Measuring the Cosmic Microwave Background polarization with POLARBEAR

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Institut Lagrange Paris (ILP)
LPNHE

Seminar @ LPC,
08/01/2016

OUTLINE

1 - CMB introduction

- ➤ Early physics
- ➤ Weak lensing

2- Observation of the CMB with POLARBEAR

- ➤ Project overview
- ➤ POLARBEAR analysis and first results
- ➤ Discussion about astrophysical and instrumental systematics effects

3 - Current and future plans for CMB observations

- ➤ POLARBEAR-II, Simons Array, Stage-IV and LiteBIRD
- ➤ Association with LSST weak lensing measurements

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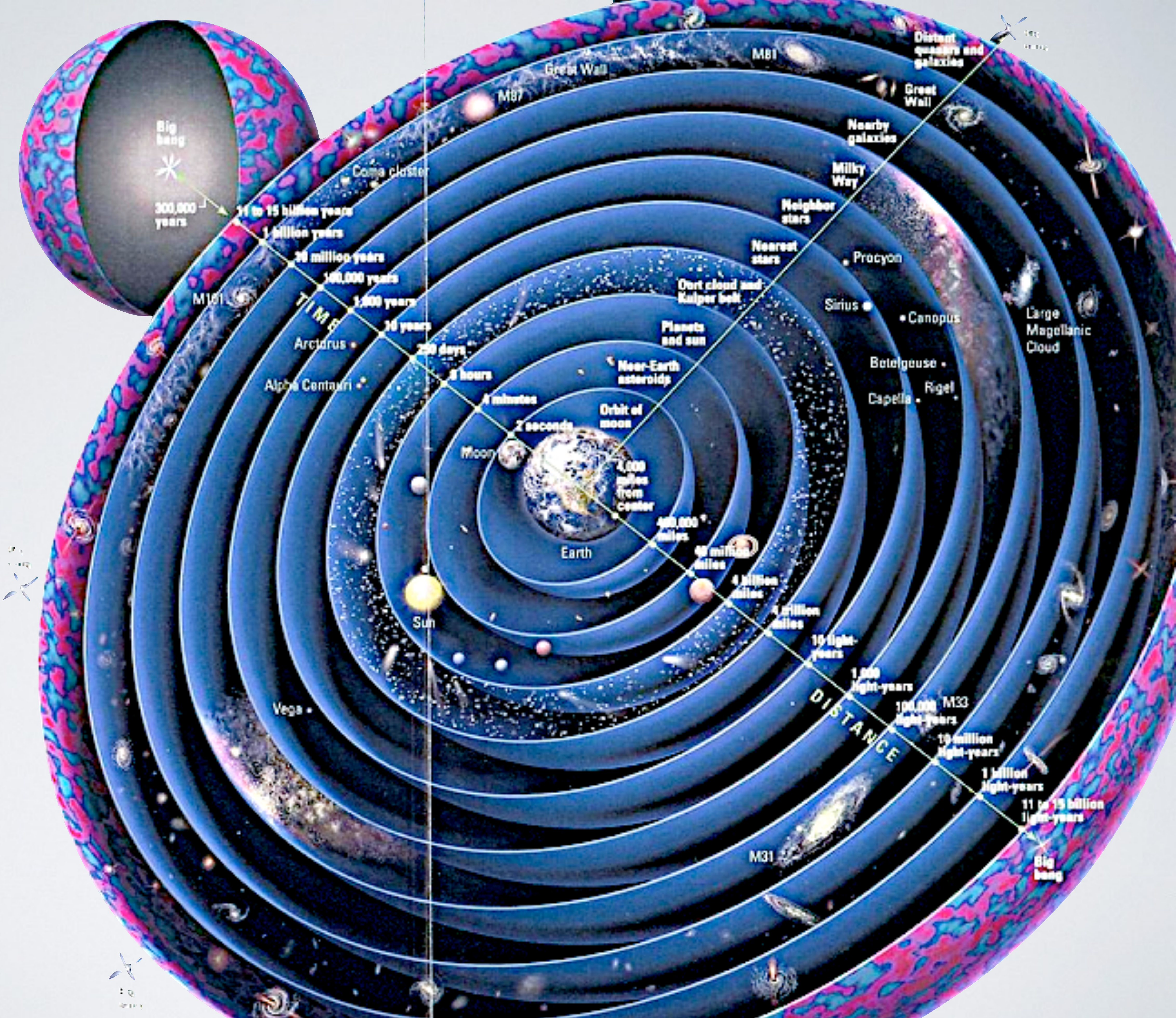
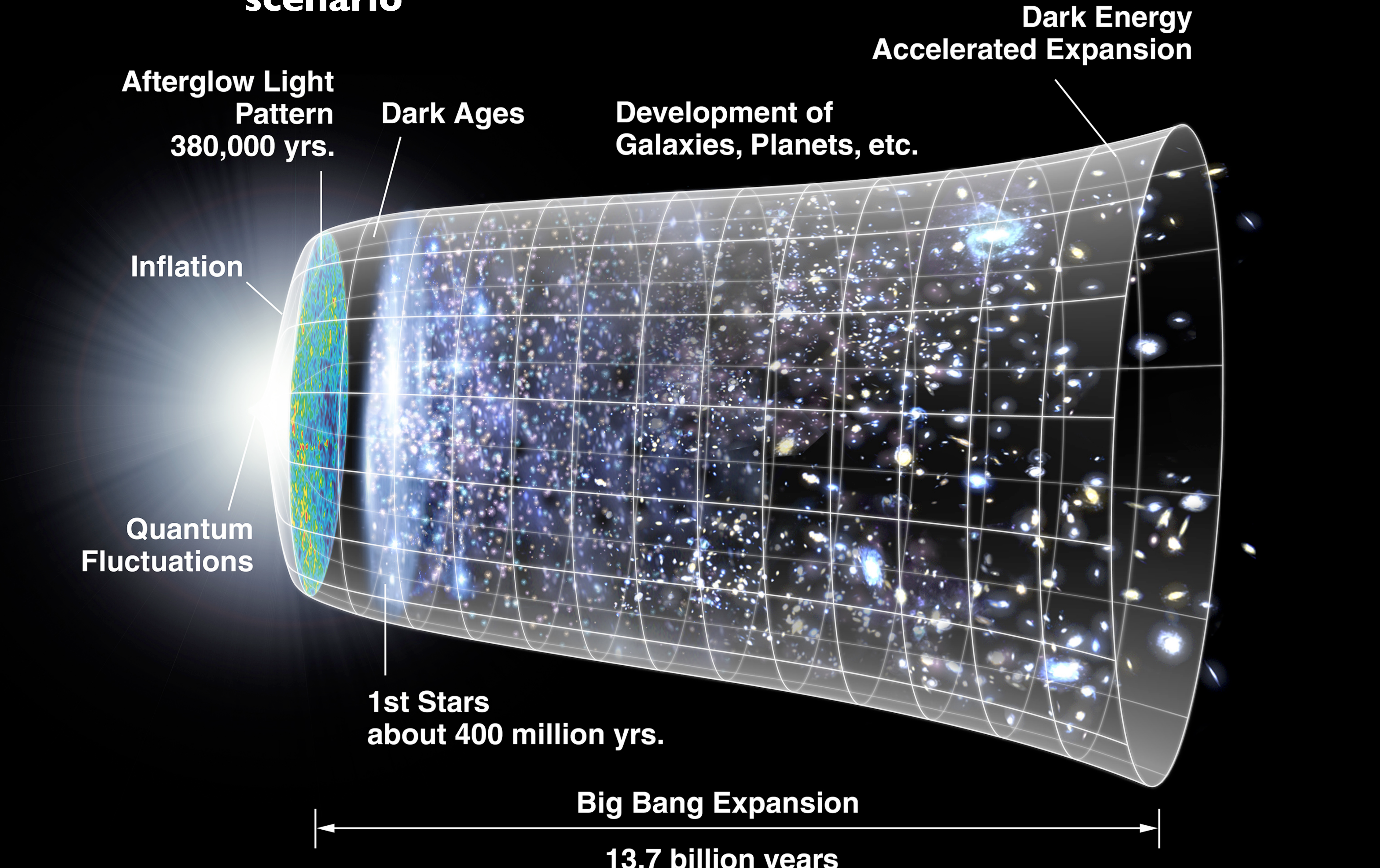
WHAT'S CMB?



from http://universe-review.ca

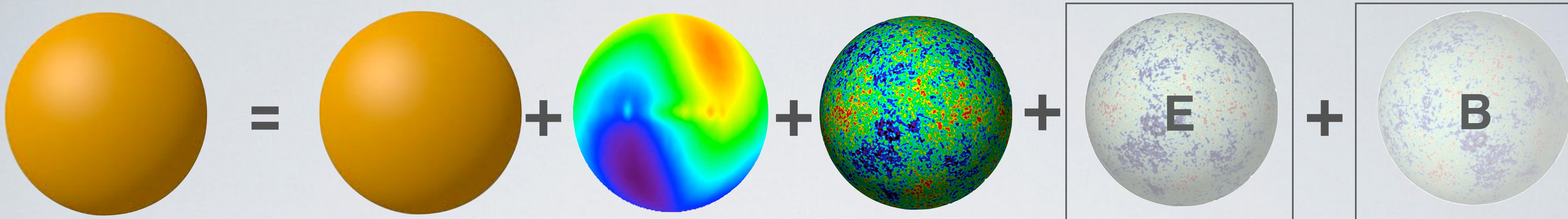
Reminder of the Big Bang scenario



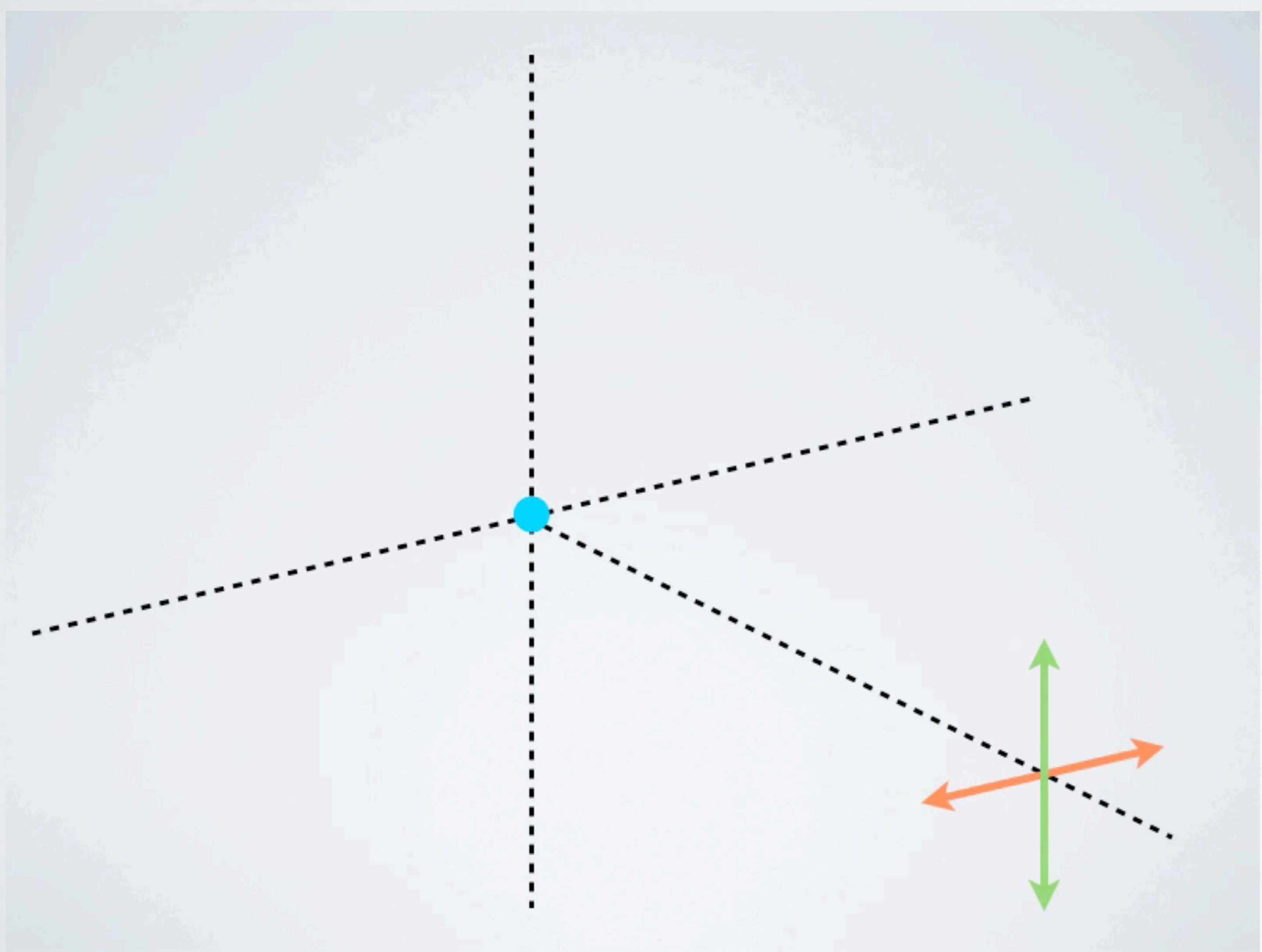
credits: WMAP

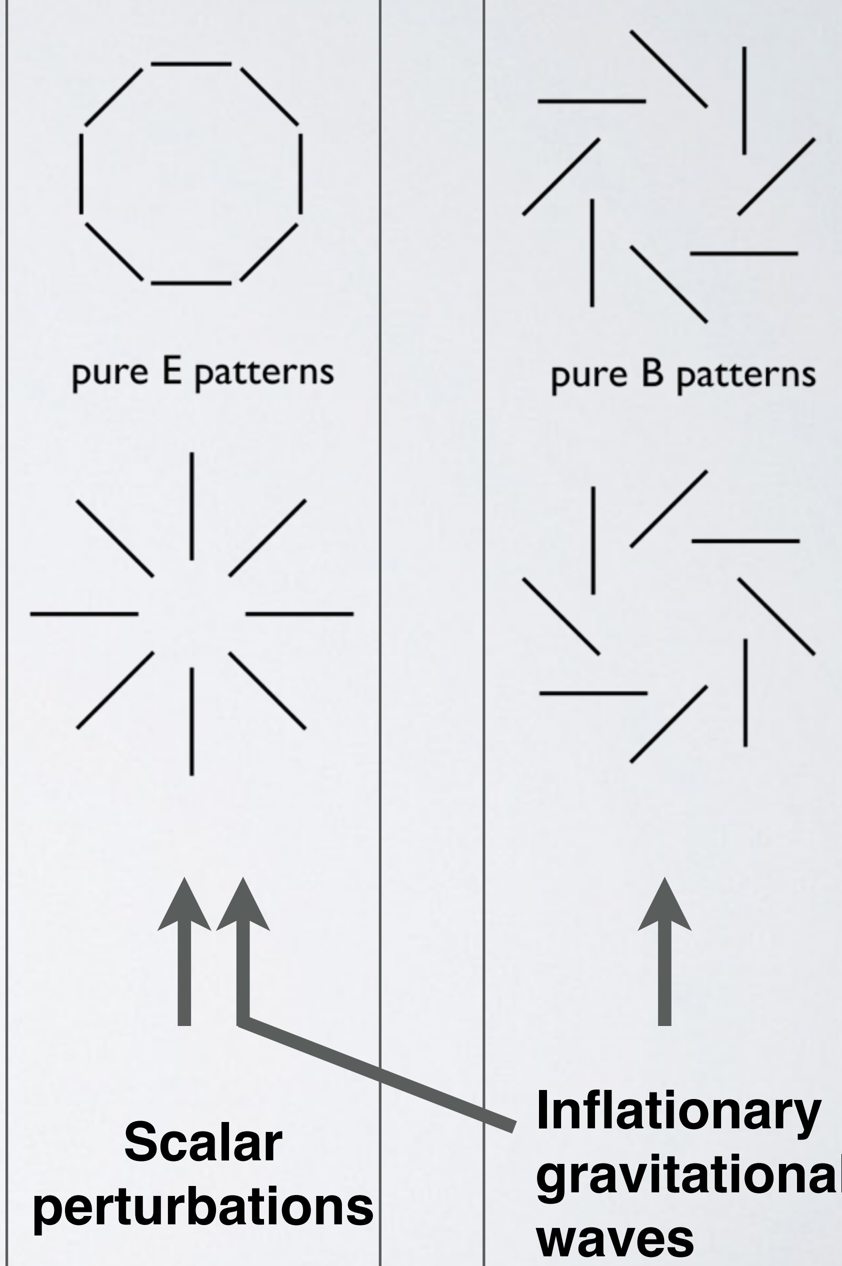
time	energy
10^{-43} sec	10^{19} GeV
10^{-35} sec	10^{15} GeV
10^{-11} sec	10^{3} GeV
10^{-6} sec	1 GeV
1 sec	1 MeV
380,000 yrs	1 eV
14 billion yrs	1 meV (3K)

Planck epoch
Quantum Gravity?



