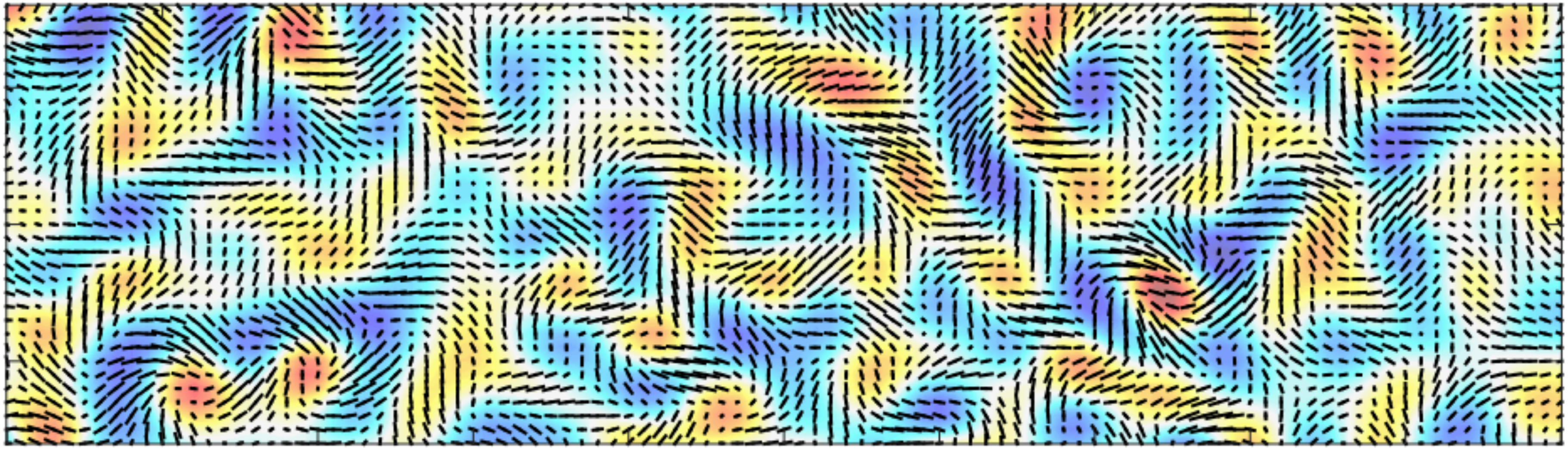
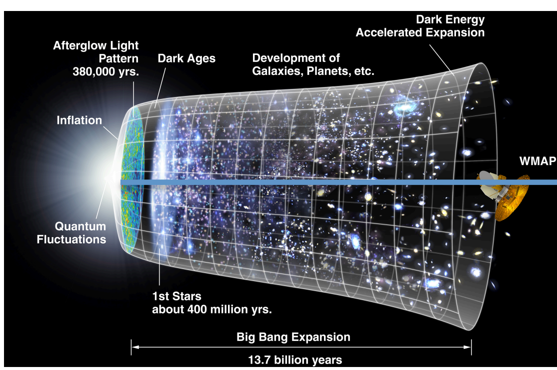
CMB Polarization and Gravitational Waves

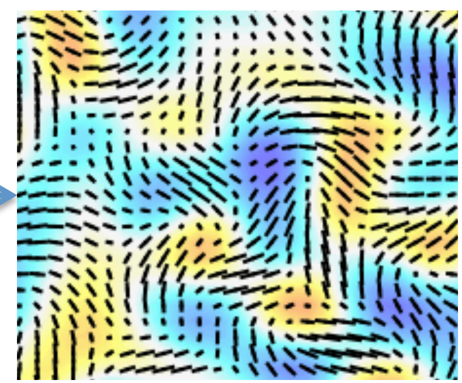


Blake Sherwin
Miller Fellow, UC Berkeley

Outline

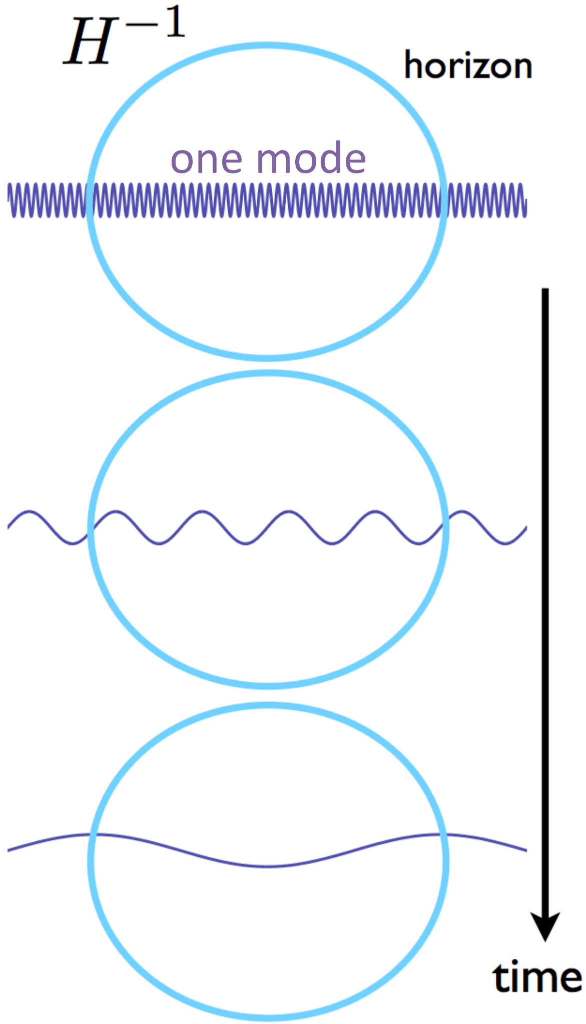
- Inflation and gravitational waves
- CMB B-mode polarization: a powerful gravity wave probe
- Current status of the measurements
- Challenges and prospects for B-mode science in the next decade





Inflation: Reminder

- Why is the universe smooth and flat on large scales, and yet has small initial density differences?
- Inflation: initial accelerated expansion of the universe, with shrinking comoving horizon
- Smooths universe and generates scalar density fluctuations from expanded quantum fluctuations (properties tested!)



Inflation and Gravitational Waves

- Also grav. waves! Action for gravitational wave strain:

$$S_h = \frac{1}{4}\int dt \int d^3\boldsymbol{x}\, a^3 {M_{\rm Pl}}^2 \left[(1/2)\left(\dot{h}_{ij}\right)^2 - \frac{1}{2a^2}\left(\partial_k h_{ij}\right)^2\right]$$

quantize: stochastic GW background with scale invariant power $\Delta_h^2(k)$

- Tensor-to-scalar ratio **r** tells us about energy of inflation!!!

$$r \equiv \frac{\Delta_h^2}{\Delta_{\mathcal{R}}^2} = 16\epsilon \simeq 0.1\left(\frac{V}{[2\times 10^{16}\,\mathrm{GeV}]^4}\right)$$

energy scale of inflation

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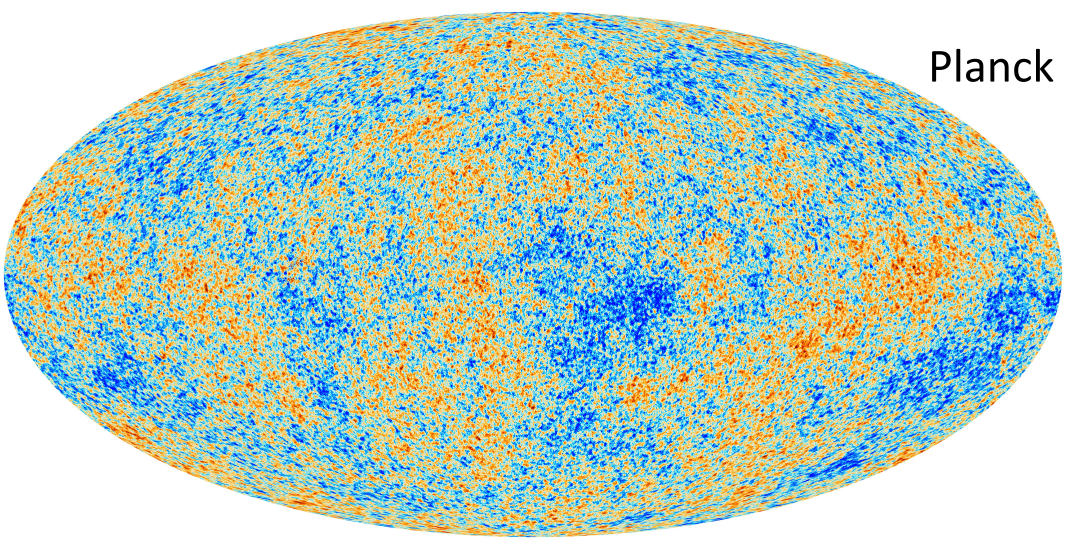
energy scale of inflation

- **Detect inflationary gravity waves to confirm inflation and measure its energy**

  [NB: r>0.001 important threshold, ruling this out will exclude many models]

The CMB

- Best current way to see these inflationary gravity waves: CMB
- Standard hot big bang picture: very early on, universe was permeated by hot and dense baryon/photon plasma
- CMB hot and cold spots arise from over- and underdensity in the photon/baryon plasma (+ potential etc.)

