The Hunt for Primordial Gravitational Waves with BICEP/Keck Array and SPIDER

Jeff Filippini

for the SPIDER and BICEP/Keck collaborations

ICHEP - August 5, 2016

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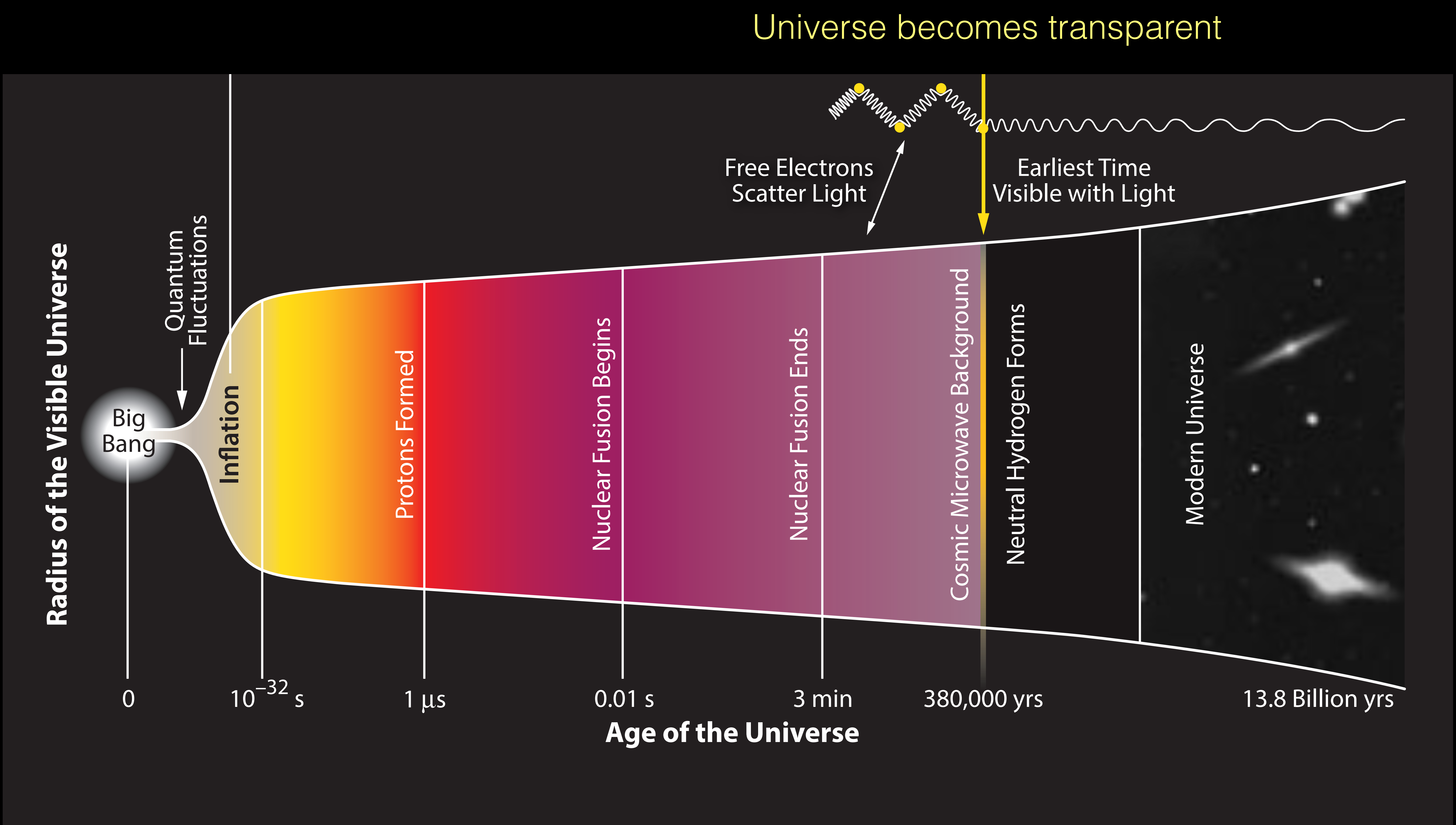
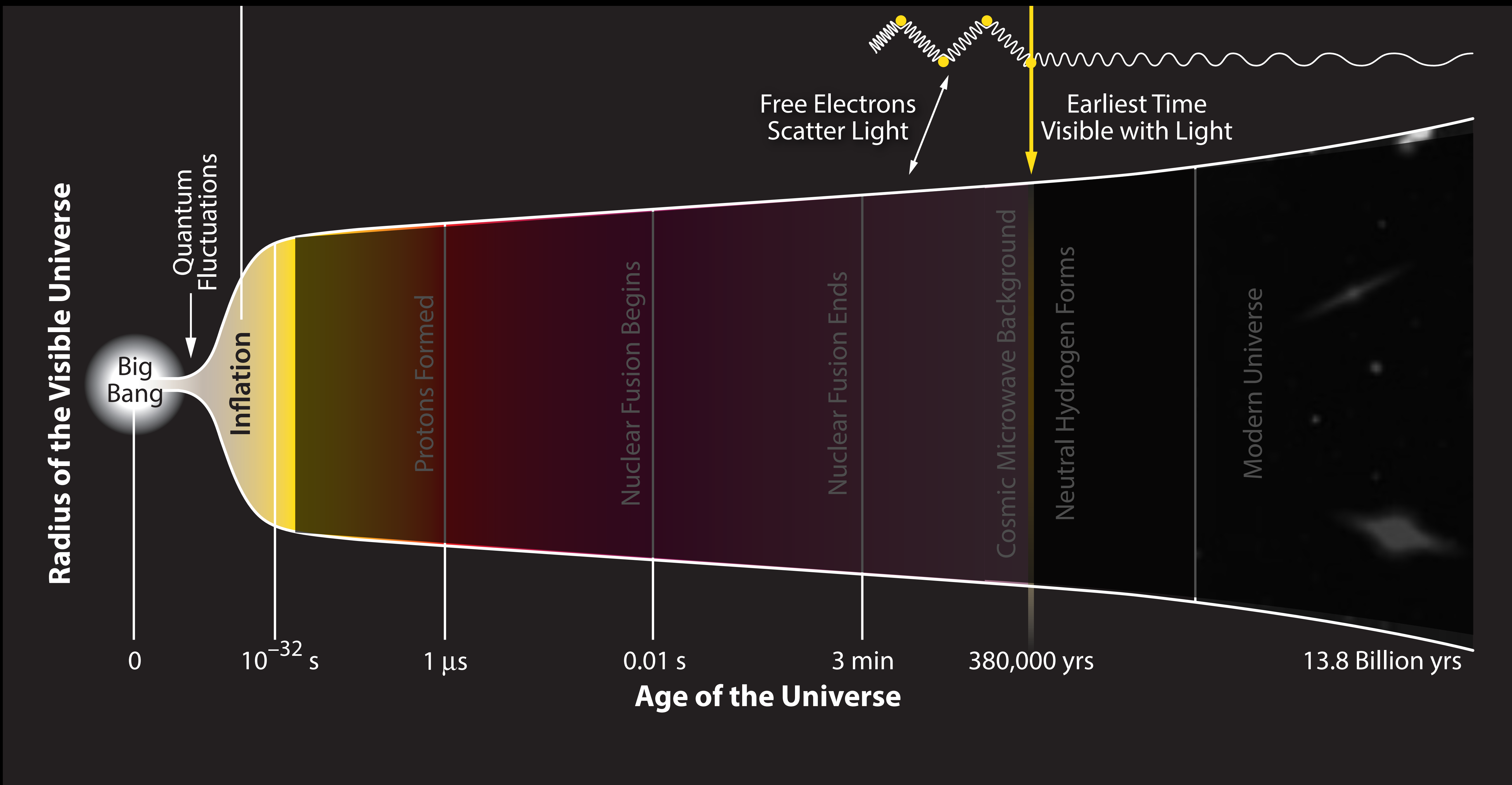
A History of Creation



A History of Creation

Universe becomes transparent

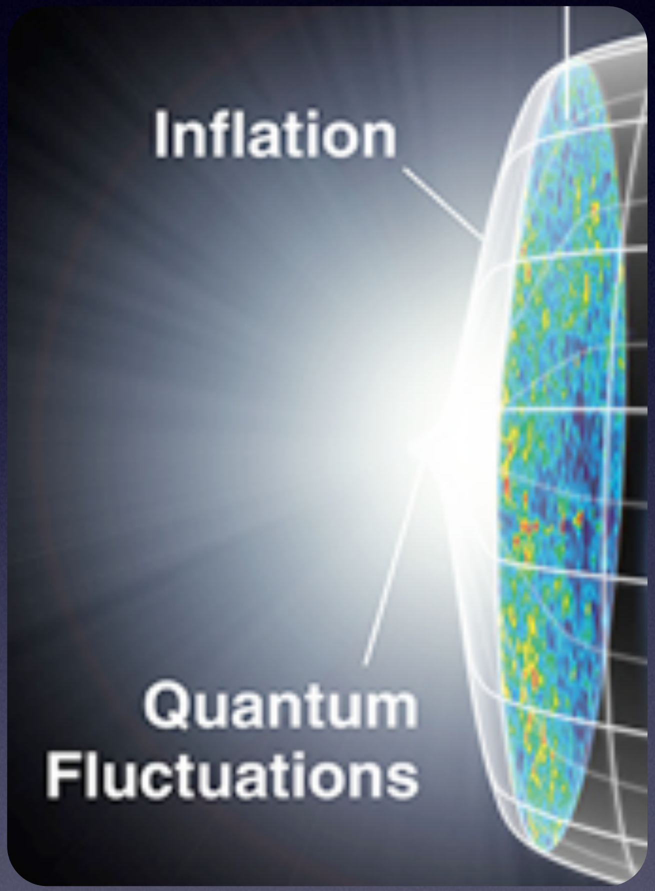


Inflation

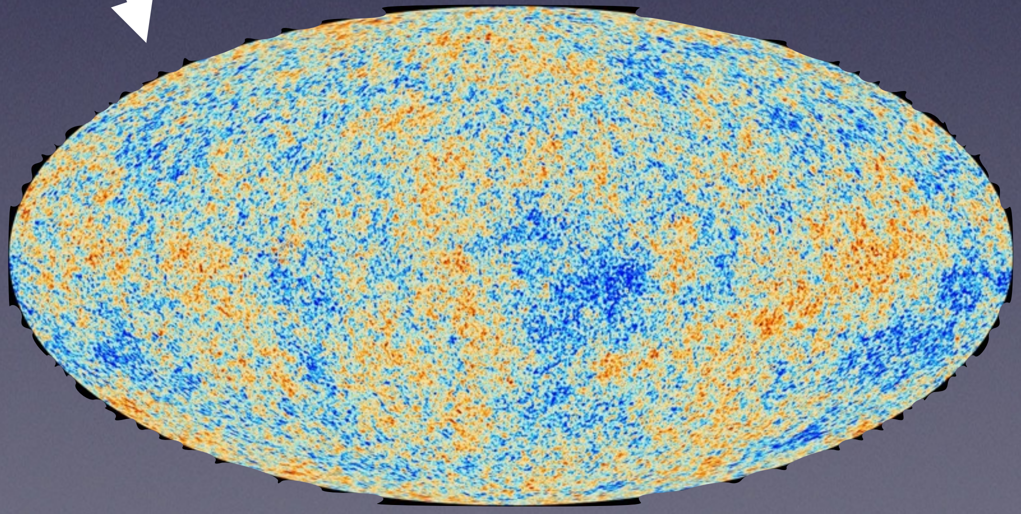
Quantum fluctuations…

"**inflaton**"

… imprinted onto cosmic scales



- ✓ Homogeneity
- ✓ Isotropy
- ✓ Nearly-flat geometry (Ω~1)
- ✓ Super-horizon fluctuations
- ✓ Nearly-scale invariant density perturbations (n_s~1)



Density perturbations

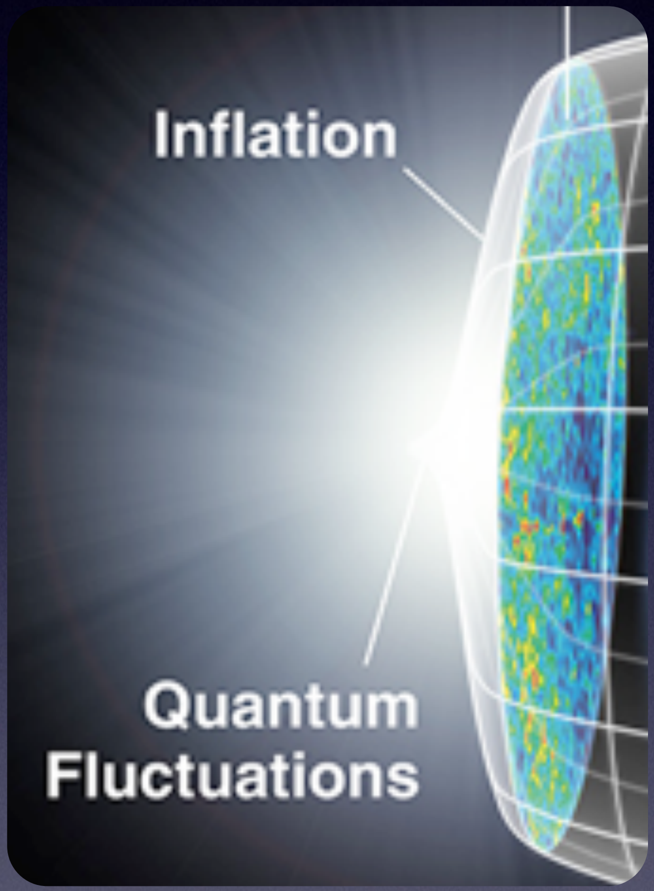
Inflation

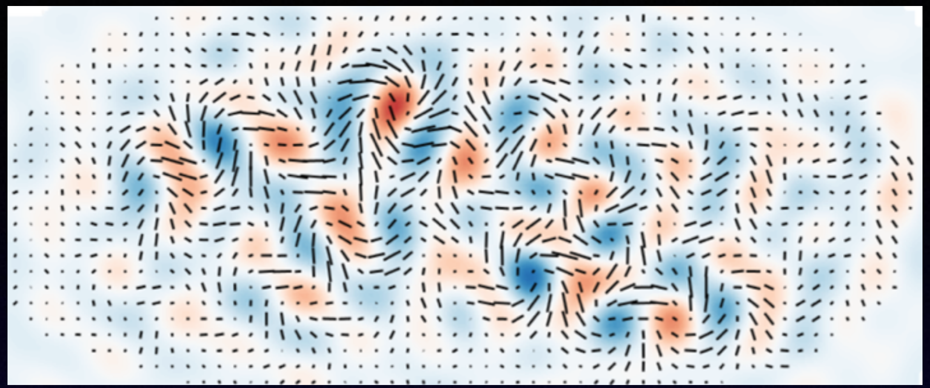
Quantum fluctuations…

“**inflaton**”

metric tensor

… imprinted onto cosmic scales

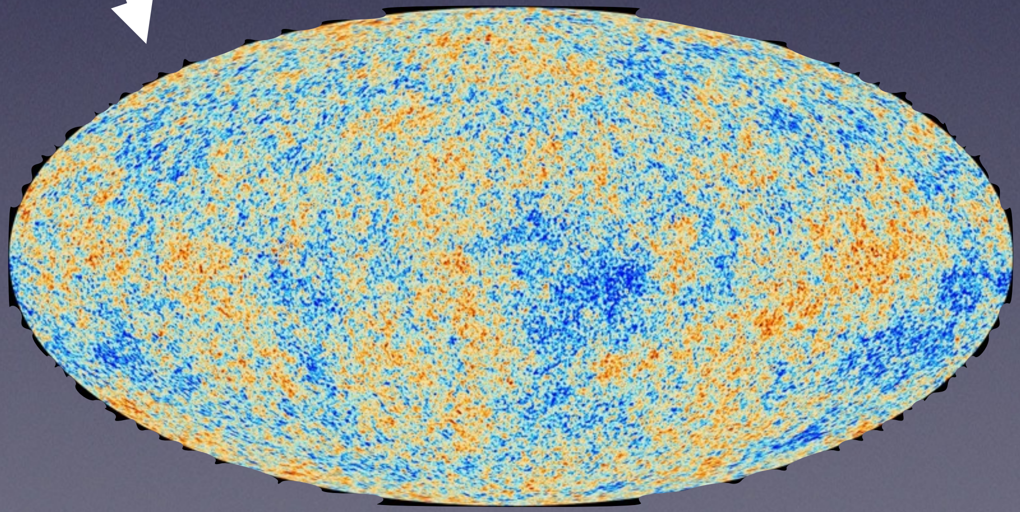




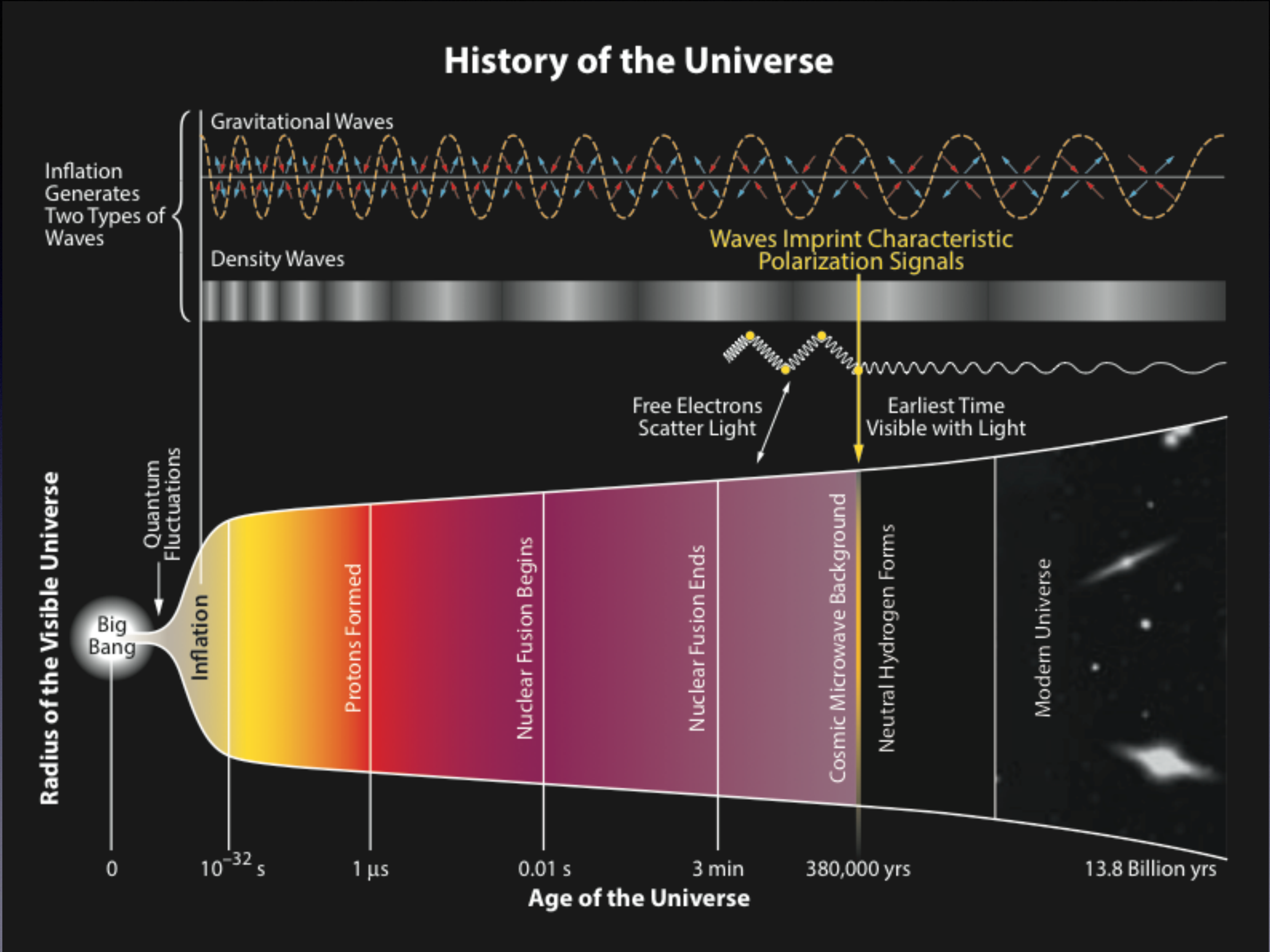
Primordial gravitational waves

$$r \approx \frac{V[\phi]}{(4 \times 10^{16}\mathrm{GeV})^4}$$

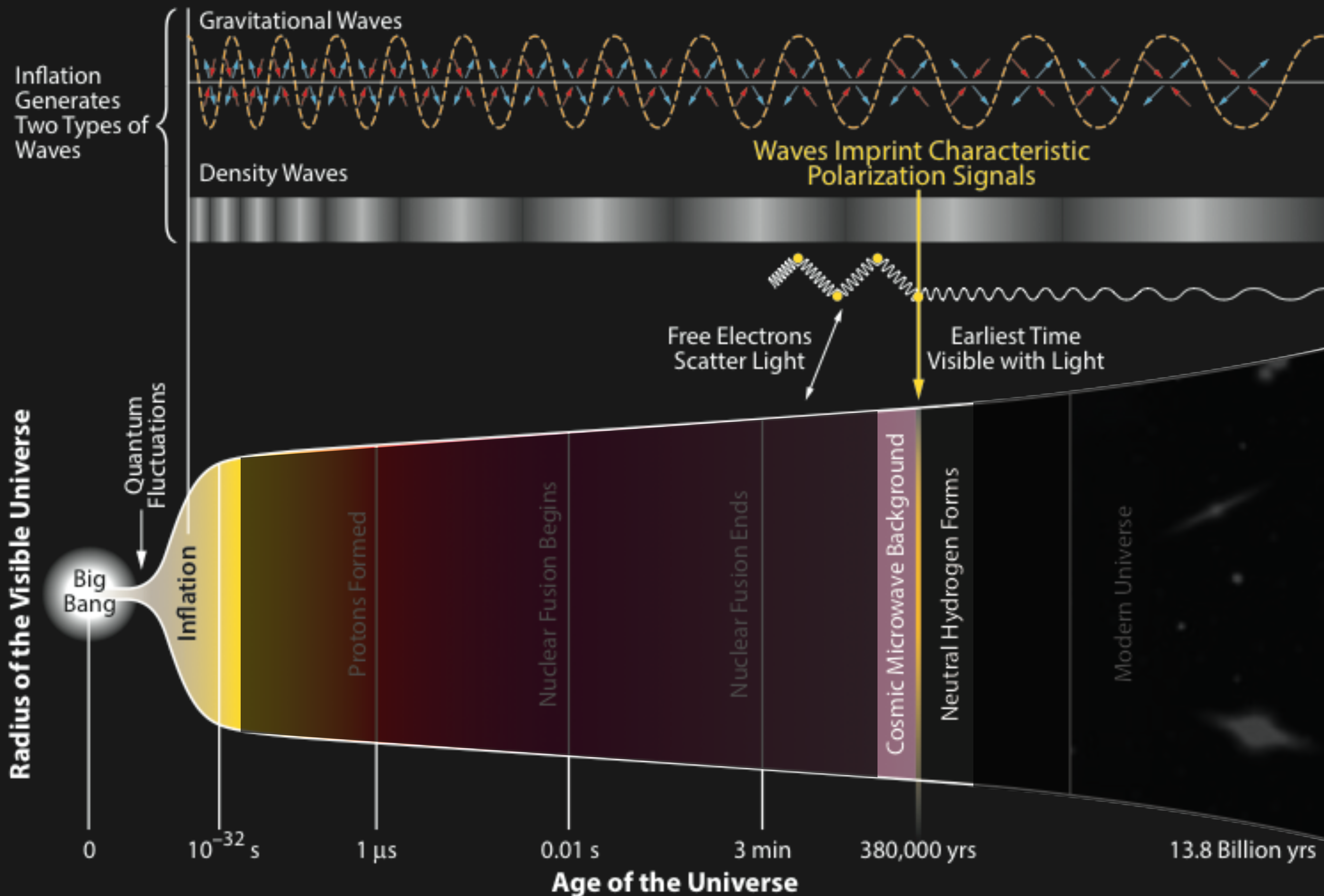
GUT-scale physics!?



