N_\ell^{BB} = N_\ell^{BB, \text{inst}} + C_\ell^{\text{fg, res}} + C_\ell^{BB, \text{del}}$$

└ parametrized as a power law i.e. $A \times \left(\frac{\ell}{\ell_0} \right)^b$

all derived cosmological constraints are marginalized over foregrounds residuals amplitude and tilt



LiteBIRD-ext

Delensing option → ↓ comp. sep. option		no delensing	CMB x CMB	CMB x CIB	CMB x LSS
cmb-only	$\Delta = 1.0$	$\alpha = 1.0$ $\sigma(r) = 3.0 \times 10^{-4}$ $\sigma(n_t) = 0.052$ $\sigma(n_s) = 3.7 \times 10^{-3}$ $\sigma(\alpha_s) = 5.6 \times 10^{-3}$	$\alpha = 0.79$ $\sigma(r) = 2.7 \times 10^{-4}$ $\sigma(n_t) = 0.049$ $\sigma(n_s) = 3.7 \times 10^{-3}$ $\sigma(\alpha_s) = 5.6 \times 10^{-3}$	$\alpha = 0.45$ $\sigma(r) = 2.1 \times 10^{-4}$ $\sigma(n_t) = 0.044$ $\sigma(n_s) = 3.4 \times 10^{-3}$ $\sigma(\alpha_s) = 4.6 \times 10^{-3}$	$\alpha = 0.46$ $\sigma(r) = 2.1 \times 10^{-4}$ $\sigma(n_t) = 0.045$ $\sigma(n_s) = 2.9 \times 10^{-3}$ $\sigma(\alpha_s) = 2.3 \times 10^{-3}$
	$r_{\text{eff}} = 0.0$	$\sigma(M_\nu) = 72$ $\sigma(w_0) = 0.16$ $\sigma(N_{\text{eff}}) = 0.15$ $\sigma(\Omega_k) = 2.8 \times 10^{-3}$	$\sigma(M_\nu) = 72$ $\sigma(w_0) = 0.16$ $\sigma(N_{\text{eff}}) = 0.15$ $\sigma(\Omega_k) = 2.8 \times 10^{-3}$	$\sigma(M_\nu) = 61$ $\sigma(w_0) = 0.15$ $\sigma(N_{\text{eff}}) = 0.11$ $\sigma(\Omega_k) = 2.5 \times 10^{-3}$	$\sigma(M_\nu) = 45$ $\sigma(w_0) = 0.11$ $\sigma(N_{\text{eff}}) = 0.074$ $\sigma(\Omega_k) = 2.3 \times 10^{-3}$
sync+dust	$\Delta = 1.7$	$\alpha = 1.0$ $\sigma(r) = 5.8 \times 10^{-4}$ $\sigma(n_t) = 0.066$ $\sigma(n_s) = 3.9 \times 10^{-3}$ $\sigma(\alpha_s) = 5.8 \times 10^{-3}$	$\alpha = 0.83$ $\sigma(r) = 5.2 \times 10^{-4}$ $\sigma(n_t) = 0.064$ $\sigma(n_s) = 3.9 \times 10^{-3}$ $\sigma(\alpha_s) = 5.8 \times 10^{-3}$	$\alpha = 0.47$ $\sigma(r) = 3.8 \times 10^{-4}$ $\sigma(n_t) = 0.057$ $\sigma(n_s) = 3.5 \times 10^{-3}$ $\sigma(\alpha_s) = 4.7 \times 10^{-3}$	$\alpha = 0.47$ $\sigma(r) = 3.8 \times 10^{-4}$ $\sigma(n_t) = 0.057$ $\sigma(n_s) = 3.0 \times 10^{-3}$ $\sigma(\alpha_s) = 2.3 \times 10^{-3}$
	$r_{\text{eff}} = 1.0 \times 10^{-4}$	$\sigma(M_\nu) = 80$ $\sigma(w_0) = 0.17$ $\sigma(N_{\text{eff}}) = 0.16$ $\sigma(\Omega_k) = 3.1 \times 10^{-3}$	$\sigma(M_\nu) = 80$ $\sigma(w_0) = 0.17$ $\sigma(N_{\text{eff}}) = 0.16$ $\sigma(\Omega_k) = 3.1 \times 10^{-3}$	$\sigma(M_\nu) = 62$ $\sigma(w_0) = 0.15$ $\sigma(N_{\text{eff}}) = 0.11$ $\sigma(\Omega_k) = 2.6 \times 10^{-3}$	$\sigma(M_\nu) = 46$ $\sigma(w_0) = 0.11$ $\sigma(N_{\text{eff}}) = 0.076$ $\sigma(\Omega_k) = 2.3 \times 10^{-3}$
sync+dust A-expansion + C-BASS	$\Delta = 7.8$	$\alpha = 1.0$ $\sigma(r) = 1.2 \times 10^{-3}$ $\sigma(n_t) = 0.087$ $\sigma(n_s) = 4.9 \times 10^{-3}$ $\sigma(\alpha_s) = 6.8 \times 10^{-3}$	$\alpha = 0.94$ $\sigma(r) = 1.2 \times 10^{-3}$ $\sigma(n_t) = 0.087$ $\sigma(n_s) = 4.9 \times 10^{-3}$ $\sigma(\alpha_s) = 6.8 \times 10^{-3}$	$\alpha = 0.51$ $\sigma(r) = 1.0 \times 10^{-3}$ $\sigma(n_t) = 0.084$ $\sigma(n_s) = 4.1 \times 10^{-3}$ $\sigma(\alpha_s) = 5.0 \times 10^{-3}$	$\alpha = 0.52$ $\sigma(r) = 1.0 \times 10^{-3}$ $\sigma(n_t) = 0.084$ $\sigma(n_s) = 3.3 \times 10^{-3}$ $\sigma(\alpha_s) = 2.3 \times 10^{-3}$
	$r_{\text{eff}} = 6.3 \times 10^{-6}$	$\sigma(M_\nu) = 1.4 \times 10^2$ $\sigma(w_0) = 0.29$ $\sigma(N_{\text{eff}}) = 0.20$ $\sigma(\Omega_k) = 5.5 \times 10^{-3}$	$\sigma(M_\nu) = 1.4 \times 10^2$ $\sigma(w_0) = 0.29$ $\sigma(N_{\text{eff}}) = 0.20$ $\sigma(\Omega_k) = 5.5 \times 10^{-3}$	$\sigma(M_\nu) = 66$ $\sigma(w_0) = 0.16$ $\sigma(N_{\text{eff}}) = 0.12$ $\sigma(\Omega_k) = 2.7 \times 10^{-3}$	$\sigma(M_\nu) = 49$ $\sigma(w_0) = 0.12$ $\sigma(N_{\text{eff}}) = 0.086$ $\sigma(\Omega_k) = 2.5 \times 10^{-3}$
sync+dust A-expansion + QUIJOTE-CMB	$\Delta = 7.3$	$\alpha = 1.0$ $\sigma(r) = 1.1 \times 10^{-3}$ $\sigma(n_t) = 0.086$ $\sigma(n_s) = 4.9 \times 10^{-3}$ $\sigma(\alpha_s) = 6.7 \times 10^{-3}$	$\alpha = 0.94$ $\sigma(r) = 1.1 \times 10^{-3}$ $\sigma(n_t) = 0.086$ $\sigma(n_s) = 4.9 \times 10^{-3}$ $\sigma(\alpha_s) = 6.7 \times 10^{-3}$	$\alpha = 0.51$ $\sigma(r) = 9.6 \times 10^{-4}$ $\sigma(n_t) = 0.082$ $\sigma(n_s) = 4.1 \times 10^{-3}$ $\sigma(\alpha_s) = 5.0 \times 10^{-3}$	$\alpha = 0.52$ $\sigma(r) = 9.6 \times 10^{-4}$ $\sigma(n_t) = 0.082$ $\sigma(n_s) = 3.3 \times 10^{-3}$ $\sigma(\alpha_s) = 2.3 \times 10^{-3}$
	$r_{\text{eff}} = 5.1 \times 10^{-6}$	$\sigma(M_\nu) = 1.4 \times 10^2$ $\sigma(w_0) = 0.28$ $\sigma(N_{\text{eff}}) = 0.20$ $\sigma(\Omega_k) = 5.3 \times 10^{-3}$	$\sigma(M_\nu) = 1.4 \times 10^2$ $\sigma(w_0) = 0.28$ $\sigma(N_{\text{eff}}) = 0.20$ $\sigma(\Omega_k) = 5.3 \times 10^{-3}$	$\sigma(M_\nu) = 66$ $\sigma(w_0) = 0.16$ $\sigma(N_{\text{eff}}) = 0.12$ $\sigma(\Omega_k) = 2.7 \times 10^{-3}$	$\sigma(M_\nu) = 48$ $\sigma(w_0) = 0.12$ $\sigma(N_{\text{eff}}) = 0.086$ $\sigma(\Omega_k) = 2.5 \times 10^{-3}$

