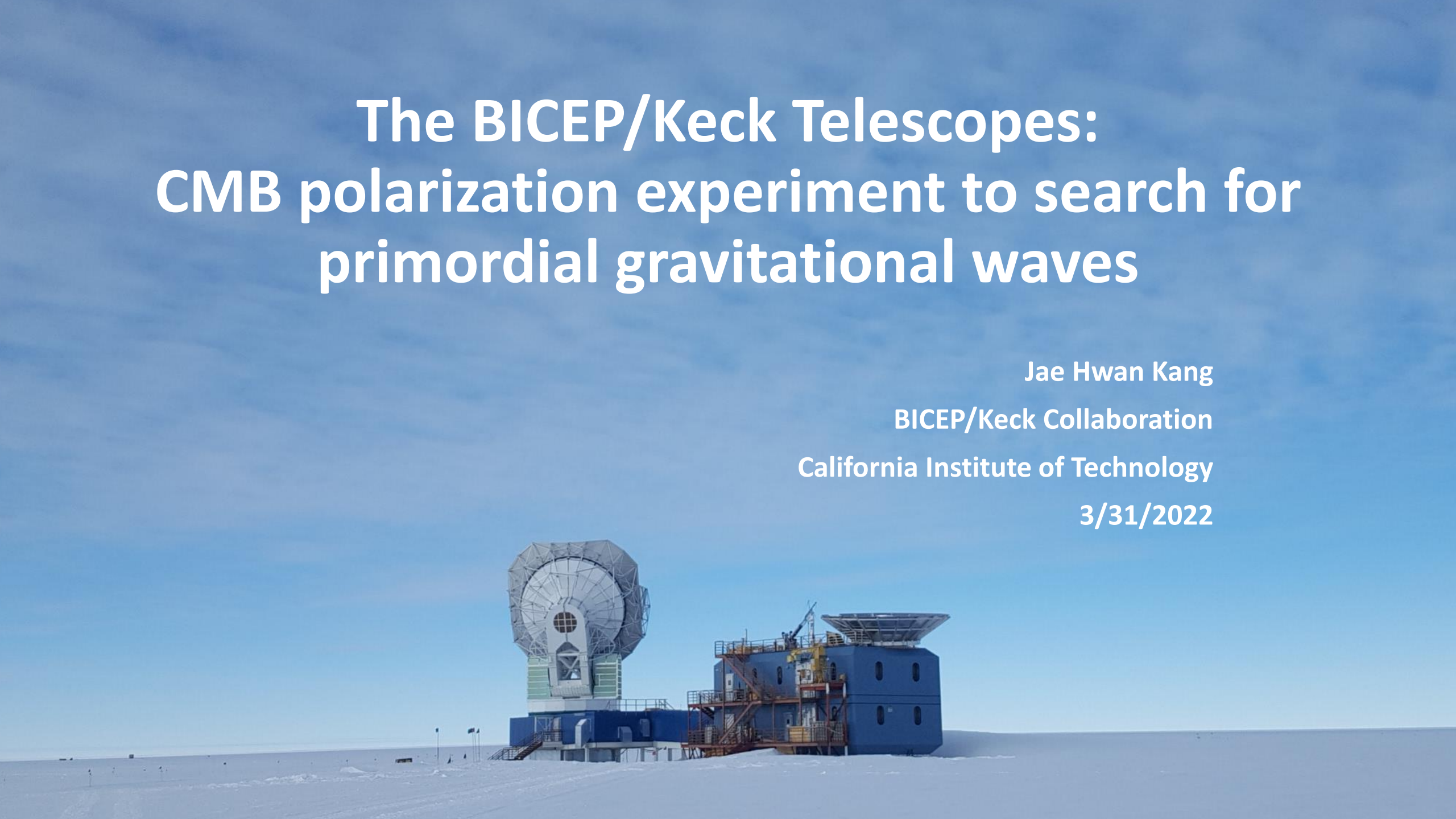
The BICEP/Keck Telescopes: CMB polarization experiment to search for primordial gravitational waves

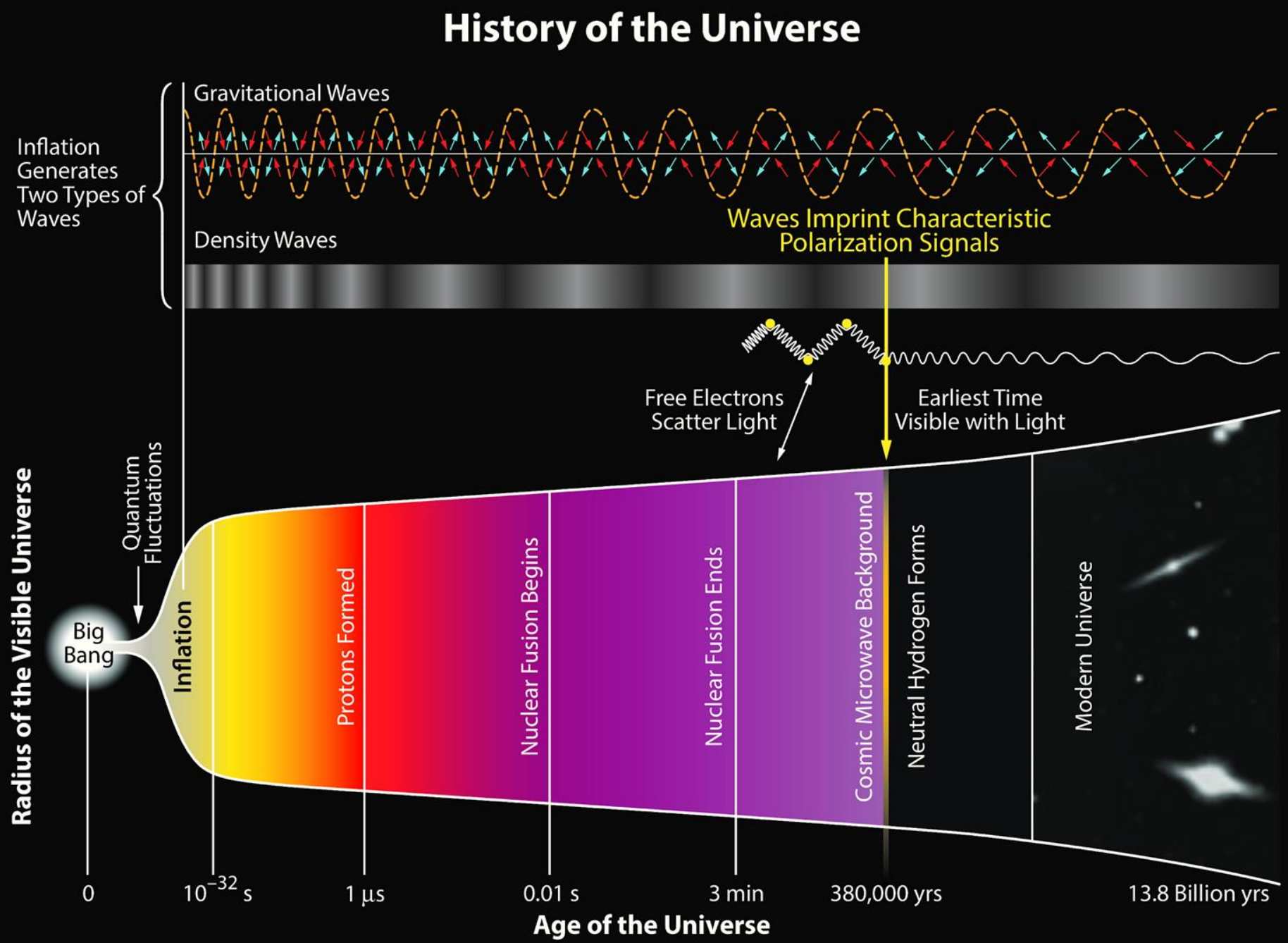
Jae Hwan Kang

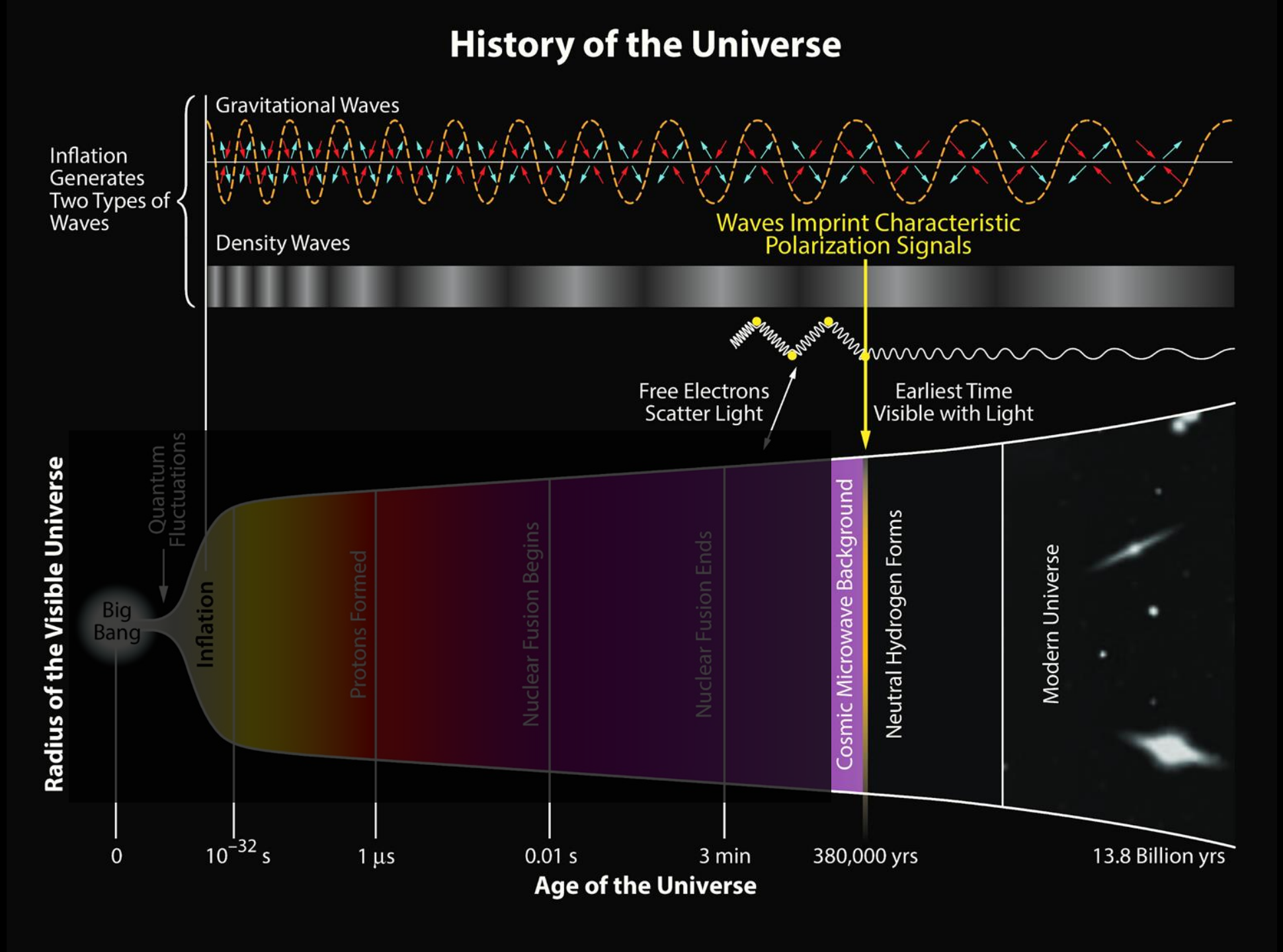
BICEP/Keck Collaboration

California Institute of Technology

3/31/2022




History of the Universe
Gravitational Waves
Inflation Generates Two Types of Waves
Density Waves
Waves Imprint Characteristic Polarization Signals
Free Electrons Scatter Light
Earliest Time Visible with Light
Radius of the Visible Universe
Quantum Fluctuations
Big Bang
Inflation
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Neutral Hydrogen Forms
Modern Universe
0
10^{-32} s
1 µs
0.01 s
3 min
380,000 yrs
13.8 Billion yrs
Age of the Universe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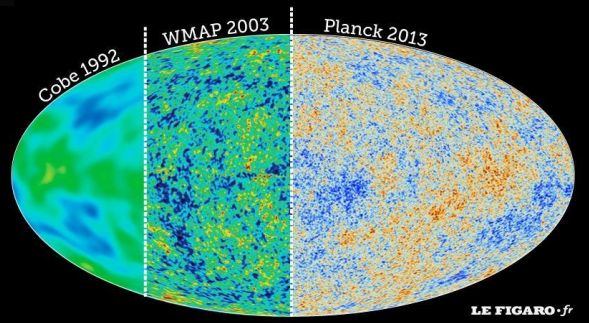

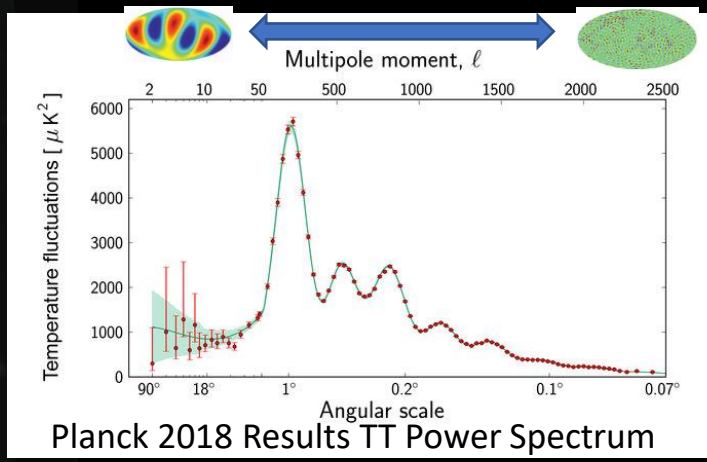

Planck 2018 Results TT Power Spectrum

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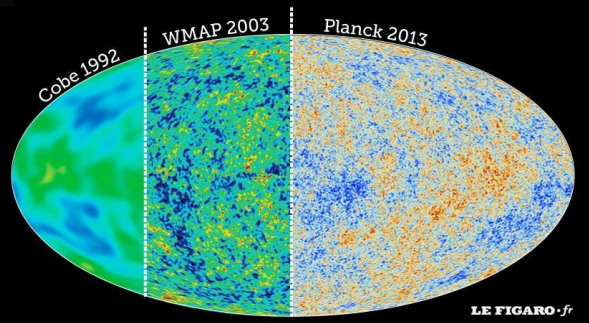
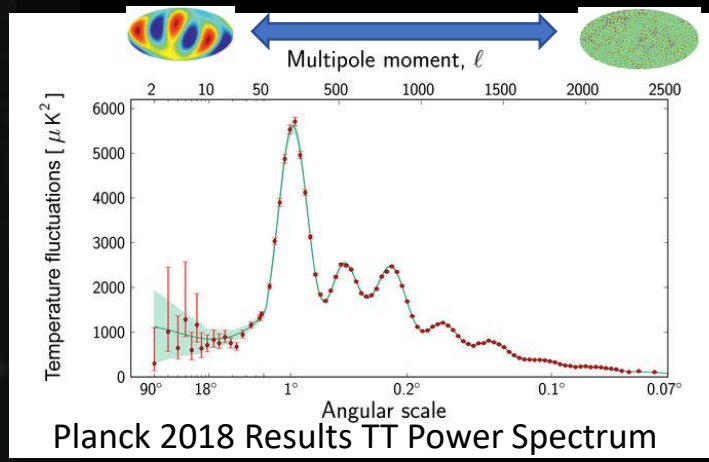




