Observations of the Cosmic Microwave Background

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Aspen Winter Conference

March 23, 2017

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Photon Detective Work

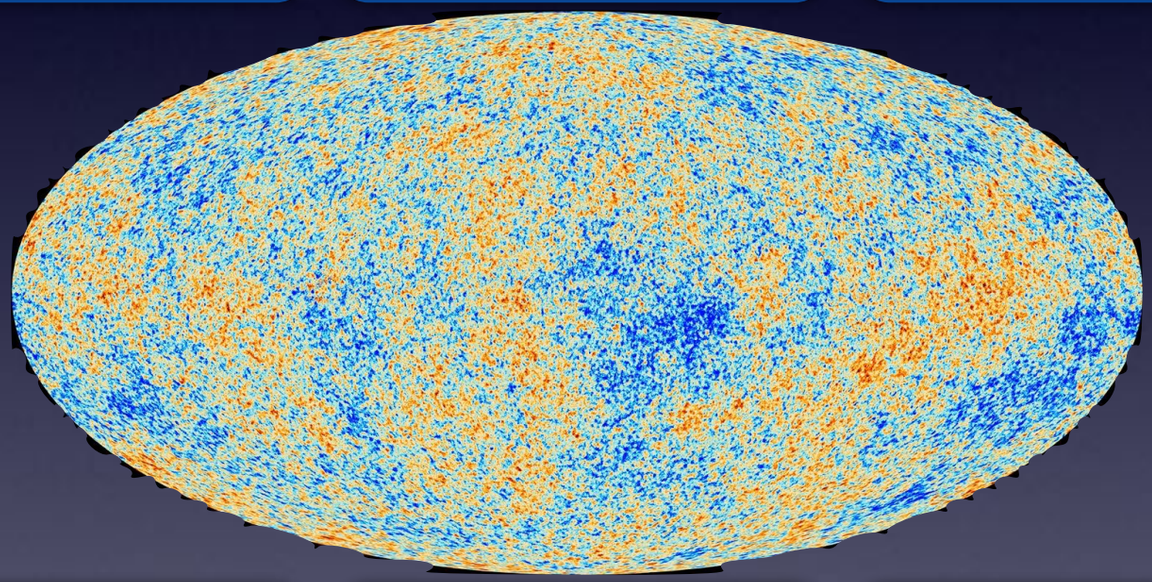
Early conditions

Primordial noise processed by plasma physics

Universe's age and contents

Primordial gravitational waves

Number of light species (e.g. ν)



Reionization by first stars

Galaxy cluster science

Neutrino masses

Cosmic backlight

Later scattering, lensing, redshift

See the CMB-S4 Science Book - arXiv:1610.02743

BLESSINGS

Early

Before structure formation

Simple

2D snapshot, linear calculations

Rich

Sensitive to many things

CURSES

Fixed Luminosity

$$\sigma_P^2/\Delta f = 2(h\nu)P + \frac{P^2}{2\Delta\nu}$$

Sample Variance

only one universe to look at

$$\frac{\sigma_{C_\ell}}{C_\ell} = \sqrt{\frac{2}{2\ell+1}} f_{sky}^{-1/2}$$

Galaxy

Gets in the way…

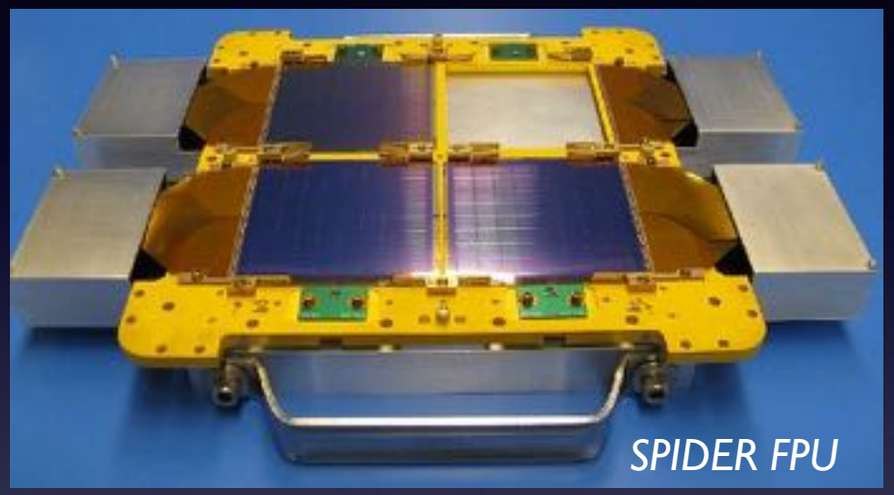
Degeneracies

Parameter confusions

Challenges

PRECISION

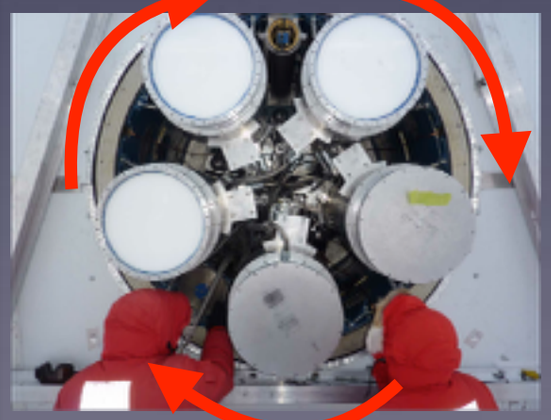
Detectors approach photon noise limit
Reduce stray photons, many detectors

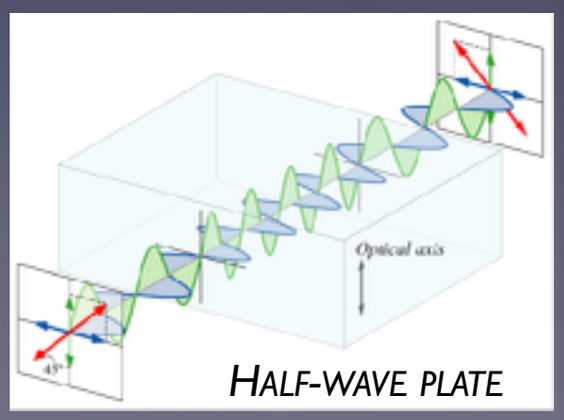


SPIDER FPU

ACCURACY

Rigid control of systematics (esp. polarized)
Instrument symmetry, signal modulation