LiteBIRD x Stage-IV

Stage-IV x LiteBIRD-ext

Delensing option → ↓ comp. sep. option		no delensing	CMB x CMB	CMB x CIB	CMB x LSS
cmb-only	$\Delta = 1.0$	$\alpha = 1.0$ $\sigma(r) = 2.6 \times 10^{-4}$ $\sigma(n_t) = 0.045$ $\sigma(n_s) = 1.8 \times 10^{-3}$ $\sigma(\alpha_s) = 1.9 \times 10^{-3}$	$\alpha = 0.16$ $\sigma(r) = 1.1 \times 10^{-4}$ $\sigma(n_t) = 0.024$ $\sigma(n_s) = 1.8 \times 10^{-3}$ $\sigma(\alpha_s) = 1.9 \times 10^{-3}$	$\alpha = 0.40$ $\sigma(r) = 1.6 \times 10^{-4}$ $\sigma(n_t) = 0.033$ $\sigma(n_s) = 1.9 \times 10^{-3}$ $\sigma(\alpha_s) = 2.0 \times 10^{-3}$	$\alpha = 0.38$ $\sigma(r) = 1.6 \times 10^{-4}$ $\sigma(n_t) = 0.033$ $\sigma(n_s) = 1.8 \times 10^{-3}$ $\sigma(\alpha_s) = 1.7 \times 10^{-3}$
	$r_{\text{eff}} = 0.0$	$\sigma(M_\nu) = 37$ $\sigma(w_0) = 0.093$ $\sigma(N_{\text{eff}}) = 0.028$ $\sigma(\Omega_k) = 1.6 \times 10^{-3}$	$\sigma(M_\nu) = 37$ $\sigma(w_0) = 0.093$ $\sigma(N_{\text{eff}}) = 0.028$ $\sigma(\Omega_k) = 1.6 \times 10^{-3}$	$\sigma(M_\nu) = 38$ $\sigma(w_0) = 0.10$ $\sigma(N_{\text{eff}}) = 0.027$ $\sigma(\Omega_k) = 1.6 \times 10^{-3}$	$\sigma(M_\nu) = 31$ $\sigma(w_0) = 0.085$ $\sigma(N_{\text{eff}}) = 0.023$ $\sigma(\Omega_k) = 1.6 \times 10^{-3}$
sync+dust	$\Delta = 1.5$	$\alpha = 1.0$ $\sigma(r) = 4.5 \times 10^{-4}$ $\sigma(n_t) = 0.054$ $\sigma(n_s) = 1.9 \times 10^{-3}$ $\sigma(\alpha_s) = 2.0 \times 10^{-3}$	$\alpha = 0.20$ $\sigma(r) = 1.4 \times 10^{-4}$ $\sigma(n_t) = 0.029$ $\sigma(n_s) = 1.9 \times 10^{-3}$ $\sigma(\alpha_s) = 2.0 \times 10^{-3}$	$\alpha = 0.40$ $\sigma(r) = 2.2 \times 10^{-4}$ $\sigma(n_t) = 0.038$ $\sigma(n_s) = 1.9 \times 10^{-3}$ $\sigma(\alpha_s) = 2.0 \times 10^{-3}$	$\alpha = 0.38$ $\sigma(r) = 2.1 \times 10^{-4}$ $\sigma(n_t) = 0.037$ $\sigma(n_s) = 1.8 \times 10^{-3}$ $\sigma(\alpha_s) = 1.7 \times 10^{-3}$
	$r_{\text{eff}} = 2.3 \times 10^{-5}$	$\sigma(M_\nu) = 38$ $\sigma(w_0) = 0.096$ $\sigma(N_{\text{eff}}) = 0.029$ $\sigma(\Omega_k) = 1.6 \times 10^{-3}$	$\sigma(M_\nu) = 38$ $\sigma(w_0) = 0.096$ $\sigma(N_{\text{eff}}) = 0.029$ $\sigma(\Omega_k) = 1.6 \times 10^{-3}$	$\sigma(M_\nu) = 39$ $\sigma(w_0) = 0.11$ $\sigma(N_{\text{eff}}) = 0.029$ $\sigma(\Omega_k) = 1.7 \times 10^{-3}$	$\sigma(M_\nu) = 31$ $\sigma(w_0) = 0.087$ $\sigma(N_{\text{eff}}) = 0.024$ $\sigma(\Omega_k) = 1.6 \times 10^{-3}$
sync+dust A-expansion + C-BASS	$\Delta = 7.1$	$\alpha = 1.0$ $\sigma(r) = 5.6 \times 10^{-4}$ $\sigma(n_t) = 0.060$ $\sigma(n_s) = 1.9 \times 10^{-3}$ $\sigma(\alpha_s) = 2.2 \times 10^{-3}$	$\alpha = 0.37$ $\sigma(r) = 3.0 \times 10^{-4}$ $\sigma(n_t) = 0.045$ $\sigma(n_s) = 1.9 \times 10^{-3}$ $\sigma(\alpha_s) = 2.2 \times 10^{-3}$	$\alpha = 0.40$ $\sigma(r) = 3.1 \times 10^{-4}$ $\sigma(n_t) = 0.047$ $\sigma(n_s) = 1.9 \times 10^{-3}$ $\sigma(\alpha_s) = 2.2 \times 10^{-3}$	$\alpha = 0.38$ $\sigma(r) = 3.0 \times 10^{-4}$ $\sigma(n_t) = 0.046$ $\sigma(n_s) = 1.9 \times 10^{-3}$ $\sigma(\alpha_s) = 1.8 \times 10^{-3}$
	$r_{\text{eff}} = 1.3 \times 10^{-6}$	$\sigma(M_\nu) = 41$ $\sigma(w_0) = 0.11$ $\sigma(N_{\text{eff}}) = 0.037$ $\sigma(\Omega_k) = 1.7 \times 10^{-3}$	$\sigma(M_\nu) = 41$ $\sigma(w_0) = 0.11$ $\sigma(N_{\text{eff}}) = 0.037$ $\sigma(\Omega_k) = 1.7 \times 10^{-3}$	$\sigma(M_\nu) = 40$ $\sigma(w_0) = 0.12$ $\sigma(N_{\text{eff}}) = 0.035$ $\sigma(\Omega_k) = 1.7 \times 10^{-3}$	$\sigma(M_\nu) = 33$ $\sigma(w_0) = 0.093$ $\sigma(N_{\text{eff}}) = 0.029$ $\sigma(\Omega_k) = 1.6 \times 10^{-3}$

Foregrounds:

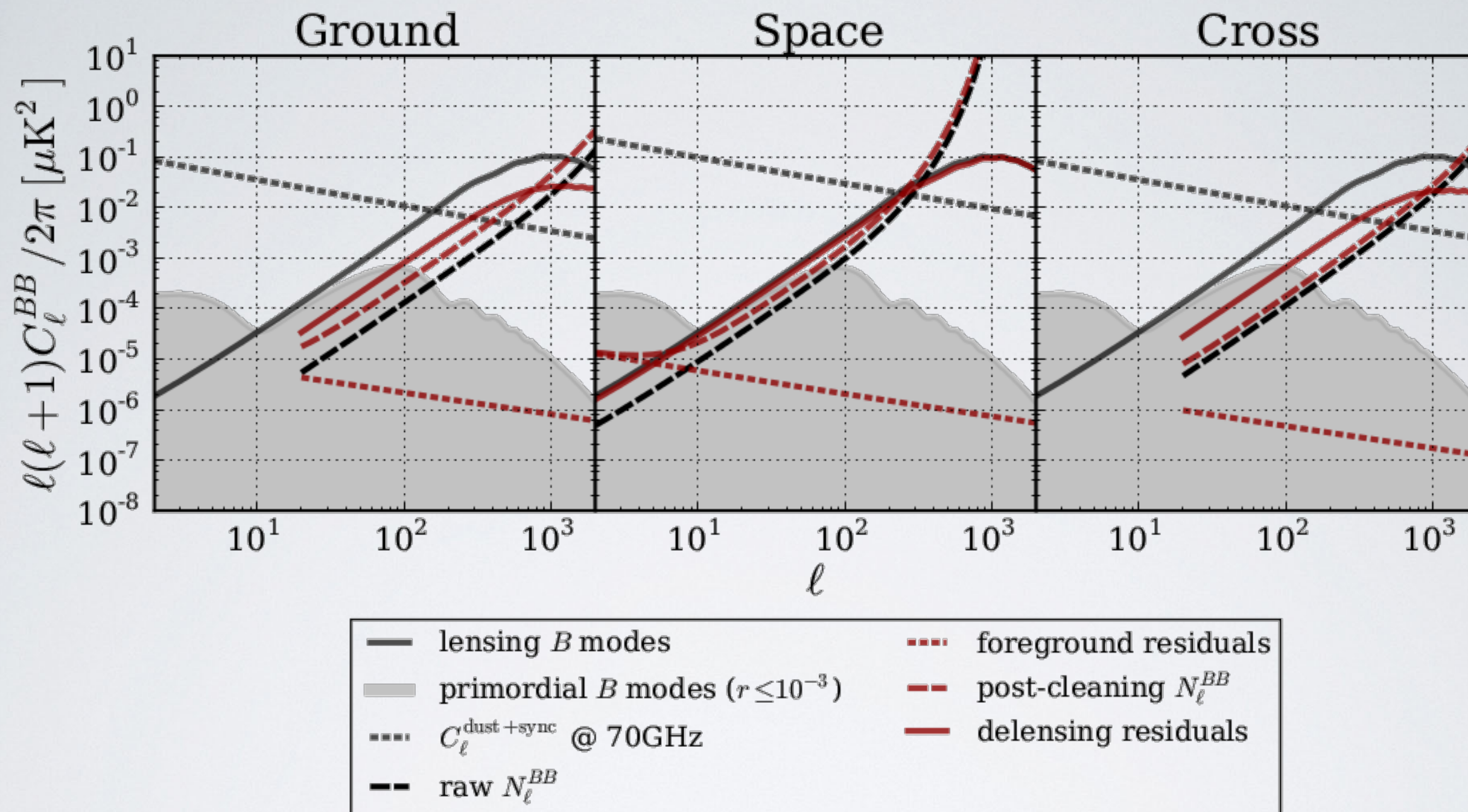
- Broad frequency-coverage + balanced sensitivities leads to low noise boost and low foregrounds residuals.
- Spatial variation of spectral indices requires **sensitive foregrounds monitors** (e.g. C-BASS, QUIOTE, sensitive frequencies above 300GHz)
/!\ inter-calibration, band-mismatch, mis-modeling, etc.