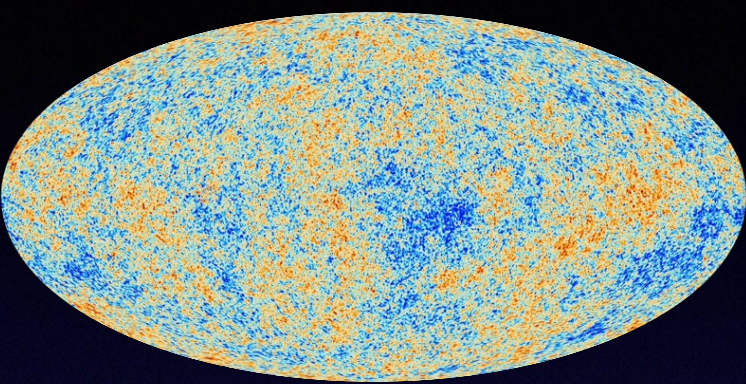
Density perturbations


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

History of the Universe



The Cosmic Microwave Background

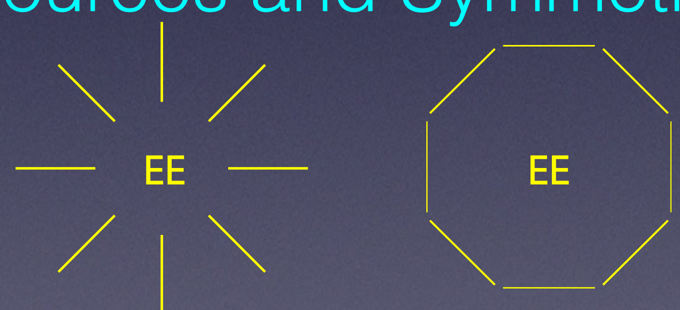


2.7K glow of primordial plasma

~10 ppm anisotropies

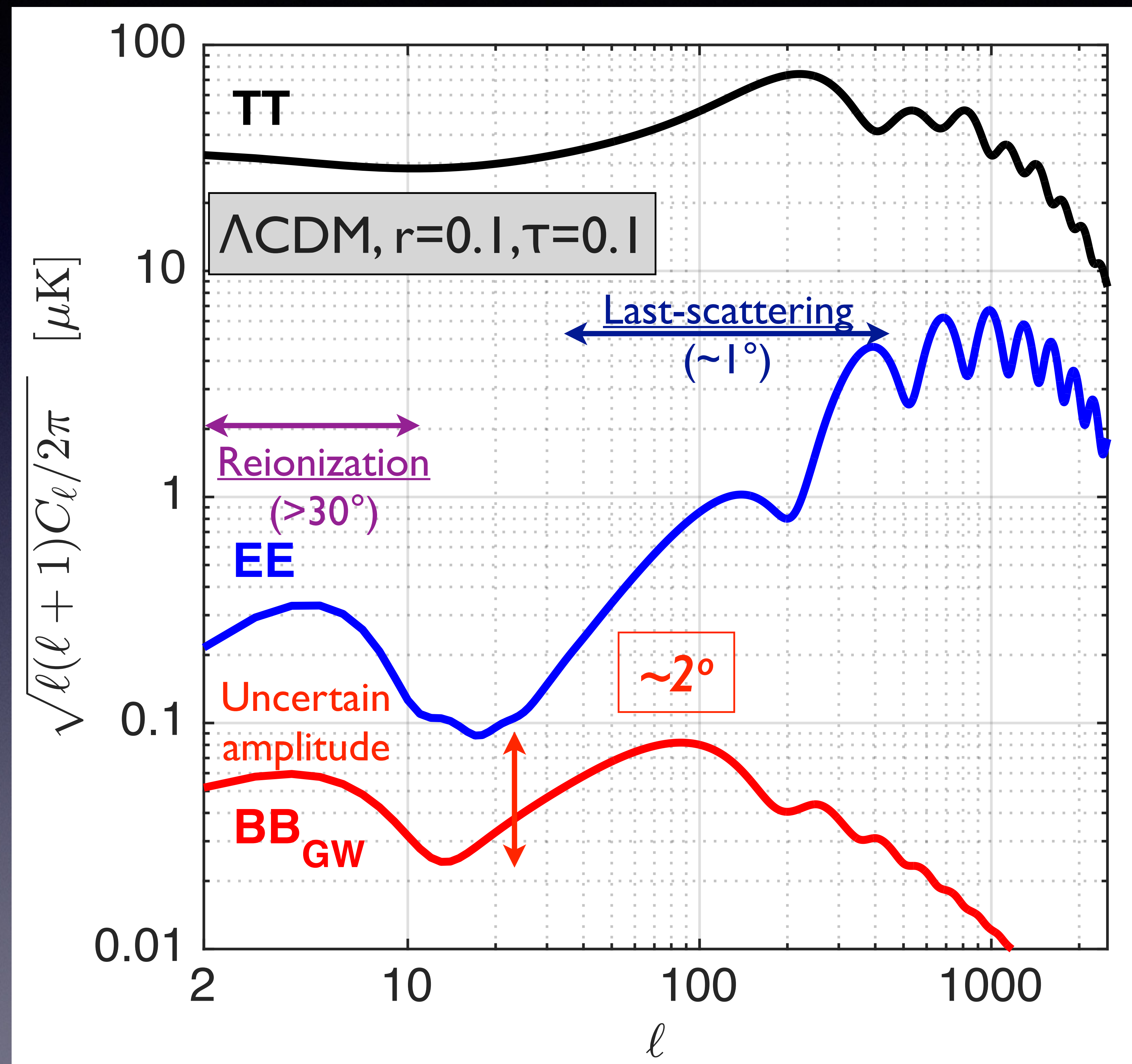
Polarized by Thompson scattering at ppm level

Sources and Symmetry

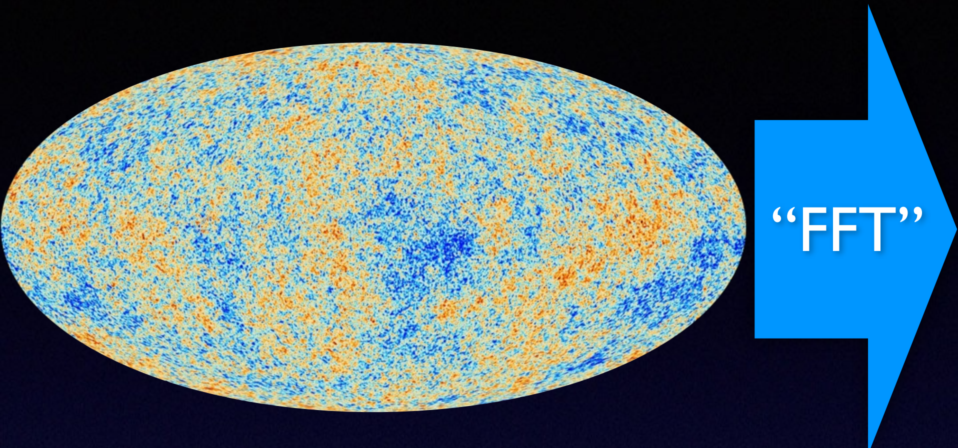


Scalar and Tensor modes

Tensor modes only



The Cosmic Microwave Background



2.7K glow of primordial plasma

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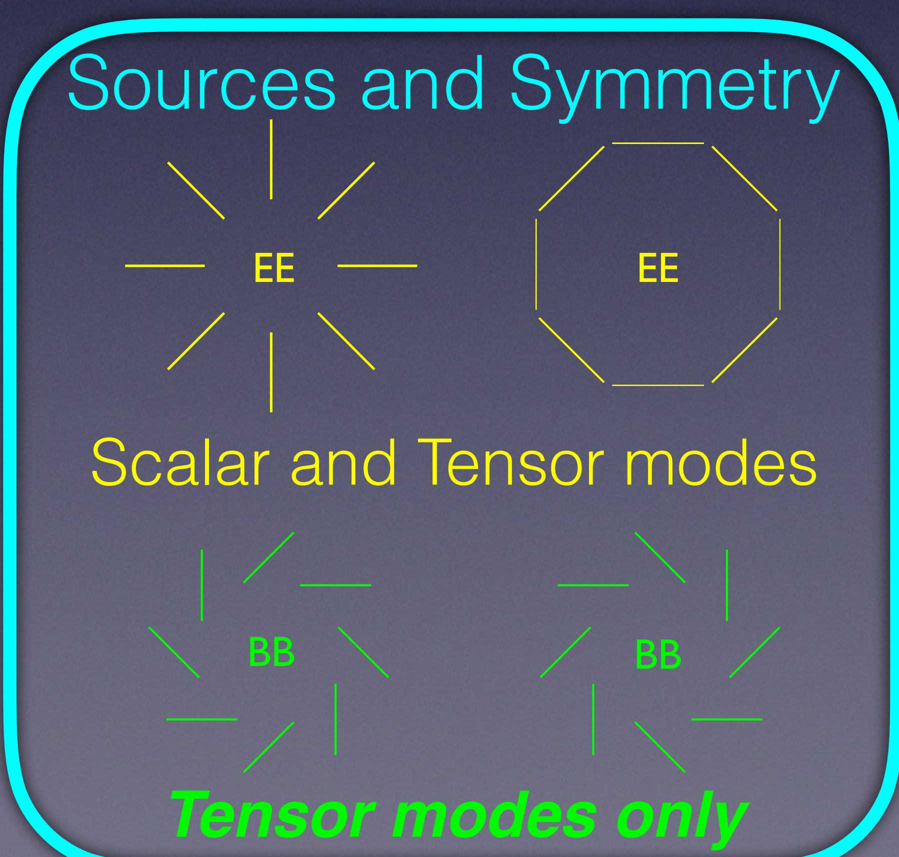
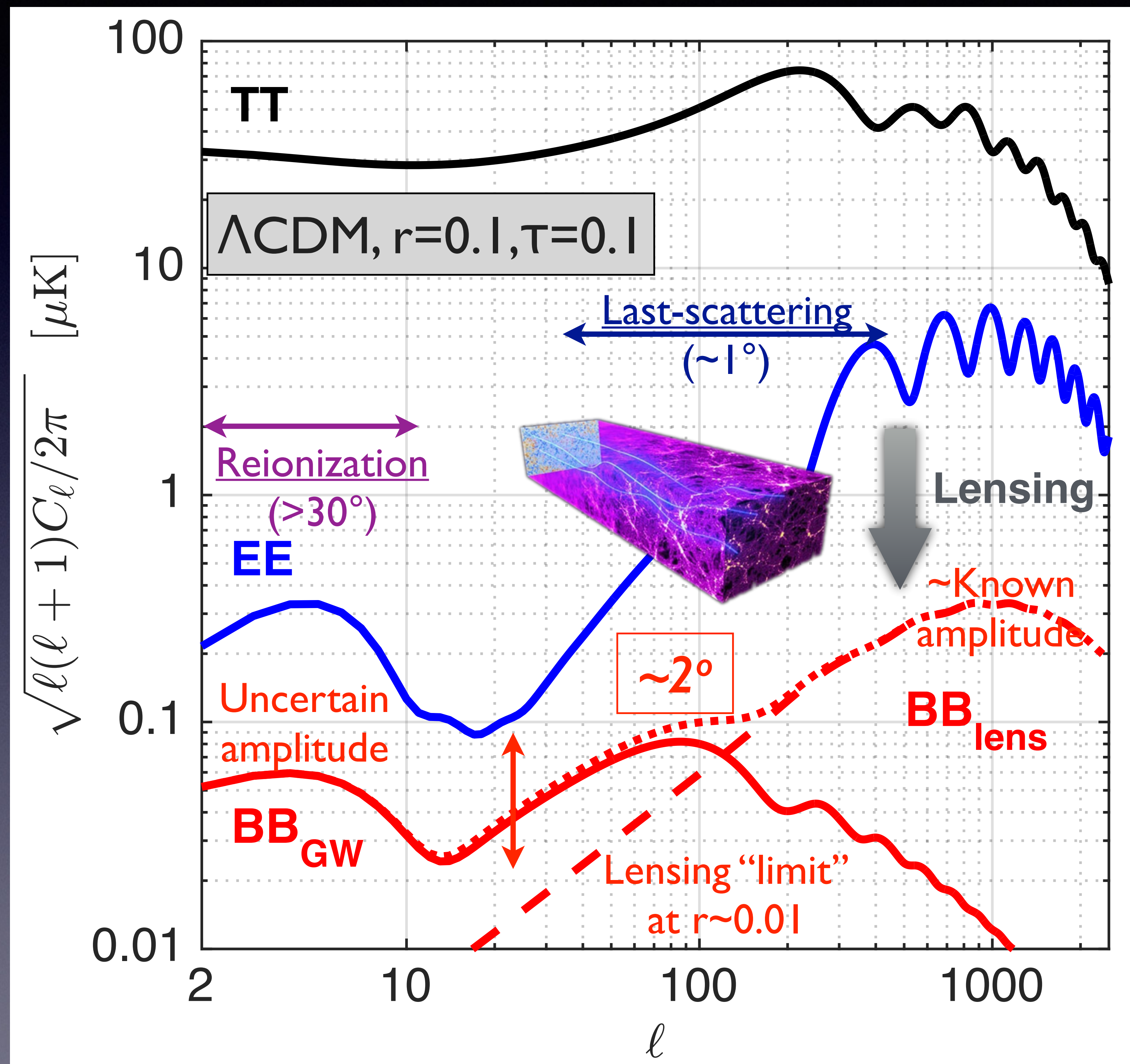
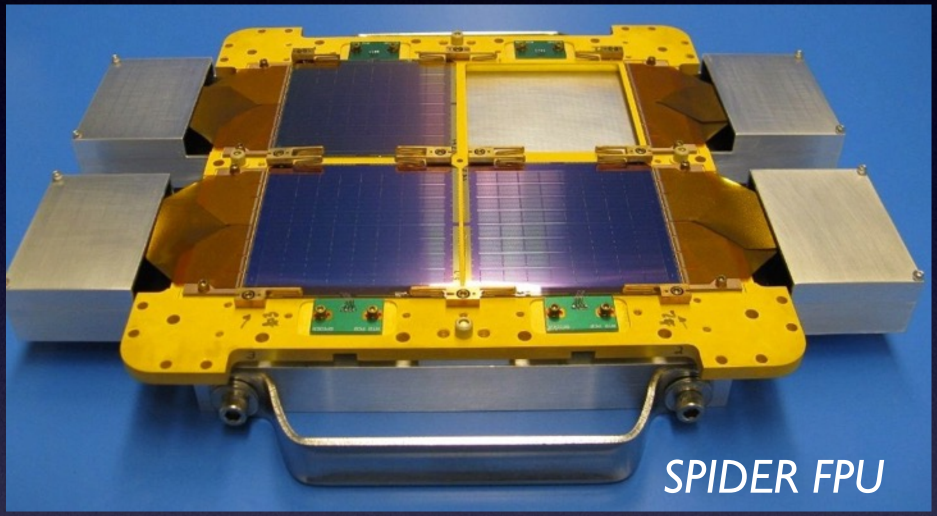




Challenges

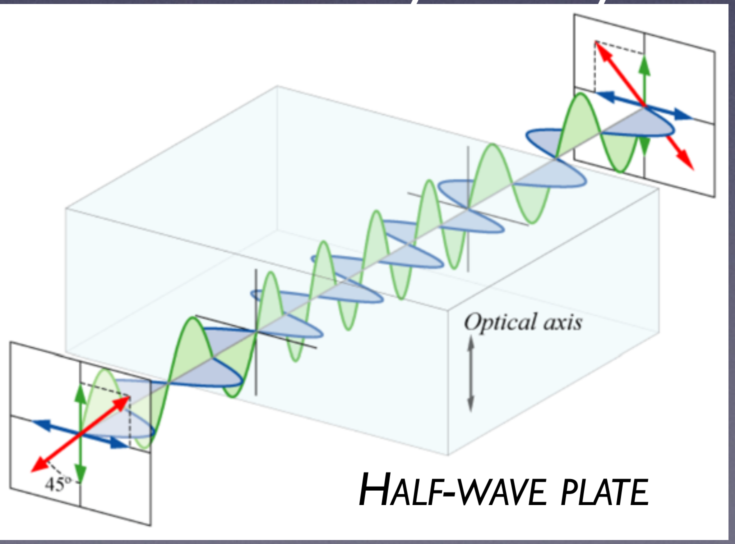
Precision

Detectors approach photon noise limit
Few photons, many detectors



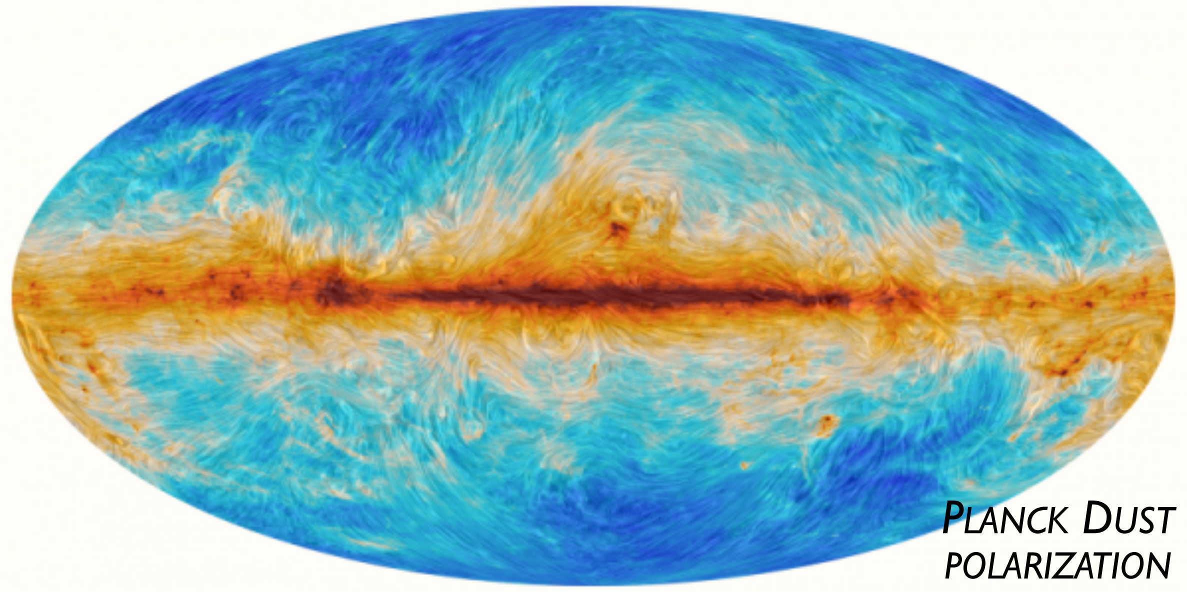
Accuracy

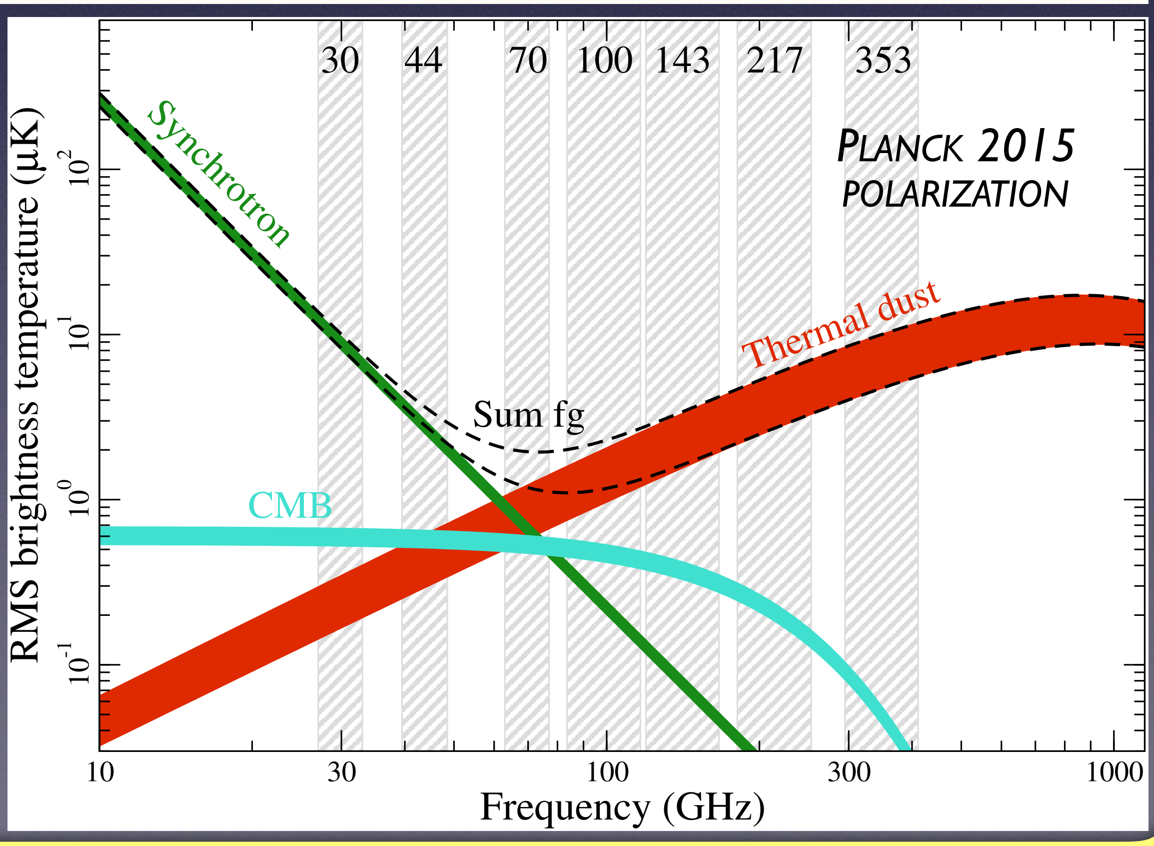
Rigid control of polarized systematics
Instrument symmetry



Clarity

Isolation of CMB from polarized foregrounds (*dust, synchrotron…*)





