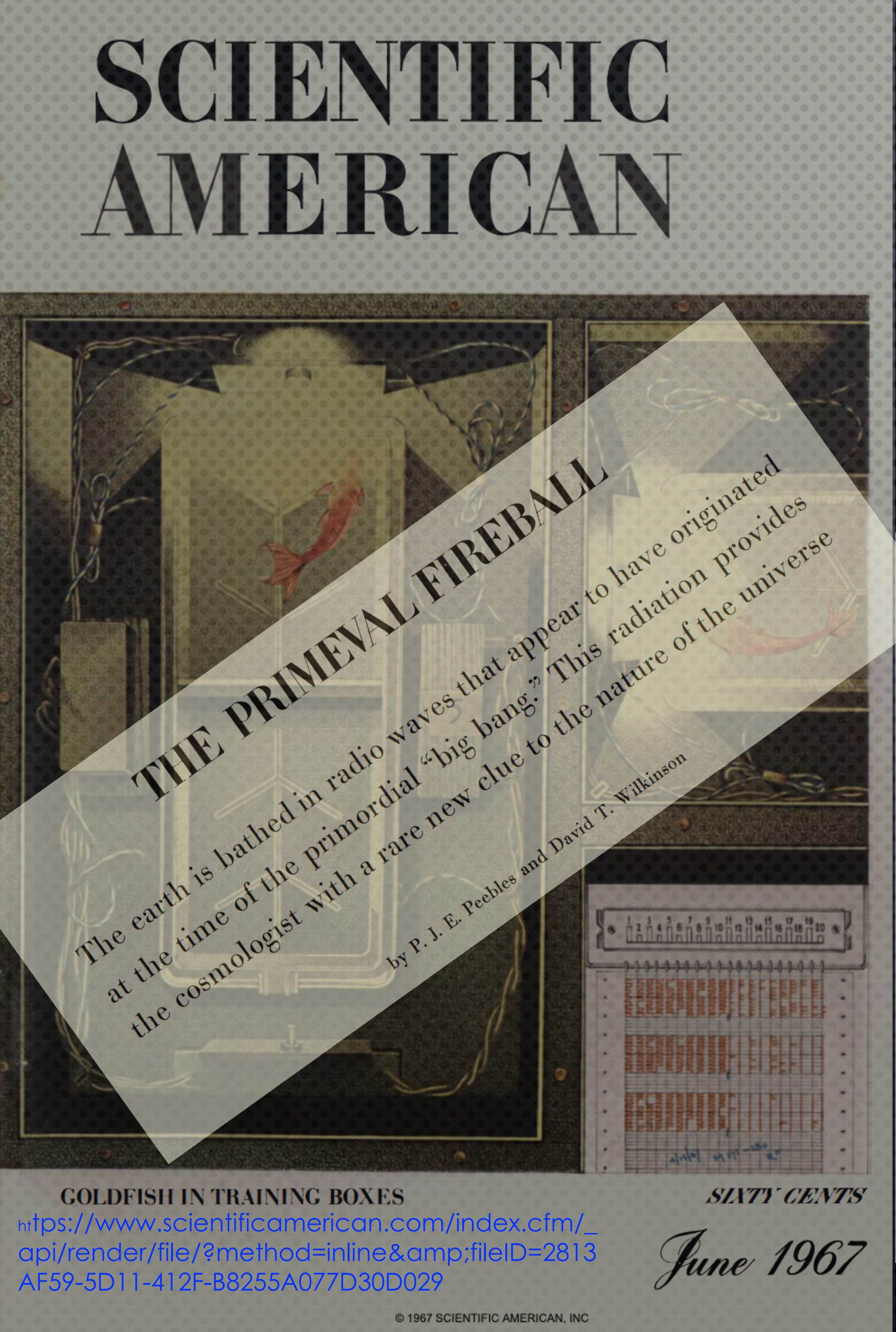
⟨Quantum|Gravity⟩Society

Primodial Gravitation Waves and the CMB

Suzanne Staggs


SCIENTIFIC AMERICAN

THE PRIMEVAL FIREBALL

The earth is bathed in radio waves that appear to have originated at the time of the primordial "big bang." This radiation provides the cosmologist with a rare new clue to the nature of the universe

