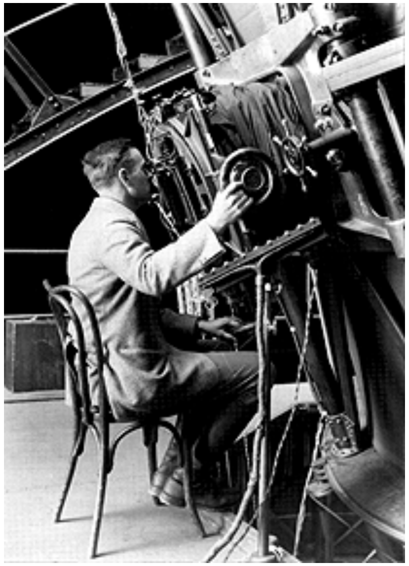
Cosmic Microwave Background, Inflation, and BICEP2

Walt Ogburn

Physics in Collision

September 20, 2014

Modern cosmology in a nutshell:



Edwin Hubble

1) The universe is expanding. (Hubble, 1920s)

2) It was once hot and dense, like the inside of the Sun.

(Alpher, Gamow, Herman, 1940s)

Bob Wilson & Arno Penzias
1978 Nobel Prize

3) You can still see the glow!
The *Cosmic Microwave Background*
(Penzias & Wilson, 1964)

⇒ acceptance of the "HOT BIG BANG"

We also have a Standard Model

All the data agree to amazing precision with the concordance cosmological model known as "ΛCDM". Just six parameters needed to fit the CMB data.

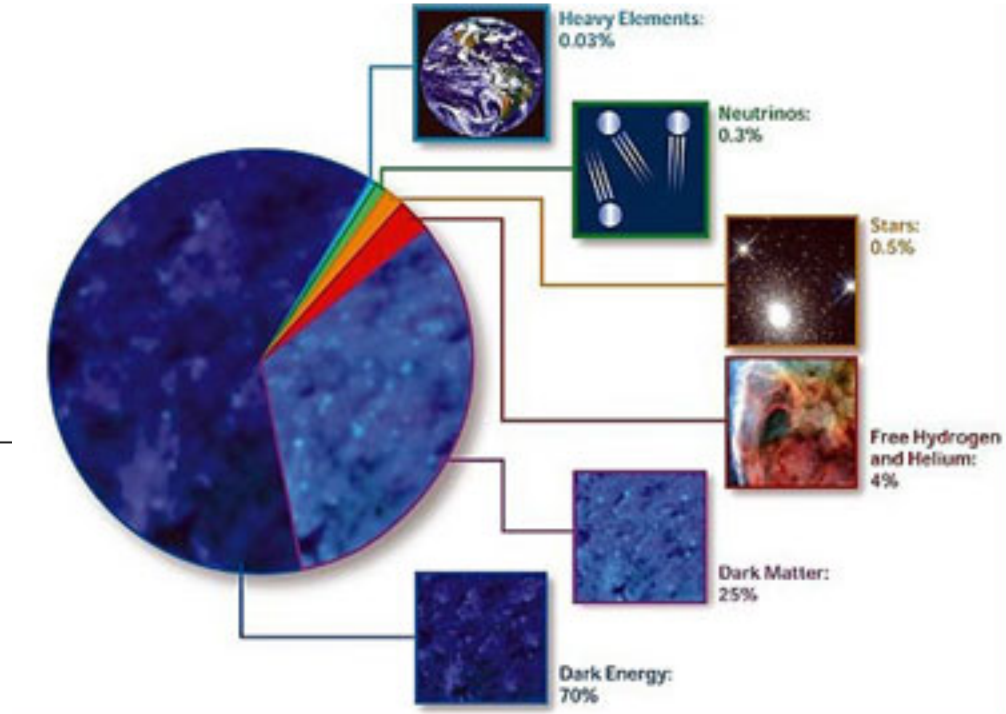


Figure: NASA

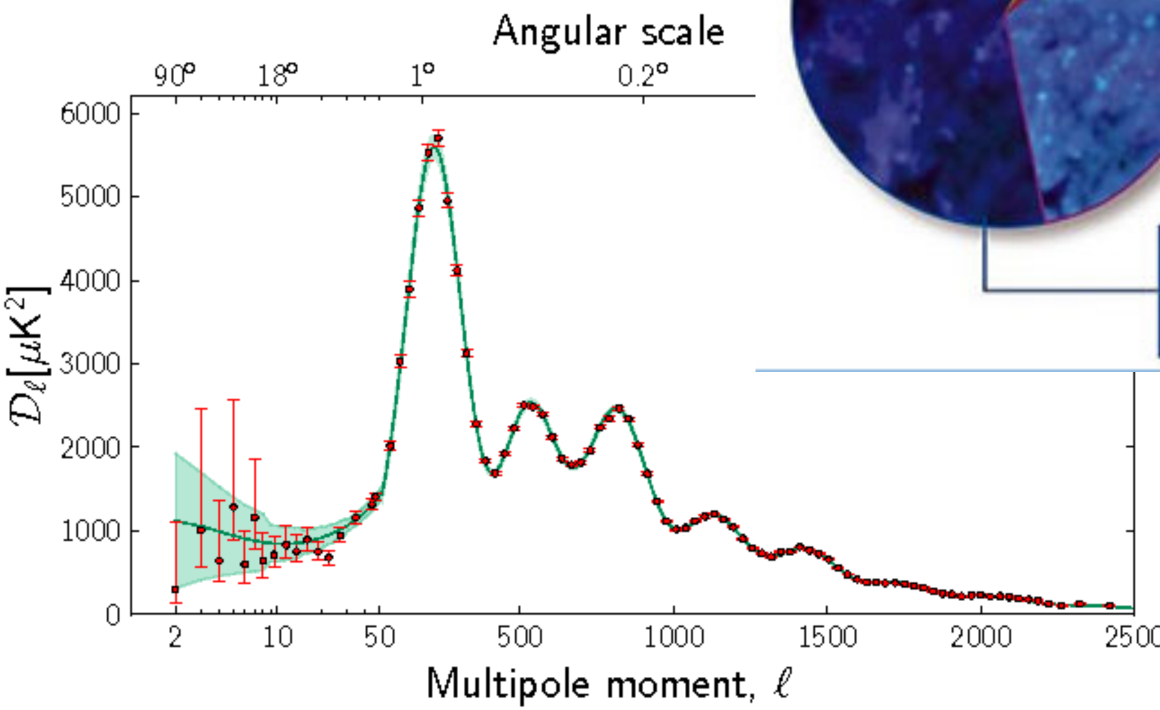
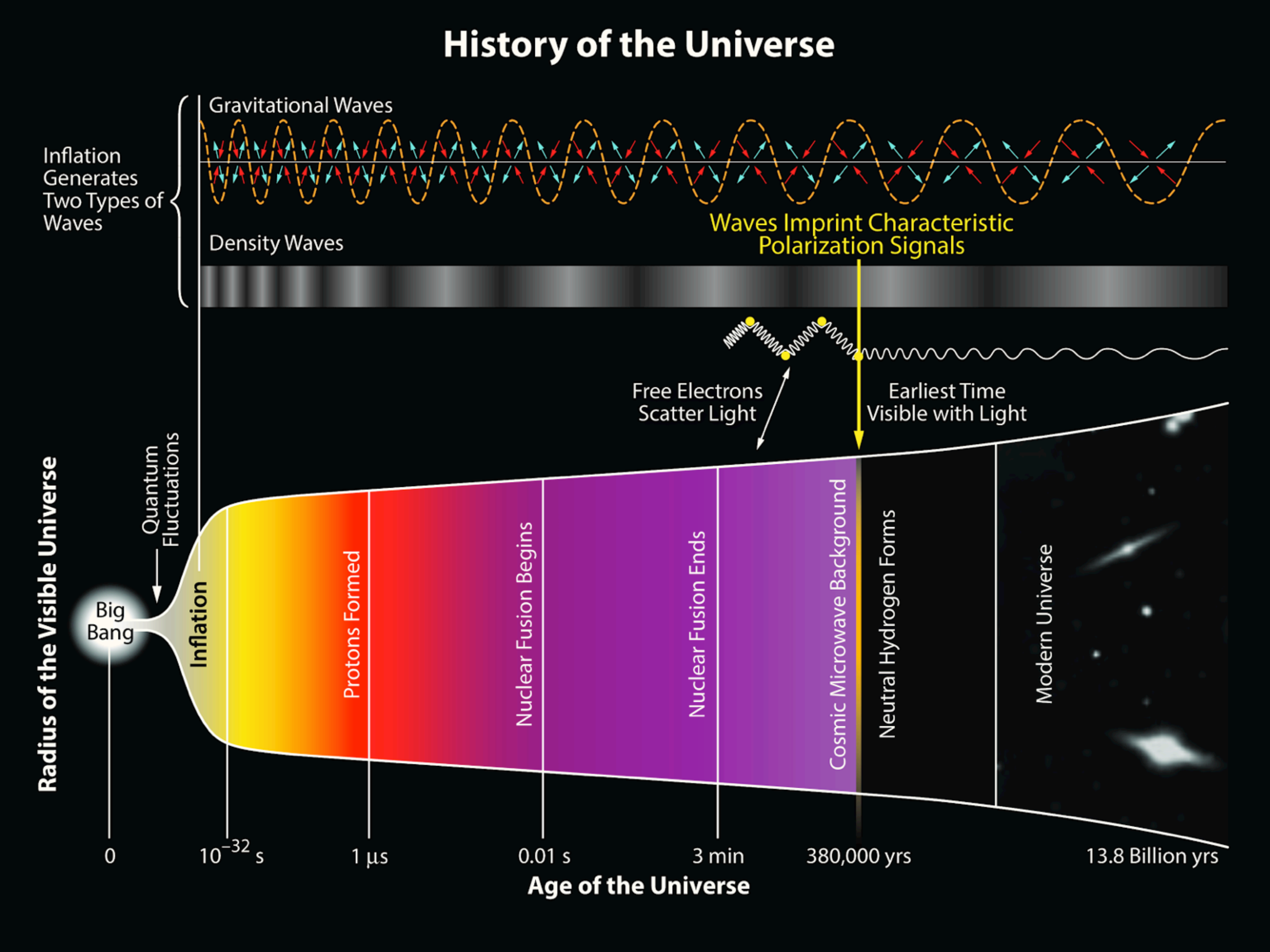


Figure: ESA/Planck Collaboration, http://sci.esa.int/jump.cfm?oid=51555



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0
10^{-32} s
1 μs
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380,000 yrs
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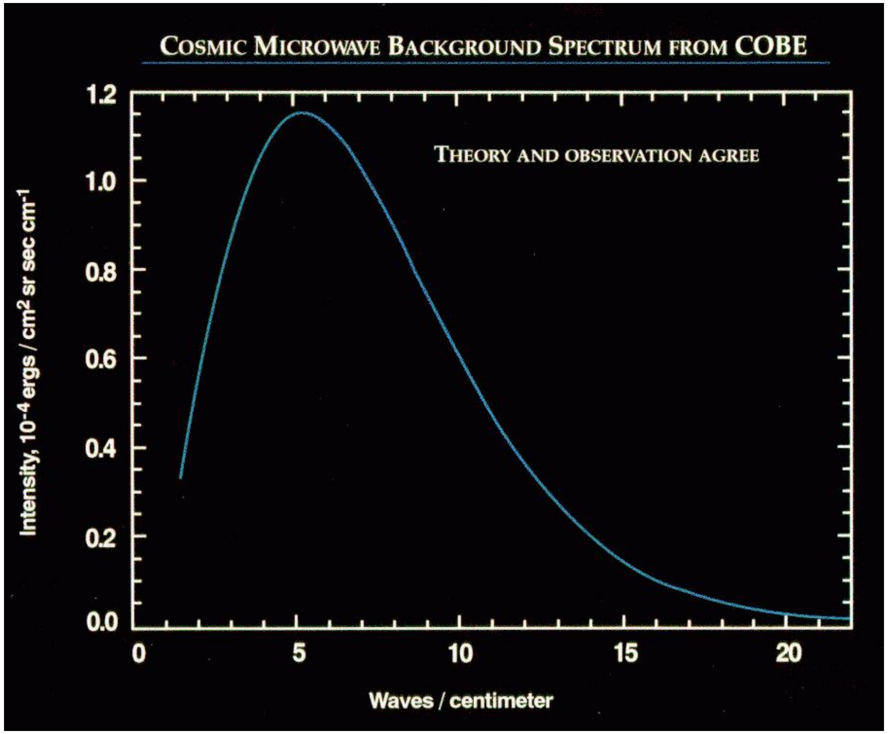
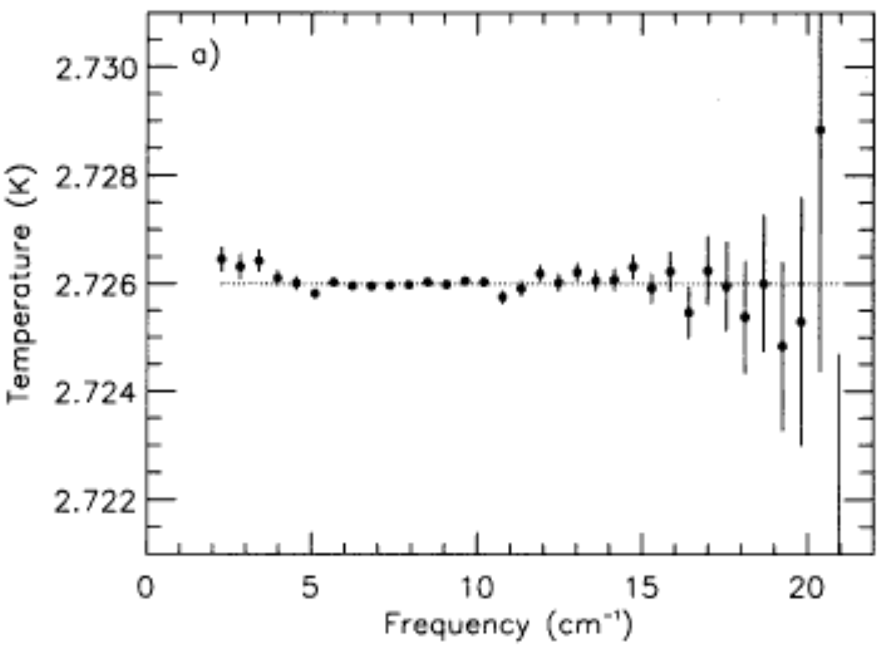
Age of the Universe

Black body spectrum observed by COBE

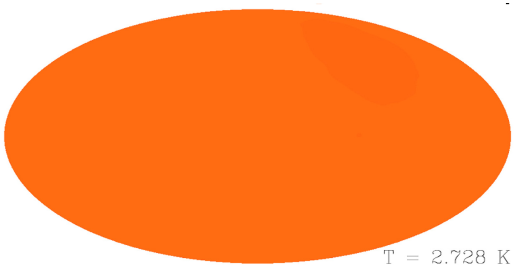




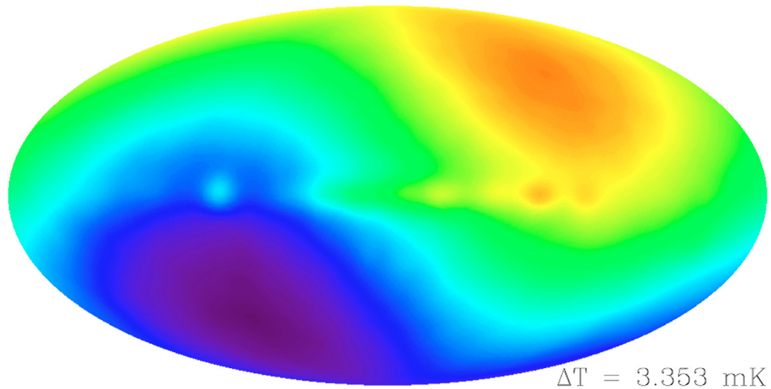
Residuals Mather et al 1994

- close to thermal equilibrium:
  temperature today of 2.726K (~ 3000K at z ~ 1000 because ν ~ (1+z))

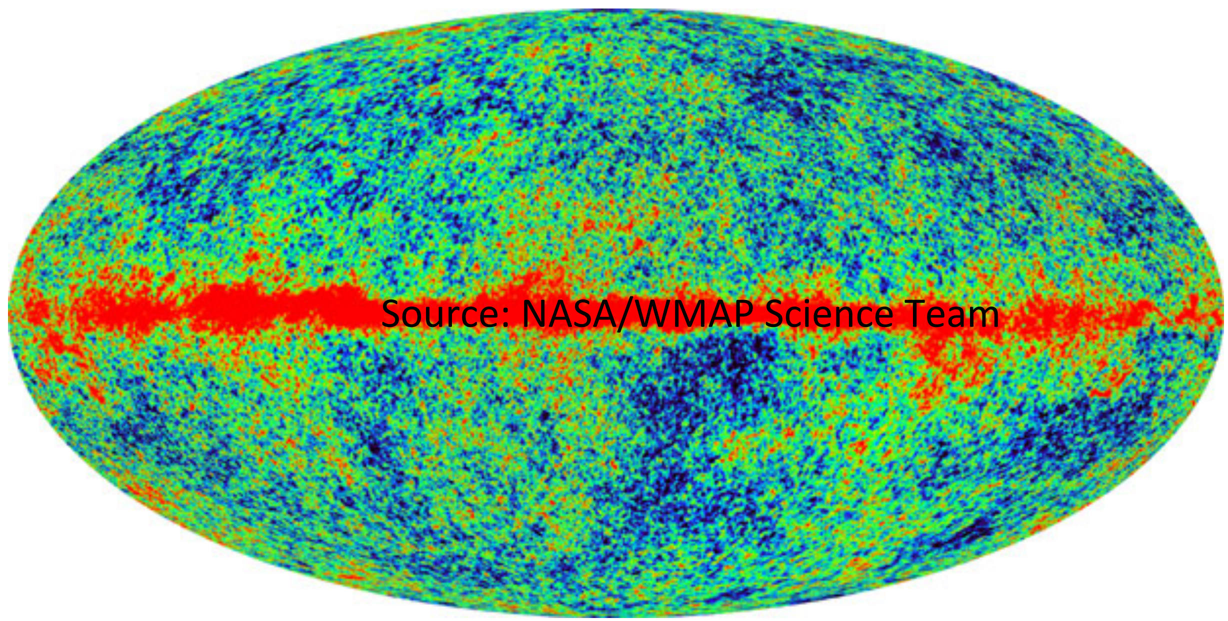
From: George Smoot, http://bccp.berkeley.edu/beach_program/presentations09/CATBsmoot.pdf



Almost perfectly uniform 2.7 K blackbody



Dipole (local motion)



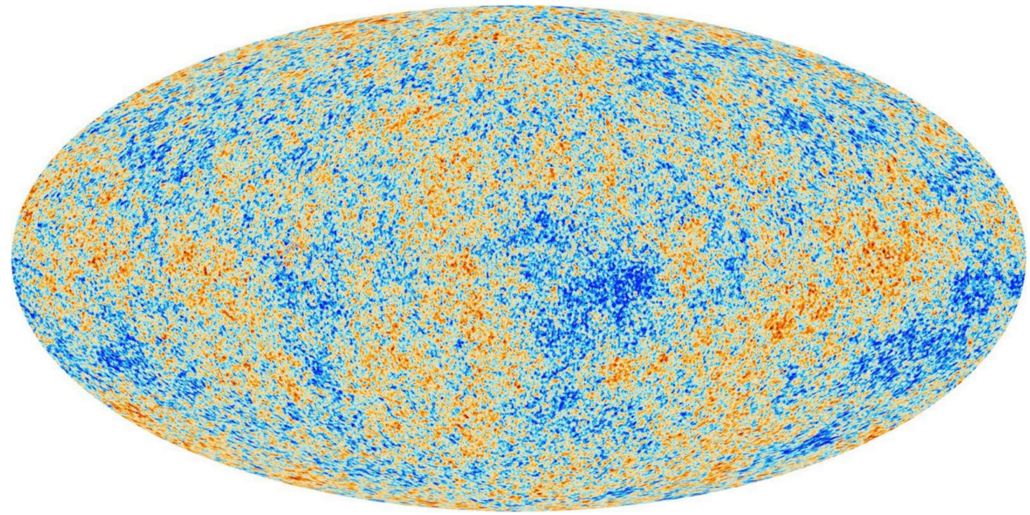
Milky Way Galaxy
+ part in 10^5 primordial
temperature anisotropy

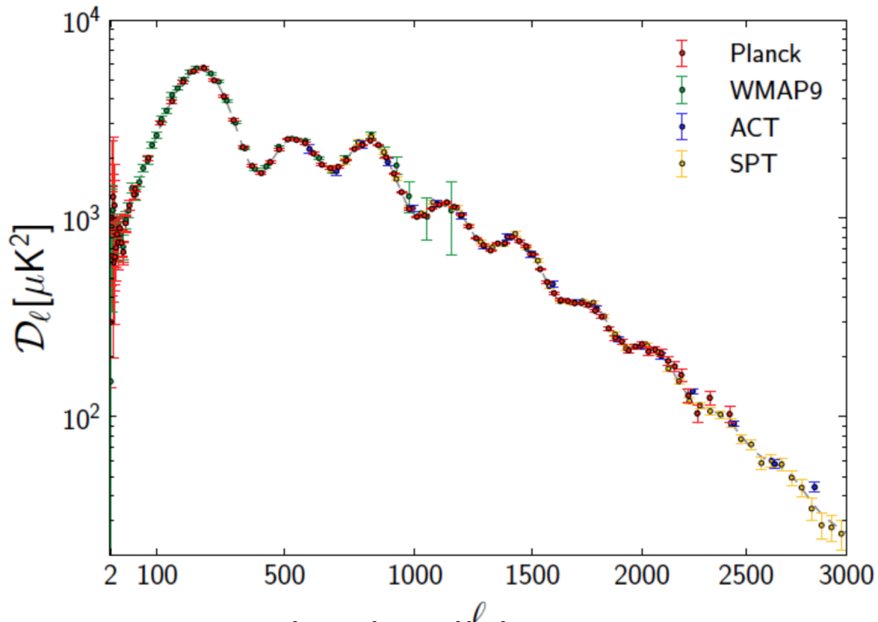
Cosmic Microwave Background (CMB)

The CMB traces the conditions of the universe at the time when atoms first began to form.