Delensing:

- **strong synergy** between ground, balloon and space instruments.
- For example: Stage IV x satellites could delens up to **70-80%**

Constraints on cosmology:

- Low multipoles are really important to reach the constraints quoted in this work
/!\ systematics
- Stage-IV x satellites leads to
$$\sigma(n_T) \gtrsim 0.03$$
$$\sigma(r=0.001) \sim 1-2e-4 \text{ with CMBxCMB iterative delensing}$$
$$\sigma(\text{neutrinos mass}) \sim 30-40\text{meV}, \sigma(N_{\text{eff}}) < 0.046$$

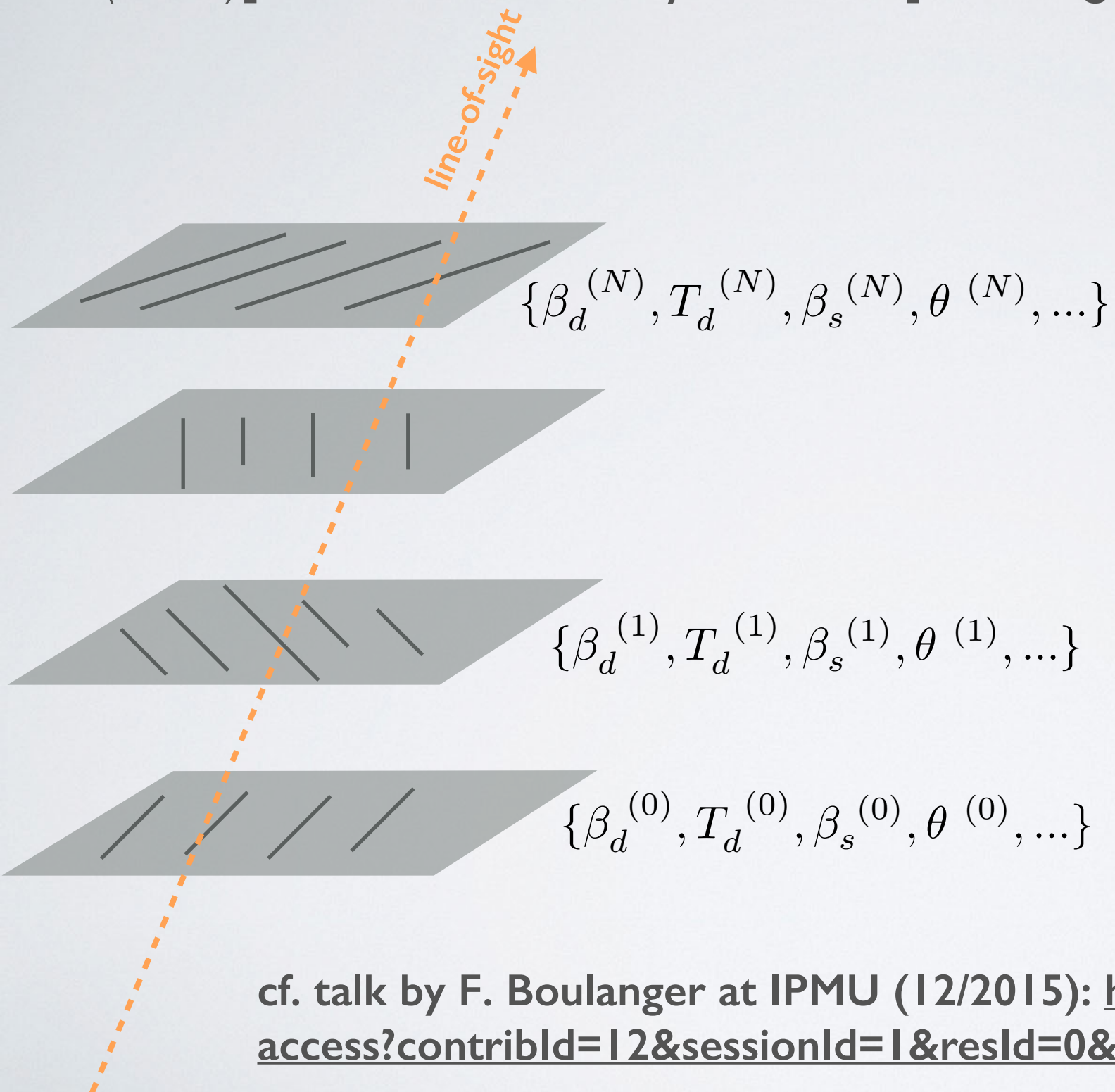


➤ user-friendly interface to the code is accessible at turkey.lbl.gov and is currently running on **NERSC** machines (accessible on demand)

```
forecast_wrapper.forecast( fsky=0.1, freqs=[95, 150, 220], uKCMBarcmin=[10.0, 10.0, 10.0], FWHM=[5.0, 3.0, 2.0], ell_max=2000, ell_min=20, Bd=1.59, prior_dust=0.0, Td=19.6, Bs=-3.1, prior_sync=0.0, components_v=[0,1,0,0], delensing_option_v=[0,1,0,0], params_dev_v=[1,1,1,1,1,1,1,1,1,1,1,1,1,1,1], information_channels_v=[1,1,1,1], planck_combination=[0] )
```


Beyond JE. et al (2015)

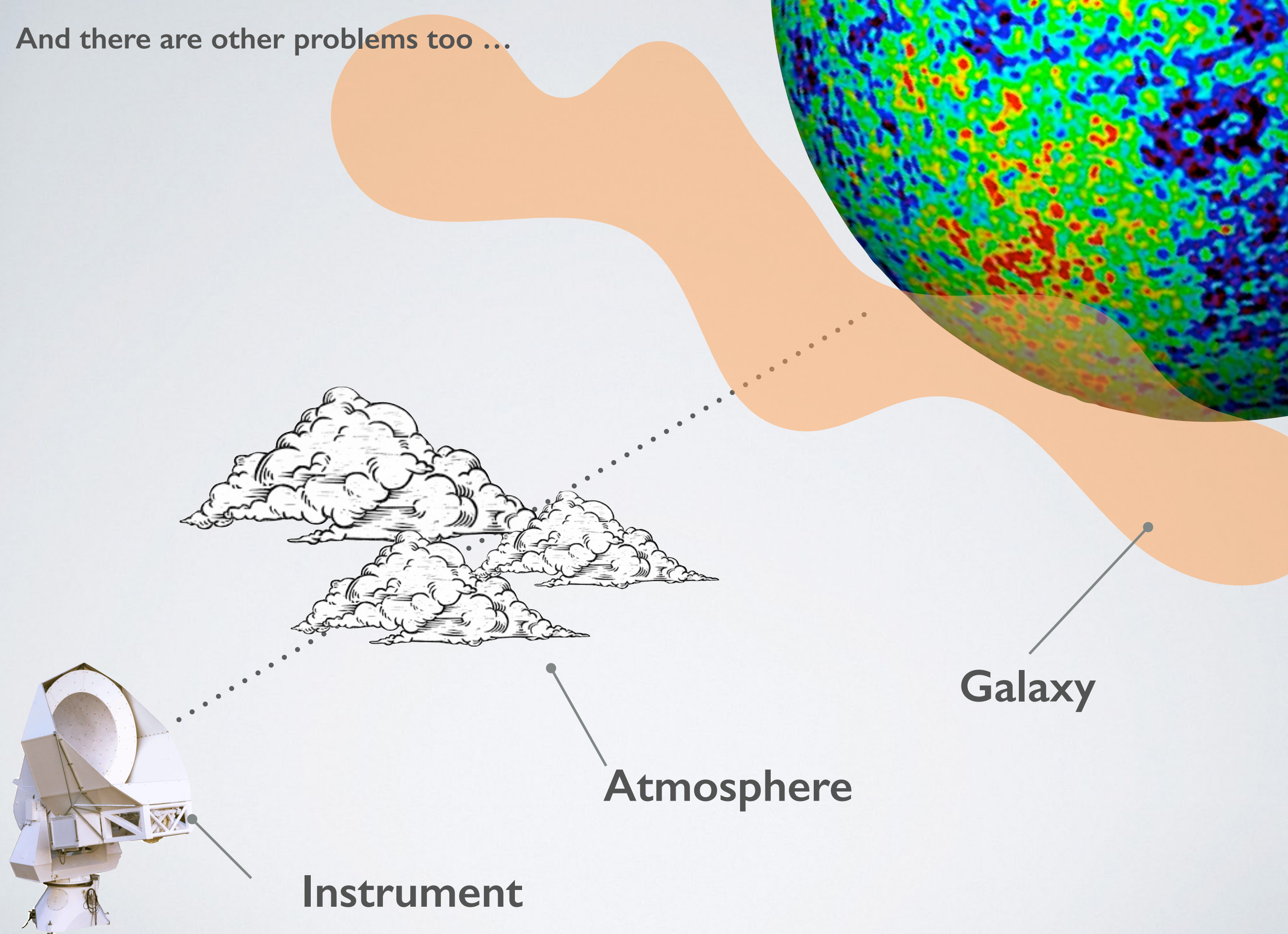
- Need for a generalized formalism to incorporate systematics due to modeling assumptions [*Remazeilles et al (2015)*, *Armitage-Caplan et al (2012)*, *Stivoli et al (2010)*] and instrumental systematics [working with D. Poletti @ APC]



Currently working with D. Poletti (grad student @ APC) on a generalization of Errard et al (2011) in the case of a systematic error regarding the modeling of foregrounds emission laws

cf. talk by F. Boulanger at IPMU (12/2015): <http://indico.ipmu.jp/indico/getFile.py/access?contribId=12&sessionId=1&resId=0&materialId=slides&confId=72>

And there are other problems too ...

