Cosmology from great heights: Measuring CMB polarization with POLARBEAR and SPIDER

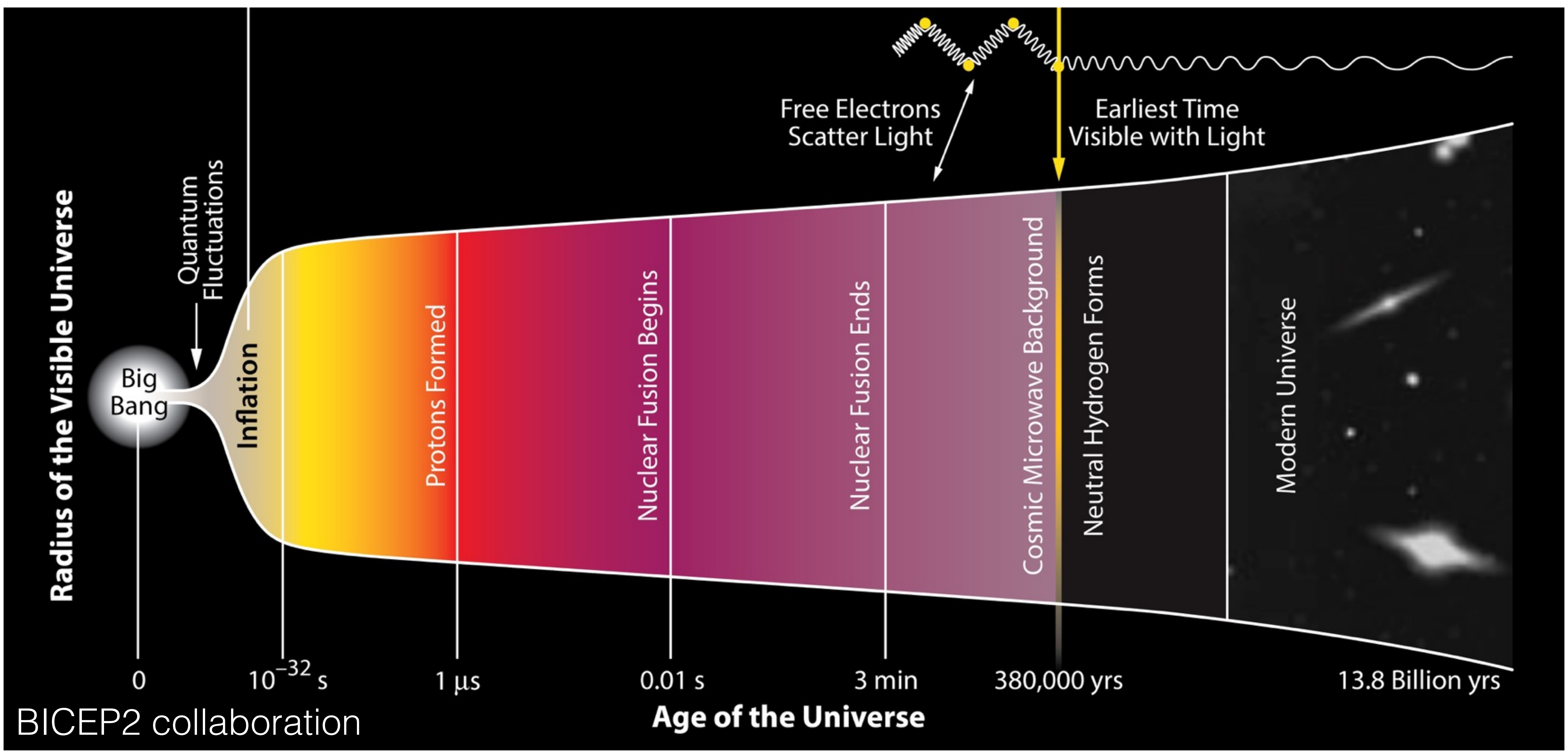
Zigmund Kermish
4-10-15
CLASSE Journal Club

Outline

- Review of the science & recent measurements
- Instrumental requirements & challenges
- POLARBEAR experiment
    - First season results
- SPIDER experiment
    - Performance of 1st flight
- Future plans

Quick CMB intro

A snapshot of the early universe!

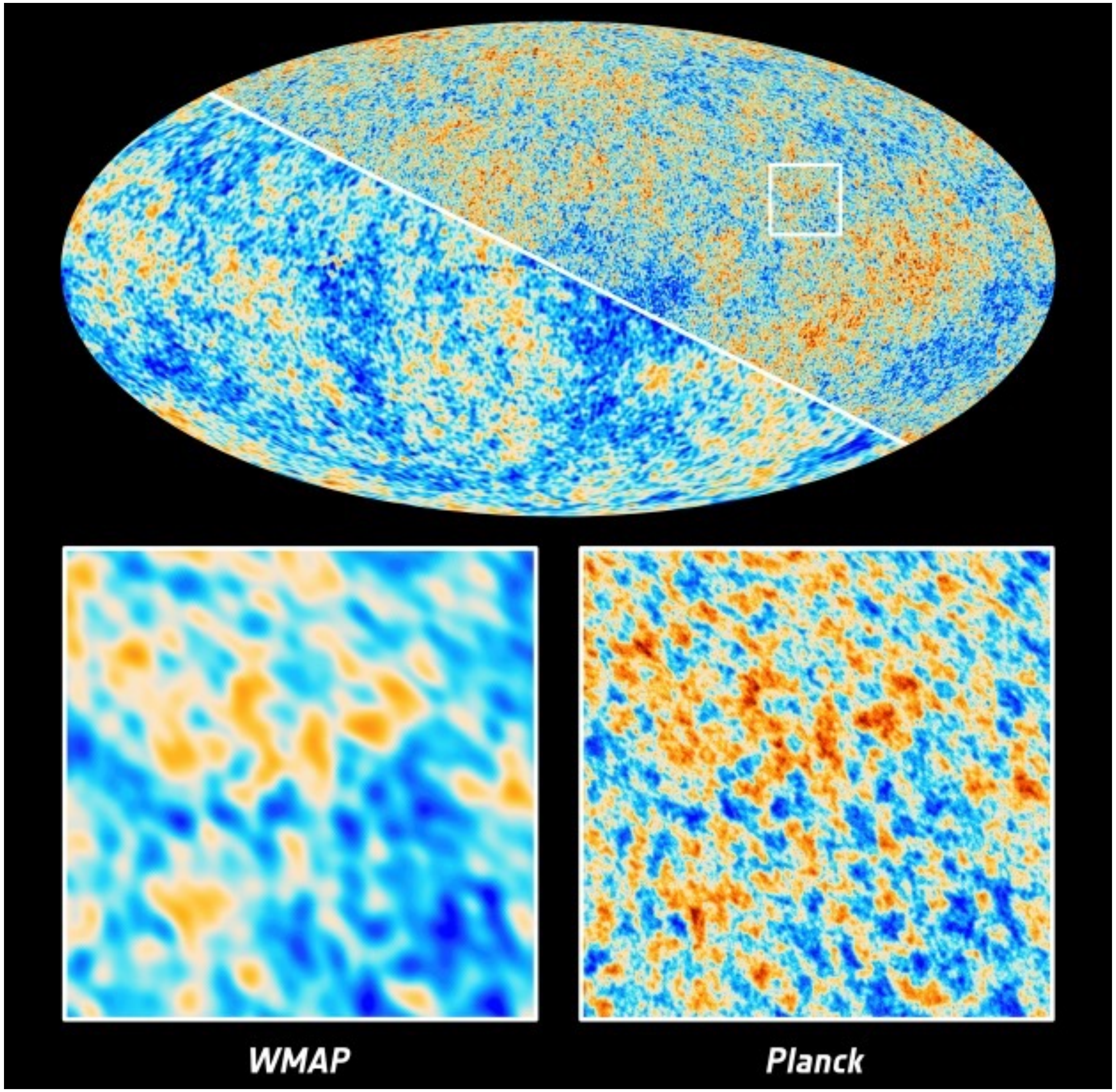


Quick CMB intro: anisotropy

- A snapshot of the distribution of matter in the early universe

(not the most exciting snapshot)

- Over/under densities reflected in hot/cold spots



Quick CMB intro: anisotropy

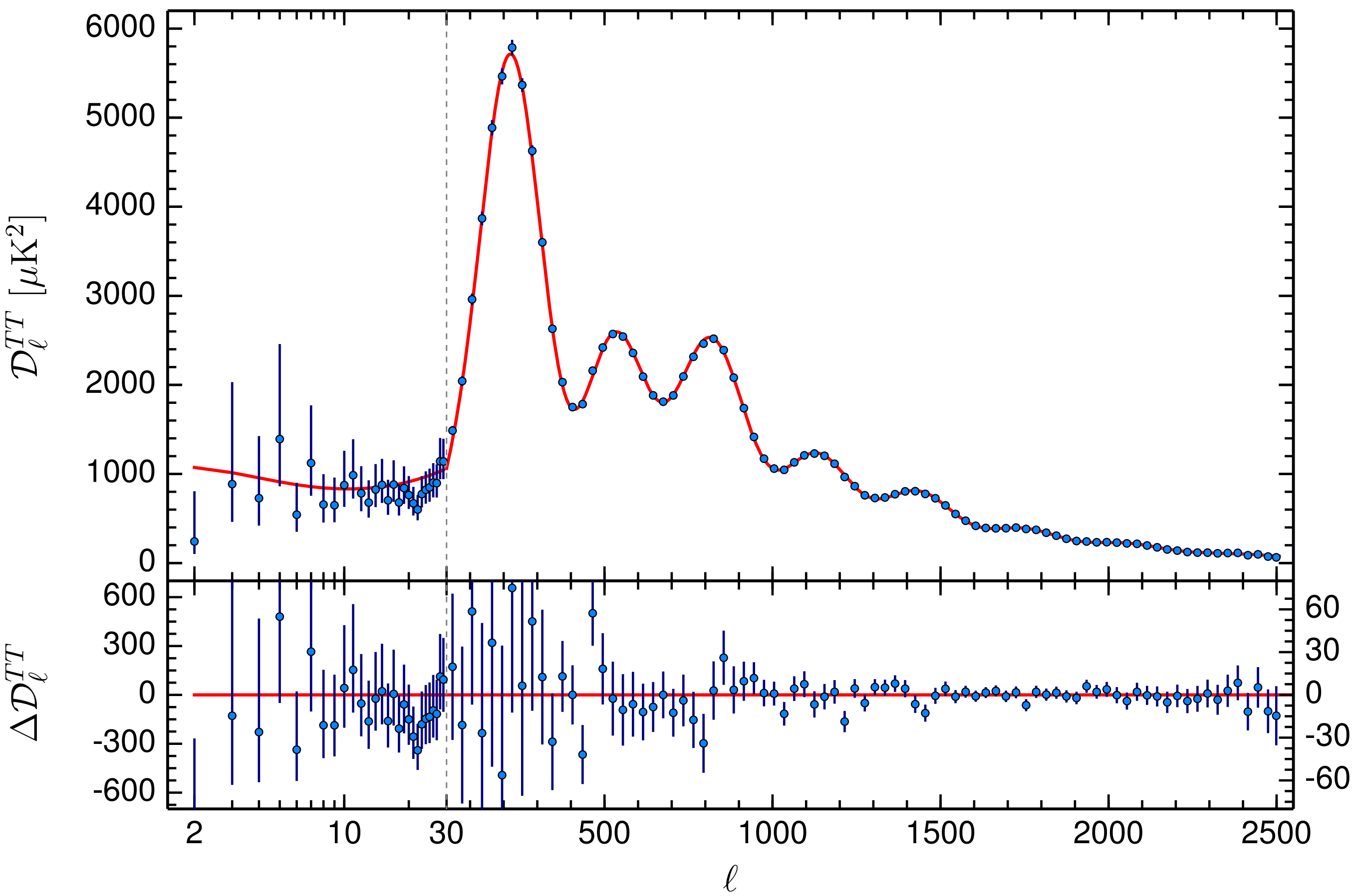
$$\frac{\Delta T(\theta,\phi)}{T} = \sum_{lm} a_{T,lm} Y_{lm}(\theta,\phi)$$

$$C_l^T = \langle a_{T,lm} a^*_{T,lm} \rangle$$

- Angular power spectrum sensitive to initial conditions and cosmological parameters

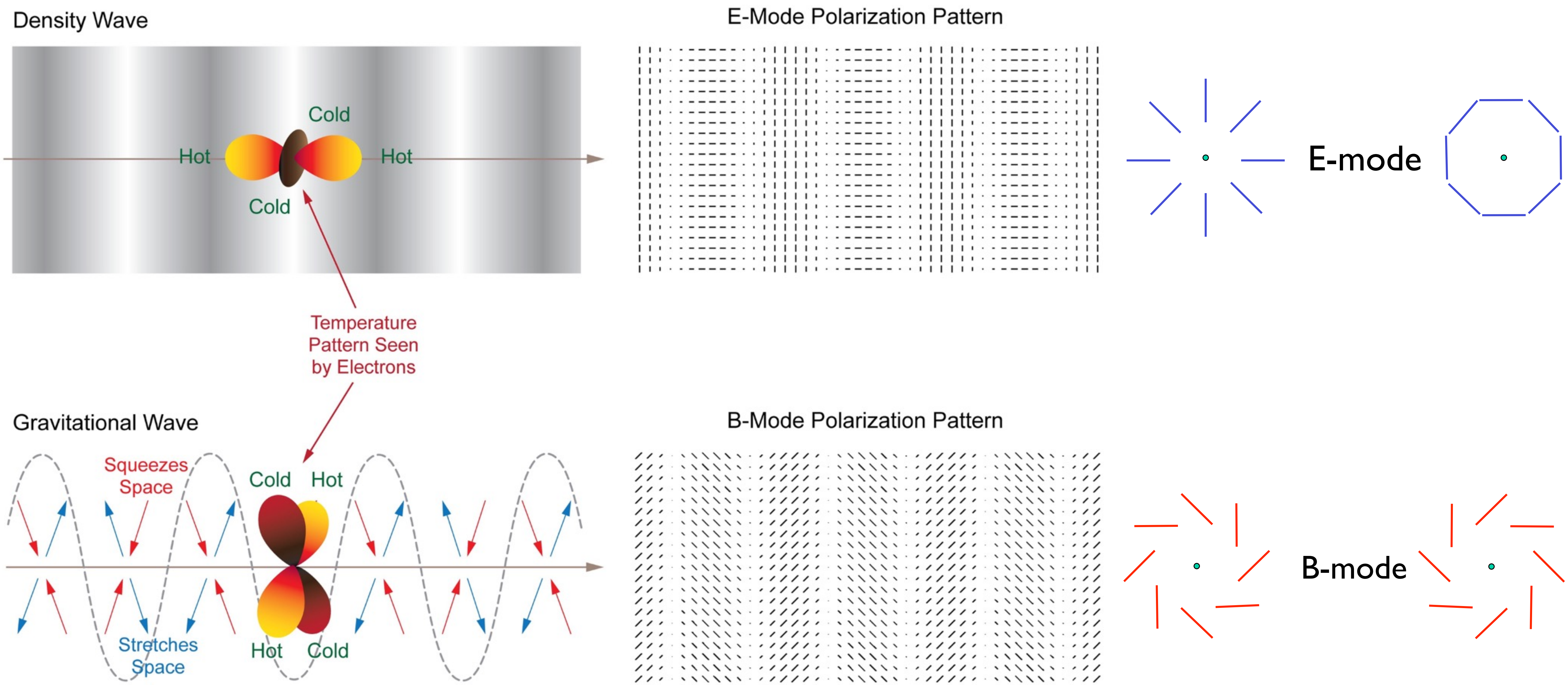
$$\Omega_b h^2, \Omega_m h^2, \Omega_k, \Omega_\Lambda$$

- Inflation predicts initial conditions from quantum fluctuations, distinct acoustic peaks (coherent phase in perturbations)



Planck (2015)

Quick CMB intro: polarization



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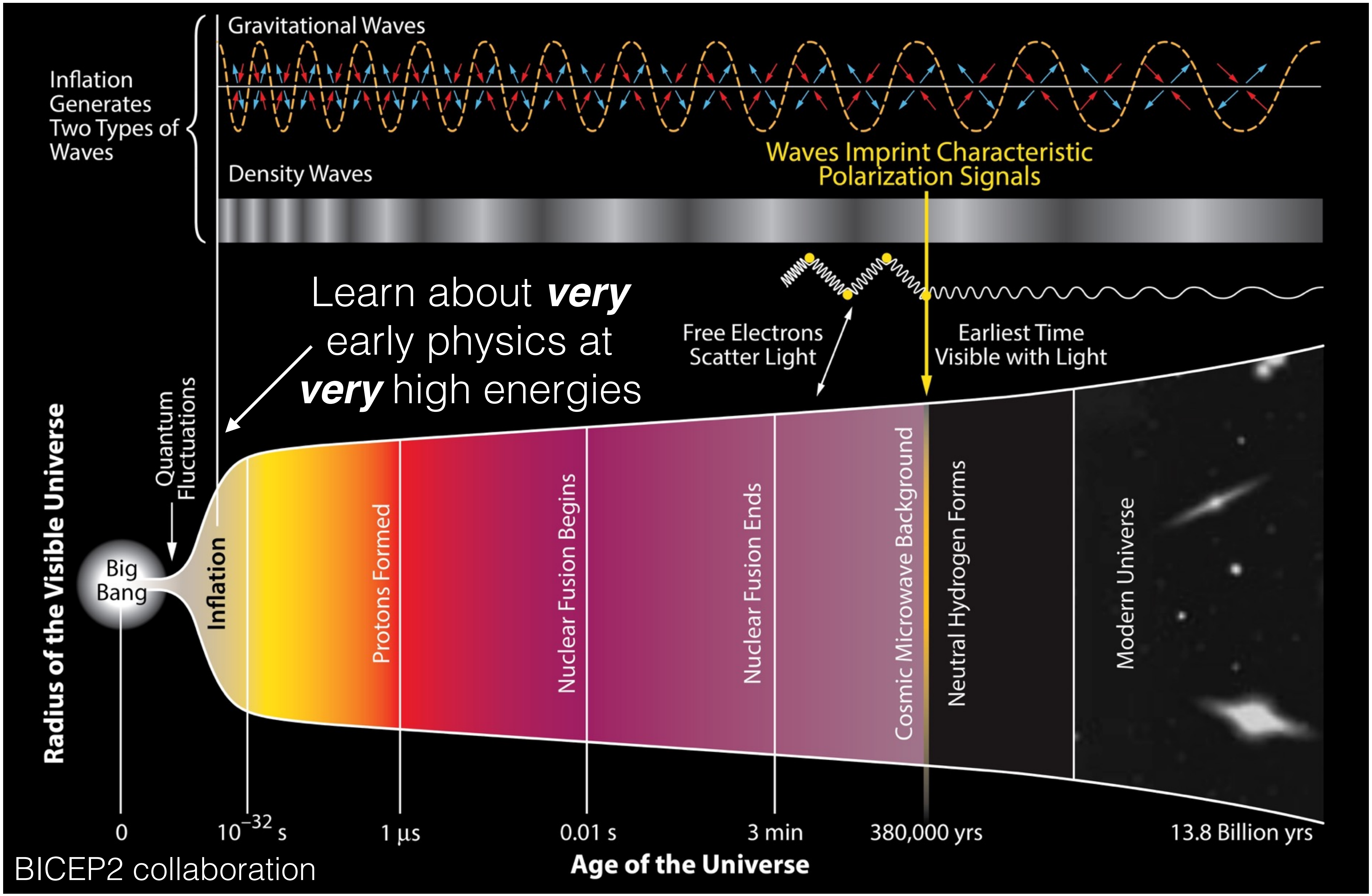

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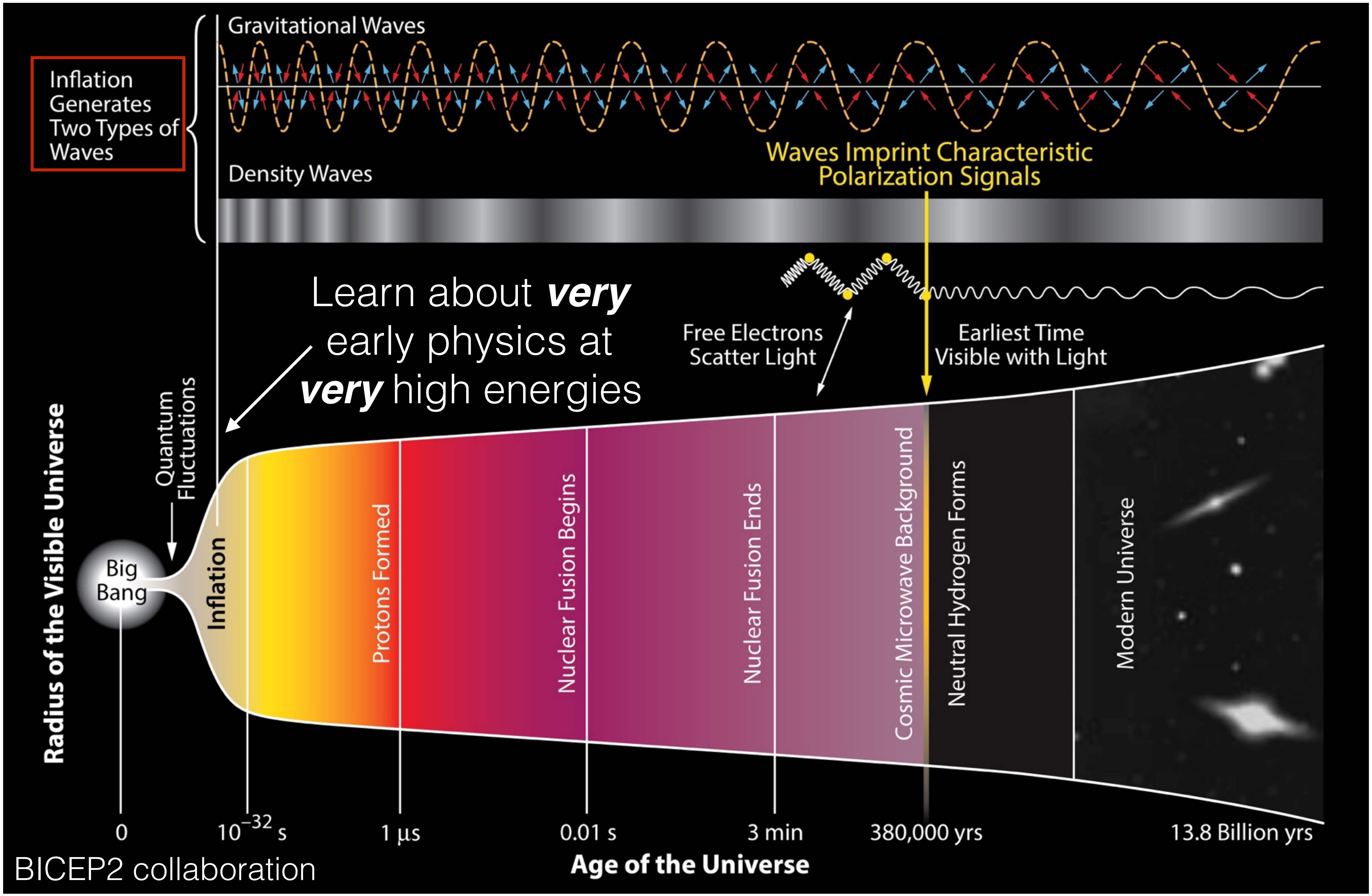

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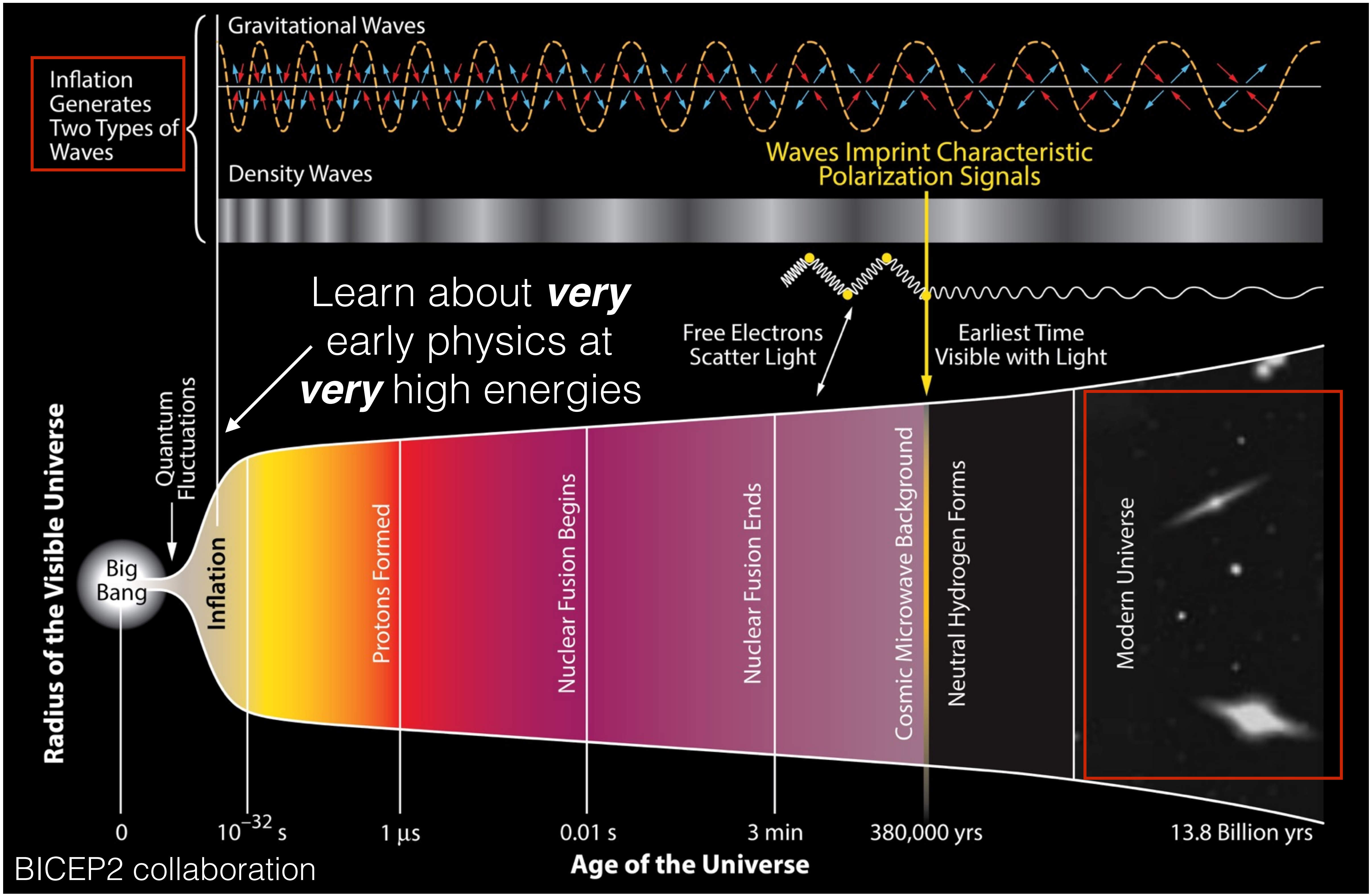
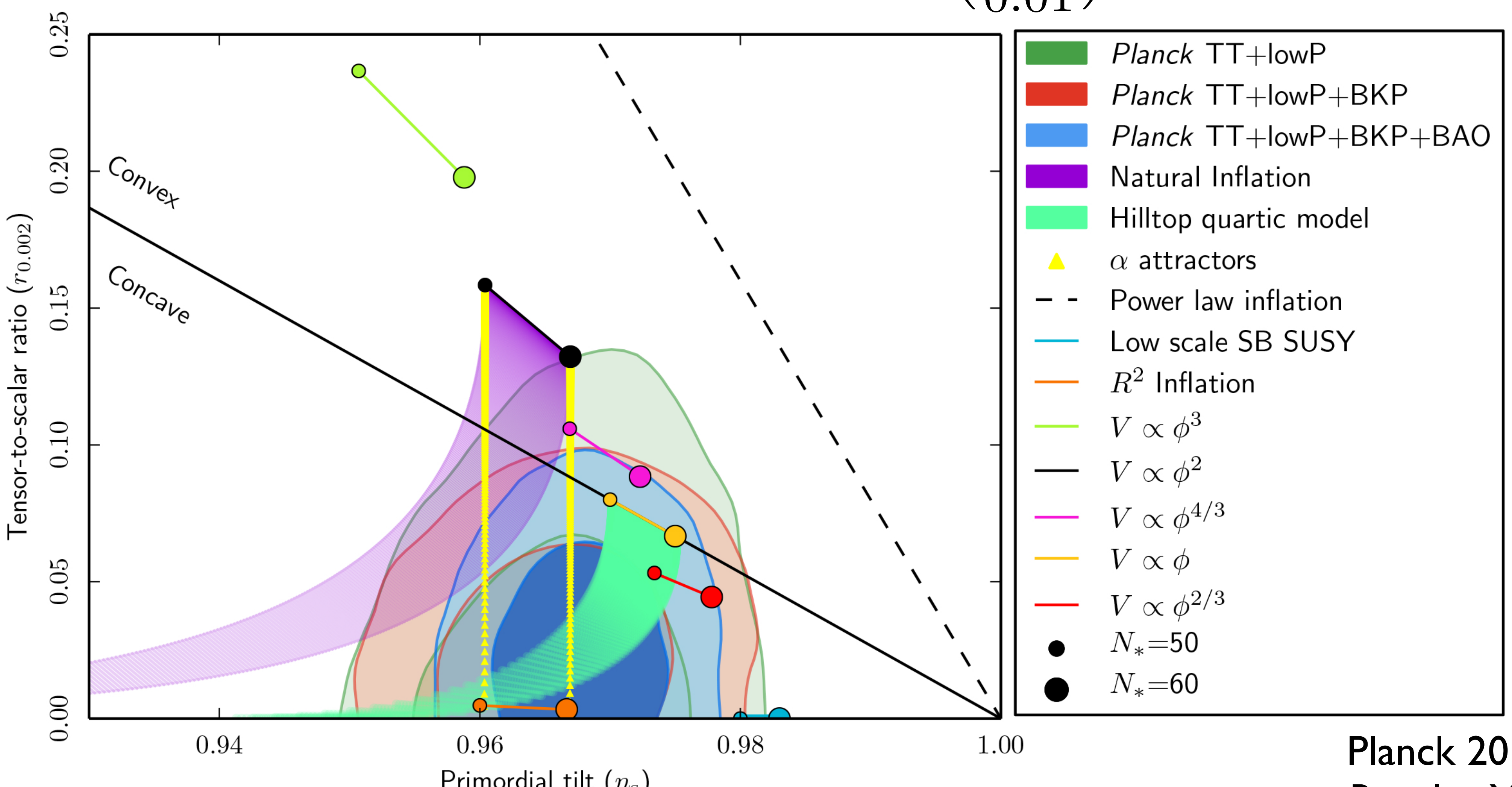


