Measurements of Degree-Scale B-mode Polarization with the BICEP/Keck Experiments at South Pole

Benjamin Racine

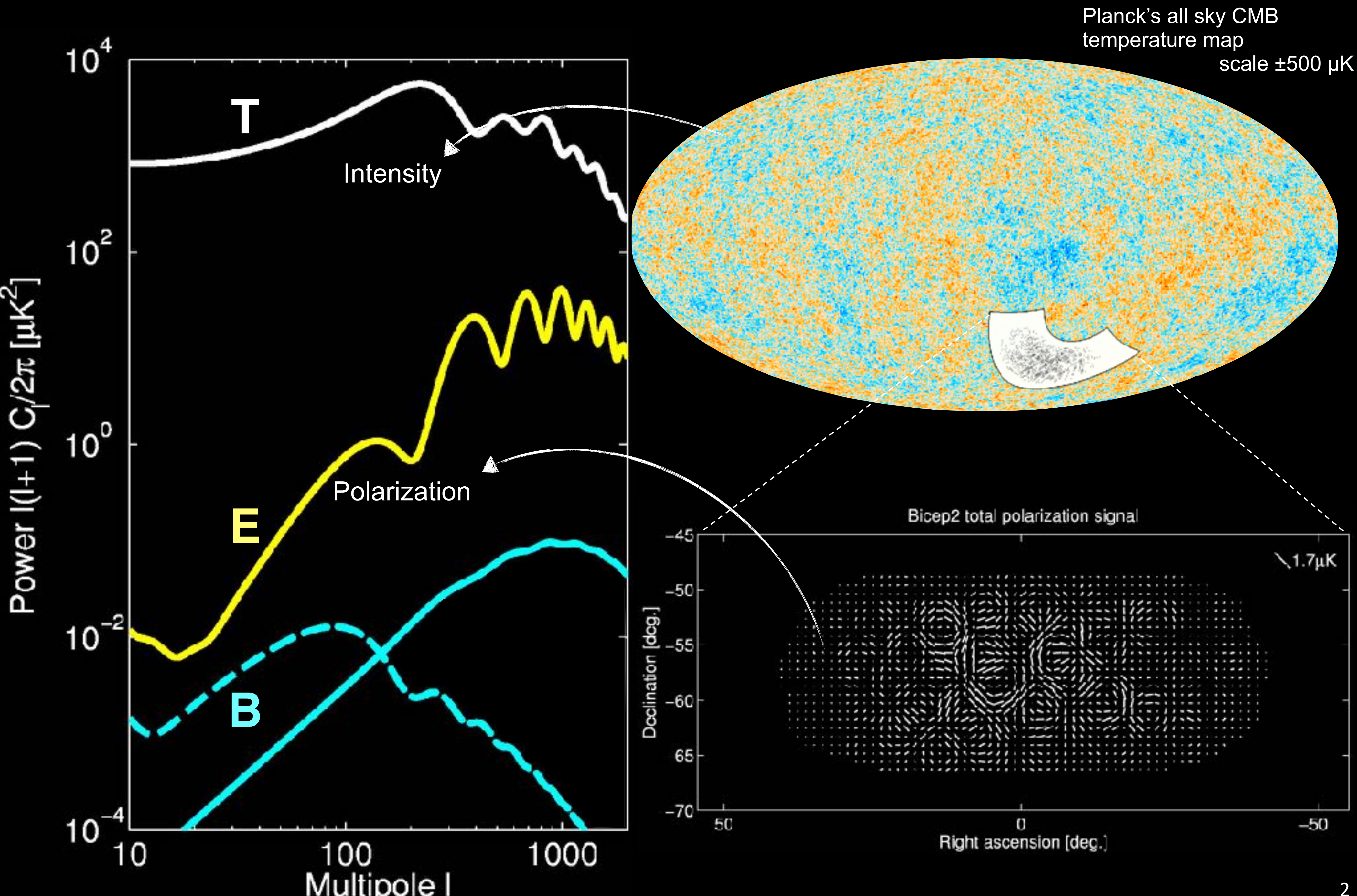
for the BICEP/Keck Collaboration

Video from Robert Schwarz

December 18th, 2019

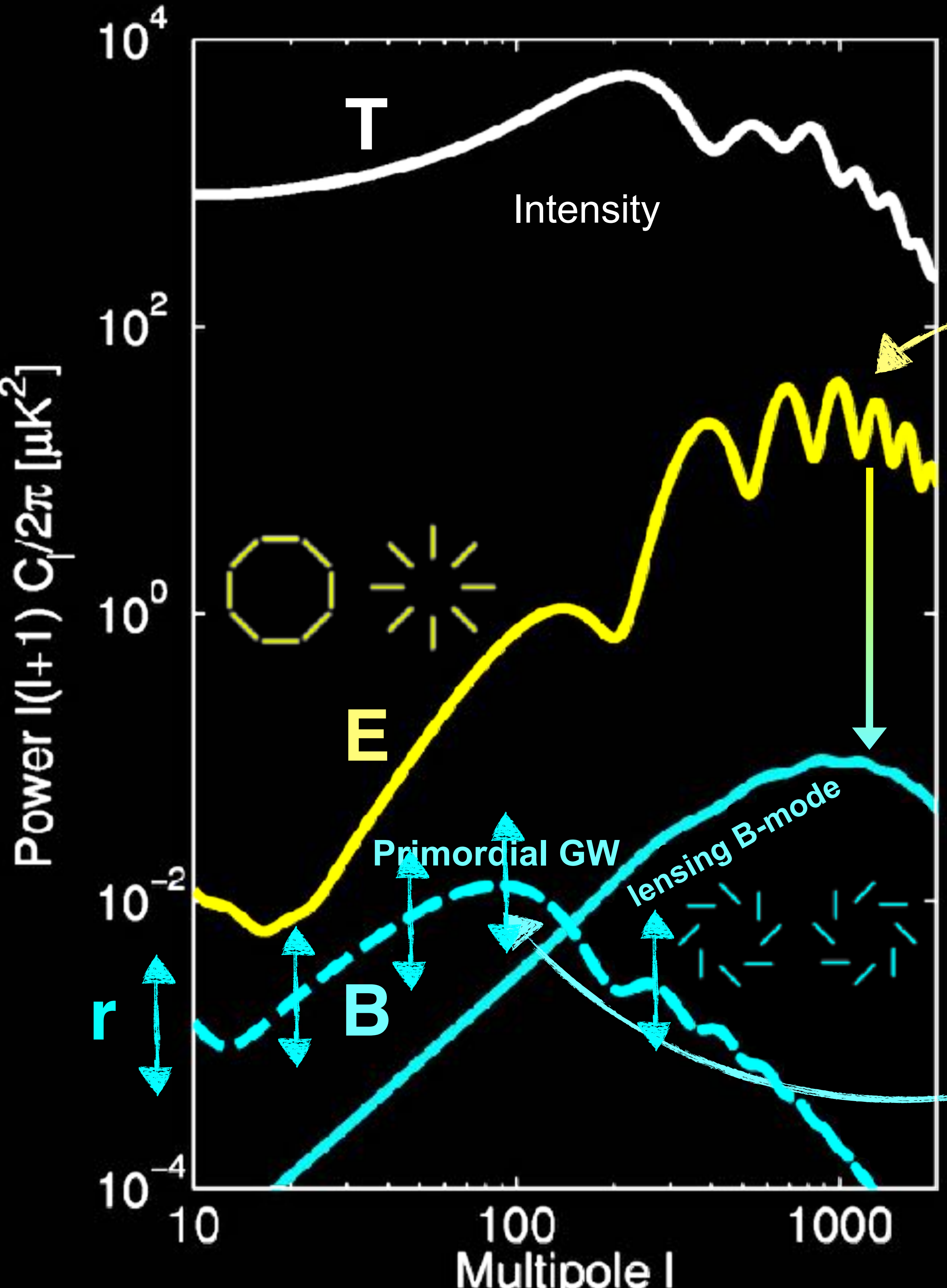
B modes from Space
MPA

CMB

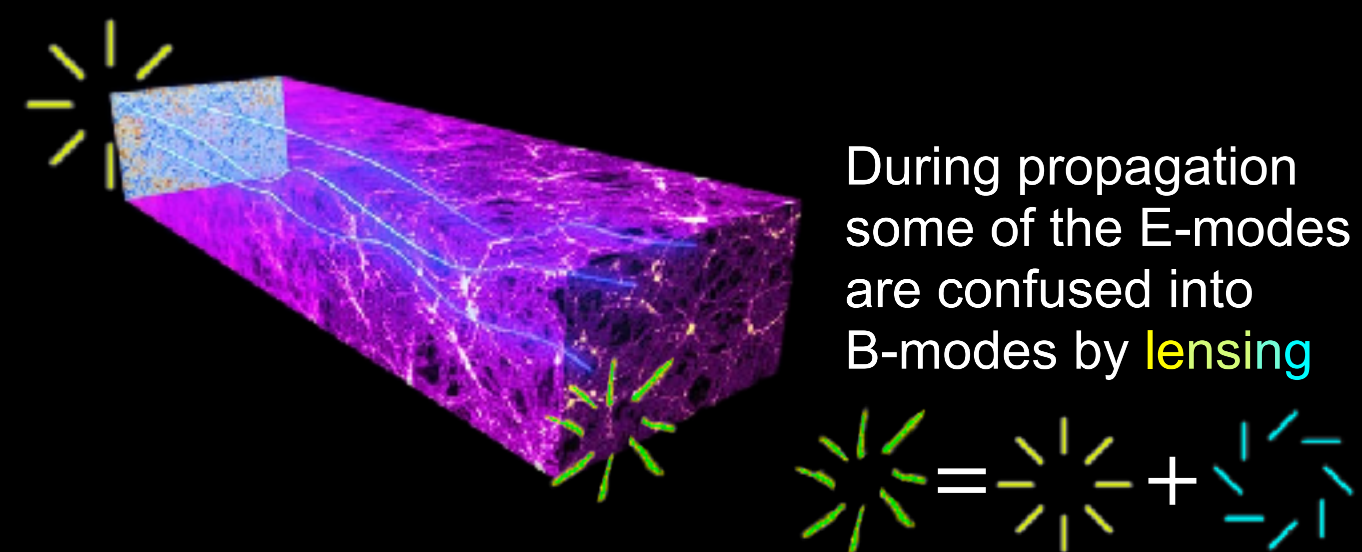


Planck's all sky CMB temperature map
scale ±500 μK
T
Intensity
E
Polarization
B
Power l(l+1) C_l/2π [μK²]
10⁴
10²
10⁰
10⁻²
10⁻⁴
10
100
1000
Multipole l
Bicep2 total polarization signal
1.7μK
Declination [deg.]
Right ascension [deg.]
-45
-50
-55
-60
65
-70
50
0
-50

CMB Polarization



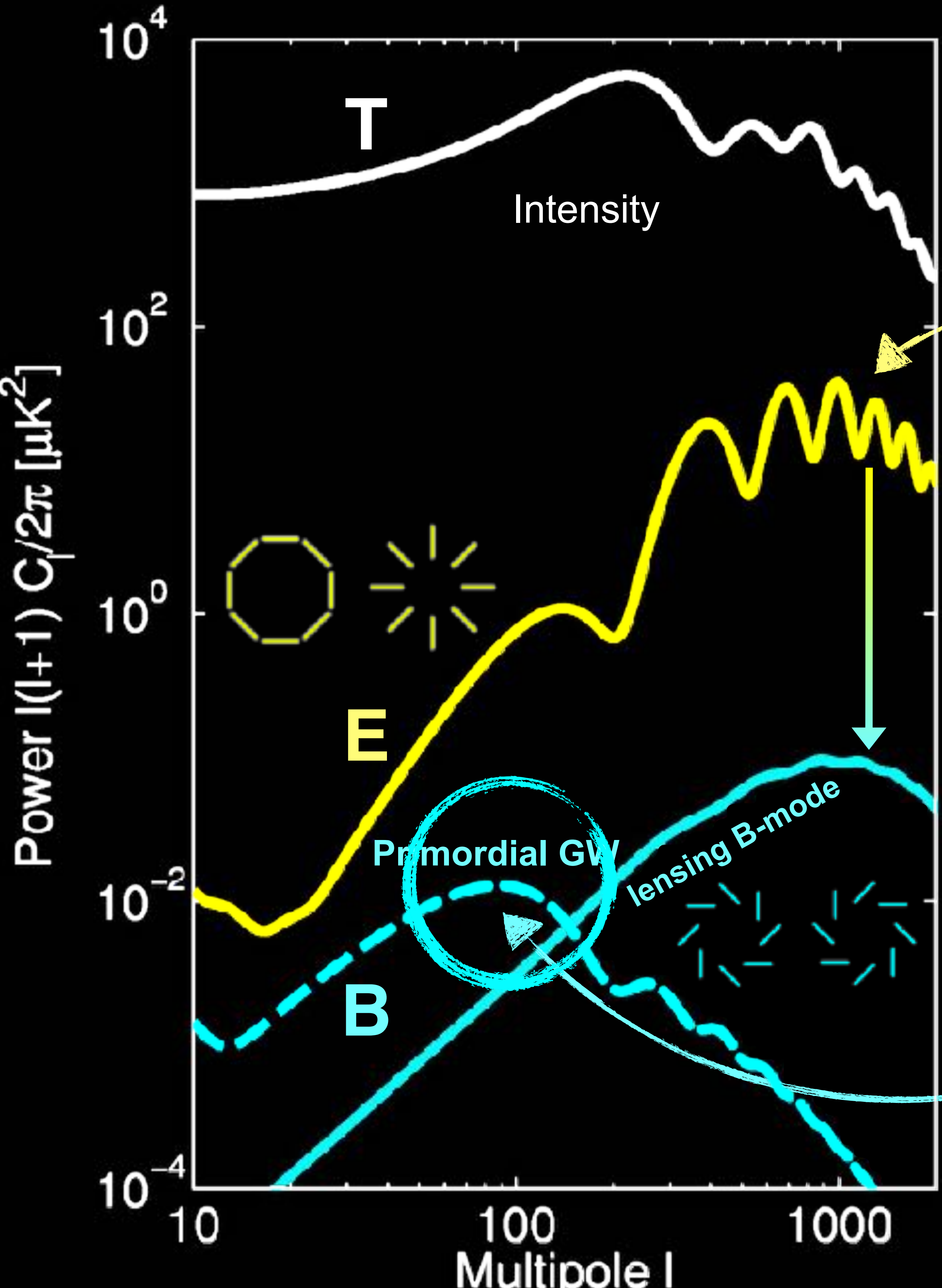
In **standard ΛCDM** only **E-modes** are present at last scattering



During propagation some of the E-modes are confused into B-modes by lensing

Primordial gravitational waves are the unique source of **B-modes**
→ peaking at l≈100 : degree scales

CMB Polarization



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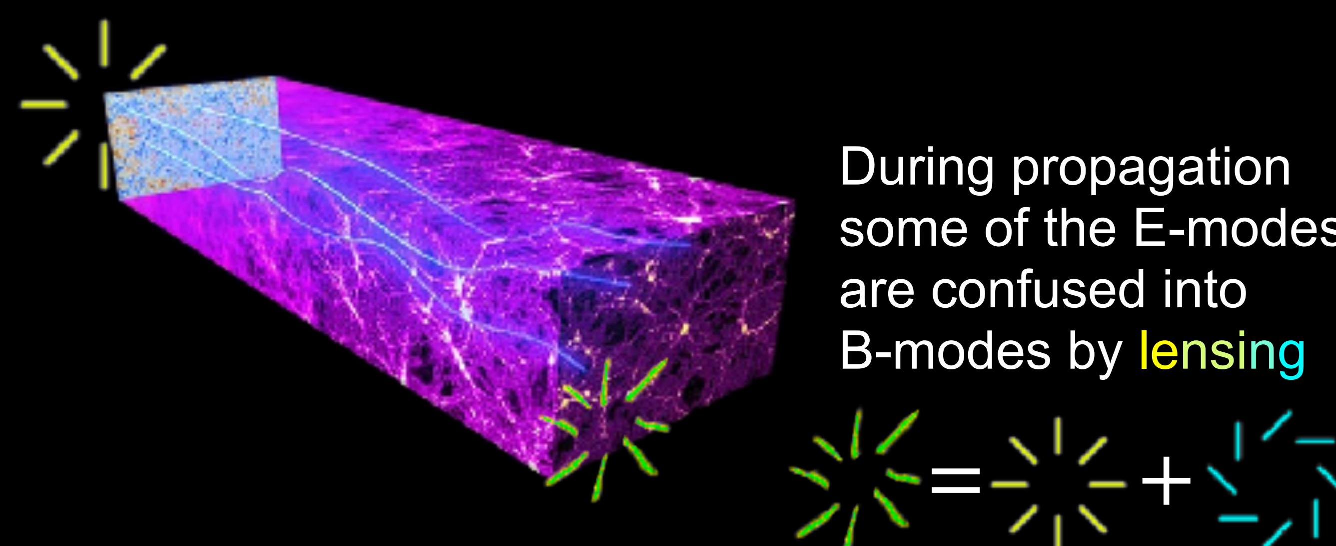

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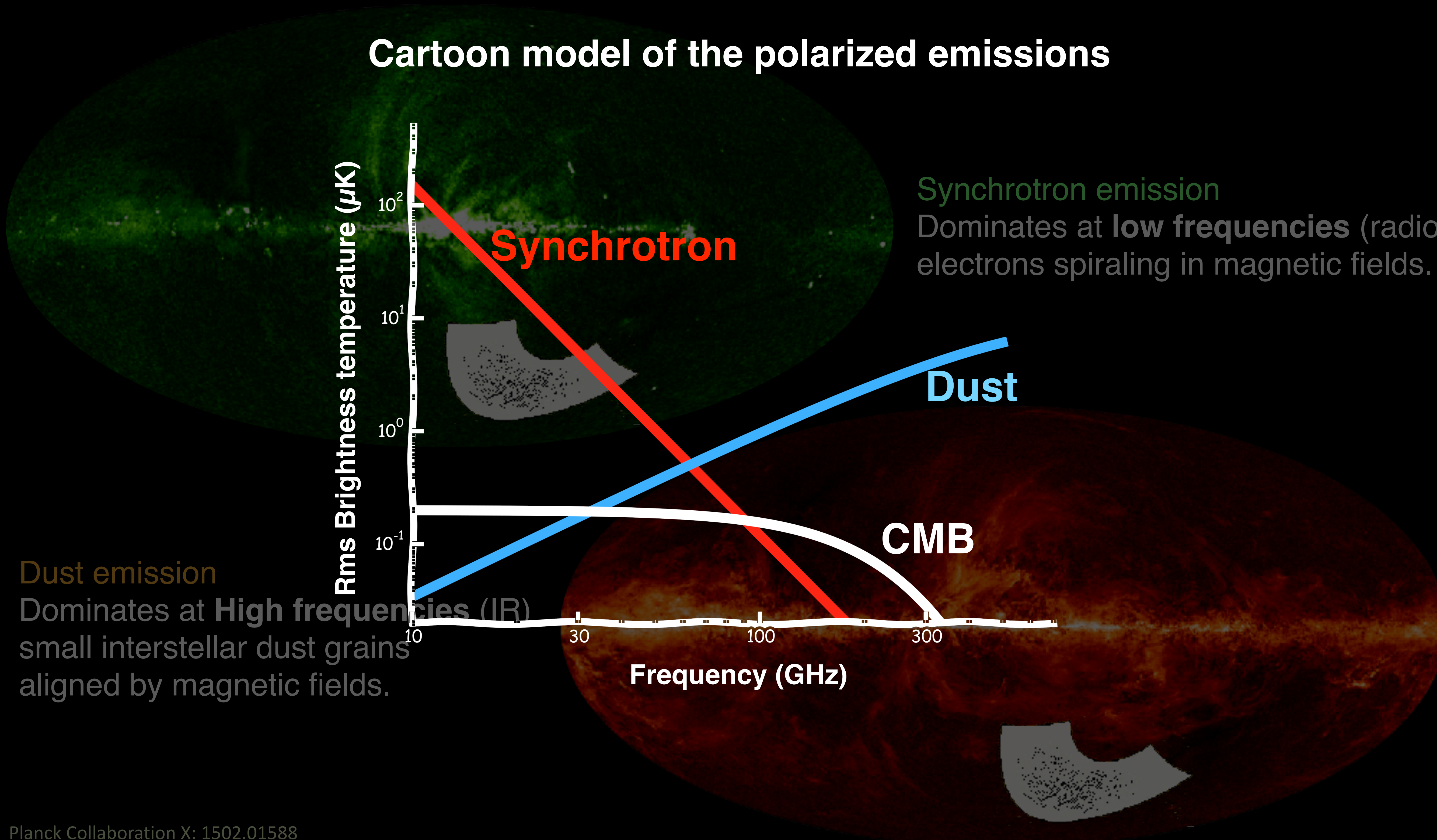
Primordial gravitational waves are the unique source of **B-modes**
→ **peaking at l≈100 : degree scales**

Galactic Foregrounds

For now, two known foregrounds can produce E and B modes



Synchrotron emission
Dominates at **low frequencies** (radio)
electrons spiraling in magnetic fields.

Dust emission
Dominates at **High frequencies** (IR)
small interstellar dust grains
aligned by magnetic fields.

Planck Collaboration X: 1502.01588

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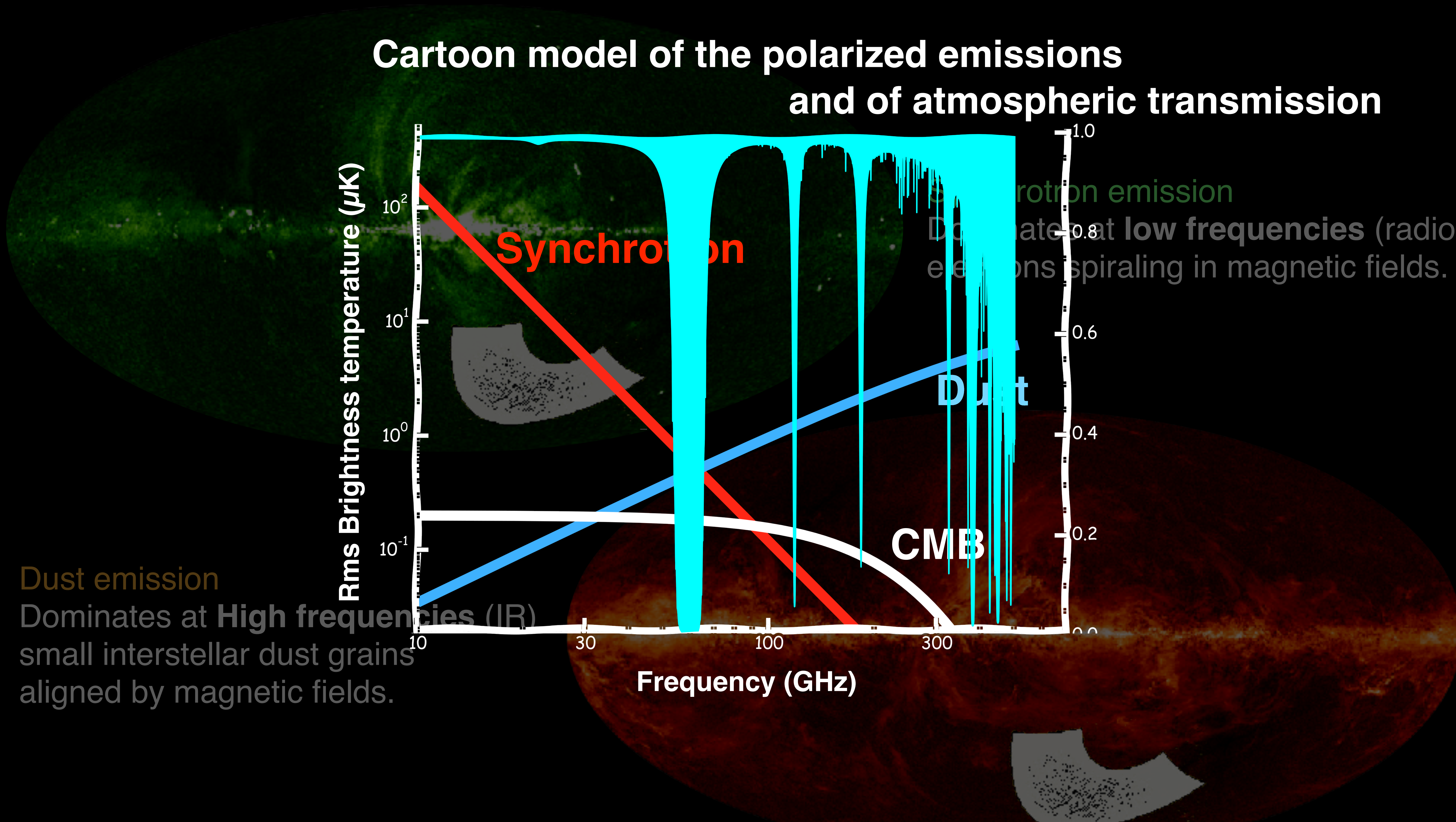
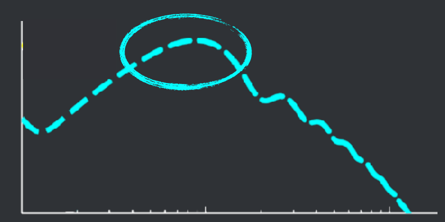
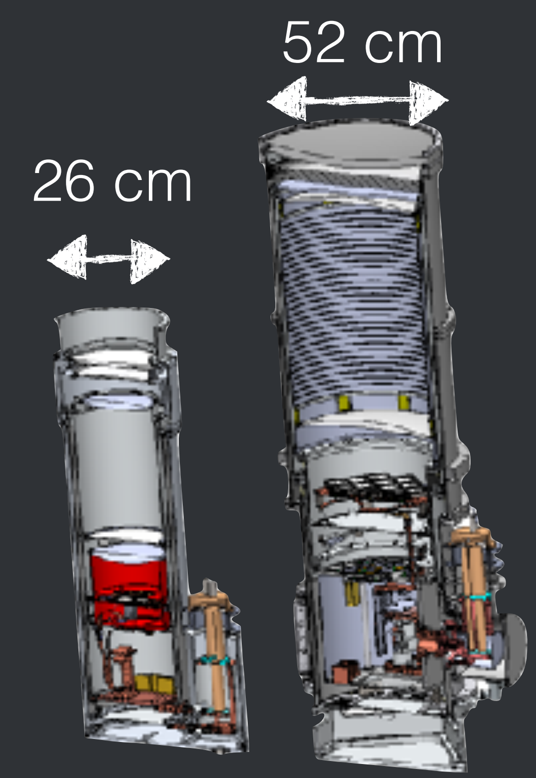


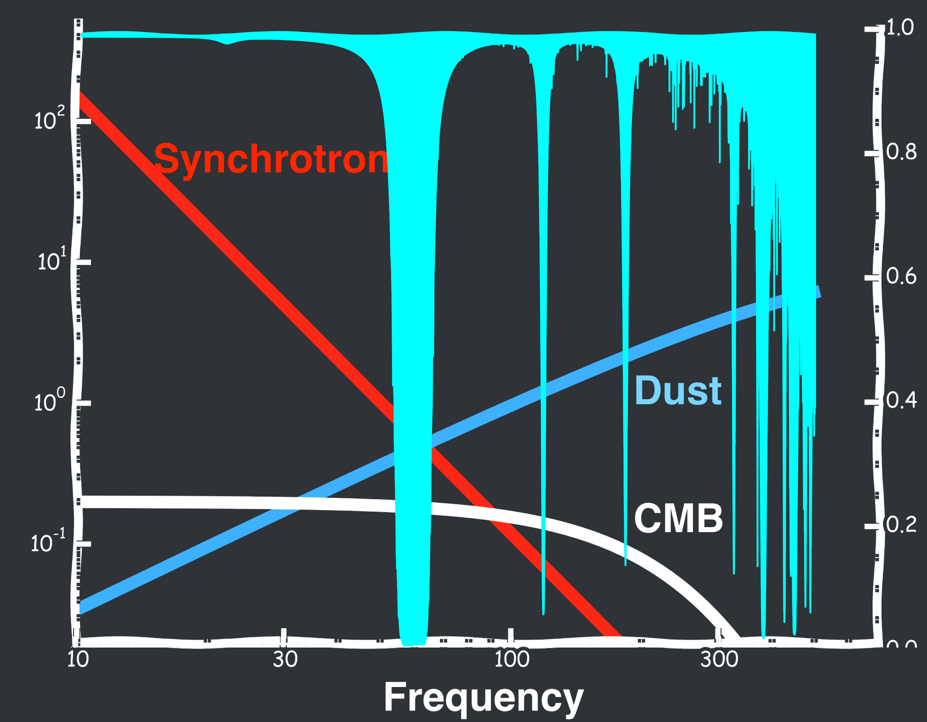
We need:



- ⋆ Large scales (~2 degrees): Need **small telescopes**



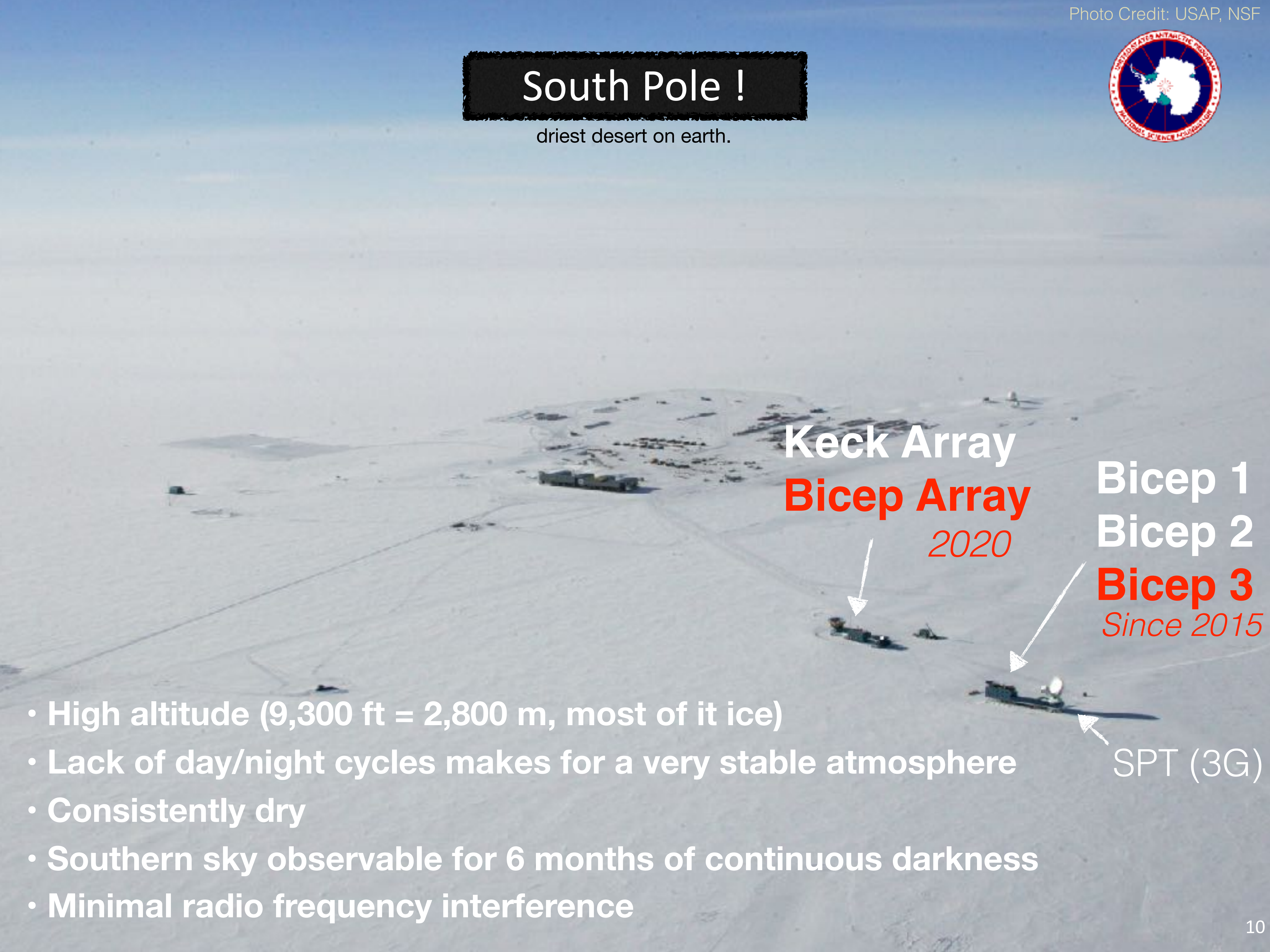
- ⋆ Multiple Frequencies: Need **good atmospheric conditions**



BICEP/Keck

South Pole !

driest desert on earth.

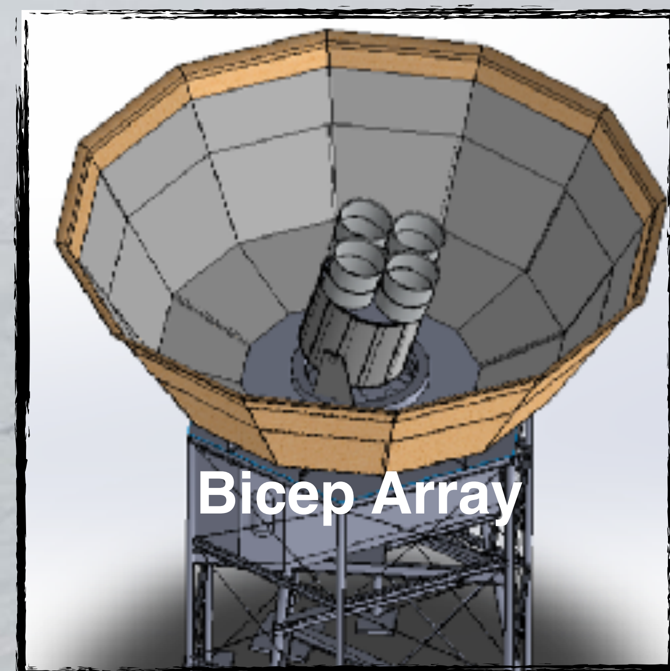


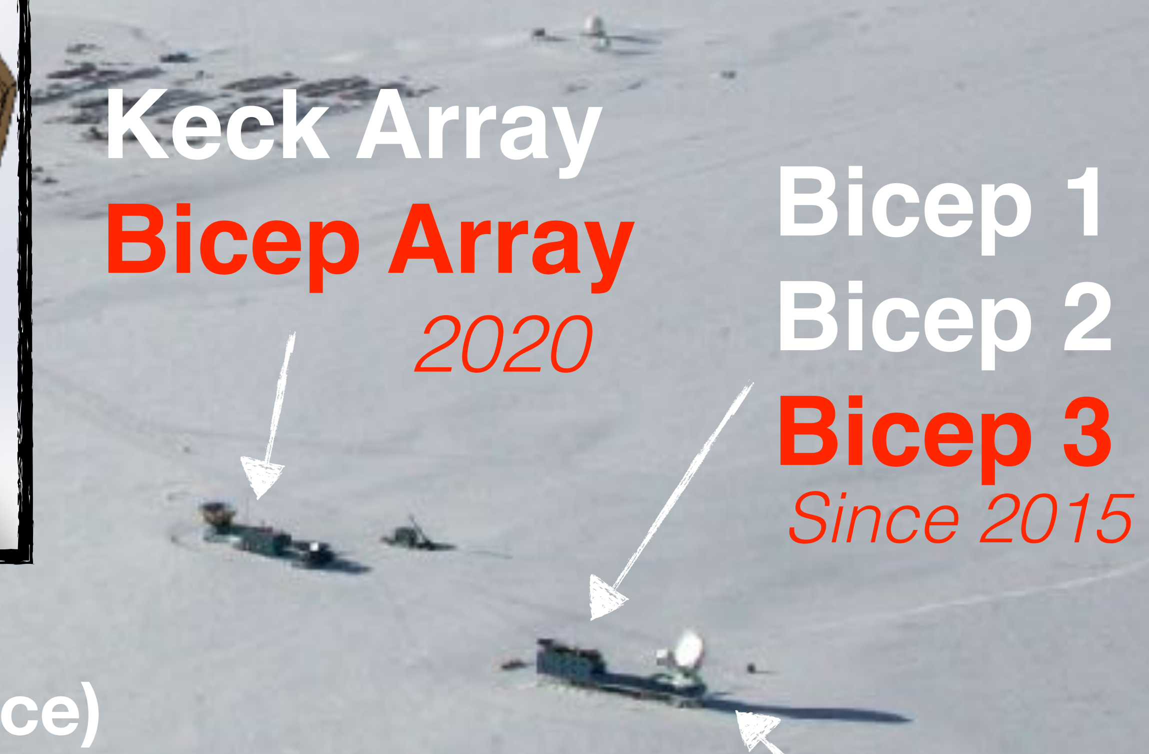
- **High altitude (9,300 ft = 2,800 m, most of it ice)**
- **Lack of day/night cycles makes for a very stable atmosphere**
- **Consistently dry**
- **Southern sky observable for 6 months of continuous darkness**
- **Minimal radio frequency interference**

Photo Credit: USAP, NSF

x5 =

x4 =





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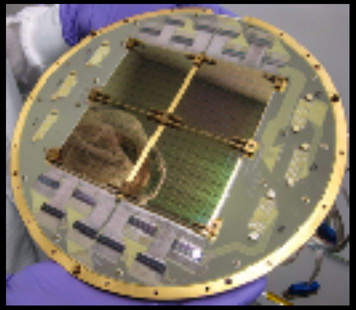
The BICEP2/Keck Telescopes

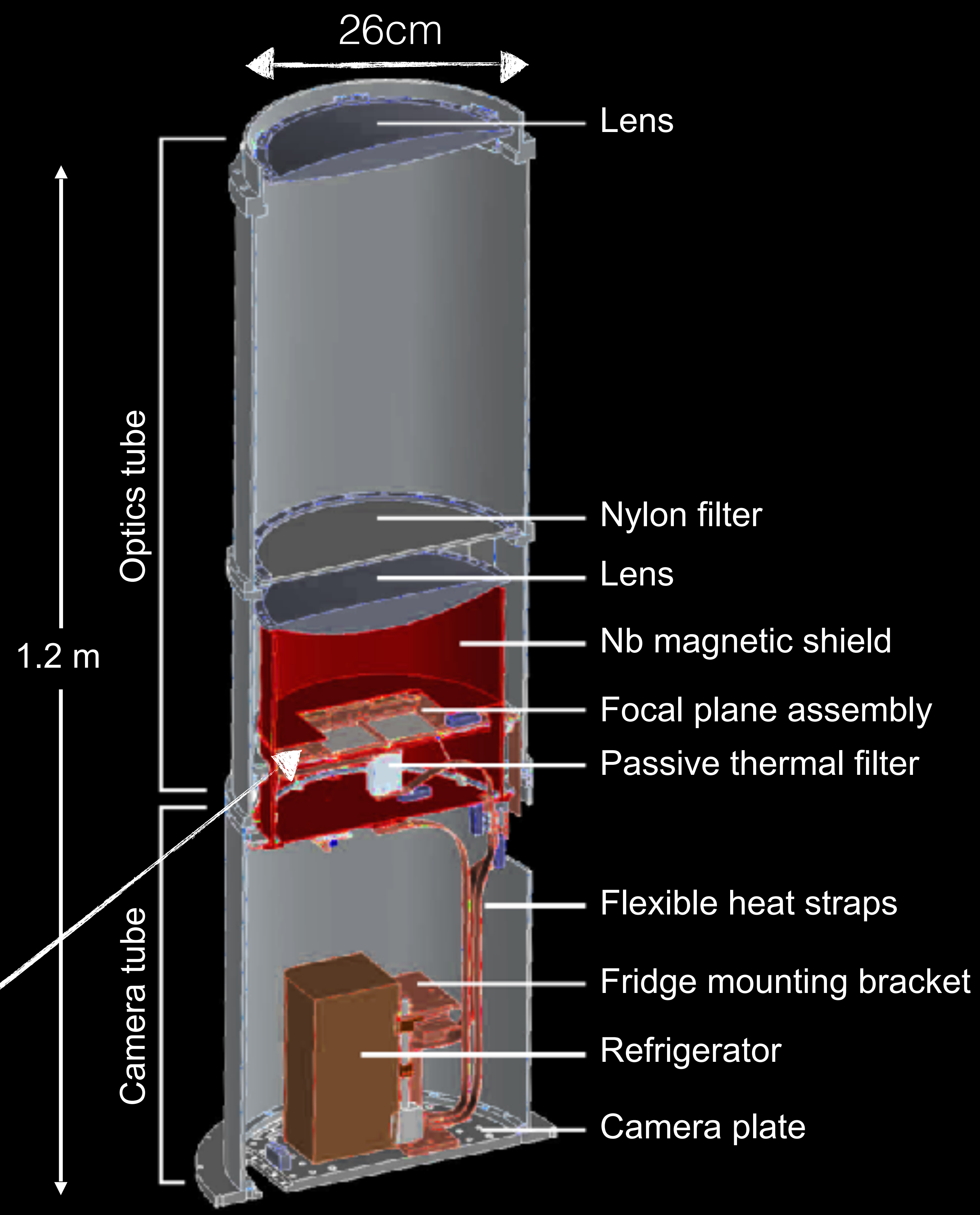
Telescope as compact as possible while still having the angular resolution to observe degree-scale features.