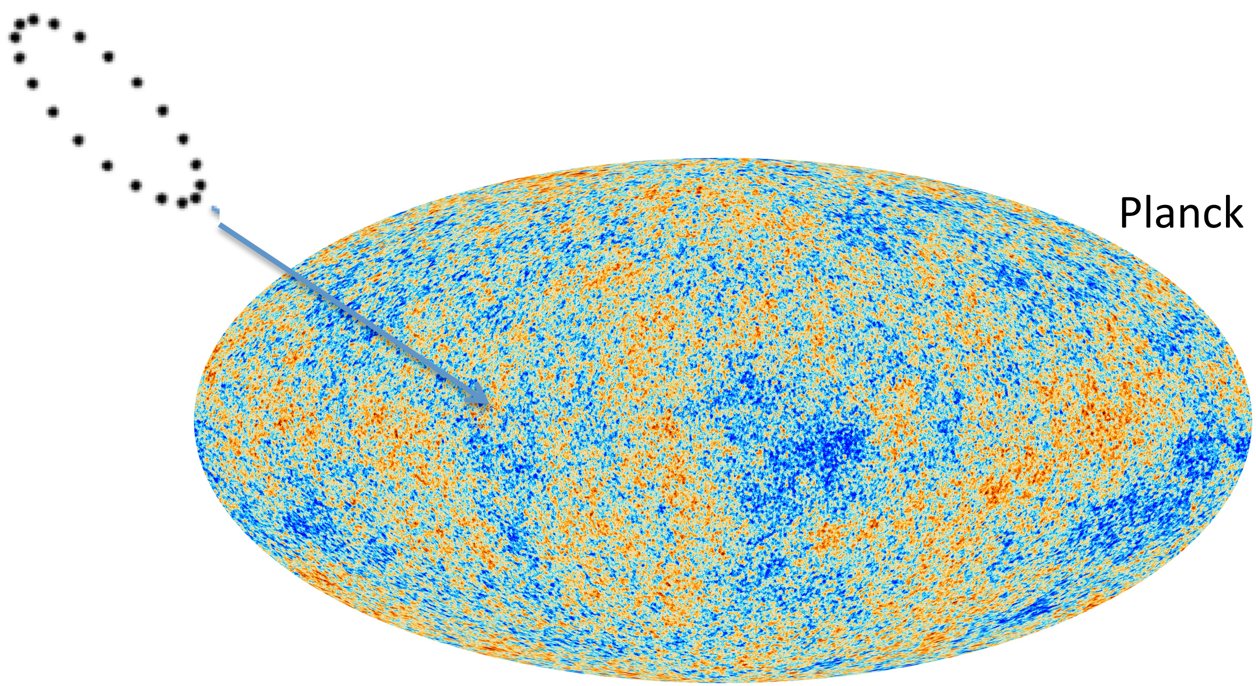


Planck CMB Map

fluctuations in 2.73 K blackbody radiation

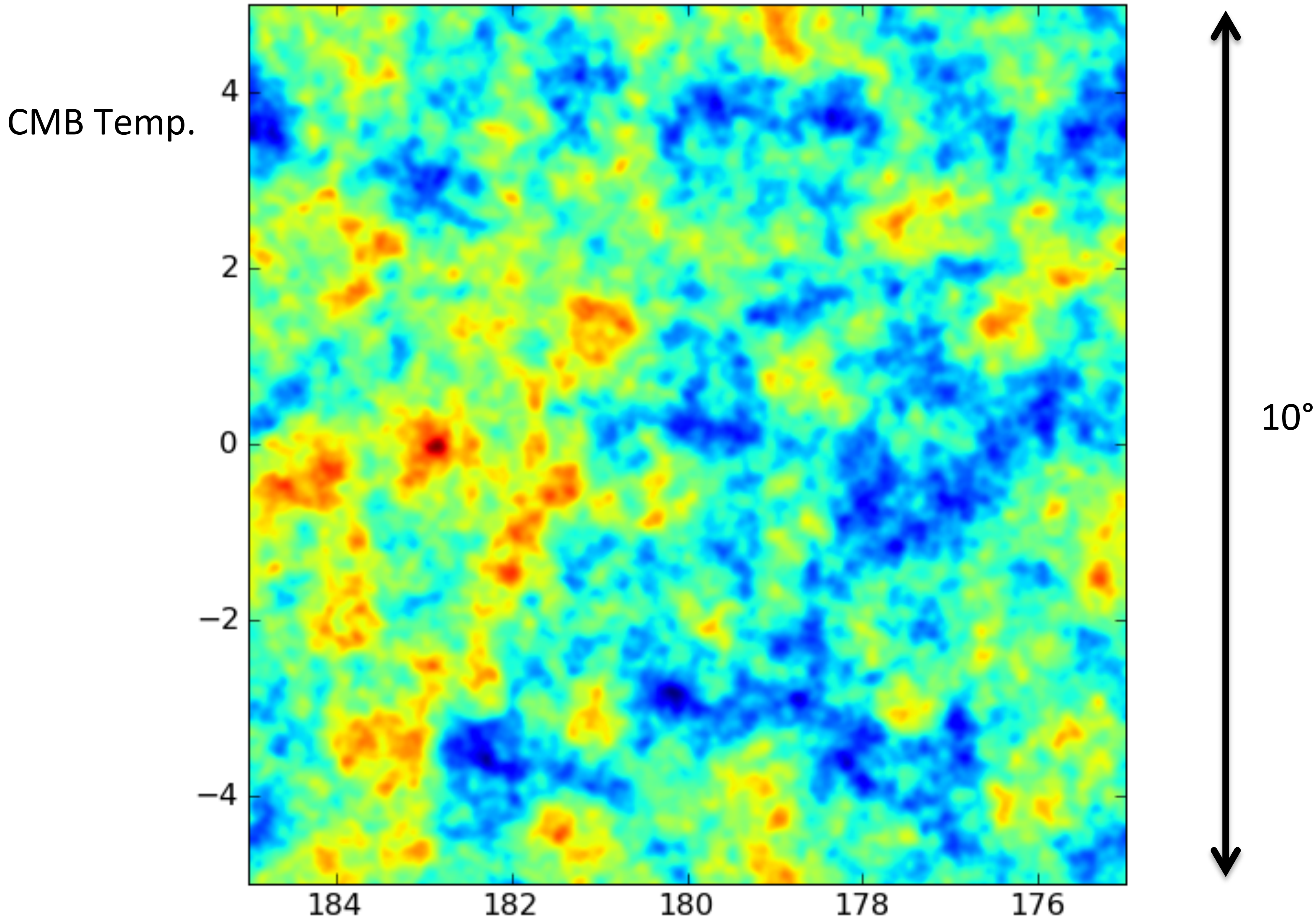
The CMB and Gravitational Waves

- CMB hot and cold spots arise from over- and underdensity in the photon/baryon plasma (+ potential etc.)
- Gravitational waves also cause this and induce CMB patterns



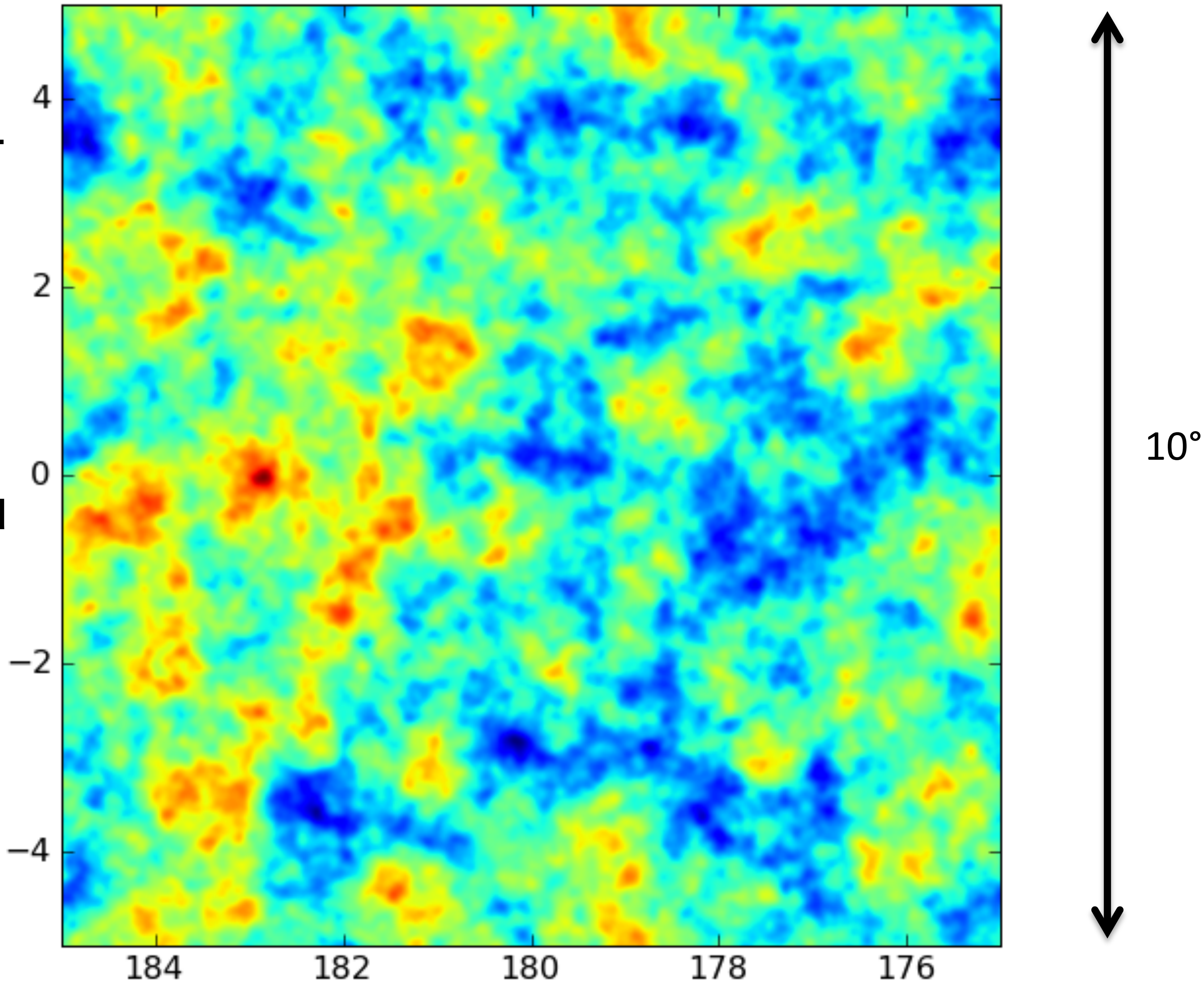
fluctuations in 2.73 K blackbody radiation

CMB temperature with no r



CMB temperature with very small r

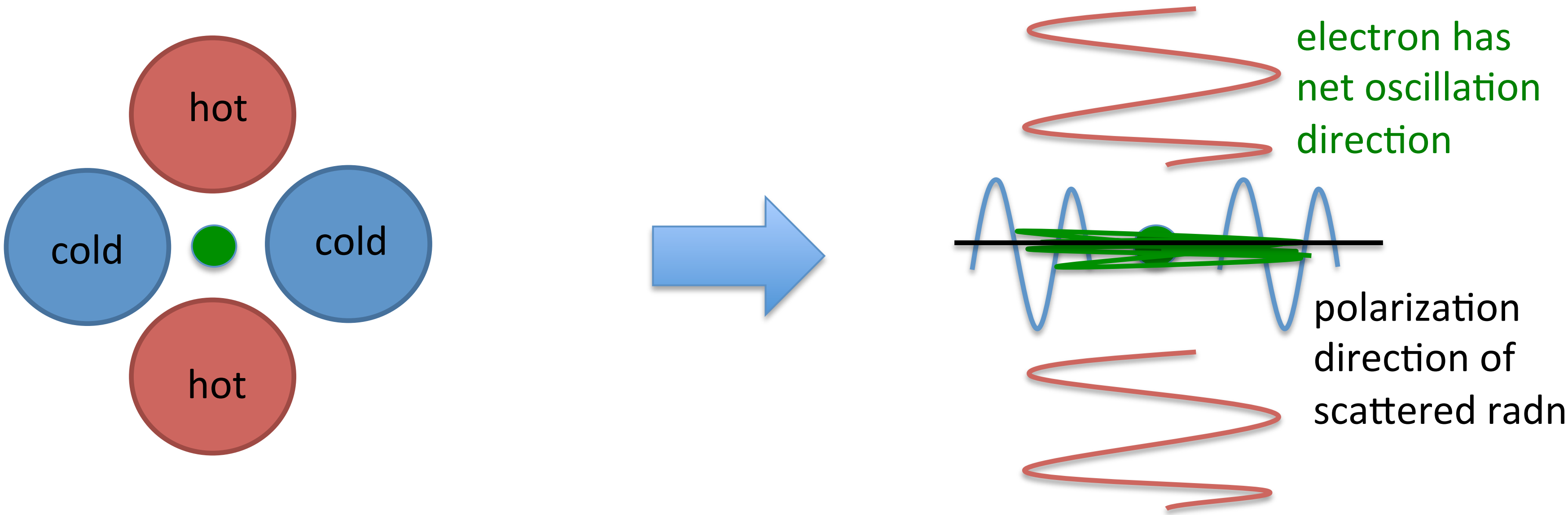
CMB Temp.
(cartoon
picture)



difficult to find r due to confusion and cosmic variance from scalar density perturbations

The CMB Is Polarized by Anisotropic Scattering

- Consider looking at an electron at the last scattering surface



- Direction in which electron is "seen" to oscillate gives direction of polarization of scattered radiation (perpendicular to hot direction)
- Hence, have net linear polarization if an electron sees a quadrupolar temperature variation

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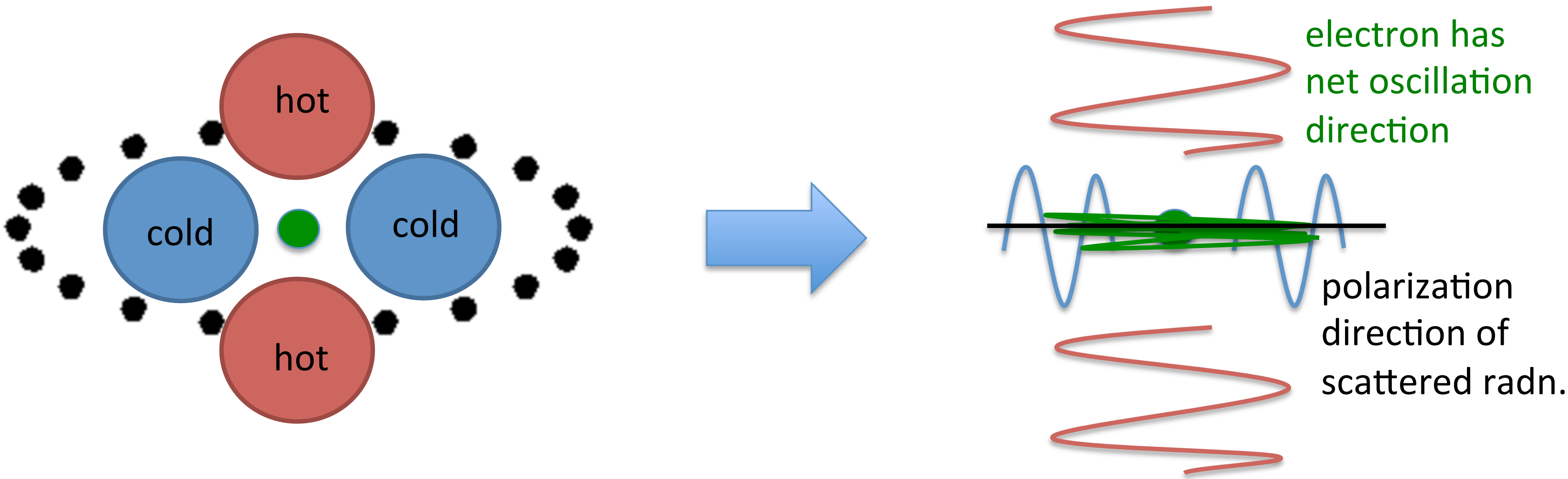
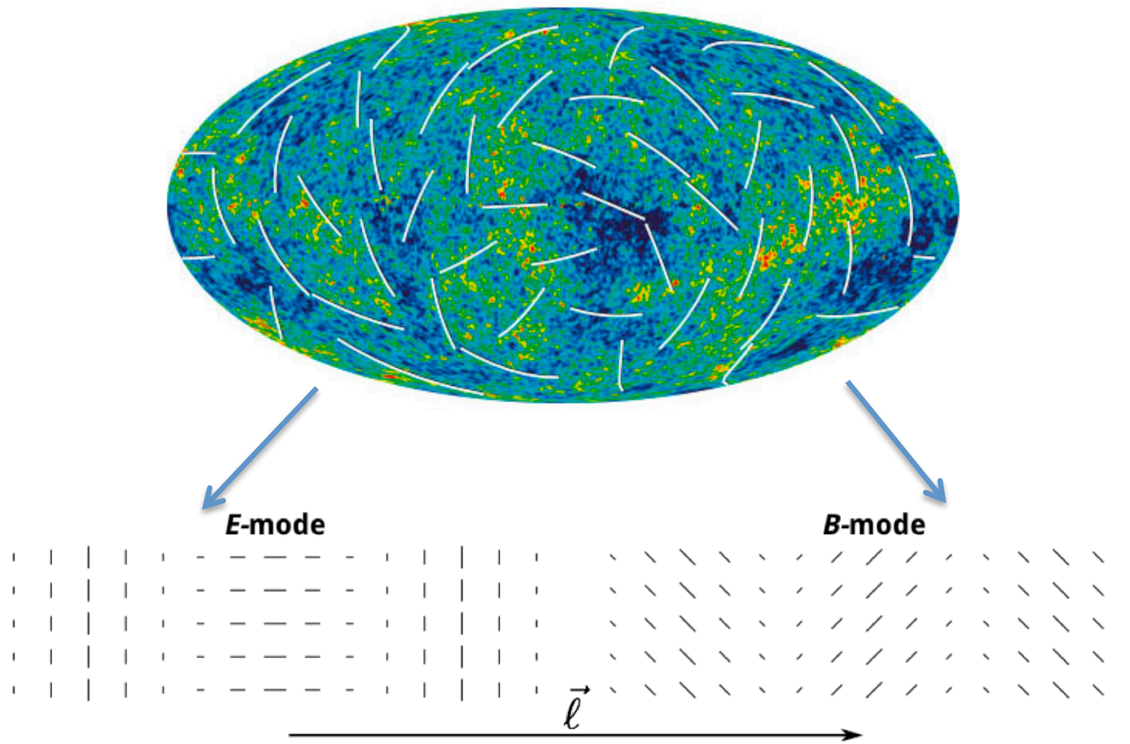