Thomson scattering





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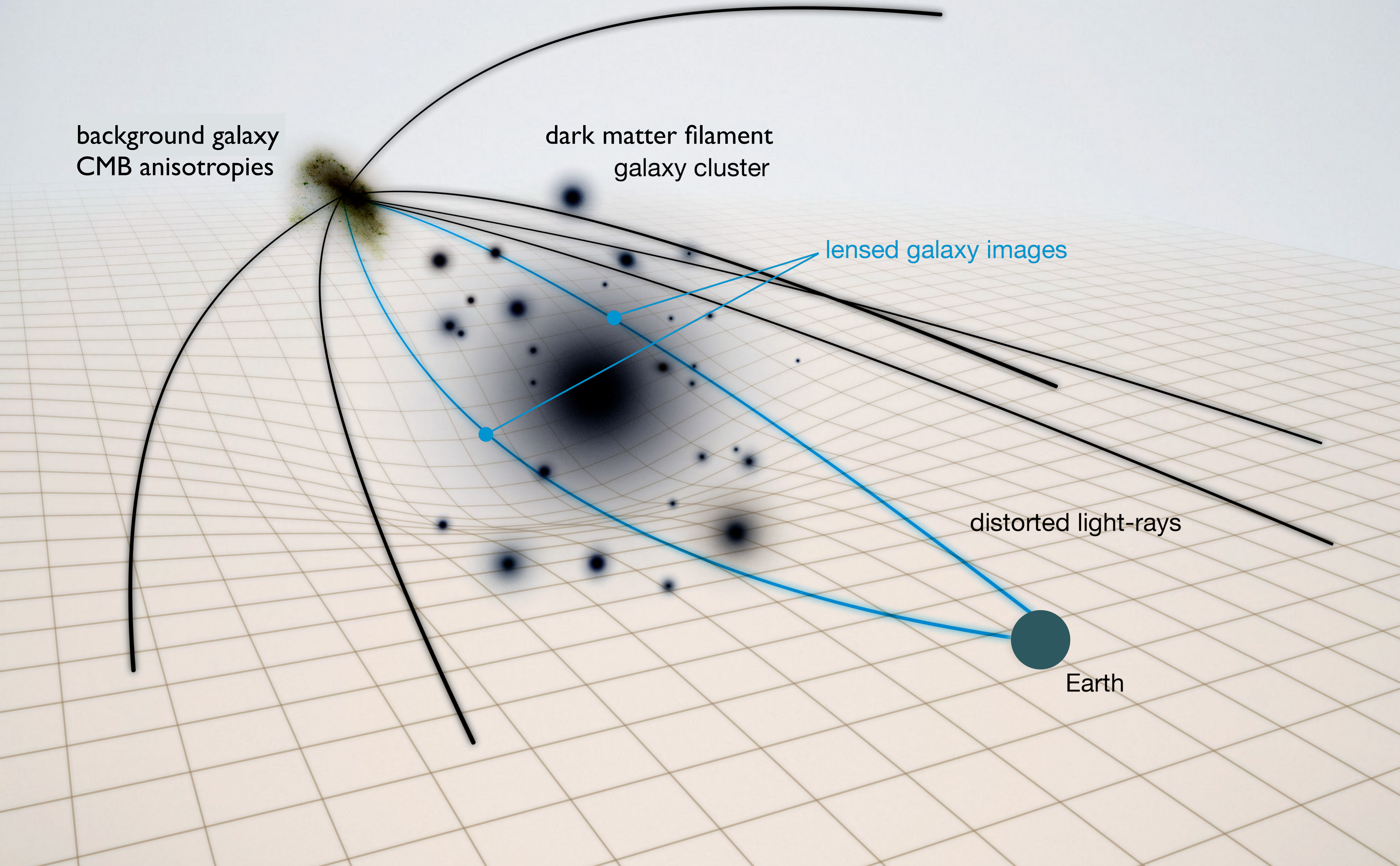
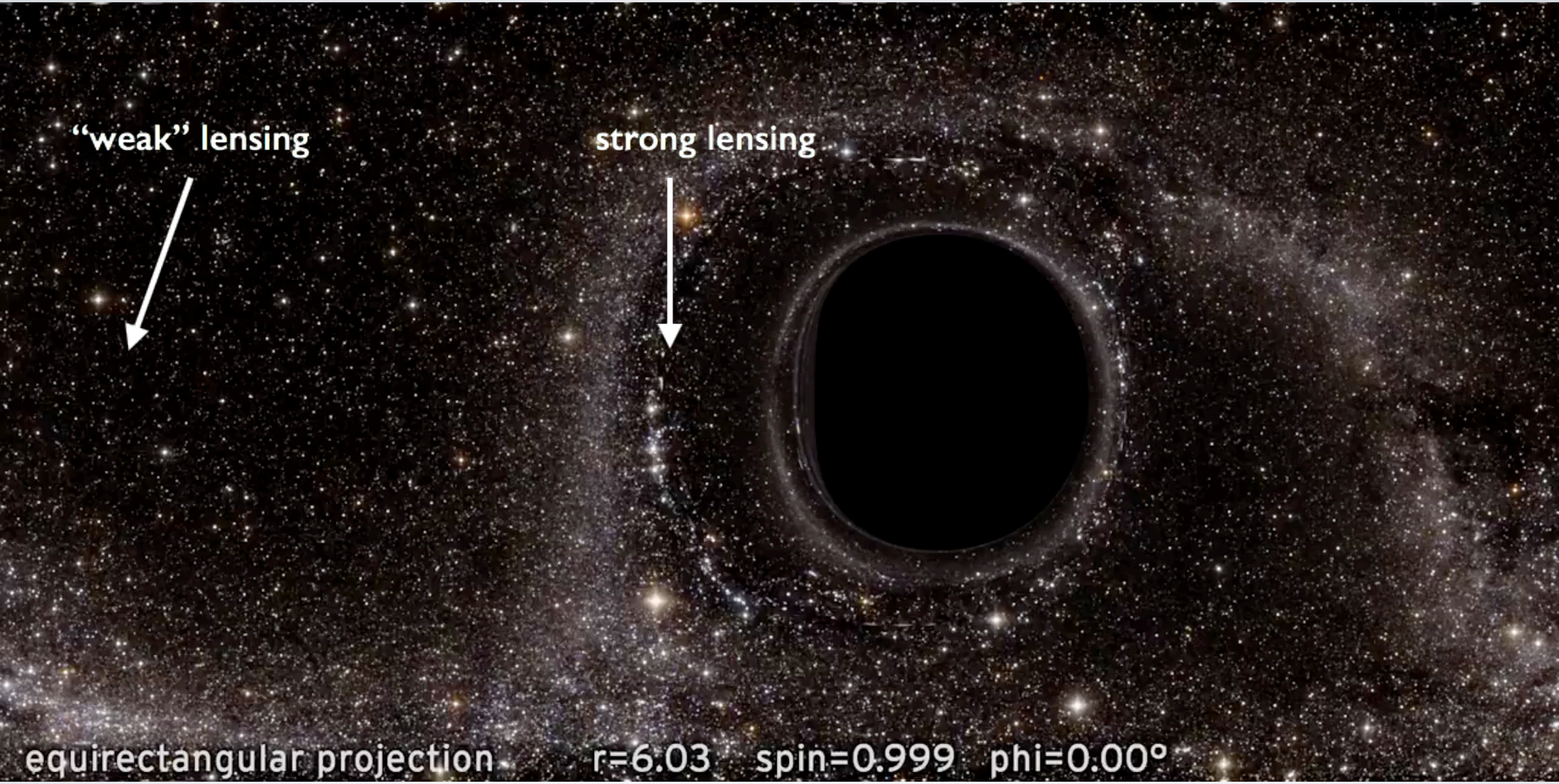
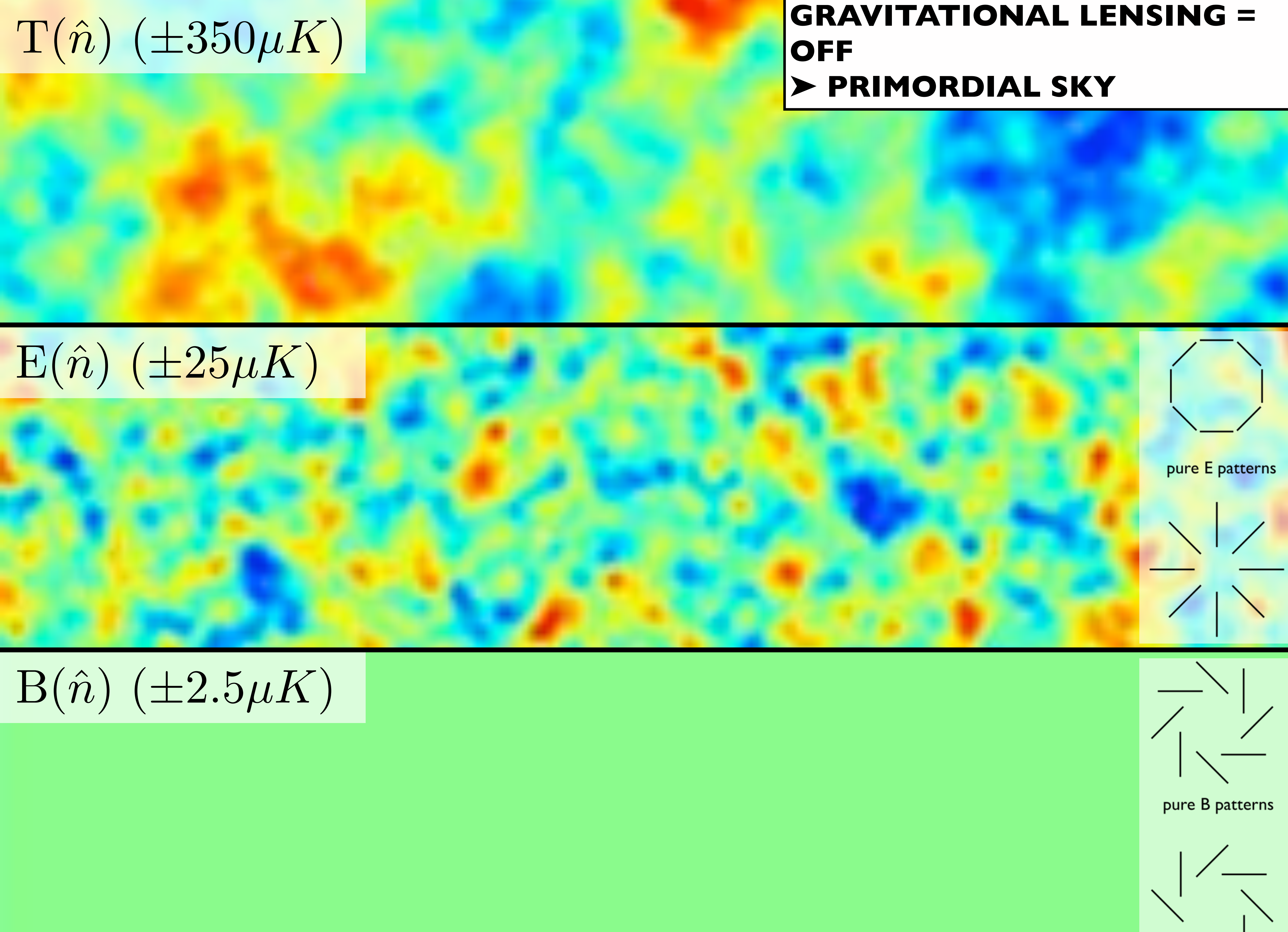
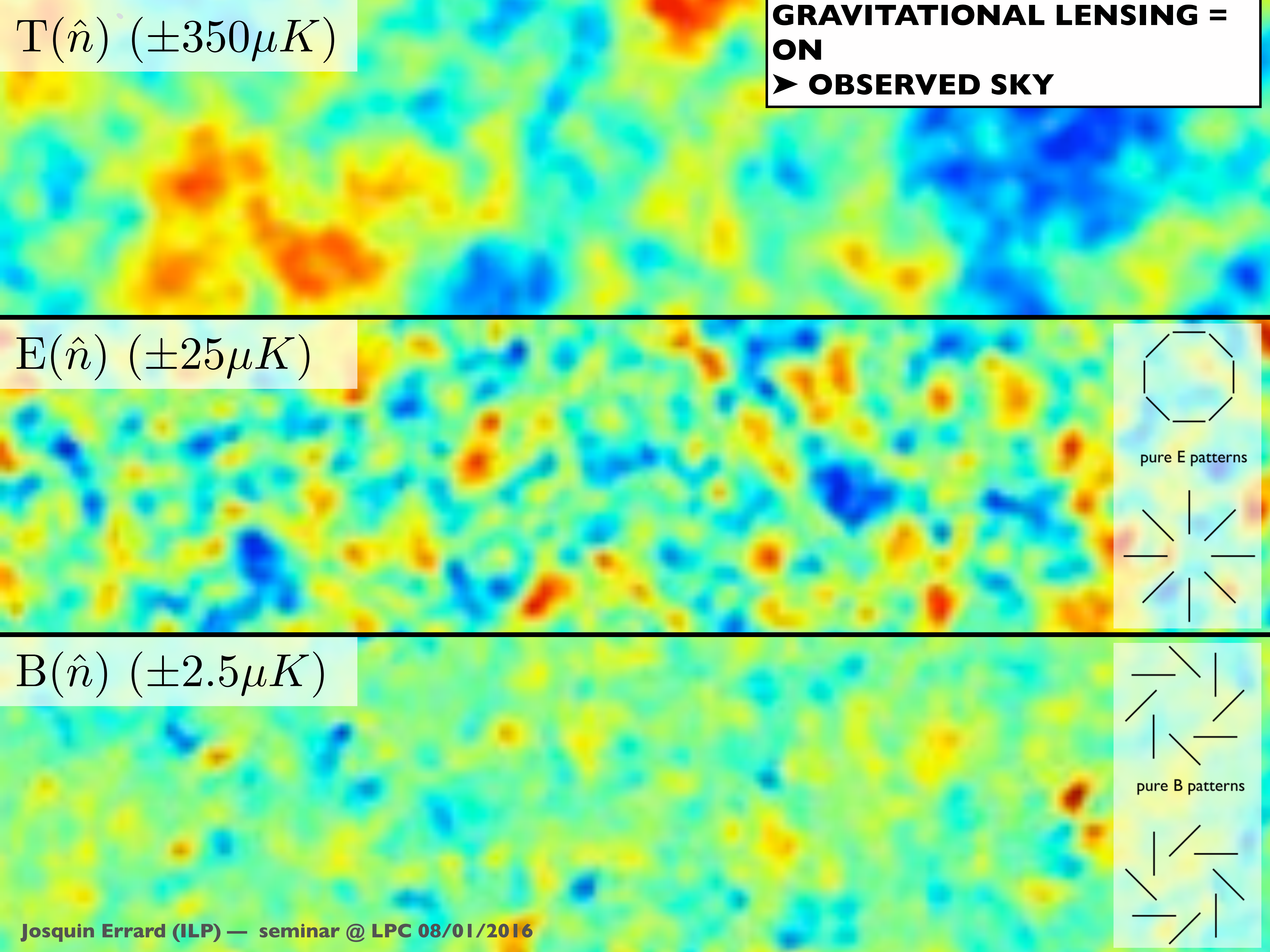


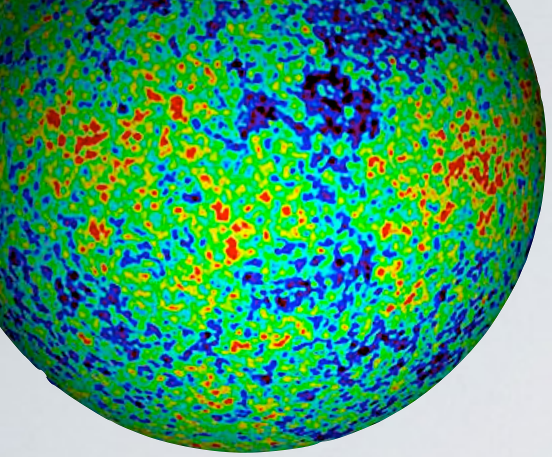
http://www.spacetelescope.org

Gravitational lensing by spinning black holes in astrophysics, and in the movie Interstellar
James et al. (2015)

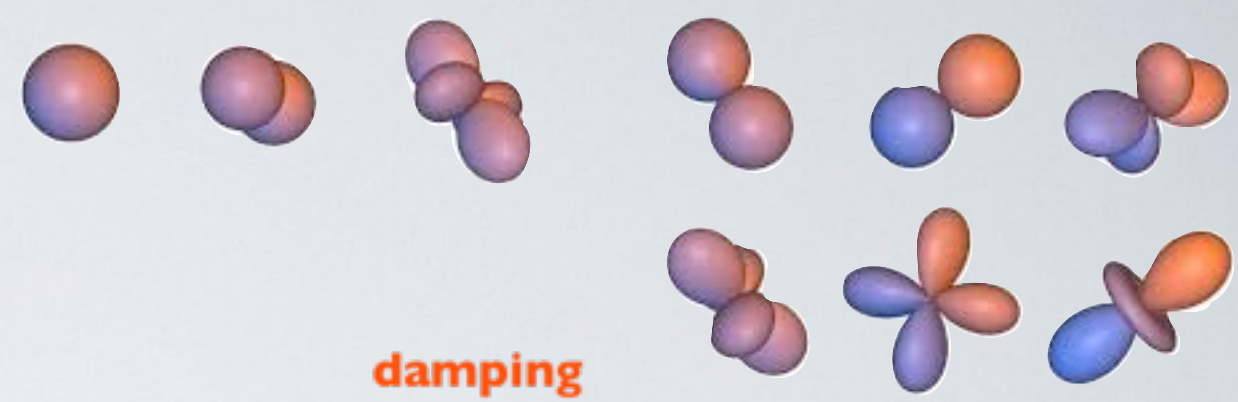


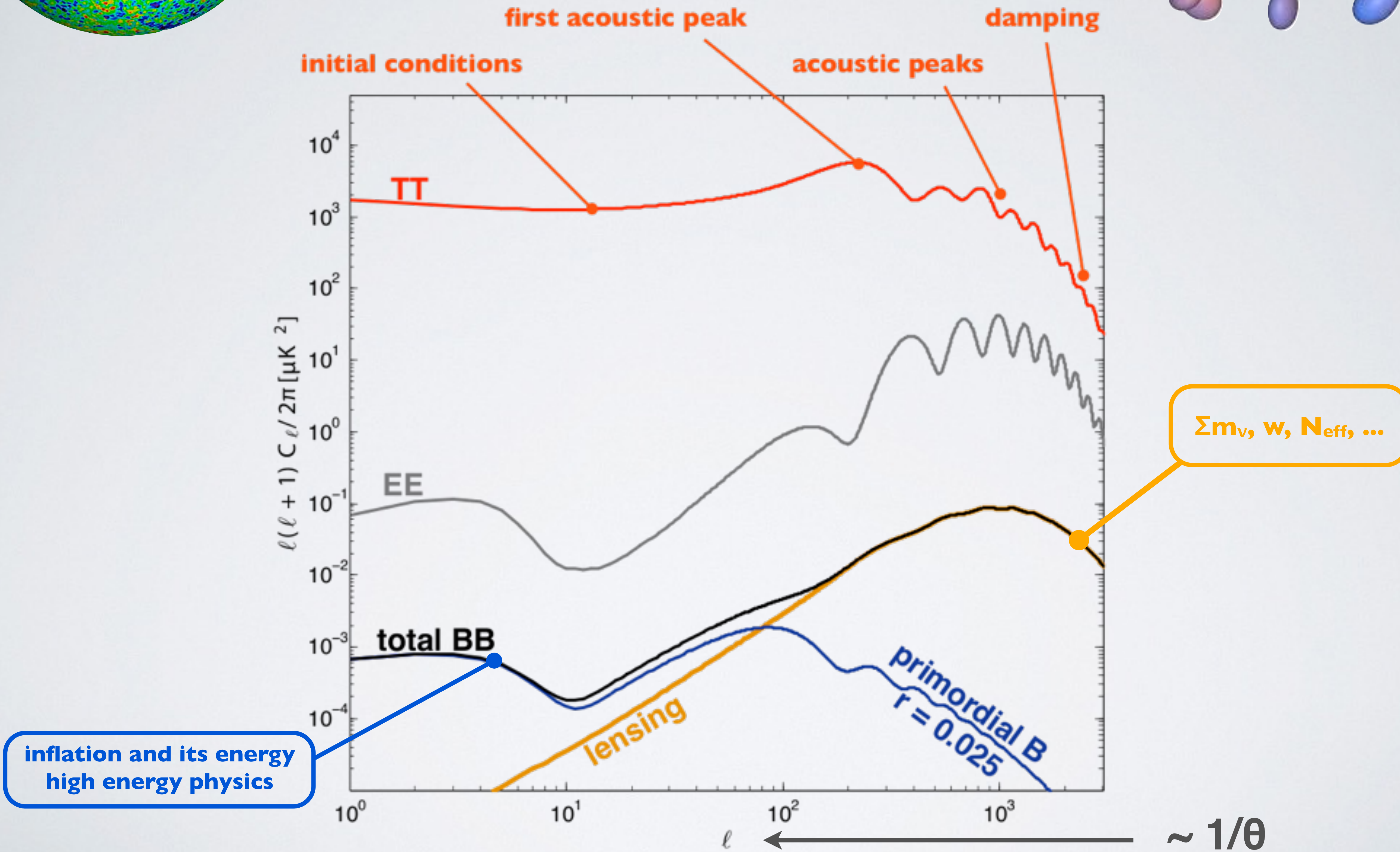

GRAVITATIONAL LENSING = OFF
➤ PRIMORDIAL SKY
$T(\hat{n})$ $(\pm 350\mu K)$
$E(\hat{n})$ $(\pm 25\mu K)$
pure E patterns
$B(\hat{n})$ $(\pm 2.5\mu K)$
pure B patterns


GRAVITATIONAL LENSING = ON
➤ OBSERVED SKY
$\mathrm{T}(\hat{n})\ (\pm 350\mu K)$
$\mathrm{E}(\hat{n})\ (\pm 25\mu K)$
pure E patterns
$\mathrm{B}(\hat{n})\ (\pm 2.5\mu K)$
pure B patterns

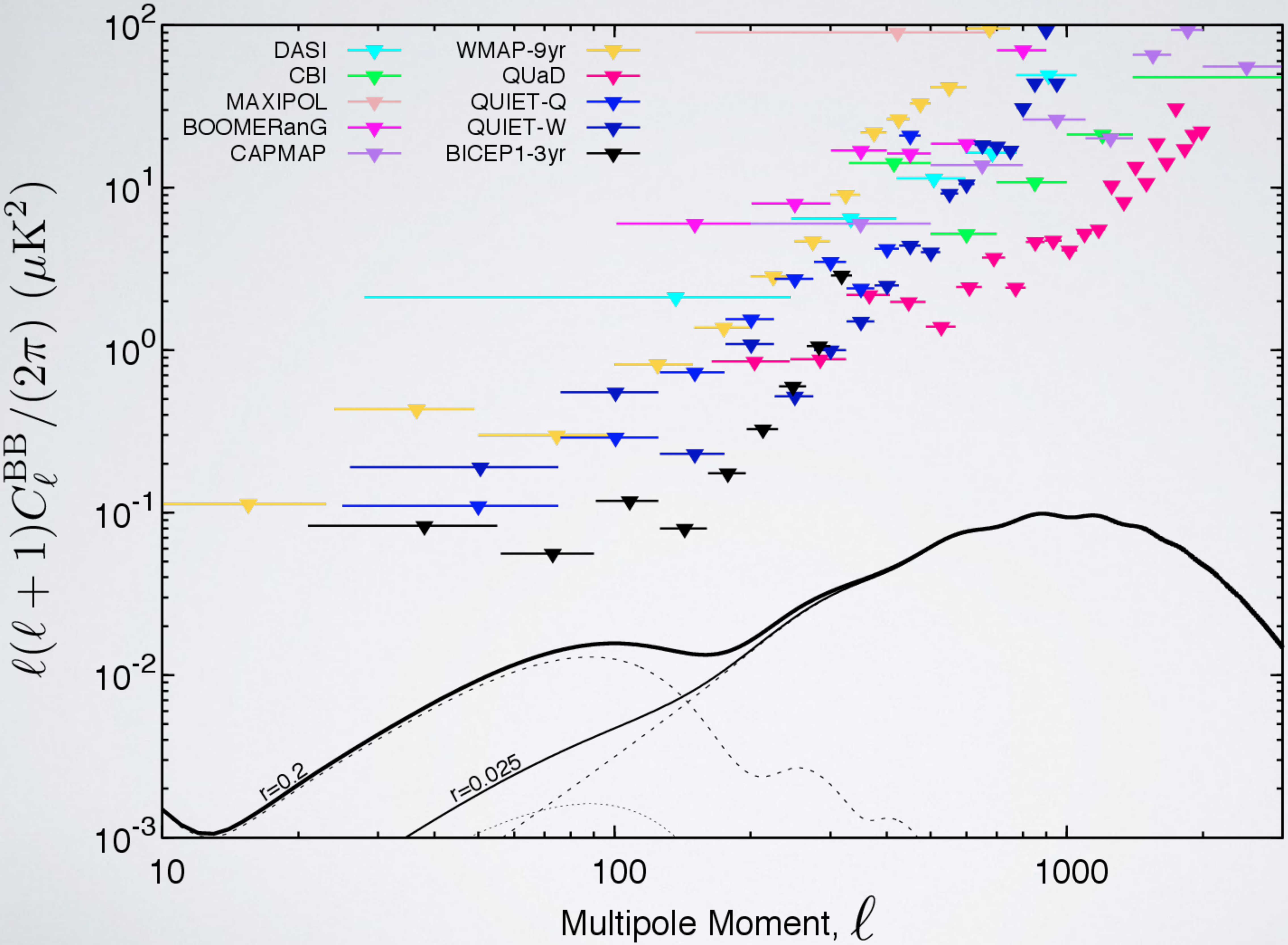


$$= \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a^T_{\ell m} Y_\ell^m(\theta, \phi)$$

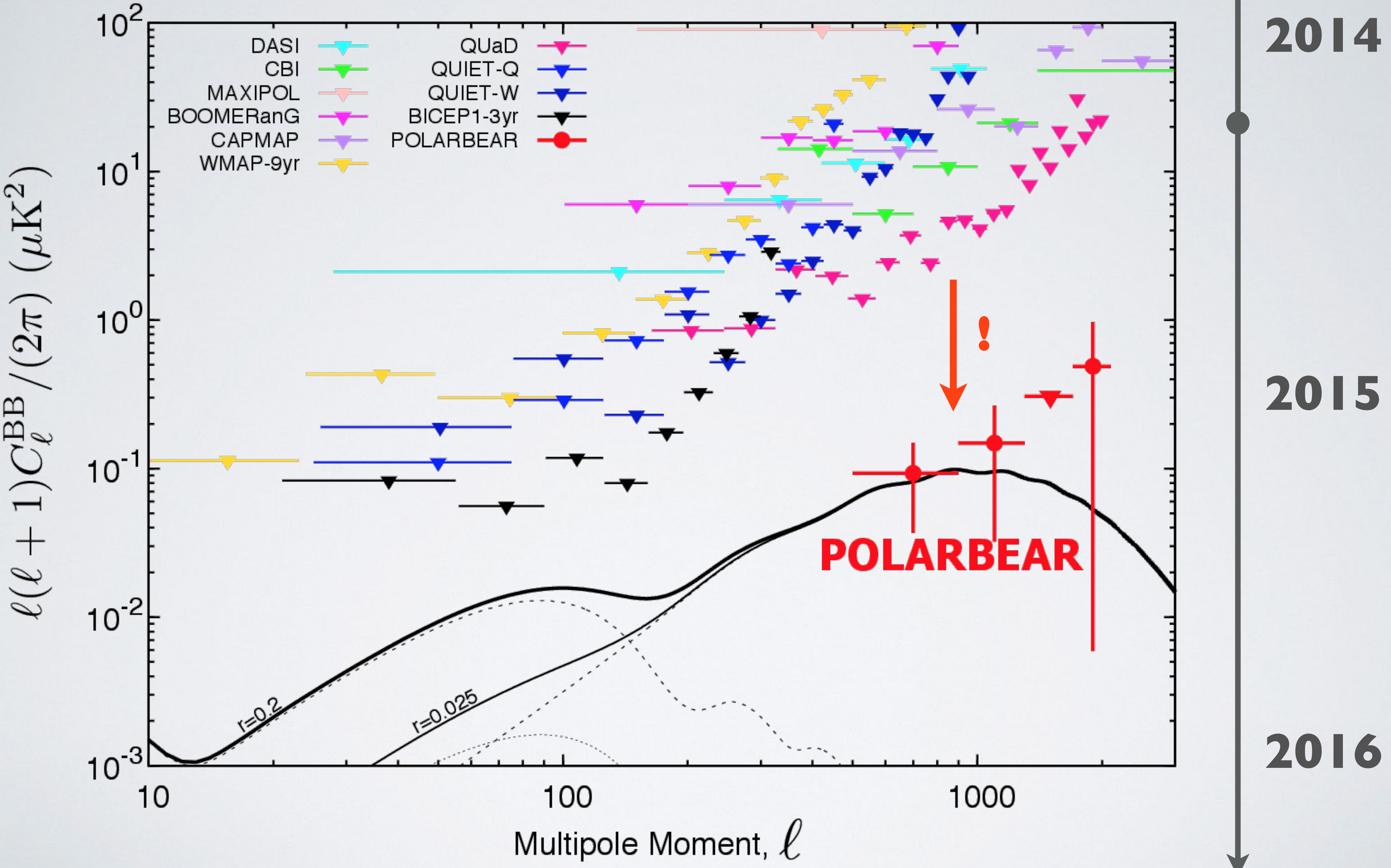




direct measurements of B-modes 2 years ago

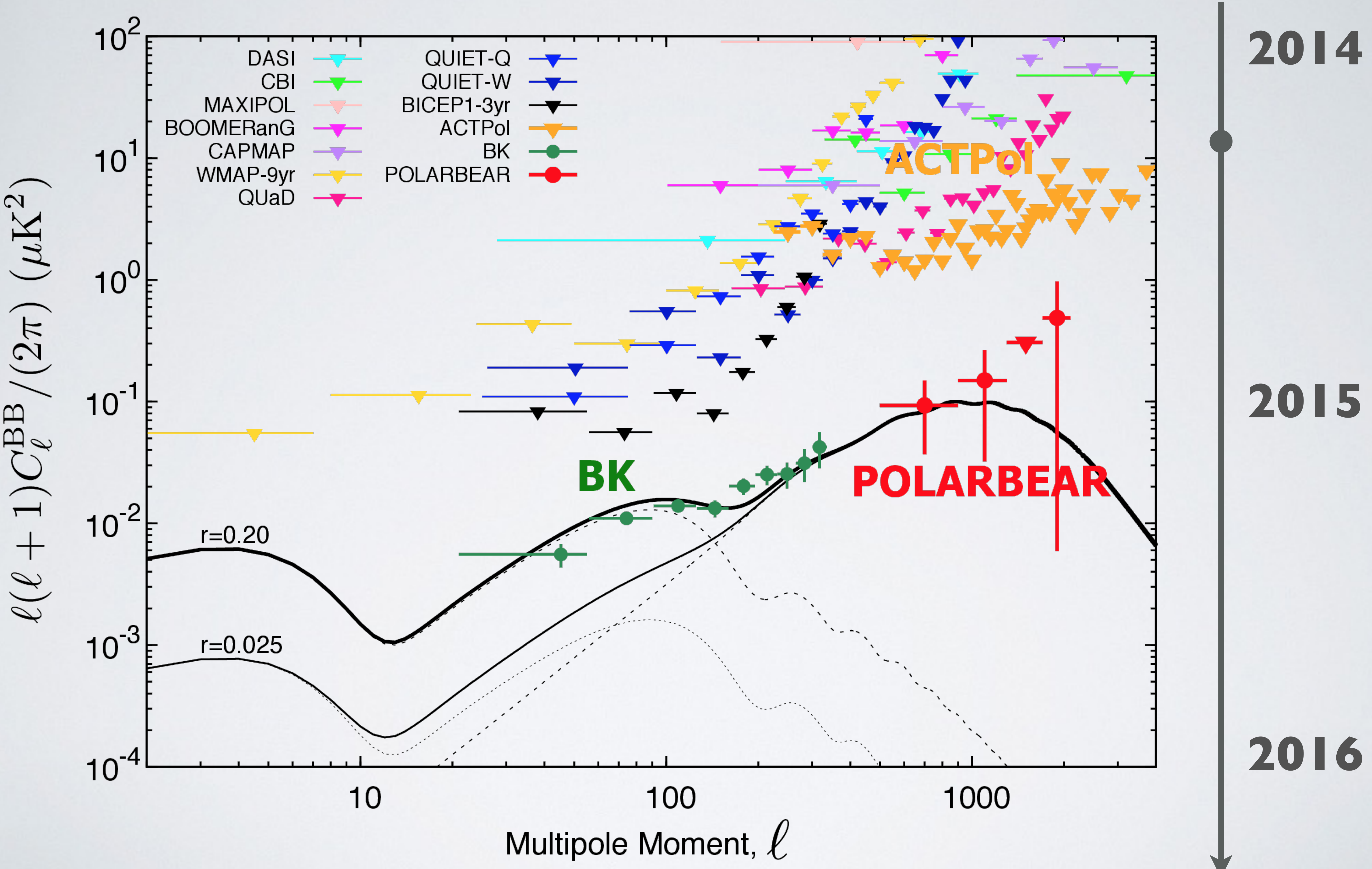


A Measurement of the Cosmic Microwave Background B-Mode Polarization Power Spectrum at Sub-degree Scales with POLARBEAR
The POLARBEAR Collaboration
The Astrophysical Journal, Volume 794, 171 (**2014**)