Optical elements cooled to 4 K.

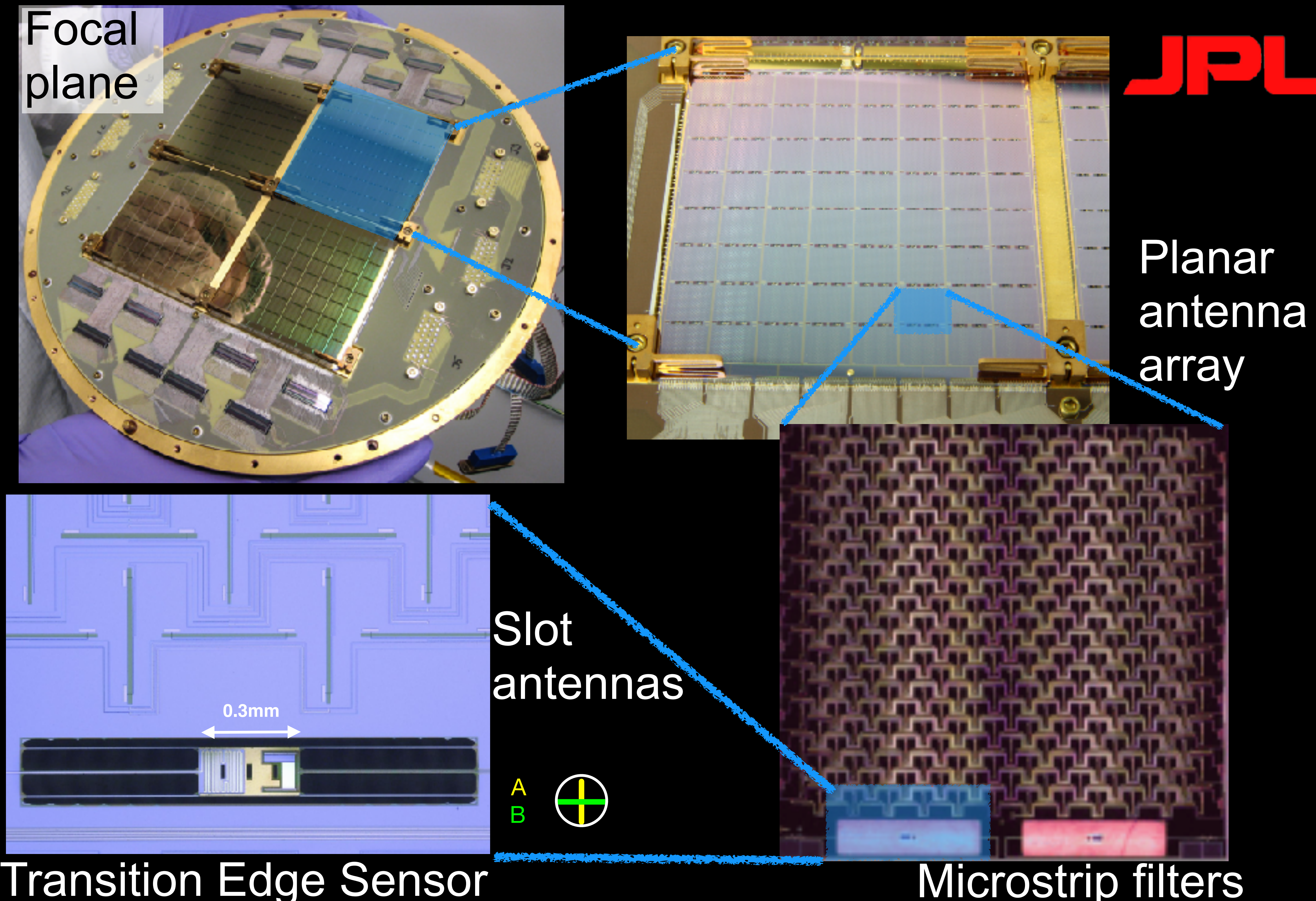
On-axis, refractive optics allow the entire telescope to rotate around boresight for polarization modulation.

A 3-stage helium sorption refrigerator further cools the detectors to 250 mK.

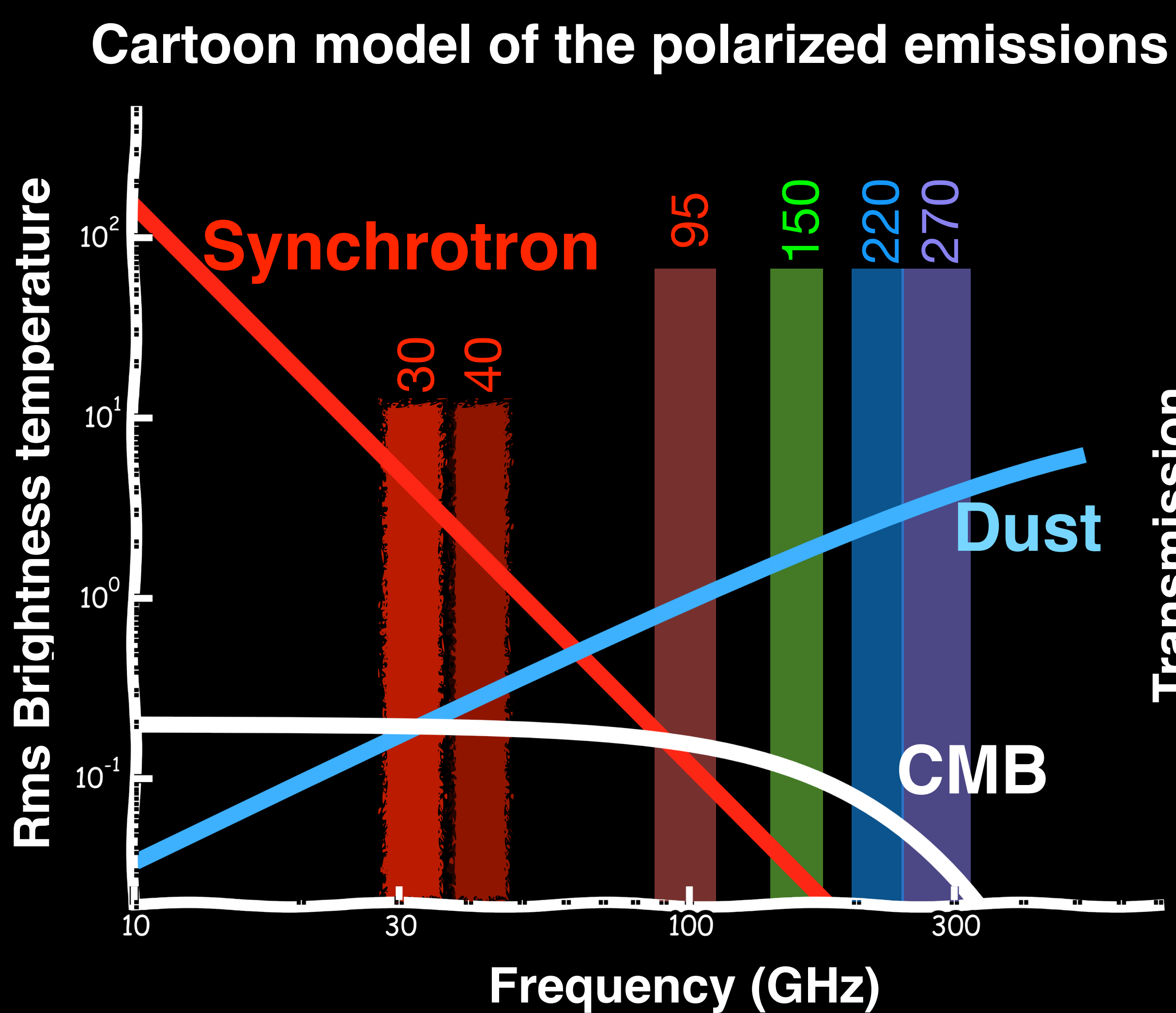


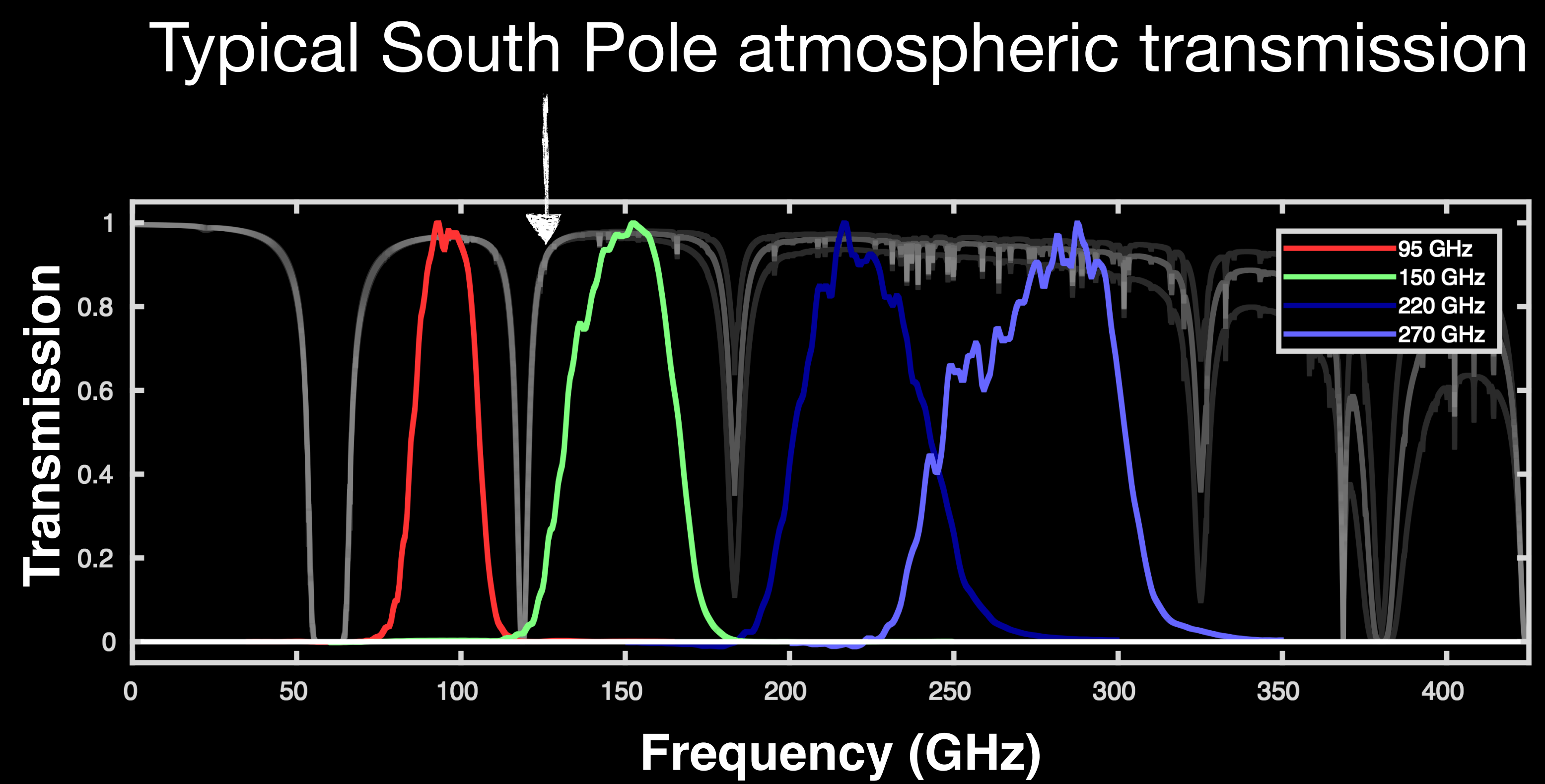


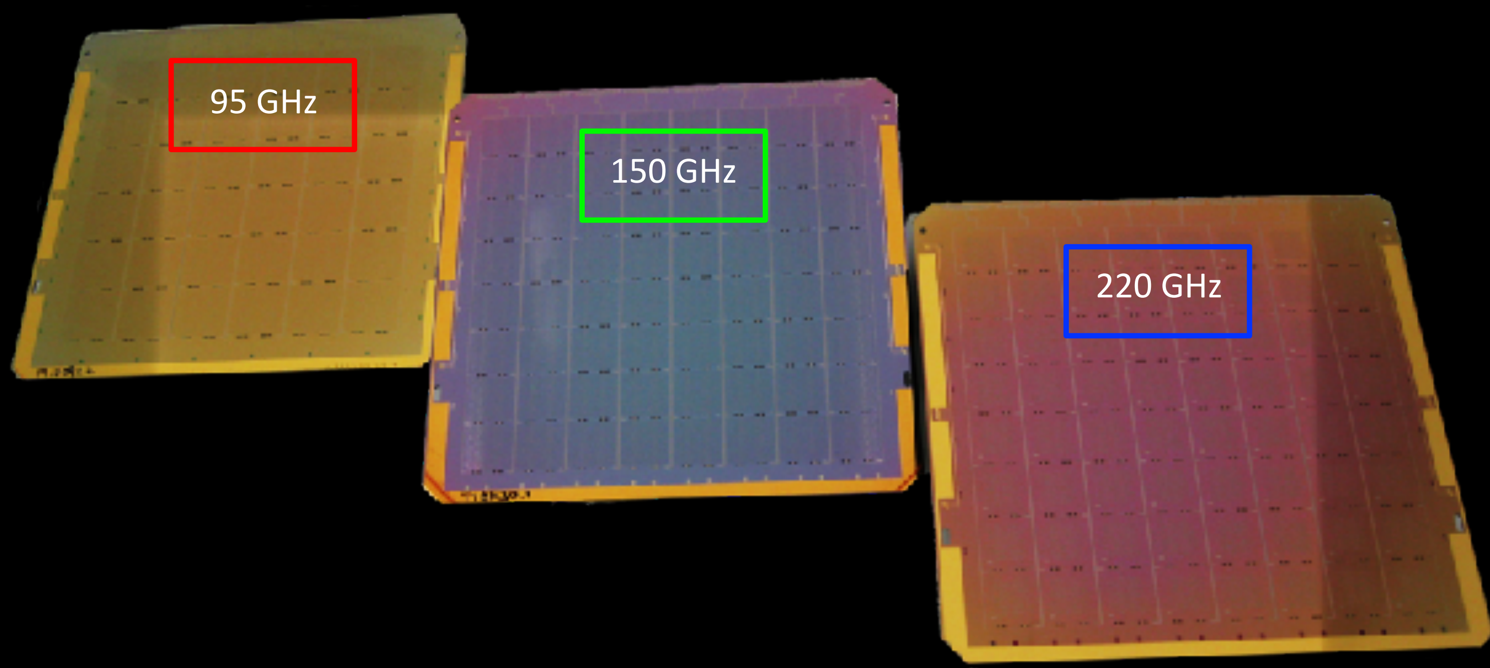
Mass-produced Superconducting Detectors



BICEP2/Keck Band Response

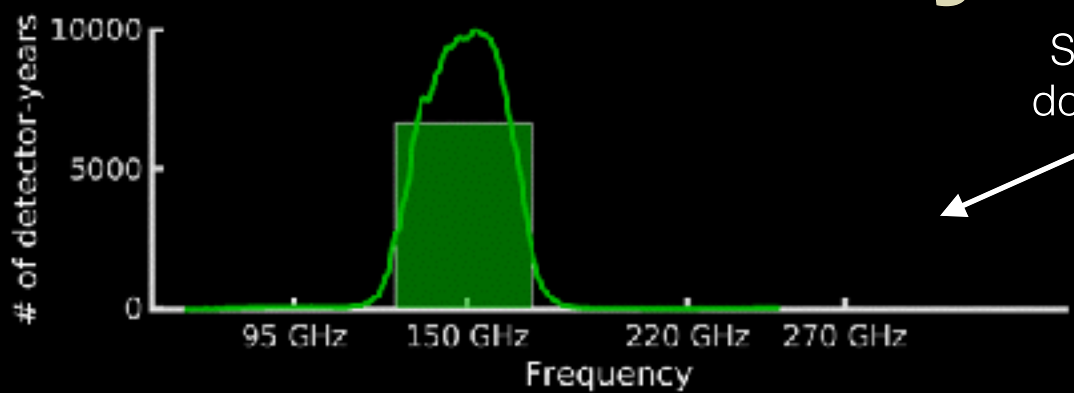






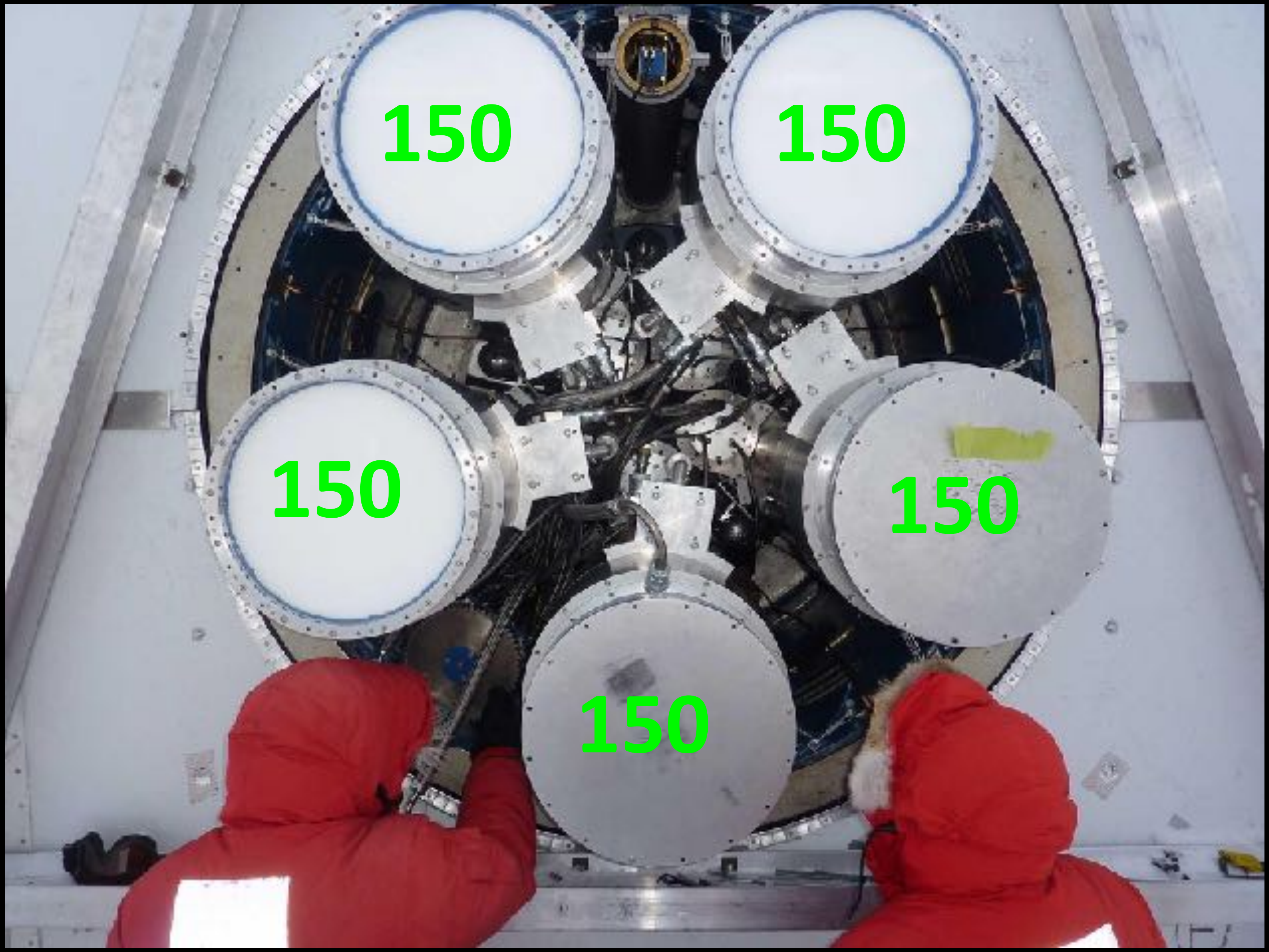
Detectors Designed to Scale in Frequency (JPL)

Keck Array Frequency Coverage



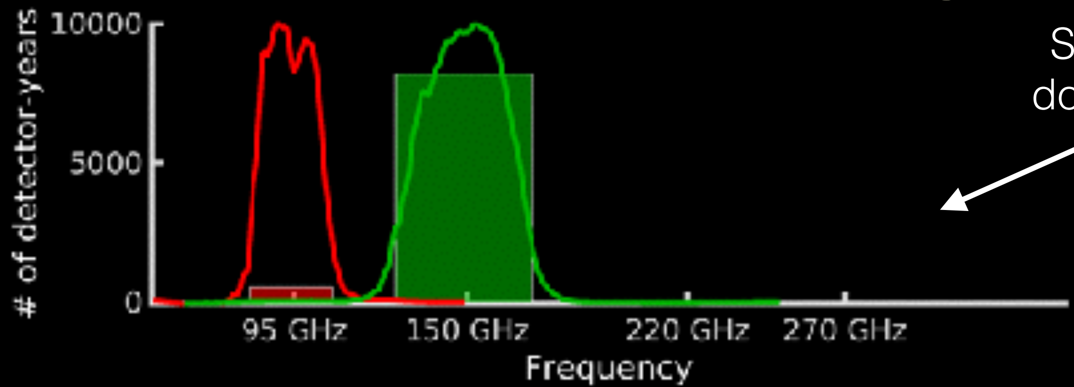
Simple raw observing effort, doesn't take into account how years performed

- Bicep2 receiver at 150 GHz in 2010-2012
- Keck Array receivers all at 150 GHz in 2012-2013



2012-2013

Keck Array Frequency Coverage



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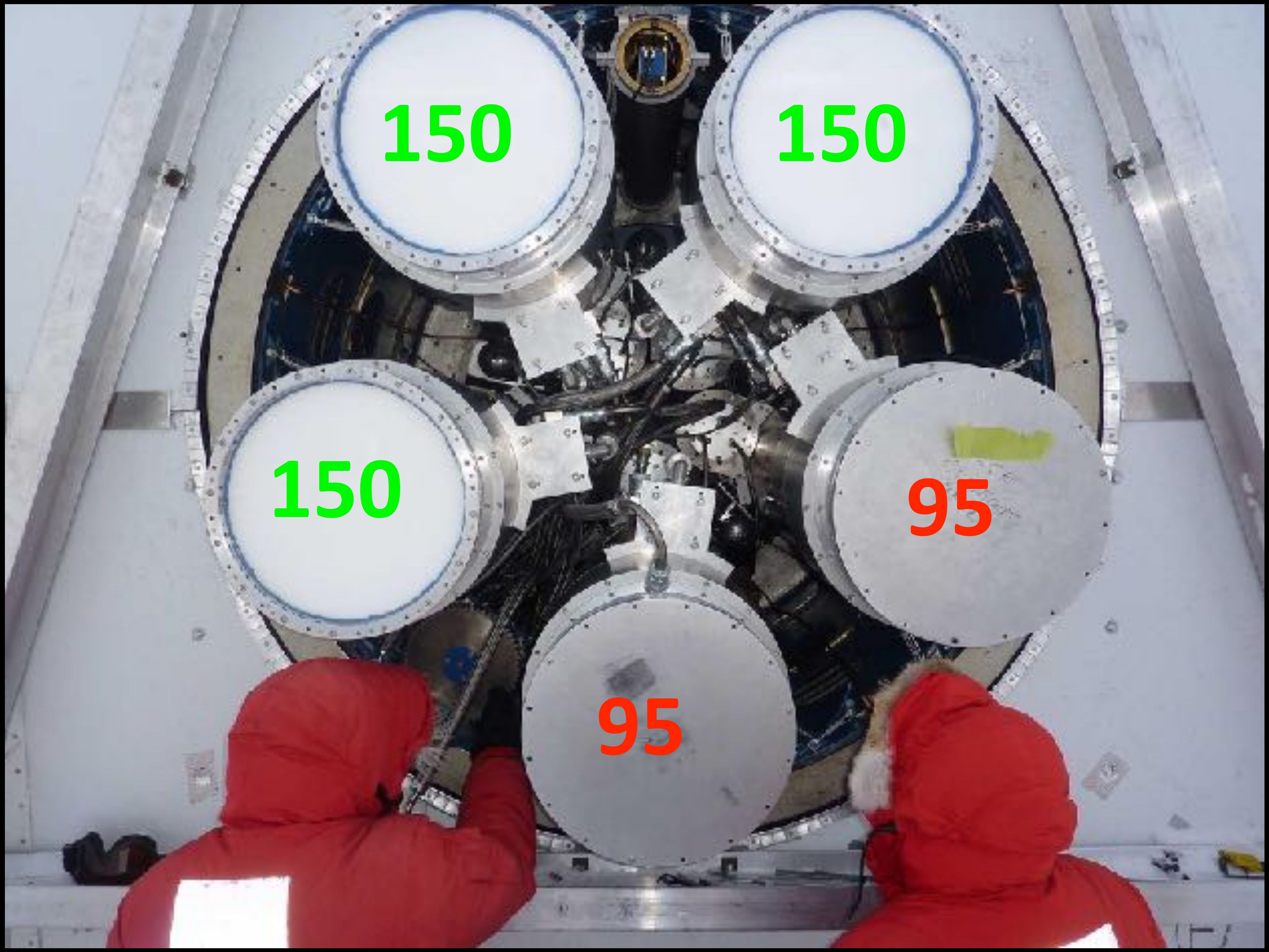


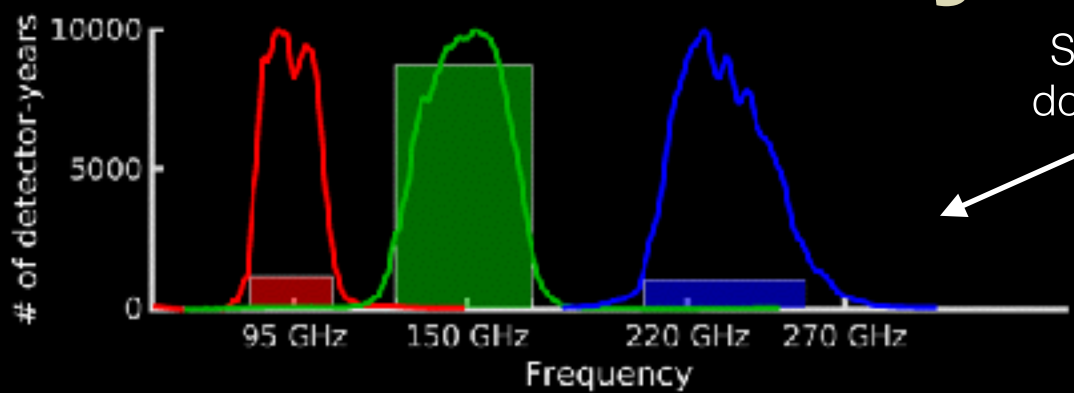
- Bicep2 receiver at 150 GHz in 2010-2012
- Keck Array receivers all at 150 GHz in 2012-2013
- replaced two 150 GHz receivers with 95 GHz receivers in 2014

2014

BK14

arxiv/1510.09217

Keck Array Frequency Coverage



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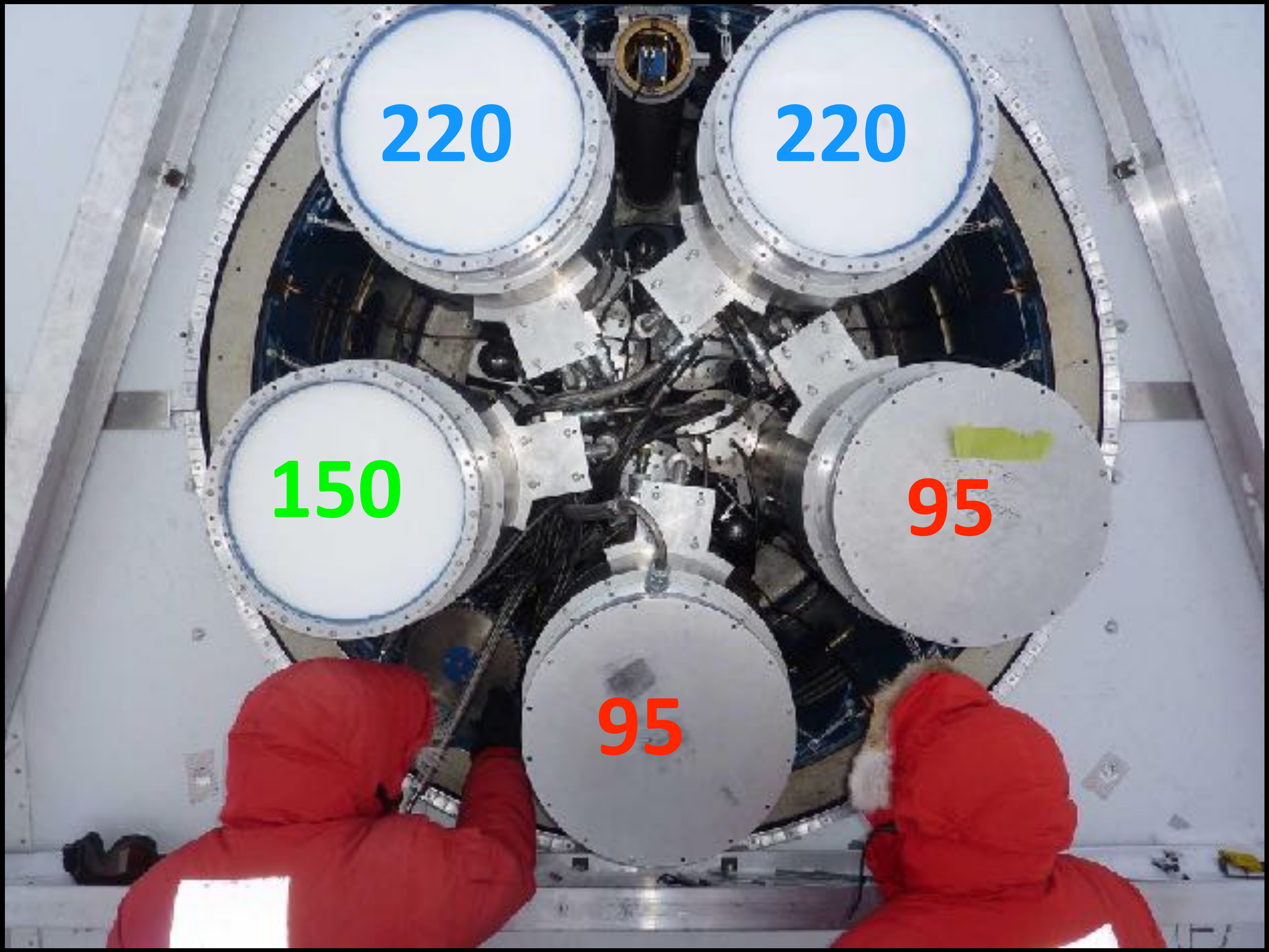


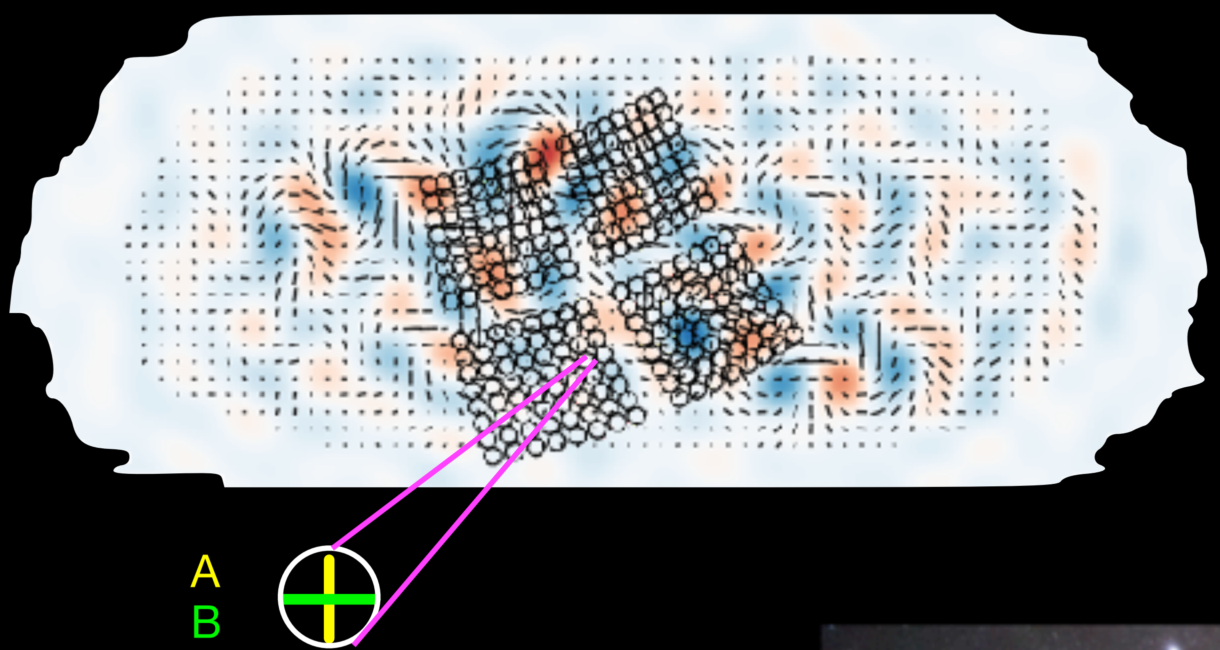
- Bicep2 receiver at 150 GHz in 2010-2012
- Keck Array receivers all at 150 GHz in 2012-2013
- replaced two 150 GHz receivers with 95 GHz receivers in 2014
- replaced two additional 150s with 220s for 2015

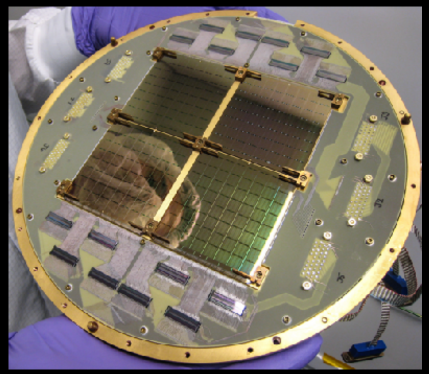
2015

BK15

arxiv/1810.05216

Scanning





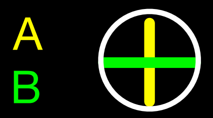
Video from Robert Schwarz

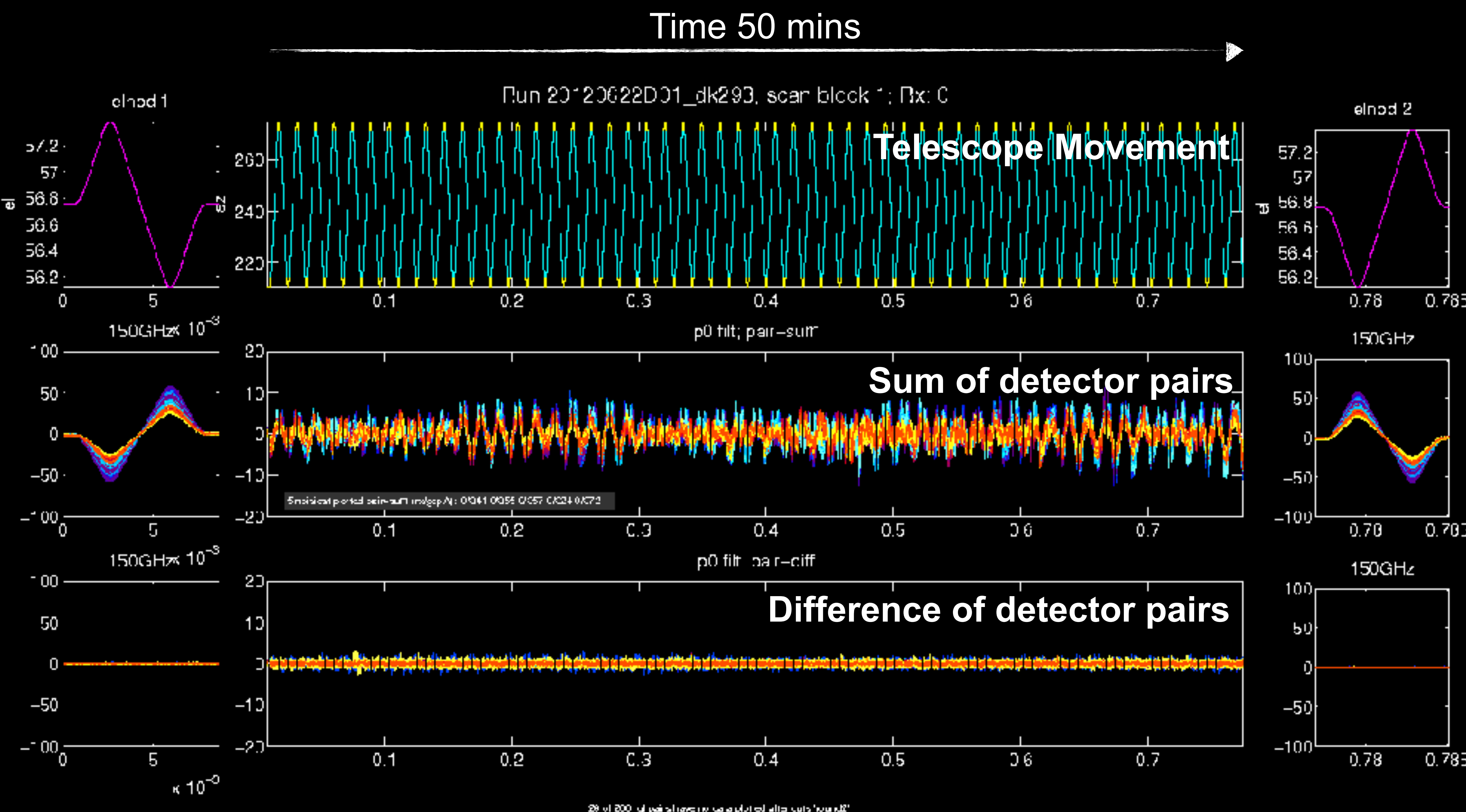
Each focal plane pixel is really *two* detectors — a horizontally polarized one and a vertically polarized one.