Precision measurements of the CMB temperature have provided a wealth of cosmological information consistent with the inflationary paradigm.

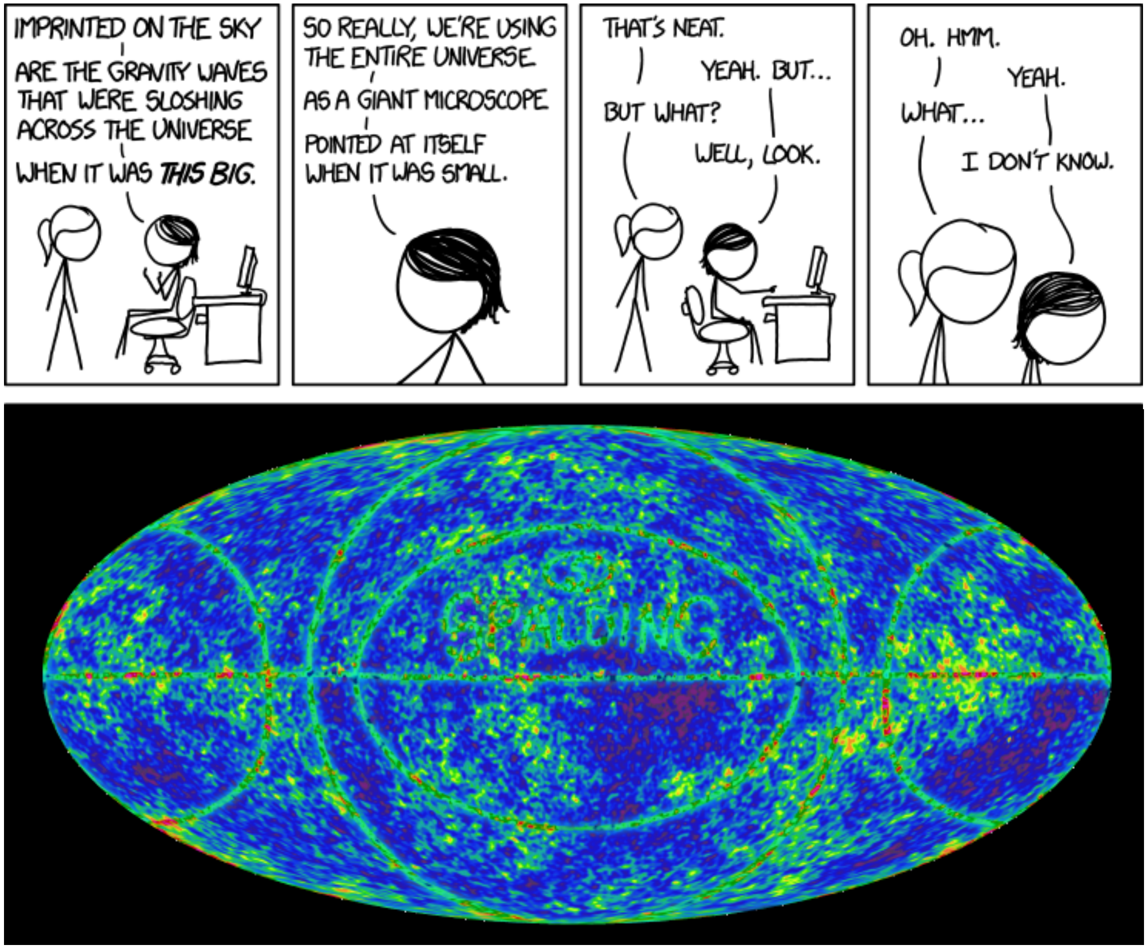
However, any imprint of the inflationary gravitational waves have so far eluded detection in the CMB.





Planck Collaboration & ESA

Inside-out view of the cosmos



Randall Munroe, XKCD: http://xkcd.com/1365/

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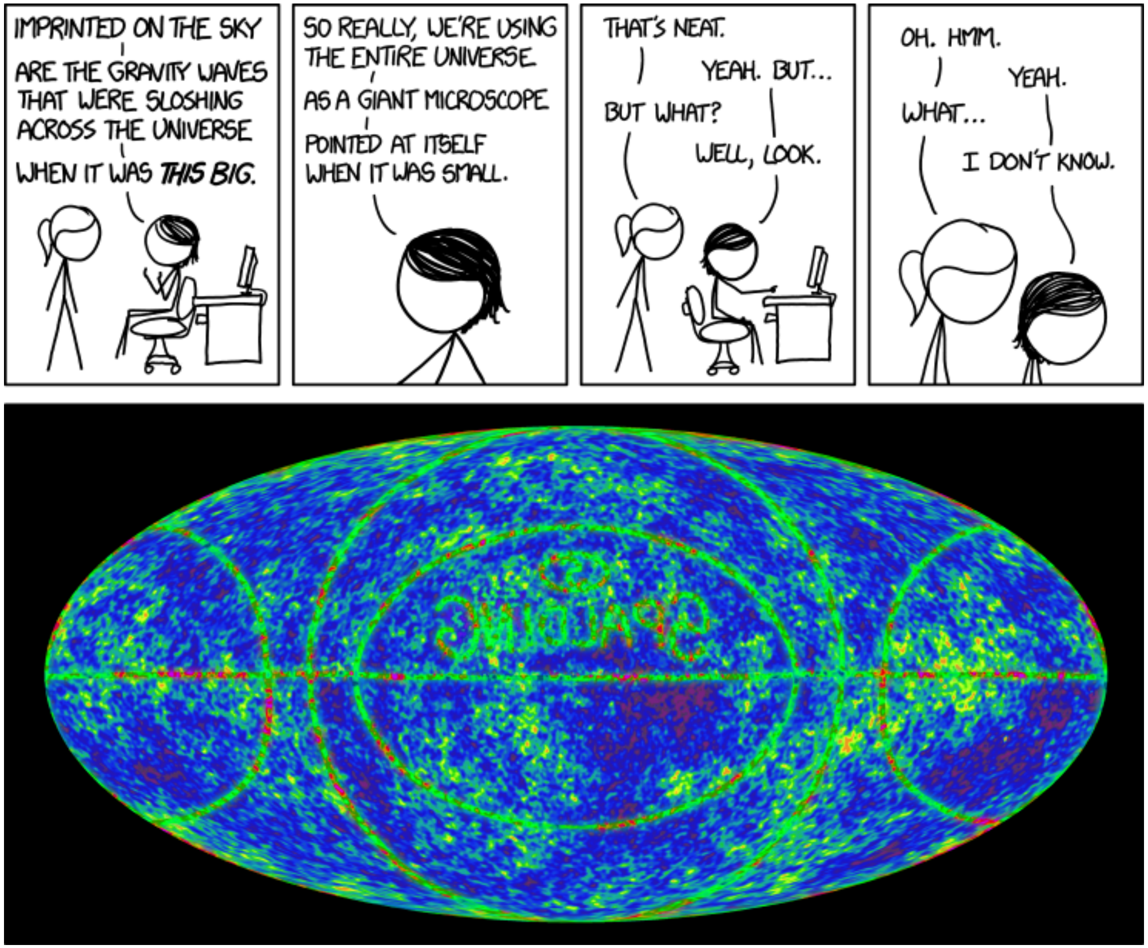
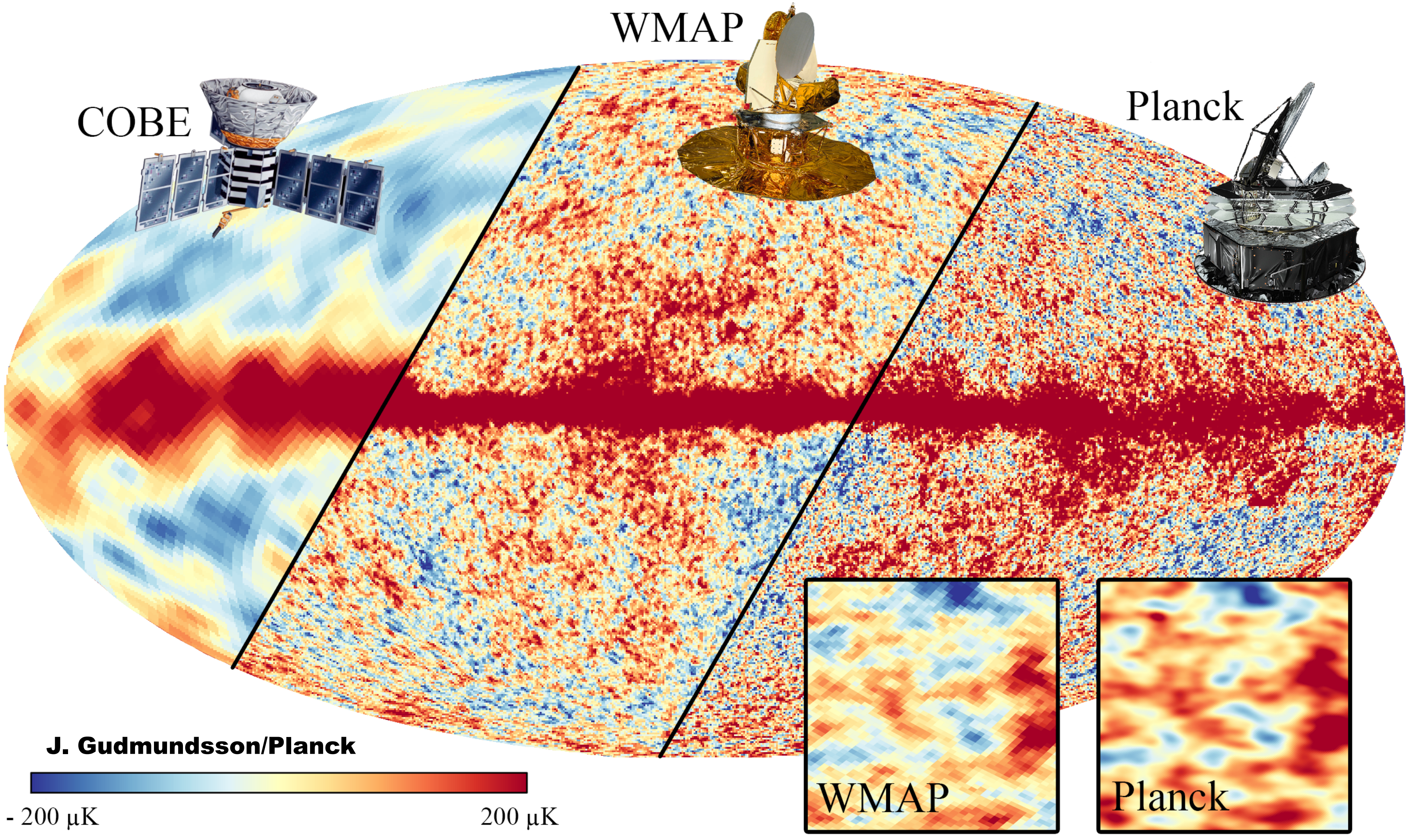


Randall Munroe, XKCD: http://xkcd.com/1365/

Progression of CMB satellites



Cosmological parameters

Tweaking the composition, geometry, and expansion history of the universe shifts the position and amplitude of the acoustic peaks and the damping tail.

Start out with a flat ("white noise") initial spectrum of fluctuations.

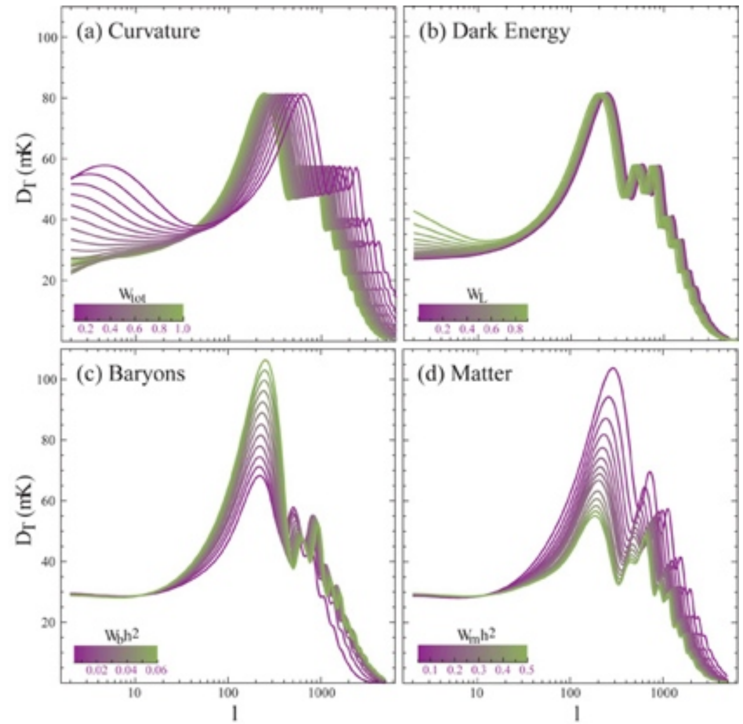


Figure: Wayne Hu, arXiv: astro-ph/0210696

ΛCDM = 6 parameters that fit everything

A_s, n_s

Amplitude & slope of primordial spectrum from inflation

$\rho_b = \Omega_b h^2$

$\rho_\Lambda = \Omega_\Lambda h^2$

$\rho_c = \Omega_c h^2$

Contents of ΛCDM universe

τ_{reion}

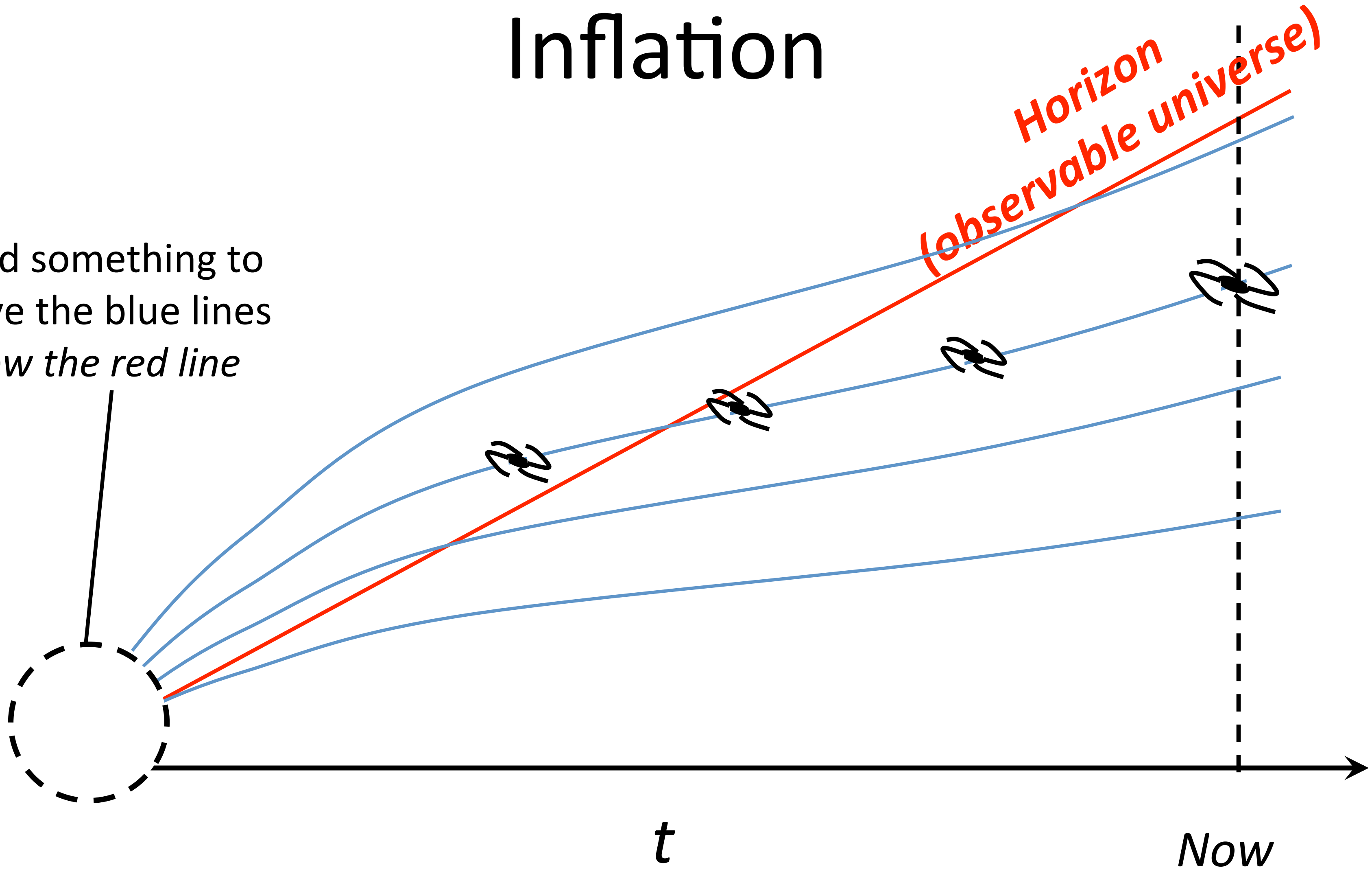
Optical depth to reionization

But ΛCDM doesn't explain everything

- Absence of magnetic monopoles
- Flatness
- Horizon problem
- Initial perturbations that give rise to structure