Planck 2018 Results TT Power Spectrum

CMB Polarization

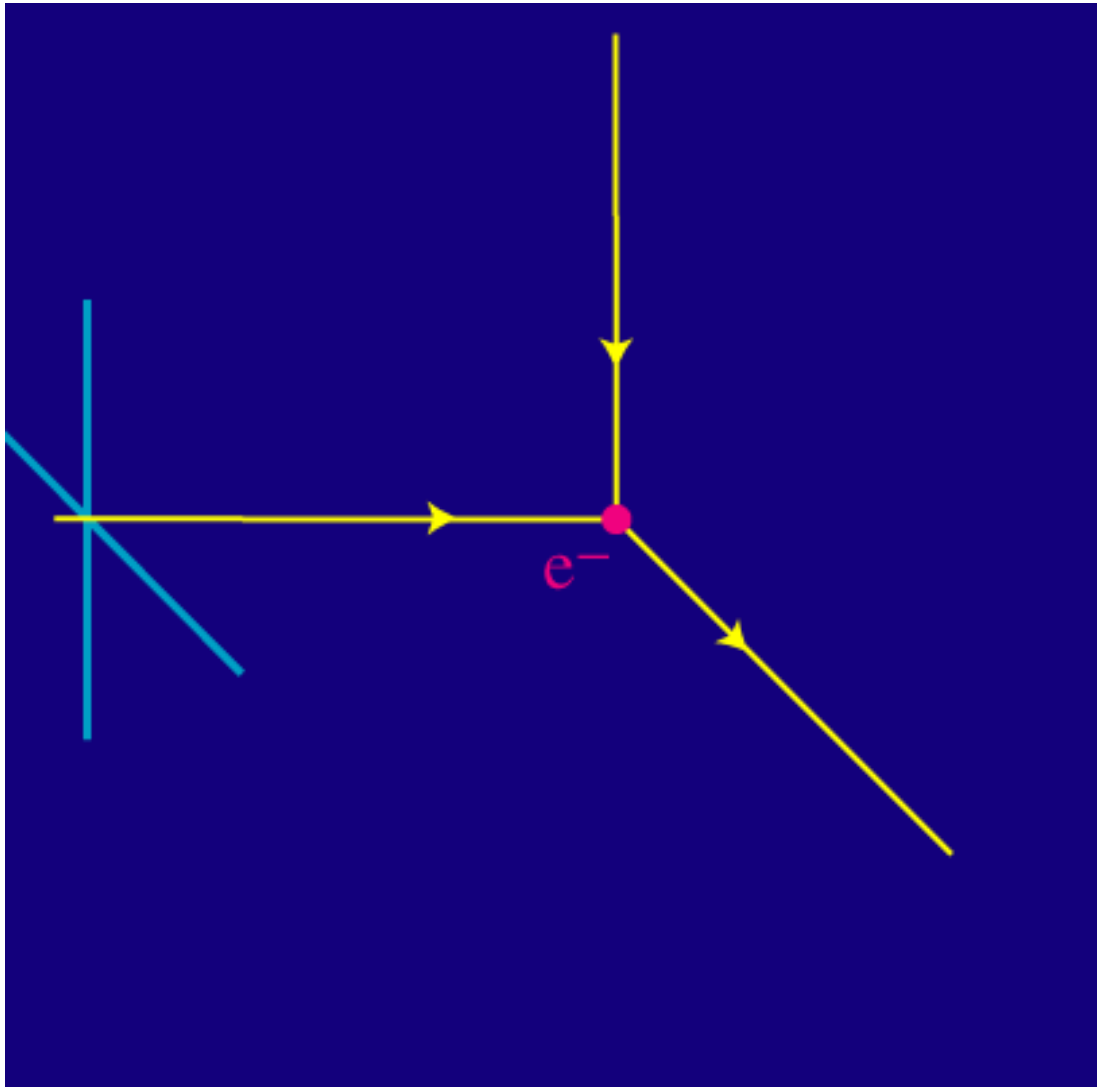
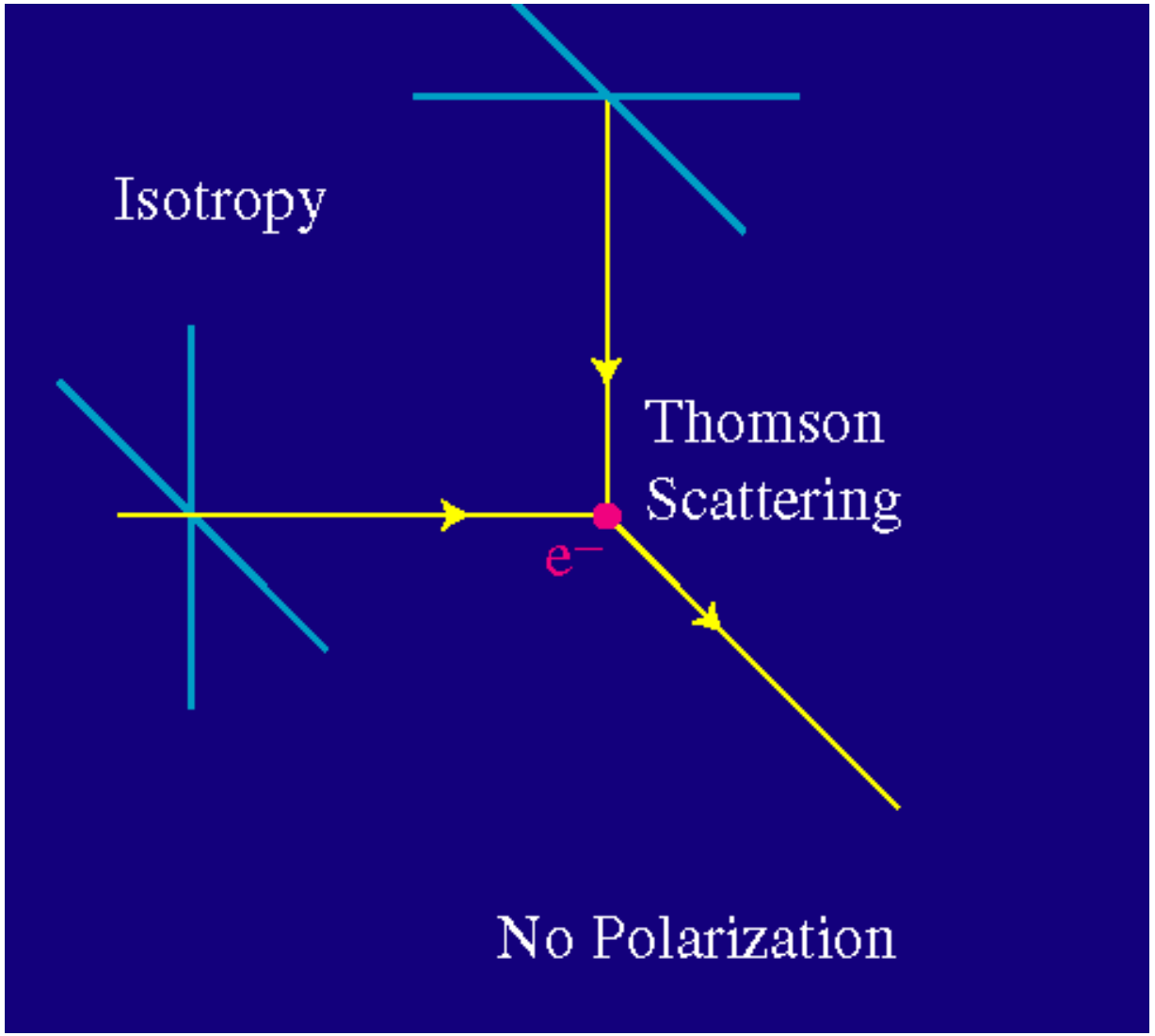


Image Cedit: Wayne Hu

CMB Polarization



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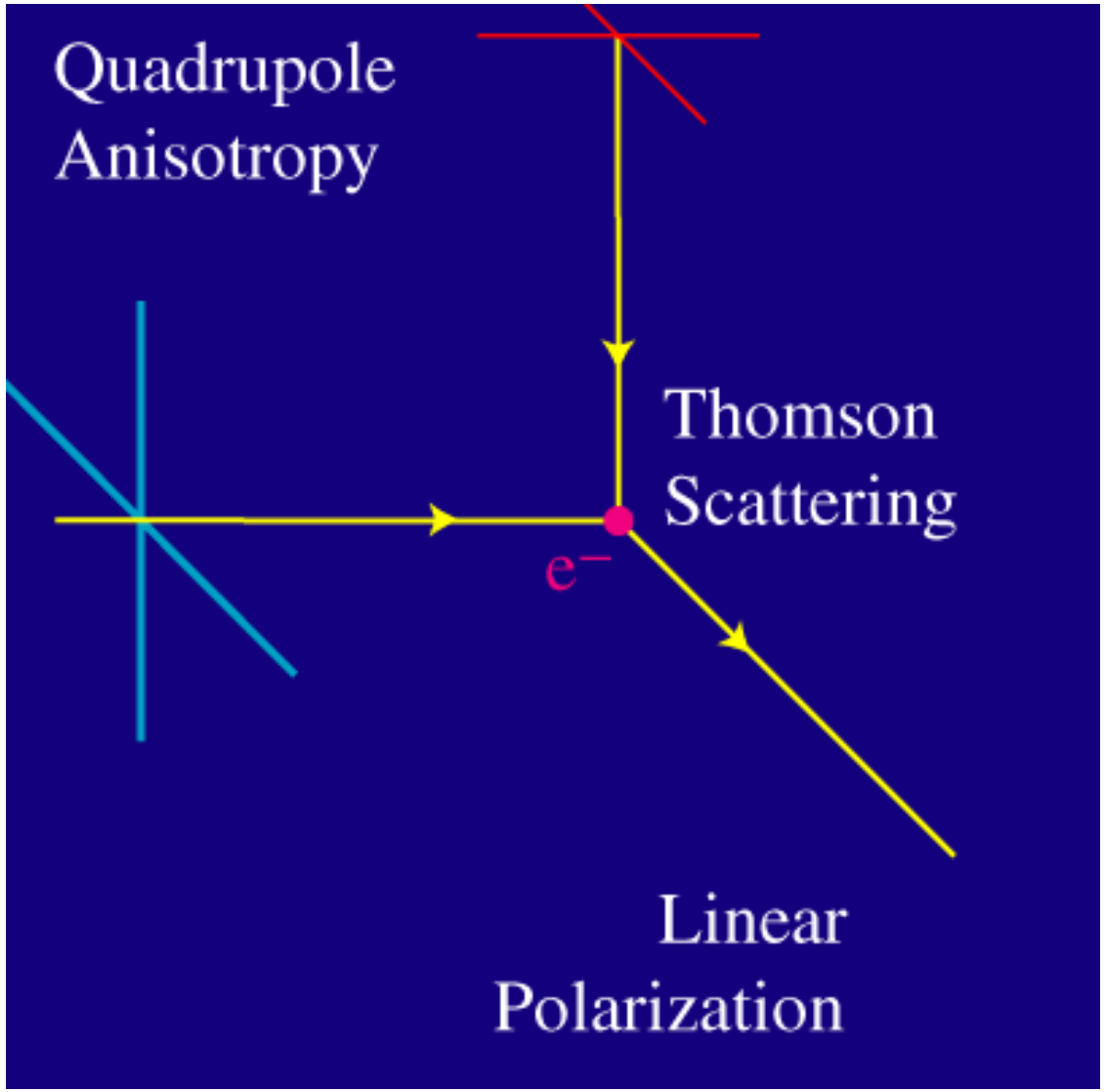
CMB Polarization



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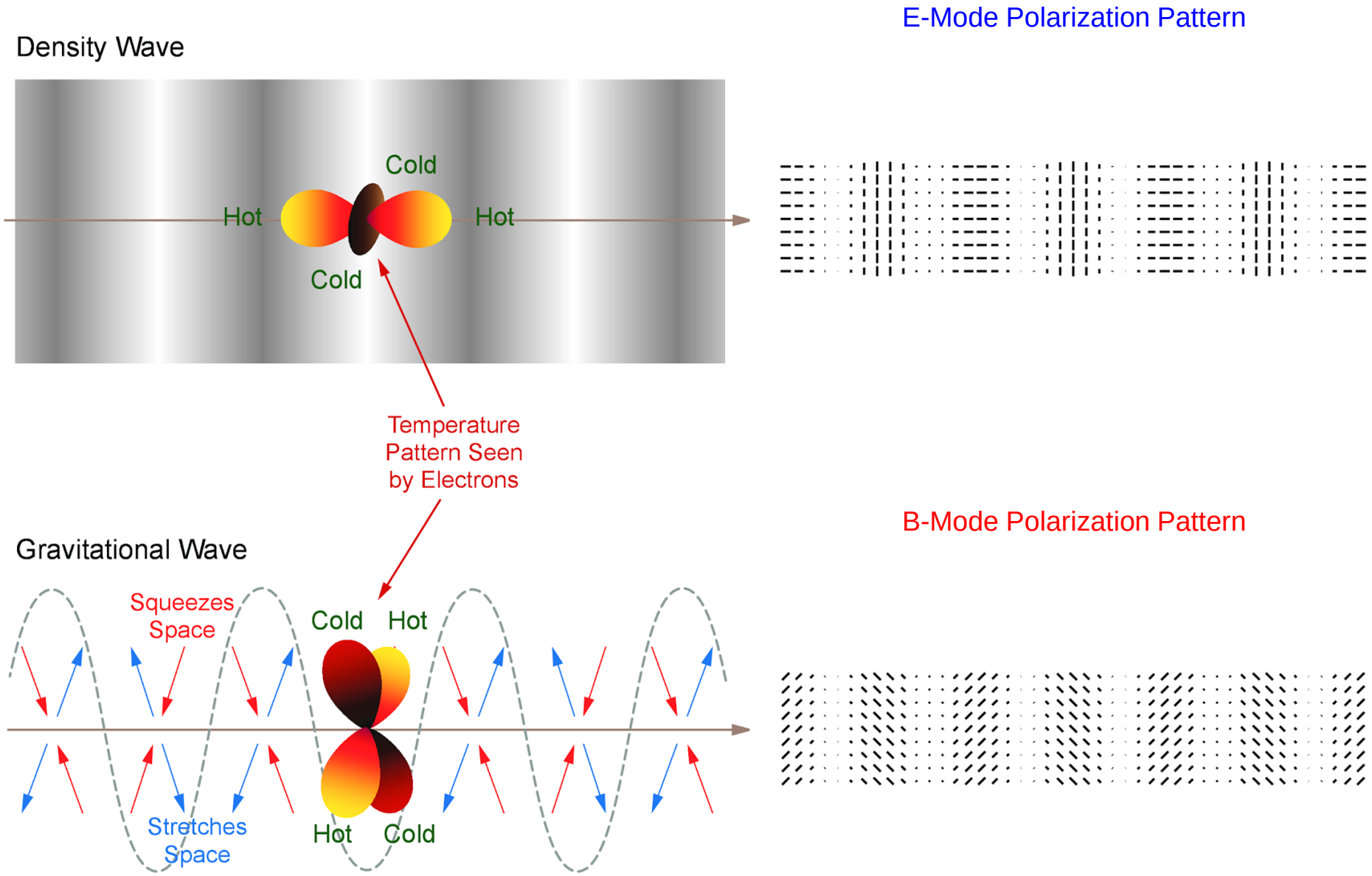
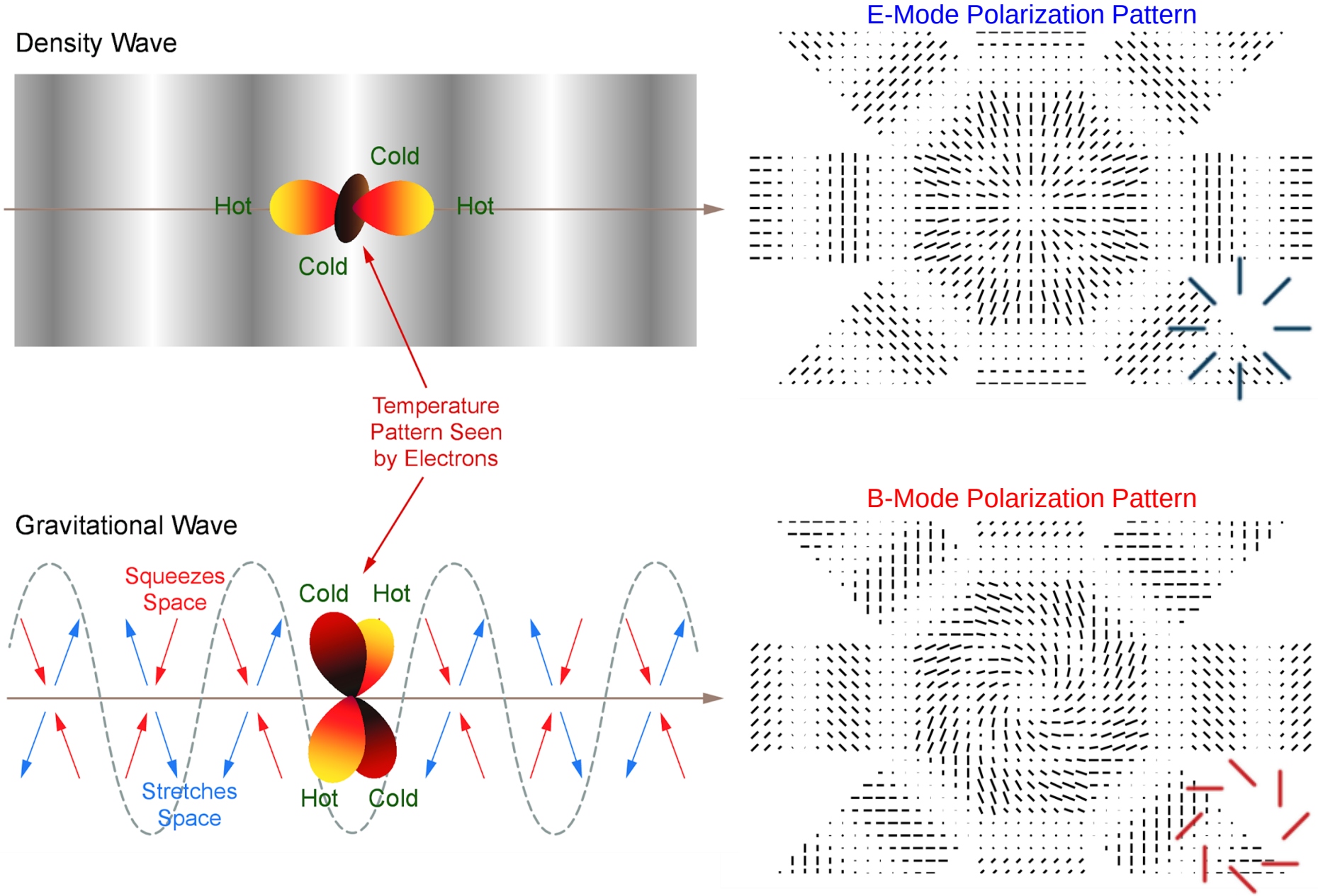


The Bicep2 Collaboration

CMB Polarization



The Bicep2 Collaboration

CMB Polarization

- Polarization encodes additional information, especially still elusive inflationary gravitational waves.
- E and B mode decomposition of linear polarization (Kamionkowski et al. 1997, Seljak and Zaldarriaga 1997)

- Density fluctuations can produce only E modes
- Inflation can produce both E modes and B modes by gravitational waves (tensor perturbation) – B mode is a key to probe inflation