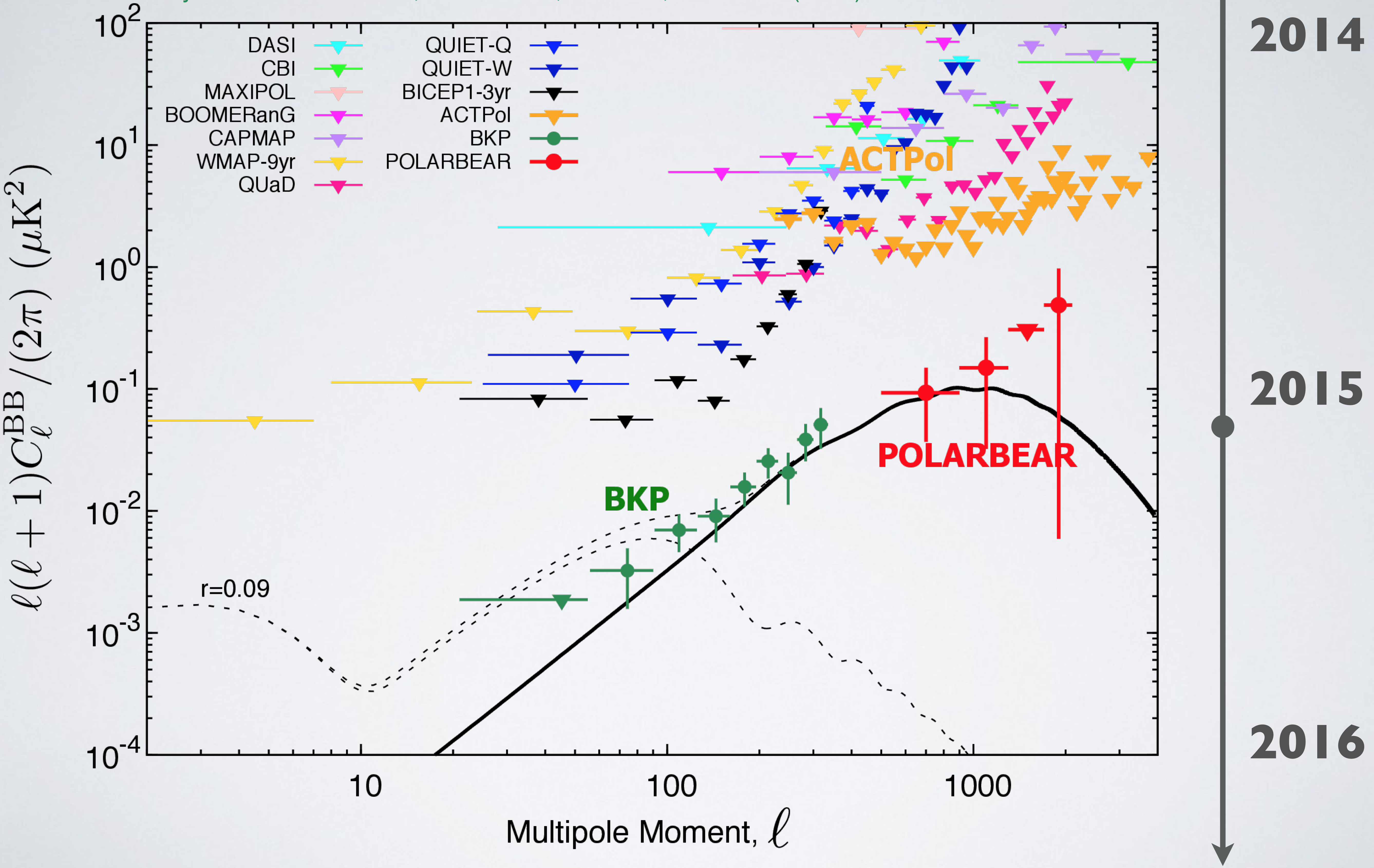


BK-V: Measurements of B-mode Polarization at Degree Angular Scales and 150 GHz by Keck Array

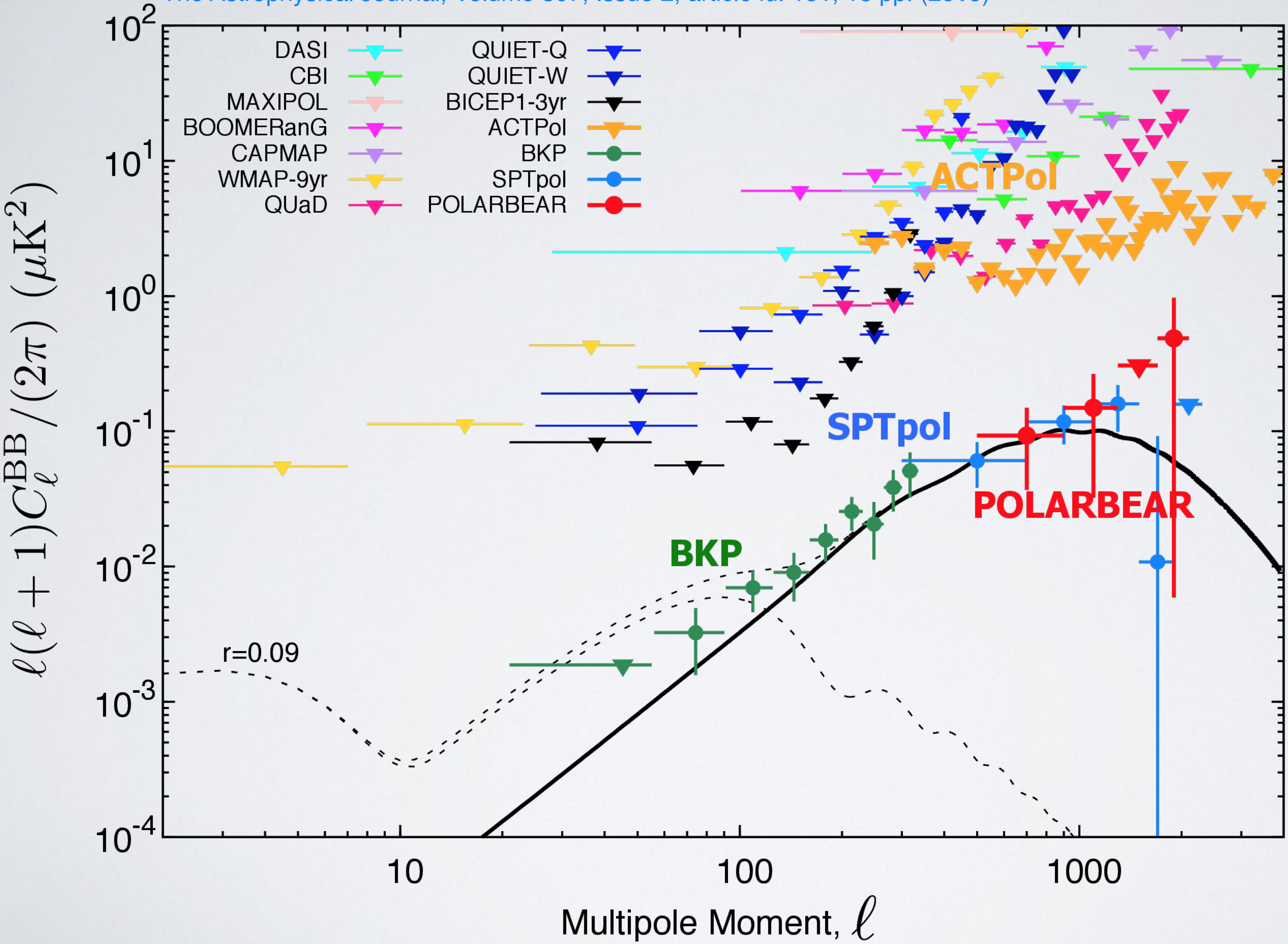
The Keck Array and BICEP2 Collaborations, ApJ 811, 126, 2015



Joint Analysis of BICEP 2 / Keck Array and Planck Data
P. Ade et al.
Physical Review Letters, Volume 114, Issue 10, id.101301 (**2015**)

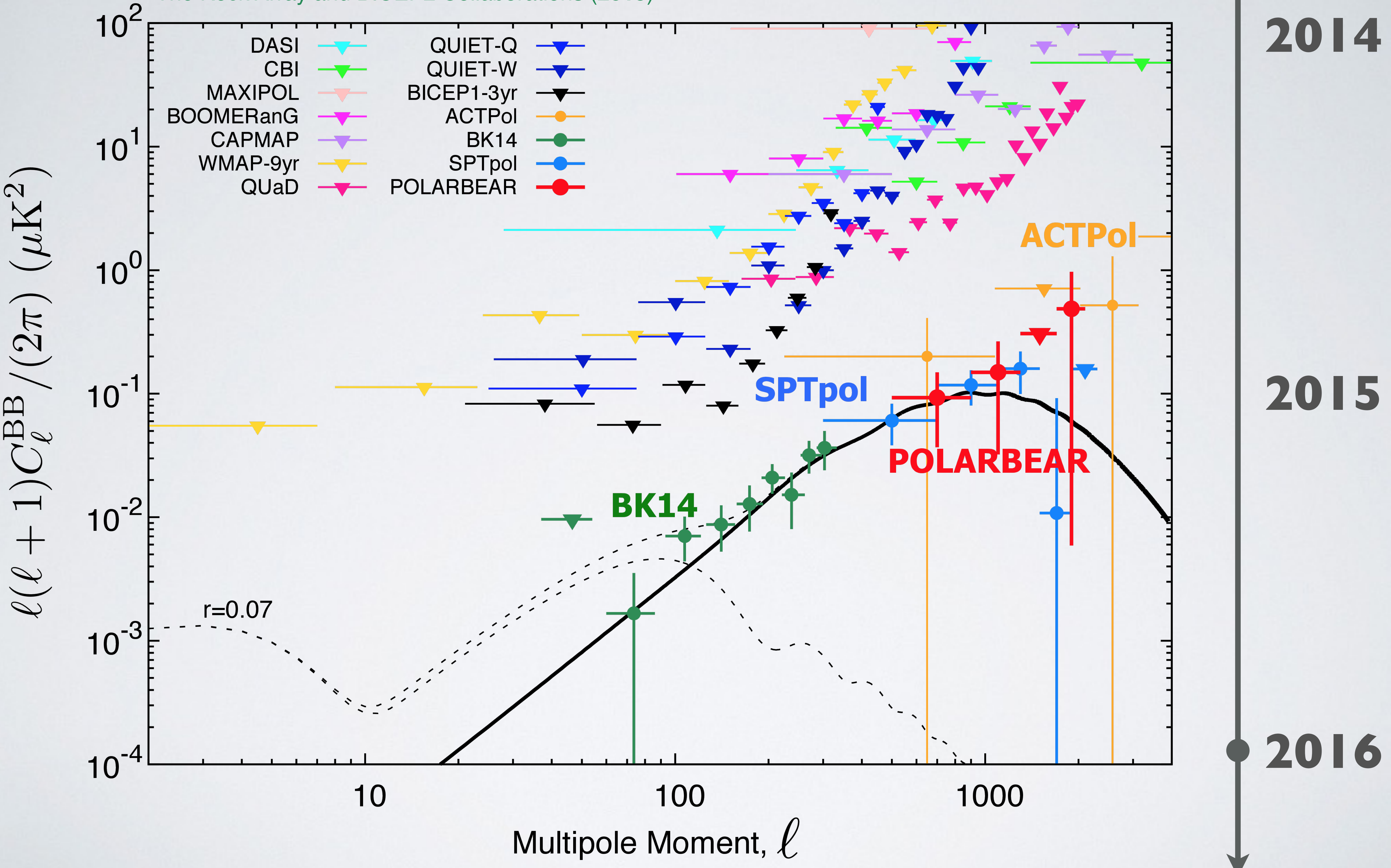


Measurements of Sub-degree B-mode Polarization in the Cosmic Microwave Background from 100 Square Degrees of SPTpol Data
R. Keisler et al.
The Astrophysical Journal, Volume 807, Issue 2, article id. 151, 18 pp. (**2015**)



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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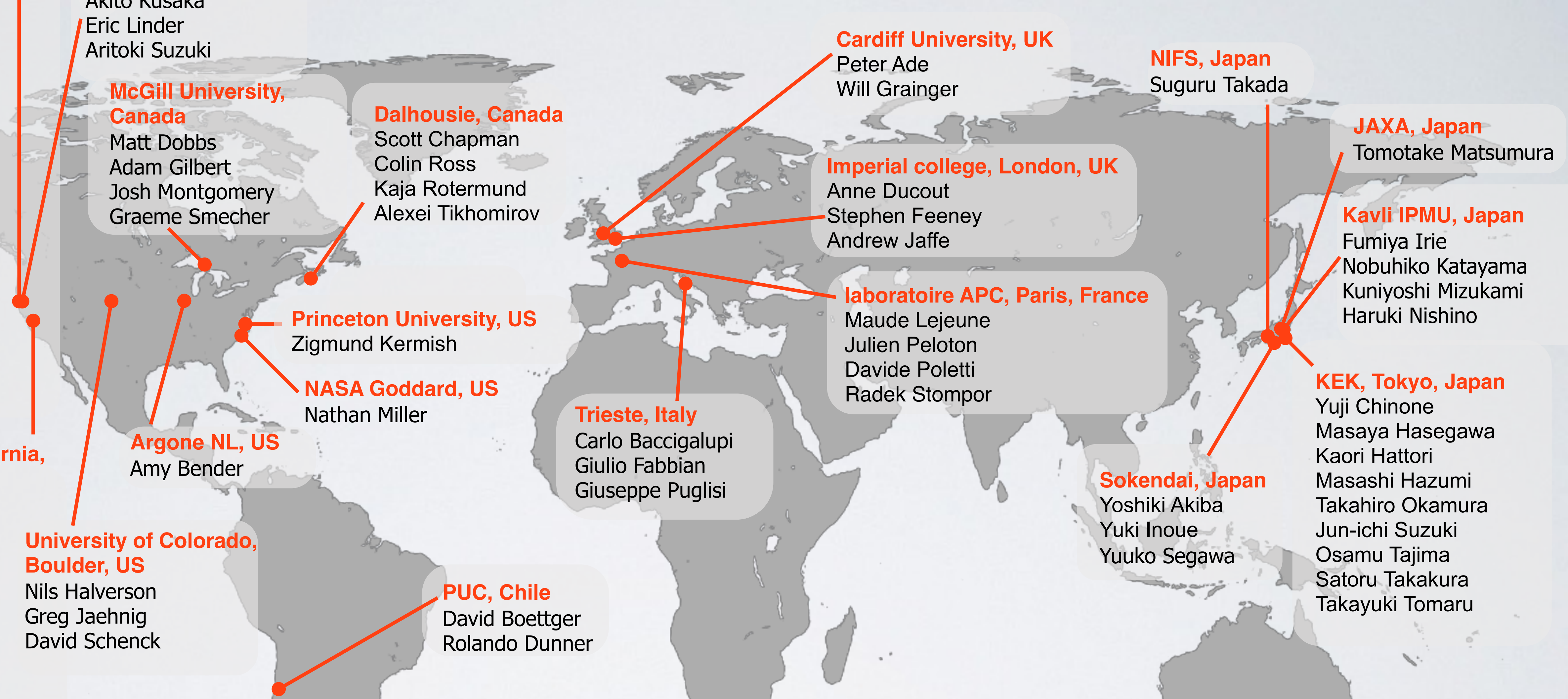
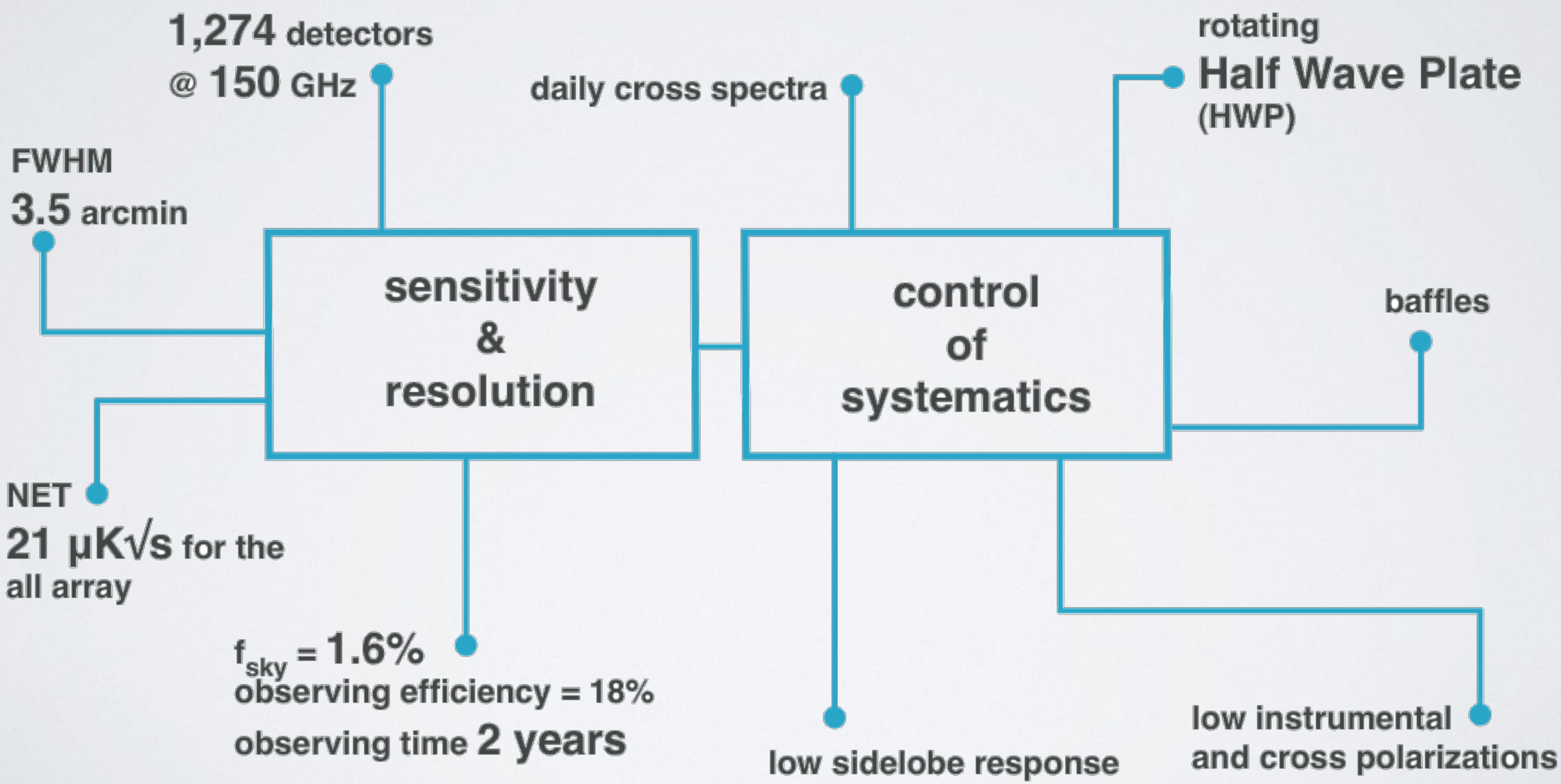
POLARBEAR collaboration



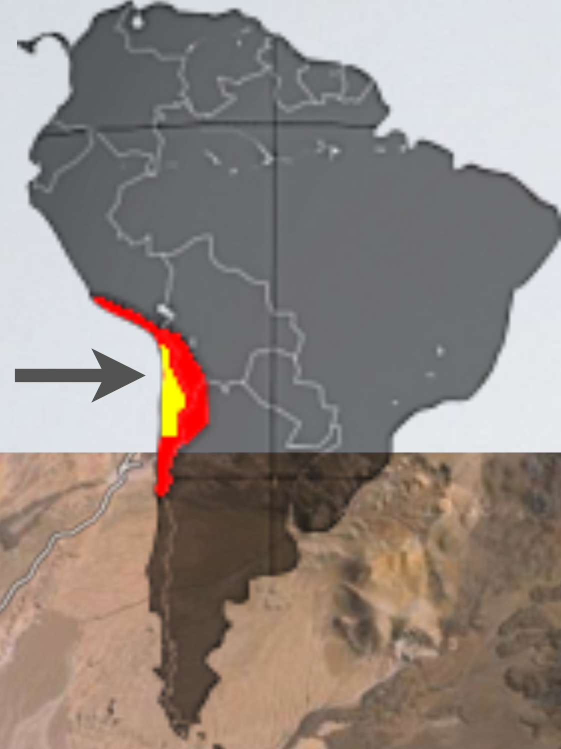
@KEK, Japan, march 2013

POLARBEAR science goals

characterize CMB polarization, especially B-modes polarization on large and small scales