Inflation

Need something to move the blue lines *below the red line*



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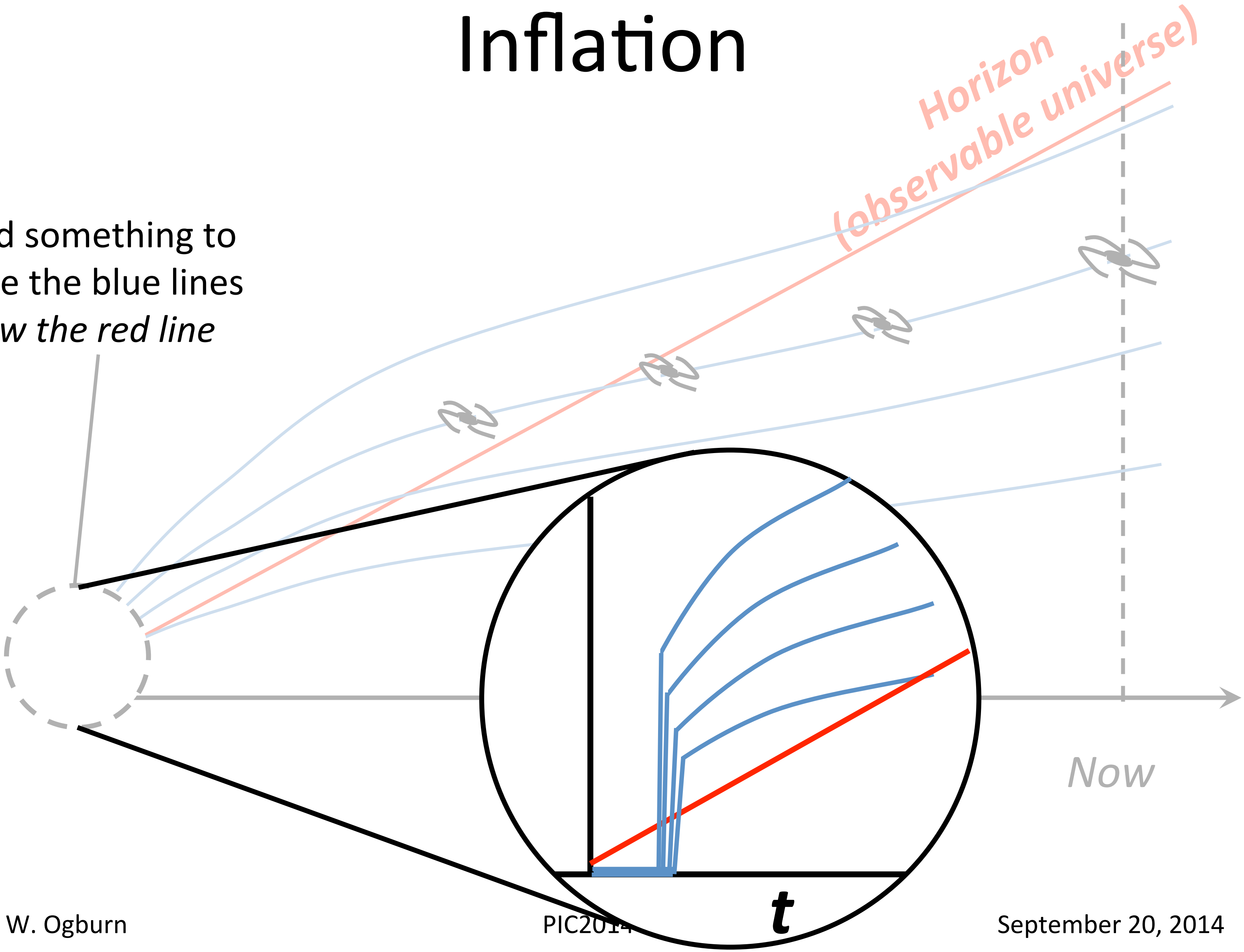
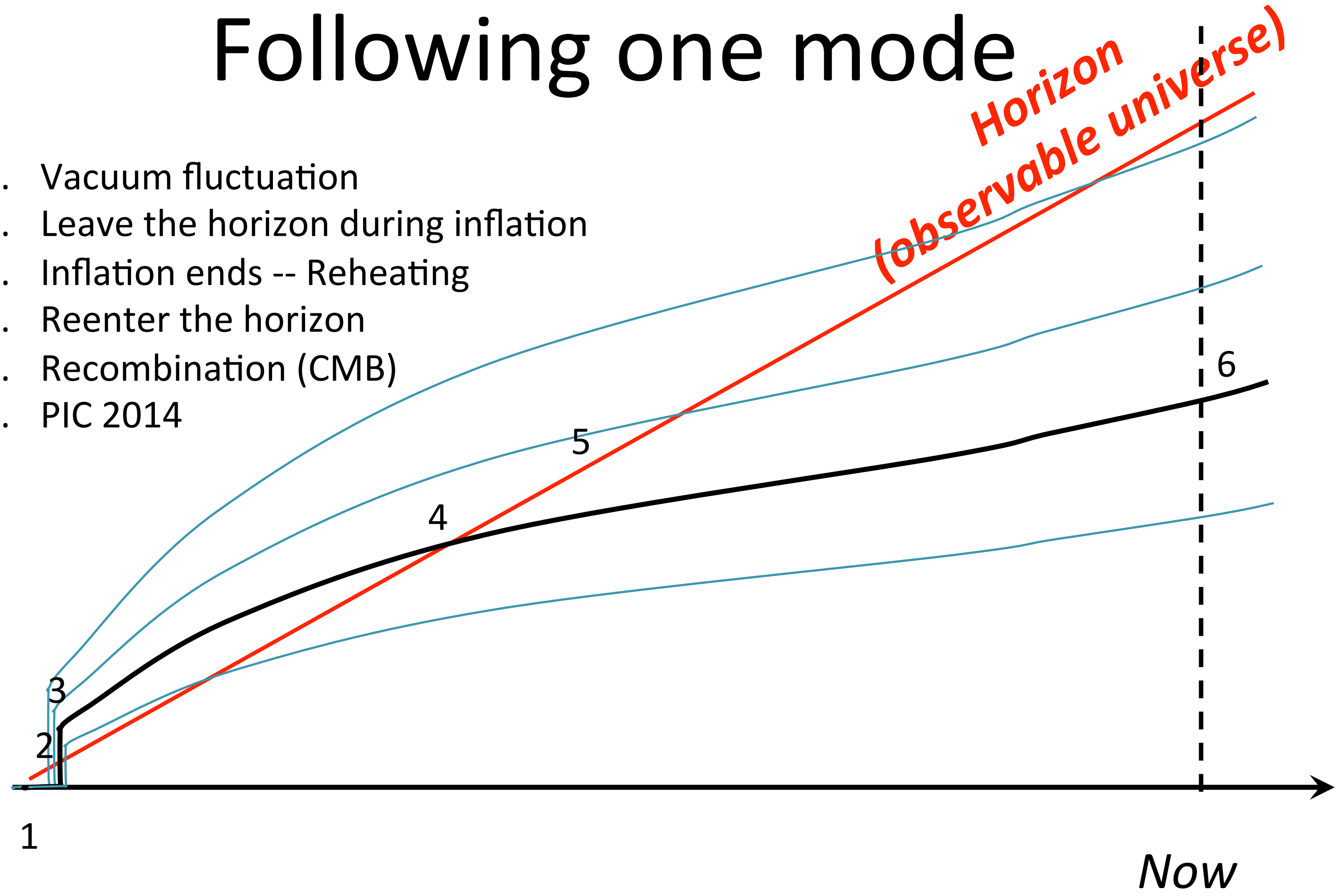
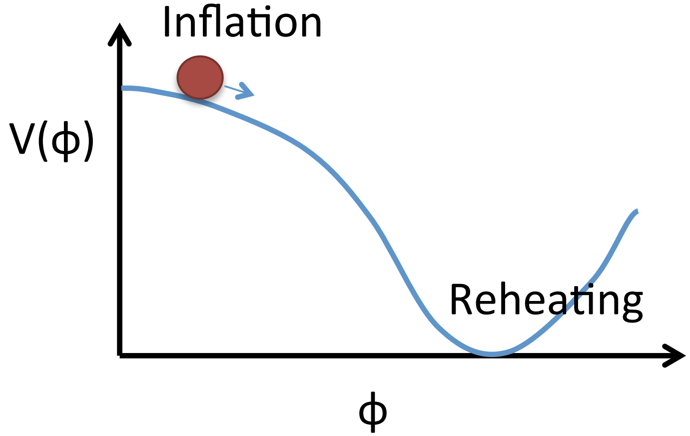


Following one mode

1. Vacuum fluctuation
2. Leave the horizon during inflation
3. Inflation ends -- Reheating
4. Reenter the horizon
5. Recombination (CMB)
6. PIC 2014



Simple slow-roll inflation



- Only one field involved: the inflaton
- Initial state: Bunch-Davies vacuum
- Canonical kinetic term $\frac{1}{2}(\partial\phi)^2$
- Smooth, slowly varying potential

Slope and curvature:
Slow roll parameters (both small)

$\varepsilon_V = M_{pl}^2 (V')^2/2V^2$

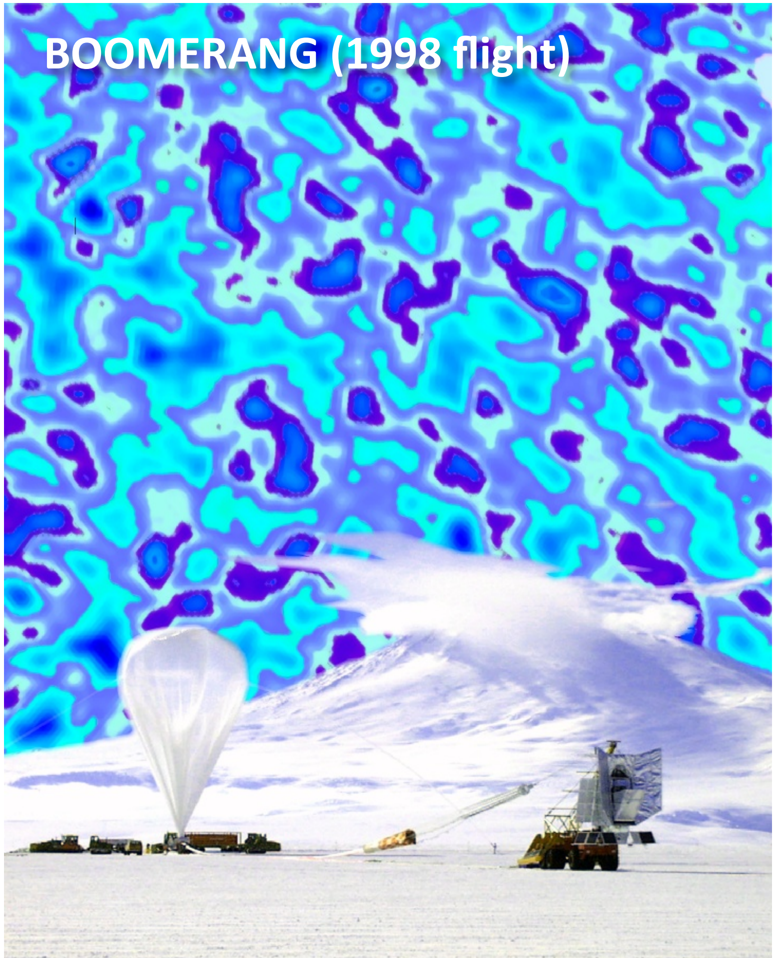
$\eta_V = M_{pl}^2 V''/V$

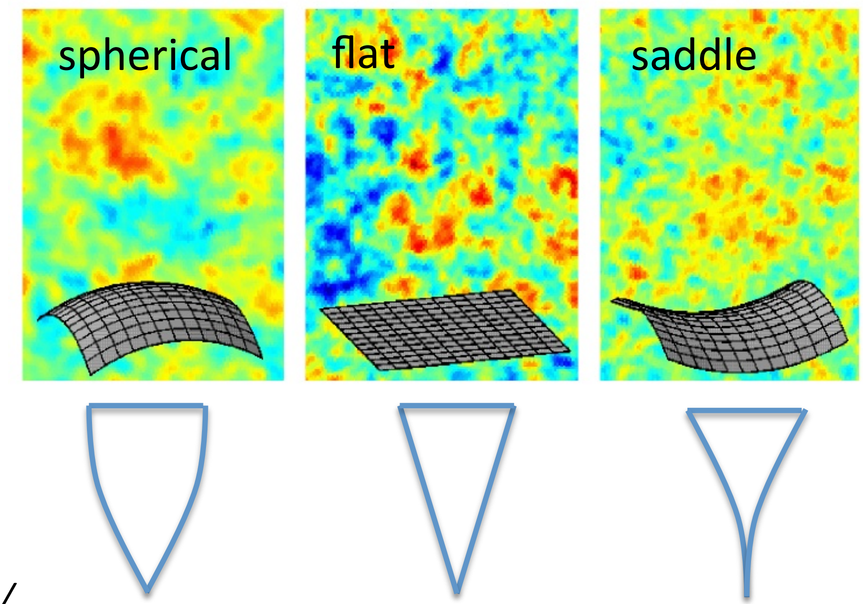
The values of ε_V and η_V determine properties of the perturbation spectrum at the end of inflation.

Tests of inflation

- Flatness
- Very large-scale features (horizon problem)
- Scale invariance
- Adiabatic perturbations
- Nongaussianity

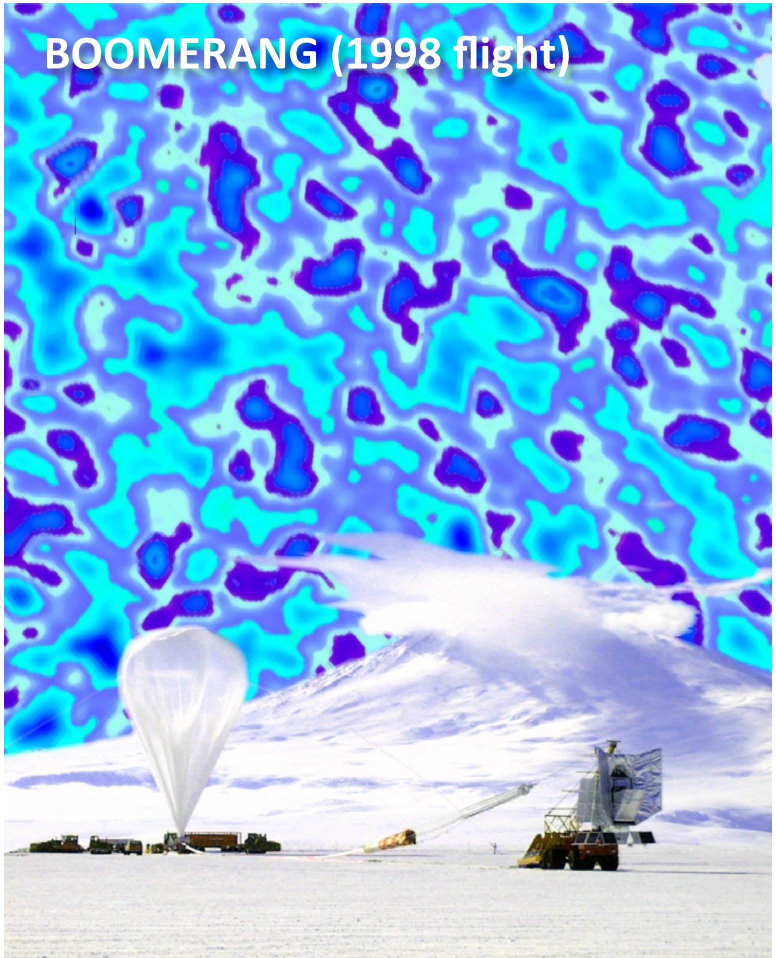
Flatness

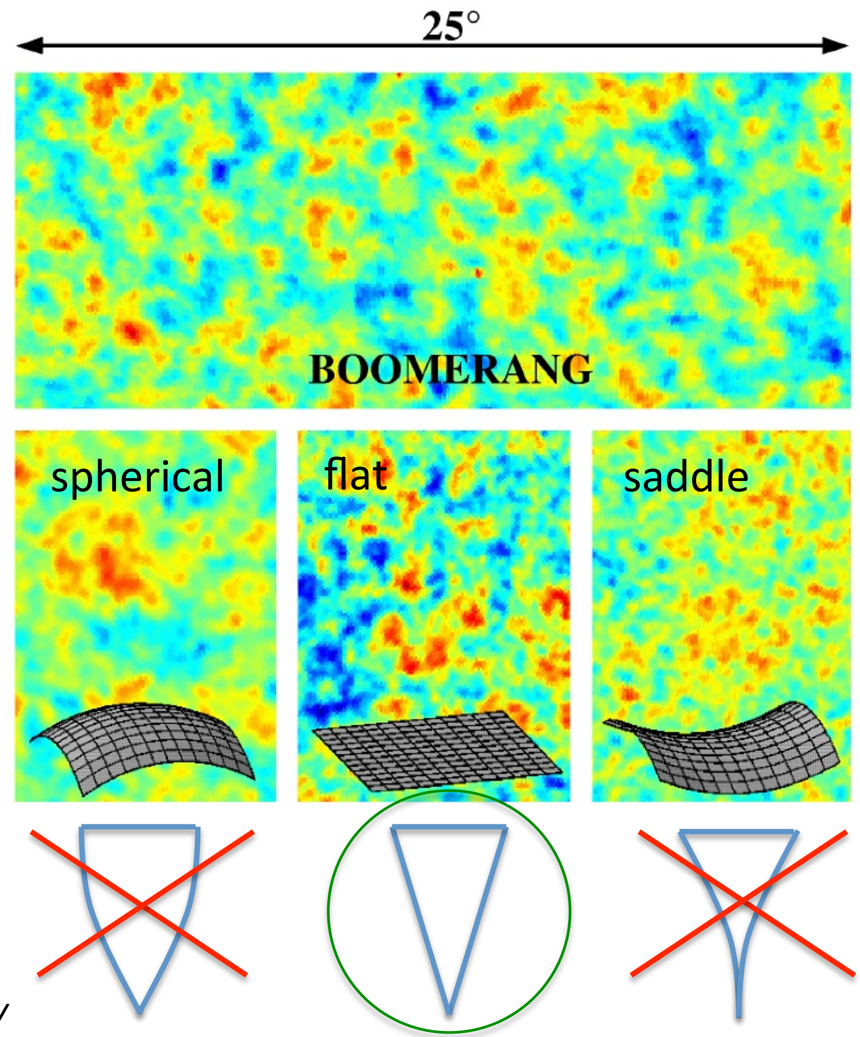




Images: BOOMERANG Collaboration
http://cmb.phys.cwru.edu/boomerang/press_images/

Flatness





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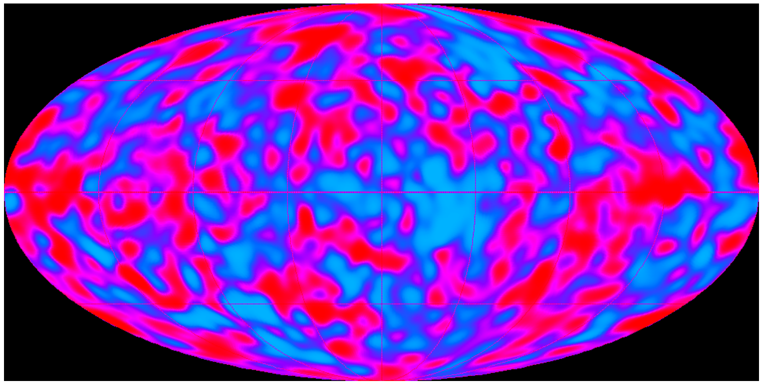
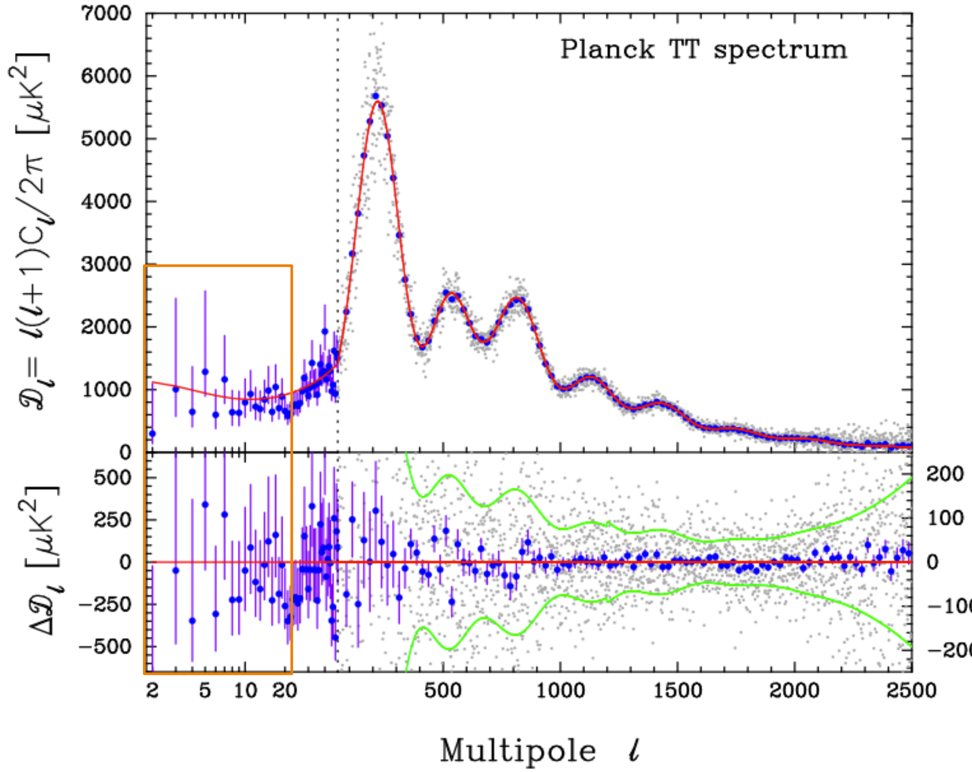
Superhorizon modes