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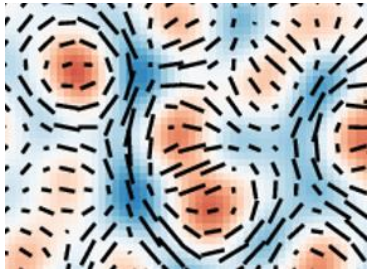
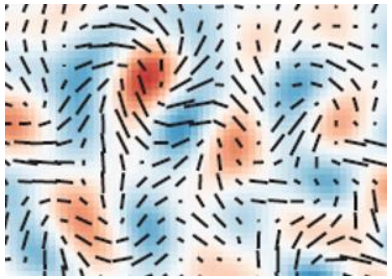
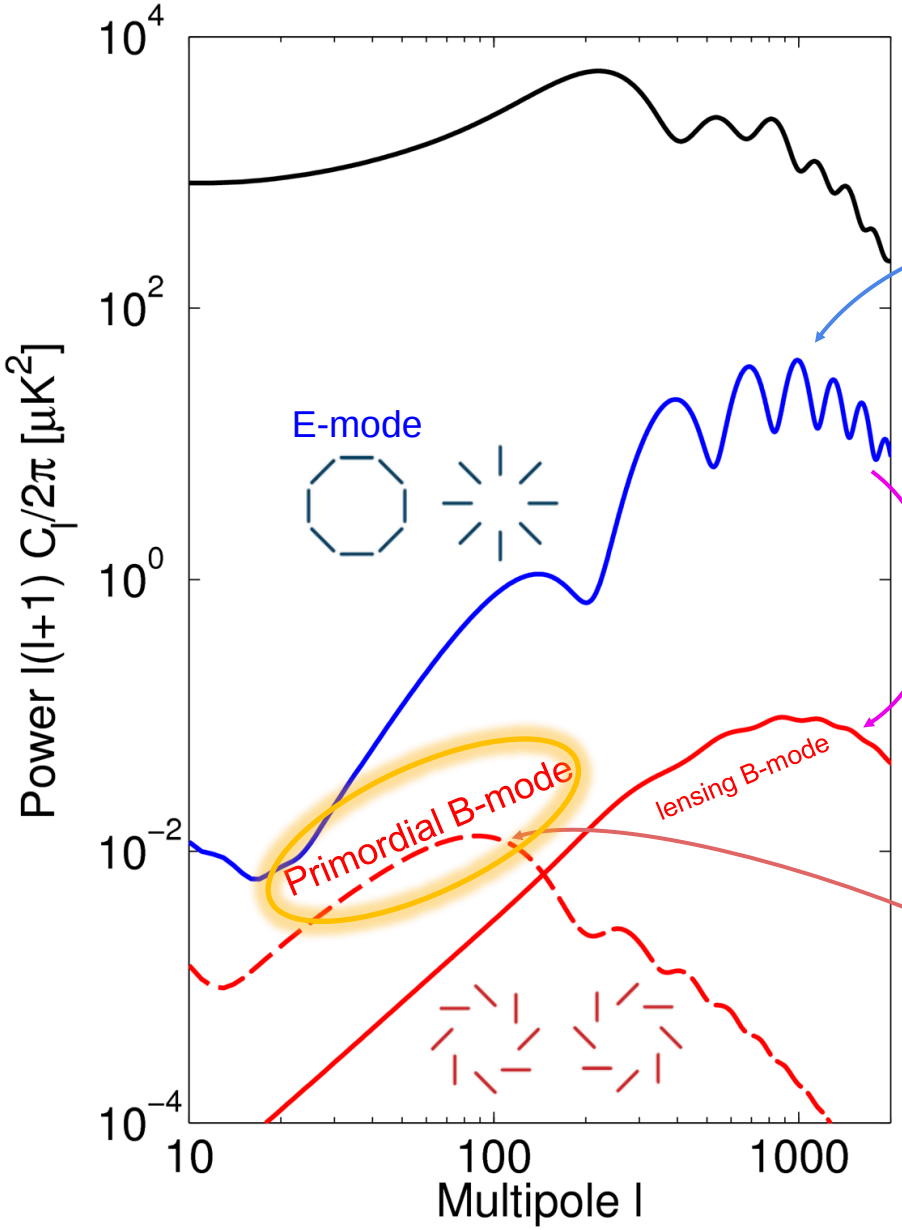
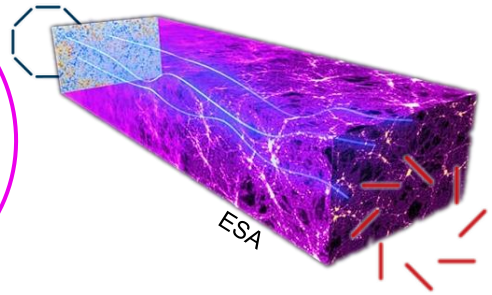
E  B 

- Density fluctuations can produce only E modes
- Inflation can produce both E modes and B modes by gravitational waves (tensor perturbation) – B mode is a key to probe inflation
- E and B mode “hot” and “cold” fluctuations can be represented by power spectra as well.

CMB Polarization Power Spectrum



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

Inflationary gravitational waves are unique source of B-modes
→ peaking at l≈100 : degree scales
→ strength: tensor-to-scalar ratio r

$$r = \frac{\Delta_t^2}{\Delta_s^2} \propto \frac{A_t^2}{A_s^2} \approx 0.1 \left(\frac{V}{\left[2 \times 10^{16} GeV\right]^4} \right)$$

The BICEP/Keck Collaboration

Stage 2

Stage 3

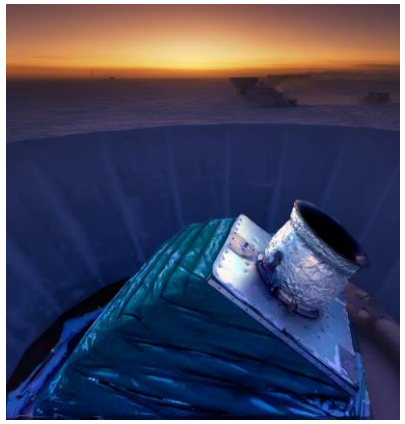
BICEP2
(2010-2012)

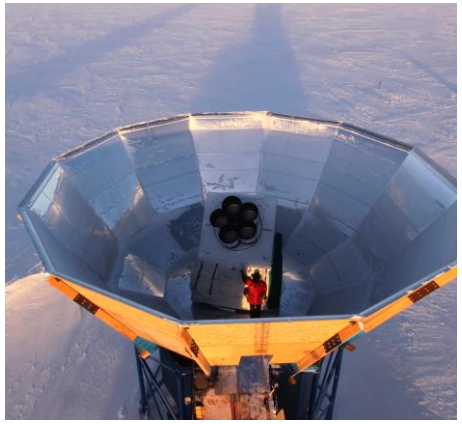
Keck Array
(2012-2019)

BICEP3
(2015-)

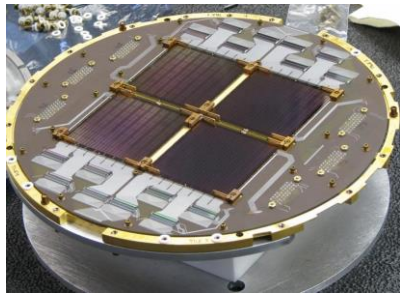
BICEP Array
(2020-)

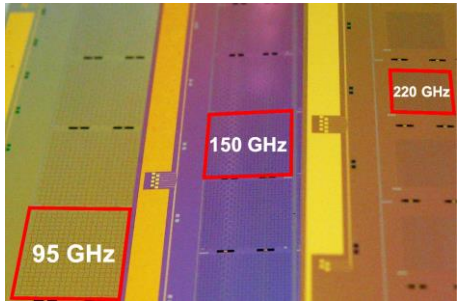
Telescope and Mount

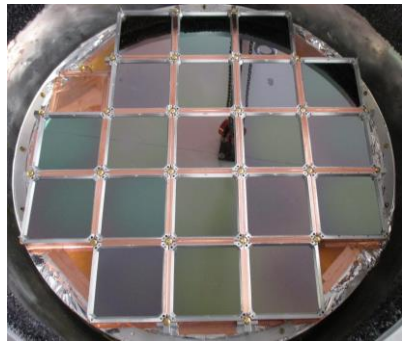


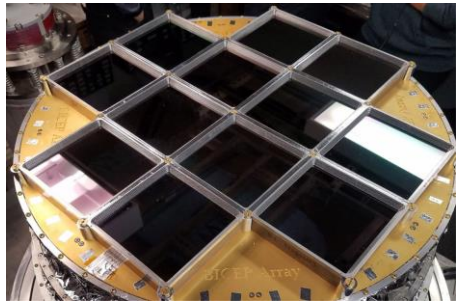


Focal Plane

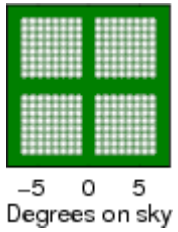


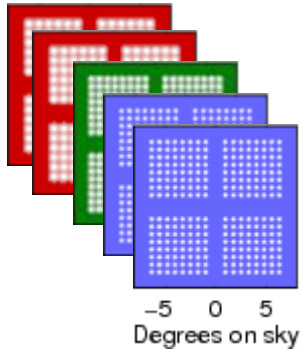


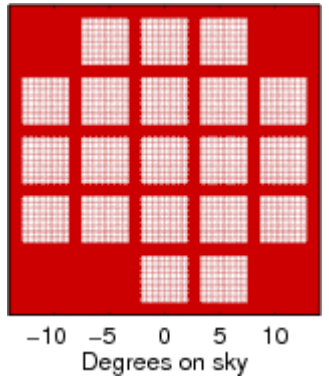


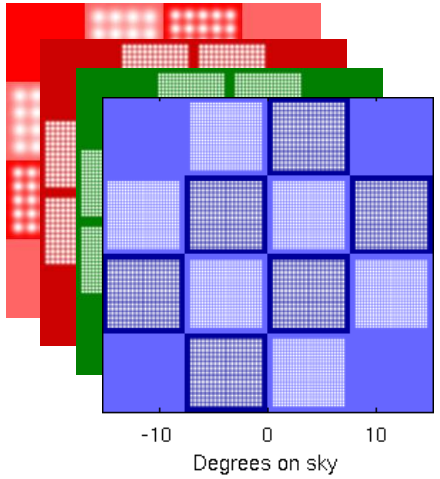


Beams on Sky

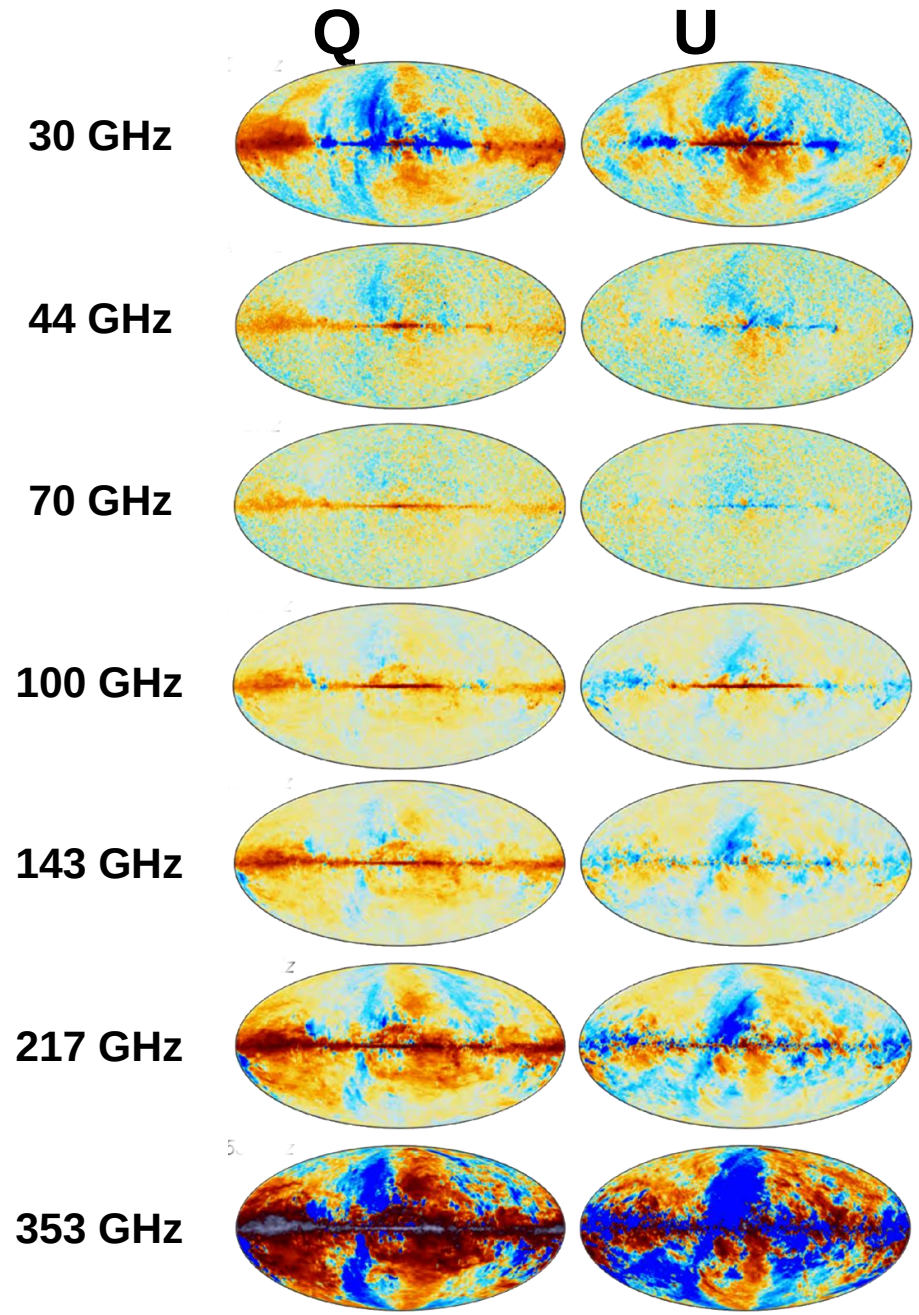






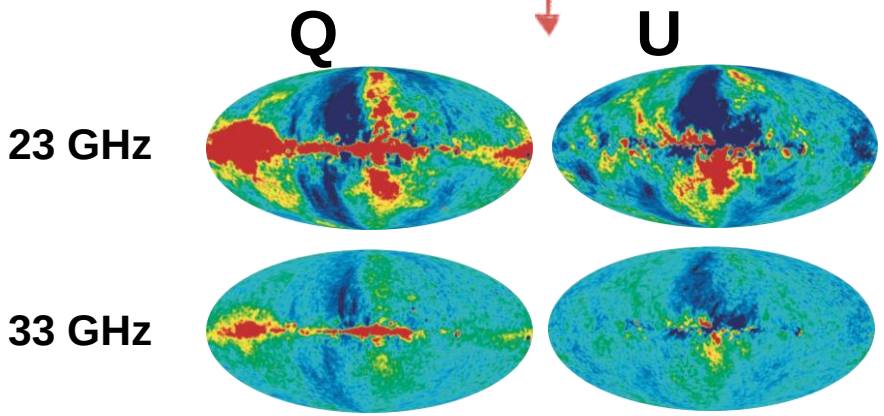


Planck



From arxiv 1502.01582

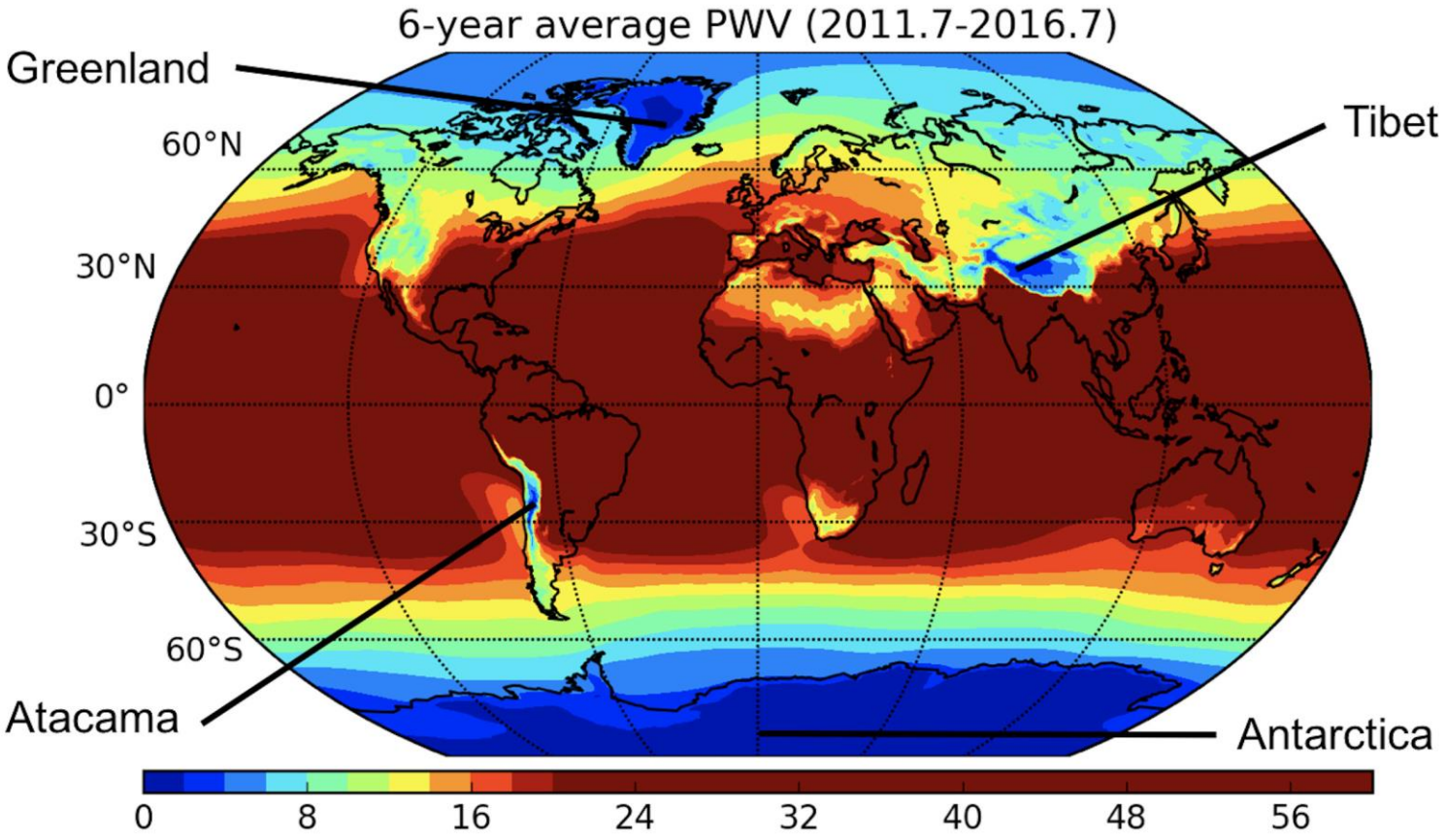
Polarized galactic **synchrotron** dominates at low frequencies