- Direction in which electron is "seen" to oscillate gives direction of polarization of scattered radiation (perpendicular to hot direction)
- Hence, have net linear polarization if an electron sees a quadrupolar temperature variation **e.g. from gravitational waves**

CMB Polarization Anisotropies

- The CMB radiation is partially linearly polarized at the 10% level

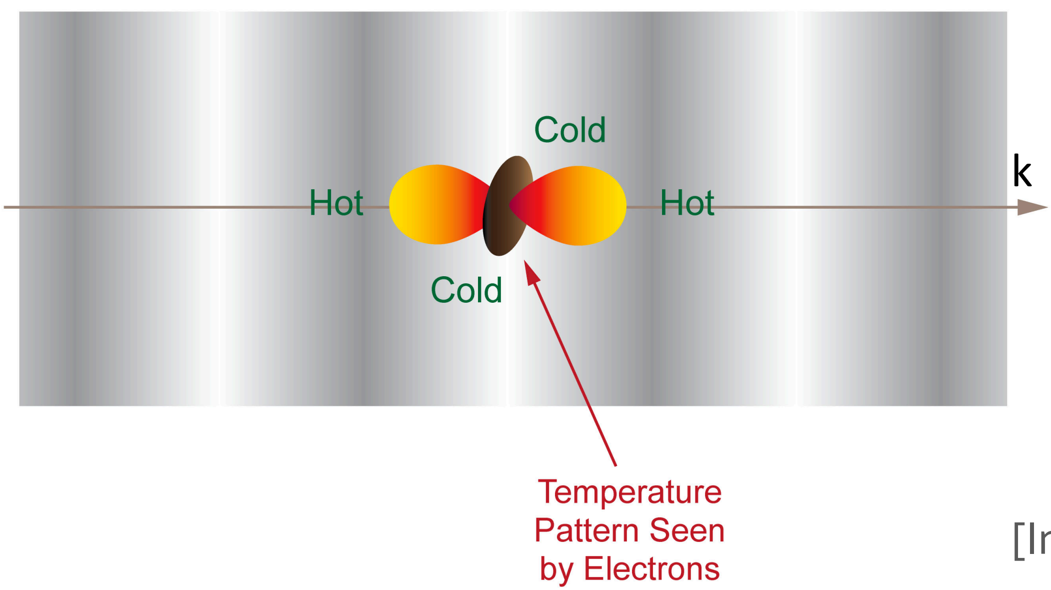


- Can decompose the polarization field into E (gradient-like) and B mode (curl-like) maps.
- Characteristic of E: polarization either parallel or perpendicular to the direction in which magnitude of polarization is changing. B: polarization at 45 degrees to this direction.

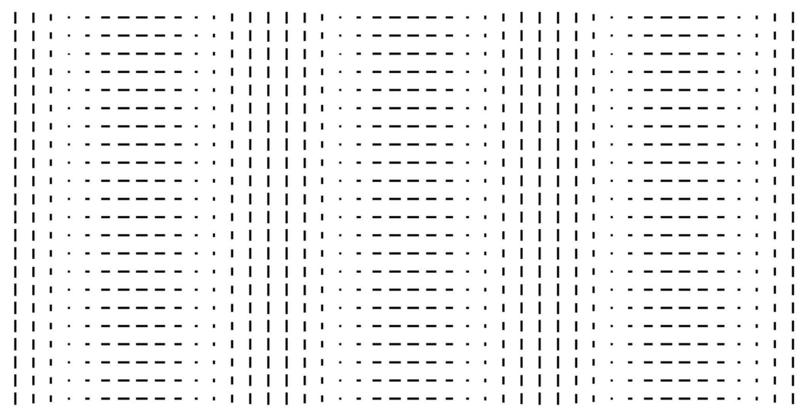
Scalar Perturbations: Only E, **no B!**

- Scalar density fluctuations can cause quadrupolar brightness fluctuations at last scatter -> polarization
- But: only E modes generated! To see this, consider one density wave on the last scattering surface
- By symmetry, see polarization must be parallel or perpendicular to k – characteristic of E

Density Wave



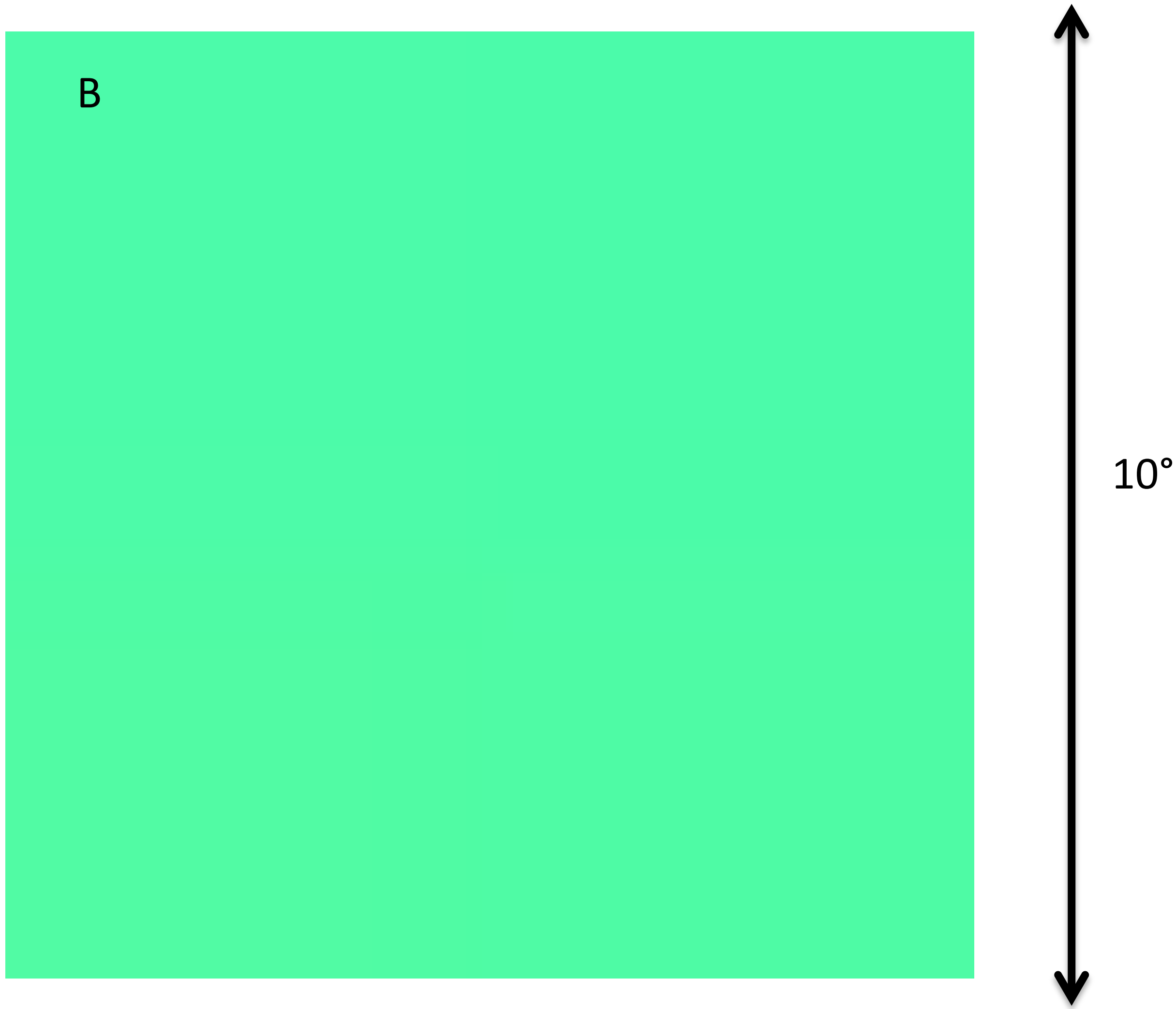
E-Mode Polarization Pattern

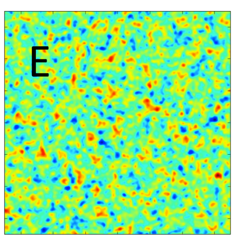


[Image credit: BICEP-2 collaboration]

CMB B polarization* with r = 0

Construct B-mode polarization: no leading order signal from scalar density perturbations!



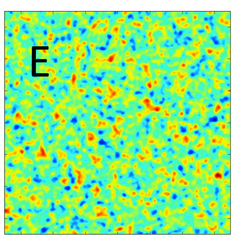


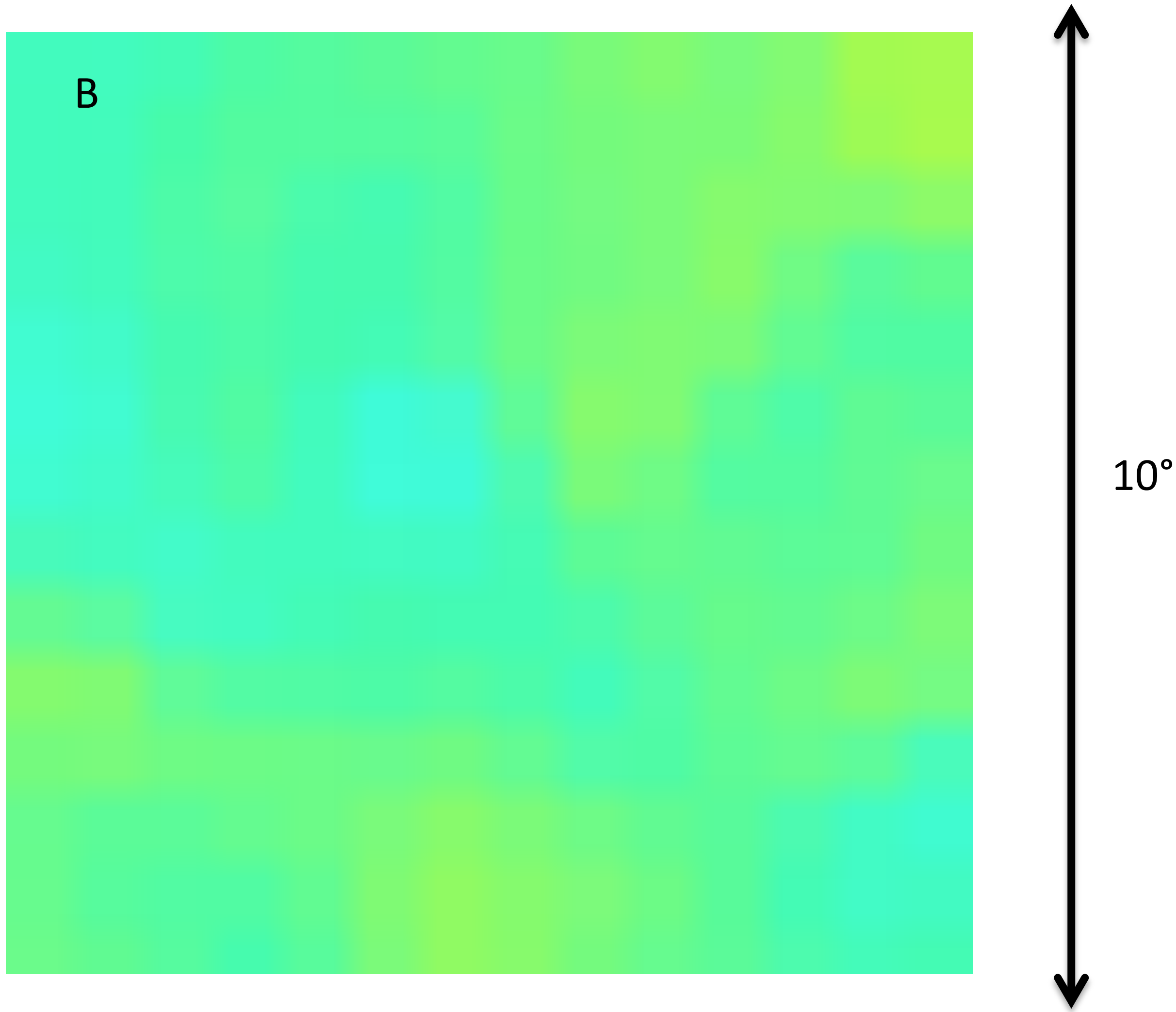
*ignoring lensing for now

CMB B polarization* with r>0

See r clearly as there is no background variance from normal (scalar) density perturbations

B-modes are a "null channel"