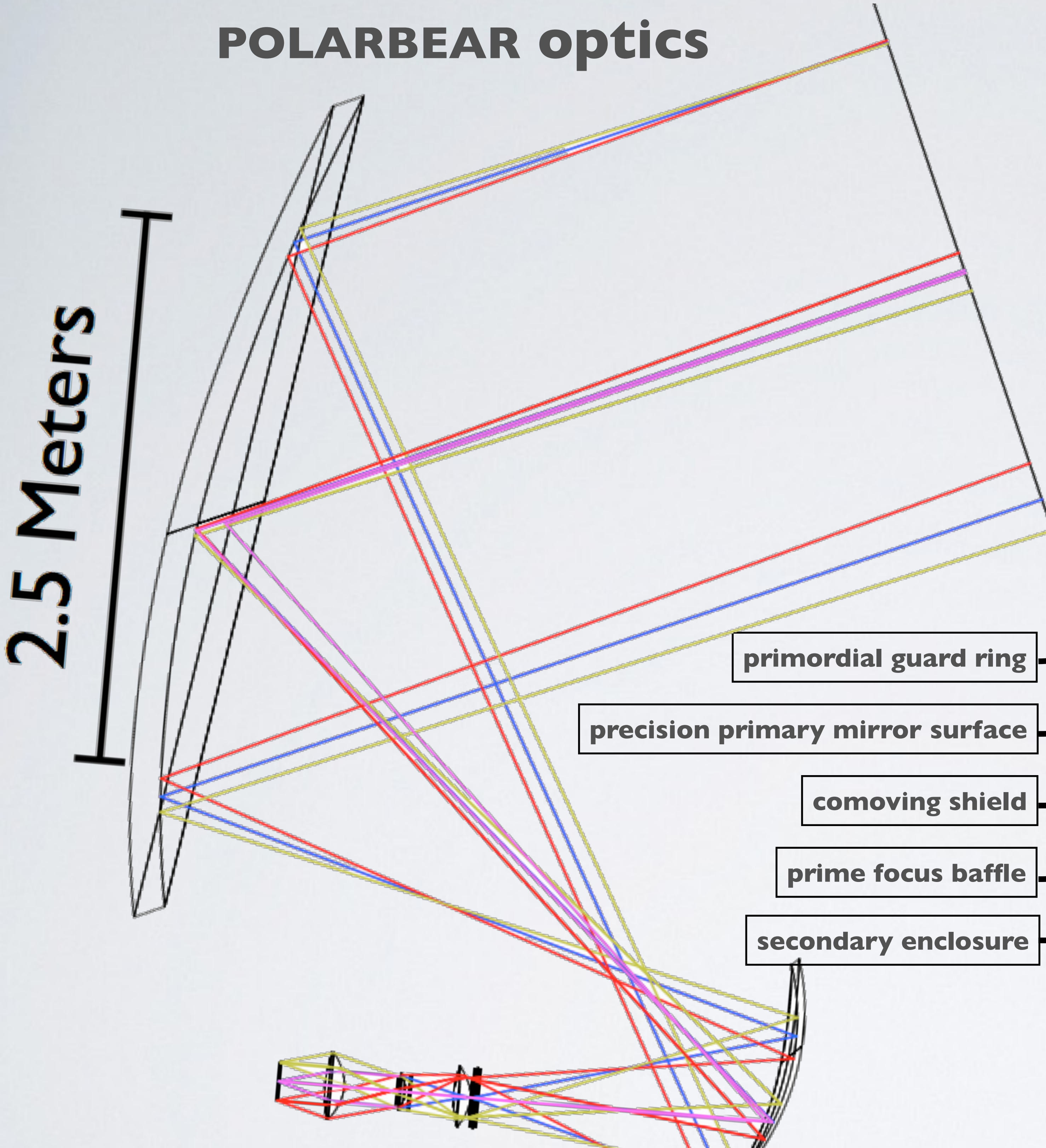


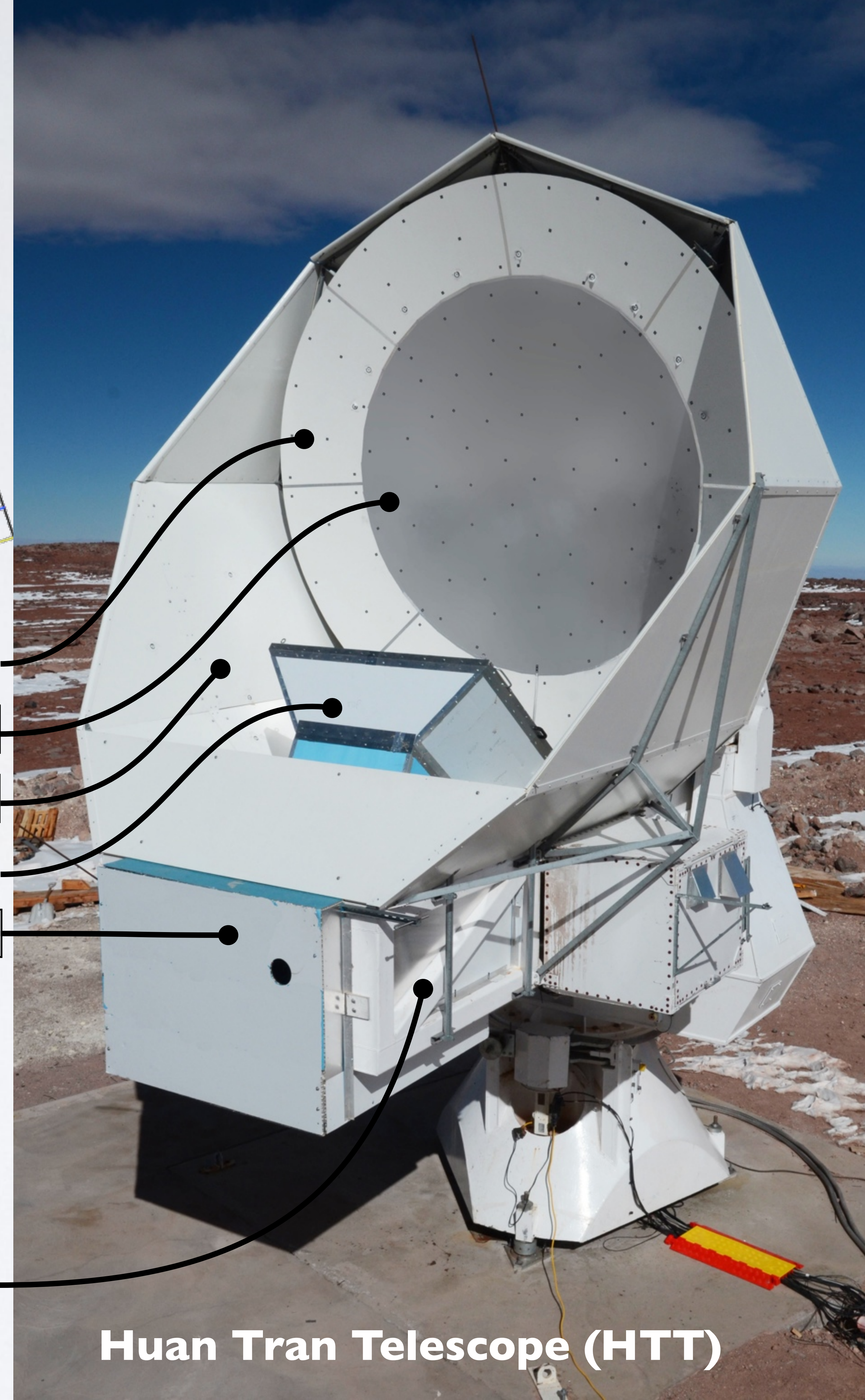
POLARBEAR site



POLARBEAR site

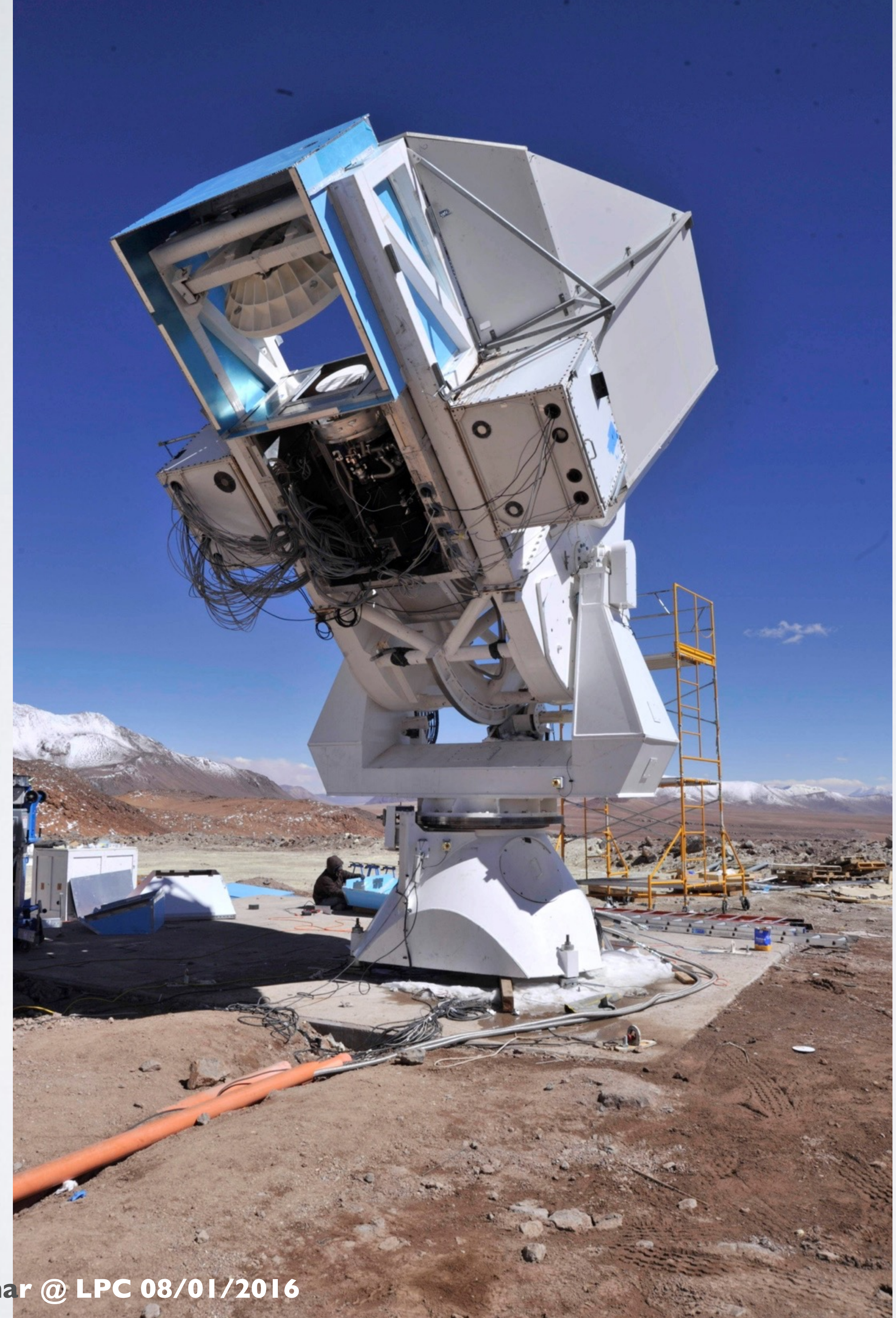
POLARBEAR optics



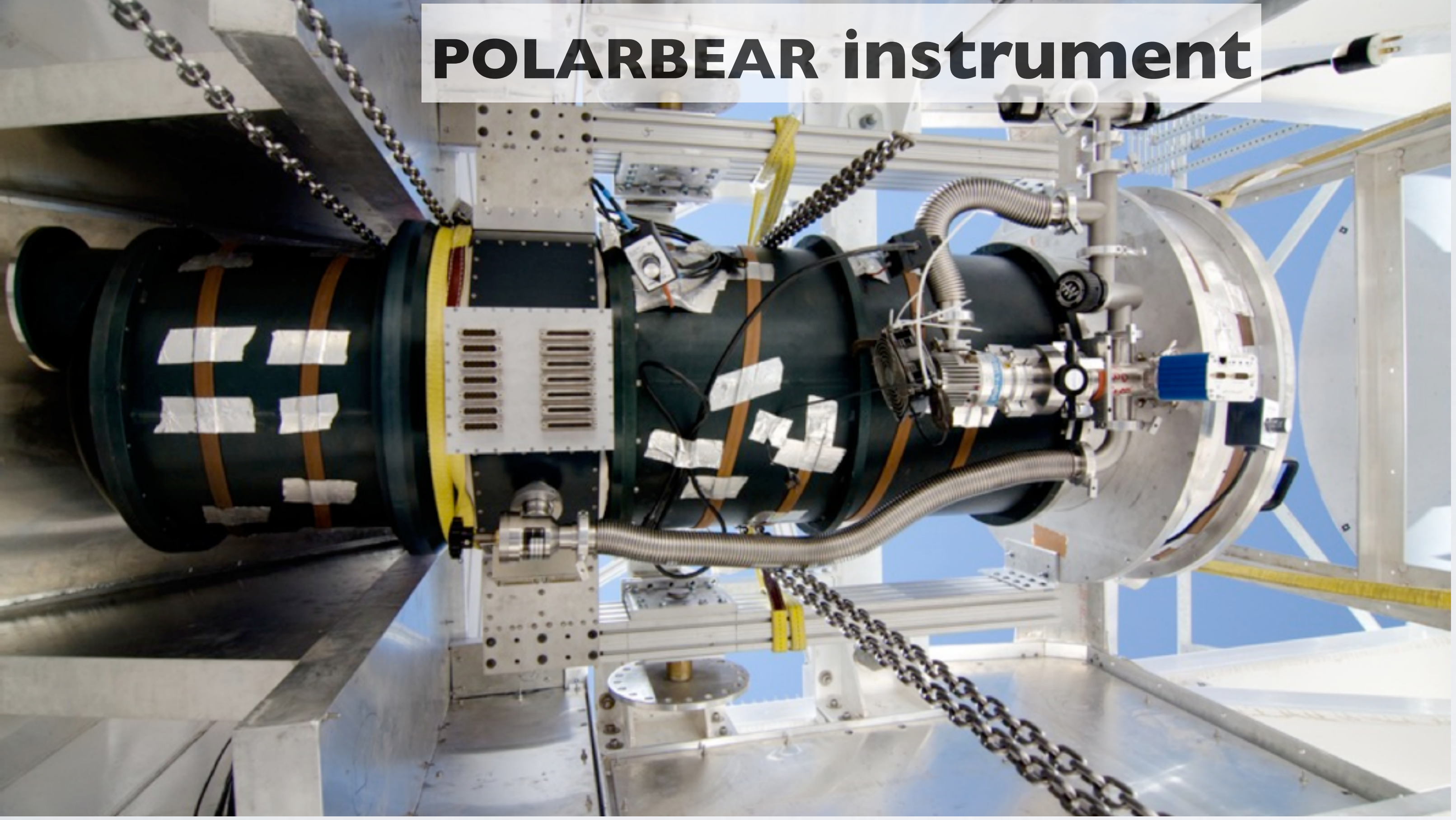


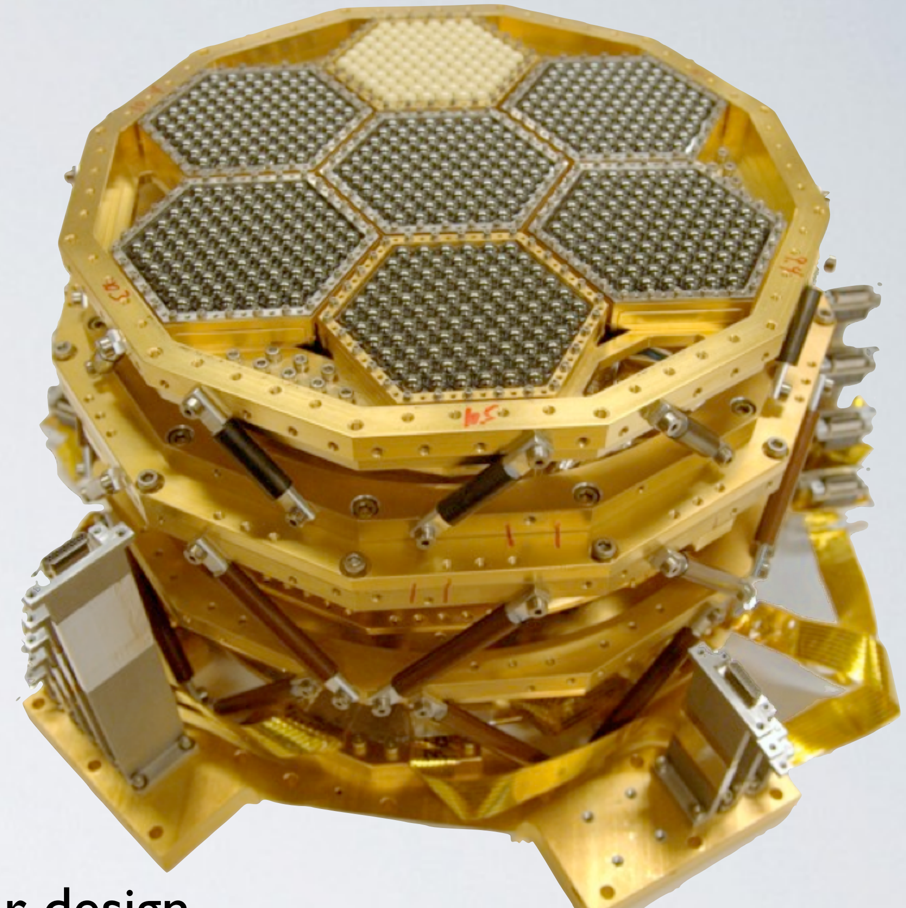
Off-axis Gregorian-Dragone

- Co-moving shield
- Low cross pol
- Large field of view – Large throughput

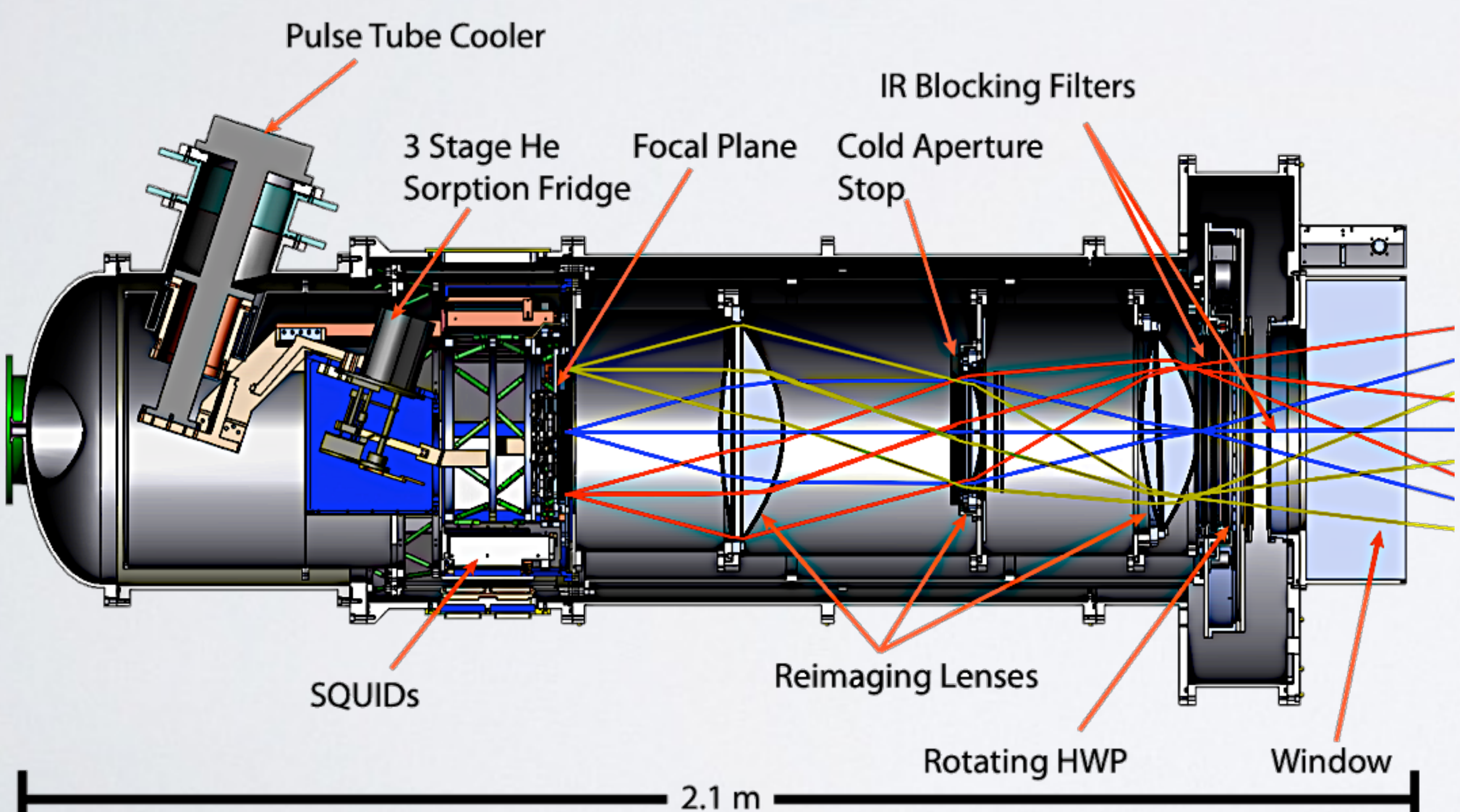


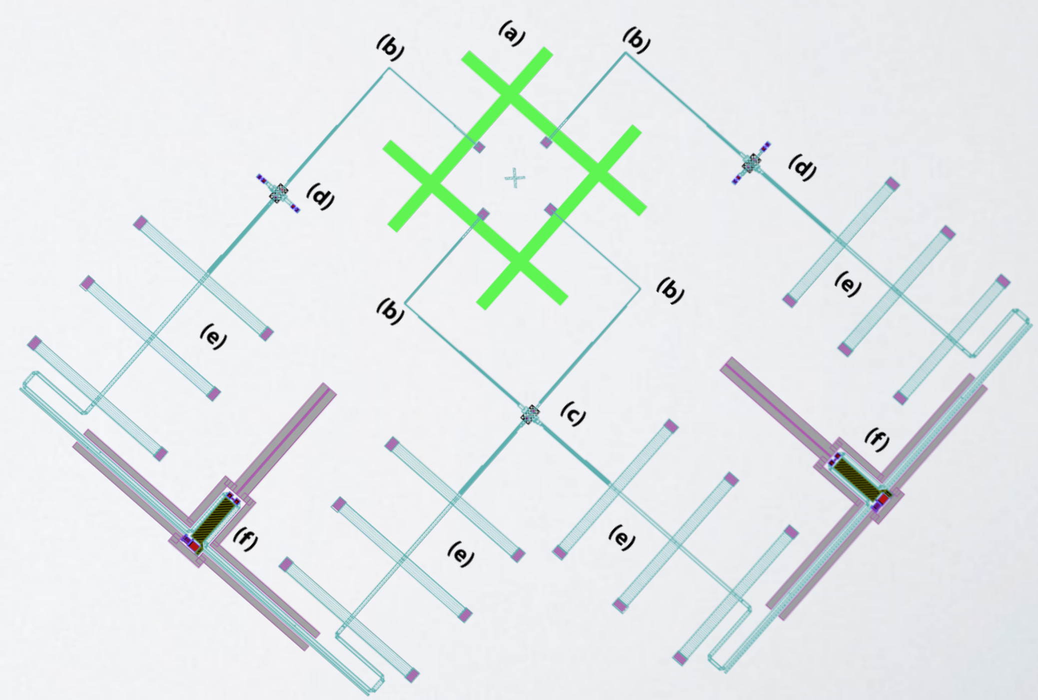
POLARBEAR instrument



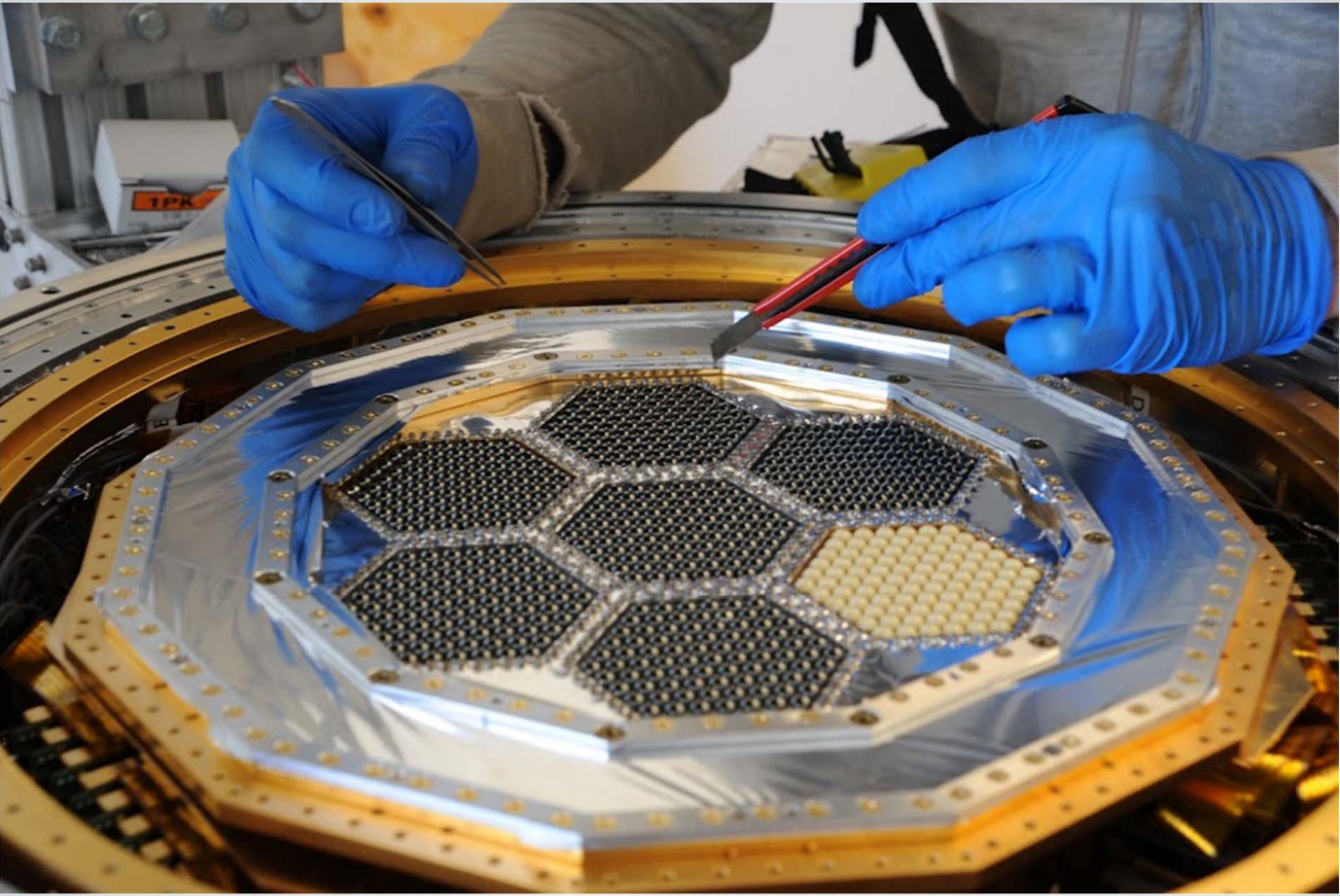


- modular design
- 7 wafers of 91 dual-polarized pixels
- planar superconducting dipole antennas with contacting lenslets
- TES detectors cooled to 250 mK