WMAP

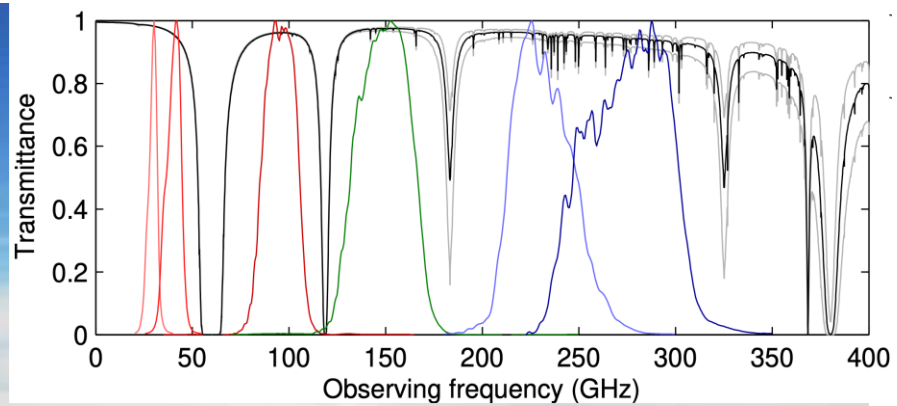
From arxiv 1212.5225

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

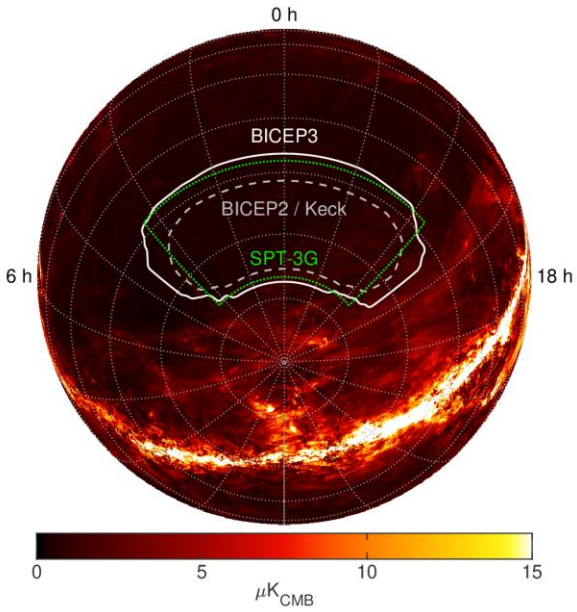


L. Hong et al., National Science Review, vol. 6, issue 1, pp. 145-154, Jan. 2019.

Observing Site: the South Pole



BICEP (2006 - 2009)
BICEP2 (2010-2012)
Keck Array (2011-2019)
BICEP3 (2015 -)
BICEP Array (2020-)

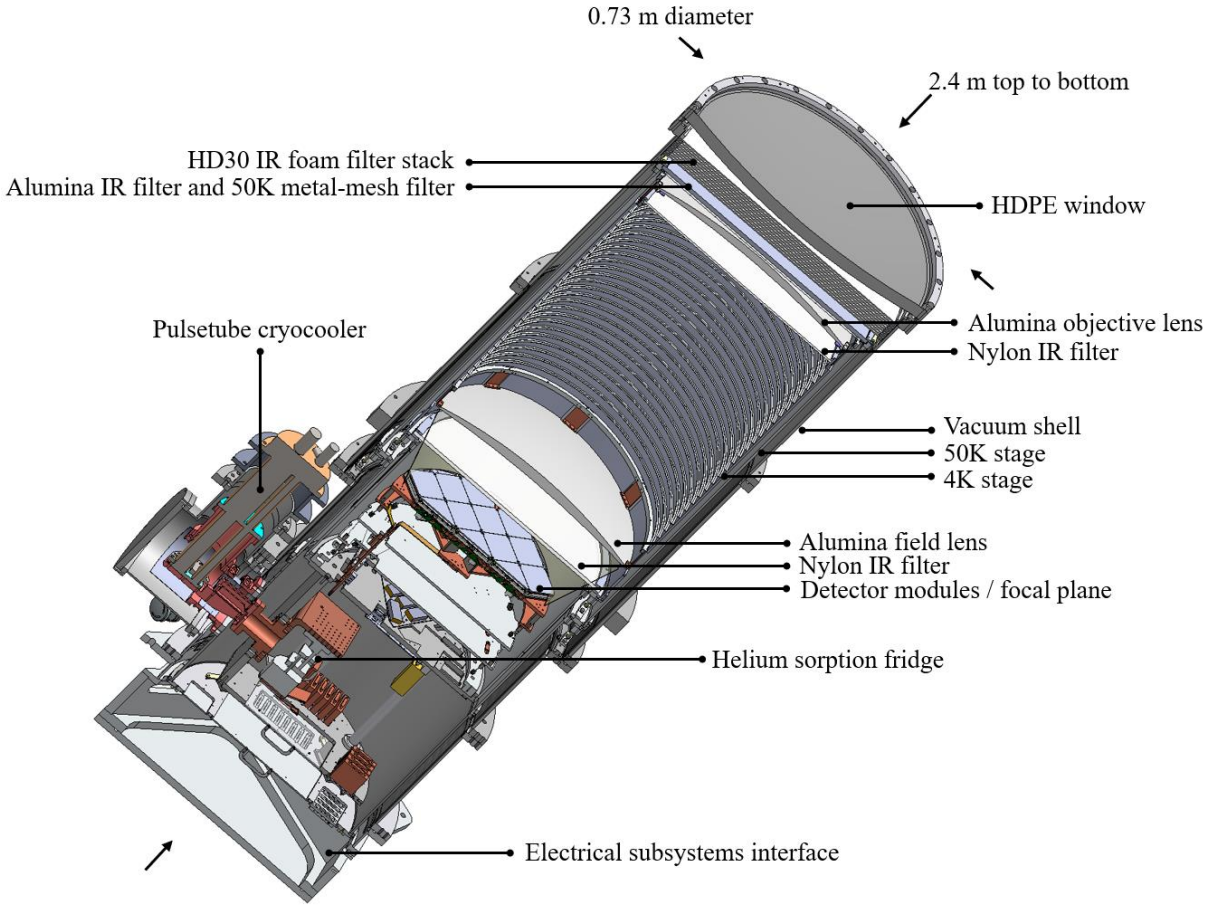


- Dry and stable atmosphere
- Continuous access to the same sky patch
- Great Logistics Support

BICEP3

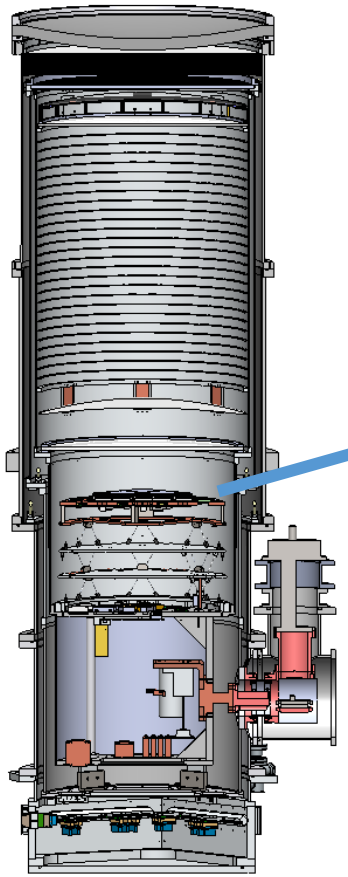
- Refracting Telescope
- Multiple stage cryostat
  - Layers of cold cylinders
- Detectors on the focal plane are at 0.275 K
- Coldness for activating detectors and having low thermal noise

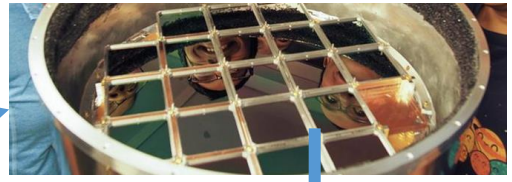
CAD cross section

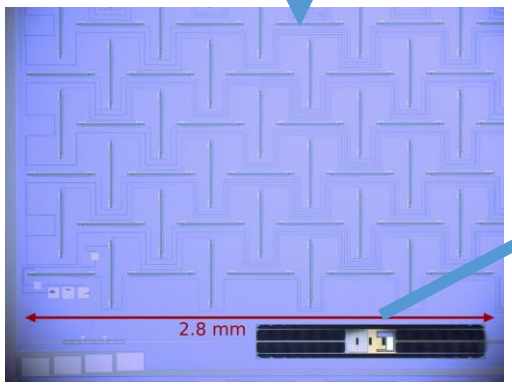


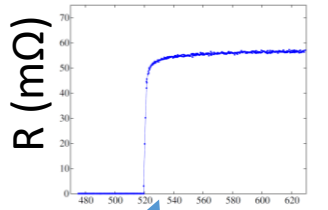
Sensitive Bolometers

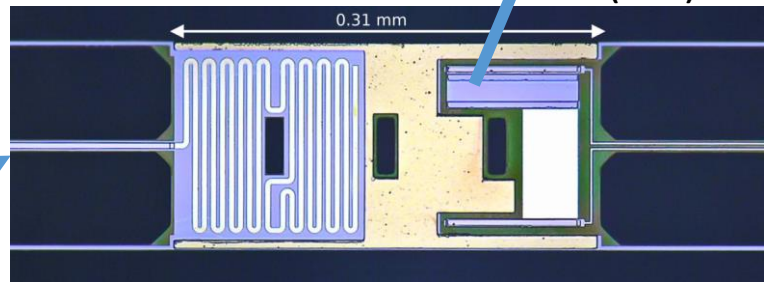
- Incoming radiation falls onto the focal plane
- Antenna arrays sensitive to polarization collect photons and deposit on a bolometer
- A TES biased at superconductor transition temperature measures the incoming signal











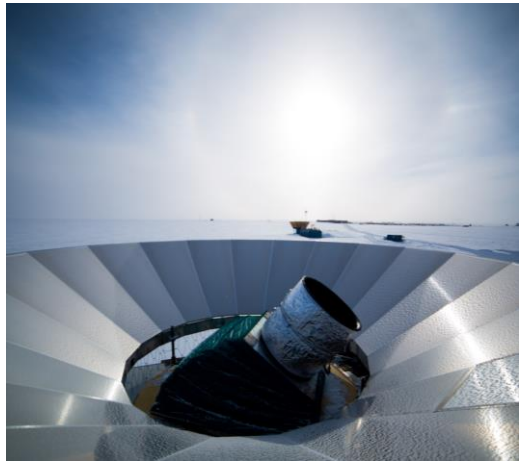
Transition Edge Sensor (TES)

Figures from BK-II, 2014

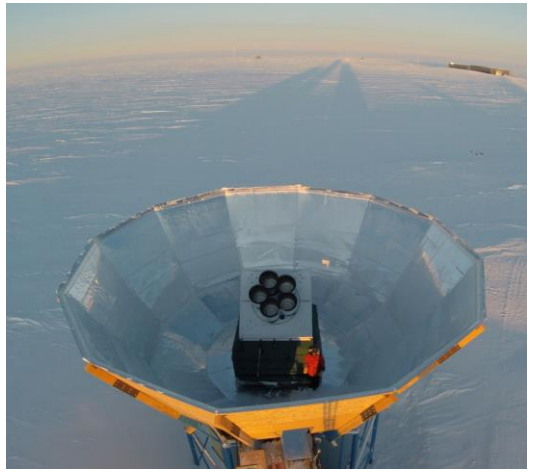
Scanning at constant elevation

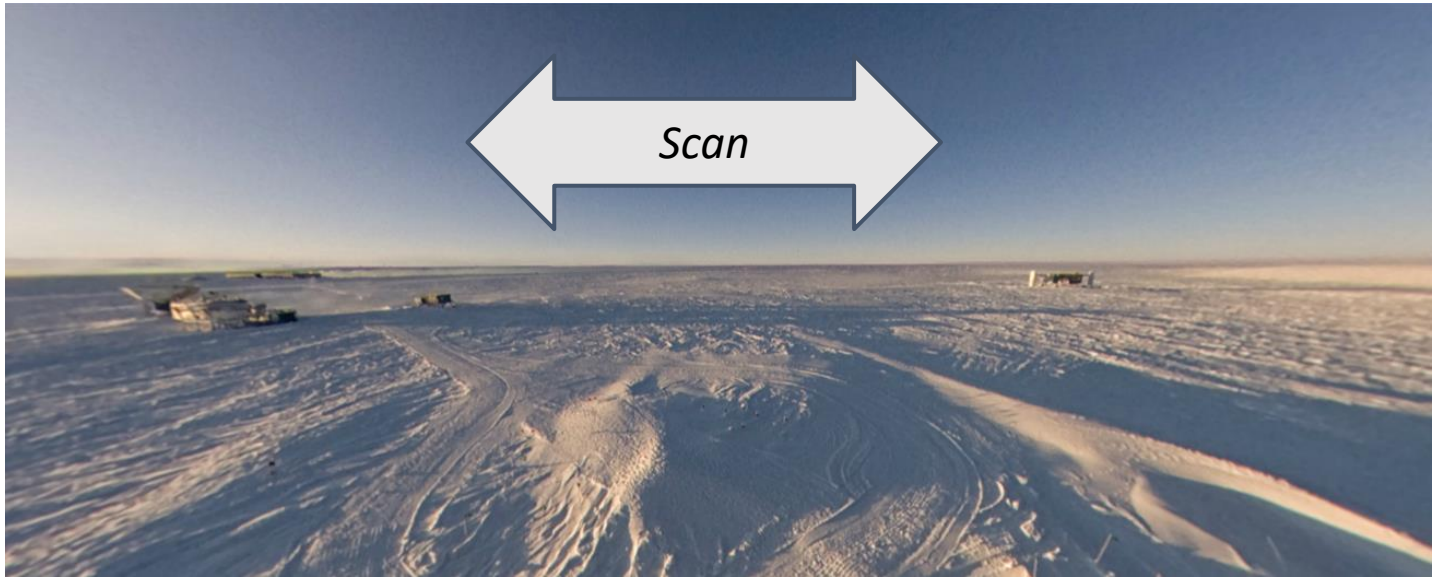
- Constant elevation – same atmosphere thickness
- Cover multiple steps in elevation