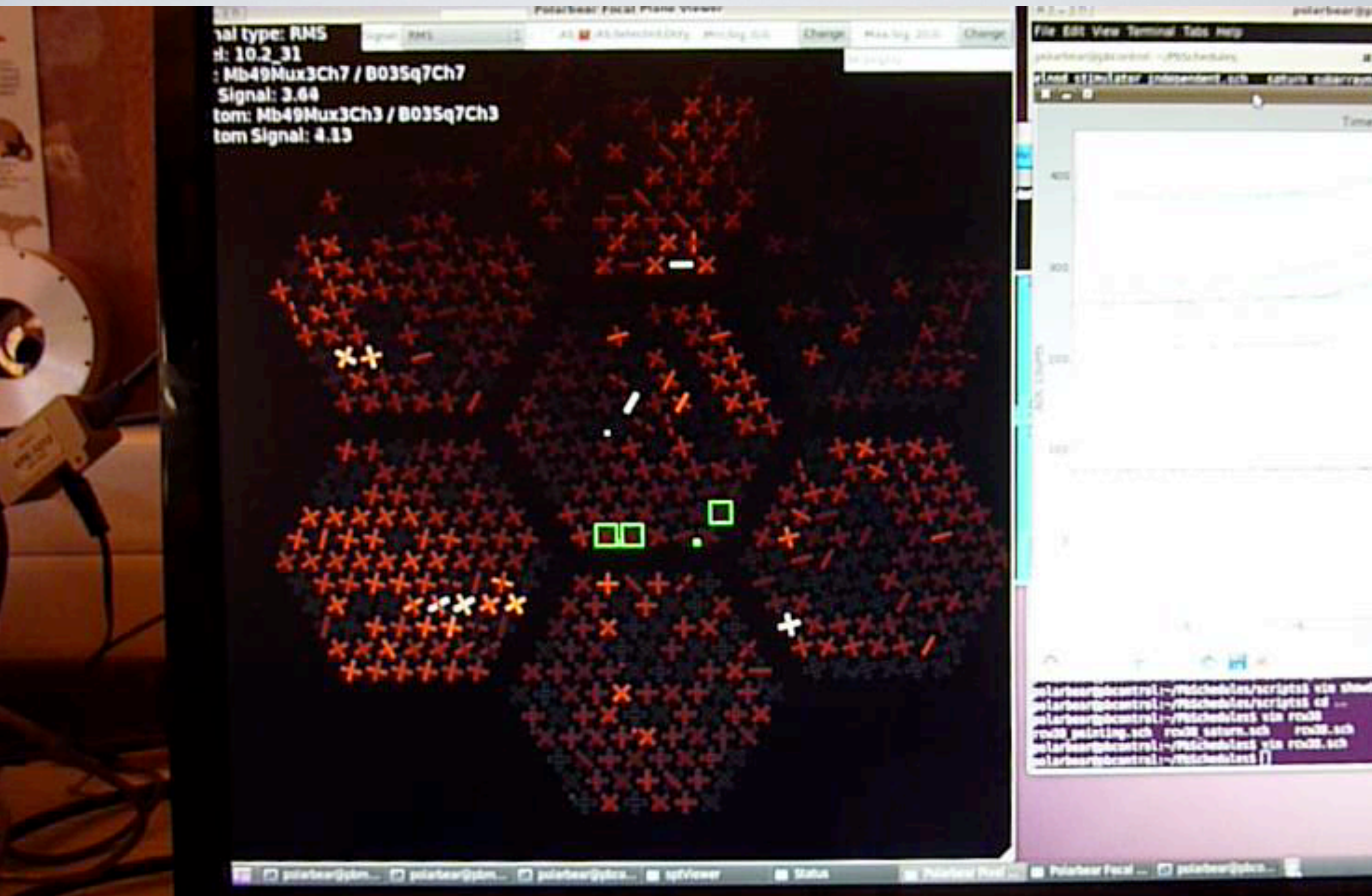


Galaxy

Atmosphere

Instrument

And there are other problems too ... like atmosphere



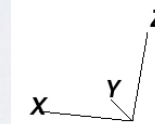
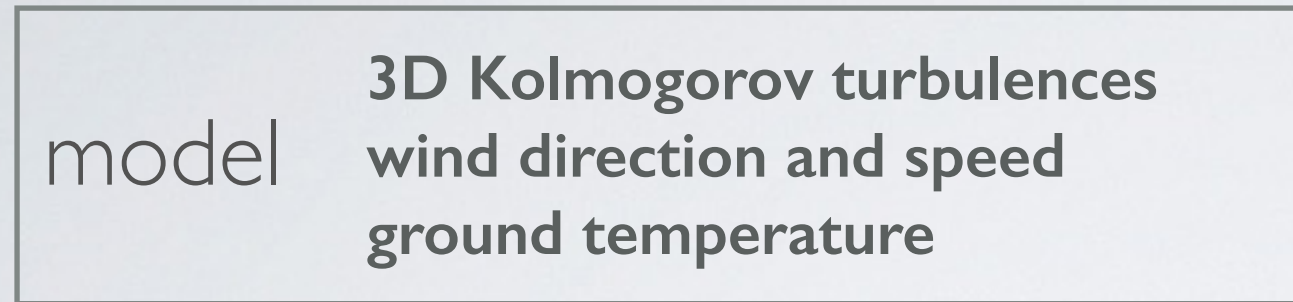
Atmospheric contamination

Modeling Atmospheric Emission for CMB Ground-based Observations

JE and the Polarbear collaboration

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

arXiv: 1501.07911



user: josquin1
Thu Nov 13 13:40:59 2014

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

typical scale for atmospheric
turbulences: $L_0 \sim 200\text{m}$

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

OUTLINE

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- 2 - Designing new projects in the presence of foregrounds and gravitational lensing
- 3- POLARBEAR-II, Simons Array, Stage-IV and LiteBIRD
- 4 - Extension: combining CMB with LSST weak lensing!

**Evidence for B-Mode Polarization of the CMB
from Cross-correlating Gravitational Lensing
with the Cosmic Infrared Background**

The POLARBEAR collaboration

Phys. Rev. Lett. 112, 131302 (2014)

**Measurement of the Cosmic Microwave
Background Polarization Lensing Power
Spectrum with the POLARBEAR Experiment**

The POLARBEAR collaboration

Phys. Rev. Lett. 113, 021301 (2014)

**A Measurement of the Cosmic Microwave
Background B-Mode Polarization Power
Spectrum at Sub-degree Scales with POLARBEAR**

The POLARBEAR Collaboration

The Astrophysical Journal, Volume 794, 171 (2014)

**POLARBEAR Constraints on Cosmic
Birefringence and Primordial Magnetic Fields**

The Polarbear collaboration

Physical Review D, Volume 92, Issue 12, id.123509
(2015)