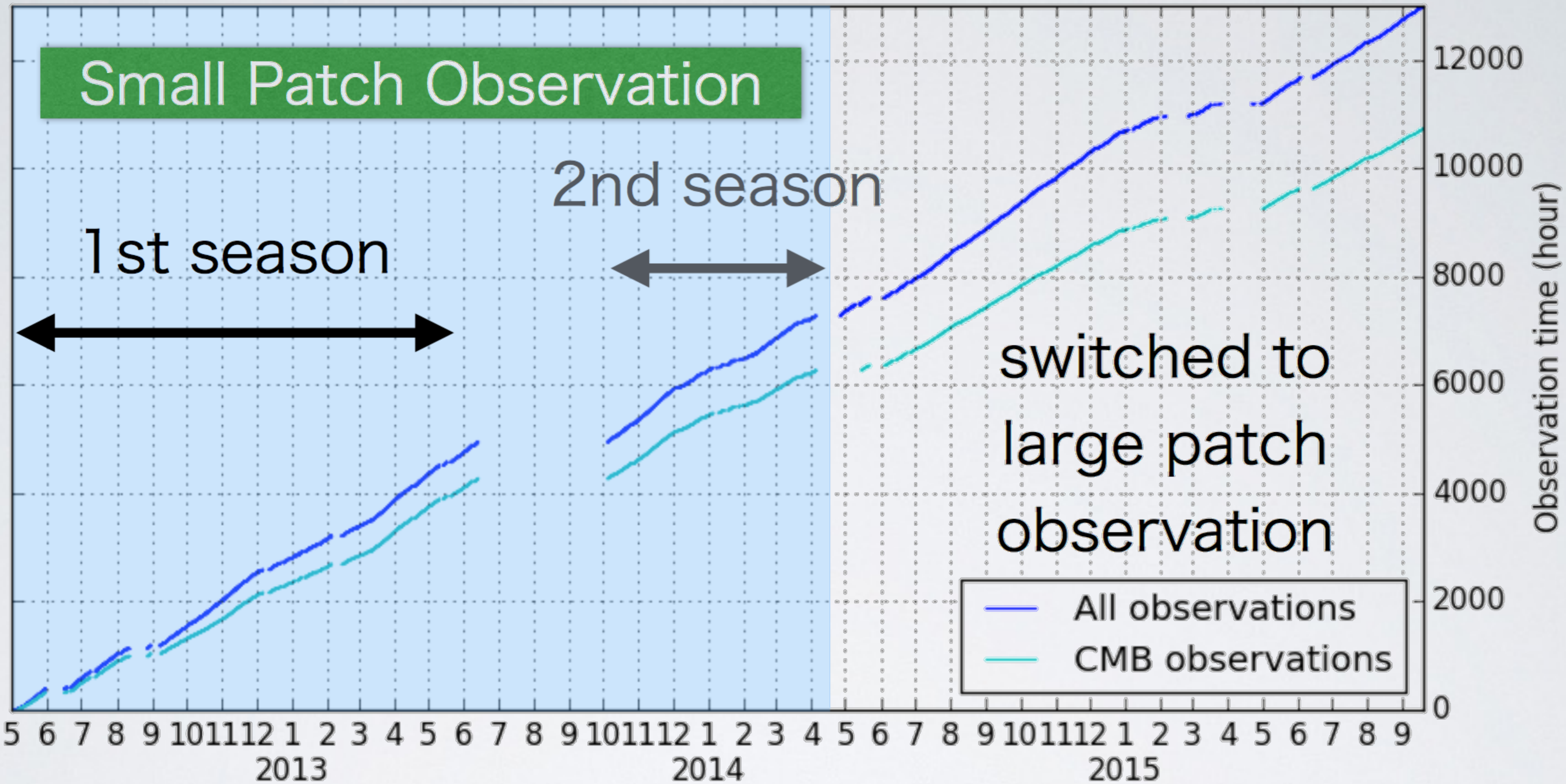




Installed focal plane



POLARBEAR observations



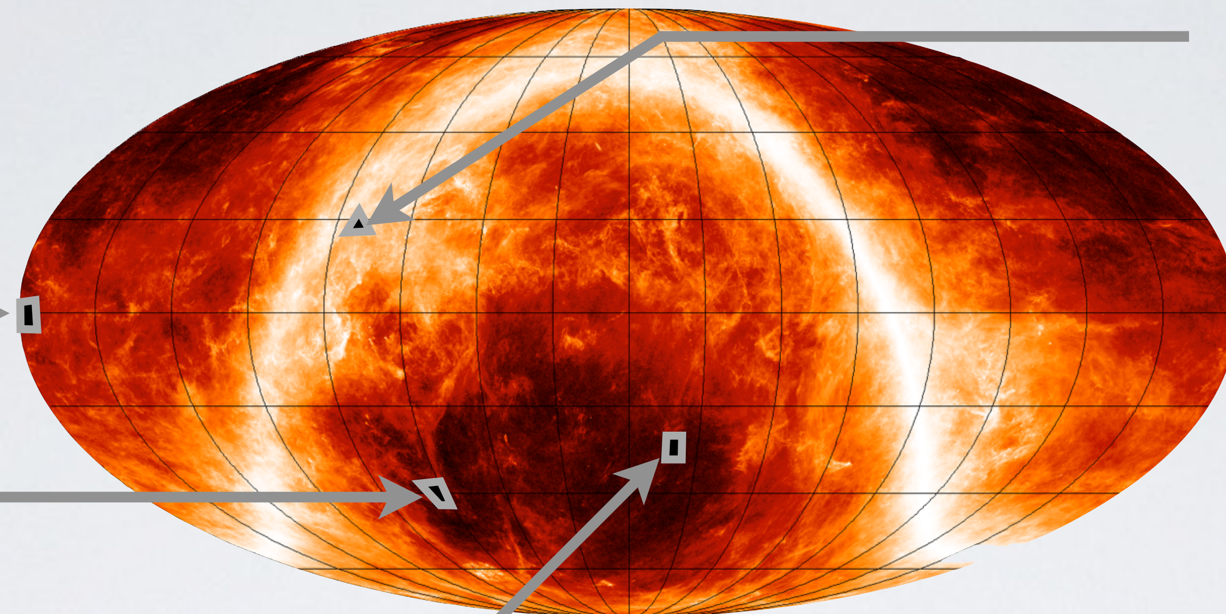
- **three 3 x 3 deg² patches during the first and second seasons (2012-2014)**
  - ★ detect lensing B-modes
  - ★ validate the instrument
- **two/three ≳ 15 x 15 deg² patches for the rest of the survey (2014-2016)**
  - ★ total neutrino mass < 75 meV (68% C.L.) when combined with Planck
  - ★ deep search for inflationary gravitational waves , enabling a detection of r = 0.025 (95% C.L.)

POLARBEAR observations

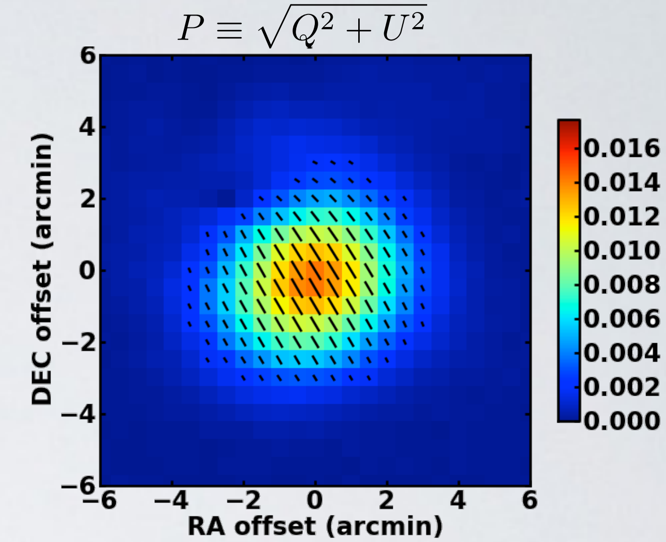
PB1RA12HAB

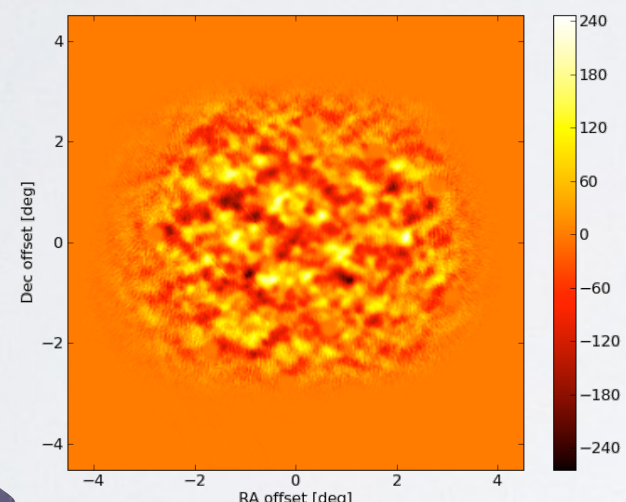
PB1LST4p5

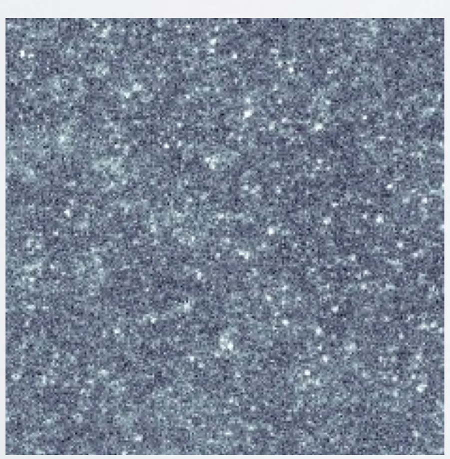
PB1RA23HAB



Tau A, a polarized sky calibrator

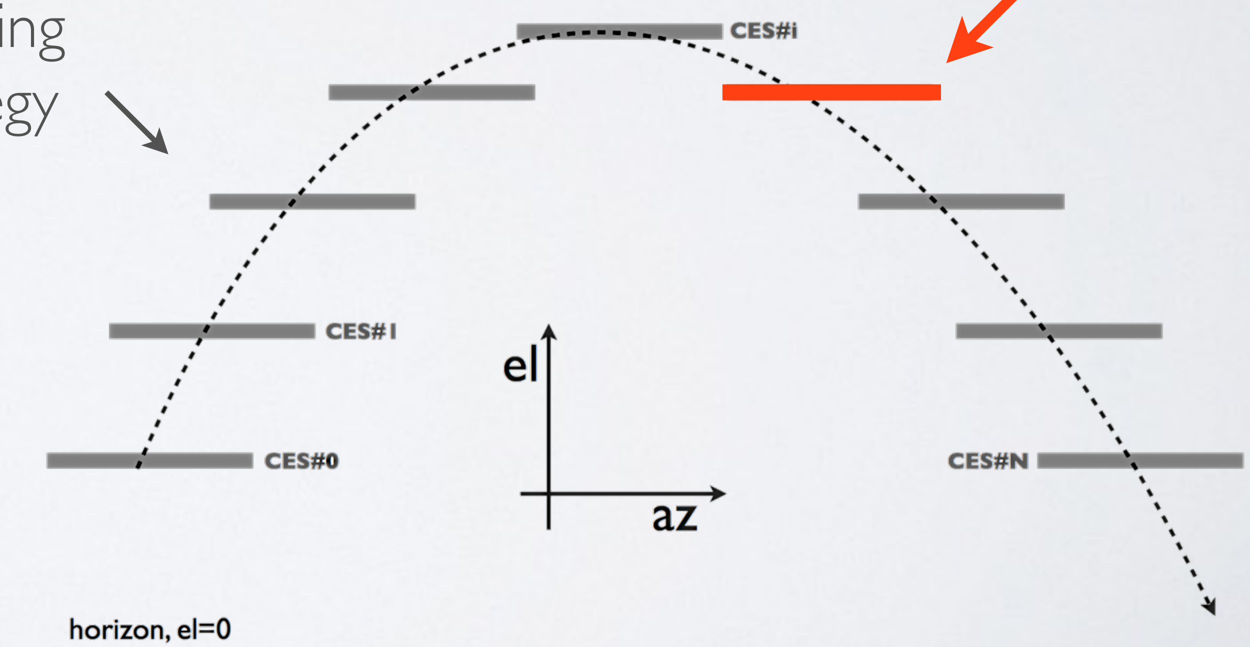






scanning strategy

constant elevation scan




sky rotates with time
POLARBEAR scans in azimuth at a constant elevation

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* my contributions

POLARBEAR pipeline(s)

biased*

pointing*
beam
Tau A
stimulator
C_l^{EB}
WMAP

signal + noise* + systematics

unbiased*

raw data

↓

calibration

↓

pre-processing

↓

map-making*

↓

coaddition*
daily I, Q, U map

↓

pseudo-spectra

↓

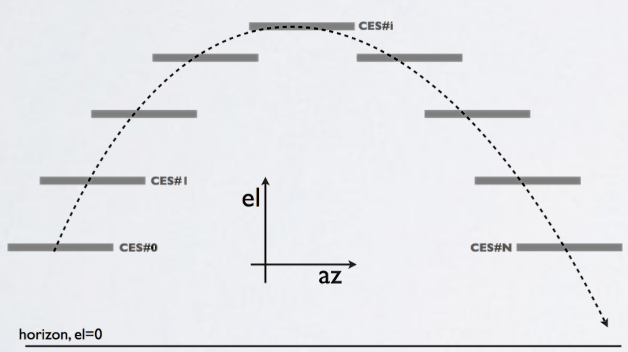
spectra

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

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

PCG

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



MASTER*
Hivon et al. (2002)

X-pure
Grain et al. (2009)

POLARBEAR results: first observations

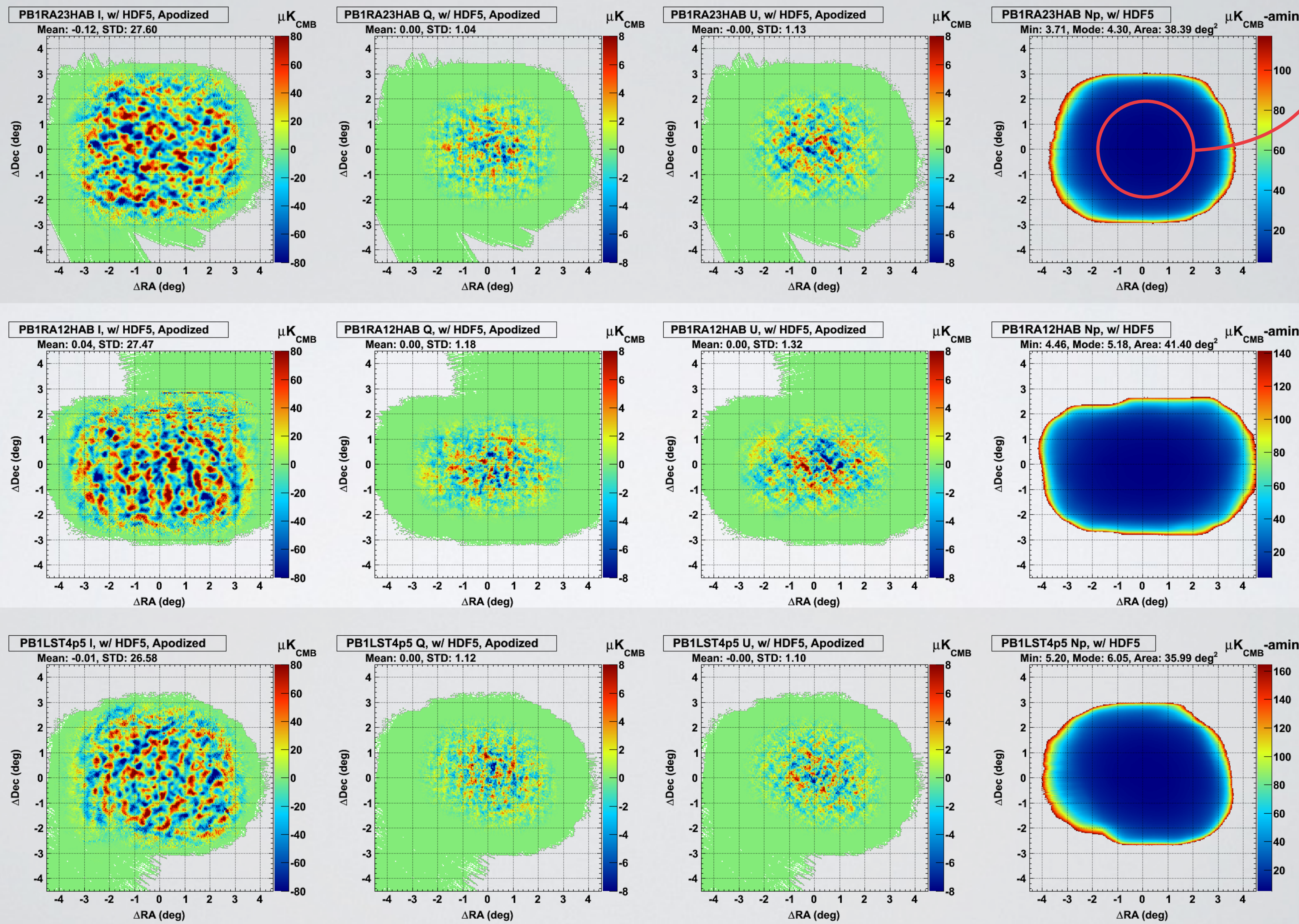
4-5 μK.arcmin !

I **Q** **U** **sensitivity in polarization**

RA23

RA12

LST4.5

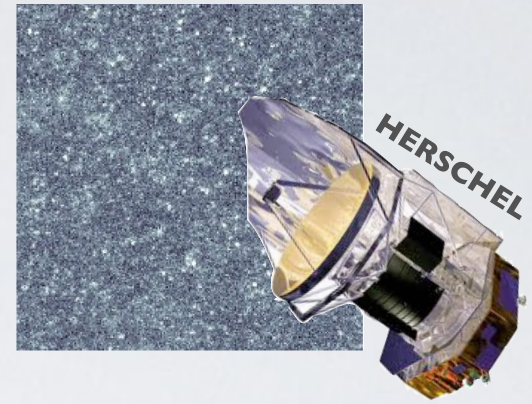


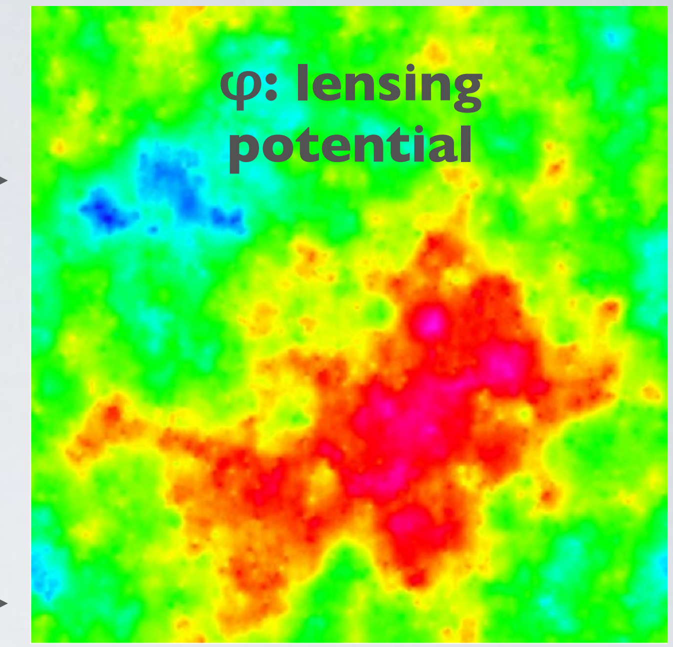
POLARBEAR results: first observations

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





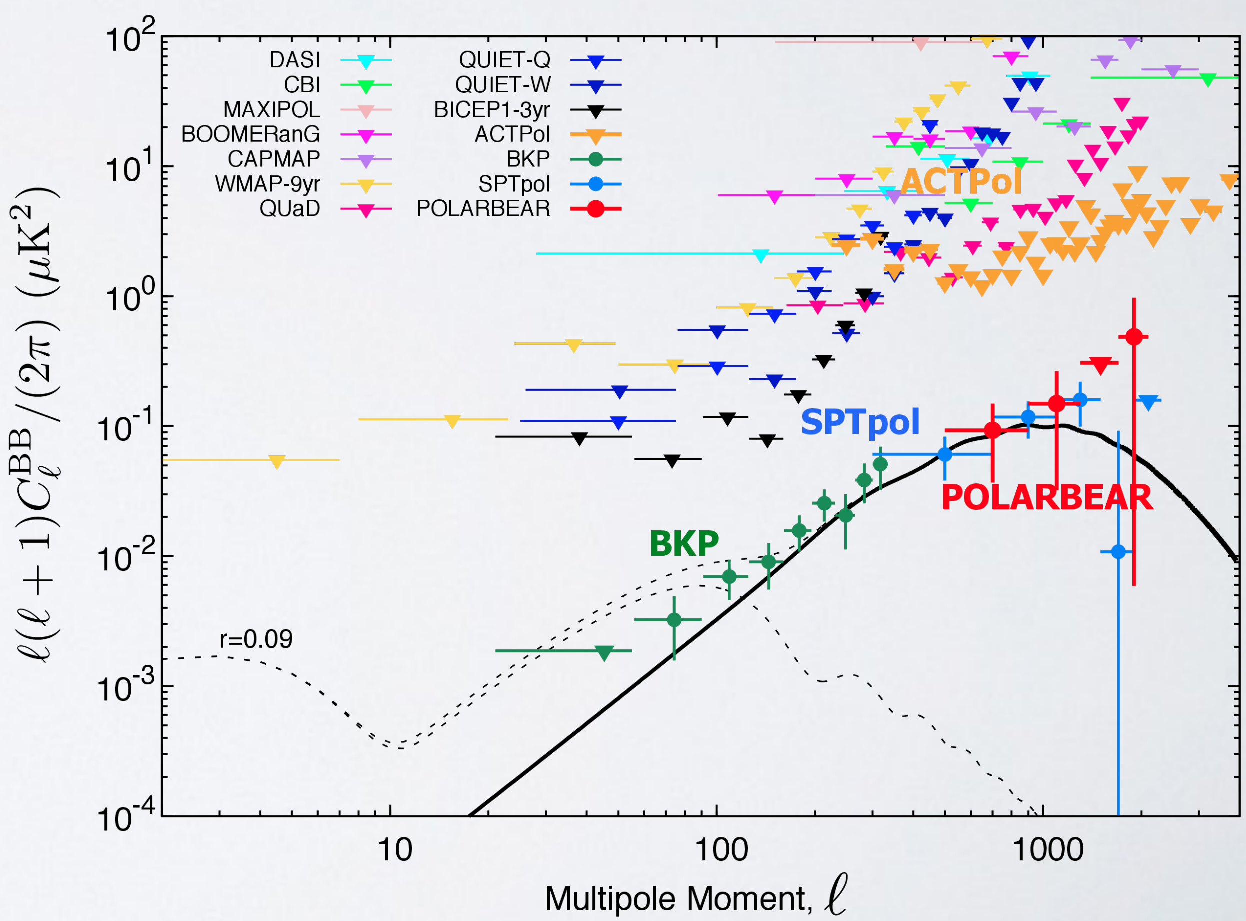
Measurement of the Cosmic Microwave Background Polarization Lensing Power Spectrum with the POLARBEAR Experiment
The POLARBEAR collaboration
Phys. Rev. Lett. 113, 021301 (**2014**)