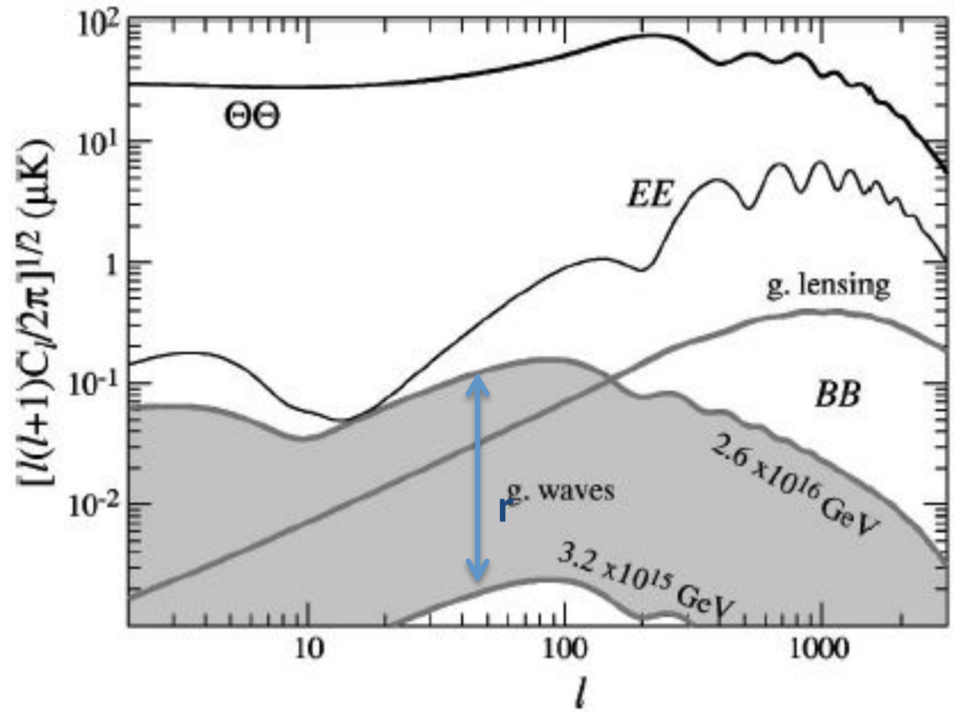


*ignoring lensing for now

The B-mode Power Spectrum

- Temperature and E-mode polarization are also sourced by large scalar density fluctuations – hard to disentangle r

- B-mode polarization is a "null channel": **only* see inflationary gravitational waves with little confusion**



Want to measure or constrain B-mode power and r!

Outline

- Inflation and gravitational waves
- CMB B-mode polarization: a powerful gravity wave probe
- Current status of the measurements
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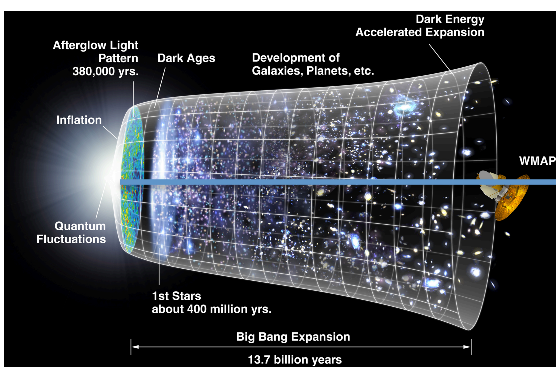
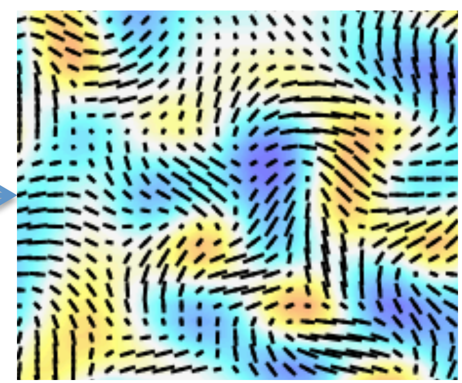
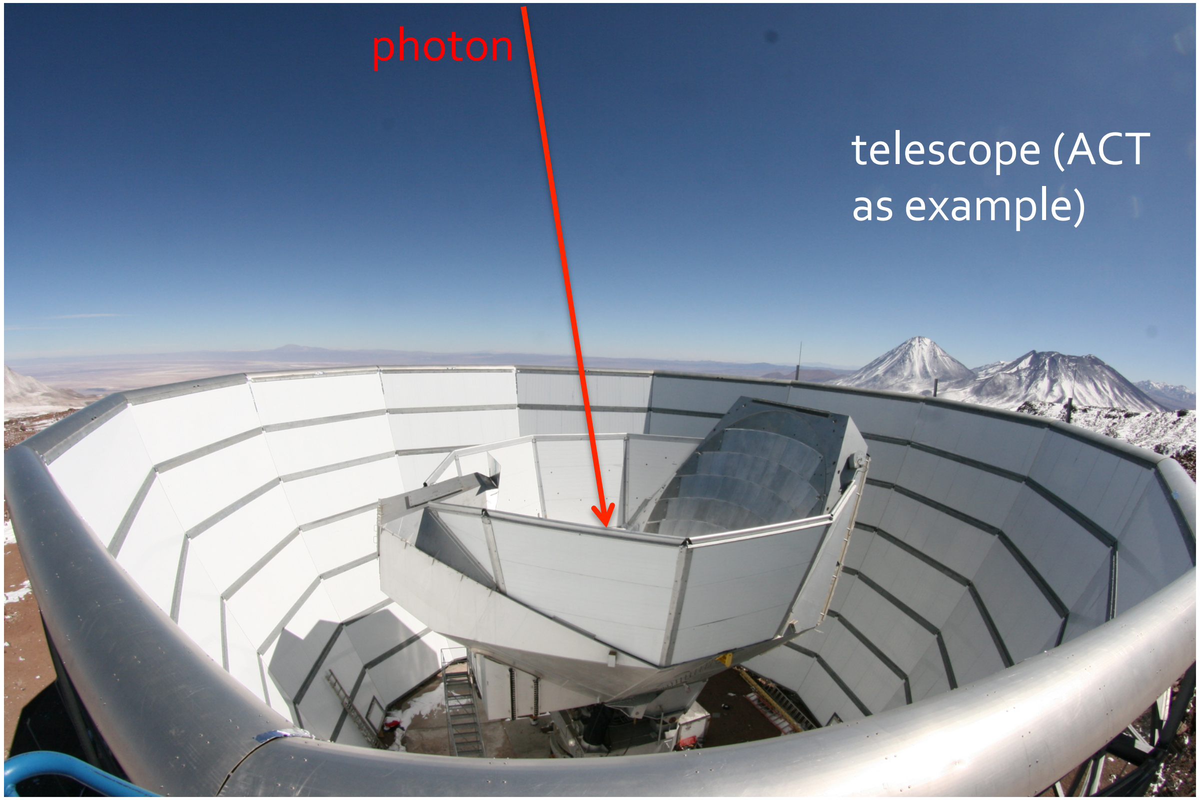
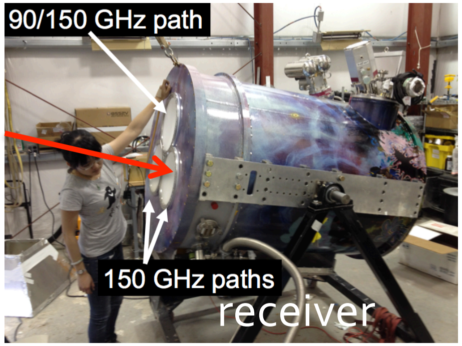