Quick CMB intro: polarization

- Degree scale B-modes help constrain energy scale of inflation

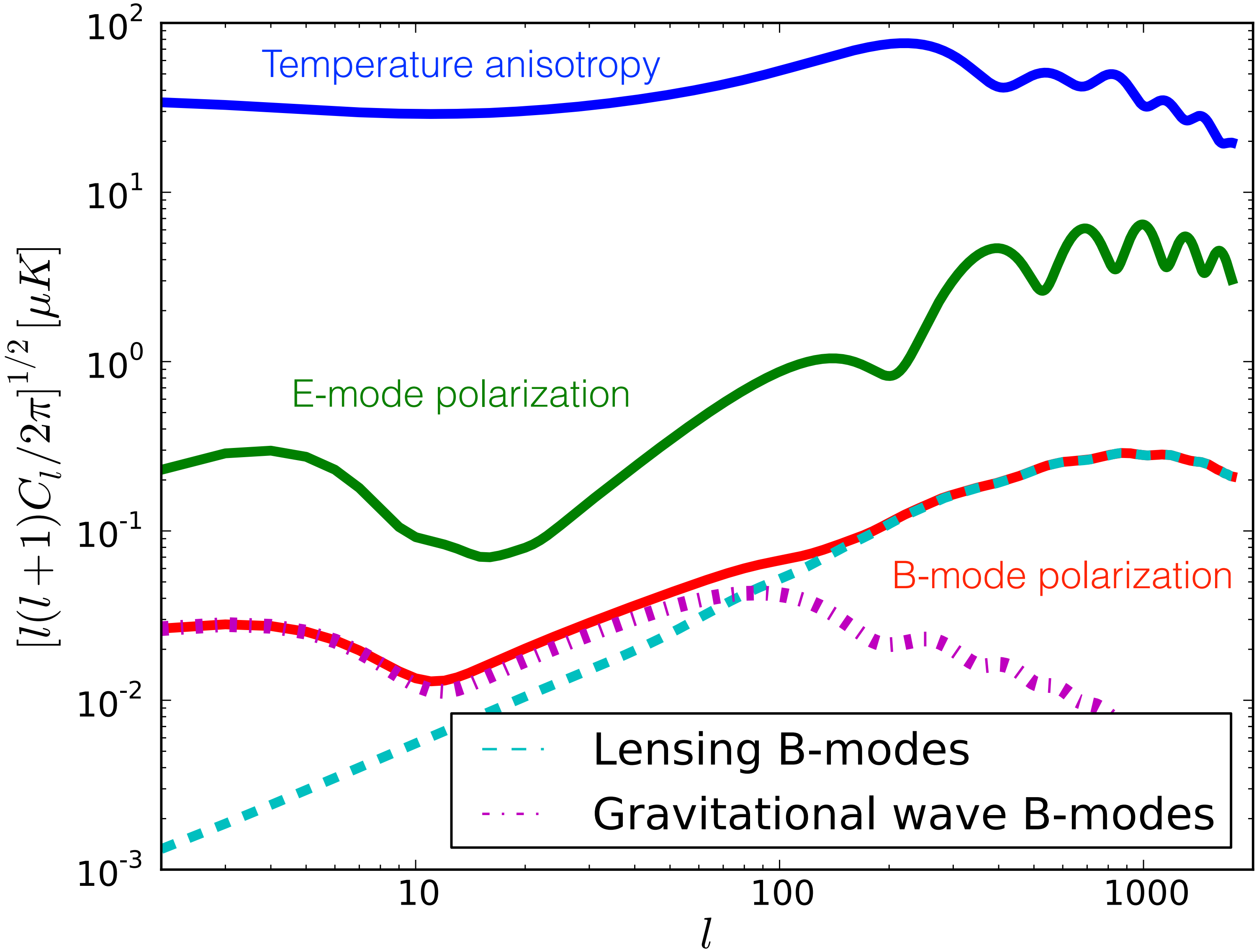
$$V^{1/4} = 1.06 \times 10^{16} GeV \left(\frac{r}{0.01}\right)^{1/4}$$



Planck 2015 Results: XX

Quick CMB intro: polarization

- Density perturbations generate:
  - Temperature anisotropies
  - E-modes
  - Seed large scale structure (which causes lensing B-modes)
- Gravitational waves generate:
  - E & B modes (unique source of ***degree*** scale B-modes)



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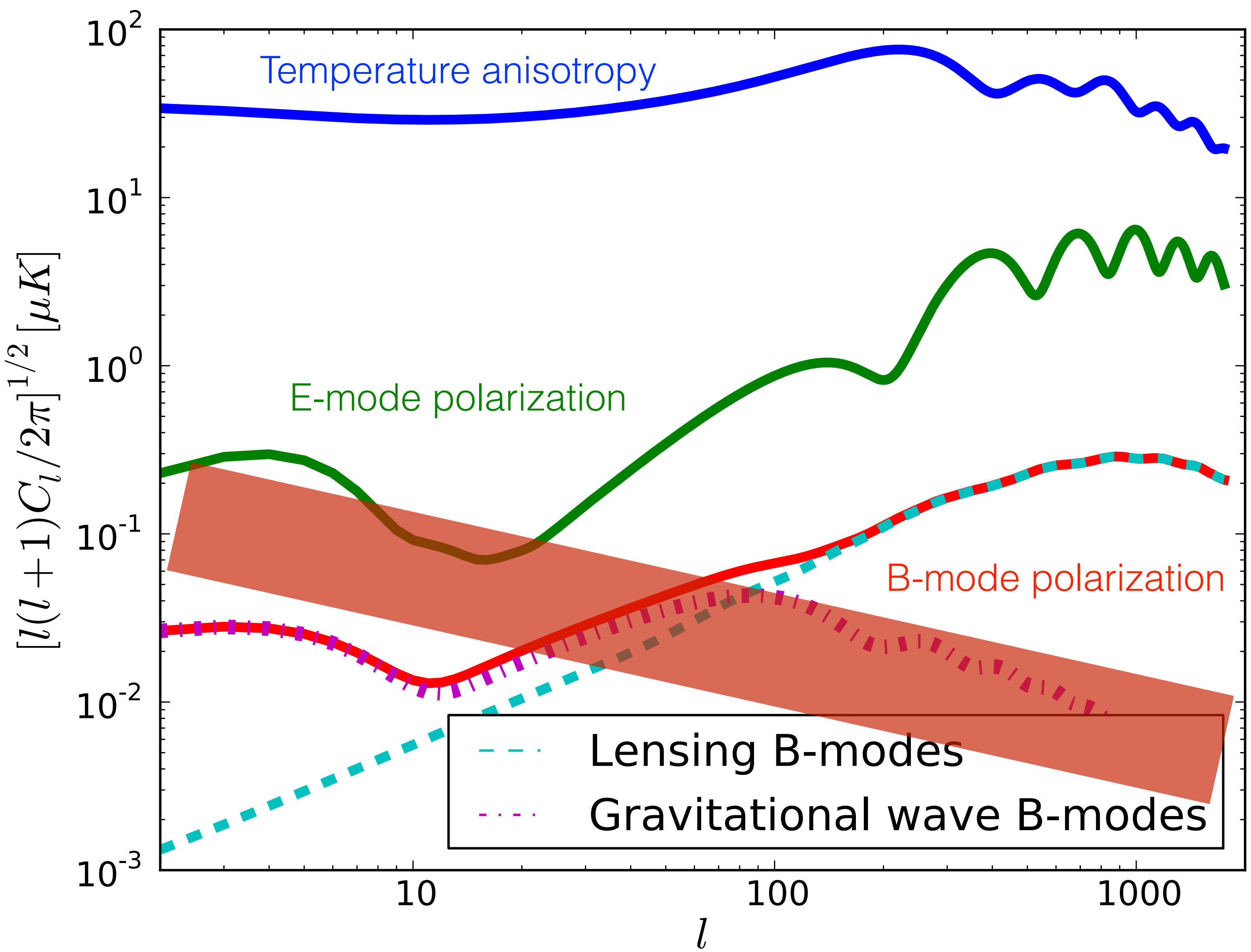
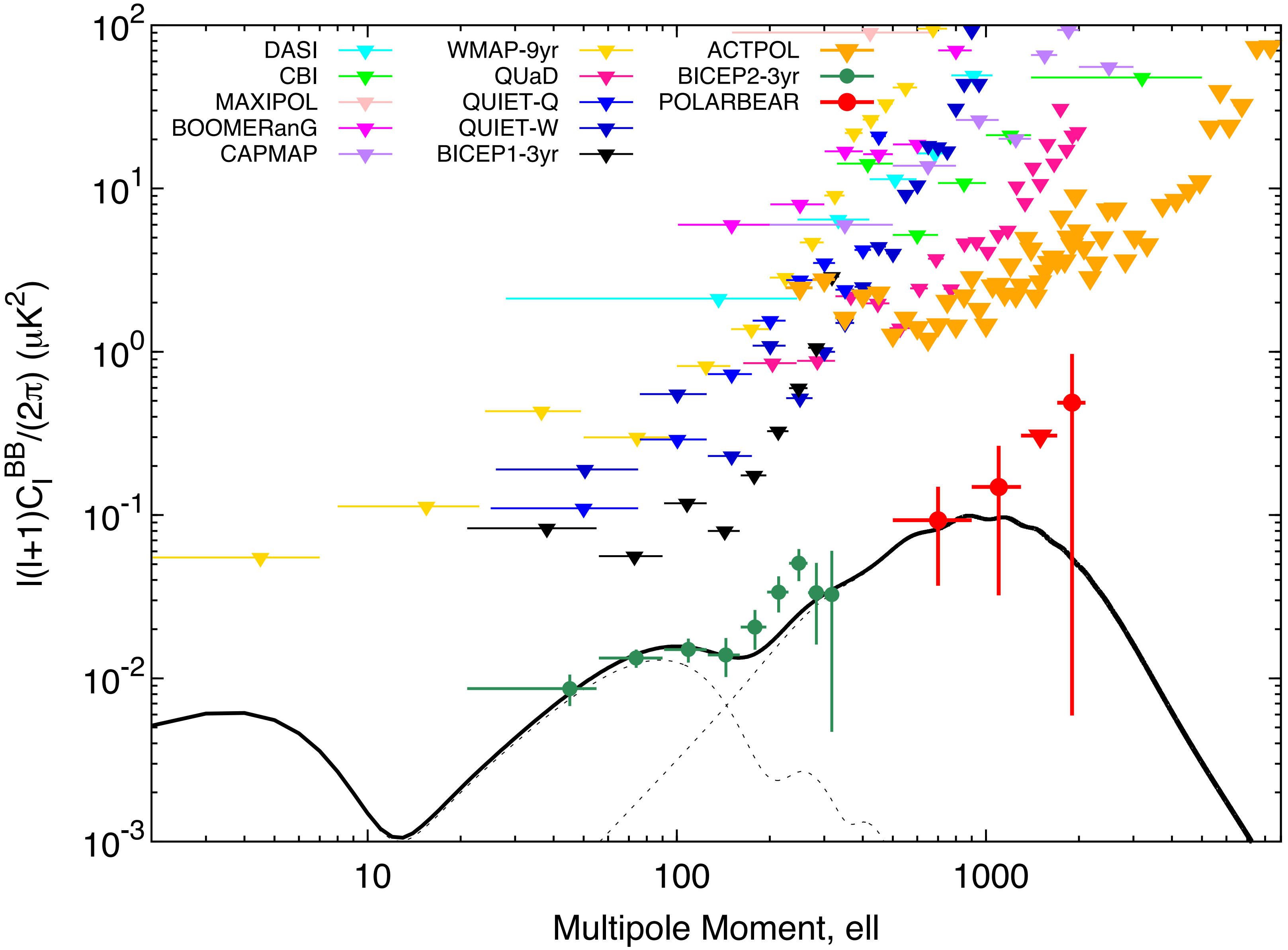


Quick CMB intro: polarization measurements

- Measuring degree scale B-mode is the current ‘holy grail’ in experimental cosmology…



Quick CMB intro: polarization measurements

SPACE & COSMOS

Space Ripples Reveal Big Bang's Smoking Gun

By DENNIS OVERBYE   MARCH 17, 2014

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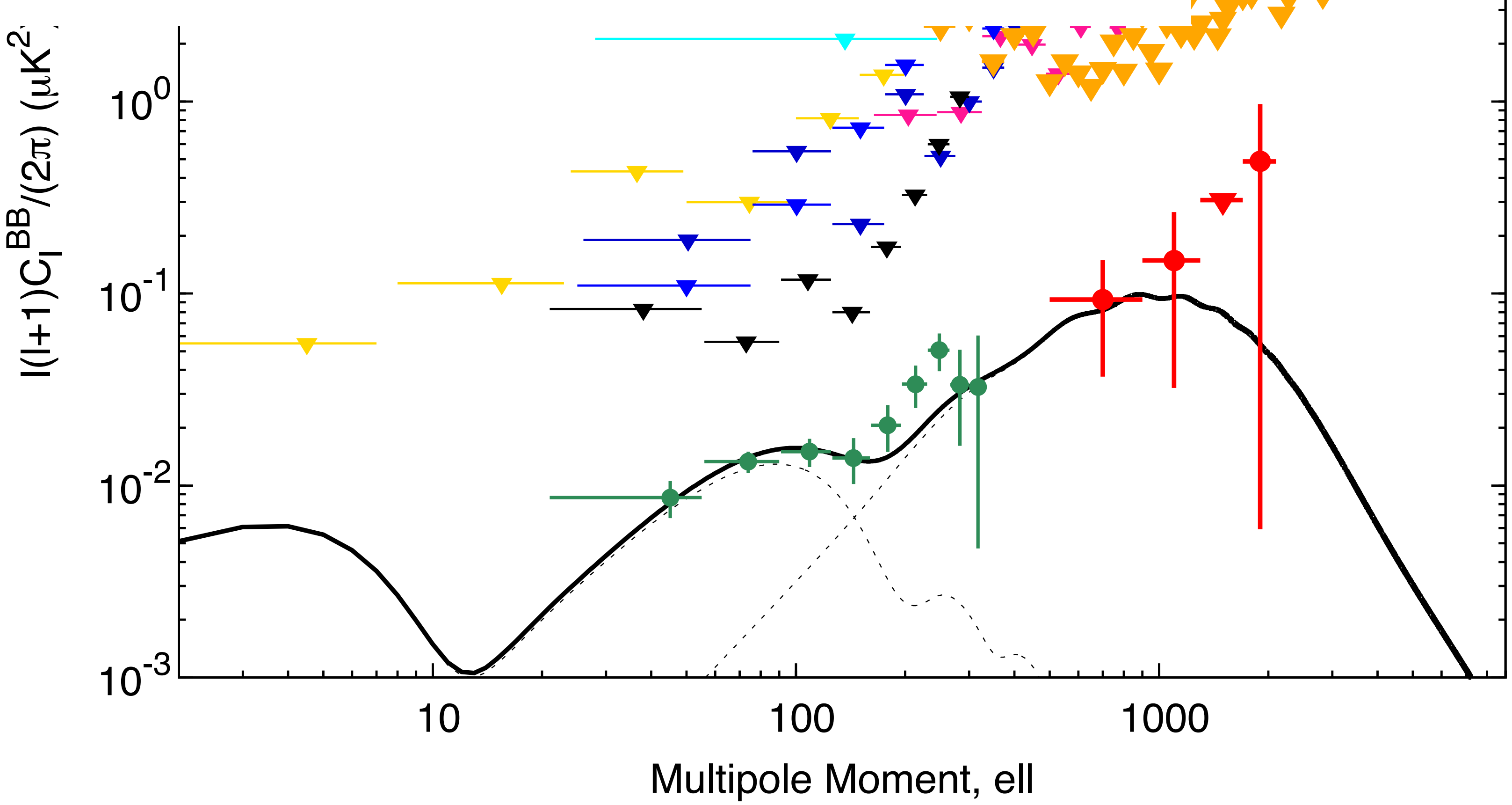

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Astronomers Hedge on Big Bang Detection Claim

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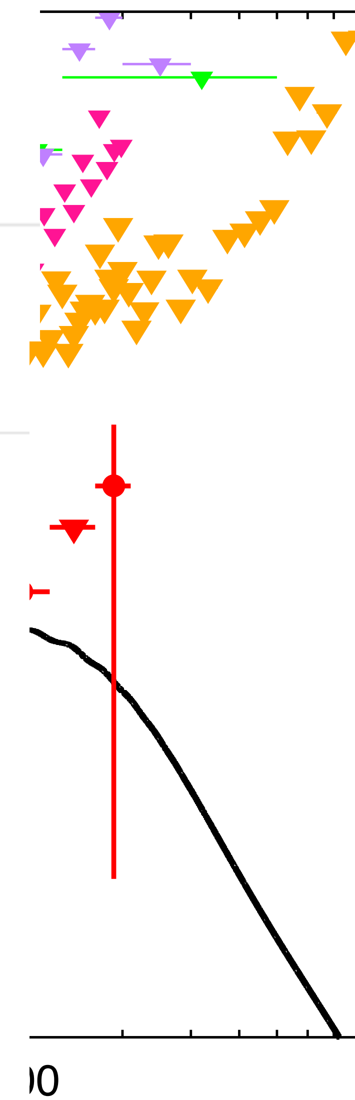

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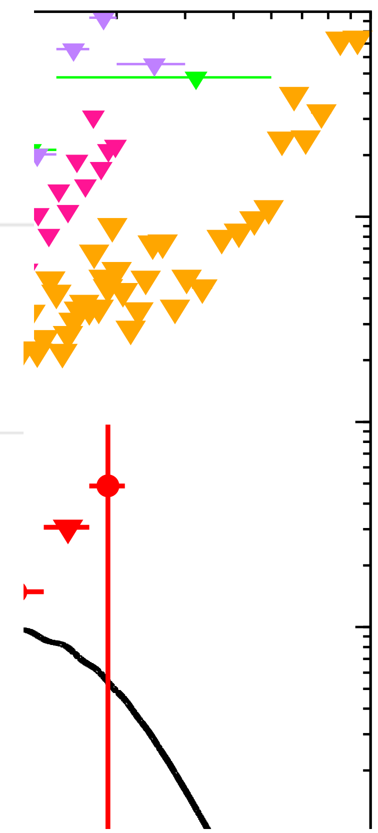

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SPACE & COSMOS

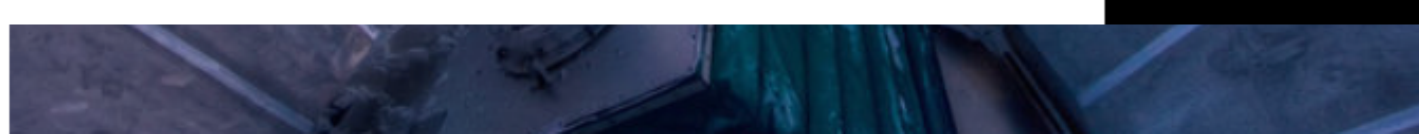
97 COMMENTS

Criticism of Study Detecting Ripples From Big Bang Continues to Expand

By DENNIS OVERBYE SEPT. 22, 2014

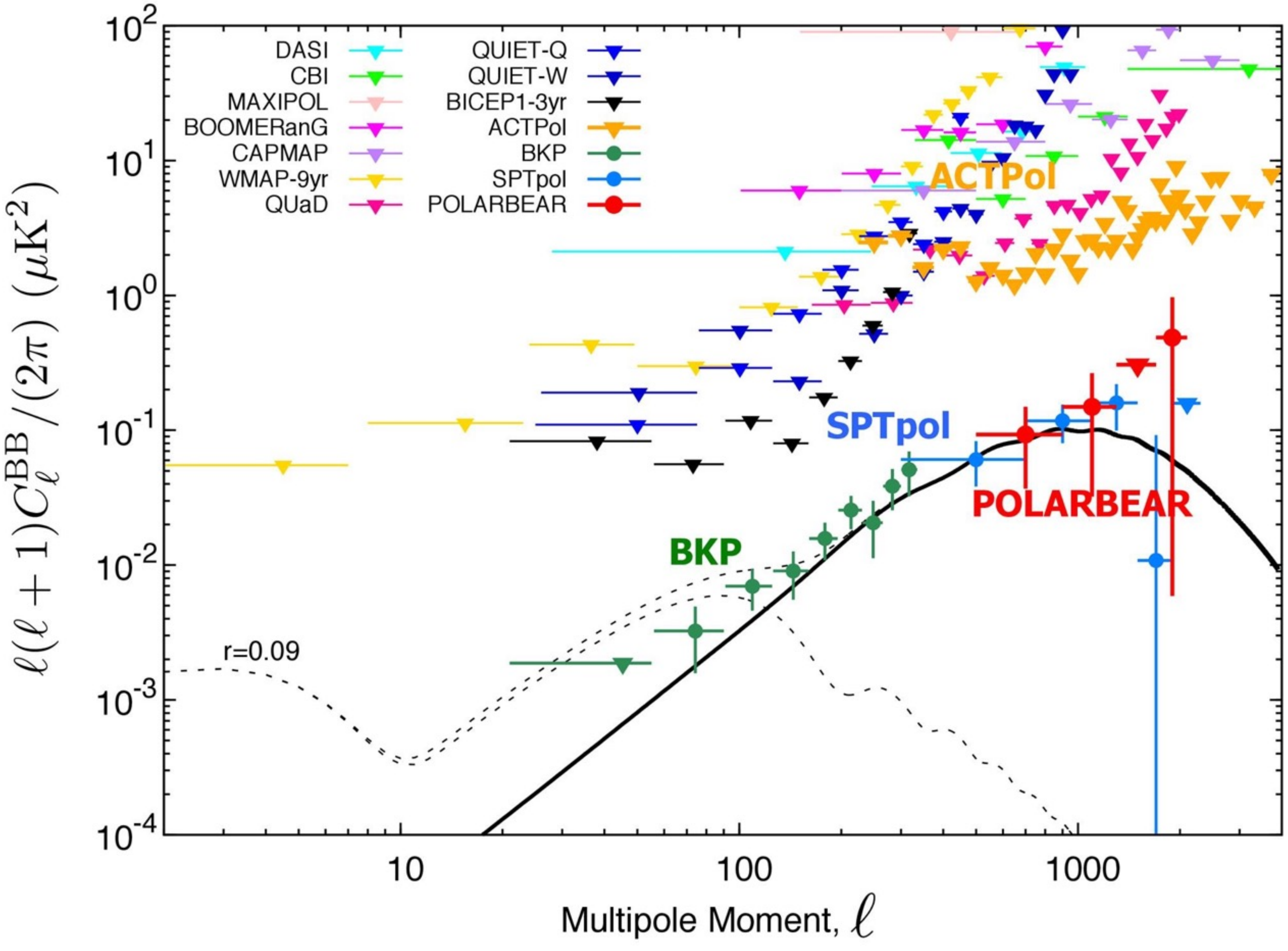
Email

Stardust got in their eyes.



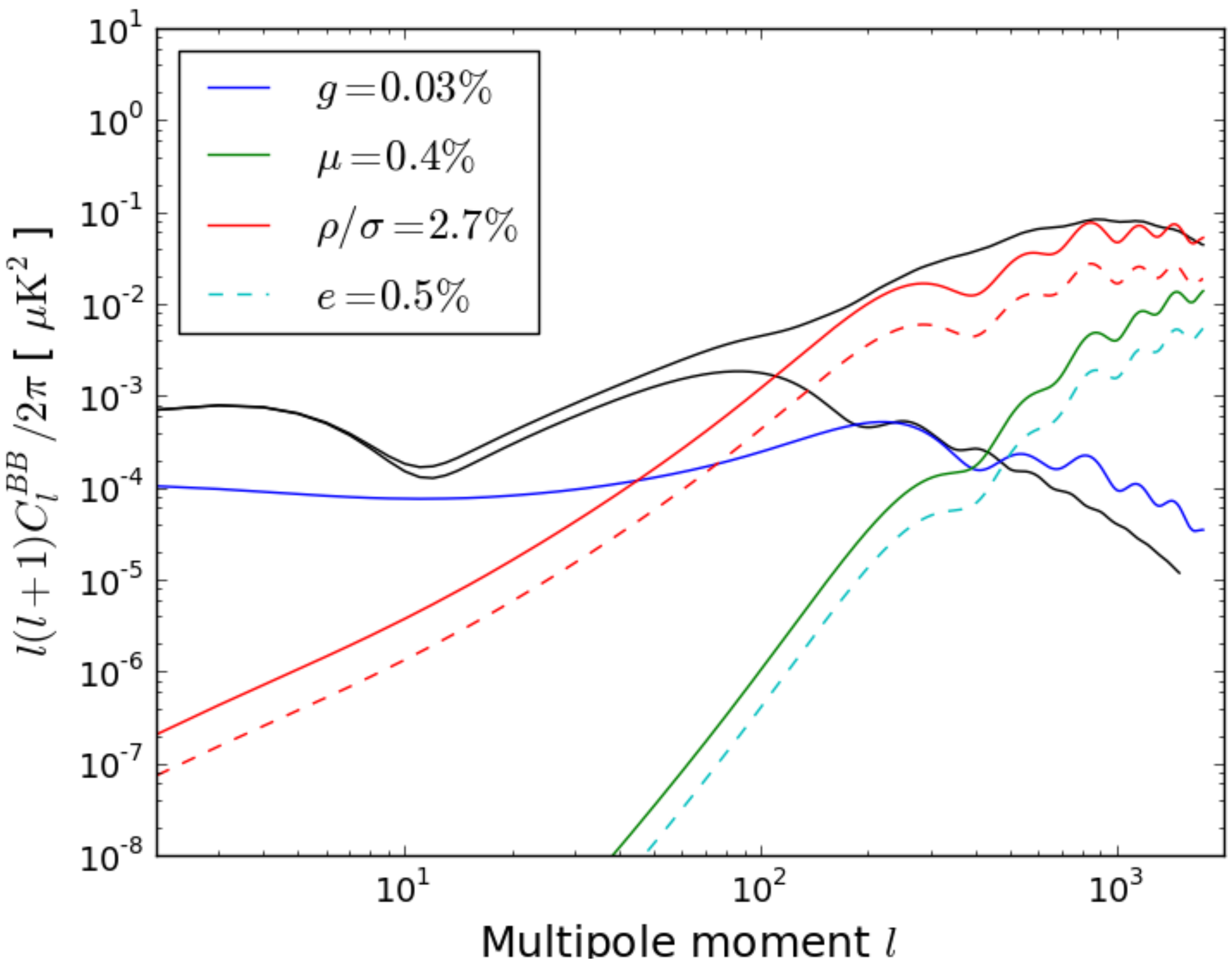
Quick CMB intro: polarization measurements

- Measuring degree scale B-mode is the current ‘holy grail’ in experimental cosmology…but it’s hard



Measuring polarization: Requirements

- Raw sensitivity (large arrays of background limited detectors)
- Control of systematic instrumental effects
    - Differential beam effects peak at ~beam scales
    - HWP & sky rotation suppress diff. gain, pointing, beam width
- Characterize & remove foregrounds on large scales (multi-frequency observations)
- Ability to 'de-lens' (high resolution)