A+B -> Full signal

A-B -> Polarization only

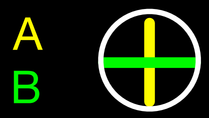
Raw Data - Typical Weather

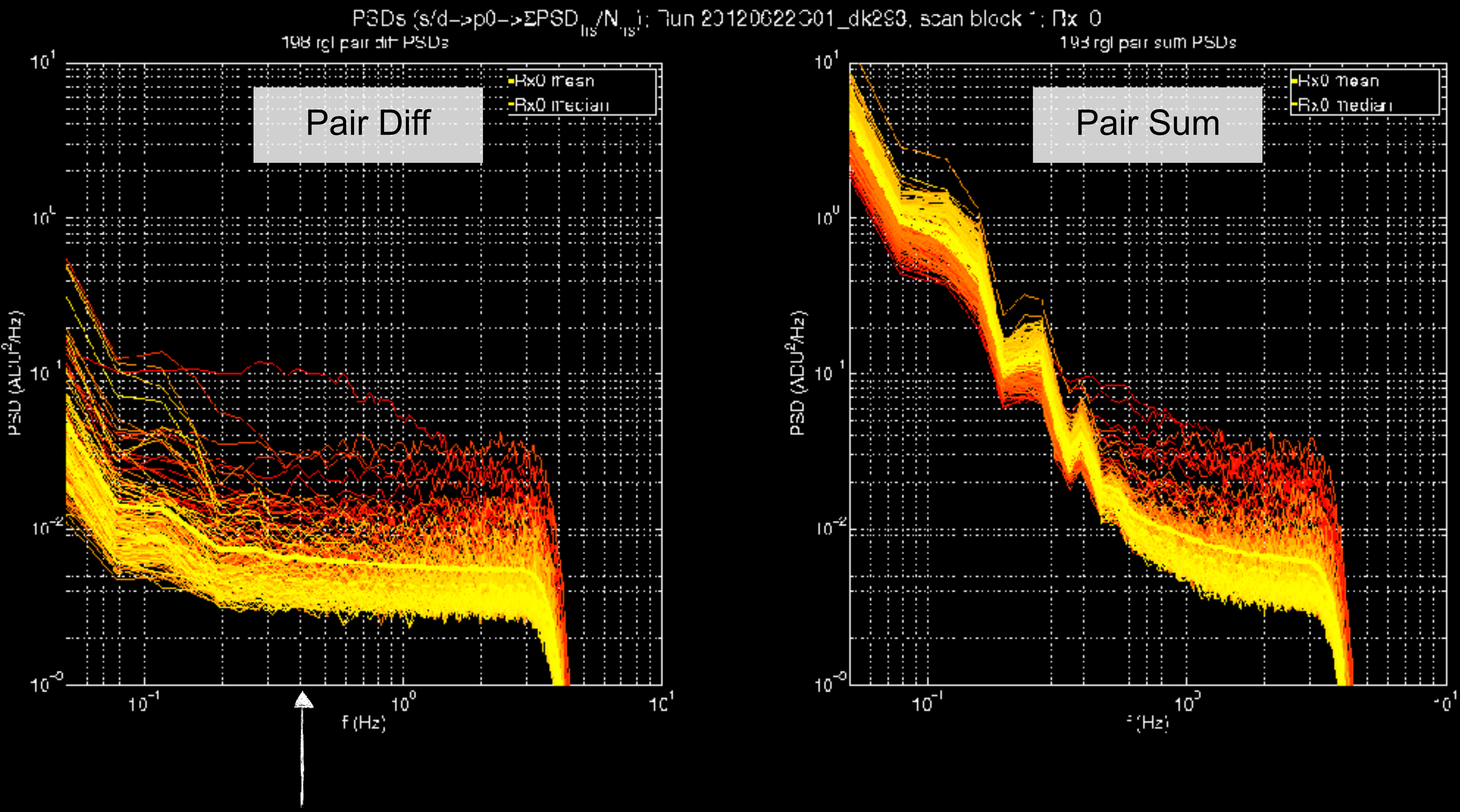




- Scanning over lumpy atmosphere → "clouds"
- Pair difference still clean → atmosphere is unpolarized

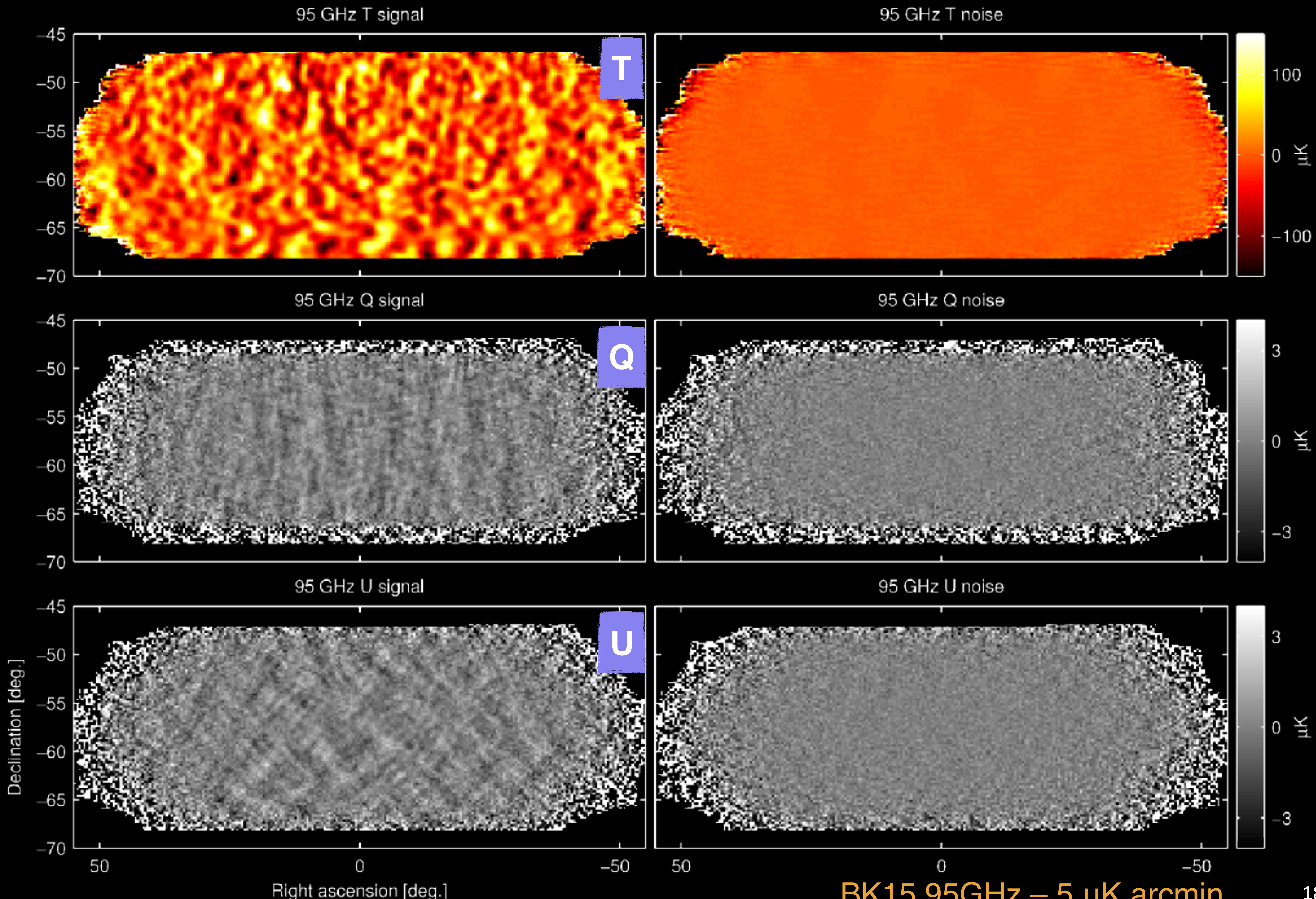
Timestream PSDs





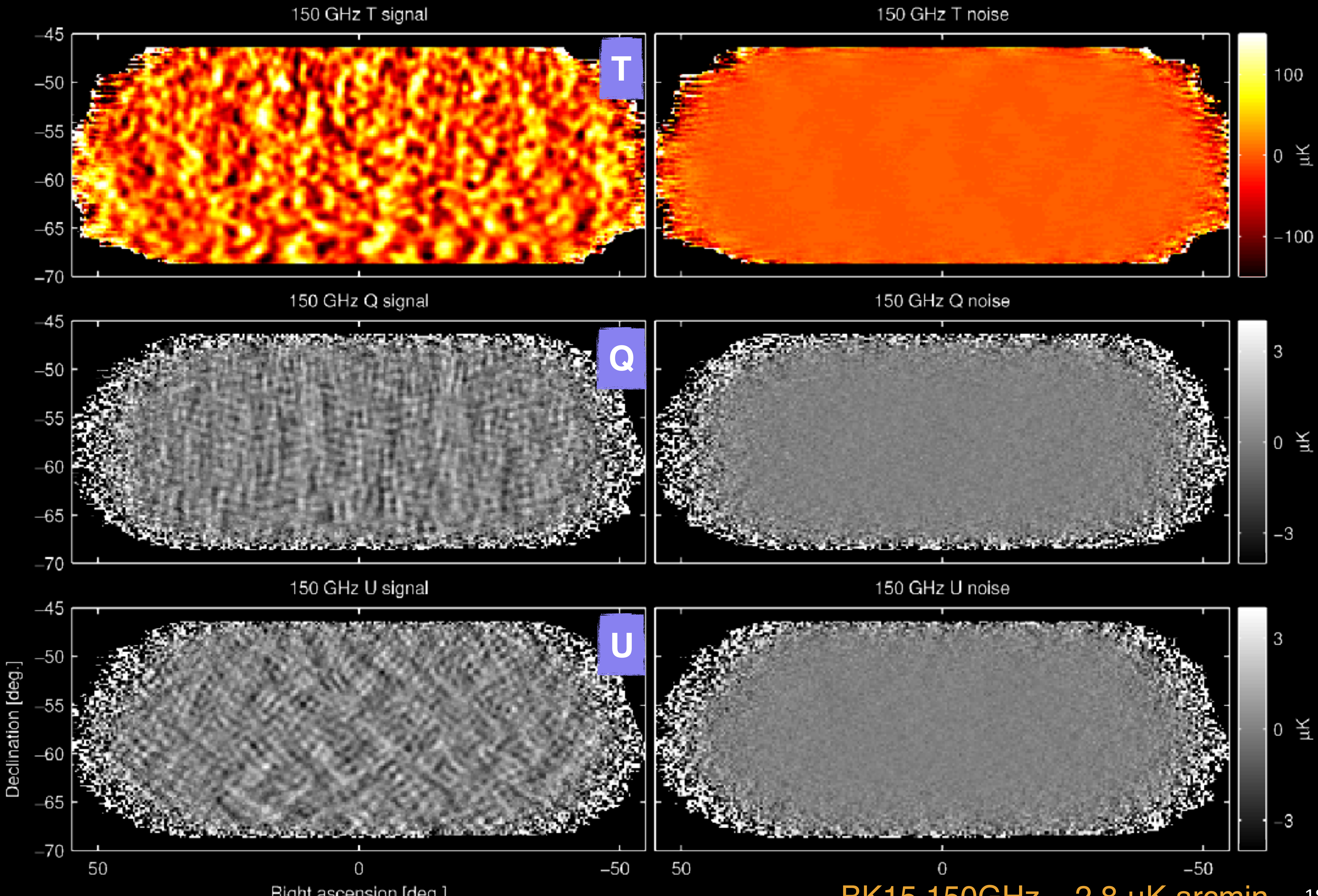
- Multipole 100 at 0.4Hz

BK15 95 GHz Maps



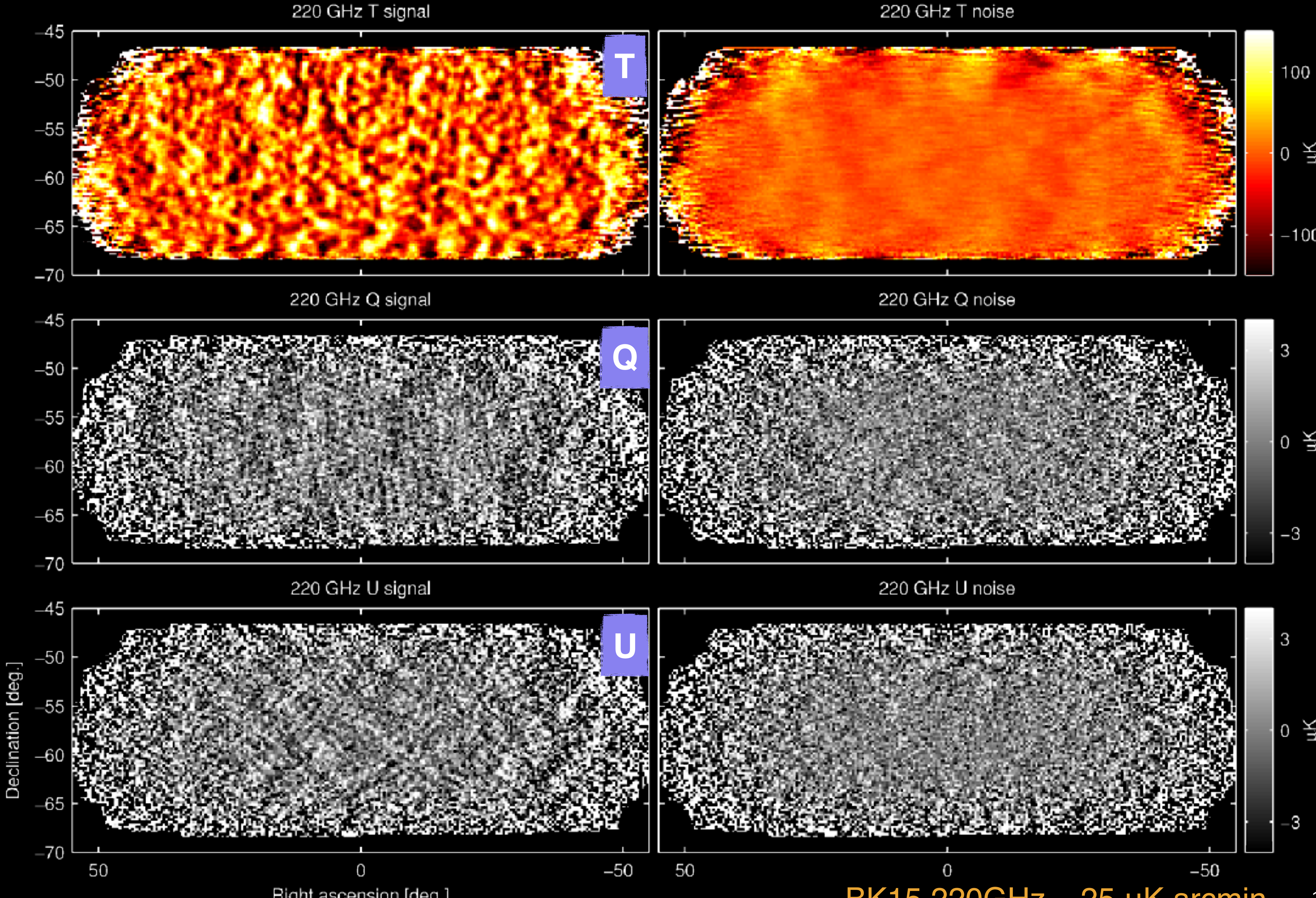
BK15 95GHz – 5 μK arcmin

BK15 150 GHz Maps



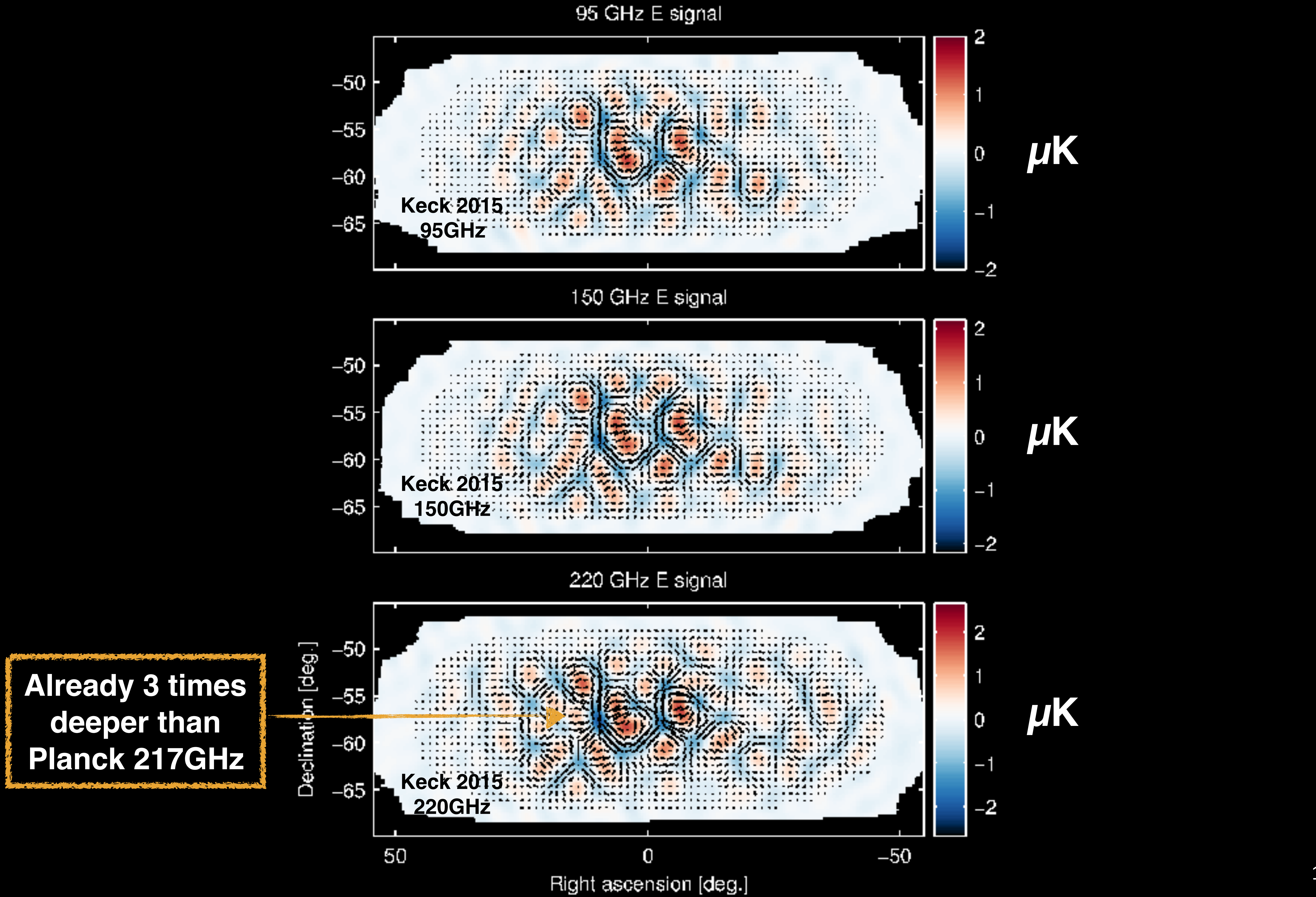
BK15 150GHz – 2.8 μK arcmin

BK15 220 GHz Maps

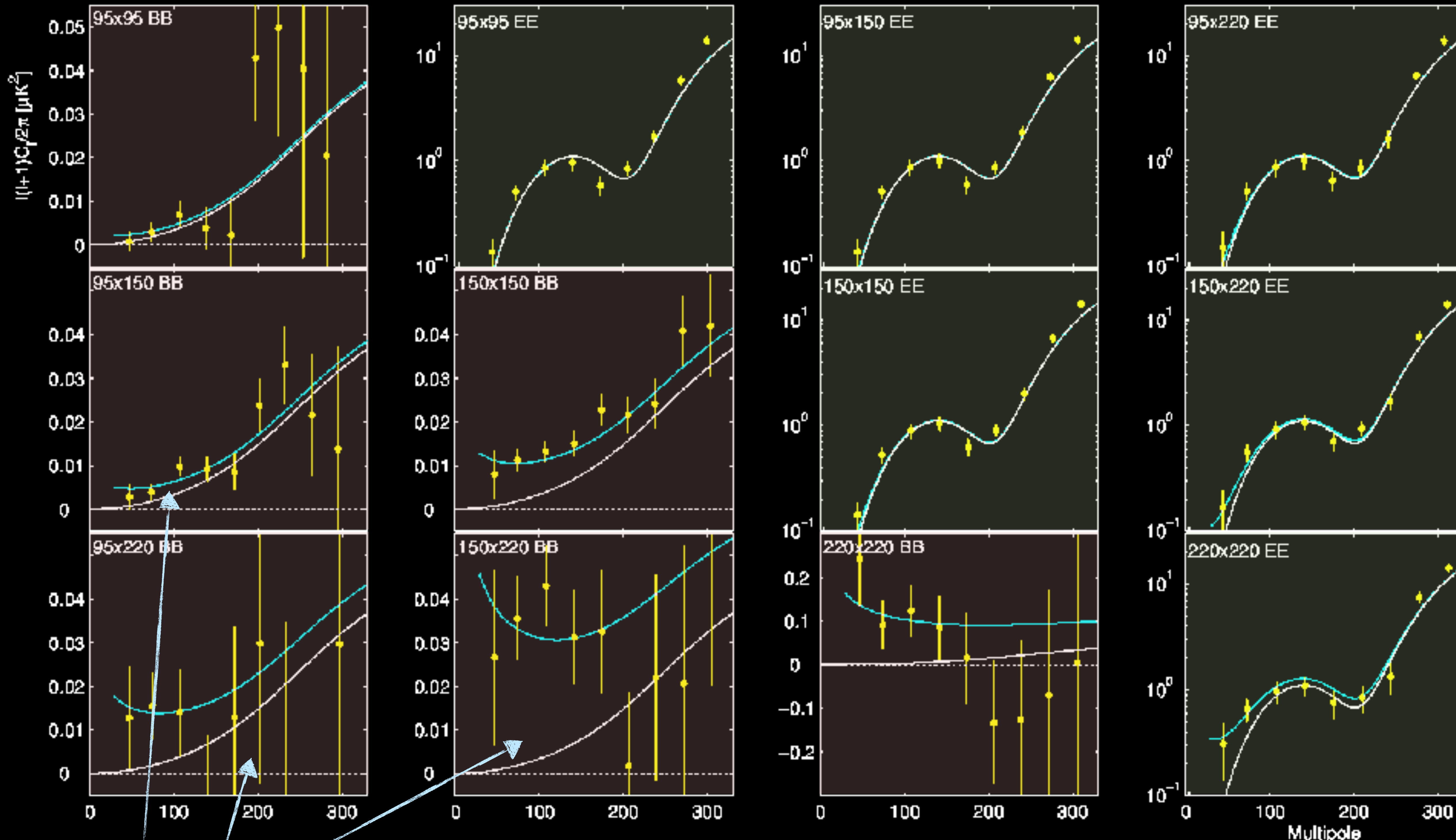


BK15 220GHz – 25 μK arcmin

Keck 2015 only E-Mode Maps



BK15 Spectra



cross-spectra only trace spatially correlated component of maps

Cyan lines: BK14 CMB + polarized dust model with r = 0

Spectra using all data up to and including 2015 - for the first time adding Keck 220GHz

Check Systematics: Jackknifes

TABLE I. Jackknife PTE values from χ^2 and χ (sum of deviations) tests for *Keck Array* 95 GHz data taken in 2014. This table is analogous to Table I of BK-I and Table 4 of BK-V.

Jackknife	Band powers 1–5 χ^2	Band powers 1–9 χ^2	Band powers 1–5 χ	Band powers 1–9 χ
Deck jackknife				
EE	0.625	0.591	0.523	0.569
BB	0.166	0.192	0.076	0.020
EB	0.876	0.539	0.814	0.445
Scan Dir jackknife				
EE	0.439	0.513	0.760	0.423
BB	0.944	0.535	0.565	0.168
EB	0.539	0.192	0.912	0.980
Tag Split jackknife				
EE	0.543	0.537	0.810	0.938
BB	0.768	0.780	0.687	0.539
EB	0.313	0.547	0.407	0.451
Tile jackknife				
EE	0.234	0.477	0.395	0.709
BB	0.050	0.072	0.012	0.046
EB	0.828	0.902	0.812	0.822
Phase jackknife				
EE	0.862	0.982	0.577	0.471
BB	0.944	0.521	0.639	0.325
EB	0.691	0.890	0.204	0.357
Mux Col jackknife				
EE	0.084	0.146	0.182	0.337
BB	0.172	0.337	0.012	0.152
EB	0.541	0.695	0.956	0.812
Alt Deck jackknife				
EE	0.098	0.076	0.030	0.036
BB	0.092	0.126	0.102	0.140
EB	0.858	0.842	0.858	0.741
Mux Row jackknife				
EE	0.232	0.289	0.699	0.918
BB	0.289	0.267	0.082	0.014
EB	0.148	0.130	0.996	0.998
Tile/Deck jackknife				
EE	0.924	0.956	0.162	0.399
BB	0.507	0.034	0.561	0.343
EB	0.477	0.361	0.954	0.994
Focal Plane inner/outer jackknife				
EE	0.477	0.335	0.200	0.792
BB	0.886	0.437	0.762	0.569
EB	0.595	0.876	0.926	0.780
Tile top/bottom jackknife				
EE	0.261	0.519	0.998	0.990
BB	0.756	0.890	0.415	0.431
EB	0.850	0.920	0.377	0.317
Tile inner/outer jackknife				
EE	0.184	0.353	0.427	0.529
BB	0.772	0.772	0.749	0.707
EB	0.407	0.038	0.934	0.667
Moon jackknife				
EE	0.569	0.701	0.228	0.251
BB	0.305	0.465	0.978	0.990
EB	0.349	0.507	0.677	0.301
A/B offset best/worst				
EE	0.635	0.267	0.104	0.431
BB	0.407	0.387	0.677	0.287
EB	0.321	0.605	0.860	0.685

Splits the 4 boresight rotations

Amplifies differential pointing in comparison to fully added data. Important check of deprojection.

Splits by time

Checks for contamination on long ("Tag Split") and short ("Scan Dir") timescales. Short timescales probe detector transfer functions.

Splits by channel selection

Checks for contamination in channel subgroups, divided by focal plane location, tile location, and readout electronics grouping

Splits by possible external contamination

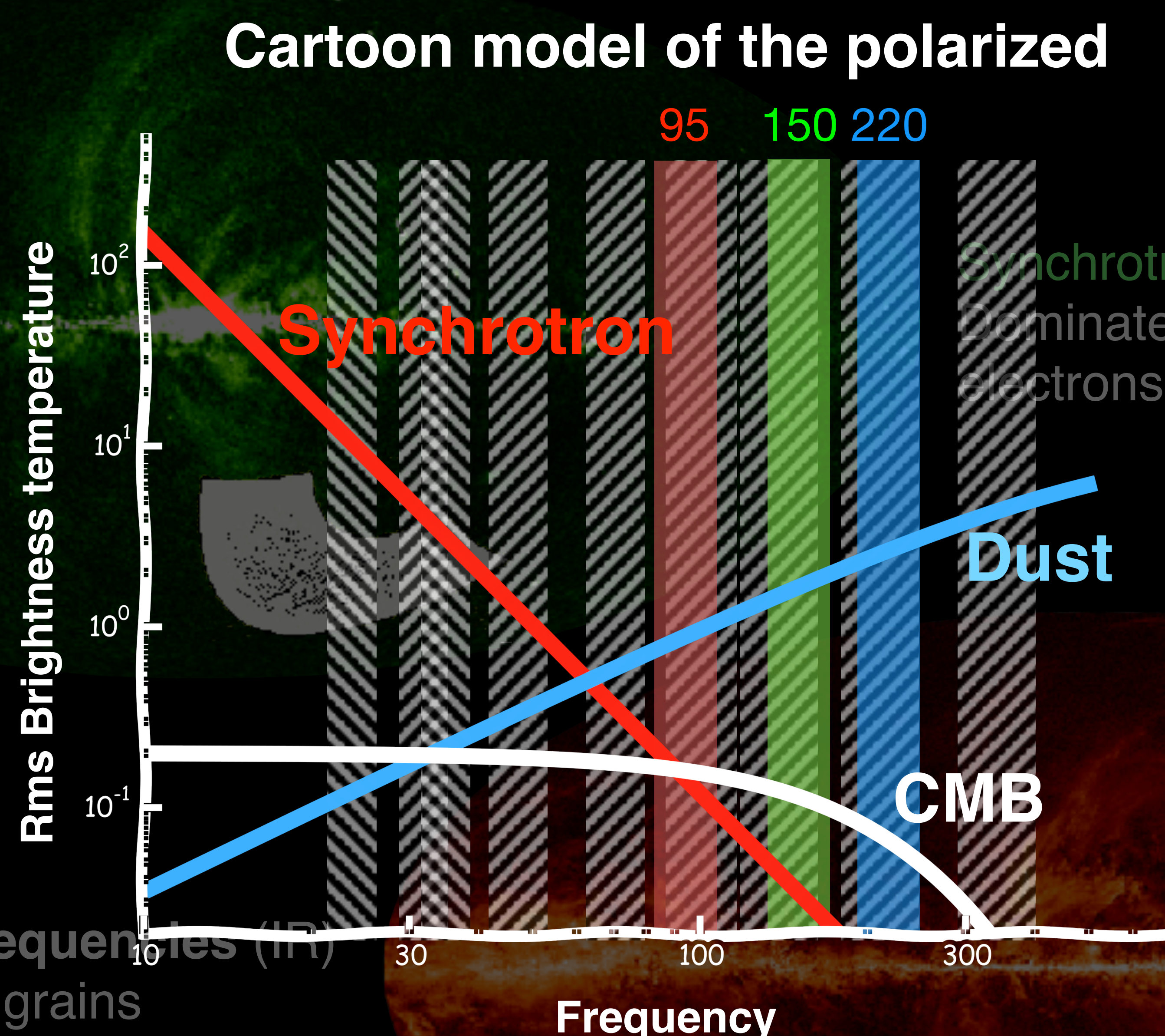
Checks for contamination from ground-fixed signals, such as polarized sky or magnetic fields, or the moon

Splits to check intrinsic detector properties

Checks for contamination from detectors with best/worst differential pointing. "Tile/dk" divides the data by the orientation of the detector on the sky.