News from the BICEP/Keck Array experiments

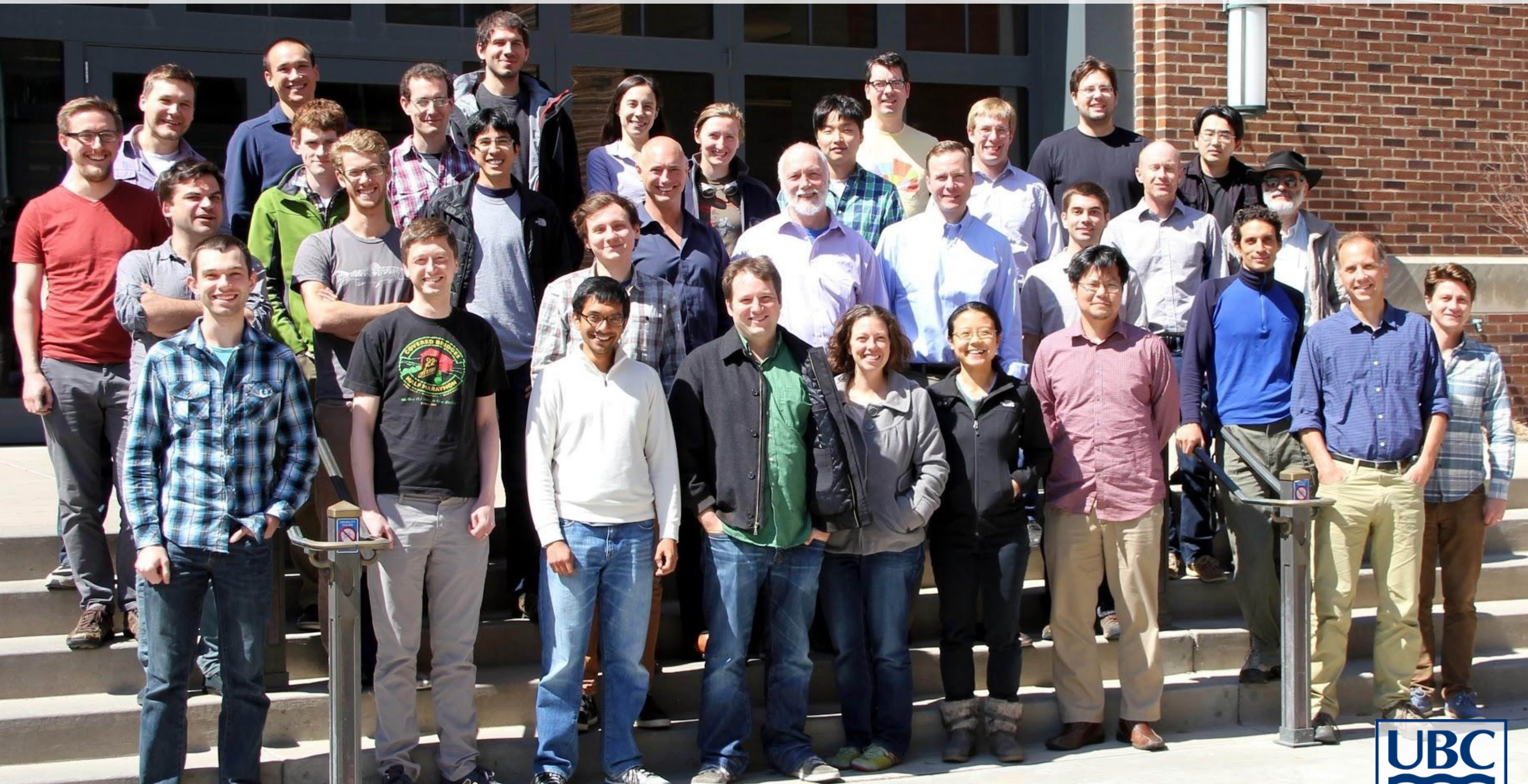
Zeeshan Ahmed
KIPAC, SLAC National Lab

August 5, 2016

ICHEP 2016

VE RI TAS
HARVARD

CALIFORNIA INSTITUTE OF TECHNOLOGY
1891



cea
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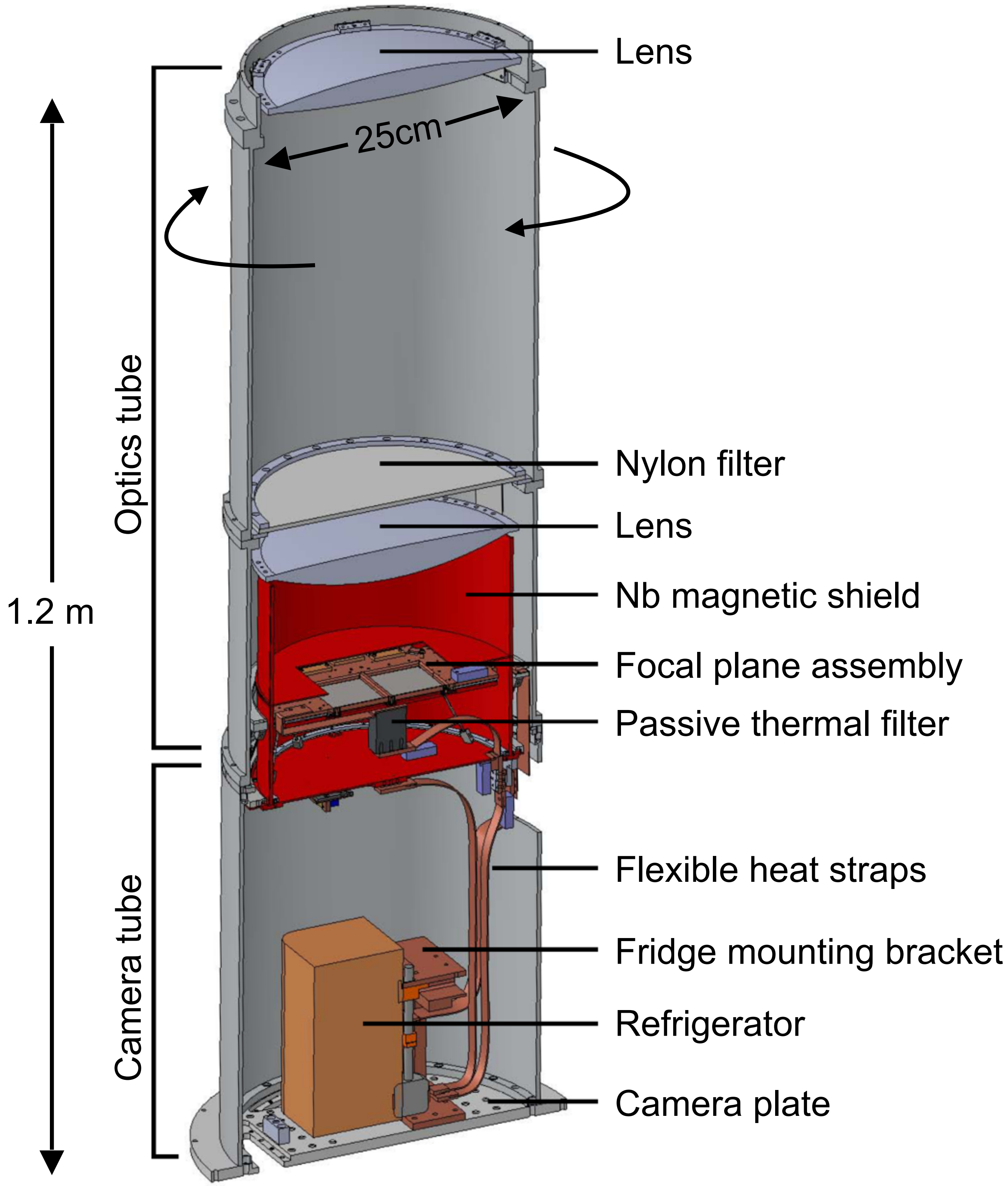
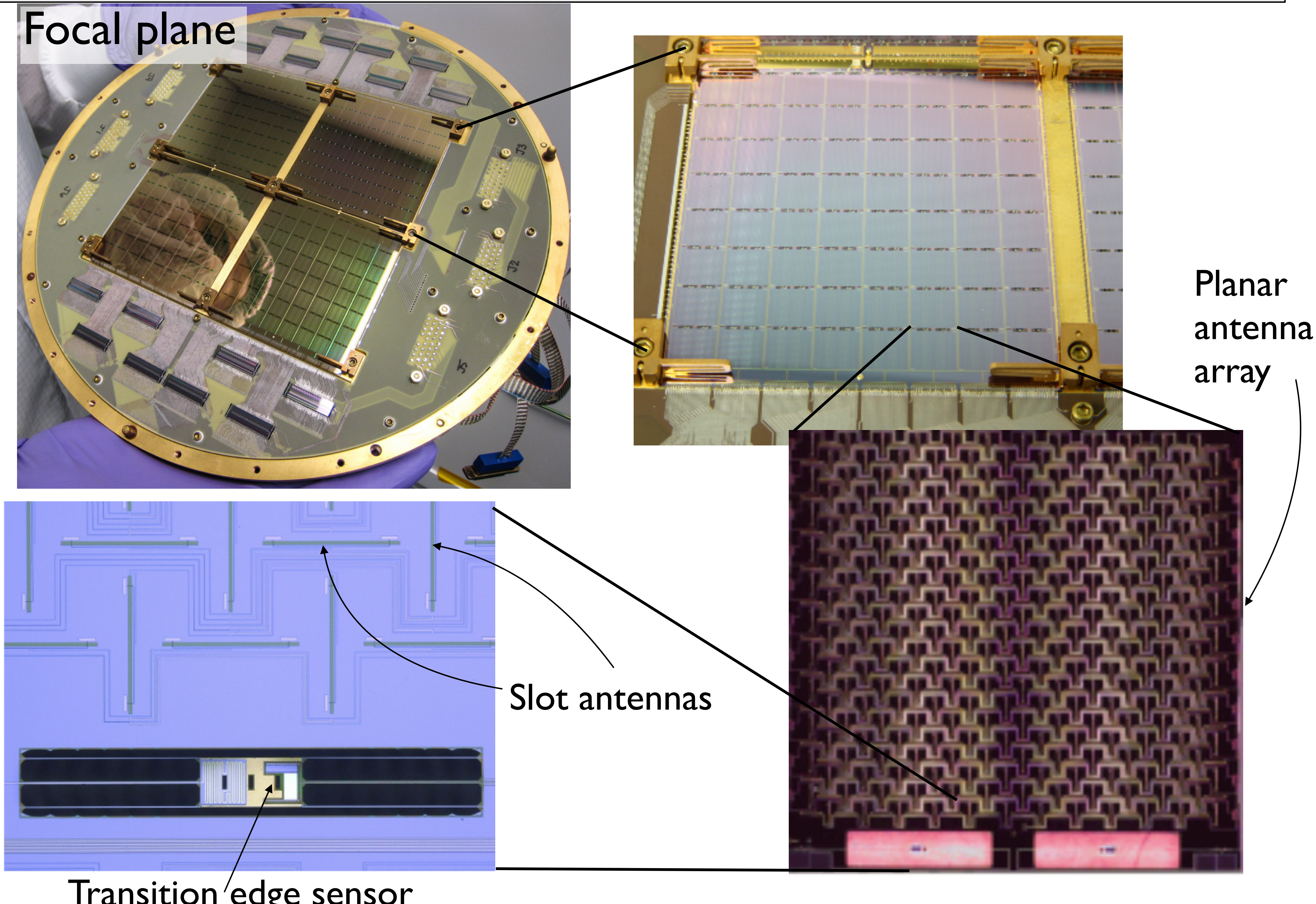
JPL
NIST
CARDIFF UNIVERSITY
UNIVERSITY OF TORONTO
UBC

Compact receiver + Cold Optical Design

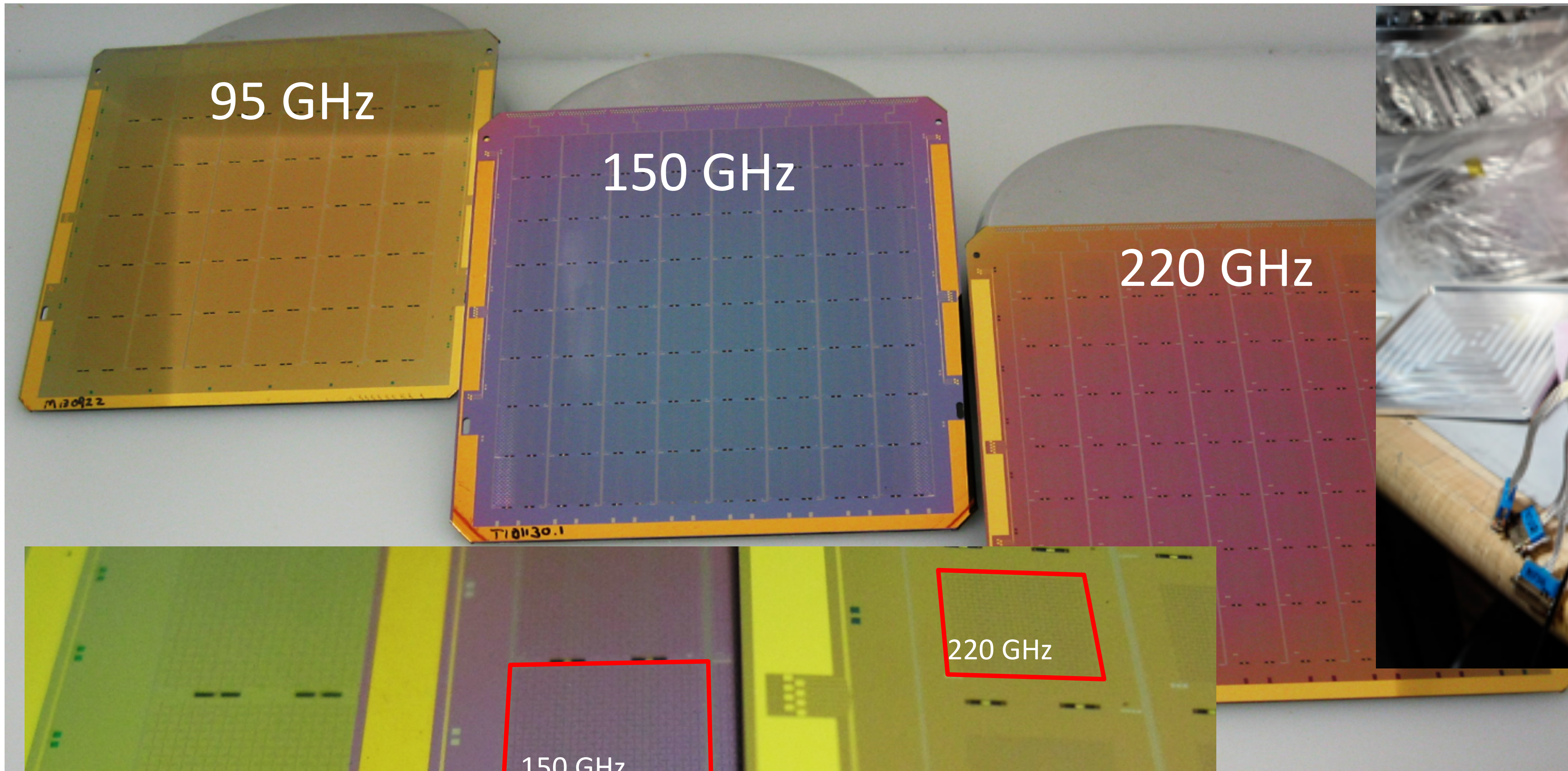
- Compact telescope to resolve only degree-scale features. *Minimum aperture for the science!*
- Entire telescope rotates around boresight for polarization modulation.
- On-axis, refractive optics
- Co-moving forebaffle to terminate sidelobes.
- Optical elements are cooled to ~4K to reduce internal loading (*photon noise*)

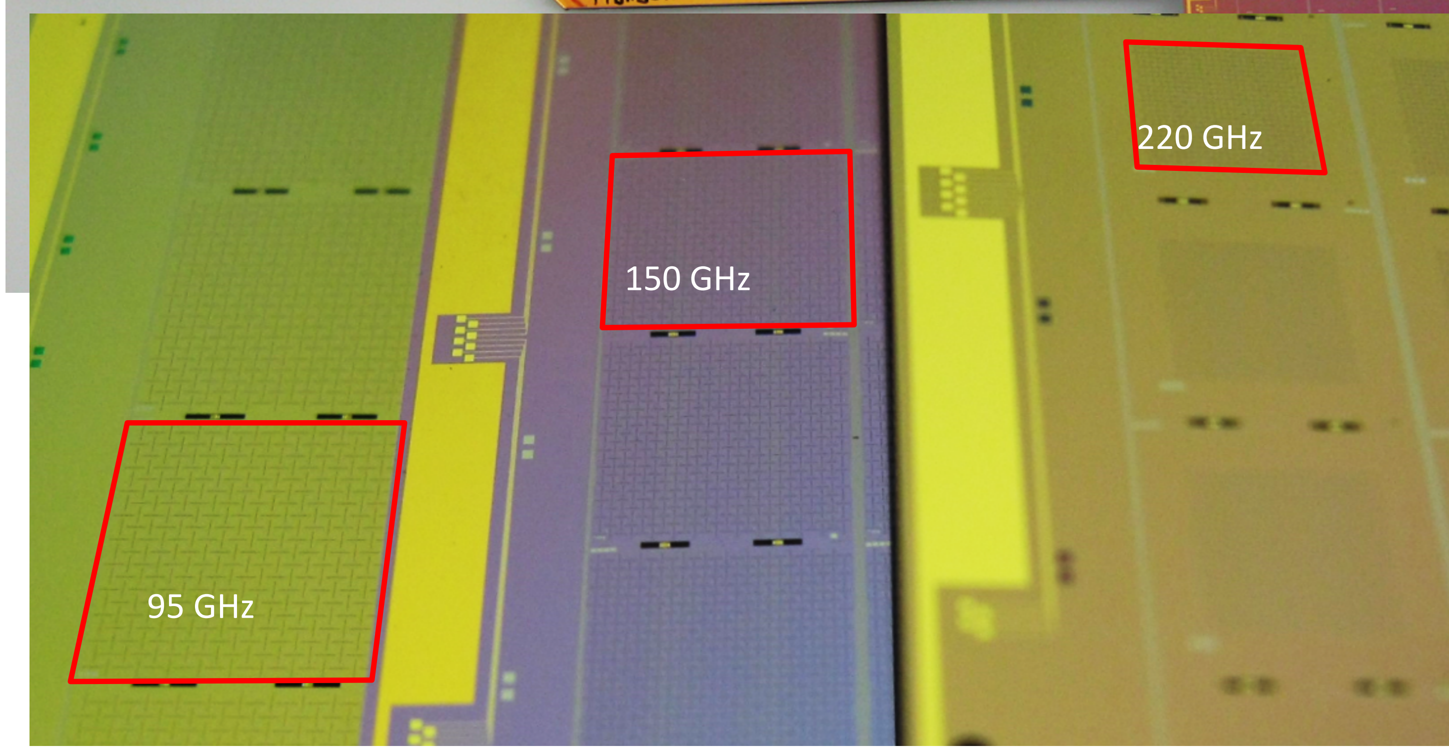


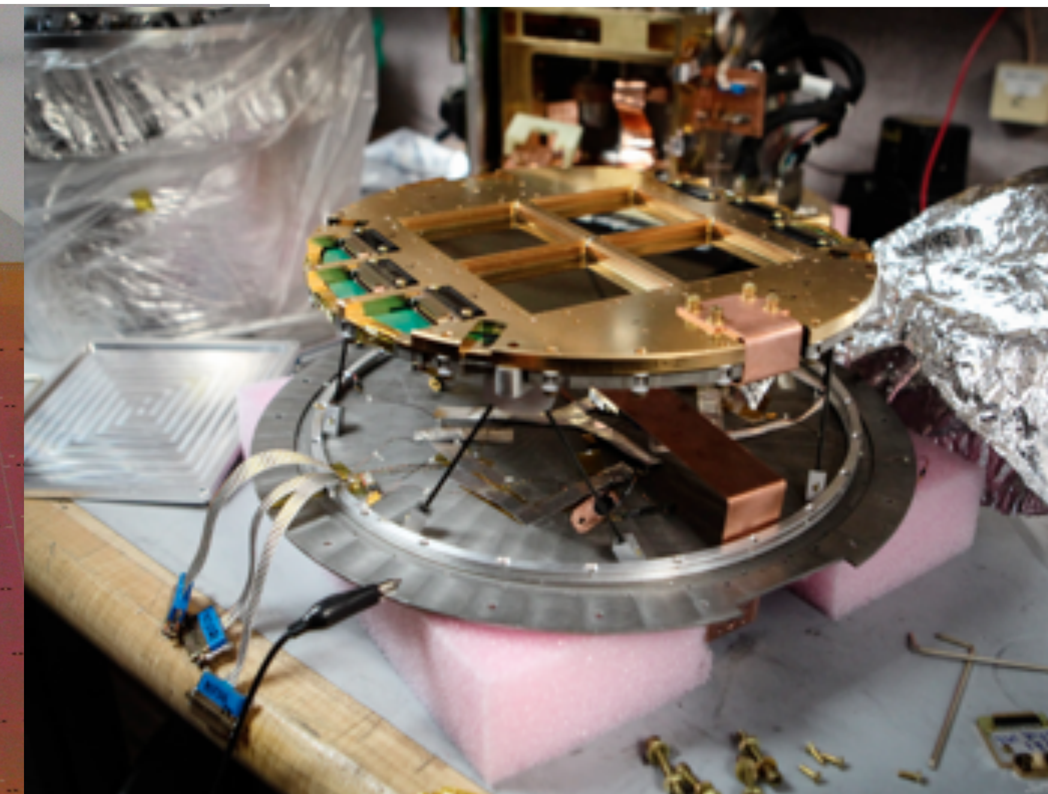
Photon-noise limited superconducting detectors



Multi-frequency to constrain CMB & foregrounds



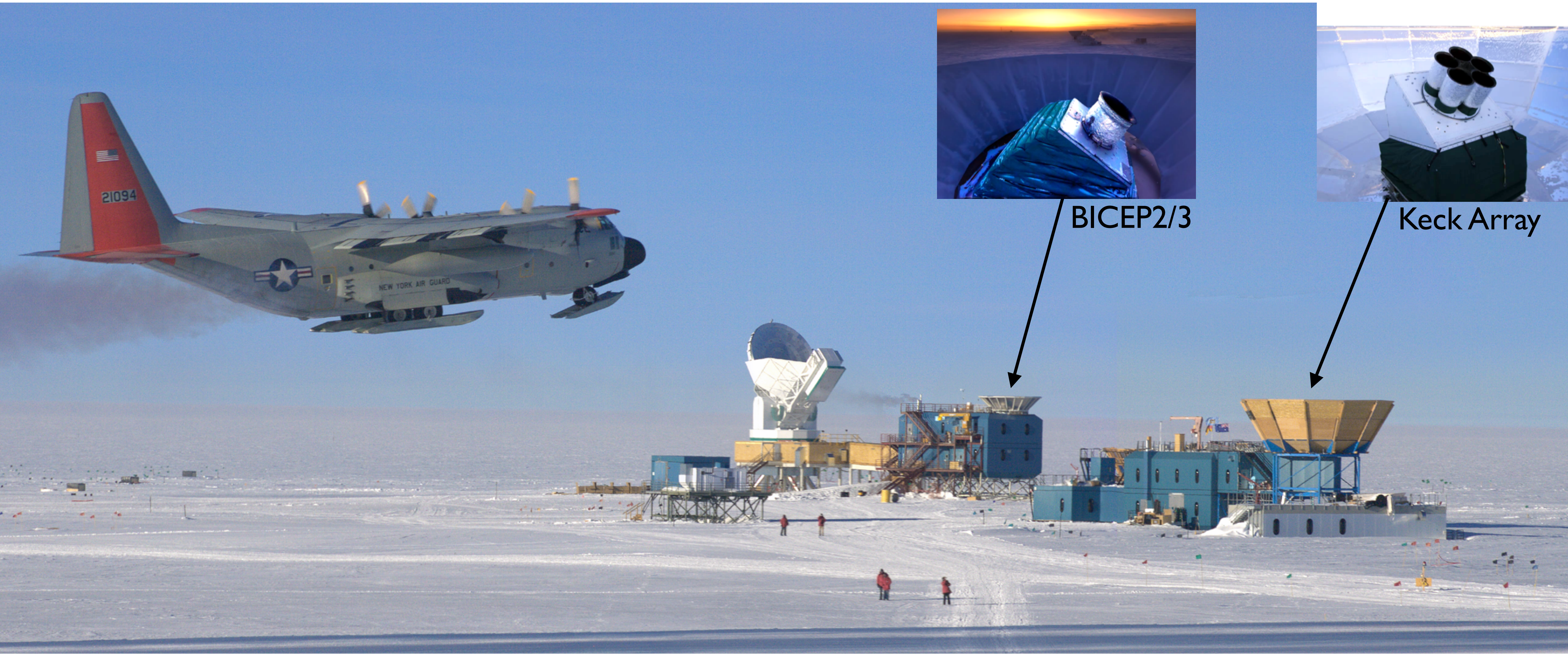




Observe at 95, 150, 220 GHz

- 150 GHz through 2014
- Added 95 GHz in 2014 and 2015
- Added 220 GHz in 2015
- Now all three frequencies

Situated at a high, dry desert

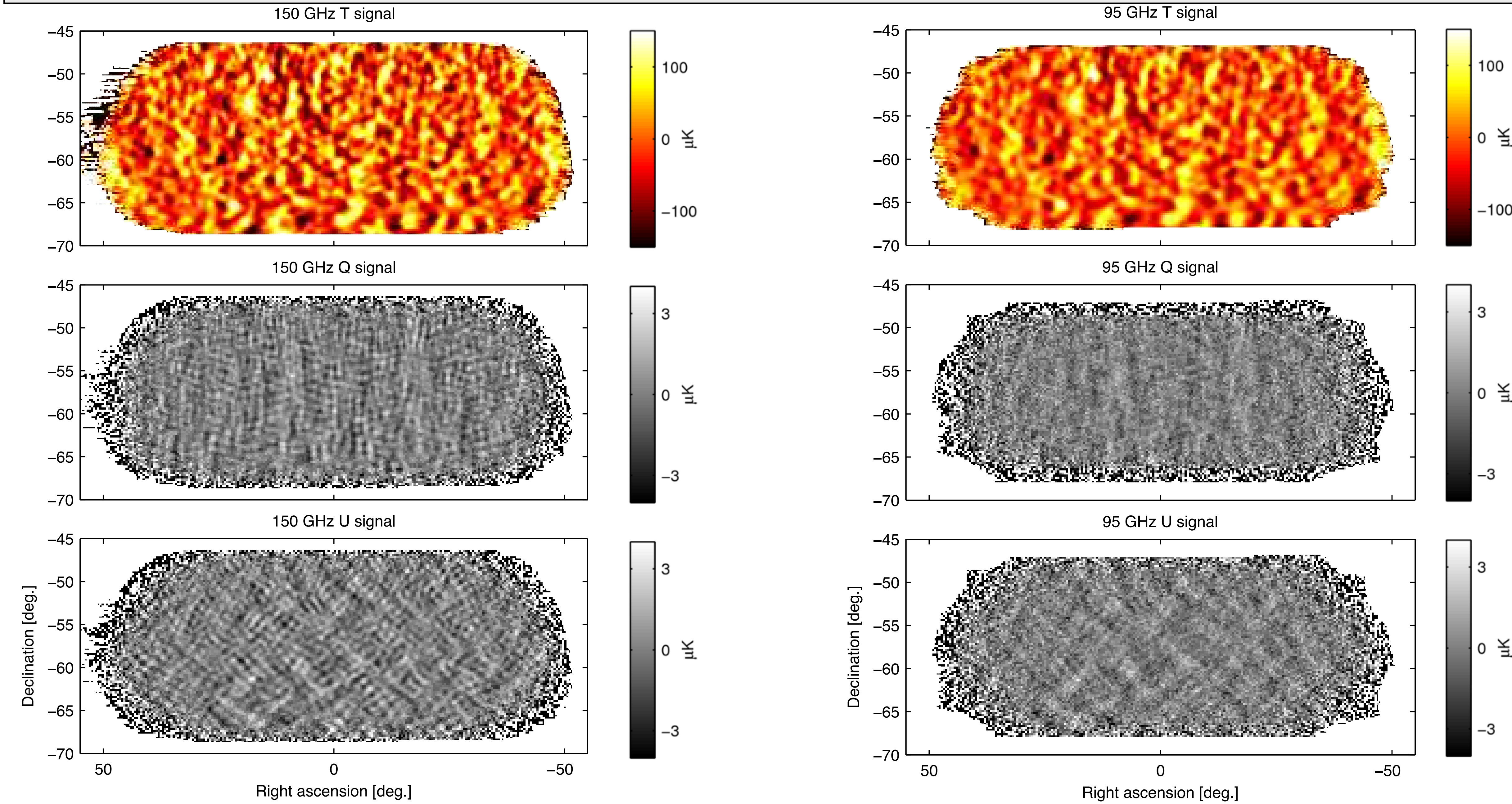


South Pole Research Station, Antarctica

~10,000ft, ~0.25mm PWV

6 months of cold, stable winter sky with uninterrupted integration

BICEP2+Keck through 2014 (150 + 95 GHz)



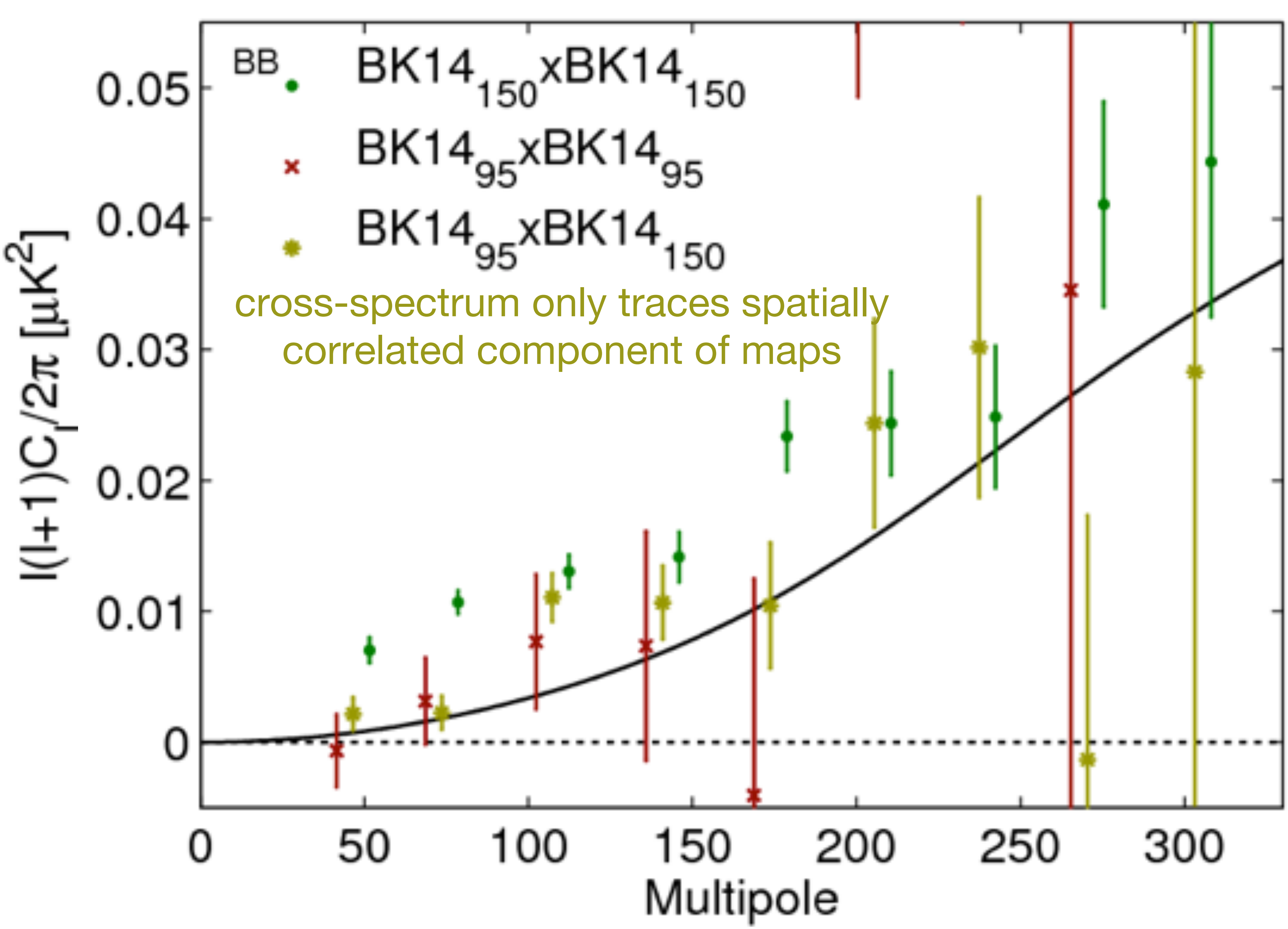
B2 + Keck thru 2014 (150 GHz) →
Final map depth: 3.0 μK'

Keck 2014 (95 GHz)→
Final map depth: 7.6 μK'

Observations focused on ~400 deg^2 patch = 1% of the sky

BK14: PRL 116.031302

Spectra (150x150, 95x95 and 95x150 GHz)