BICEP3



Keck Array

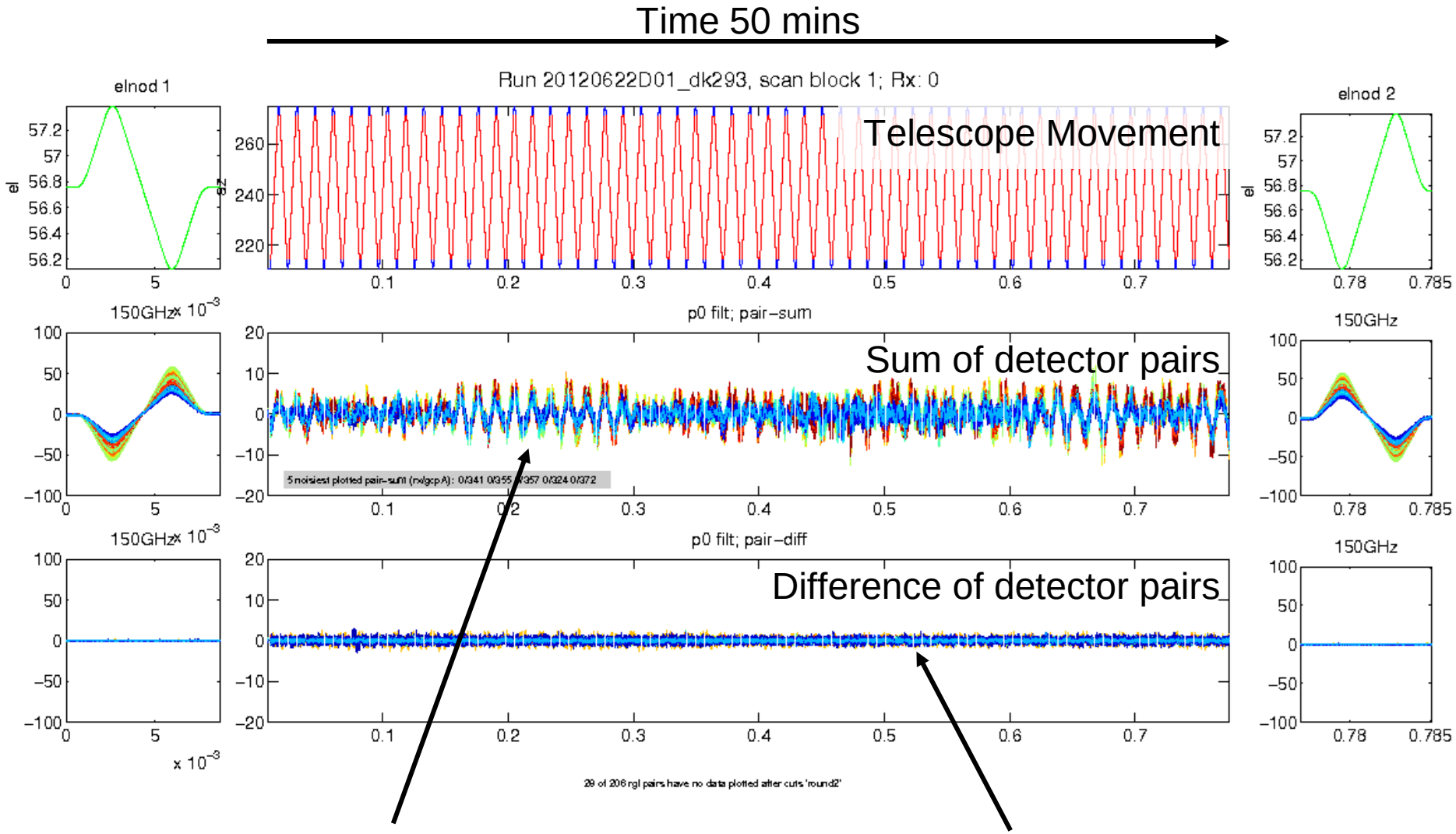




Keck Array scans during the winter

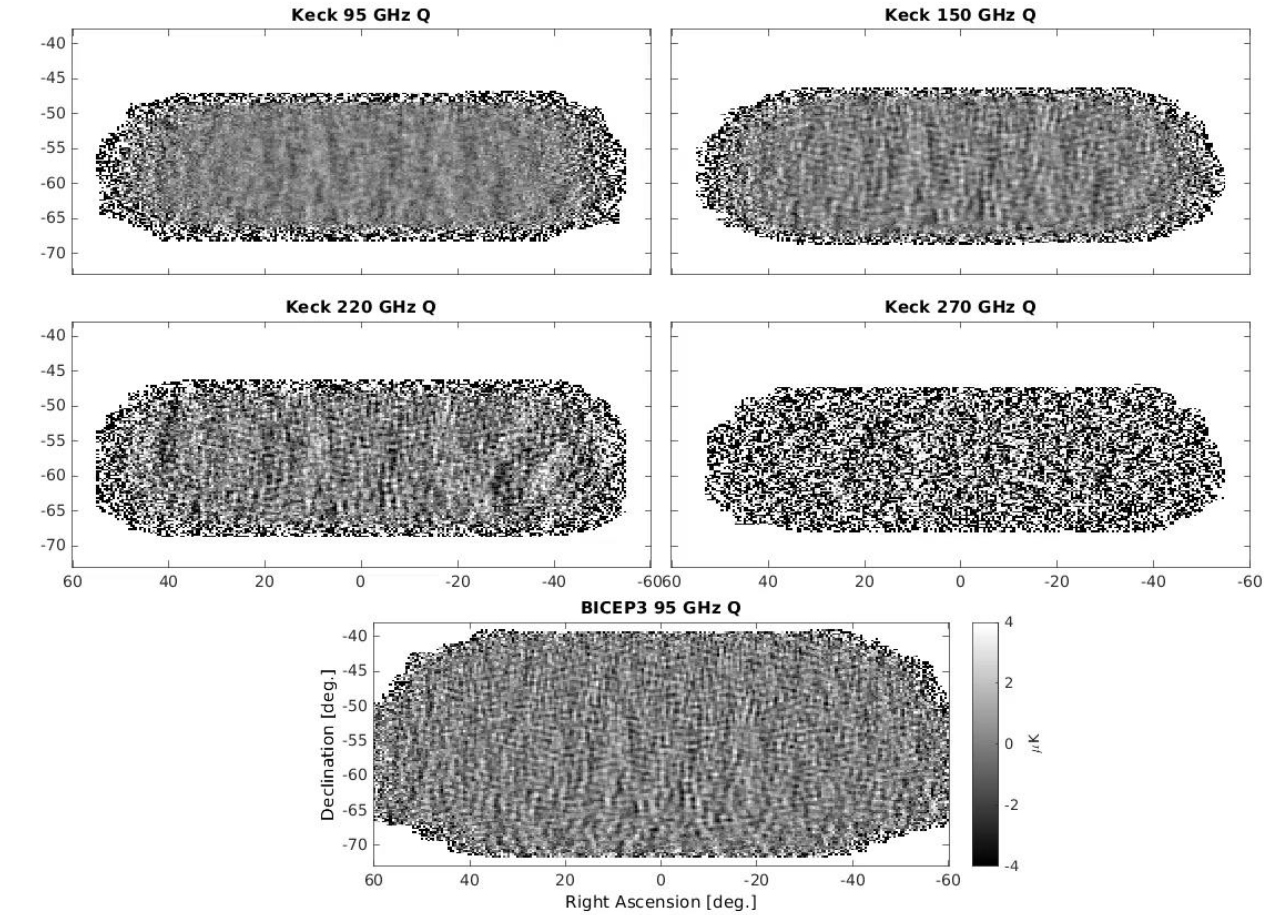
- https://vimeo.com/98550894 video by Robert Schwarz

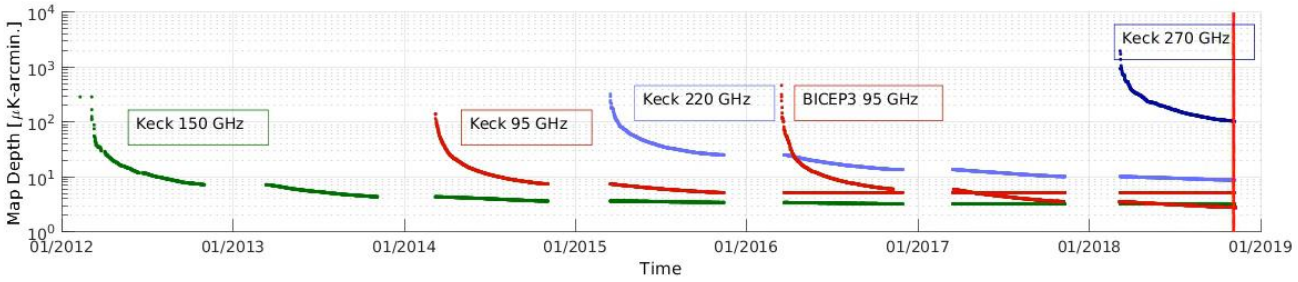
Raw Data Timestream



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

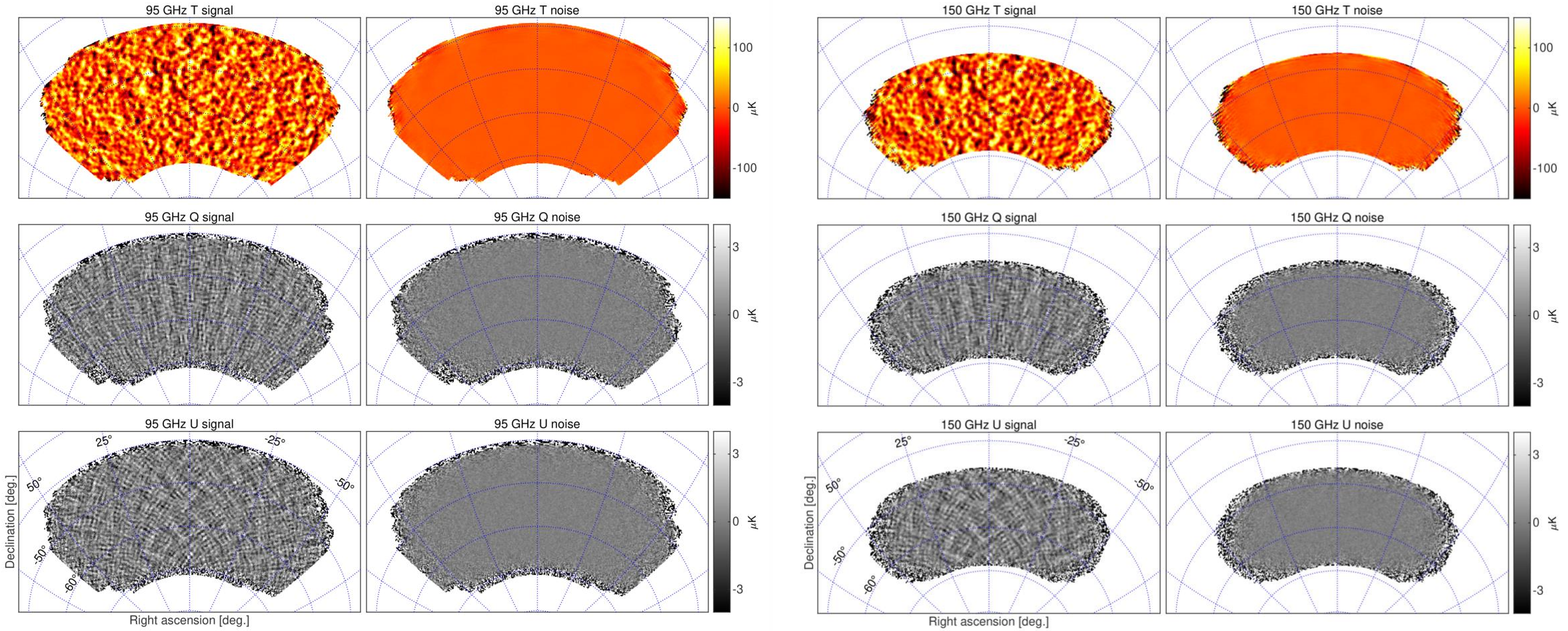
Map Depth





BK14 **BK15** **BK18**

Temperature and Polarization (Q, U) maps



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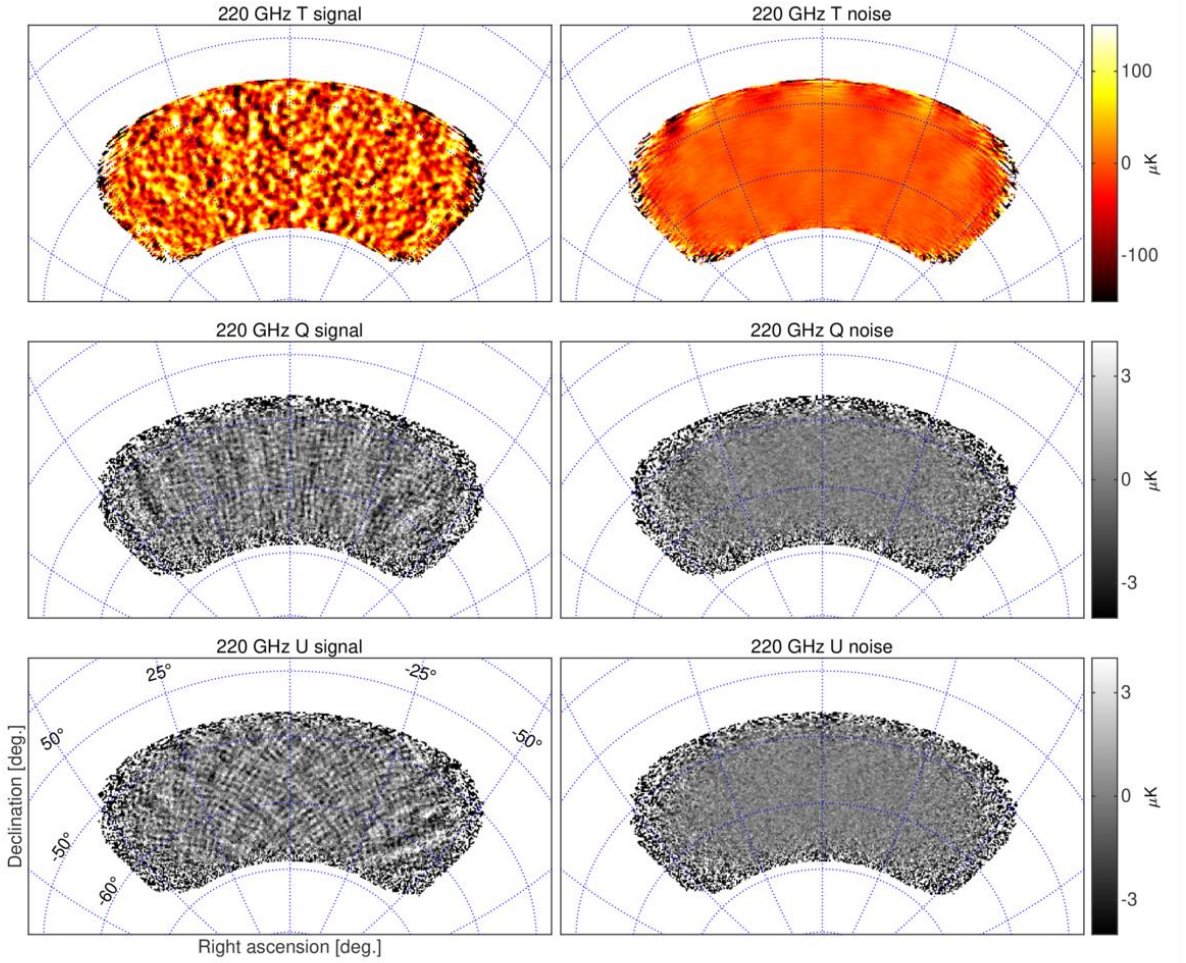
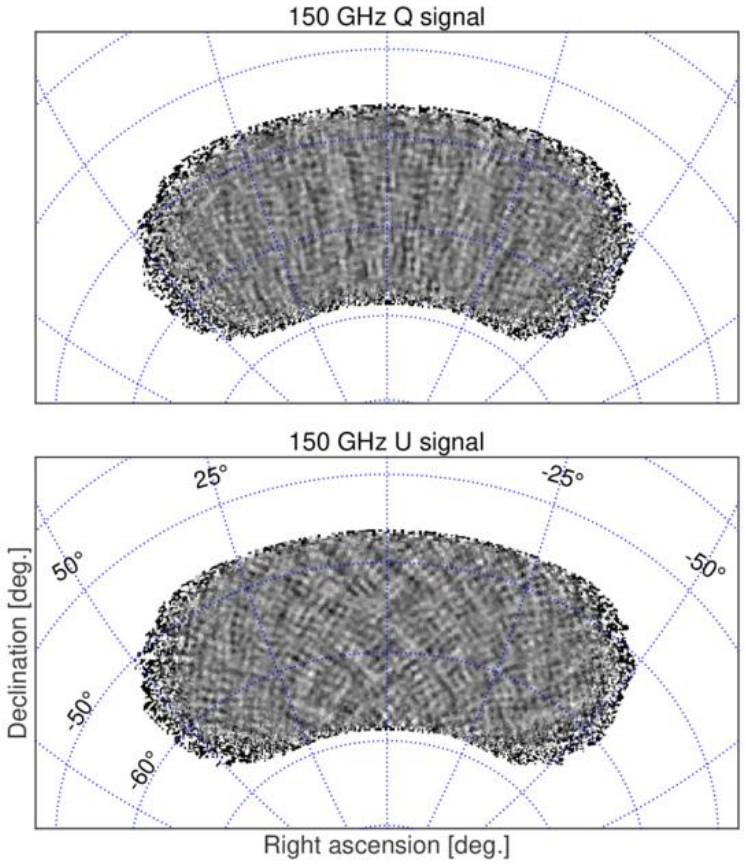
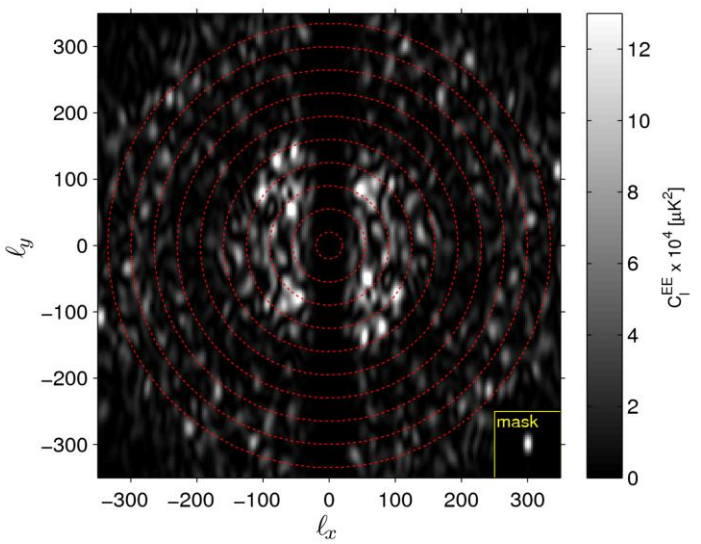