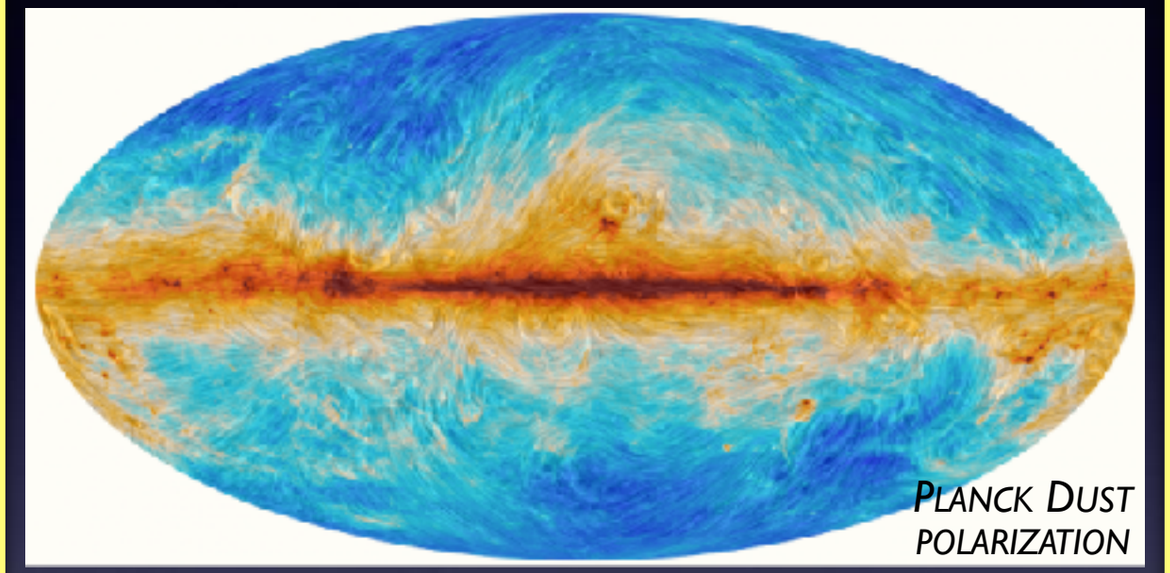




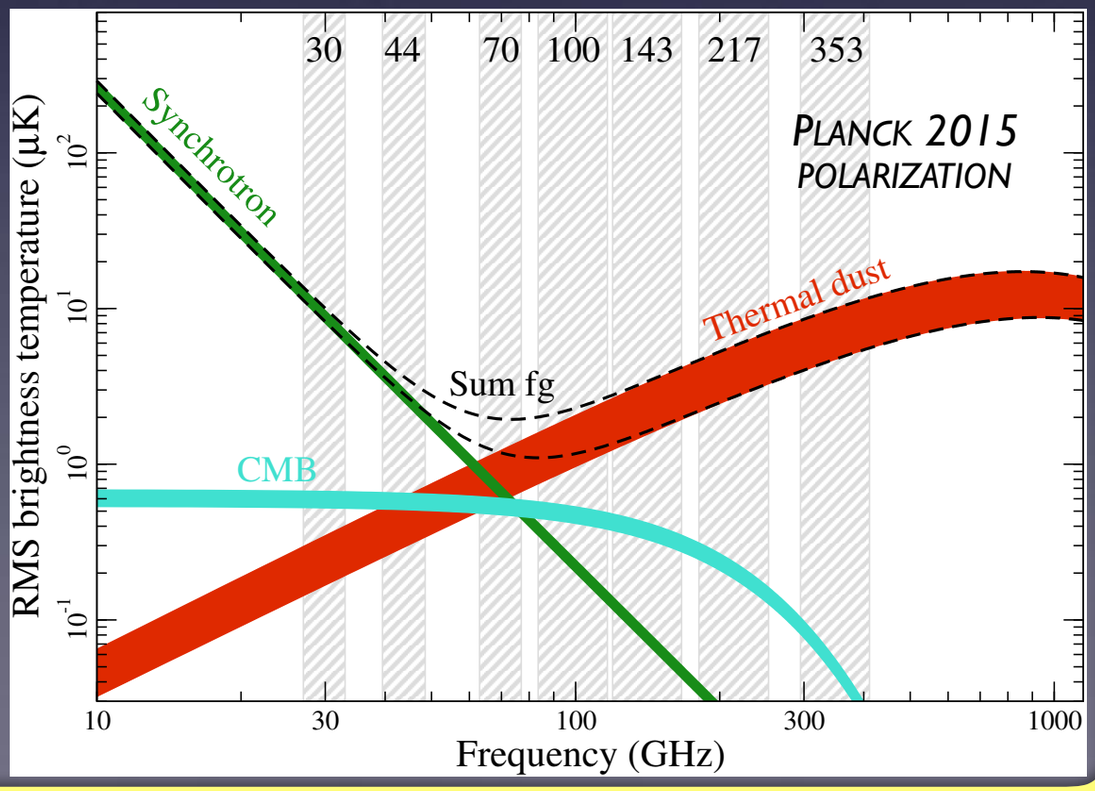
HALF-WAVE PLATE

CLARITY

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



PLANCK DUST POLARIZATION

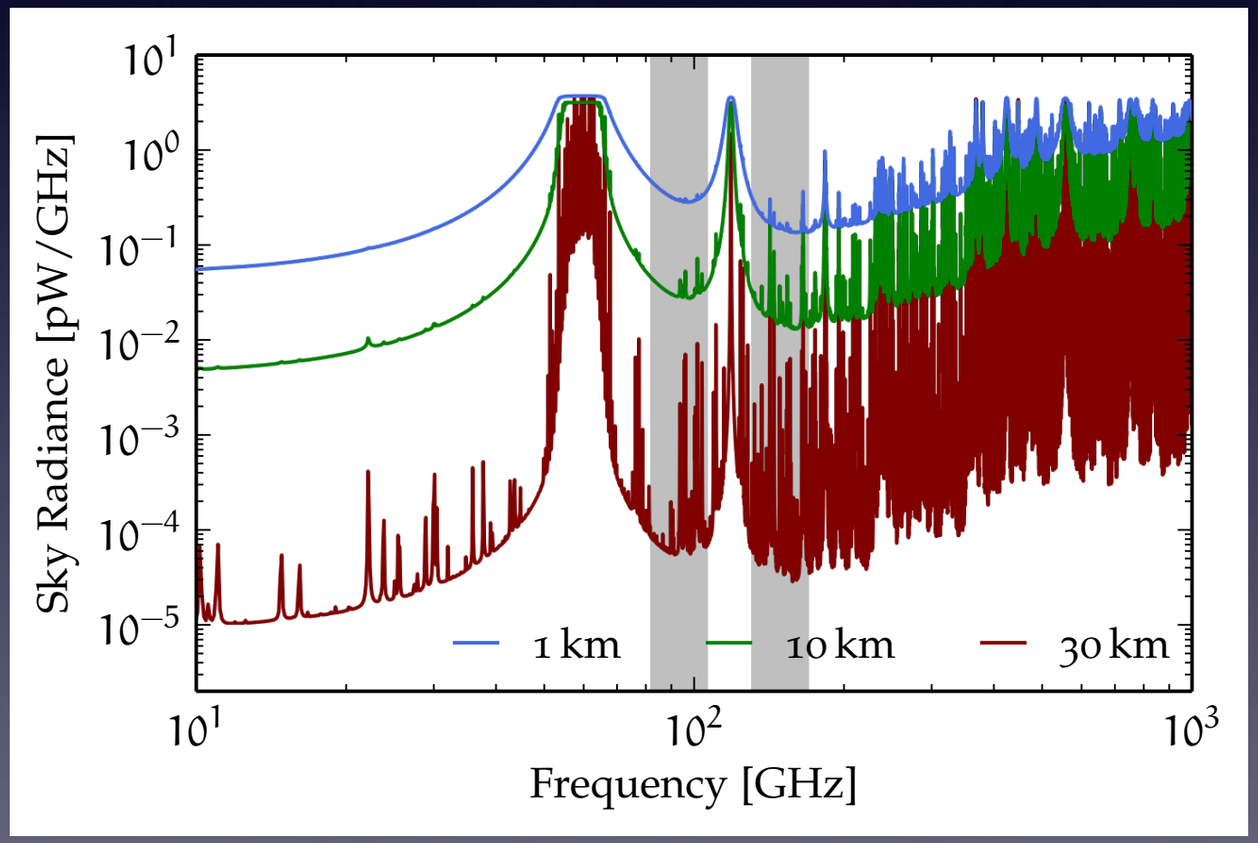


PLANCK 2015 POLARIZATION

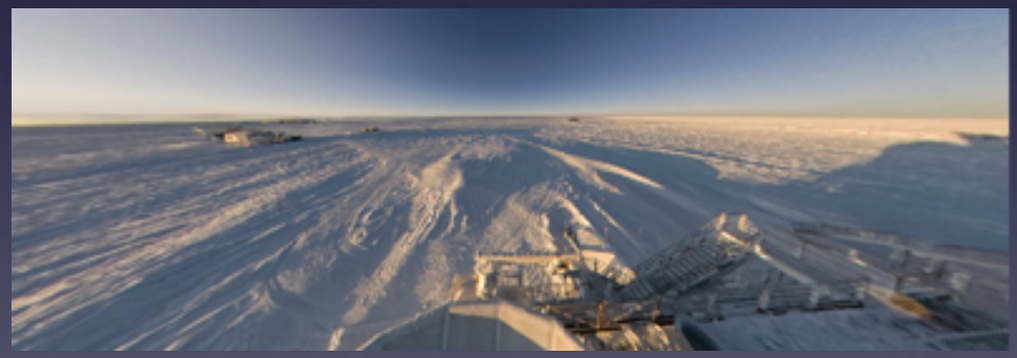
Atmosphere

Atmosphere contributes:

- **Photon noise**: Patm >> Pcmb on Earth, limits mapping speed
- **Fluctuations**: (and 1/f noise) limit stability recovering large angular scales



Earth observations limited to specific windows
(40, 90, 150, 220)
Space unrestricted, balloons almost so



Atmospheric fluctuations much milder in polarization than temperature (esp. South Pole)

Observing Platforms

Ground

Long integration times (years)
Fast development / refit cycle
Large dishes possible
Atmosphere limits:

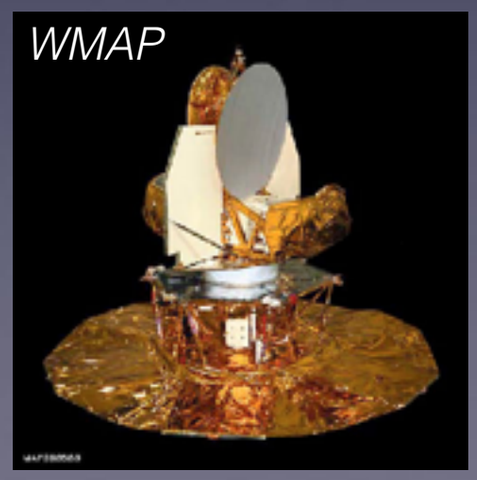
- Mapping speed (photon noise)
- Frequency coverage
- Largest angular scales

Balloon

40 km: atmospheric limits lifted!
Technology proving for satellites
Limited dish size (~2m or less)
Intermediate development cycle
Short integration times (weeks)

Space

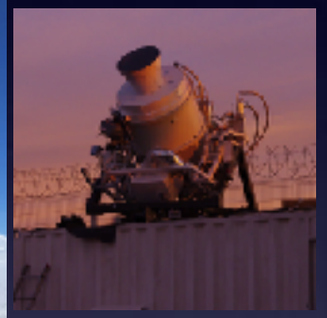
Unrestricted frequency coverage
Fast mapping speed, full sky
Long integration times (years)
Limited dish size (~2m or less)
Long development cycle (*old technology!*)
Expensive and rare



Some Major Strategies

Inflationary GW (r)

Small sky area, very deep
Many frequencies (foregrounds!!)
Small aperture (degree-scale)



Survey Instrument

Large sky area, as deep as possible
Large aperture, overlap with other surveys

Aperture

Lensing, m_ν

N_{eff}

Clusters

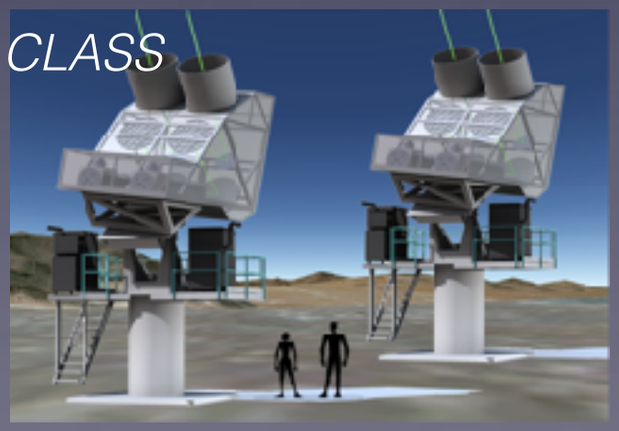
Polarbear (3.5m)

ACT (6m)

SPT (10m)

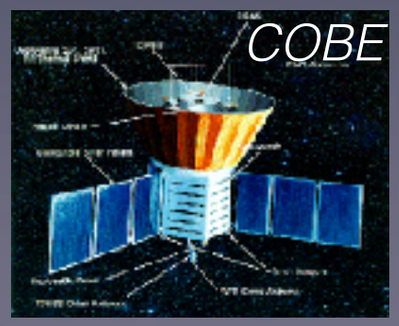
Reionization Depth (τ)

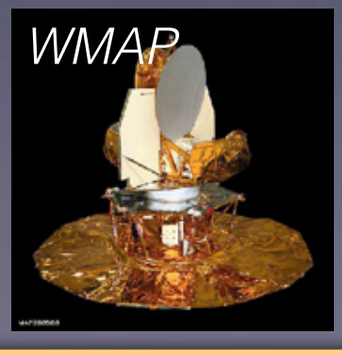
Nearly full-sky, less deep
Many frequencies (foregrounds!!)
Small aperture



Satellite

Full-sky, many frequencies, mid-sized aperture

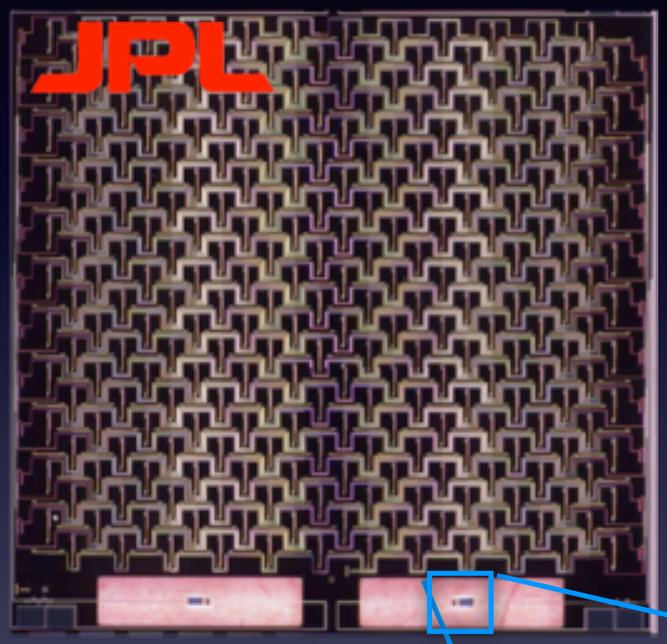


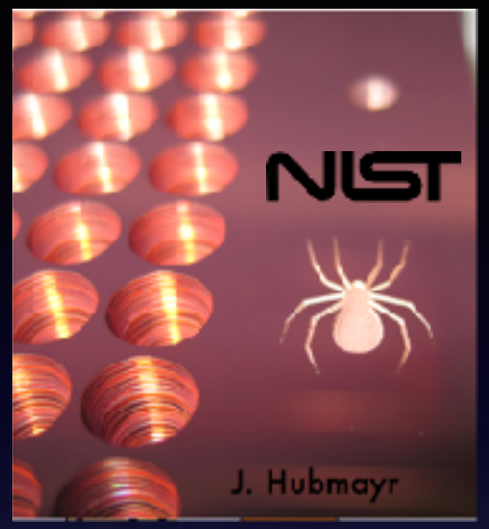


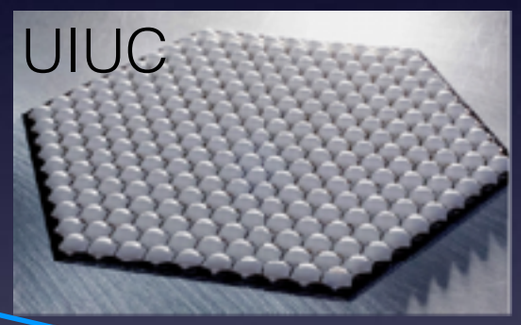
Detector Technology

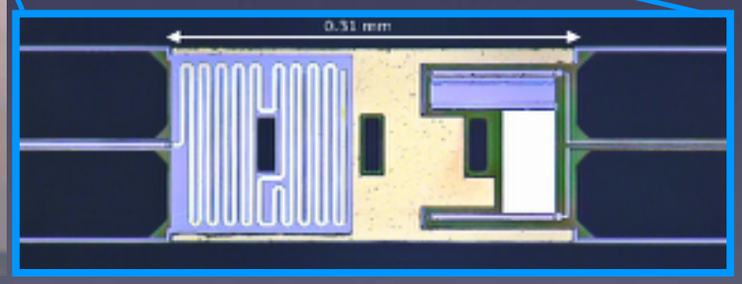
Beam forming elements

Horns, antennas, lenses









Sub-Kelvin sensors

- NTD bolometer (*pre-2006*)
- Transition edge sensor (**TES**)
- Kinetic inductance detector (**KID**)
- SQUID readout (*HEMT for KIDs*)