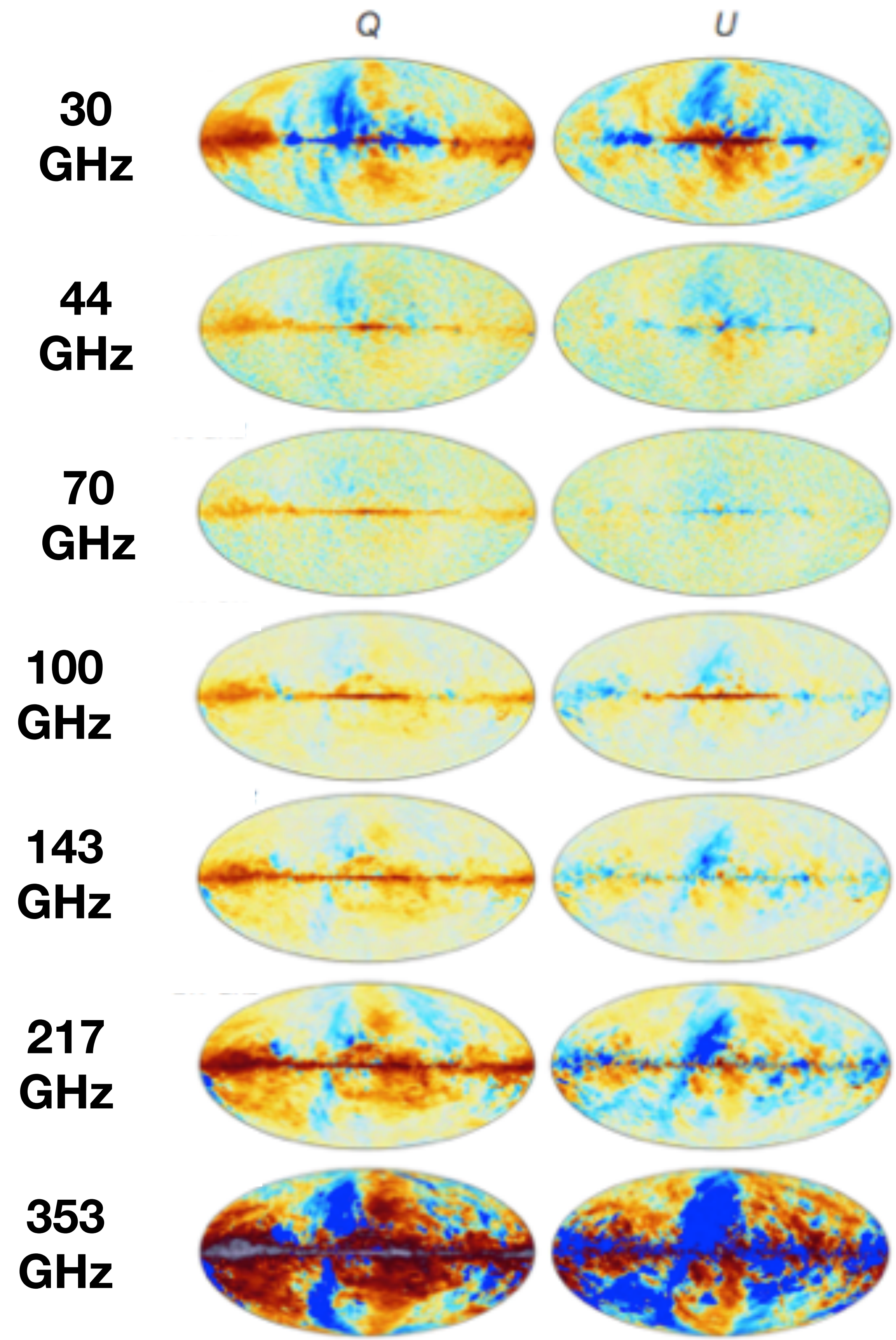
BK14: PRL 116.031302

Add data from Planck and WMAP

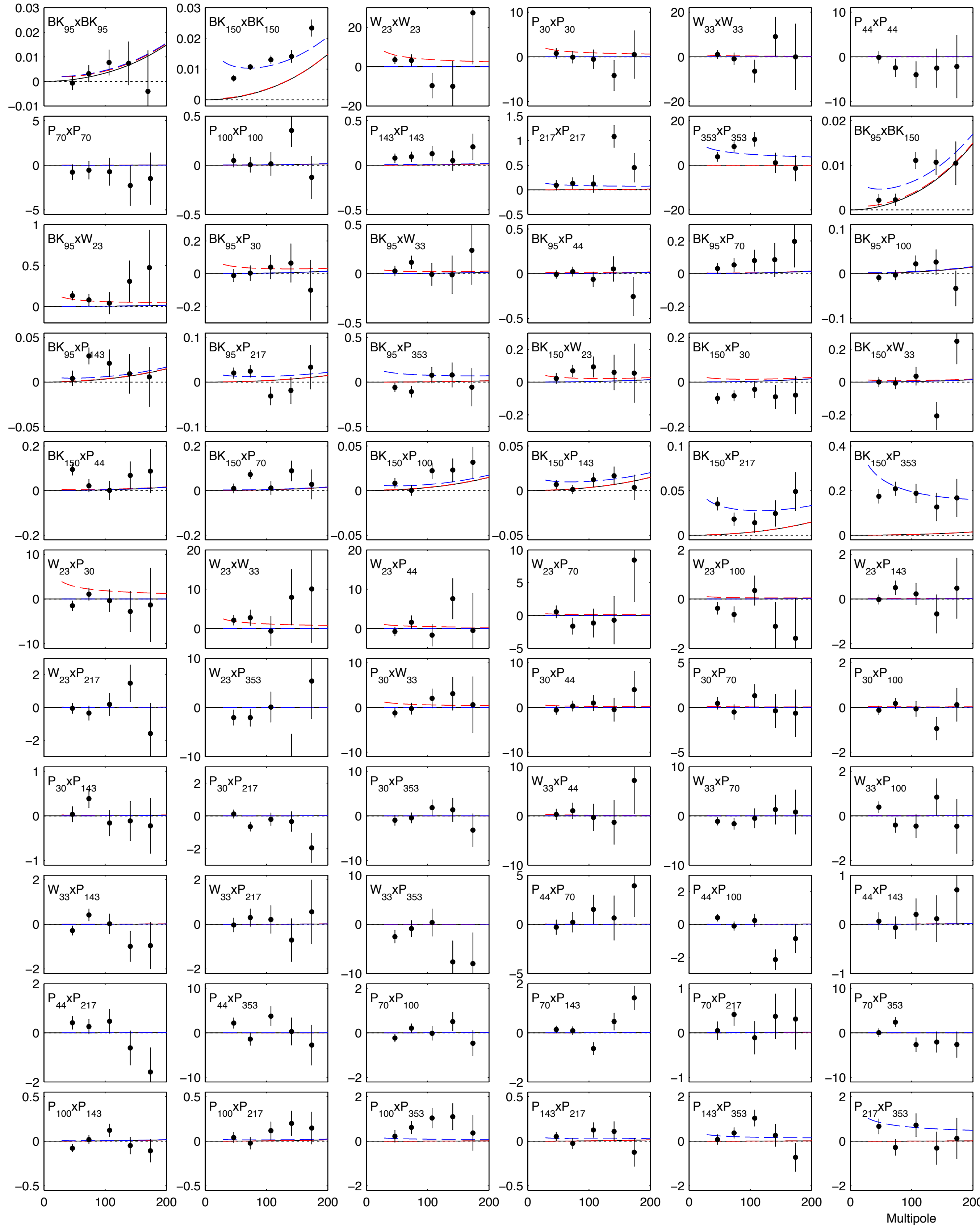
Polarized galactic **synchrotron** dominates at low frequencies

Planck provides polarization measurements in 7 other bands at lower S/N, but can be included in analysis. Two WMAP bands as well.

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



Take all possible auto- and cross- spectra! (66 of them)

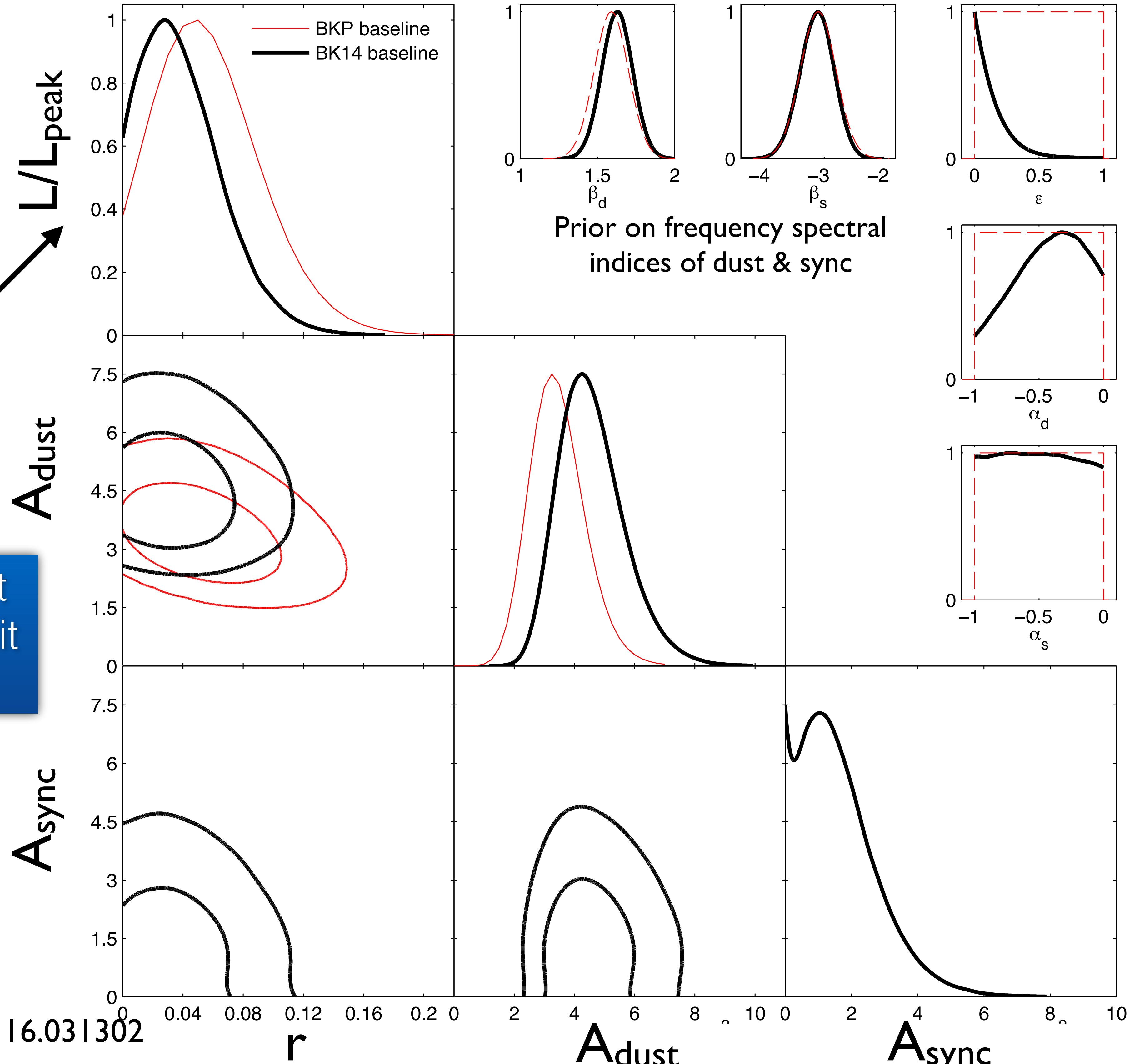


BK14: PRL 116.031302

Joint likelihood of all spectra vs 8-parameter model

r<0.09
(95% CL)

First B result
below TT limit
r<0.11

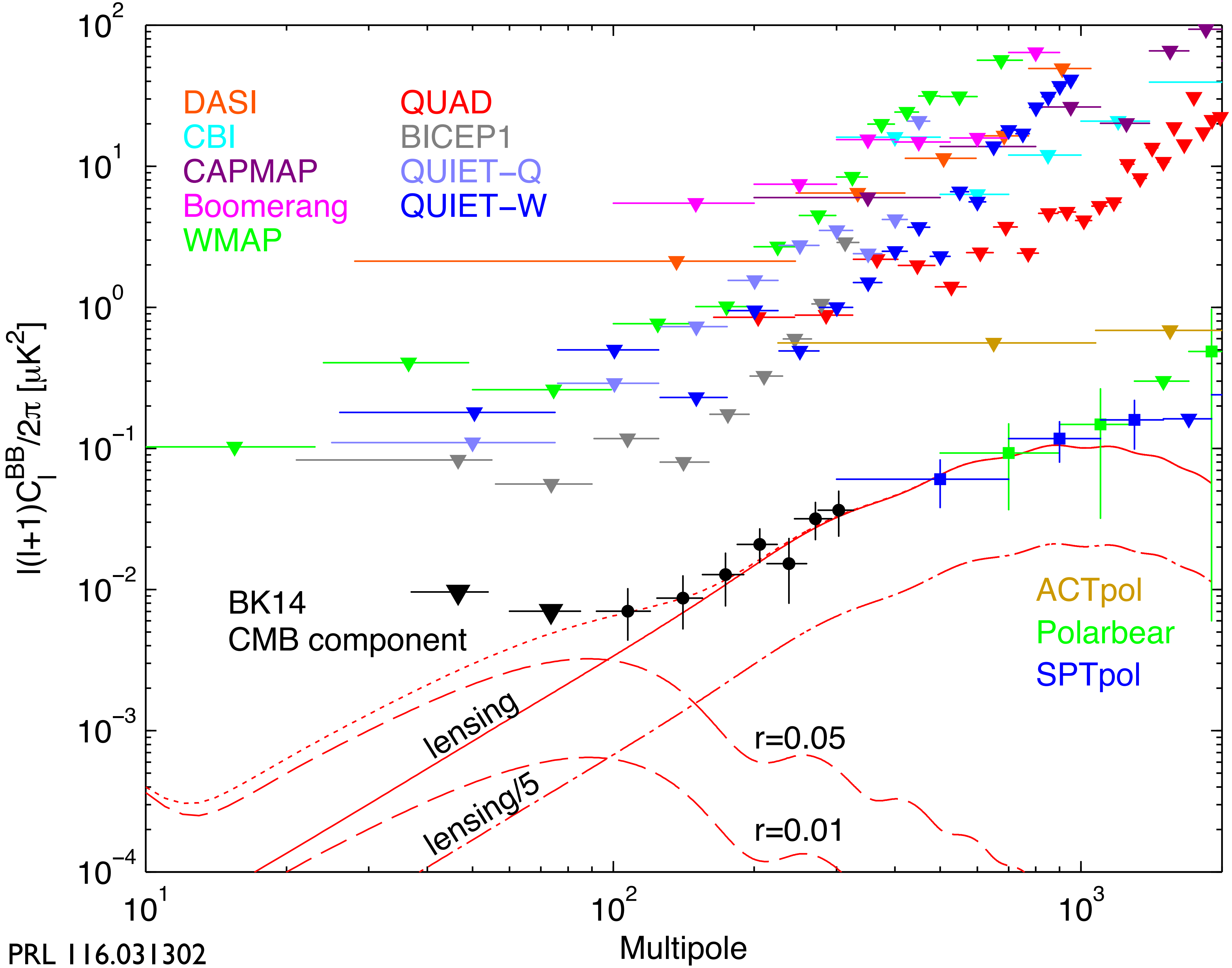


Allow Dust/Sync correlation

Allow generous variation in spatial spectral indices of dust & sync

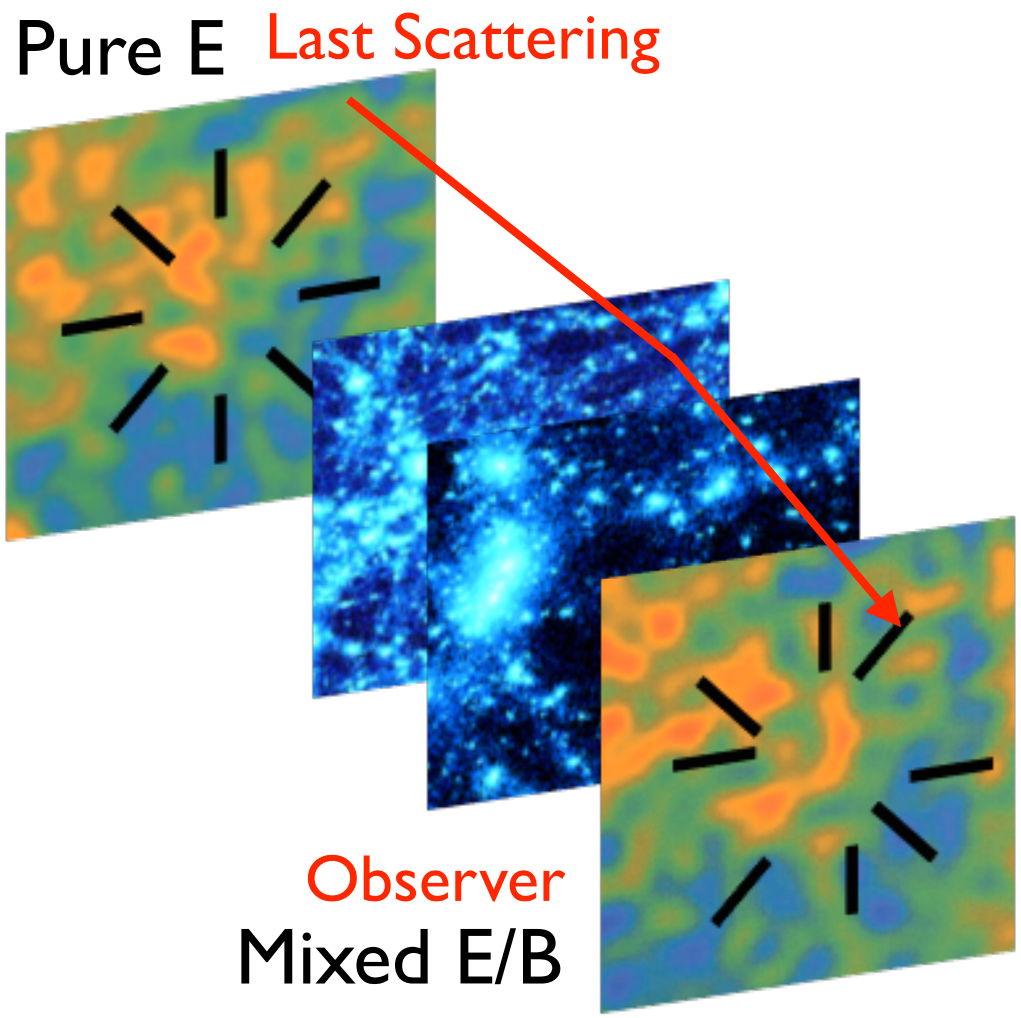
BK14: PRL 116.031302

CMB component of BB power spectrum



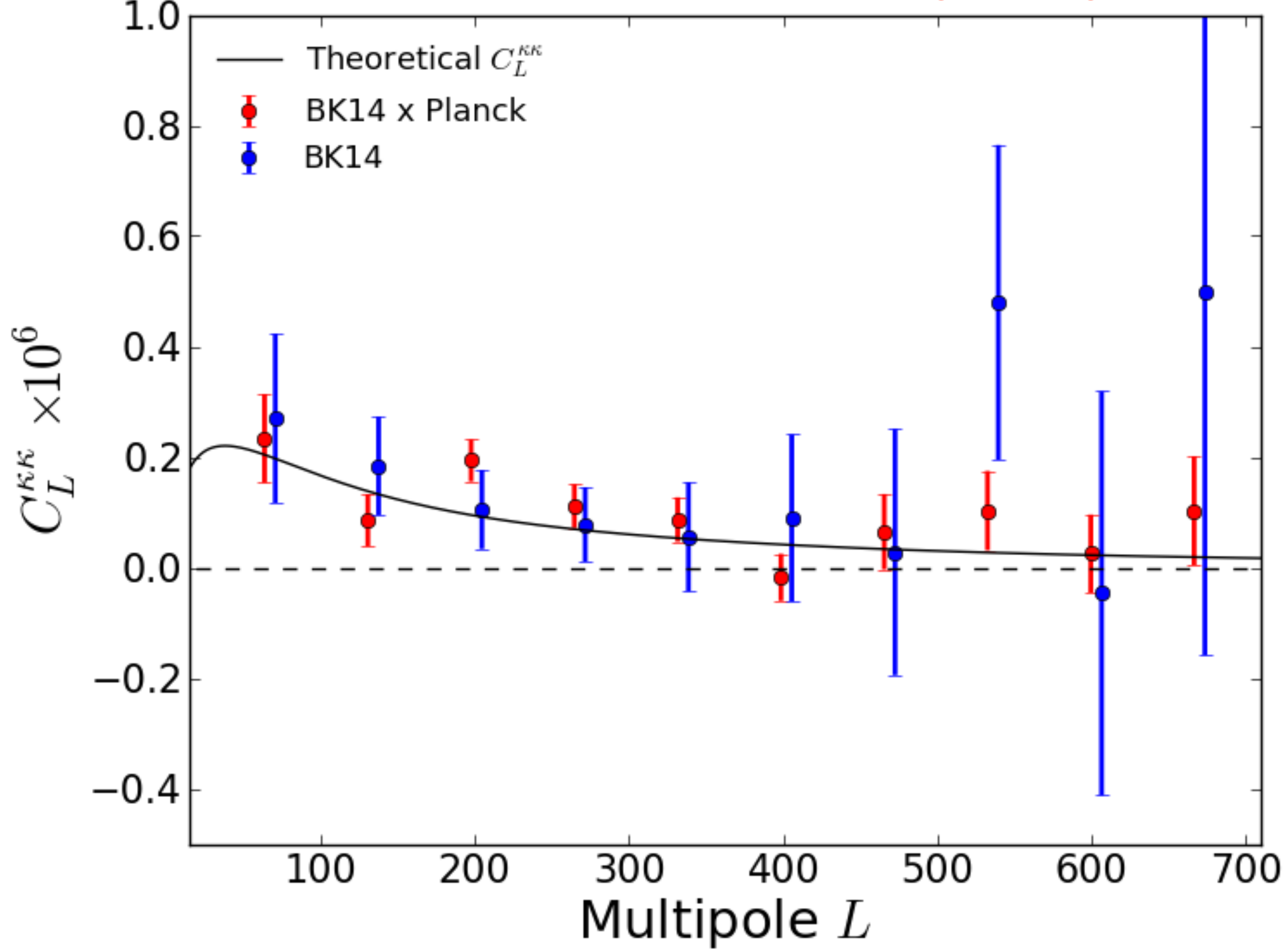
BK14: PRL 116.031302

Measurement of Gravitational Lensing



$$B_{\vec{\ell}} = \int d\vec{L}\, w_{\vec{\ell},\vec{L}} E_{\vec{L}} \kappa_{\vec{\ell}-\vec{L}}$$

Lensing Convergence

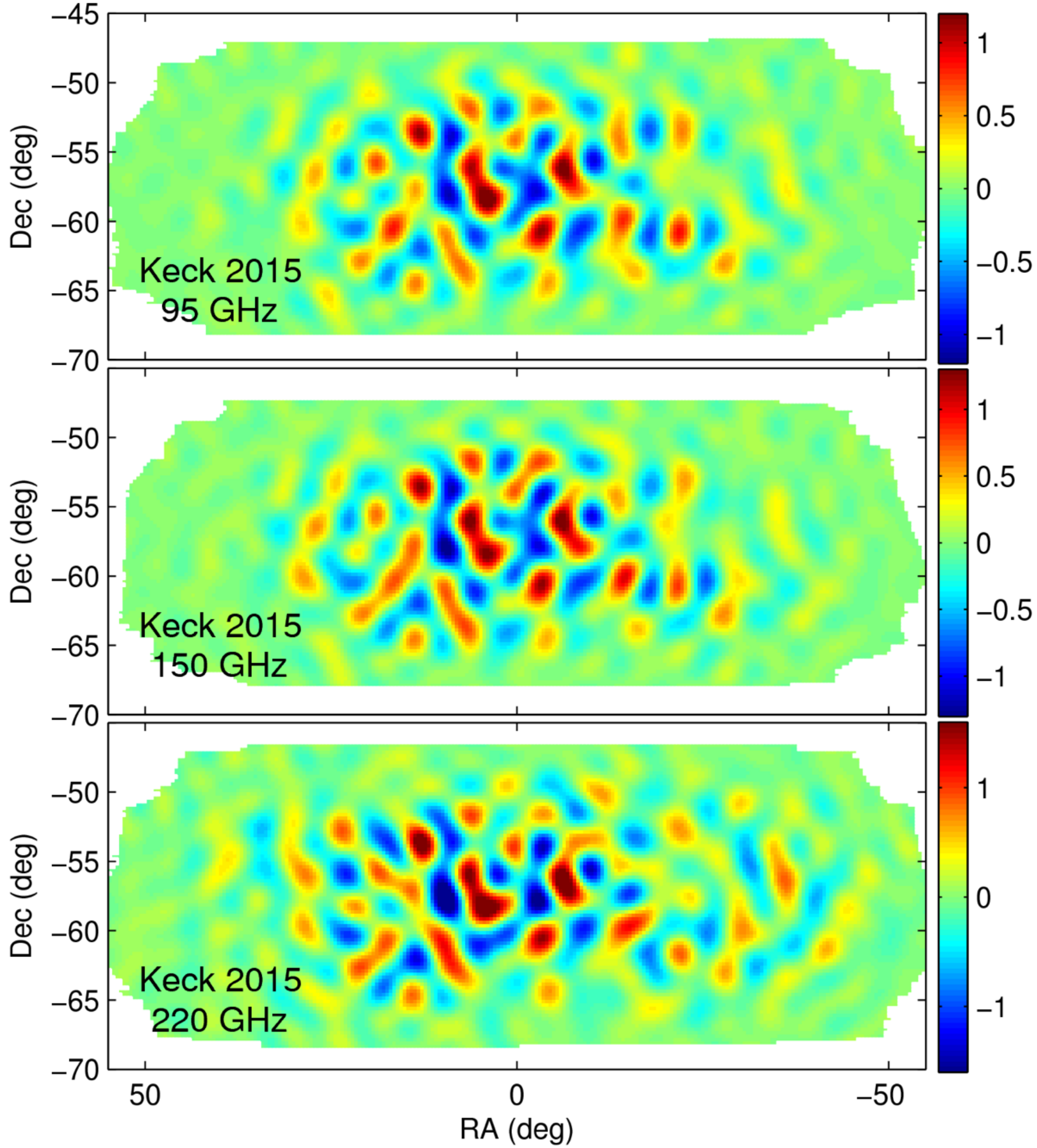


Despite modest resolution (0.5°), BK map depth (3μK') enables direct reconstruction of lensing potential ϕ using only information at ell≤700