Galactic Foregrounds

For now, two known foregrounds can produce E and B modes



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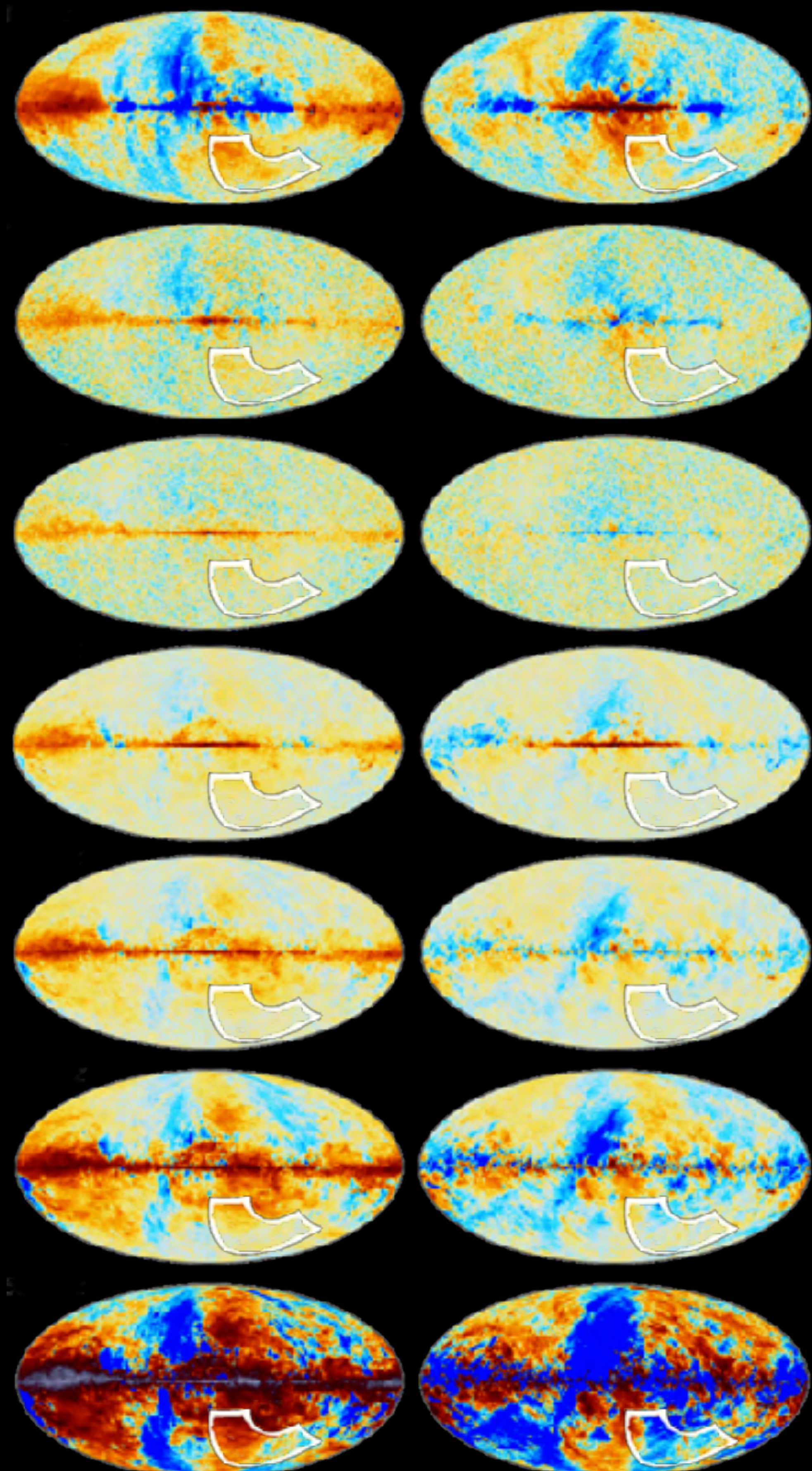
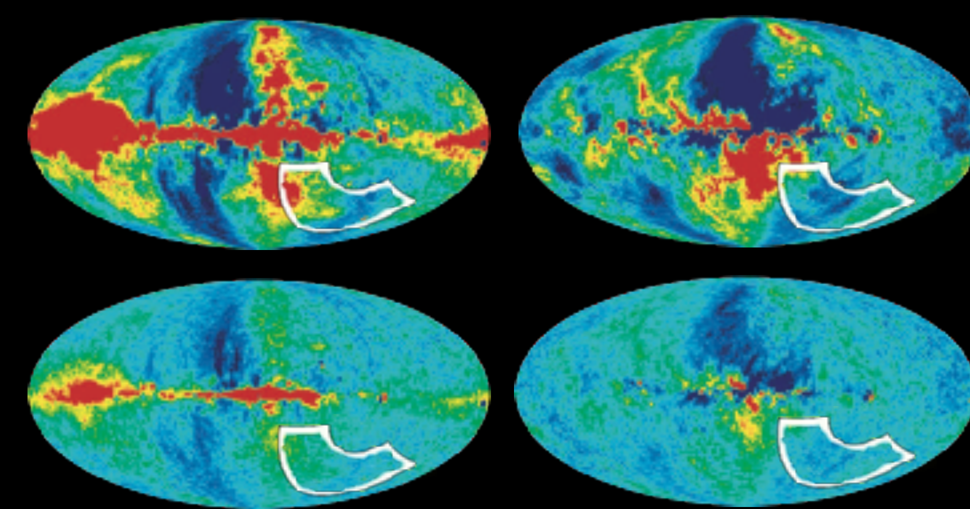
Planck Collaboration X: 1502.01588

Planck polarized maps at 7 frequencies + WMAP at 2 frequencies



Polarized galactic **synchrotron** dominates at low frequencies

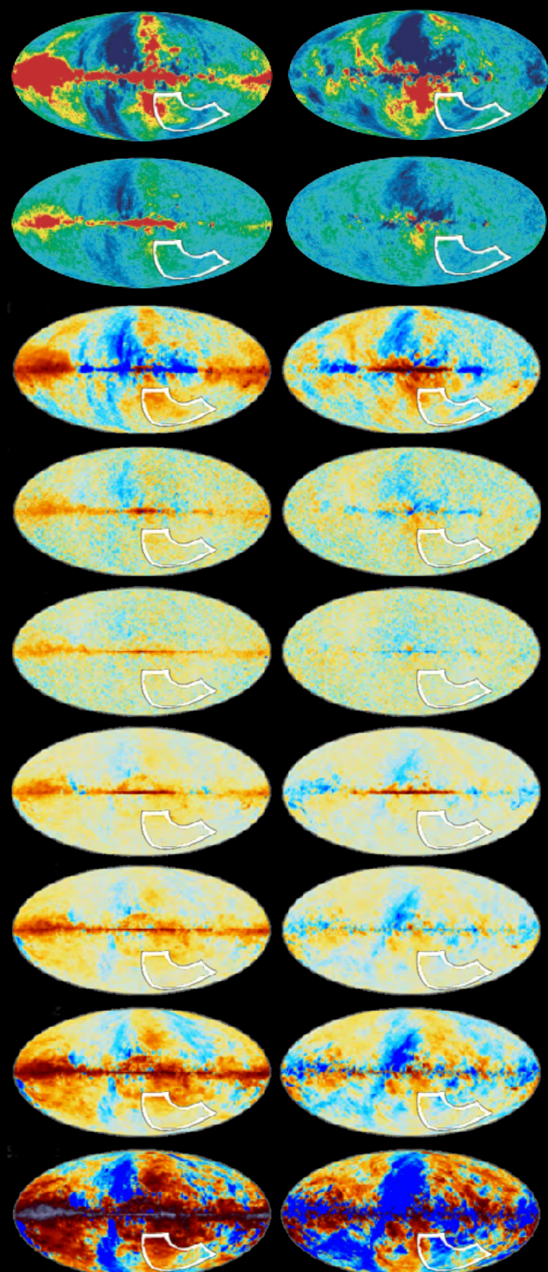


From arxiv 1212.5225

Polarized thermal emission (~20K) from galactic **dust** aligned in magnetic fields dominates at high frequencies

From arxiv 1502.01582

Maps



23 GHz

33 GHz

30 GHz

44 GHz

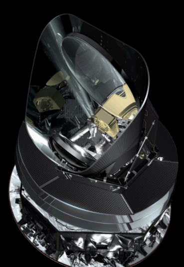
70 GHz

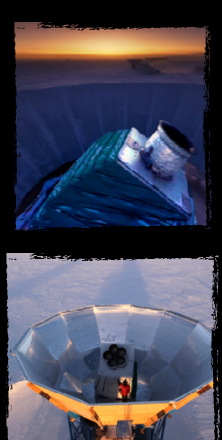
100 GHz

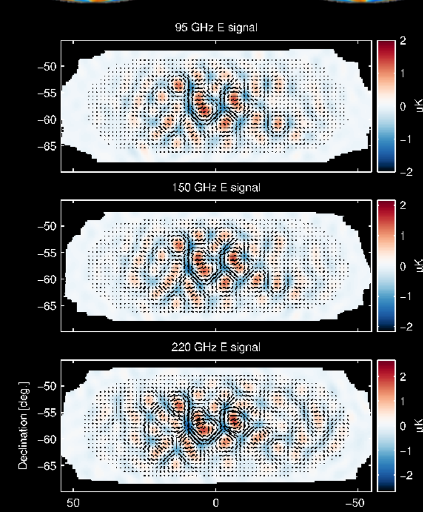
143 GHz

217 GHz

353 GHz





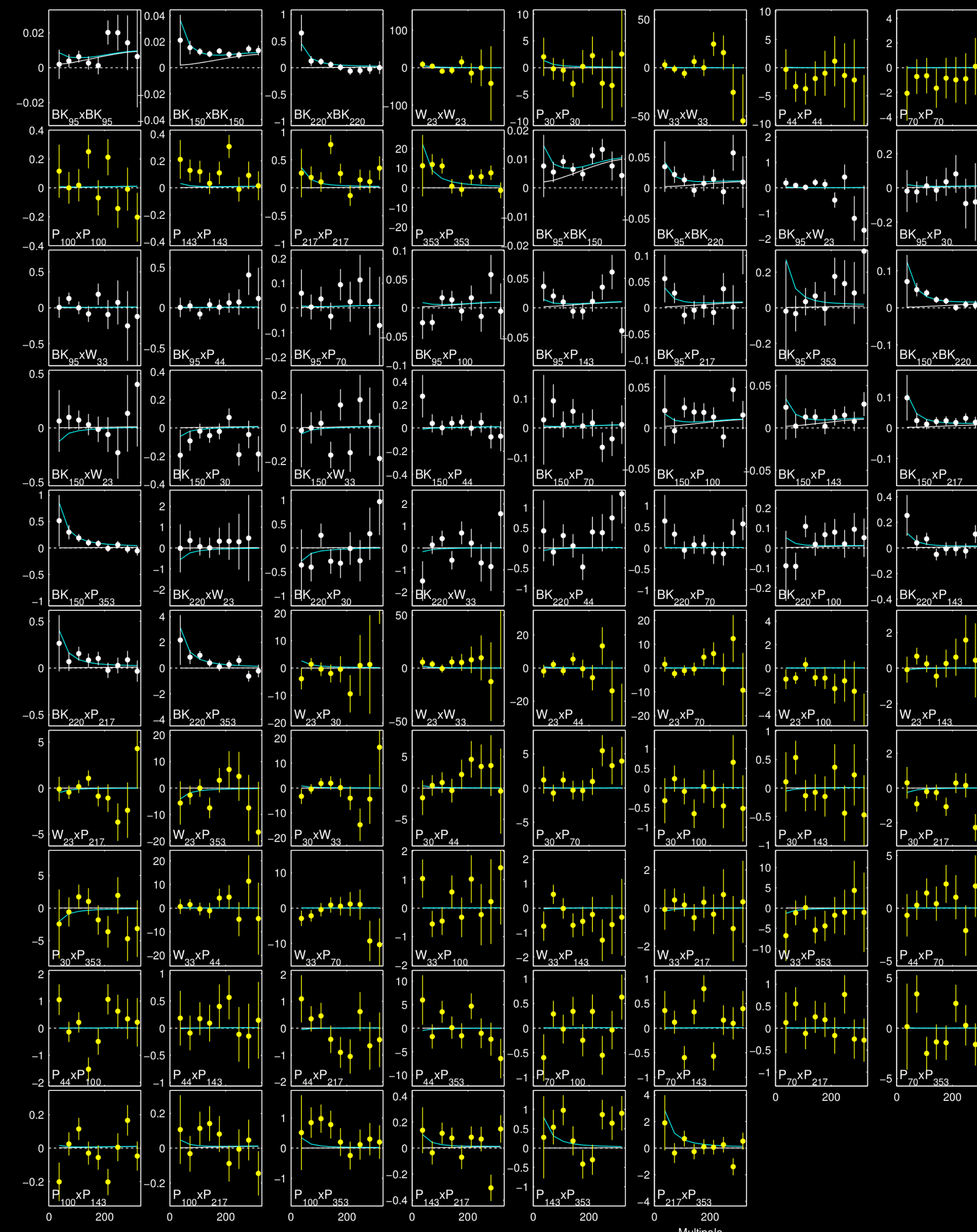


95 GHz

150 GHz

220 GHz

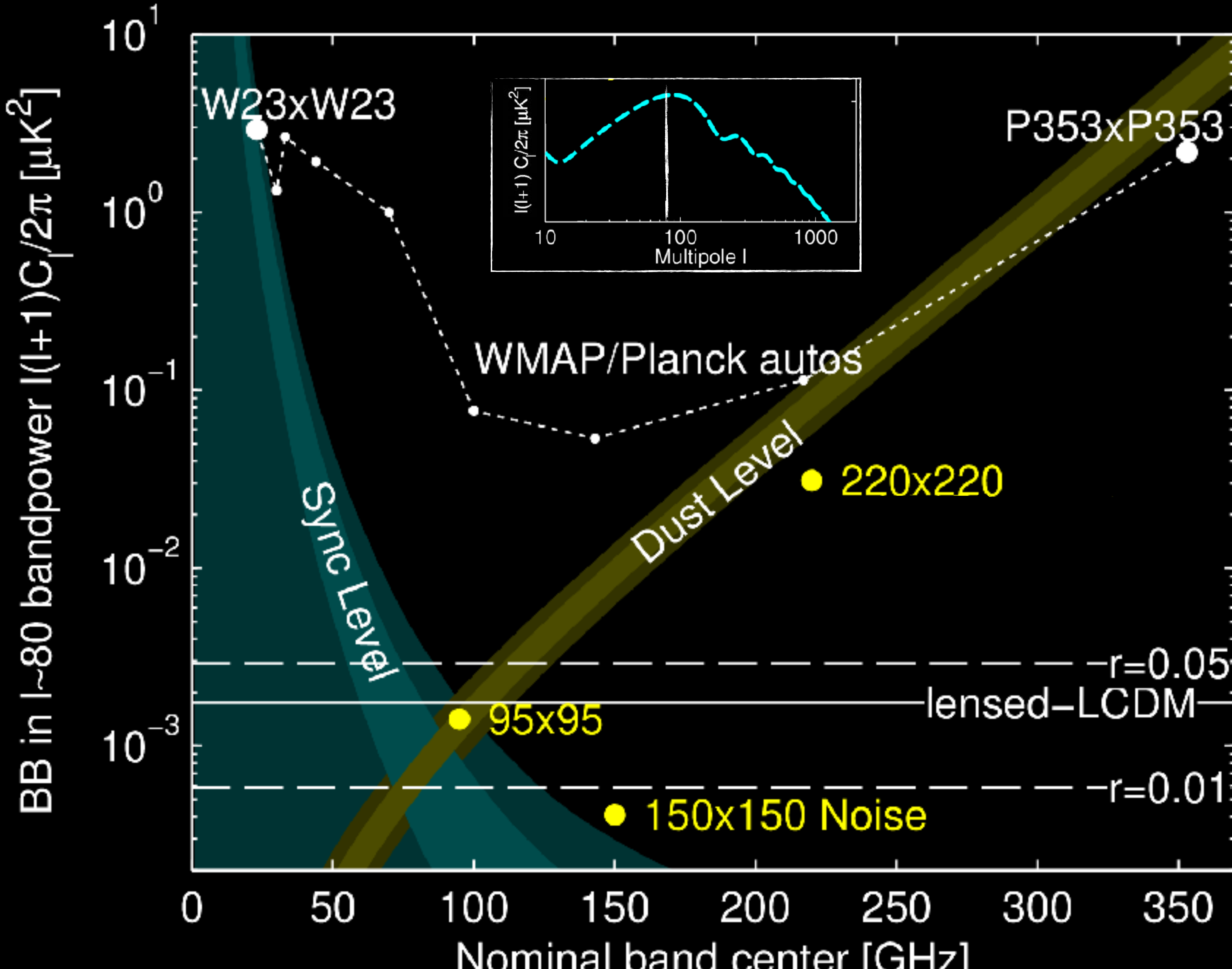
Auto and cross-spectra between BICEP2 + Keck Array and all WMAP/Planck maps



BK15: 78 spectra

Statistics for all spectra and covariance matrix derived from simulations of signal and noise.

BK15 Band Sensitivity (at ℓ ~ 80)



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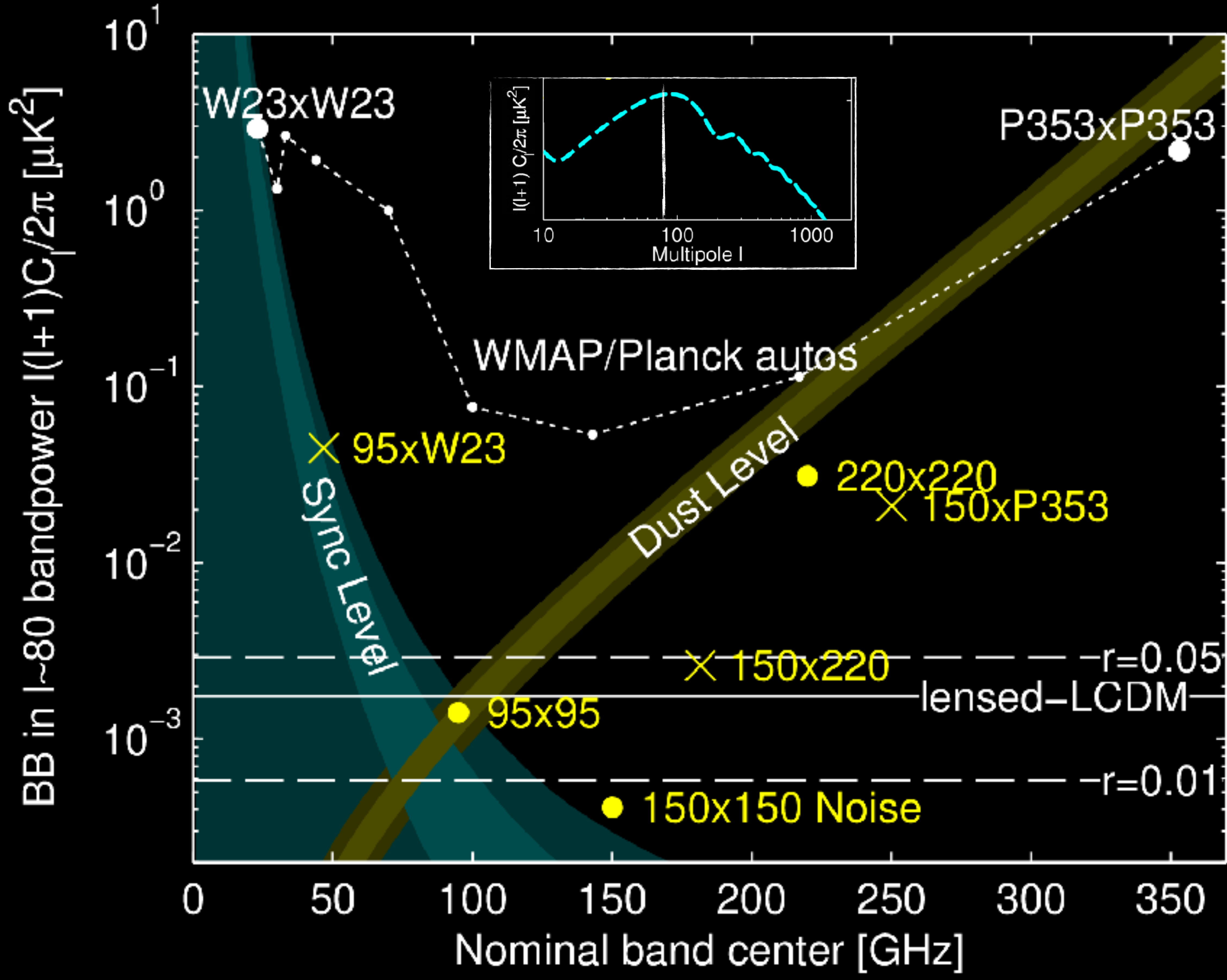
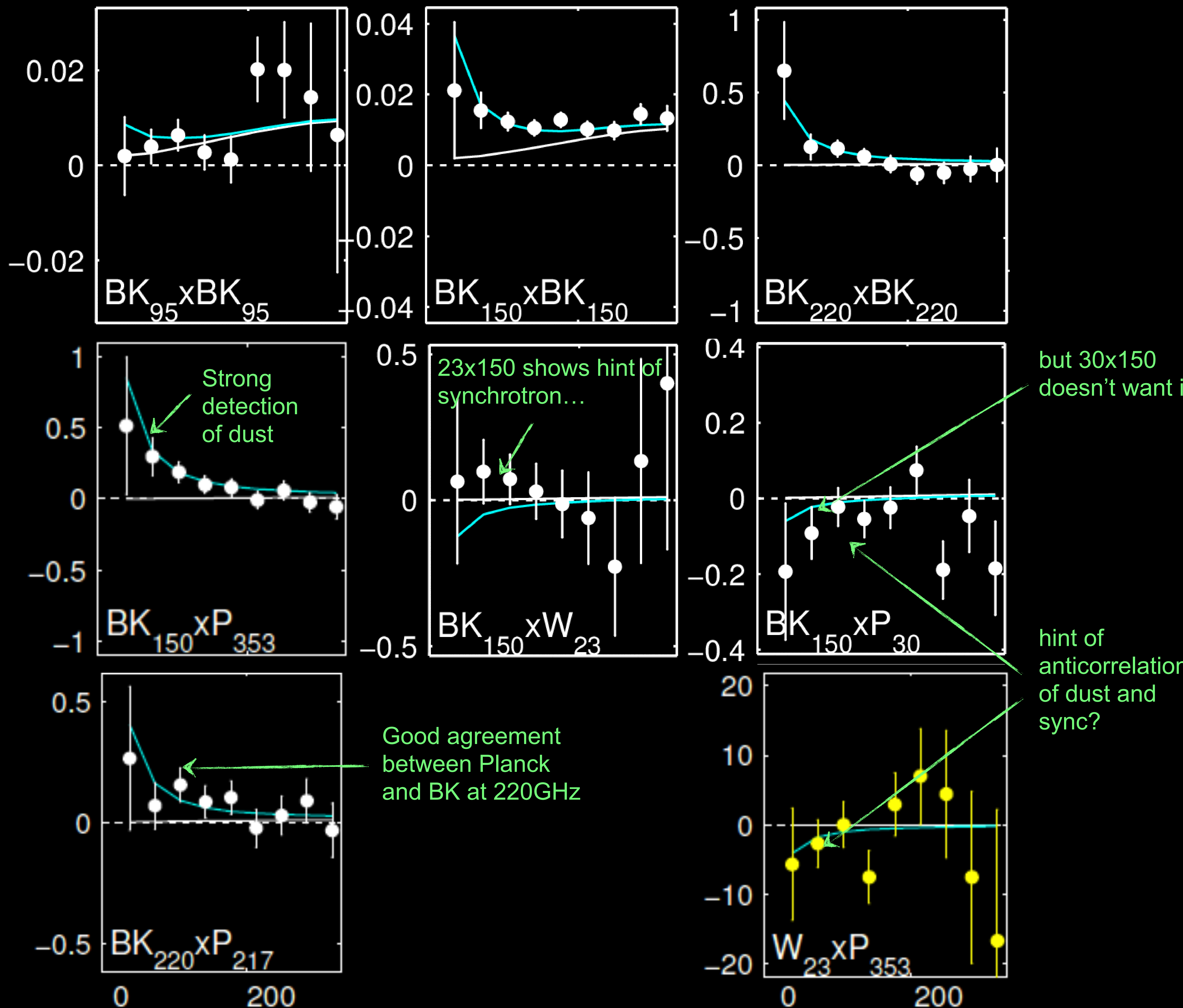


selected samples of auto- and cross-spectra



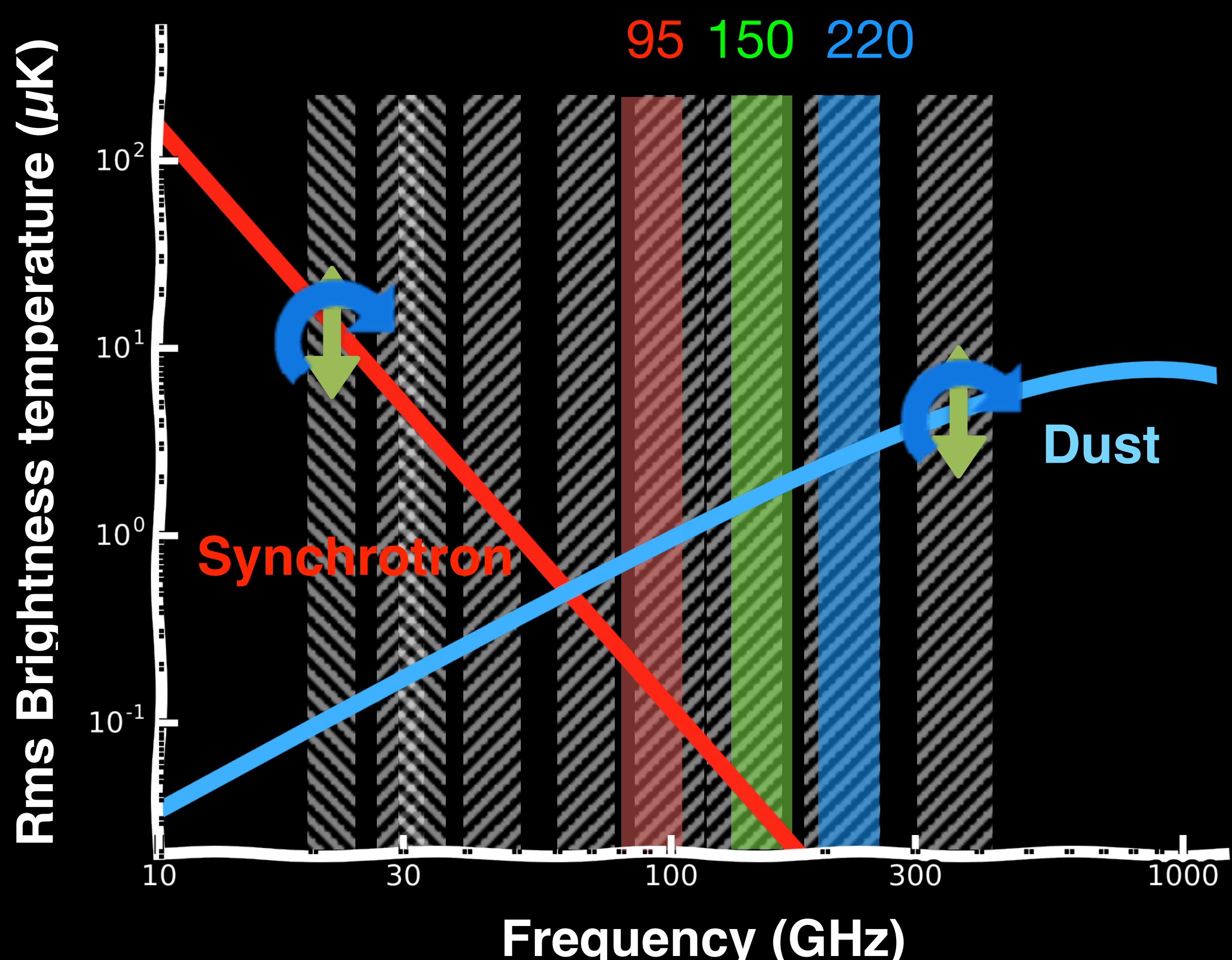
Multicomponent Likelihood Analysis

Hamimeche Lewis: 0801.0554

Take the joint likelihood of all the spectra simultaneously
vs. model for BB : ΛCDM lensing expectation
+ r + 7 foreground parameters

foreground model = dust + synchrotron

Cartoon model



A_{dust} ↕ A_{synch}

β_{dust} ↷ β_{synch}

amplitudes @ l=80

frequency spectral indices

Multicomponent Likelihood Analysis

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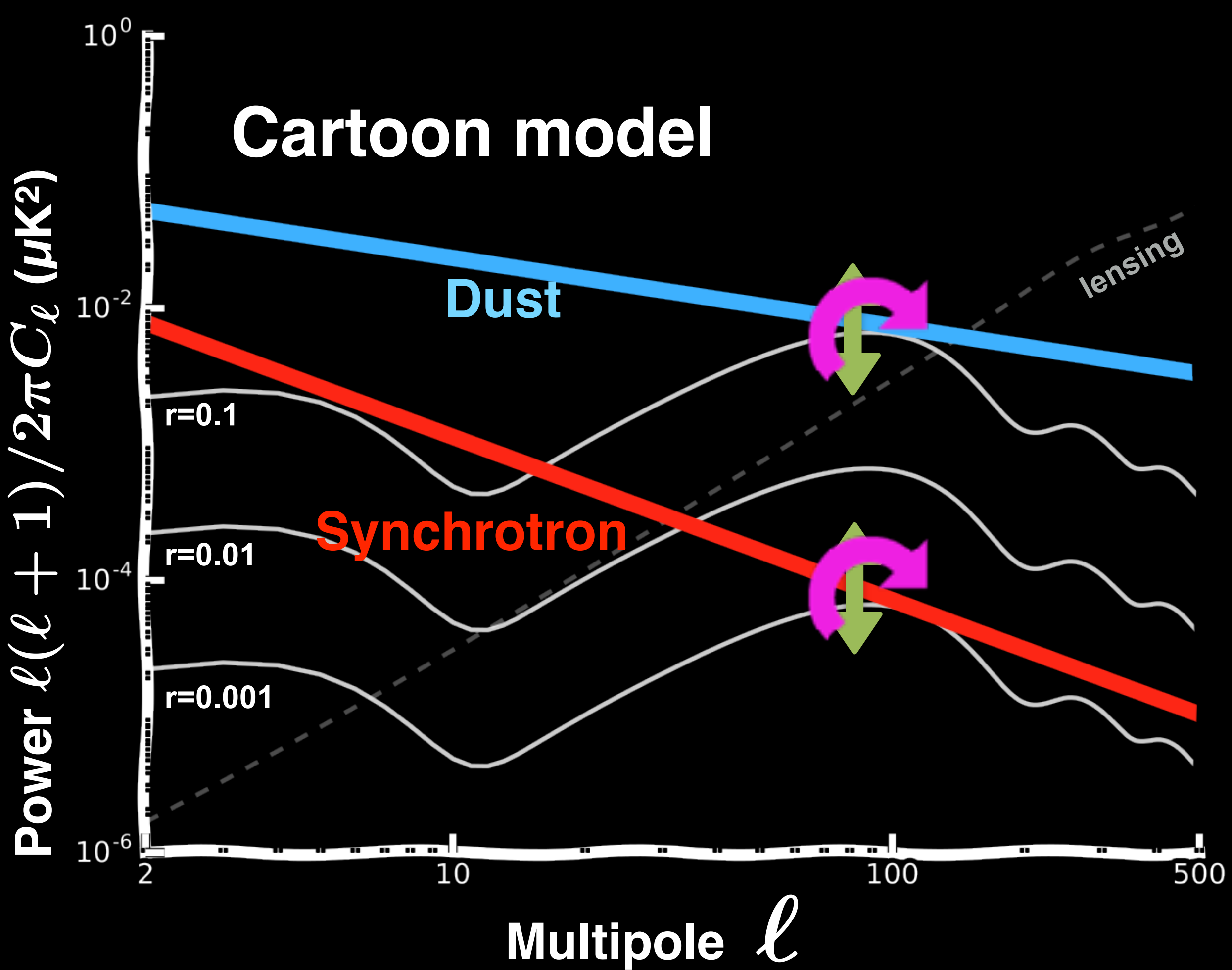
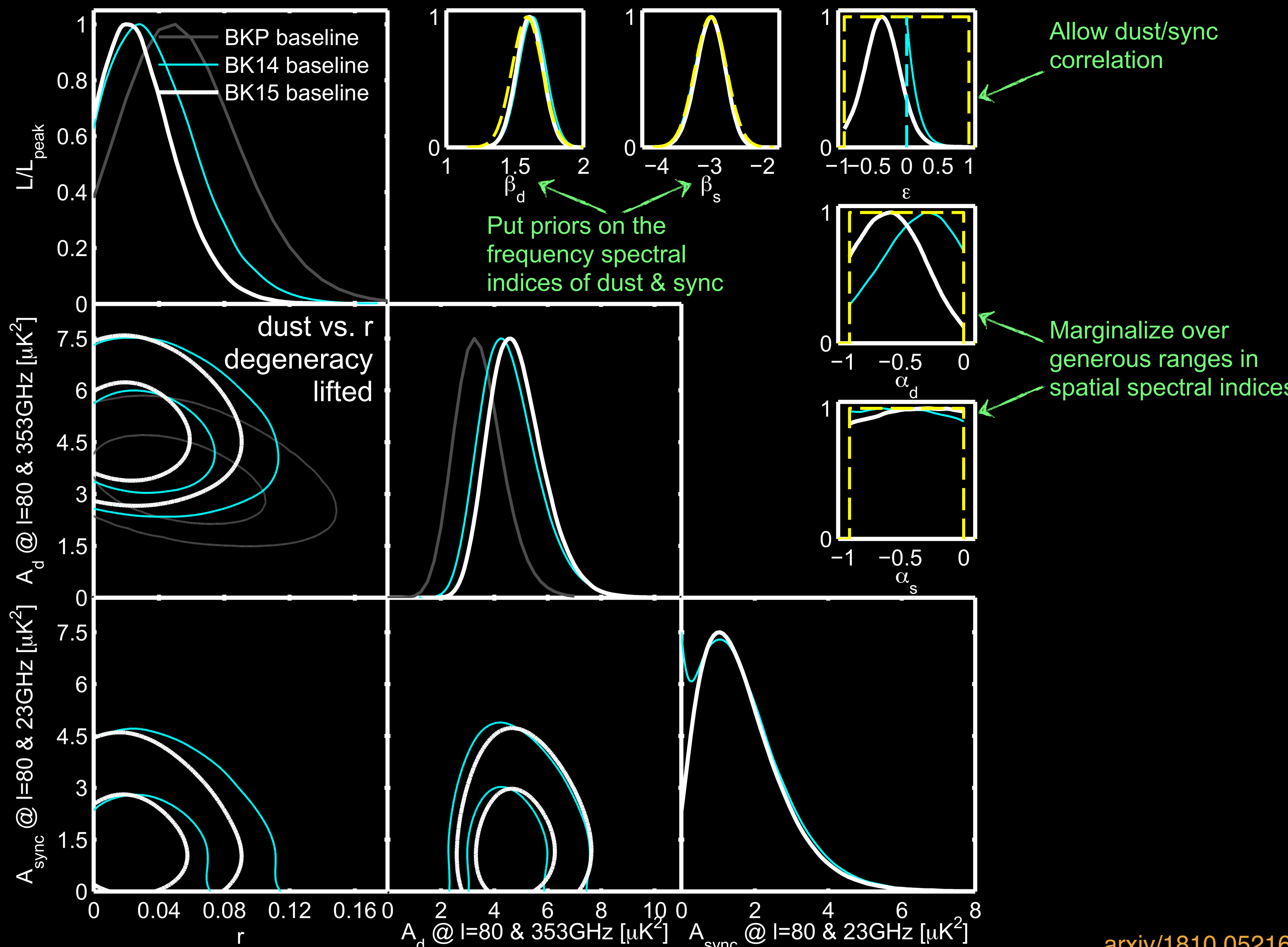


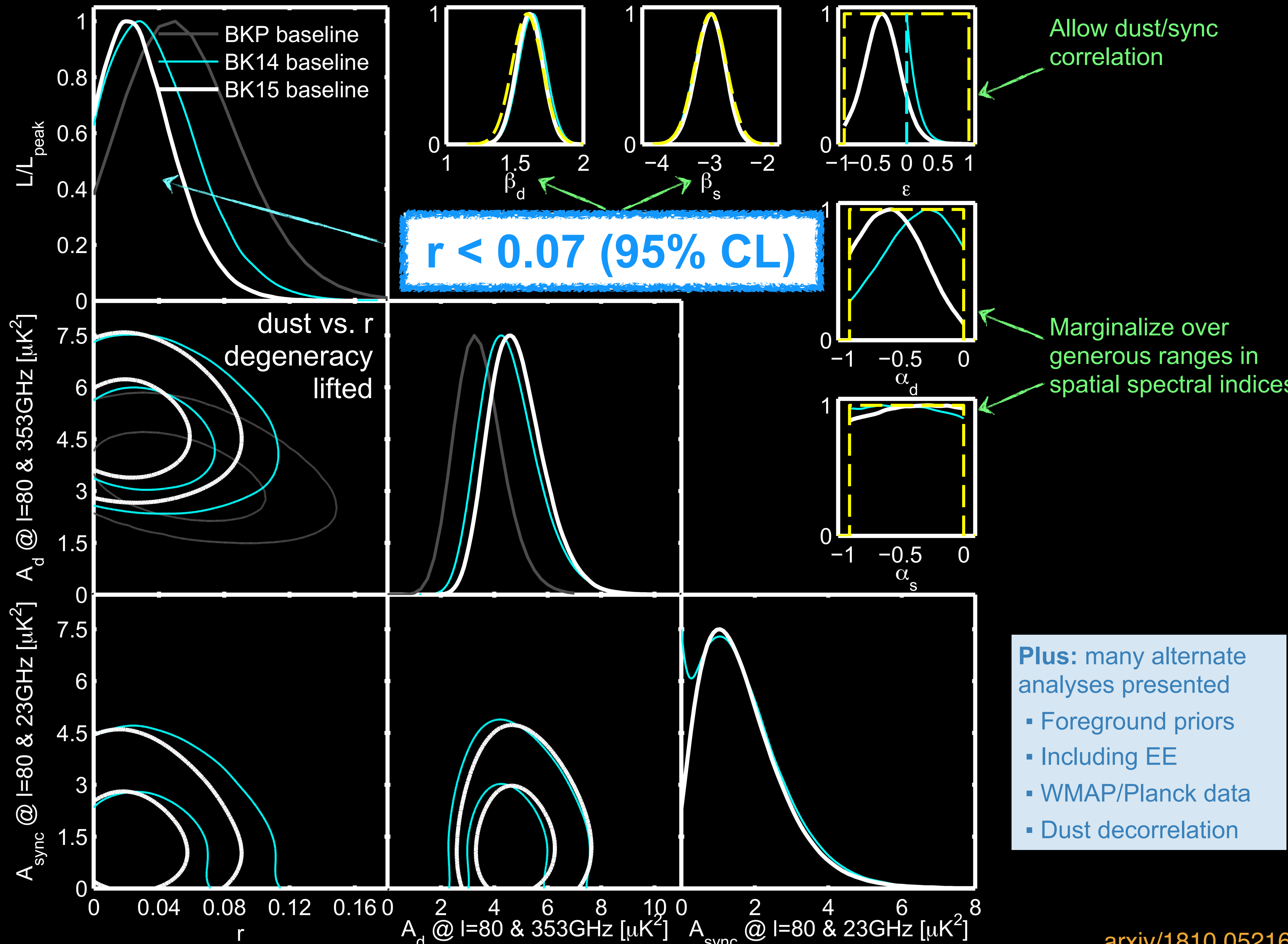
dust		synch	
A_{dust}	↕	A_{synch}	amplitudes @ l=80
β_{dust}	↷	β_{synch}	frequency spectral indices
α_{dust}	↷	α_{synch}	spatial spectral indices
	ε		dust/synch spatial correlation