Q, U maps to EE and BB spectra

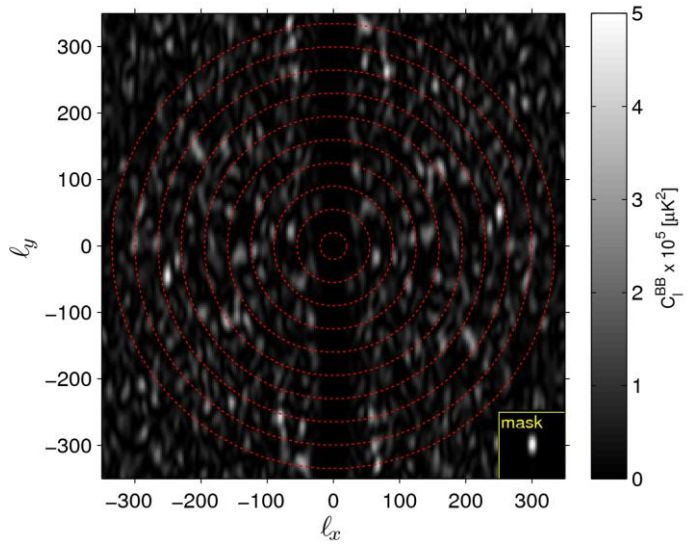


BK18 150 GHz

EE

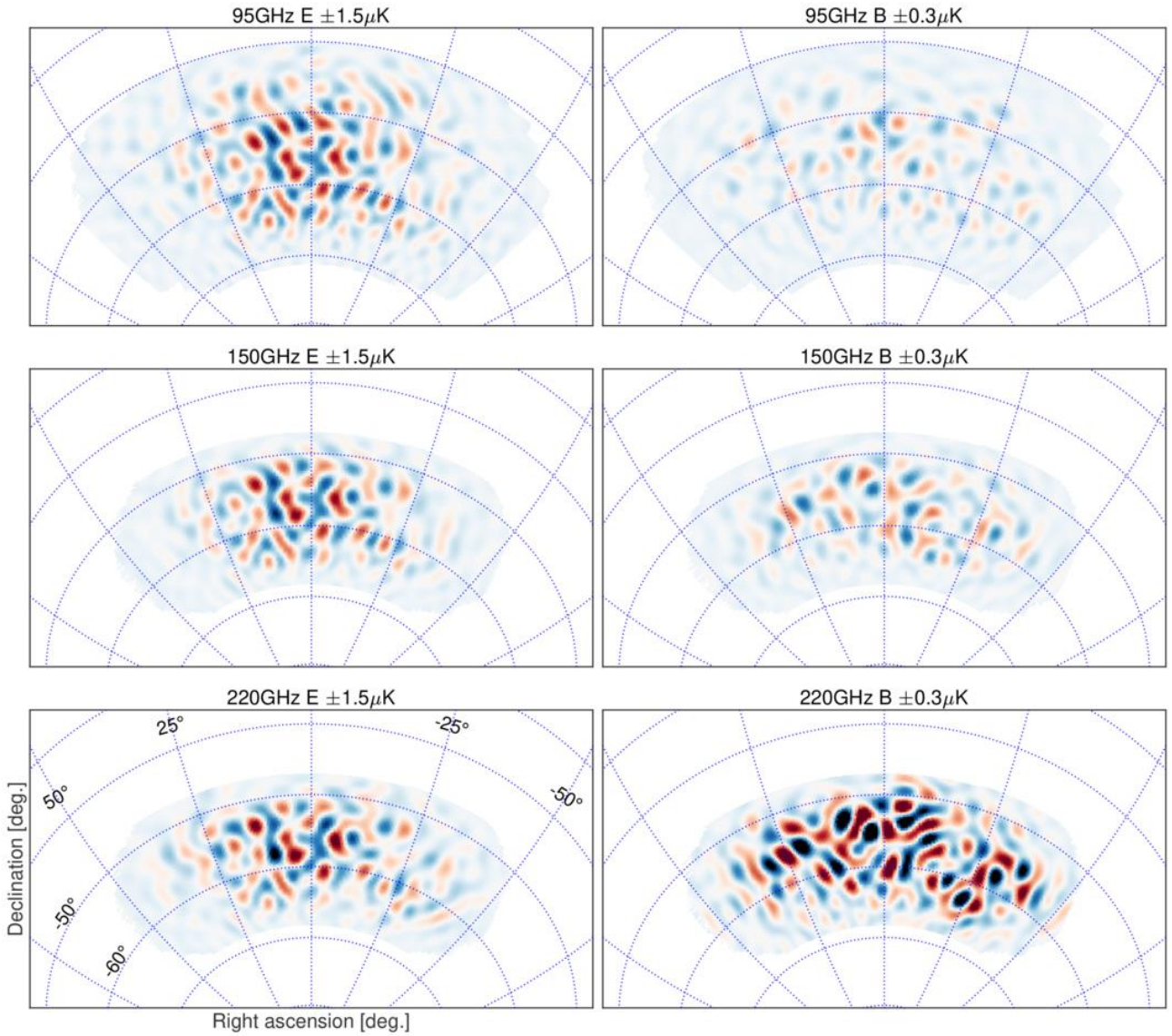


BB



From an example simulation for lensed-LCDM+noise+r=0 for illustration

BK18 E- and B-mode maps



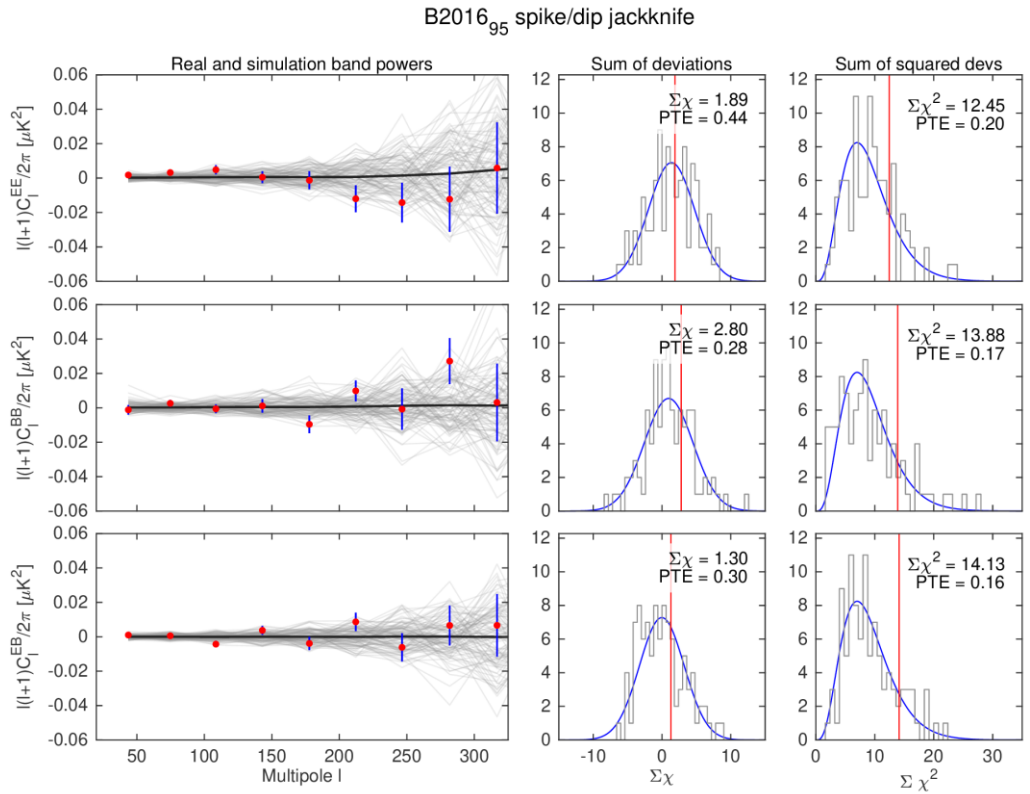
E-mode (left column) and *B*-mode (right column) maps at 95, 150 and 220 GHz in CMB units, and filtered to degree angular scales ($50<\ell<120$).

The *E* maps are dominated by ΛCDM signal, and hence are highly correlated across all three bands.

The 95 GHz *B* map is approximately equal parts lensed-ΛCDM signal and noise. At 150 and 220 GHz the *B* maps are dominated by polarized dust emission.

Systematics Check

- Great sensitivity comes with great control of systemics
- T->P leakage by beam mismatch is controlled by deprojection
- Unblind BB spectra after jackknife tests check
  - Jackknife: split data by observed time, boresight orientation, etc. to check possible contamination



arXiv:2110.00482

Table 11. Jackknife PTE values from χ and χ^2 tests.

	2016		2017		2018	
	χ	χ^2	χ	χ^2	χ	χ^2
Band Power	1-5/1-9					
Deck jackknife						
EE	0.501/0.383	0.754/0.719	0.982/0.992	0.050/0.108	0.022/0.172	0.122/0.092
BB	0.936/0.998	0.443/0.226	0.731/0.419	0.848/0.563	0.567/0.924	0.130/0.152
EB	0.319/0.283	0.840/0.866	0.263/0.589	0.932/0.838	0.265/0.307	0.832/0.868
Scan dir jackknife						
EE	0.277/0.112	0.956/0.275	0.449/0.453	0.066/0.070	0.198/0.437	0.804/0.459
BB	0.764/0.872	0.525/0.196	0.283/0.433	0.162/0.407	0.168/0.172	0.012/0.030
EB	0.904/0.431	0.697/0.591	0.076/0.228	0.517/0.816	0.838/0.527	0.806/0.798
Temporal split jackknife						
EE	0.998/0.996	0.084/0.257	0.028/0.068	0.277/0.295	0.146/0.467	0.395/0.152
BB	0.098/0.200	0.261/0.255	0.263/0.531	0.331/0.317	0.826/0.946	0.822/0.719
EB	0.958/0.772	0.461/0.713	0.956/0.936	0.020/0.044	0.070/0.034	0.497/0.499
Tile jackknife						
EE	0.257/0.150	0.429/0.623	0.403/0.529	0.559/0.248	0.002/0.004	0.004/0.018
BB	0.527/0.713	0.323/0.495	0.952/0.852	0.455/0.816	0.697/0.862	0.705/0.371
EB	0.707/0.493	0.776/0.872	0.381/0.633	0.517/0.311	0.946/0.984	0.146/0.257
Azimuth jackknife						
EE	0.575/0.866	0.140/0.259	0.776/0.727	0.916/0.962	0.834/0.545	0.695/0.687
BB	0.014/0.126	0.082/0.068	0.178/0.425	0.435/0.667	0.487/0.279	0.860/0.665
EB	0.357/0.415	0.846/0.212	0.487/0.068	0.904/0.363	0.876/0.998	0.164/0.040
Mux col jackknife						
EE	0.309/0.429	0.335/0.363	0.731/0.745	0.232/0.625	0.681/0.946	0.894/0.778
BB	0.665/0.182	0.960/0.423	0.116/0.070	0.840/0.950	0.210/0.657	0.573/0.108
EB	0.451/0.681	0.944/0.992	0.335/0.339	0.423/0.415	0.248/0.353	0.988/0.924
Alt deck jackknife						
EE	0.982/0.996	0.220/0.166	0.972/0.954	0.172/0.405	0.056/0.182	0.102/0.214
BB	0.062/0.635	0.307/0.170	0.251/0.236	0.050/0.100	0.054/0.467	0.152/0.042
EB	0.198/0.192	0.477/0.790	0.411/0.731	0.238/0.118	0.667/0.429	0.513/0.814
Mux row jackknife						
EE	0.776/0.796	0.144/0.068	0.914/0.824	0.345/0.447	0.741/0.359	0.707/0.719
BB	0.822/0.725	0.539/0.631	0.425/0.631	0.561/0.800	0.515/0.673	0.890/0.583
EB	0.850/0.471	0.060/0.166	0.677/0.573	0.383/0.677	0.367/0.601	0.870/0.844
Tile and deck jackknife						
EE	0.631/0.421	0.788/0.878	0.439/0.427	0.888/0.920	0.886/0.926	0.715/0.902
BB	0.902/0.904	0.531/0.477	0.601/0.786	0.441/0.407	0.411/0.567	0.349/0.695
EB	0.311/0.461	0.429/0.569	0.842/0.709	0.204/0.377	0.896/0.944	0.733/0.485
Focal plane inner or outer jackknife						
EE	0.355/0.635	0.822/0.311	0.204/0.224	0.579/0.633	0.174/0.120	0.208/0.327
BB	0.800/0.922	0.711/0.555	0.663/0.928	0.617/0.295	0.148/0.194	0.204/0.283
EB	0.483/0.760	0.303/0.373	0.836/0.974	0.711/0.549	0.132/0.130	0.880/0.635
Tile top or bottom jackknife						
EE	0.942/0.641	0.064/0.010	0.768/0.960	0.505/0.397	0.910/0.679	0.204/0.463
BB	0.974/0.764	0.124/0.012	0.224/0.703	0.046/0.090	0.226/0.705	0.774/0.503
EB	0.353/0.717	0.675/0.593	0.786/0.932	0.411/0.451	0.136/0.345	0.148/0.174
Tile inner or outer jackknife						
EE	0.745/0.665	0.397/0.798	0.828/0.870	0.756/0.930	0.002/0.012	0.014/0.124
BB	0.337/0.667	0.224/0.421	0.196/0.667	0.956/0.818	0.810/0.924	0.076/0.138
EB	0.820/0.900	0.840/0.922	0.216/0.405	0.583/0.756	0.321/0.545	0.321/0.635
Moon jackknife						
EE	0.218/0.709	0.485/0.487	0.860/0.882	0.780/0.878	0.904/0.683	0.104/0.160
BB	0.976/0.824	0.255/0.607	0.996/0.946	0.108/0.246	0.206/0.164	0.142/0.385
EB	0.487/0.900	0.778/0.693	0.088/0.128	0.583/0.463	0.840/0.912	0.701/0.064
A and B offset best and worst jackknife						
EE	0.860/0.794	0.723/0.924	0.571/0.661	0.315/0.537	0.860/0.625	0.908/0.565
BB	0.453/0.561	0.022/0.044	0.970/0.972	0.194/0.293	0.860/0.942	0.814/0.780
EB	0.435/0.455	0.259/0.549	0.806/0.760	0.421/0.285	0.806/0.623	0.776/0.551

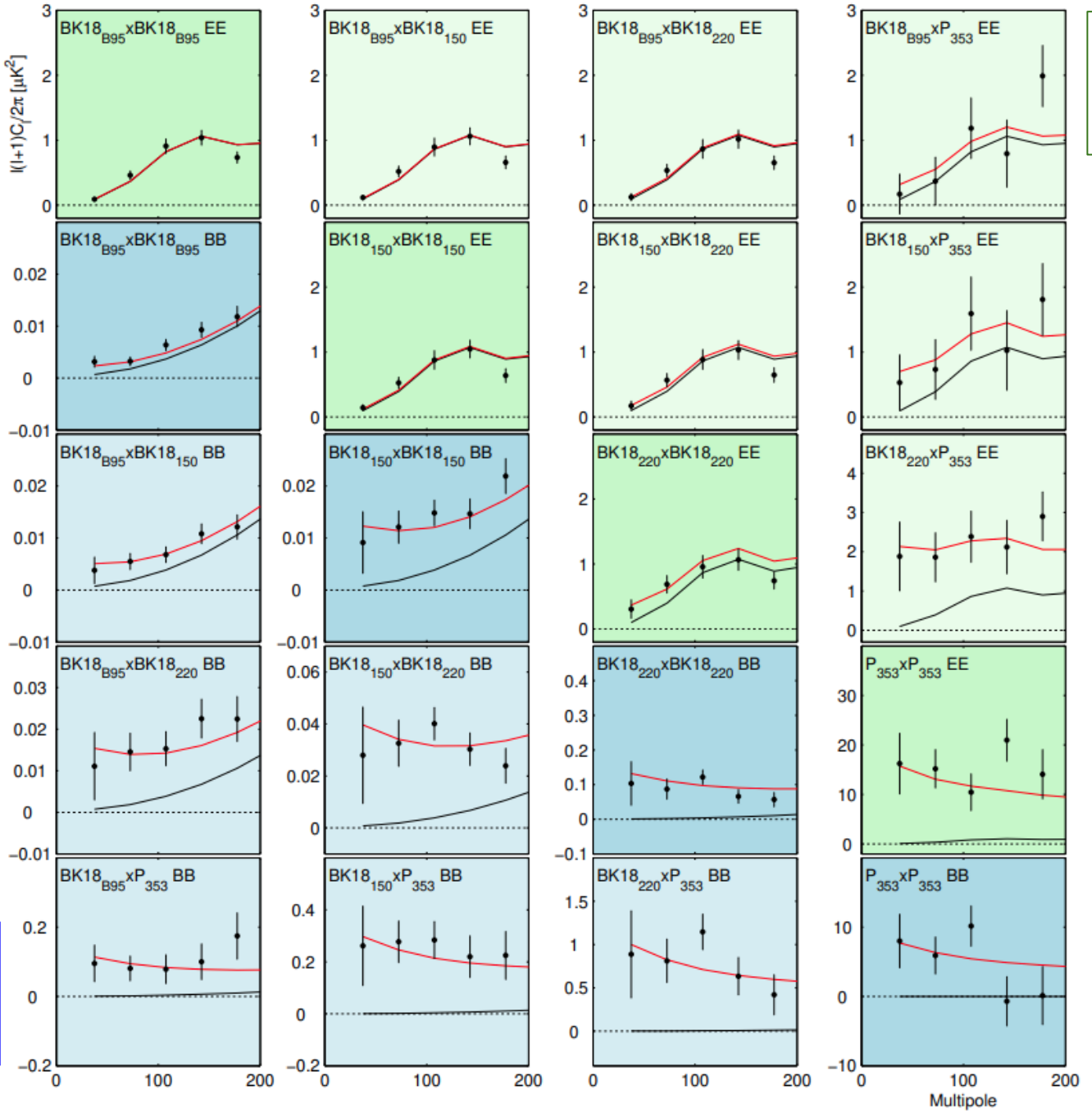
BK18 auto/cross spectra between: BICEP3 95GHz, BICEP2/Keck 150GHz, Keck 220GHz, and Planck 353GHz