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



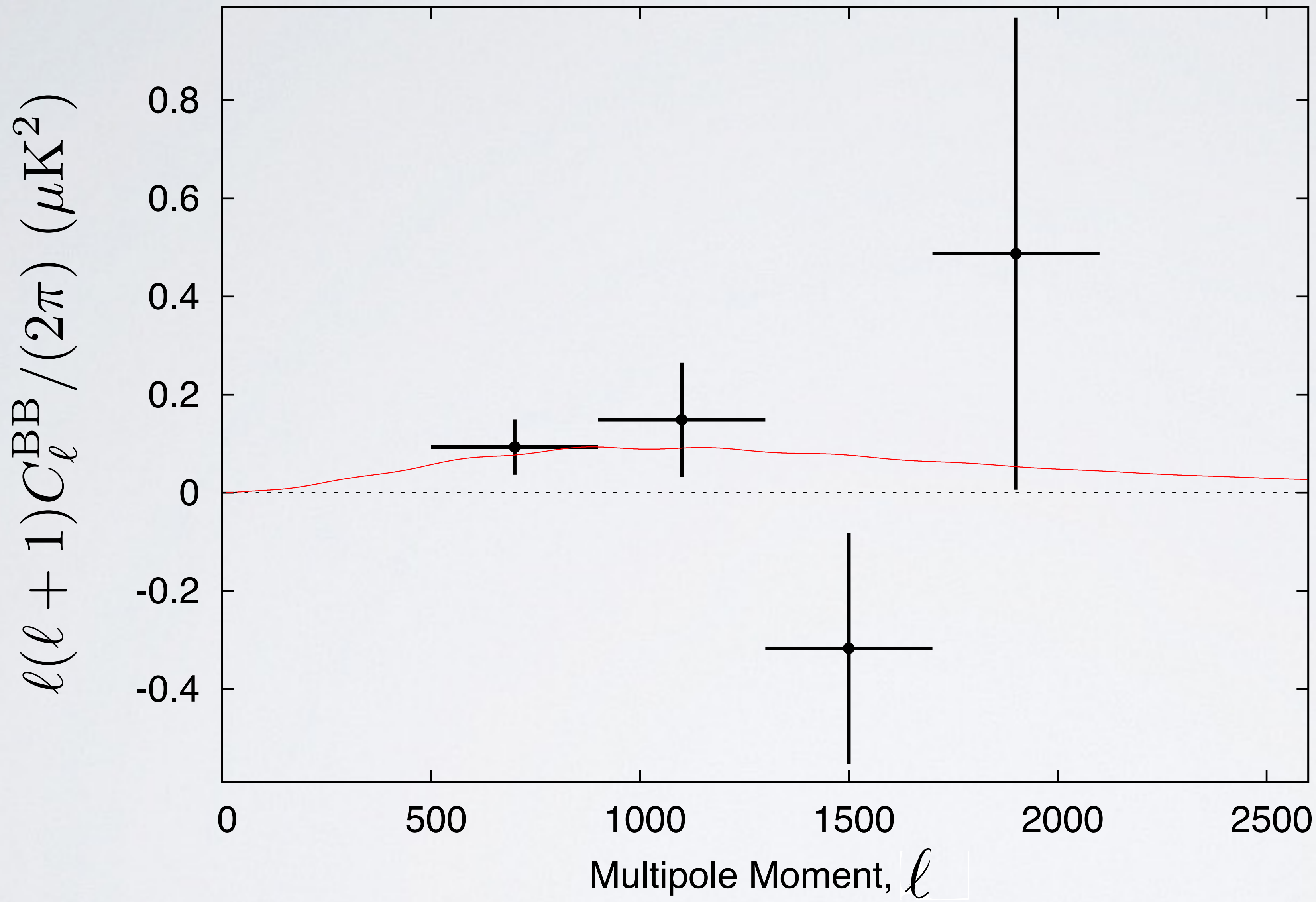
CMB lensing results

> 2-point correlation

$$A_{BB} = 1.12 \pm 0.61(\mathrm{stat})^{+0.04}_{-0.10}(\mathrm{sys}) \pm 0.07(\mathrm{multi})$$

SPTpol 2015 results: $A_{\mathrm{lens}} = 1.08 \pm 0.26$

Planck 2015 results: $A^{\hat{B}} = 0.93 \pm 0.08$



Combining three published results: **4.7σ rejection of "no lensing B-modes"**

➤ 97.2% rejection of "no lensing B-modes"
- including possible systematic instrumental biases
- including estimate of foreground bias

New result! (with the 1st season data)

POLARBEAR Constraints on Cosmic Birefringence and Primordial Magnetic Fields
The Polarbear collaboration
Physical Review D, Volume 92, Issue 12, id.123509 (2015)
arXiv: 1509.02461

- cosmic birefringence: rotation of CMB polarization orientation

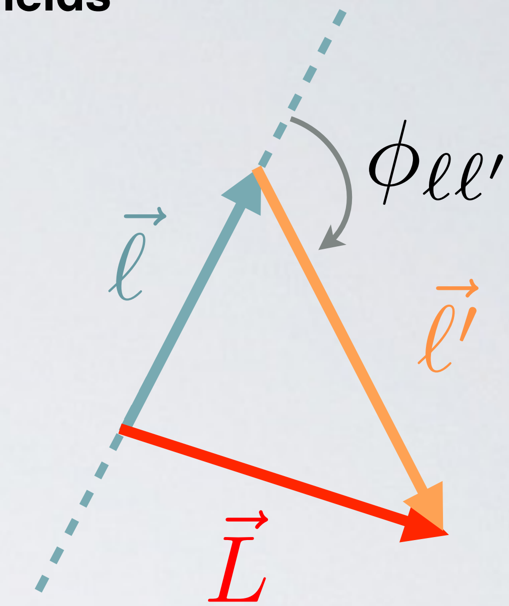
$$(Q \pm iU)(\mathbf{n}) = (\tilde{Q} \pm i\tilde{U})(\mathbf{n})e^{\pm 2i\alpha(\mathbf{n})}$$

- possible causes:
  - ⋆ Faraday rotation by a Primordial Magnetic Field (PMF) (some inflationary scenarios predicts PMFs)
  - ⋆ Parity-violating interactions e.g., parity violation in electromagnetism? (coupling photons and pseudo-scalar field, etc)

- way to measure it:
  - ⋆ measure specific feature in B-mode spectrum (for PMF)
  - ⋆ measure correlations between E- and B-modes (produced by cosmic birefringence & expected to vanish in standard cosmological model)

POLARBEAR Constraints on Cosmic Birefringence and Primordial Magnetic Fields
The Polarbear collaboration
Physical Review D, Volume 92, Issue 12, id.123509 (2015)
arXiv: 1509.02461

$$\alpha_{EB}(\vec{L}) \propto \sum_{\vec{\ell}} E(\vec{\ell})B(\vec{\ell'}) \cos(2\phi_{\ell\ell'})$$



$$\langle \alpha_{EB}(\vec{L}) \alpha^*_{EB}(\vec{L'}) \rangle \rightarrow$$

- consistent with zero
- limit on equivalent PMF < 93 nG (for scale-invariant FR spectrum) at 95% C.L.

Another PMF constraint comes from B-mode power spectrum

- Metric perturbations from PMF could contribute to CMB B-mode
- Vector mode contribution is distinguishable with lensing B-mode

$\downarrow$

- no evidence for PMF B-mode
- upper limit on PMF < 3.9 nG (95% C.L.)

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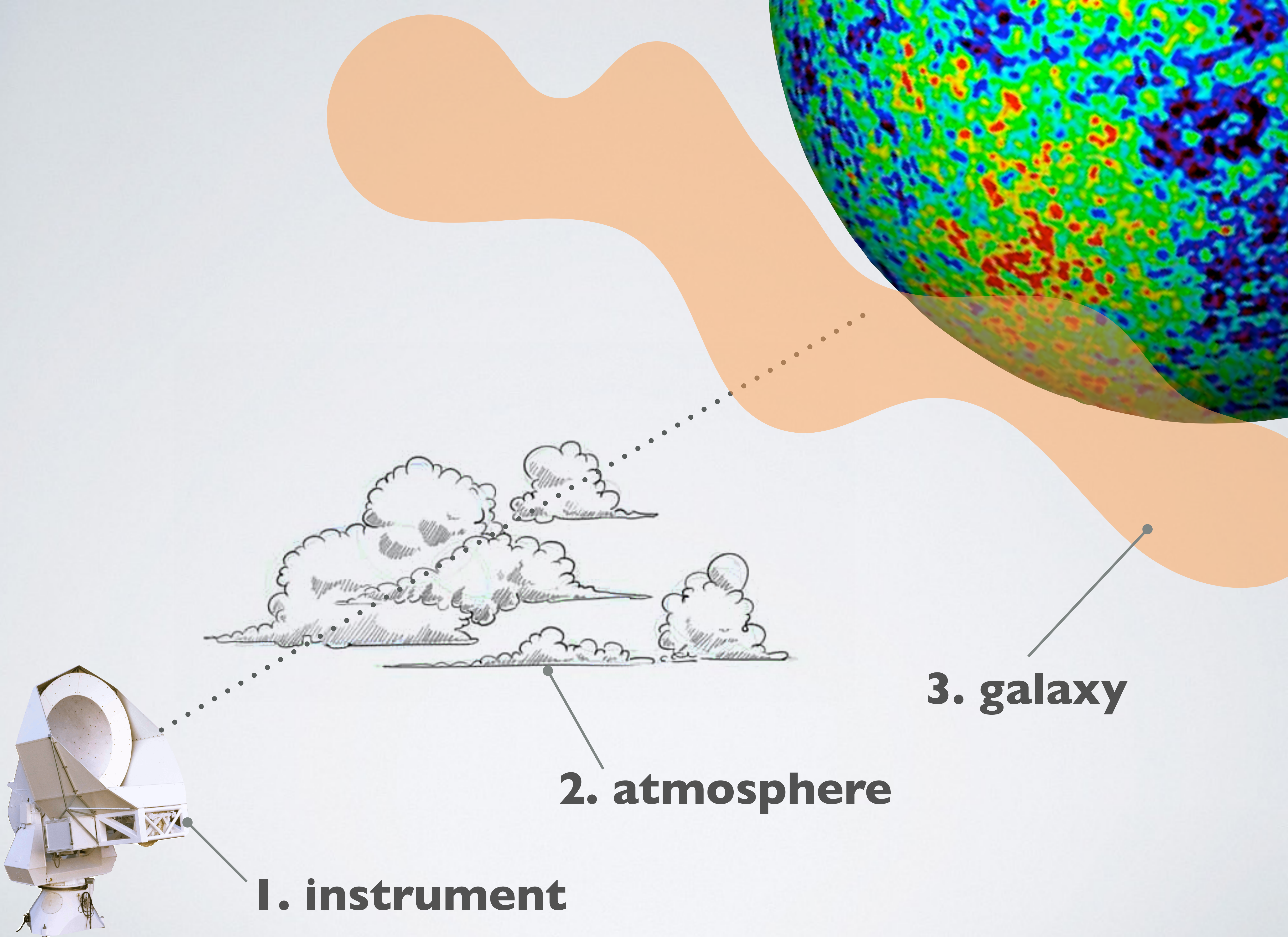
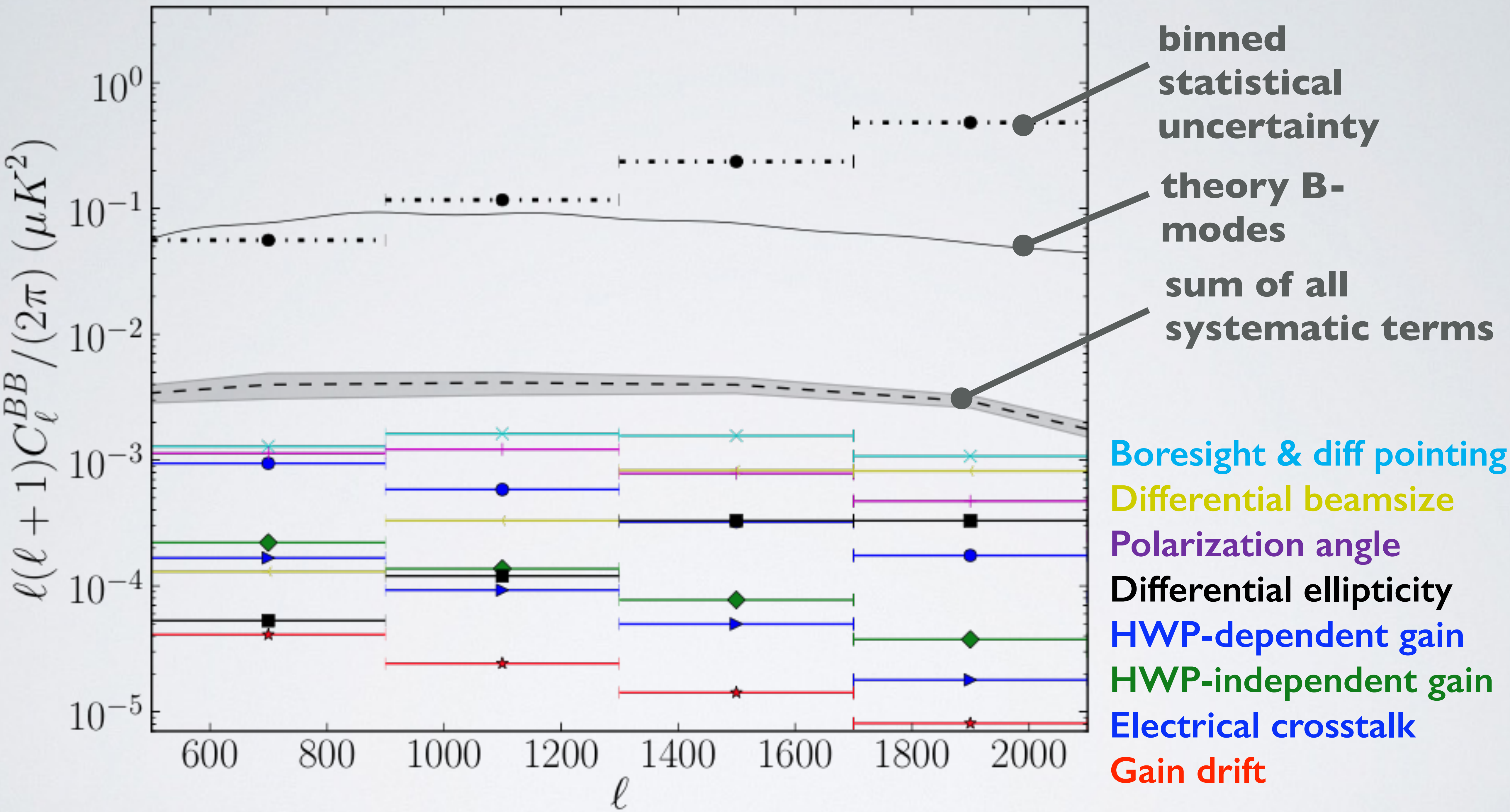

3. galaxy
2. atmosphere
1. instrument

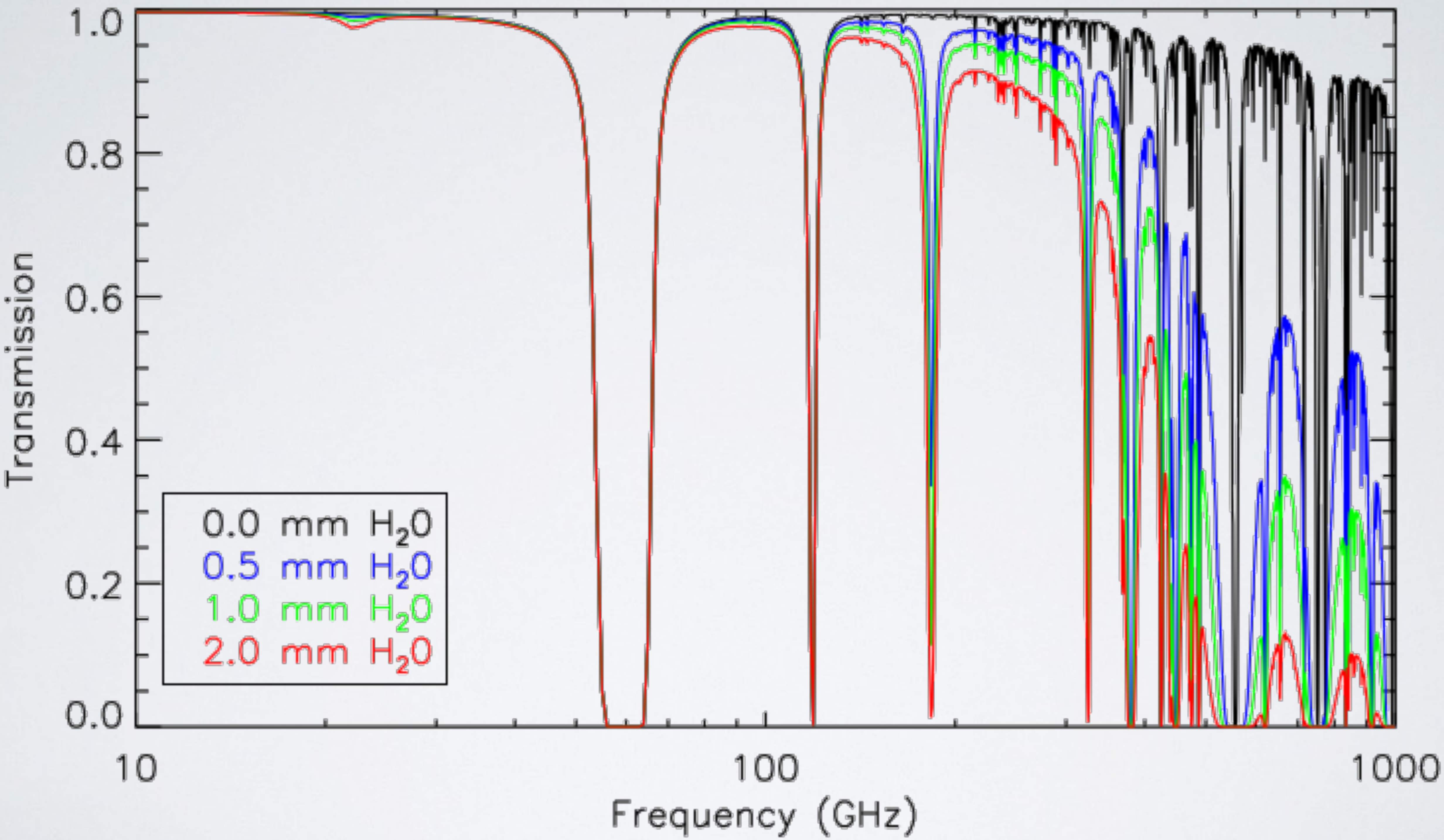
I. Instrumental systematic error estimation

End-to-end simulations using measured instrument characteristics and cross-checks



➤ we confirmed all known systematics are much smaller than statistical uncertainty before "unblinding" the spectrum

2. Atmospheric contamination



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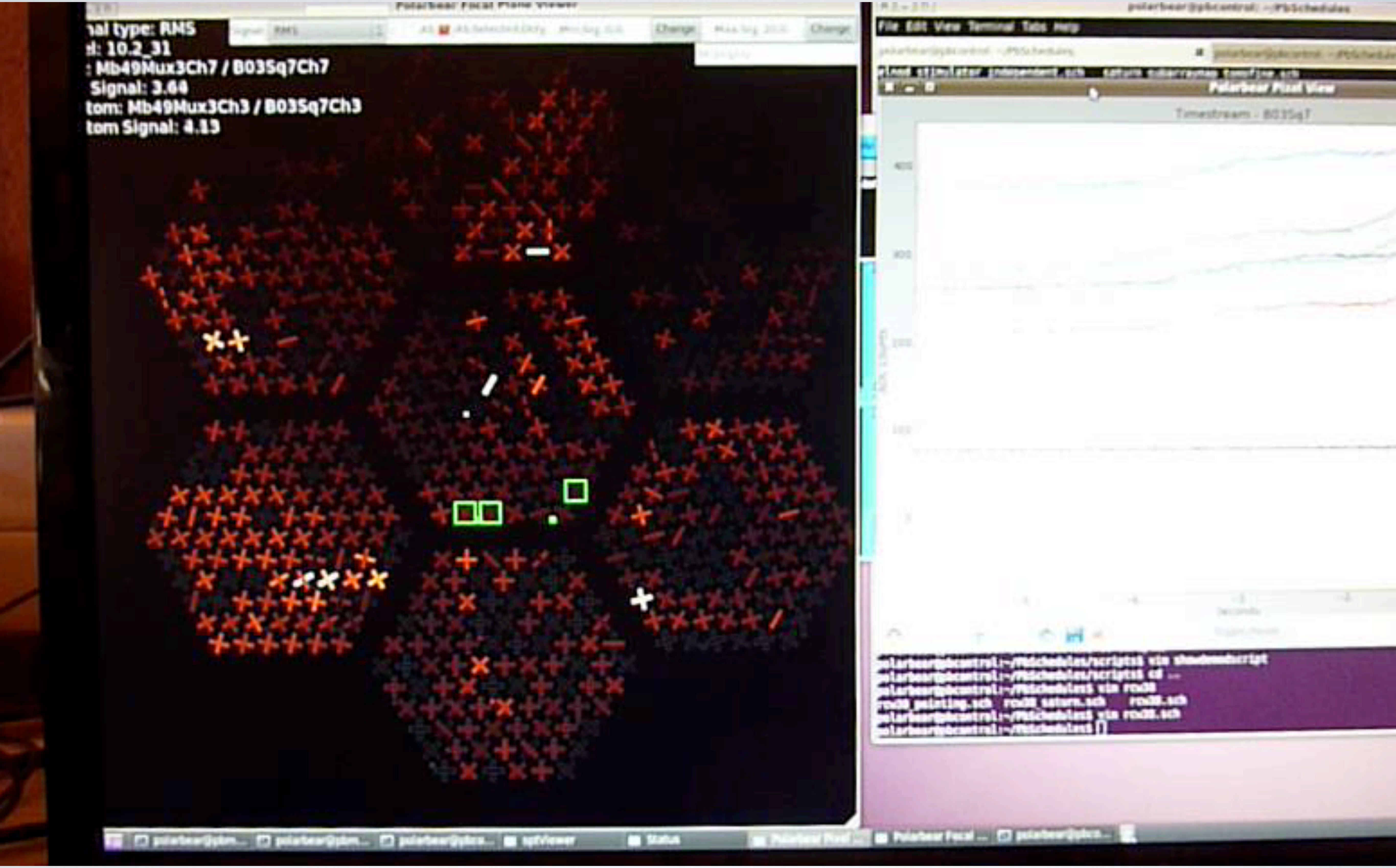
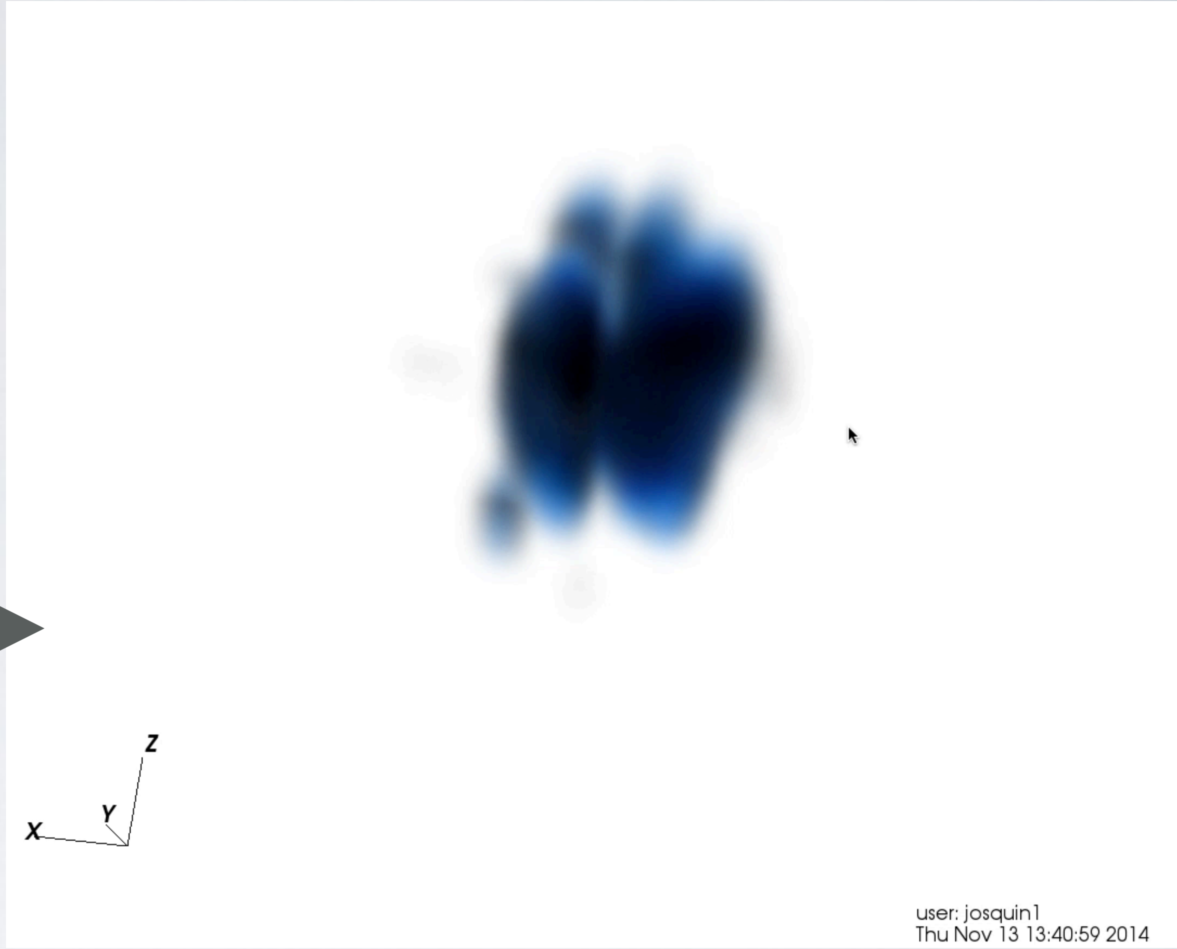