New BK15 Results



arxiv/1810.05216

New BK15 Results

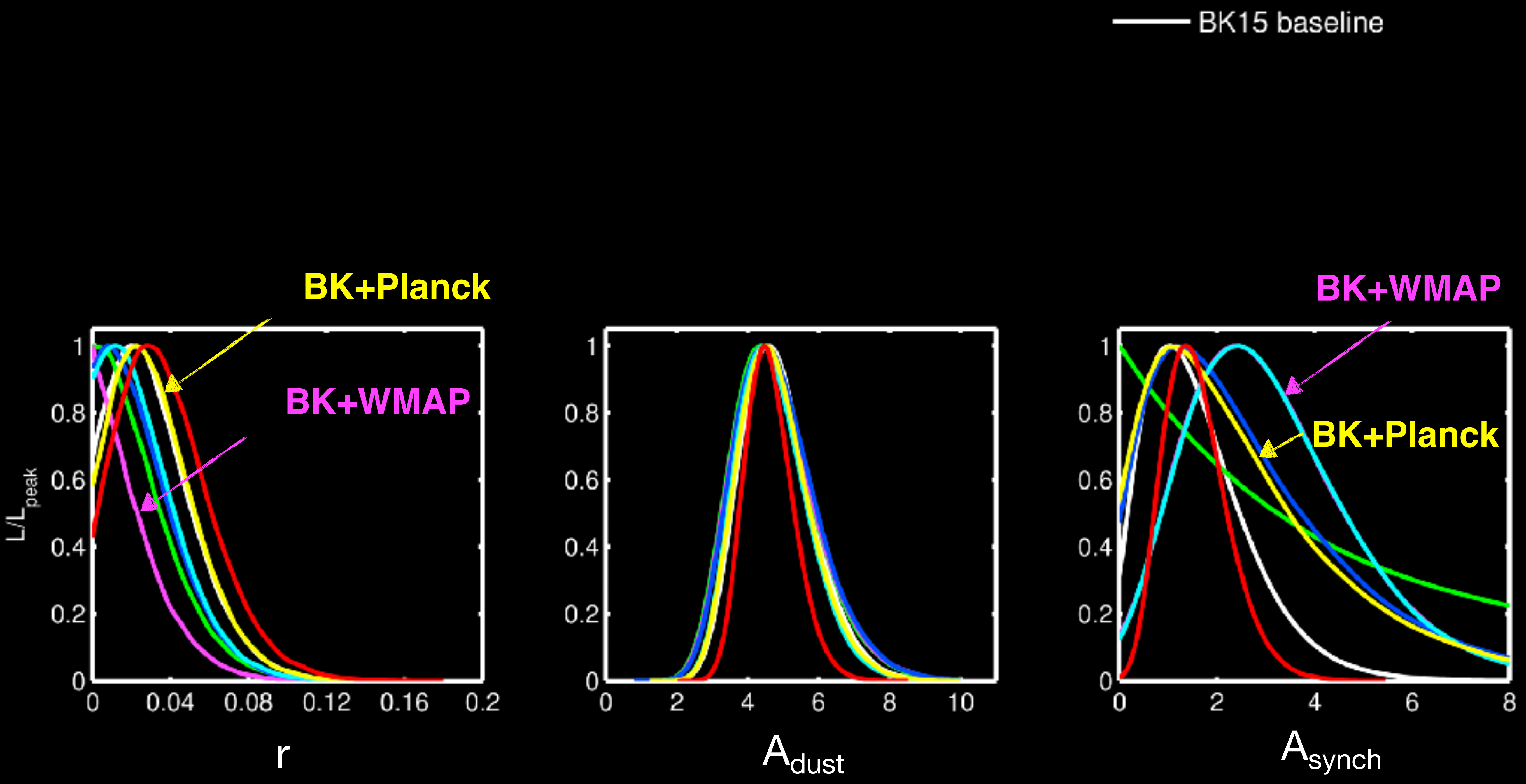


Plus: many alternate analyses presented

- Foreground priors
- Including EE
- WMAP/Planck data
- Dust decorrelation

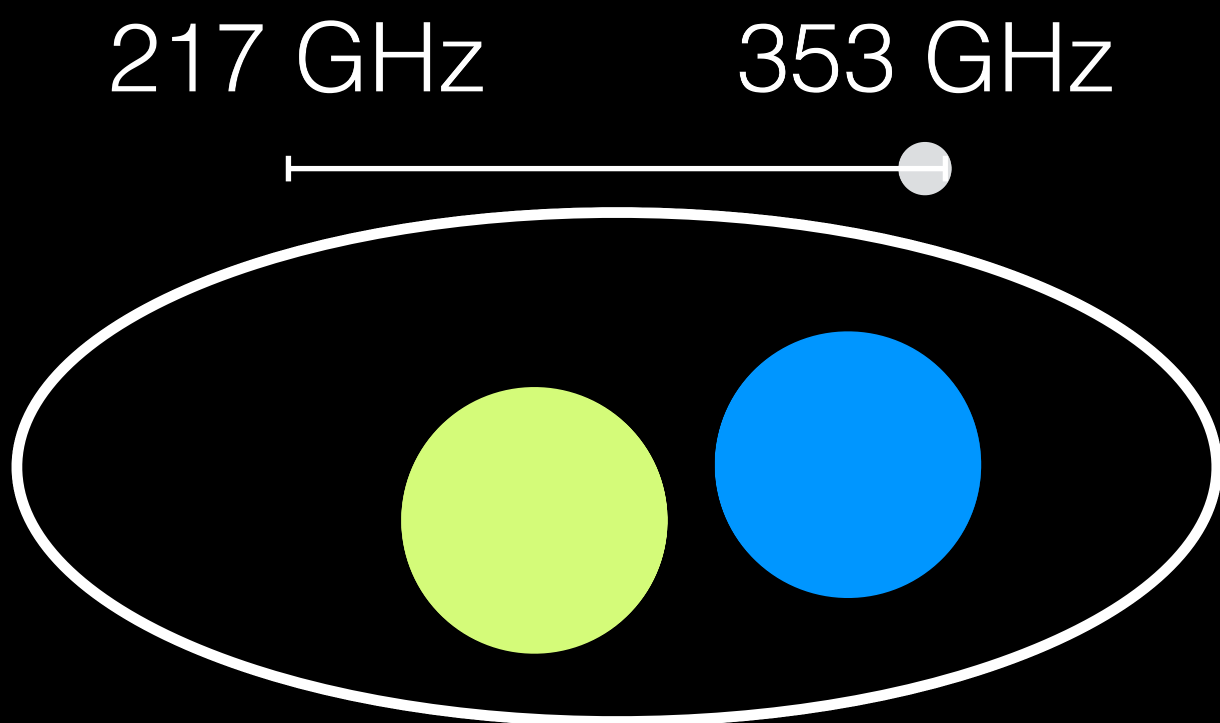
arxiv/1810.05216

BK15 Results: Variations with Data Selection



Dust Decorrelation?

See Aumont, Hensley…



Planck 2018 arxiv/1801.04945

Planck 2018 results. XI. Polarized dust foregrounds

Planck Collaboration: Y. Akrami[46,48], M. Ashdown[55,4], J. Aumont[82], C. Baccigalupi[69], M. Ballardini[17,32], A. J. Banday[82,7], R. B. Barreiro[50], N. Bartolo[22,51], S. Basak[75], K. Benabed[44,81], J.-P. Bernard[82,7], M. Bersanelli[25,36], P. Bielewicz[67,7,69], J. R. Bond[6], J. Borrill[10,79], F. R. Bouchet[44,77], F. Boulanger[57,43,44 *], A. Bracco[68,45], M. Bucher[2,5], C. Burigana[35,23,37], E. Calabrese[73], J.-F. Cardoso[44], J. Carron[18], H. C. Chiang[20,5], C. Combet[60], B. P. Crill[52,9], P. de Bernardis[24], G. de Zotti[33,69], J. Delabrouille[2], J.-M. Delouis[44,81], E. Di Valentino[53], C. Dickinson[53], J. M. Diego[50], A. Ducout[44,42], X. Dupac[28], G. Efstathiou[55,47], F. Elsner[64], T. A. Enßlin[64], E. Falgarone[56], Y. Fantaye[3,15], K. Ferrière[82,7], F. Finelli[32,37], F. Forastieri[23,38], M. Frailis[34], A. A. Fraisse[20], E. Franceschi[32], A. Frolov[76], S. Galeotta[34], S. Galli[54], K. Ganga[2], R. T. Génova-Santos[49,12], T. Ghosh[72,8], J. González-Nuevo[13], K. M. Górski[52,83], A. Gruppuso[32,37], J. E. Gudmundsson[80,20], V. Guillet[43,59], W. Handley[55,4], F. K. Hansen[48], D. Herranz[50], Z. Huang[74], A. H. Jaffe[42], W. C. Jones[20], E. Keihänen[19], R. Keskitalo[10], K. Kiiveri[19,31], J. Kim[64], N. Krachmalnicoff[69], M. Kunz[11,43,3], H. Kurki-Suonio[19,31], J.-M. Lamarre[56], A. Lasenby[4,55], M. Le Jeune[2], F. Levrier[56], M. Liguori[22,51], P. B. Lilje[48], V. Lindholm[19,31], M. López-Caniego[28], P. M. Lubin[21], Y.-Z. Ma[53,71,66], J. F. Macías-Pérez[60], G. Maggio[34], D. Maino[25,36,39], N. Mandolesi[32,23], A. Mangilli[7], P. G. Martin[6], E. Martínez-González[50], S. Matarrese[22,51,30], J. D. McEwen[65], P. R. Meinhold[21], A. Melchiorri[24,40], M. Migliaccio[78,41], M.-A. Miville-Deschênes[58], D. Molinari[23,32,38], A. Moneti[44], L. Montier[82,7], G. Morgante[32], P. Natoli[23,78,38], L. Pagano[43,56], D. Paoletti[32,37], V. Pettorino[1], F. Piacentini[24], G. Polenta[78], J.-L. Puget[43,44], J. P. Rachen[14], M. Reinecke[64], M. Remazeilles[53], A. Renzi[51], G. Rocha[52,9], C. Rosset[2], G. Roudier[2,56,52], J. A. Rubiño-Martín[49,12], B. Ruiz-Granados[49,12], L. Salvati[43], M. Sandri[32], M. Savelainen[19,31,62], D. Scott[16], J. D. Soler[63], L. D. Spencer[73], J. A. Tauber[29], D. Tavagnacco[34,26], L. Toffolatti[13,32], M. Tomasi[25,36], T. Trombetti[35,38], J. Valiviita[19,31], F. Vansyngel[43], B. Van Tent[61], P. Vielva[50], F. Villa[32], N. Vittorio[27], I. K. Wehus[52,48], A. Zacchei[34], and A. Zonca[70]

(Affiliations can be found after the references)

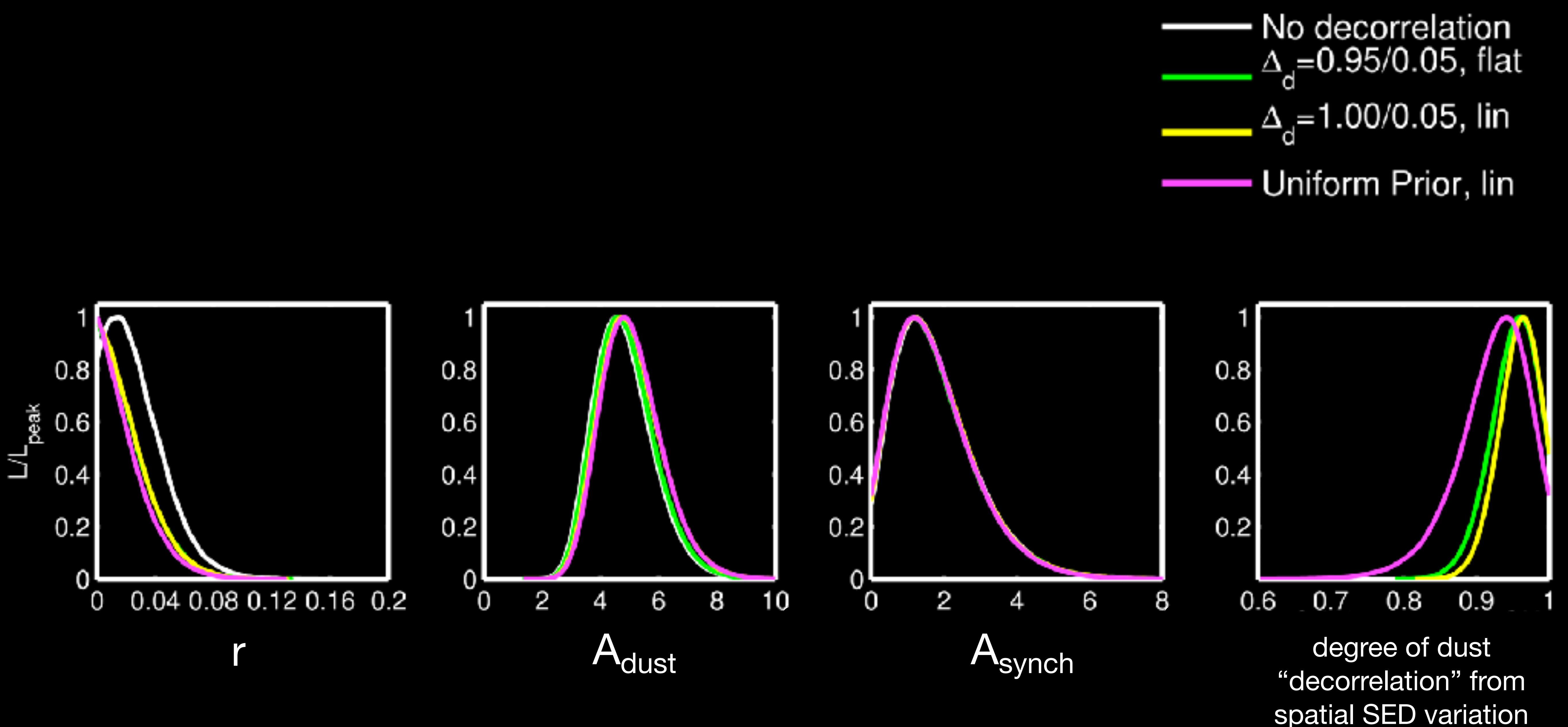
Preprint online version: July 19, 2018

ABSTRACT

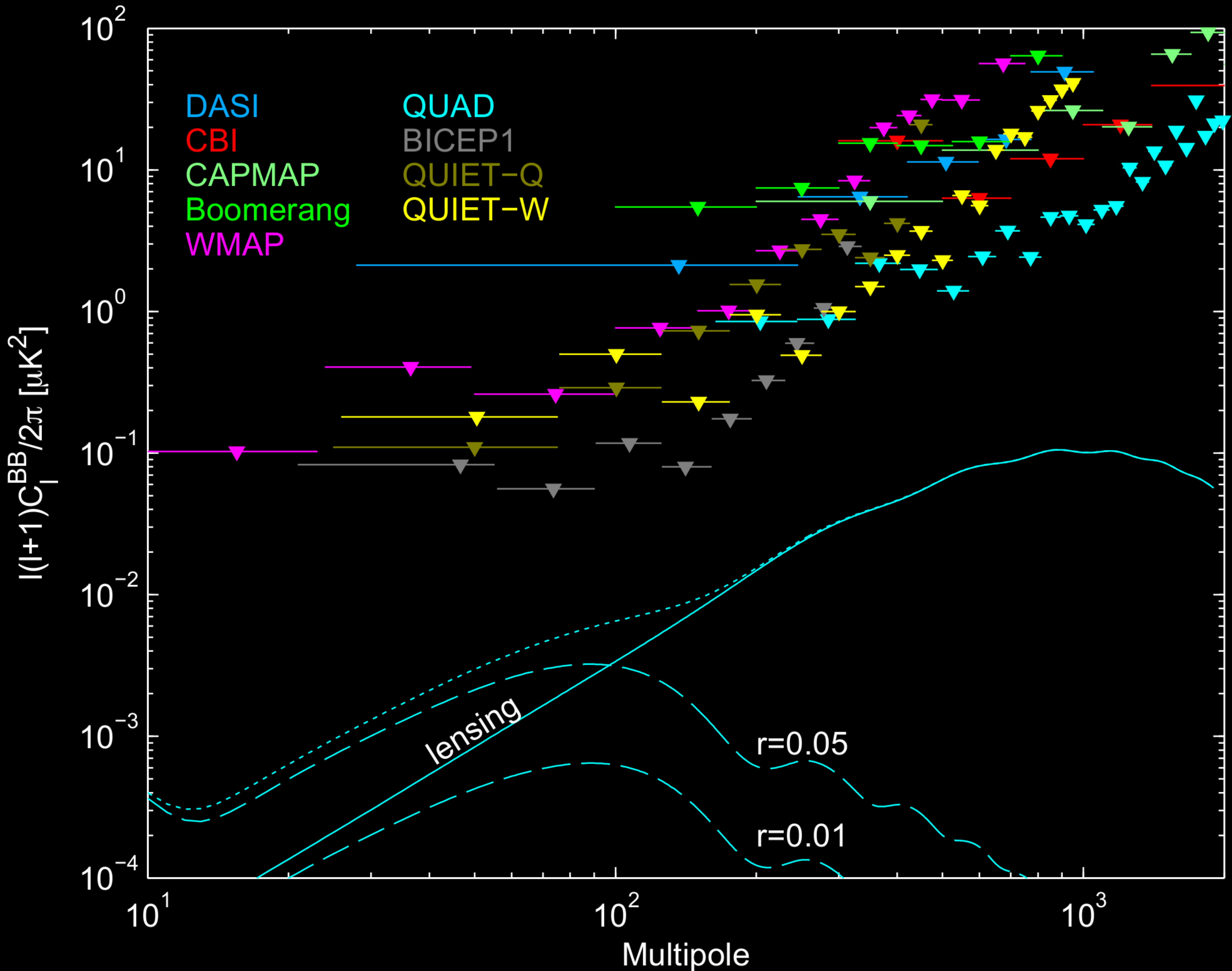
The study of polarized dust emission has become entwined with the analysis of the cosmic microwave background (CMB) polarization in the quest for the curl-like B-mode polarization from primordial gravitational waves and the low-multipole E-mode polarization associated with the reionization of the Universe. We use the new *Planck* PR3 maps to characterize Galactic dust emission at high latitudes as a foreground to the CMB polarization and use end-to-end simulations to compute uncertainties and assess the statistical significance of our measurements. We present *Planck* EE, BB, and TE power spectra of dust polarization at 353 GHz for a set of six nested high-Galactic-latitude sky regions covering from 24 to 71 % of the sky. We present power-law fits to the angular power spectra, yielding evidence for statistically significant variations of the exponents over sky regions and a difference between the values for the EE and BB spectra, which for the largest sky region are $\alpha_{EE} = -2.42 \pm 0.02$ and $\alpha_{BB} = -2.54 \pm 0.02$, respectively. The spectra show that the TE correlation and E/B power asymmetry discovered by *Planck* extend to low multipoles that were not included in earlier *Planck* polarization papers due to residual data systematics. We also report evidence for a positive TB dust signal. Combining data from *Planck* and WMAP, we determine the amplitudes and spectral energy distributions (SEDs) of polarized foregrounds, including the correlation between dust and synchrotron polarized emission, for the six sky regions as a function of multipole. This quantifies the challenge of the component-separation procedure that is required for measuring the low-ℓ reionization CMB E-mode signal and detecting the reionization and recombination peaks of primordial CMB B modes. The SED of polarized dust emission is fit well by a single-temperature modified blackbody emission law from 353 GHz to below 70 GHz. For a dust temperature of 19.6 K, the mean dust spectral index for dust polarization is $\beta_d^P = 1.53 \pm 0.02$. The difference between indices for polarization and total intensity is $\beta_d^P - \beta_d^I = 0.05 \pm 0.03$. By fitting multi-frequency cross-spectra between *Planck* data at 100, 143, 217, and 353 GHz, we examine the correlation of the dust polarization maps across frequency. We find no evidence for a loss of correlation and provide lower limits to the correlation ratio that are tighter than values we derive from the correlation of the 217- and 353-GHz maps alone. If the *Planck* limit on decorrelation for the largest sky region applies to the smaller sky regions observed by sub-orbital experiments, then frequency decorrelation of dust polarization might not be a problem for CMB experiments aiming at a primordial B-mode detection limit on the tensor-to-scalar ratio $r \simeq 0.01$ at the recombination peak. However, the *Planck* sensitivity precludes identifying how difficult the component-separation problem will be for more ambitious experiments targeting lower limits on r.

We find no evidence for a loss of correlation.
… might not be a problem for CMB experiments aiming at a primordial B-mode detection limit on the tensor-to-scalar ratio r ~ 0.01…

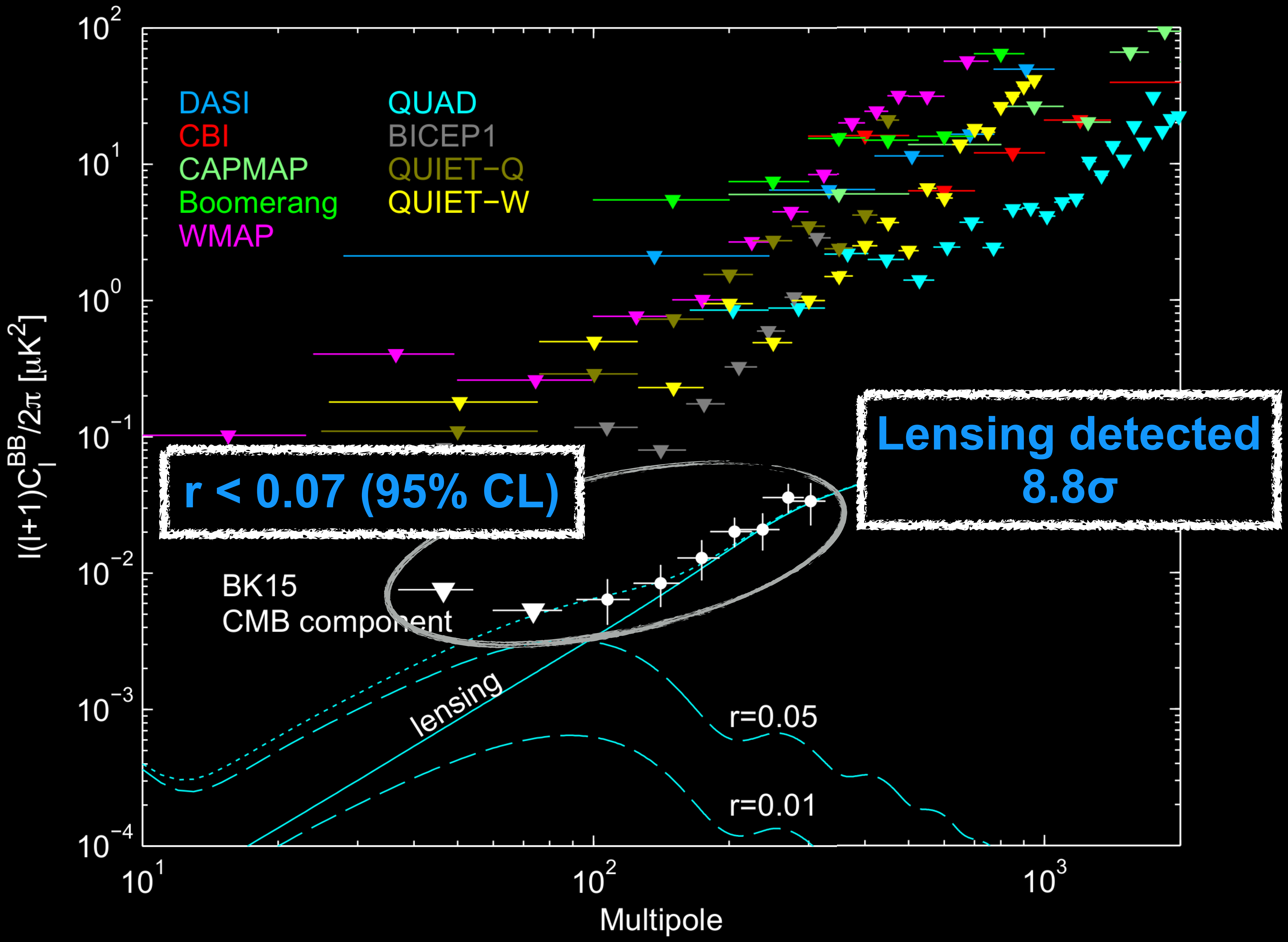
BK15 Results: Variations with Dust Modeling



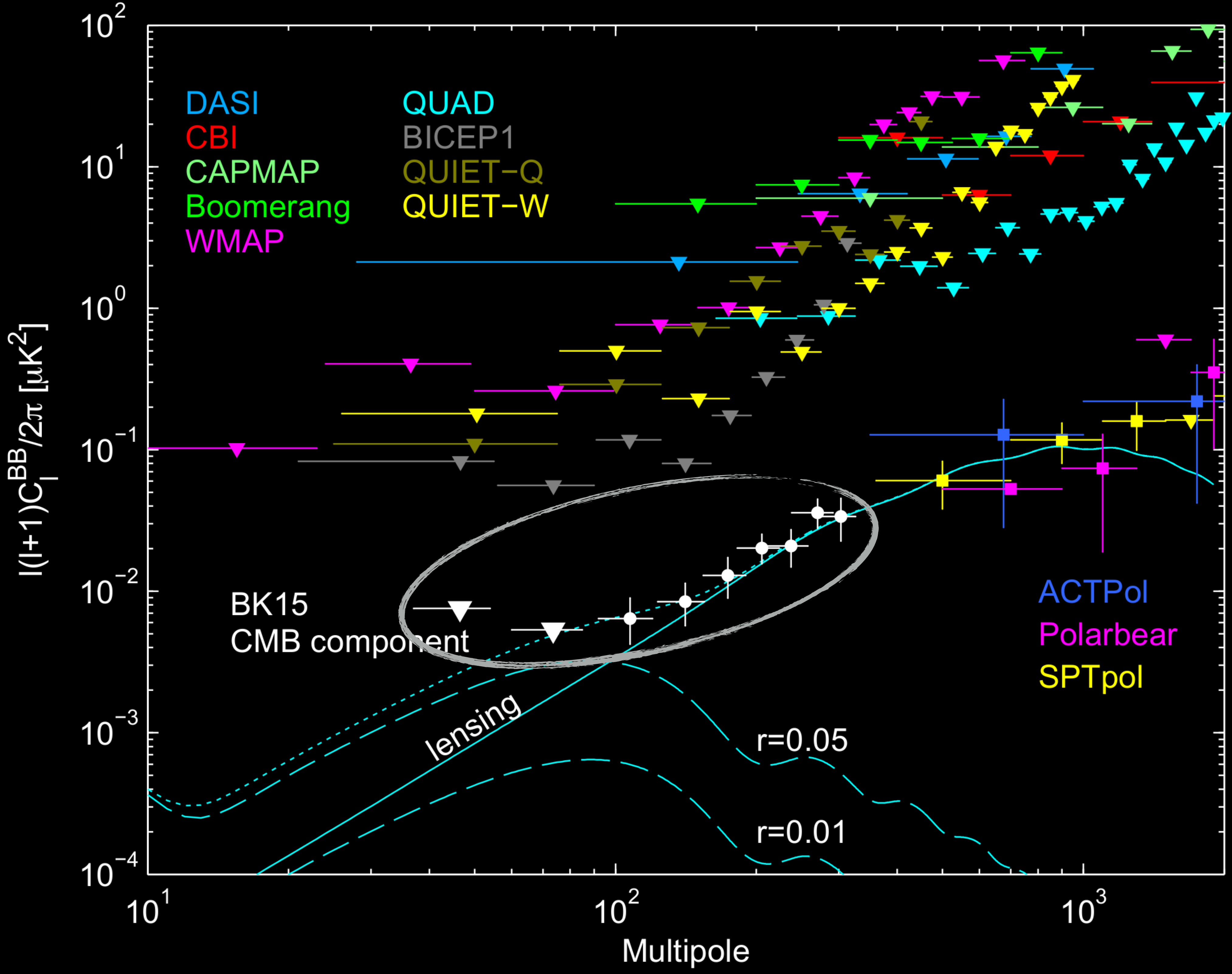
B modes before 2014



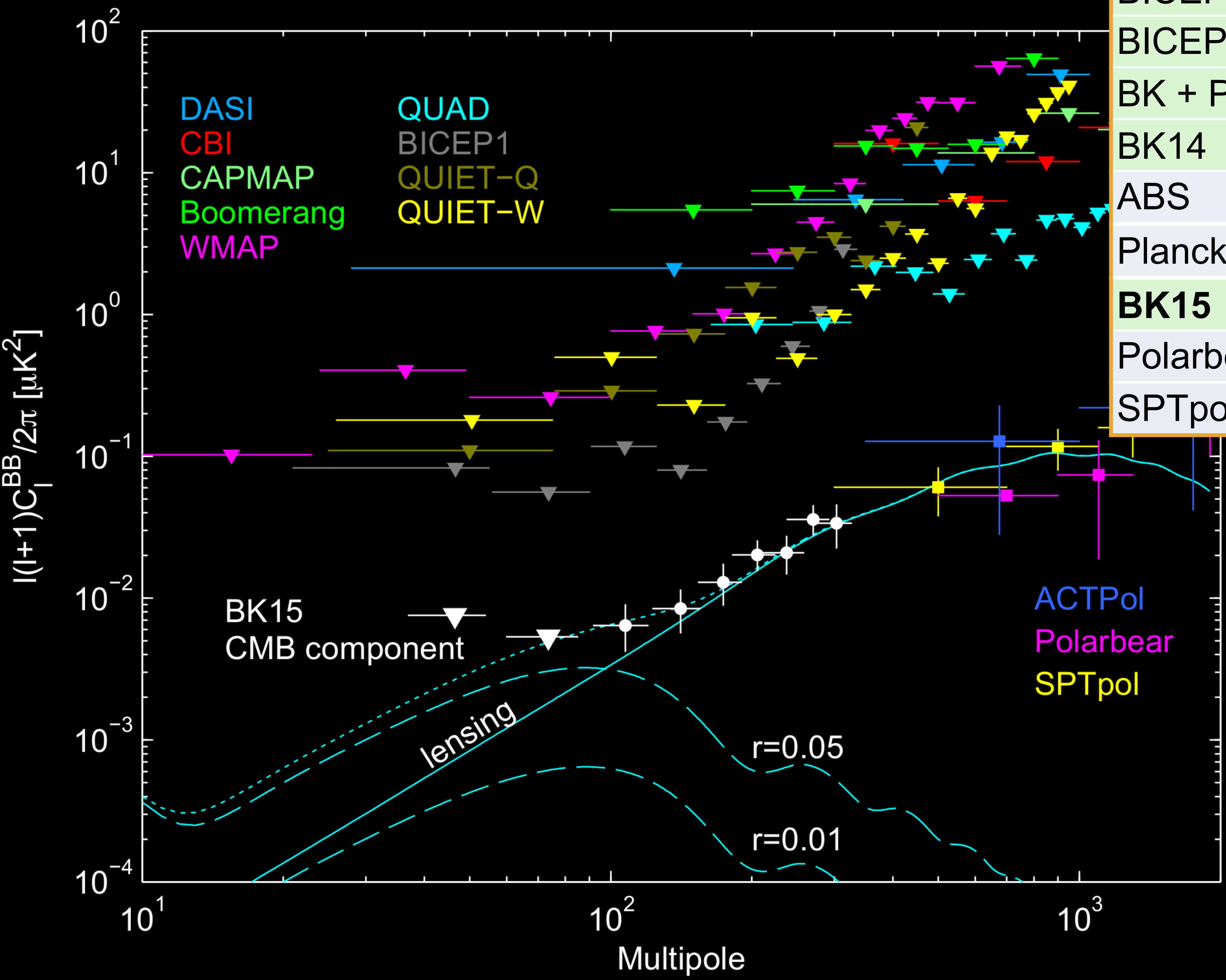
B modes today



B modes today

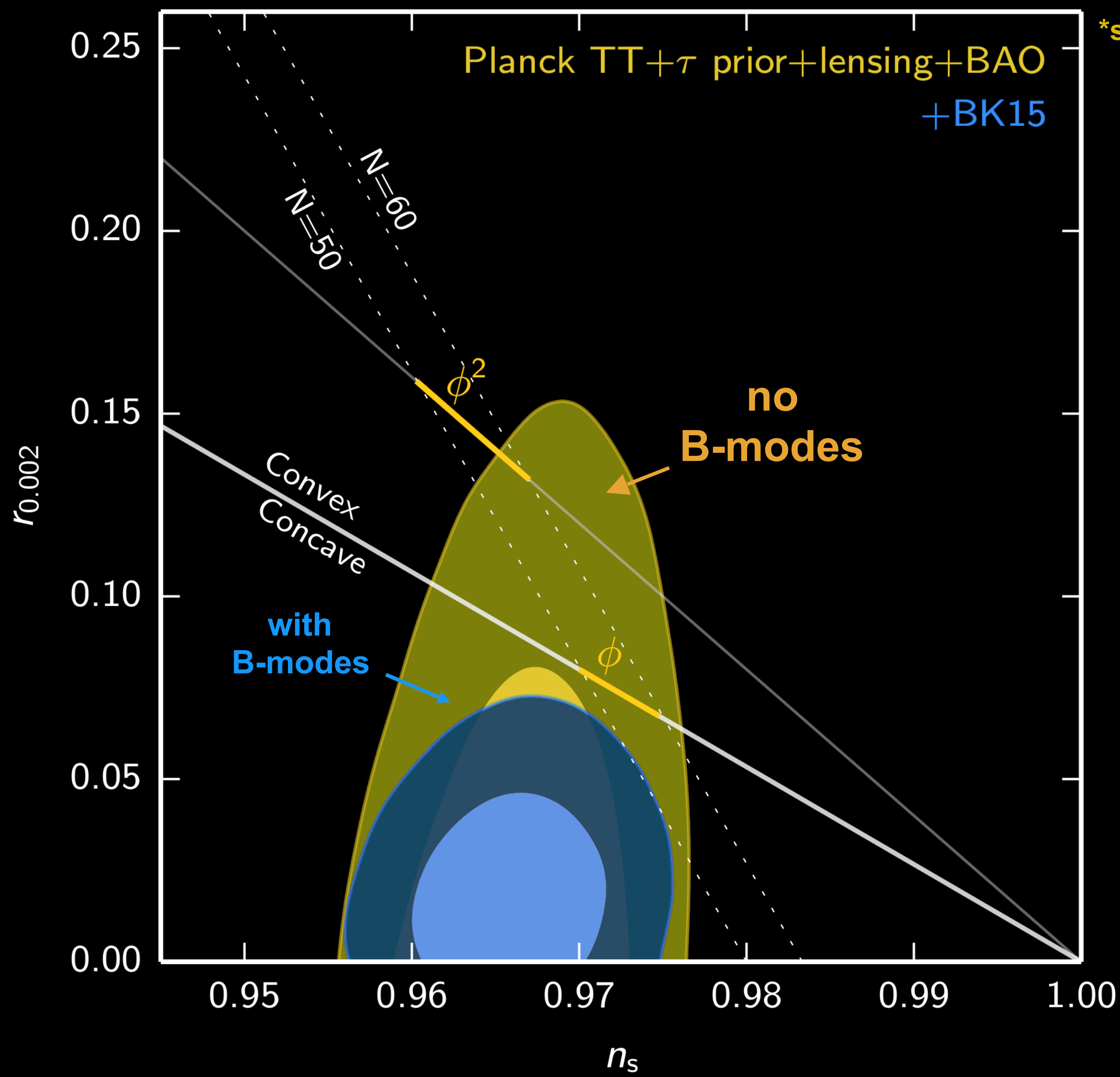


B modes t



Published B-Mode Sensitivity to r			
Experiment	**Year**	**Bands [GHz]**	**σ(r)**
DASI	2004	26…36	7.5
BICEP1 2yr	2009	100, 150	0.28
WMAP 7yr	2010	30…60	1.1
QUIET-Q	2010	43	0.97
QUIET-W	2012	95	0.85
BICEP1 3yr	2013	100, 150	0.25
BICEP2	2014	150	0.10
BK + Planck	2015	150 + Planck	0.034
BK14	2015	95, 150 + P	0.024
ABS	2018	150	0.7
Planck	2018	30 … 353	~0.2
BK15	**2018**	**95, 150, 220 + P**	**0.02**
Polarbear	2019	150 + P	0.3
SPTpol	2019	150 + 95	0.22