Measured amplitude (5.8σ) is in good agreement with the BB results!

arXiv: 1606.01968, ApJ in review

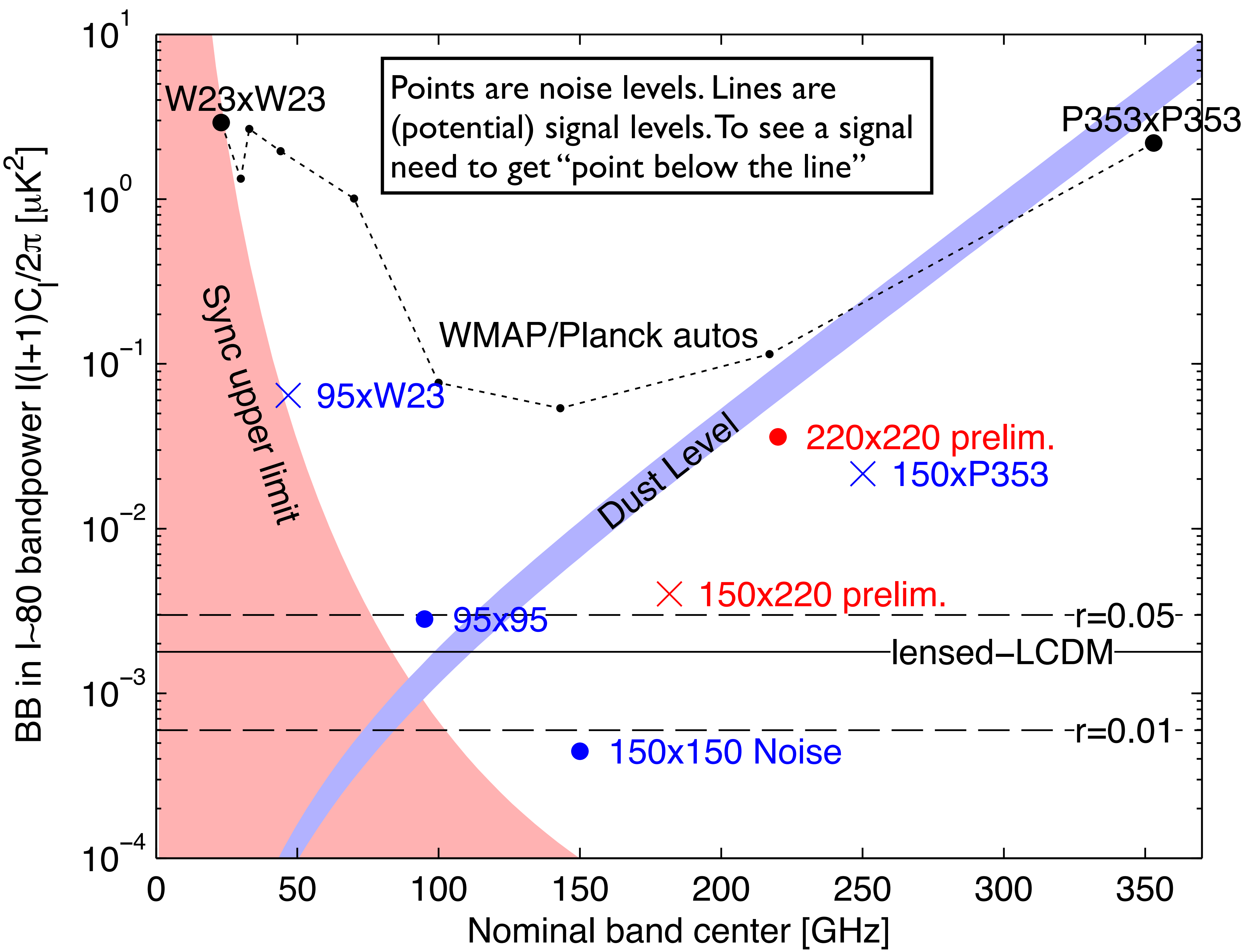
BK 2015 E-mode maps teaser



LCDM E-modes with high S/N at three frequencies

Keck 220 GHz now deeper than Planck 217 GHz!

BK noise levels vs. foregrounds



BK14: PRL 116.031302

BICEP receiver evolution: Stage 2 to Stage 3

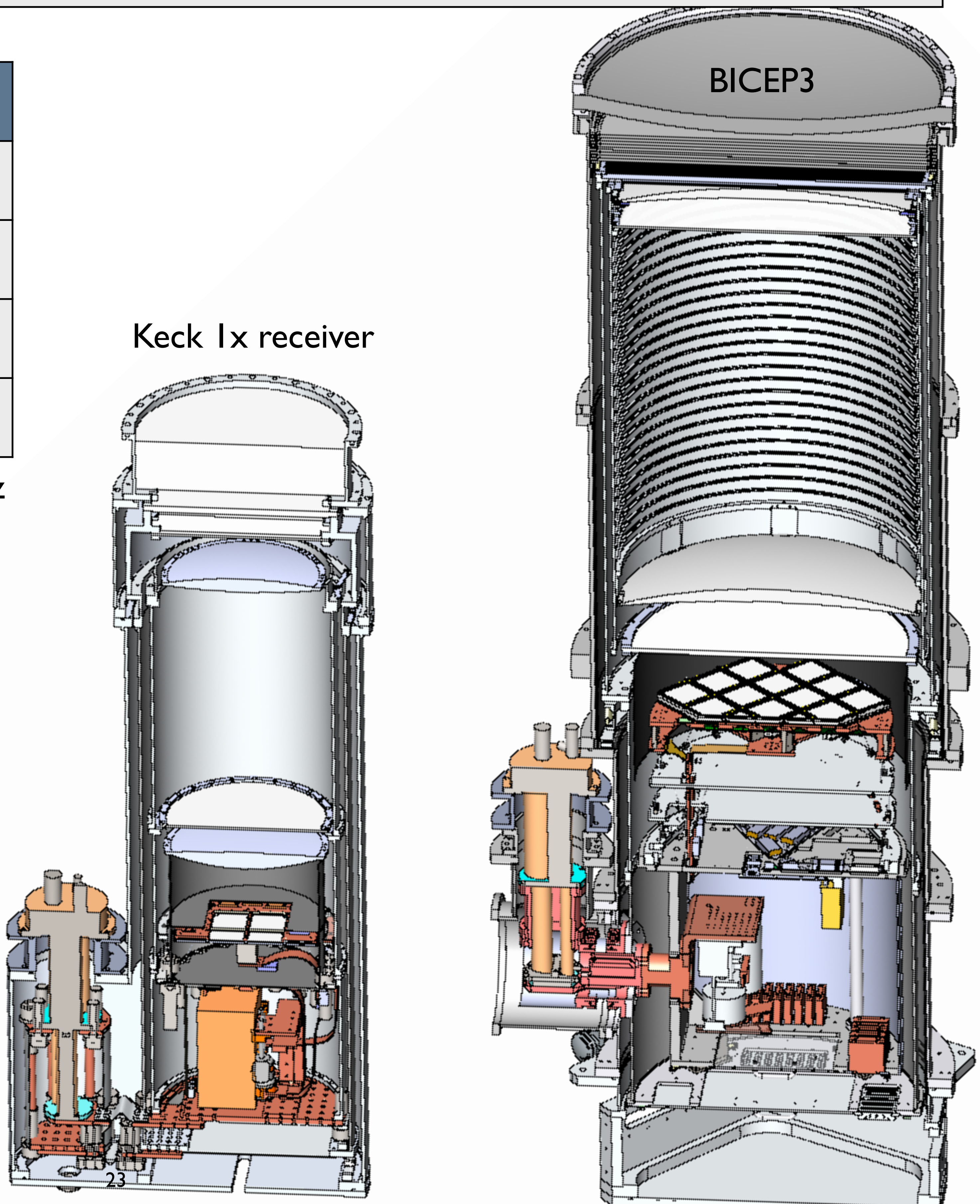
	B2/Keck	BICEP3
Window	260mm	680mm
Optics	f/2.2	f/1.6
FOV	15 deg	27 deg
Dets	288	2560

*comparisons at 95 GHz

Both designs use:

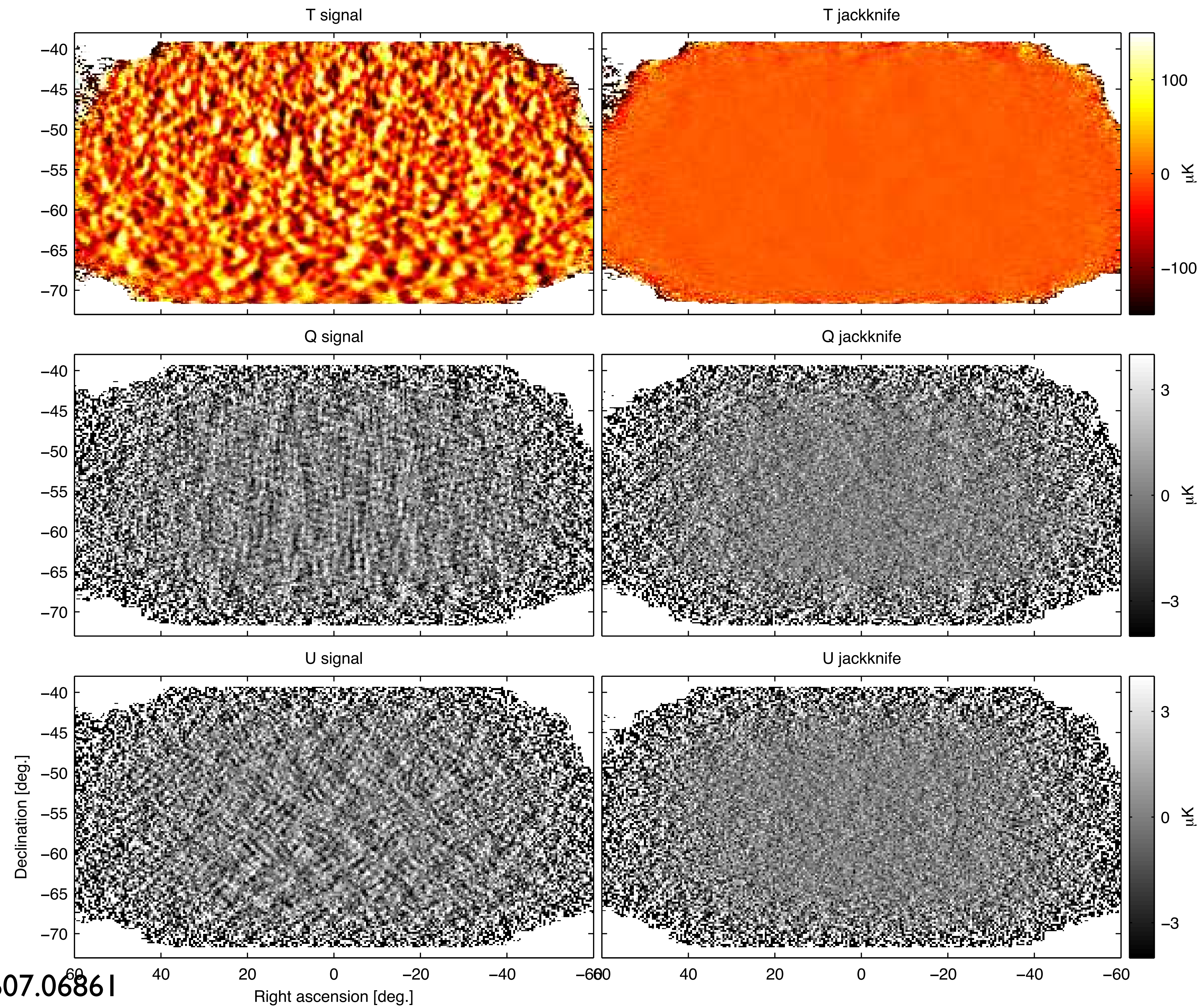
1x pulsetube cryocooler (~30K, ~3K)

1x He3/He4 sorption fridge (~250mK focal plane)



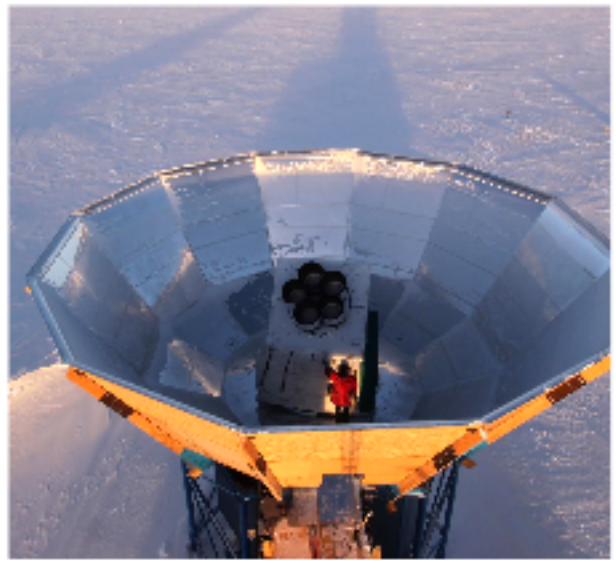
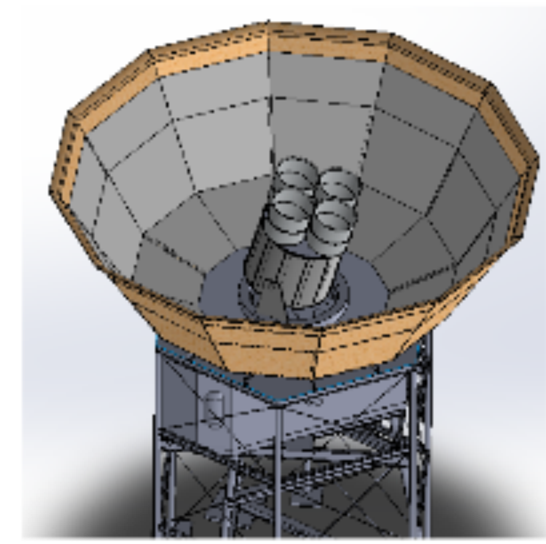
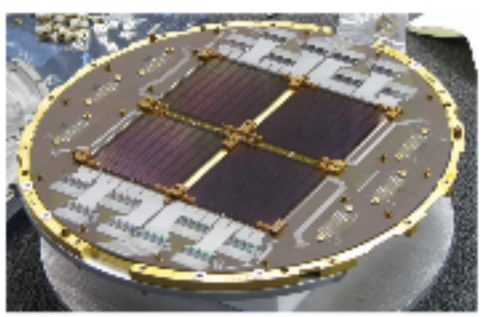
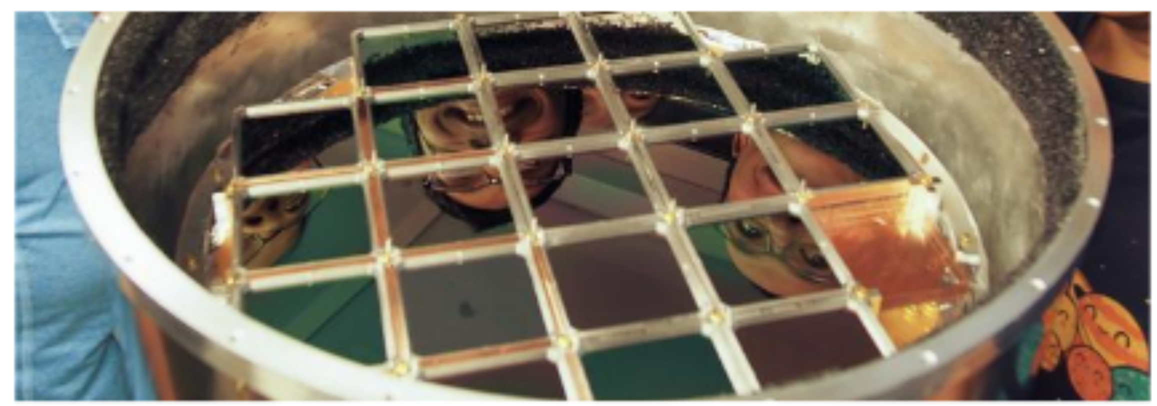
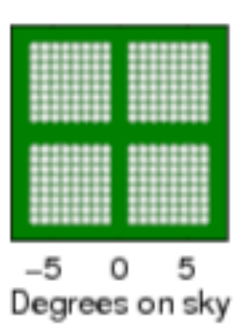
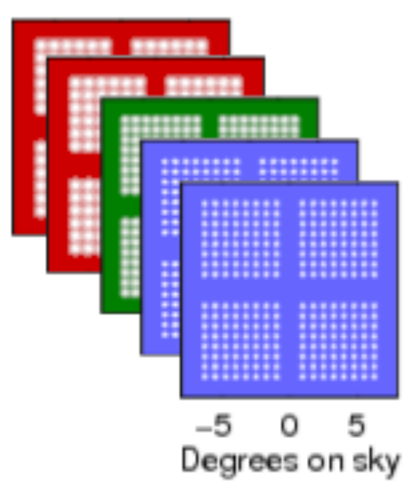
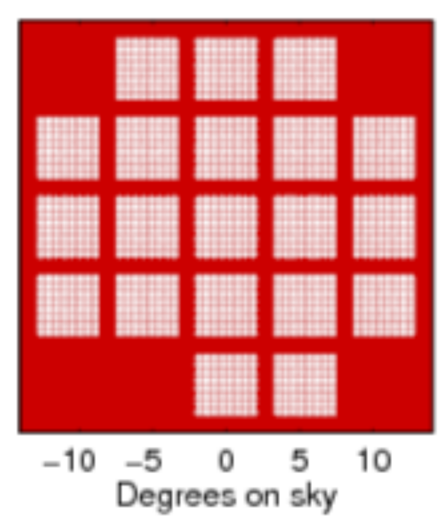
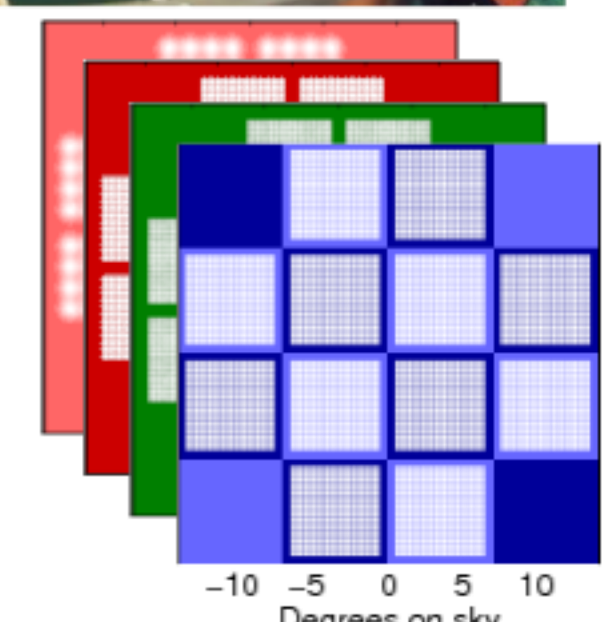
arXiv: 1407.5928
arXiv: 1607.04668
arXiv: 1607.04567
arXiv: 1607.06861

First 700 hours of BICEP3 2016 science data



arXiv: 1607.06861

BICEP/Keck Program Progress

	BICEP2 (2010-2012)	Keck Array (2012-2017)	BICEP3 (2015-)	BICEP Array (2018-)
Telescope and Mount				
Focal Plane				
Beams on Sky				

BICEP Array (planned Keck Array upgrade)

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**	837	**21**	**2,000**
270	512	1310	17	800
BICEP3				
95	**2560**	288	**24**	213,000
BICEP Array				
35	384	268	68	37,000
95	3456	288	24	287,000
150	7776	313	15	453,000
220	9408	837	11	37,000
270	9408	1310	9	15,000

*Bolded numbers represent measured quantities from BK14 analysis
All other quantities scaled by frequency and/or NET

Survey Weight=2(Map Area)/(Map Noise)^2

arXiv: 1607.04668

Conclusions

- BICEP/Keck observations combined with Planck and WMAP data have produced most stringent constraints to date on inflationary gravitational waves
- Dust and gravitational lensing detected at high significance. No synchrotron yet
- Third generation receiver, BICEP3, taking science data in field. Will serve as baseline design for Keck Array upgrade in 2018

SPIDER

Exploring the Dawn of Time from Above the Clouds

Jeff Filippini
for the SPIDER collaboration

ICHEP - August 5, 2016

SPIDER
SEARCHING FOR THE ECHOES OF INFLATION

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

The SPIDER Program

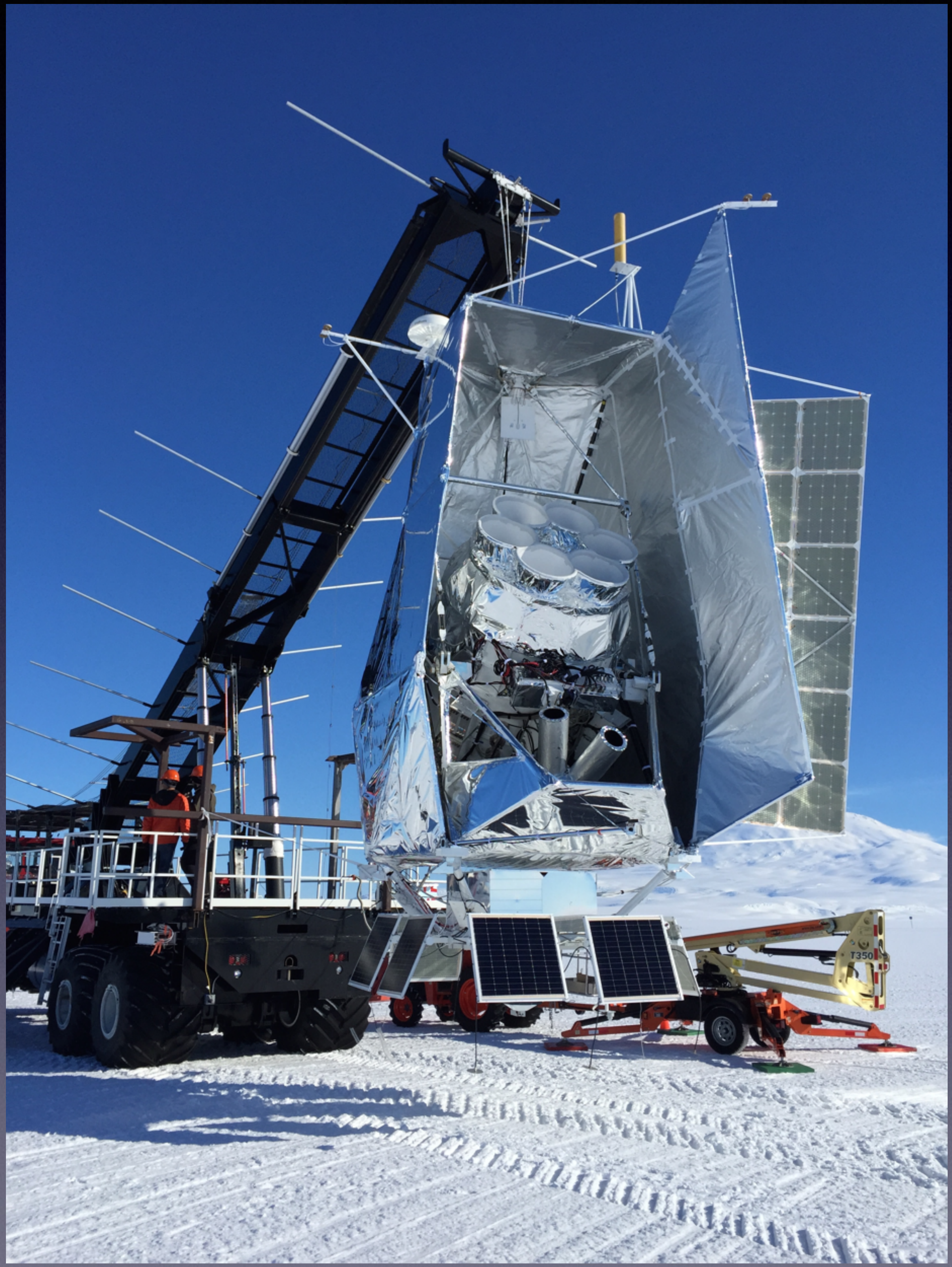
A balloon-borne payload to identify primordial B-modes on degree angular scales in the presence of foregrounds

1. Verify angular power spectrum
   Many modes
   high fidelity from ~10 < l < 300

2. Verify statistical isotropy
   Large (~10%) sky coverage

3. Verify frequency spectrum
   Multiple colors, (esp. 200+ GHz)

Rahlin et al., SPIE, arXiv:1407.2906
Fraisse et al., JCAP 04 (2013) 047
Filippini et al., SPIE, arXiv:1106.2158
O'Dea et al., ApJ 738, 63 (2011)
….