➤ **second season being analyzed ...**

POLARBEAR site

POLARBEAR



QUIET

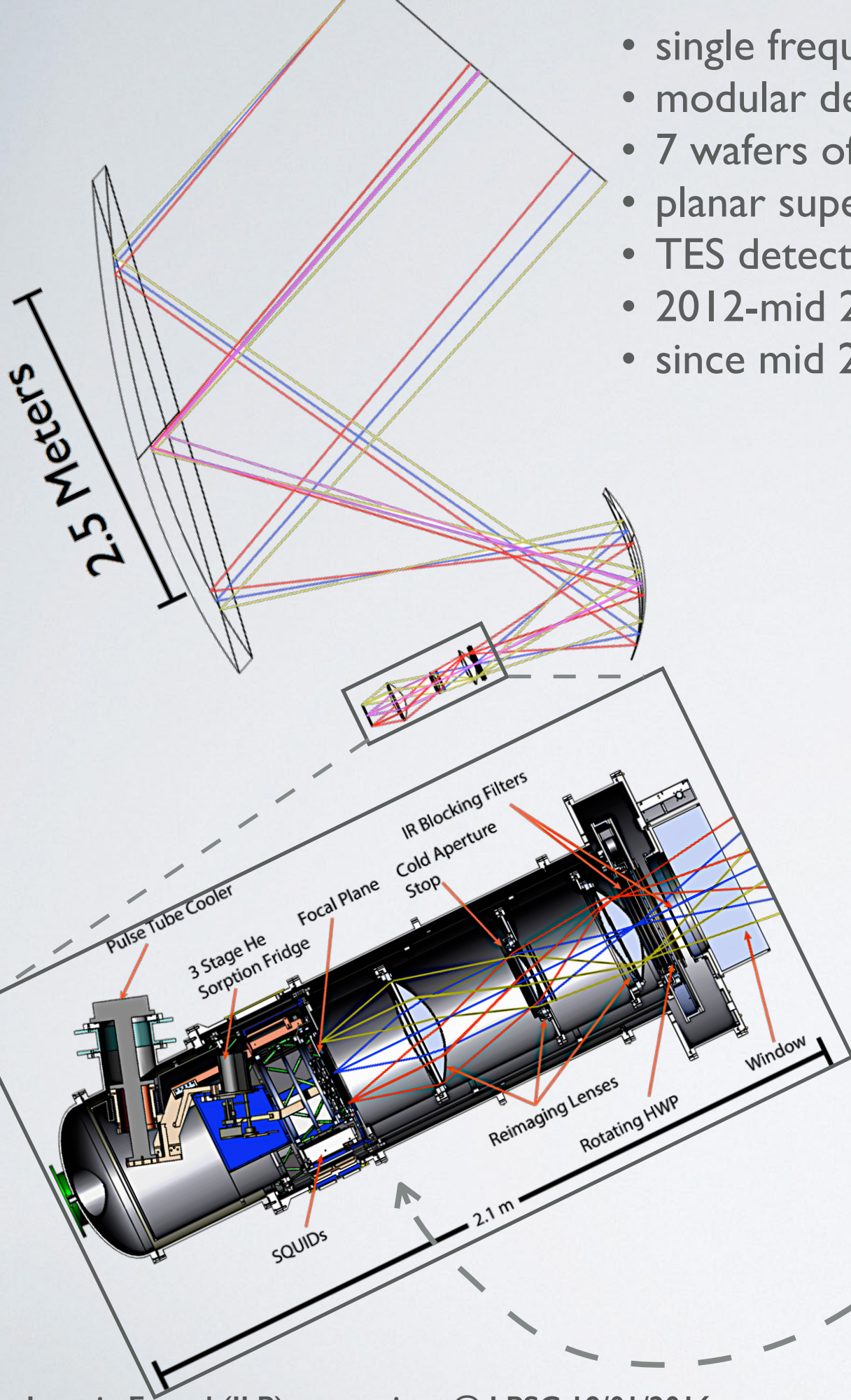


ALMA

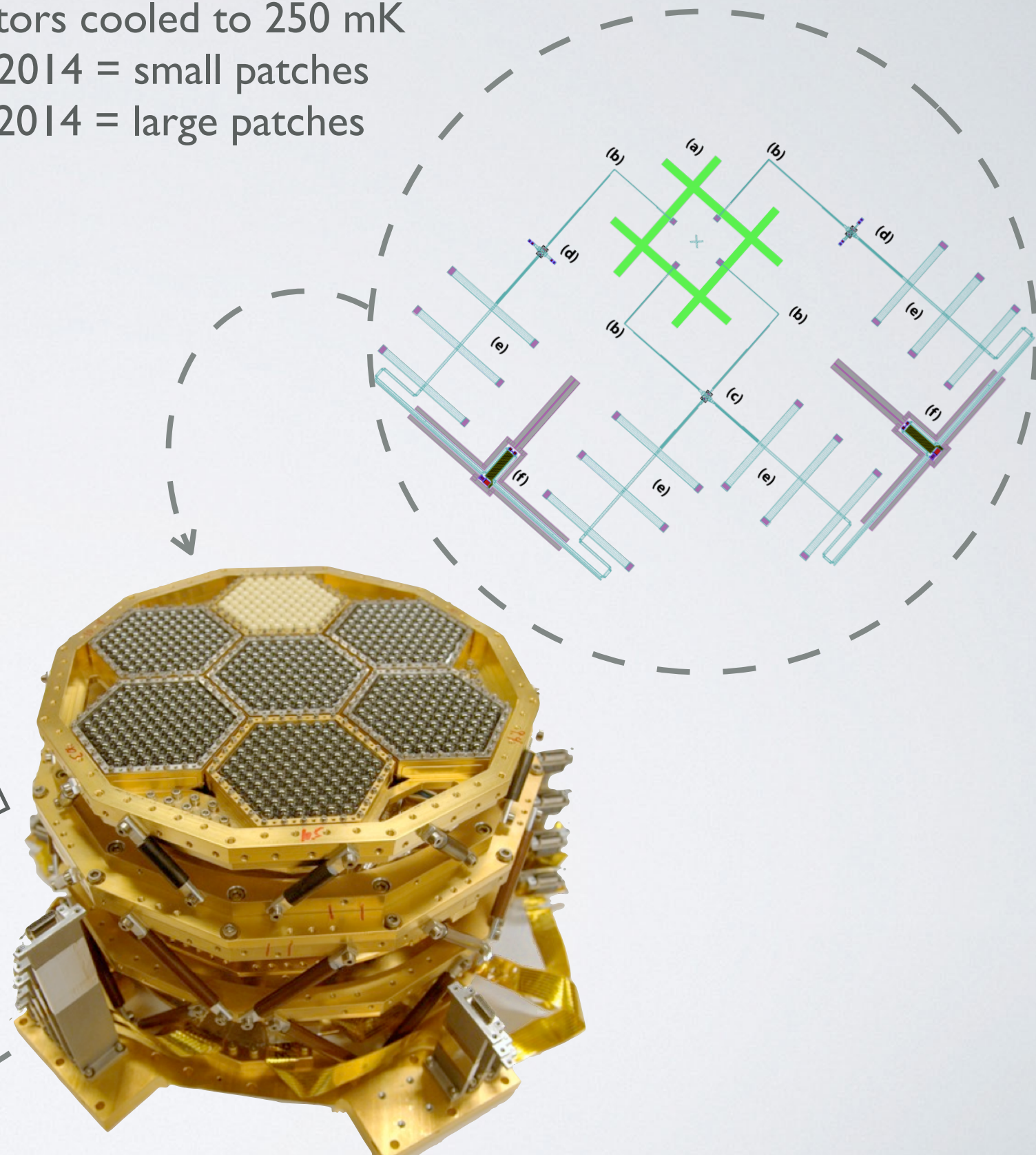


APEX





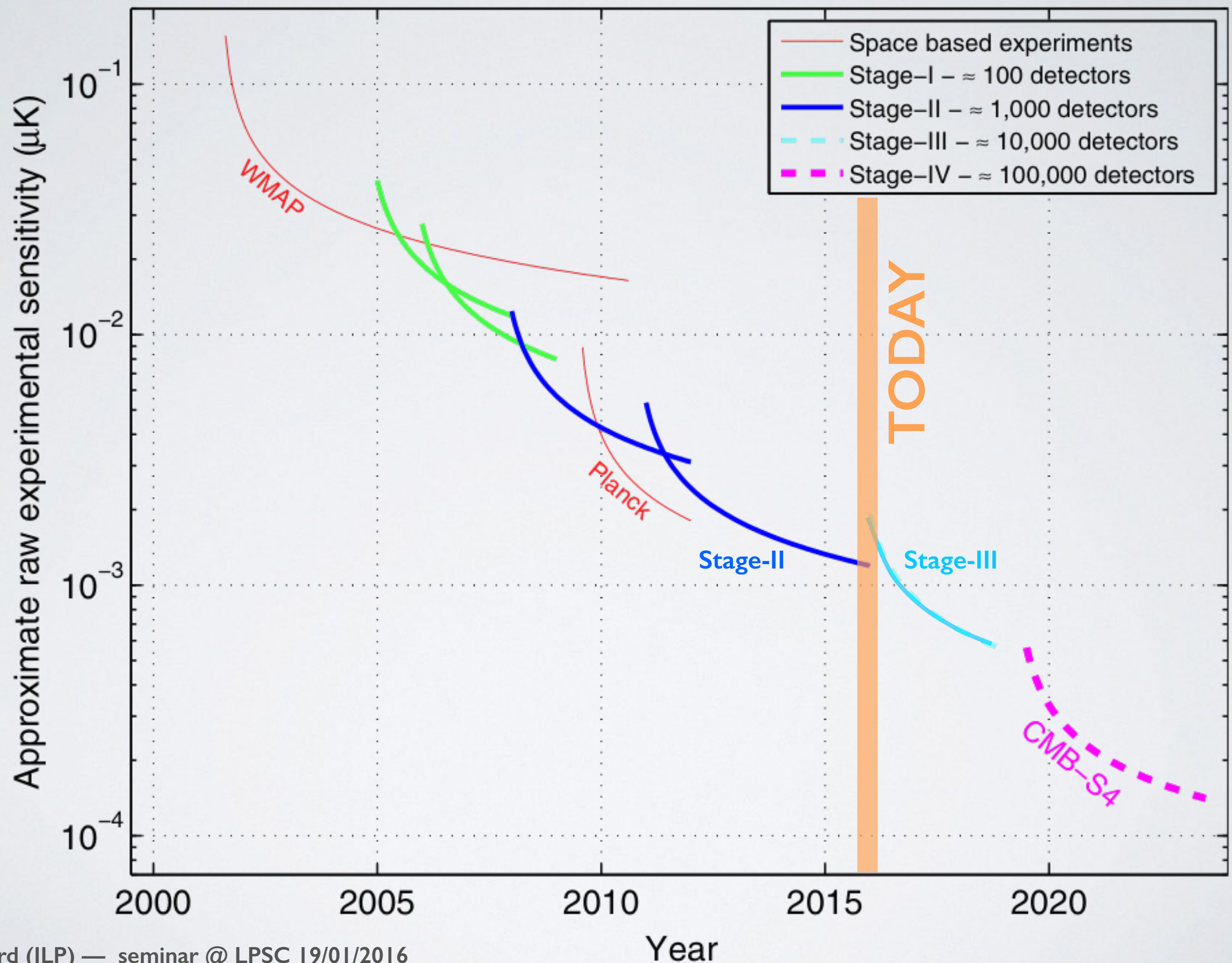
- single frequency: 150GHz
- modular design
- 7 wafers of 91 dual-polarized pixels
- planar superconducting dipole antennas with contacting lensless
- TES detectors cooled to 250 mK
- 2012-mid 2014 = small patches
- since mid 2014 = large patches



Neutrino Physics from the Cosmic Microwave Background and Large Scale Structure

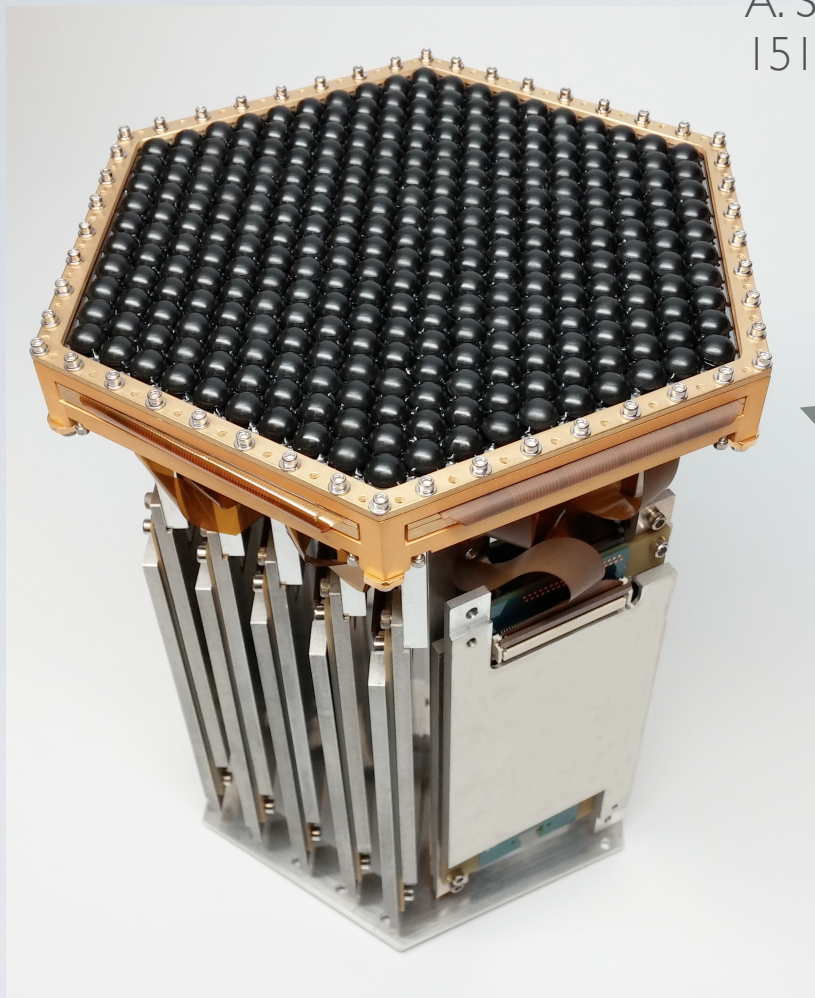
Abazajian, K. N. et al.

