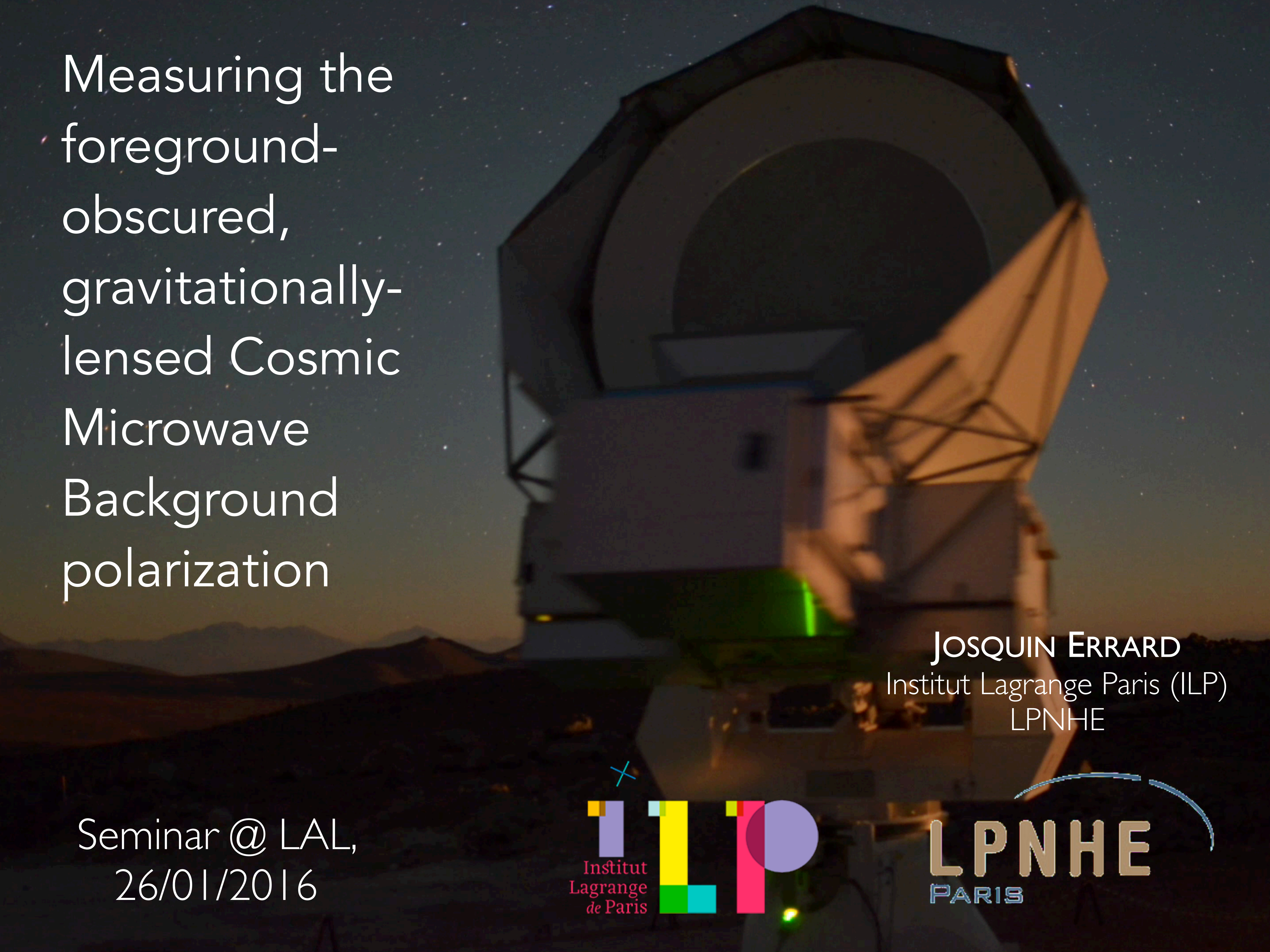

Measuring the foreground-obscured, gravitationally-lensed Cosmic Microwave Background polarization

Josquin Errard
Institut Lagrange Paris (ILP)
LPNHE

Seminar @ LAL,
26/01/2016

OUTLINE

1 - CMB polarization and constraints on B-modes

2 - POLARBEAR-I

3 - Designing new projects in the presence of foregrounds and gravitational lensing

4- POLARBEAR-II, Simons Array, Stage-IV and LiteBIRD

5 - Extension: combining CMB with LSST weak lensing!

OUTLINE

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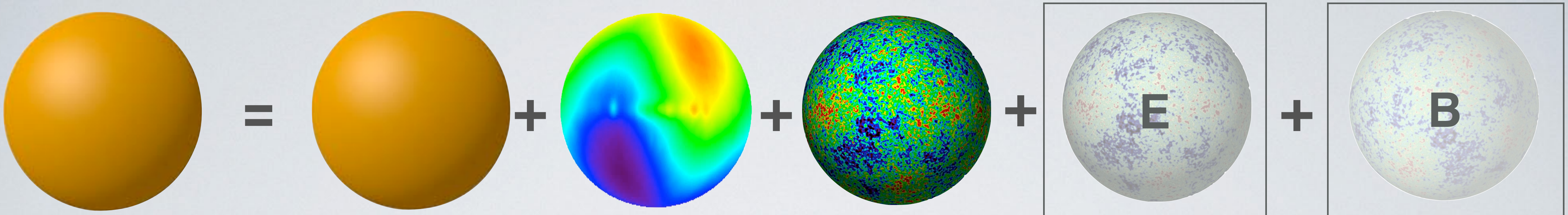


T = 2.7 K

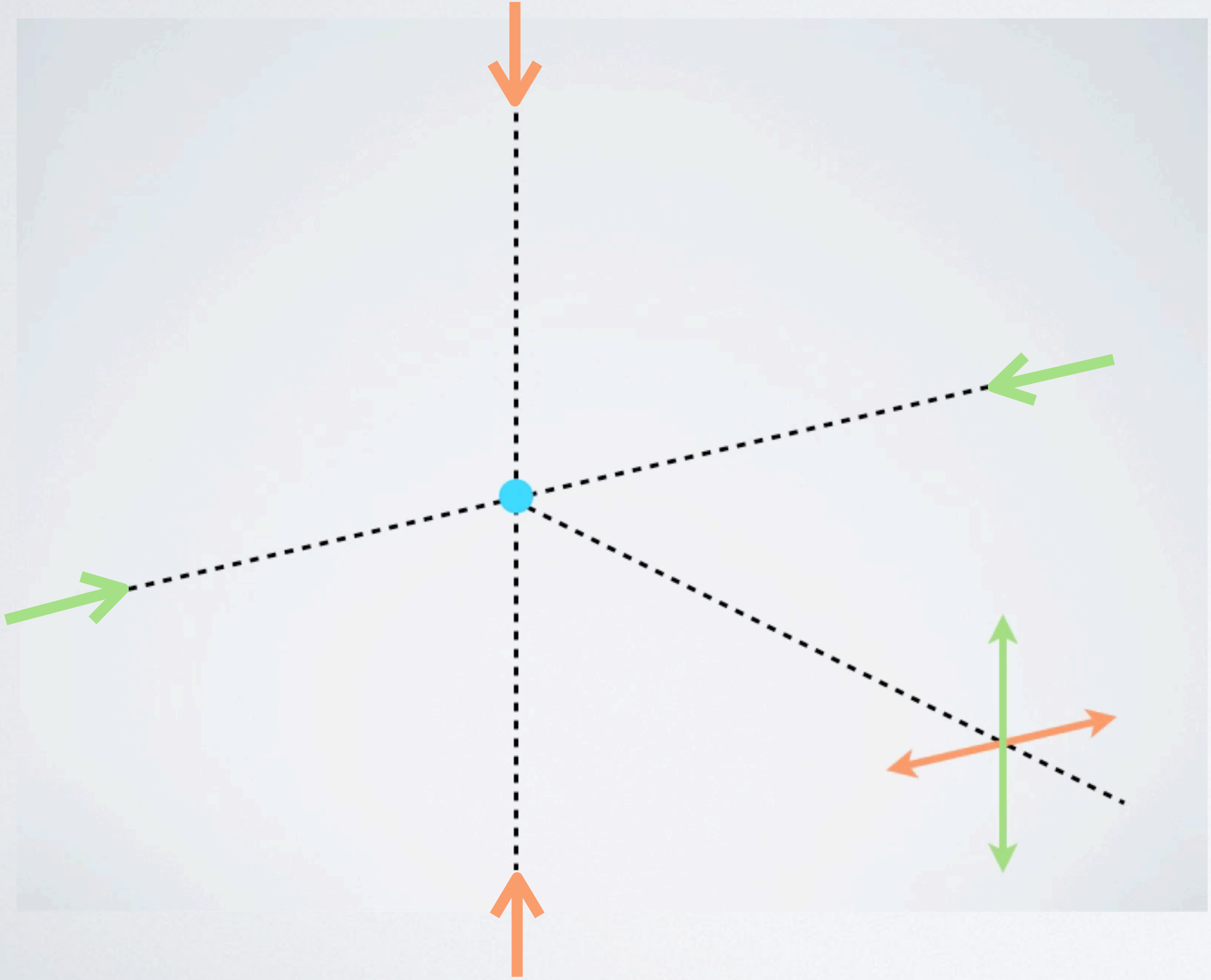
$\Delta T/T \sim 10^{-3}$

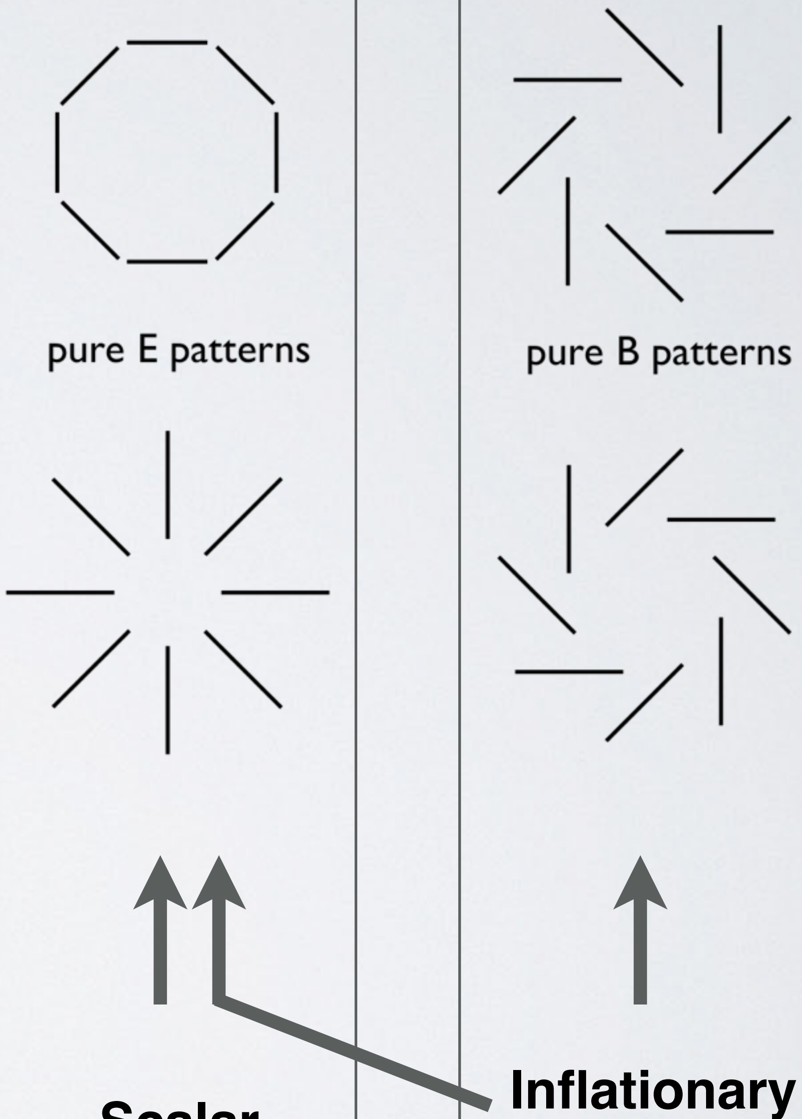
$\Delta T/T \sim 10^{-5}$

$\Delta E/T \sim 10^{-6}$

$\Delta B/T \sim 10^{-7\text{-}8}$

Thomson scattering



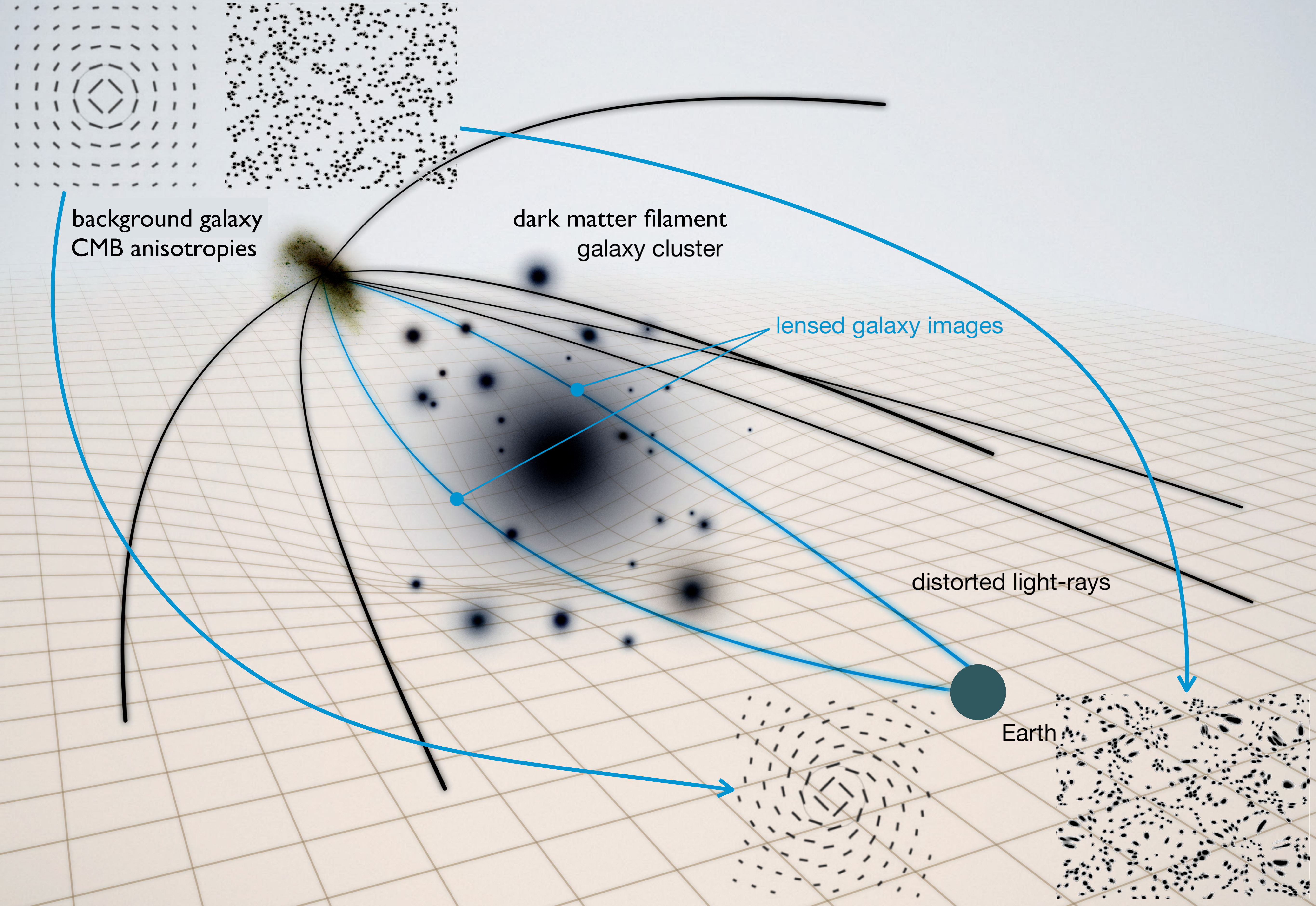


pure E patterns

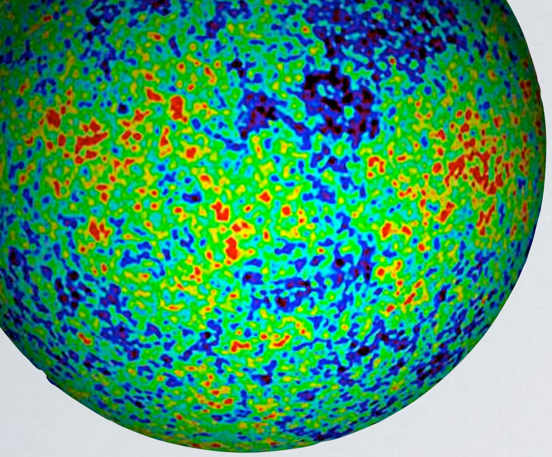
pure B patterns

Scalar perturbations

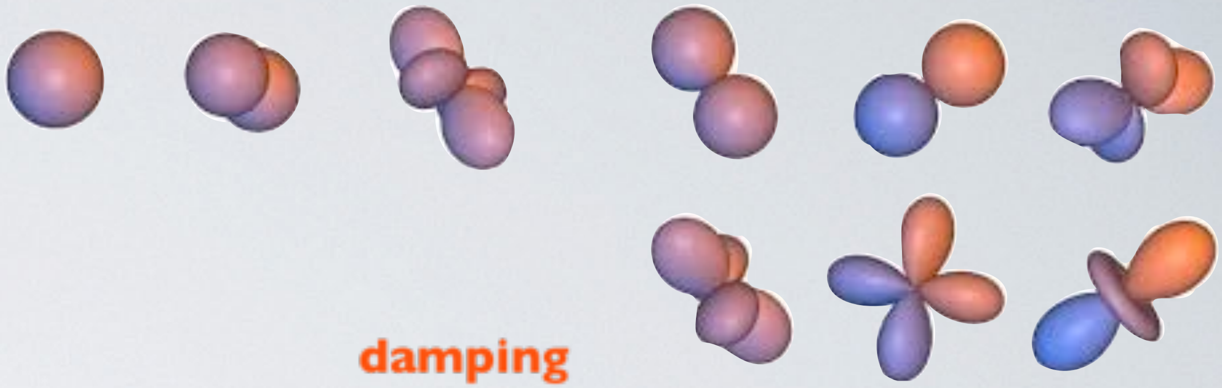
Inflationary gravitational waves

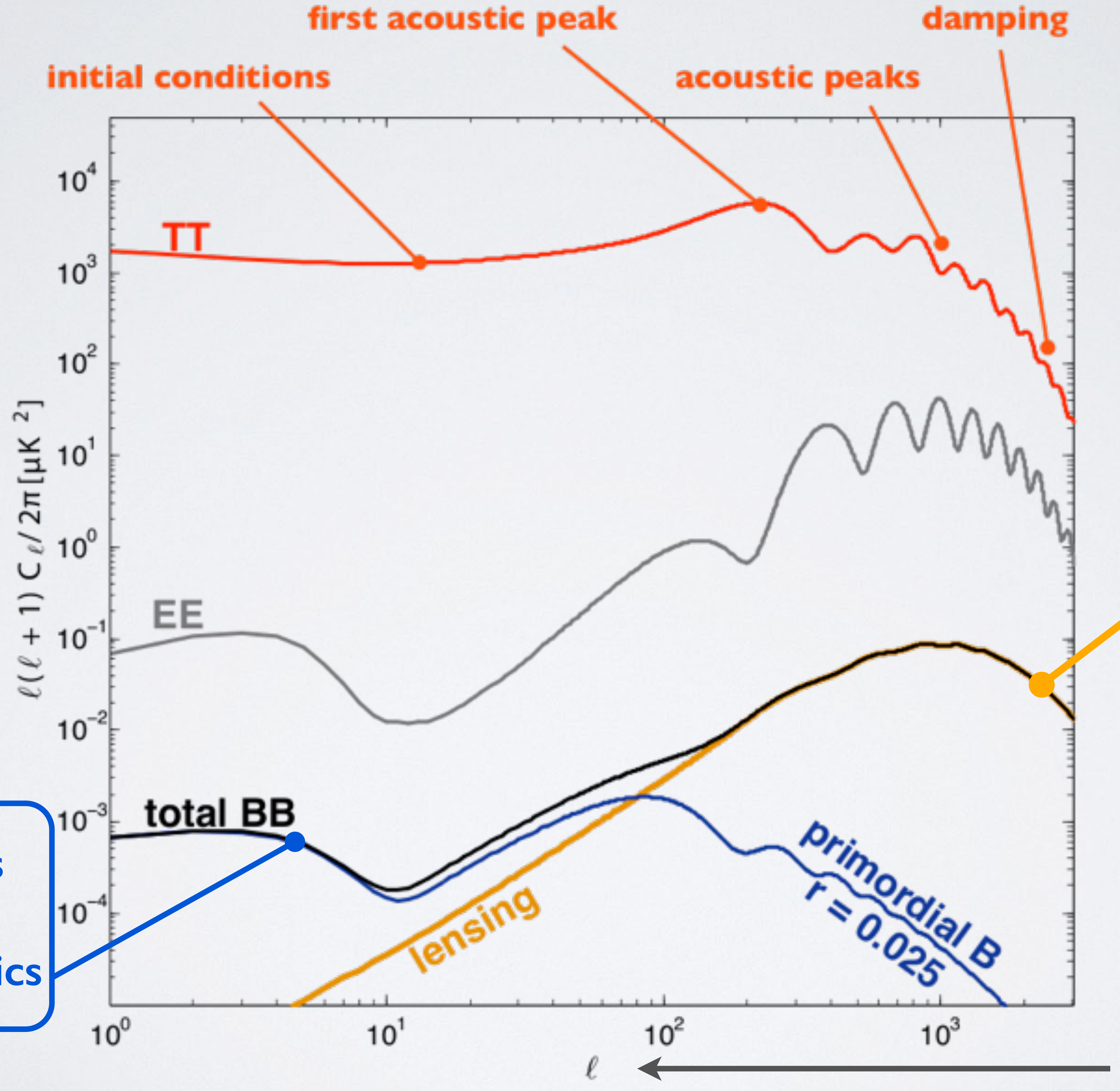


http://www.spacetelescope.org



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



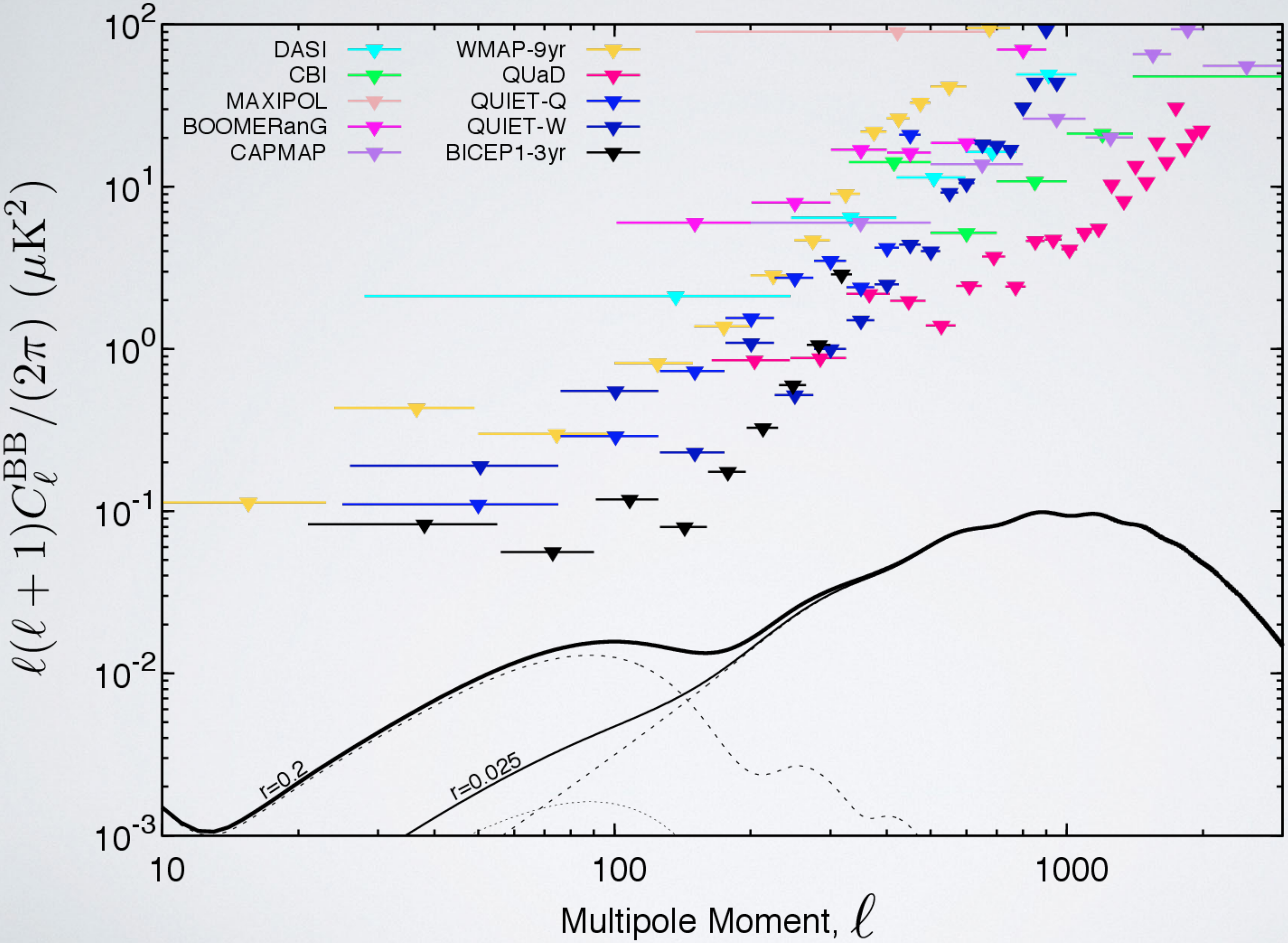


~ 1/θ

Large scale structures
Σm_ν, w, N_{eff}, ...