2. Atmospheric contamination

Modeling Atmospheric Emission for CMB Ground-based Observations
Errard, J. 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



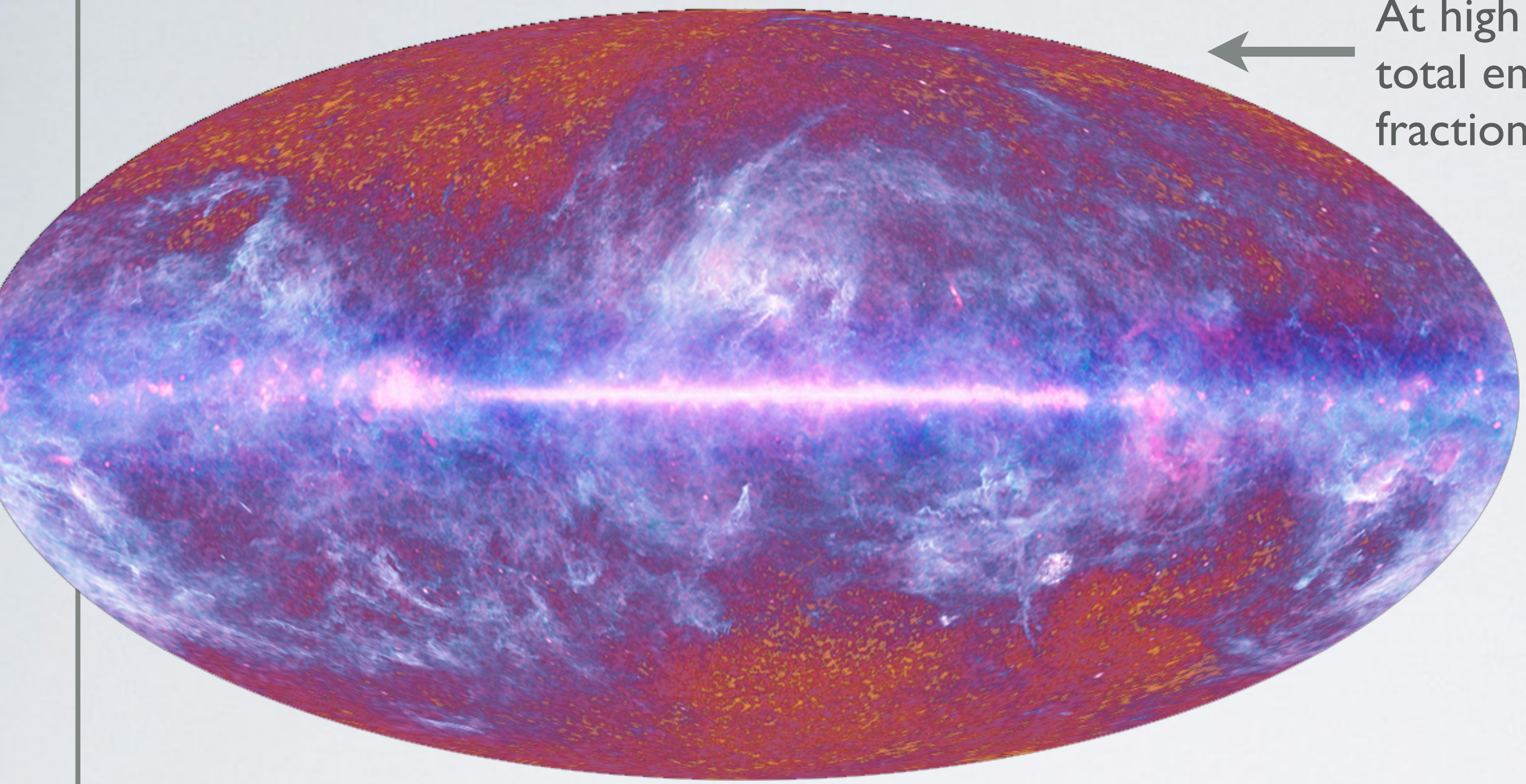
POLARBEAR
scientific data

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

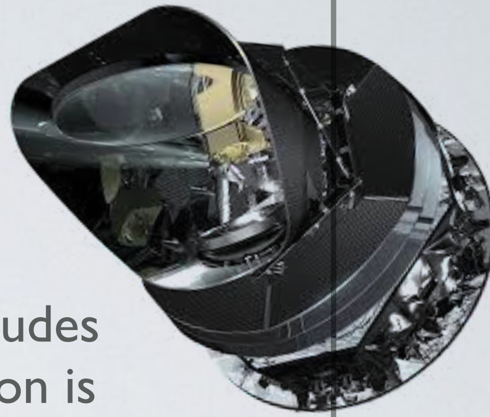
typical scale for atmospheric turbulences: Lo ~ 200m

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

3. Galaxy



At high galactic latitudes, where the total emission is low, the polarization fraction can be as high as **15-20%**



At low galactic latitudes the polarized fraction is lower but the total emission is higher.

- By analyzing 400-square-degree patches covering the sky outside the Galactic plane, the Planck team has convincingly shown that **there are no regions of the sky in which B-mode emission from dust can be neglected when attempting to extract the inflationary B-modes at frequencies above ~100 GHz**
- The polarization of galactic dust can not be neglected because **(1) the derived central value of the polarized intensity is high, and (2) the noise in the current data leads to appreciable uncertainty**

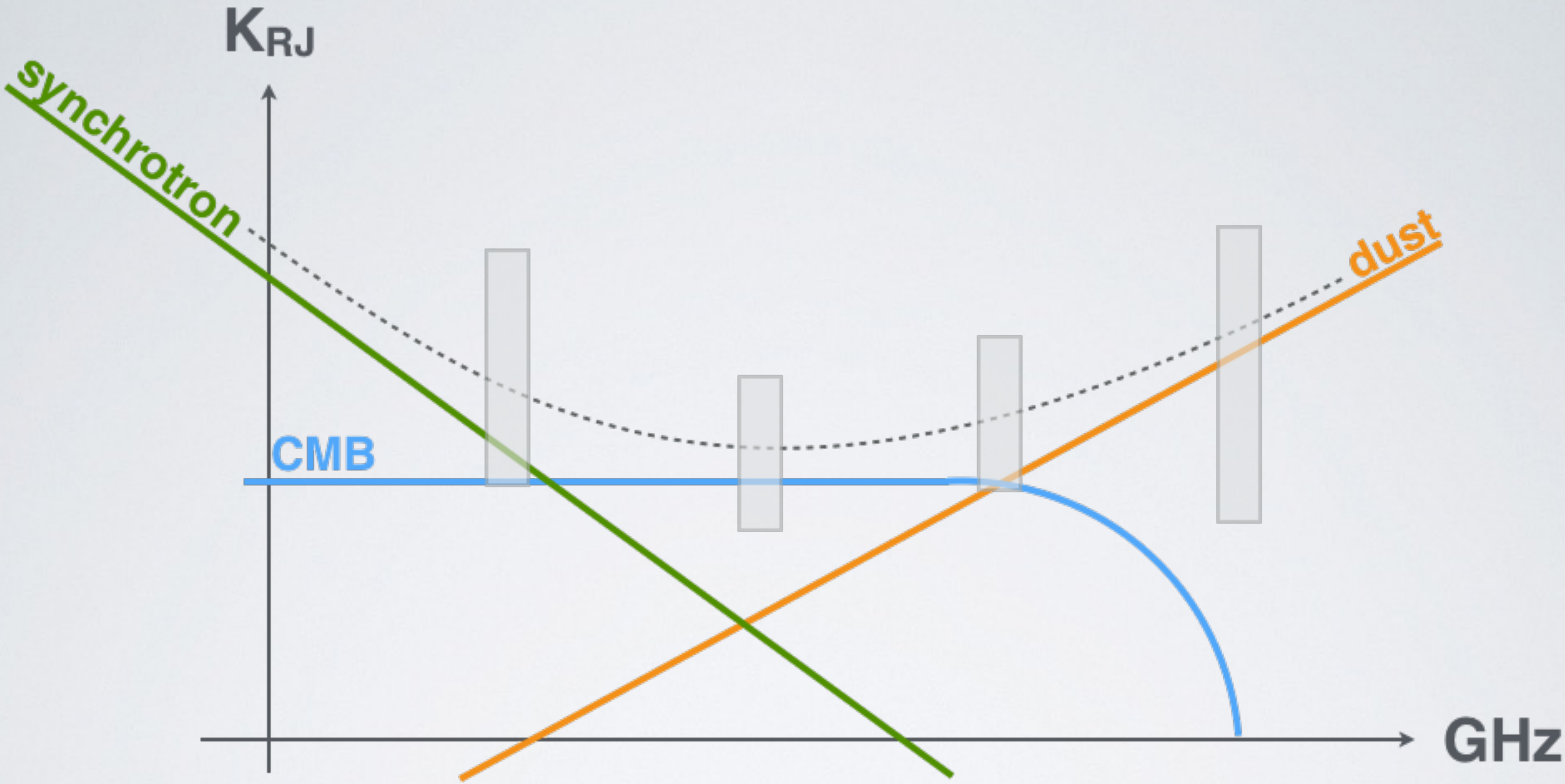
BICEP2/Keck, Planck Collaborations, :, P. A. R. Ade, N. Aghanim, Z. Ahmed, R. W. Aikin, K. D. Alexander, M. Arnaud, J. Aumont, and et al. A Joint Analysis of BICEP2/Keck Array and Planck Data. *ArXiv e-prints*, February 2015.

Planck Collaboration, R. Adam, P. A. R. Ade, N. Aghanim, M. Arnaud, J. Aumont, C. Baccigalupi, A. J. Banday, R. B. Barreiro, J. G. Bartlett, and et al. Planck intermediate results. XXX. The angular power spectrum of polarized dust emission at intermediate and high Galactic latitudes. *ArXiv e-prints*, September 2014.

Planck Collaboration, R. Adam, P. A. R. Ade, N. Aghanim, M. I. R. Alves, M. Arnaud, M. Ashdown, J. Aumont, C. Baccigalupi, A. J. Banday, and et al. Planck 2015 results. X. Diffuse component separation: Foreground maps. *ArXiv e-prints*, February 2015.

Planck Collaboration, P. A. R. Ade, N. Aghanim, D. Alina, M. I. R. Alves, C. Armitage-Caplan, M. Arnaud, D. Arzoumanian, M. Ashdown, F. Atrio-Barandela, and et al. Planck intermediate results. XIX. An overview of the polarized thermal emission from Galactic dust. *ArXiv e-prints*, May 2014.

3. Galaxy



from the measurements performed at different frequencies, we have to:

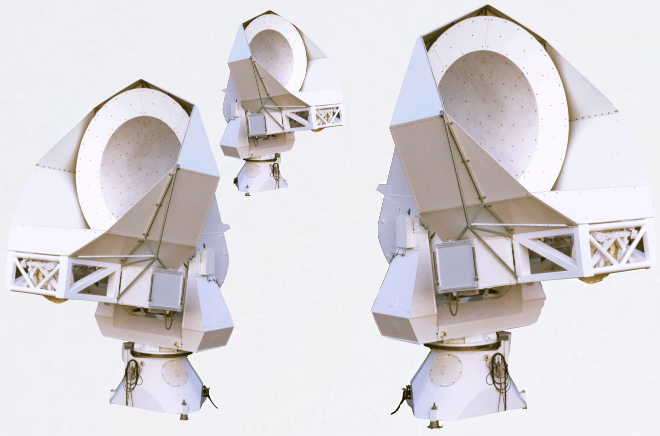
1- estimate the frequency scaling laws of each sky component (e.g., synchrotron, dust)

2- clean the CMB from other signals

Hot topics in the community today:

- how complex is the sky?
- how many frequencies (with which sensitivities) are needed to disentangle CMB from foregrounds?
- can we do it from the ground?
- can we combine ground-based and space instruments?

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



x

good angular resolution
poor frequency coverage
partial sky coverage

bad angular resolution
good frequency coverage
all sky observations

OUTLINE

1 - CMB introduction

- ➤ Early physics
- ➤ Weak lensing

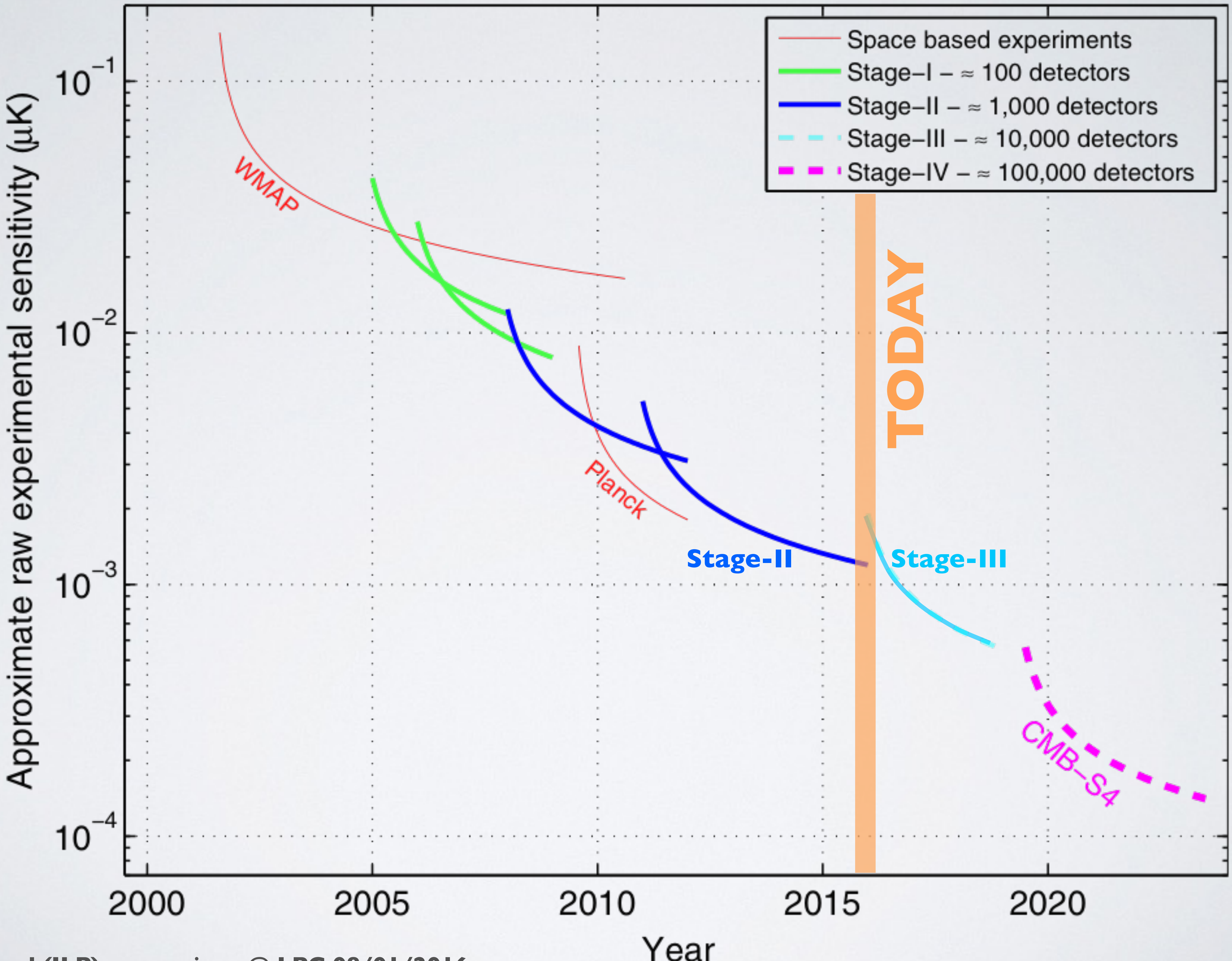
2- Observation of the CMB with POLARBEAR

- ➤ Project overview
- ➤ POLARBEAR analysis and first results
- ➤ Discussion about astrophysical and instrumental systematics effects

3 - Current and future plans for CMB observations

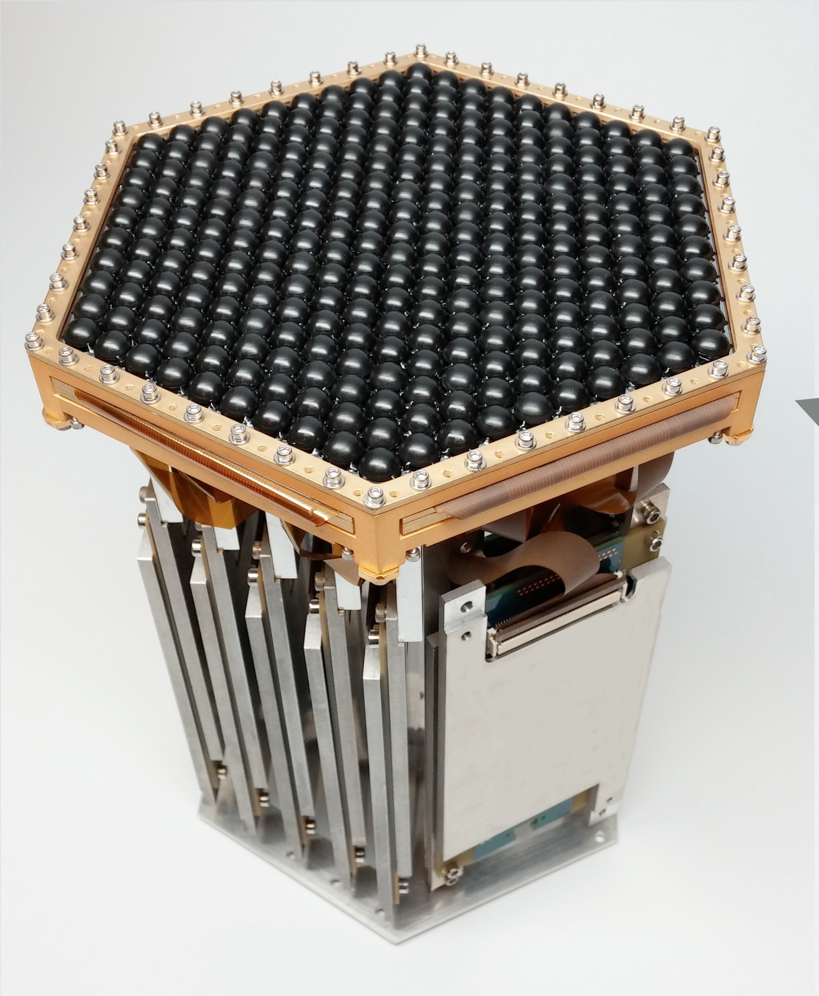
- ➤ POLARBEAR-II, Simons Array, Stage-IV and LiteBIRD
- ➤ Association with LSST weak lensing measurements

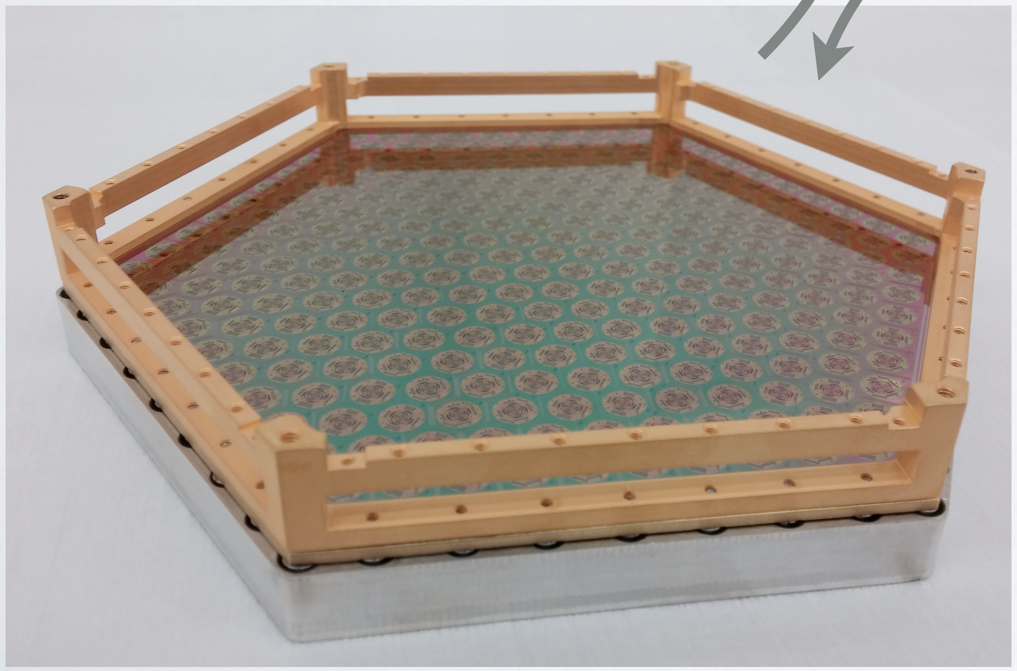
Neutrino Physics from the Cosmic Microwave Background and Large Scale Structure
Abazajian, K. N. et al.
Astroparticle Physics, Volume 63, p. 66-80 (2015) arXiv: 1309.5383