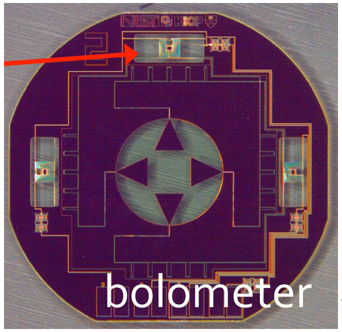


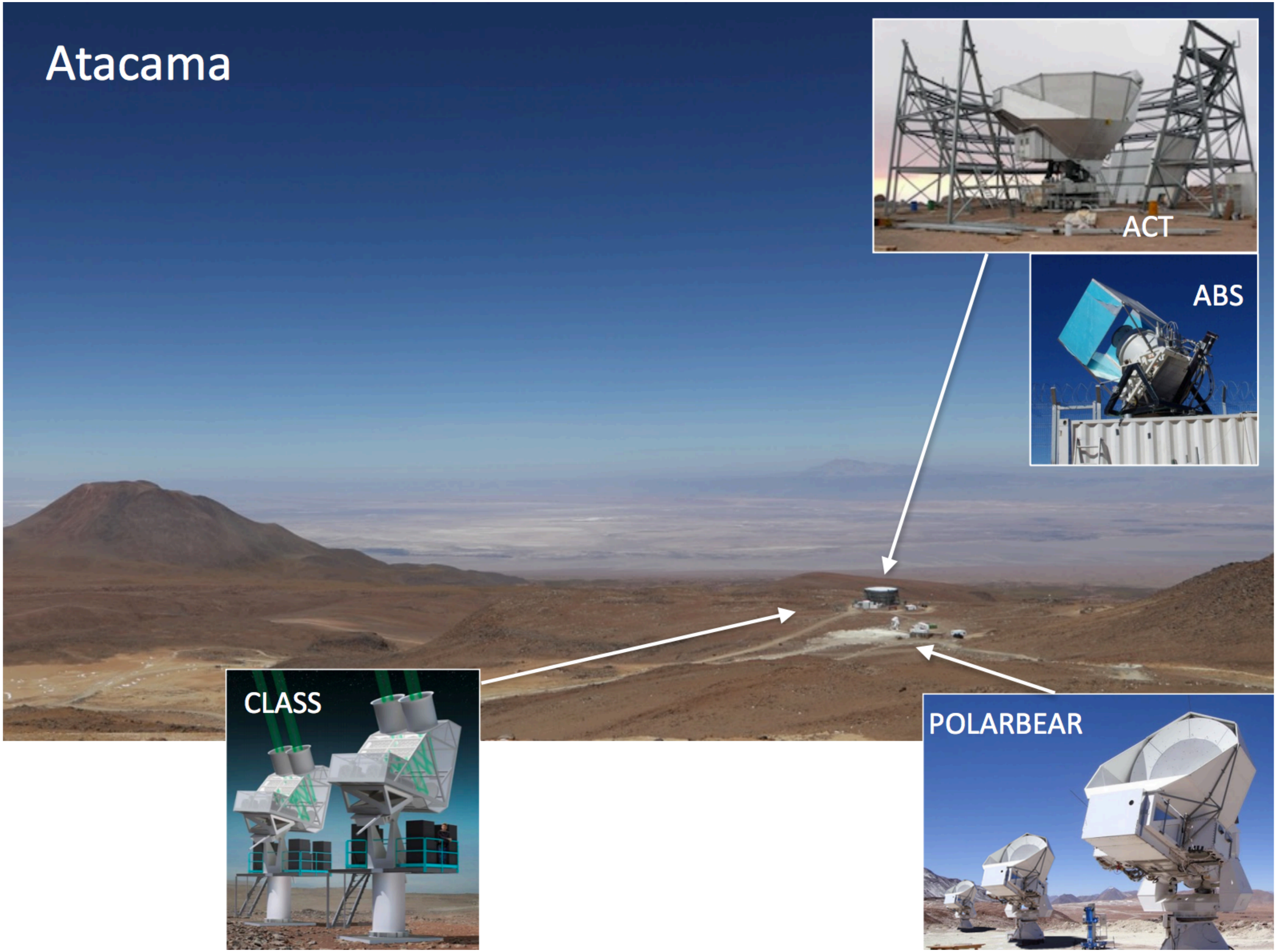
Measuring Polarization: CMB Telescopes

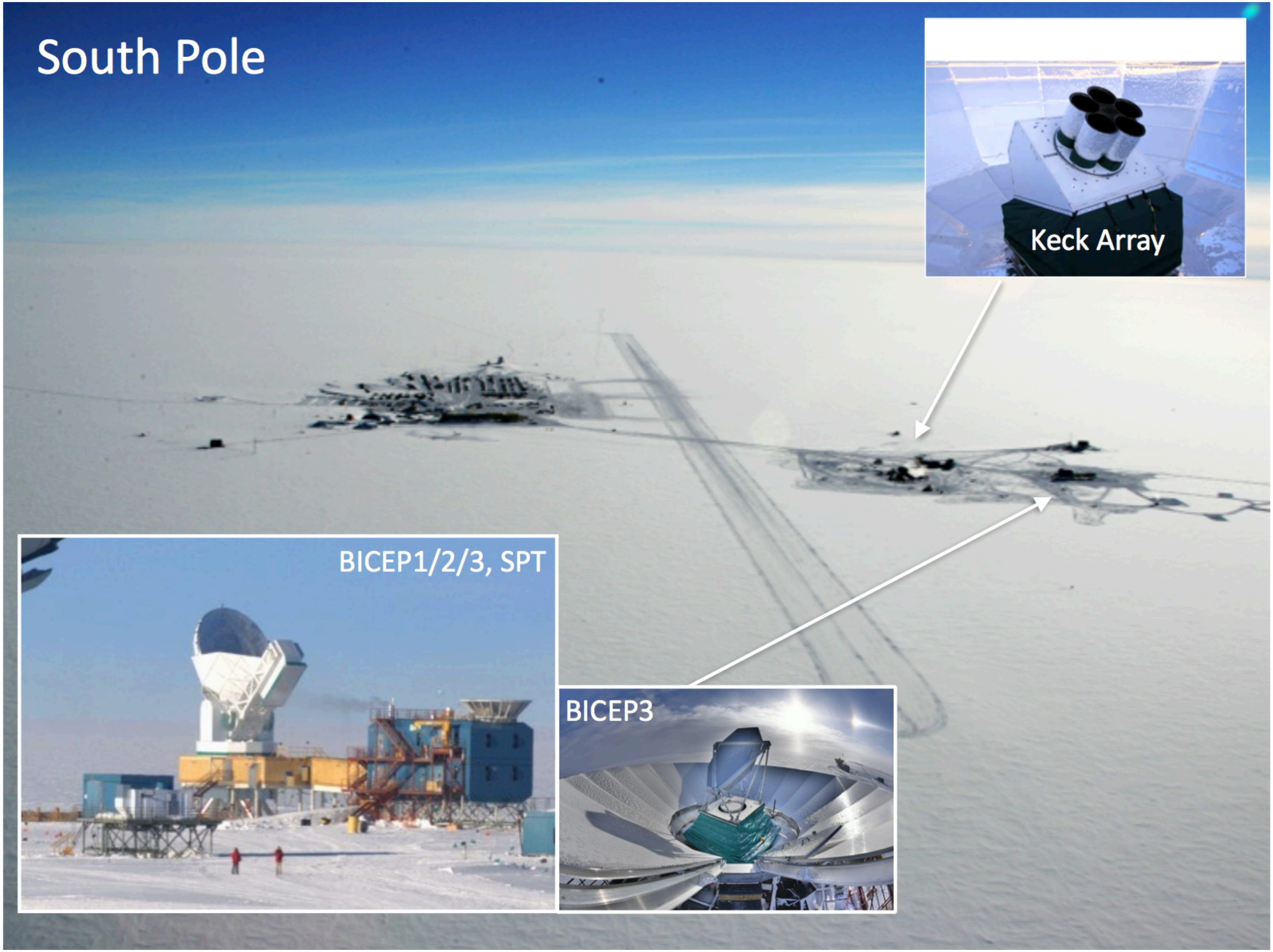
- Polarization-sensitive receivers containing large number of TES bolometers
- Located at high-and-dry sites







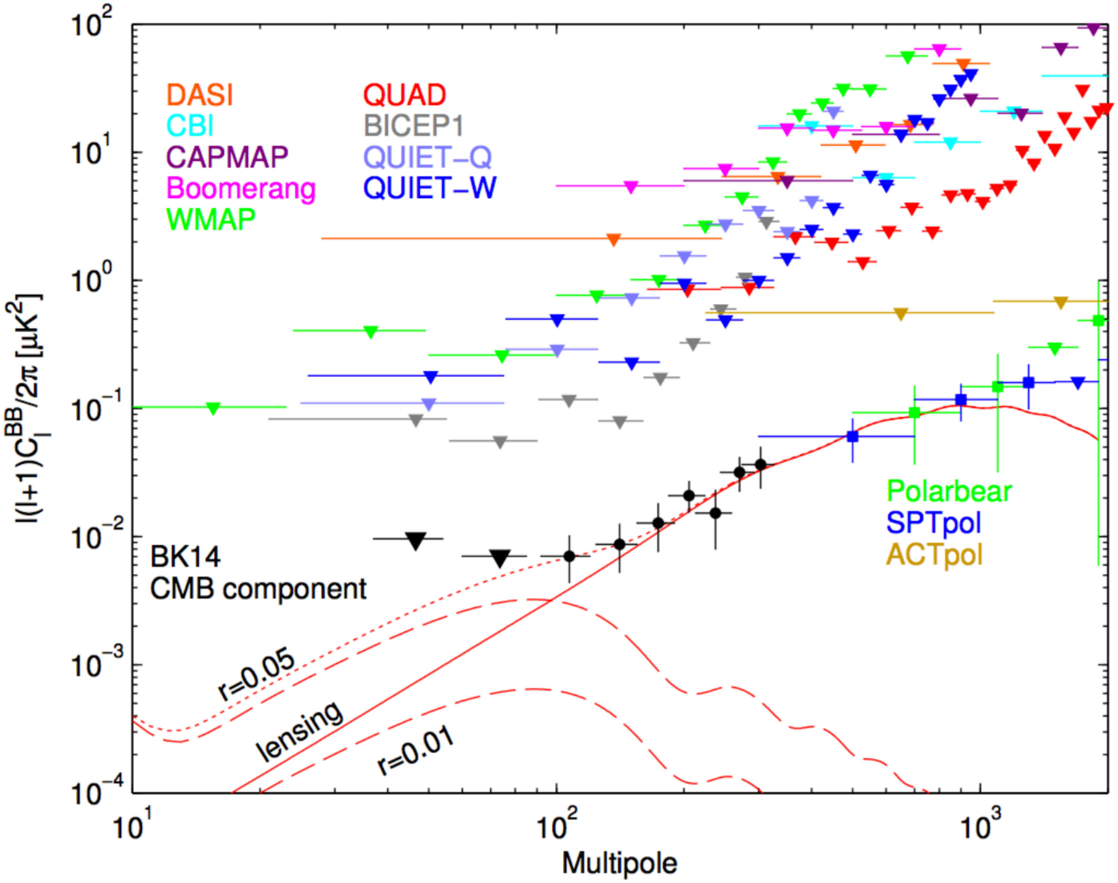

Atacama
ACT
ABS
CLASS
POLARBEAR


South Pole
Keck Array
BICEP1/2/3, SPT
BICEP3

Ongoing and **Upcoming** CMB Experiments

- High-resolution
  - ACTPol [>**AdvACT**]
  - Polarbear [>**SimonsArray**]
  - SPTPol [>**SPT3G**]
- Large-scale polarization (B-modes)
  - BICEP2/KeckArray [>**BICEP3**]
  - ABS, SPIDER, CLASS….
- All to merge to form **CMB Stage-IV**
  (also, satellites like LiteBIRD)

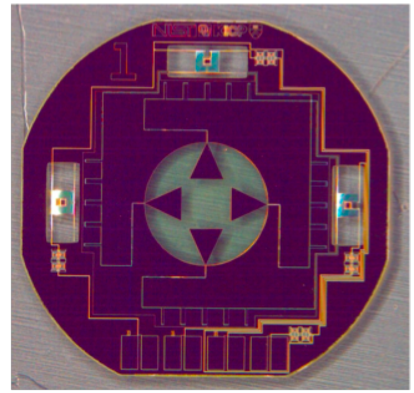
Current State of the Field



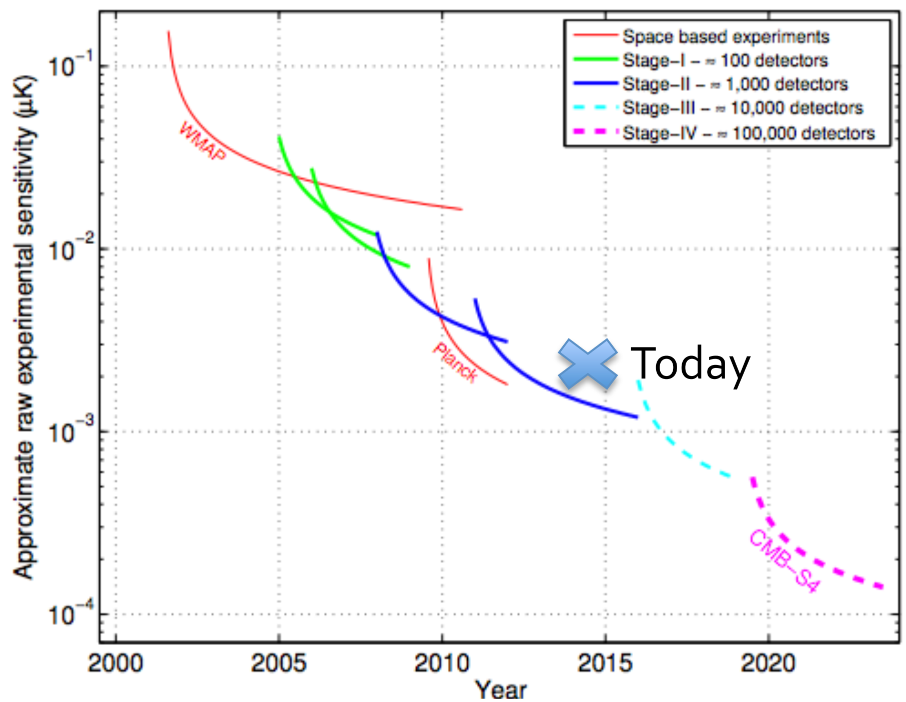
- Upper limit only: **r<0.09 at 95% confidence** – BICEP/Keck 2015
- Want to progress by at least 2 orders of magnitude to rule out r~0.001 – **challenges?**

Challenge I – Experiment Sensitivity (+Systematics)

- Need lower noise to measure very small r
- TES bolometers – detectors photon shot noise limited
- **Solution: increase numbers!**
- described in stages with more detectors/ lower noise

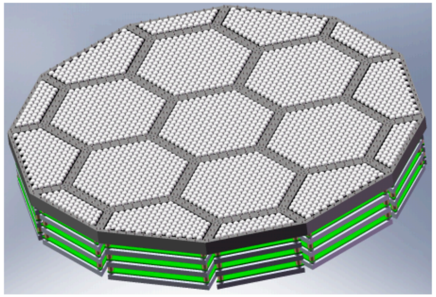


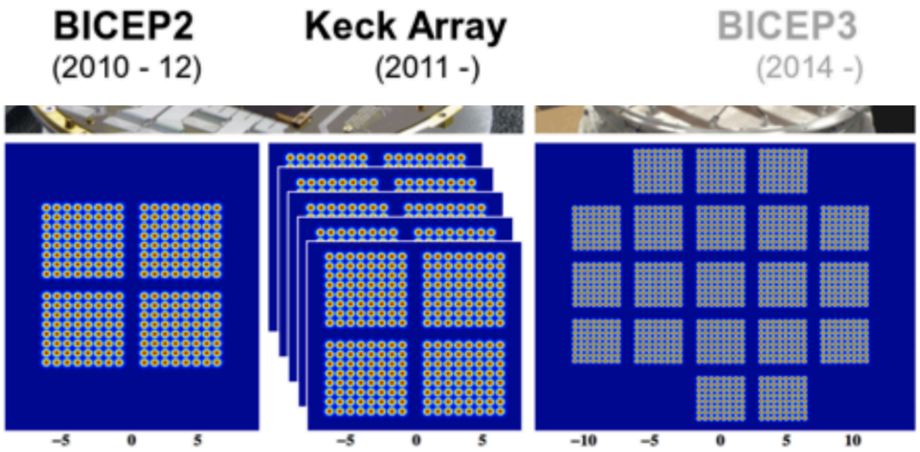
ACTPol/SPTpol detector



Challenge I – Experiment Sensitivity

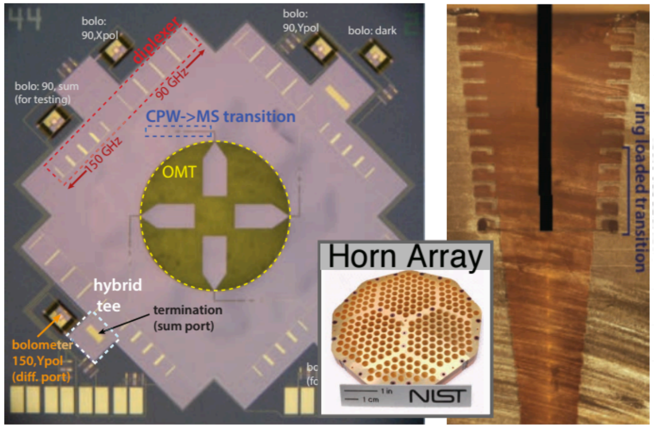
Technology development

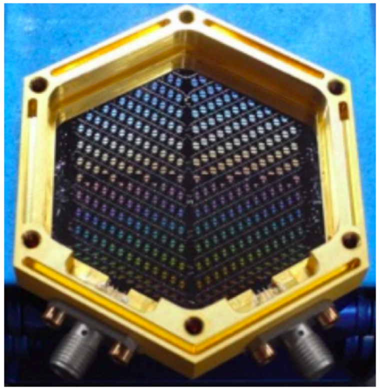




SPT-3G focal plane design

More detectors (+ more telescopes)
Multichroic TES detectors, KIDS detectors
Efficient throughput with broadband lens coatings