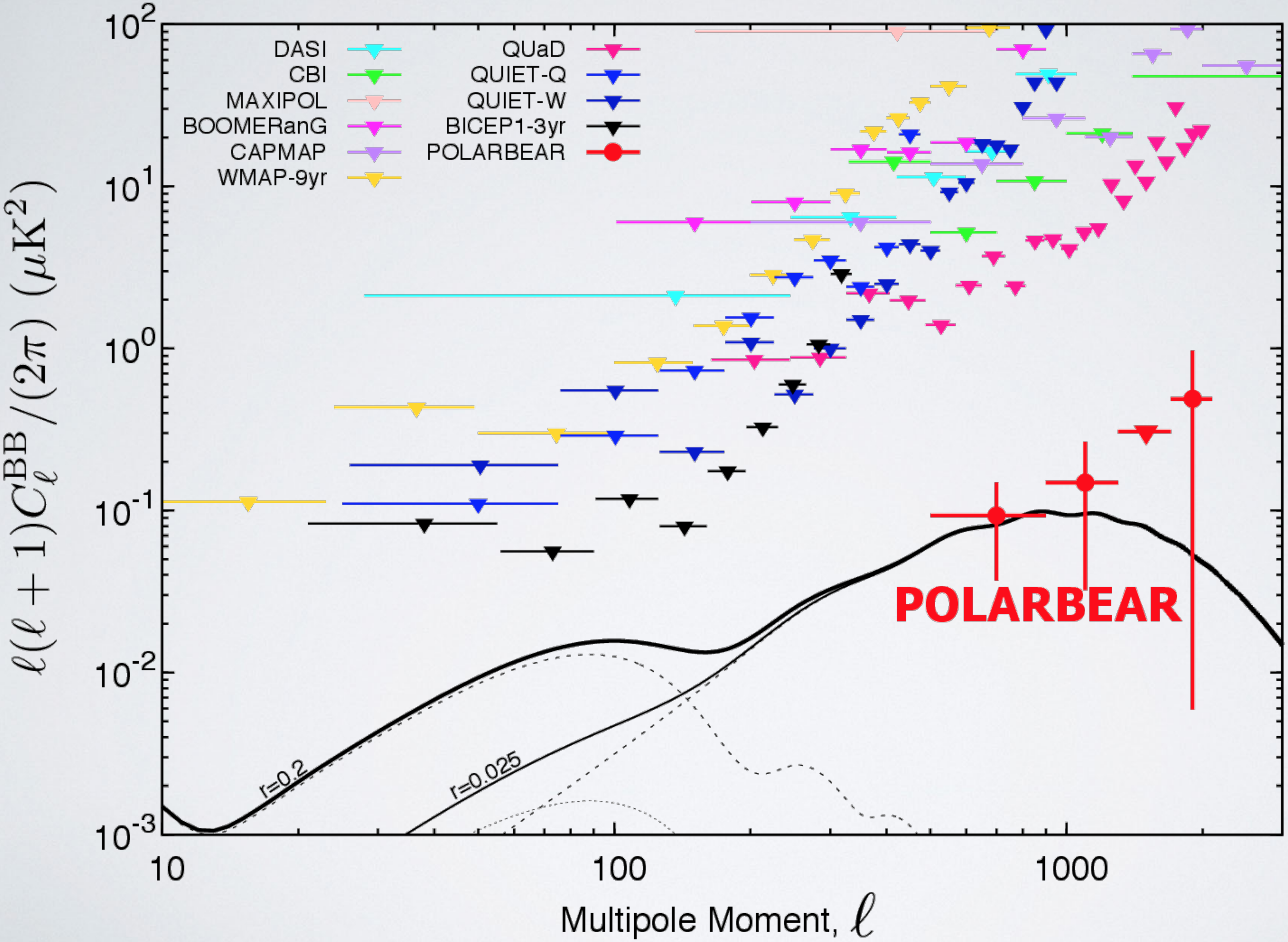
inflation and its energy
high energy physics

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**)



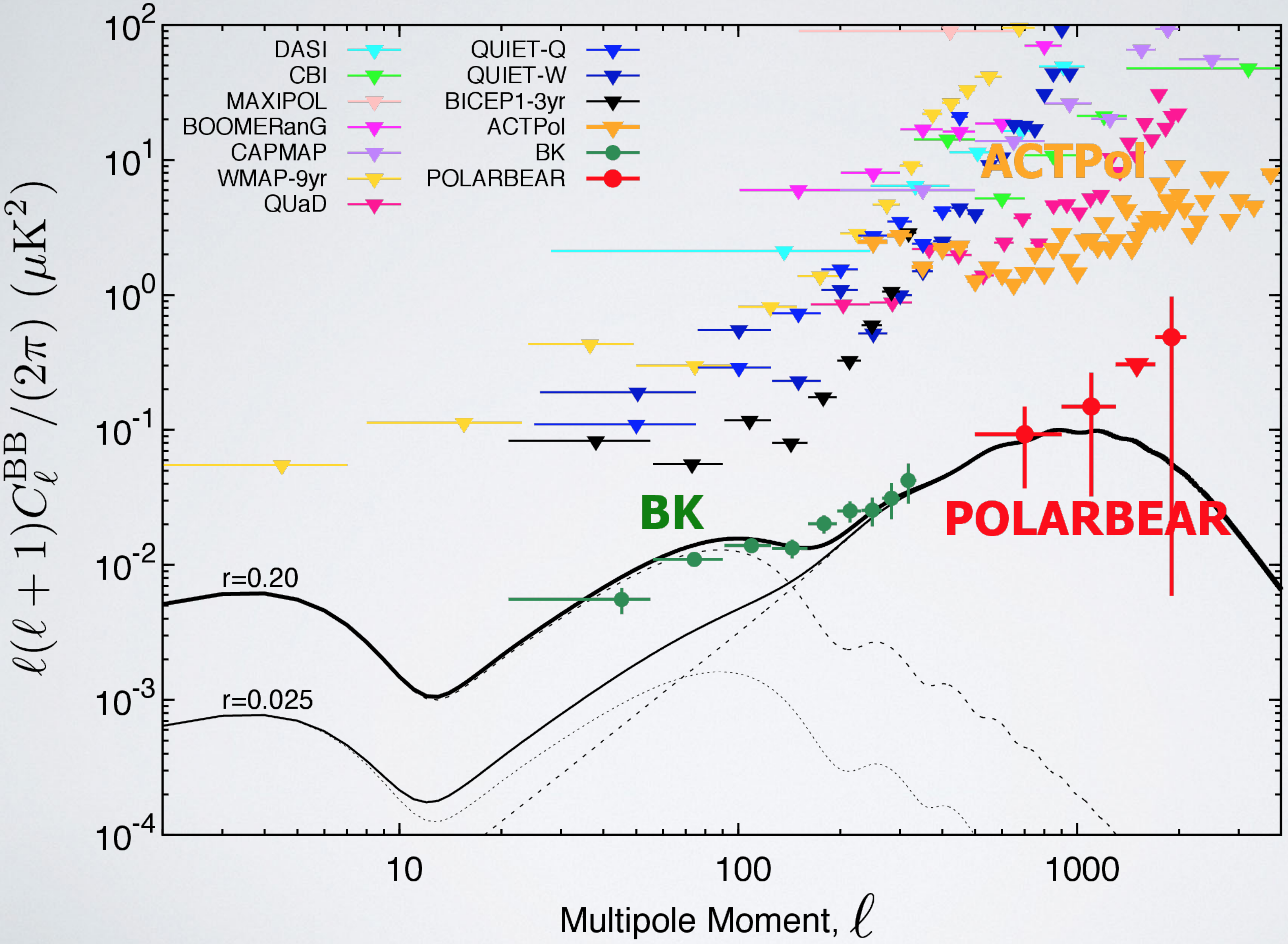
2014

2015

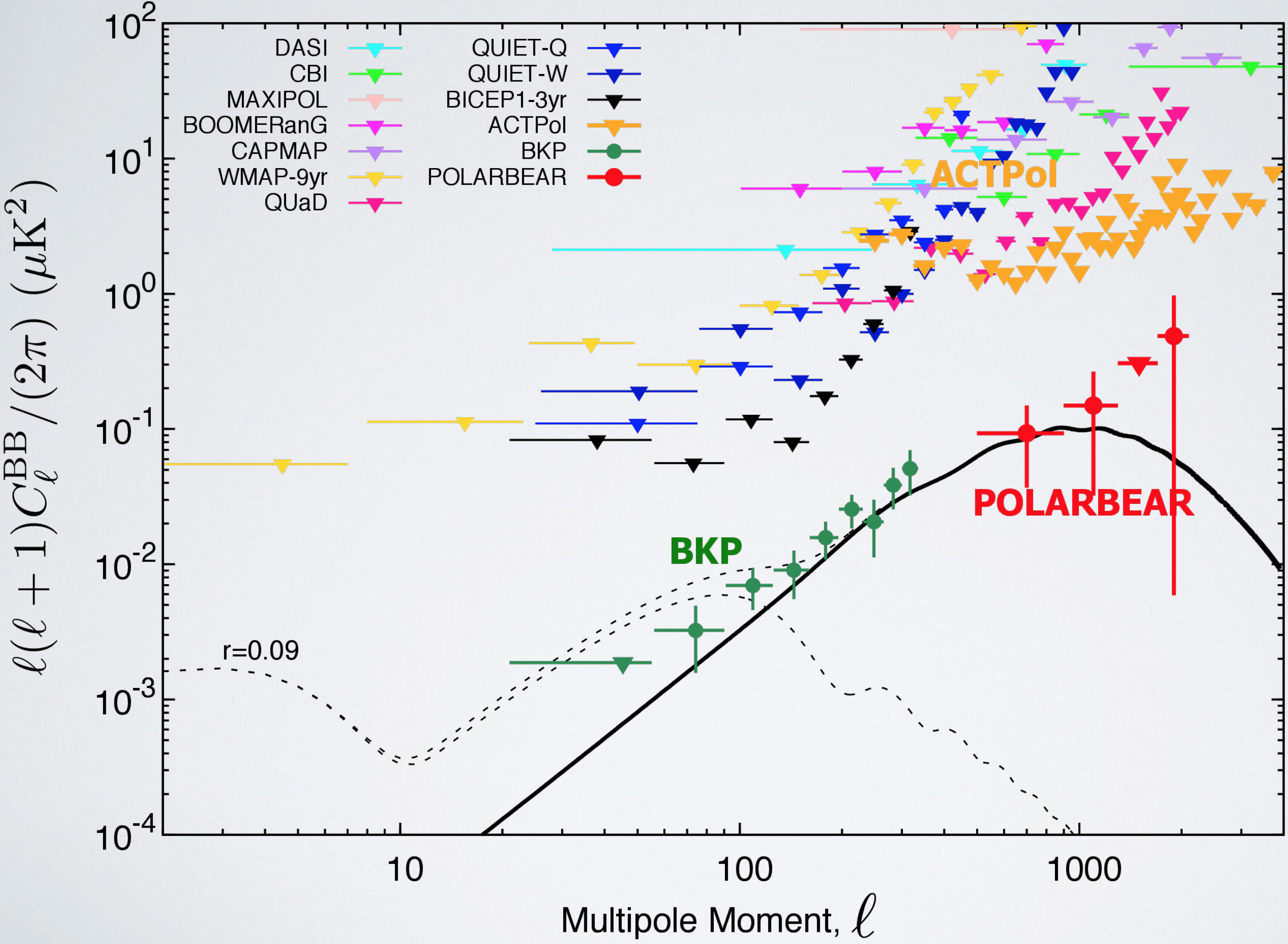
2016

BK-V: Measurements of B-mode Polarization at Degree Angular Scales and 150 GHz by Keck Array

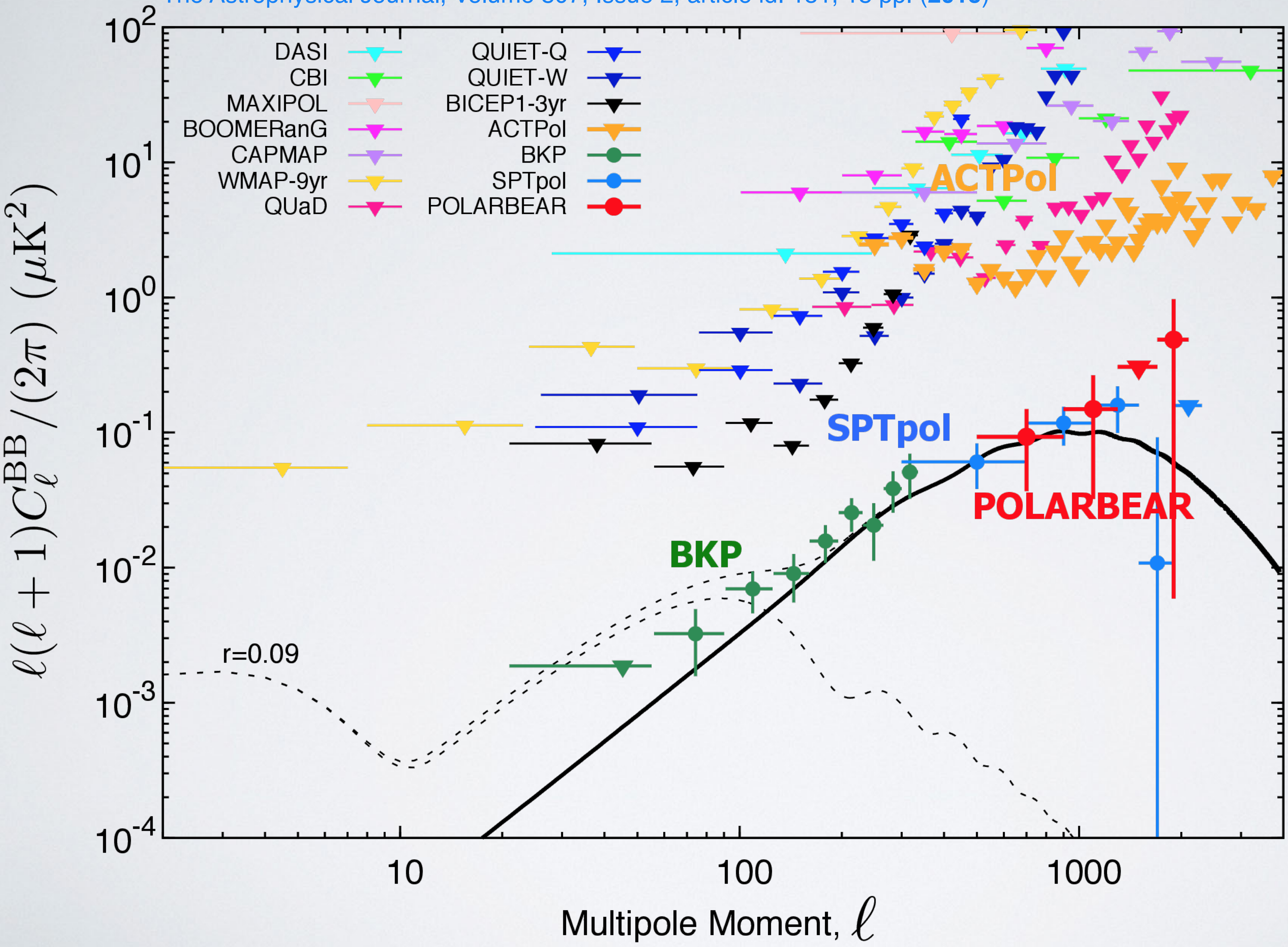
The Keck Array and BICEP2 Collaborations, ApJ 811, 126, 2015



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**)



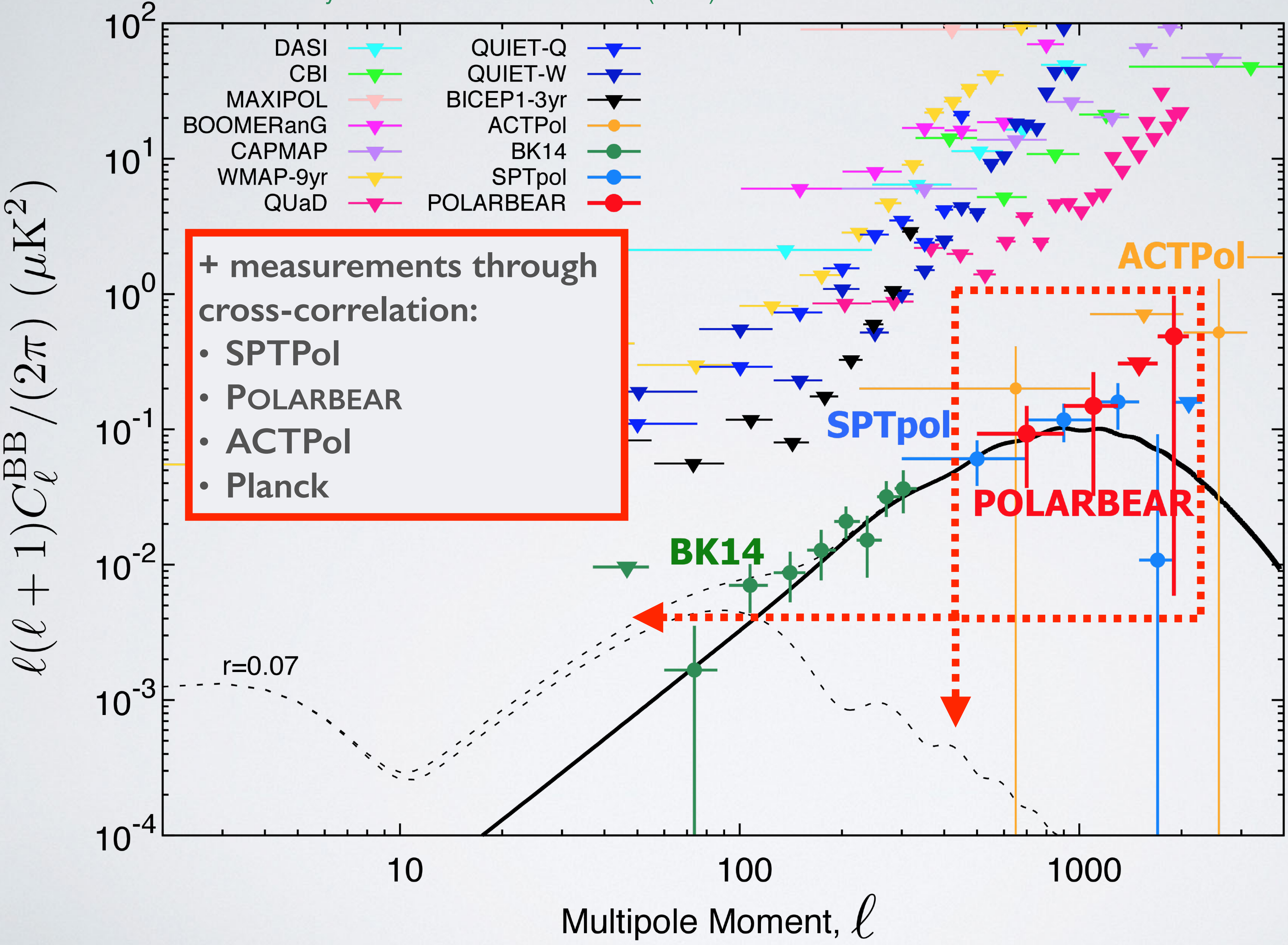
2014

2015

2016

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

The Keck Array and BICEP2 Collaborations (**2015**)



+ measurements through cross-correlation:

- SPTPol
- POLARBEAR
- ACTPol
- Planck

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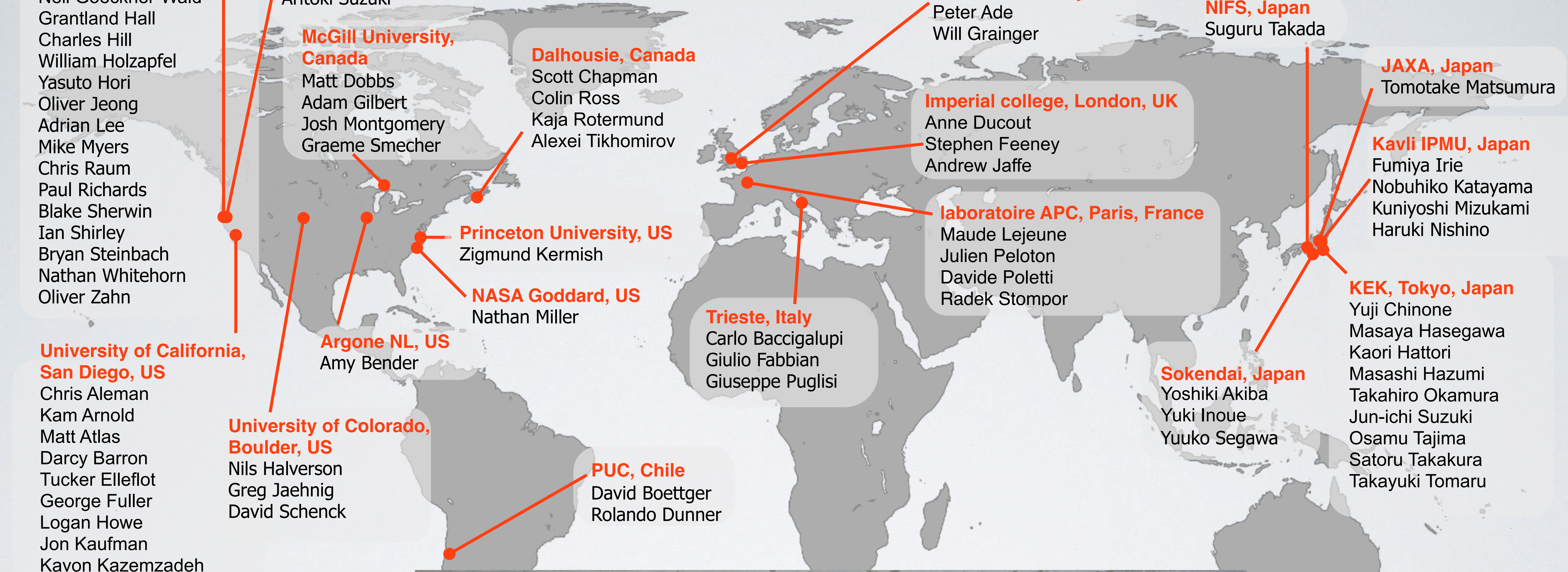
POLARBEAR collaboration



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Ari Cukierman
Tijmen de Haan
Josquin Errard
Neil Goeckner-Wald
Grantland Hall
Charles Hill
William Holzapfel
Yasuto Hori
Oliver Jeong
Adrian Lee
Mike Myers
Chris Raum
Paul Richards
Blake Sherwin
Ian Shirley
Bryan Steinbach
Nathan Whitehorn
Oliver Zahn

LBNL, Berkeley, US
Julian Borrill
Reijo Keskitalo
Theodore Kisner
Akito Kusaka
Eric Linder
Aritoki Suzuki

McGill University, Canada
Matt Dobbs
Adam Gilbert
Josh Montgomery
Graeme Smecher

Dalhousie, Canada
Scott Chapman
Colin Ross
Kaja Rotermund
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Cardiff University, UK
Peter Ade
Will Grainger

NIFS, Japan
Suguru Takada

JAXA, Japan
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NASA Goddard, US
Nathan Miller

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Gabriel Rebeiz
Praween Siritanasak
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Amit Yadav
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University of Colorado, Boulder, US
Nils Halverson
Greg Jaehnig
David Schenck

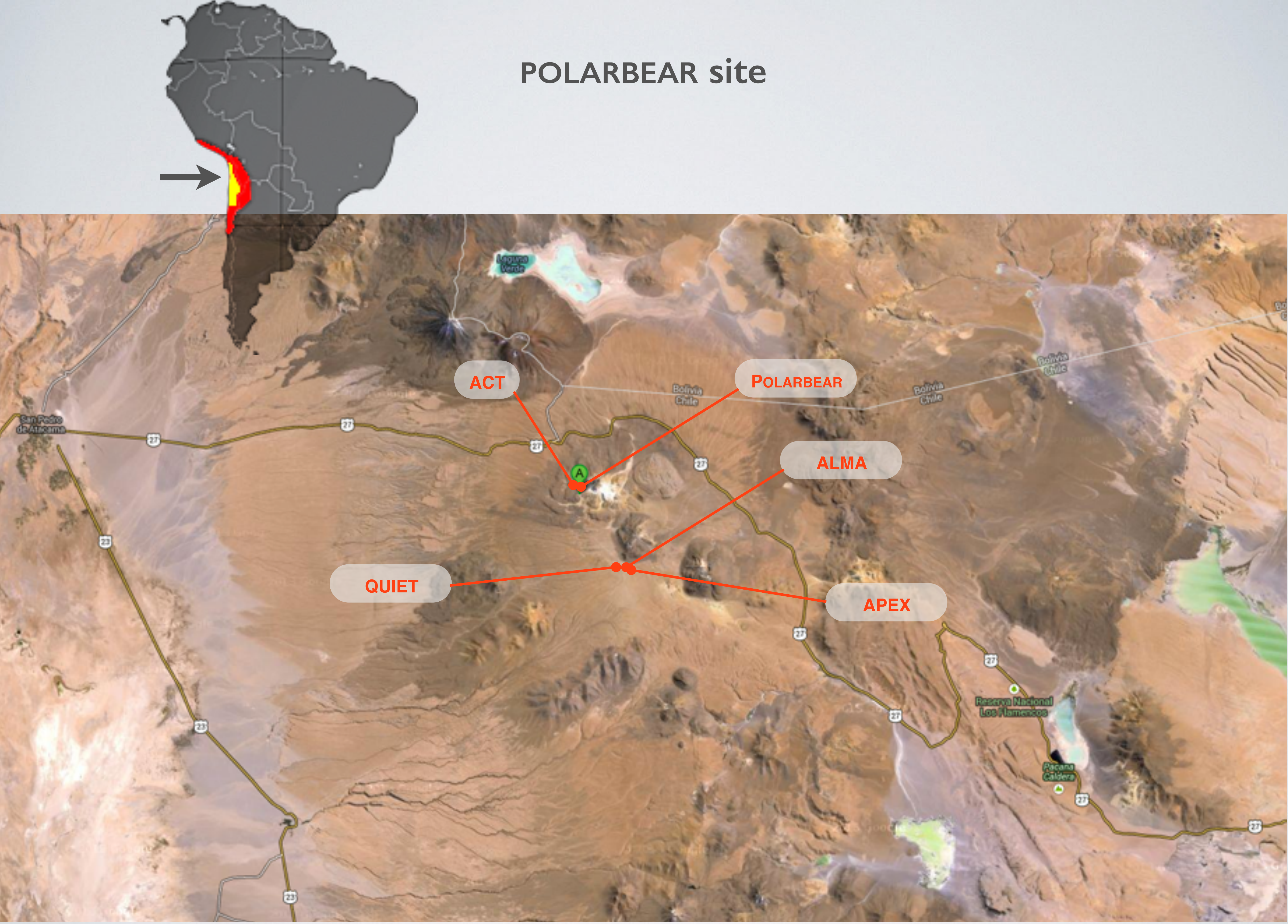
Sokendai, Japan
Yoshiki Akiba
Yuki Inoue
Yuuko Segawa

PUC, Chile
David Boettger
Rolando Dunner

University of Melbourne, AU
Christian Reichardt

@KEK, Japan, march 2013

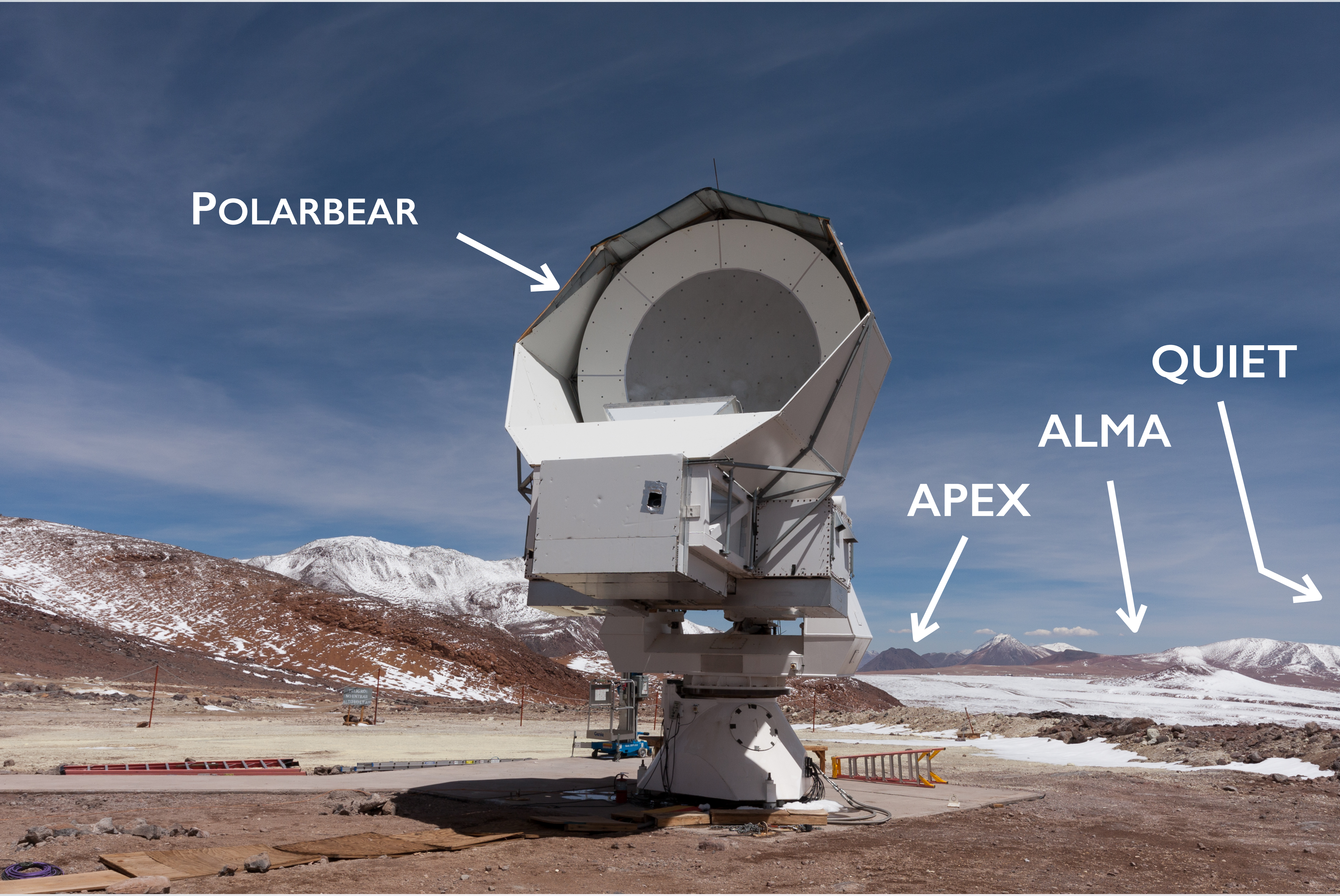
POLARBEAR site



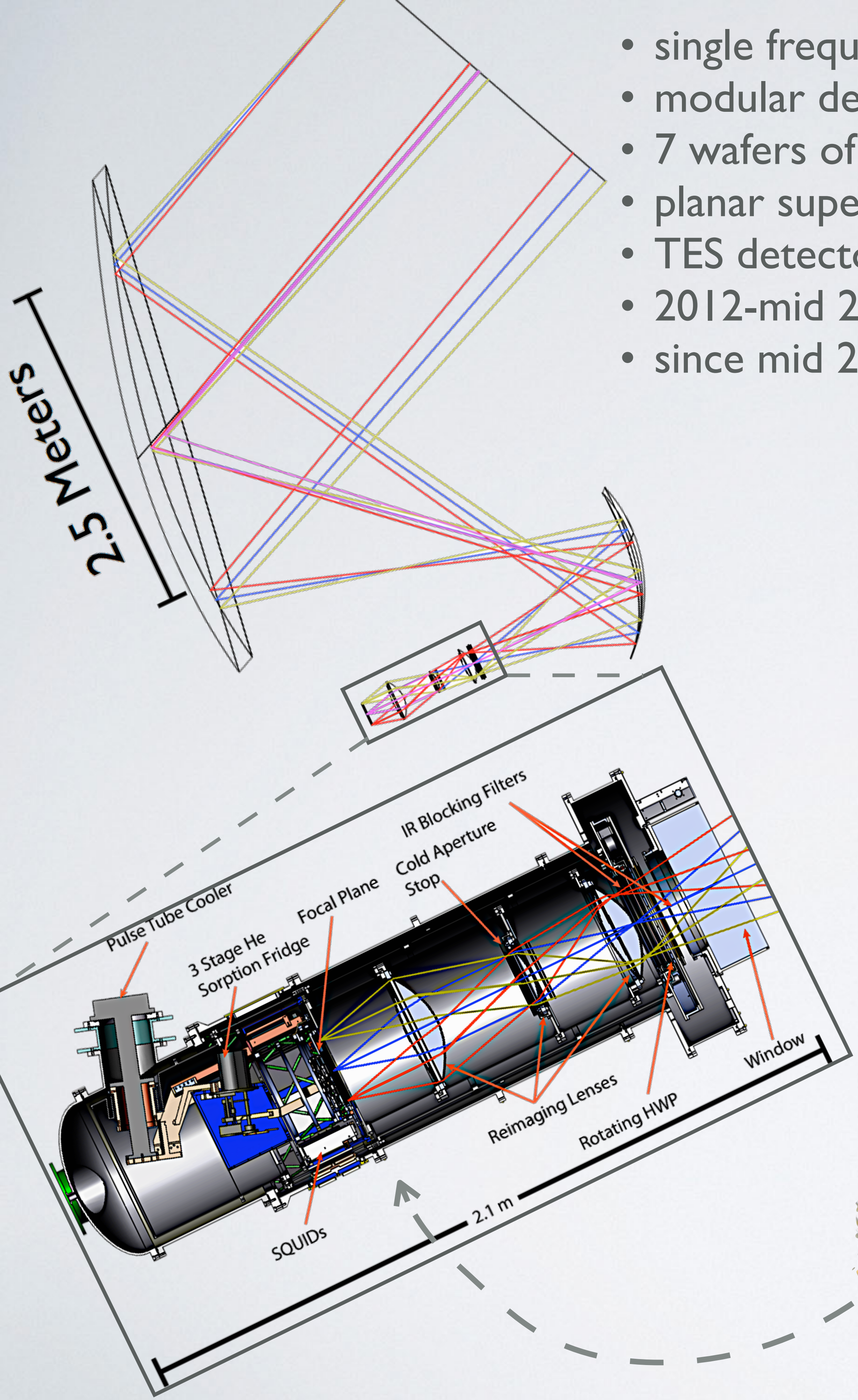
POLARBEAR-I

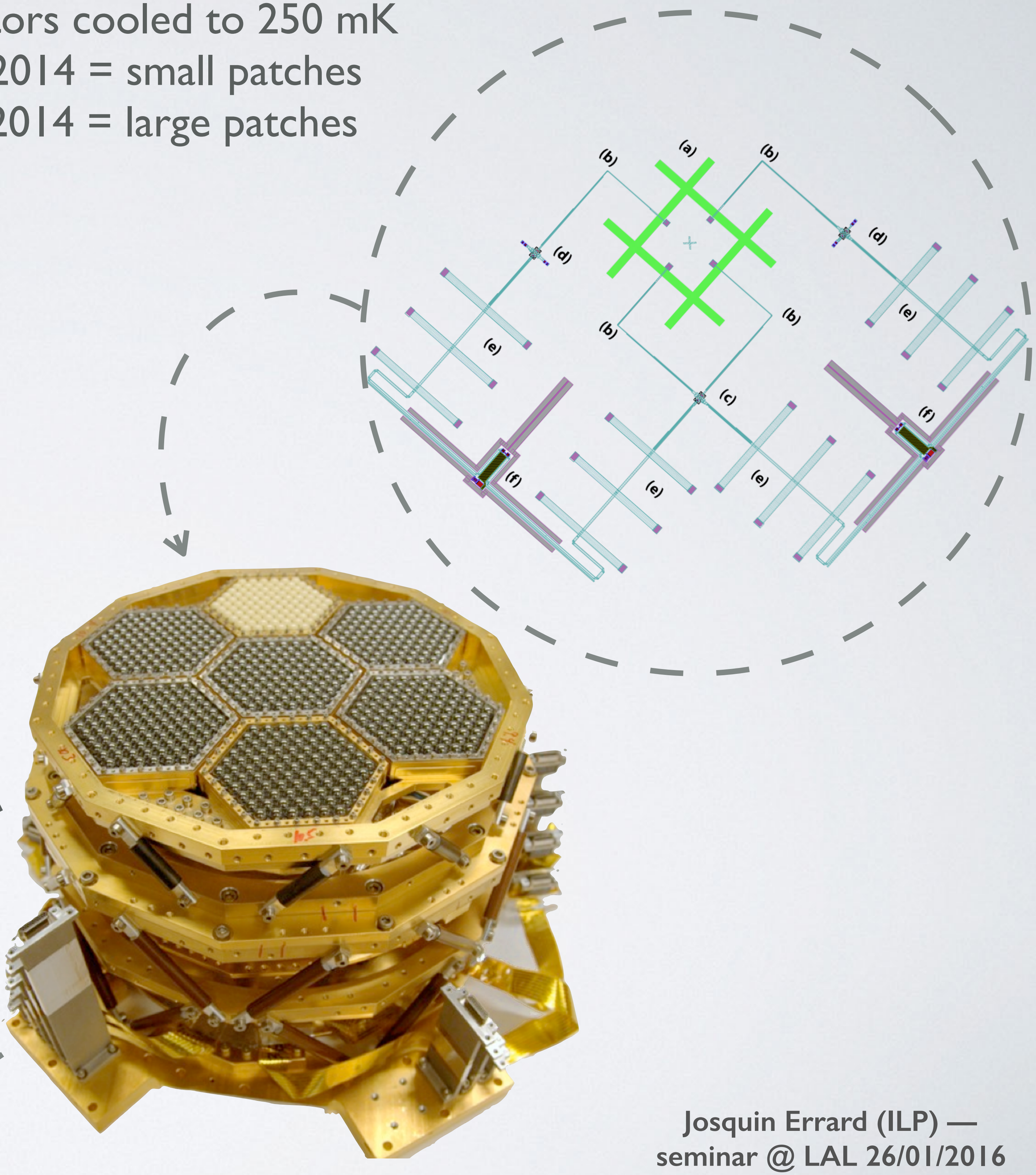
17,000 feet = 5,200m
no life
no oxygen
+ active volcanoes
+ anti-personnel mines

POLARBEAR site

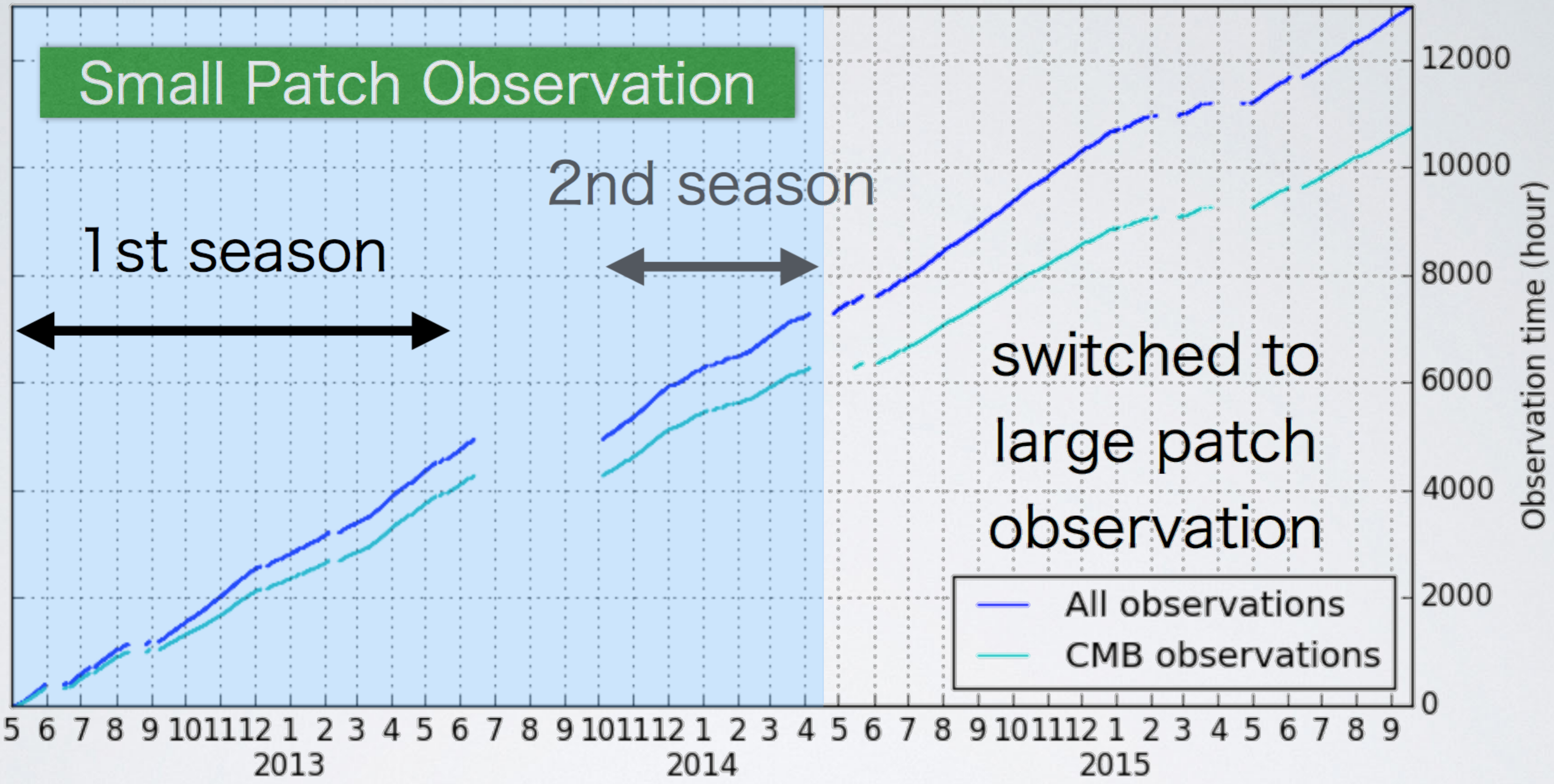


- single frequency:150GHz
- modular design
- 7 wafers of 91 dual-polarized pixels
- planar superconducting dipole antennas with contacting lensless
- TES detectors cooled to 250 mK
- 2012-mid 2014 = small patches
- since mid 2014 = large patches





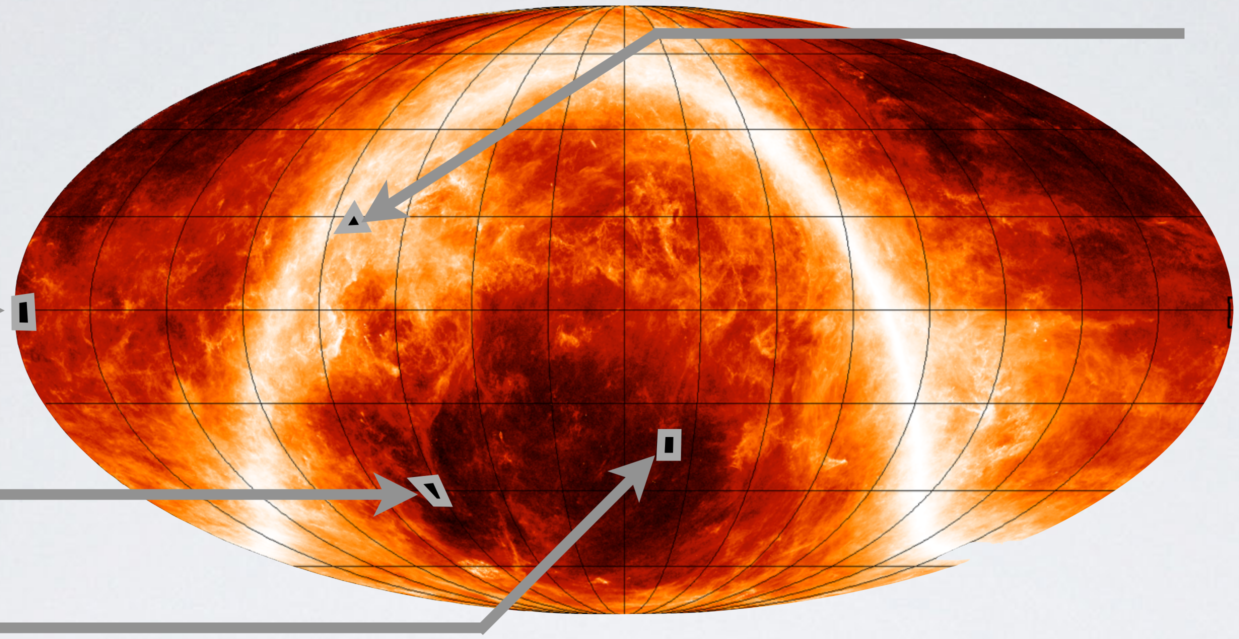
POLARBEAR observations



- three 3 x 3 deg^2 patches during the first and second seasons (2012-2014)
  - ★ detect lensing B-modes
  - ★ validate the instrument

- two/three ≳ 15 x 15 deg^2 patches for the rest of the survey (2014-2016)
  - ★ total neutrino mass < 75 meV (68% C.L.) when combined with Planck
  - ★ deep search for inflationary gravitational waves , enabling a detection of r = 0.025 (95% C.L.)