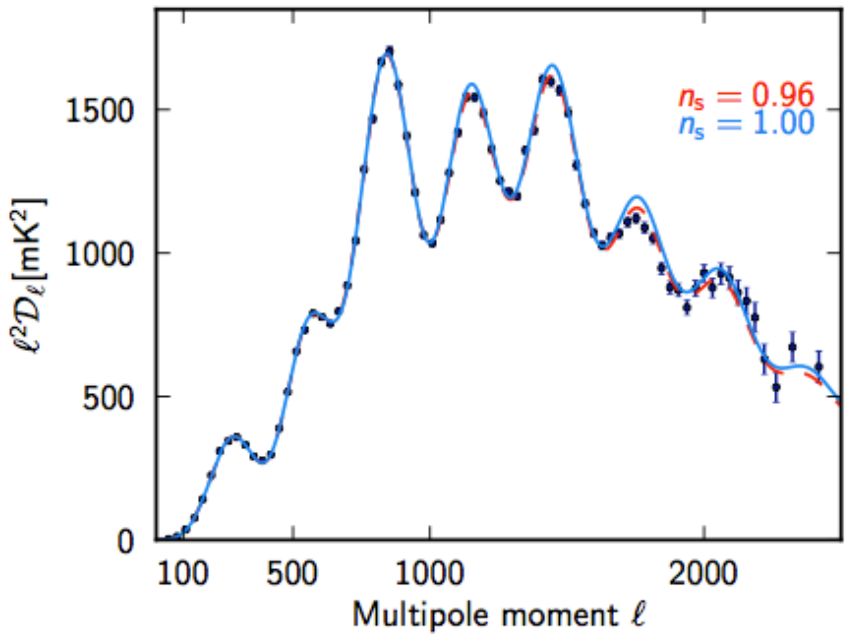
COBE DMR: 7° beam.
First detection of intrinsic CMB anisotropies, all > horizon scale at decoupling!



Need an explanation both for the uniformity and the anisotropies on large angular scales. Inflation provides both.

Planck 2013 results. XVI. Cosmological parameters
http://arxiv.org/abs/1303.5076, Astron. & Astrophys. (2014)

Scale invariance



Inflation predicts a nearly flat initial spectrum. Acoustic oscillations create peaks but overall tilt may remain.

Planck:
n_s=0.959 ± 0.007
from CMB alone

Slow roll inflation:
$n_s - 1 \approx 2\eta_V - 6\varepsilon_V$

Planck 2013 results. XVI. Cosmological parameters
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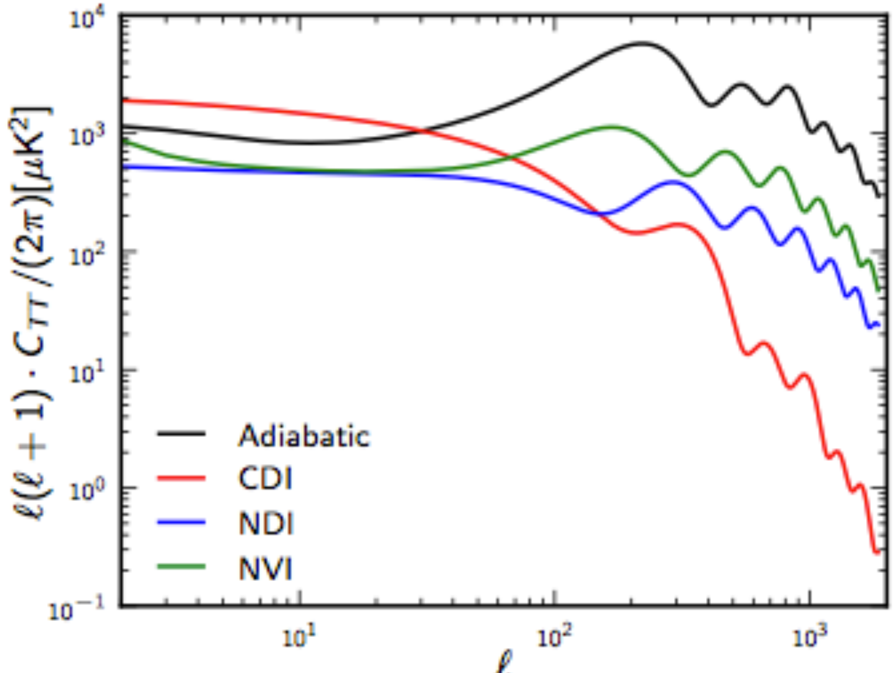
Adiabatic Perturbations



Planck 2013 results. XXII. Constraints on inflation
http://arxiv.org/abs/1303.5082, A&A 566 A54, June 2014

Inflation with a single field generates density perturbations with everything in lockstep: curvature, matter, radiation.

If multiple fields are involved, they can change the mix without changing the total density (or curvature). These are "isocurvature".

Planck allows CDI=7%, NDI=9%, NVI=5% at 95% CL. Limited by low power at large angular scales.

Nongaussianity

Many models including ekpyrotic cosmology often predict departures from gaussianity. Parametrized by bispectrum amplitudes f_{NL}.

Planck finds

$f_{NL}^{local} = 2.7 \pm 5.8$

$f_{NL}^{equil} = -42 \pm 75$

$f_{NL}^{ortho} = -25 \pm 39$

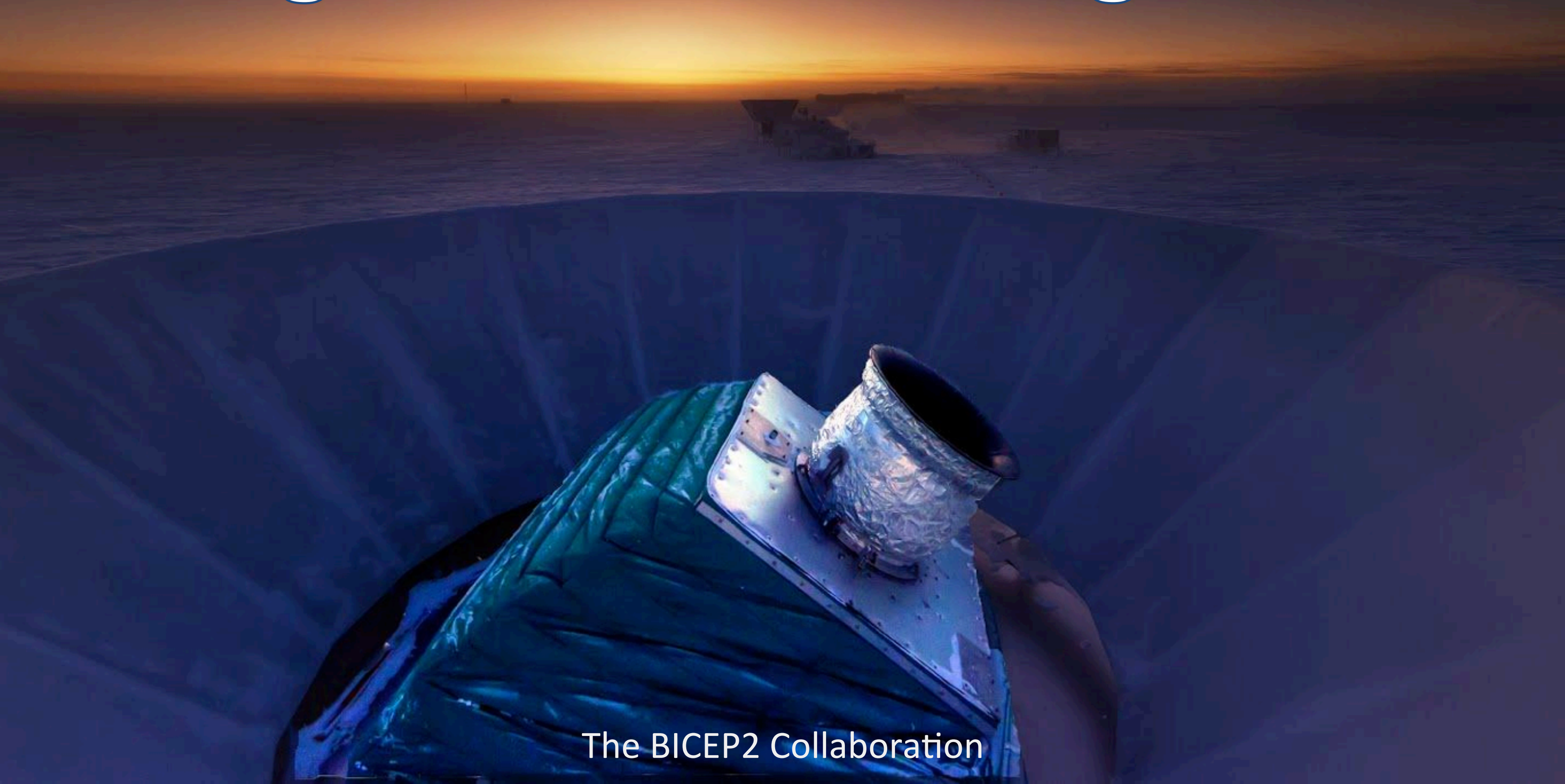
Slow roll predicts $f_{NL} \sim O(\varepsilon, \eta)$.

Planck 2013 Results. XXIV. Constraints on primordial non-Gaussianity
http://arxiv.org/abs/1303.5084, Astron. & Astrophys. (2014)

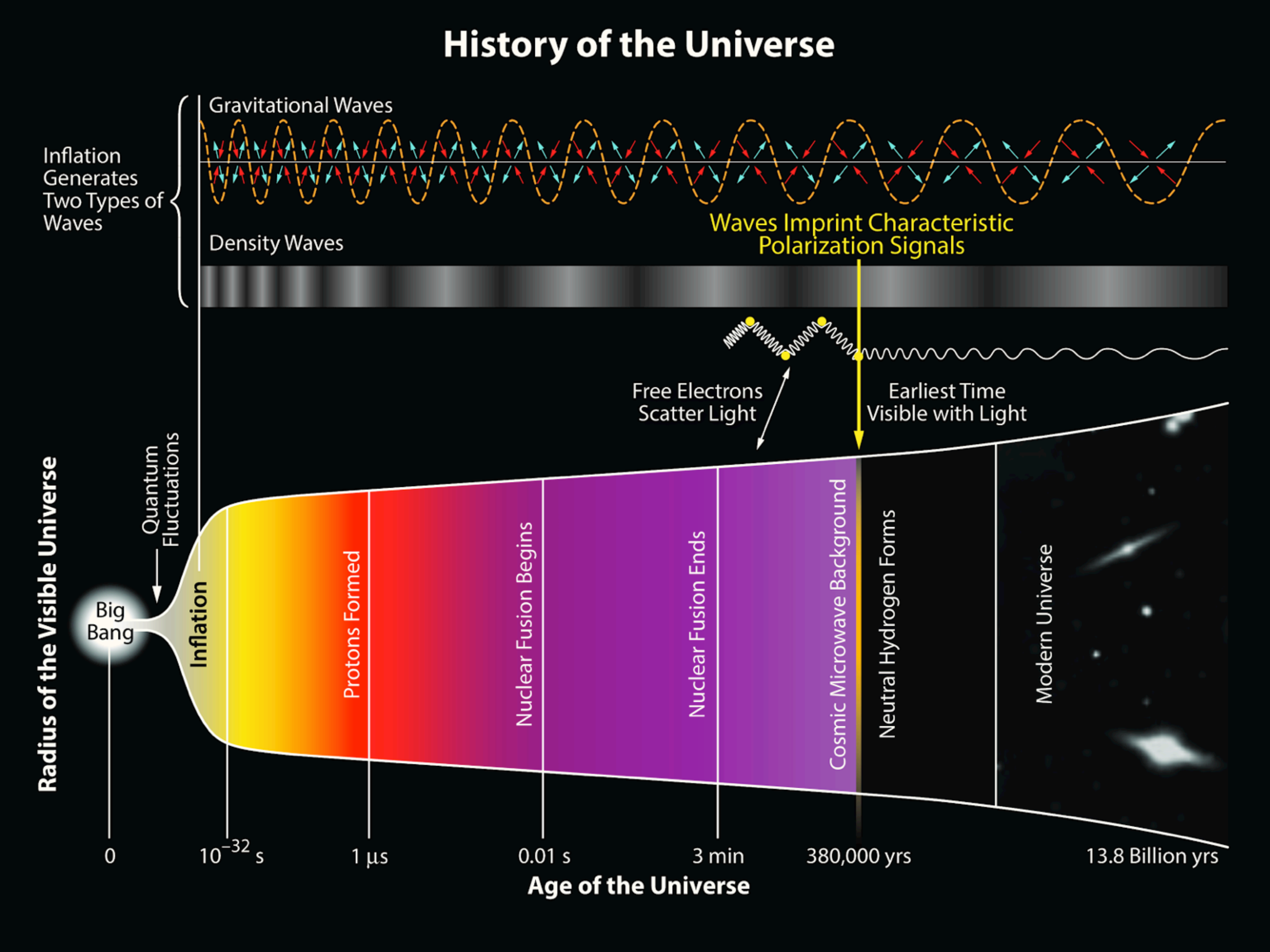
Summary

- Precision measurements by Planck are consistent with single-field slow-roll inflation.
- Often manifest as absence of deviation from simplest possible behavior.
- Would like to have a positive signal of inflation.

Detection of B-mode Polarization at Degree Scales using BICEP2



The BICEP2 Collaboration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Age of the Universe

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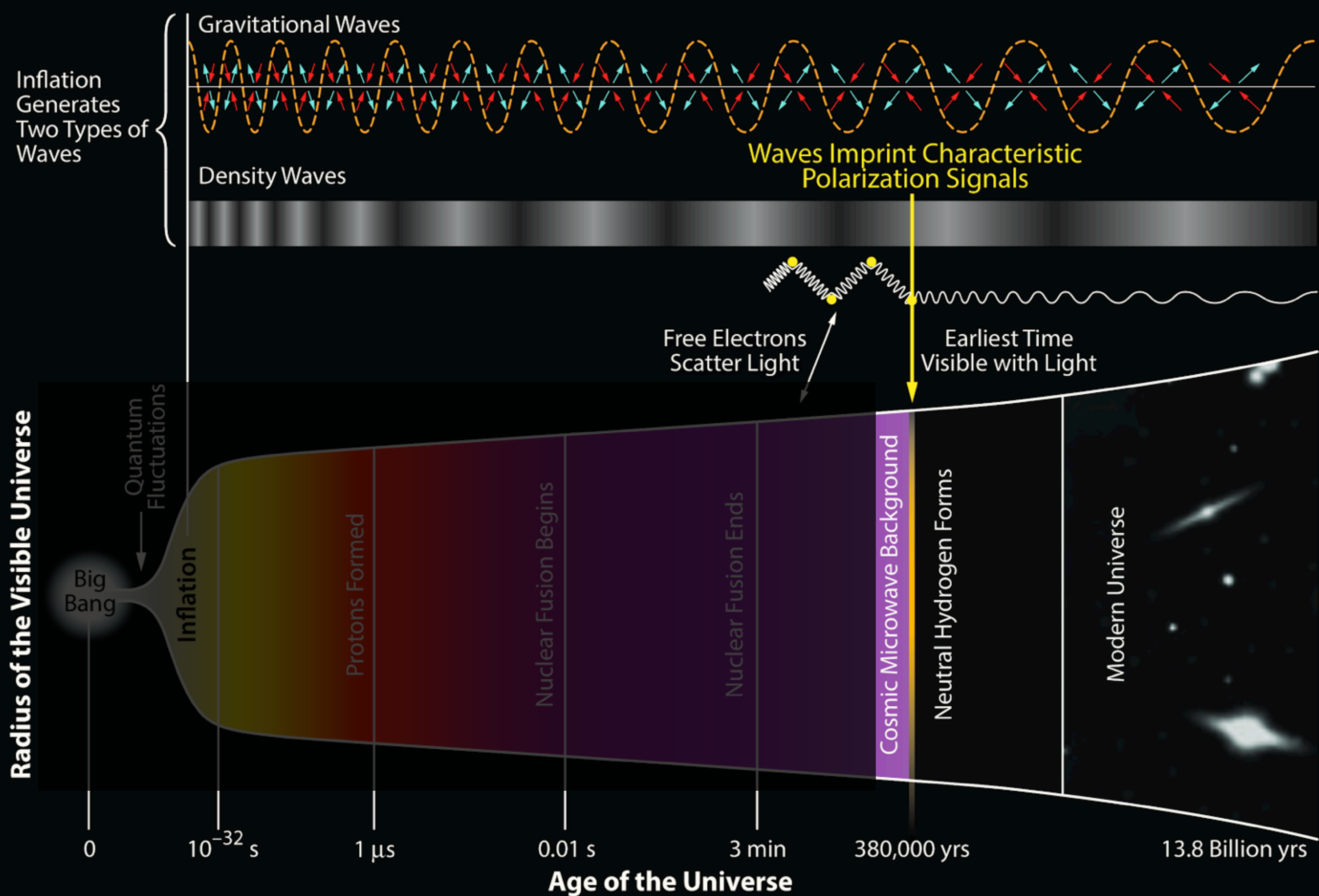