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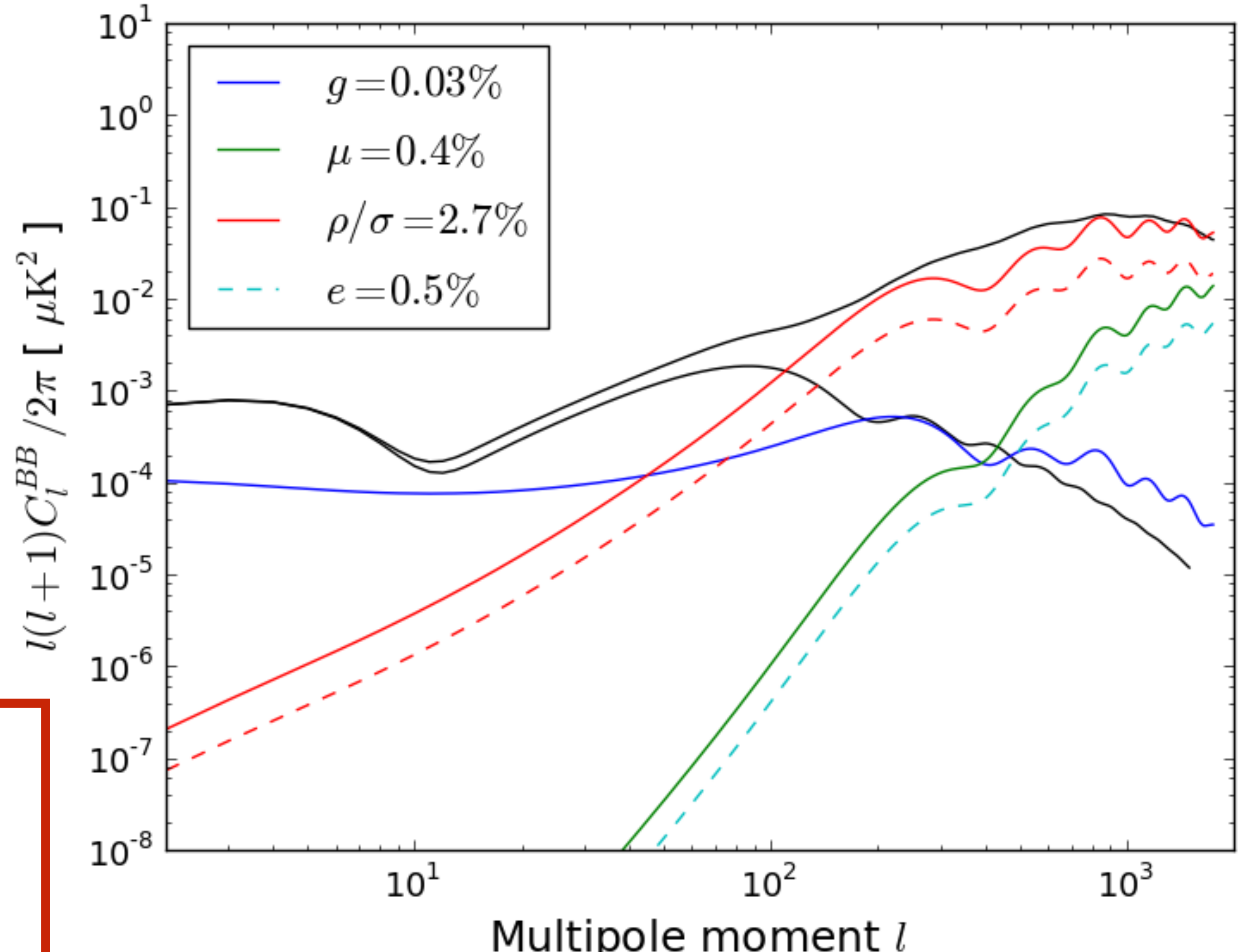
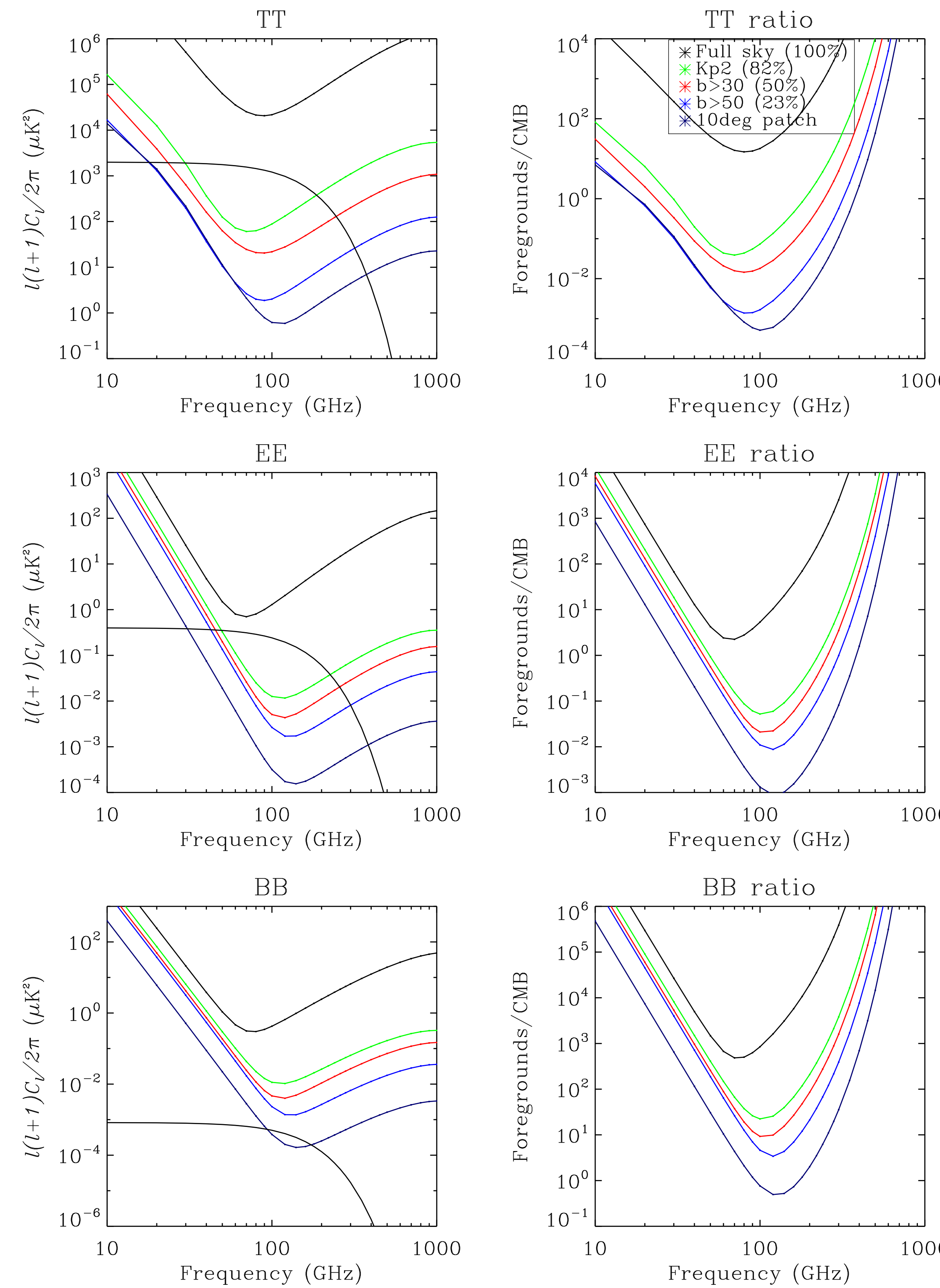


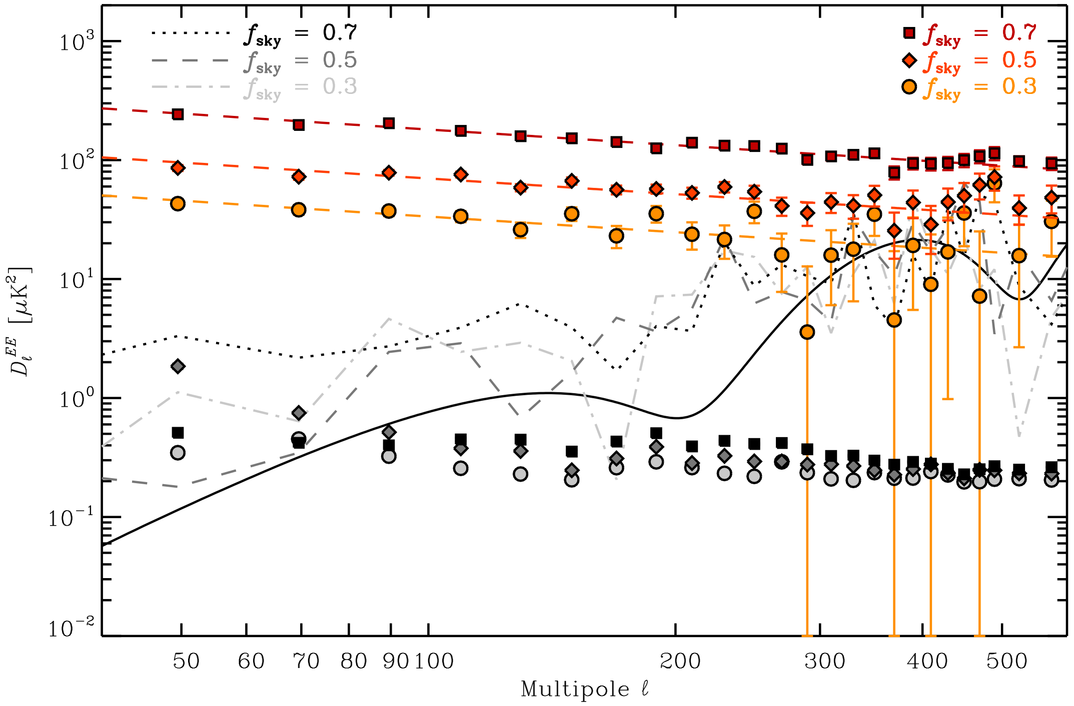
Measuring polarization: foregrounds

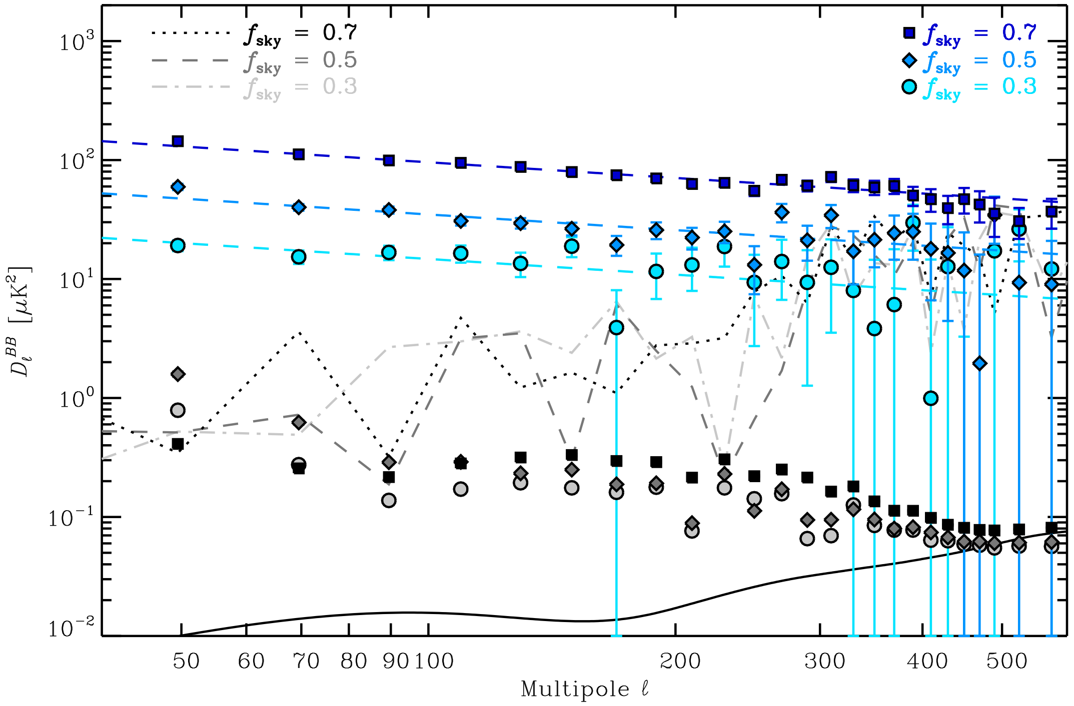
- Many efforts focused on smaller patches in ‘cleaner’ regions of the sky
- 150GHz minimum for foregrounds, several single frequency instruments deployed
- We didn’t have ***measurements*** of the the polarized fraction of foregrounds — these were known risks



Dunkley et al. 2008

Measuring polarization: foregrounds





- Planck gave us measurements of the polarized fraction of dust across the full sky @ 353GHz
- Single frequency observations are ***not adequate***

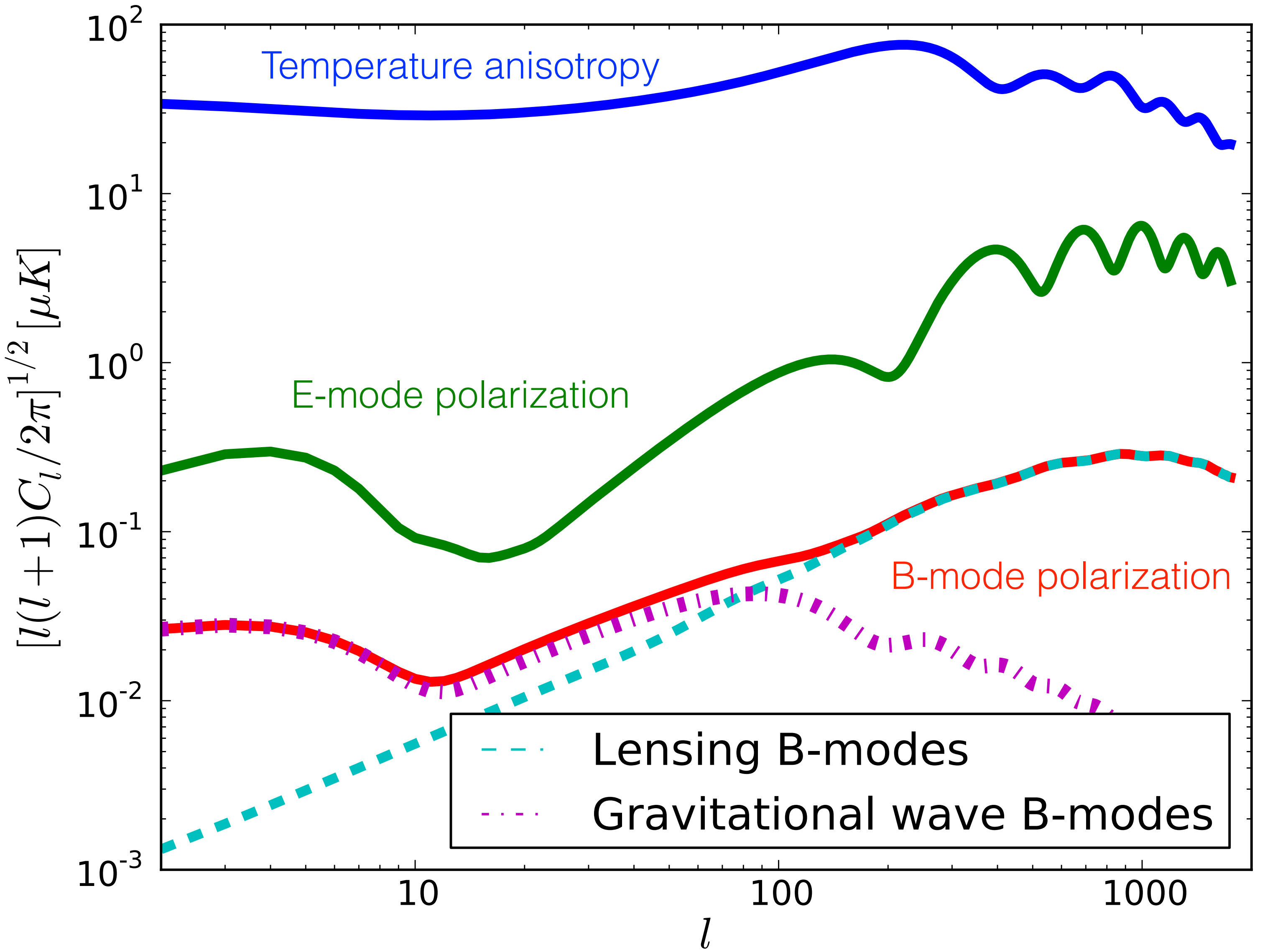
ABSTRACT

The polarized thermal emission from diffuse Galactic dust is the main foreground present in measurements of the polarization of the cosmic microwave background (CMB) at frequencies above 100 GHz. In this paper we exploit the uniqueness of the *Planck* HFI polarization data from 100 to 353 GHz to measure the polarized dust angular power spectra C_ℓ^{EE} and C_ℓ^{BB} over the multipole range $40 < \ell < 600$ well away from the Galactic plane. These measurements will bring new insights into interstellar dust physics and allow a precise determination of the level of contamination for CMB polarization experiments. Despite the non-Gaussian and anisotropic nature of Galactic dust, we show that general statistical properties of the emission can be characterized accurately over large fractions of the sky using angular power spectra. The polarization power spectra of the dust are well described by power laws in multipole, $C_\ell \propto \ell^\alpha$, with exponents $\alpha^{EE,BB} = -2.42 \pm 0.02$. The amplitudes of the polarization power spectra vary with the average brightness in a way similar to the intensity power spectra. The frequency dependence of the dust polarization spectra is consistent with modified blackbody emission with $\beta_d = 1.59$ and $T_d = 19.6$ K down to the lowest *Planck* HFI frequencies. We find a systematic difference between the amplitudes of the Galactic *B*- and *E*-modes, $C_\ell^{BB}/C_\ell^{EE} = 0.5$. We verify that these general properties are preserved towards high Galactic latitudes with low dust column densities. We show that even in the faintest dust-emitting regions there are no "clean" windows in the sky where primordial CMB *B*-mode polarization measurements could be made without subtraction of foreground emission. Finally, we investigate the level of dust polarization in the specific field recently targeted by the BICEP2 experiment. Extrapolation of the *Planck* 353 GHz data to 150 GHz gives a dust power $\mathcal{D}_\ell^{\mathcal{BB}} \equiv \ell(\ell+1)C_\ell^{BB}/(2\pi)$ of $1.32 \times 10^{-2}\,\mu K^2_{CMB}$ over the multipole range of the primordial recombination bump ($40 < \ell < 120$); the statistical uncertainty is $\pm 0.29 \times 10^{-2}\,\mu K^2_{CMB}$ and there is an additional uncertainty $(+0.28, -0.24) \times 10^{-2}\,\mu K^2_{CMB}$ from the extrapolation. This level is the same magnitude as reported by BICEP2 over this ℓ range, which highlights the need for assessment of the polarized dust signal even in the cleanest windows of the sky. The present uncertainties are large and will be reduced through an ongoing, joint analysis of the *Planck* and BICEP2 data sets.

Planck 2014
Intermediate Results XXX

Measuring polarization: lensing

- Small scale B-modes created by gravitational lensing of E-modes
  - Large-scale-structure formation science
    - Neutrino masses
    - Dark energy
  - Delensing necessary to characterize inflationary signal
- Other small scale B-mode sources:
  - Cosmological Birefringence
  - Primordial magnetic fields



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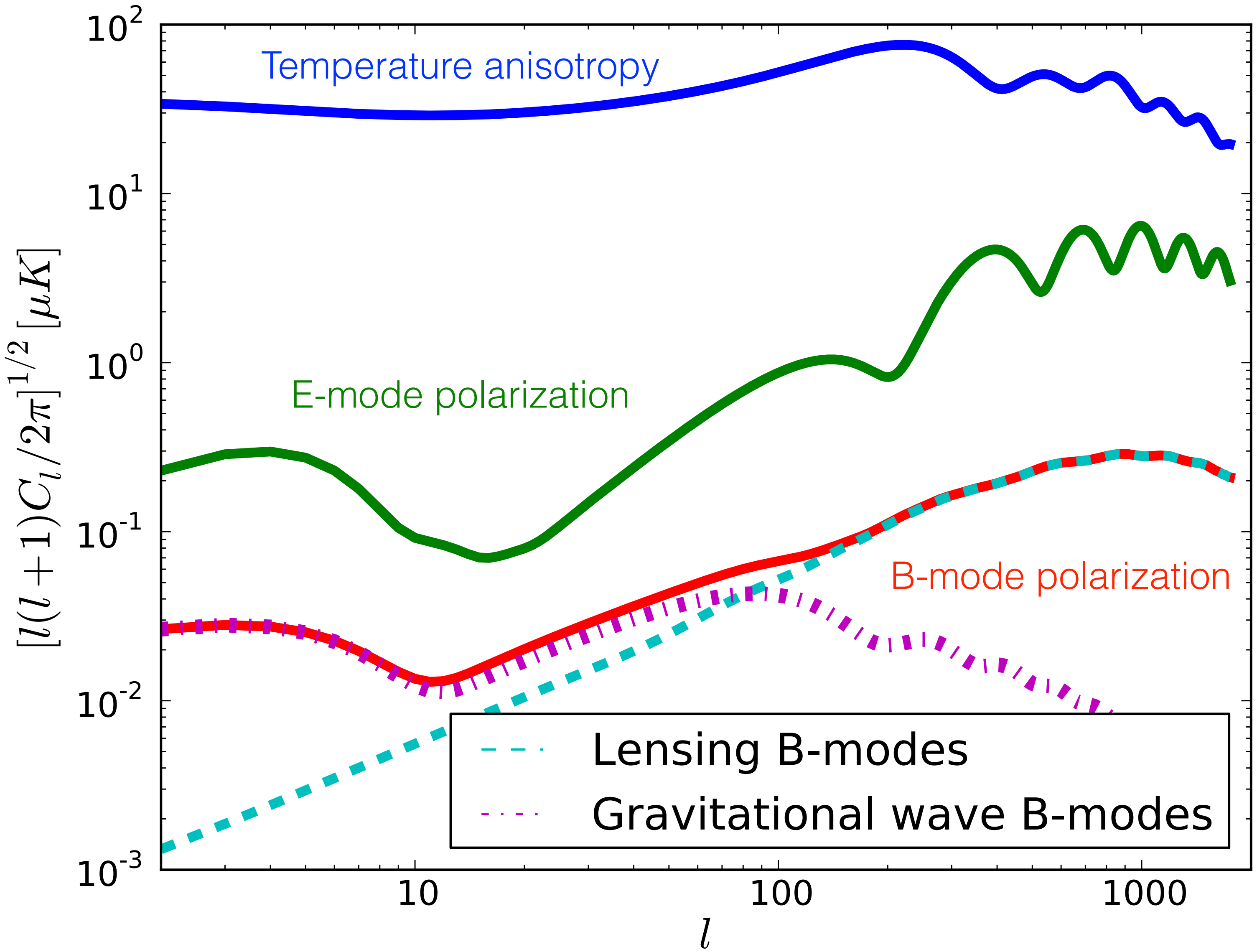
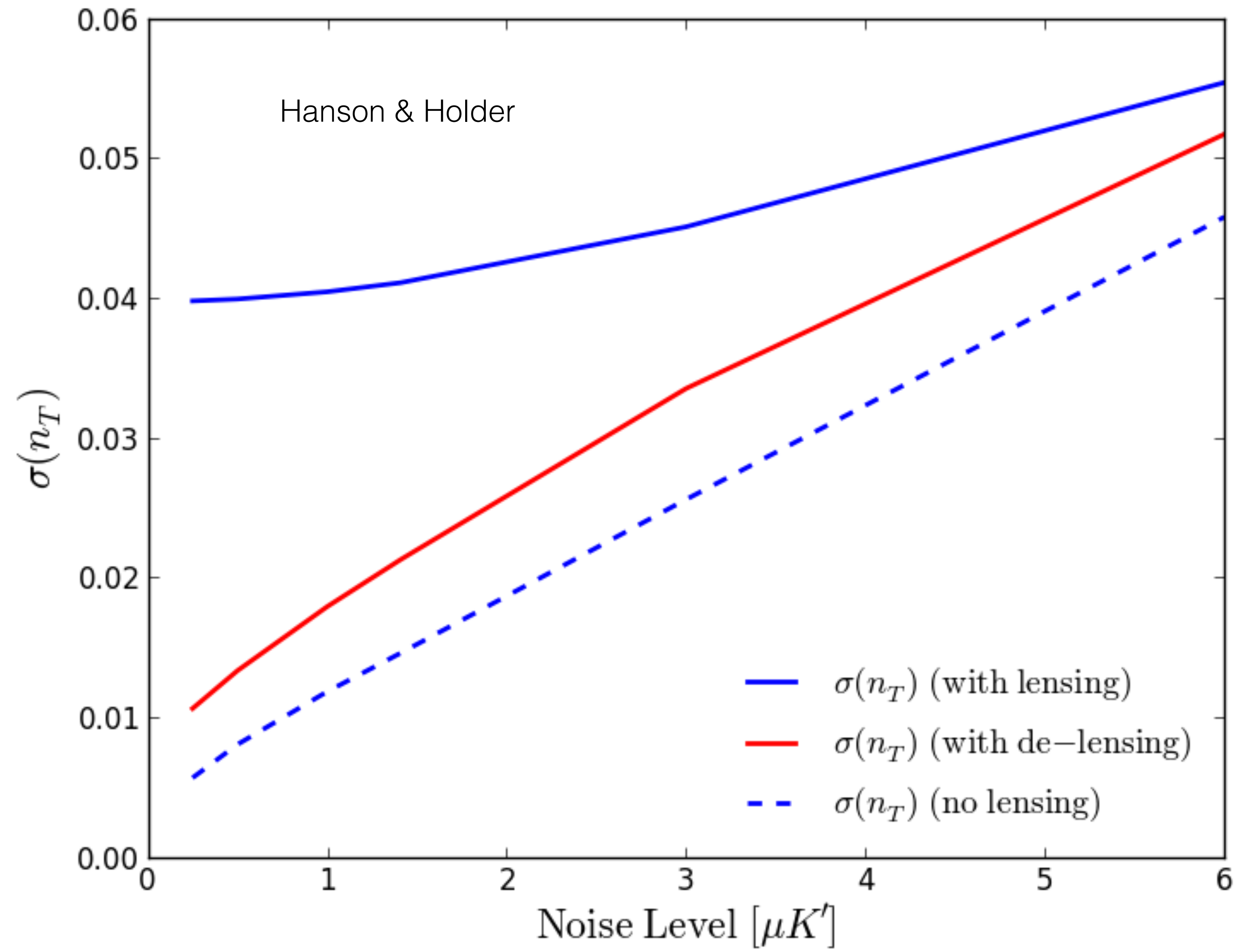


Measuring polarization: lensing

- *If* r is large: De-lensing can enable tests of the consistency relation*:

$$r = -8n_t$$

- De-lensing necessary to probe lower values of r



*single field, slow roll

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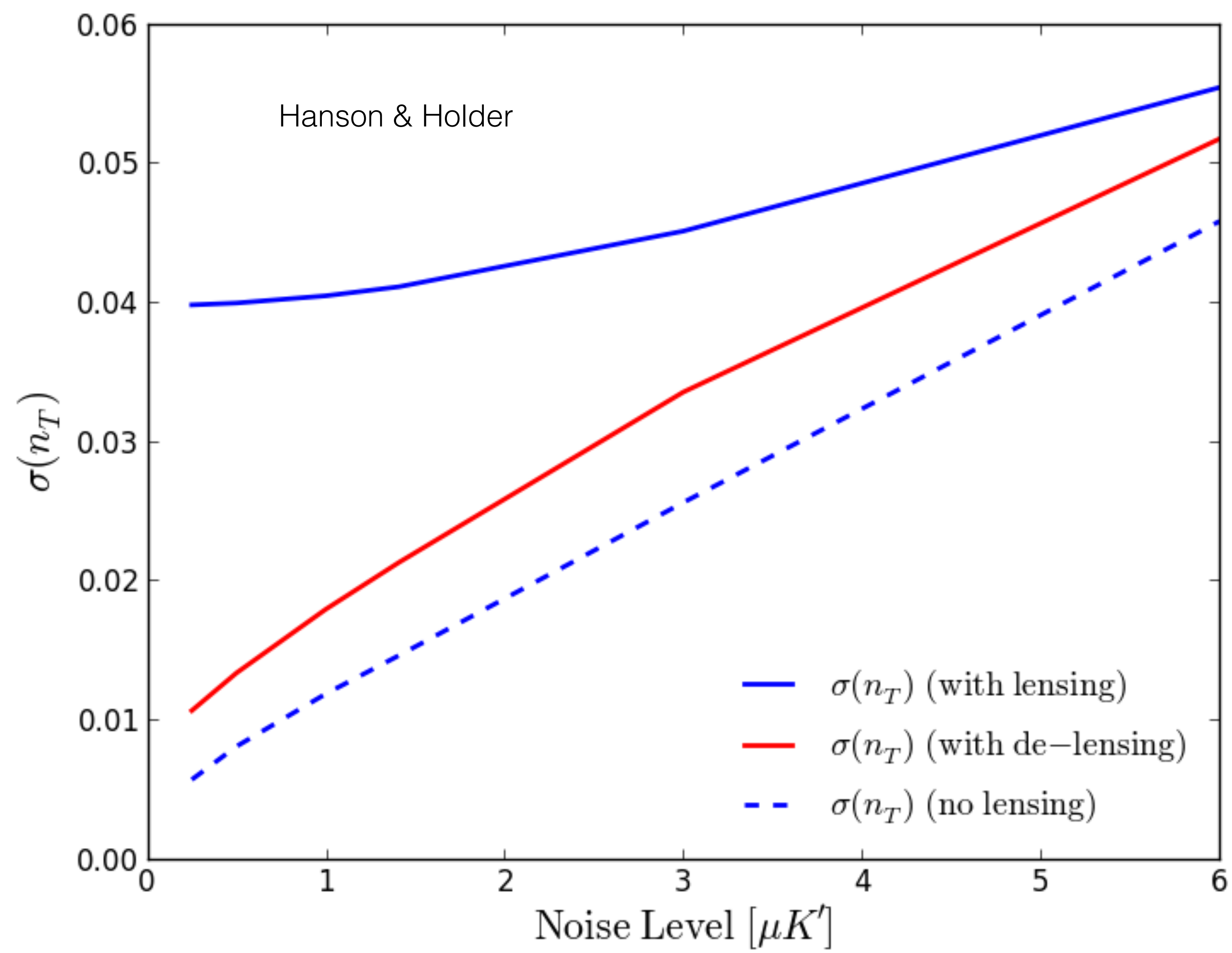

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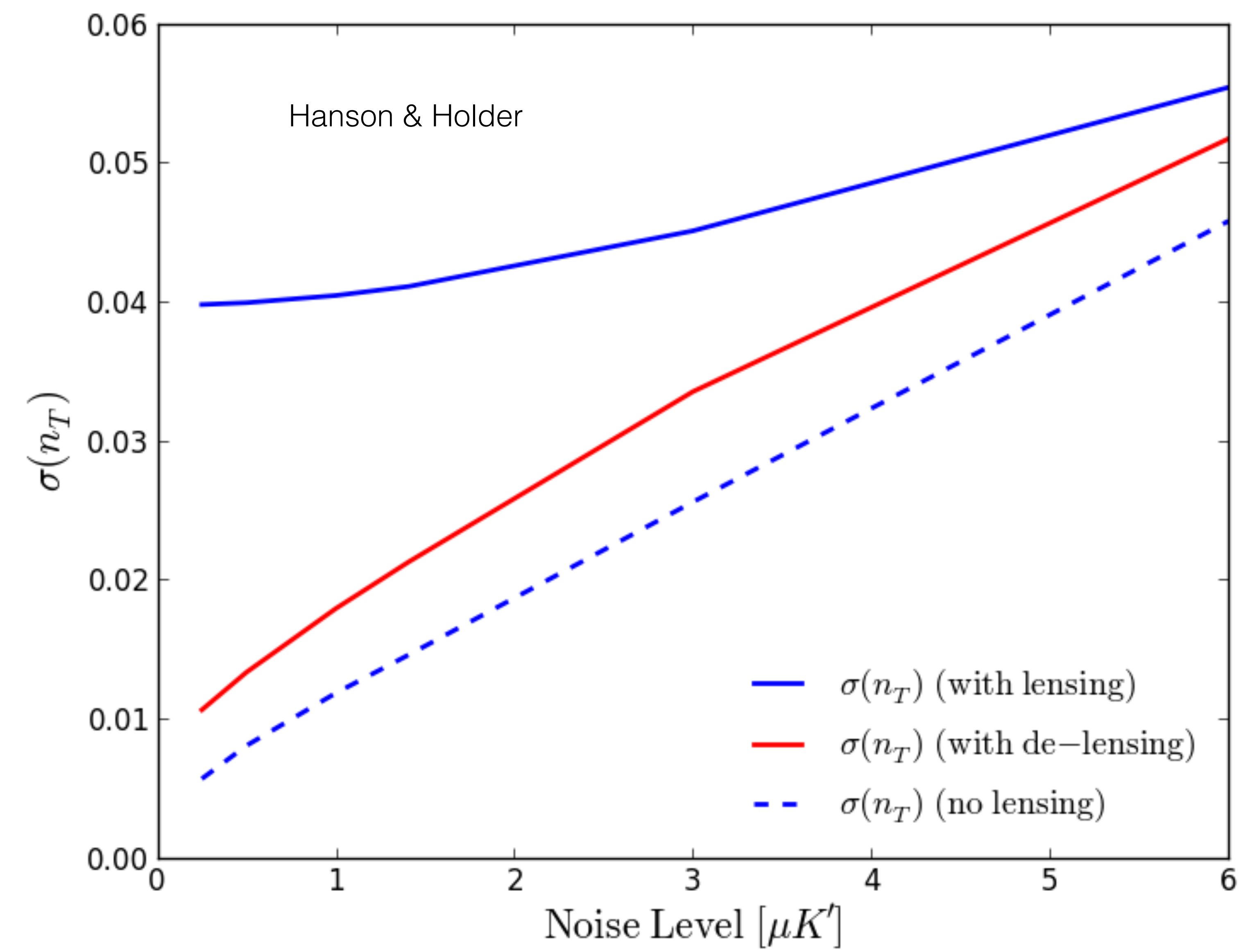