Astroparticle Physics, Volume 63, p. 66-80 (2015) arXiv: 1309.5383



POLARBEAR-II

see **The POLARBEAR-2 and the Simons Array Experiments**
A. Suzuki et al (2015)
1512.07299



frequencies
of pixels
NET bolometer
NET array
polarization sensitivity
field of view
beam sizes
observation time

specifications

95 and 150 GHz

1897 (7588 bolometers)

500 $\mu\text{K}\sqrt{\text{s}}$

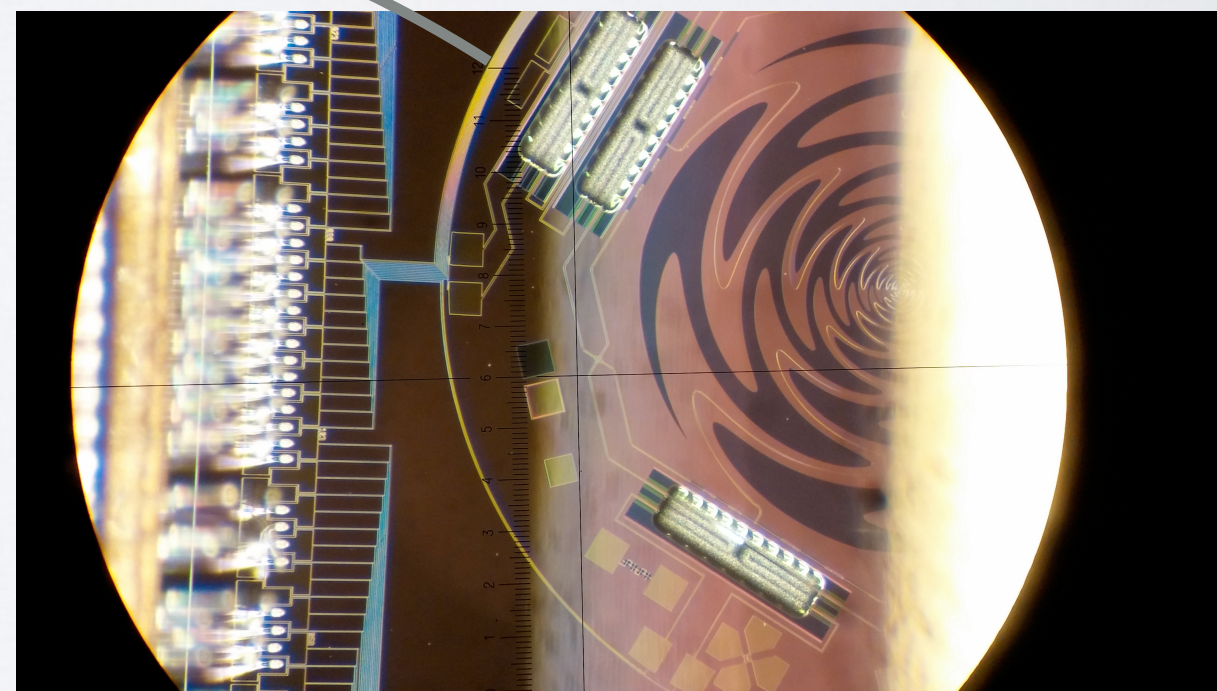
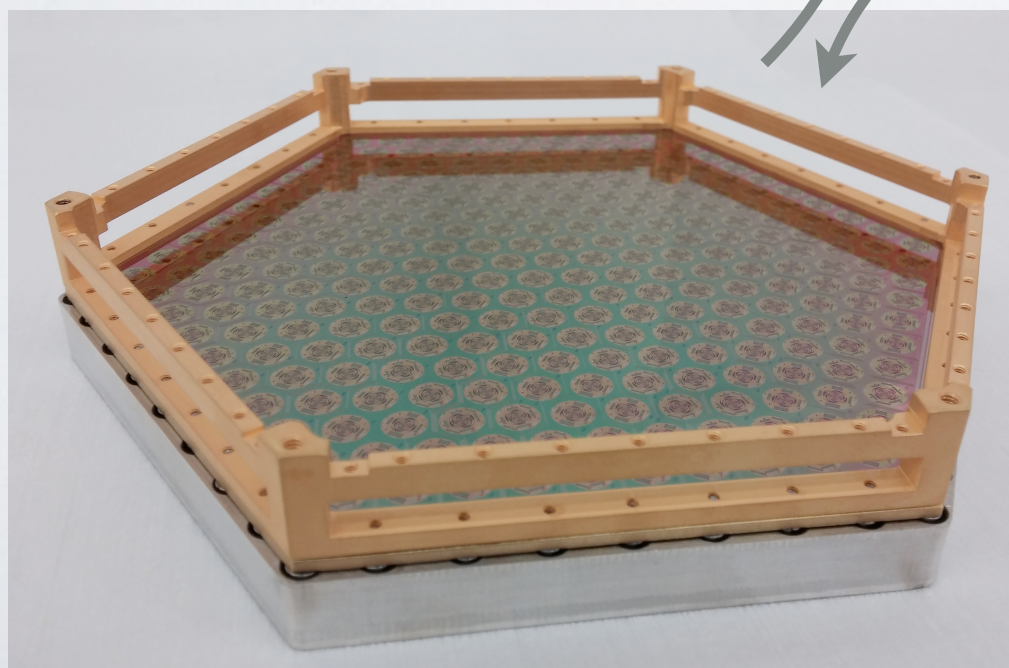
5.7 $\mu\text{K}\sqrt{\text{s}}$

10.7 $\mu\text{K}\cdot\text{arcmin}$
(20% sky coverage, 18% obs. eff.)

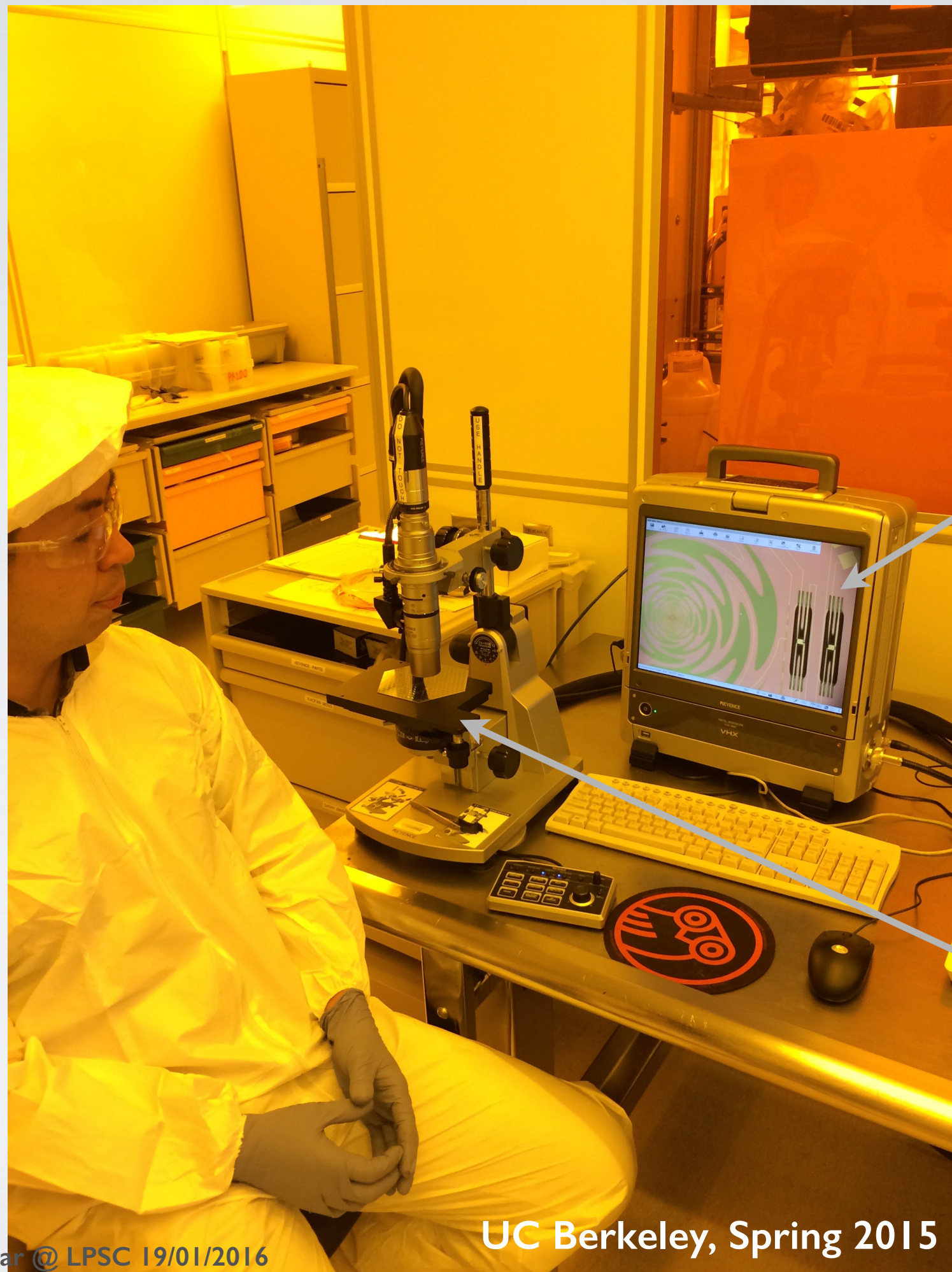
4.8 deg

5.2 arcmin @ 95 GHz
3.5 arcmin @ 150 GHz

3 years



Toki Suzuki
(UCB) →



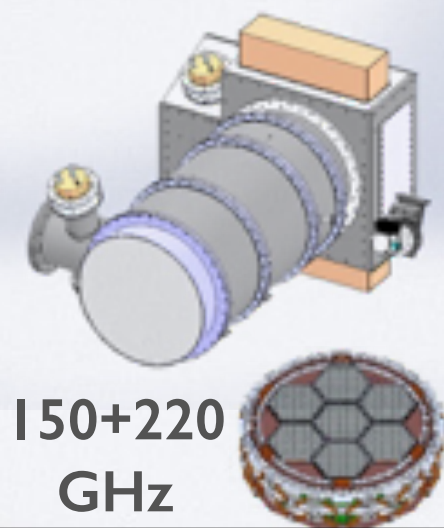
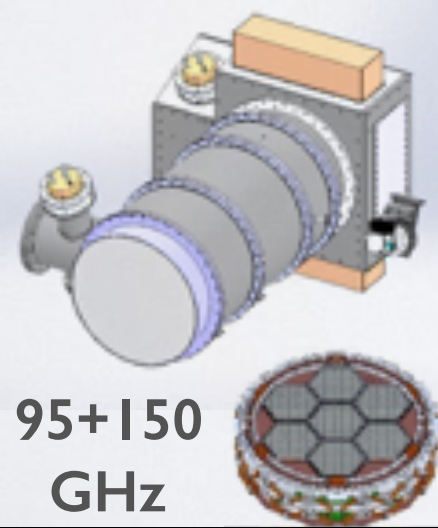
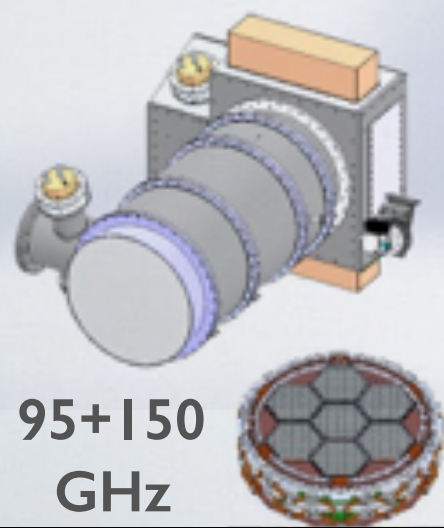
→ PB2 pixel