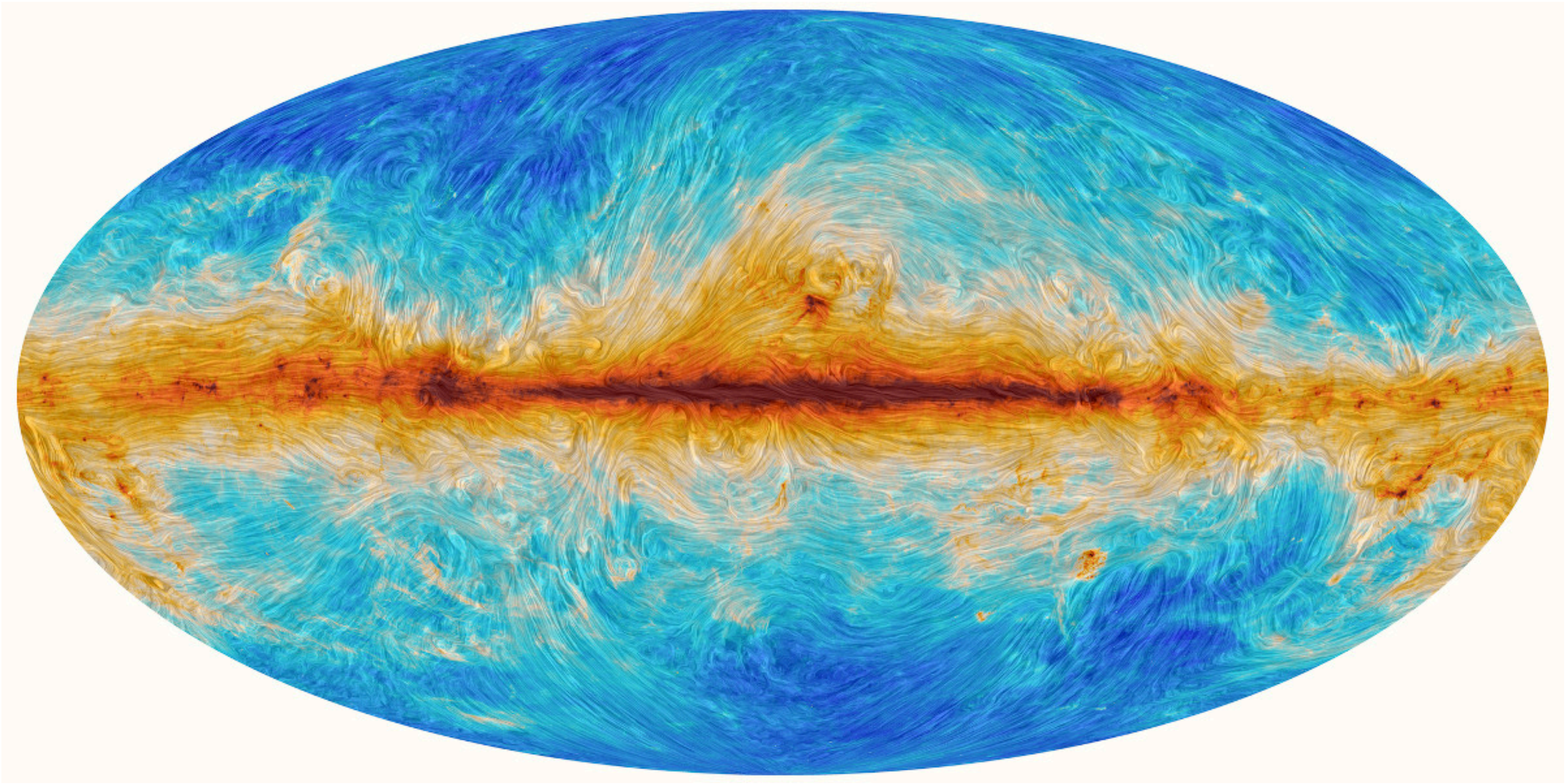


90/150 GHz dichroic, ACTPol (also PolarBear, SPTPol)

GroundBIRD KIDS arrays

Challenge II - Foregrounds

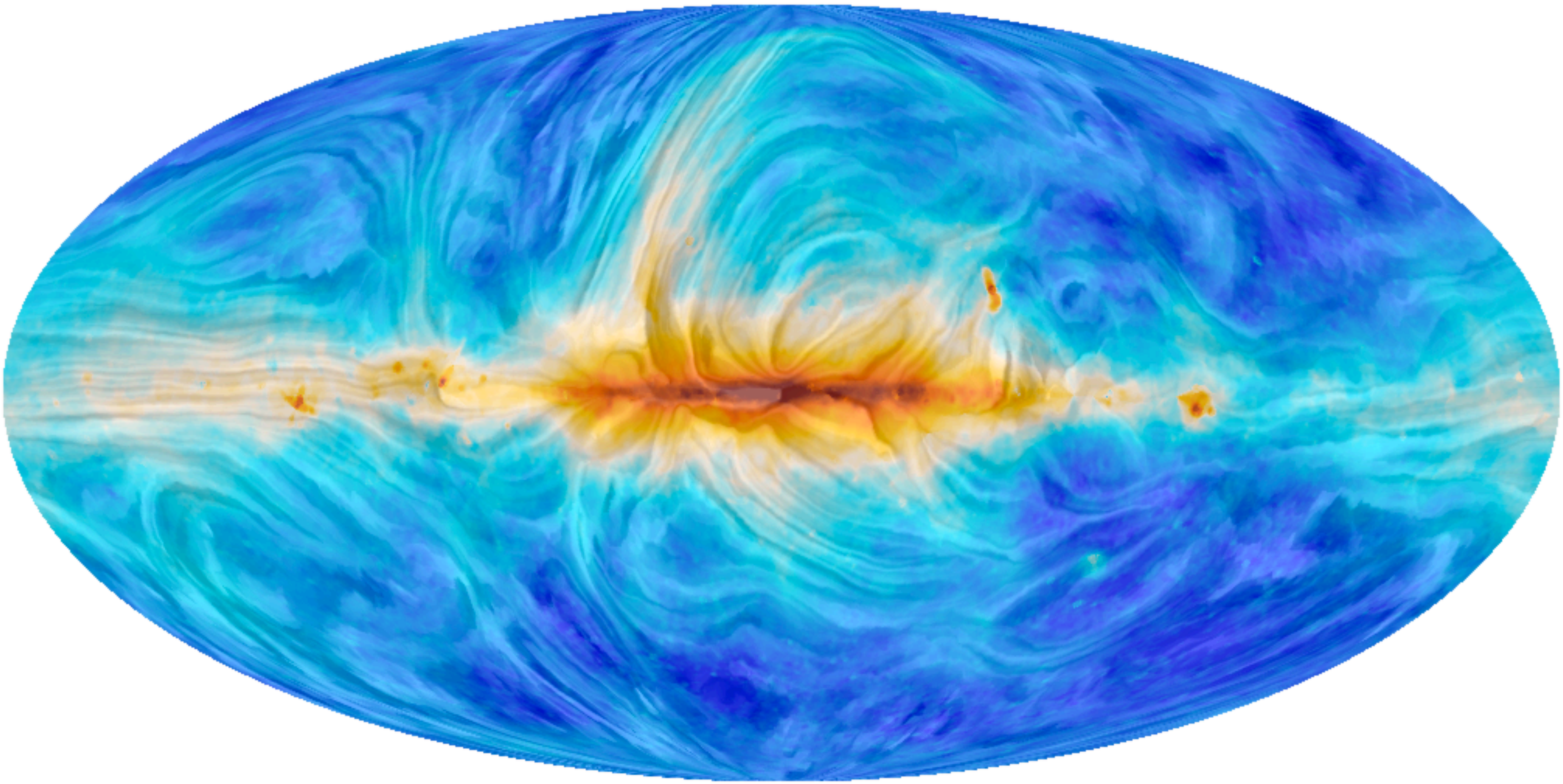
- Galactic emission also sources B-mode polarization.



Dust Polarization (Planck)

Challenge II - Foregrounds

- Galactic emission also sources B-mode polarization.

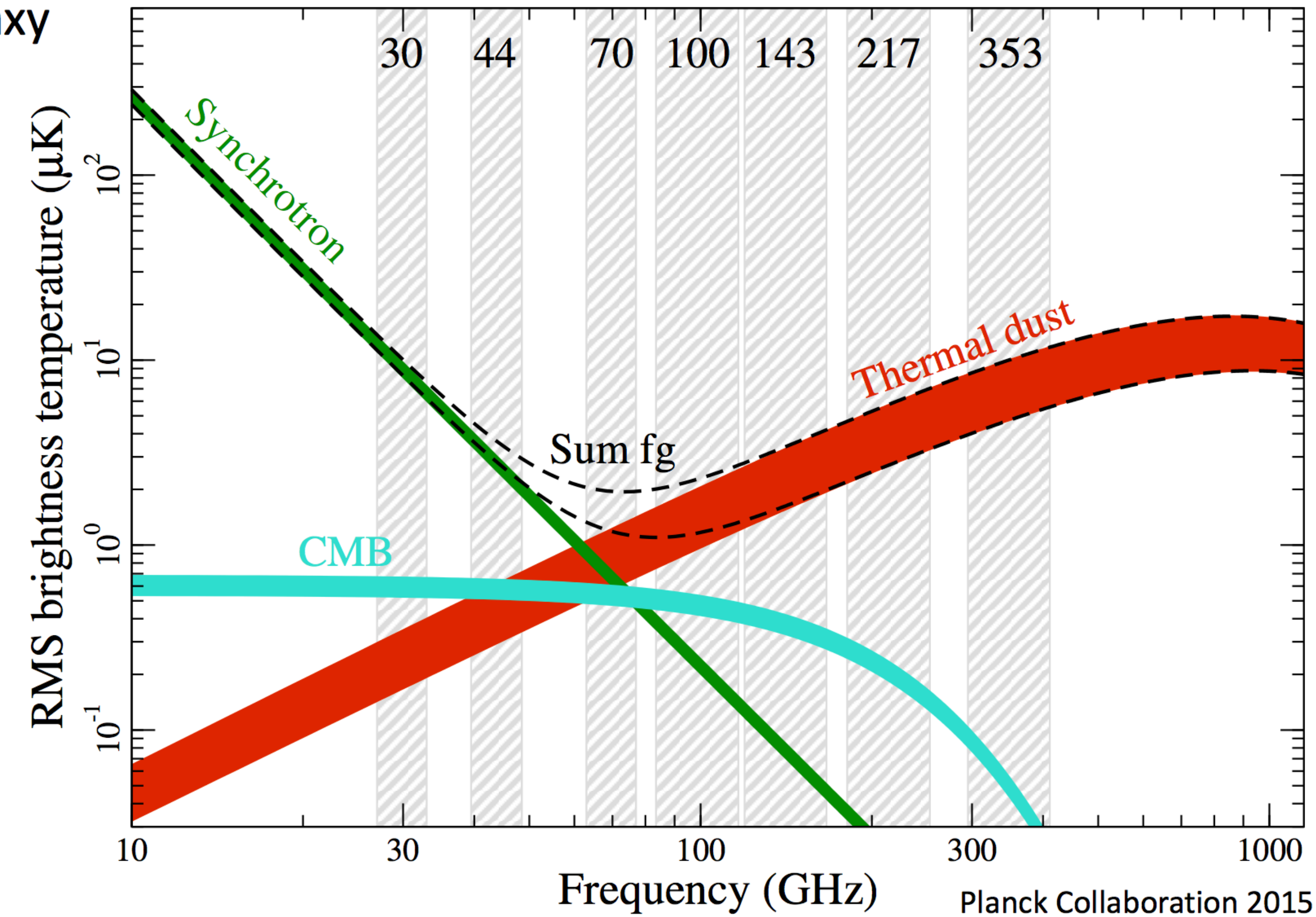


Synchrotron Polarization

Challenge II - Foregrounds

- Galactic emission also sources B-mode polarization.
- BICEP-2 lesson: need multifrequency data for any detection

The Galaxy

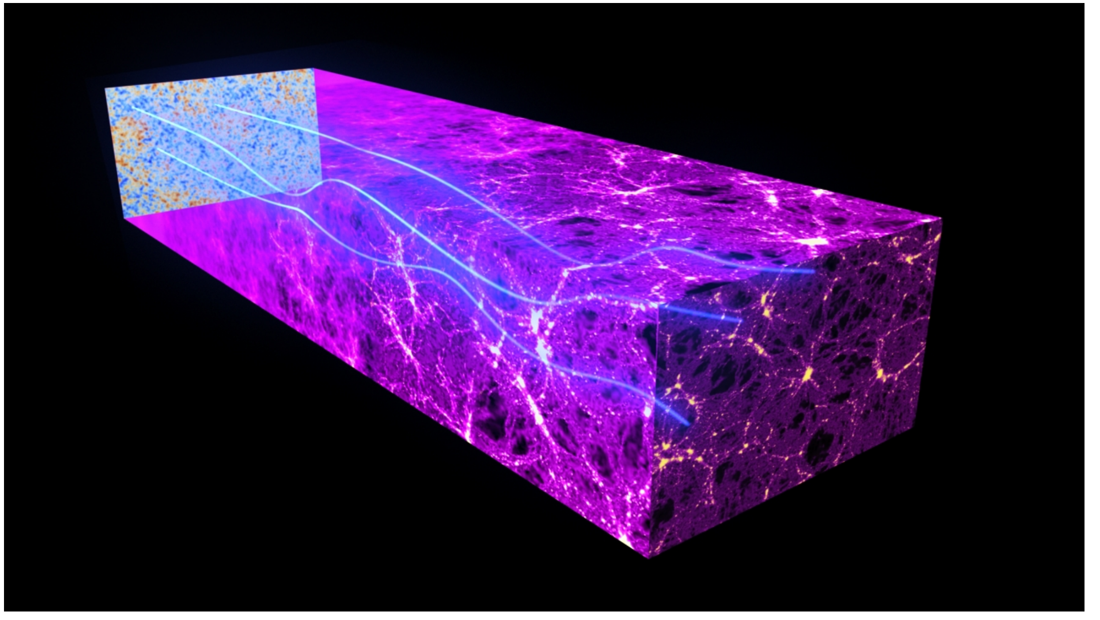


Planck Collaboration 2015

Foregrounds: Solution?

- True B-mode signal has a 2.73K blackbody spectrum.
- Foregrounds have different frequency dependence
- **Can use multifrequency observations** to separate signal from foregrounds (can also test for isotropy and Gaussianity)
- But: challenges in modeling foreground frequency scaling for high-precision subtraction (how complex are foregrounds?)