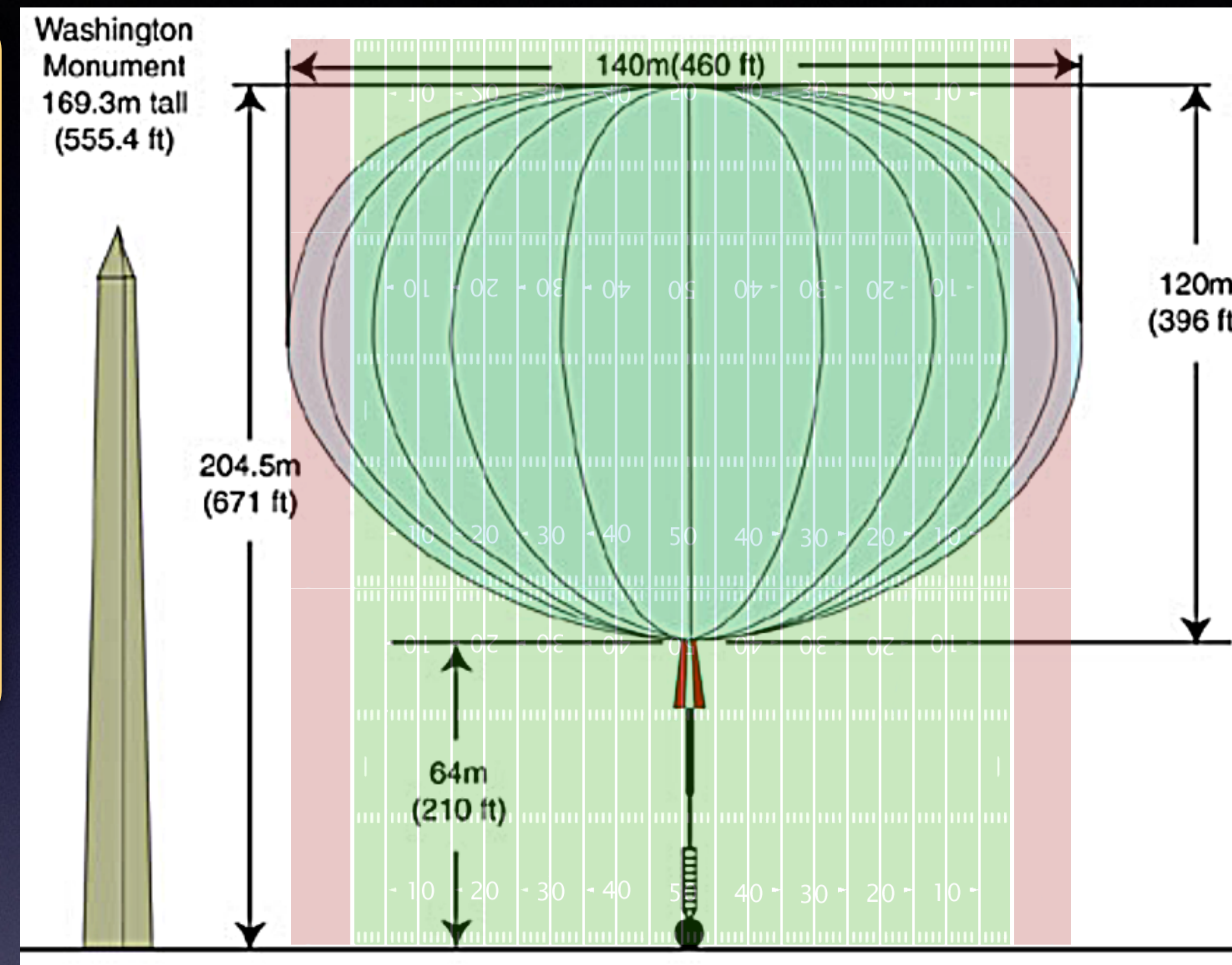
Balloonatics

SPIDER
SEARCHING FOR THE ECHOES OF INFLATION

NASA
NSF
CSA ASC
C.S.B.F. PALESTINE, TEXAS
NSERC CRSNG
JPL
ALFRED P. SLOAN FOUNDATION 1934
CALIFORNIA INSTITUTE OF TECHNOLOGY 1891
the David & Lucile Packard FOUNDATION
UNIVERSITY OF TORONTO
CASE WESTERN RESERVE UNIVERSITY EST. 1826
CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD
UBC
NIST
PRINCETON UNIVERSITY
CITA ICAT Canadian Institute for Theoretical Astrophysics L'institut canadien d'astrophysique théorique
Imperial College London
UNIVERSITAS OSLOENSIS MDCCCXI
UNIVERSITY OF KWAZULU-NATAL INYUVESI YAKWAZULU-NATALI
ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN
UNIVERSITET STOCKHOLMS

Why Ballooning?

- **High sensitivity** to approach CMB photon noise limit
- Access to **higher frequencies** obscured from the ground
- Retain **larger angular scales** due to dimmer atmospheric fluctuations (*filtering*)
- **Technology pathfinder** for orbital missions



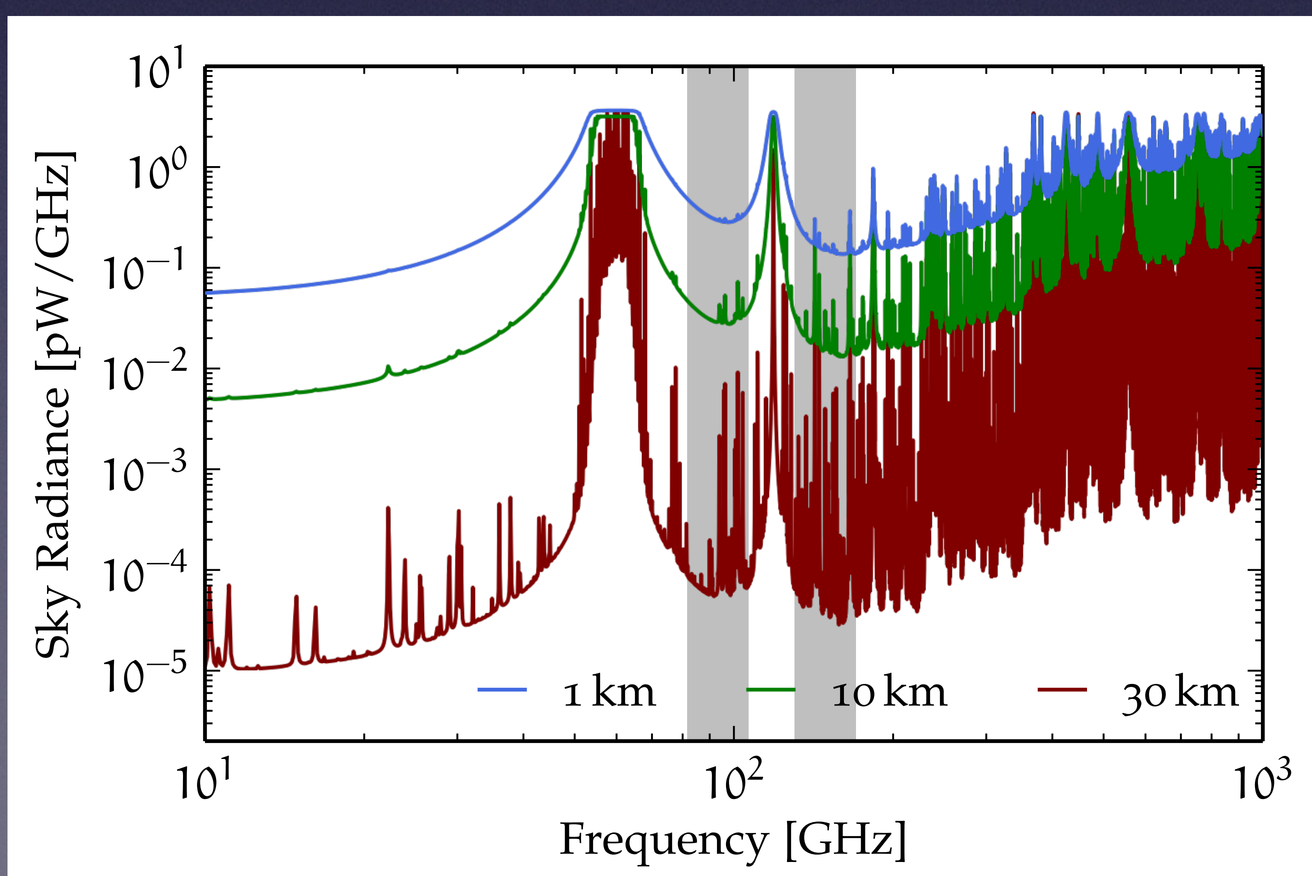
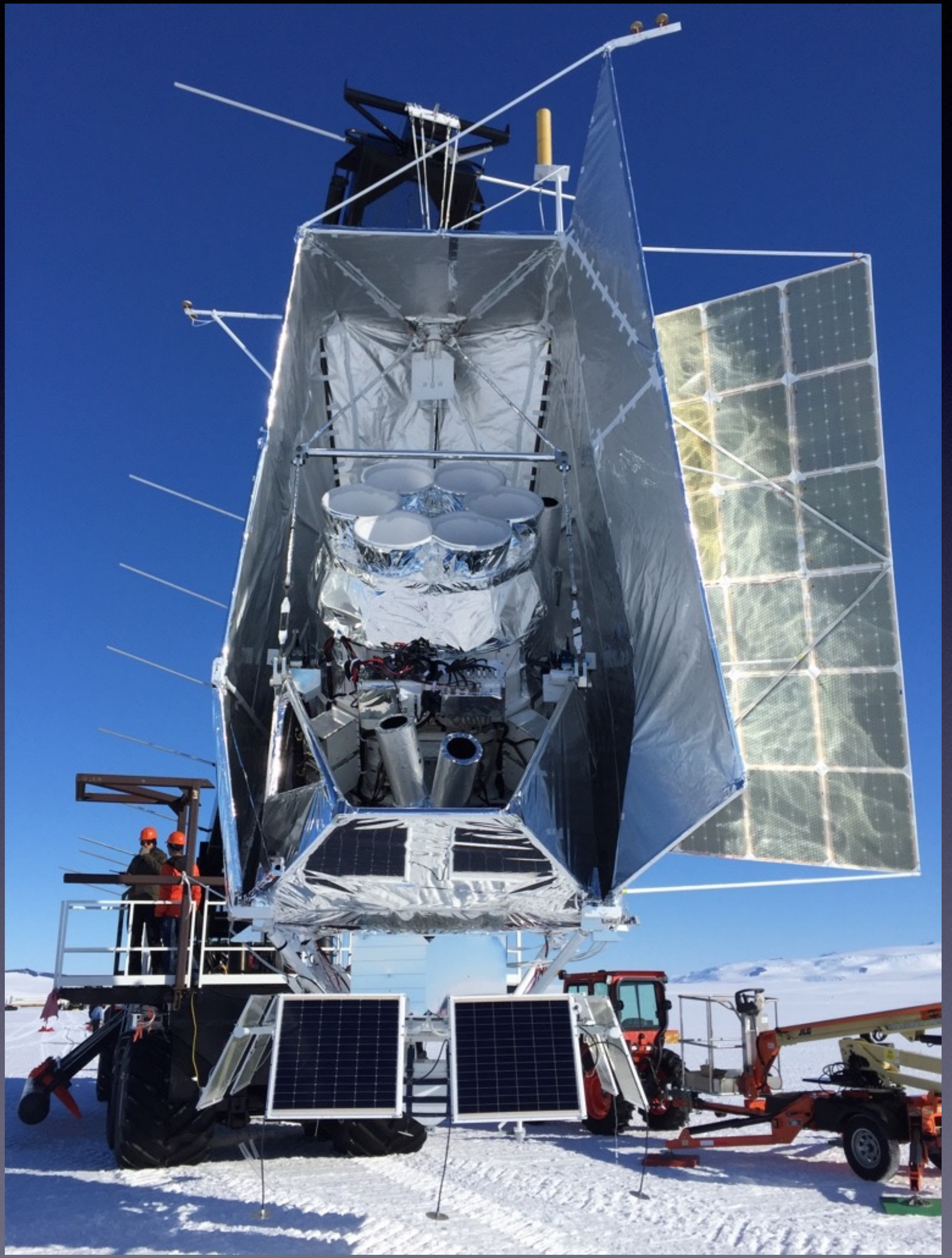


FIGURE BY A.S. RAHLIN (AM MODEL)

- Limited integration time (~weeks)
- Stringent weight/power constraints
- Very limited bandwidth demands ***nearly autonomous operations!***

The SPIDER Payload

- 1300L shared **LHe cryostat** (4K, 1.6K)
- Lightweight **carbon fiber** frame
- Mylar **sun shields** for thermal control
- **Attitude control**
    - Reaction wheel (*azimuth*)
    - Linear elevation drives (*elevation*)



Pointing reconstruction

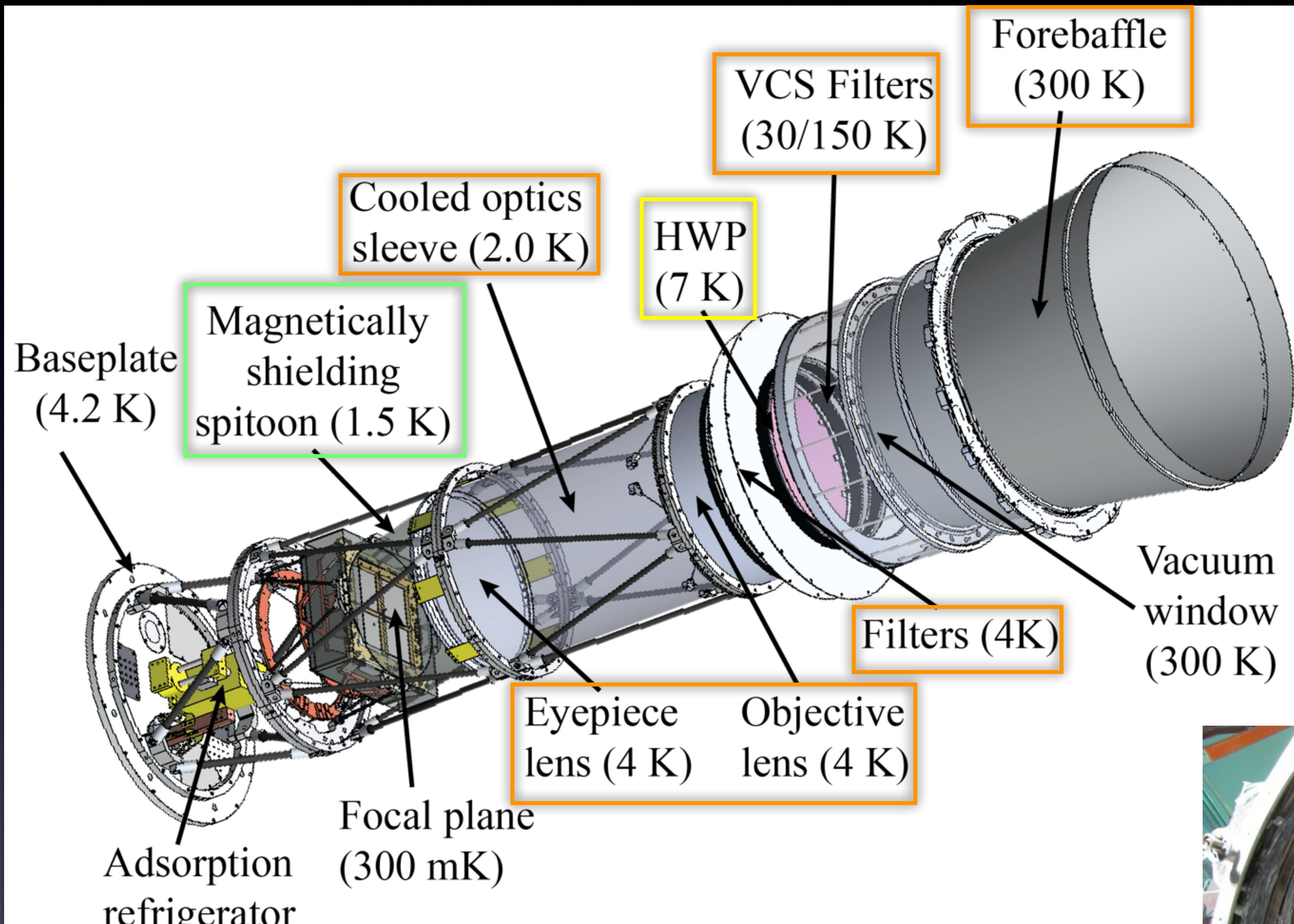
In-flight (**~1' accuracy**)

- Differential GPS
- Magnetometer
- Pinhole sun sensors

Post-flight (**~6" accuracy**)

- 3-axis gyroscopes
- Orthogonal star cameras on deck
- Fixed boresight star camera

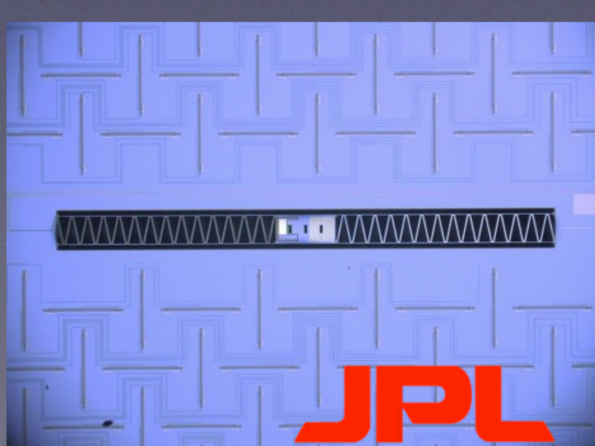
SPIDER Receivers



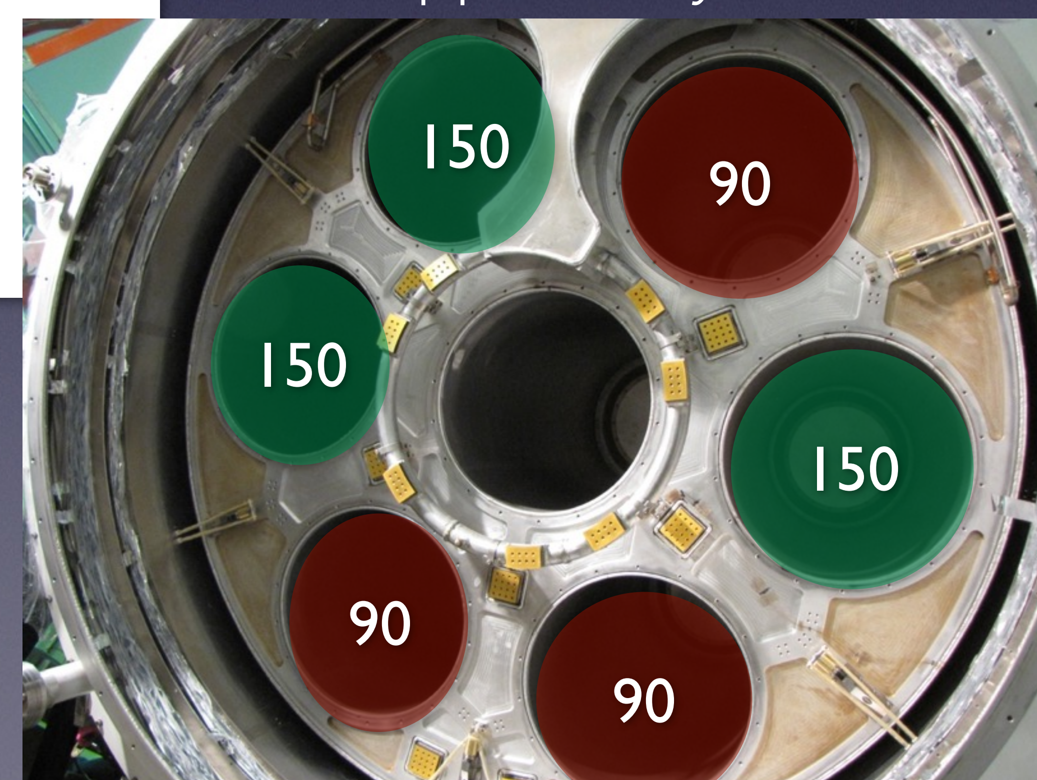
Loading reduction
4K refractive optics
Infrared blockers
Cold internal baffling
Reflective forebaffle

Magnetic shielding
Multi-layer focal plane

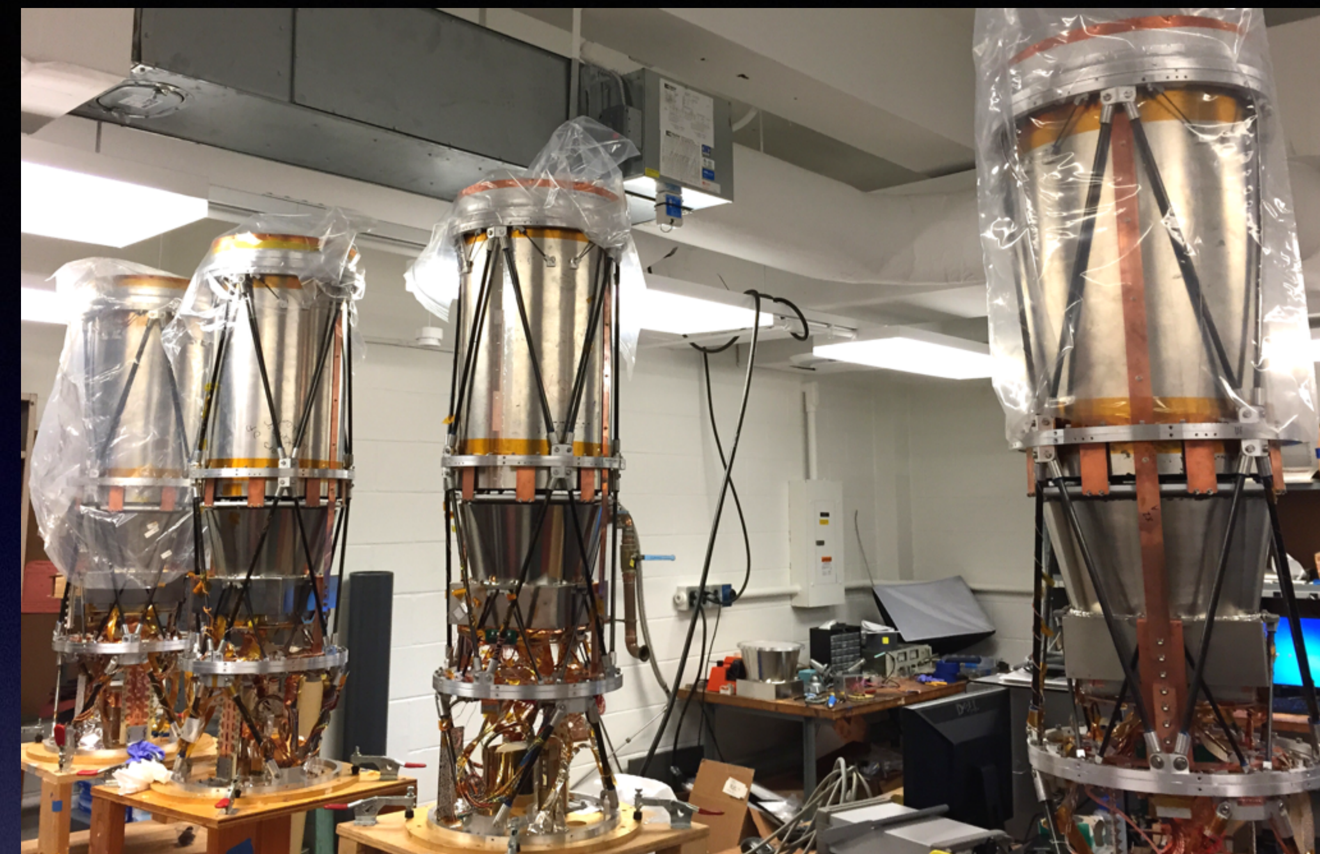
Polarization modulation
Cold half-wave plate
Custom worm drive
Stepped *daily*

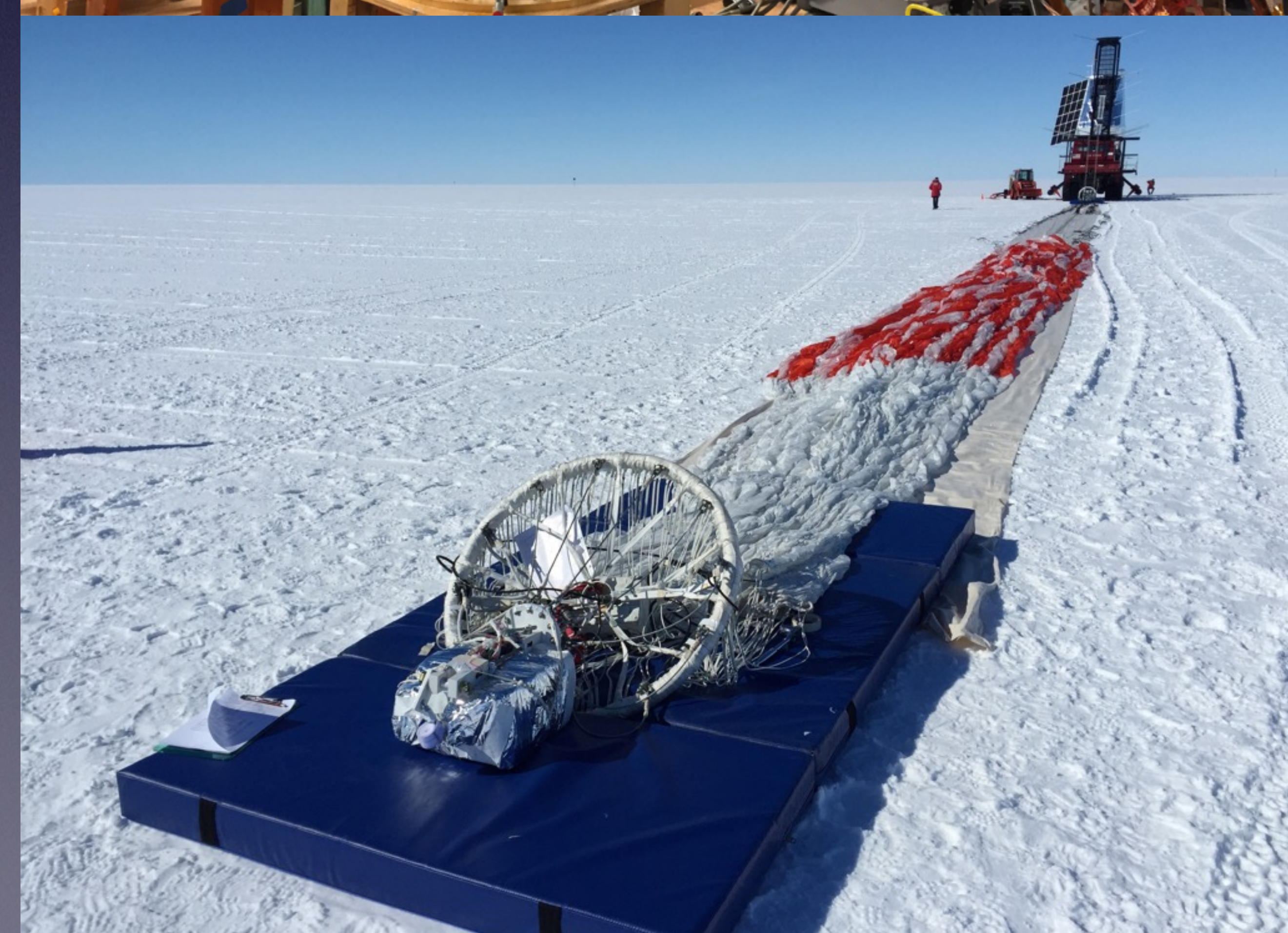


First flight (2015)
3x **94 GHz**: 42' fwhm
3x **150 GHz**: 30' fwhm
2400 TESs (96 dark)



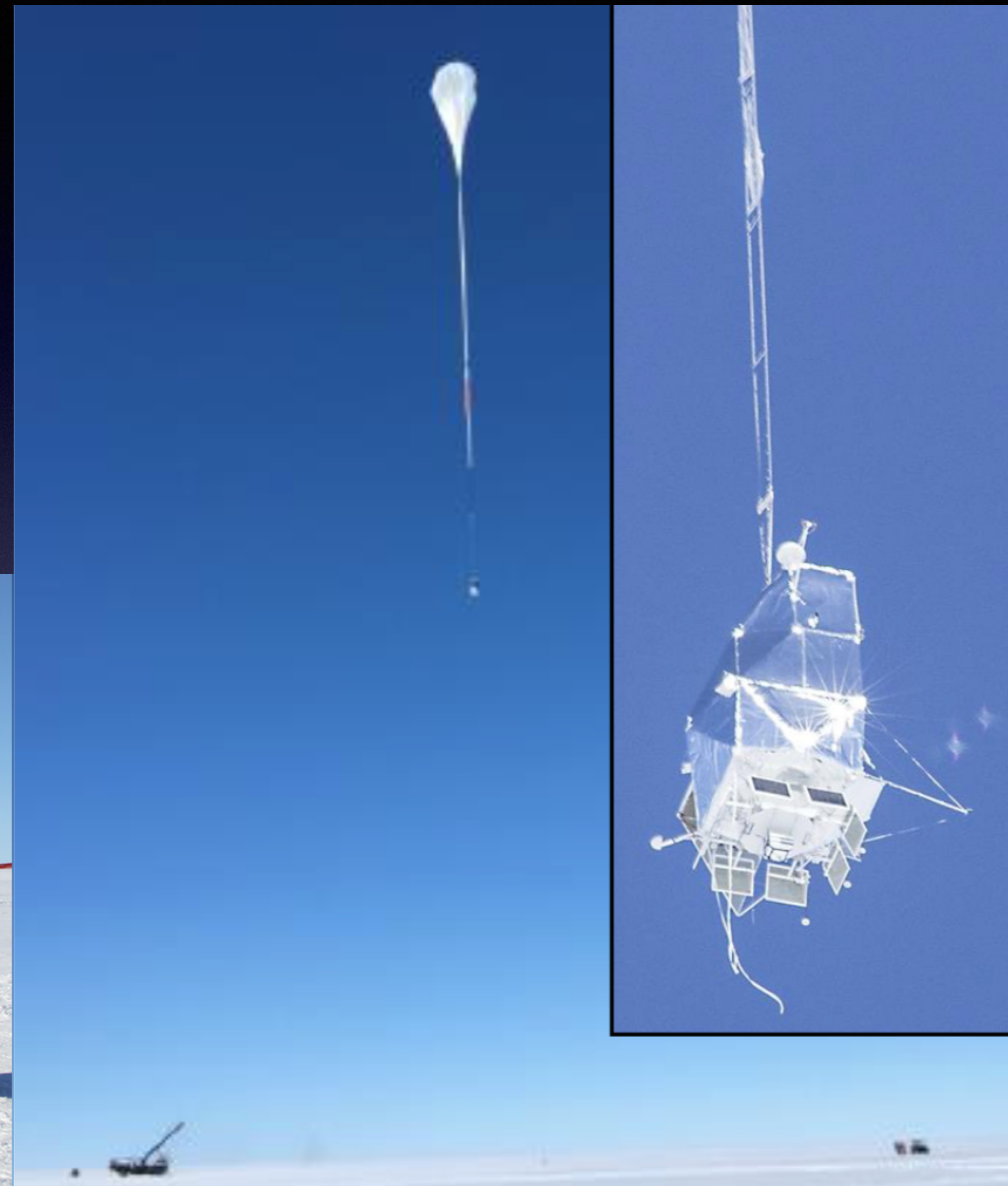
Antarctica 2014-15





SPIDER Aloft!