*single field, slow roll

Measuring polarization: a general strategy

- Multi-chroic (specifically foreground sensitive) measurements on degree and larger scales

- High resolution measurements to enable delensing (and LSS science)

POLARBEAR Collaboration

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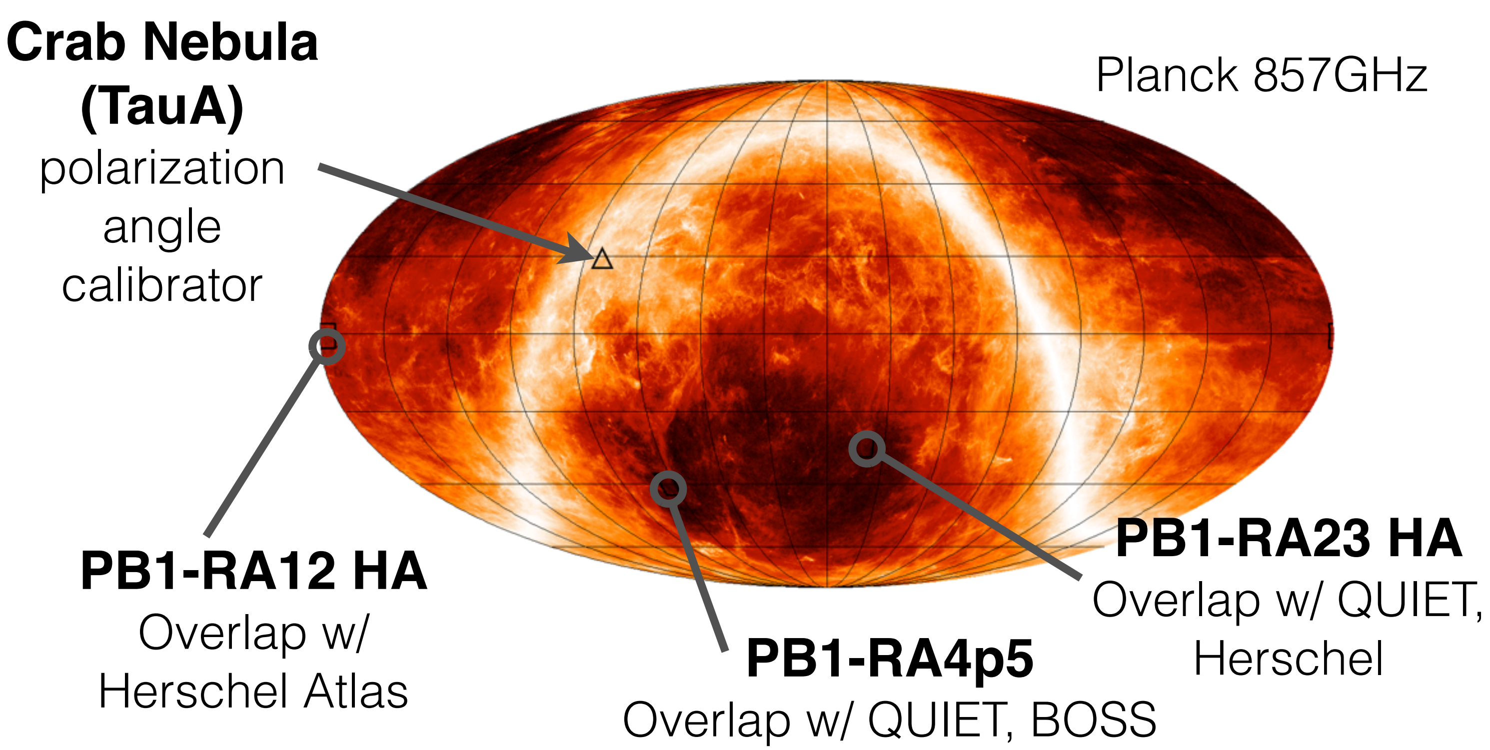
Naitonal Institute for Fusion Science
Suguru Takada

Dalhousie University
Scott Chapman
Colin Ross
Kaja Rotermund
Alexei Tikhomirov

POLARBEAR Collaboration

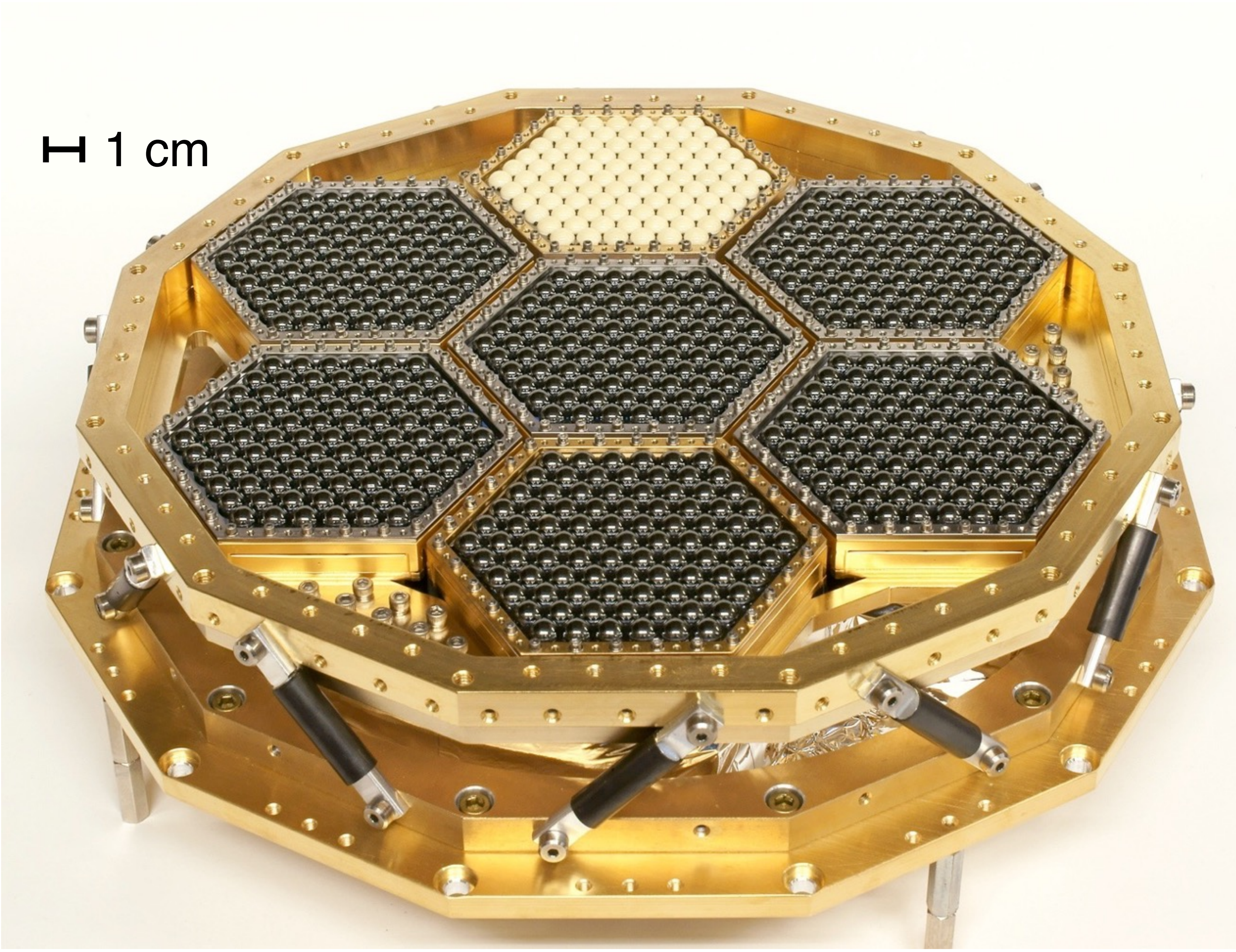
The POLARBEAR experiment

- CMB polarization dedicated experiment in Atacama Desert
- 80% of the sky accessible with *el* > 30
- Targeting large and small scales (3.5′ beam)
- First season: deep integration for sub-degree signal @ 150GHz on 3° x 3° patches



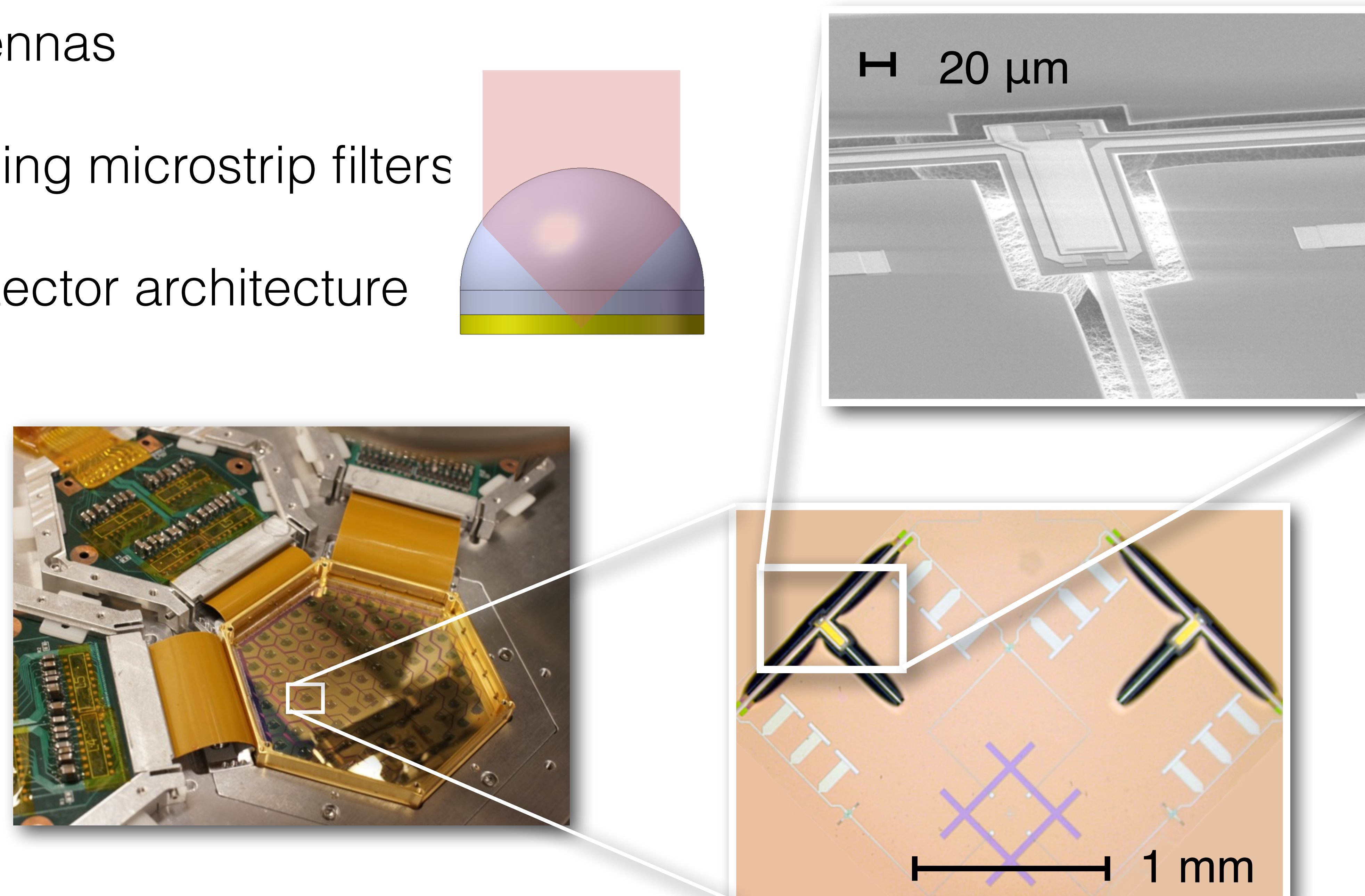
POLARBEAR: Focal plane

- Modular design
- 7 wafers of 91 dual-polarized pixels
- Radiation coupled to silicon wafers with contacting lenslets
- Cooled to 0.25K



POLARBEAR: Focal plane

- Dual polarization double-slot dipole antennas
- Band-defining microstrip filters
- Unique detector architecture in the field



POLARBEAR: results overview

- 4-point correlation:
  Polarized lensing reconstruction
  First direct evidence of polarization lensing

  arXiv:1312.6646 — PRL 113, 021301 (2014) Editor's Suggestion

- 3-point correlation:
  Polarized CMB cross correlation with tracers of dark matter

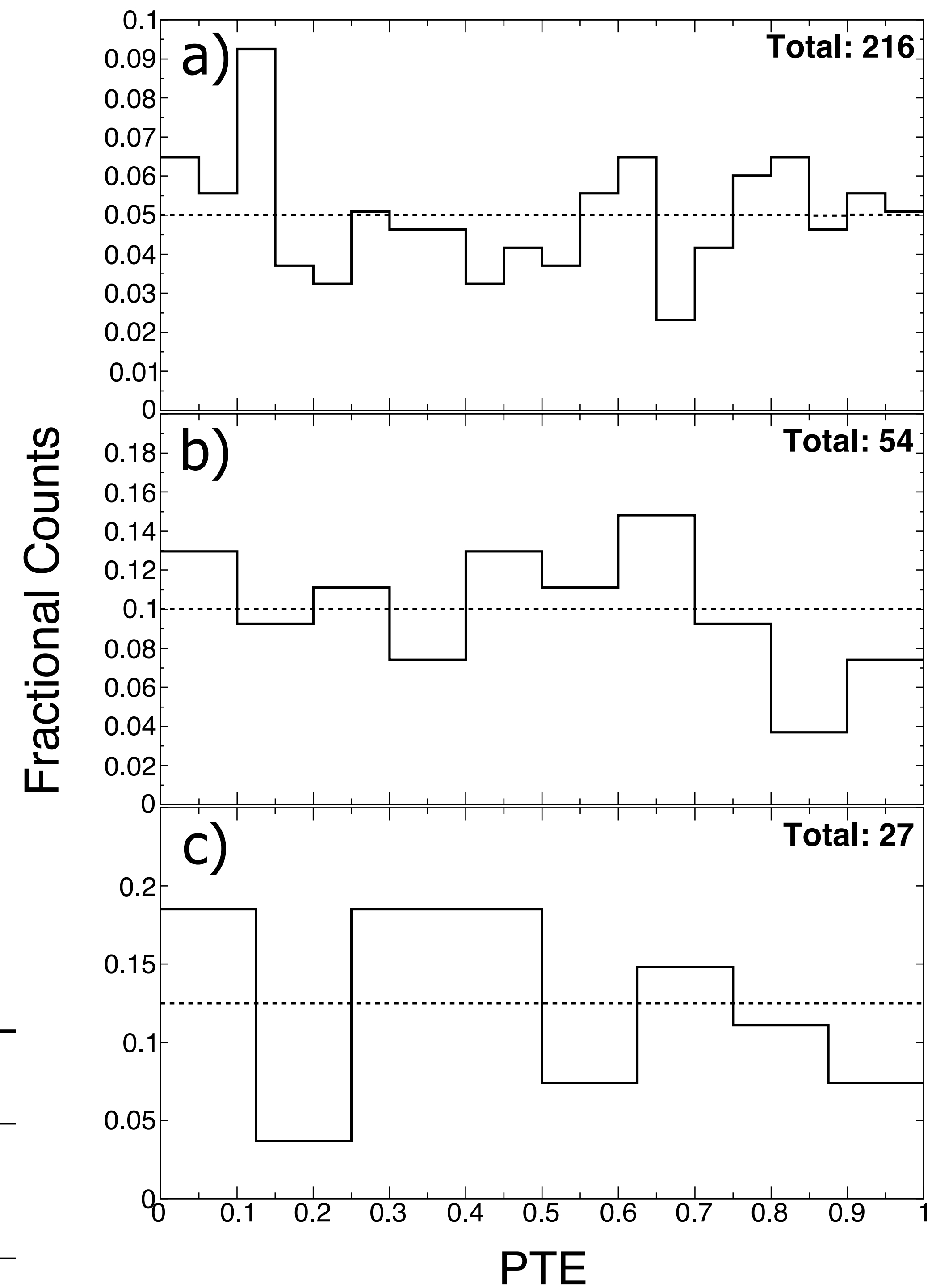
  arXiv:1312.6645 — PRL 112, 131302 (2014) Editor's Suggestion

- 2-point correlation:
  First direct measurement of B-mode power spectrum

  arXiv:1403.2369 — APJ 794, 171 (2014)

POLARBEAR: Null tests

- ***Blind*** analysis framework: Only null spectra viewed for C_l^{BB} & C_l^{dd} until null tests pass & systematic errors validated to be small
- Null-test (jack-knives) suite to estimate systematic error contamination:
  9 tests per patch, 27 total
- No outliers, distribution of PTEs consistent with uniform

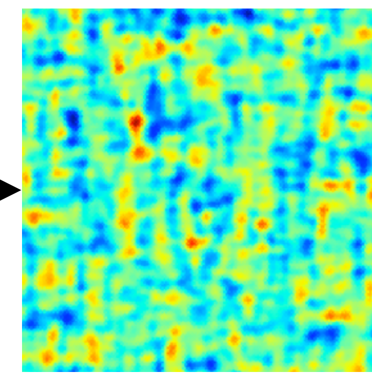


Patch	average of $\chi_{\rm null}(b)$	extreme of $\chi^2_{\rm null}(b)$	extreme of $\chi^2_{\rm null}$ by EB/BB	extreme of $\chi^2_{\rm null}$ by test	total $\chi^2_{\rm null}$
RA4.5	11.6%	16.6%	20.6%	21.8%	14.0%
RA12	92.4%	84.2%	60.8%	23.8%	52.6%
RA23	75.2%	61.6%	6.0%	7.0%	18.6%

POLARBEAR: Systematic error simulations

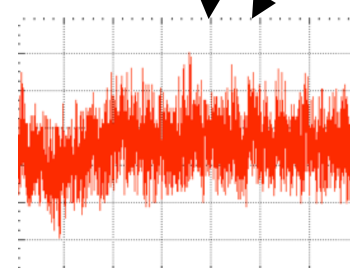
Input cosmology (BB=0)
Input beam

High resolution maps

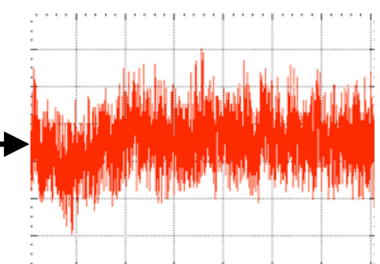


TOD simulation

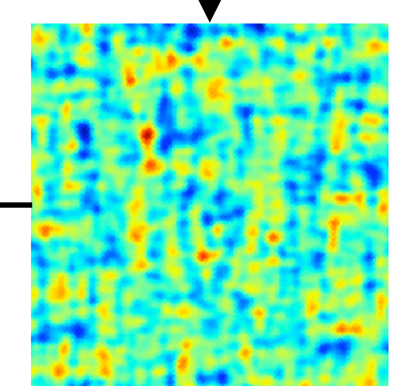
- Pointing
- Beams



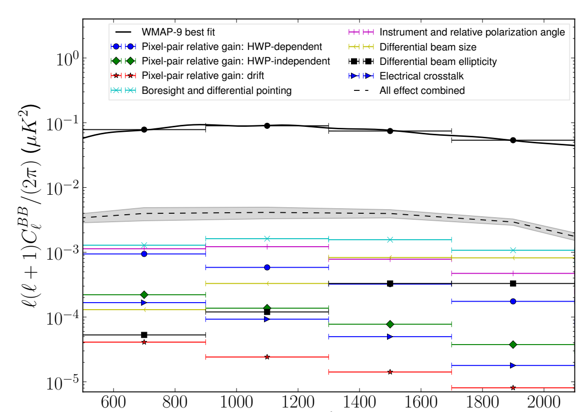
Inject systematics



Mapmaking @ standard resolution



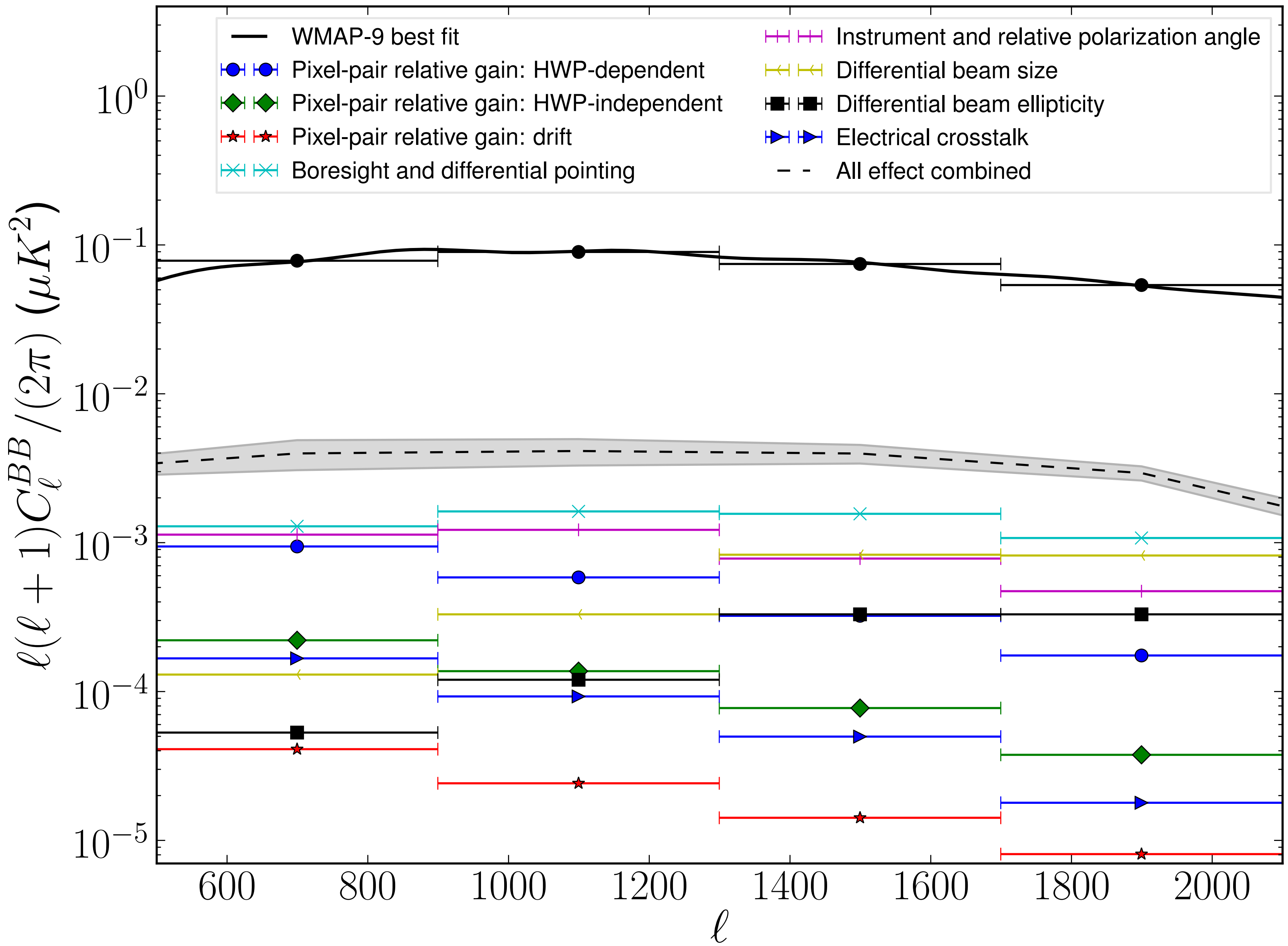
Power spectrum estimation



- Input measured errors and systematic instrumental effects
- Simulate spurious B-mode impact through pipeline

POLARBEAR: Systematic error simulations

- Differential beam systematics
- Pointing uncertainties
- Detector polarization angle uncertainties
- Electrical crosstalk



POLARBEAR results: 4-point

- Lensing displaces polarization fields by deflection field **d**

$$(Q \pm iU)(\mathbf{n}) = (\tilde{Q} \pm i\tilde{U})(\mathbf{n} + \mathbf{d}(\mathbf{n}))$$

- Reconstruction of the deflection field from CMB polarization *E* and *B* field maps, estimate deflection PS from 4-point

$$d_{EE}(\mathbf{L}) = \frac{A_{EE}(L)}{L} \int \frac{d^2\mathbf{l}}{(2\pi)^2} E(\mathbf{l})E(\mathbf{l}') \frac{C_l^{EE}\mathbf{L}\cdot\mathbf{l}}{\hat{C}_l^{EE}\hat{C}_{l'}^{EE}} \cos 2\phi_{\mathbf{l}\mathbf{l}'},$$

$$\mathbf{L} = \mathbf{l} + \mathbf{l}'$$

$$d_{EB}(\mathbf{L}) = \frac{A_{EB}(L)}{L} \int \frac{d^2\mathbf{l}}{(2\pi)^2} E(\mathbf{l})B(\mathbf{l}') \frac{C_l^{EE}\mathbf{L}\cdot\mathbf{l}}{\hat{C}_l^{EE}\hat{C}_{l'}^{BB}} \sin 2\phi_{\mathbf{l}\mathbf{l}'}$$

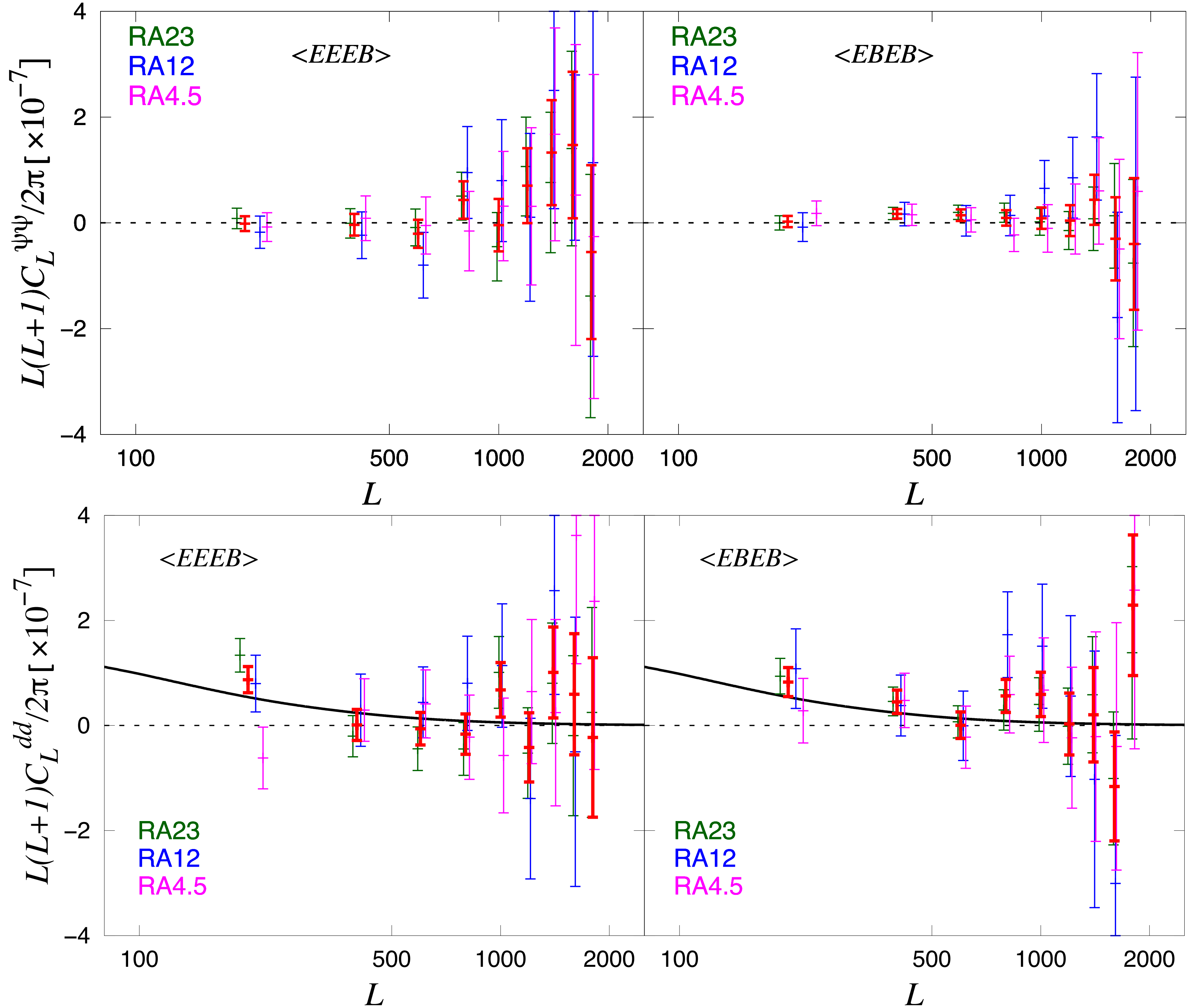
$$\begin{aligned}\langle d_\alpha(\mathbf{L}) d^*_\beta(\mathbf{L}')\rangle &= (2\pi)^2\delta(\mathbf{L}-\mathbf{L}')(\boxed{C_L^{dd}} + N^{(0)}_{\alpha\beta}(L) \\ &+ \text{higher-order terms})\end{aligned}$$

$$\{\alpha, \beta\} = \{EE, EB\}, \{EB, EB\}$$

Chosen to require B-modes

POLARBEAR results: 4-point

- Additional null tests (9 swap-patch, 6 curl) evaluated and passed
- Single channel and patch combined