Challenge II - CMB Lensing

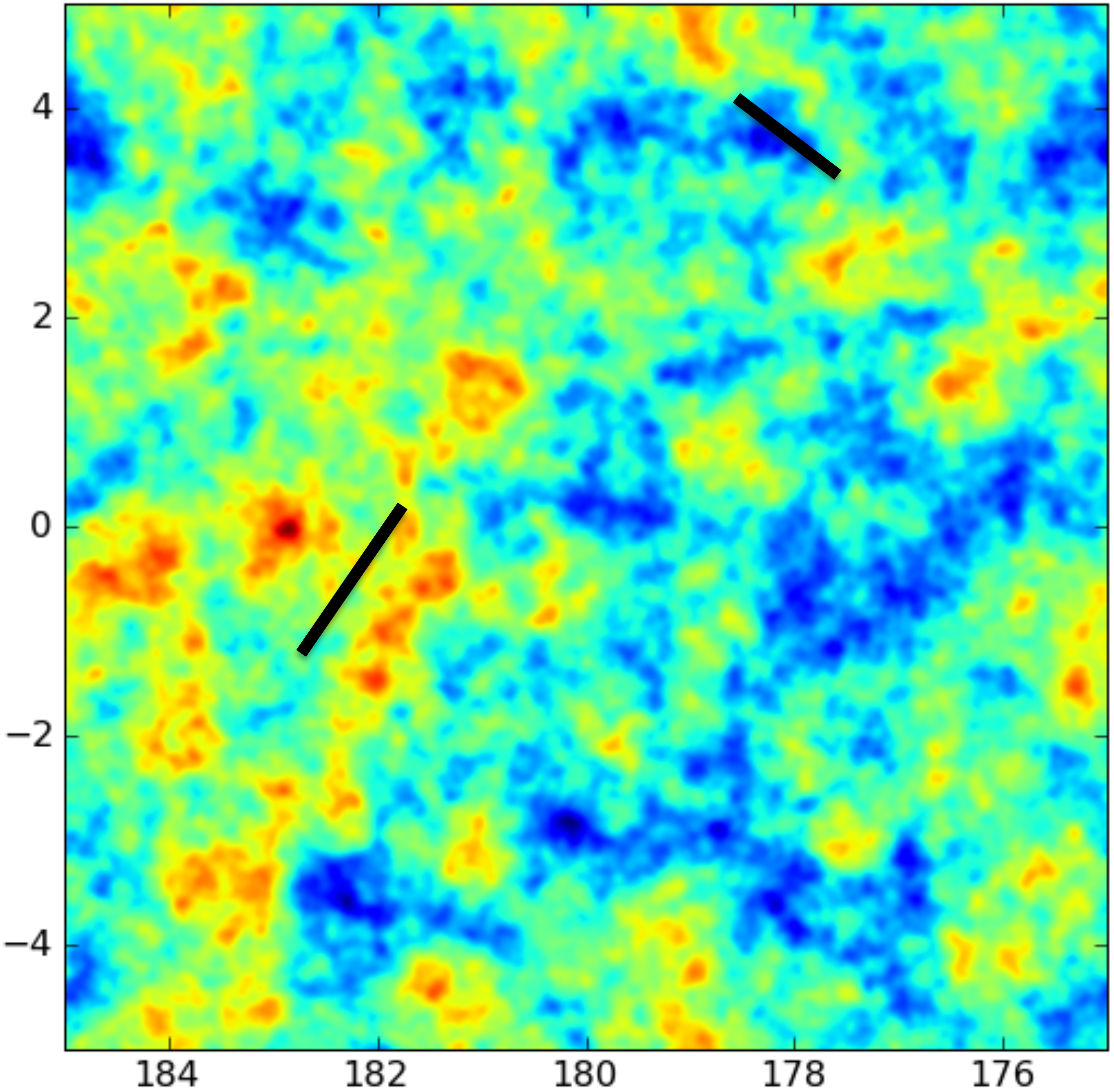


- Cosmic Microwave Background (CMB) photons are gravitationally lensed by large scale mass distribution
- Many small deflections remap the CMB, define deflection d
- Converts some E-modes into small scale lensing B-modes!

$$B(\mathbf{l}) \sim \int d\mathbf{l}' f(\mathbf{l}') E(\mathbf{l}') \mathbf{d}(\mathbf{l} - \mathbf{l}')$$

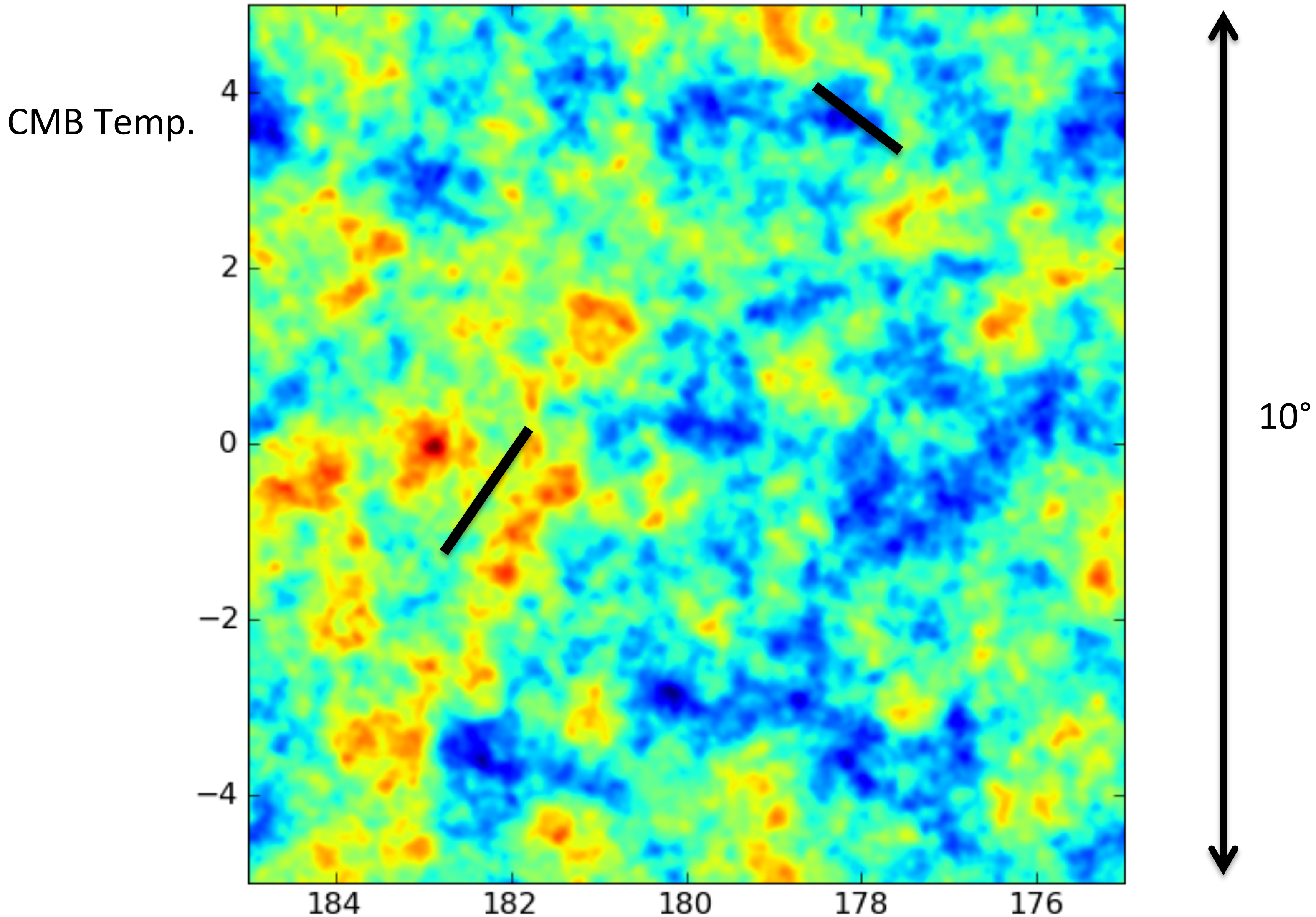
Unlensed CMB

CMB Temp.