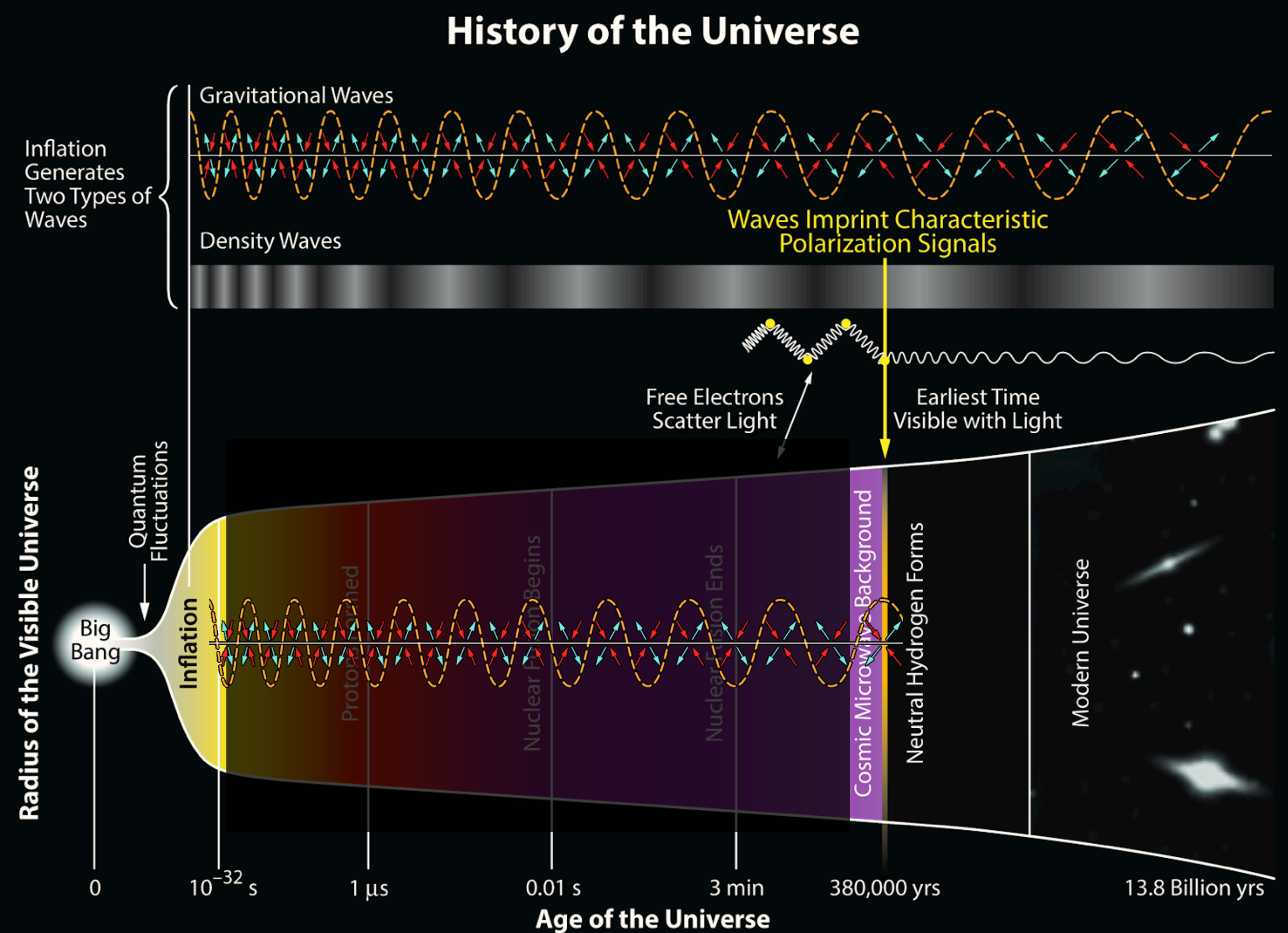
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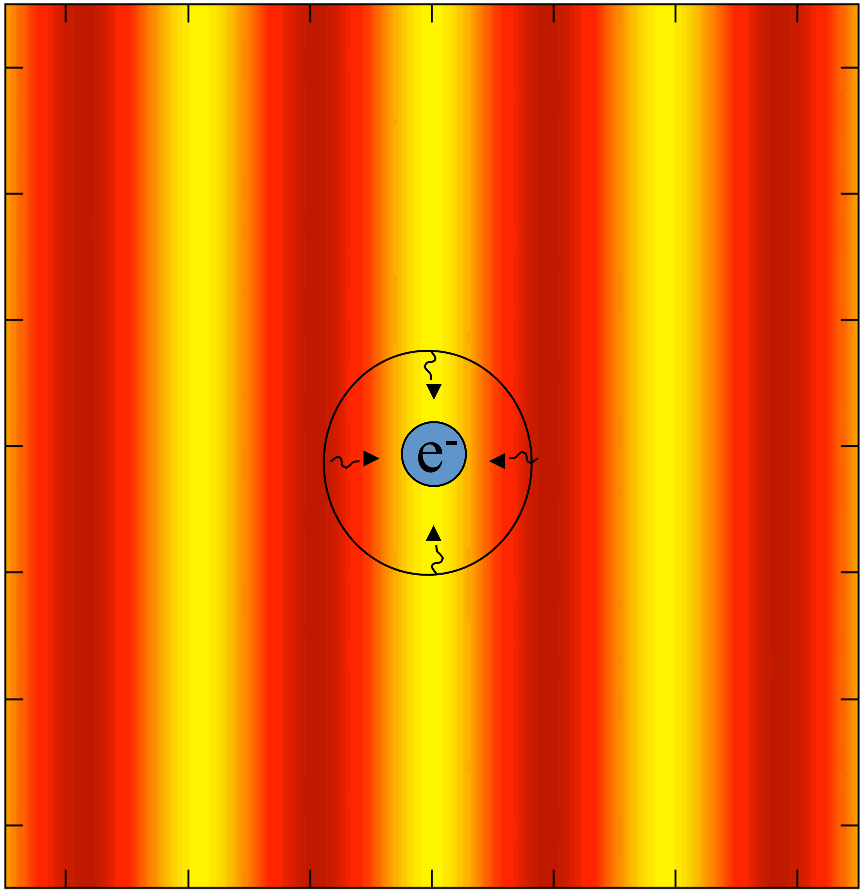
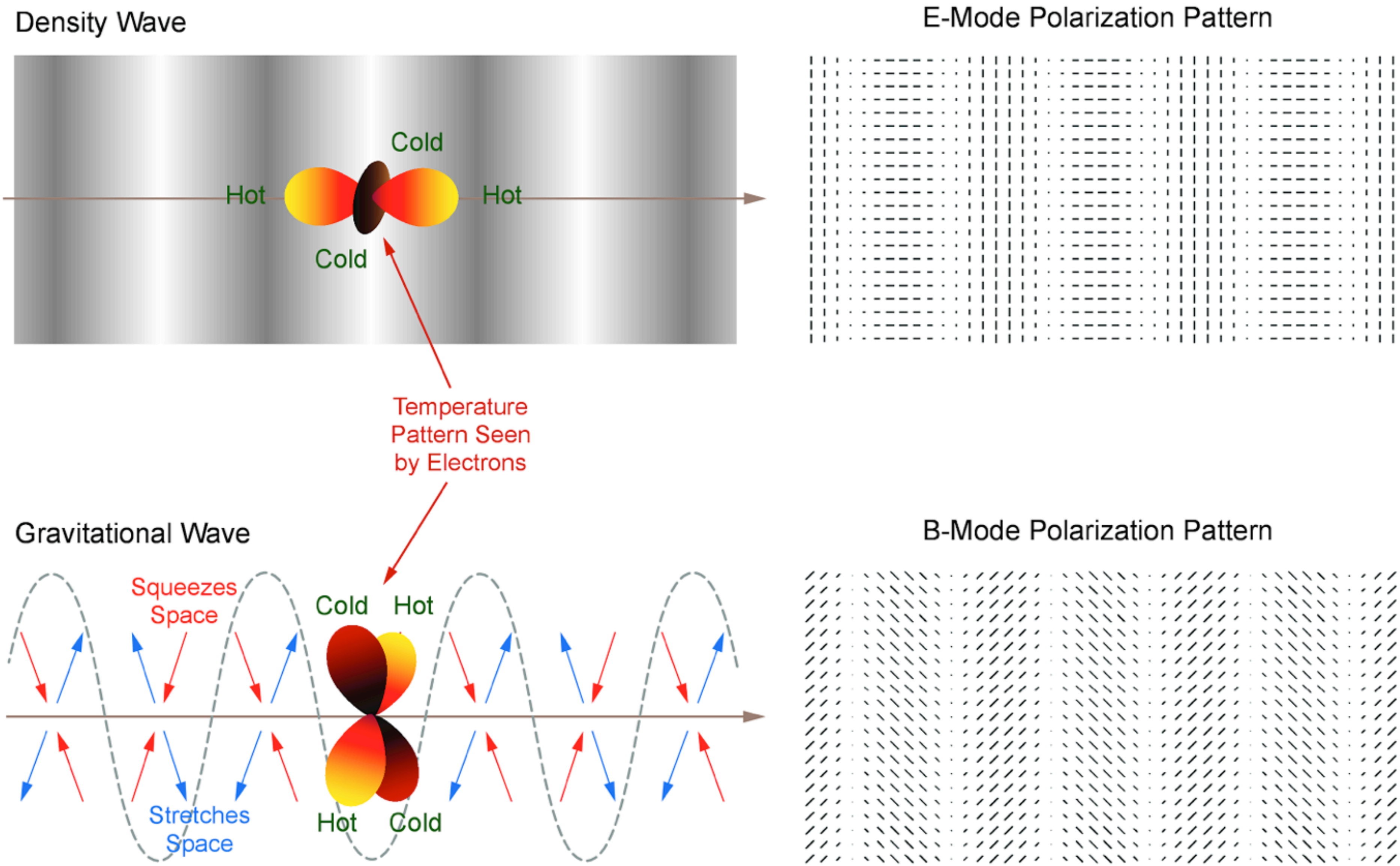
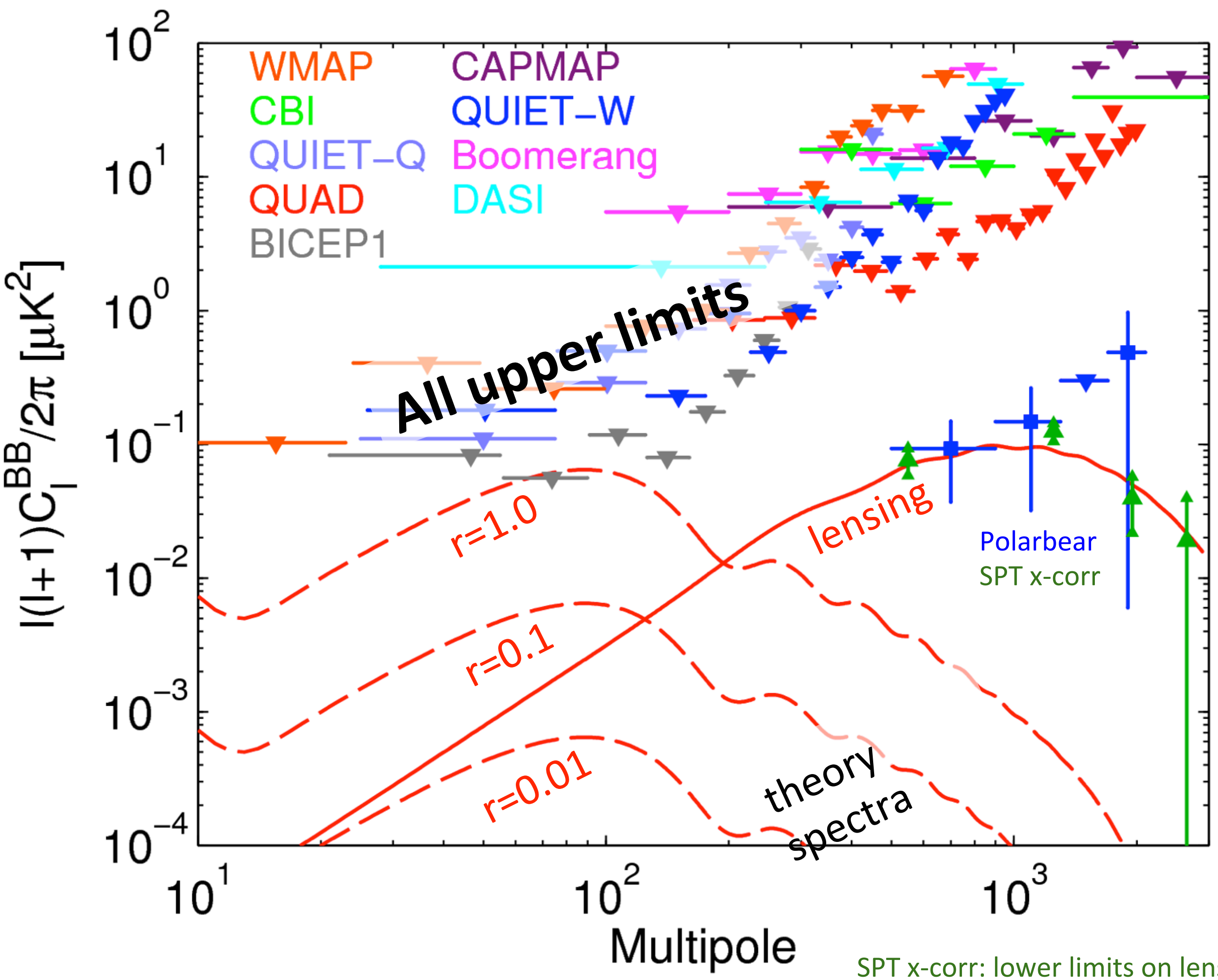
CMB polarization: scattering from sound waves



CMB polarization



Search for Inflationary B-modes



In simple inflationary gravitational wave models the

tensor-to-scalar ratio r

is the only parameter to the B-mode spectrum.

Up to now: just upper limits from searches for Inflationary B-modes

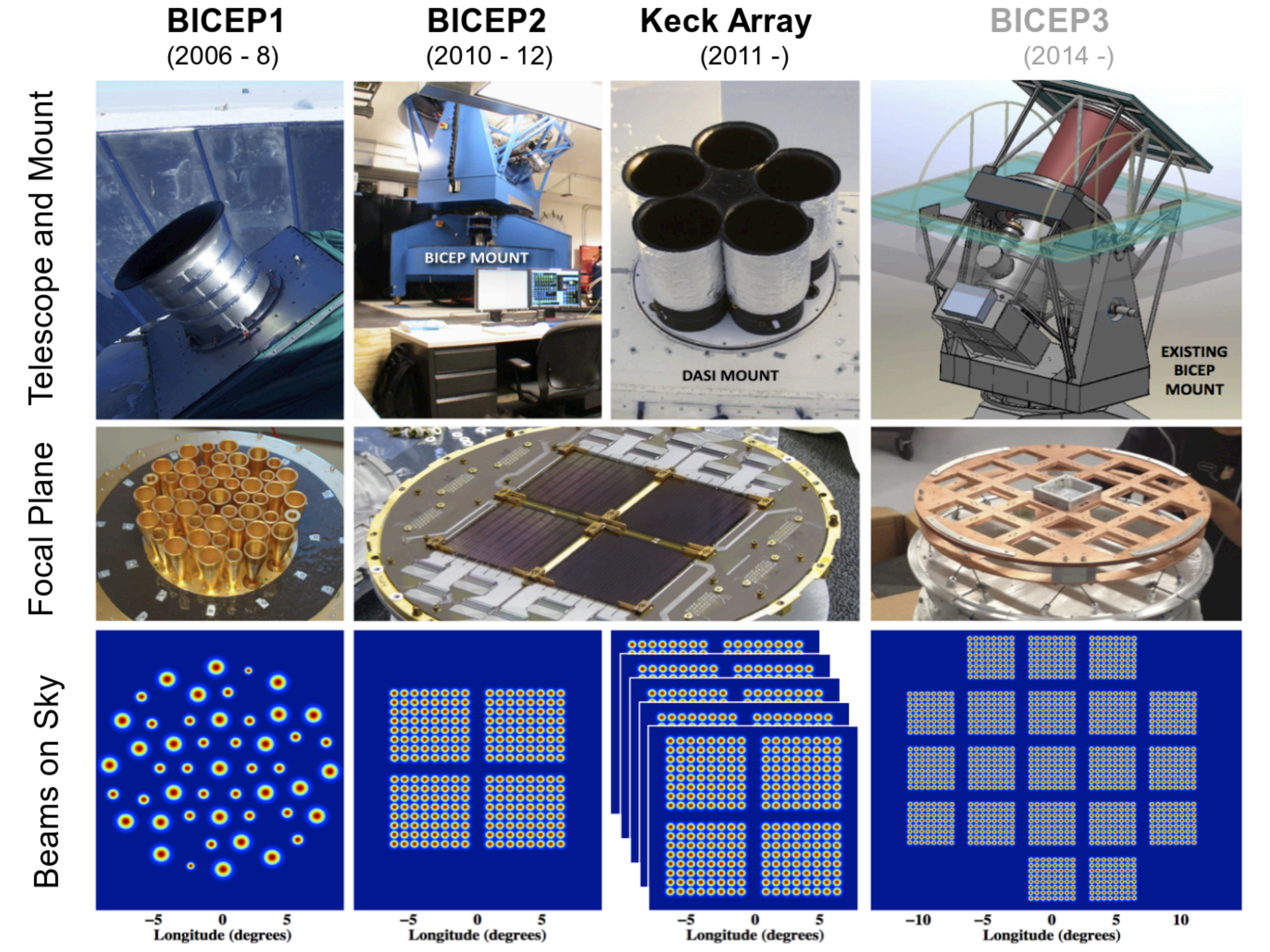
Best limit on r from BICEP1:

r < 0.7 (95% CL)

At high multipoles lensing B-mode dominant.

Slow roll inflation:
$r \approx 16\varepsilon V \approx -8n_t$

SPT x-corr: lower limits on lensing B-mode from cross correlation using the CIB



BICEP1
(2006 - 8)
BICEP2
(2010 - 12)
Keck Array
(2011 -)
BICEP3
(2014 -)
Telescope and Mount
BICEP MOUNT
DASI MOUNT
EXISTING
BICEP
MOUNT
Focal Plane
Beams on Sky
−5
0
5
Longitude (degrees)
−5
0
5
Longitude (degrees)
−5
0
5
Longitude (degrees)
−10
−5
0
5
10
Longitude (degrees)

Experimental Strategy

→ Small aperture telescope
→ Target the 2 degree peak of the B-mode
→ Integrate continuously from South Pole

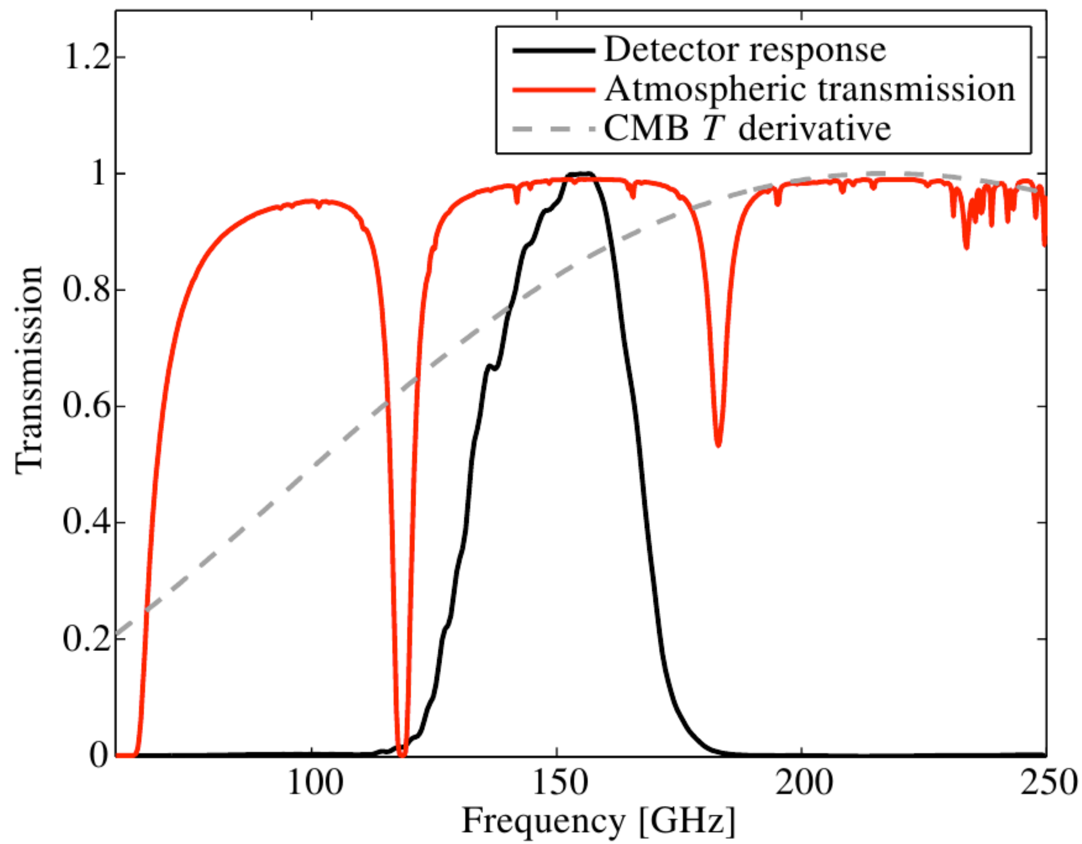
BICEP2 Frequency Response

The dry South Pole atmosphere provides excellent observing conditions most of the year.