BOLOMETER

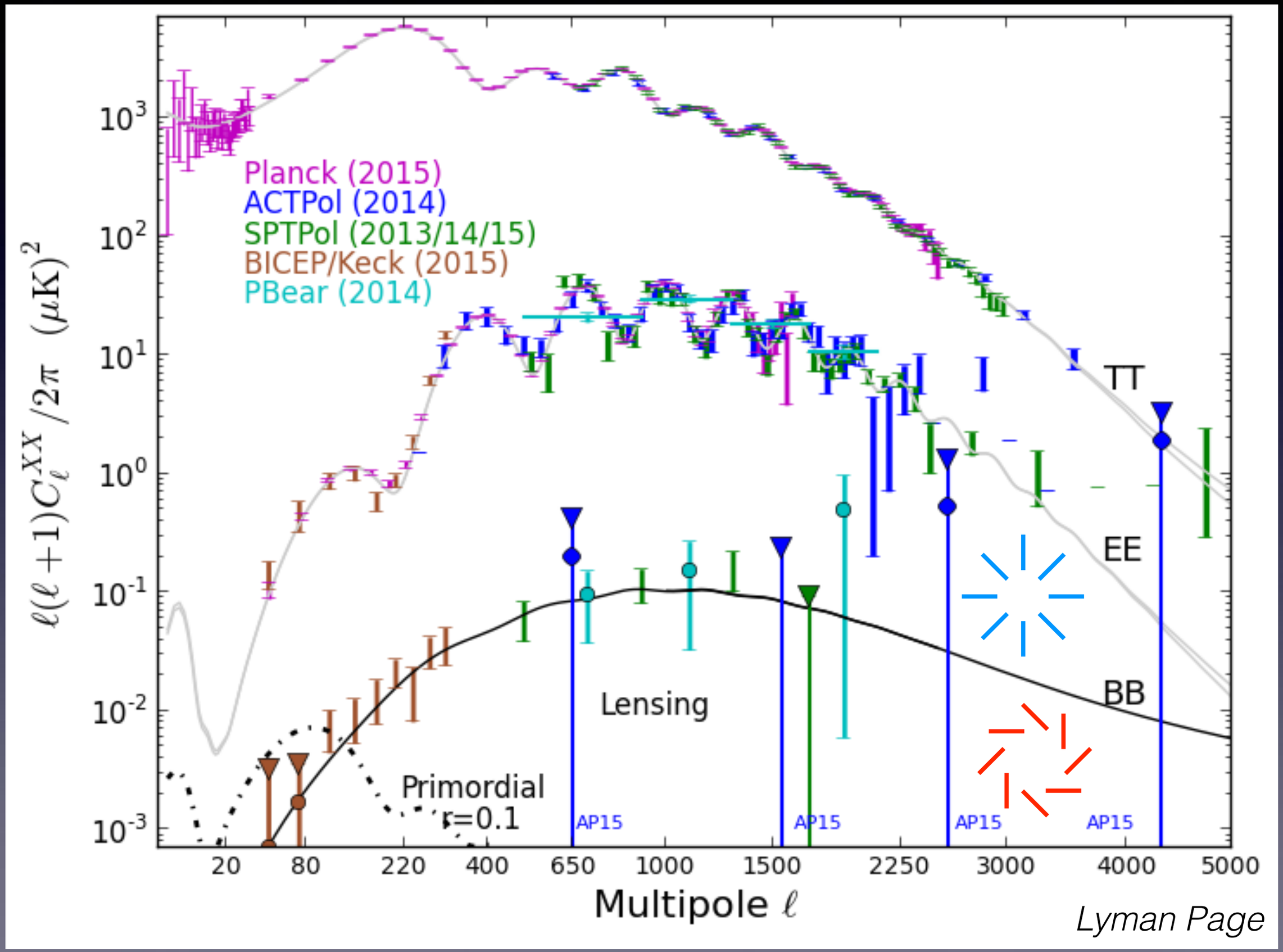
$$\sigma_P \approx \sqrt{\frac{4k_B T^2 G_{link}}{t}}$$

Key current driver: Mass production

Photolithographically patterned arrays

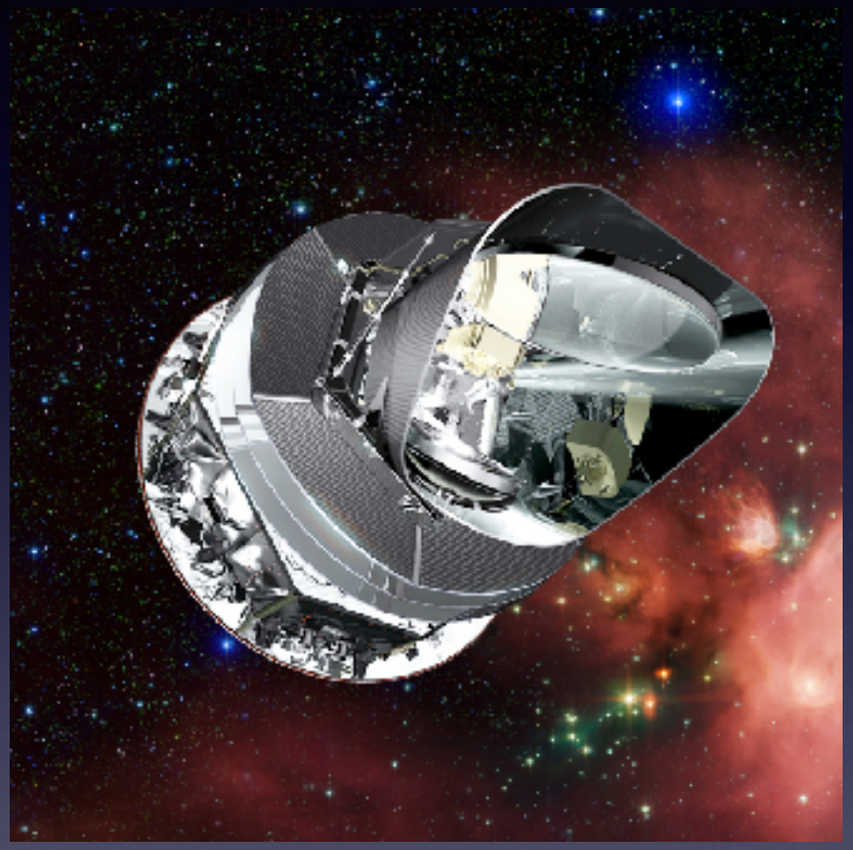
10^4-sensor multiplexed readout systems

The State of the Art

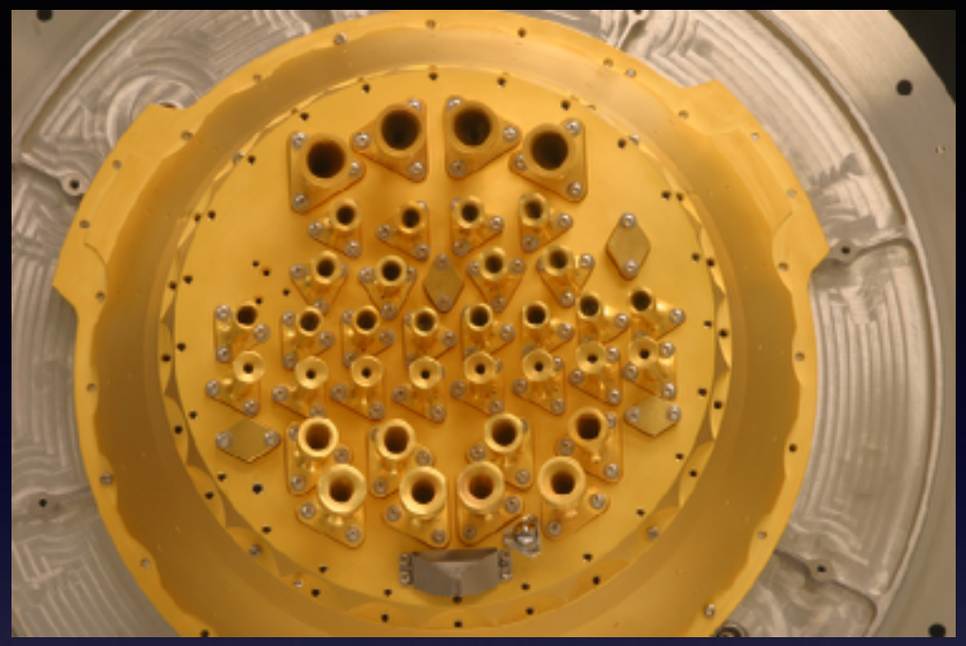


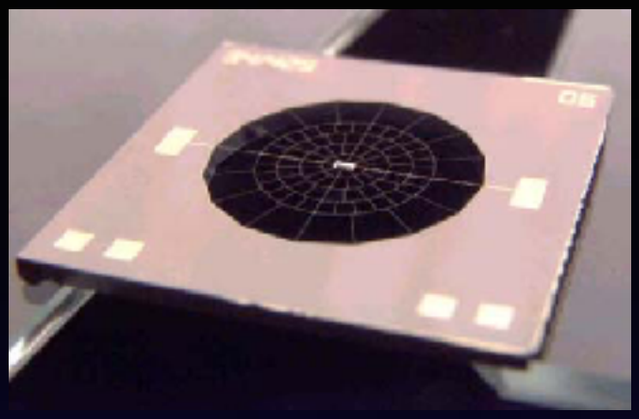
Lyman Page

Planck

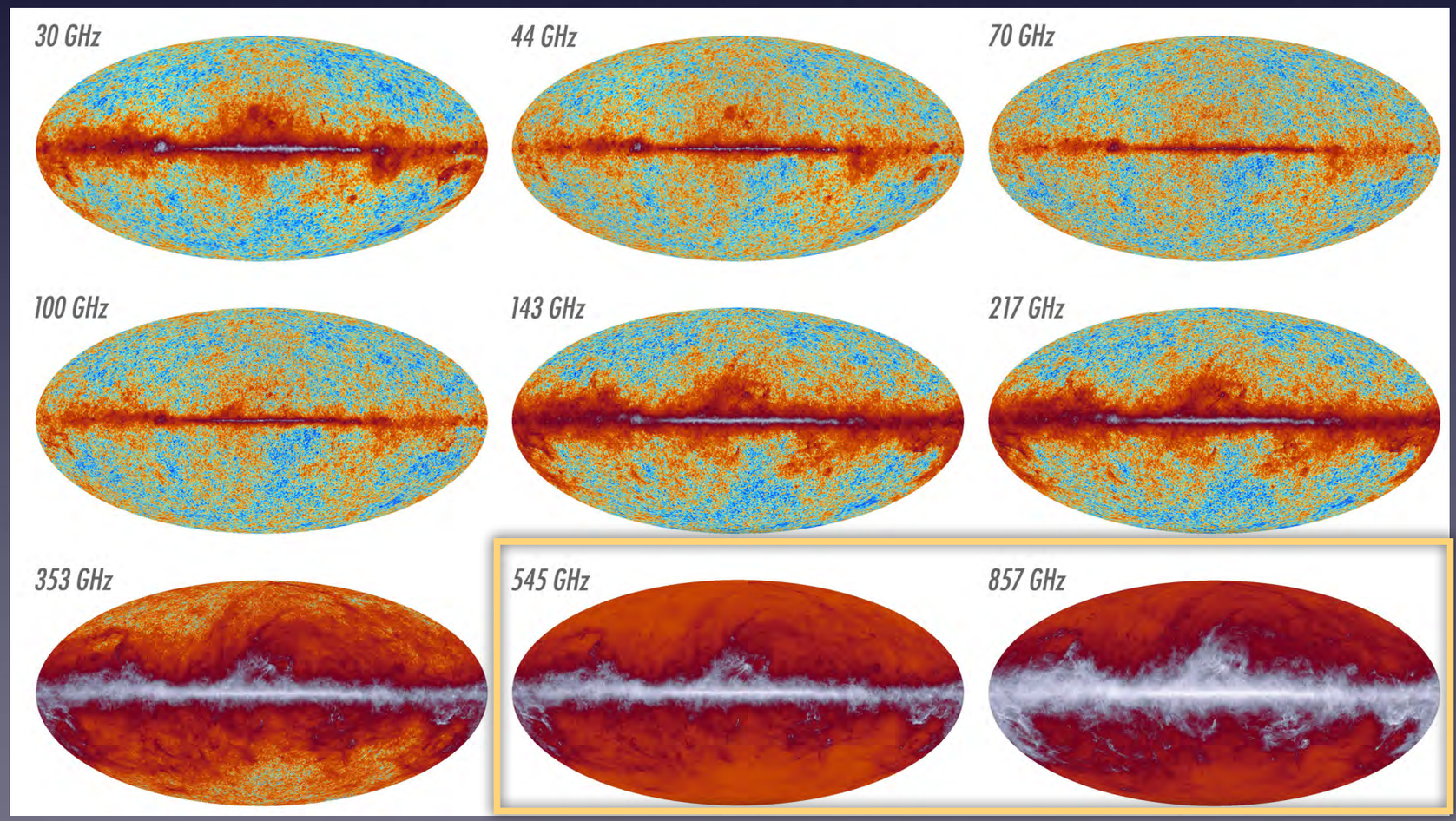


ESA / NASA
Launched May 2009
2.5 years data from L2
1.5m aperture
9 bands (*7 polarized*)