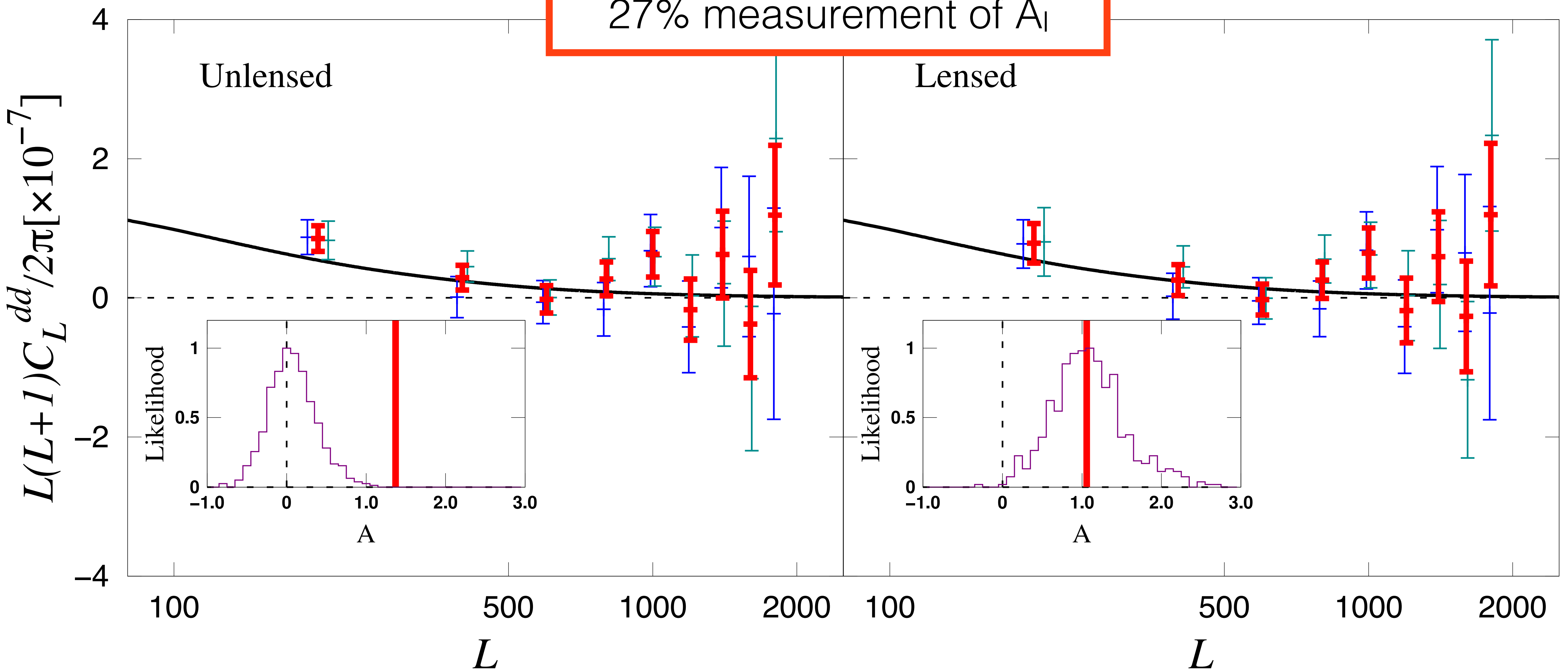


POLARBEAR results: 4-point

- *First* polarization only deflection power spectrum measurement

- Probes lensing integrated along all red shifts

4.2σ evidence of B-modes
27% measurement of A_l



POLARBEAR results: 3-point

- Construct lensing convergence (κ) maps from polarization *E* and *B* field maps

- Cross correlate with CIB flux maps (2 fields have overlap)

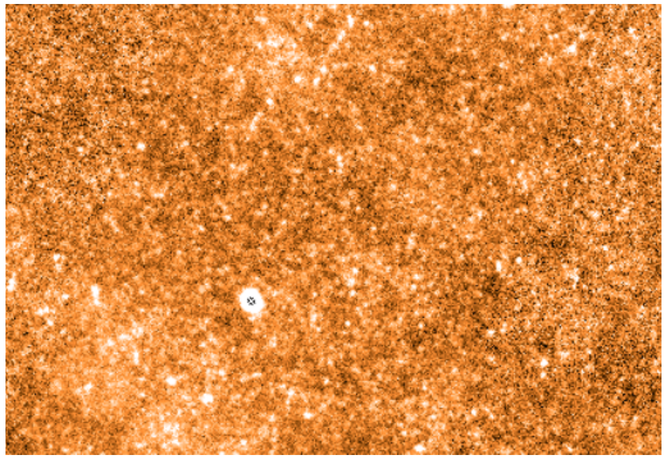
$$\kappa = -\frac{1}{2}\nabla \cdot \mathbf{d}$$

$$\hat{\kappa}_{EB}(\mathbf{L}) = \int \frac{\mathrm{d}^2\mathbf{l}}{(2\pi)^2} g^{EB}(\mathbf{L},\mathbf{l}) E(\mathbf{l}) B(\mathbf{L}-\mathbf{l})$$

$$\hat{\kappa}_{EE}(\mathbf{L}) = \int \frac{\mathrm{d}^2\mathbf{l}}{(2\pi)^2} g^{EE}(\mathbf{L},\mathbf{l}) E(\mathbf{l}) E(\mathbf{L}-\mathbf{l})$$

X

HERSCHEL/SPIRE
H-atlas data



RA12

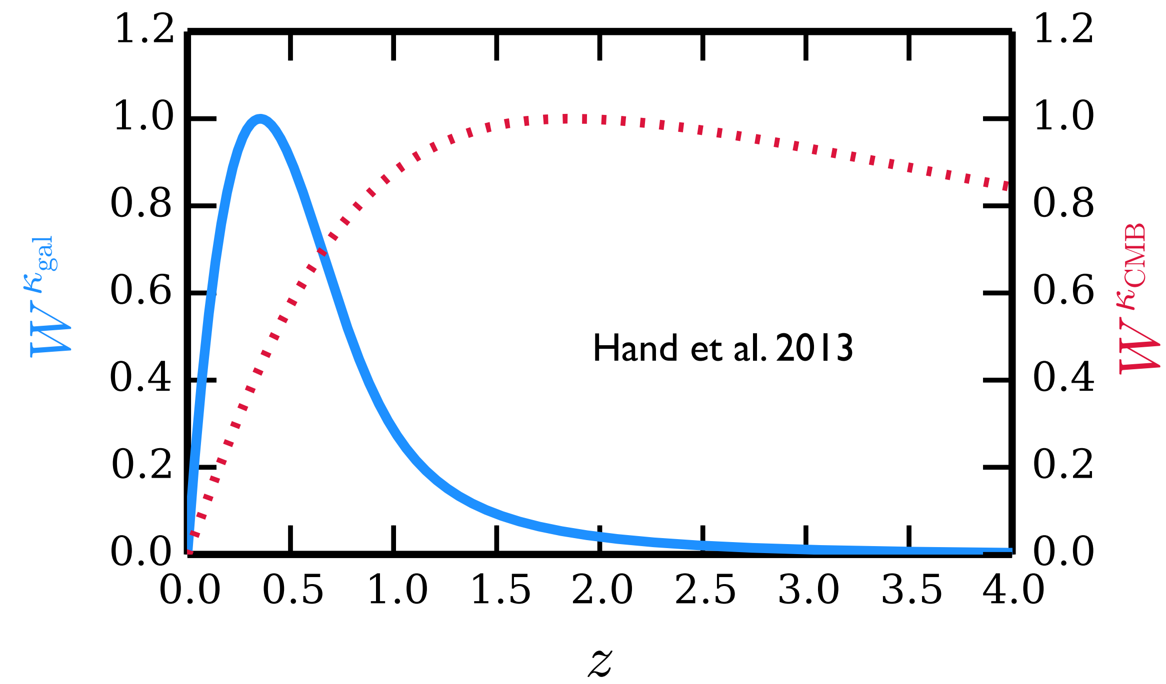
POLARBEAR results: 3-point

- Cross-correlation dependent on cosmology and redshift distribution of CIB sources

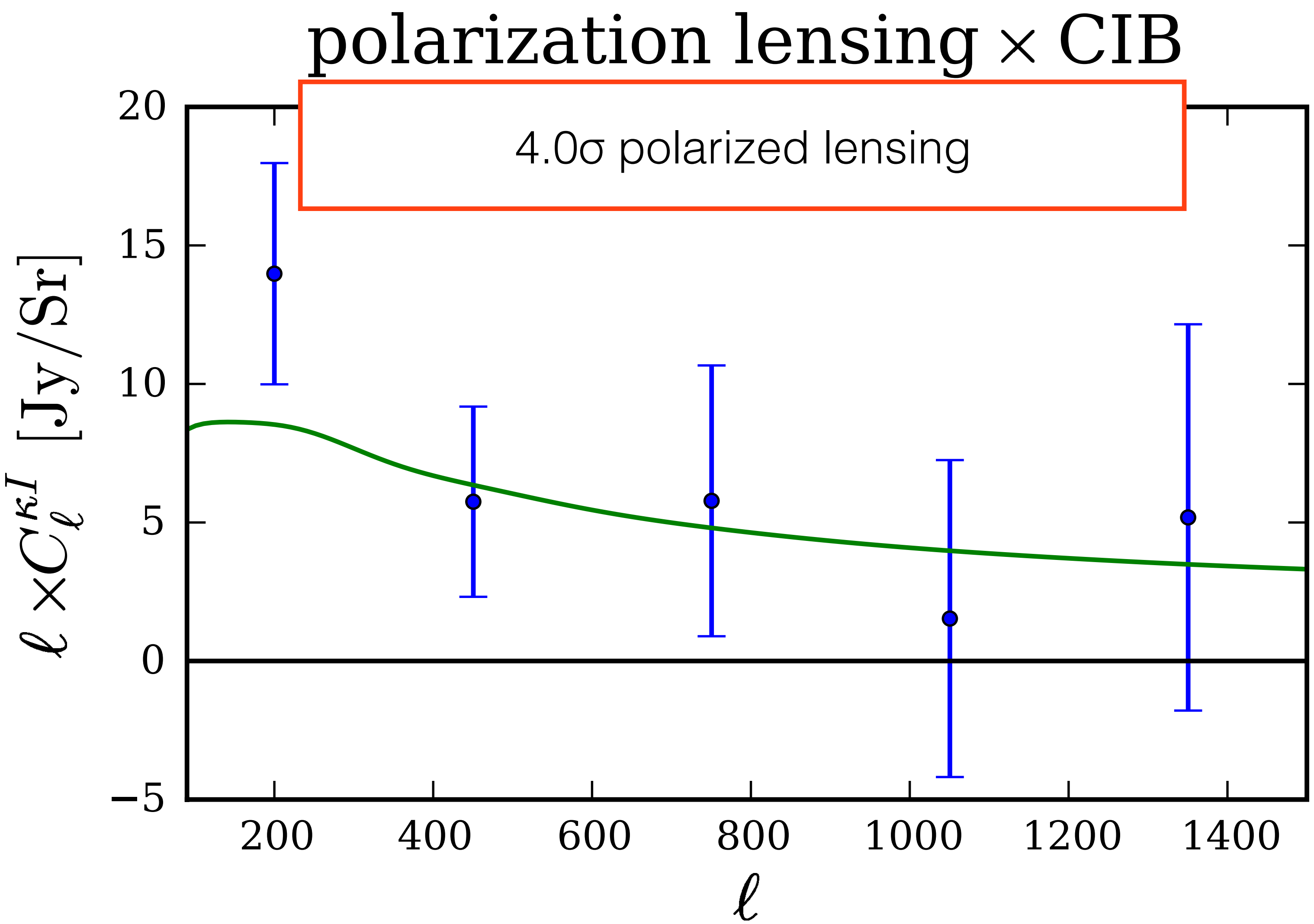
$$C_\ell^{\kappa I} = \int \frac{dz H(z)}{\eta^2(z)} W^\kappa(z) W^I(z) P(k = \ell/\eta(z), z)$$

$$W^\kappa(z) = \frac{3}{2H(z)} \Omega_0 H_0^2 (1+z) \eta(z) \frac{\left(\eta^{LS} - \eta(z)\right)}{\eta^{LS}}$$

$$W^I(z) = \frac{3}{2} \Omega_m H_0^2 \frac{(1+z)}{H(z)} \frac{\eta(z)}{c} \int_z^\infty dz' \frac{dN^I}{dz'} \frac{\eta(z') - \eta(z)}{\eta(z')}$$



POLARBEAR results: 3-point

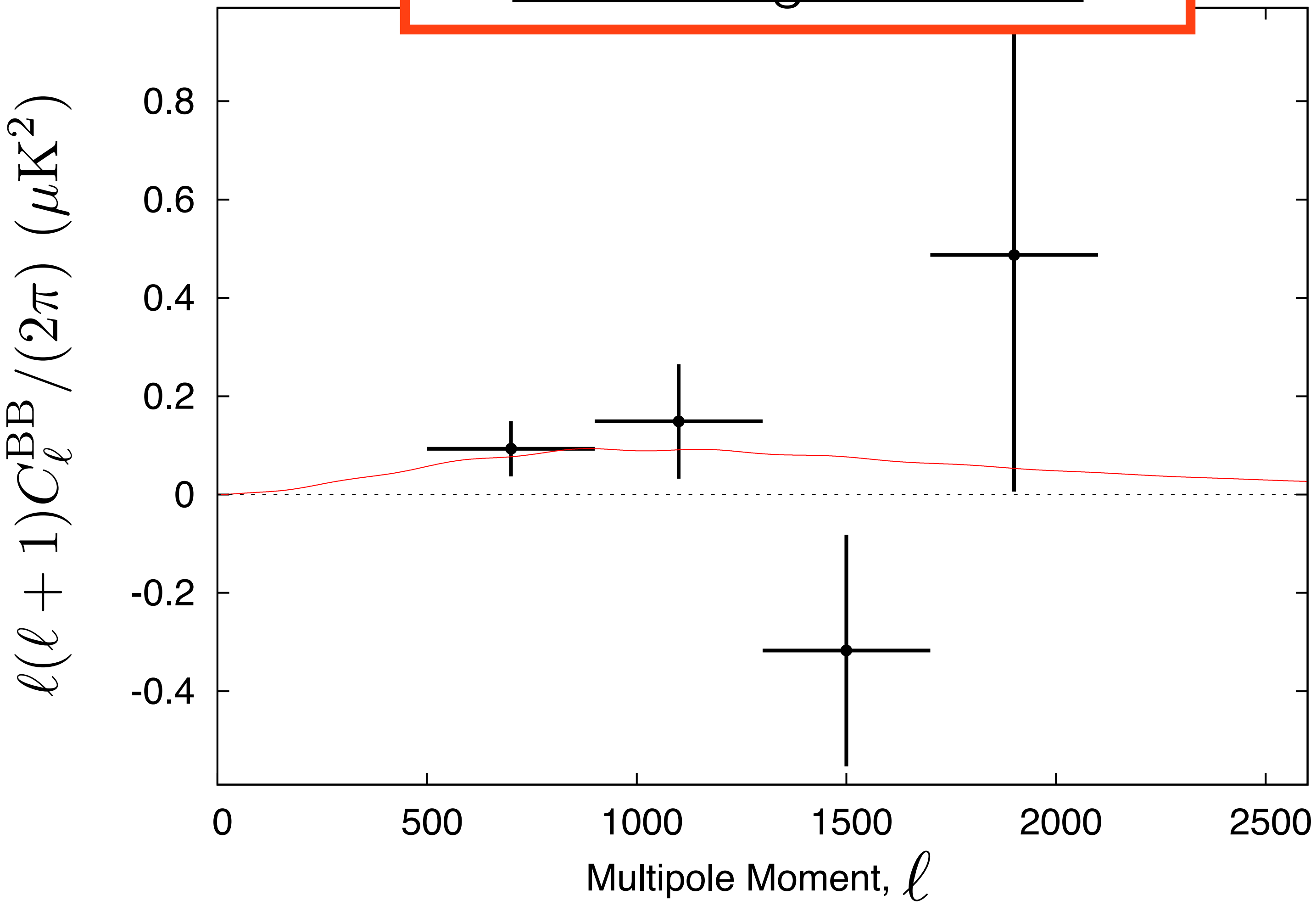


POLARBEAR results: 2-point

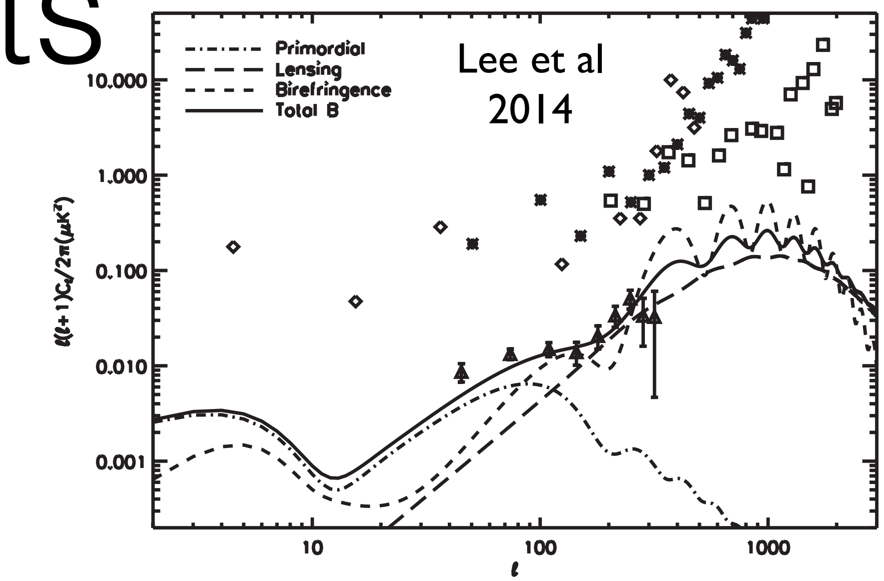
$$A_{BB} = 1.12 \pm 0.61(\mathrm{stat})^{+0.04}_{-0.10}(\mathrm{sys}) \pm 0.07(\mathrm{multi})$$

97.2% rejection of
"no lensing B-modes"

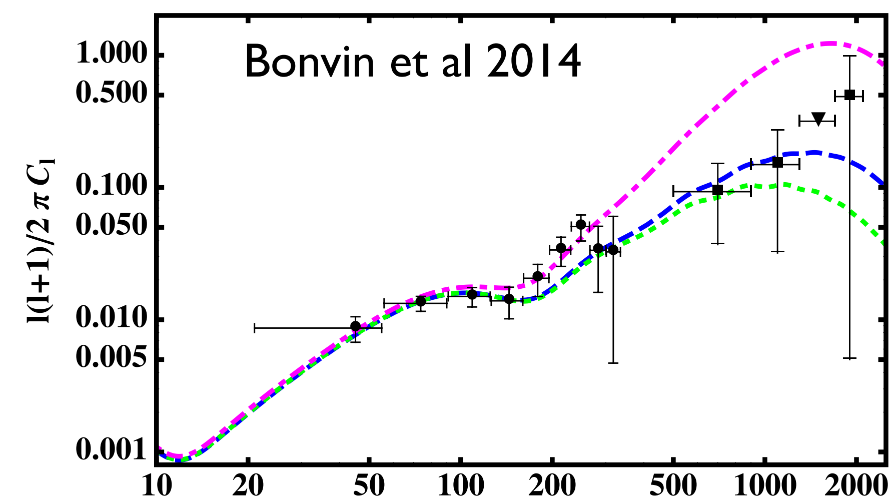
- *First* direct B-mode power spectrum measurement
- Probes lensing & other possible sources (anisotropic birefrengence)

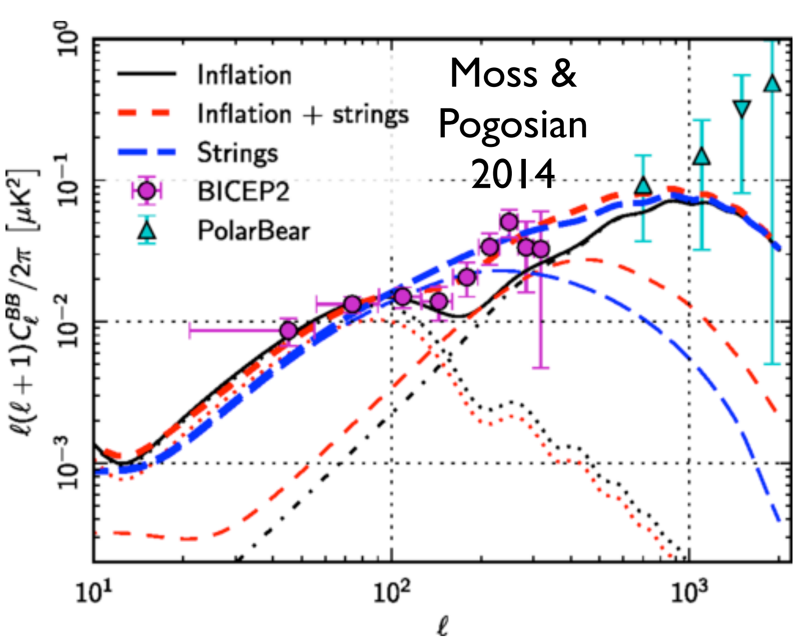


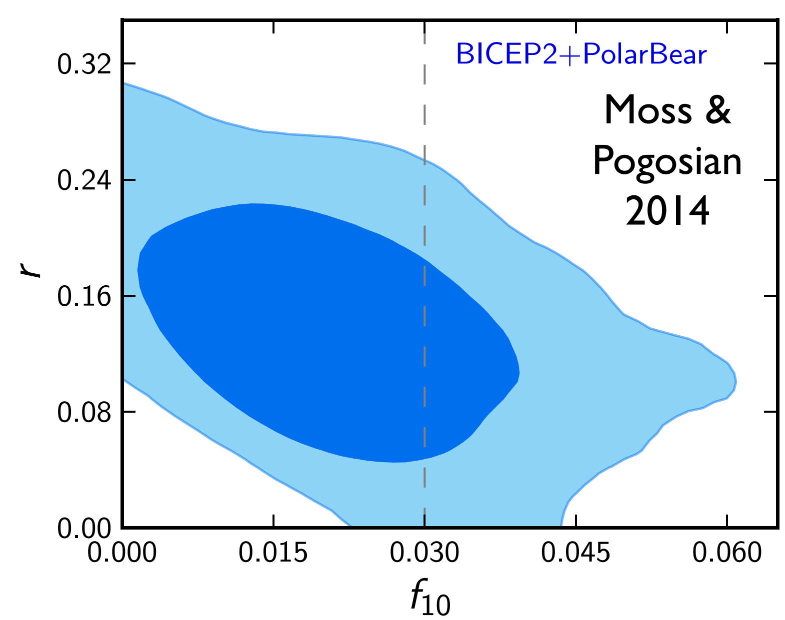
POLARBEAR results: other constraints

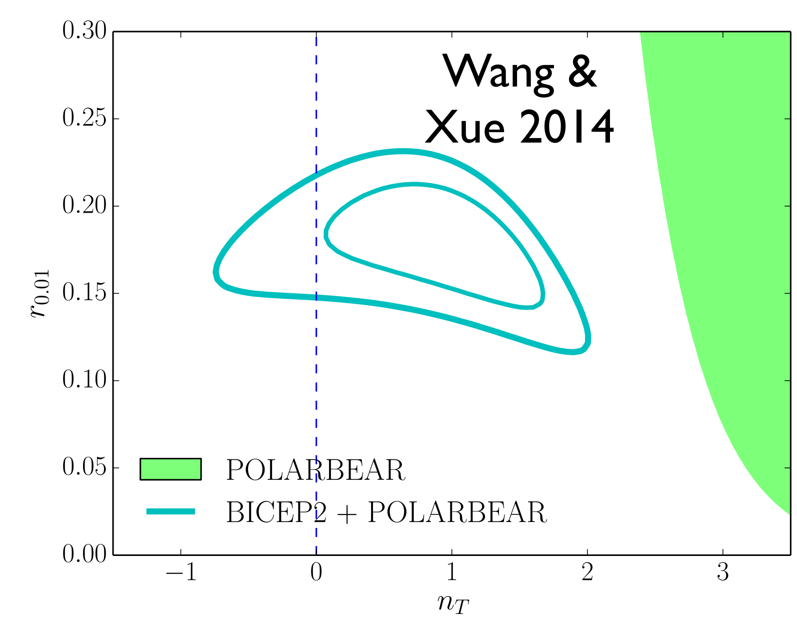


- Alternative B-mode sources
  - Cosmic defects/vector modes (Moss & Pogosian)
  - Primordial magnetic fields (Bonvin et al.)
  - Cosmic birefringence*
- Alternatives to inflation
  - String gas cosmologies (Wang & Xue)









POLARBEAR results: summary

- 4.2σ evidence of B-modes from 4-point
- 4.0σ evidence of polarization lensing from 3-point
- 4.7σ combined significance evidence of B-modes


SPIDER

SPIDER

Princeton University
W. Jones
A. Fraisse
Z. Kermish
M. Hasselfield
A.S. Rahlin
J. Gudmundsson
A. Gambrel
E. Young

Case Western Reserve Univesity
J. Ruhl
S. Bryan
J. Nagy
S. Wen
R. Bihary

UKZN
C. Chiang

University of Toronto
C.B. Netterfield
J.R. Bond
S. Benton
M. Farhang
L. Fissel
N. Gandillo
J. Hartley
I. Padilla
J. Soler
J. Shariff

University of British Columumbia
M. Halpern
M. Amiri
D. Wiebe

Caltech/JPL
J. J. Bock
B. P. Crill
O. Doré
J. P. Filippini
S. Golwala
W. Holmes
V. V. Hristov
R. O'Brient
P. V. Mason
L. Moncelsi
T. A. Morford
M. C. Runyan
A. Trangsrud
R. S. Tucker
A. D. Turner

APC
K. Ganga

Cardiff University
P. Ade
E. Pascale
C. Tucker

Imperial College
C. Contaldi
C. Clark

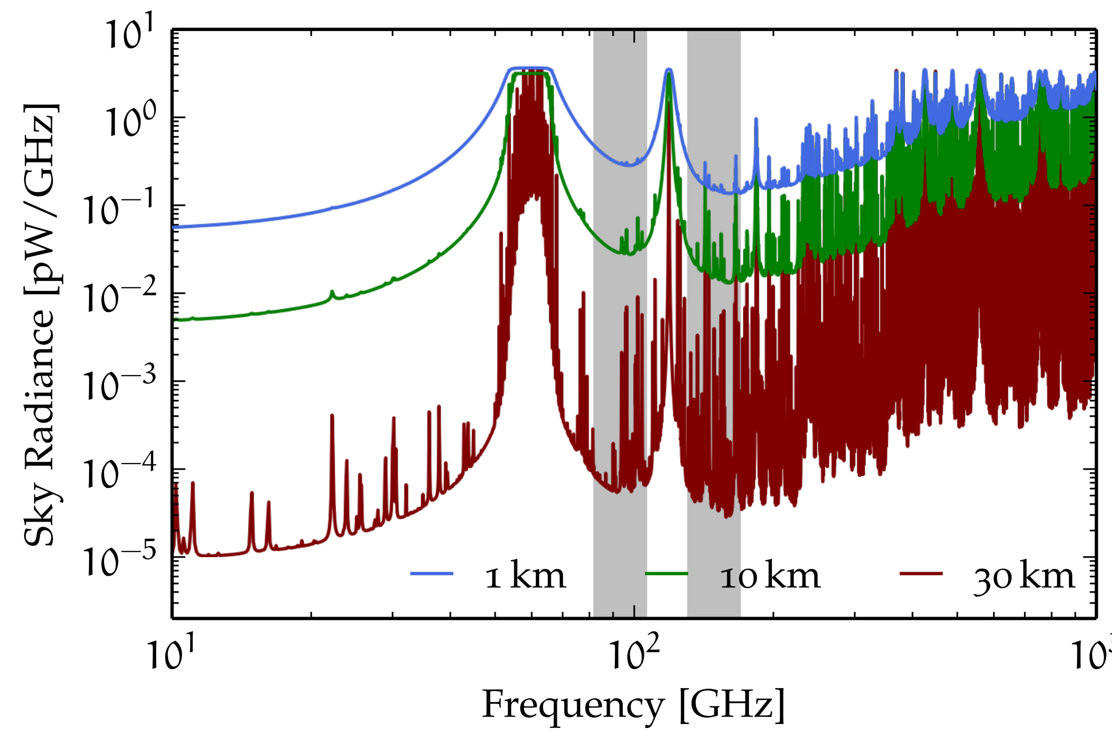
Cambridge
C. MacTavich

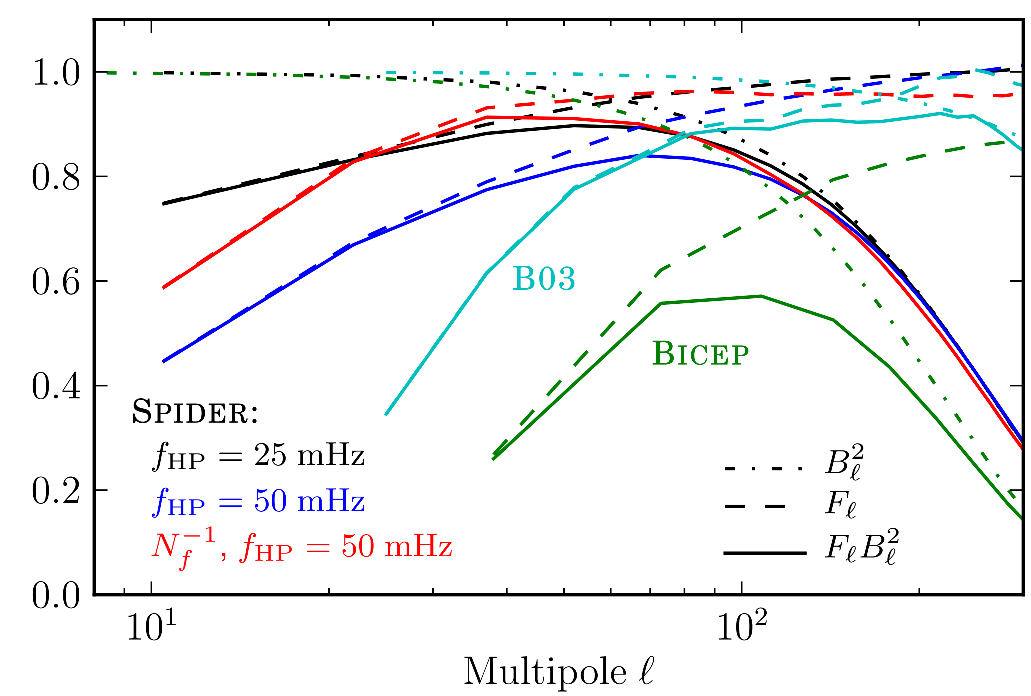
Stanford
K.D. Irwin
C.L. Kuo

NIST
Carl Reintsema
George Hilton

Why ballooning?
The good

- Reduced loading from atmosphere
  - Increased sensitivity ➠ larger sky
  - Better stability ➠ larger scales
  - Observe in > 220GHz channels
- Access to large sky fractions
- Space-like performance of a satellite mission for a fraction of the cost