The 28% fractional bandwidth fits within an atmospheric transmission window straddled by oxygen and water lines.

In this window, the atmosphere is transparent to microwaves.

The detector passband is defined by a filter printed directly onto the focal plane wafers.



VE RI TAS
HARVARD

CALIFORNIA INSTITUTE OF TECHNOLOGY
1891

DE LA RECHERCHE À L'INDUSTRIE
cea

UCSD

JPL

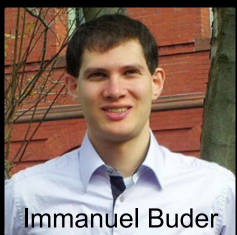
NIST

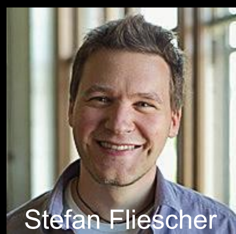
CARDIFF
UNIVERSITY

UNIVERSITY OF
TORONTO

UBC

The BICEP2 Postdocs





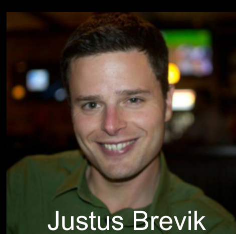
BICEP2 Winterovers

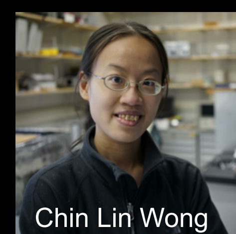
2010

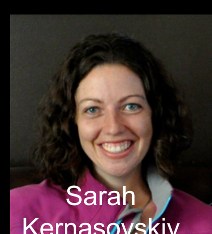
2011

2012

The BICEP2 Graduate Students





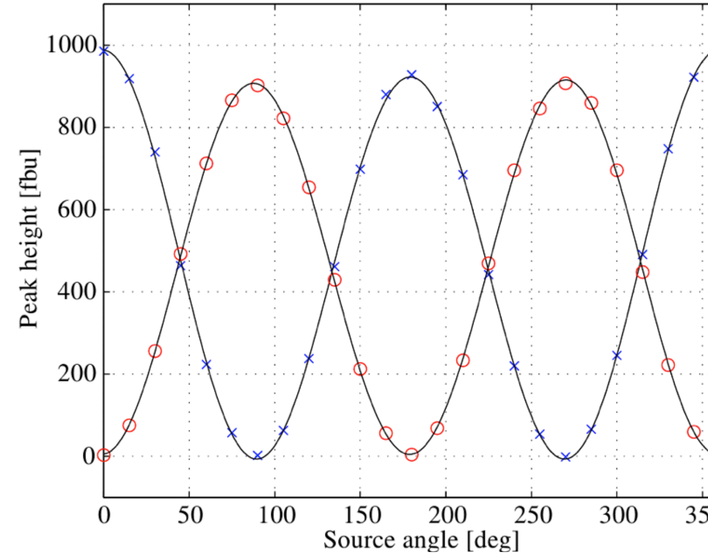


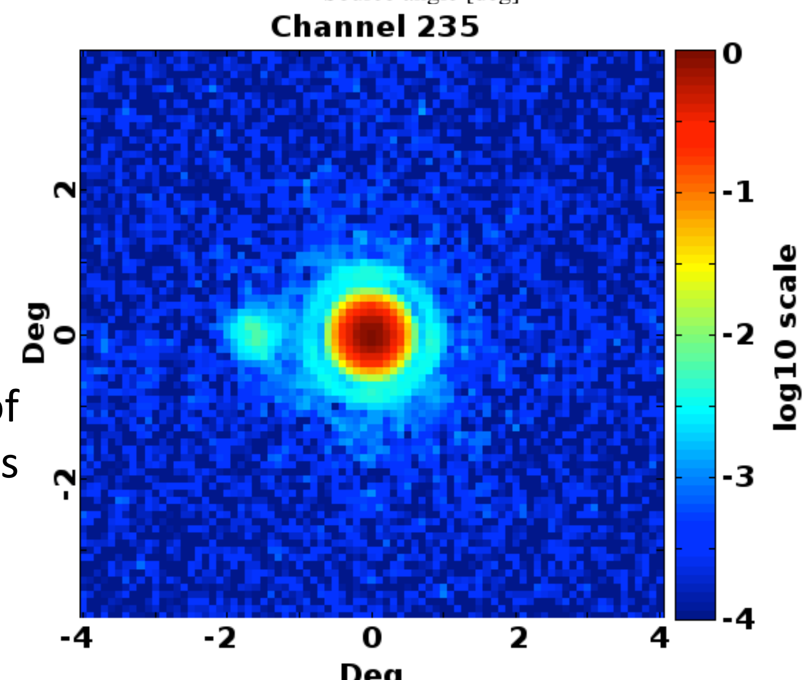
Calibration Measurements

For instance...

Far field beam mapping

Detector Polarization Calibration

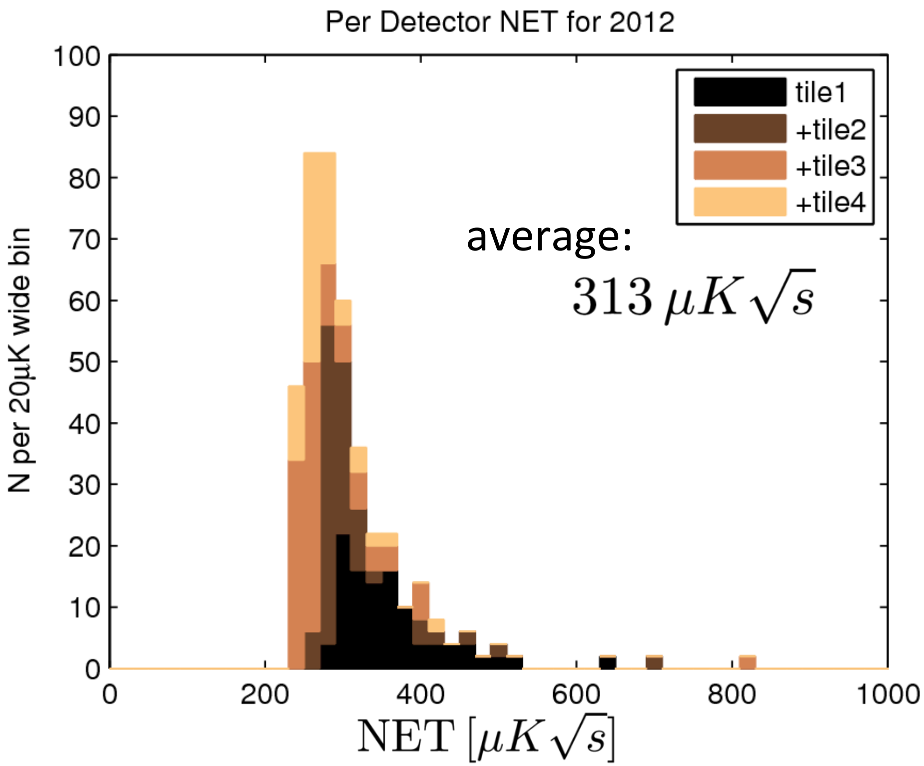




Hi-Fi beam maps of individual detectors

Detailed description in Instrument Paper, ApJ 792, 62 (2014), arXiv:1403.4302 [astro-ph.CO]

BICEP2 Sensitivity



Histogram shows per-detector noise equivalent temperature (NET) for data taken in 2012

Our recipe for high sensitivity:

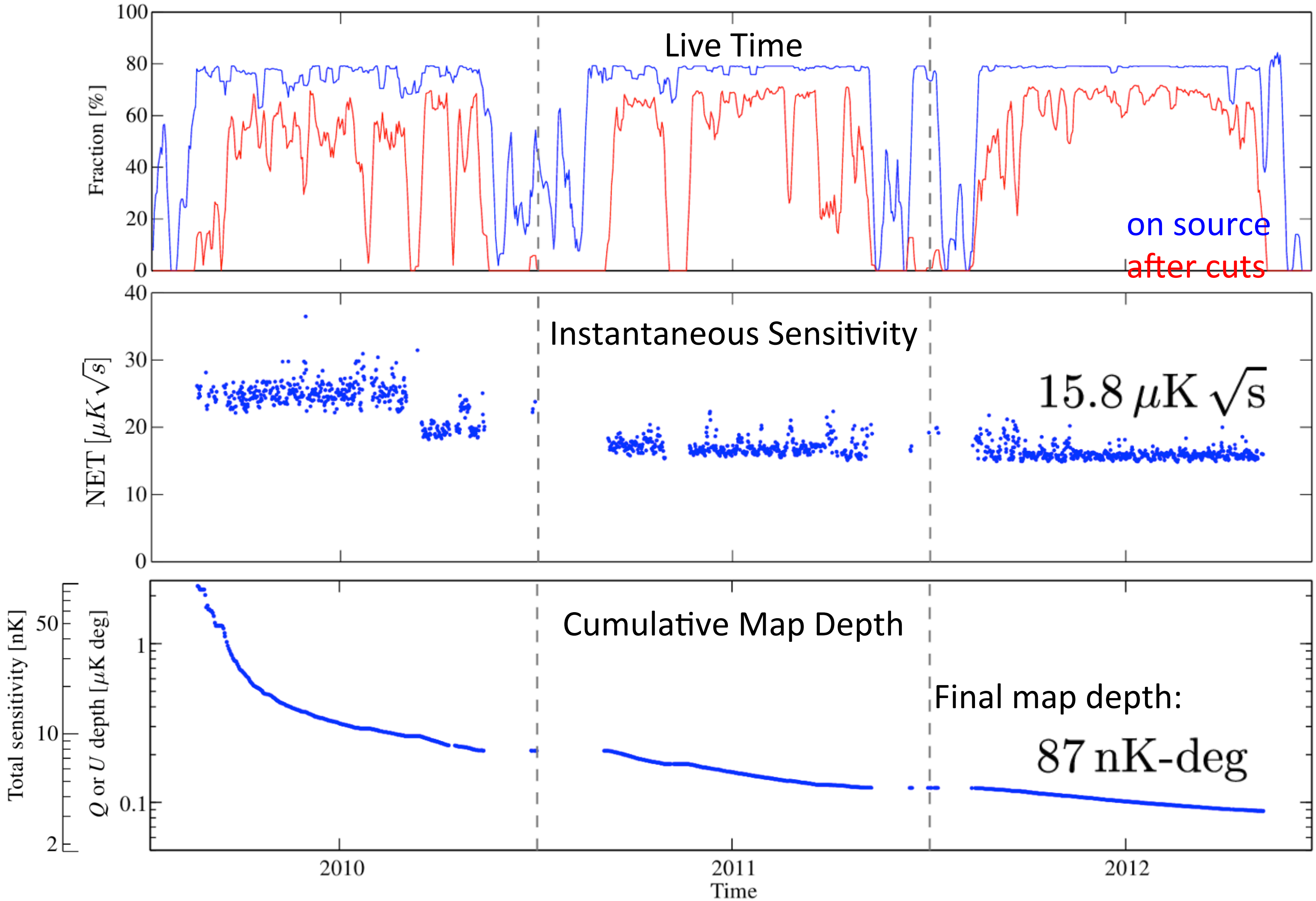
→ High optical efficiency
  40% end-to-end

→ Cold optics
  Low loading/photon noise
  Low thermal conductance, and thus low phonon noise