HFI: 54 “spiderweb”-style bolometers
LFI: 11 radiometers

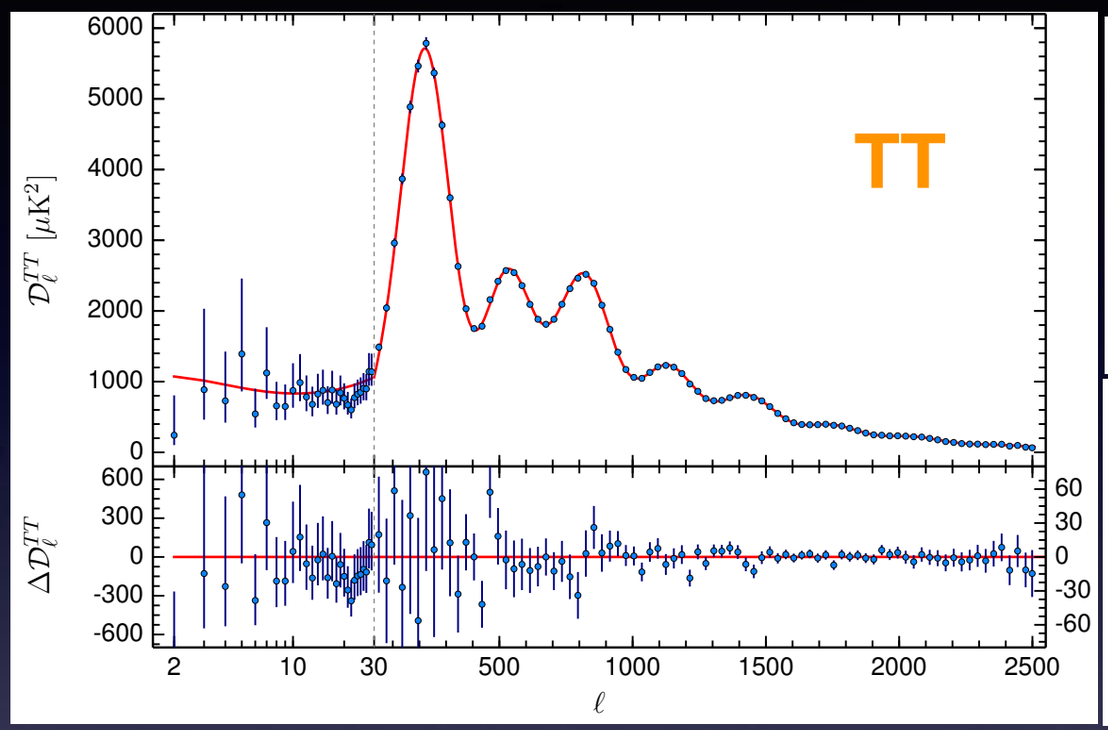


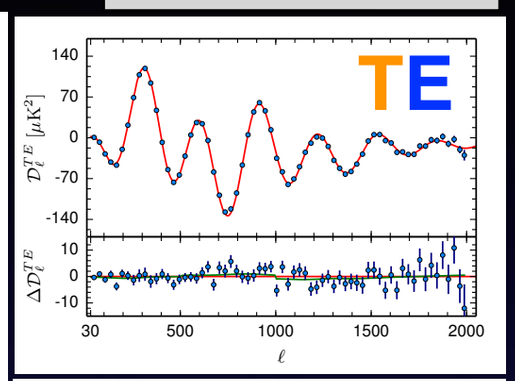
Unpolarized bands

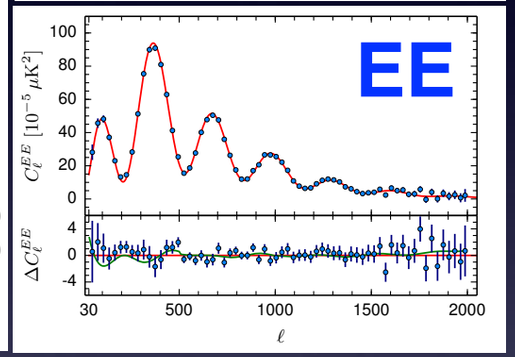
(a few) Planck results

Standard Cosmology (2016)

Planck 2015 XIII







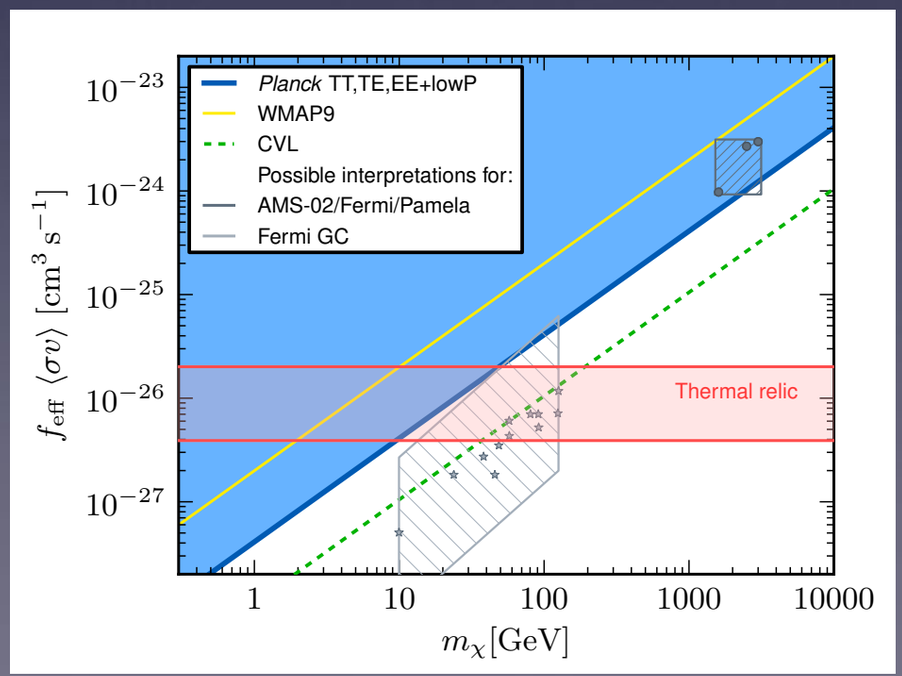
Parameter	PlanckTTTEEE+SIMlow 68% limits
$\Omega_b h^2$	0.02218 ± 0.00015
$\Omega_c h^2$	0.1205 ± 0.0014
$100\theta_{MC}$	1.04069 ± 0.00031
τ	0.0596 ± 0.0089
$\ln(10^{10} A_s)$	3.056 ± 0.018
n_s	0.9619 ± 0.0045
H_0	66.93 ± 0.62
Ω_m	0.3202 ± 0.0087
σ_8	0.8174 ± 0.0081
$\sigma_8 \Omega_m^{0.5}$	0.4625 ± 0.0091
$\sigma_8 \Omega_m^{0.25}$	0.6148 ± 0.0086
z_{re}	8.24 ± 0.88
$10^9 A_s e^{-2\tau}$	1.886 ± 0.012
Age/Gyr	13.826 ± 0.025

1-Parameter Extensions

Parameter	PlanckTTTEEE+SIMlow 95% limits
Ω_K	$-0.039^{-0.032}_{-0.034}$
Σm_ν [eV]	<0.340
N_{eff}	$2.91^{+0.39}_{-0.37}$
Y_P	$0.244^{+0.026}_{-0.026}$
$dn_s/d\ln k$	$-0.003^{-0.014}_{-0.013}$
$r_{0.002}$	<0.111
w	$-1.59^{+0.58}_{-0.46}$
A_L	$1.15^{+0.13}_{0.12}$

Planck Intermediate Results XLVII (2016)

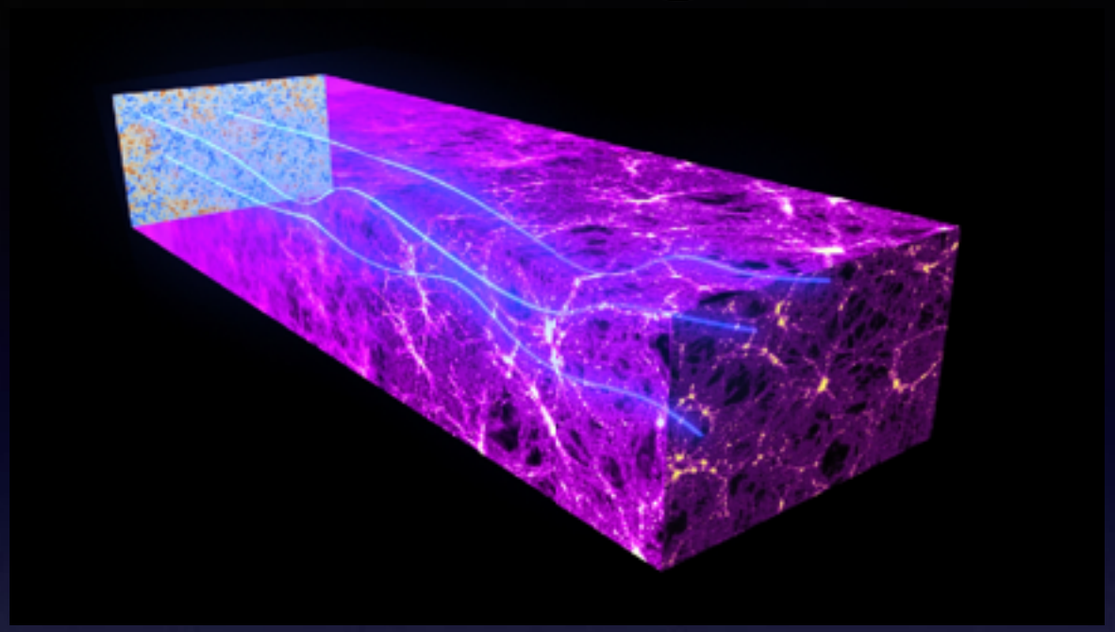
Planck 2015 XIII



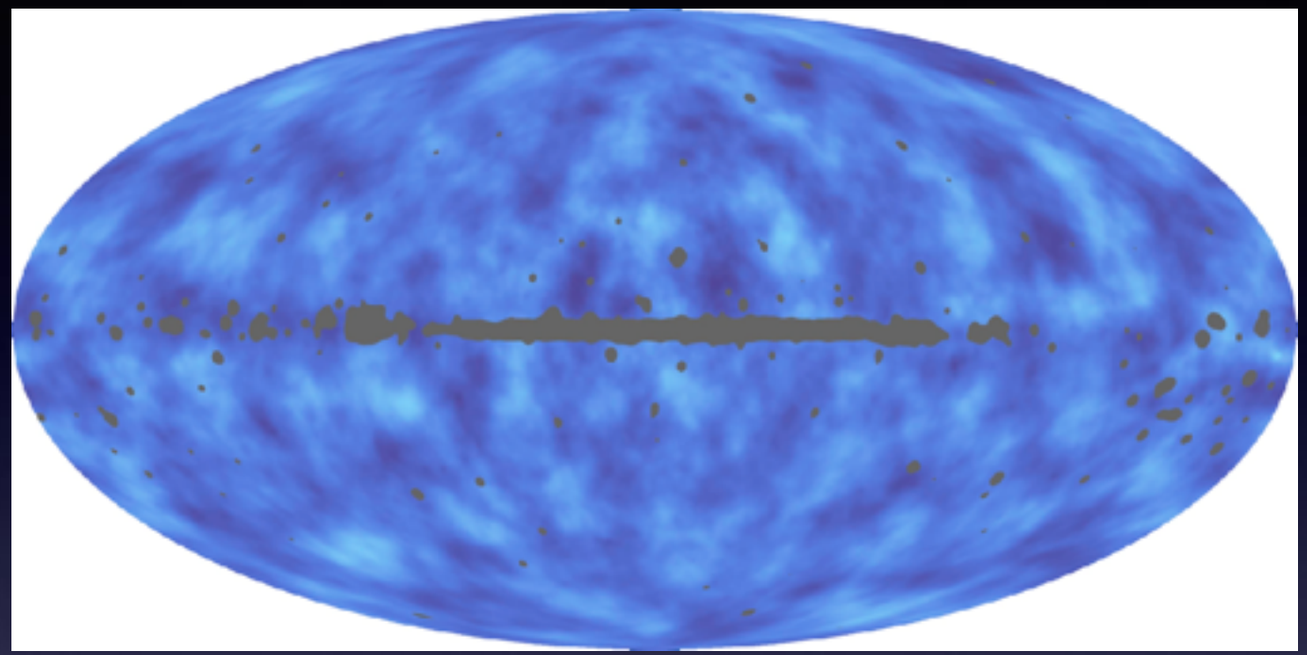
Constraints on:

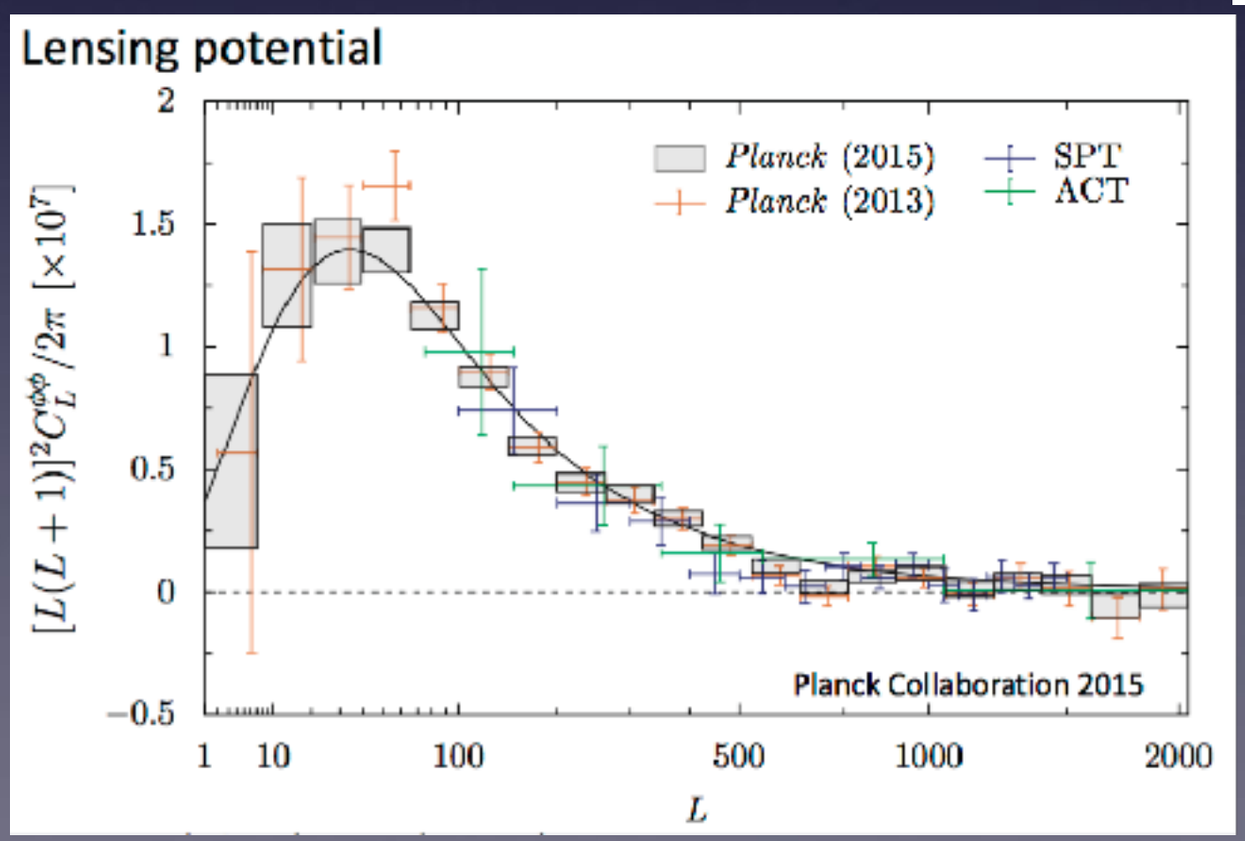
- Neutrinos / dark radiation
- Non-gaussianity
- Dark matter annihilation
- Galactic dust physics
- Source catalog
- …

CMB Lensing



Planck lensing potential





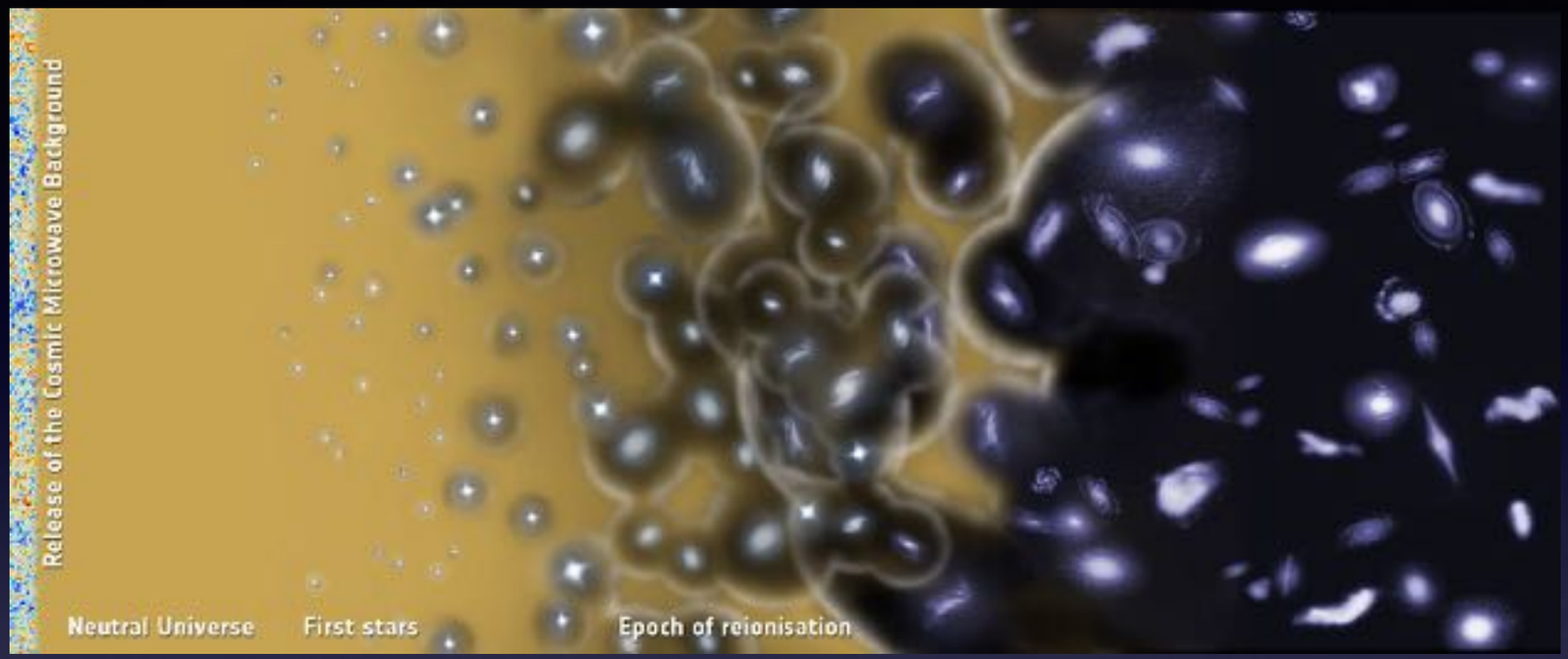
LSS lenses CMB: ~3’ typical shifts with ~degree coherence

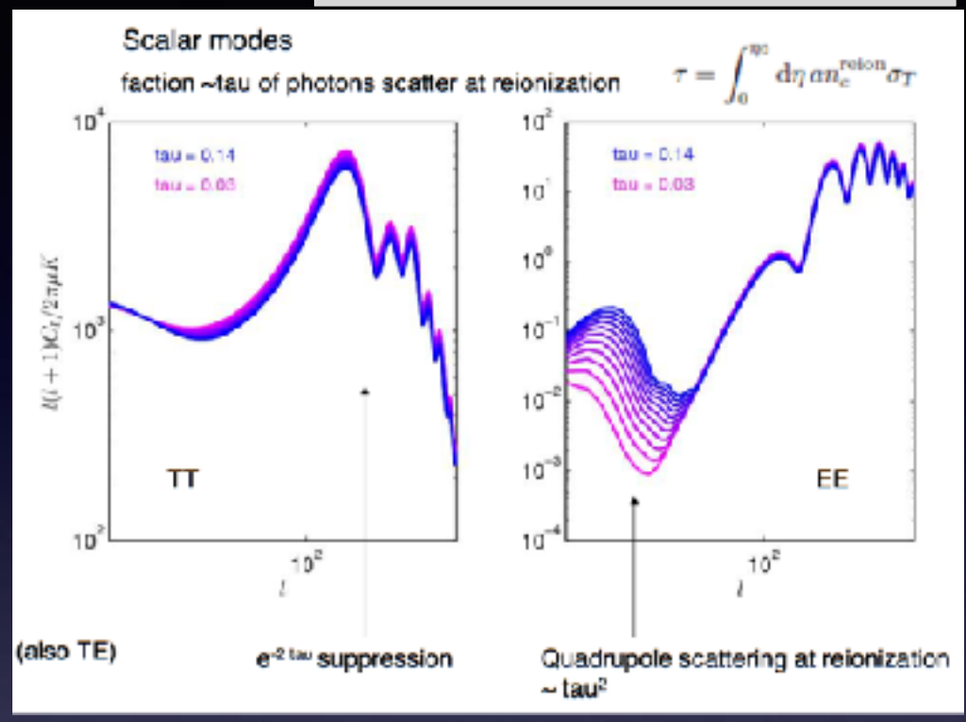
Distorts TEB, mixes E/B, introduces non-gaussianity

Reconstruct lensing potential with TT, EE, EB… 2-point Power spectrum is 4-point

Reionization Depth

Antony Lewis - Stockholm 2009





Free electrons **damp** primordial anisotropies, generate **EE at l<15**

Sensitive to **reionization history** (incl. late energy injections)

Key to breaking **degeneracies** with e.g. lensing normalization (important for neutrino mass!)

$$\tau = 0.055 \pm 0.009$$

(*EE-only estimator*)
Planck Intermediate Results
XLVI + XLVII (2016)

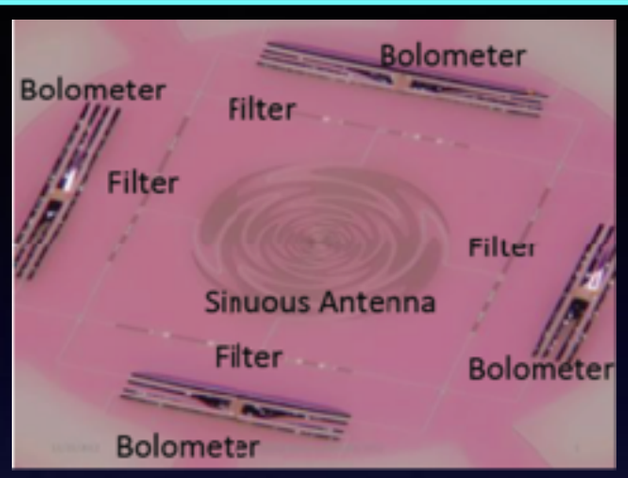
Below WMAP value (dust contaminated)
Cosmic variance at this level is ~0.006

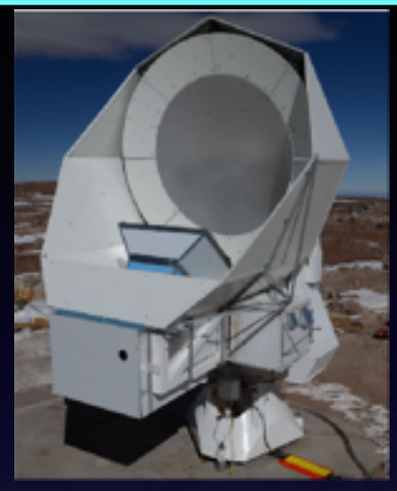
Enormously difficult measurement for Planck: foregrounds, cosmic rays, drifts, ADC issues, …

Ground: Large Apertures

POLARBEAR / SIMONS ARRAY

- 3.5m reflectors in Atacama: lensing BB
- Multichroic arrays, lenslet coupled
- Soon 3x covering 95-220: Simons Array



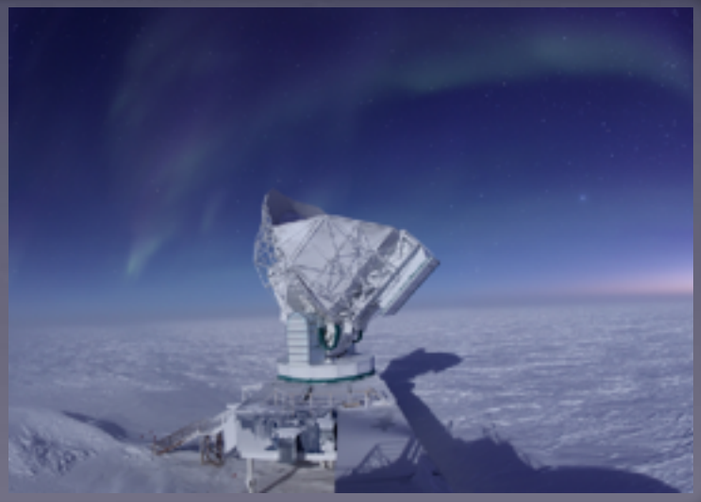


ATACAMA COSMOLOGY TELESCOPE

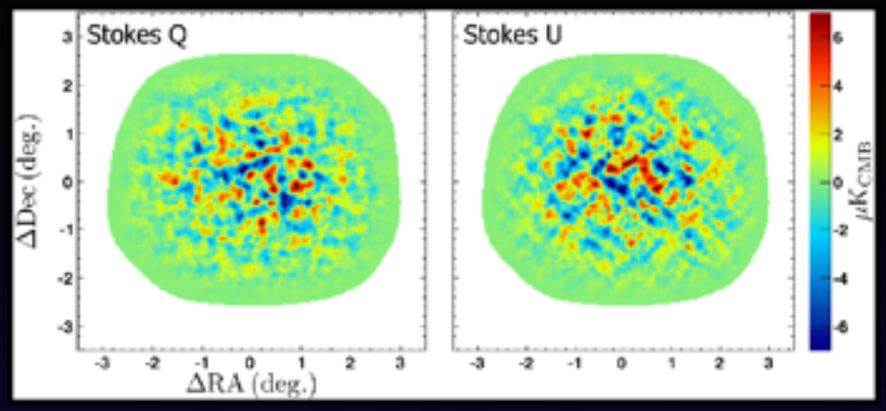
- 6m reflector in Atacama: small scales, clusters, lensing
- Multichroic arrays, feed horn coupled
- New camera deployed 2016: Advanced ACTpol