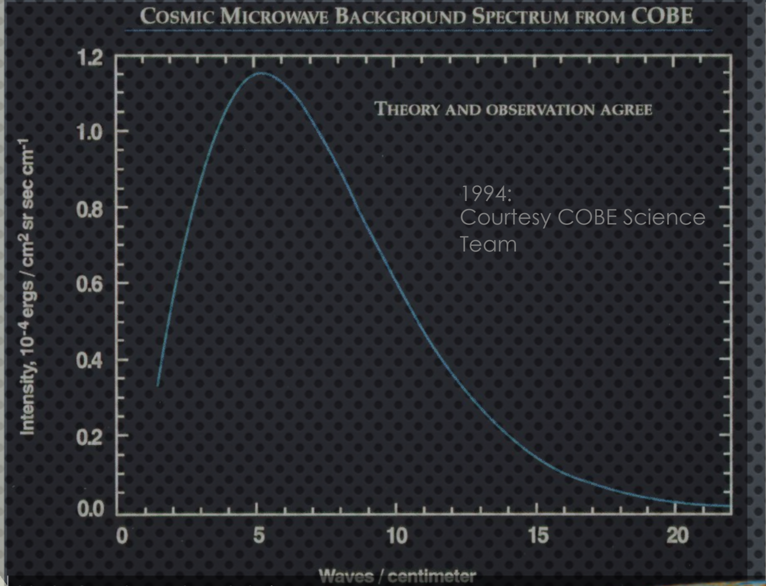
by P. J. E. Peebles and David T. Wilkinson

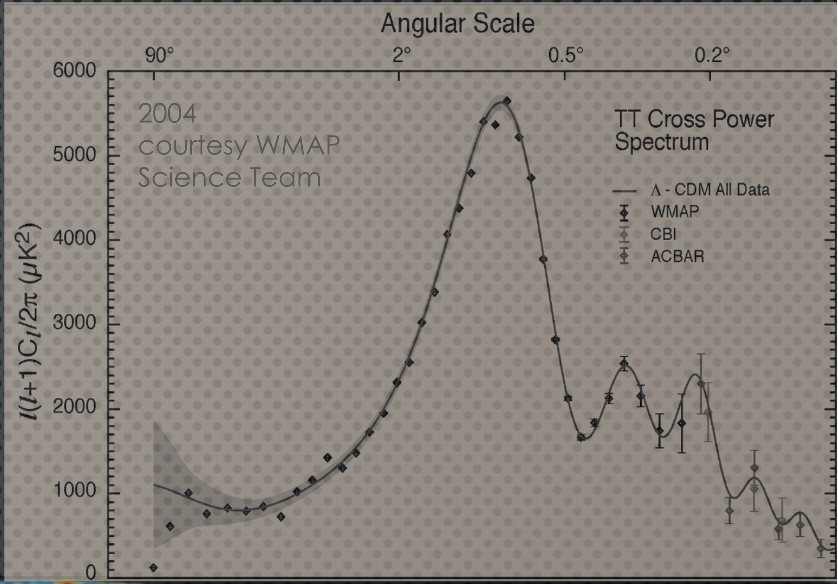
GOLDFISH IN TRAINING BOXES

SIXTY CENTS

June 1967

https://www.scientificamerican.com/index.cfm/_api/render/file/?method=inline&fileID=2813AF59-5D11-412F-B8255A077D30D029