POLARBEAR observations

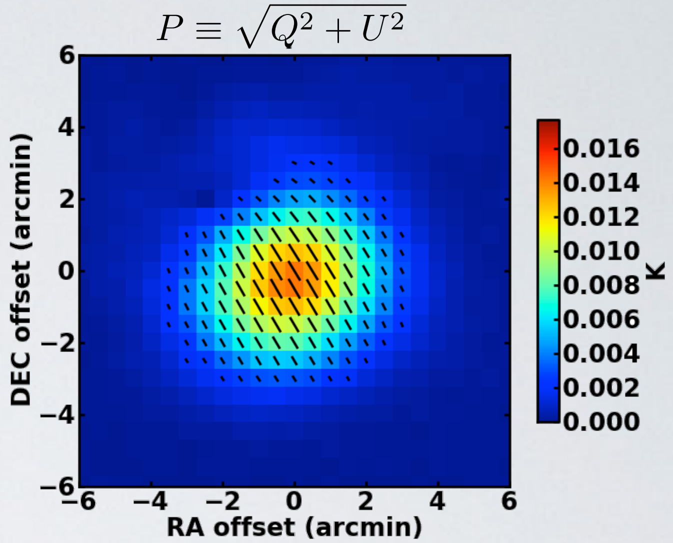


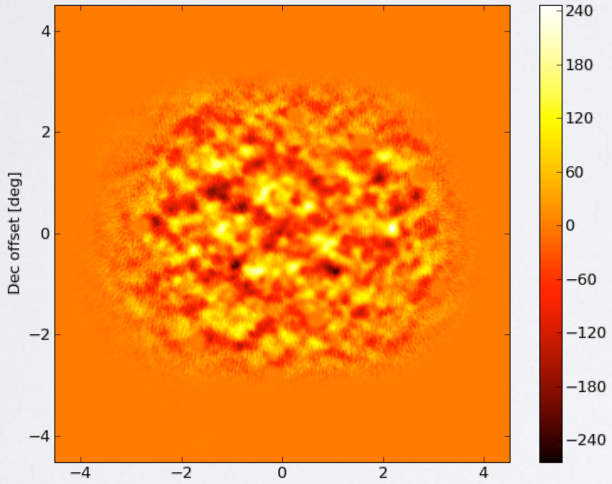
PB1RA12HAB

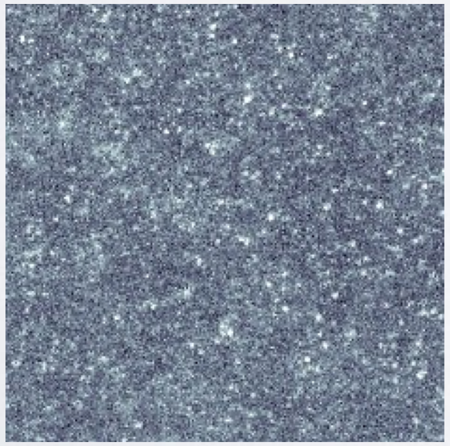
PB1LST4p5

PB1RA23HAB

Tau A, a polarized sky calibrator

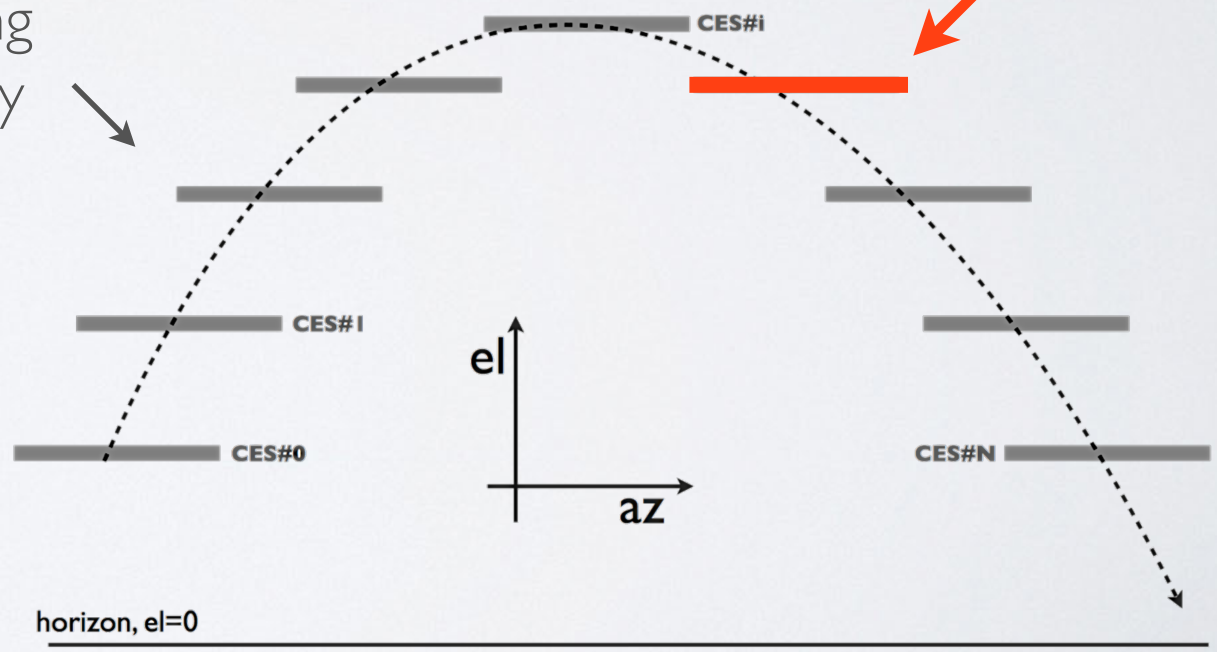






scanning strategy

constant elevation scan

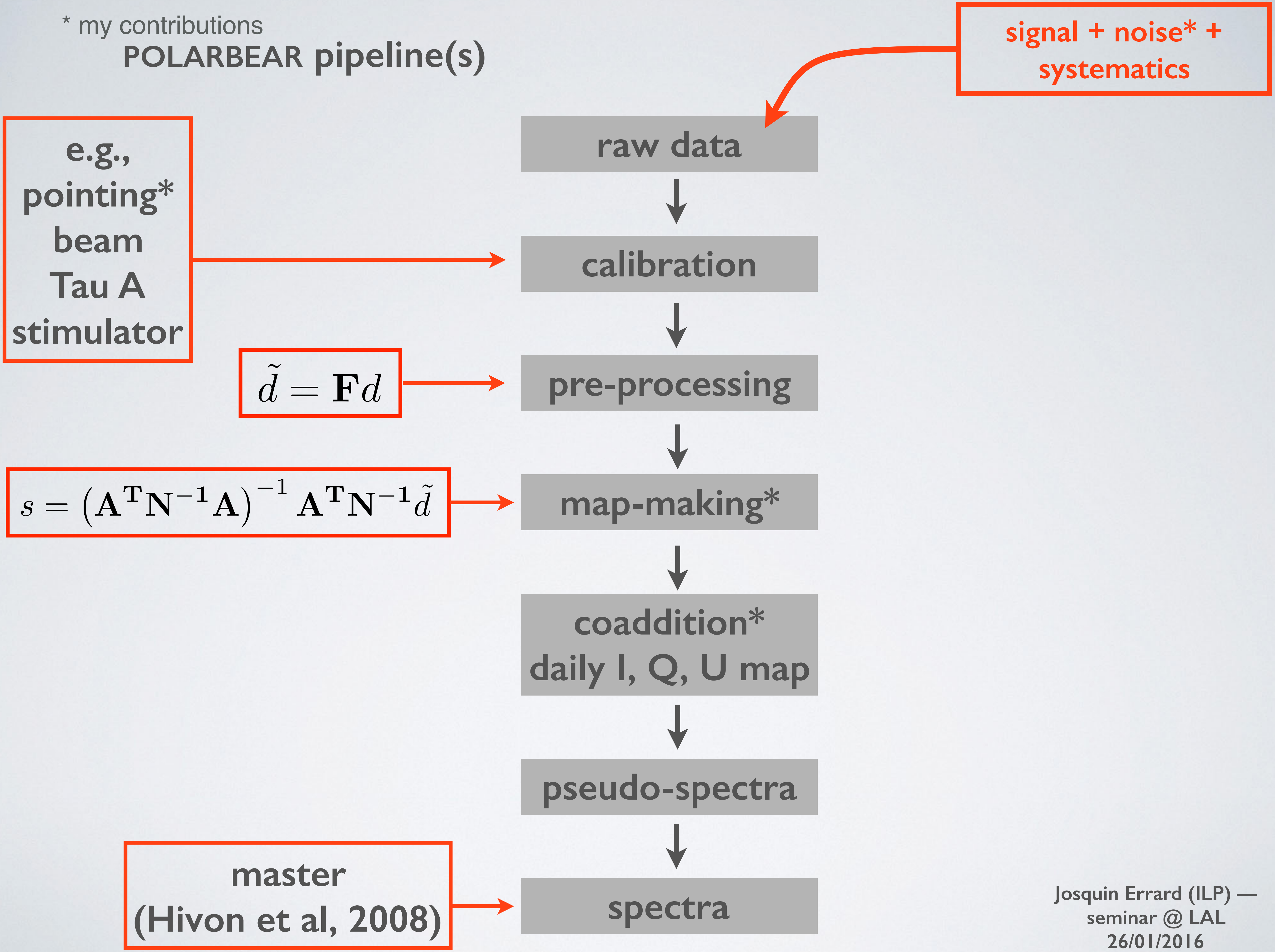


sky rotates with time →

POLARBEAR scans in azimuth at a constant elevation →

* my contributions

POLARBEAR pipeline(s)



signal + noise* + systematics

raw data

e.g., pointing* beam Tau A stimulator

calibration

$\tilde{d} = \mathbf{F} d$

pre-processing

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

map-making*

coaddition* daily I, Q, U map

pseudo-spectra

master (Hivon et al, 2008)

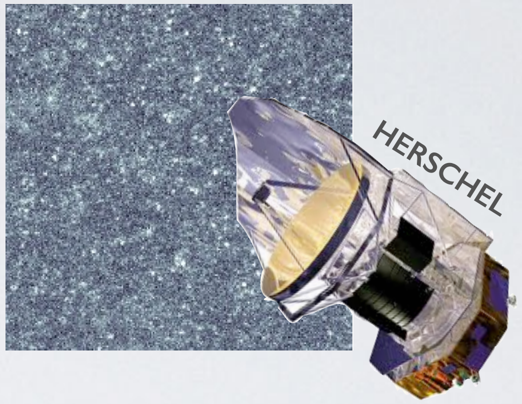
spectra

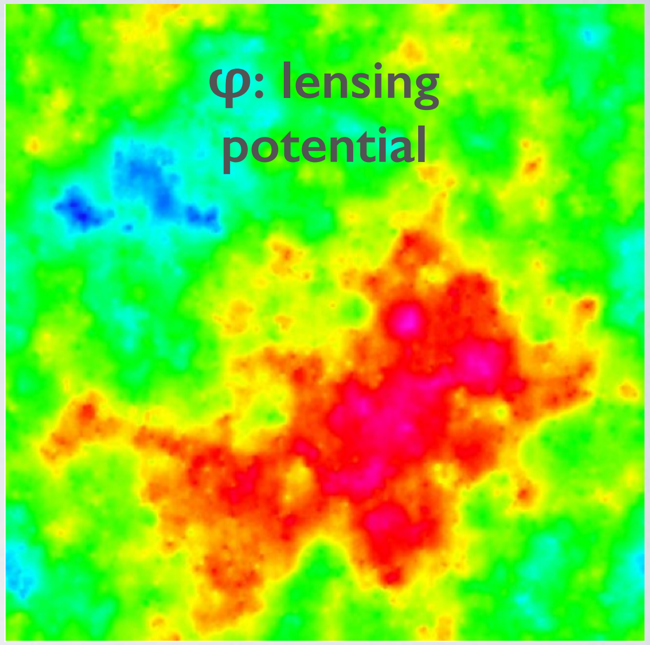
POLARBEAR results: first observations

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**)

3-point correlation

X





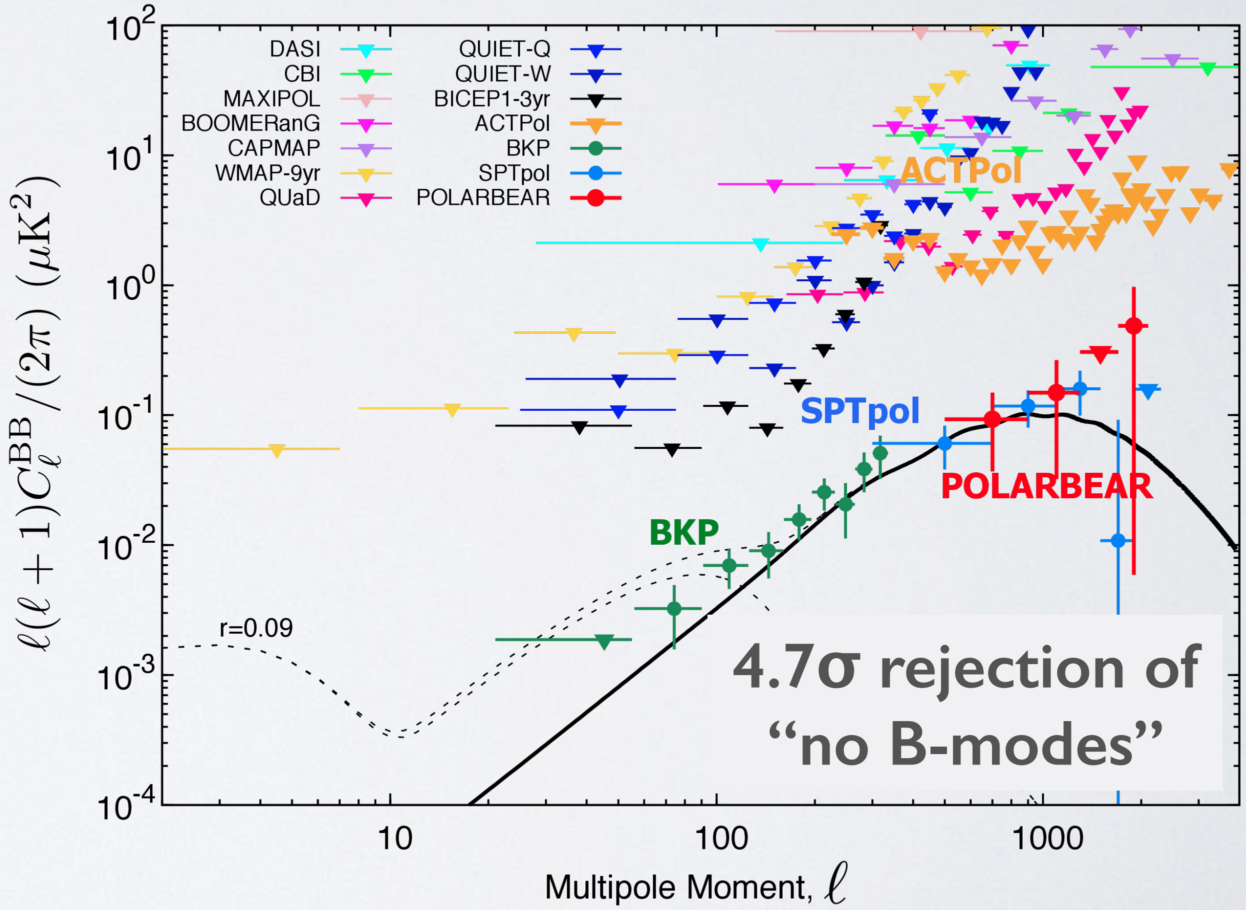
Measurement of the Cosmic Microwave Background Polarization Lensing Power Spectrum with the POLARBEAR Experiment
The POLARBEAR collaboration
Phys. Rev. Lett. 113, 021301 (**2014**)

4-point correlation

polarization only

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**)

2-point correlation



4.7σ rejection of "no B-modes"

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 …

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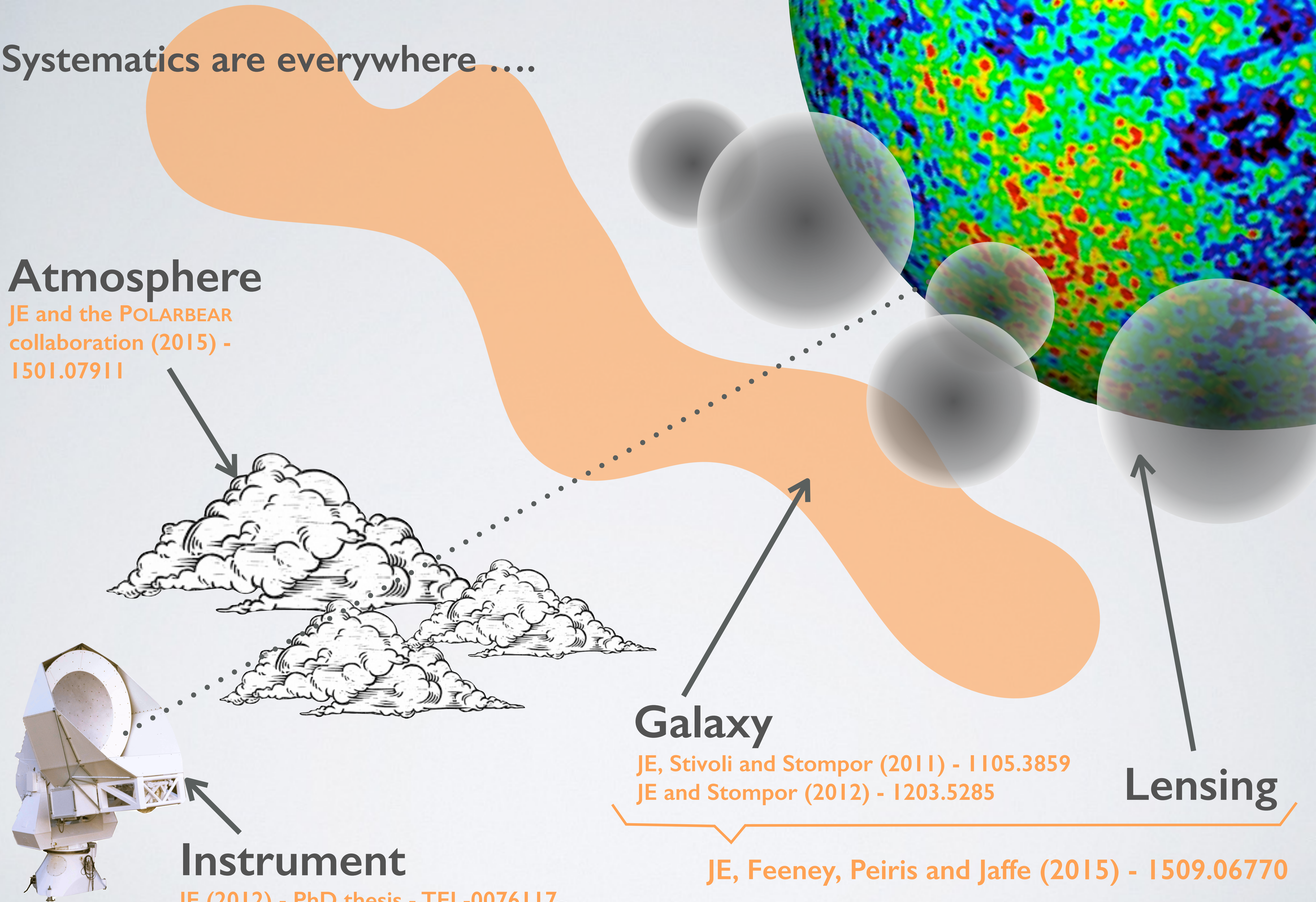
Systematics are everywhere ….