SOUTH POLE TELESCOPE

- 10m reflector at S. Pole:
  small scales, clusters, lensing
- Multichroic arrays, lenslet coupled
- New camera deployed 2016: SPT-3G

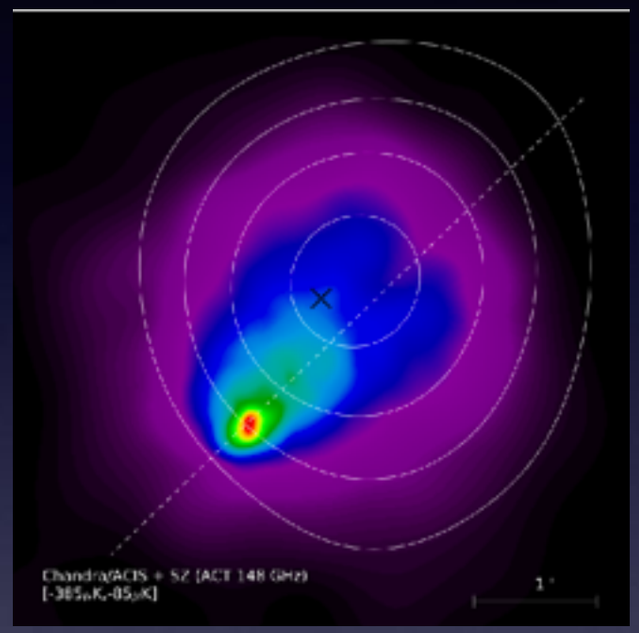


Some Key Results



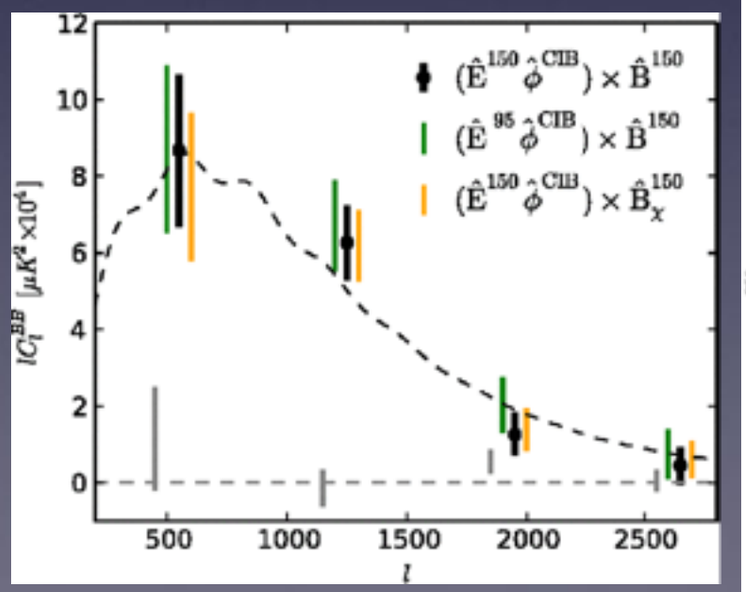
POLARBEAR

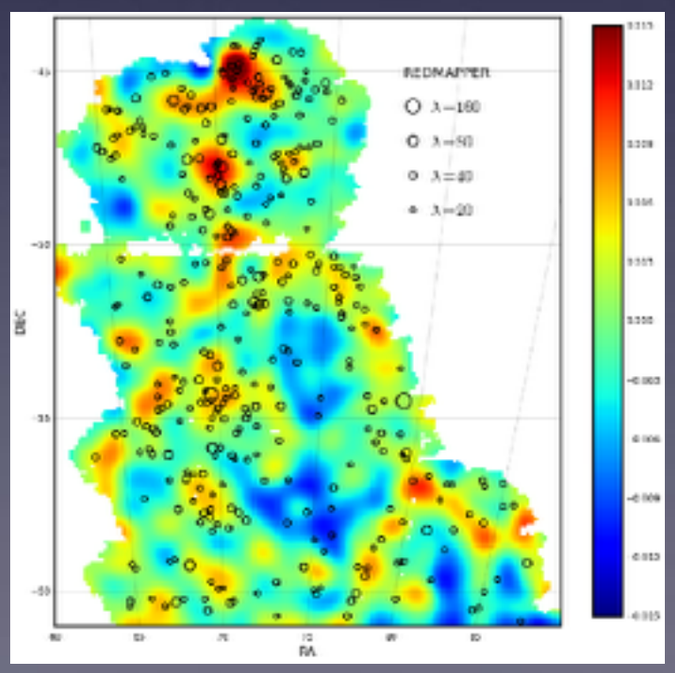
- 2014: CMB lensing, correlation with CIB, 4pt



ATACAMA COSMOLOGY TELESCOPE

- 2012: "El Gordo" (most massive high-z cluster), lensing potential, kSZ detection, dark energy
- 2013: cluster catalog
- 2014: T,E spectra, B limits, correlation with CIB





SOUTH POLE TELESCOPE

- 2011: SZ cluster catalog
- 2013: BB lensing correlation with CIB
- 2015: BB lensing detection
- 2016: kSZ detection, DES correlation, de-lensing CMB with CIB

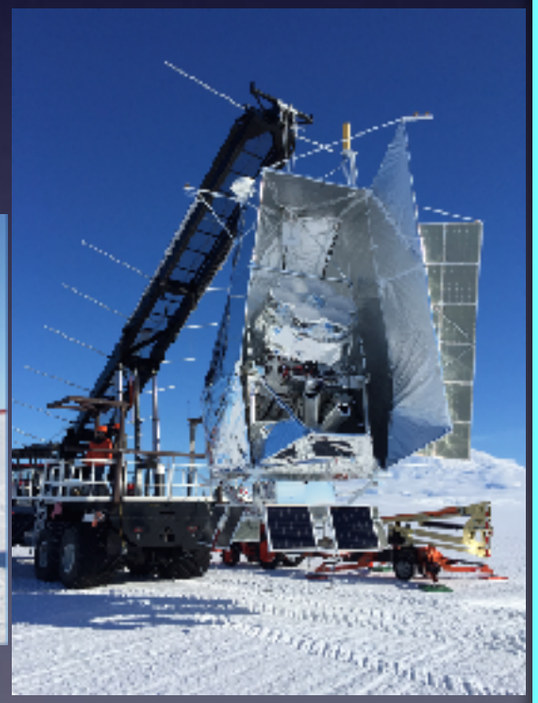
Inflation Machines

BICEP / KECK ARRAY

- 0.3m monochromatic refractors
  BICEP2: 150 GHz; Keck 95-270 GHz
- Symmetric, rotatable telescopes
- Data 2010-, publications 2014-
- ~1% sky fraction

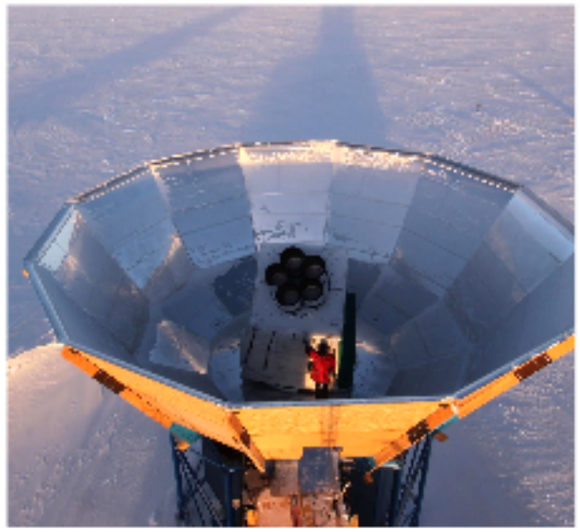
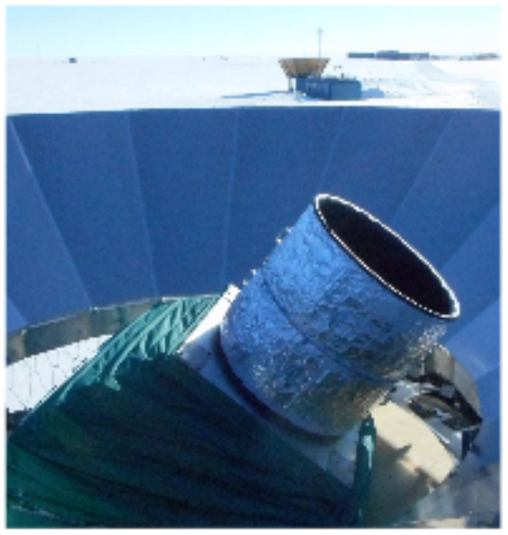
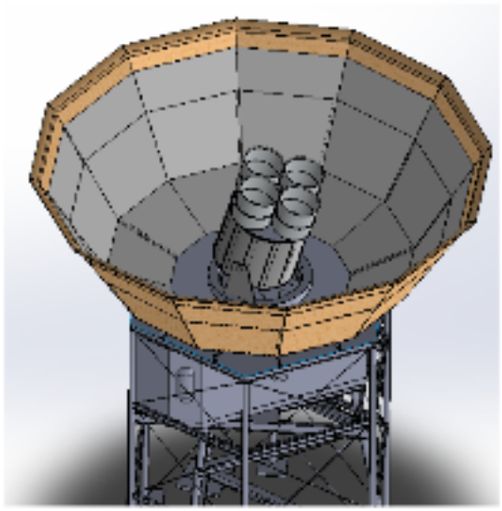
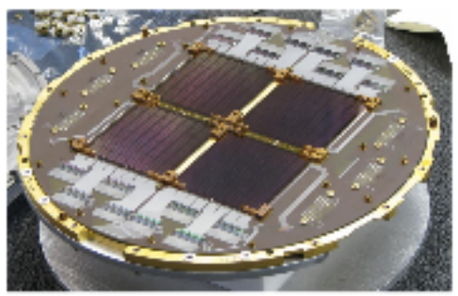
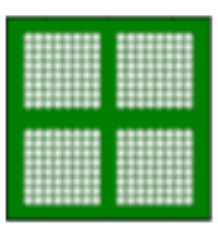
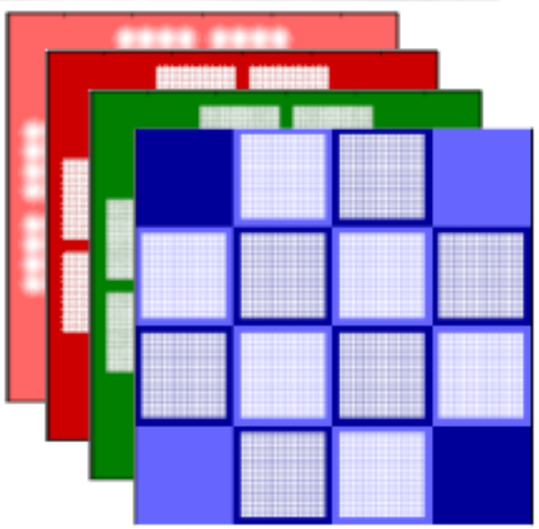
SPIDER

- 0.3m monochromatic refractors
  S1: 95, 150 GHz; S2: 95-280 GHz
- Stepped half-wave plate
- Data 2015, under analysis
- ~10% sky fraction