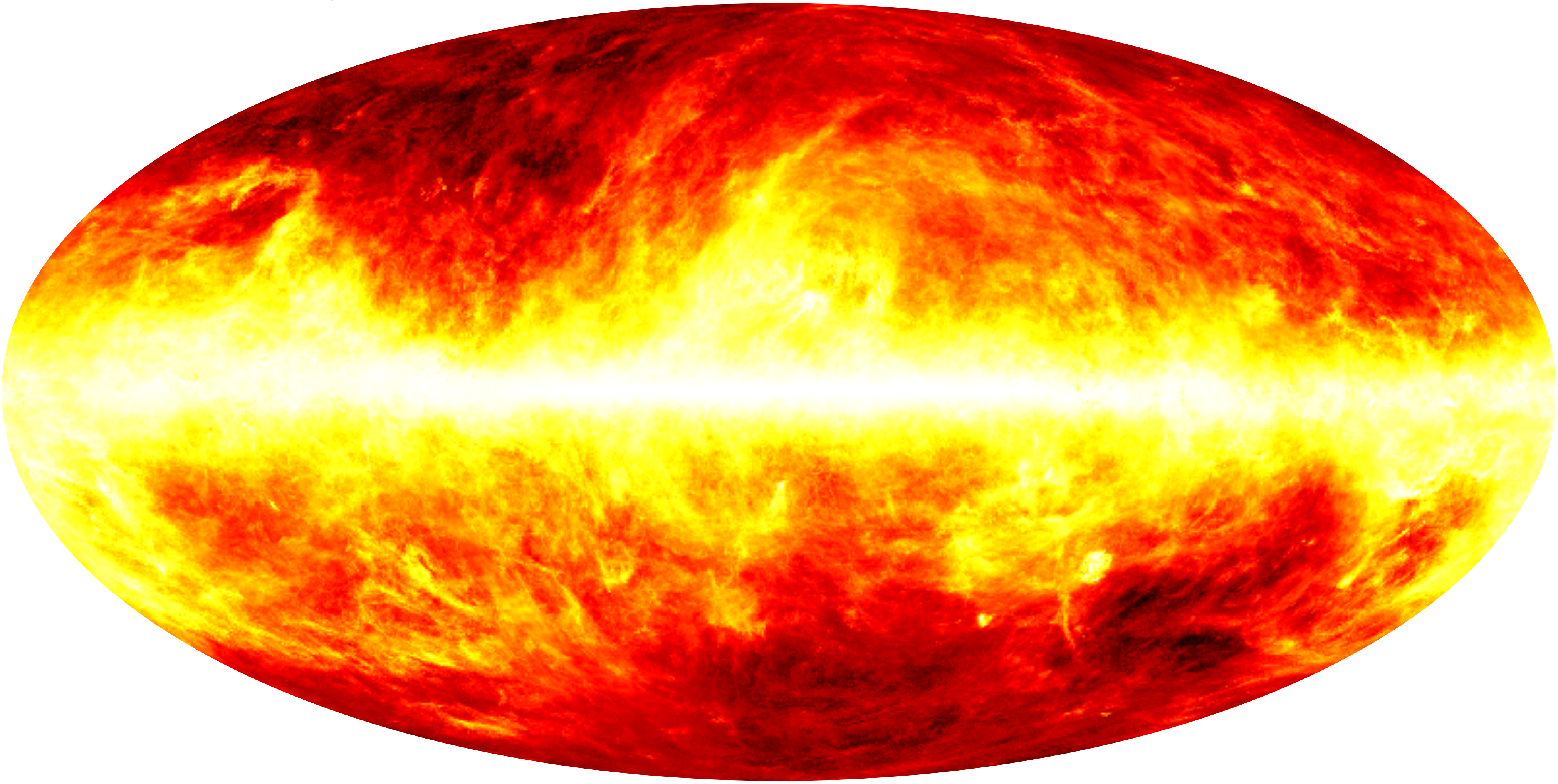


Why ballooning?
The bad

- Mass and power constraints
- Limited time-frame for debugging, calibration, etc. on the ground
- Low bandwidth data transmission in-flight, data drives must be recovered post-flight
- All the challenges of satellite mission, without the same resources (great training for students!)

SPIDER: sky coverage

- Map cleanest 10% (6.5% hits-weighted) of the southern celestial hemisphere
- Limited by sun and galaxy



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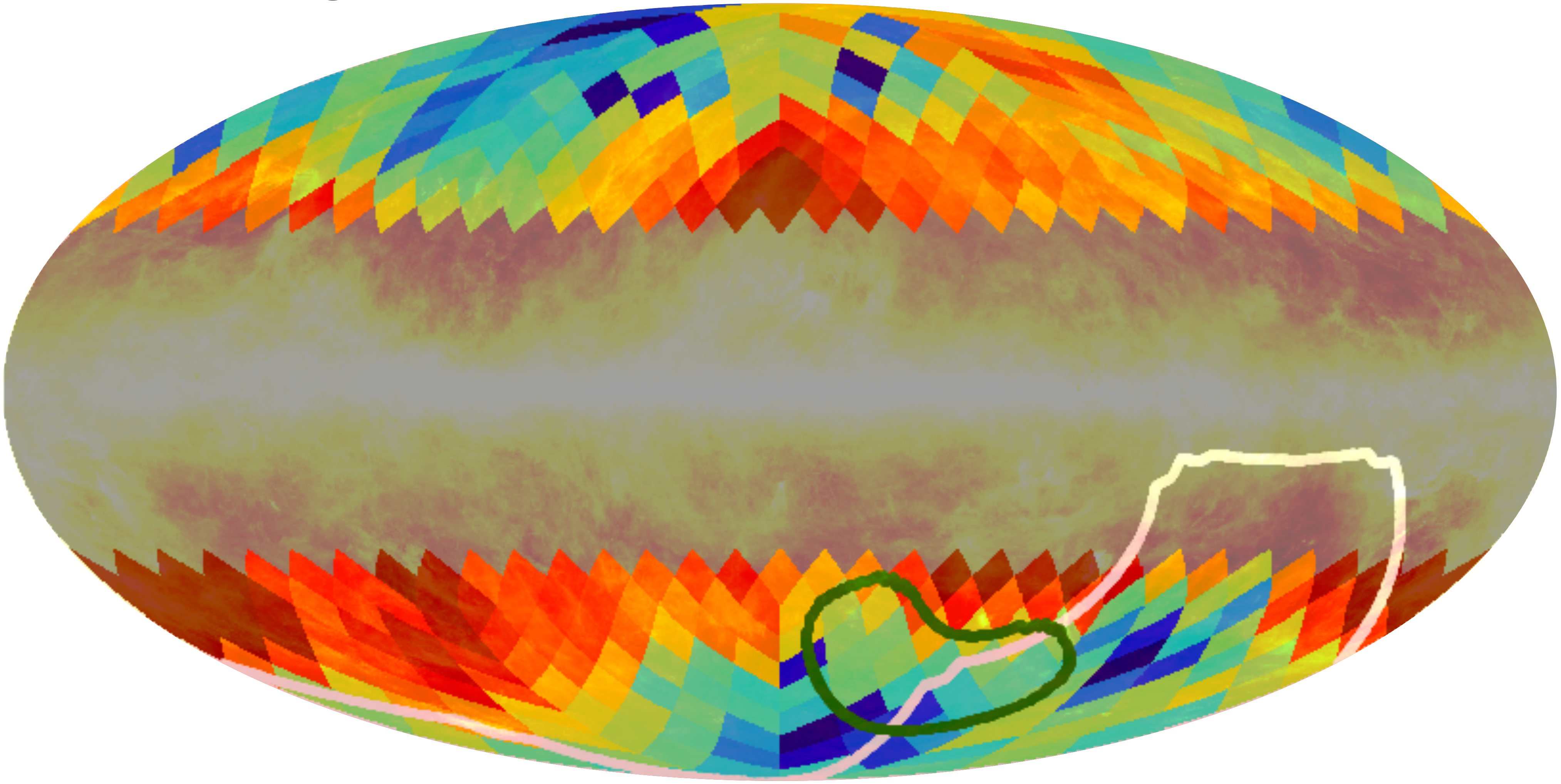
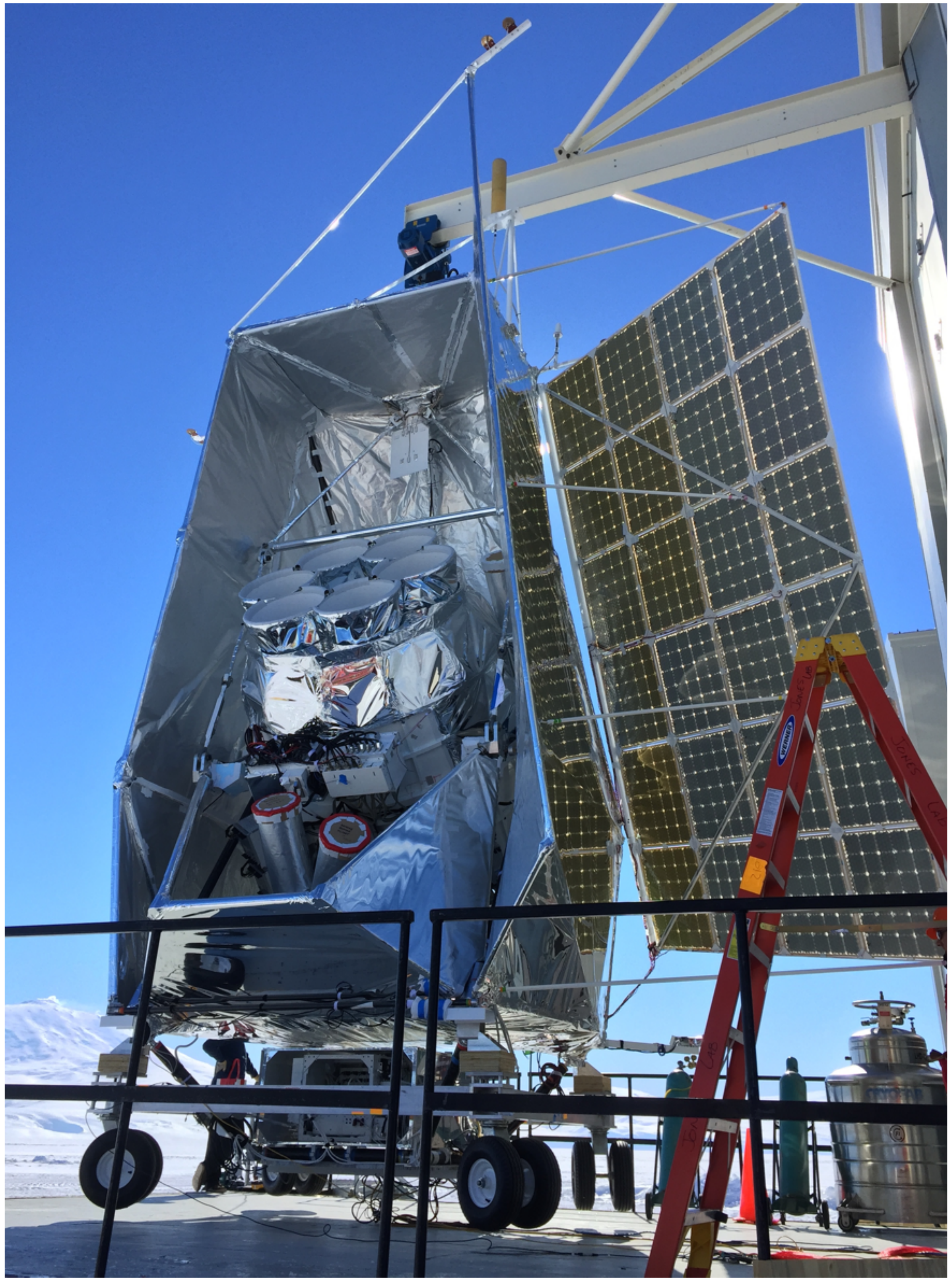
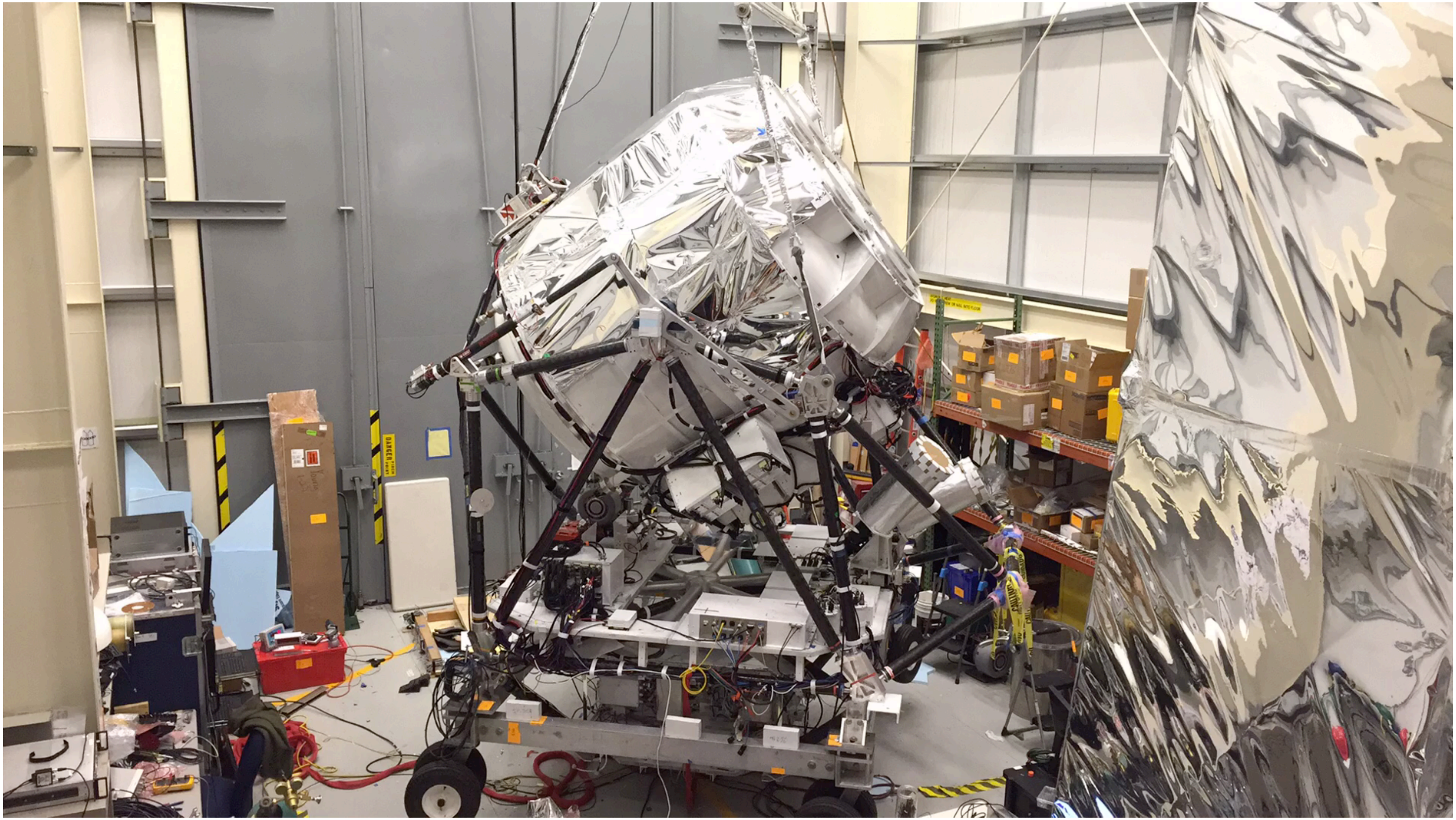


SPIDER: the instrument

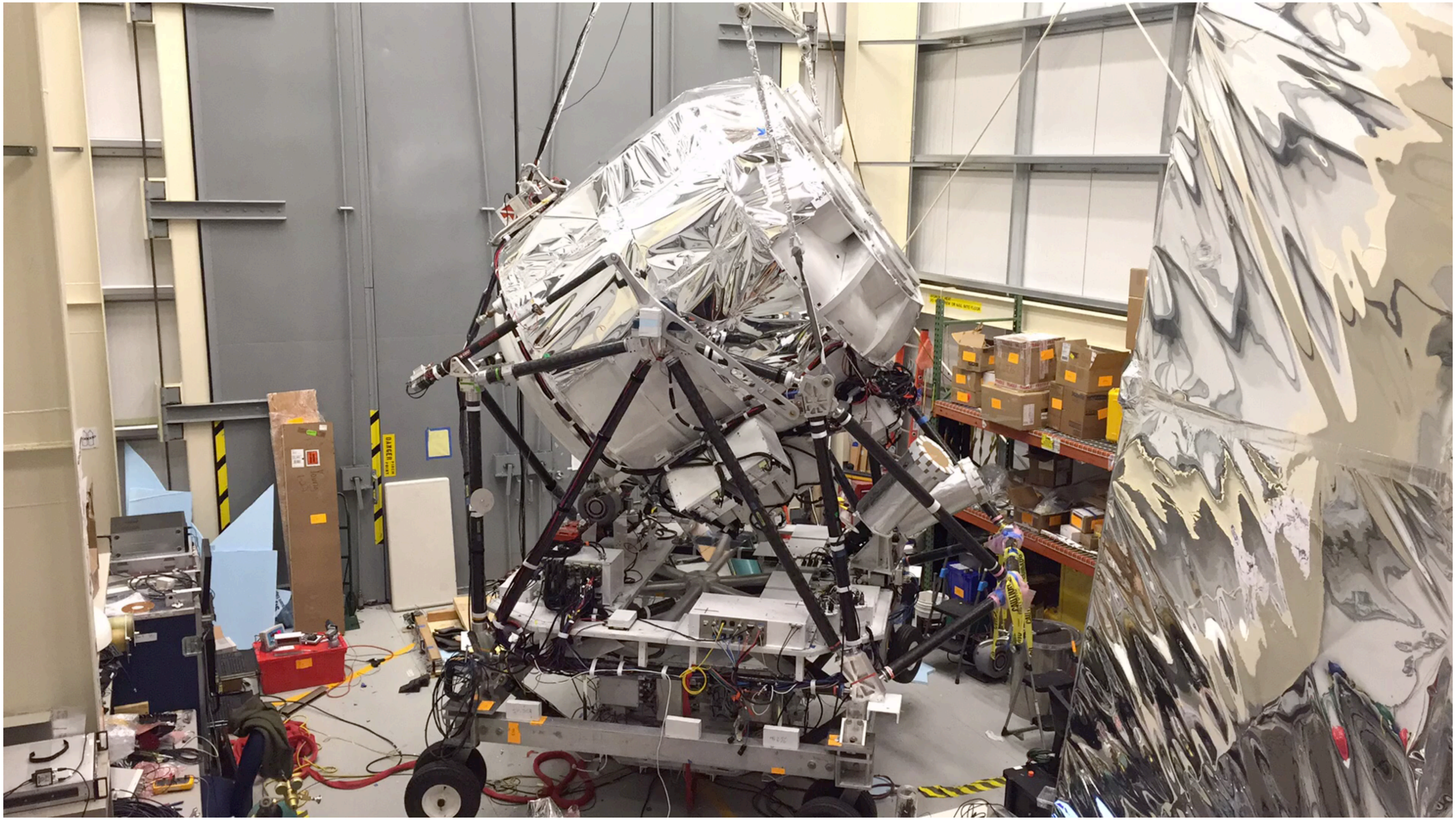
- Lightweight, carbon fiber gondola frame and sun shields
- Largest cryogenic vessel on a balloon payload
- Reaction wheel + pivot for fast az scanning
- Redundant pointing systems for in-flight and post-flight reconstruction
  - star cameras
  - dGPS
  - gyros
  - pinhole sun sensors
  - magnetometer
- Designed for nearly autonomous observations



SPIDER: the instrument

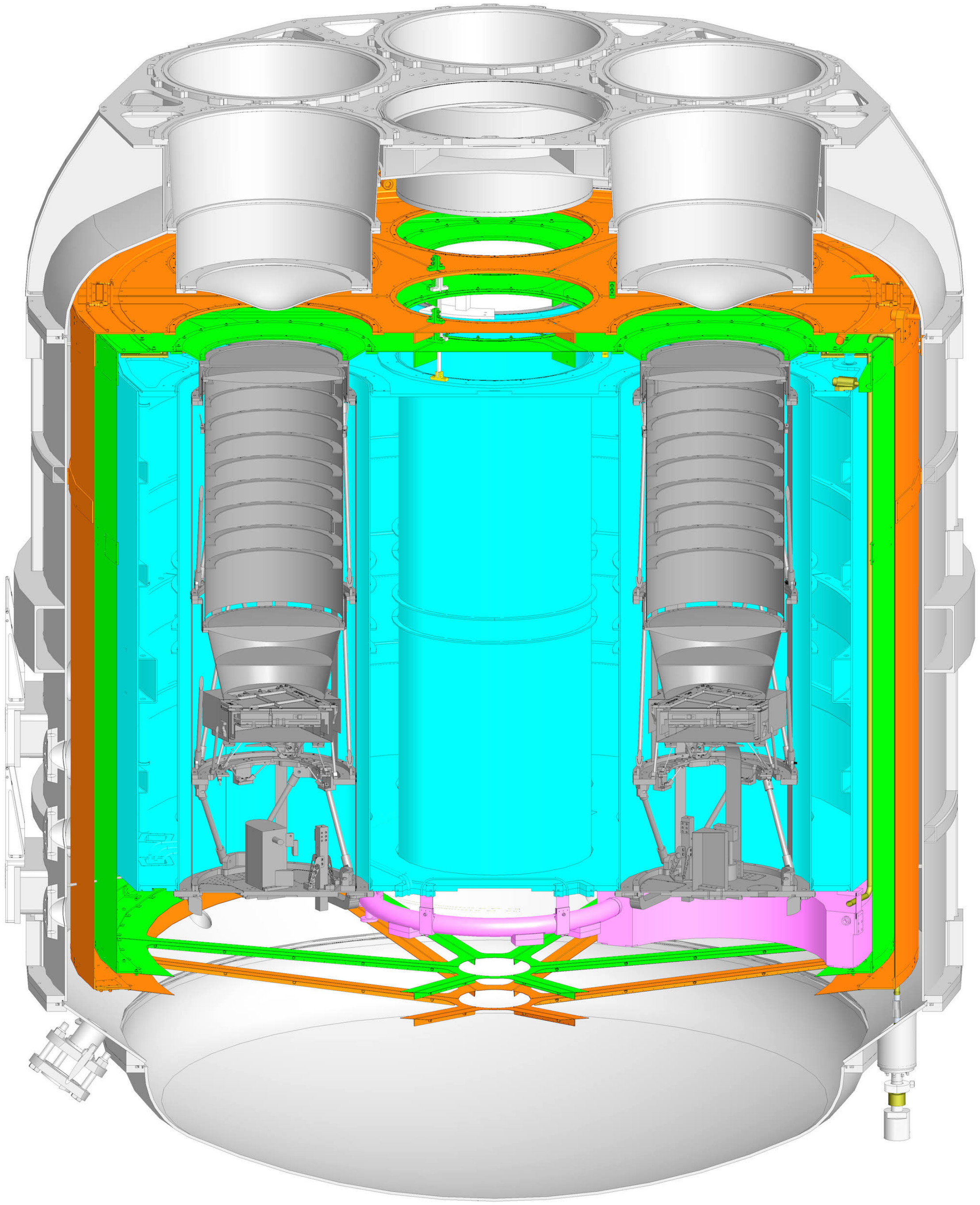


SPIDER: the instrument



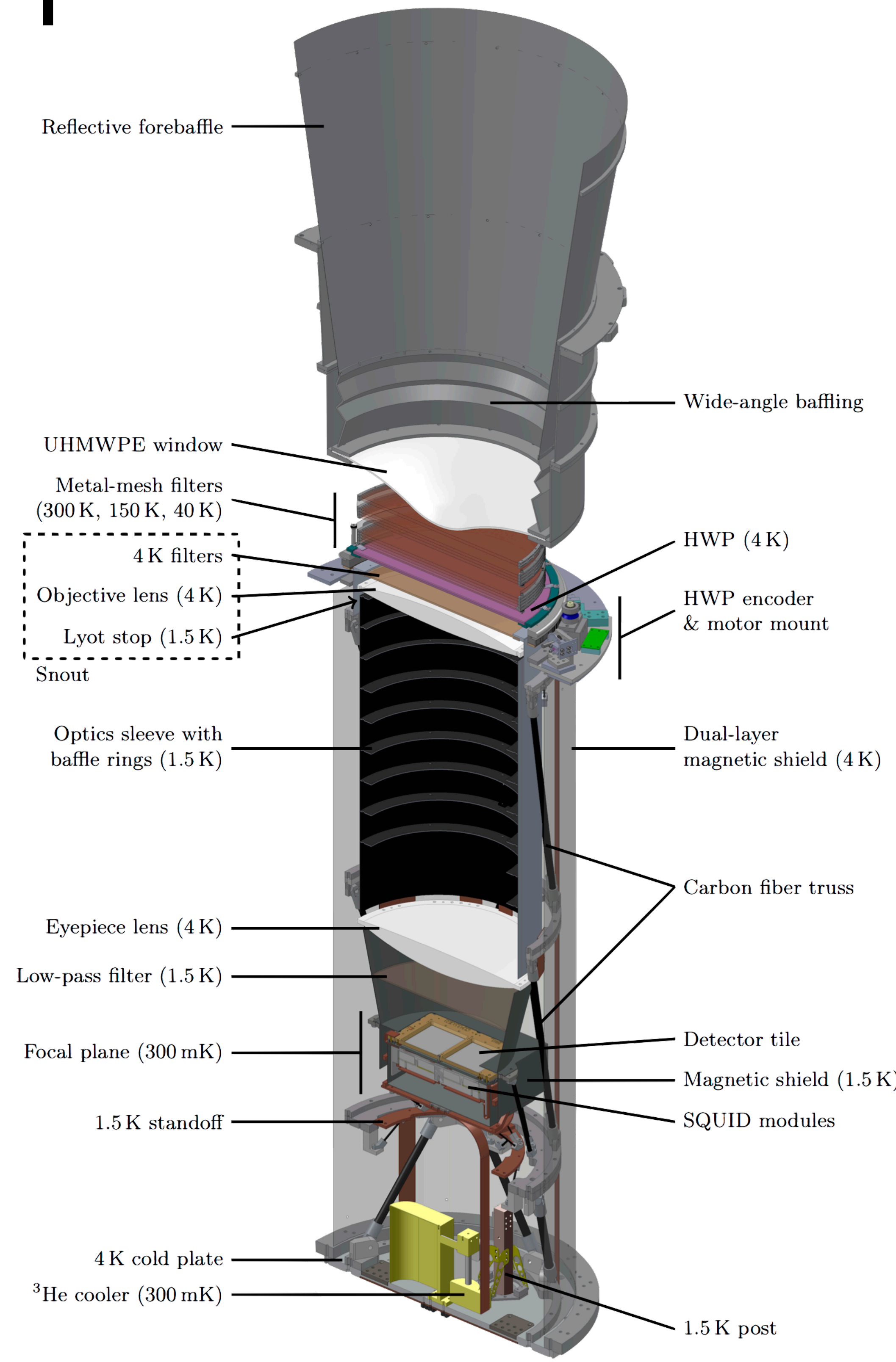
SPIDER: the instrument

- Lightweight, 1300 liter LHe4 *only* cryostat (4K)
  - Vapor cooled shields at 30 and 115K
- Capillary-fed 20 liter superfluid LHe4 tank (1.5K)
- 6 independent telescope inserts