Atmosphere

JE and the POLARBEAR collaboration (2015) - 1501.07911

Instrument

JE (2012) - PhD thesis - TEL-00761117
The Polarbear collaboration (2014) - 1403.2369

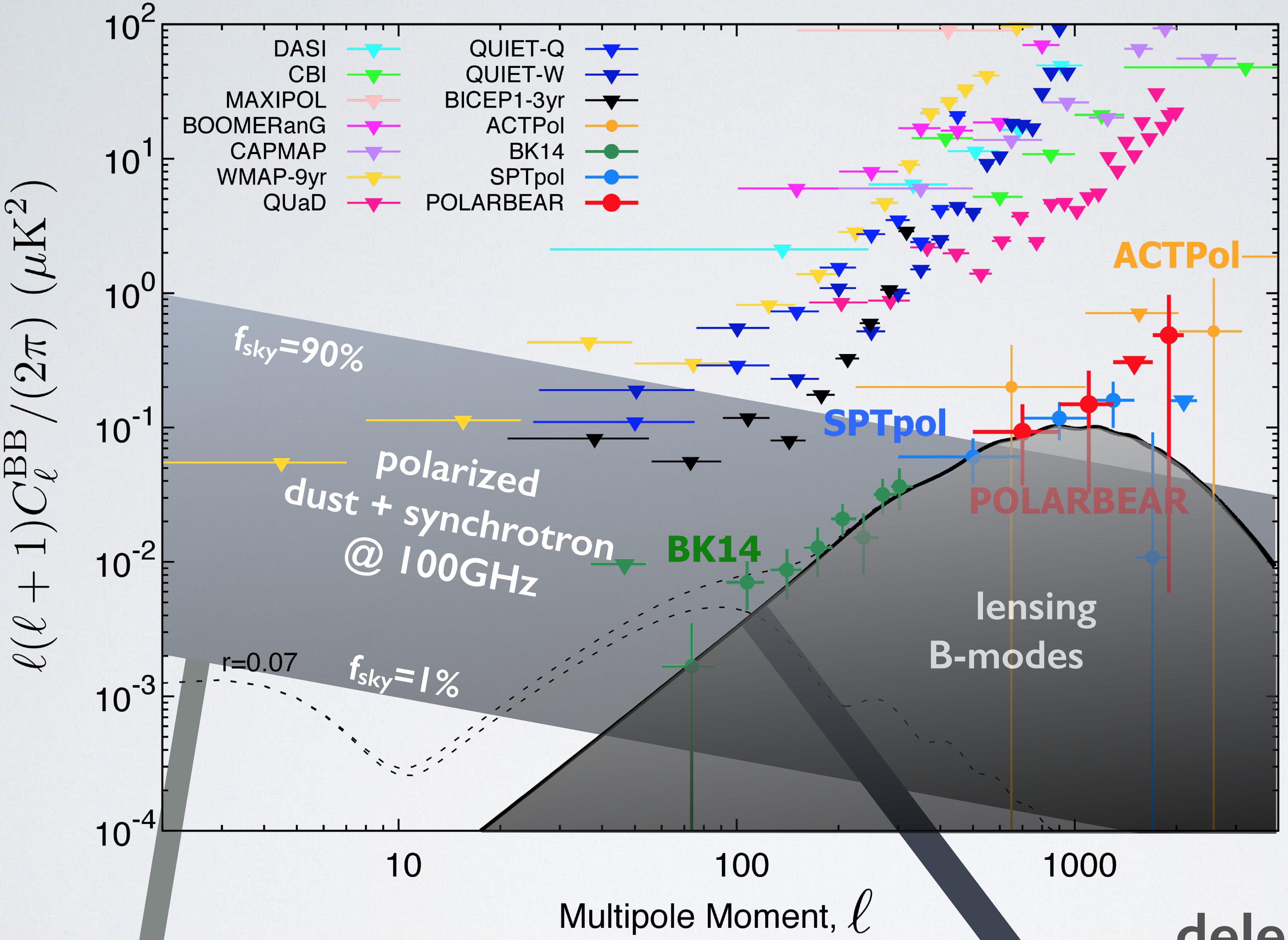
Galaxy

JE, Stivoli and Stompor (2011) - 1105.3859
JE and Stompor (2012) - 1203.5285

Lensing

JE, Feeney, Peiris and Jaffe (2015) - 1509.06770

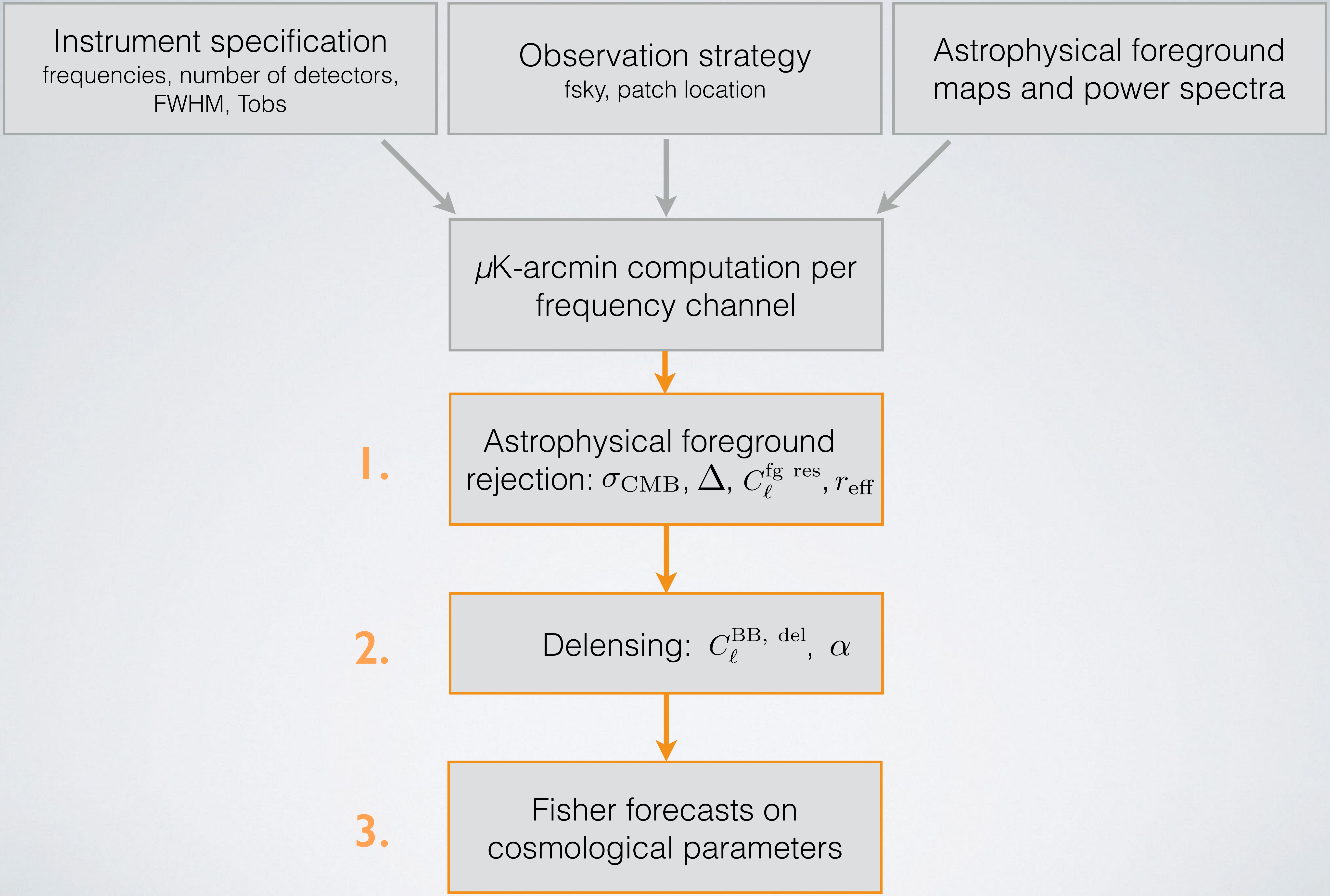
JE., S. Feeney et al (2015) — arXiv: 1509.06770



foregrounds cleaning

delensing

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



Instrument specification
frequencies, number of detectors, FWHM, Tobs

Observation strategy
fsky, patch location

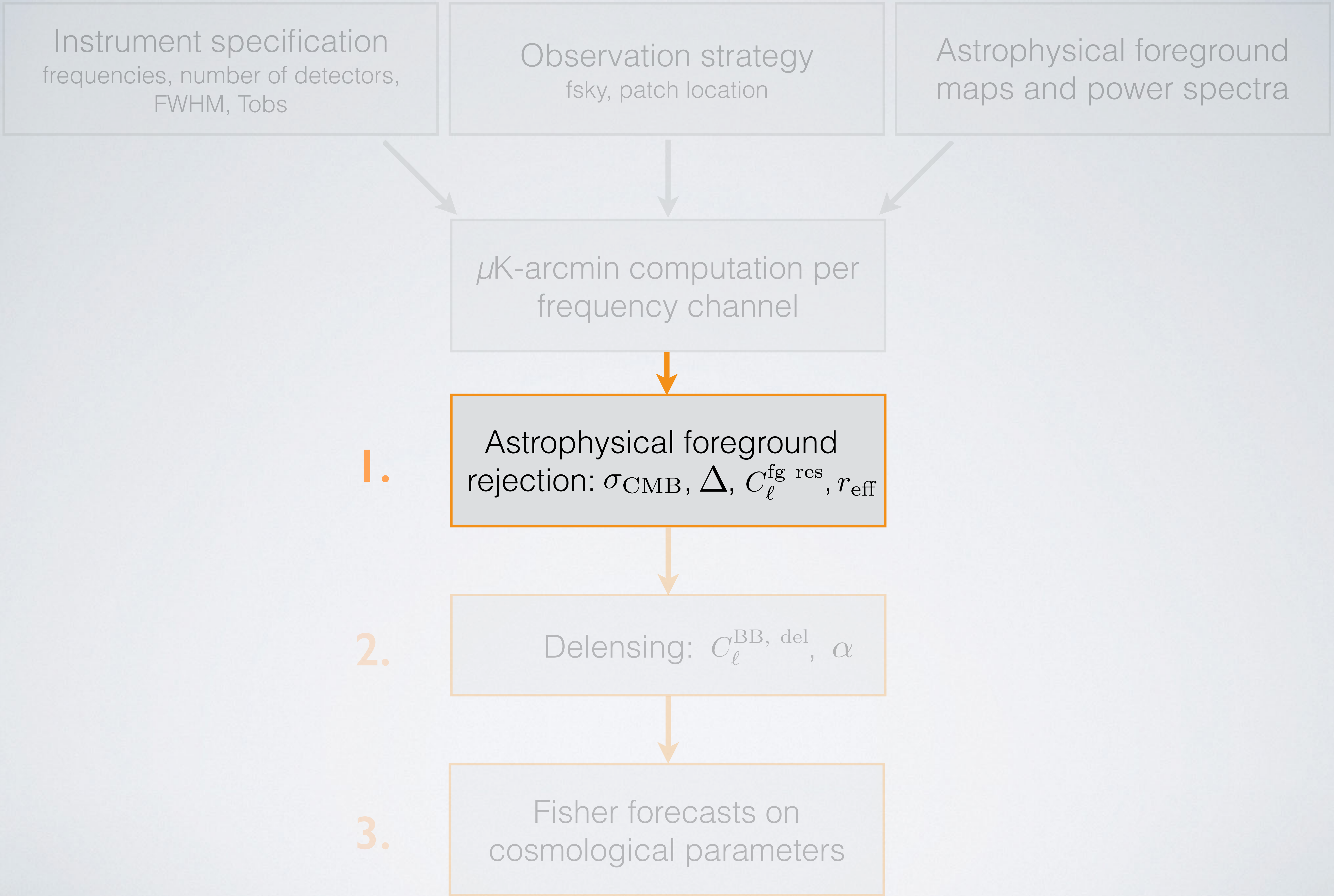
Astrophysical foreground maps and power spectra

μK-arcmin computation per frequency channel

1. Astrophysical foreground rejection: $\sigma_{\rm CMB}$, Δ, $C_\ell^{\rm fg\ res}$, $r_{\rm eff}$

2. Delensing: $C_\ell^{\rm BB,\ del}$, α

3. Fisher forecasts on cosmological parameters



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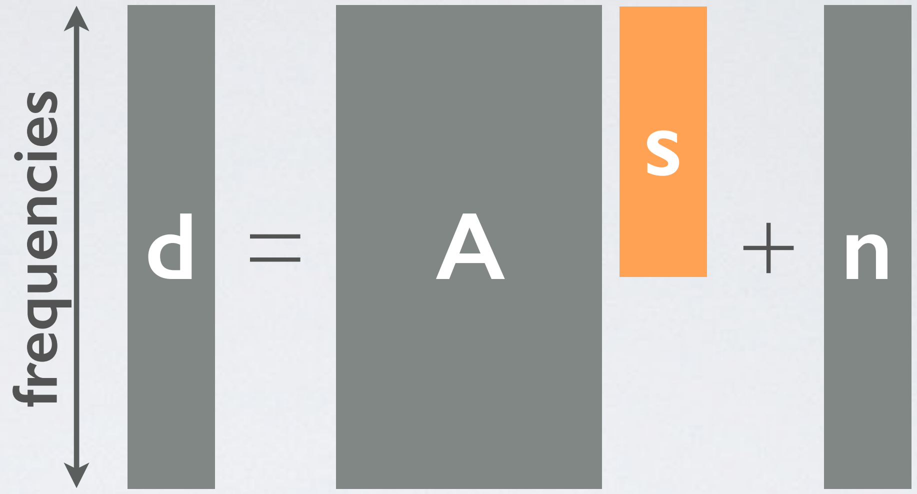
3\. Fisher forecasts on cosmological parameters

Component separation: rendition of parametric max-L component separation

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

data modeling
for each sky pixel:



1. estimation of the mixing matrix A

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

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

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

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

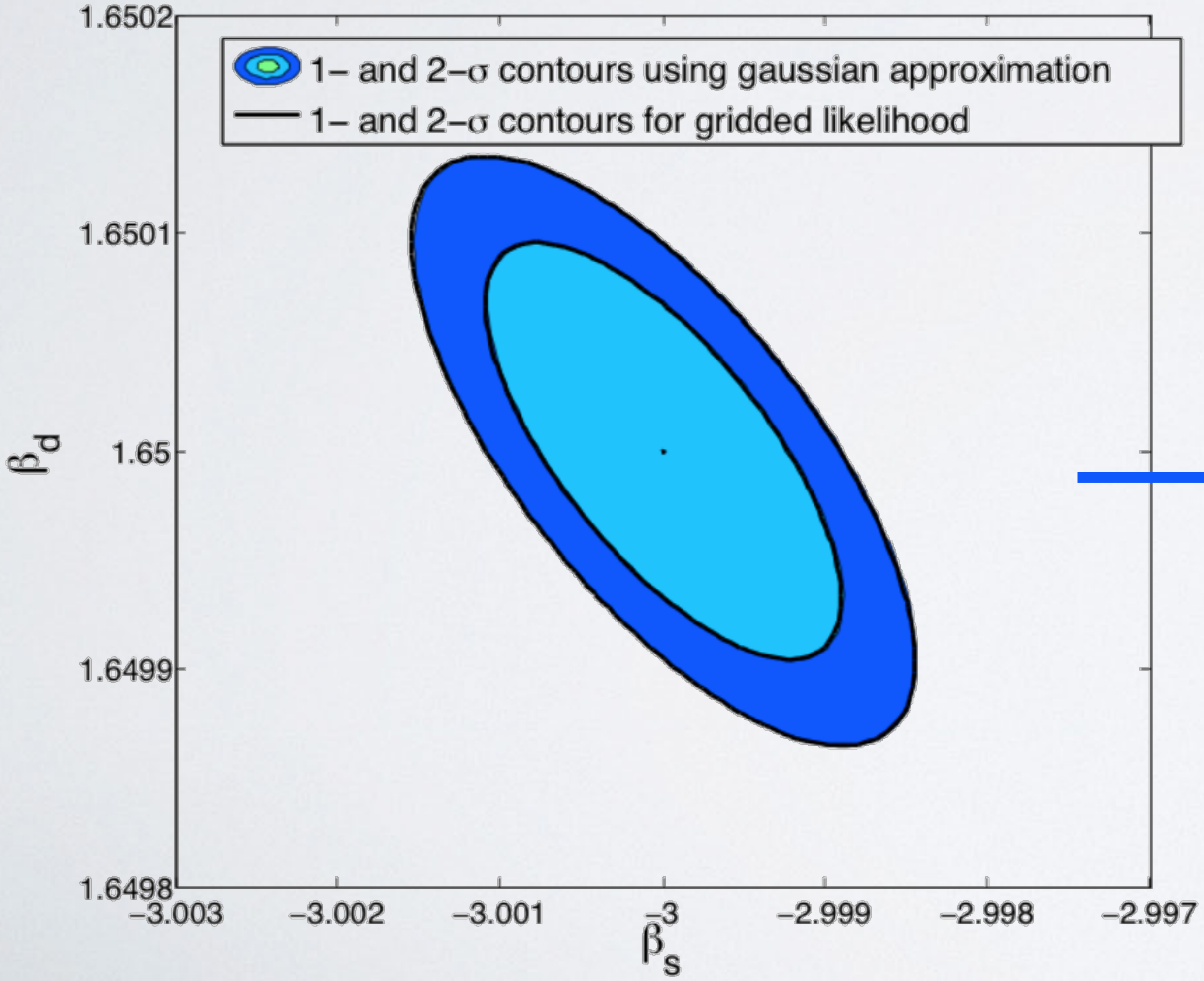
Component separation: rendition of parametric max-L component separation

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

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

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

$$= \underbrace{\text{constant} - (\mathbf{A}^T\mathbf{N}^{-1}\mathbf{d})^T(\mathbf{A}^T\mathbf{N}^{-1}\mathbf{A})^{-1}(\mathbf{A}^T\mathbf{N}^{-1}\mathbf{d})}_{-2\log\mathcal{L}_{\text{spec}}(\beta)} + \log\left|(\mathbf{A}^T\mathbf{N}^{-1}\mathbf{A})^{-1}\right|$$



[JE., 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

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

[JE. et al (2011)]

$$= -\,\mathrm{tr}\left\{\left[\frac{\partial \mathbf{A}}{\partial\beta}^T \mathbf{N}^{-1}\mathbf{A}\,\boxed{\left(\mathbf{A}^T\mathbf{N}^{-1}\mathbf{A}\right)^{-1}}\,\mathbf{A}^T\mathbf{N}^{-1}\frac{\partial\mathbf{A}}{\partial\beta'} - \frac{\partial \mathbf{A}}{\partial\beta}^T\mathbf{N}^{-1}\frac{\partial\mathbf{A}}{\partial\beta'}\right]\boxed{\sum_p \mathbf{s}(p)\,\mathbf{s}^T(p)}\right\}$$

noise in the reconstructed maps

information about sky components

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

[Stivoli et al (2010)]

↳ **prediction of error bars for parametric methods like COMMANDER**

not perfect recovery of input spectral parameters ➤ foregrounds residuals

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

linear combination of various frequency maps ➤ boosted noise

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

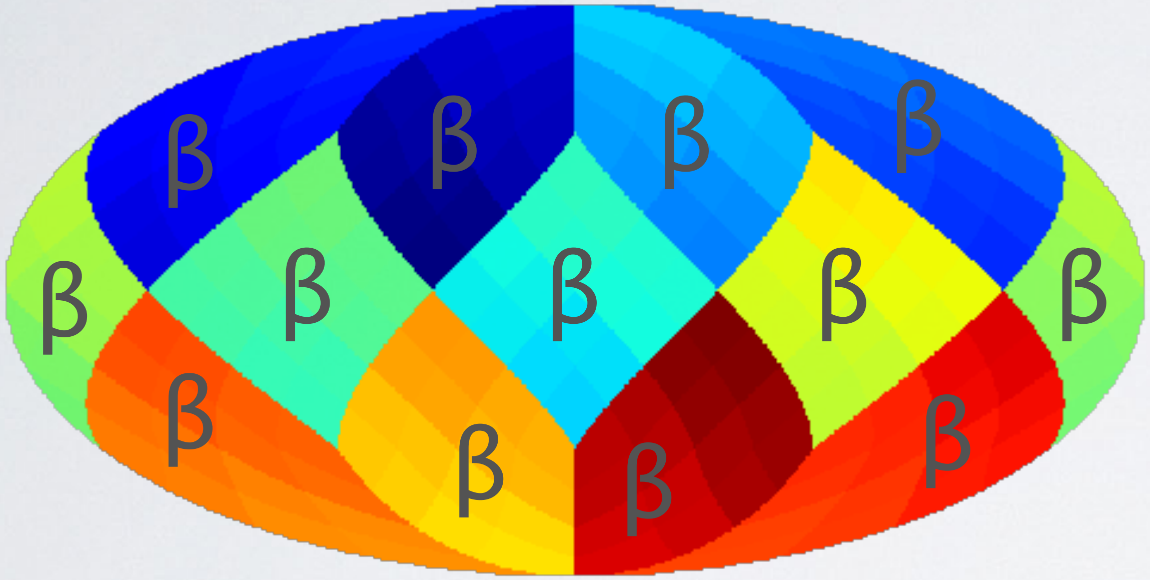
post component separation noise

simple quadratic combination of sensitivities in all channels

[JE. et al (2015)]

Component separation: spatial variation of spectral indices

“n_p-approach”



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

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

“A-expansion approach”