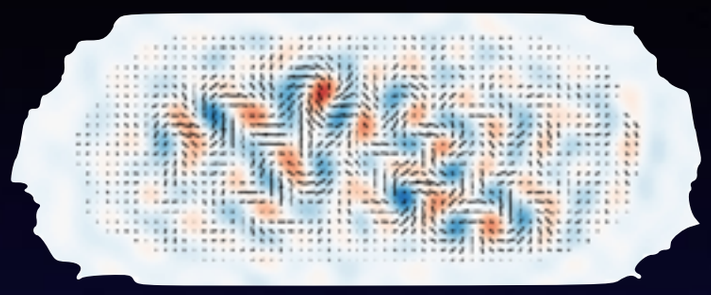


Also: **CLASS** (70% of sky from Atacama, fast pol modulation for reionization),
ABS (150 GHz refractor from Atacama, fast HWP rotation)
EBEX, **PIPER** (balloons), …

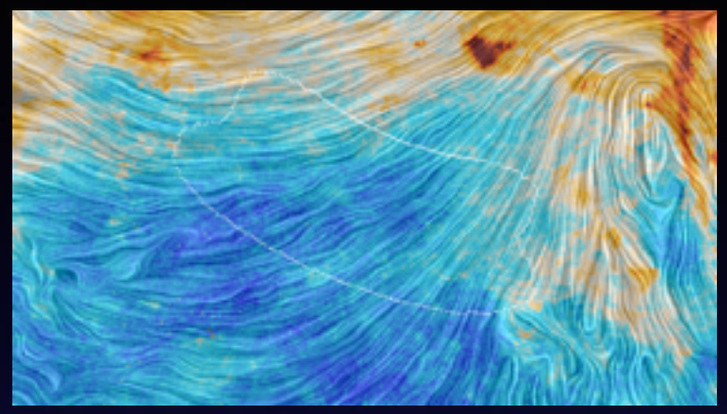
BICEP/Keck Program

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

BICEP / Keck (+Planck)



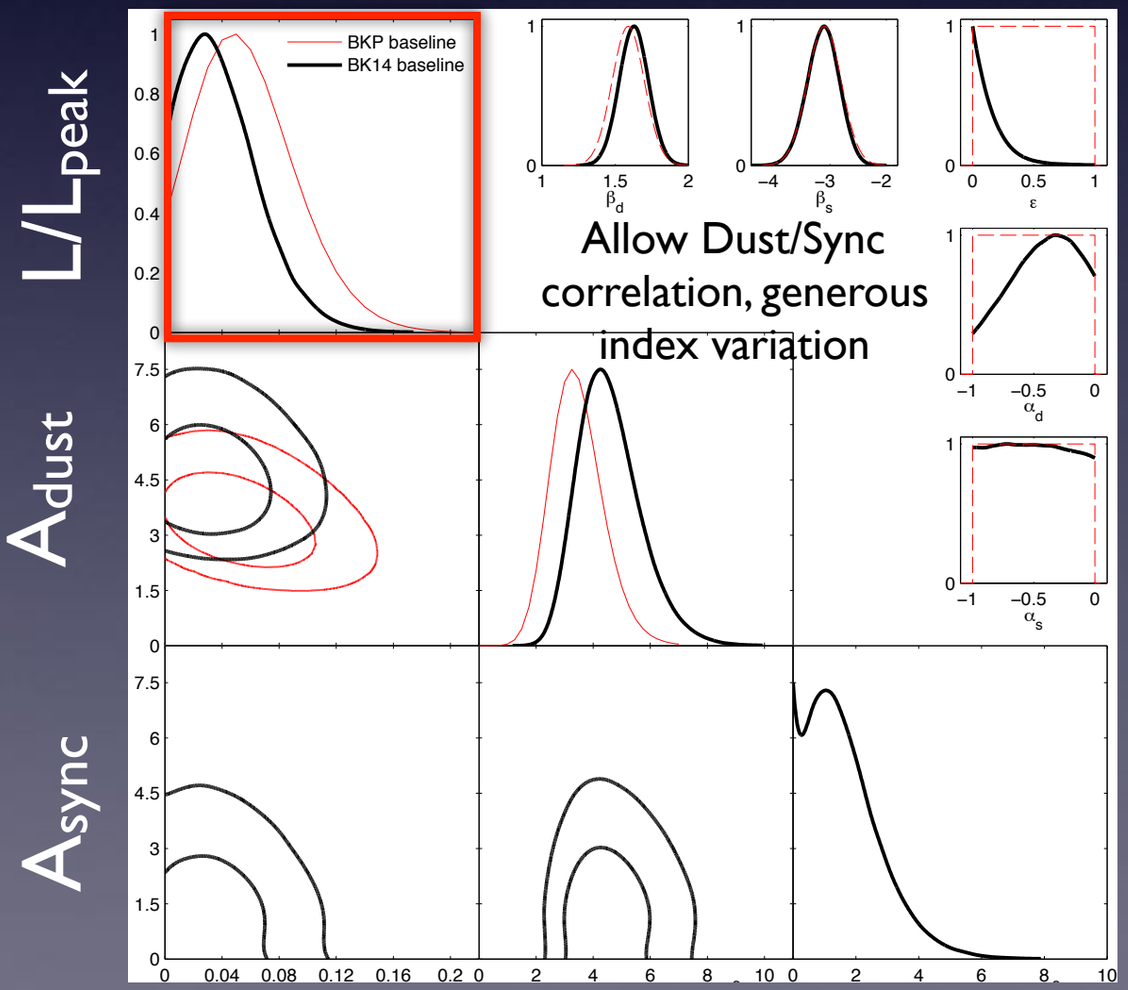
BICEP2 150 GHz

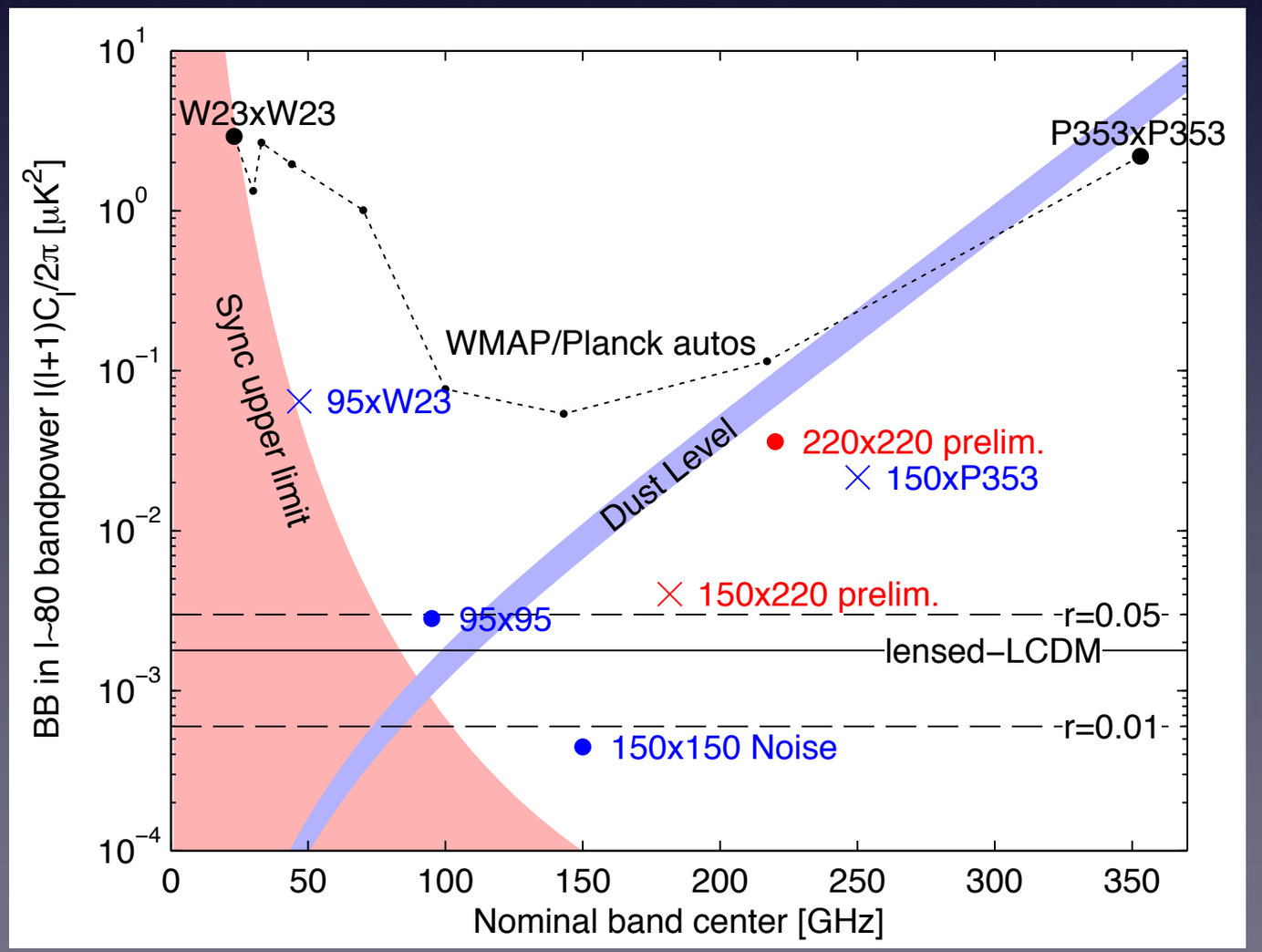


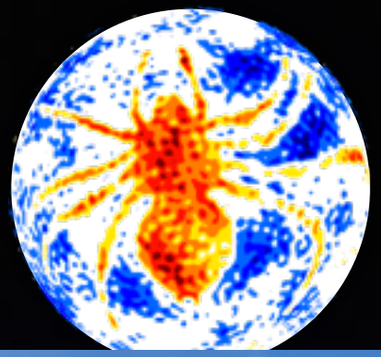
Planck 353 GHz

BICEP2/Keck Array 2015
r<0.09 (BB w/ Planck cleaning)
r<0.07 (BB + Planck TT, etc.)
raw σ(r) = 0.006 ⟹ foregrounds!

150+95+P: PRL 116.031302 (2015)
Also lensing: ApJ **833**, 228 (2016)
220 GHz results coming soon…