Adding Planck 2015 Temperature

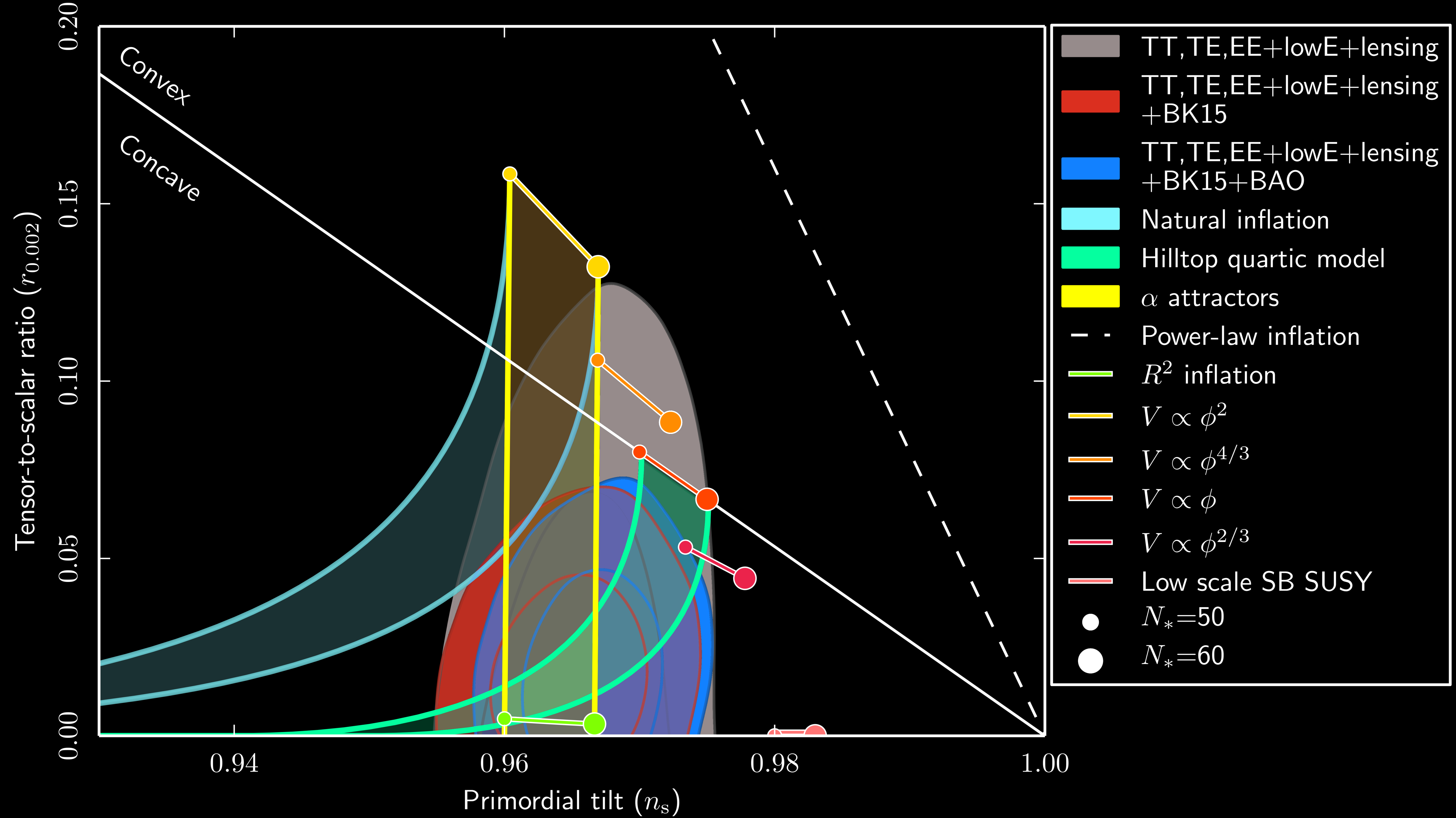


*slight change in external data and tau prior

BK15 $r_{.05} < 0.06$

arxiv/1810.05216

Adding Planck 2015 Temperature

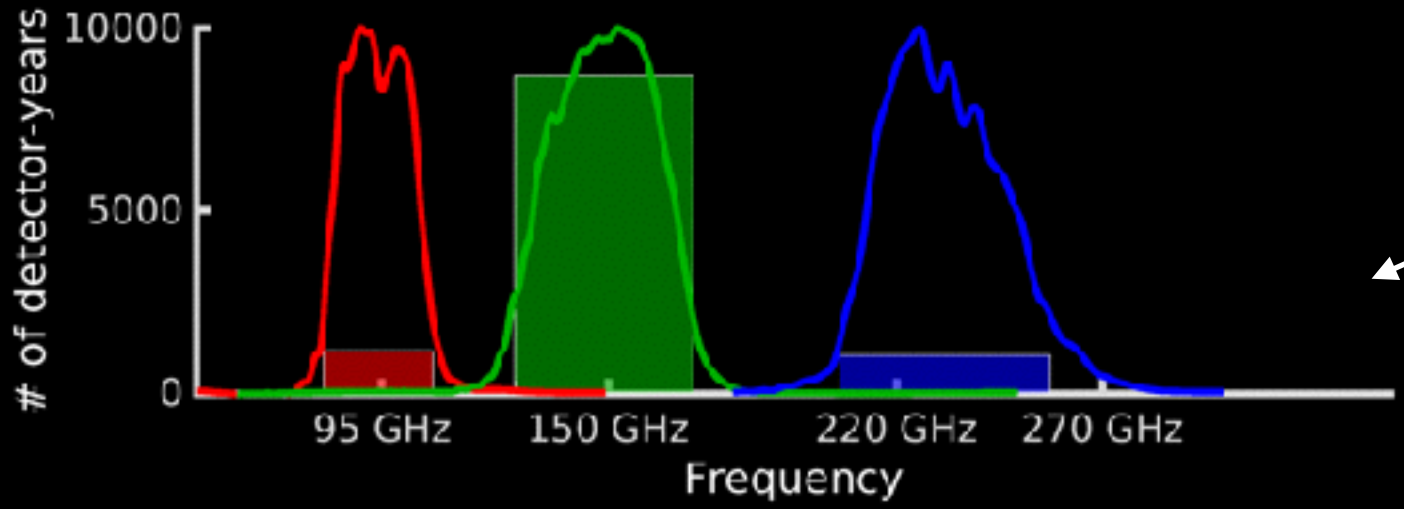


arxiv/1807.06211

What since 2015?

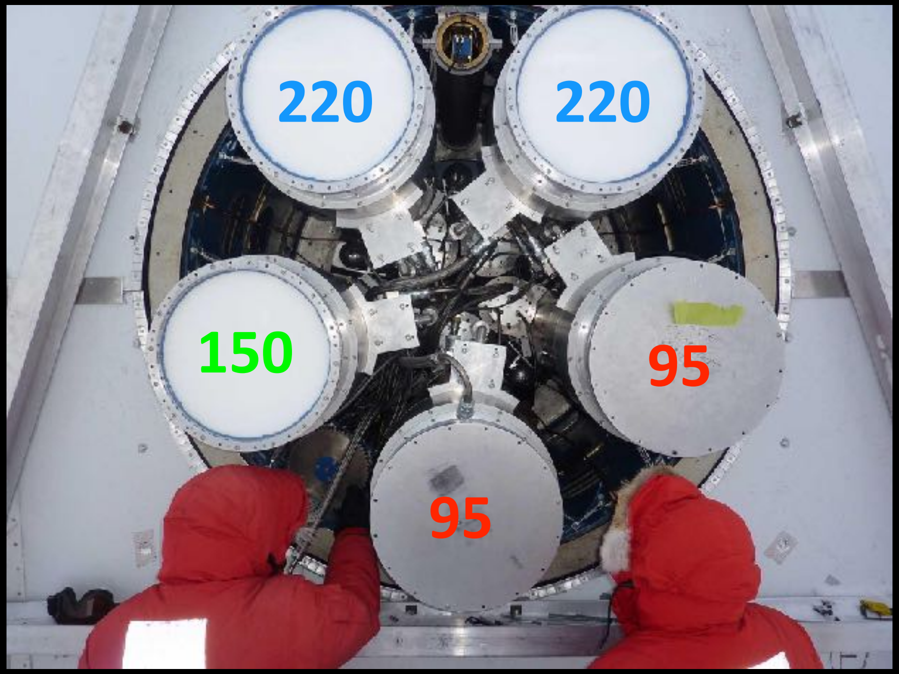
BICEP2
2010-2012

Keck Array
2012-…

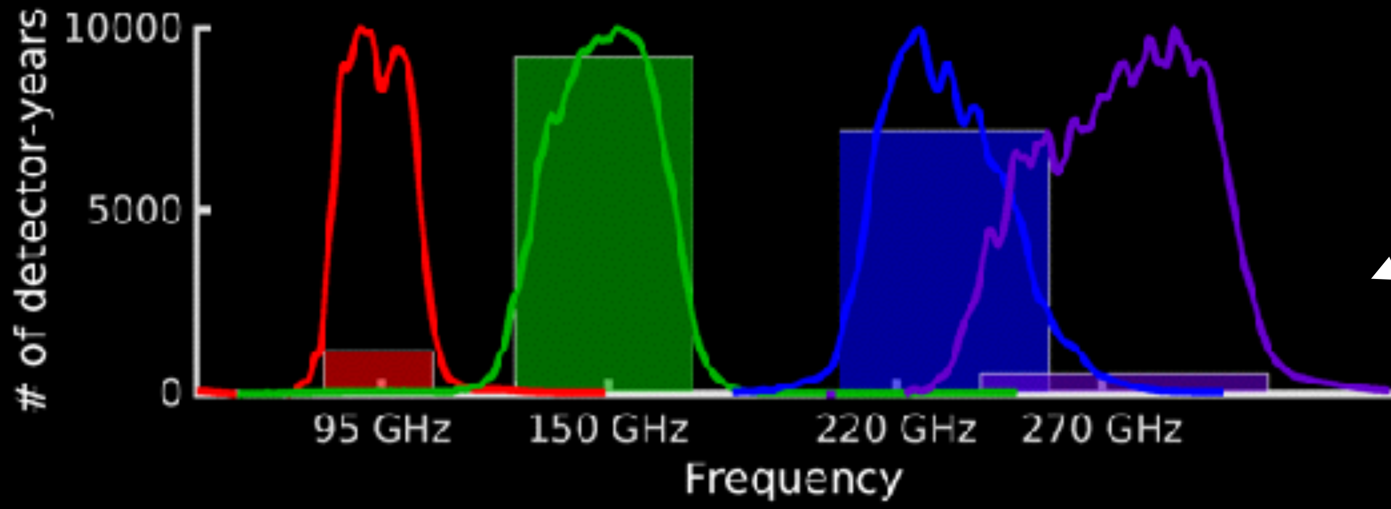


Simple raw observing effort, doesn't take into account how years performed

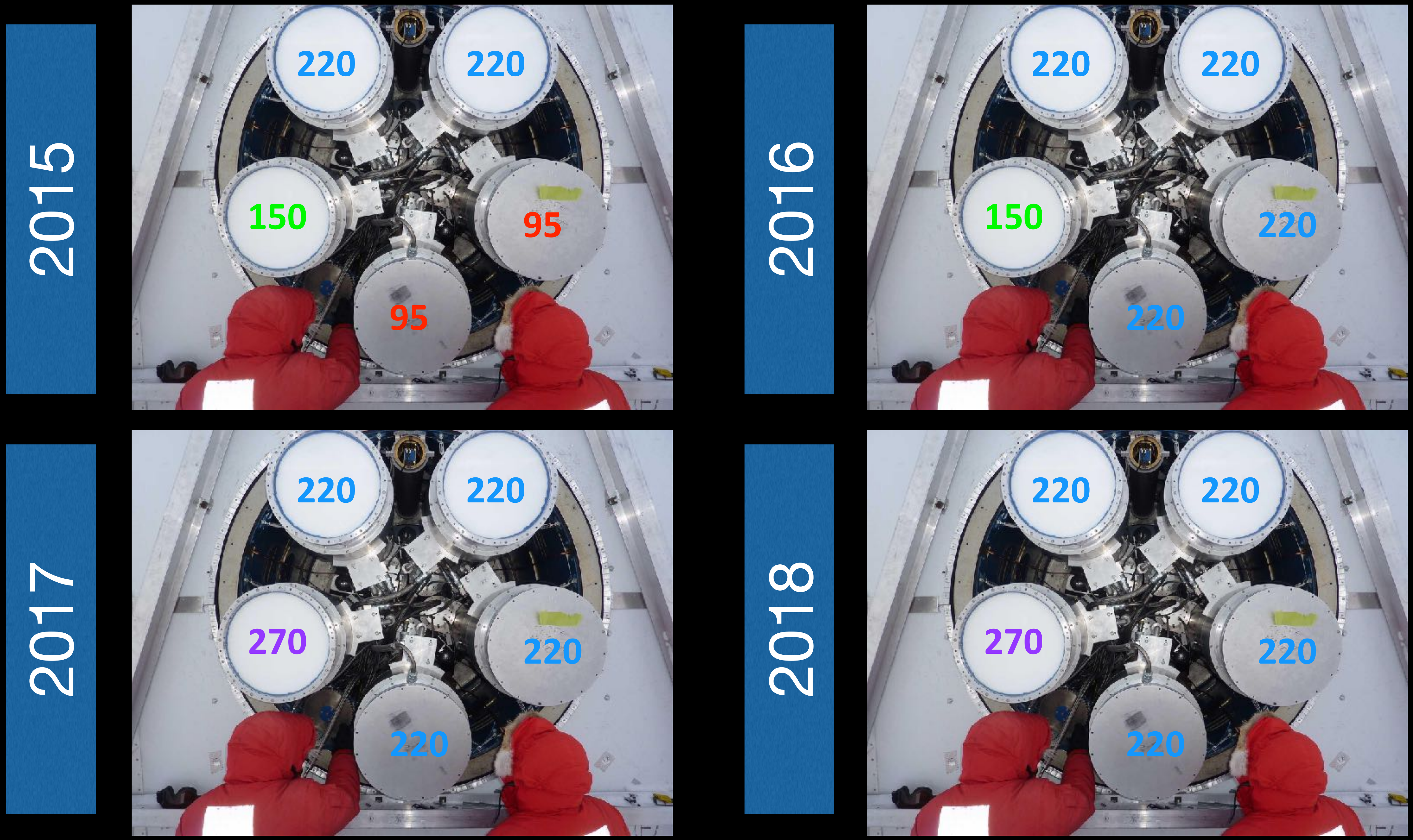
2015



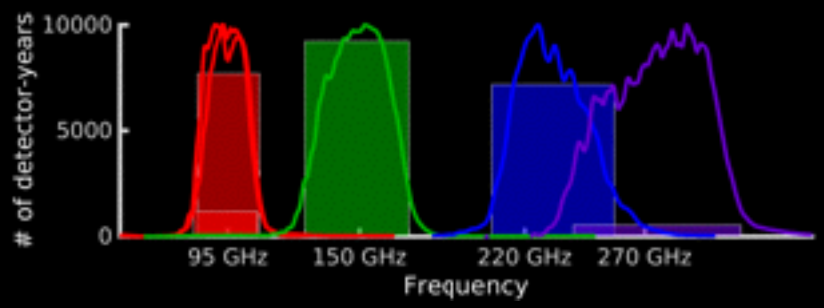
BICEP2
2010-2012
Keck Array
2012-…



Simple raw observing effort, doesn't take into account how years performed



BICEP3: Super Receiver

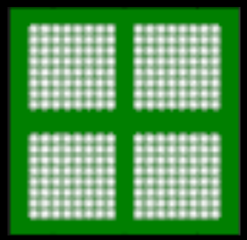


All 95 GHz

2560 detectors in modular focal plane

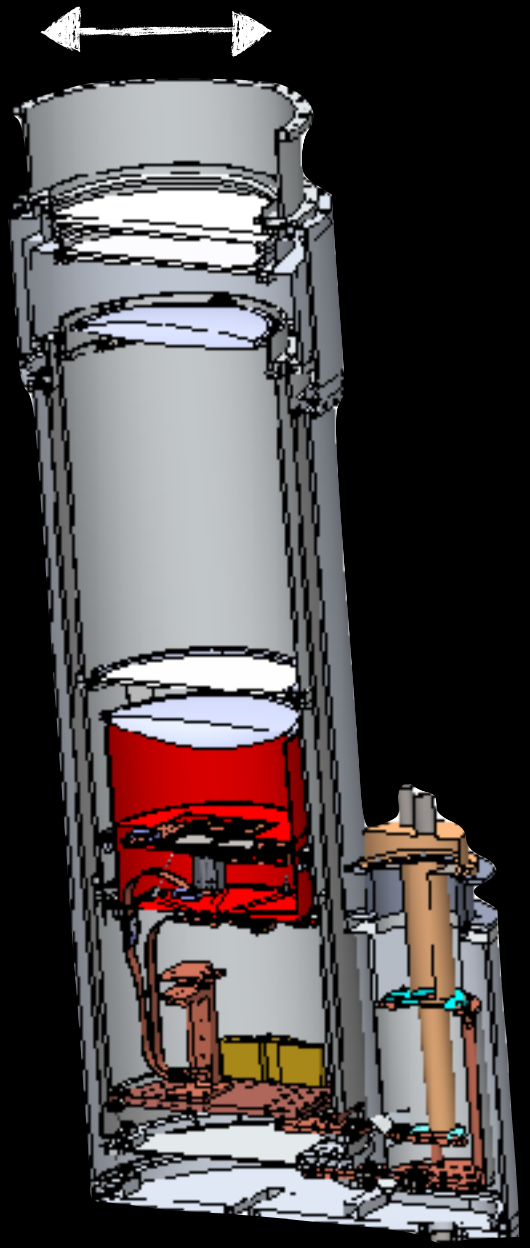
Large-aperture optics and infrared filtering

> 10x optical throughput of single BICEP2/Keck receiver

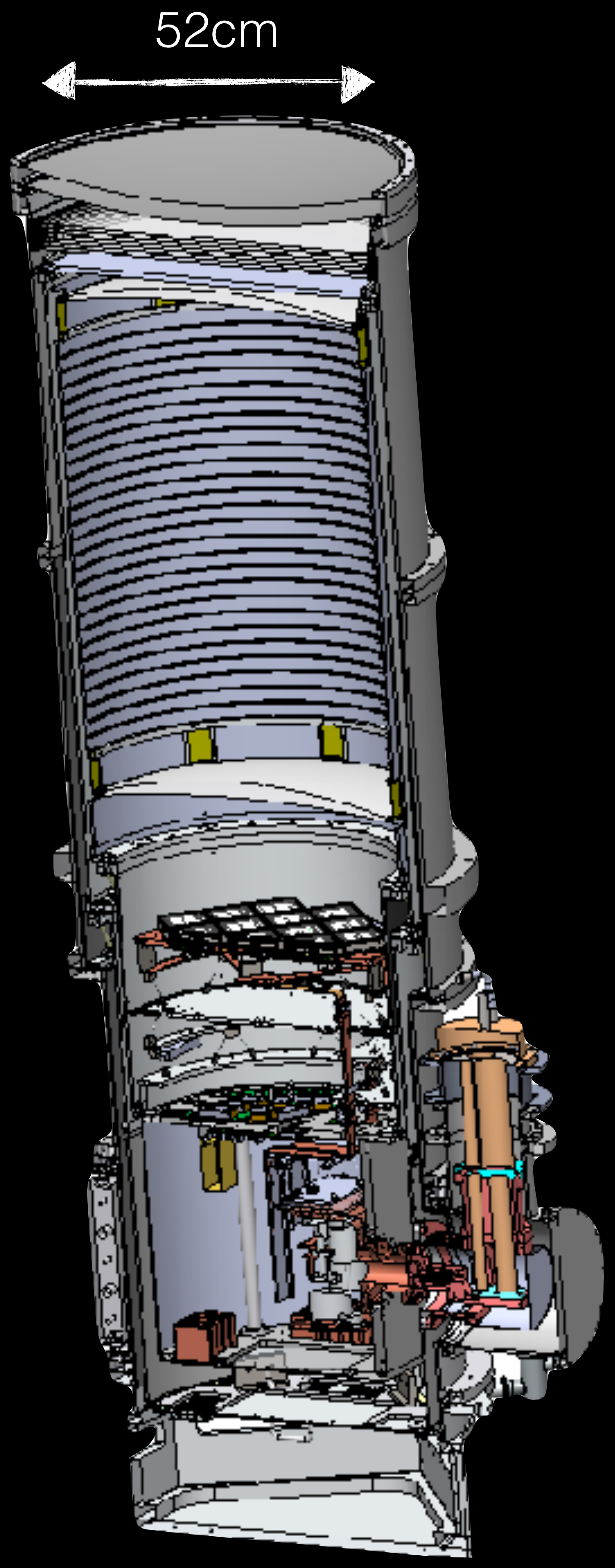


Bicep2

Bicep3

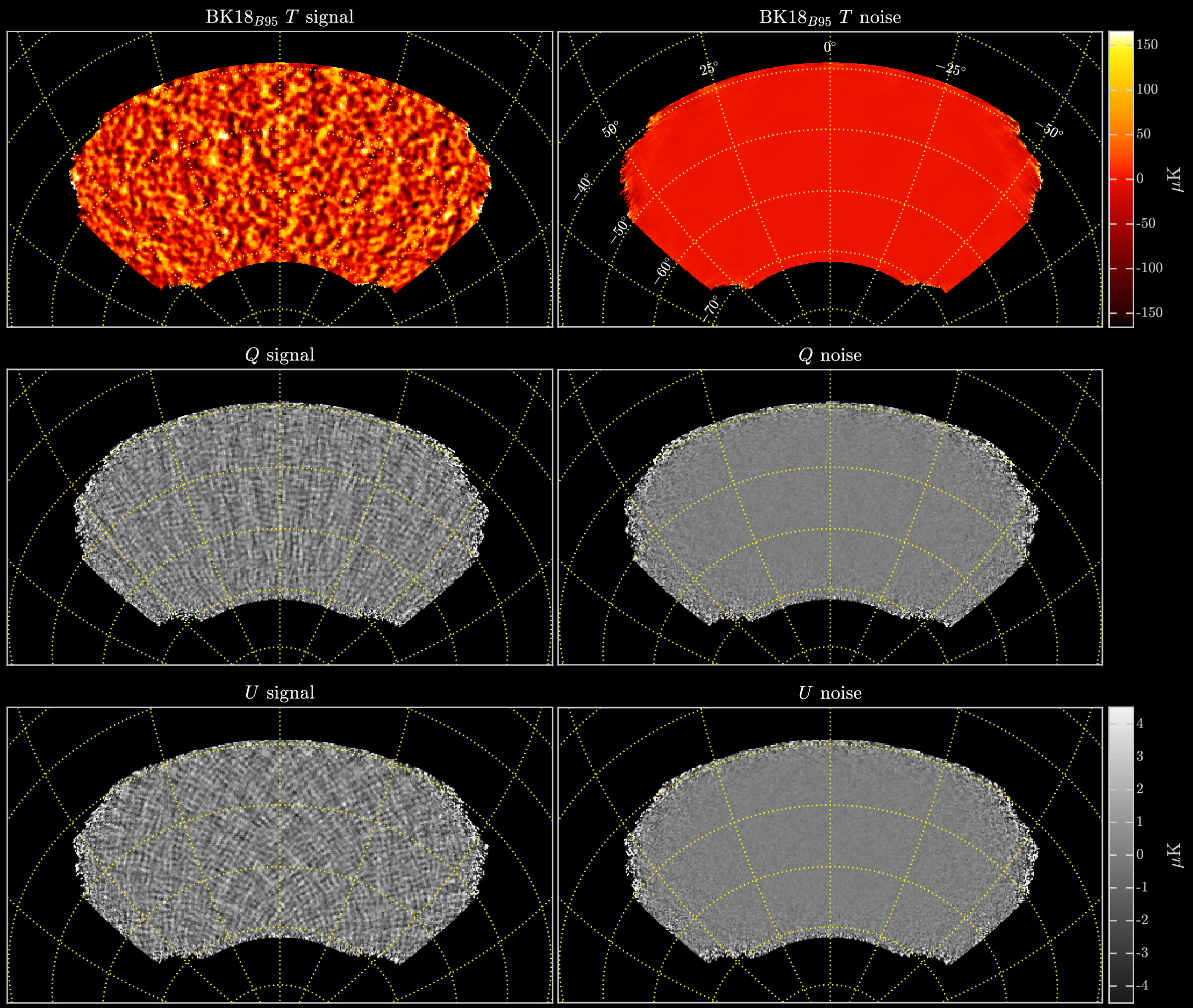


Keck receiver

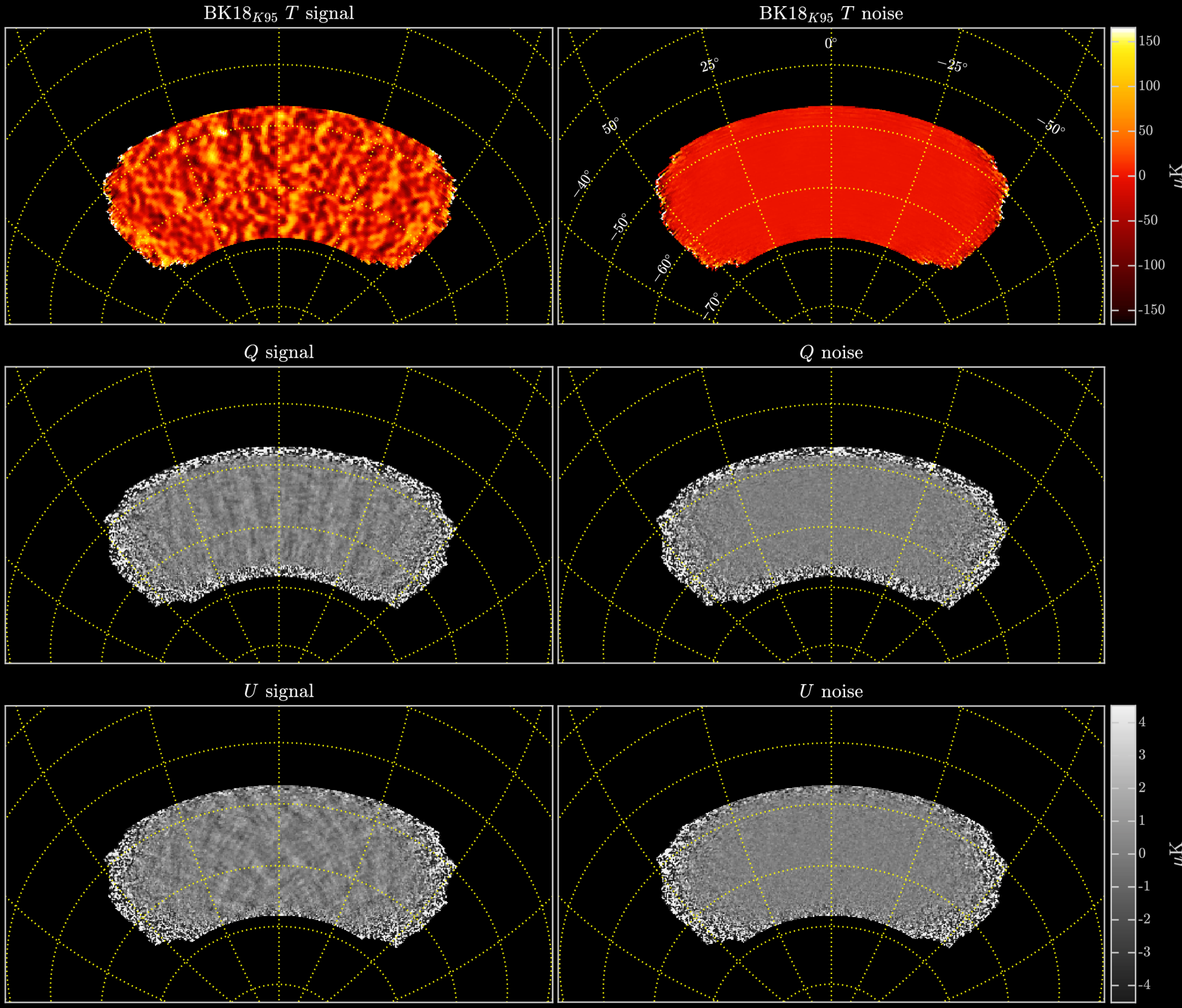


BICEP3

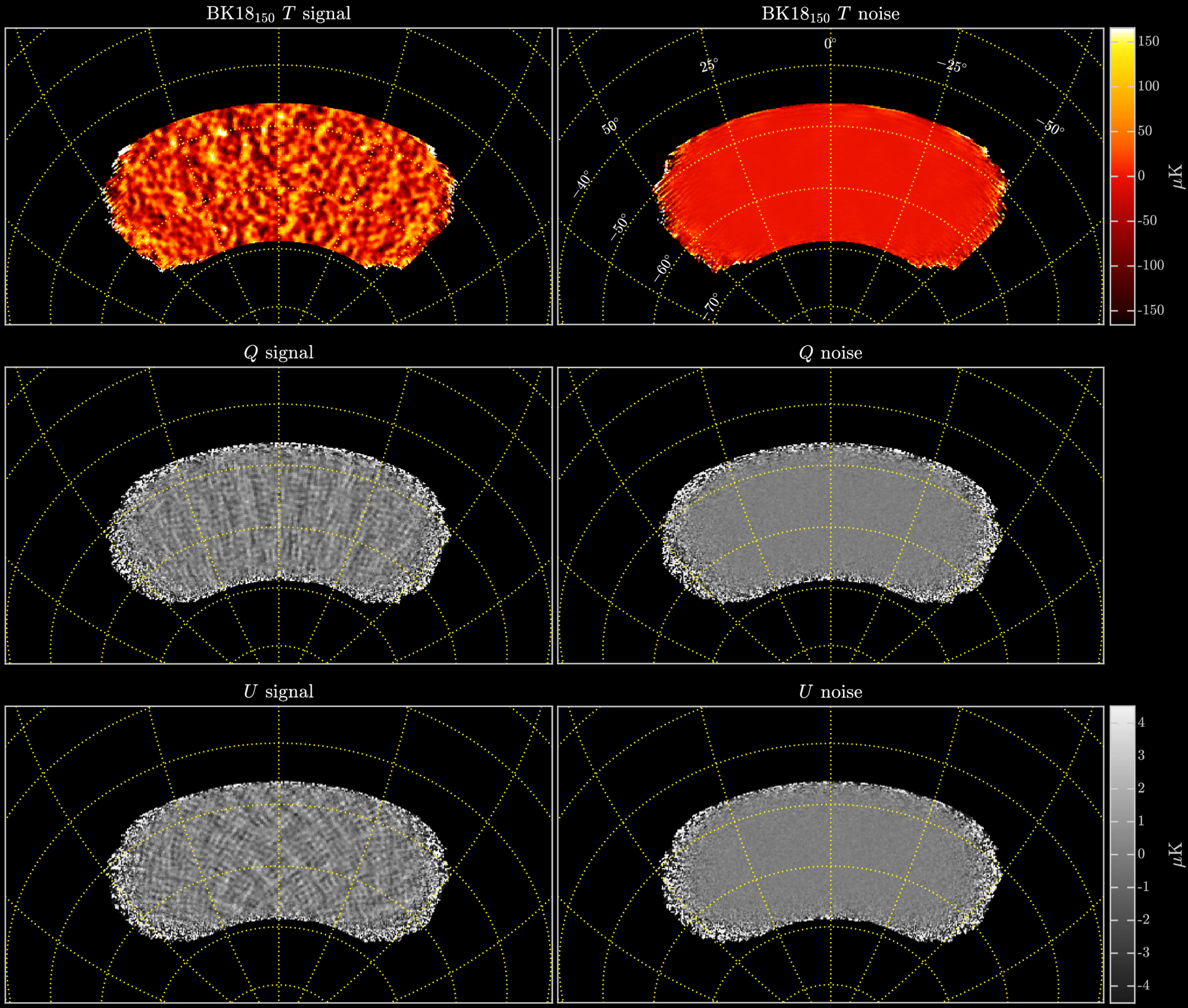
Preliminary BICEP3 95GHz – 2.8 μK arcmin



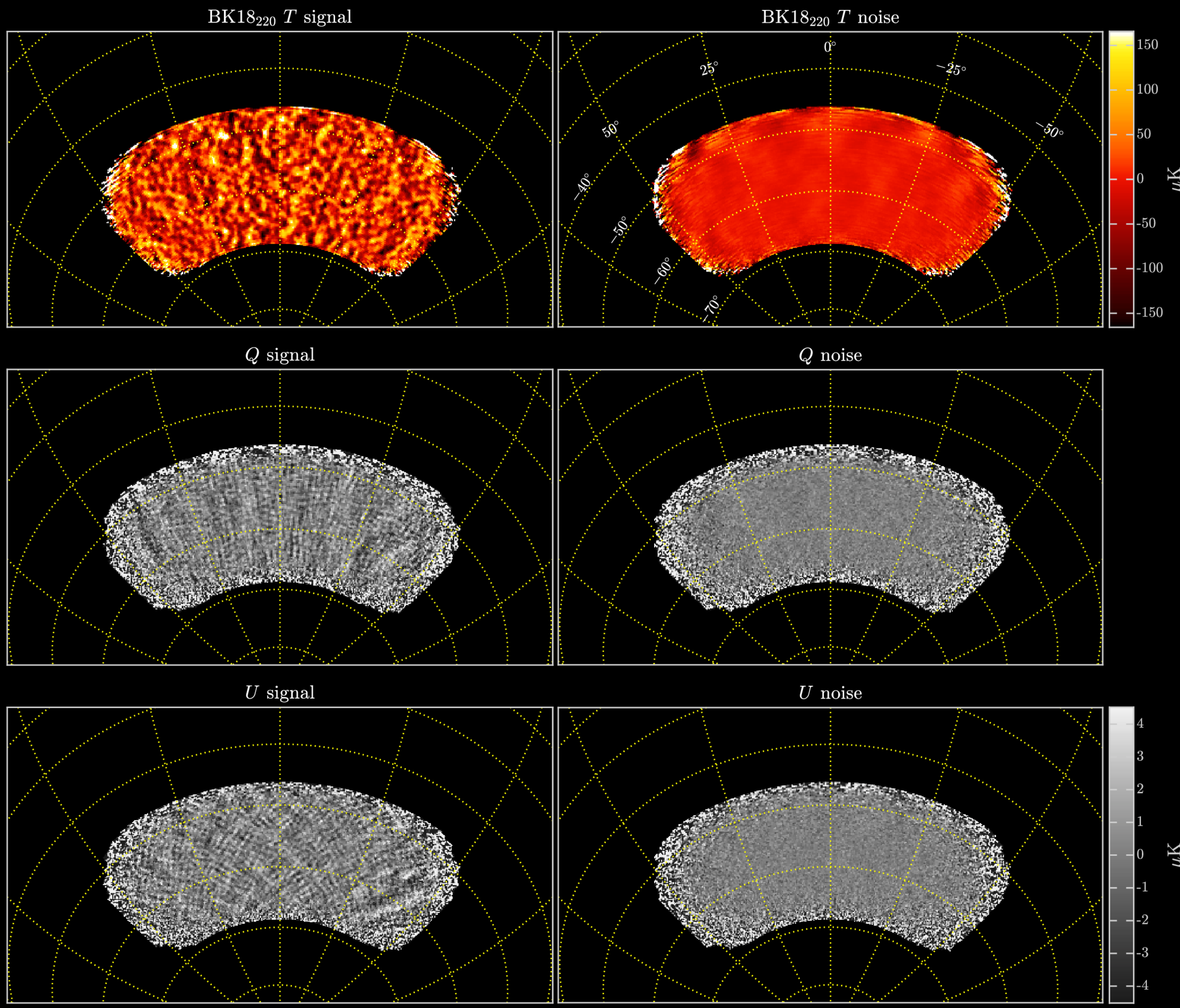
Preliminary BICEP2-Keck 95GHz – 5.2 μK arcmin