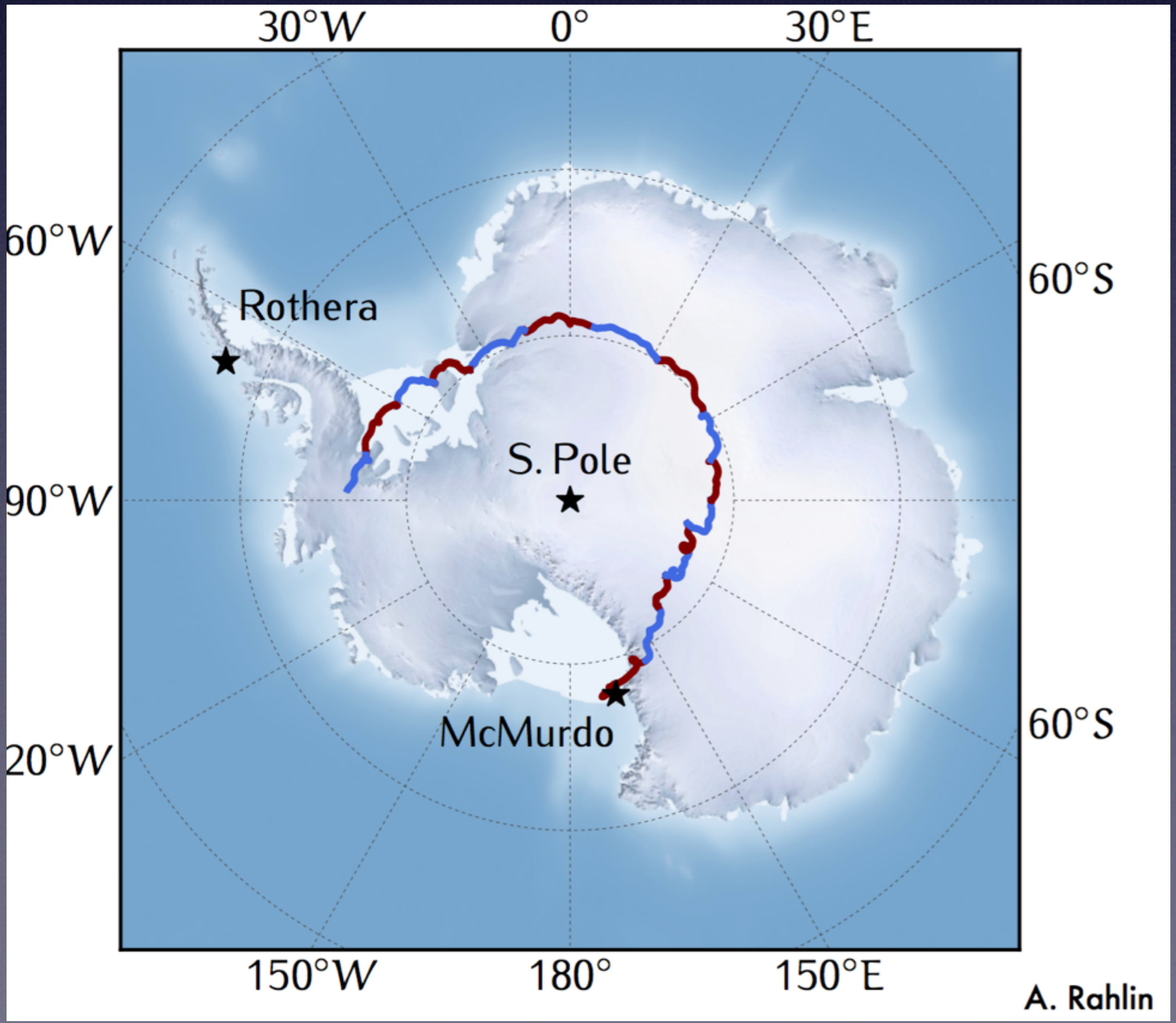
- January 1-18, 2015: 16 days at 36 km
- All systems operational (*except dGPS, no science impact*)

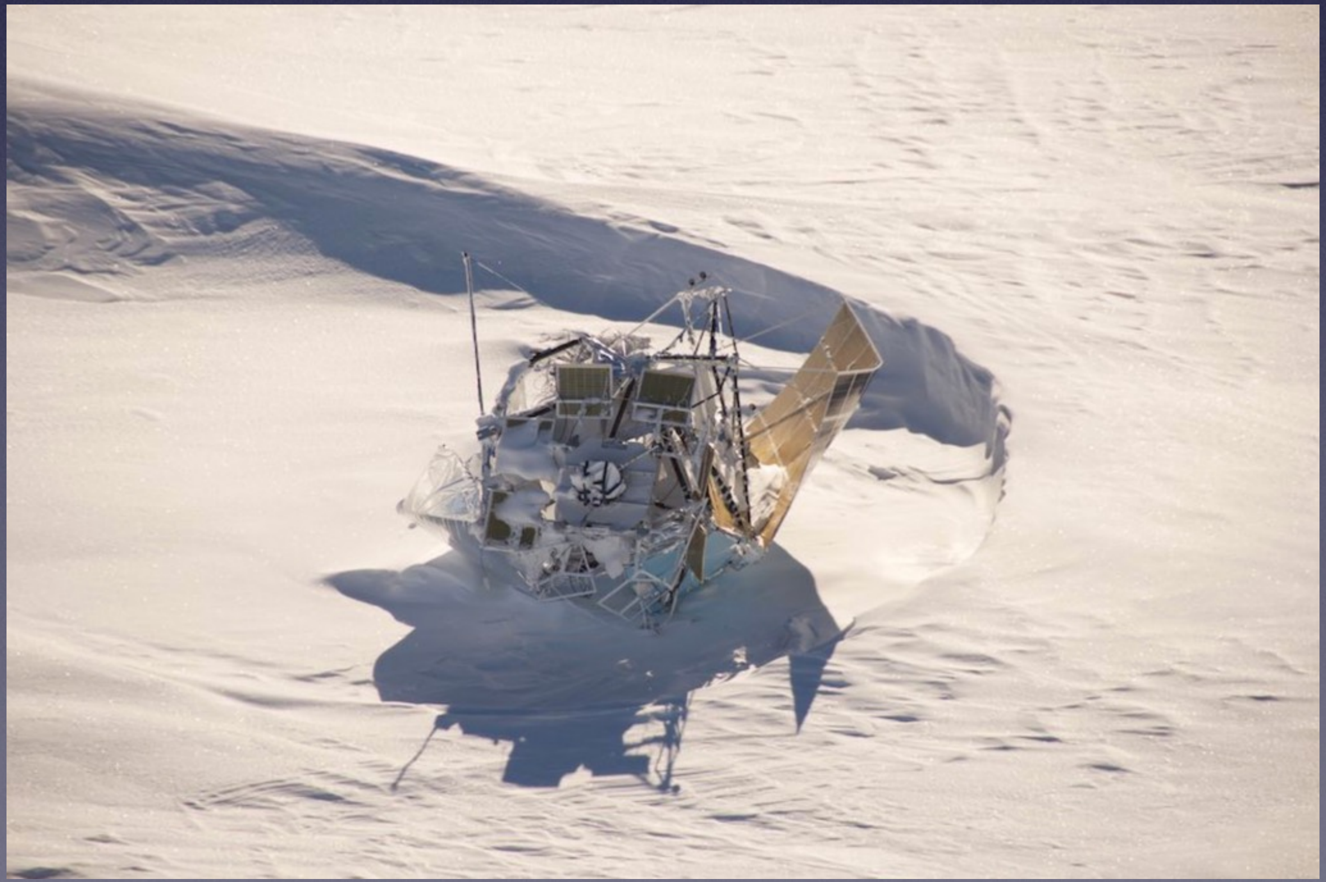


RECOVERY

Full payload recovery courtesy of the British Antarctic Survey

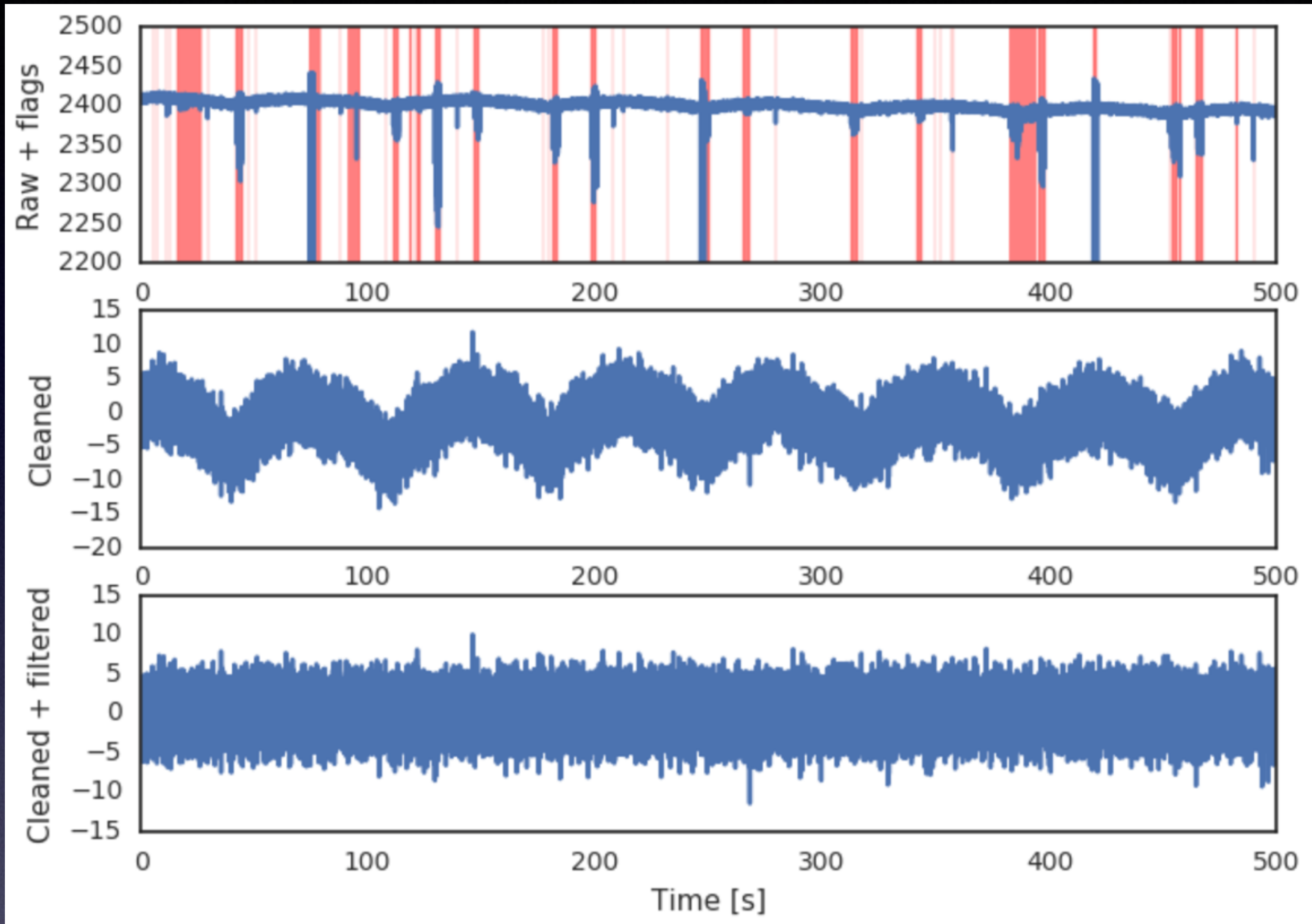
- **Data disks**: Feb. 4, 2015
- **Payload**: Nov. 2015
  All hardware back in our hands!





In-Flight Performance

- 1.56 TB of data
  - Cosmic ray flagging negligible
  - No obvious magnetic pickup
  - RFI flagging significant
  - ~30% total flagging so far
- Very low stray photon load
- Sensitivities (NETs) consistent with expectations (~*160 uK$_{cmb}$-rts / det*)
- All HWPs turned reliably



	In-band	Instrument NET (det/total)
94 GHz	**≲0.25 pW**	**~7 μK$_{cmb}$-√s (~80% used)**
150 GHz	**≲0.35 pW**	**~6 μK$_{cmb}$-√s (~70% used)**
Boomerang 150 GHz	*~0.5 pW*	*~60 μK$_{cmb}$-√s*
BICEP2 150 GHz	*4.7 pW*	*~16 μK$_{cmb}$-√s*

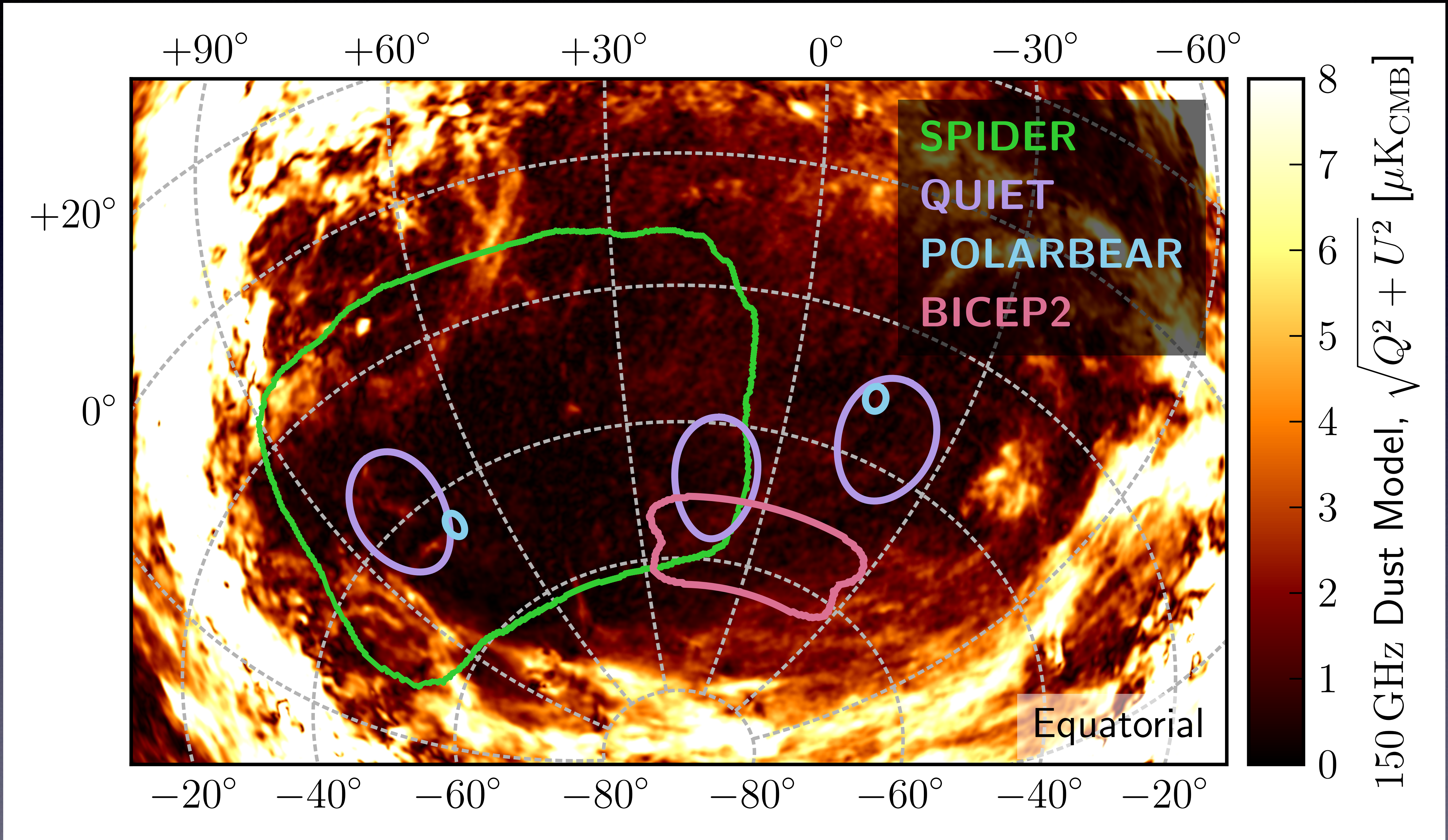
***Preliminary** estimates*

CMB calibration

Conservative detector, data selections

SPIDER's Sky

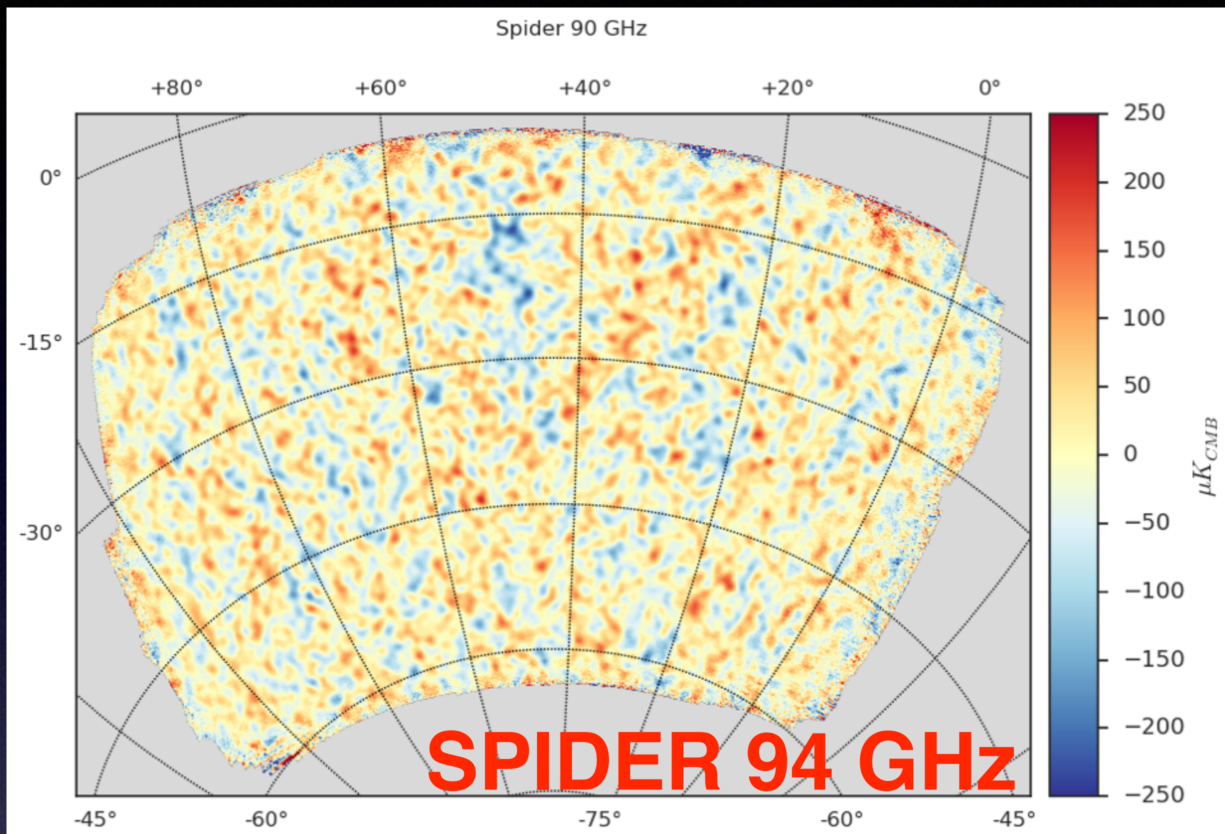
Planck Commander dust model

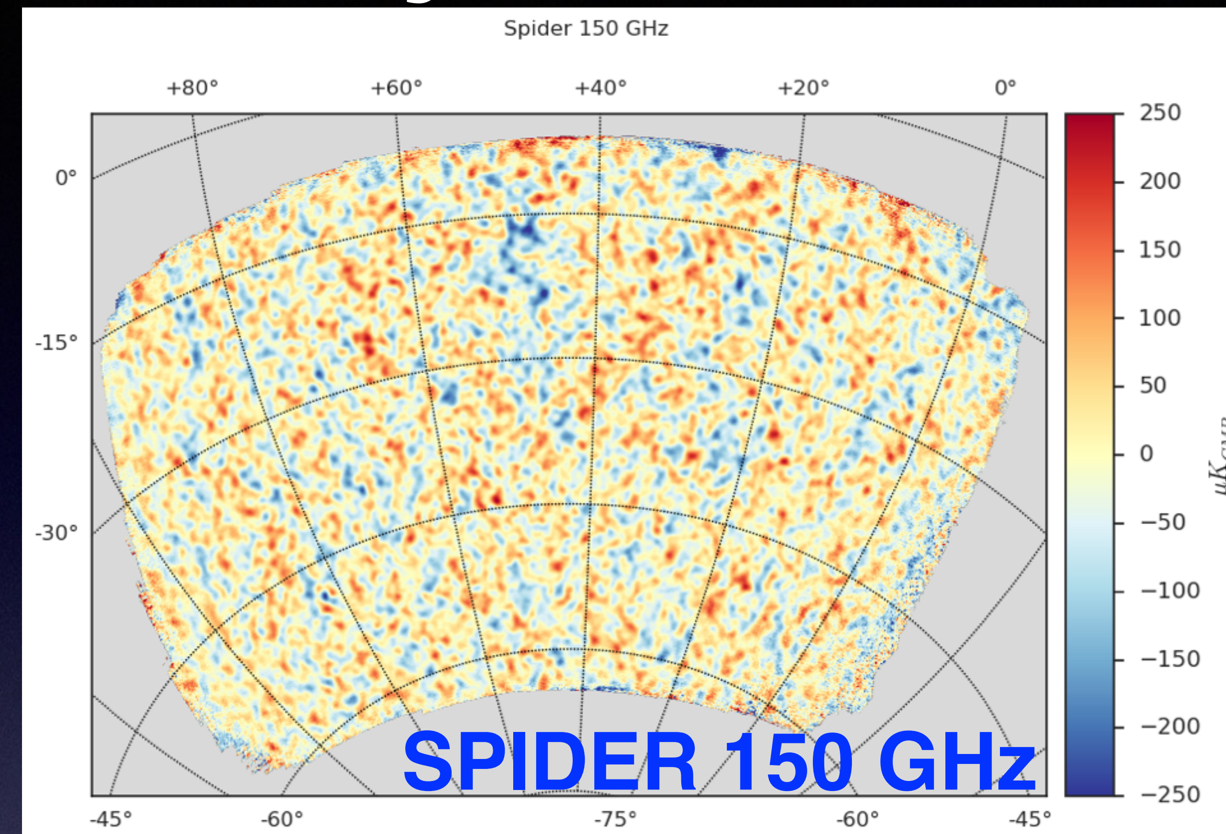


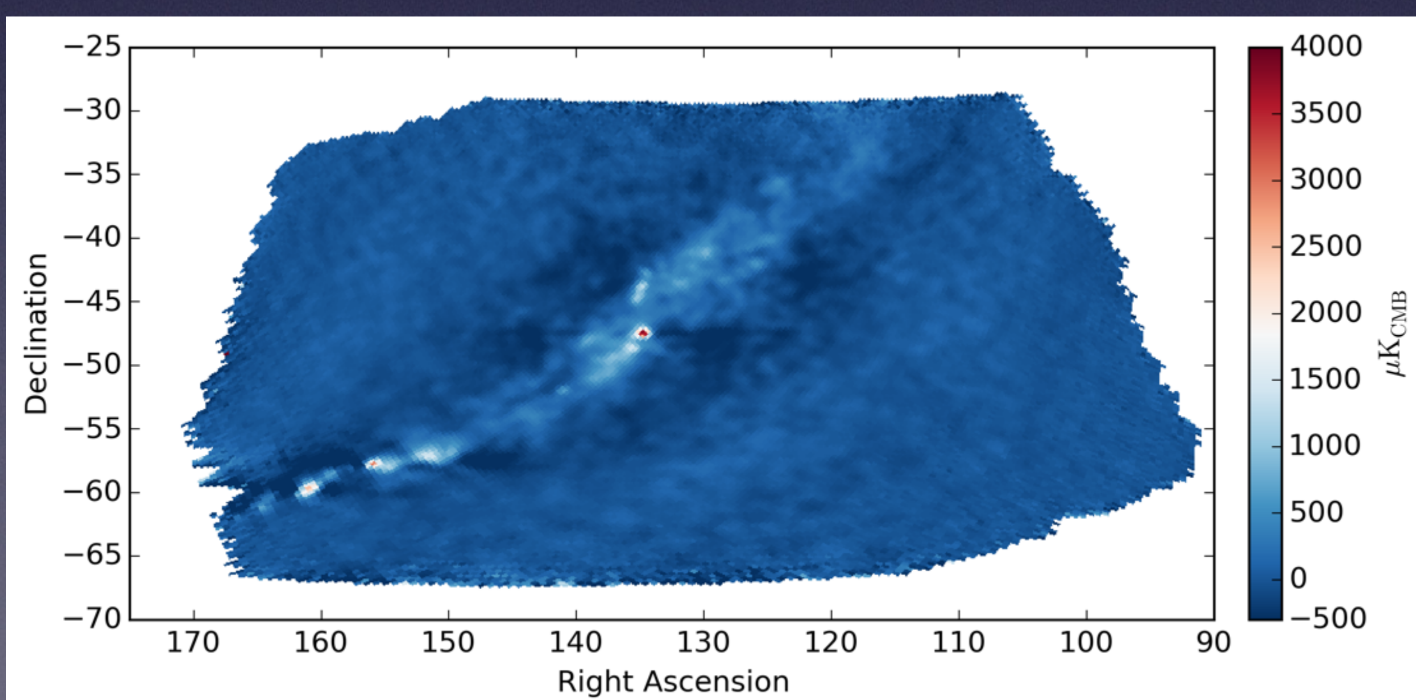
Sky coverage 12.3% (6.3% hit-weighted)

e.g. BICEP2/Keck: 2.4% (0.9%)