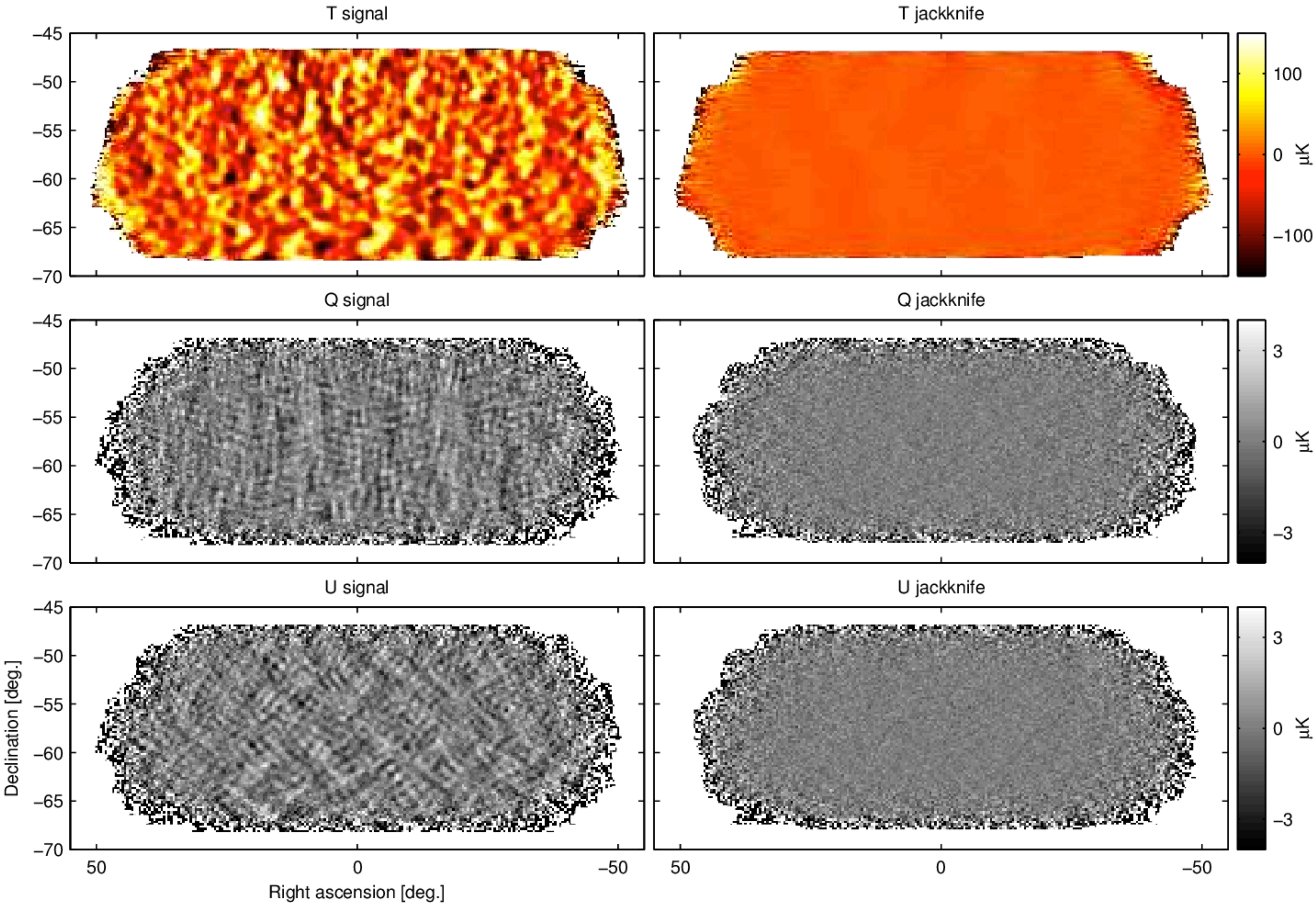
→ High detector count

Total Sensitivity for full BICEP2 instrument: $15.8\,\mu K\sqrt{s}$

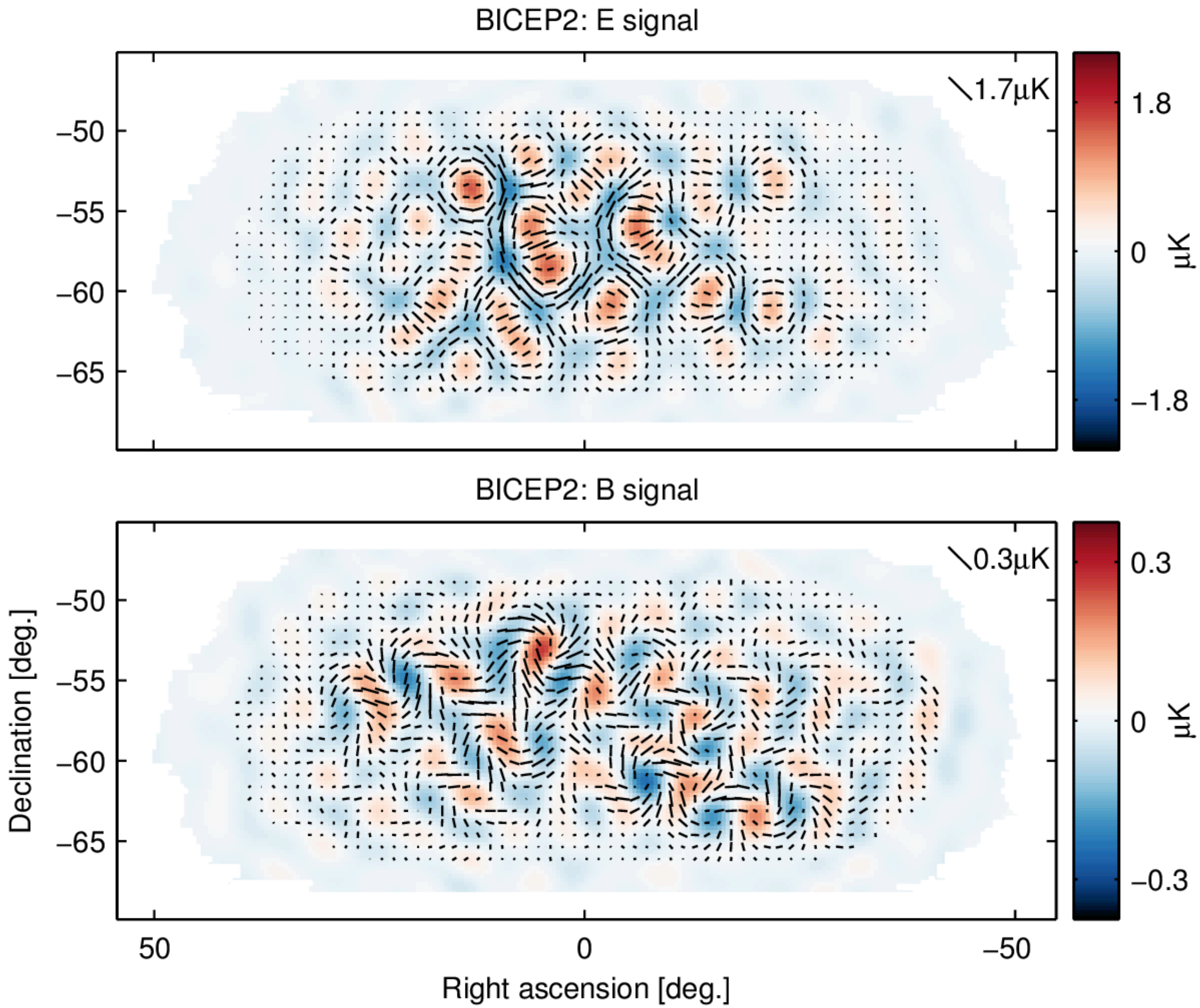
BICEP2 3-year Data Set



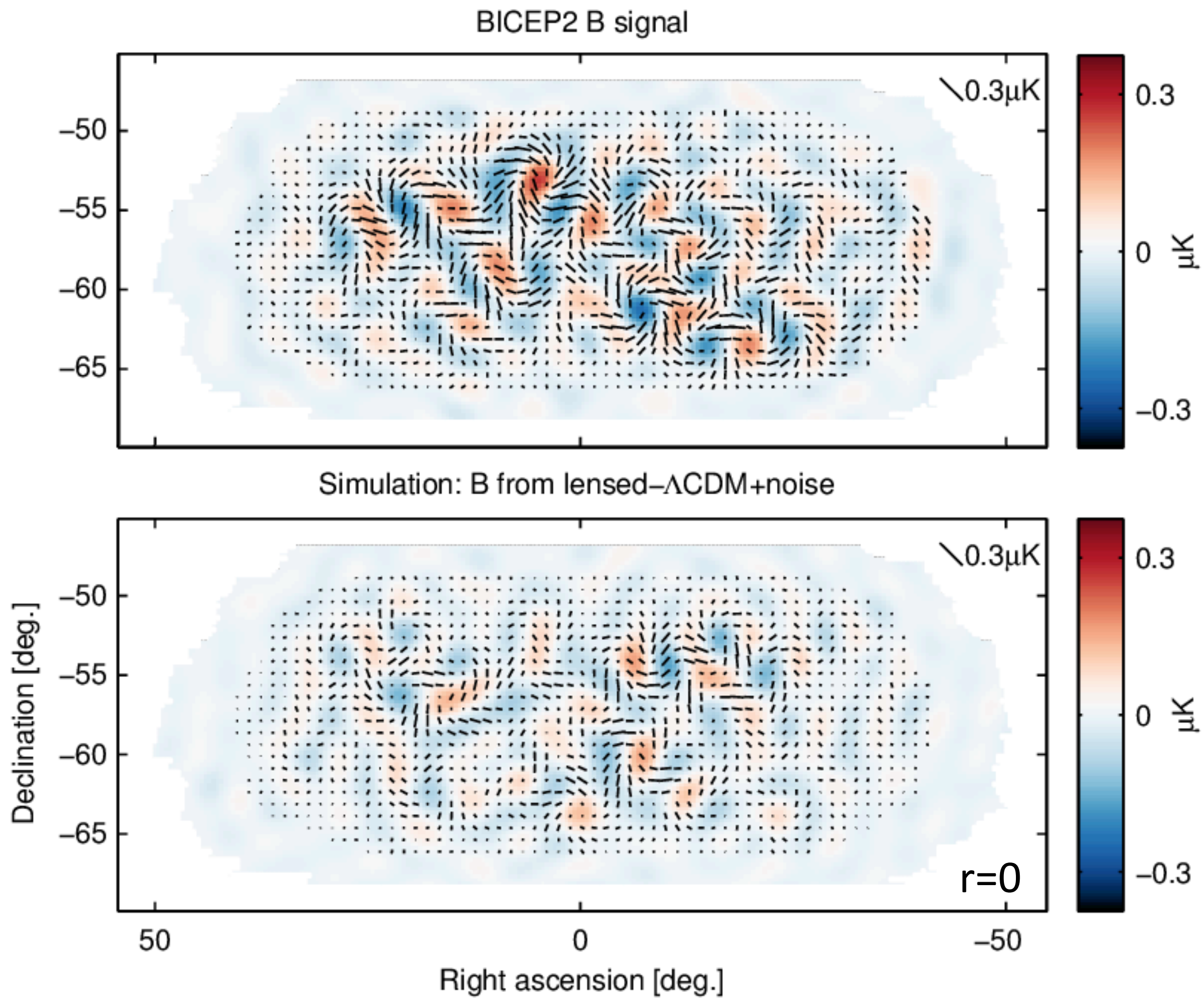
BICEP2 T and Stokes Q/U Maps



BICEP2 E- and B-mode Maps



B-mode Map vs. Simulation



Analysis calibrated by 500 lensed-ΛCDM+noise simulations.

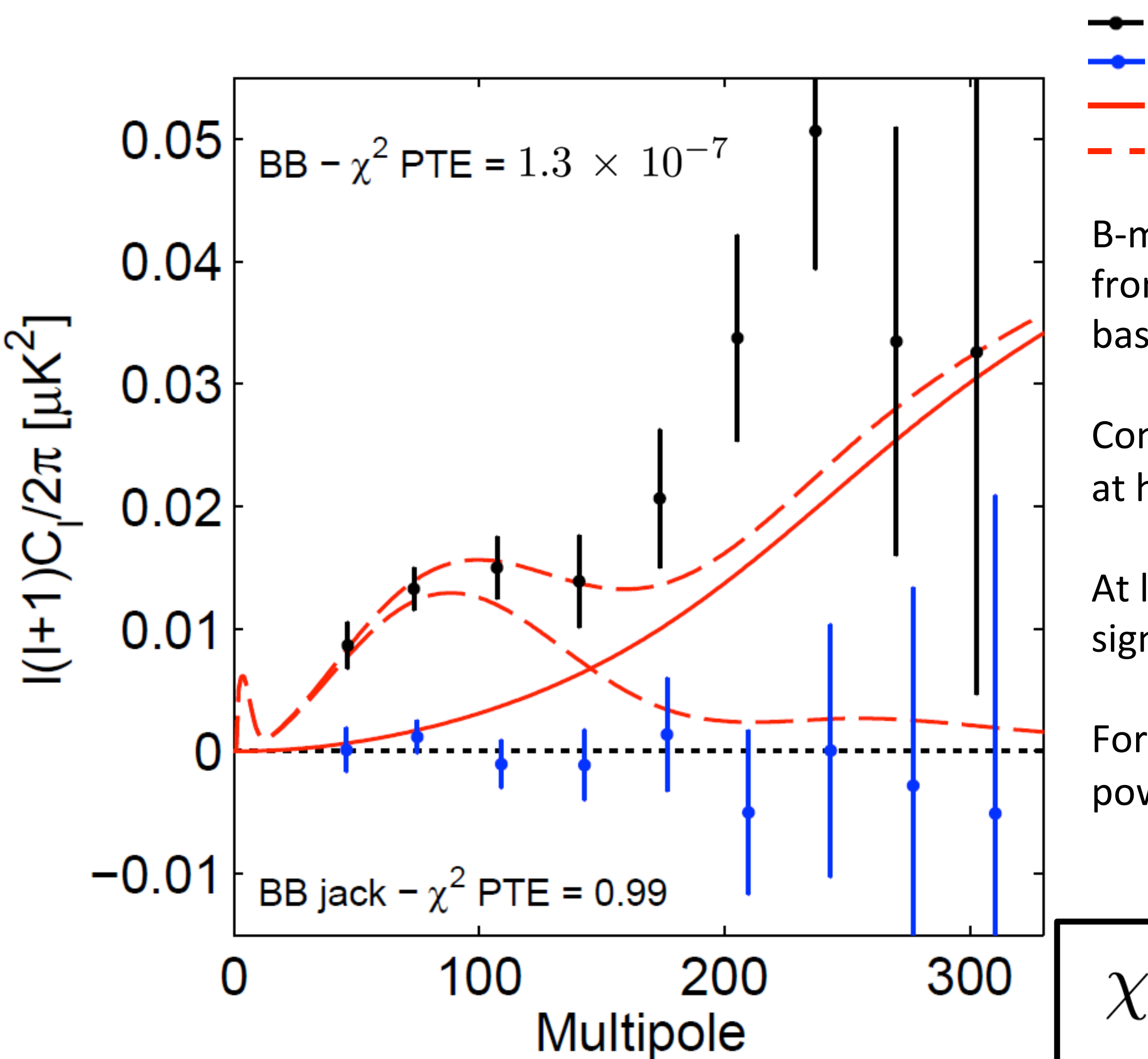
The simulations repeat the full observation at the timestream level -- including all filtering operations.

Allows us to perform arbitrary filtering operations.

The resulting removal and mixing of modes is controlled observing their impact on the distribution of simulated realizations.

From the simulations we derive the uncertainties on our measurements.

BICEP2 B-mode Power Spectrum



B-mode power spectrum estimated directly from Q&U maps, including map based "purification" to avoid E→B mixing

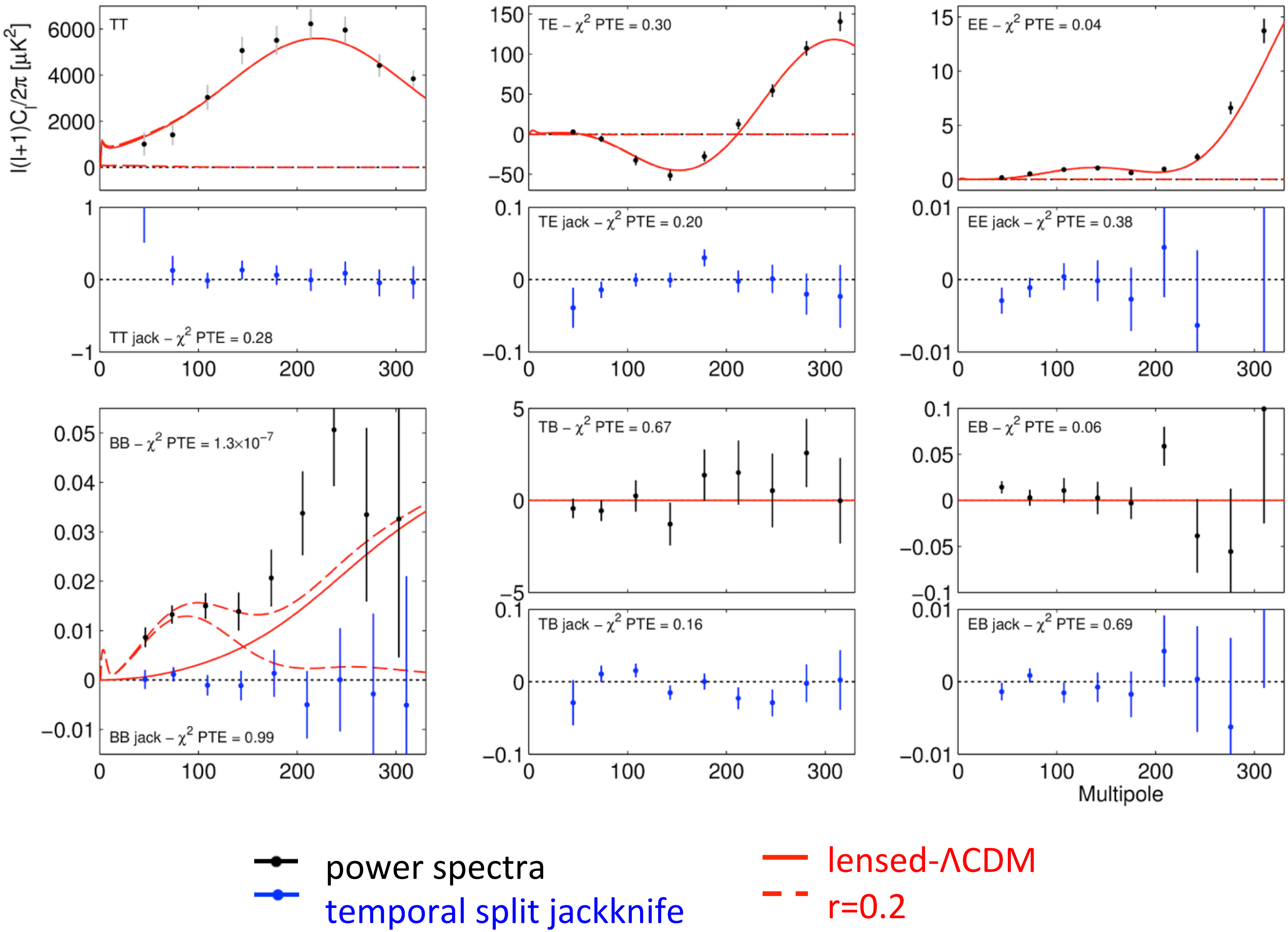
Consistent with lensing expectation at higher l.

At low l excesses over lensed-ΛCDM at high signal-to-noise.

For the hypothesis that the measured band powers come from lensed-ΛCDM we find:

χ^2 PTE	1.3×10^{-7}
significance	$5.2\,\sigma$

Temperature and Polarization Spectra



Check Systematics: Jackknifes

TABLE 1
JACKKNIFE PTE VALUES FROM χ^2 AND χ (SUM-OF-DEVIATION) TESTS

Jackknife	Bandpowers 1–5 χ^2	Bandpowers 1–9 χ^2	Bandpowers 1–5 χ	Bandpowers 1–9 χ
Deck jackknife				
EE	0.046	0.030	0.164	0.299
BB	0.774	0.329	0.240	0.082
EB	0.337	0.643	0.204	0.267
Scan Dir jackknife				
EE	0.483	0.762	0.978	0.938
BB	0.531	0.573	0.896	0.551
EB	0.898	0.806	0.725	0.890
Tag Split jackknife				
EE	0.541	0.377	0.916	0.938
BB	0.902	0.992	0.449	0.585
EB	0.477	0.689	0.856	0.615
Tile jackknife				
EE	0.004	0.010	0.000	0.002
BB	0.794	0.752	0.565	0.331
EB	0.172	0.419	0.962	0.790
Phase jackknife				
EE	0.673	0.409	0.126	0.339
BB	0.591	0.739	0.842	0.944
EB	0.529	0.577	0.840	0.659
Mux Col jackknife				
EE	0.812	0.587	0.196	0.204
BB	0.826	0.972	0.293	0.283
EB	0.866	0.968	0.876	0.697
Alt Deck jackknife				
EE	0.004	0.004	0.070	0.236
BB	0.397	0.176	0.381	0.086
EB	0.150	0.060	0.170	0.291
Mux Row jackknife				
EE	0.052	0.178	0.653	0.739
BB	0.345	0.361	0.032	0.008
EB	0.529	0.226	0.024	0.048
Tile/Deck jackknife				
EE	0.048	0.088	0.144	0.132
BB	0.908	0.840	0.629	0.269
EB	0.050	0.154	0.591	0.591
Focal Plane inner/outer jackknife				
EE	0.230	0.597	0.022	0.090
BB	0.216	0.531	0.046	0.092
EB	0.036	0.042	0.850	0.838
Tile top/bottom jackknife				
EE	0.289	0.347	0.459	0.599
BB	0.293	0.236	0.154	0.028
EB	0.545	0.683	0.902	0.932
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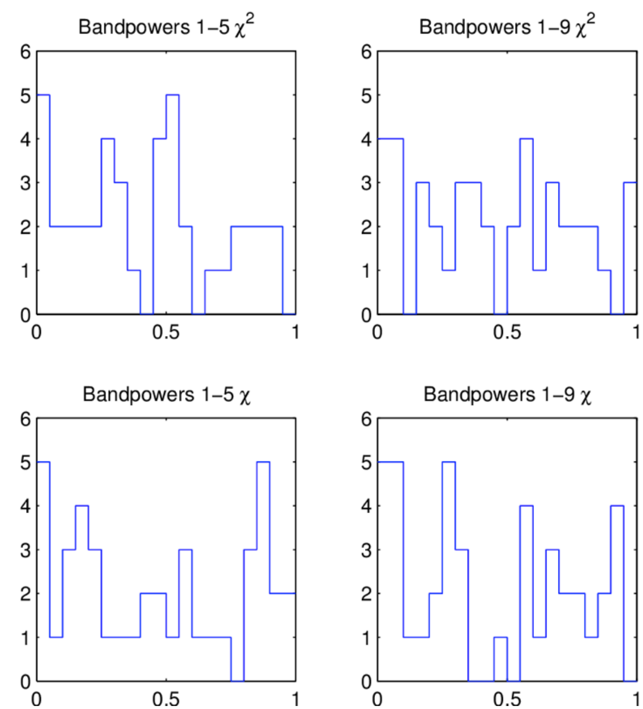
EE	0.727	0.533	0.128	0.485
BB	0.255	0.086	0.421	0.036
EB	0.465	0.737	0.208	0.168
Moon jackknife				
EE	0.499	0.689	0.481	0.679
BB	0.144	0.287	0.898	0.858
EB	0.289	0.359	0.531	0.307
A/B offset best/worst				
EE	0.317	0.311	0.868	0.709
BB	0.114	0.064	0.307	0.094
EB	0.589	0.872	0.599	0.790

14 jackknife tests applied to 3 spectra, 4 statistics

All 4 statistics defined from the jackknife tests result in uniform probability to exceed (PTE) distributions:



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Splits the 4 boresight rotations

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

Splits by time

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

Splits by channel selection

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

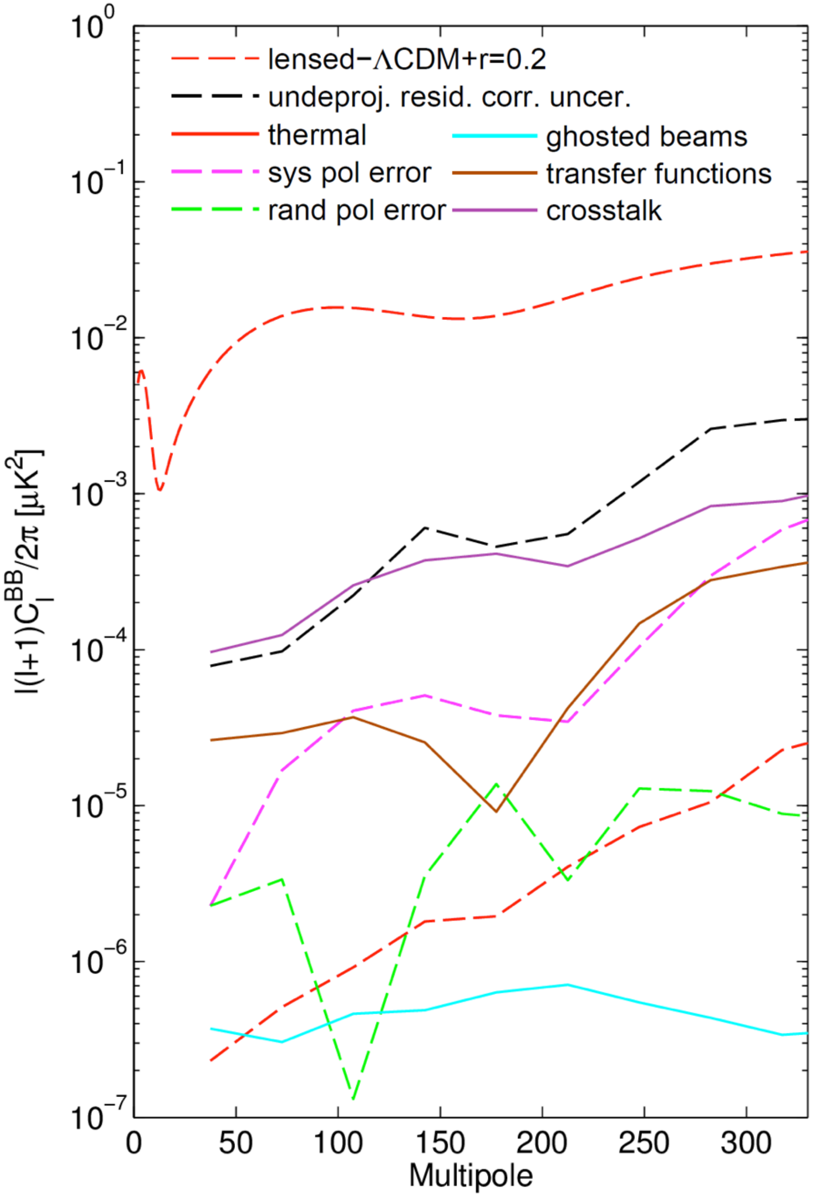
Splits by possible external contamination