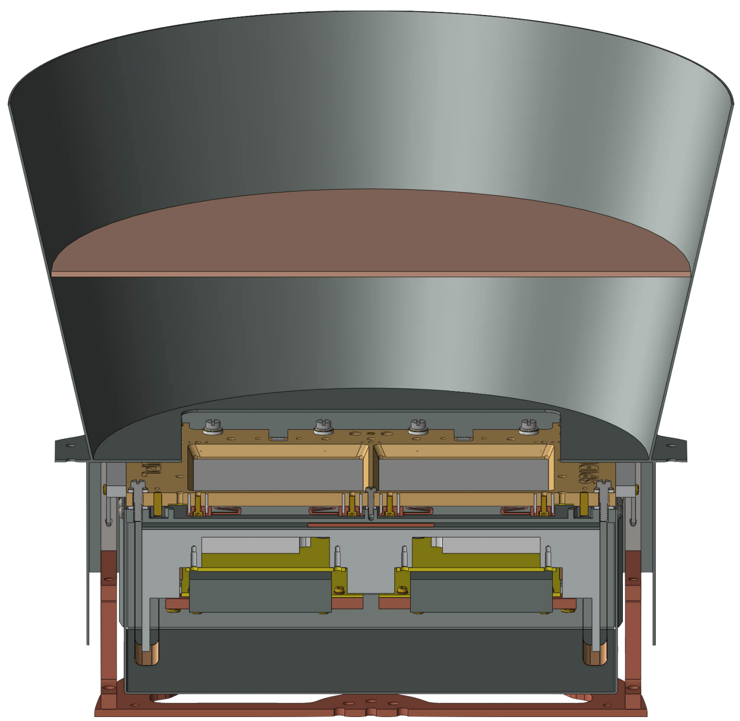


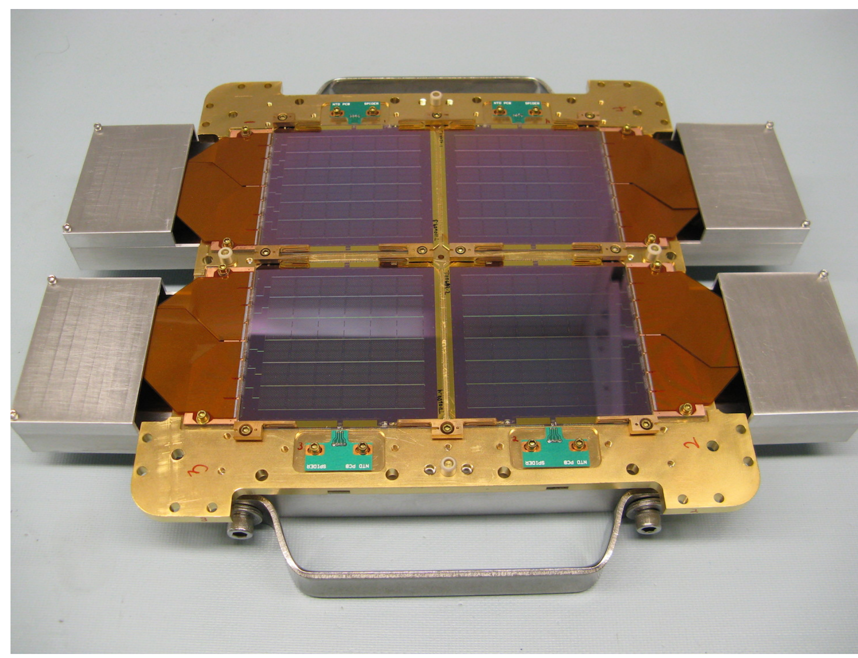
SPIDER: telescope inserts

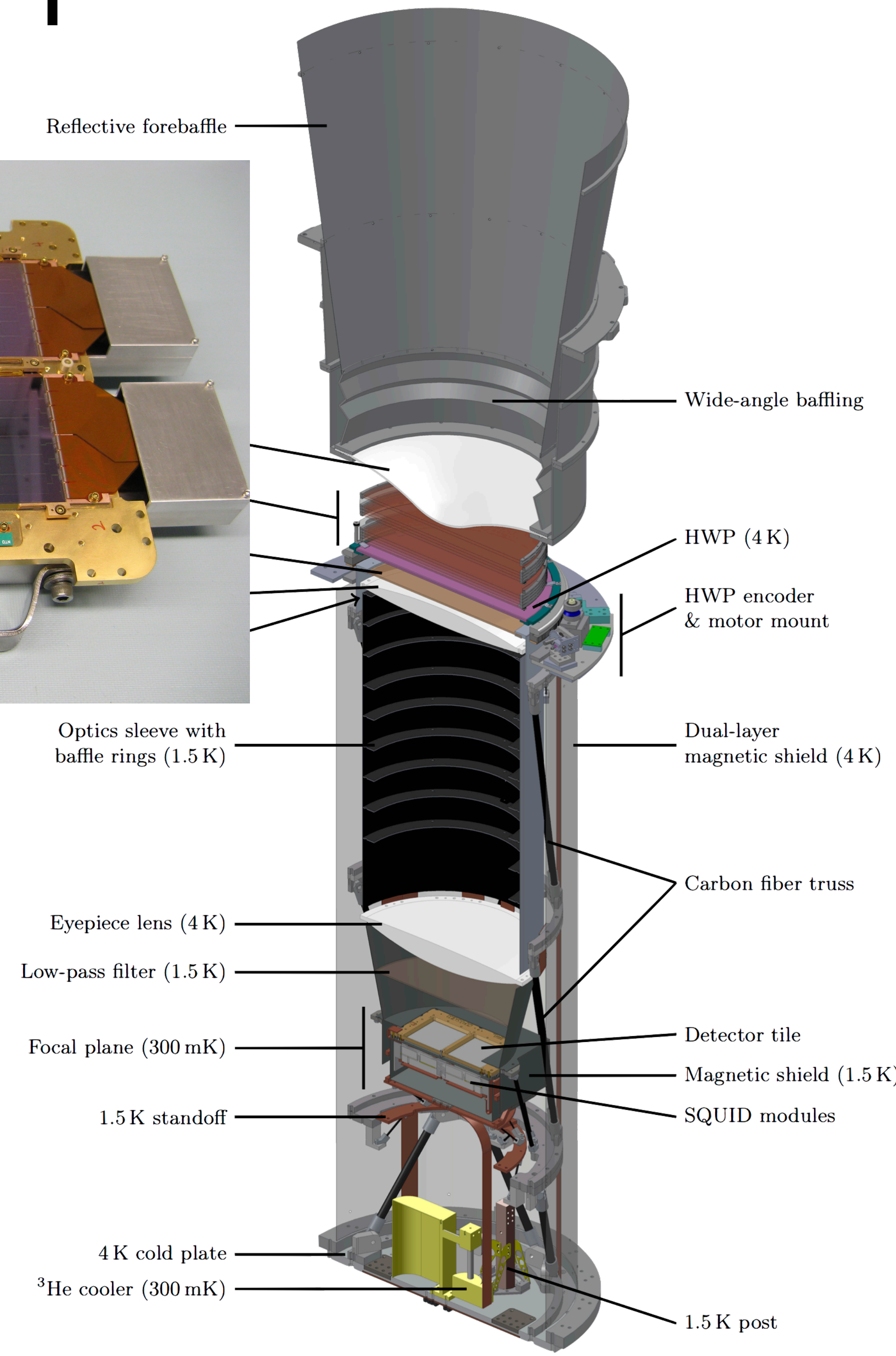
- Reflective forebaffle
- 1.5K stop and baffle
- Cooled HWP (AR-coated sapphire), worm-gear drive
- AR-coated polyethylene lenses cooled to 4K
- Stringent magnetic shielding
- Fully lithographed phased-array slot antenna coupled TES detectors
- ^{3}He adsorption fridges for ~300mK focal plane temperatures



SPIDER: telescope inserts





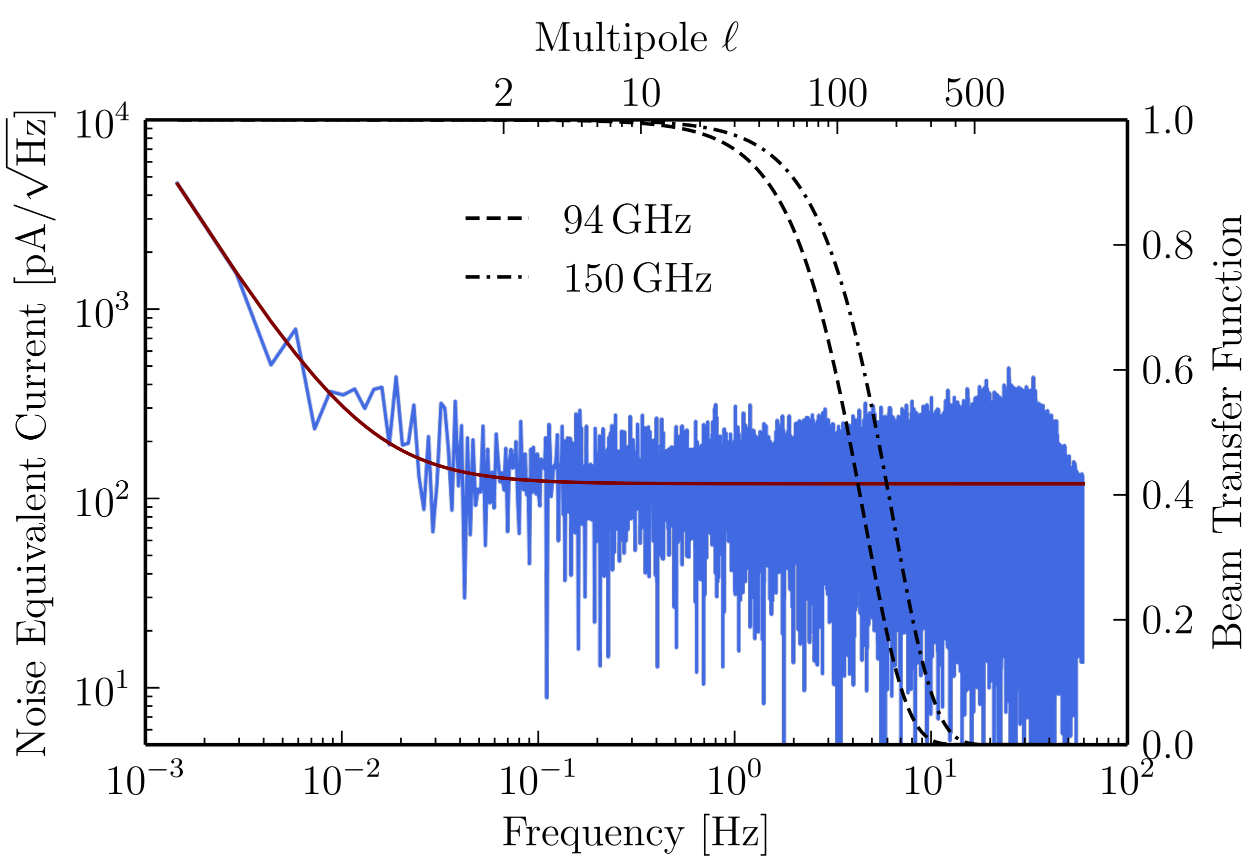


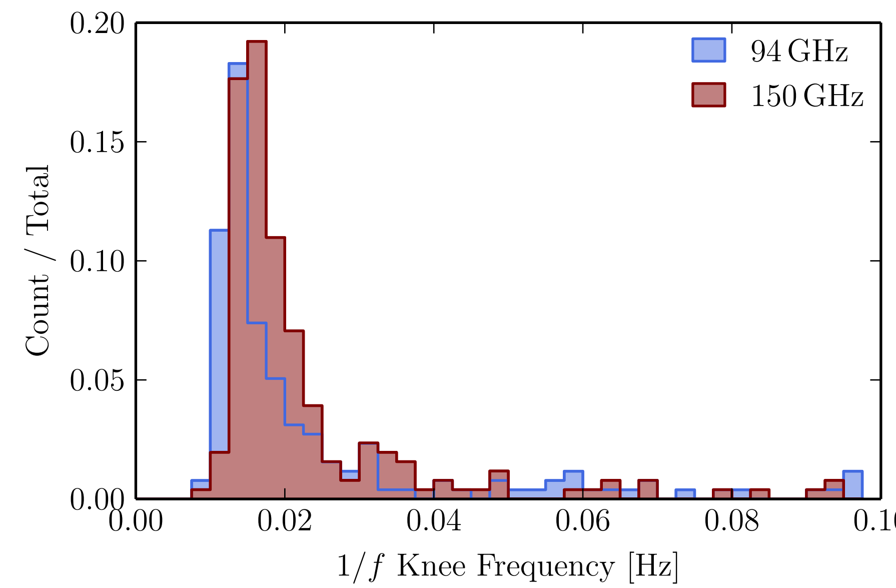
- Stringent magnetic shielding
- Fully lithographed phased-array slot antenna coupled TES detectors
- ^{3}He adsorption fridges for ~300mK focal plane temperatures

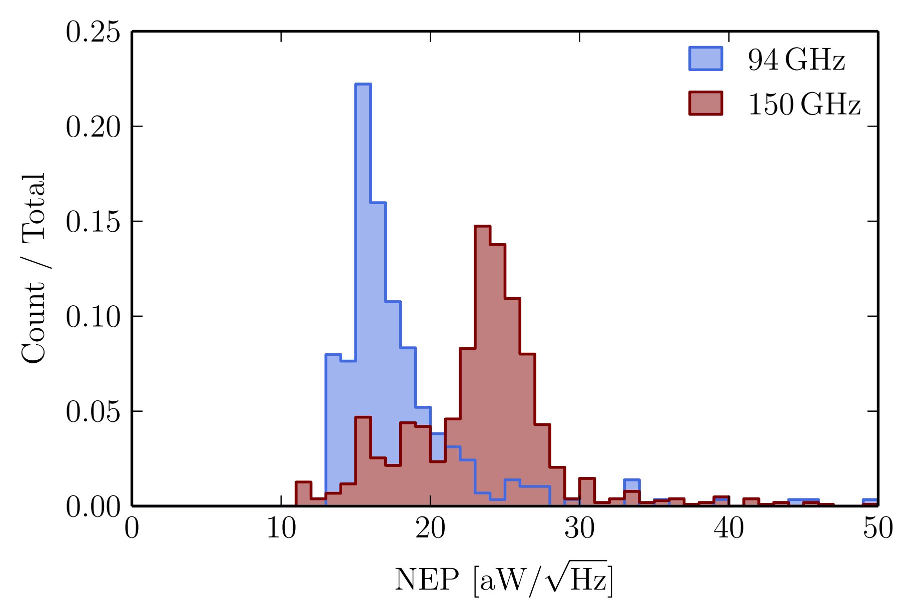
SPIDER: detector performance*

- Low 1/f knee
- White noise in science band of 0.5-8Hz (scan speed 3.6 °/s)

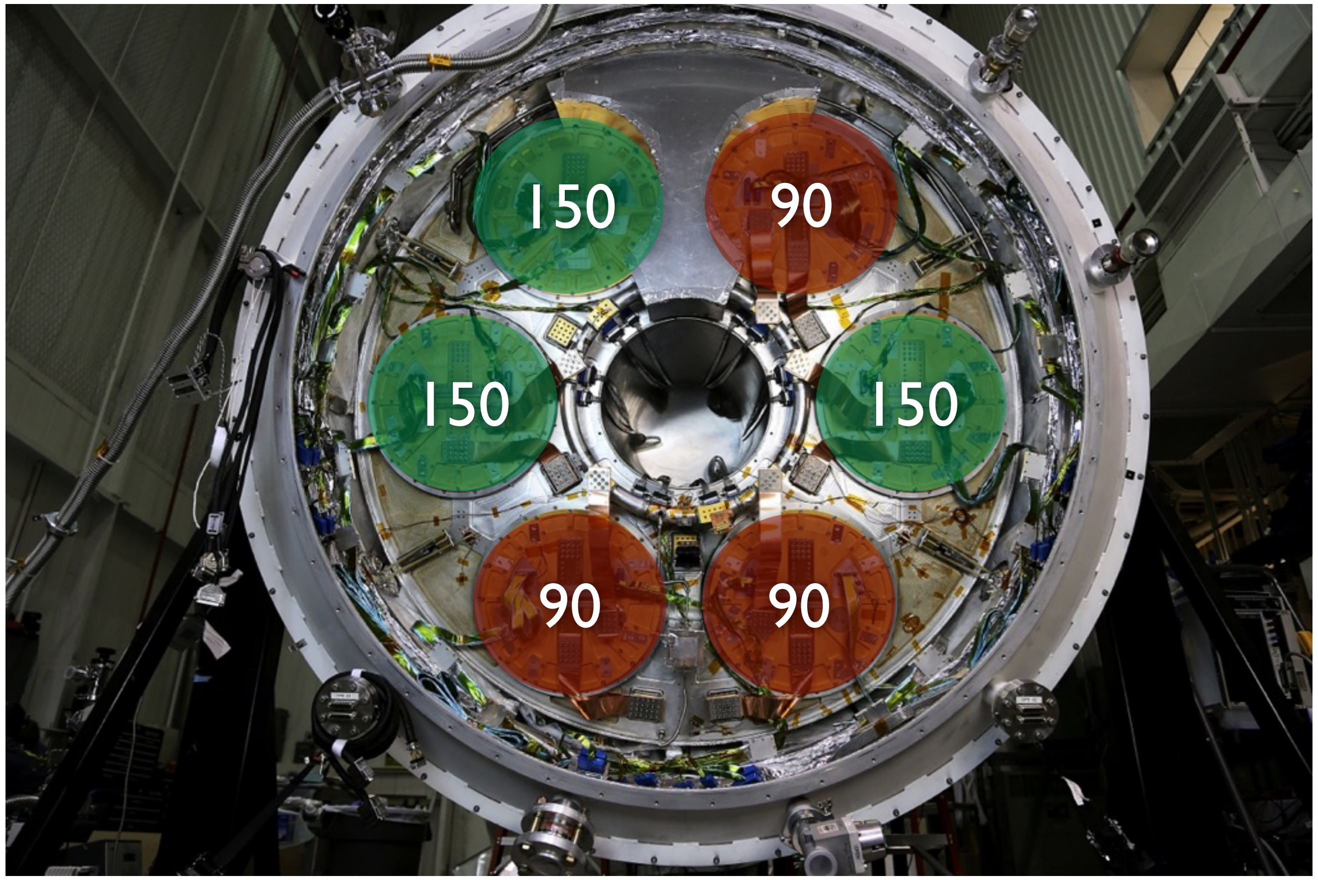
*pre-flight
__ground-based__
measurements







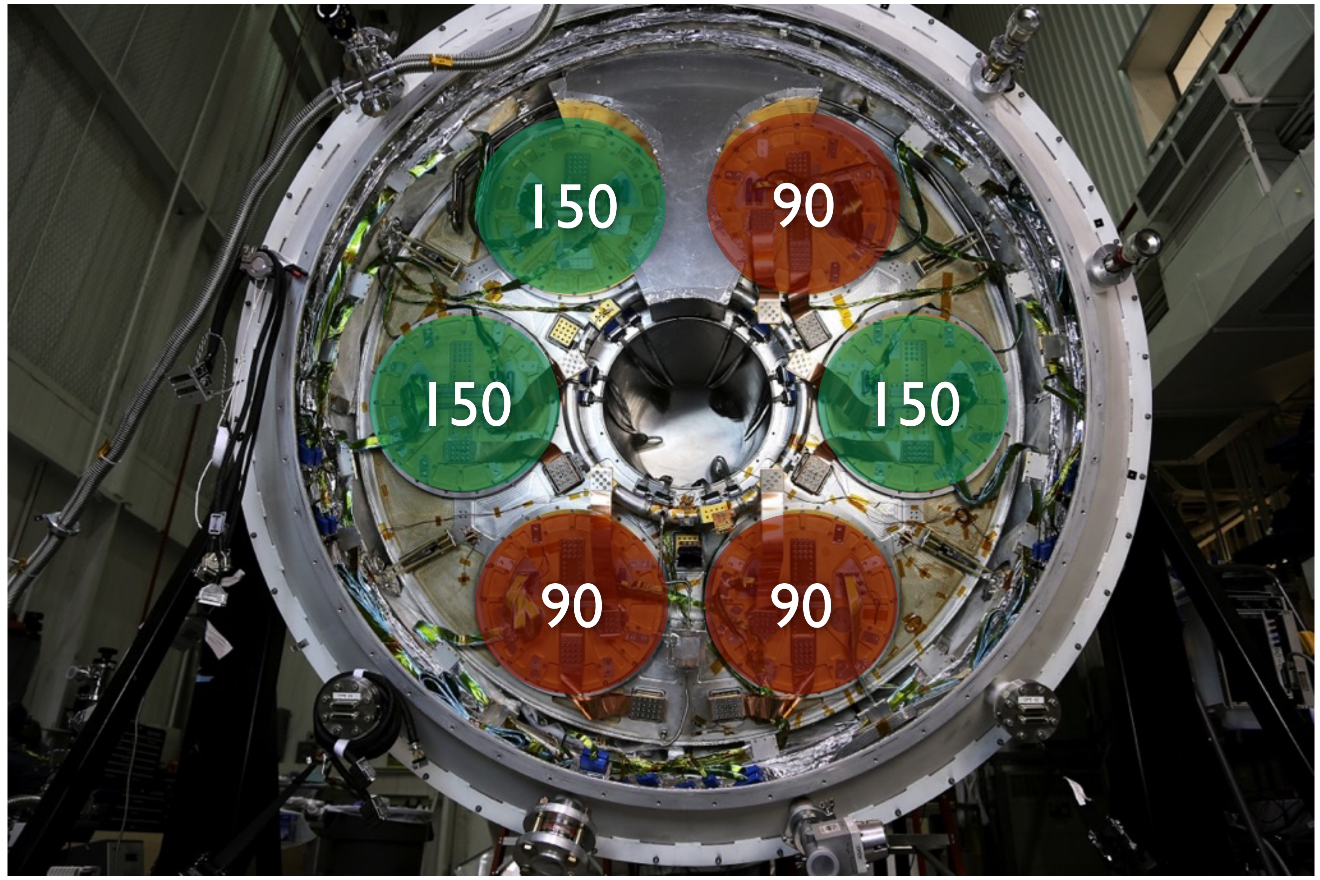
SPIDER: 1st flight specs*



*predicted NETs from *ground-based* measurements

Band [GHz]	Bandwidth [GHz]	Beam FWHM [arcmin]	# pixels	# TESs	Single-det sensitivity [μK$_{cmb}$ √s]	Instrument sensitivity [μK$_{cmb}$ √s]	tobs (days)	fsky	LDB depth [μK$_{cmb}$ - arcmin]	LDB depth [μK$_{cmb}$ - degree]
90	22	51	(3x) 136	816	140	5.3	20.0	8.0%	15.0	0.25
150	36	31	(3x) 248	1488	140	3.9	20.0	8.0%	11.1	0.19
		Total	1152	2304		*(85% yield assumed)*			*(85% obs. eff. assumed)*	

SPIDER: 1st flight specs



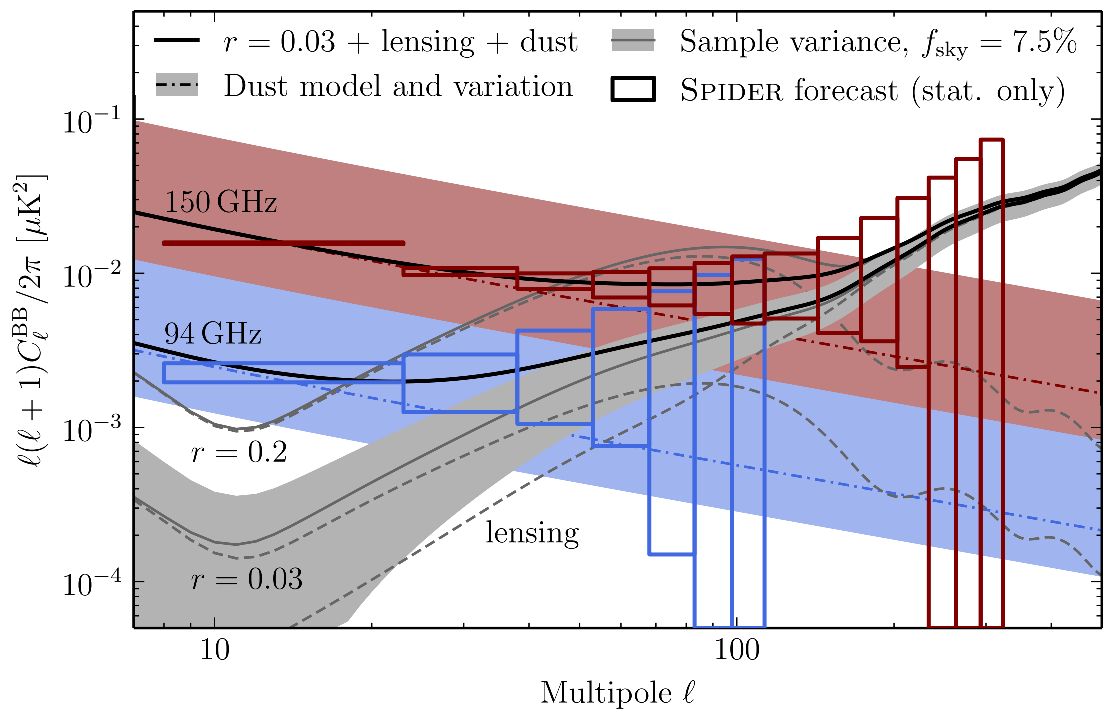
~6(9)x higher instantaneous sensitivity than *Planck* for 150 (90) GHz
~2(3)x deeper maps with 20 day flight

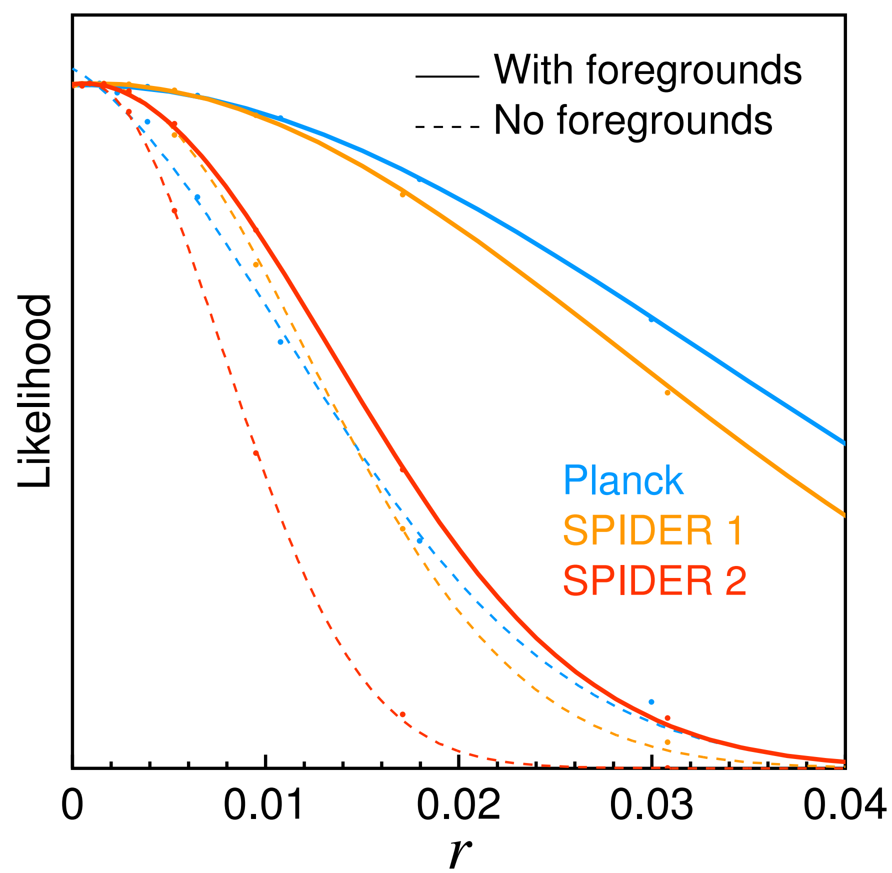
Band [GHz]	Beam FWHM [arcmin]	# pixels	# TESs	Single-det sensitivity [μK$_{cmb}$ √s]	Instrument sensitivity [μK$_{cmb}$ √s]	tobs (days)	fsky	HFI depth [μK$_{cmb}$ - arcmin]	HFI depth [μK$_{cmb}$ - degree]
Planck 90	9.5	4	8	132	46.7	1440.0	100.0%	50.7	0.84
Planck 150	7.1	4	8	65	23.0	1440.0	100.0%	24.9	0.42