→ PB2 wafer

SIMONS ARRAY = 3 x POLARBEAR-II

SIMONS FOUNDATION

conceptual



> 22 K detectors
3/4 bands: 95, 150 and 220/280 GHz
fsky ~ 50 %

The Simons Array: expanding POLARBEAR to three multi-chroic telescopes
Arnold et al., SPIE proceedings (2014)

Planned to deploy in 2020-2025:

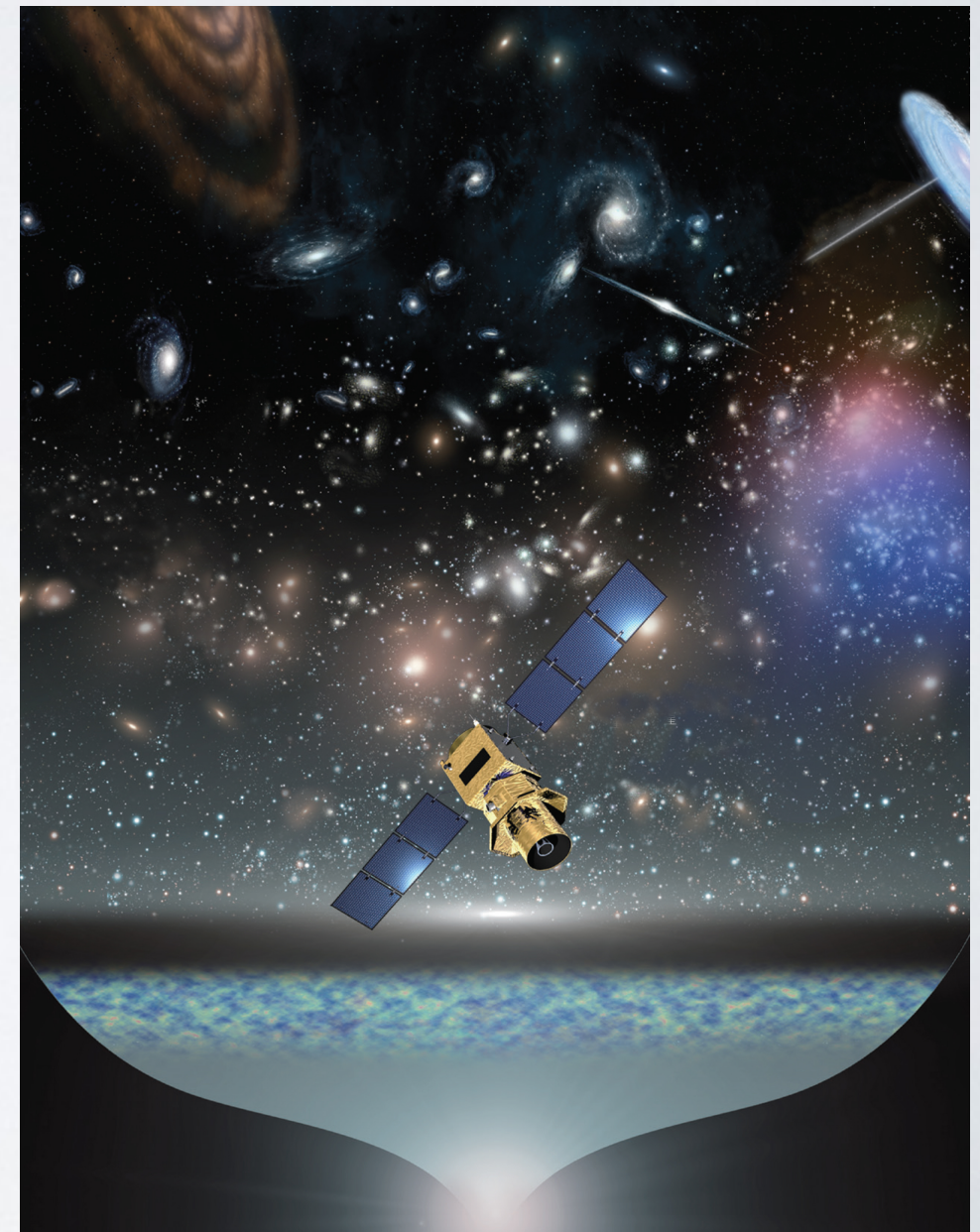
Stage-IV

consortium of US ground-based efforts
(Simons Array + BICEP3 + AdvACTPol +
SPT-3G)



LiteBIRD

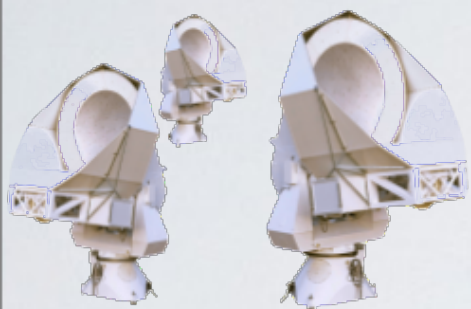
JAXA satellite for primordial B-modes
exploration currently in phase A
+ NASA MO in phase A



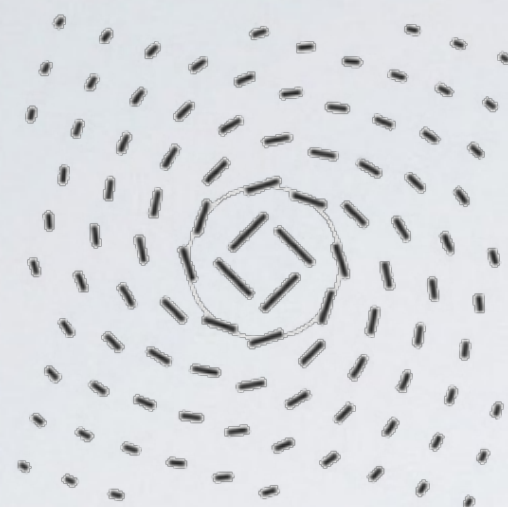
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mesure de la
polarisation
du CMB

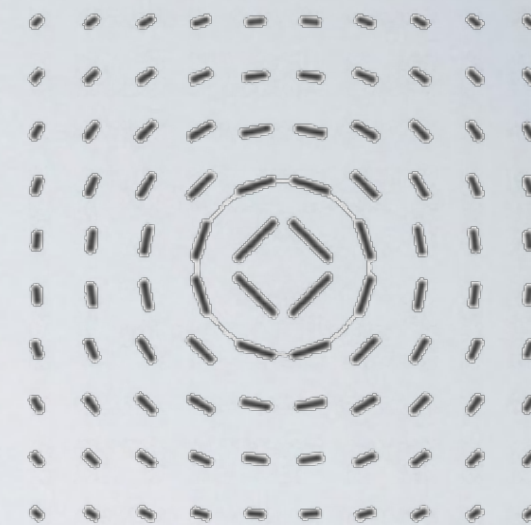


mesure du
cosmic shear

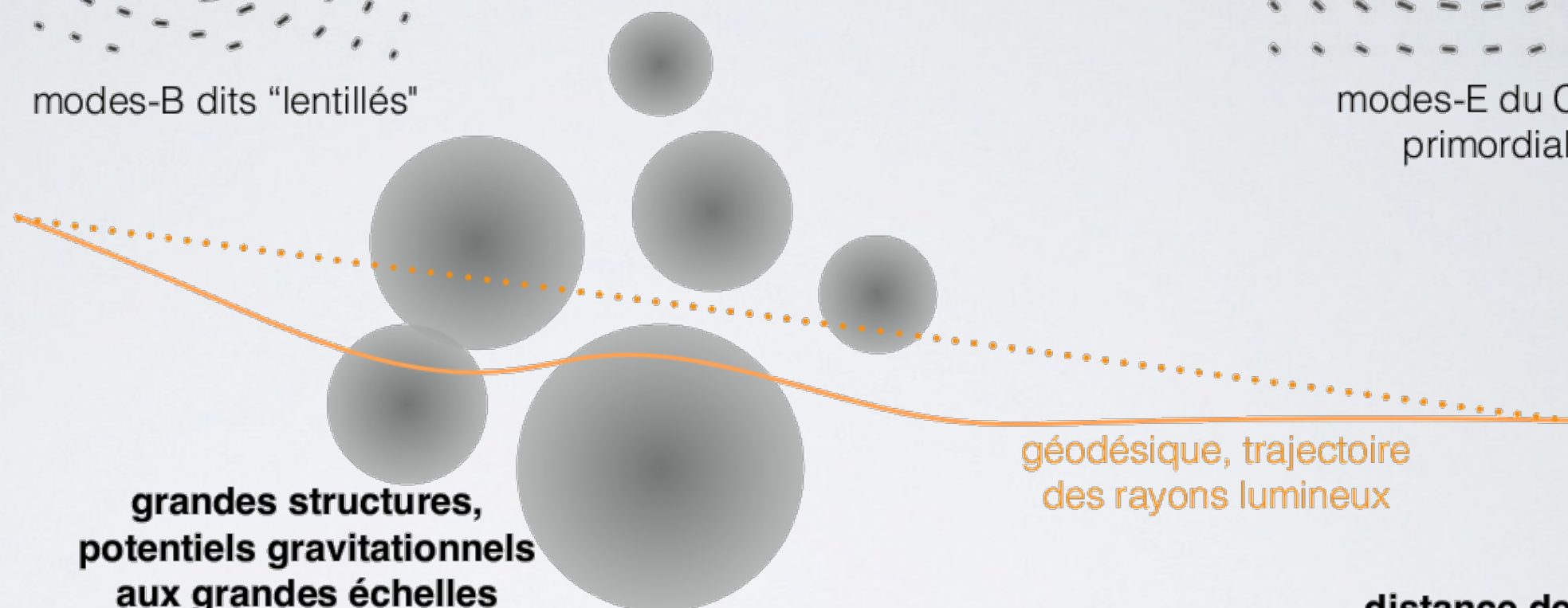


modes-B dits "lentillés"