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

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

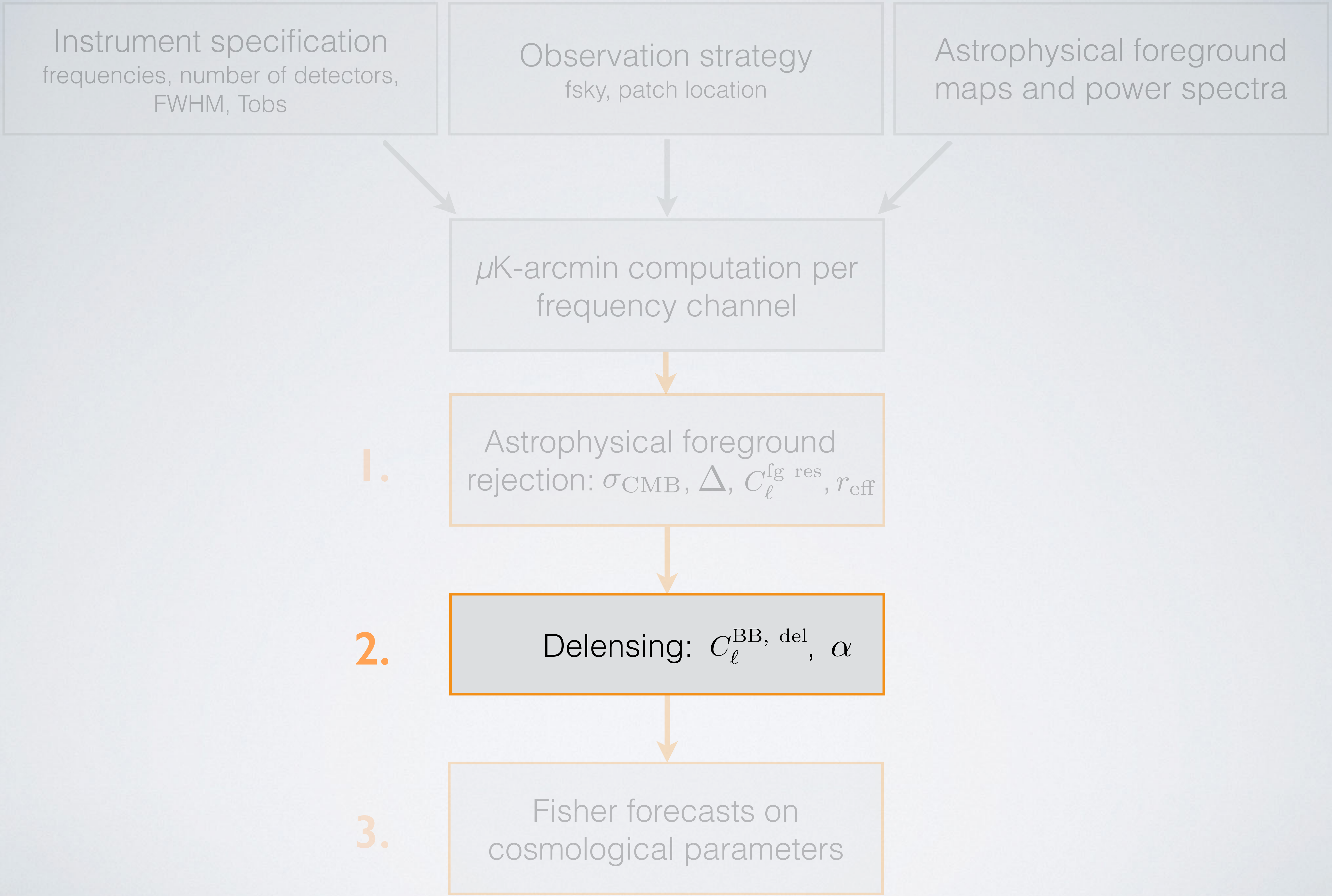
$$\mathbf{A} = \left[\mathbf{A}_{\rm cmb}, \mathbf{A}_{\rm dust}, \frac{\partial \mathbf{A}_{\rm dust}}{\partial \beta_d}, \mathbf{A}_{\rm sync}, \frac{\partial \mathbf{A}_{\rm sync}}{\partial \beta_s}\right]$$

compared to the “n_p-approach”:

higher boosted noise, Δ ↗

lower foregrounds residuals, $r_{\rm eff}$ ↘

[JE. et al (2015)]



Instrument specification
frequencies, number of detectors, FWHM, Tobs

Observation strategy
fsky, patch location

Astrophysical foreground maps and power spectra

μK-arcmin computation per frequency channel

1. Astrophysical foreground rejection: $\sigma_{\rm CMB}$, Δ, $C_\ell^{\rm fg\ res}$, $r_{\rm eff}$

2. **Delensing: $C_\ell^{\rm BB,\ del}$, α**

3. Fisher forecasts on cosmological parameters

Iterative delensing

CMB x CMB

[Seljak & Hirata et al (2004)]

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

[Okamoto & Hu et al (2003)]

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

CMB x CIB

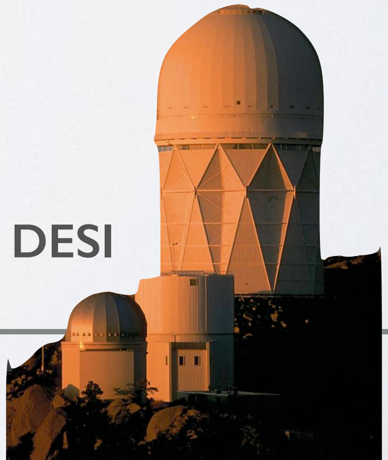
$$C_\ell^{\phi\phi} + N_\ell^{\phi\phi} \rightarrow C_\ell^{\phi\phi}/\rho_\ell^2$$

[Sherwin & Schmittfull (2015)]

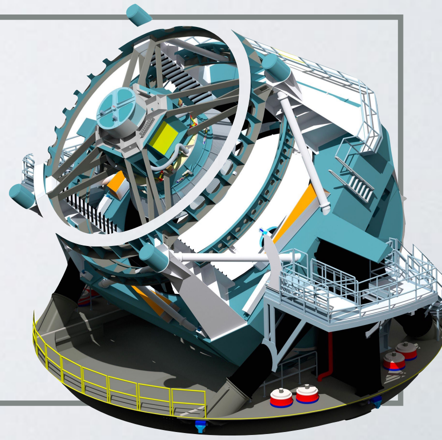
CMB x LSS

$$\frac{(C_\ell^{\phi\phi})^2}{C_\ell^{\phi\phi}+N_\ell^{\phi\phi}} \rightarrow C_\ell^{\phi\phi,\, z_{\rm max}}$$

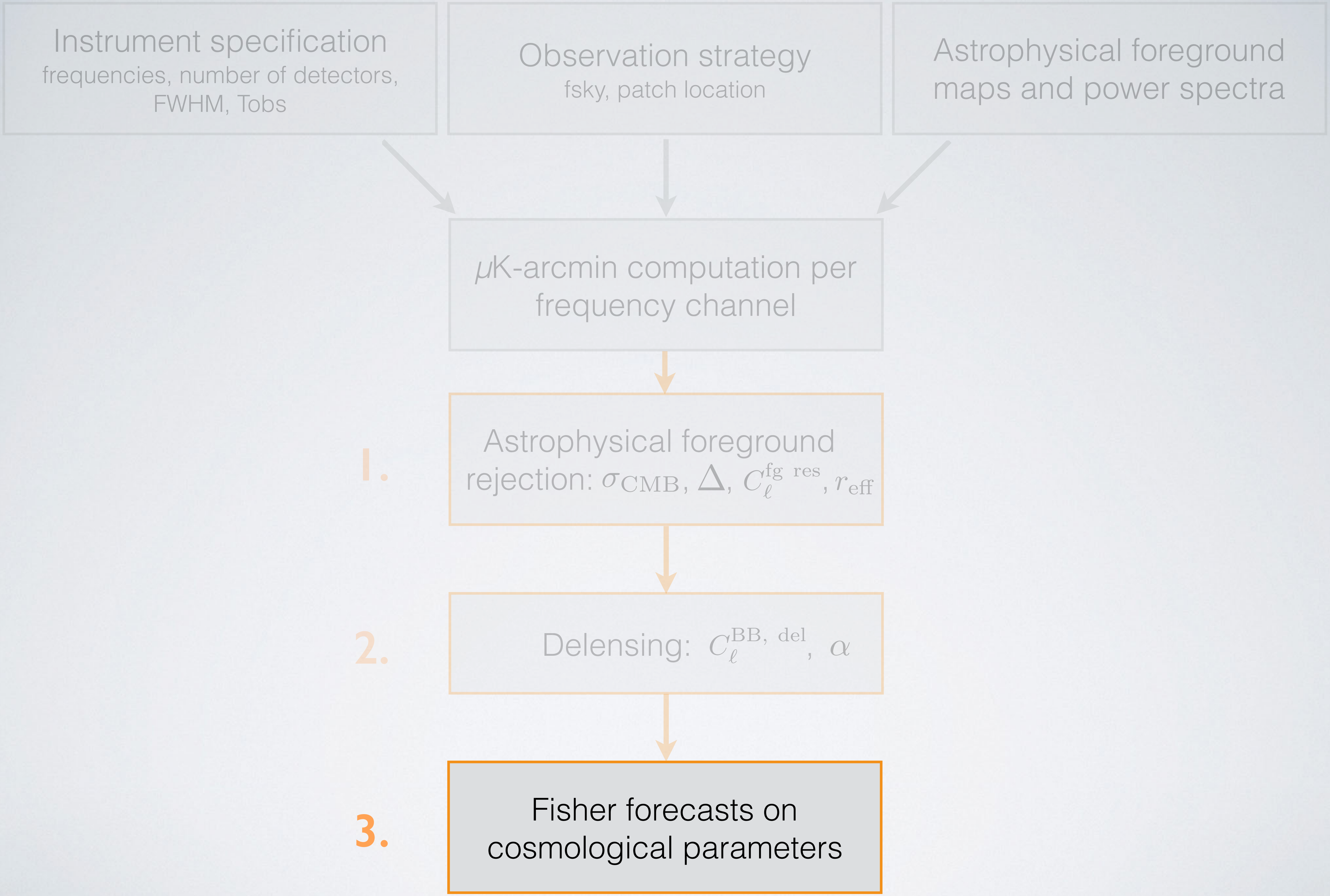
[Smith et al (2012)]



DESI



LSST



Instrument specification
frequencies, number of detectors, FWHM, Tobs

Observation strategy
fsky, patch location

Astrophysical foreground maps and power spectra

μK-arcmin computation per frequency channel

1. Astrophysical foreground rejection: $\sigma_{\rm CMB}$, Δ, $C_\ell^{\rm fg\ res}$, $r_{\rm eff}$

2. Delensing: $C_\ell^{\rm BB,\ del}$, α

3. Fisher forecasts on cosmological parameters

Constraints on cosmological parameters: formalism

$$F_{ij} = \sum_{\ell=\ell_min}^{\ell_max} \frac{2\ell+1}{2} f_{sky} \mathrm{tr}\left(\boldsymbol{C}_\ell^{-1} \frac{\partial \boldsymbol{C}_\ell}{\partial \theta_i} \boldsymbol{C}_\ell^{-1} \frac{\partial \boldsymbol{C}_\ell}{\partial \theta_j} \right) ,$$

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

inclusion of delensing, foregrounds residuals and post component separation noise

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

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

[JE. et al (2015)]

LiteBIRD

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

LiteBIRD x Stage-IV

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

[JE. et al (2015)]

Results of JE. et al (2015)

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, QUIJOTE, 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**

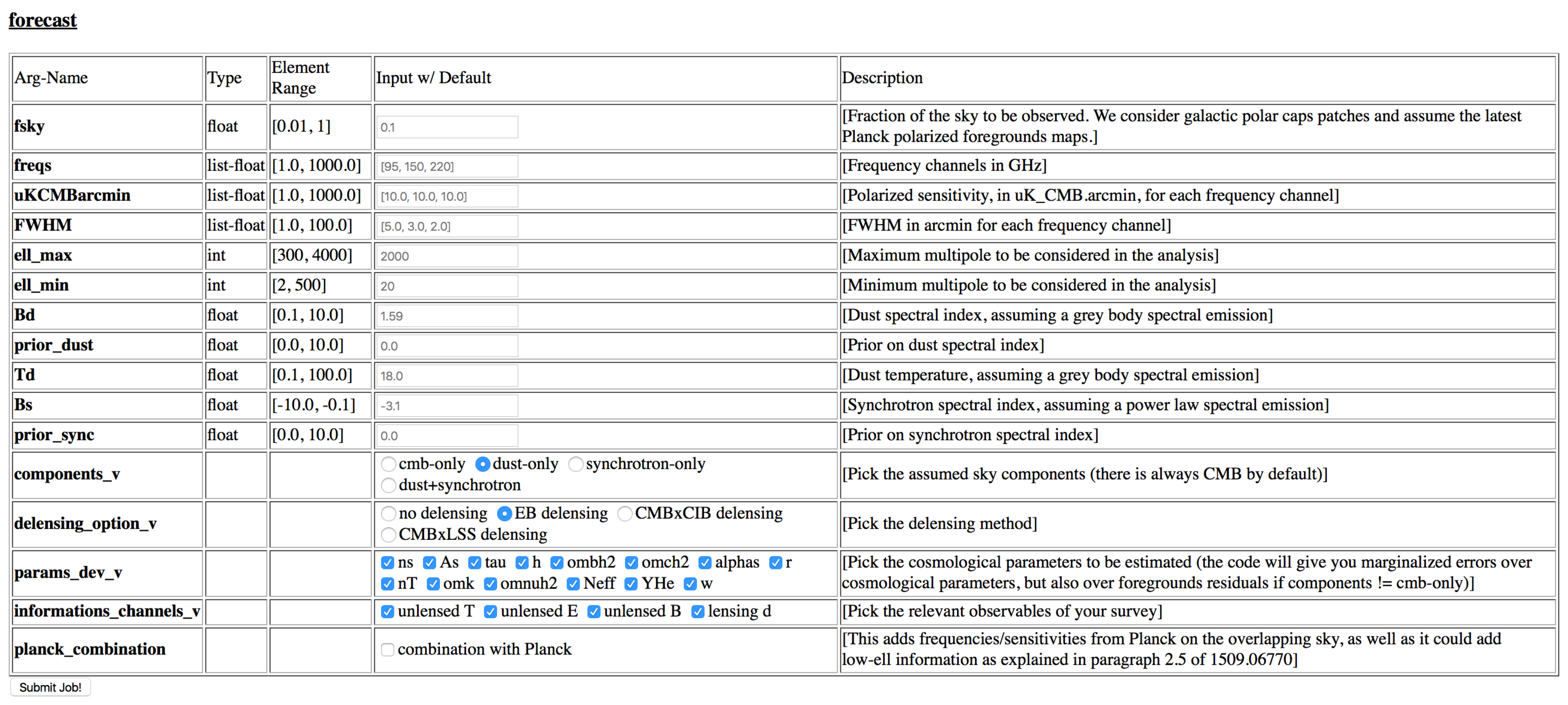
  $\sigma(r=0.001) \sim$ **1-2e-4** with CMBxCMB iterative delensing

  σ(neutrinos mass) ~ **30-40meV**, σ(Neff) < **0.046**

[JE. et al (2015)]

Results of JE. et al (2015)

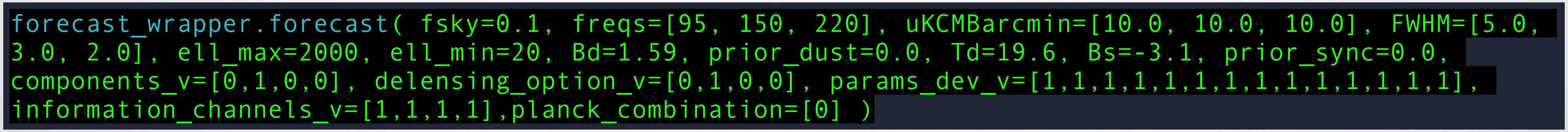
- ➤ user-friendly interface to the code is accessible at **turkey.lbl.gov**



forecast

Arg-Name	Type	Element Range	Input w/ Default	Description
fsky	float	[0.01, 1]	0.1	[Fraction of the sky to be observed. We consider galactic polar caps patches and assume the latest Planck polarized foregrounds maps.]
freqs	list-float	[1.0, 1000.0]	[95, 150, 220]	[Frequency channels in GHz]
uKCMBarcmin	list-float	[1.0, 1000.0]	[10.0, 10.0, 10.0]	[Polarized sensitivity, in uK_CMB.arcmin, for each frequency channel]
FWHM	list-float	[1.0, 100.0]	[5.0, 3.0, 2.0]	[FWHM in arcmin for each frequency channel]
ell_max	int	[300, 4000]	2000	[Maximum multipole to be considered in the analysis]
ell_min	int	[2, 500]	20	[Minimum multipole to be considered in the analysis]
Bd	float	[0.1, 10.0]	1.59	[Dust spectral index, assuming a grey body spectral emission]
prior_dust	float	[0.0, 10.0]	0.0	[Prior on dust spectral index]
Td	float	[0.1, 100.0]	18.0	[Dust temperature, assuming a grey body spectral emission]
Bs	float	[-10.0, -0.1]	-3.1	[Synchrotron spectral index, assuming a power law spectral emission]
prior_sync	float	[0.0, 10.0]	0.0	[Prior on synchrotron spectral index]
components_v			○ cmb-only ● dust-only ○ synchrotron-only ○ dust+synchrotron	[Pick the assumed sky components (there is always CMB by default)]
delensing_option_v			○ no delensing ● EB delensing ○ CMBxCIB delensing ○ CMBxLSS delensing	[Pick the delensing method]
params_dev_v			☑ ns ☑ As ☑ tau ☑ h ☑ ombh2 ☑ omch2 ☑ alphas ☑ r ☑ nT ☑ omk ☑ omnuh2 ☑ Neff ☑ YHe ☑ w	[Pick the cosmological parameters to be estimated (the code will give you marginalized errors over cosmological parameters, but also over foregrounds residuals if components != cmb-only)]
informations_channels_v			☑ unlensed T ☑ unlensed E ☑ unlensed B ☑ lensing d	[Pick the relevant observables of your survey]
planck_combination			☐ combination with Planck	[This adds frequencies/sensitivities from Planck on the overlapping sky, as well as it could add low-ell information as explained in paragraph 2.5 of 1509.06770]

- ➤ code is currently running on NERSC machines (accessible on demand)