SPIDER: 1st flight prospects

- High r detection possible with 1st flight data

- r < 0.03 at 3σ with 200+ GHz data





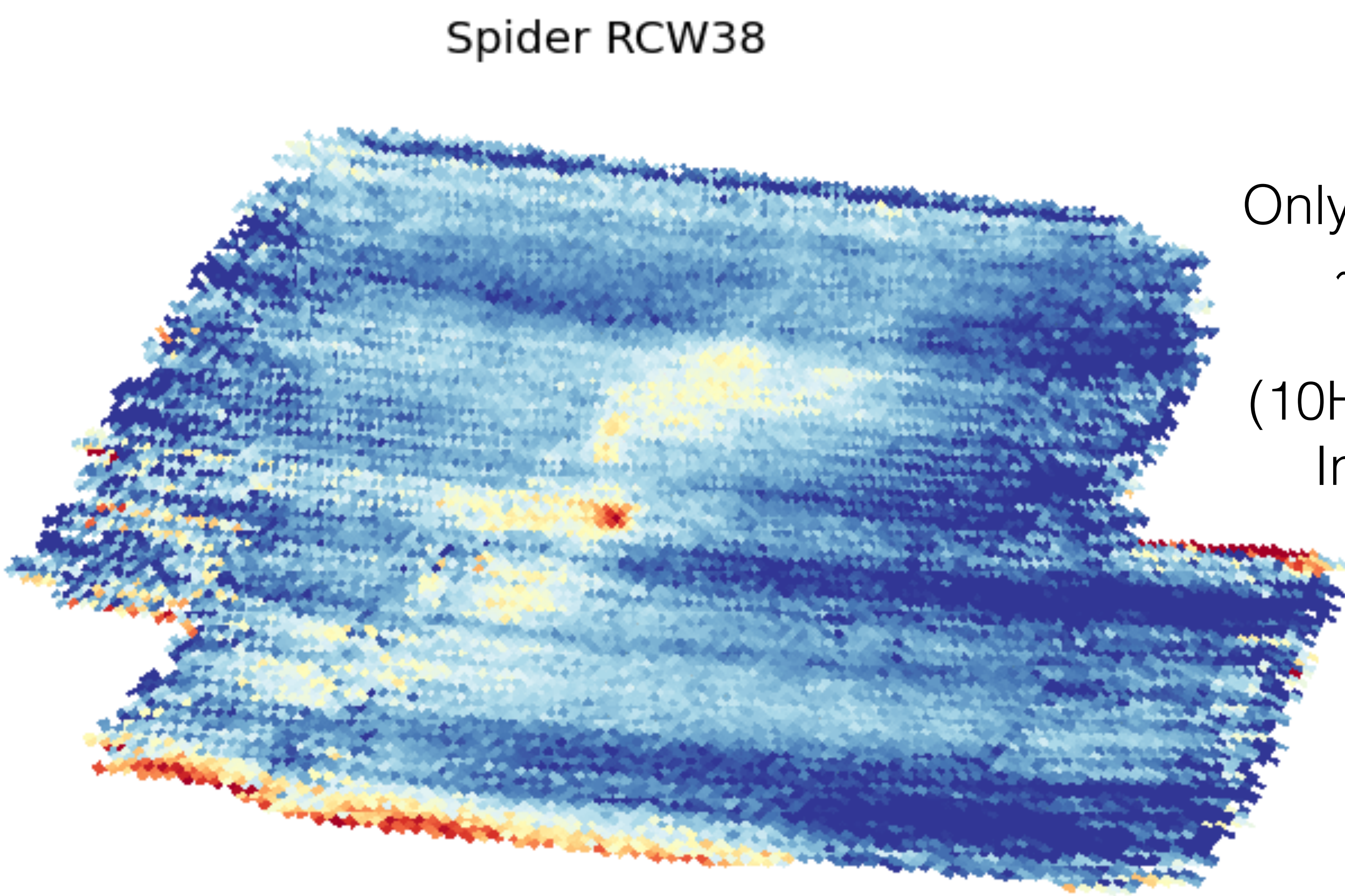
SPIDER: current status

Video by J. Gudmundsson

SPIDER: current status

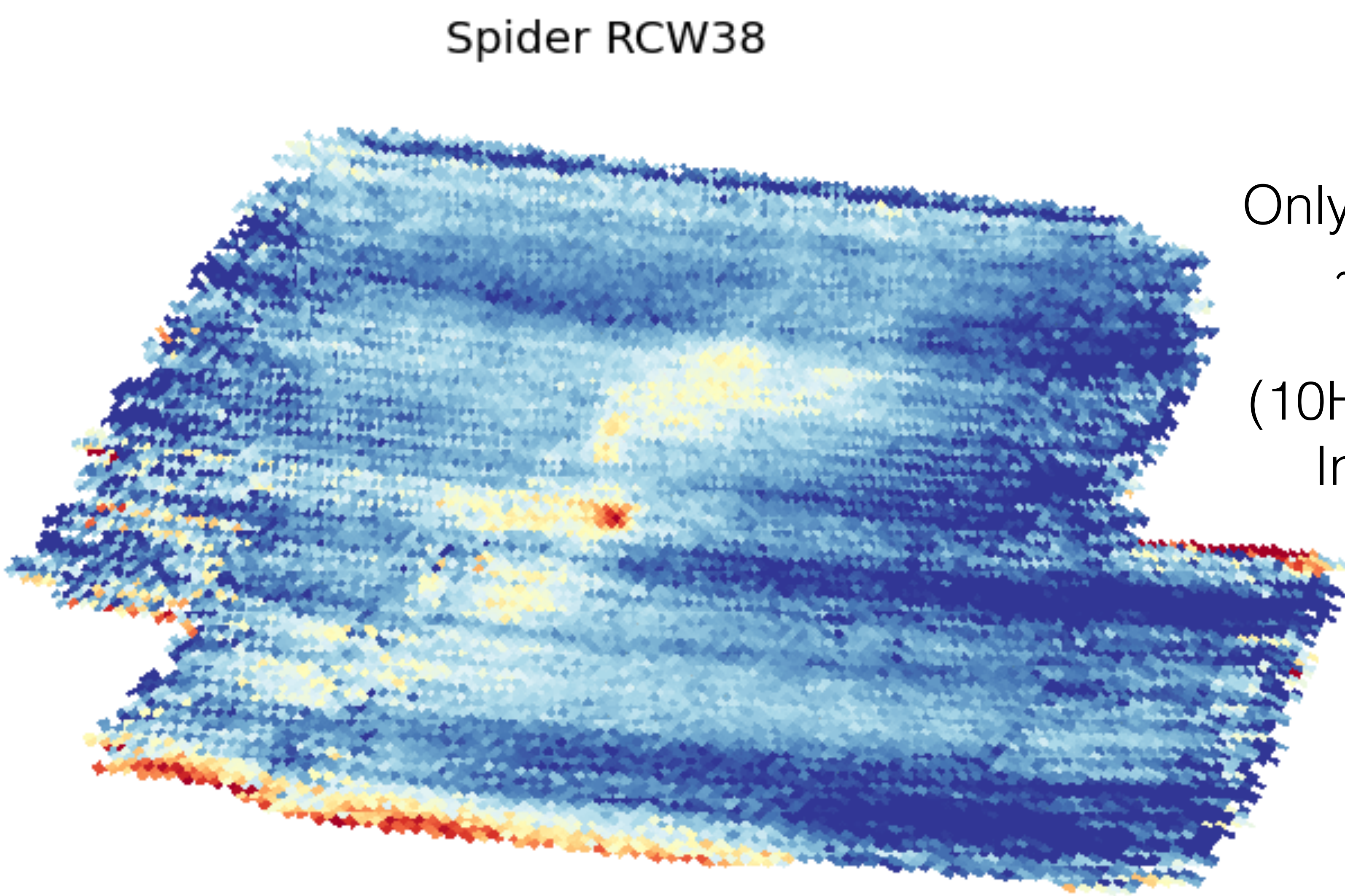
Video by J. Gudmundsson

SPIDER: in-flight performance



Preliminary analysis
Minimal signal processing
Only ~40 detectors from single insert
~14 minutes observation time
Down-sampled data
(10Hz detectors, lower on encoders)
In-flight pointing reconstruction

SPIDER: in-flight performance



Preliminary analysis
Minimal signal processing
Only ~40 detectors from single insert
~14 minutes observation time
Down-sampled data
(10Hz detectors, lower on encoders)
In-flight pointing reconstruction

SPIDER: in-flight performance

Summary

- Detector NETs ~140-180 μK√s with ~2000* detectors at 90GHz and 150GHz (P_{opt} < 0.5pW)
- Should have surpassed *Planck* 2015 average map depths on cleanest 10% (6.5% hits-weighted) of southern hemisphere
- In-flight pointing reconstruction seems good
- Cosmic rays seem to be a non-issue

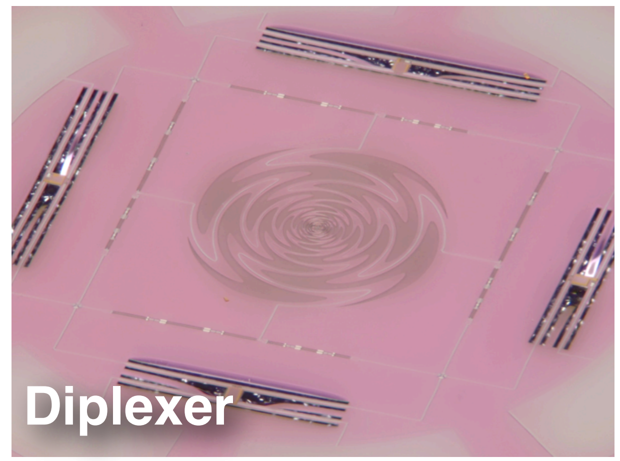
*Preliminary in-flight yield looks good, but not fully surveyed

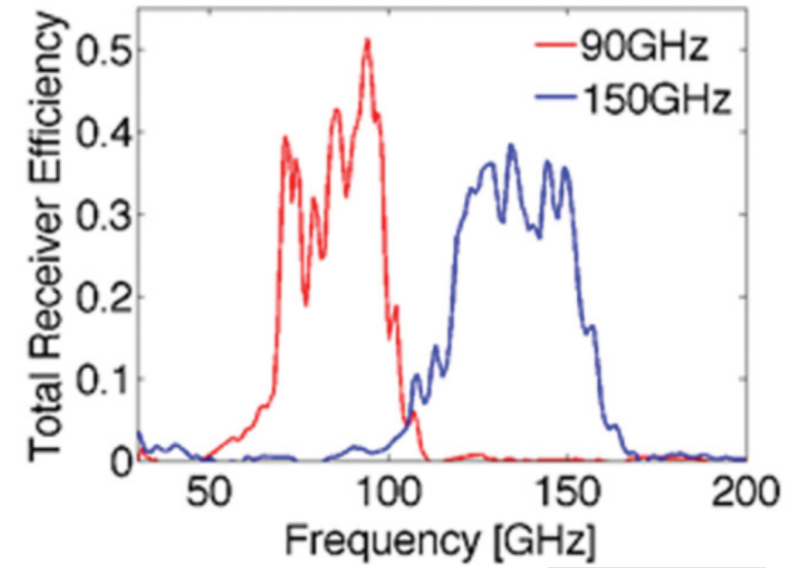
What's next?

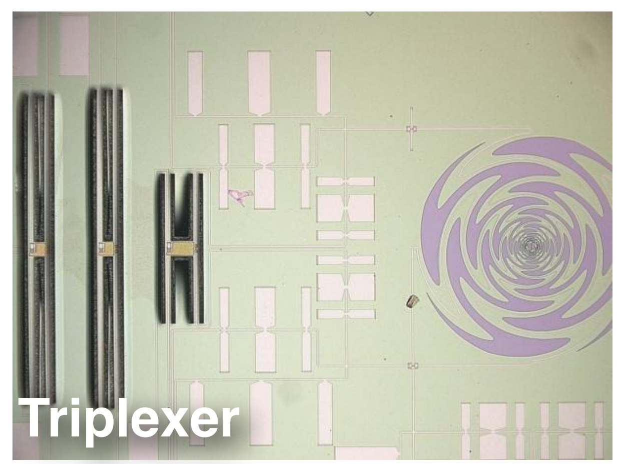
POLARBEAR Future plans: more frequencies

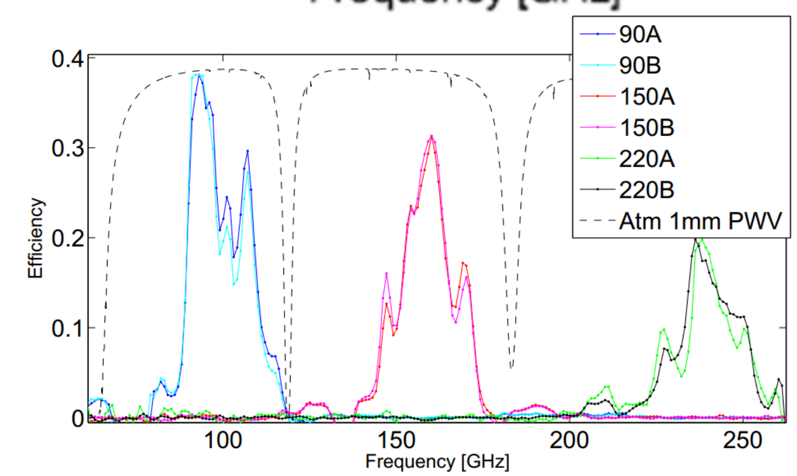
- Broad-band, dual polarization sinuous antenna
- Filter desired spectral bands to individual bolometers
- Challenge to achieve broad-band throughput in optical elements
- Several experiments (PB-2, SPT3G, LiteBIRD, EBEX6K) slated to use this technology

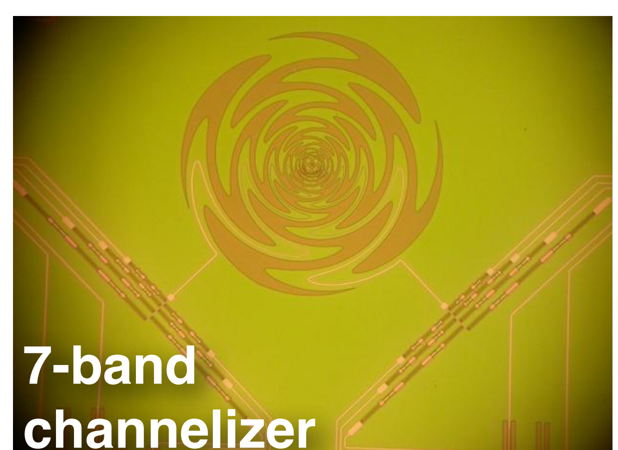
R. O'brient, A. Suzuki

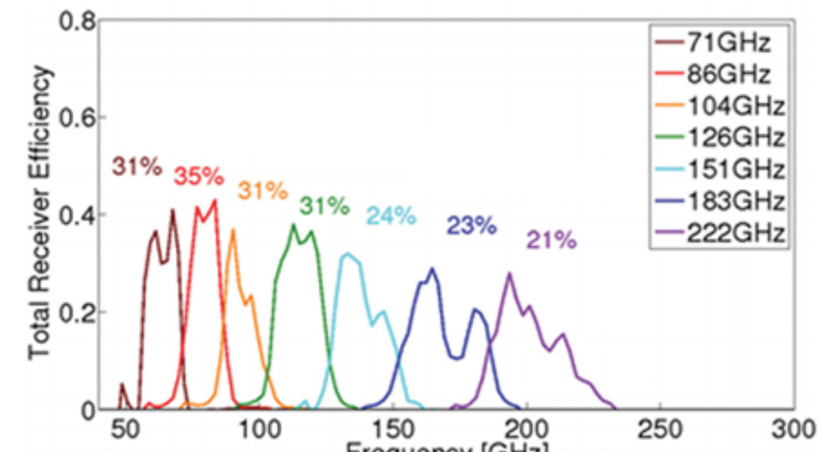












POLARBEAR: Future plans

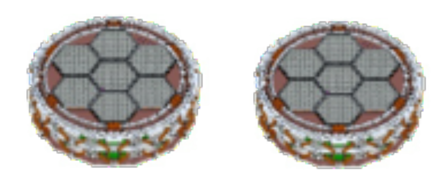
POLARBEAR-1 new season

- extended scans
- deeper integration
- measurement of large scale B-modes
- constraint on r

SIMONS ARRAY

SIMONS FOUNDATION

- three frequencies: 95 + 150 + 220 GHz
- > 22,000 detectors
- σ(Σmν) ~ 19meV w/DESI BAO+Planck



2014

2015

2016

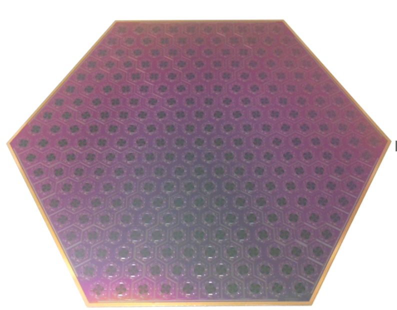
2017

POLARBEAR-2

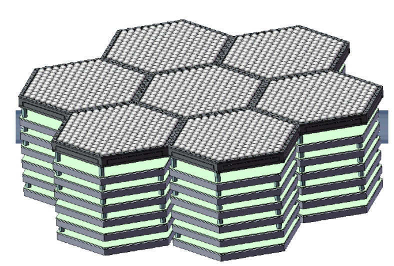
- 1,897 sinuous antenna (7588 detectors)
- two frequencies: 95 + 150 GHz

sinuous antenna

x271

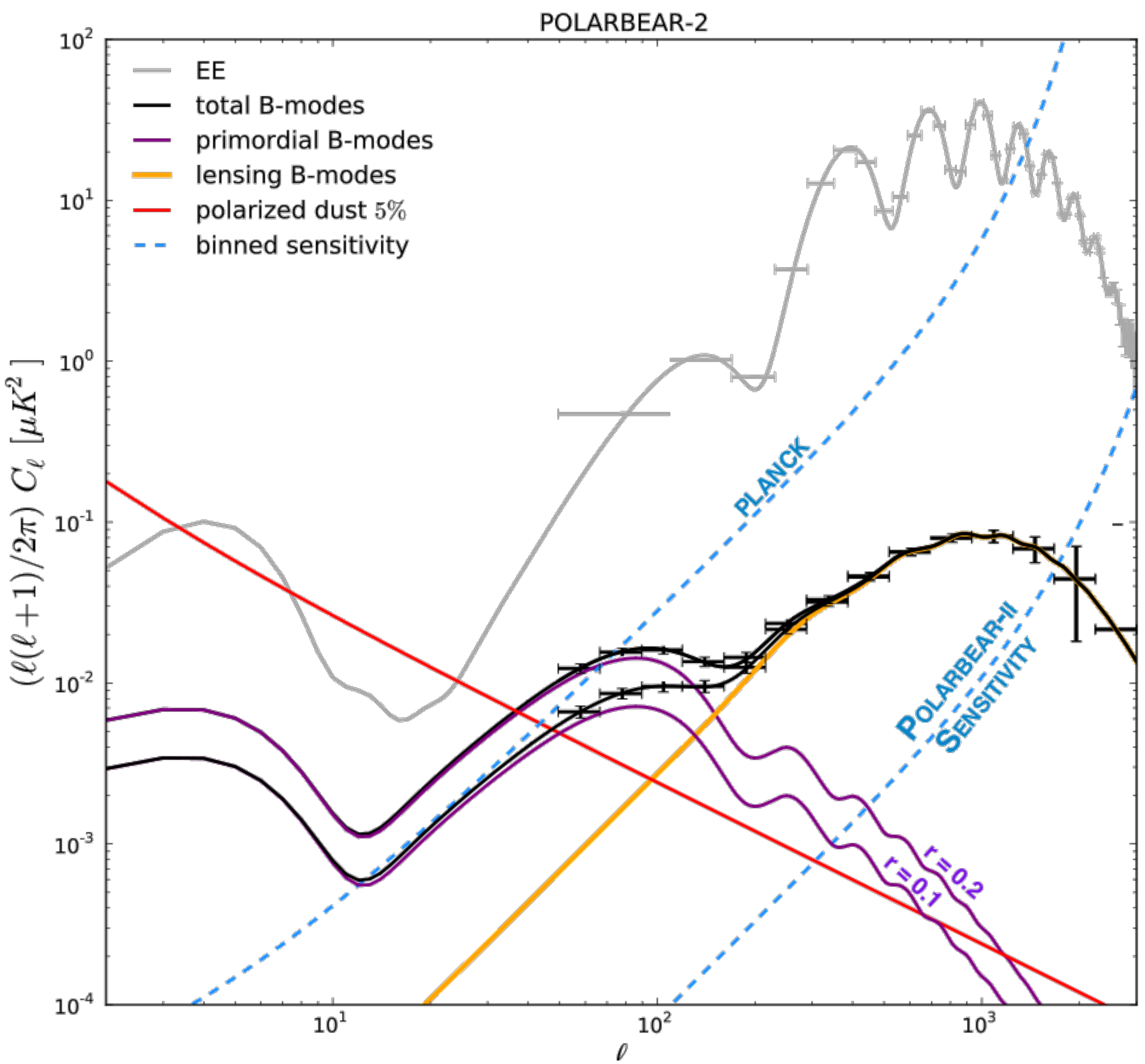


x7



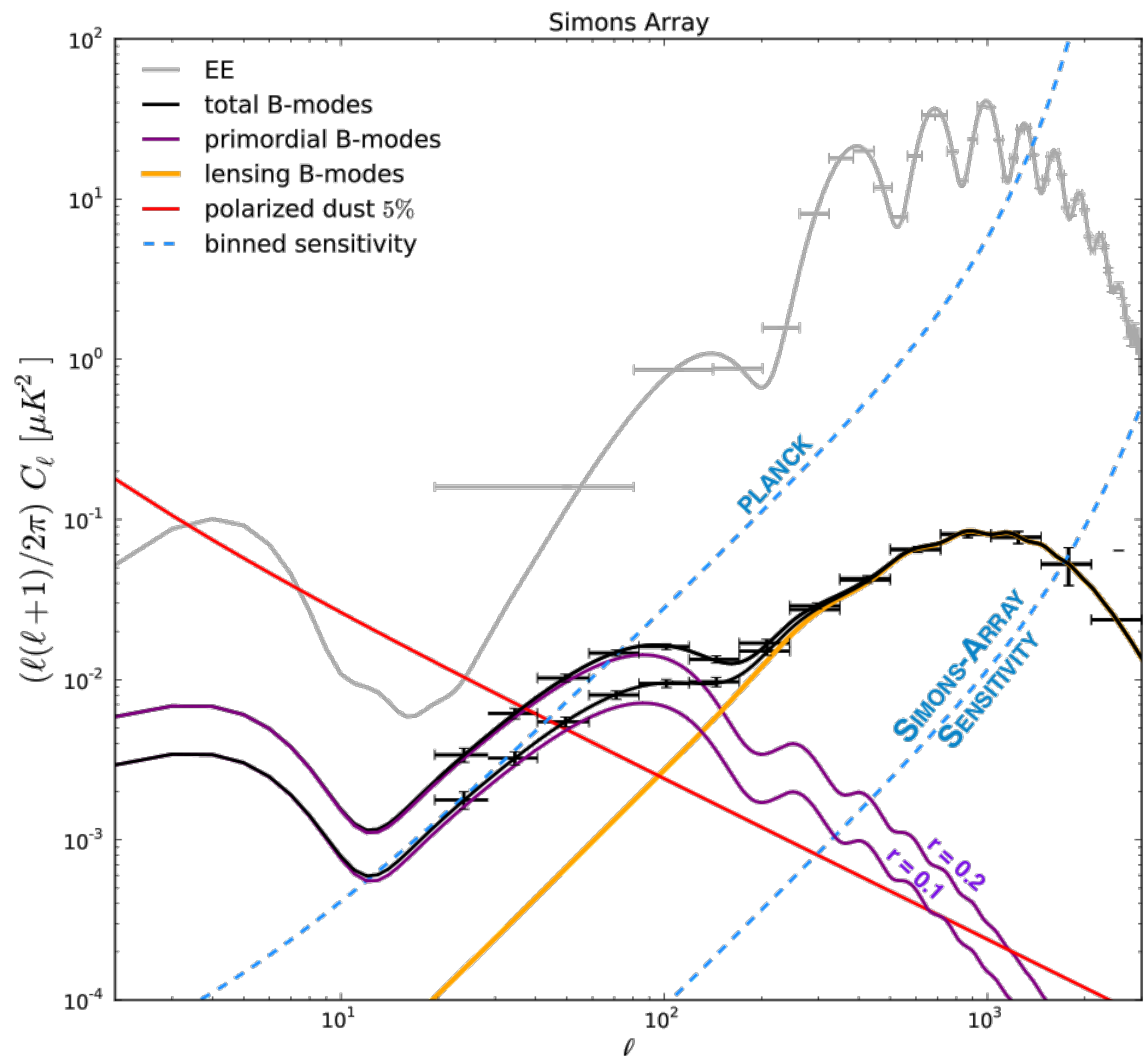
Future plans: POLARBEAR-2

- 5.8 / 5.8 μK√s (95 / 150 GHz) (combined: 4.1 μK√s)
- r ~ 0.01 (95% CL)
- Σm_ν=90 meV (68% CL) (Σm_ν=65 meV w/ PLANCK)



Future plans: Simons Array

- 22,764 (!!!!) detectors across 3 telescopes
- 95 / 150 + 150 / 220 GHz focal plans
- r ~ 0.002 (95% CL)
- Σm_{ν} = 70 meV (68% CL)
  Σm_{ν} = 19 meV w/ PLANCK + DESI BAO



SPIDER: future plans more frequencies!

- Busy with analysis of data from first flight
- Second flight 2017 / 2018*
    - New cryostat already being made
    - Add >220 GHz channels

*Dependent on recovery

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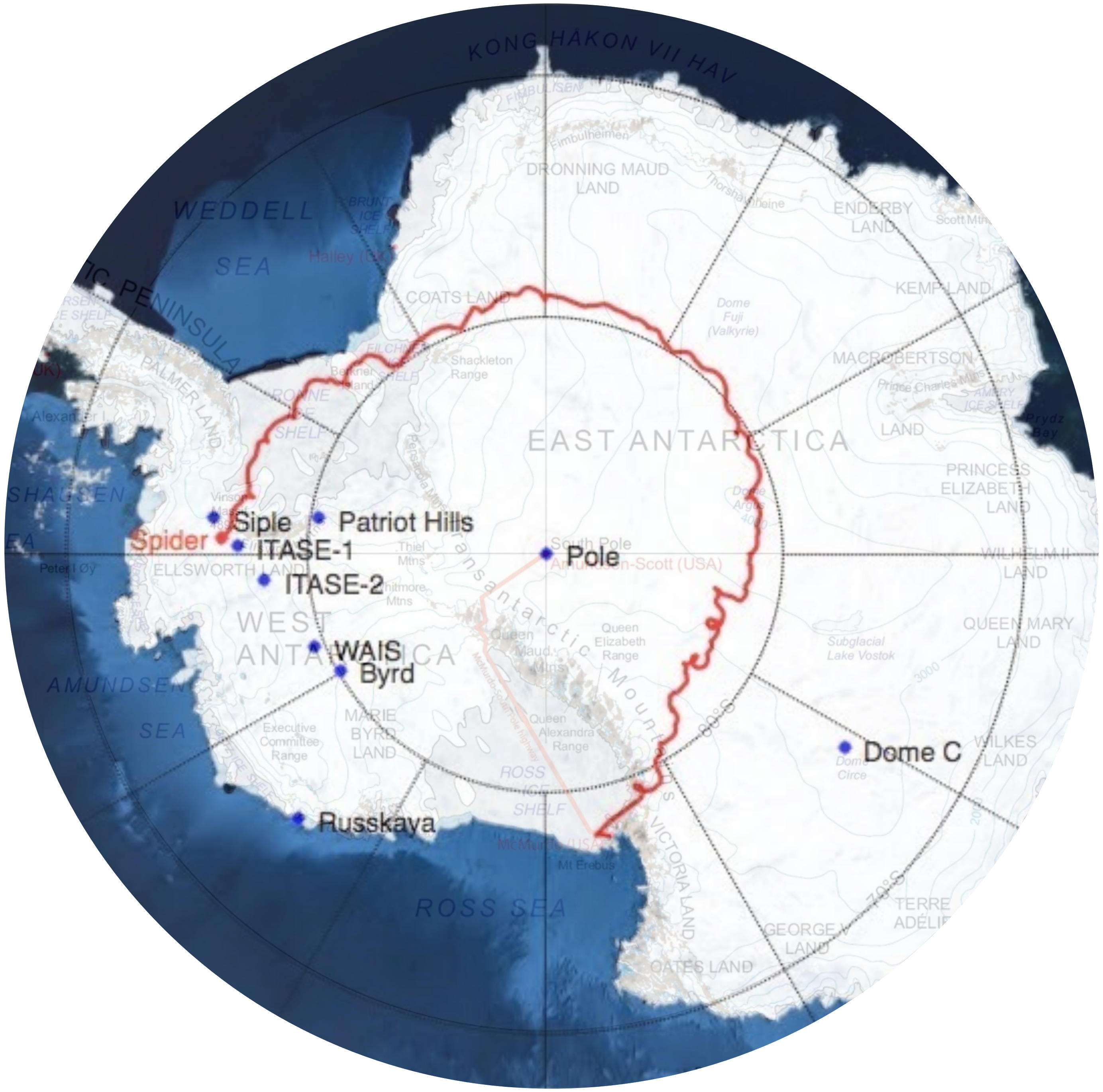

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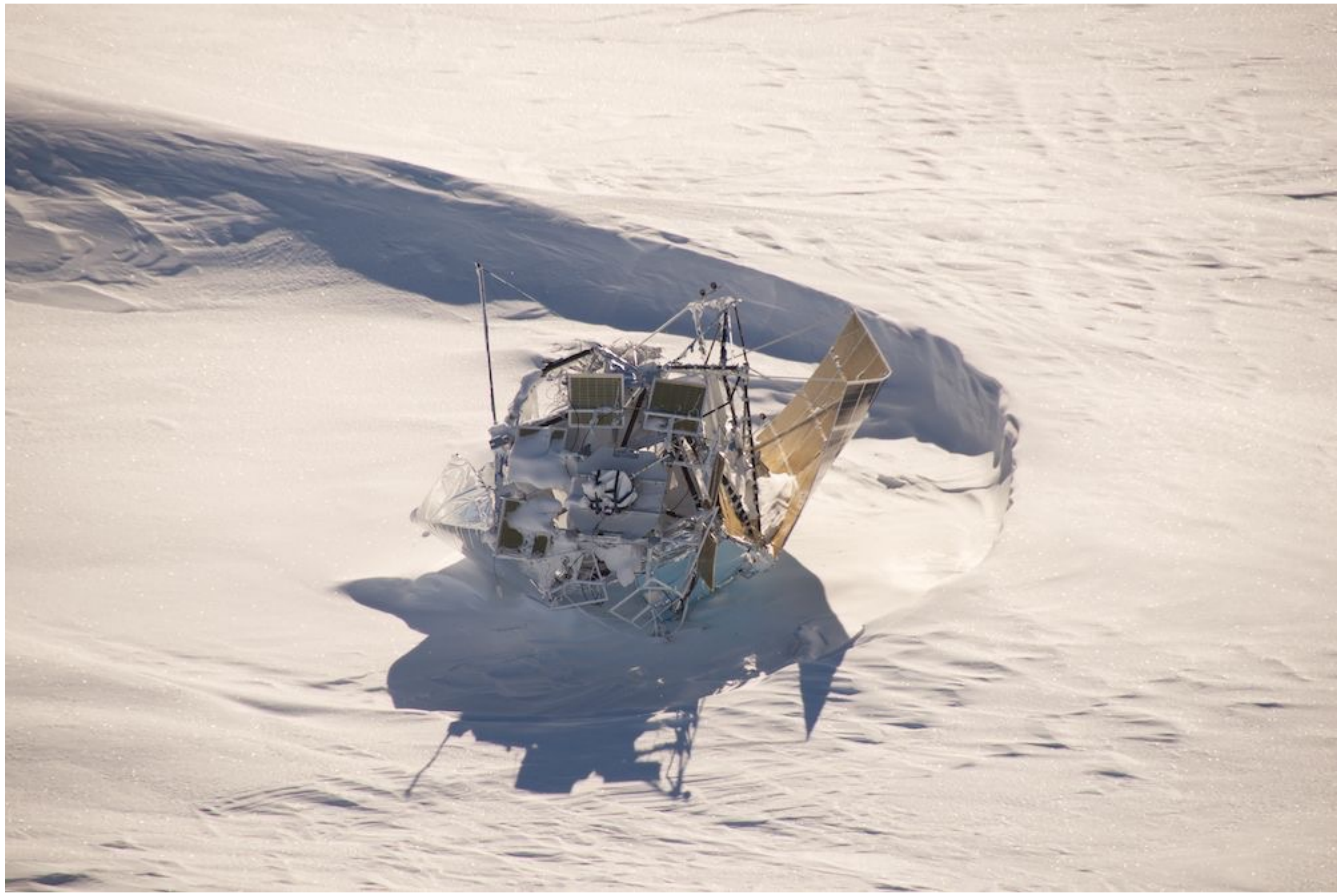

*Dependent on recovery

Conclusions

- POLARBEAR probing small scales & pushing large scales and higher frequencies from the ground with next generation instruments

- SPIDER going after large scales, able to probe higher frequencies from balloon platform in future flights

Thank you!!