effet des lentilles
gravitationnelles



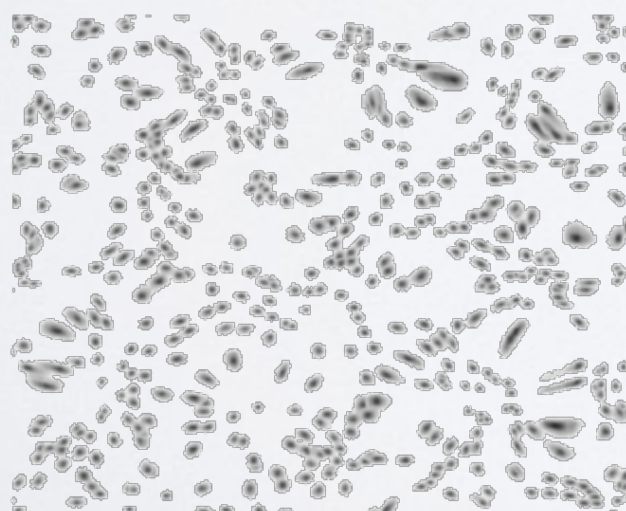
modes-E du CMB
primordial



grandes structures,
potentiels gravitationnels
aux grandes échelles

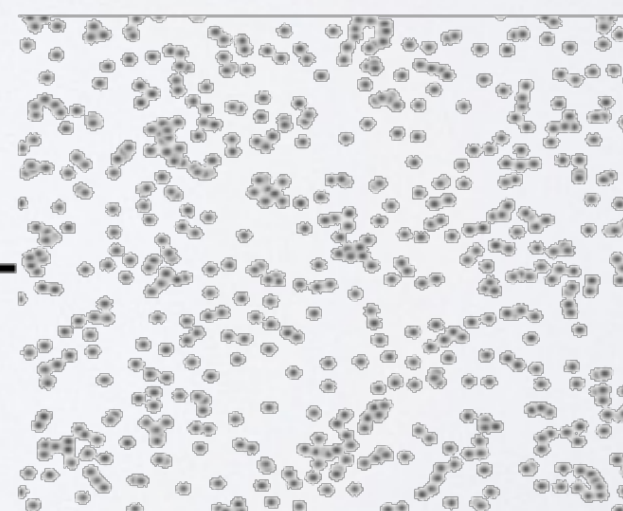
géodésique, trajectoire
des rayons lumineux

distance depuis
l'observateur →



galaxies observées

effet des lentilles
gravitationnelles



galaxies lointaines

correlation between CMB lensing et cosmic shear:

$$C_{\ell}^{\kappa_{CMB} \kappa_{CS}} = \int_0^{\chi_*} dz \frac{d\chi}{\chi(z)^2} W_{CMB}(z) W_{CS}(z) P_{\delta} \left(\frac{\ell}{\chi(z)}, z \right)$$

distance to last scattering surface

comoving distance at a redshift z

lensing kernel for CMB and Cosmic Shear (CS)

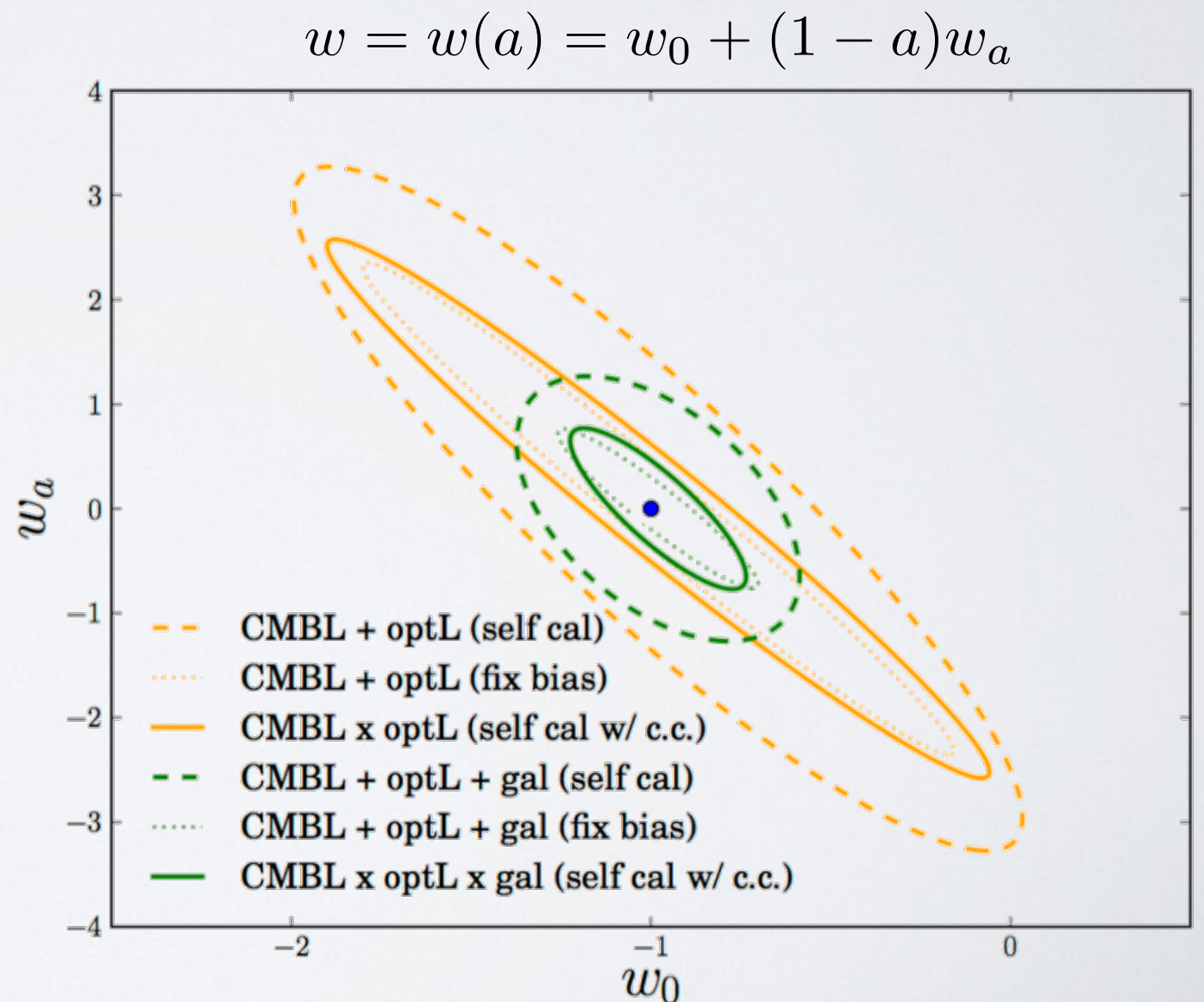
power spectrum of matter density perturbations

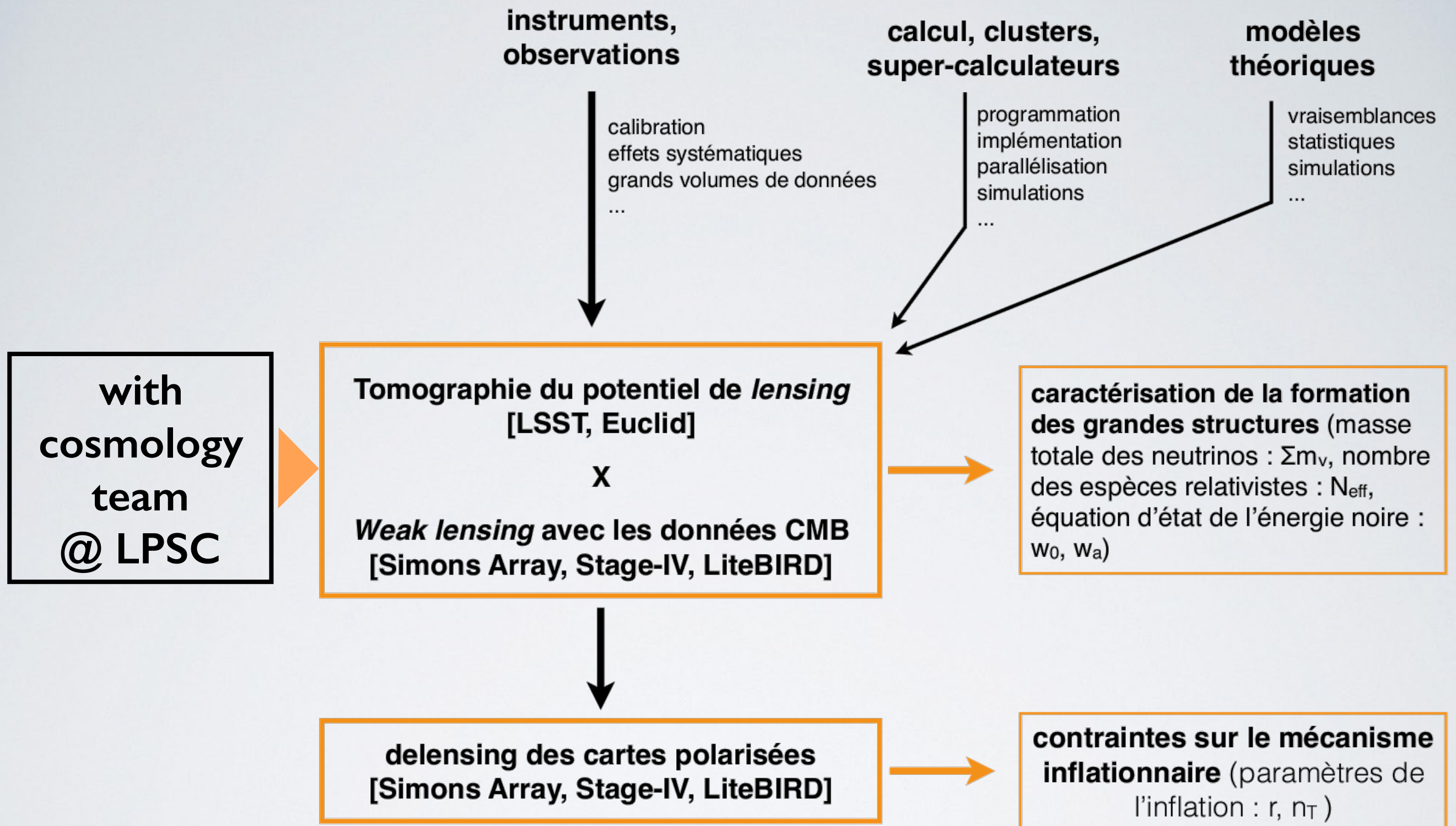
Can CMB lensing help cosmic shear surveys?

Das, S., Errard, J. and Spergel, D. (2013)

arXiv: 1311.2338

+ Valinotto (2012,2013)





Robust forecasts on fundamental physics from the foreground-obscured, gravitationally- lensed CMB polarization
 JE, Feeney, S. M., Peiris, H.V. and Jaffe, A. H. (2015)
 arXiv: 1509.06770