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

Splits to check intrinsic detector properties

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

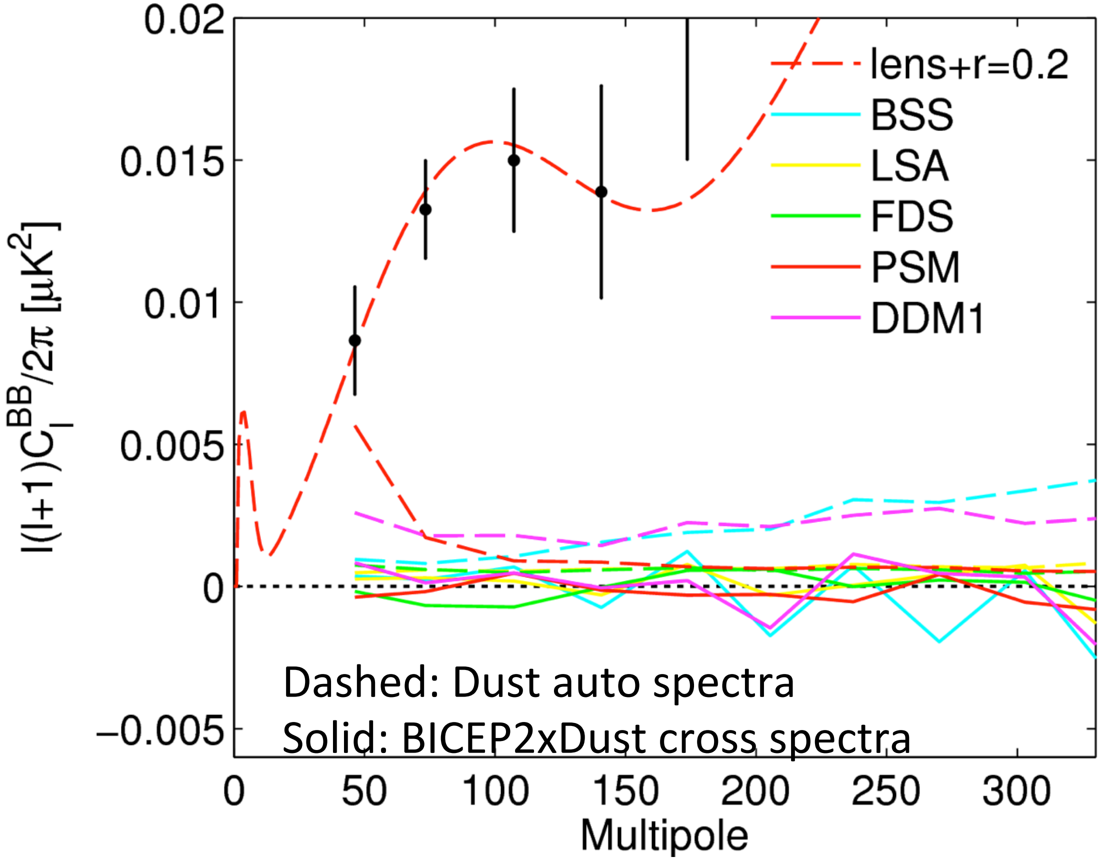
Systematics beyond Beam imperfections

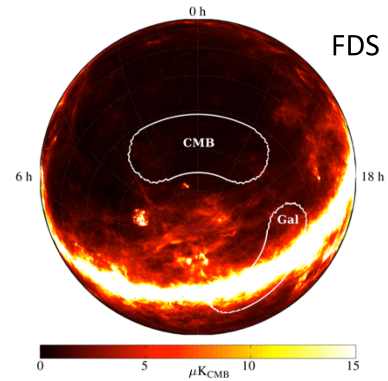


All systematic effects that we could imagine were investigated!

We find with high confidence that the apparent signal *cannot be explained* by instrumental systematics

Polarized Dust Foreground Projections





The BICEP2 region was chosen to on the basis of extremely low unpolarized dust power.

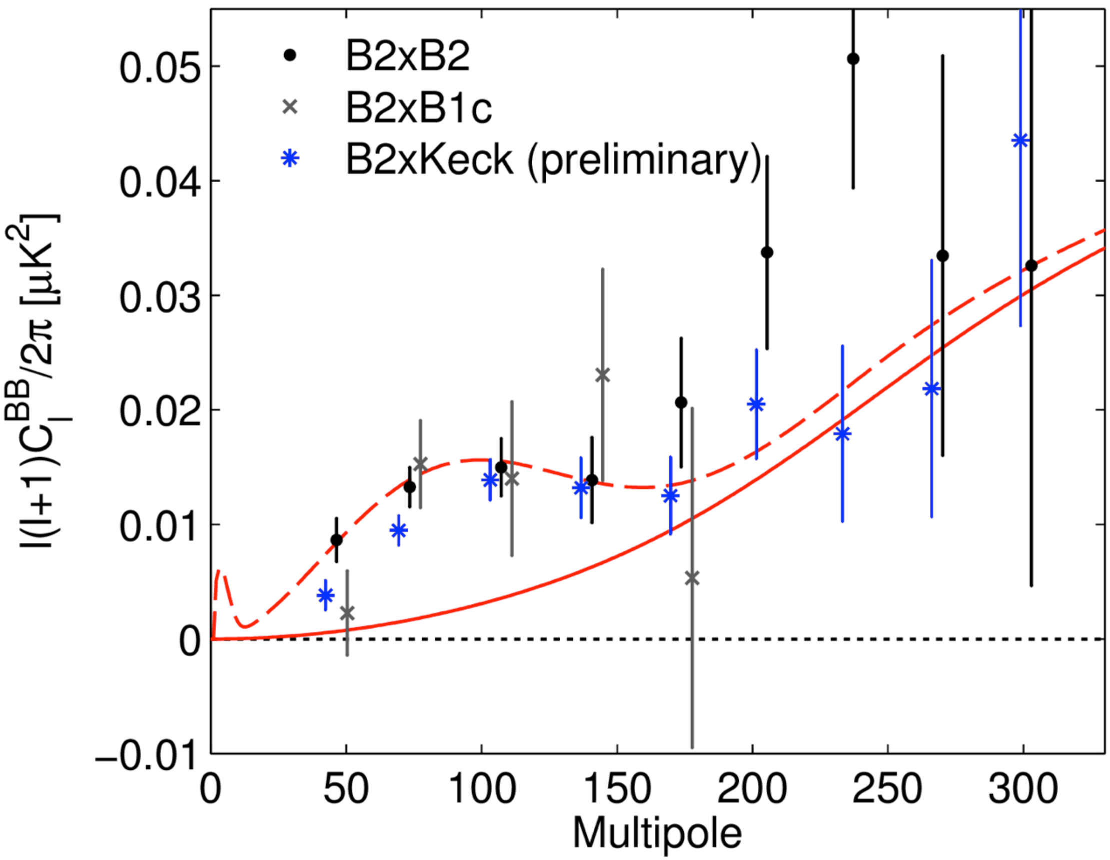
Use various models of polarized dust emission to estimate dust power.

Result: All dust auto spectra well below observed signal level. (and cross spectra consistent with zero.)

But considerable uncertainty remains...

Additional Cross Spectra

Form cross spectrum between BICEP2 and BICEP1 combined (100 + 150 GHz):

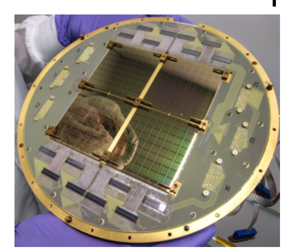


BICEP2 auto spectrum compatible with B2xB1c cross spectrum

~3σ evidence of excess power in the cross spectrum

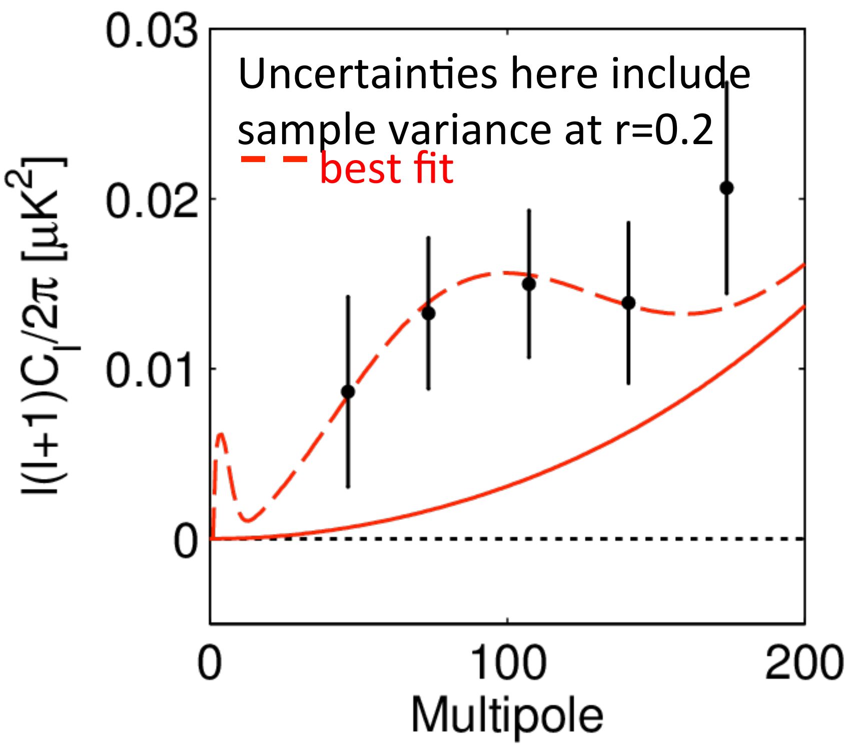
Additionally form cross spectrum with 2 years of data from *Keck Array*, the successor to BICEP2

Excess power is also evident in the B2xKeck cross spectrum



Cross spectra:
Powerful additional evidence against a systematic origin of the apparent signal

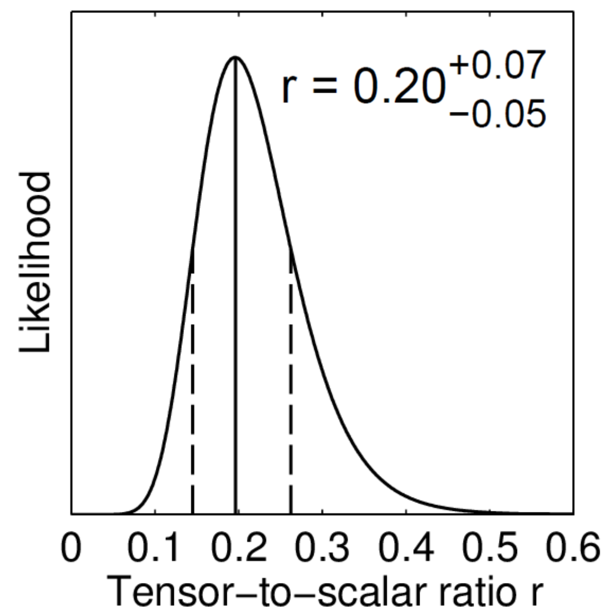
Constraint on Tensor-to-scalar Ratio r



Substantial excess power in the region where the inflationary gravitational wave signal is expected to peak

Find the most likely value of the tensor-to-scalar ratio r

Apply "direct likelihood" method, uses:
→ lensed-ΛCDM + noise simulations
→ weighted version of the 5 bandpowers
→ B-mode sims scaled to various levels of r (n_T=0)



Within this simplistic model we find:

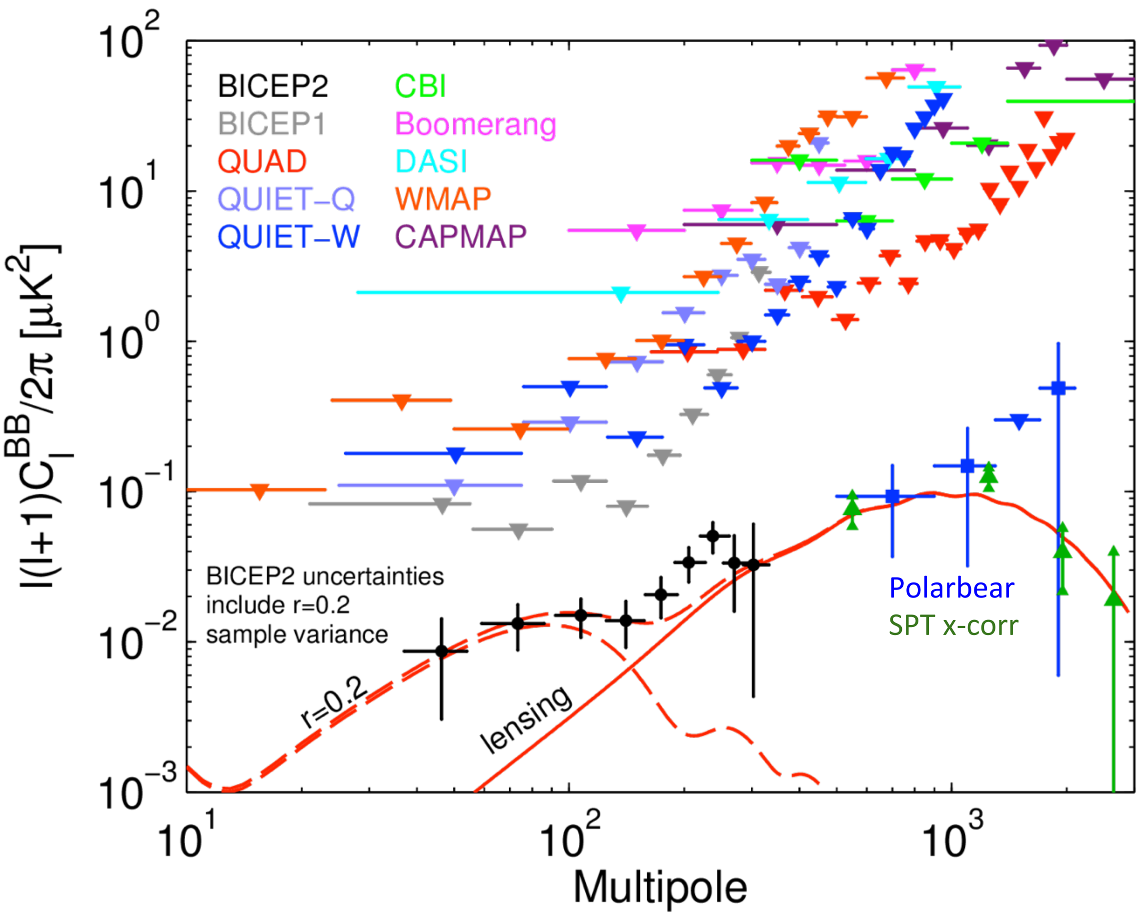
r = 0.2 with uncertainties dominated by sample variance

PTE of fit to data: 0.9
→ model is perfectly acceptable fit to the data

r=0 ruled out at 7.0σ

Conclusions

BICEP2 and upper limits from other experiments:



http://bicepkeck.org

Most sensitive CMB polarization maps ever made

Power spectra perfectly consistent with lensed-ΛCDM except:
5.2σ excess in the B-mode spectrum at low multipoles!

Extensive studies and jackknife test strongly argue against systematics as the origin

Foregrounds do not appear to be a large fraction of the signal:

→ foreground projections
→ lack of cross correlations
→ CMB-like spectral index
→ shape of the B-mode spectrum

Constraint on tensor-to-scalar ratio r in simple inflationary gravitational wave model:

$$r = 0.20^{+0.07}_{-0.05}$$

Since March 17…

- Intense media and science community interest…
- Early instrumental & stat queries… mostly seem to have faded
- Concerns seem to have boiled down to:

  Polarized dust foreground may be stronger than previously projected…

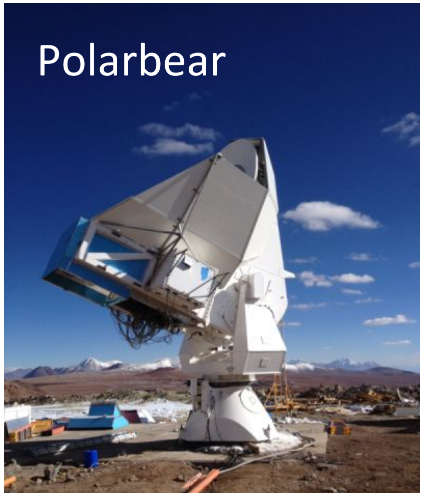
- In May, four new papers on dust polarization have appeared from Planck
  - They mask out low foreground regions like ours

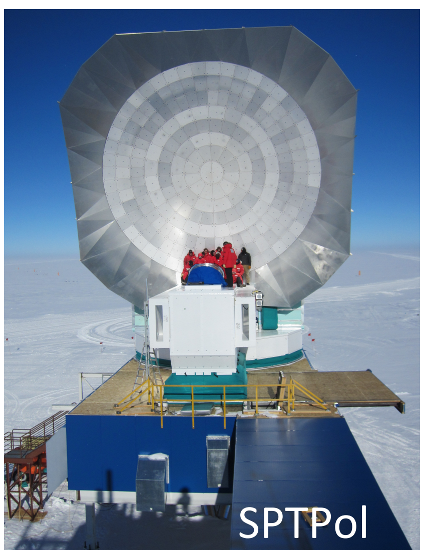
    (due to "non small systematics and not dust dominated")
  - Trend to higher polarization in low dust regions. 4% mode, but > 10% in some regions
- BICEP2 paper published in PRL in June (with some mods in response to ref comments)
  - B-mode detection + analysis are secure.
  - Uncertainty on interpretation has increased. "Could it be dust?
  - BICEP1 + BICEP2 internal constraints are not statistically strong. Dust models may not be reliable.
  - Getting new data more important than ever.
- Joint analysis underway with Planck, combining maps to cross spectra

  → Most powerful way to overcome limitations of noise/systematics

  in Planck maps of polarized dust in our region.

Coming soon





Many experiments making rapid progress!

- SPTpol has data in the can over same sky patch at 100 and 150 GHz
  - Should be able to see signal alone and/or in cross correlation with BICEP2/Keck – analysis started
- Polarbear, ACTpol have exciting results – pushing toward degree-scales

- ABS running, CLASS soon…

- Balloons:
  - EBEX has data in the can (220?
  - Spider will fly later this year.
  - PIPER will fly sometime soon.

Coming soon...

- Keck 2014 is running right now with 2 receivers at 100GHz
  - Sensitivity of BICEP1 already surpassed, soon will **tighten foreground constraint**
  - **BICEP3** deploys in 3 months, doubles Keck's power, all at 100 GHz

- Planck will weigh in soon
  - Hints of higher dust, but limited by noise/systematics
  - Joint BICEP2 + Planck map-based analysis should offer best constraints

- Ground + balloon efforts are moving VERY FAST!
  - SPTpol, Polarbear, ACTpol, ABS, Spider, EBEX, CLASS, PIPER...

- Most powerful way to advance the science **is more data, all used together**.