Black lines are LCDM

Red lines are LCDM+foreground

Blue panels are BB spectra

Green panels are EE spectra



Multicomponent likelihood analysis

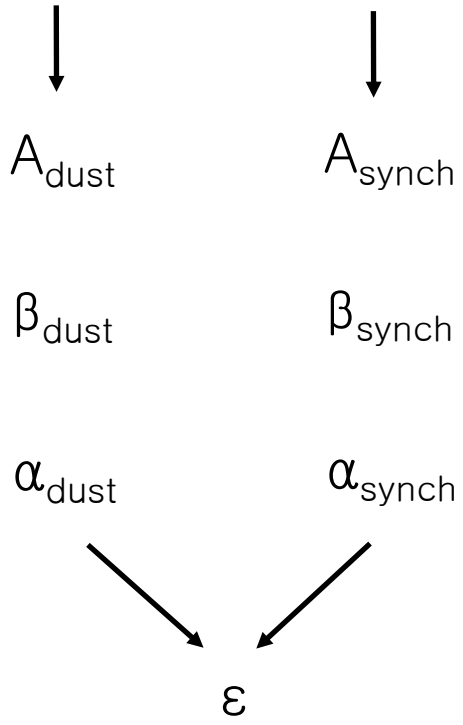
Take the joint likelihood of all the spectra simultaneously vs. model for BB that is the ΛCDM lensing expectation + 7 parameter foreground model + r

foreground model = dust + synchrotron

Foreground power spectra between maps X and Y:

$$D_{\ell,BB}^{X\times Y} = A_d f_d^X f_d^Y \left(\frac{\ell}{80}\right)^{\alpha_d} + A_s f_s^X f_s^Y \left(\frac{\ell}{80}\right)^{\alpha_s} + \epsilon\sqrt{A_d A_s}\left(f_d^X f_s^Y + f_s^X f_d^Y\right)\left(\frac{\ell}{80}\right)^{(\alpha_d+\alpha_s)/2}$$

where the frequency scalings f_d and f_s depend on spectral indices β_d and β_s



amplitudes @ l=80

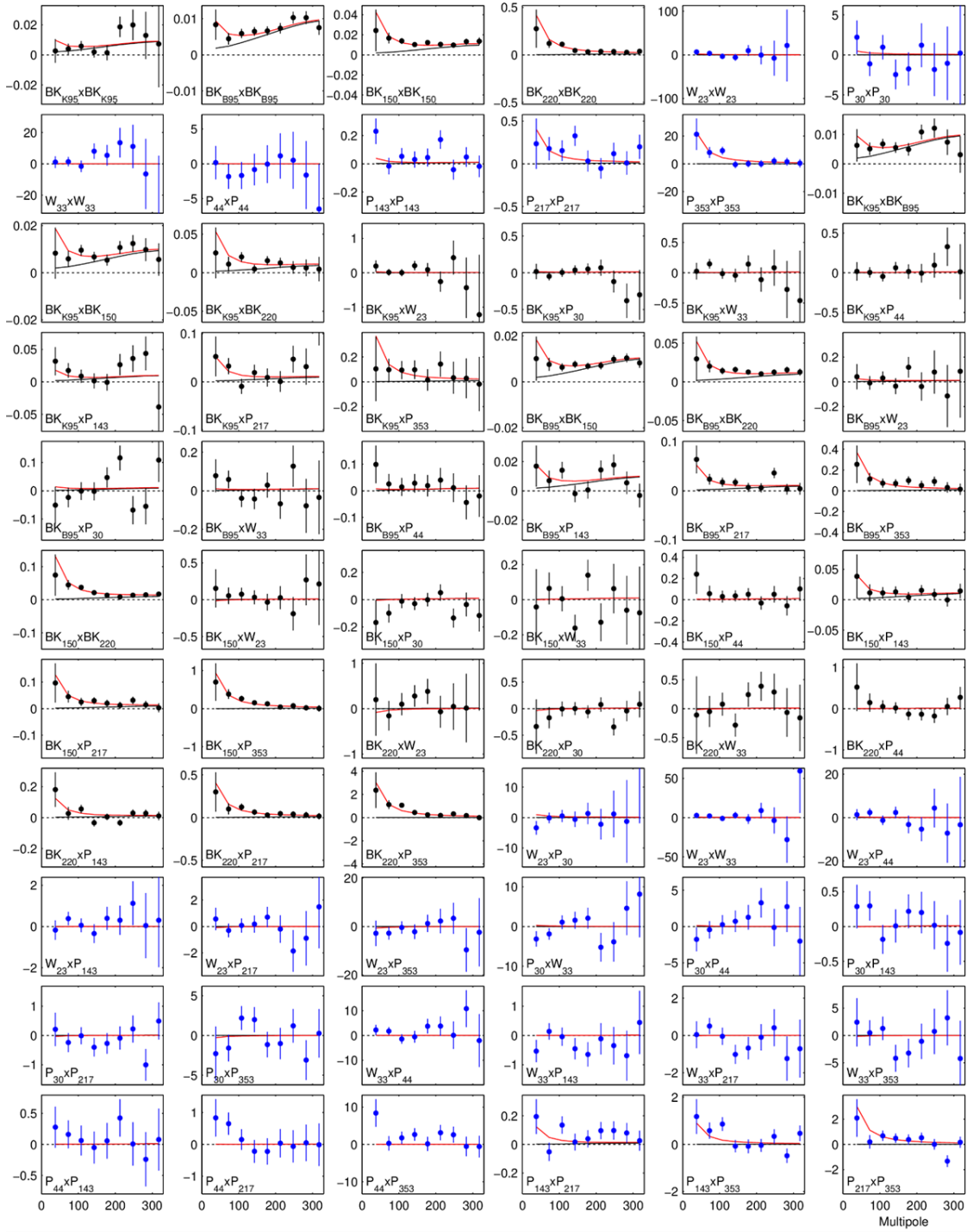
frequency spectral indices

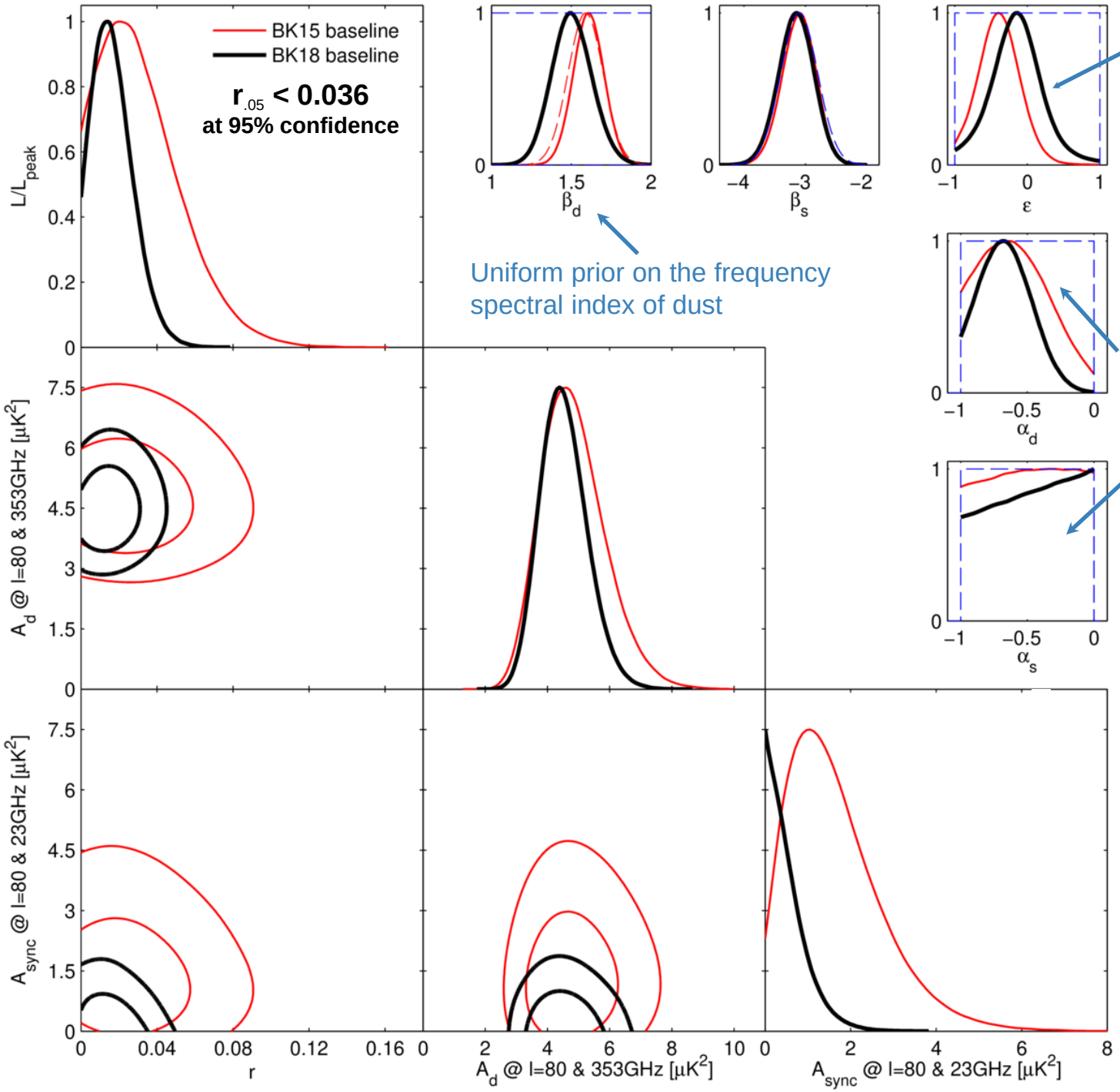
spatial spectral indices

dust/synch spatial correlation

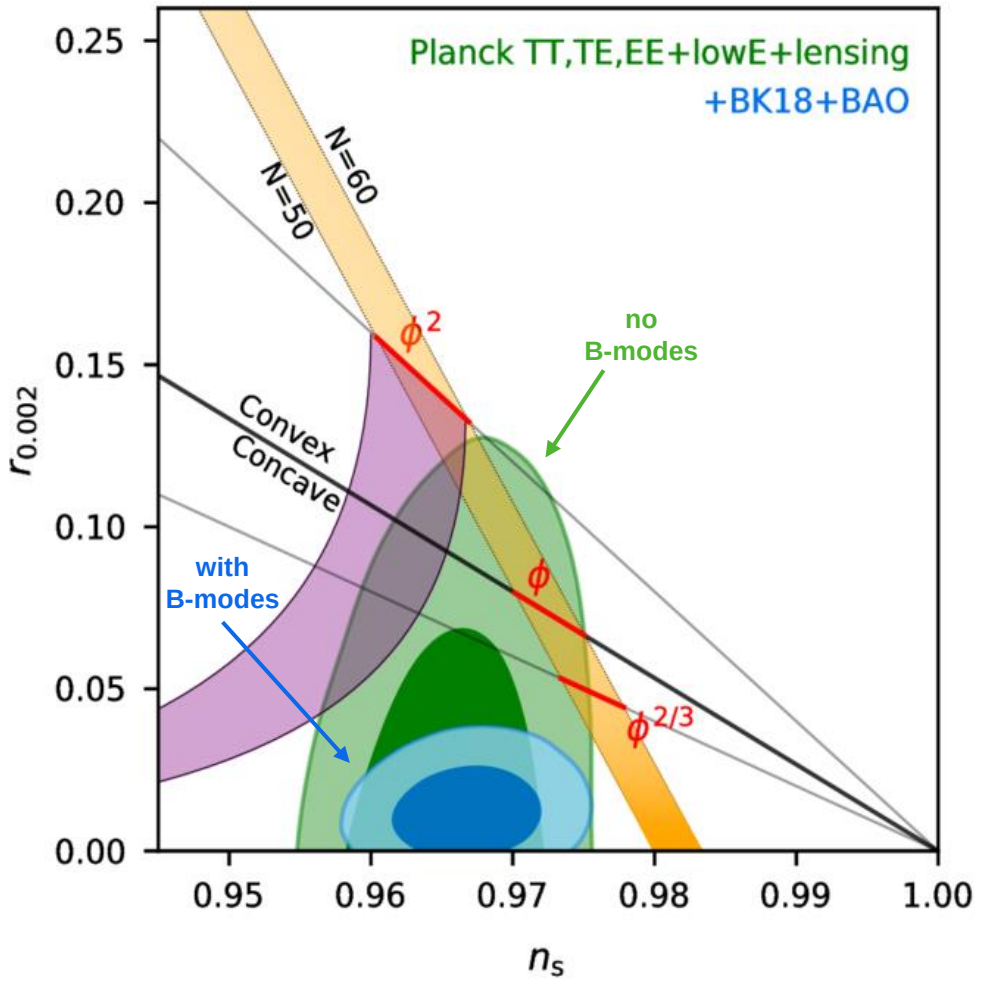
BK18

All auto and cross spectra





BK18
arxiv/2110.00483

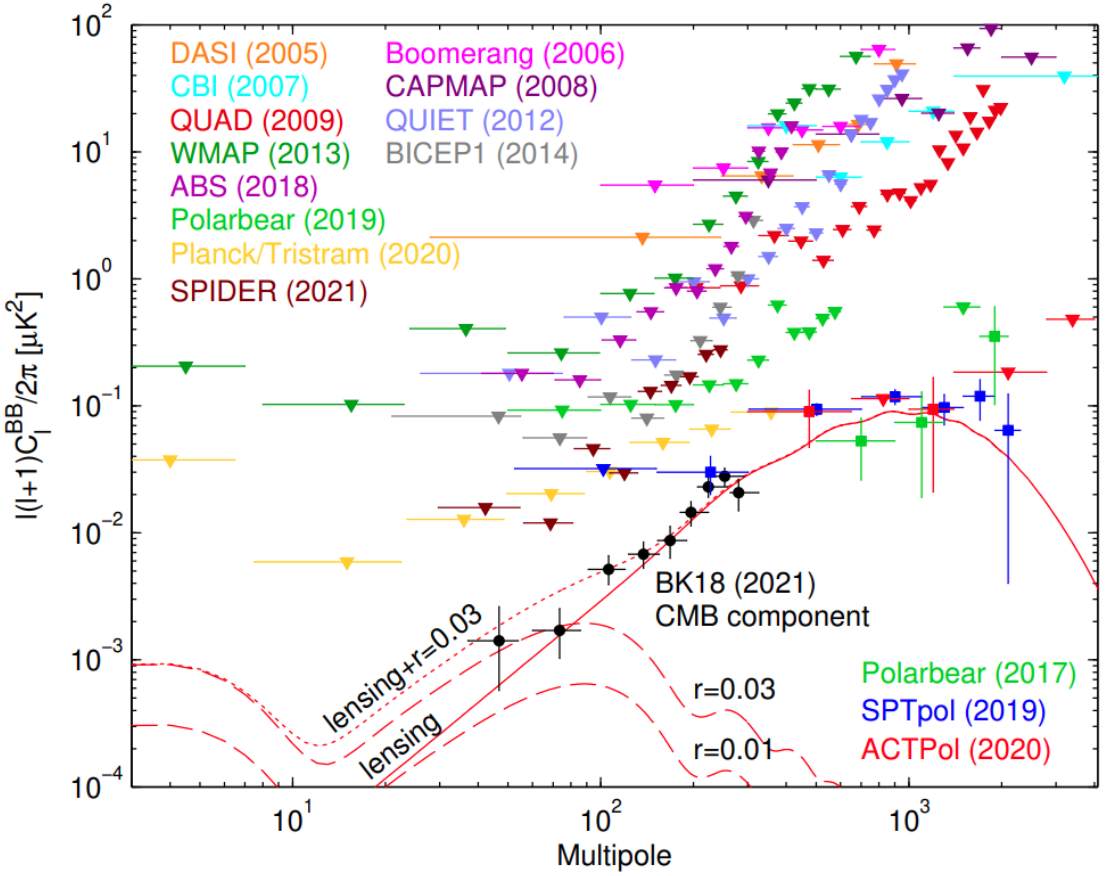


$r_{.05} < 0.035$

BK18

arxiv/2110.00483

Constraints on Inflation to Date (in 2022)

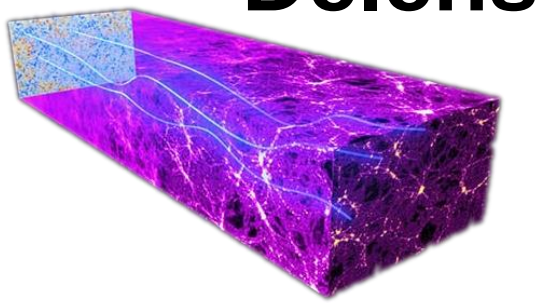


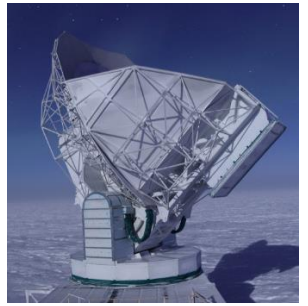
Posted B-Mode Sensitivity to r			
Experiment	**arxiv post**	**Bands [GHz]**	**σ(r)**
DASI	0409357	26…36	7.5
BICEP1 2yr	0906.1181	100, 150	0.28
WMAP 7yr	1001.4538	30…60	1.1
QUIET-Q	1012.3191	43	0.97
QUIET-W	1207.5034	95	0.85
BICEP1 3yr	1310.1422	100, 150	0.25
BICEP2	1403.3985	150	0.10
BK13 + Planck	1502.00612	150 + Planck	0.034
BK14 + WP	1510.09217	95, 150 + WP	0.024
ABS	1801.01218	150	0.7
Planck	1807.06209	30...353	~0.2
BK15 + WP	1810.05216	95,150,220+WP	0.020
Polarbear	1910.02608	150 + P	0.3
SPTpol	1910.05748	95 + 150	0.22
Planck/Tristram	2010.01139	30...353	0.07
SPIDER	2103.13334	95 + 150	0.13
BK18 + WP	2110.00483	95,150,220+WP	0.009
Polarbear	2203.02495	150 + P	~0.16

What limits BK18?