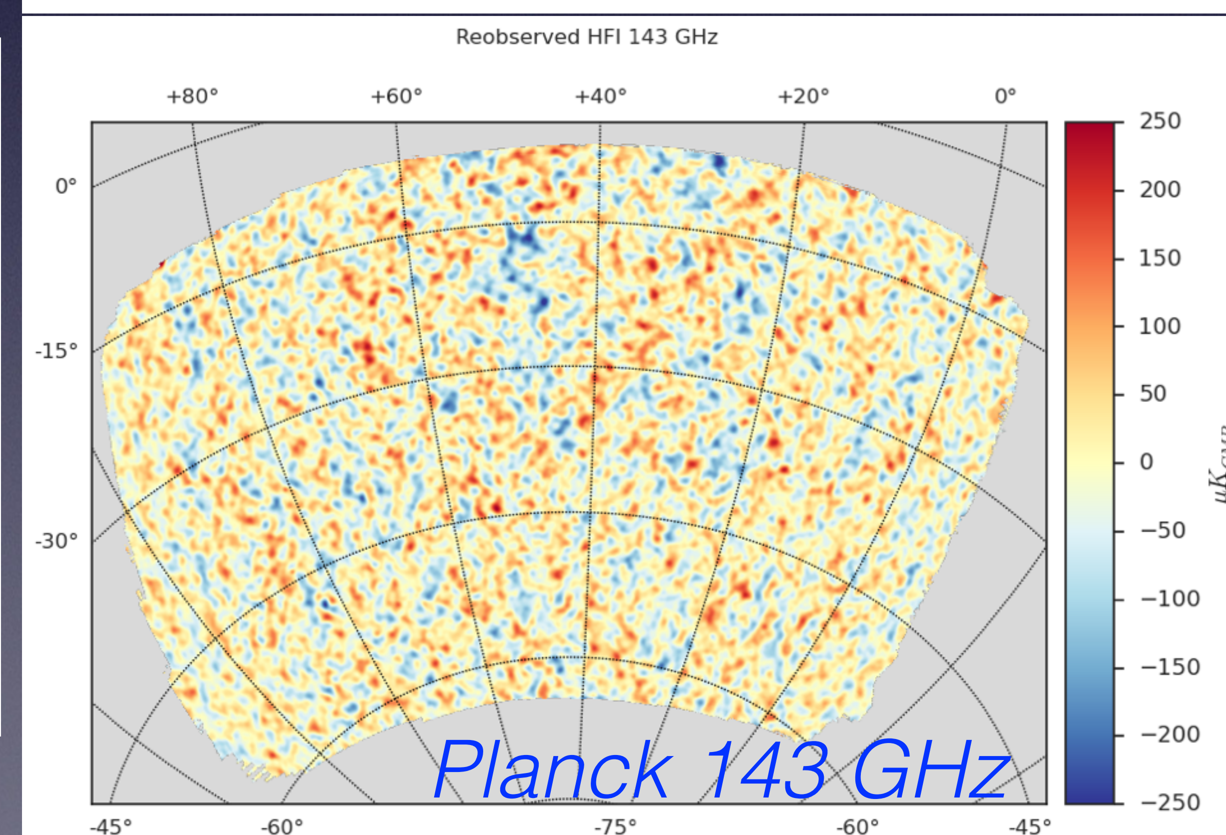
SPIDER's Sky







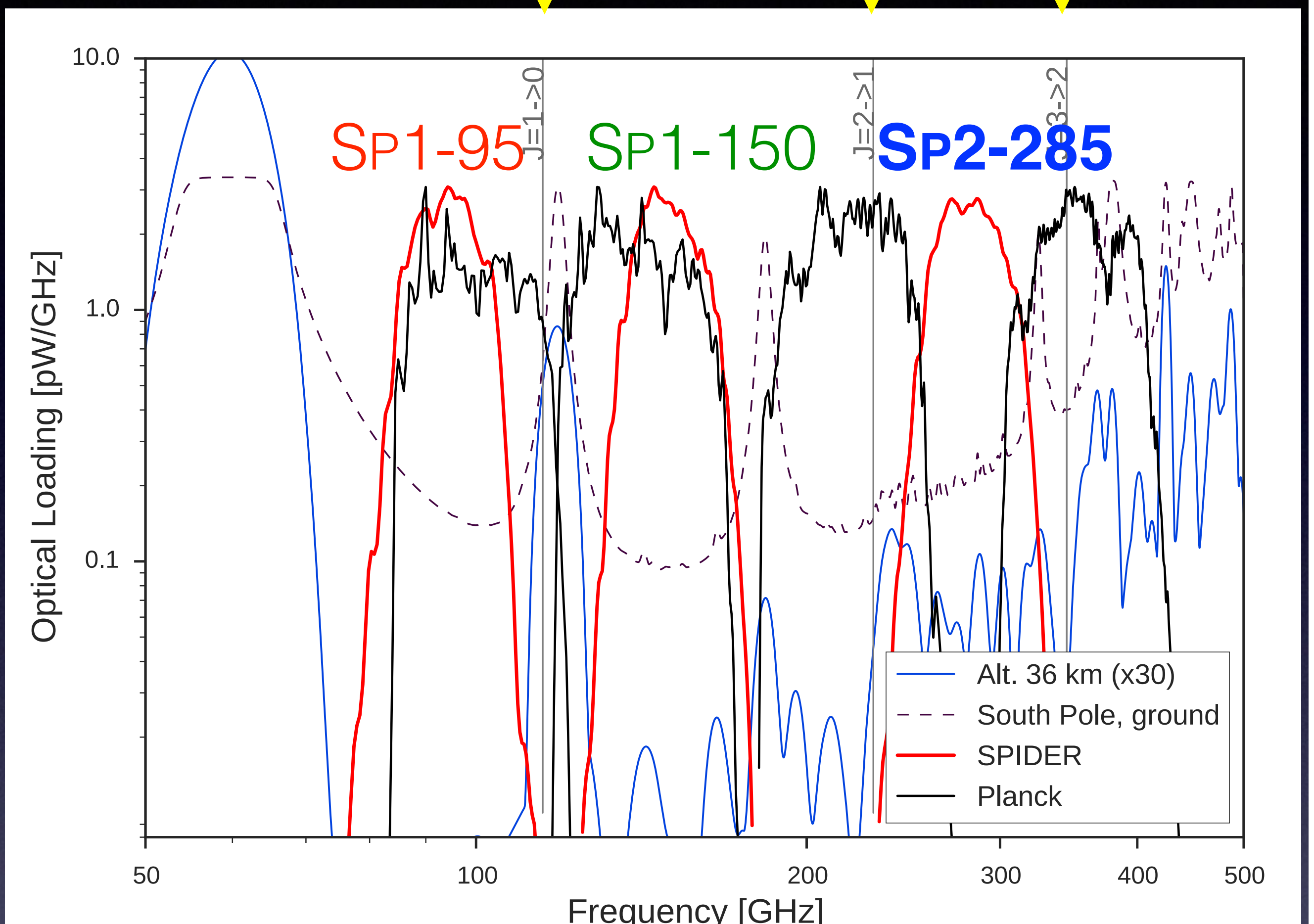
SPIDER 150 GHz: RCW38

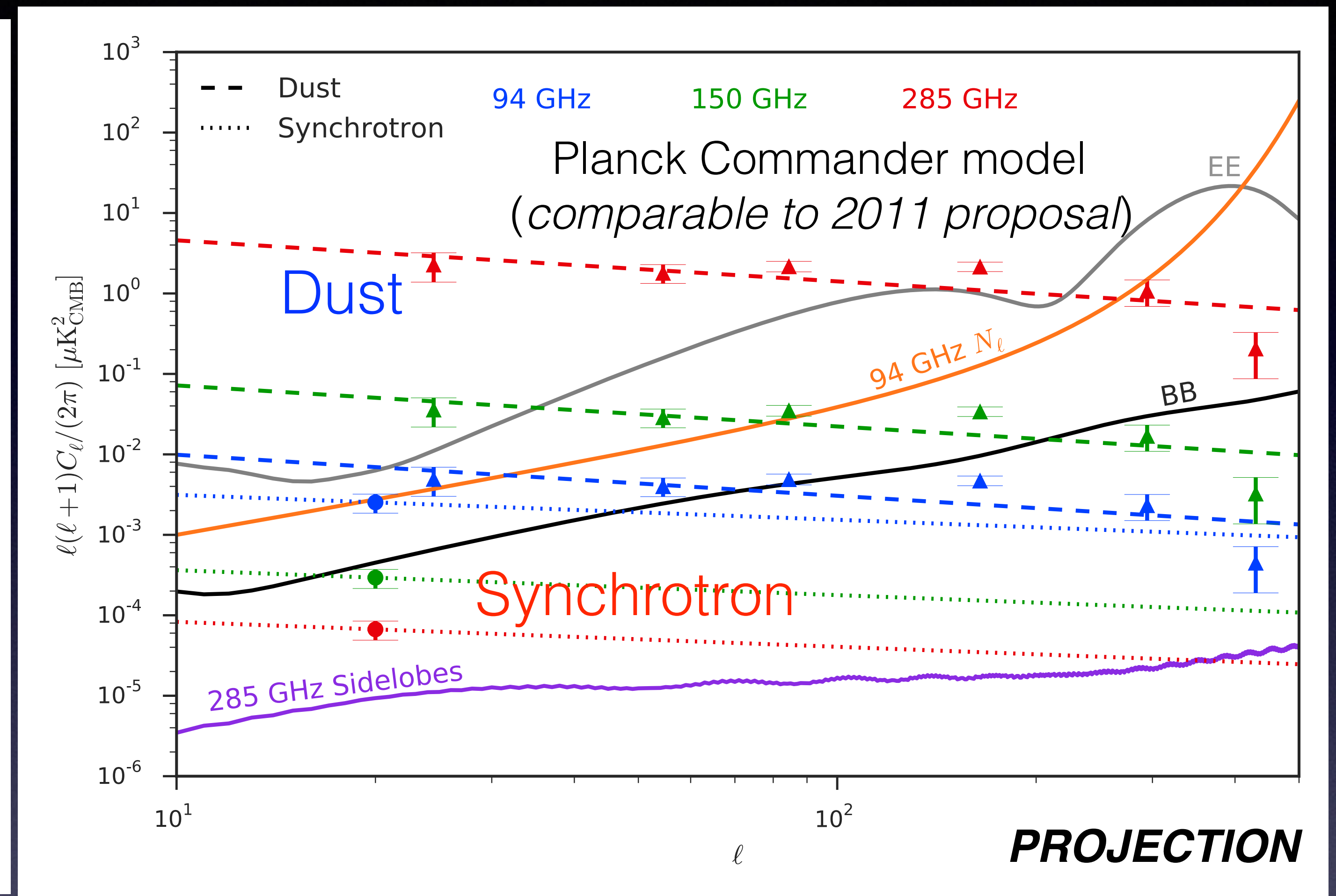


Analysis in progress: *temperature, polarization look good, stay tuned!*

Dust Polarization

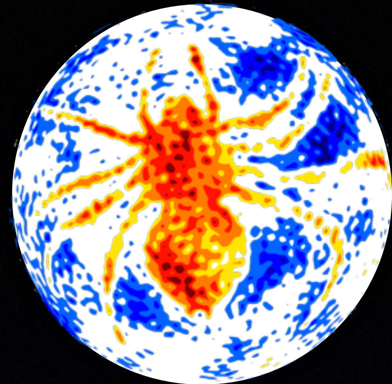
Avoid galactic CO lines





SPIDER was designed to wrestle with foregrounds

- High signal-to-noise detection of non-CMB polarization *visible in first flight data*
- Visible correlation with Planck data-informed dust model *with higher sensitivity*
- $\Longrightarrow$ *Post-Planck sensitivities at high frequencies are crucial!*



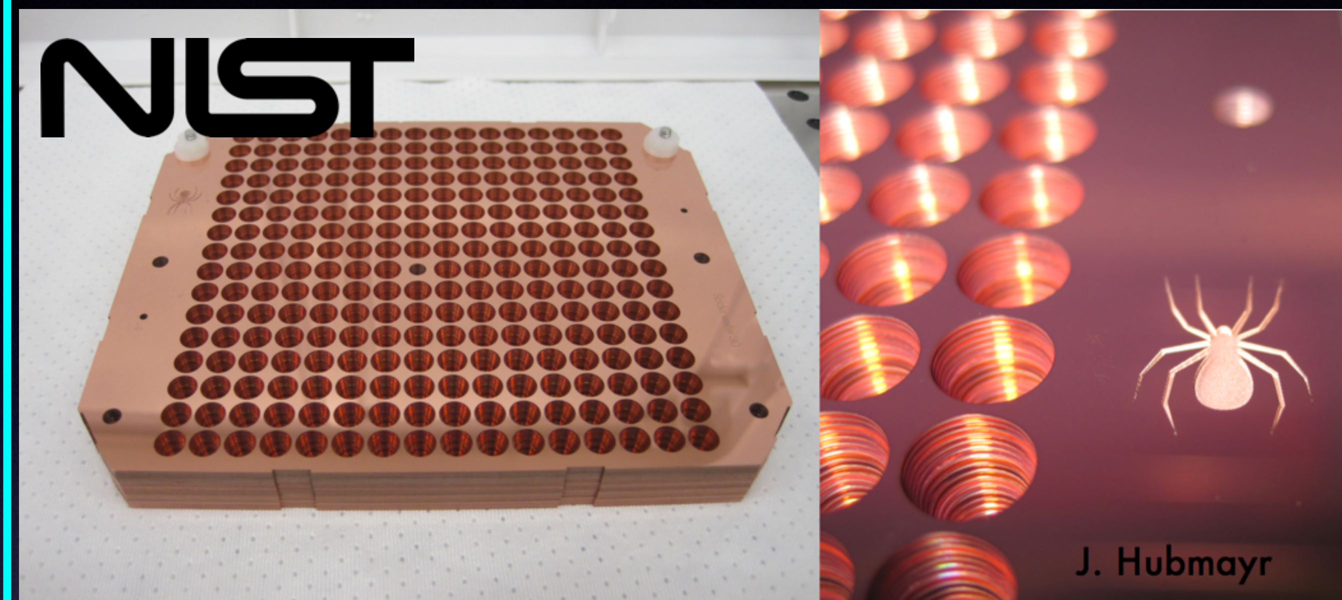
SPIDER II

Second flight *(NASA APRA 2016)*
targeting 2017 - 2018 austral summer

- Expanded frequency coverage (285 GHz) to resolve foregrounds
- Successful recovery enables significant hardware reuse
- New flight cryostat complete, undergoing final testing

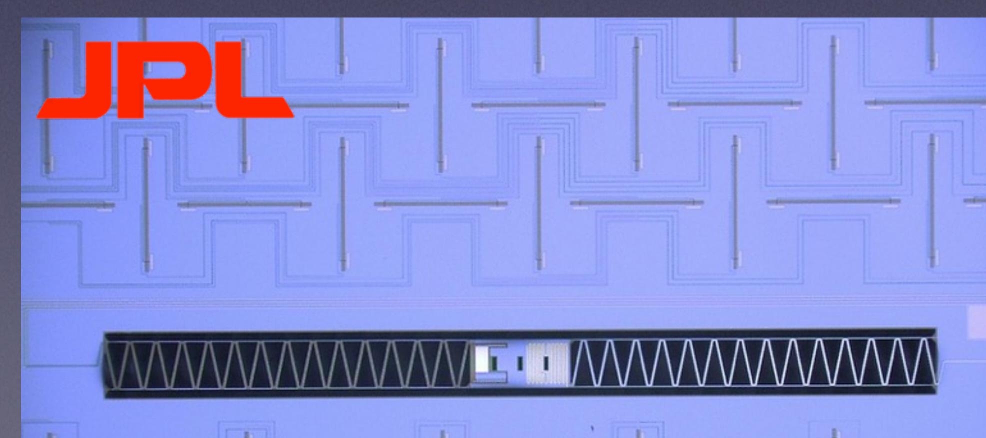
Meyer Tool (Chicago)

SPIDER II Receivers



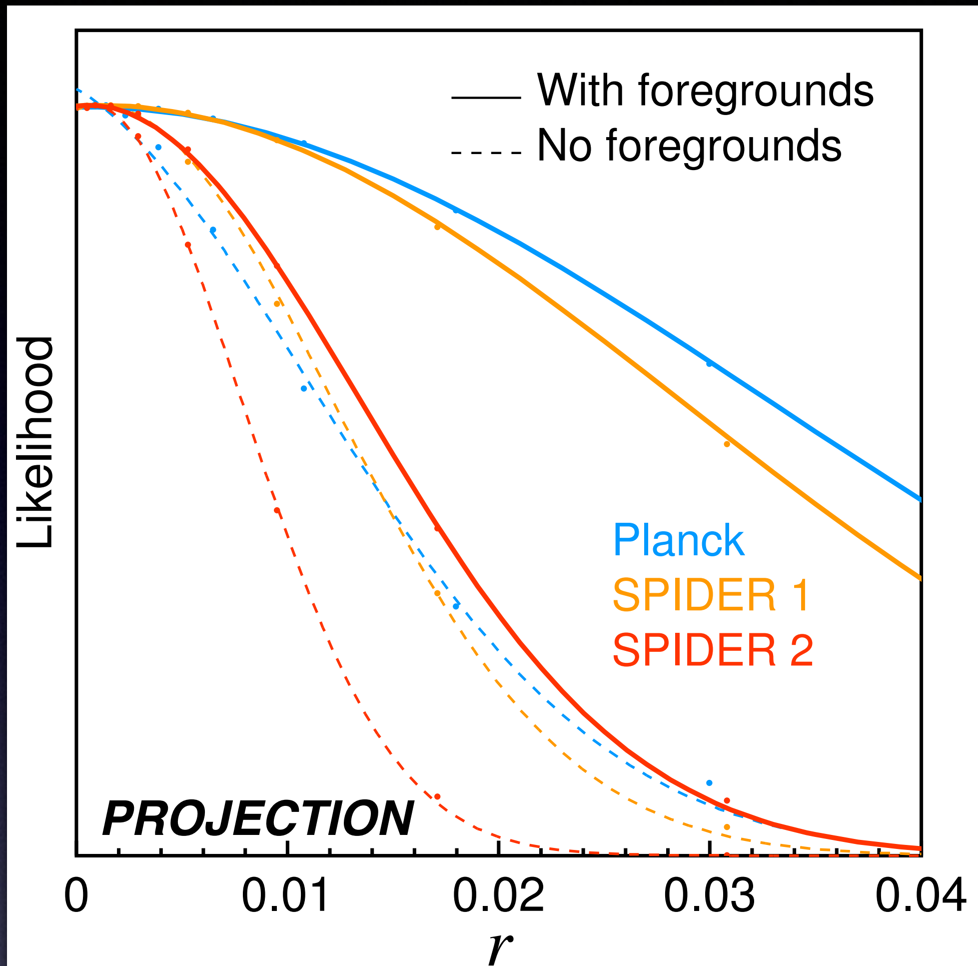
Hubmayr et al., SPIE, arXiv:1606.09396

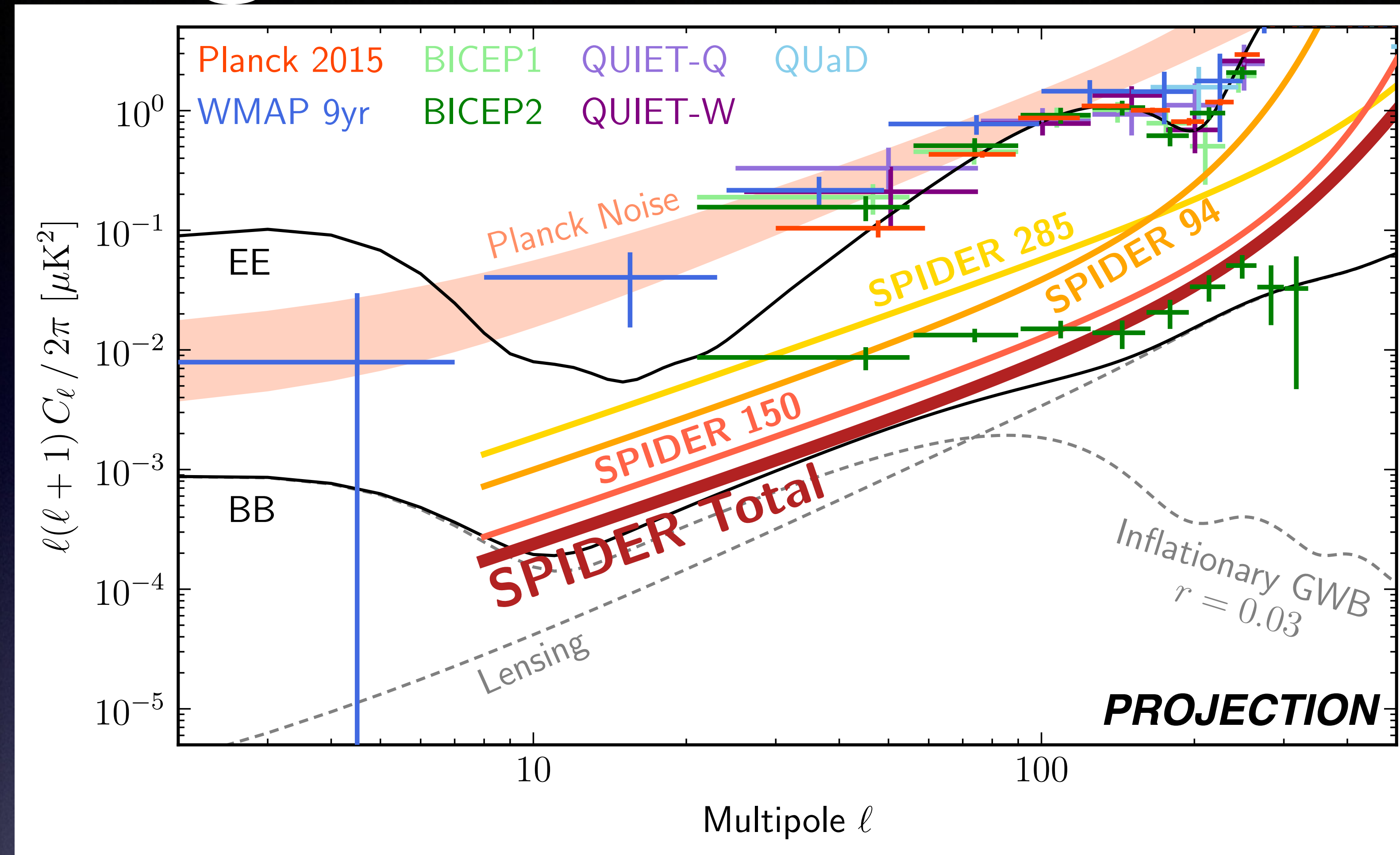
3x 285 GHz feedhorn-coupled arrays
Stacked silicon wafer feed horn arrays
Arrays in fabrication at **NIST**



up to 2 **JPL** 230 GHz receivers(*in fab*)
+ existing **JPL** 95 / 150 GHz receivers

Looking Ahead





Second flight targets 3σ detection of r=0.03 in the presence of foregrounds

The future?

- **ULDB** ("super-pressure") nearing maturity
  100-day mid-latitude flights ⇒τ?

- **Satellite** proposals: LiteBIRD, CORE, EPIC, …?

Summary

- Primordial gravitational waves remain elusive…
- Post-Planck foreground maps are a key requirement for the field
- SPIDER's first flight was very successful, data analysis is well underway
- Stay tuned for SPIDER-2 in 2017-18, with new high-frequency channels and instrument improvements

Thank you!