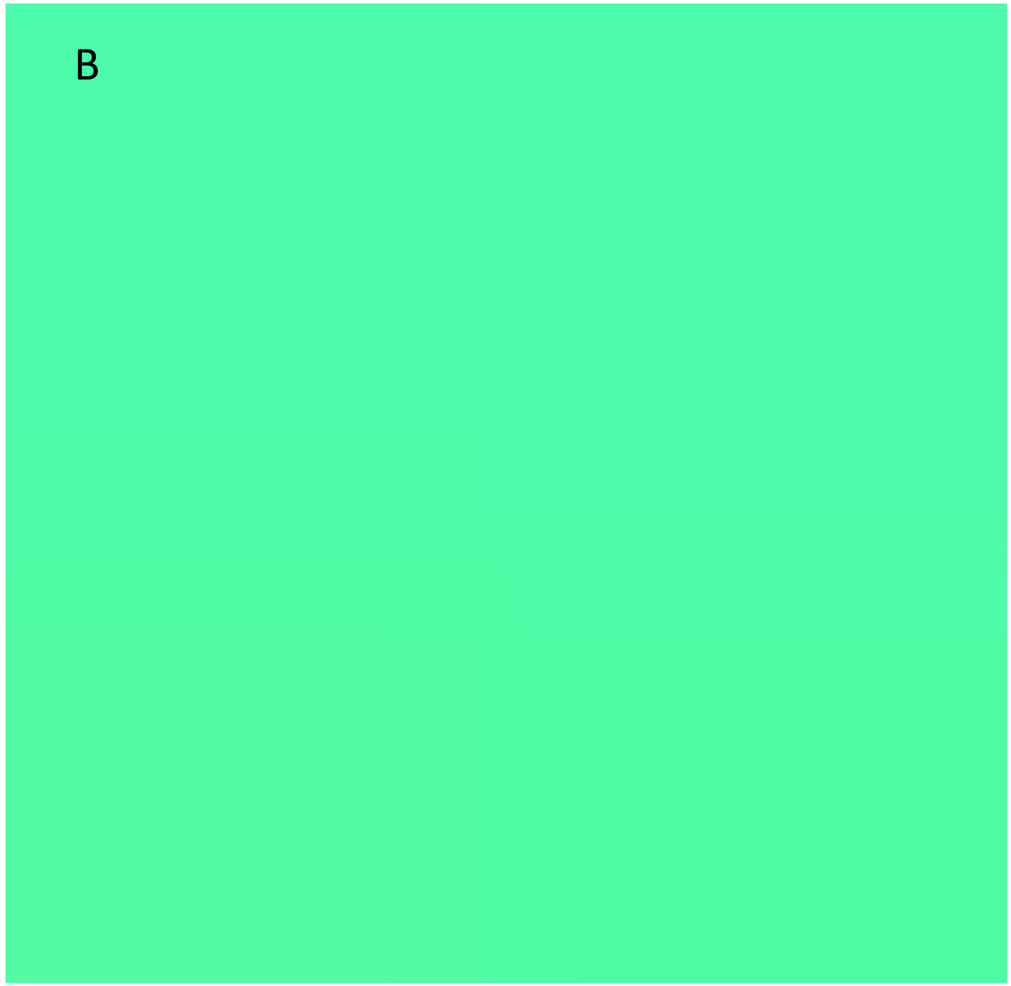


10°

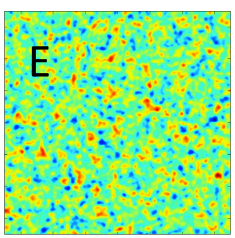
Lensed CMB



Unlensed CMB B-Polarization

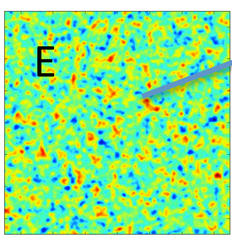


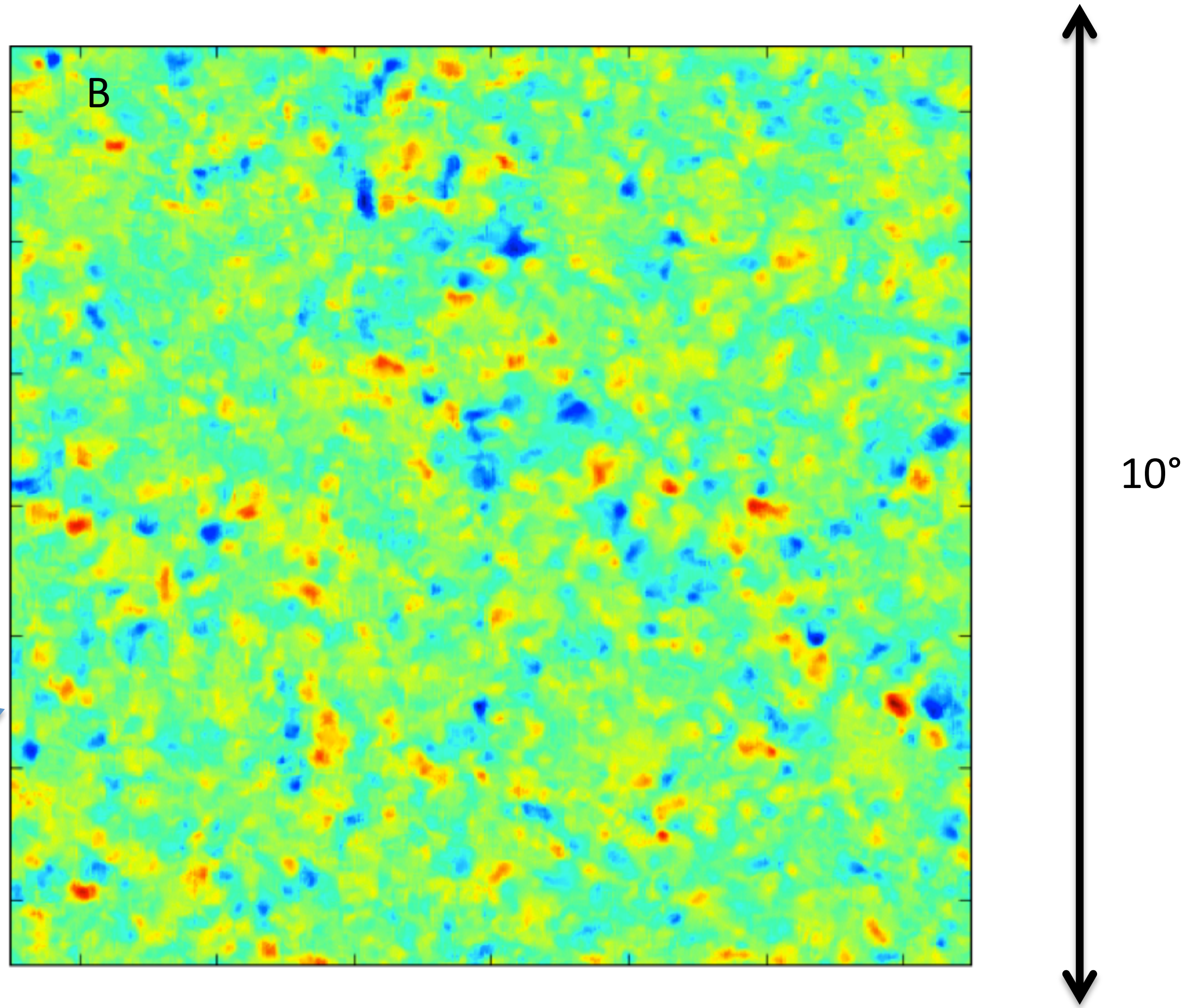
10°



Lensed CMB B-Polarization

Gravitational lensing converts E- to B-polarization

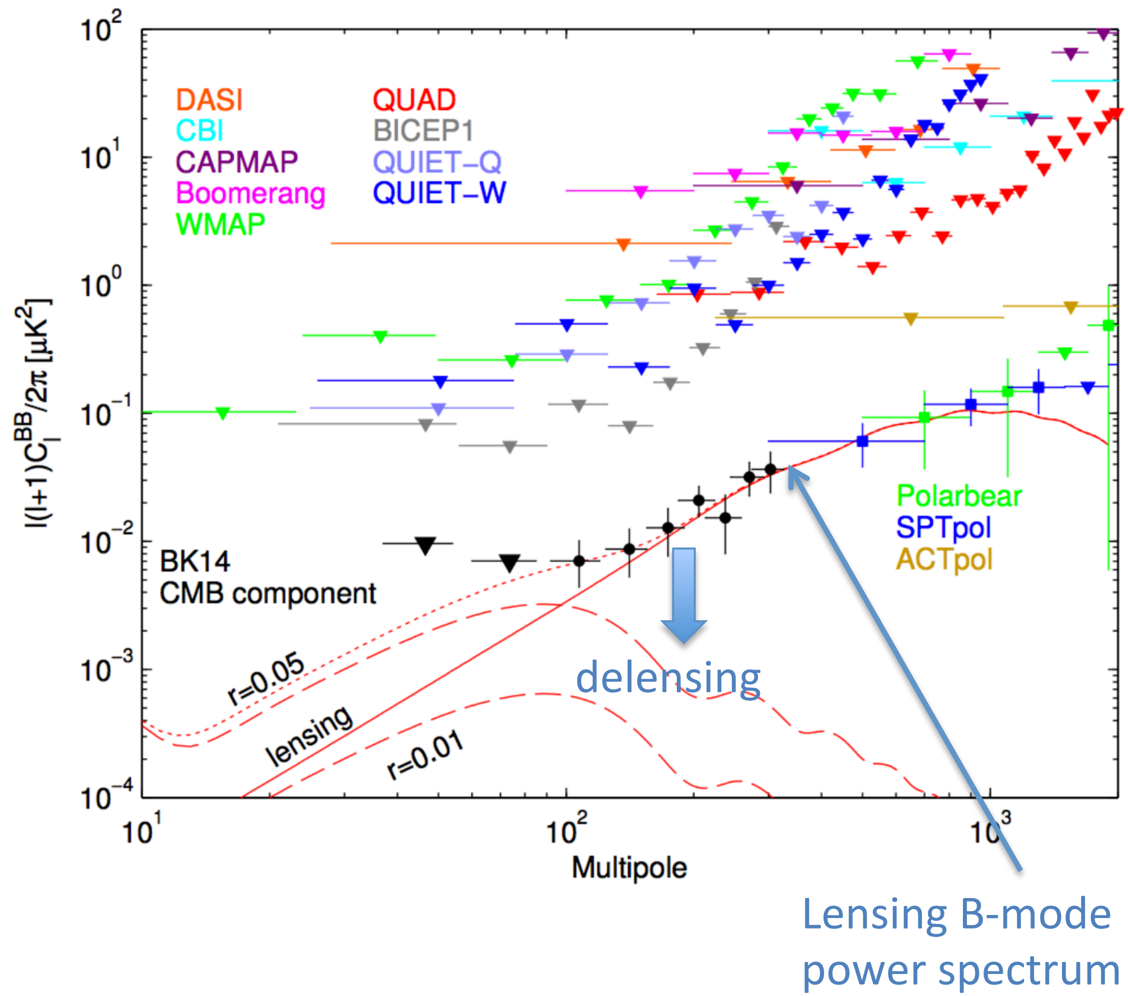




$$B \sim E * d$$

The Need for Delensing

- Lensing B lies on top of any primordial signal
  $B = B_{primordial}(r) + \mathbf{B_{lensing}}$
- Hence lensing B-mode contribute noise
- **Lensing noise is now limiting** – need to remove lensing B to find signal beneath! (want to reach r~0.001)

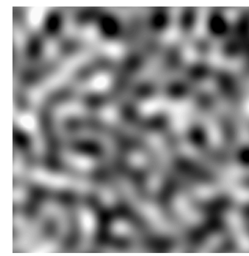


[POLARBEAR Collaboration 2014 incl. B. Sherwin, BICEP2 Collaboration 2014]

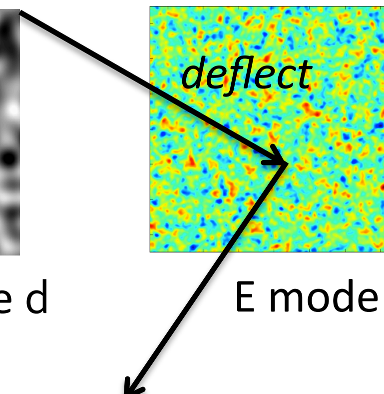
Solution: Delensing The CMB

- How to reduce lensing noise?
- Delensing: construct $B_{lensing}$ map from measured d and E and subtract: $B - B_{lensing}$
- **Need high-res data** and good delensing algorithms!

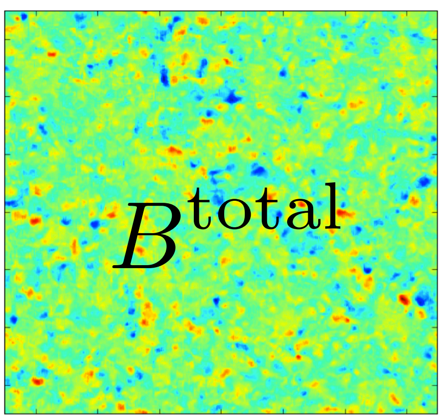
$$B \sim E * d$$



lensing estimate d



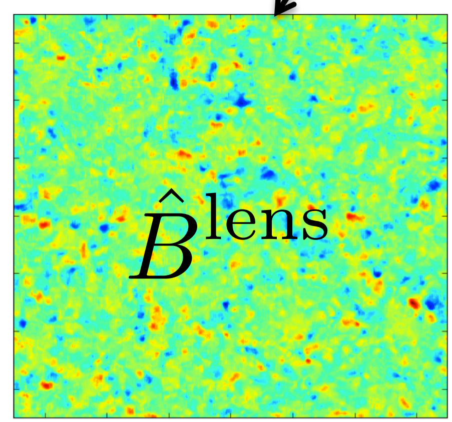
E mode map



measured B map – tensors + lensing

subtract

−

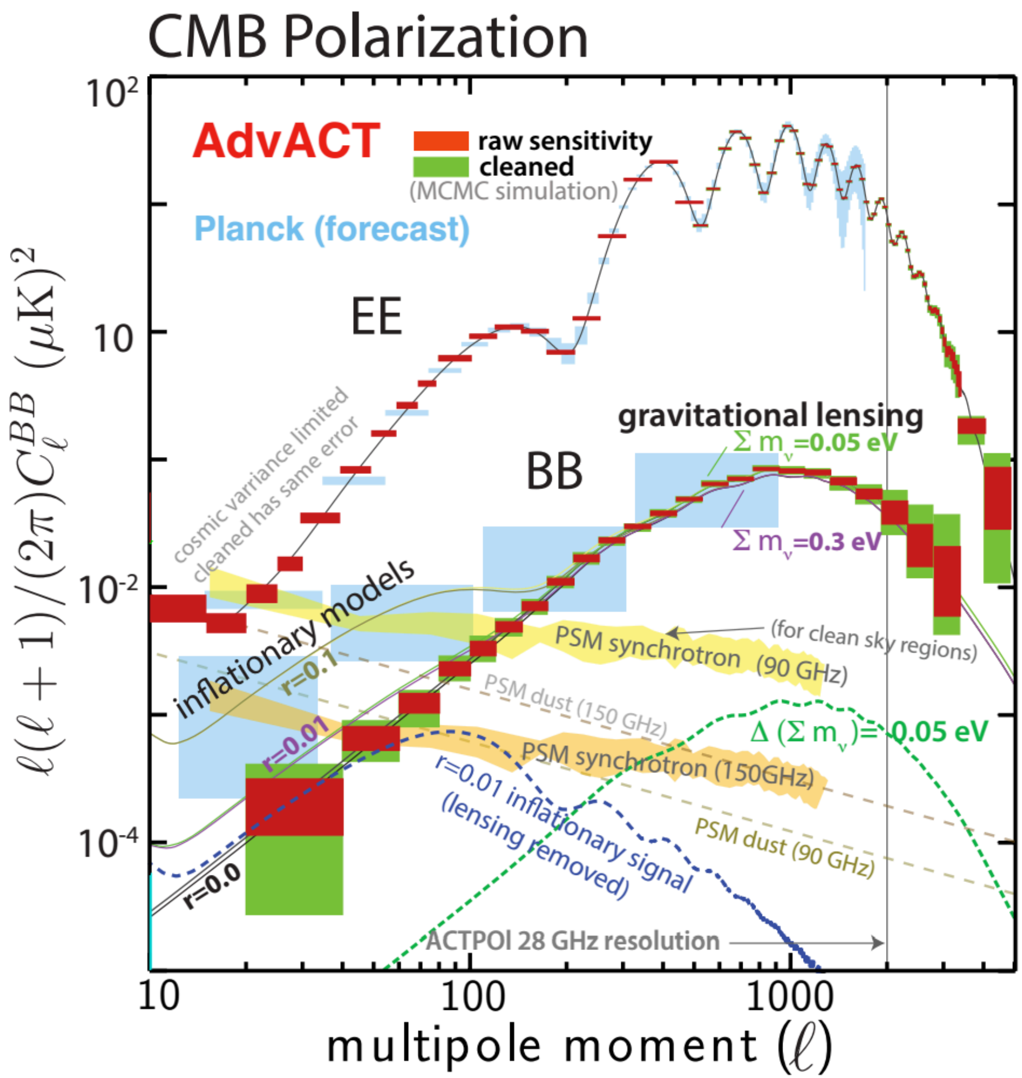


estimate of lensing B (from d+E)

[Sherwin & Schmittfull 2015]

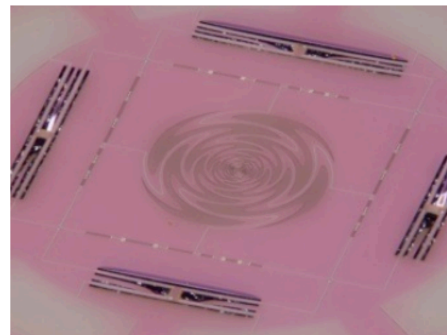
Upcoming Experiments – AdvACT / Simons Array / SPT-3G

- Challenges: sensitivity, foregrounds, lensing
- Stage-3 experiments will meet these challenges (2016-2019)
- Multi-freq. for foregrounds, high-res for delensing- will probe **r~0.004** (by 2019)



Upcoming Experiments – CMB Stage IV

- Ultra-low noise (all groups merge!)
- Multi-freq. for foregrounds, high-res. for delensing
- Stage-IV will probe r well **below r~0.001** (by 2025)
- **Either find inflationary gravity waves or rule out a broad class of (large field) inflation models!**



Summary

- Measuring the background of inflationary gravitational waves would confirm inflationary models, determine energy scale of inflation!!
- Best way to measure is with the CMB B-mode polarization
- Challenges: sensitivity, foregrounds, lensing
- Amazing improvements in ground based CMB data over next ~5 -10 years will allow us to determine if r>0.001