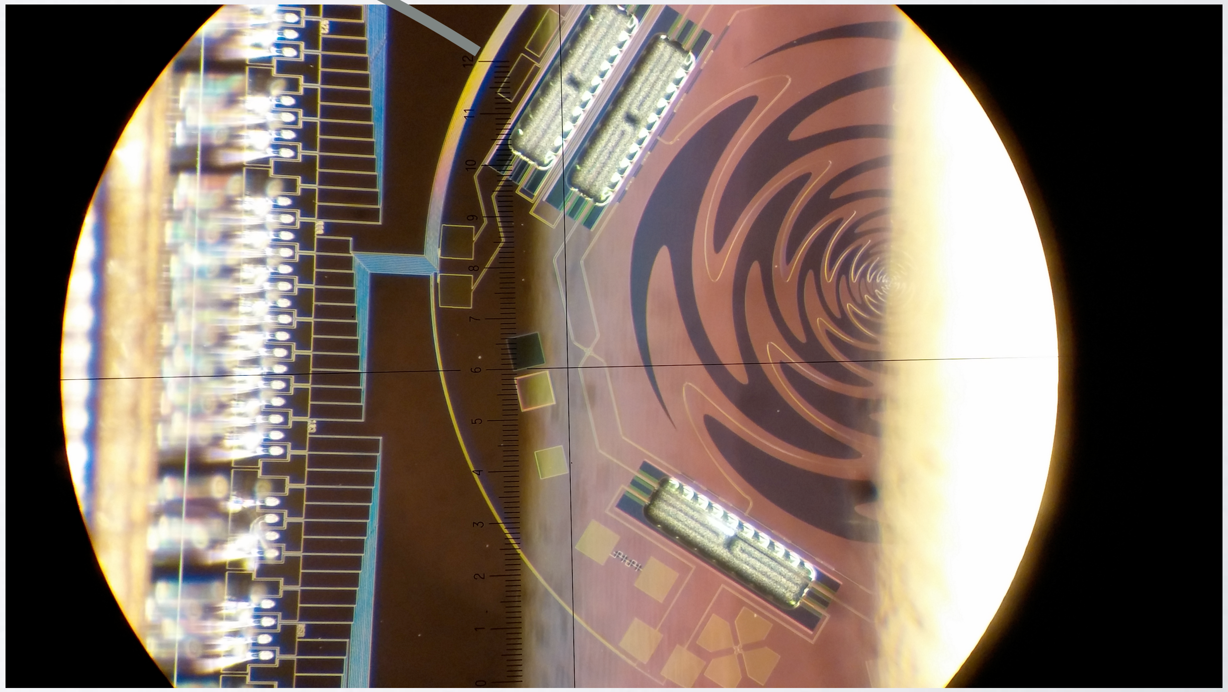


POLARBEAR-II

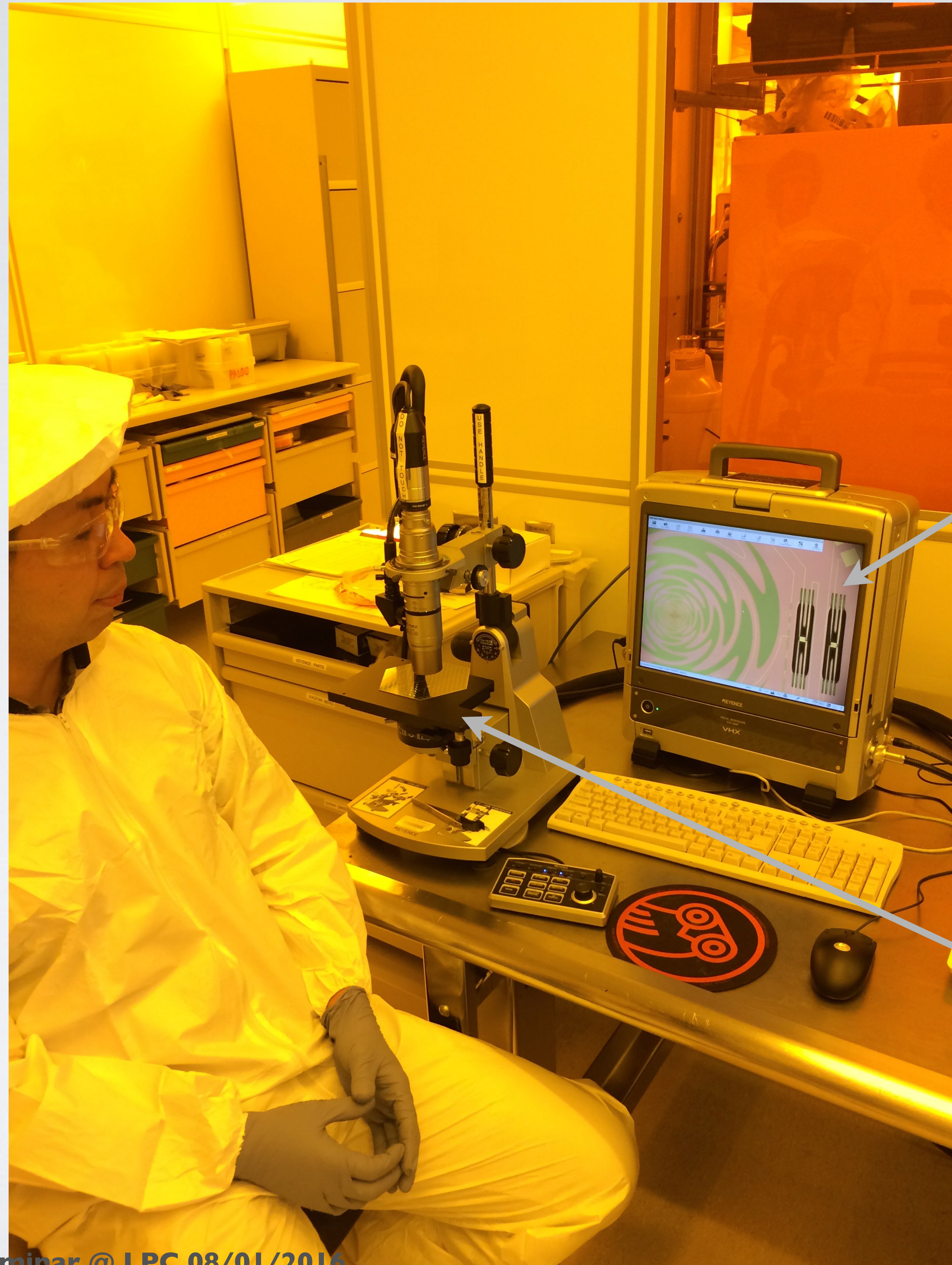
	specifications
frequencies	95 and 150 GHz
# of pixels	1897 (7588 bolometers)
NET bolometer	500 uK√s
NET array	5.7 uK√s
polarization sensitivity	10.7 uK.arcmin (20% sky coverage, 18% obs. eff.)
field of view	4.8 deg
beam sizes	5.2 arcmin @ 95 GHz 3.5 arcmin @ 150 GHz
observation time	3 years







Toki Suzuki (UCB)

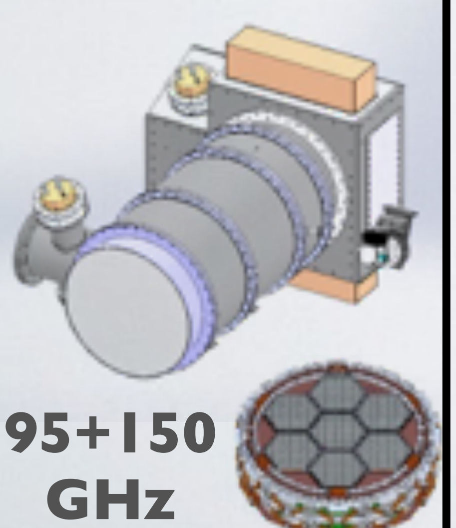


PB2 pixel

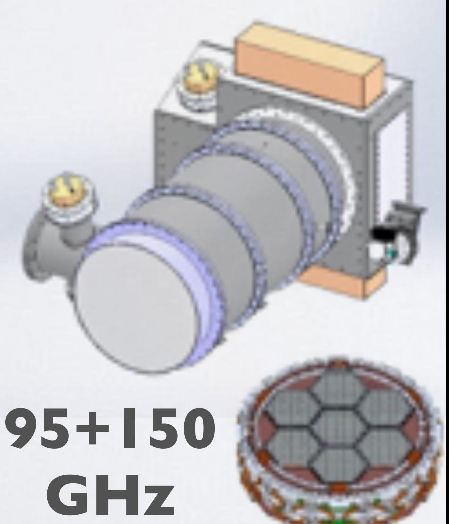
PB2 wafer

Simons Array = 3 x POLARBEAR-II

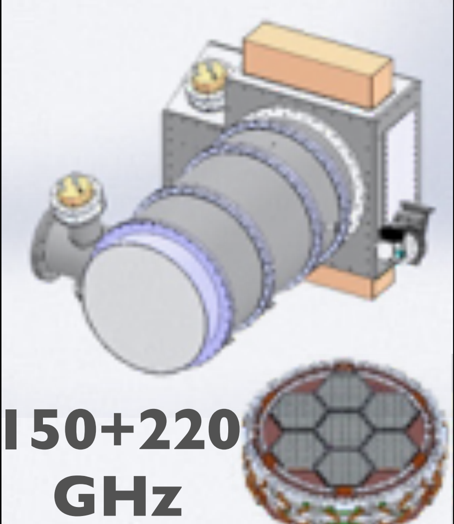
SIMONS FOUNDATION



95+150 GHz



95+150 GHz



150+220 GHz

> 22 K detectors
3/4 bands: 95, 150 and 220/280 GHz
fsky ~ 65%

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

Planned to deploy in 2020-2025:

Stage-IV

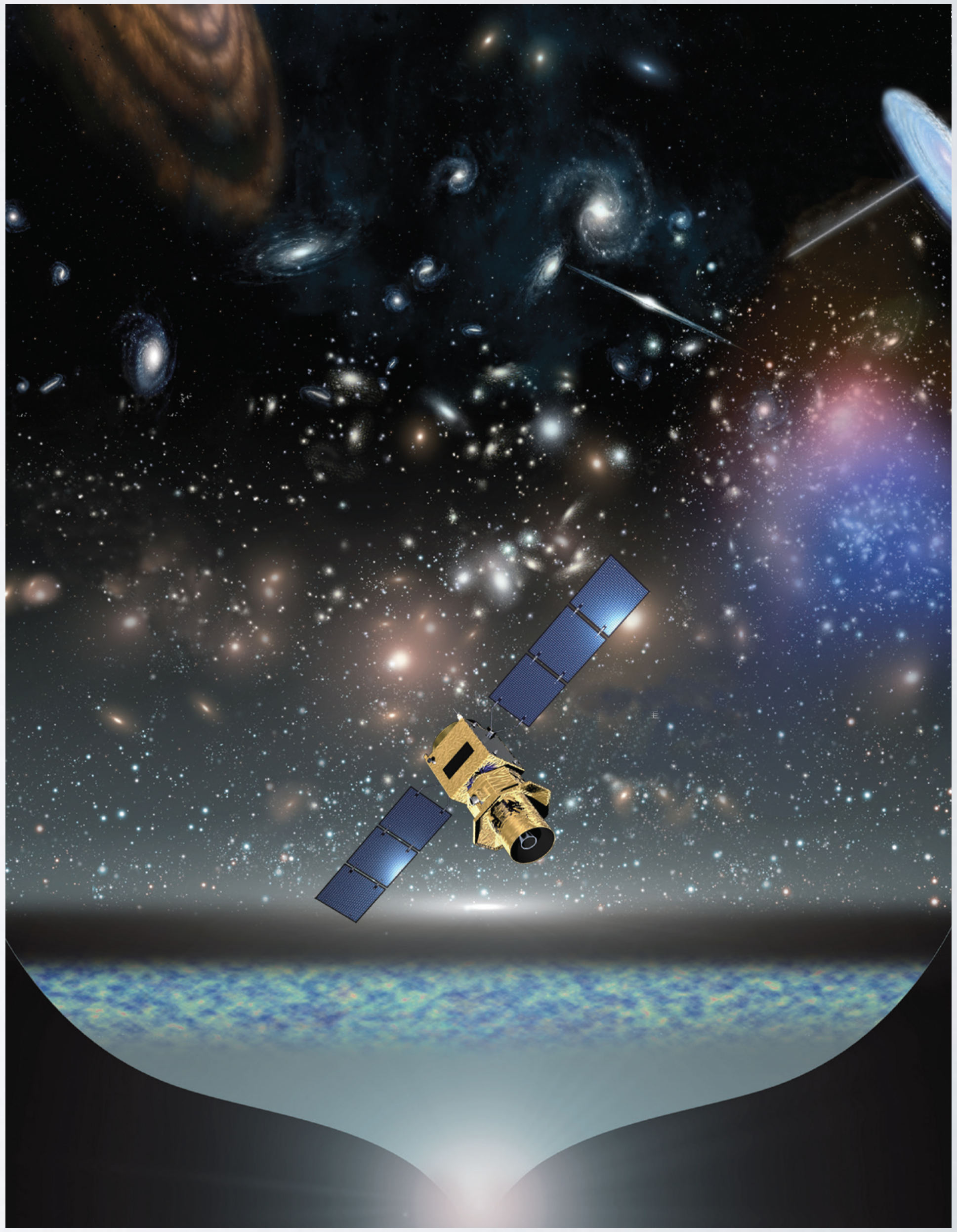
consortium of US ground-based efforts

(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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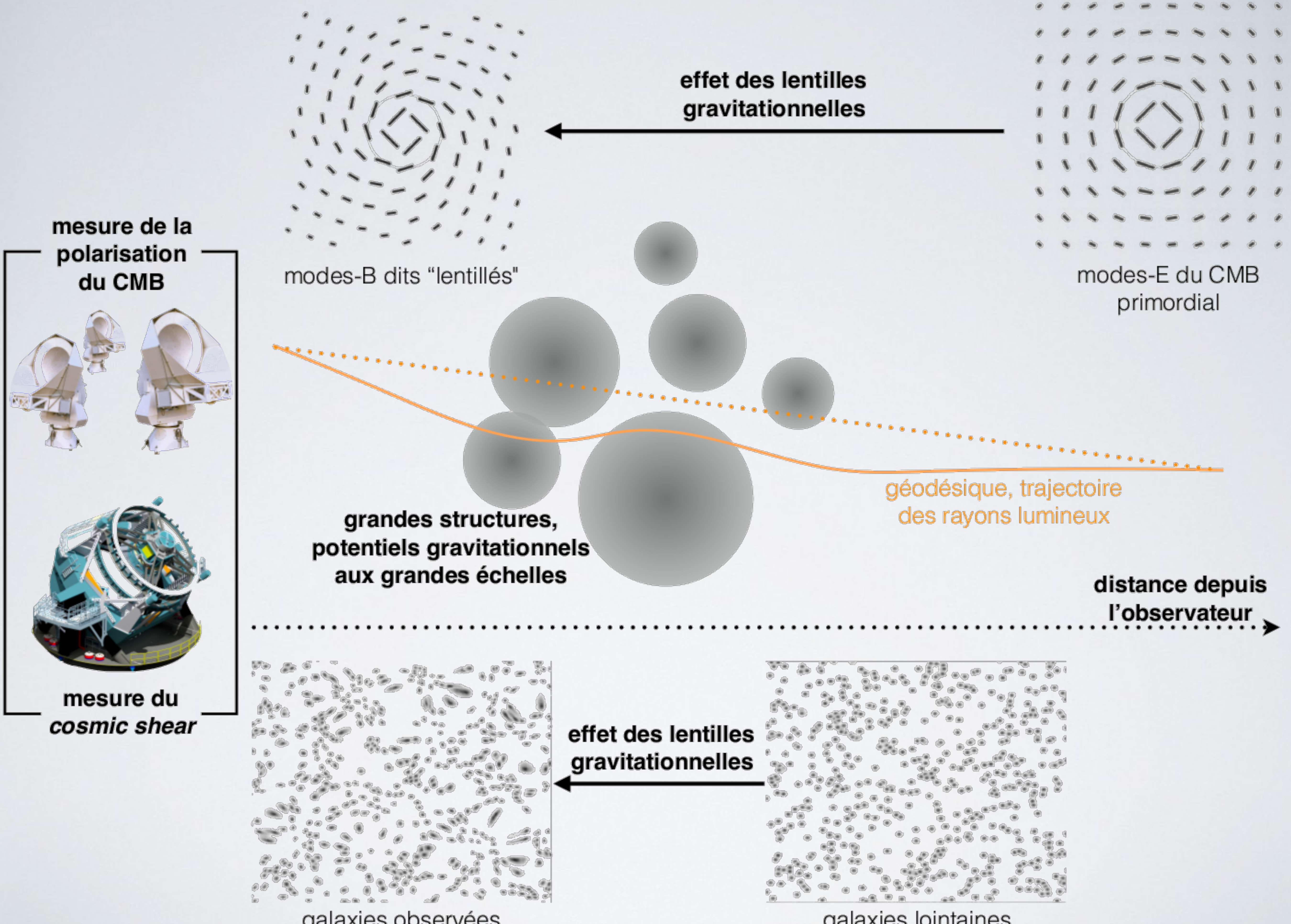

effet des lentilles gravitationnelles
modes-B dits "lentillés"
modes-E du CMB primordial
mesure de la polarisation du CMB
géodésique, trajectoire des rayons lumineux
grandes structures, potentiels gravitationnels aux grandes échelles
distance depuis l'observateur
mesure du *cosmic shear*
effet des lentilles gravitationnelles
galaxies observées
galaxies lointaines

correlation between CMB lensing et cosmic shear:

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

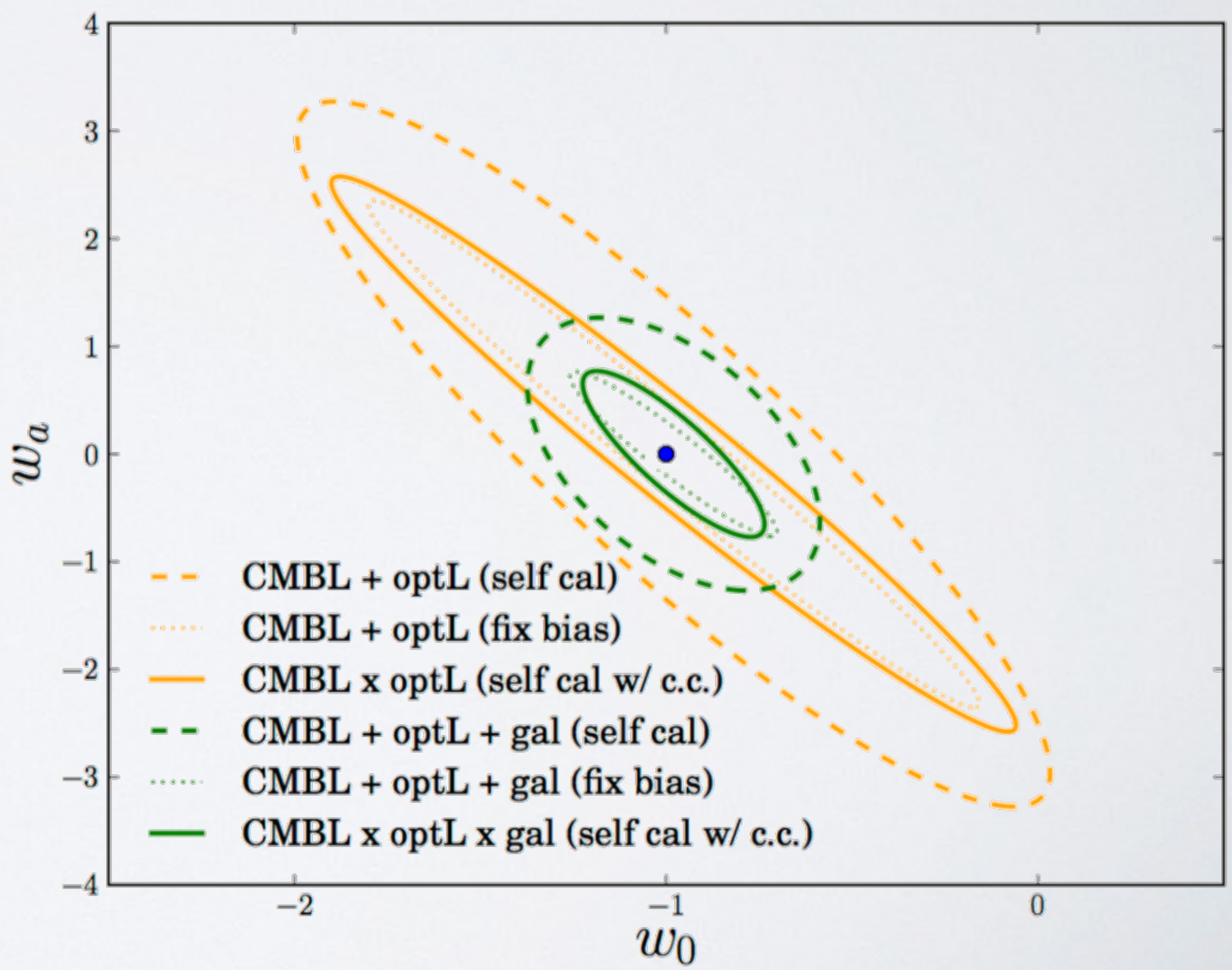
distance to last scattering surface

comoving distance at a redshift z

lensing kernel for CMB and Cosmic Shear (CS)

power spectrum of matter density perturbations

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



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

+ Valinotto (2012,2013)

instruments, observations

calibration
effets systématiques
grands volumes de données
...

calcul, clusters, super-calculateurs

programmation
implémentation
parallélisation
simulations
...

modèles théoriques

vraisemblances
statistiques
simulations
...

with LSST team @ LPC !

strong expertise on LSST analysis pipeline and image analysis

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

X

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

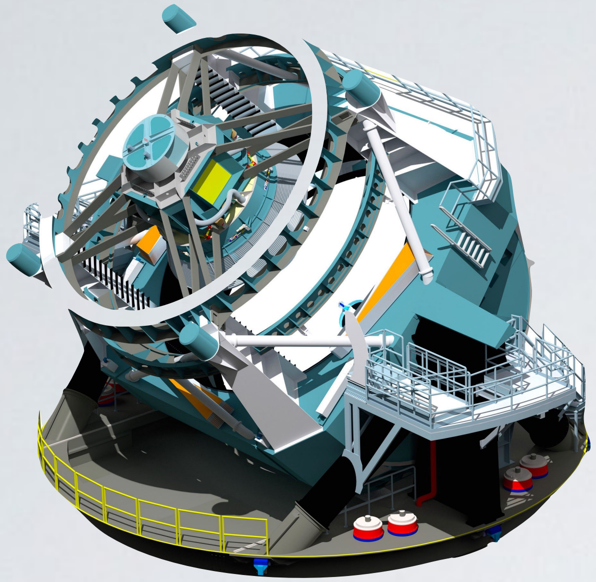
caractérisation de la formation des grandes structures (masse totale des neutrinos : Σm_ν, nombre des espèces relativistes : N_{eff}, équation d'état de l'énergie noire : w_0, w_a)

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

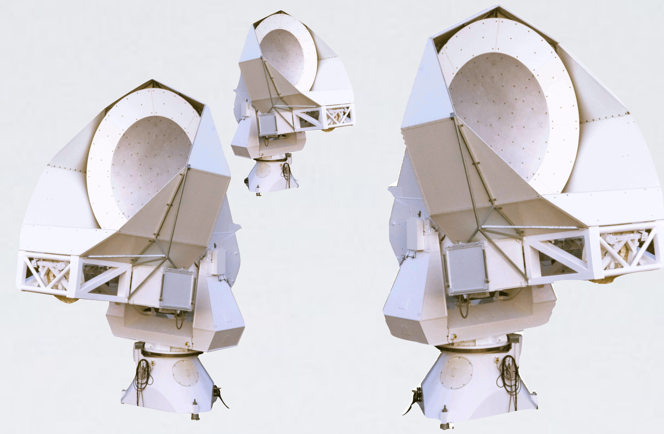
contraintes sur le mécanisme inflationnaire (paramètres de l'inflation : r, n_T)

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

Conclusions



x



x

estimation of gravitational potential ϕ

foregrounds mapping

dark matter tomography with cosmic shear

- cosmic shear will be a sensitive tool to estimate the lensing potential
- it will be used to constraint the physics governing the formation of large scale structures (e.g., neutrino mass, dark energy behavior)
- robustness of the reconstruction using the correlation with CMB observations

delensing the B-modes to constrain the inflationary mechanism

- use of estimated lensing potential to delens polarized CMB maps
- unique constraints on tensor-to-scalar ratio r and spectral index n_T.

Thank you