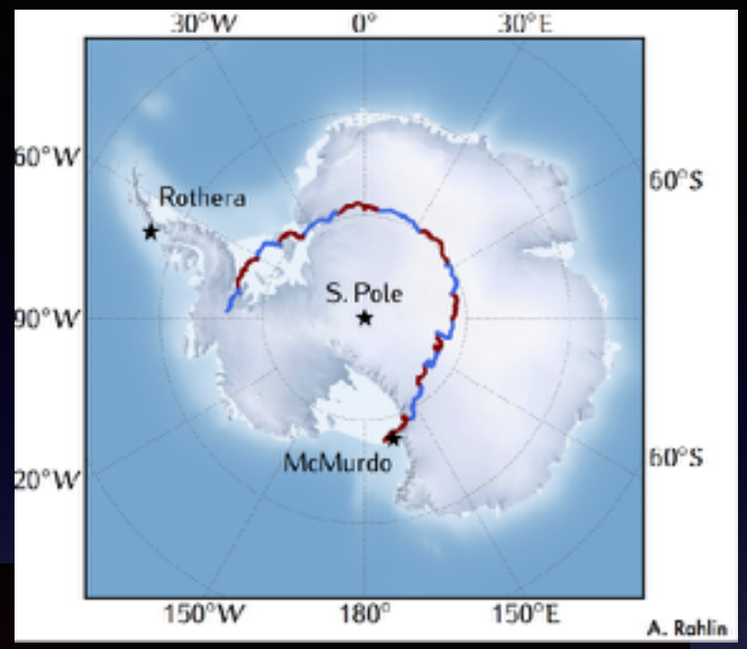


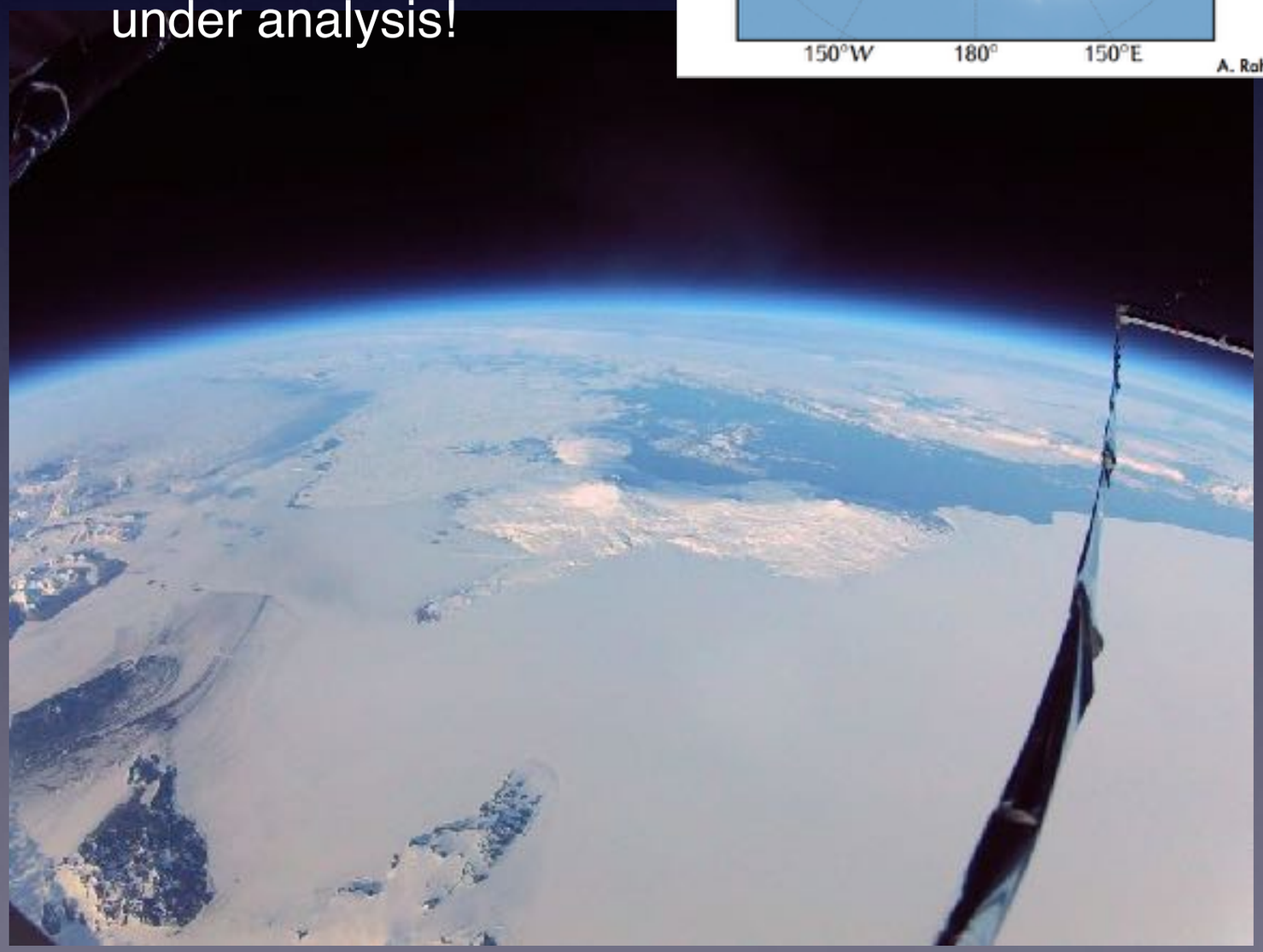


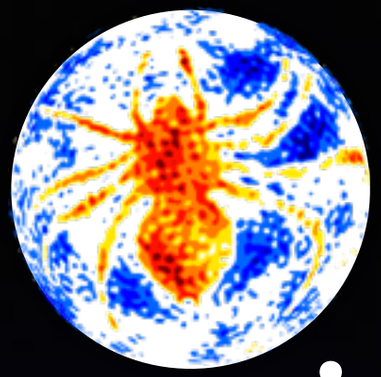


SPIDER 2015

- Antarctic LDB flight: Jan. 1-18, 2015
- 95, 150 GHz; 2400 TES detectors
- Data on ~10% of sky under analysis!

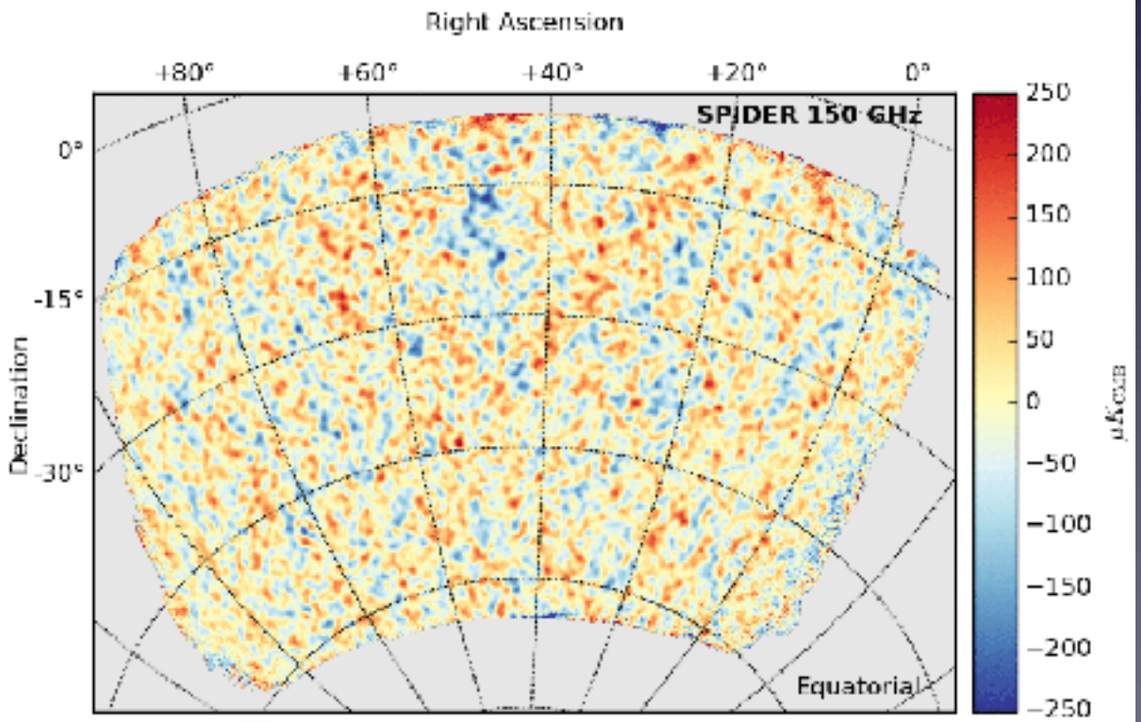




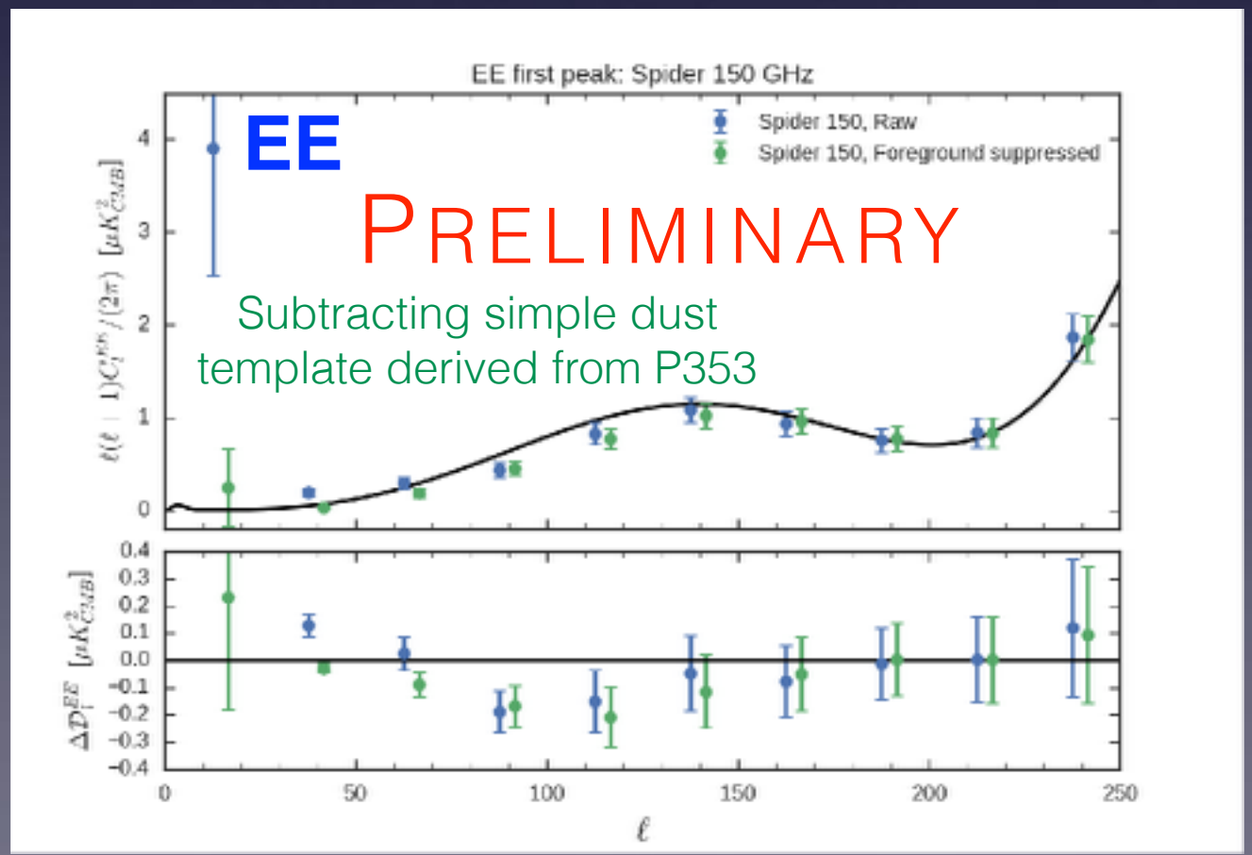


SPIDER 2015

- Data on ~10% of sky under analysis, looking great
  - Clear detections of TT, TE, EE, foregrounds
  - Work ongoing: foreground cleaning, fine systematics
  - *Constraint on circular polarization coming very soon!*
- SPIDER-2 under construction: adds 285 GHz band, 2018 flight
- Goal: 3σ detection of r=0.03 *in the presence of foregrounds*



PRELIMINARY

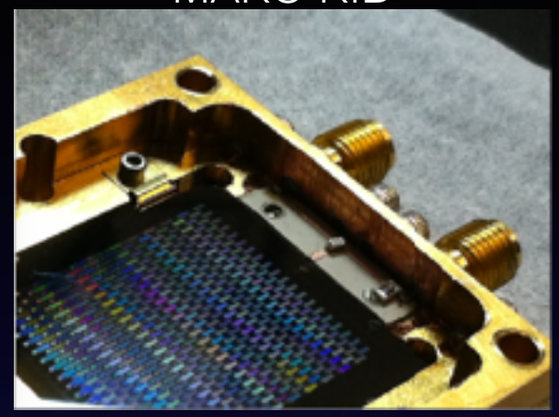


Looking Ahead

PRE-2020

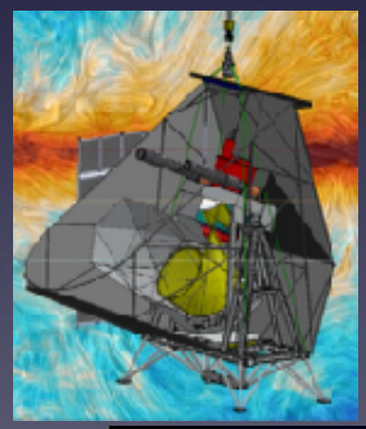
- On the ground: AdvACTpol, BICEP Array, CLASS, SPT-3G, Simons Observatory (Atacama), …
- Balloons: SPIDER, EBEX results; SPIDER-2, PIPER
- Technology: GHz multiplexing, optical elements, …

MAKO KID



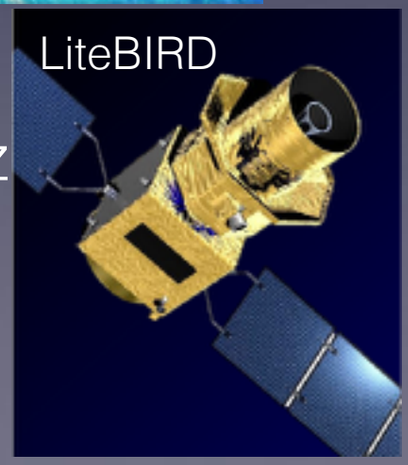
2020-25

- CMB-Stage 4 (DOE-P5): Collaborative effort for next-gen ground-based CMB science (megapixel level), O($100M)
  Test key inflation models (r~0.001), detect m_ν, N_{eff}, much more!
  See S4 Science Book (1610.02743); Instrument Book imminent
- Balloons: EBEX upgrade; BFORE for reionization?



2025 -

- Satellite proposals for full sky, many frequencies
  - LiteBIRD (Japan): Degree-scale, ~2kpix, 50-300 GHz
  - Inflation Probe (US), CORE (EU): ~5-10kpix, 30-1000 GHz
  - PIXIE (US): Interferometer, 30-6000 GHz



Thank you!