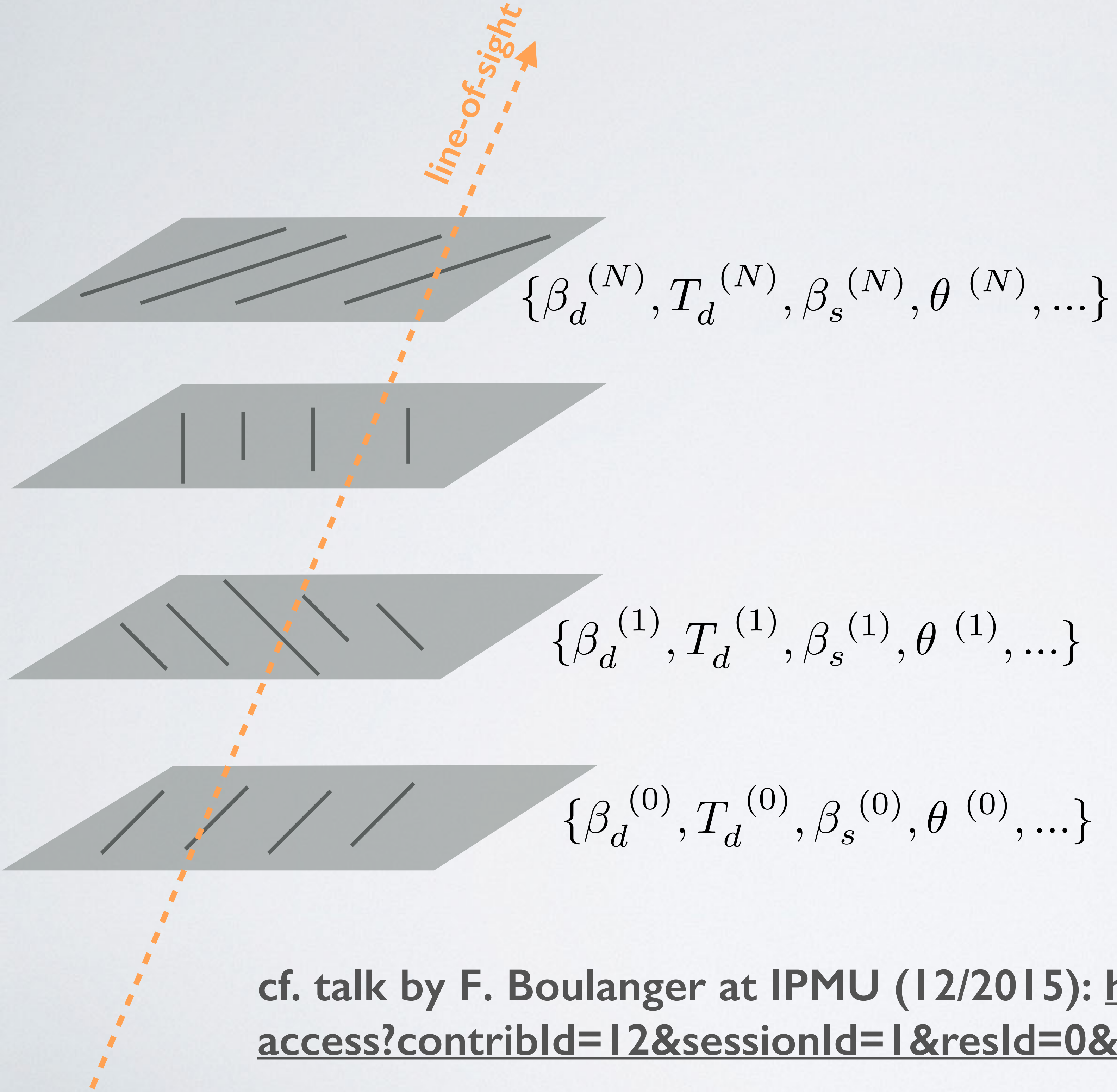


```
forecast_wrapper.forecast( fsky=0.1, freqs=[95, 150, 220], uKCMBarcmin=[10.0, 10.0, 10.0], FWHM=[5.0,
3.0, 2.0], ell_max=2000, ell_min=20, Bd=1.59, prior_dust=0.0, Td=19.6, Bs=-3.1, prior_sync=0.0,
components_v=[0,1,0,0], delensing_option_v=[0,1,0,0], params_dev_v=[1,1,1,1,1,1,1,1,1,1,1,1,1,1],
information_channels_v=[1,1,1,1],planck_combination=[0]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

[JE. et al (2015)]

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]



$\{\beta_d{}^{(N)}, T_d{}^{(N)}, \beta_s{}^{(N)}, \theta^{\ (N)}, ...\}$

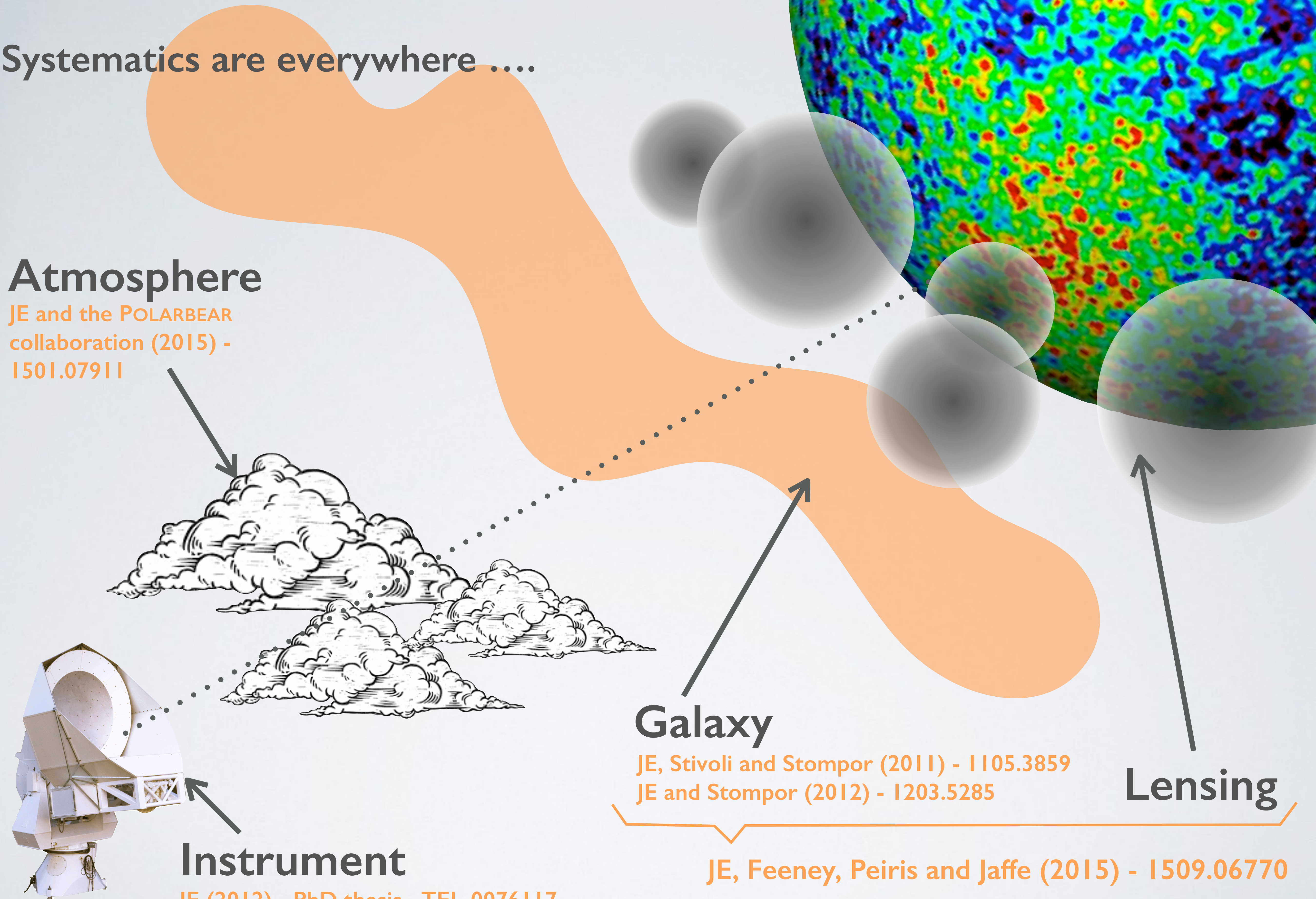
$\{\beta_d{}^{(1)}, T_d{}^{(1)}, \beta_s{}^{(1)}, \theta^{\ (1)}, ...\}$

$\{\beta_d{}^{(0)}, T_d{}^{(0)}, \beta_s{}^{(0)}, \theta^{\ (0)}, ...\}$

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

Systematics are everywhere ….



Atmosphere

JE and the POLARBEAR collaboration (2015) - 1501.07911

Galaxy

JE, Stivoli and Stompor (2011) - 1105.3859
JE and Stompor (2012) - 1203.5285

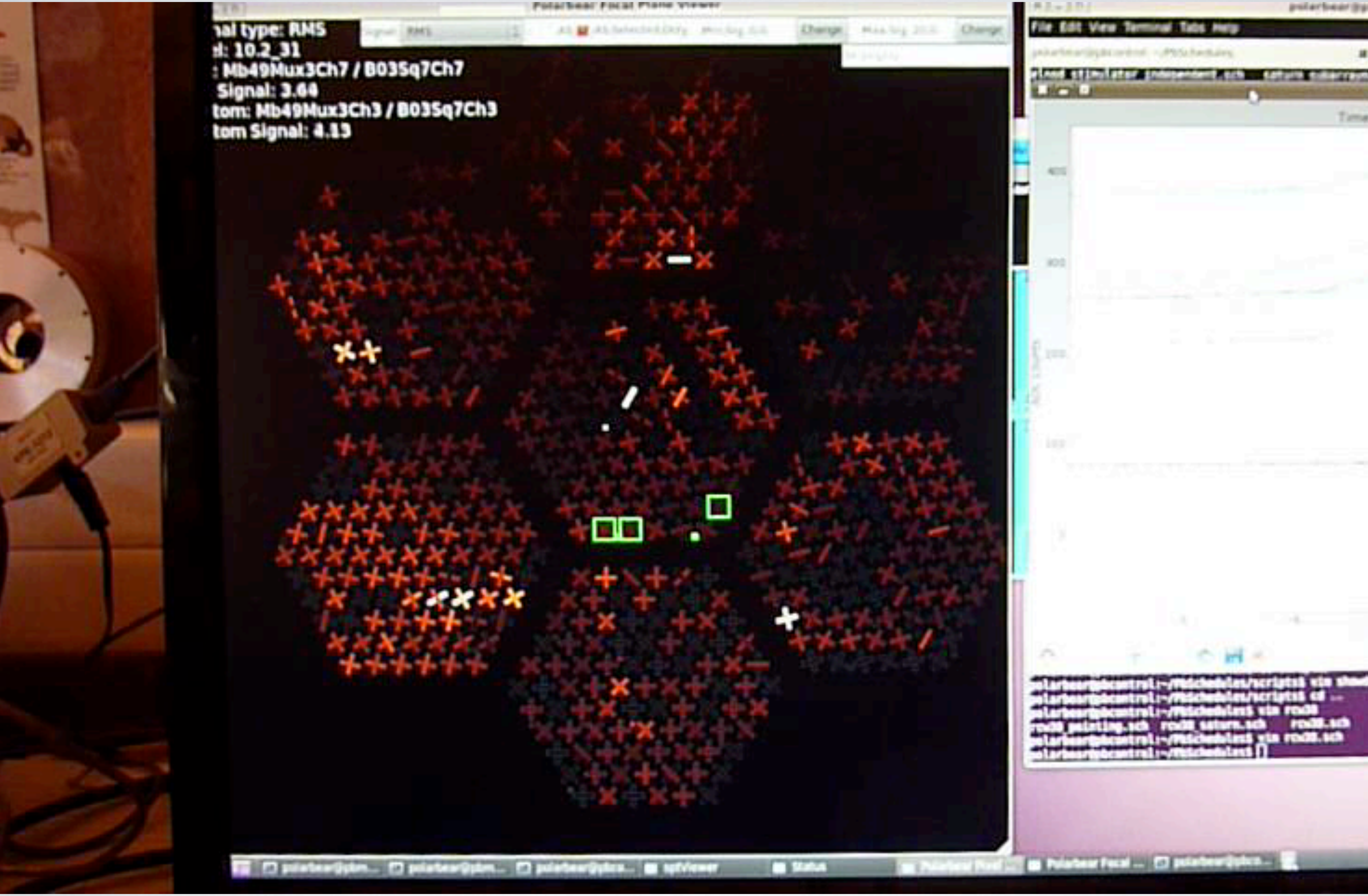
Lensing

JE, Feeney, Peiris and Jaffe (2015) - 1509.06770

Instrument

JE (2012) - PhD thesis - TEL-00761117
The Polarbear collaboration (2014) - 1403.2369

And there are other problems too … like atmosphere



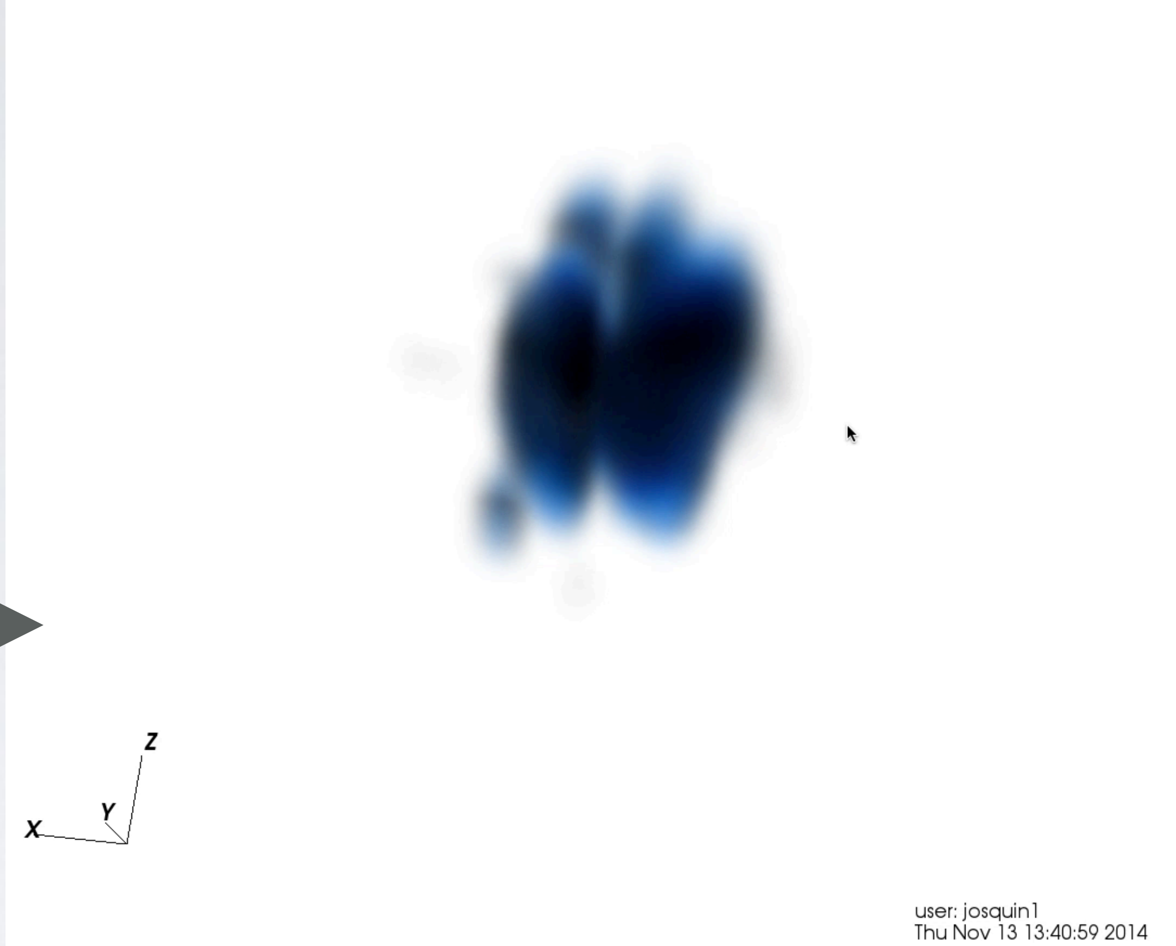
nal type: RMS
d: 10.2_31
: Mb49Mux3Ch7 / B03Sq7Ch7
Signal: 3.64
tom: Mb49Mux3Ch3 / B03Sq7Ch3
tom Signal: 4.13

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

model

3D Kolmogorov turbulences
wind direction and speed
ground temperature



POLARBEAR
scientific data

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

typical scale for atmospheric turbulences: Lo ~ 200m

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

OUTLINE

1 - CMB polarization and constraints on B-modes

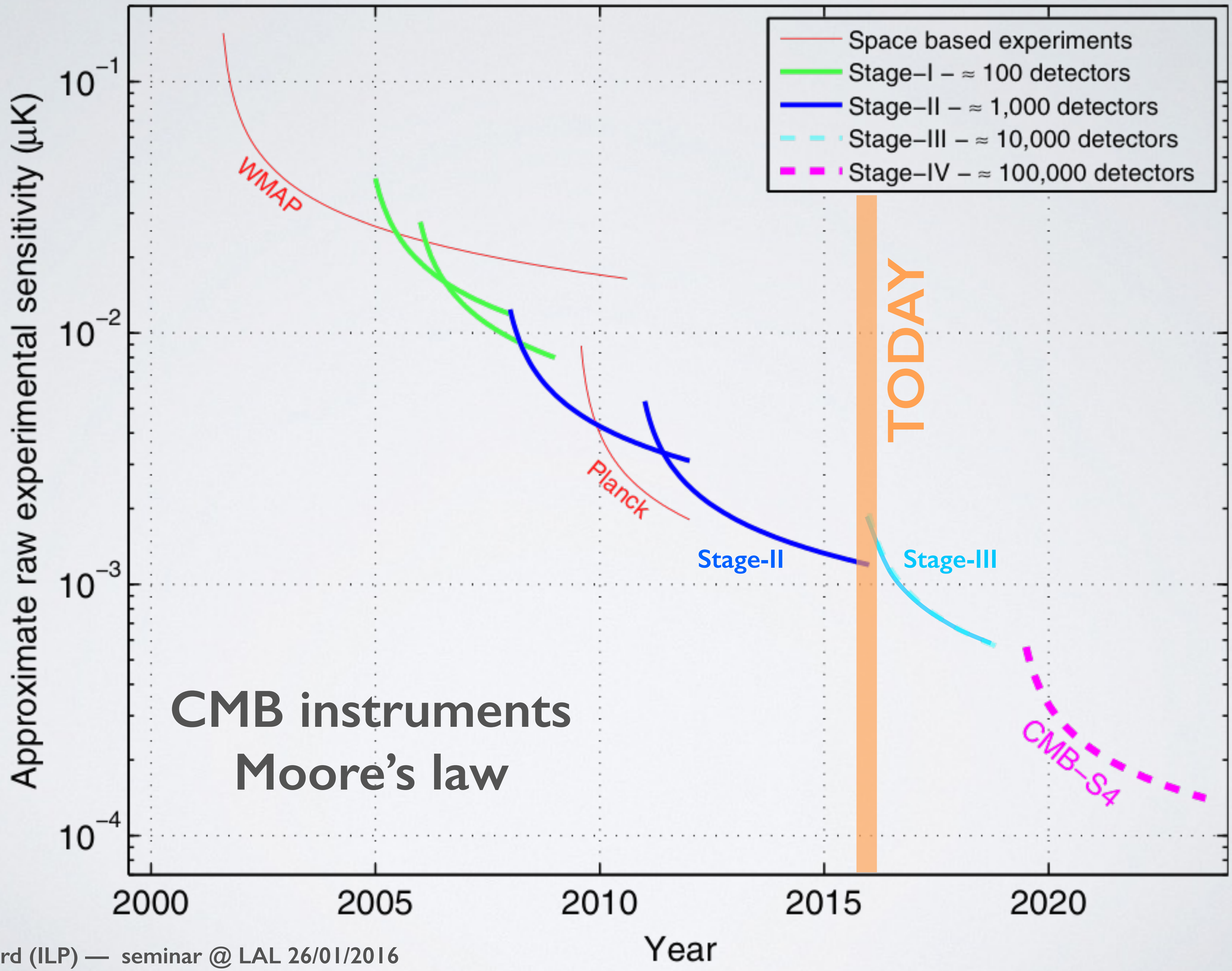
2 - POLARBEAR-1

3 - Designing new projects in the presence of foregrounds and gravitational lensing

4- POLARBEAR-II, Simons Array, Stage-IV and LiteBIRD

5 - Extension: combining CMB with LSST weak lensing!

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

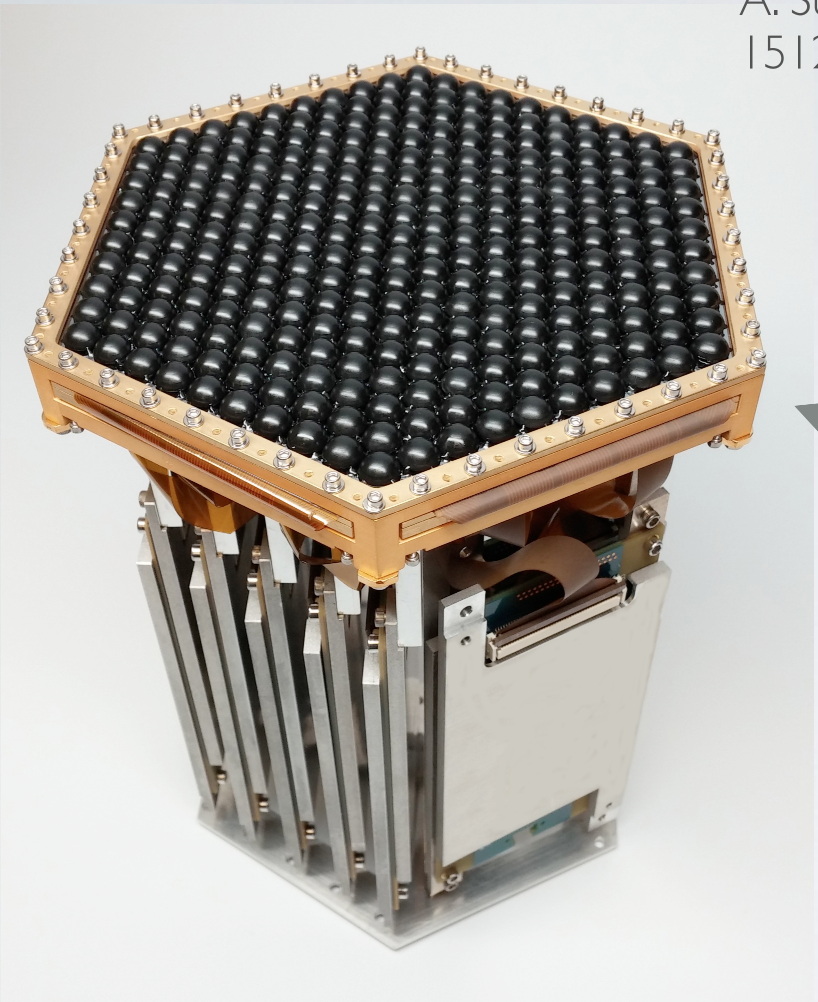


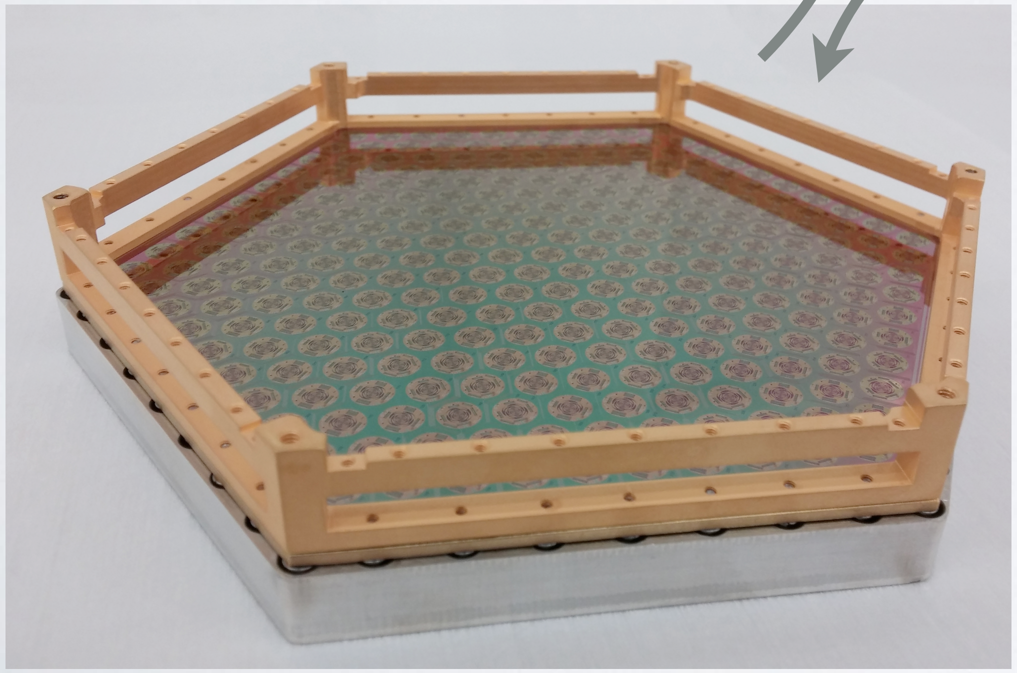
CMB instruments
Moore's law

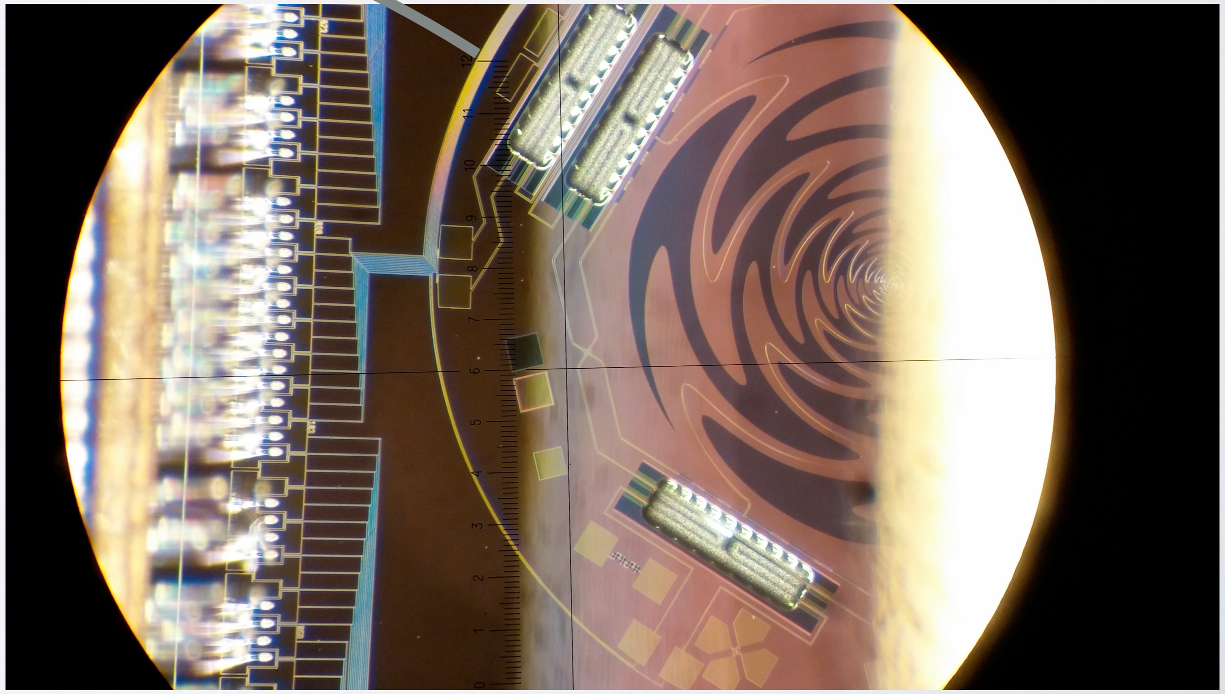
POLARBEAR-II

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

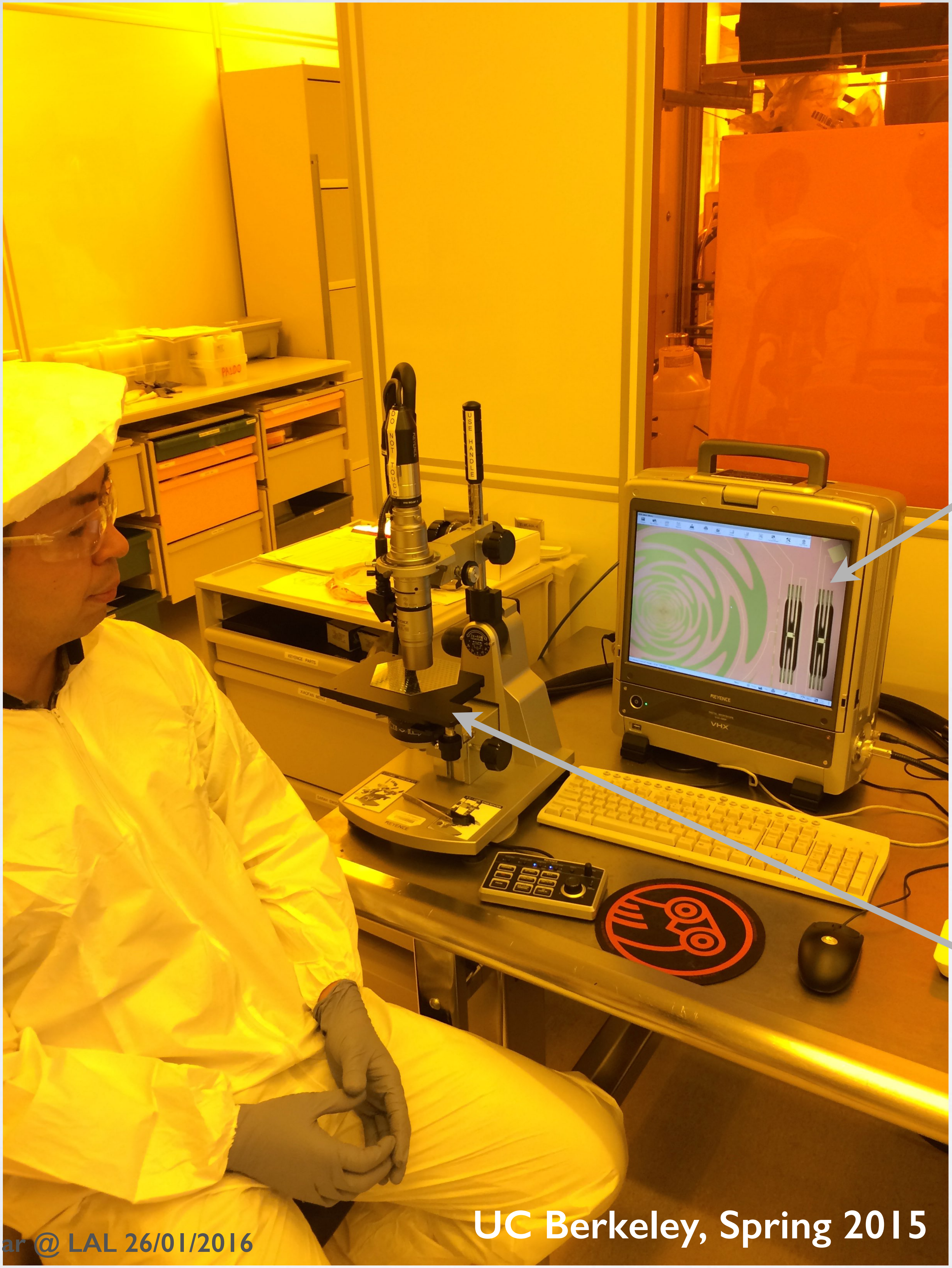
	specifications
frequencies	95 and 150 GHz
# of pixels	1897 (7588 bolometers)
NET bolometer	500 uK√s
NET array	5.7 uK√s
polarization sensitivity	10.7 uK.arcmin (20% sky coverage, 18% obs. eff.)
field of view	4.8 deg