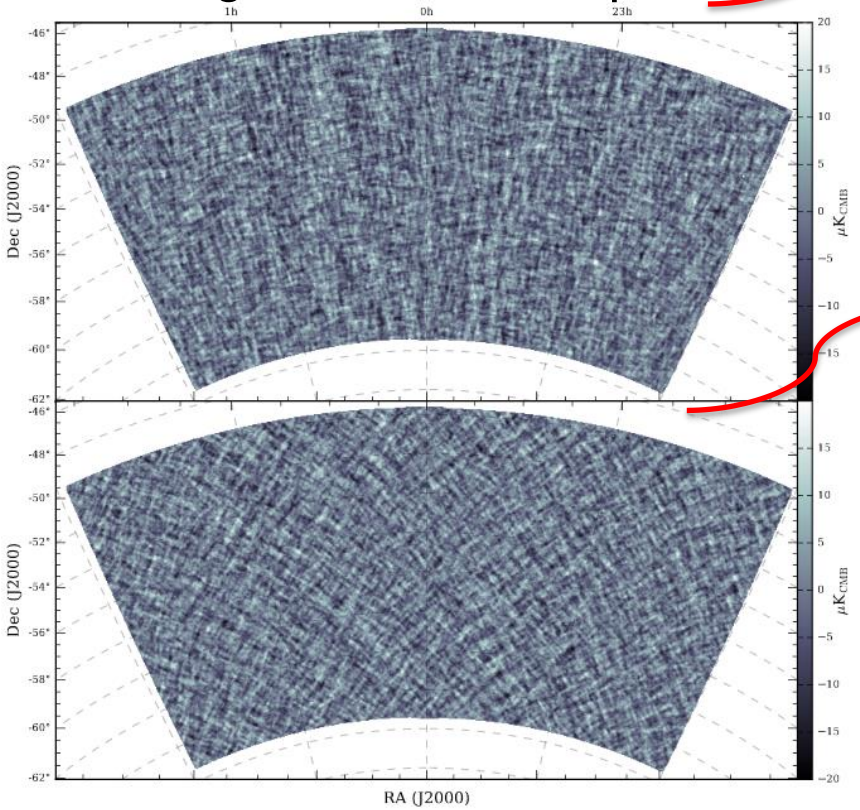
- BK18 mainline simulations with dust and lensing give $\sigma(r)$=0.009
- Running without foreground parameters on simulations where the dust amplitude is set to zero gives $\sigma(r)$=0.007
  - The above is as it should be - we have correctly tuned the relative sensitivity of the 95/150/220 bands such that we don't suffer much penalty due to the presence of foregrounds.
- Running on simulations which contain no lensing gives $\sigma(r)$=0.004
  - The sample variance of the achromatic lensing foreground is a major limiting factor - we need delensing via high resolution measurements.
- Running without foreground parameters on simulations which have neither dust or lensing gives $\sigma(r)$=0.002

Delensing with SPT-3G data

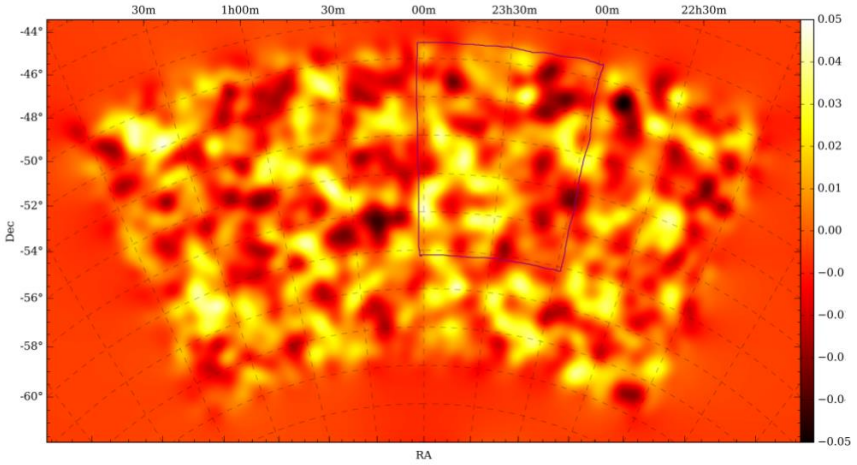




High resolution maps

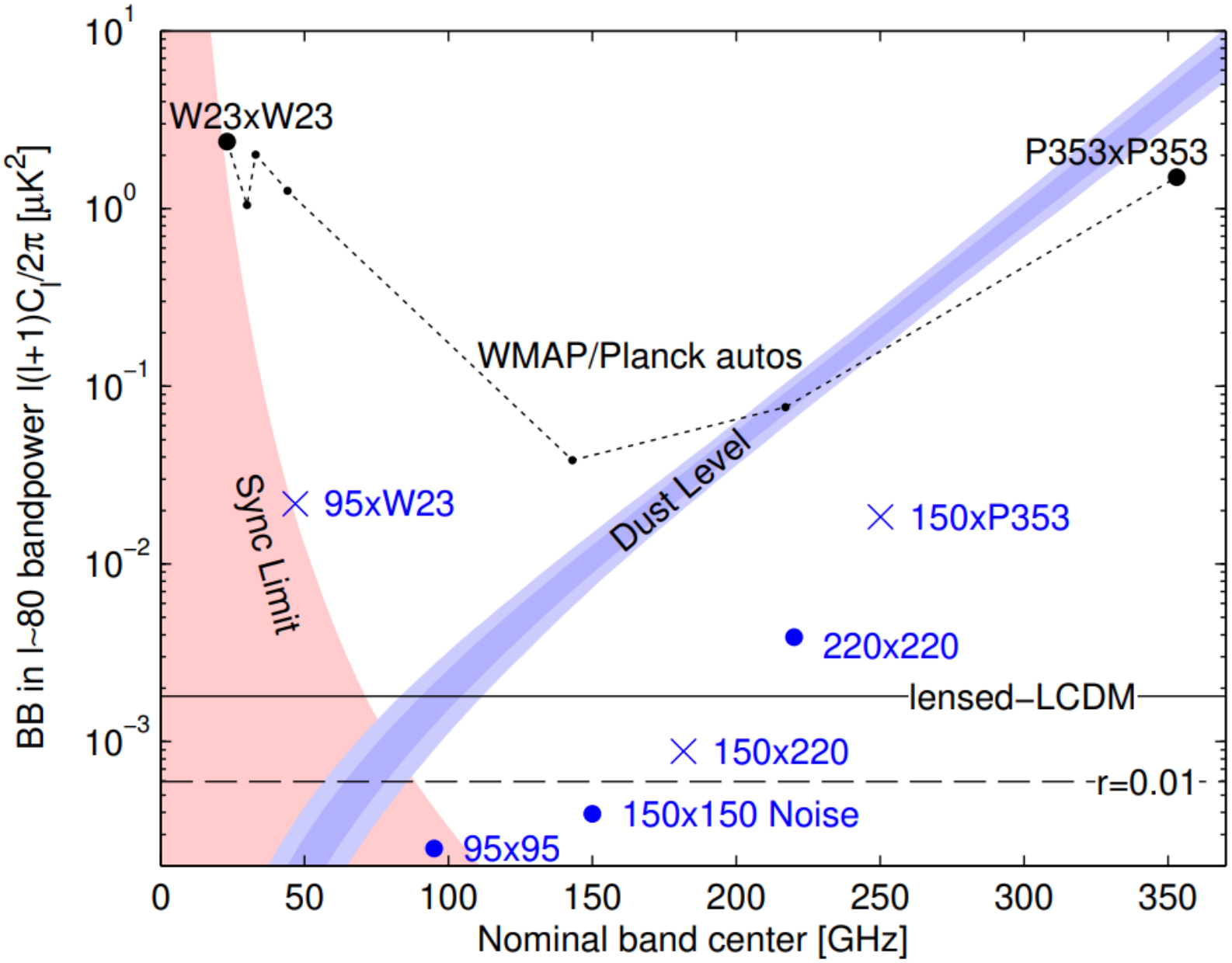


Can be used to reconstruct the lensing deflection map…



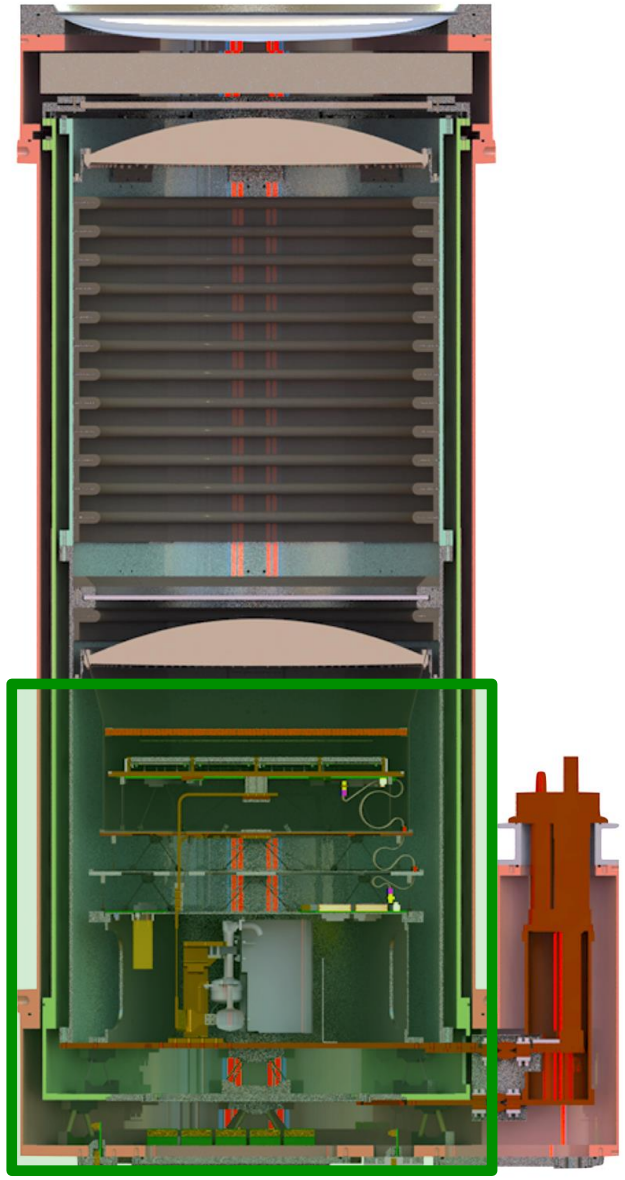
…which can then be used to calculate and remove the lensing signal enabling a deeper search for inflationary gravitational waves

BK18 ell=80 bandpower noise/signal

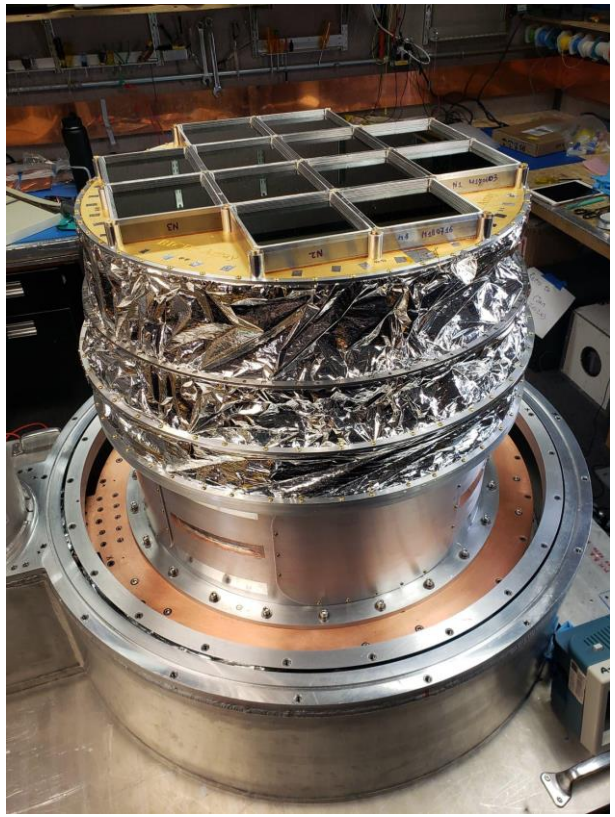


The BICEP/Keck Collaboration

BICEP Array Upgrades



BA1 Camera insert

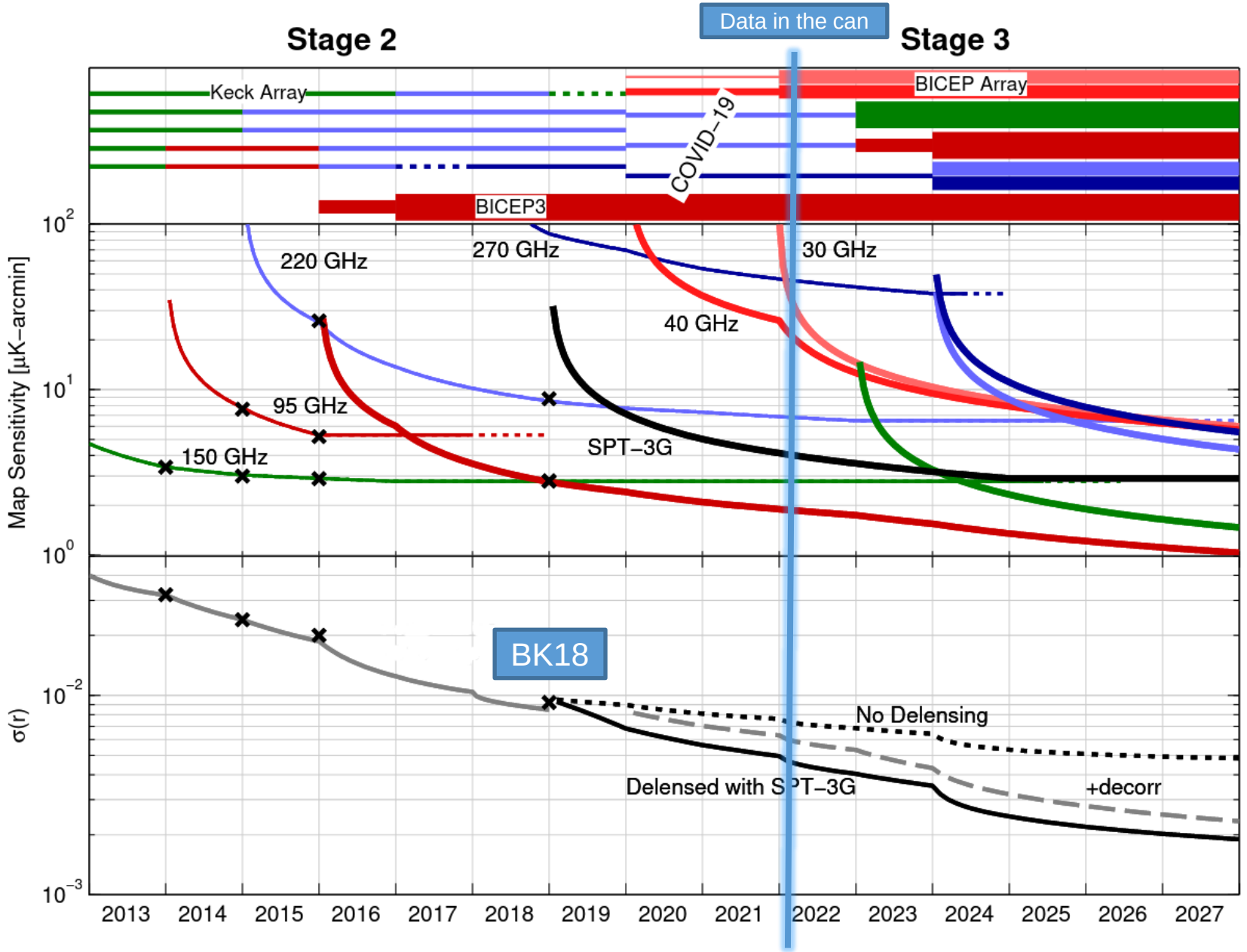


BICEP Array Mount 2020 Jan

Receiver Observing Band (GHz)	Nominal Number of Detectors	Nominal Single Detector NET ($\mu K_{cmb}\sqrt{s}$)	Beam FWHM (arcmin)	Survey Weight Per Year $(\mu K_{cmb})^{-2}$ yr^{-1}
Keck Array				
95	**288**	**288**	**43**	**24,000**
150	**512**	**313**	**30**	**30,000**
220	**512**	**746**	**21**	**2,750**
270	**512**	1,310	**17**	800
BICEP3				
95	**2,560**	**265**	**24**	**240,000**
BICEP Array				
30	157	260	76	19,500
40	379	318	57	20,500
95	4,056	265	24	380,000
150	7,776	313	15	455,600
220	8,112	746	11	58,600
270	12,288	1,310	9	19,200

arXiv: 2012.04047

Achieved and projected sensitivity



Summary

- 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 2016-2018 data (from BK15 to BK18)
  - Goes from $r_{0.05} < 0.07$ to $r_{0.05} < 0.036$, with $\sigma(r) = 0.02$ to $\sigma(r) = 0.009$
  - For the first time, no priors from other regions of sky
- We can keep going:
  - BICEP Array mount and first receiver at 30/40GHz running
  - Delensing in conjunction with SPT-3G

BICEP/Keck Publications

BICEP/Keck Results Papers

Series of results papers from the BICEP2 and Keck Array experiments, starting with initial BICEP2 results in March 2014.

- **BK-XV: The BICEP3 CMB Polarimeter and the First Three Year Data Set**
  *The BICEP/Keck Collaboration, ApJ **927**, 77, 2022*
  PDF / figures / arXiv / ADS
- **BK-XIV: Improved constraints on axion-like polarization oscillations in the cosmic microwave background**
  *The BICEP/Keck Collaboration, Phys. Rev. D **105**, 022006, 2022*
  PDF / figures / arXiv / ADS
- **BK-XIII: Improved Constraints on Primordial Gravitational Waves using Planck, WMAP, and BICEP/Keck Observations through the 2018 Observing Season**
  *The BICEP/Keck Collaboration, Phys. Rev. Lett. **127**, 151301, 2021*
  PDF / figures / arXiv / ADS / Data Products
- **BK-XII: Constraints on axion-like polarization oscillations in the cosmic microwave background**
  *The BICEP/Keck Collaboration, Phys. Rev. D **103**, 042002, 2021*
  PDF / figures / arXiv / ADS
- **BK-XI: Beam Characterization and Temperature-to-Polarization Leakage in the BK15 Dataset**
  *The Keck Array and BICEP2 Collaborations, ApJ **844**, 114, 2019*
  PDF / figures / arXiv / ADS
- **BK-X: Constraints on Primordial Gravitational Waves Using Planck, WMAP, and New BICEP2/Keck Observations through the 2015 Season**
  *The Keck Array and BICEP2 Collaborations, Phys. Rev. Lett. **121**, 221301, 2018*
  PDF / figures / arXiv / ADS / Data Products

More on bicepkeck.org

Thank you!
Q&A