Preliminary BICEP2-Keck 150GHz – 2.8 μK arcmin

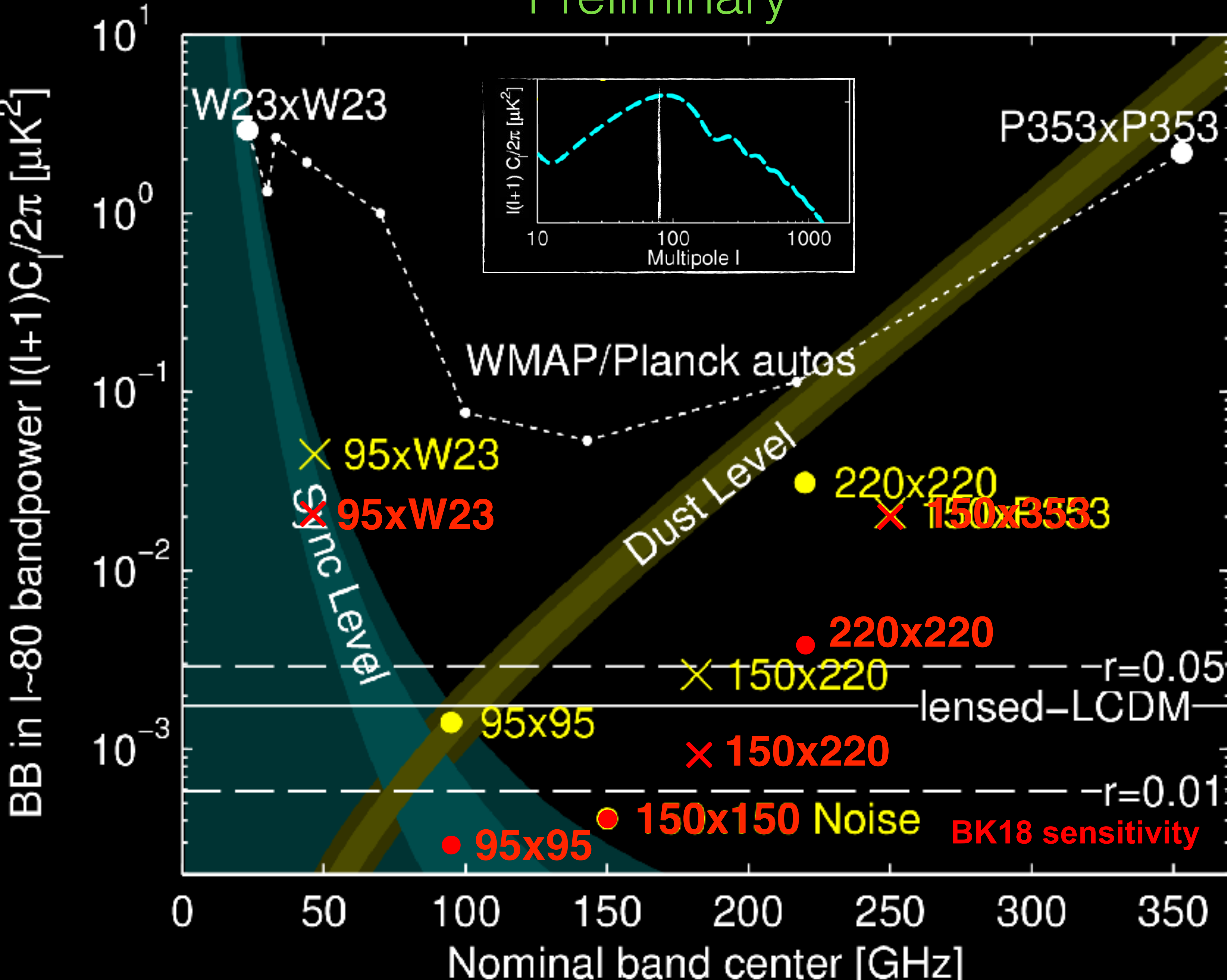


Preliminary BICEP2-Keck 220GHz – 8.5 μK arcmin

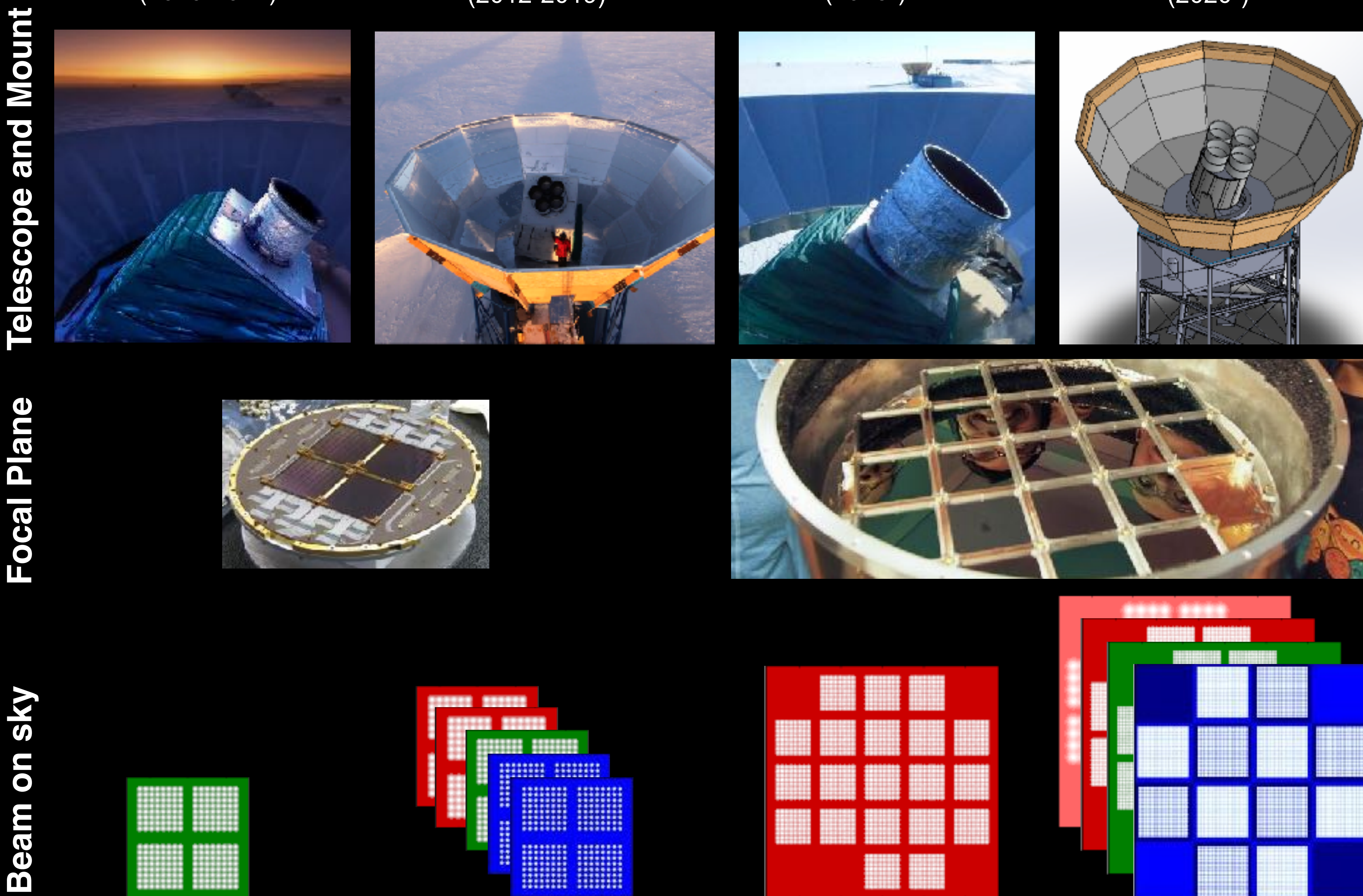


BK18 Band Sensitivity (at ℓ ~ 80)

Preliminary



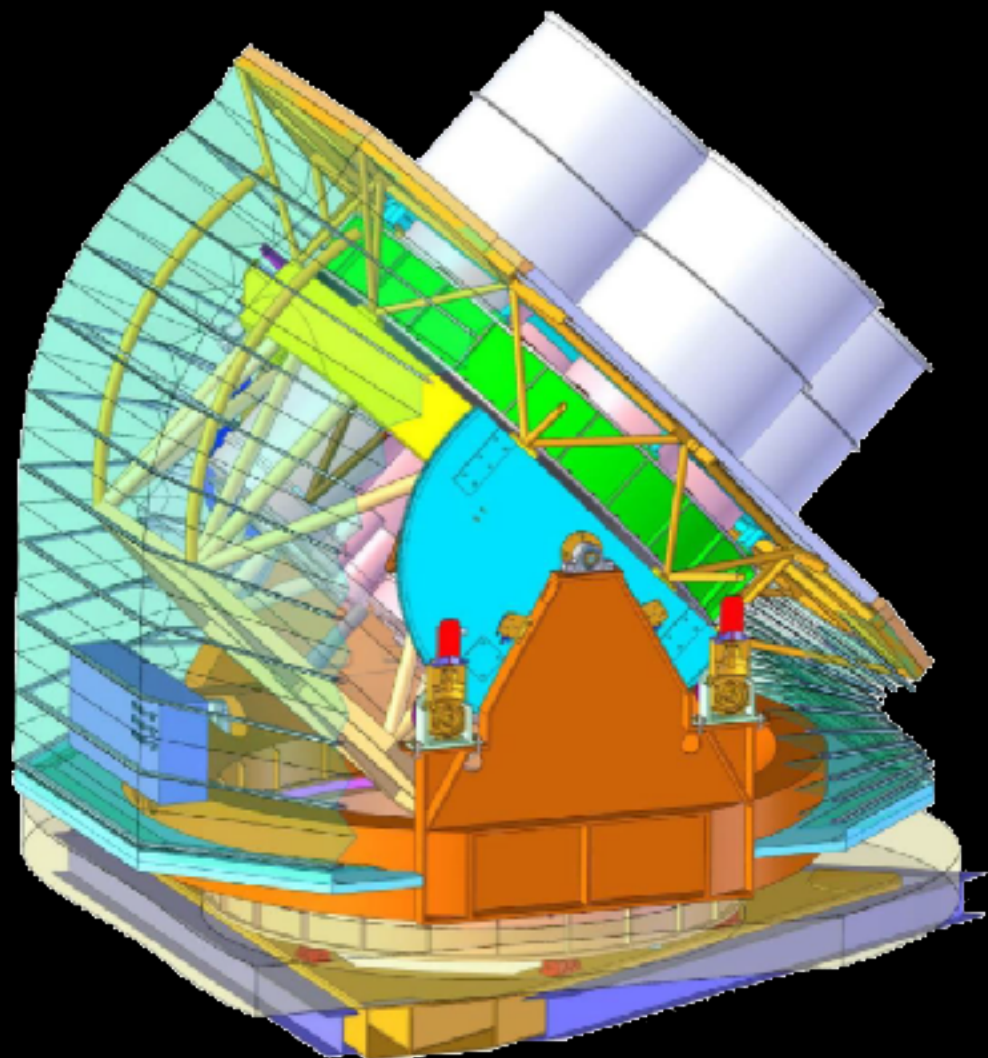
	Stage 2		Stage 3	
	BICEP2 (2010-2012)	**Keck Array** (2012-2019)	**BICEP3** (2015-)	**BICEP Array** (2020-)



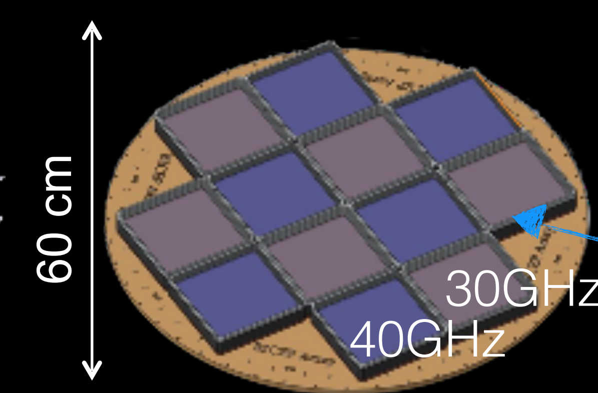
detectors:	500	2500	2500	30000

See B. Schmitt's Poster

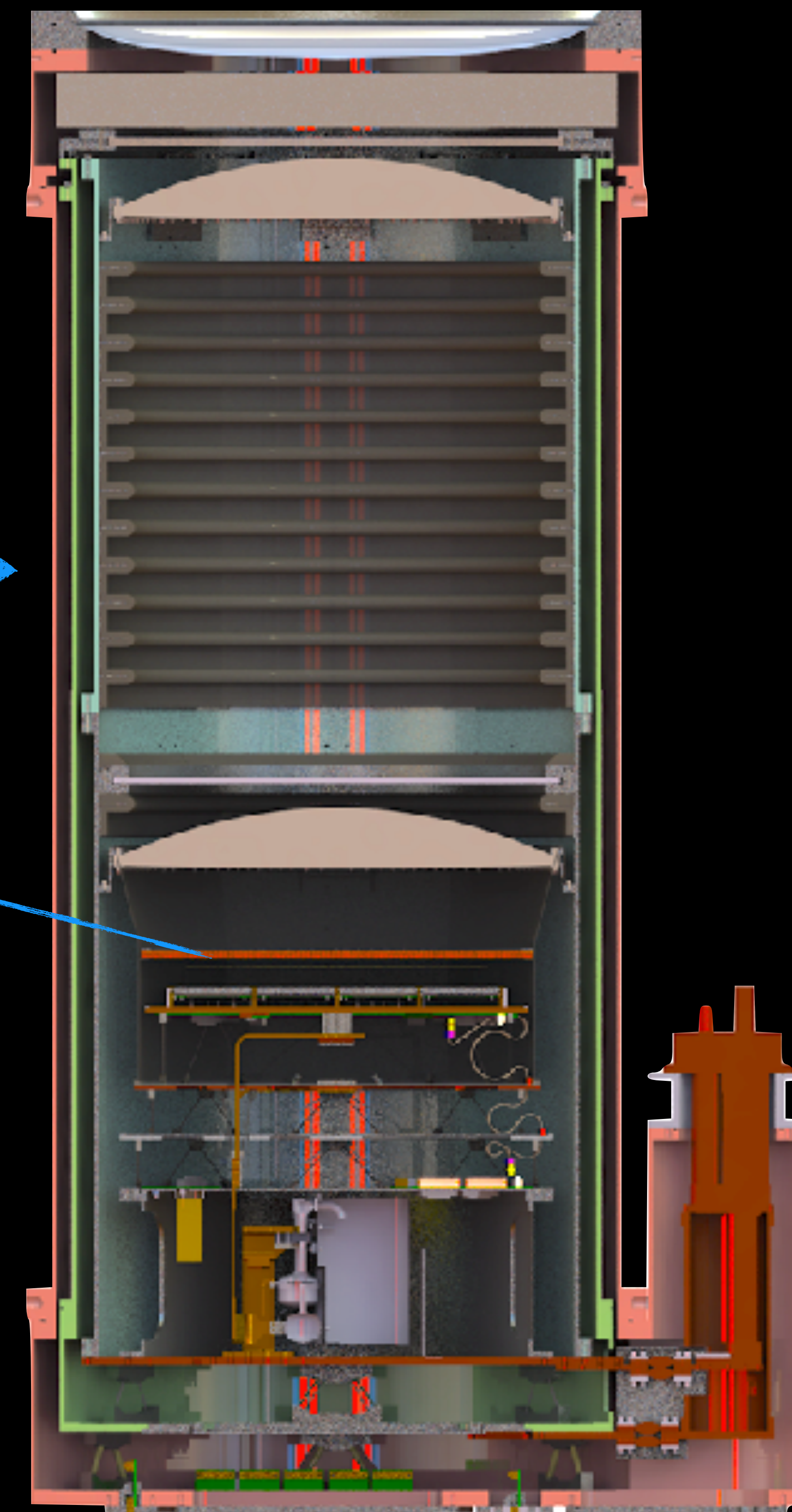
BICEP Array Under Construction



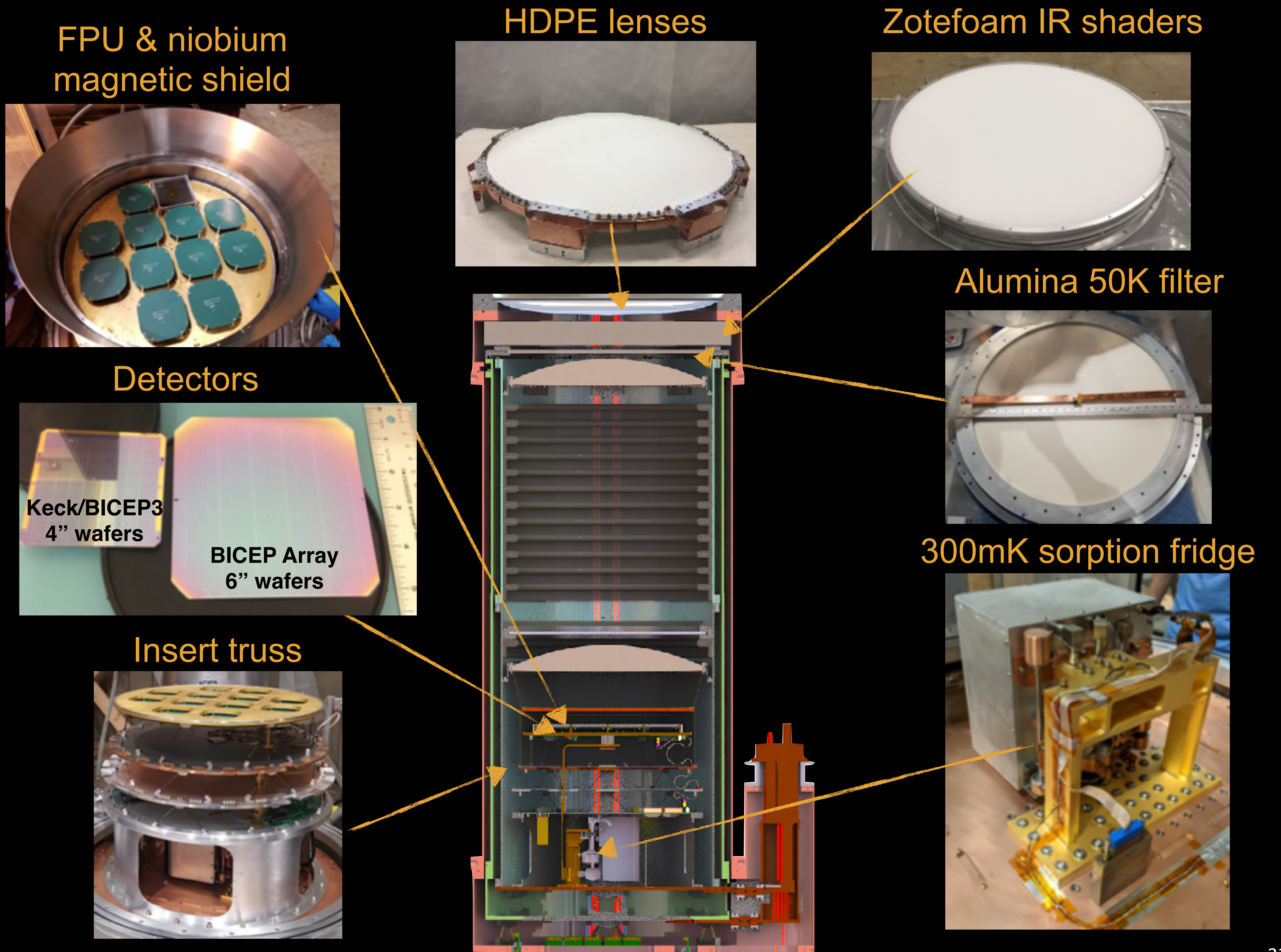
4 wide-field receivers
30/40 GHz
95 GHz
150 GHz
220/270 GHz



Focal plane layout



Frequency	30/40 GHz	95 GHz	150 GHz	220/270 GHz
Tiles	12	12	12	12
# Detectors	192/300	3456	7776	13824/16224
# Det/ Tile	32/50	288	648	1152/1352
Beam FWHM (arcmin)	76/57	24	15	10/8.5
NET per det (uK-rts)	268/334	267	315	900/1800
Instr. NET (uK-rts)	21/21	4.93	3.87	8.3/15
3-yr map depth (uK-arcmin)	7.5/7.5	1.9	1.4	3.0/5.5


FPU & niobium magnetic shield
HDPE lenses
Zotefoam IR shaders
Alumina 50K filter
Detectors
Keck/BICEP3 4” wafers
BICEP Array 6” wafers
300mK sorption fridge
Insert truss