beam sizes	5.2 arcmin @ 95 GHz 3.5 arcmin @ 150 GHz
observation time	3 years







Toki Suzuki (UCB)



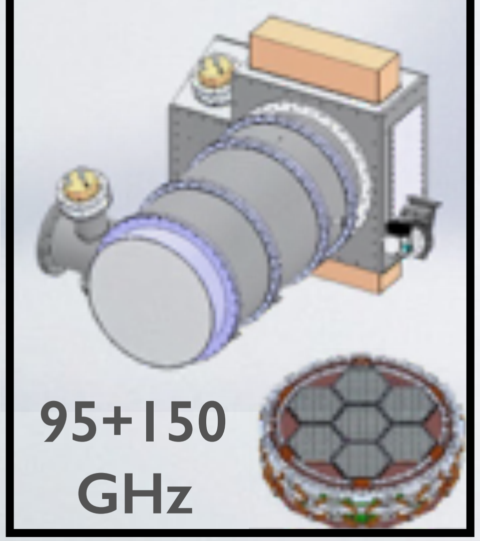
PB2 pixel

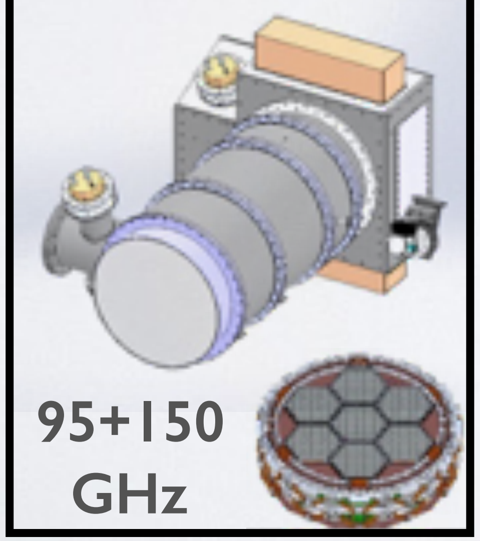
PB2 wafer

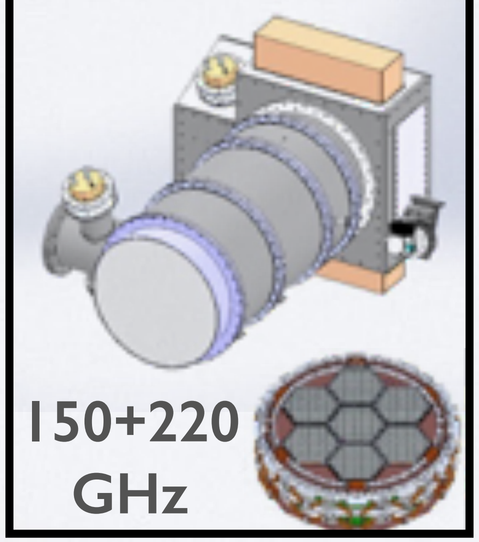
UC Berkeley, Spring 2015

SIMONS ARRAY = 3 X POLARBEAR-II

SIMONS FOUNDATION


95+150 GHz


95+150 GHz


150+220 GHz

> 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

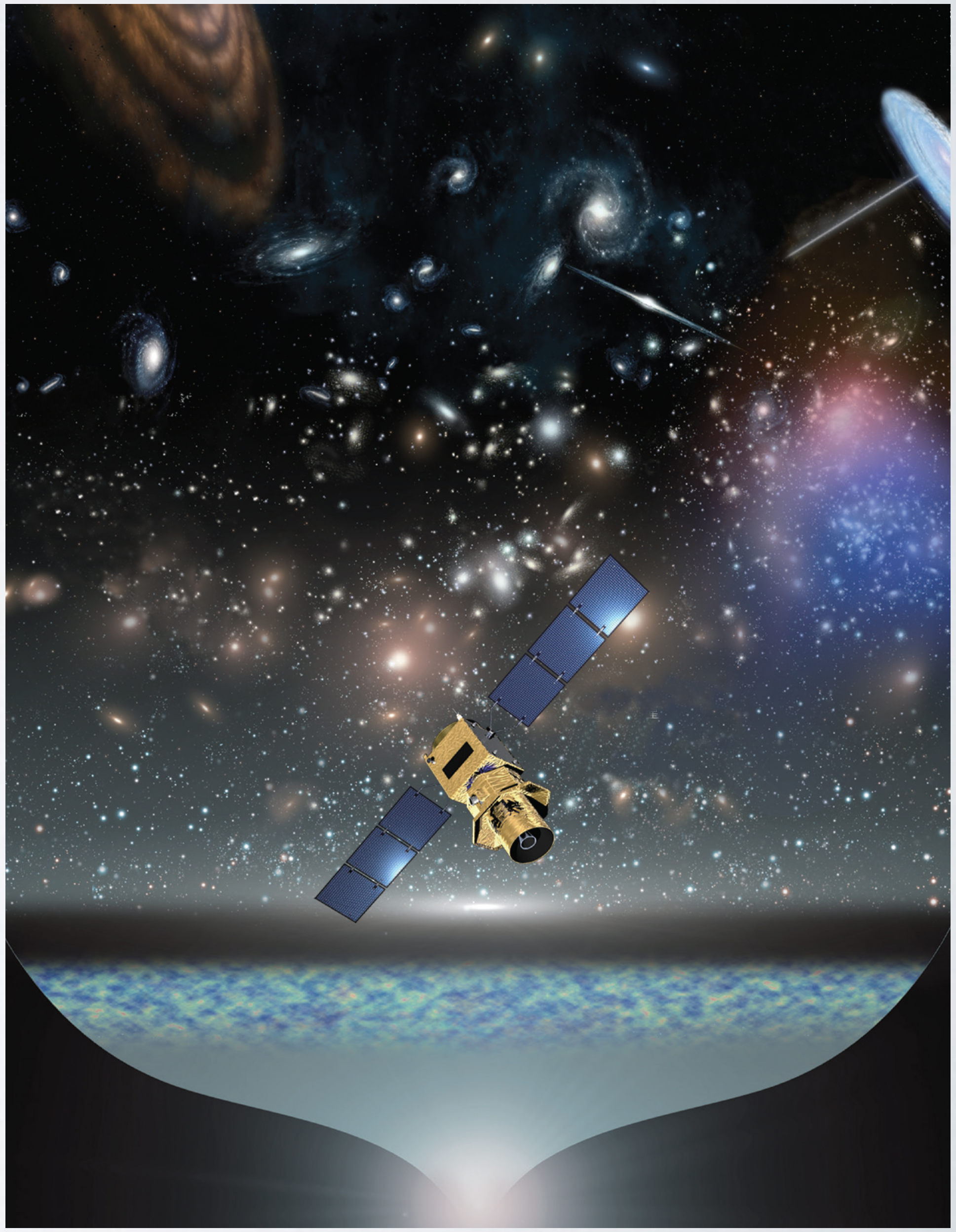
consortium of US ground-based efforts
(Simons Array + BICEP3 + AdvACTPol + SPT-3G)

LiteBIRD

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

coordinator of the component separation working group

participation to the development of forecasting tools for LiteBIRD



OUTLINE

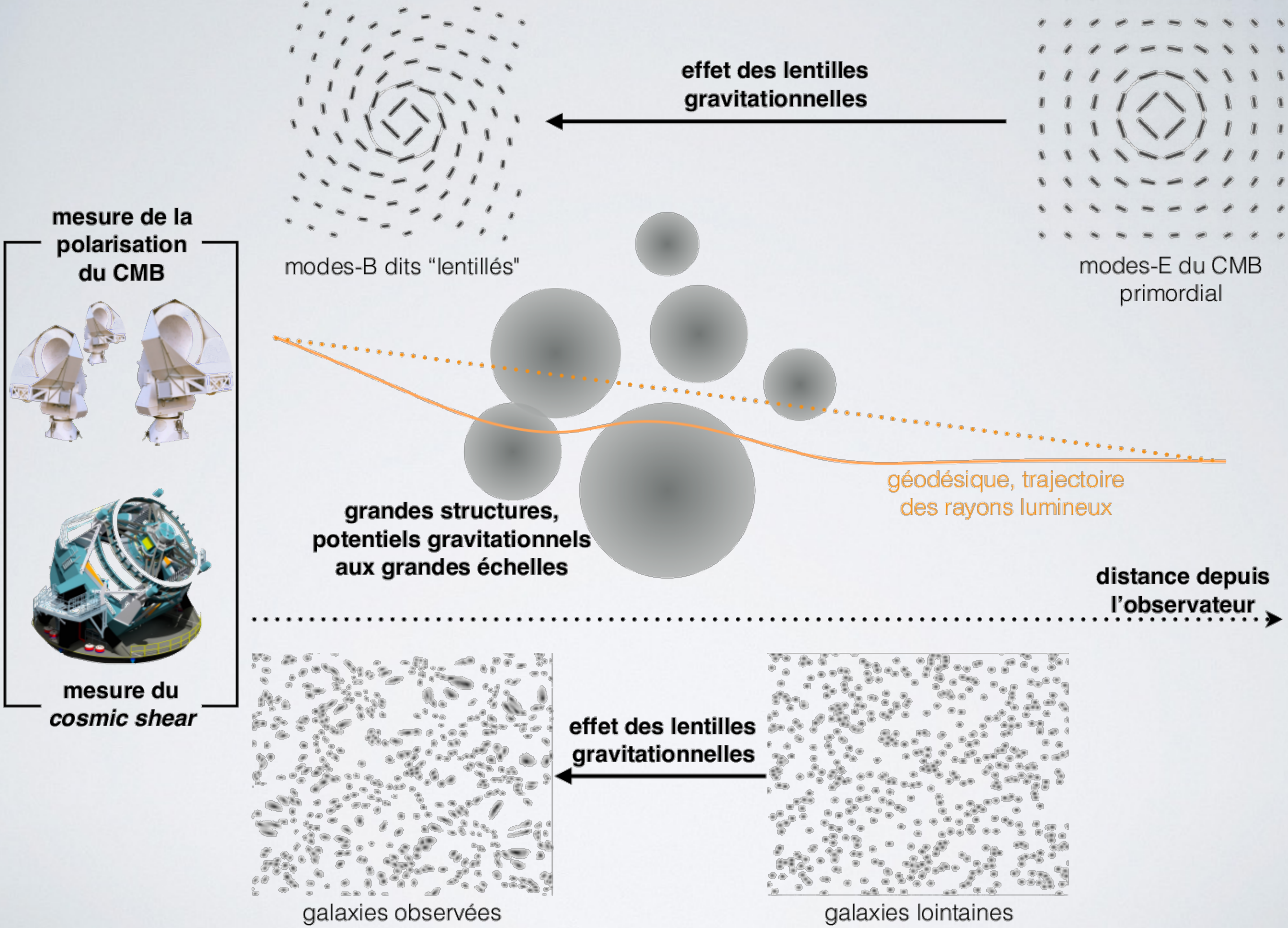
1 - CMB polarization and constraints on B-modes

2 - POLARBEAR-I

3 - Designing new projects in the presence of foregrounds and gravitational lensing

4- POLARBEAR-II, Simons Array, Stage-IV and LiteBIRD

5 - Extension: combining CMB with LSST weak lensing!



effet des lentilles gravitationnelles

modes-B dits “lentillés”

modes-E du CMB primordial

mesure de la polarisation du CMB

géodésique, trajectoire des rayons lumineux

grandes structures, potentiels gravitationnels aux grandes échelles

distance depuis l’observateur

mesure du *cosmic shear*

effet des lentilles gravitationnelles

galaxies observées

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

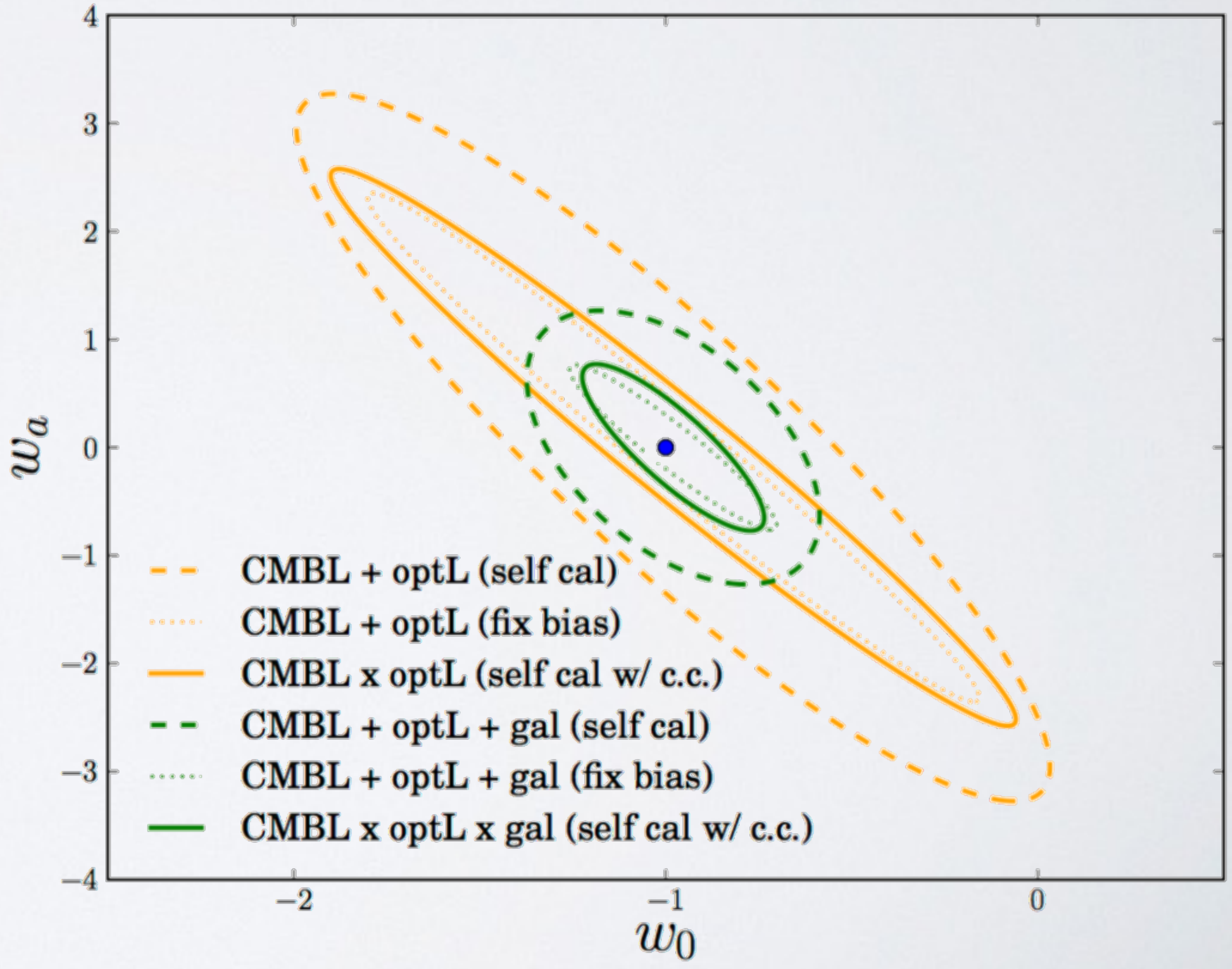
lensing kernel for CMB and Cosmic Shear (CS)

power spectrum of matter density perturbations

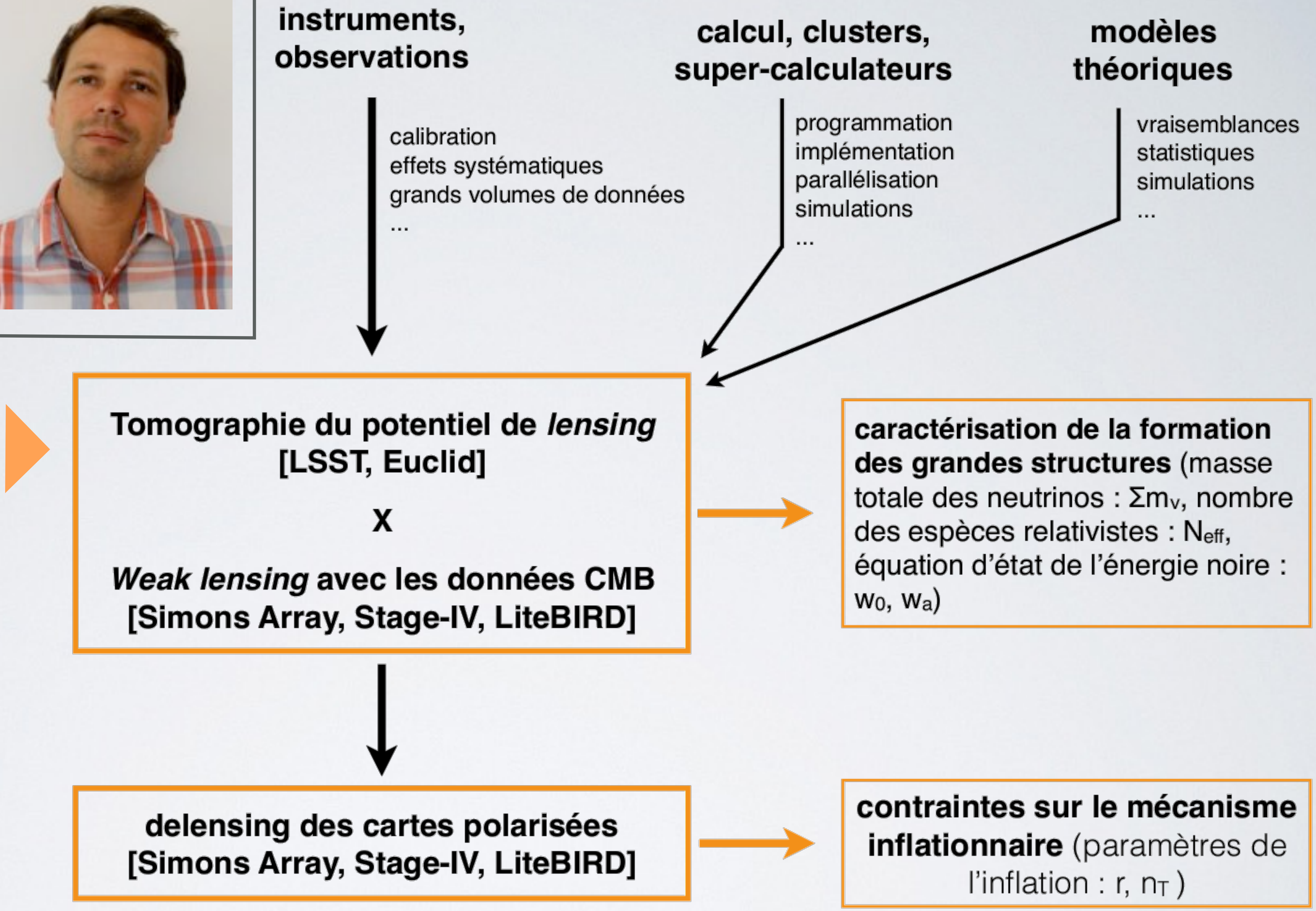
Can CMB lensing help cosmic shear surveys?
Das, S., Errard, J. and Spergel, D. (2013)
arXiv: 1311.2338

+ Valinotto (2012,2013)

$$w = w(a) = w_0 + (1-a)w_a$$



working with the weak lensing team @ LPNHE (Pierre Astier and Augustin Guyonnet)



instruments, observations

calibration
effets systématiques
grands volumes de données
...

calcul, clusters, super-calculateurs

programmation
implémentation
parallélisation
simulations
...

modèles théoriques

vraisemblances
statistiques
simulations
...

Tomographie du potentiel de *lensing* [LSST, Euclid]

x

***Weak lensing* avec les données CMB [Simons Array, Stage-IV, LiteBIRD]**

caractérisation de la formation des grandes structures (masse totale des neutrinos : Σm_ν, nombre des espèces relativistes : N_{eff}, équation d'état de l'énergie noire : w_0, w_a)

delensing des cartes polarisées [Simons Array, Stage-IV, LiteBIRD]

contraintes sur le mécanisme inflationnaire (paramètres de l'inflation : r, n_T)

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