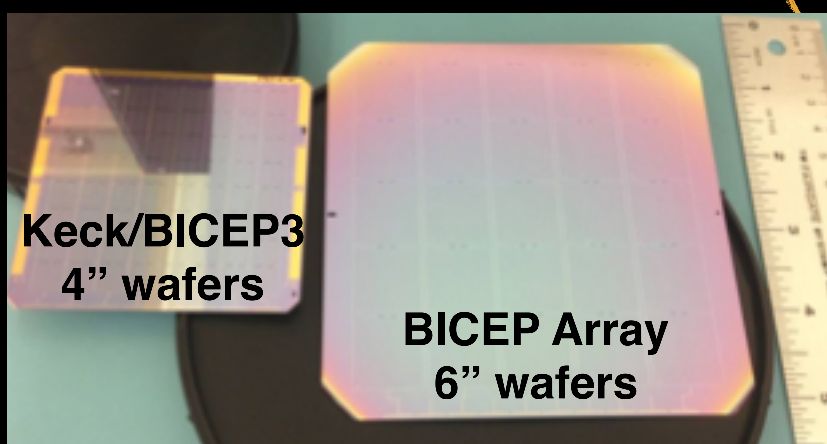

HDPE lenses
Zotefoam IR shaders

FPU & niobium magnetic shield

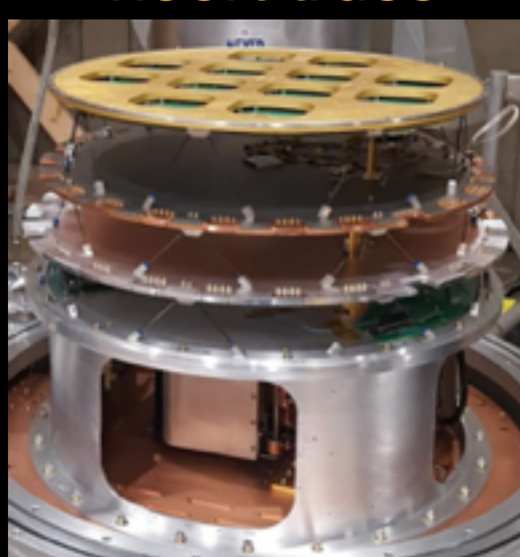
HDPE lenses

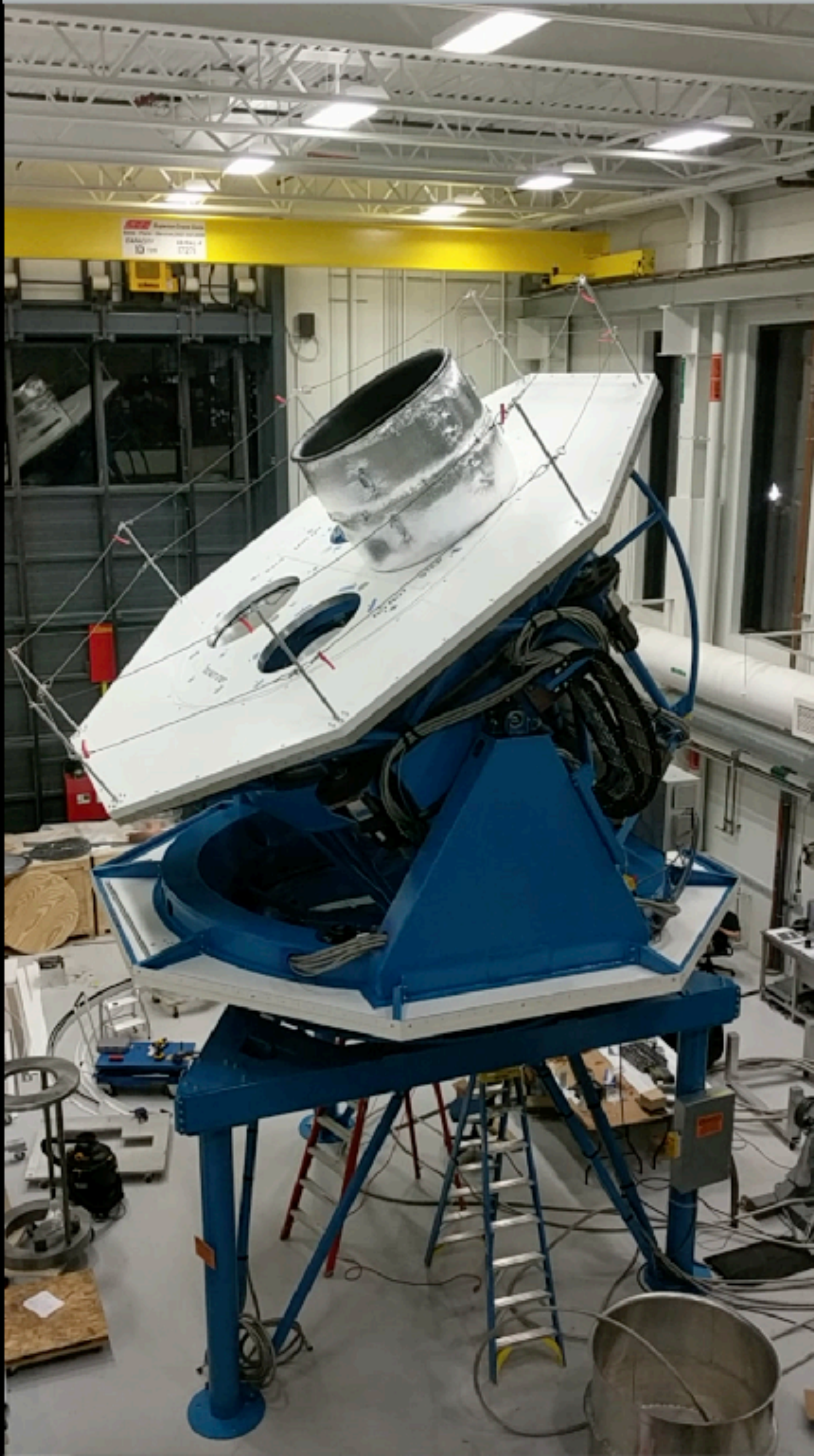
Zotefoam IR shaders

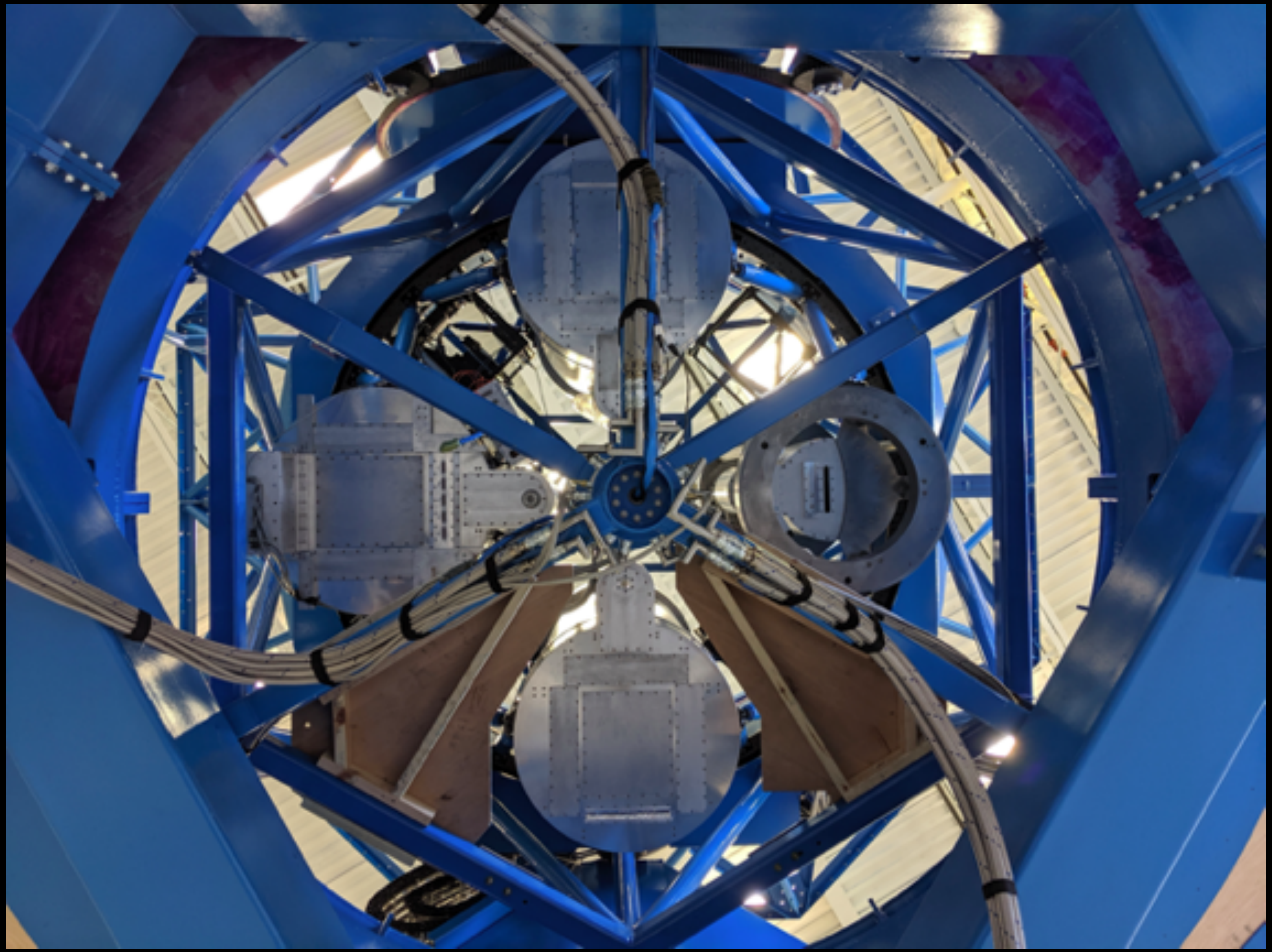
Detectors



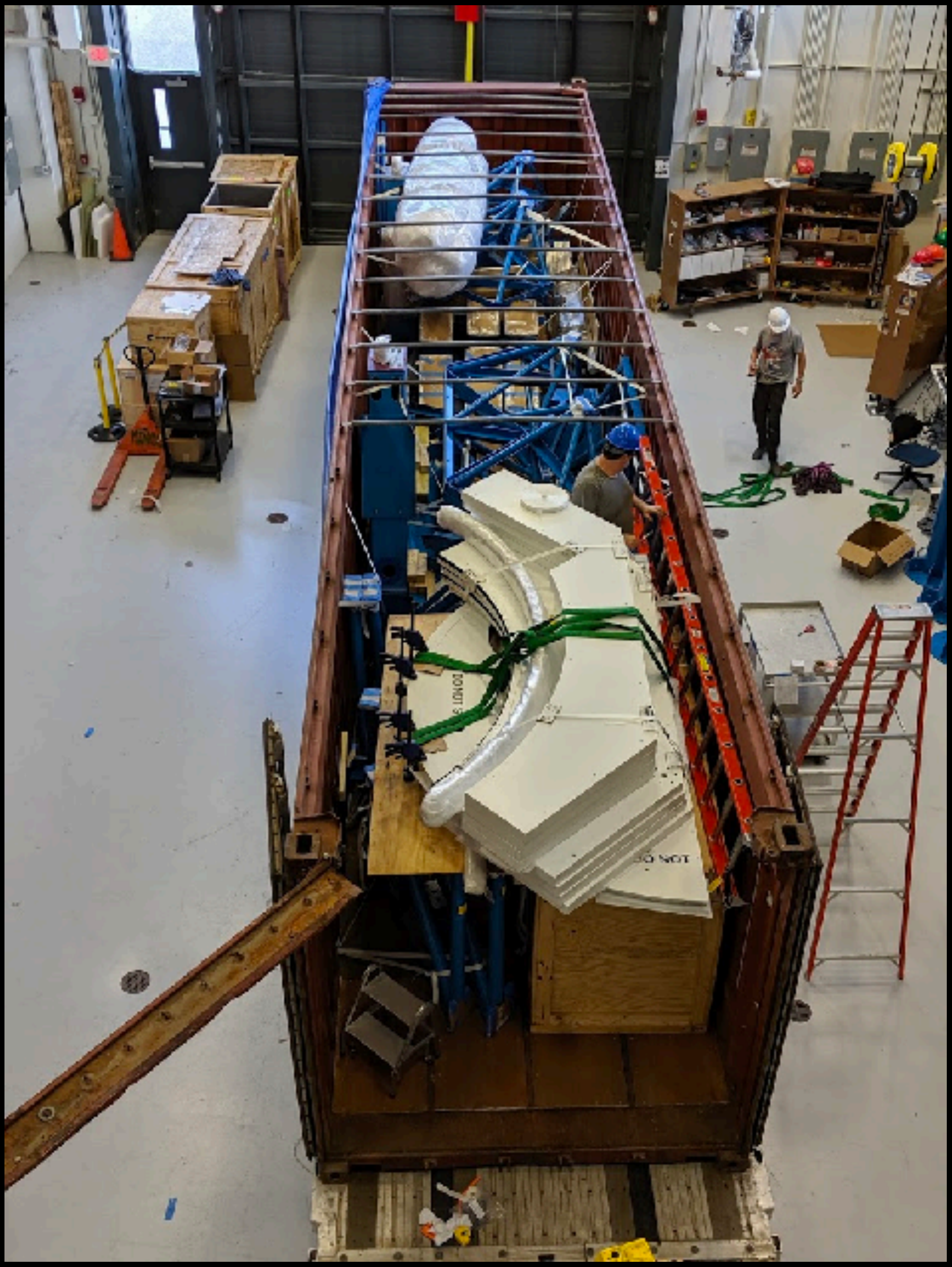
Insert truss





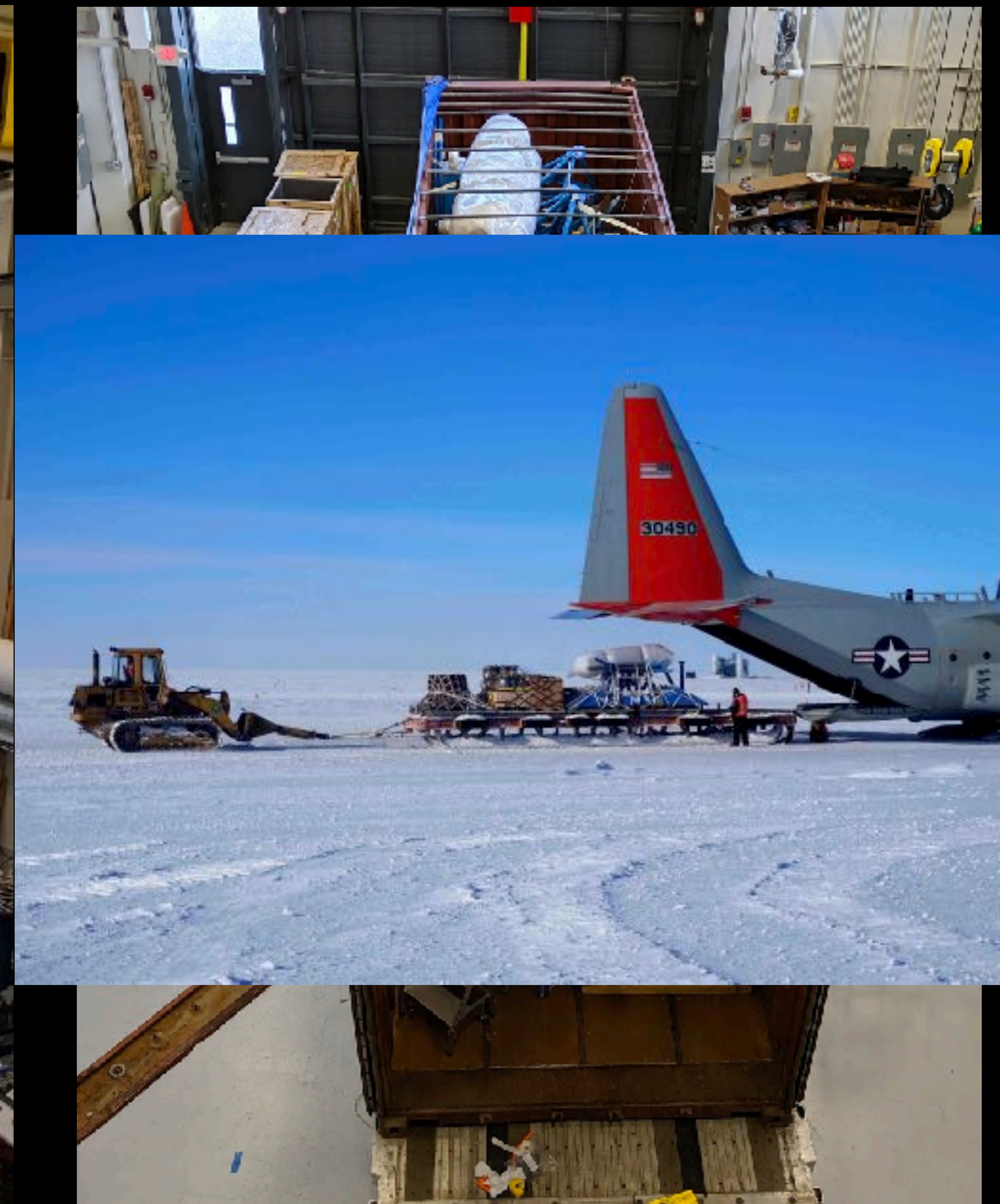


Assembled in Minnesota

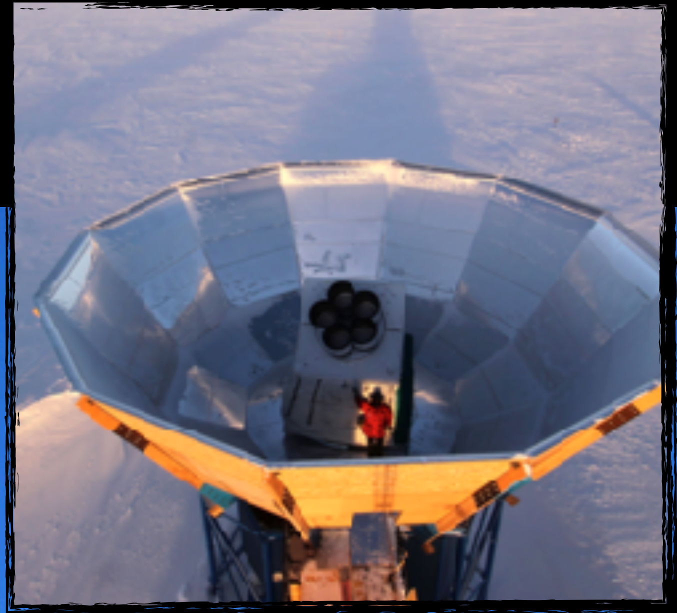


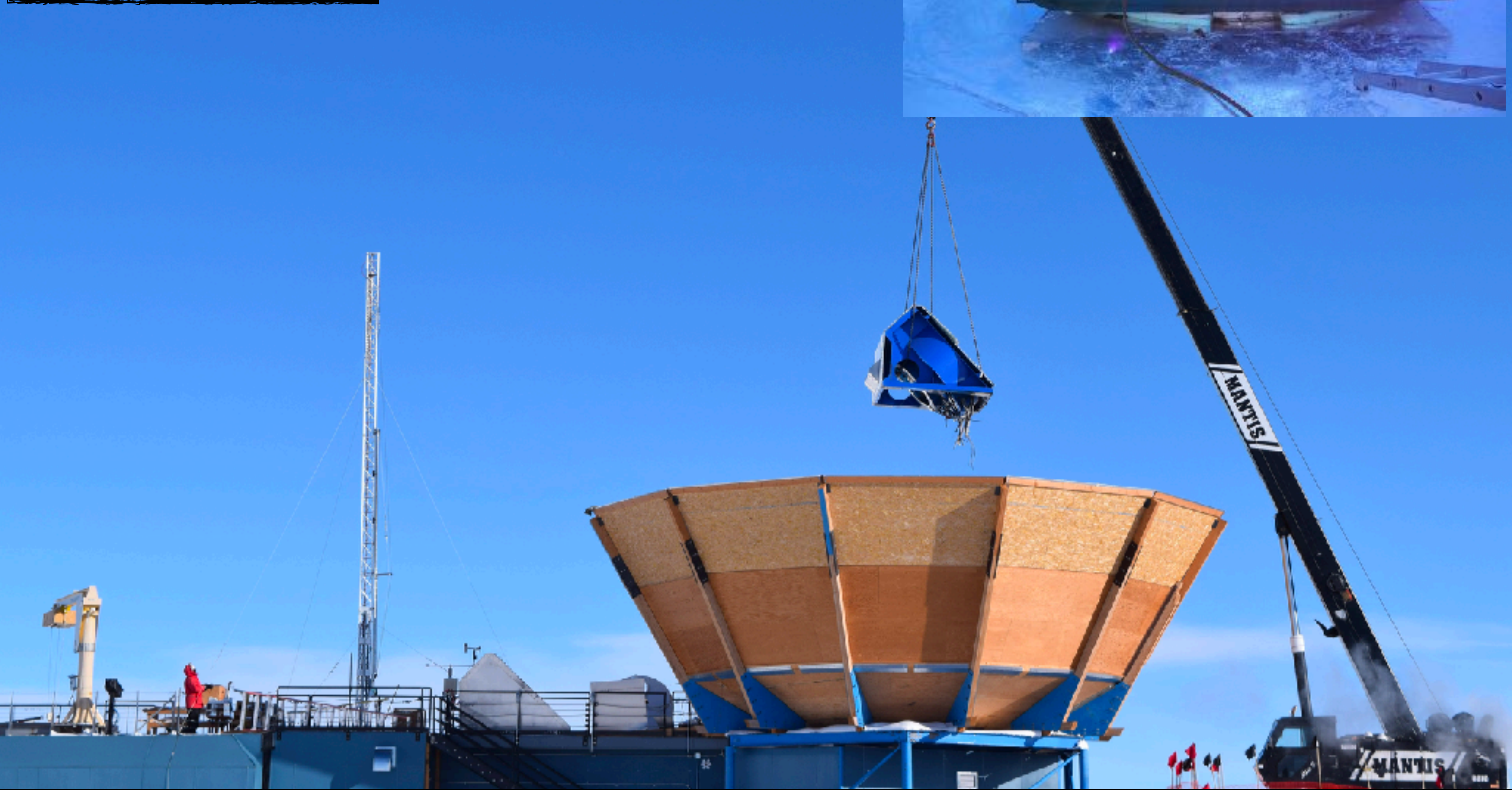
Disassembled and now at Pole

Assembled in Minnesota

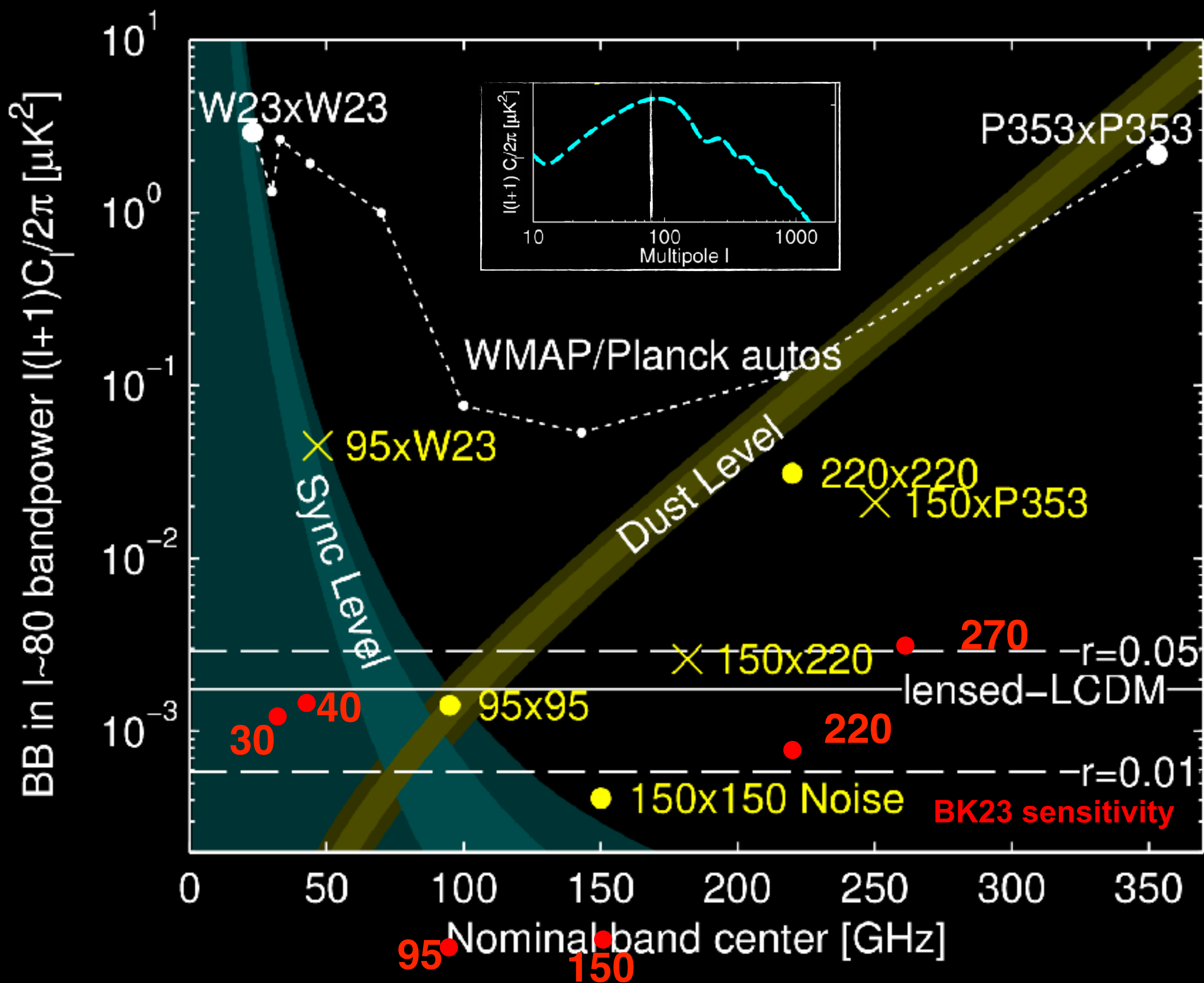


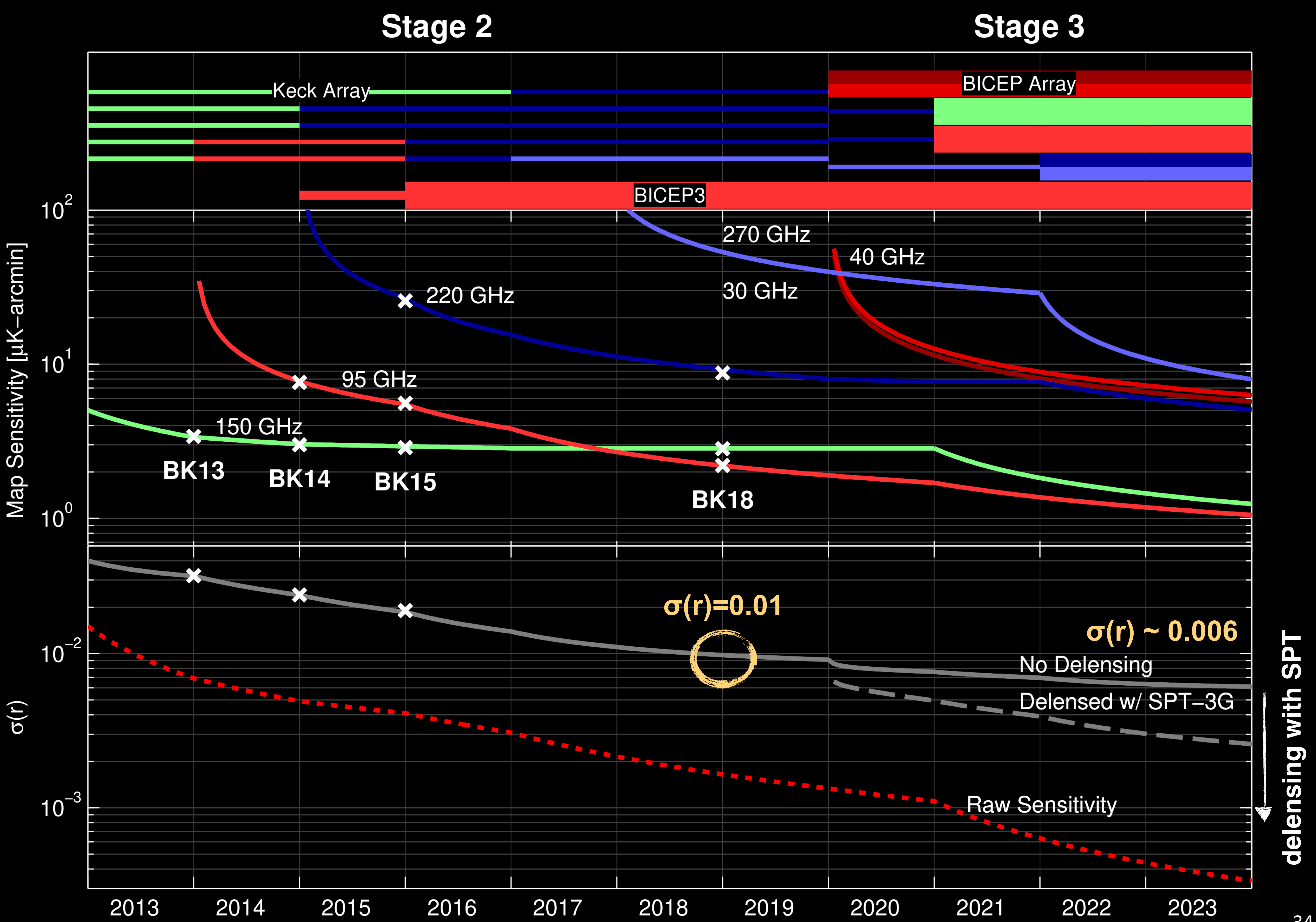
Disassembled and now at Pole




MANTIS

BK23 Band Sensitivity (at ℓ ~ 80)



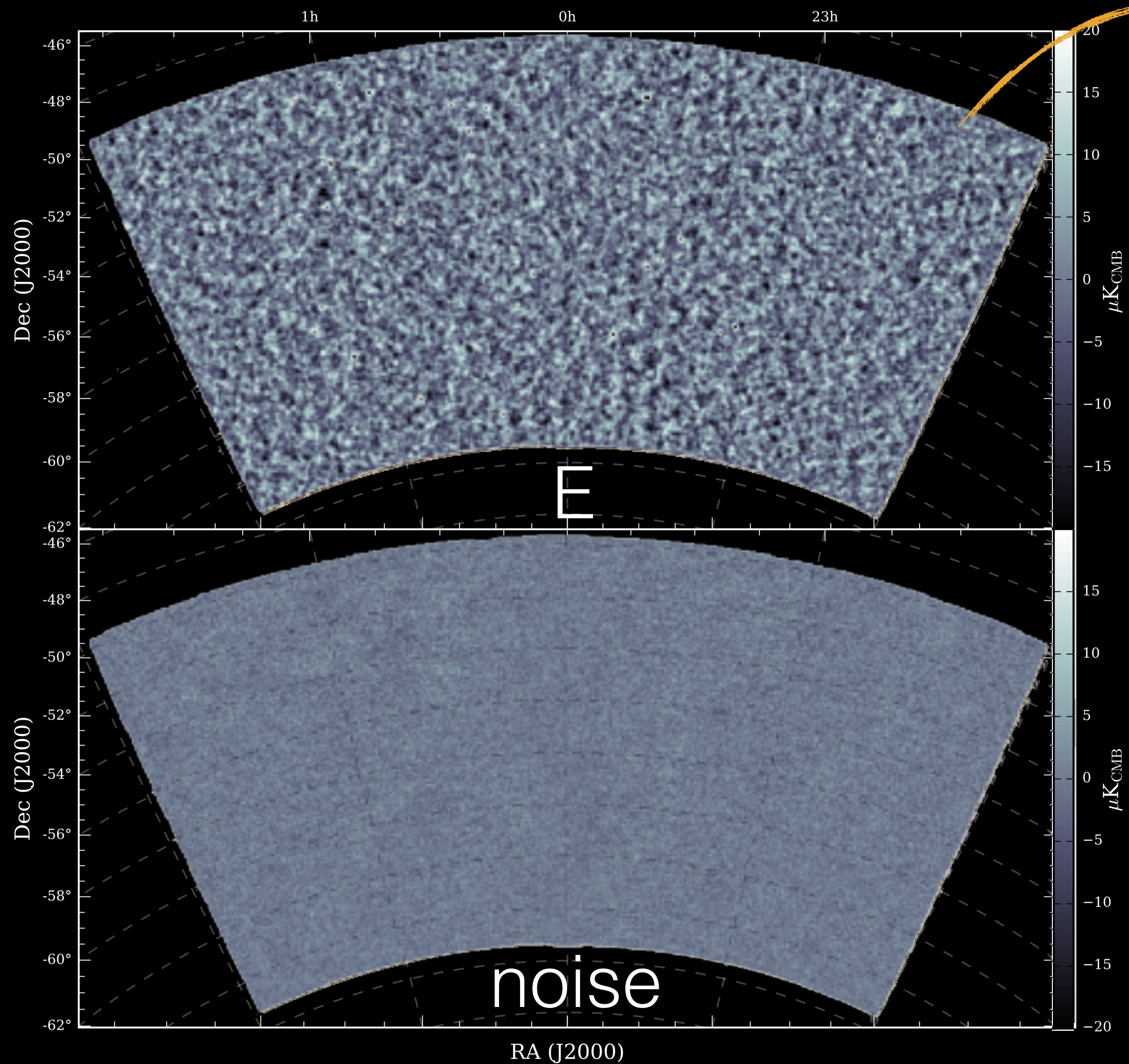


Stage 2
Stage 3
Keck Array
BICEP Array
BICEP3
Map Sensitivity [μK−arcmin]
10^2
10^1
10^0
270 GHz
40 GHz
30 GHz
220 GHz
95 GHz
150 GHz
BK13
BK14
BK15
BK18
σ(r)
10^{-2}
10^{-3}
σ(r)=0.01
σ(r) ~ 0.006
No Delensing
Delensed w/ SPT−3G
Raw Sensitivity
delensing with SPT
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023

BK + SPT3G delensing

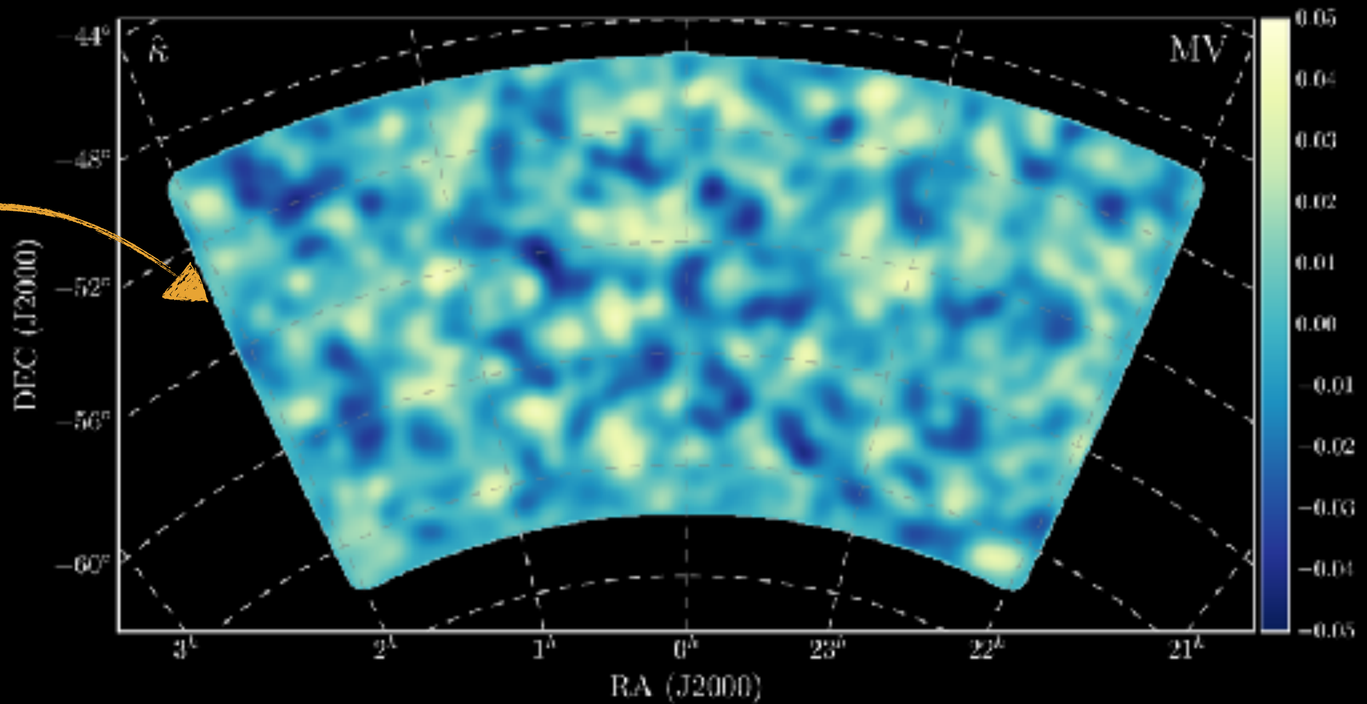
Kimmy Wu's talk

Deep high resolution E maps



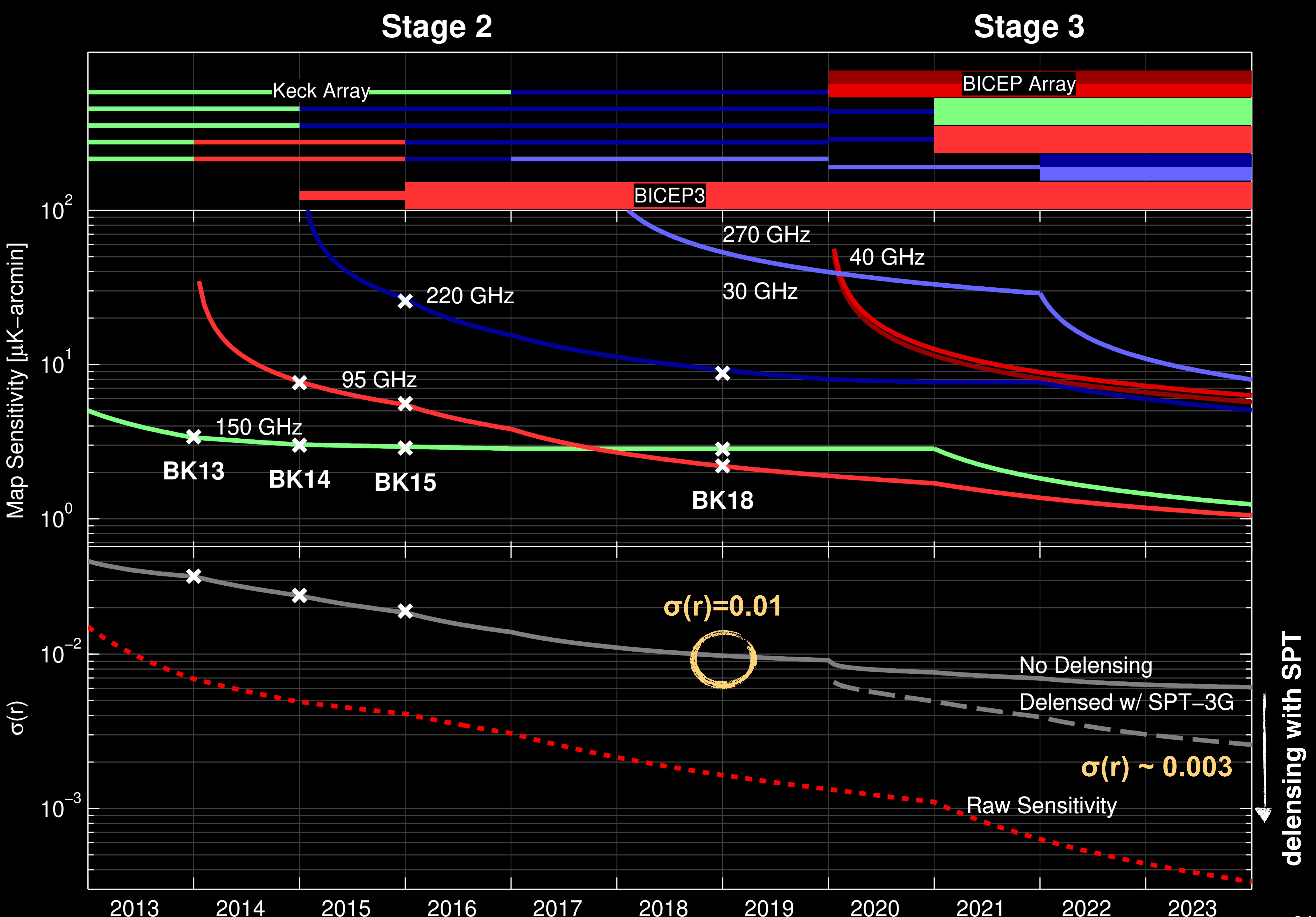
Henning et al. (SPTpol) 1707.09353

Reconstruct the lensing deflection map



Wu et al. (SPTpol) 1905.05777

Use it to estimate the lensing B modes in BK maps, enabling deeper search for primordial gravitational waves


Stage 2
Stage 3
Keck Array
BICEP Array
BICEP3
Map Sensitivity [μK−arcmin]
270 GHz
40 GHz
30 GHz
220 GHz
95 GHz
150 GHz
BK13
BK14
BK15
BK18
σ(r)
σ(r)=0.01
No Delensing
Delensed w/ SPT−3G
σ(r) ~ 0.003
Raw Sensitivity
delensing with SPT
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023

SPO :

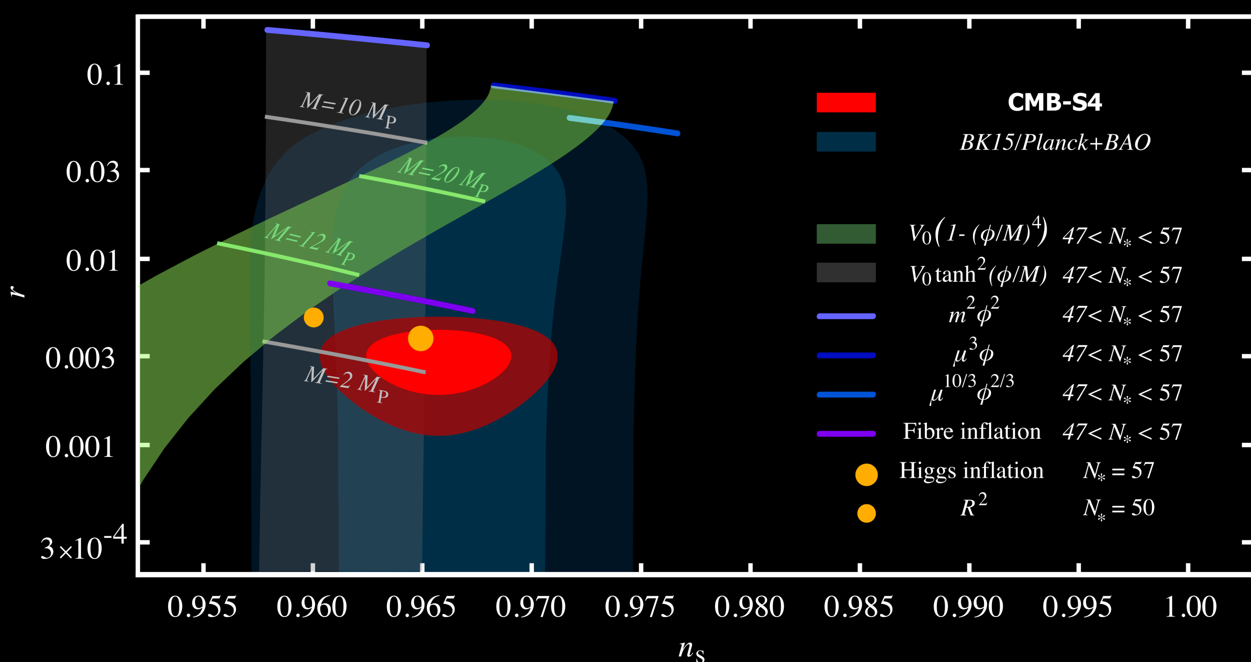
- Coordination of South Pole CMB programs (Stage 3)
- Build on BICEP/Keck and SPT collaborations
- Path to S4: sharing data and lessons, develop infrastructure and methods
- …

CMB-S4

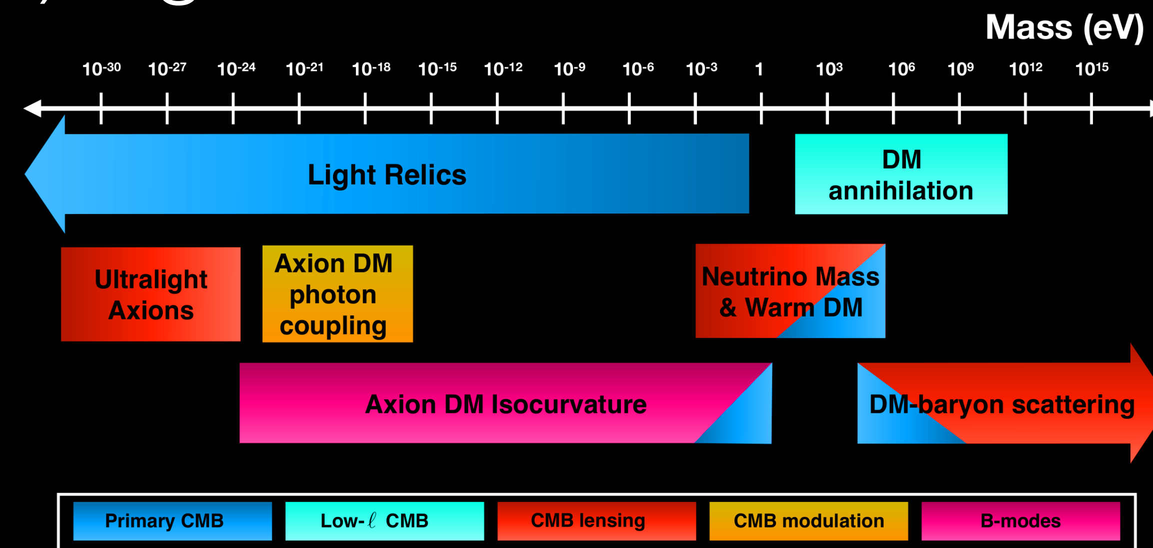
2027-…

See
CMB-S4 Decadal Survey
APC White Paper
1908.01062

1) Gravitational waves

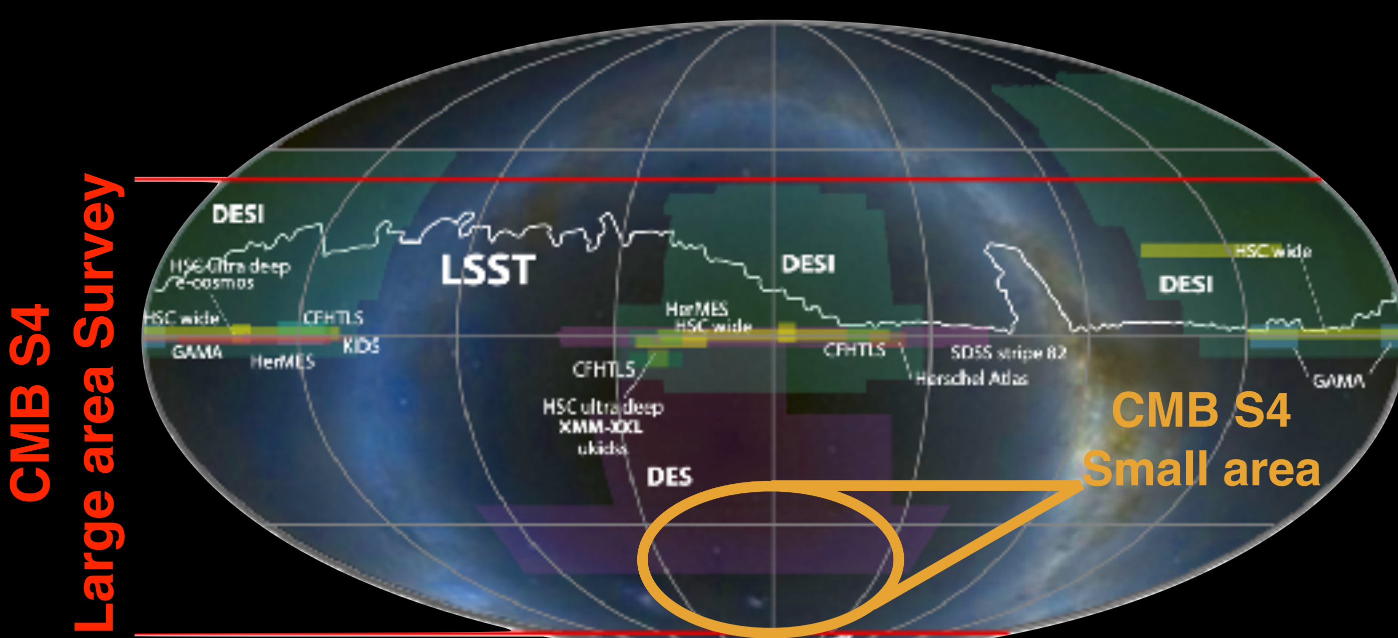


2) Light Relics, DM, neutrinos

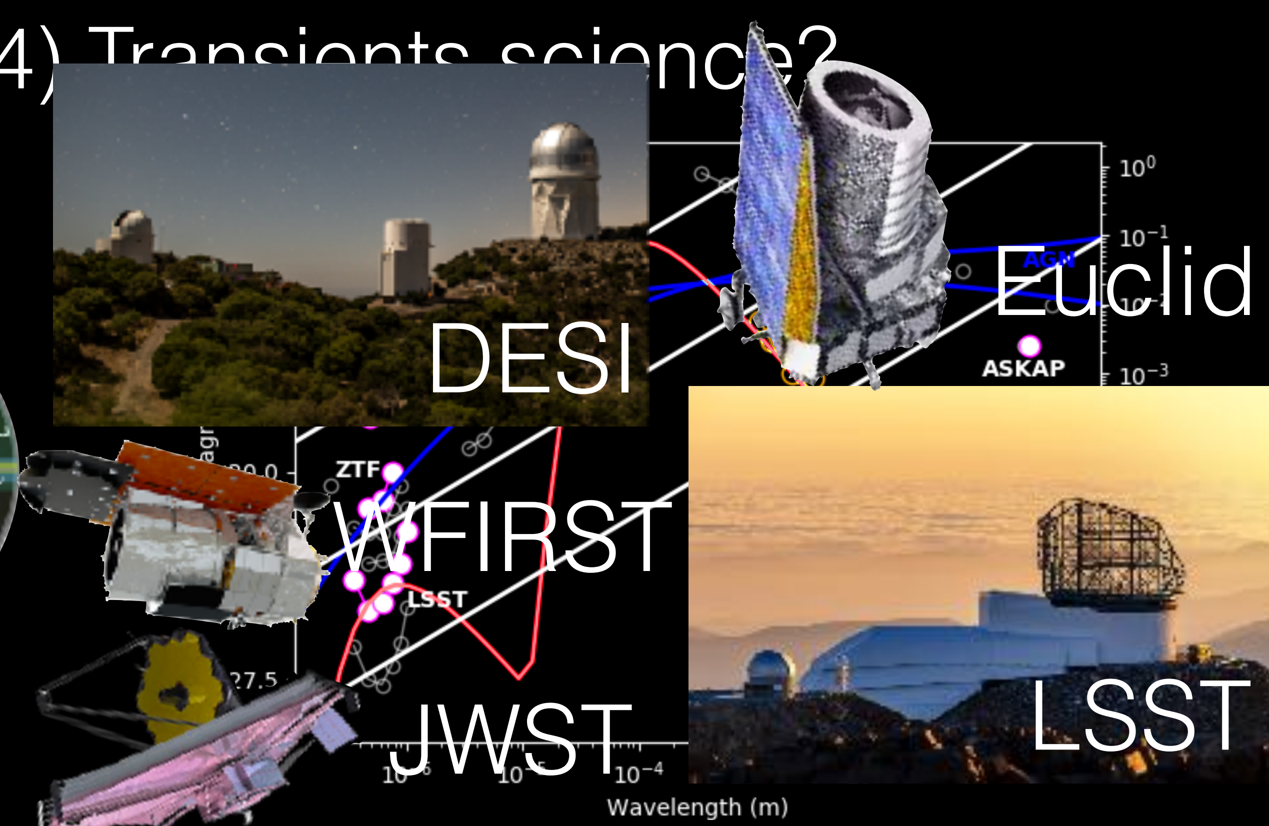


light relics, axions, neutrino mass, and dark matter properties

3) Microwave Survey 30-270 Ghz



4) Transients science?



See
CMB-S4 Decadal Survey
APC White Paper
1908.01062

Last meeting 2 months ago in UCSD

Conclusions

- BICEP/Keck lead the field in the quest to detect or set limits on inflationary gravitational waves:
- Best published sensitivity to date
- Best proven systematic control at degree angular scales

- Adding 2015 data including, for the first time 220GHz data:
- incremental improvement: $r_{0.05}<0.09$ goes to $r_{0.05}<0.07$

- Planck 18 + BK14 $r_{0.002}<0.064$ 1807.06211
- Planck 15 + BK15 $r_{0.05}<0.06$ 1810.05216

  [$r_{0.002}<0.055$]

- We can explore more data/model variations

- And we can go much further:
- BICEP3 data in the can at 95GHz are now as deep as 150GHz
- Delensing using SPT/SPT3G
- …and we have BIG plans for the future: BICEP Array – σ(r)=0.003

  S4 – σ(r)=0.0005