2013: Courtesy Planck Science Team

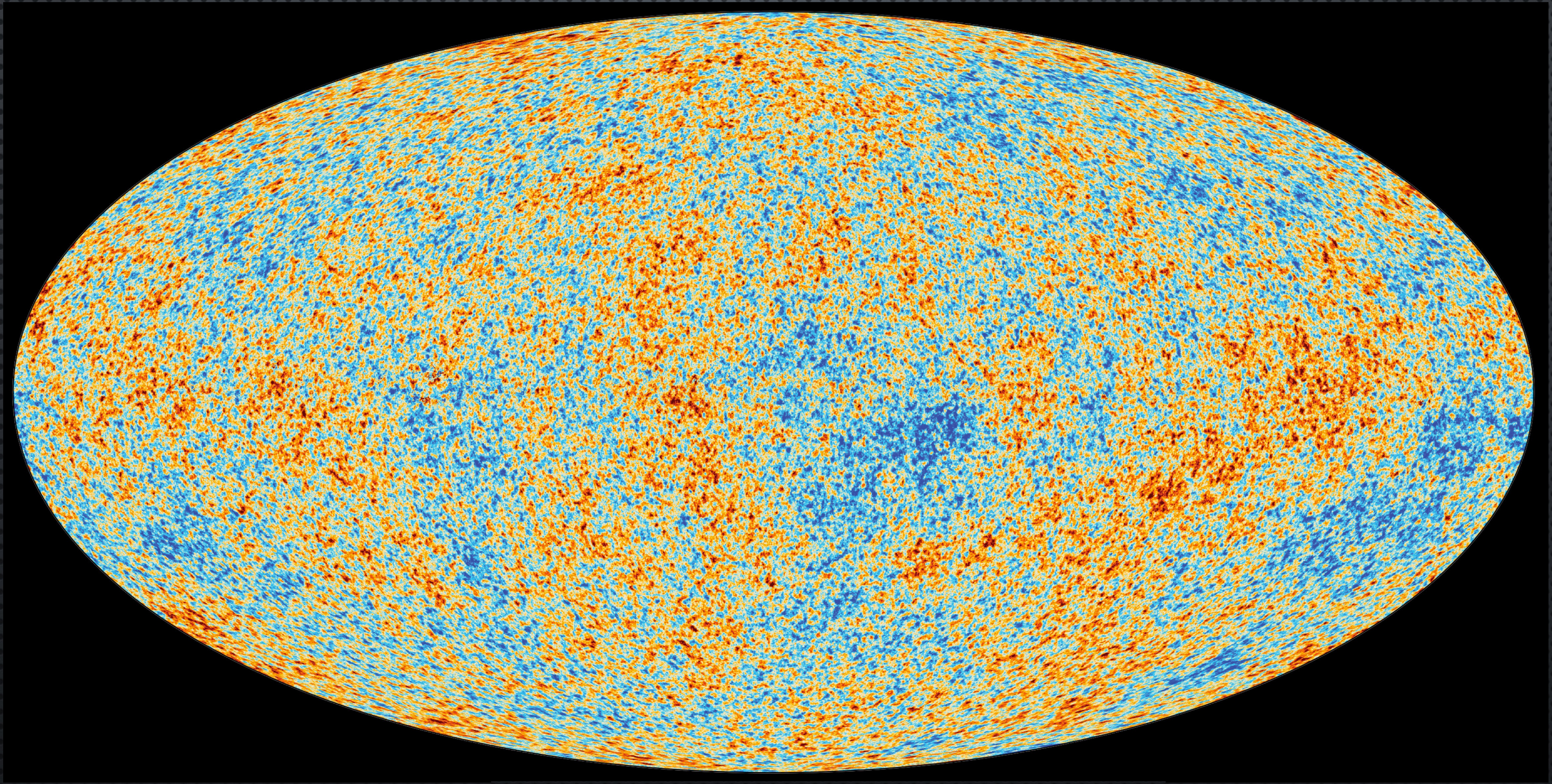
PRIMORDIAL GRAVITATIONAL WAVES AND THE CMB

Suzanne Staggs

17 Aug 2022

Quantum Gravity Conference

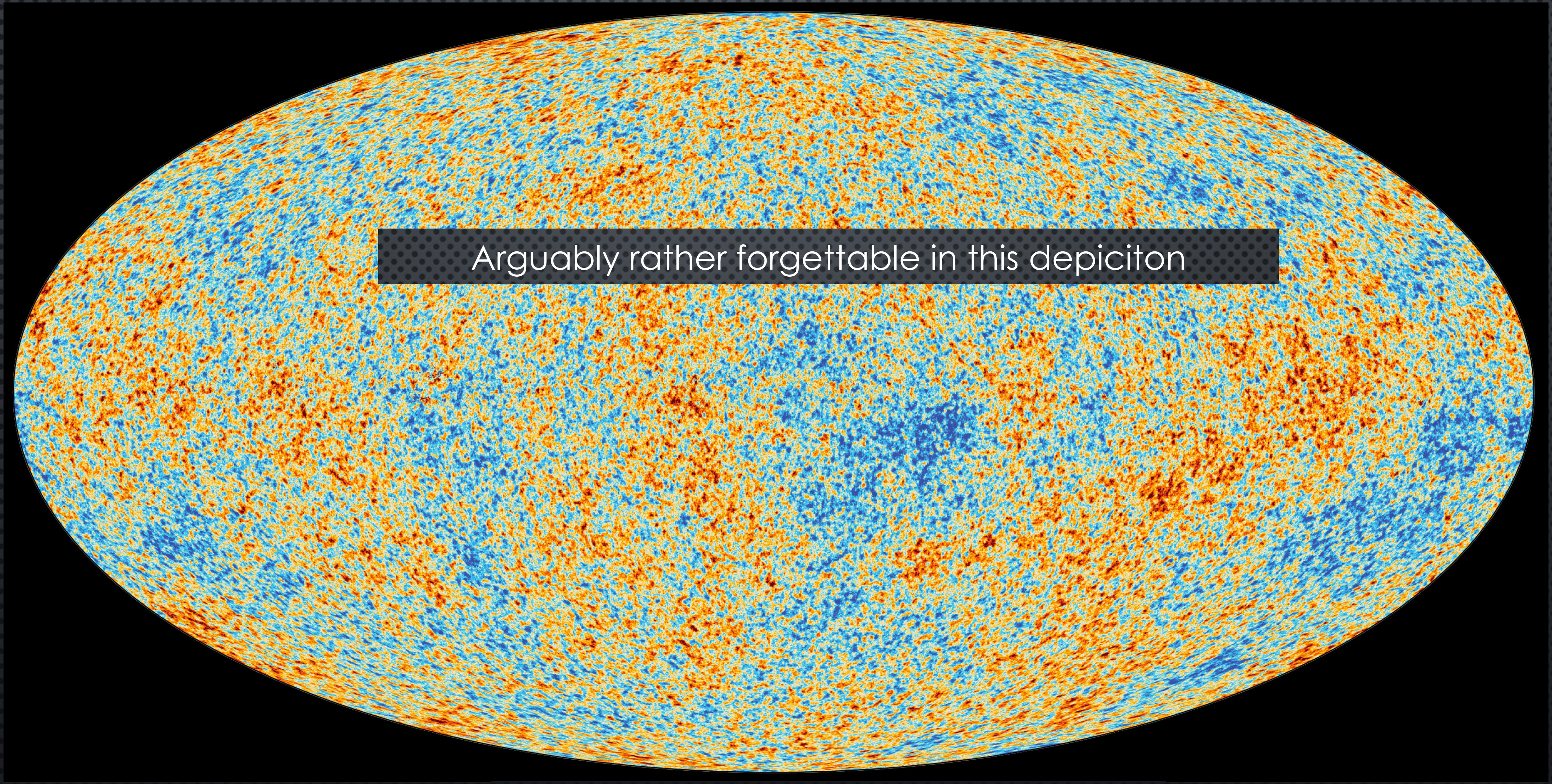
VISUALIZING THE COSMIC MICROWAVE BACKGROUND



Images compliments of the ESA/Planck science team

The CMB over the full sky – red and blue differ by ~ 100 mK

VISUALIZING THE COSMIC MICROWAVE BACKGROUND



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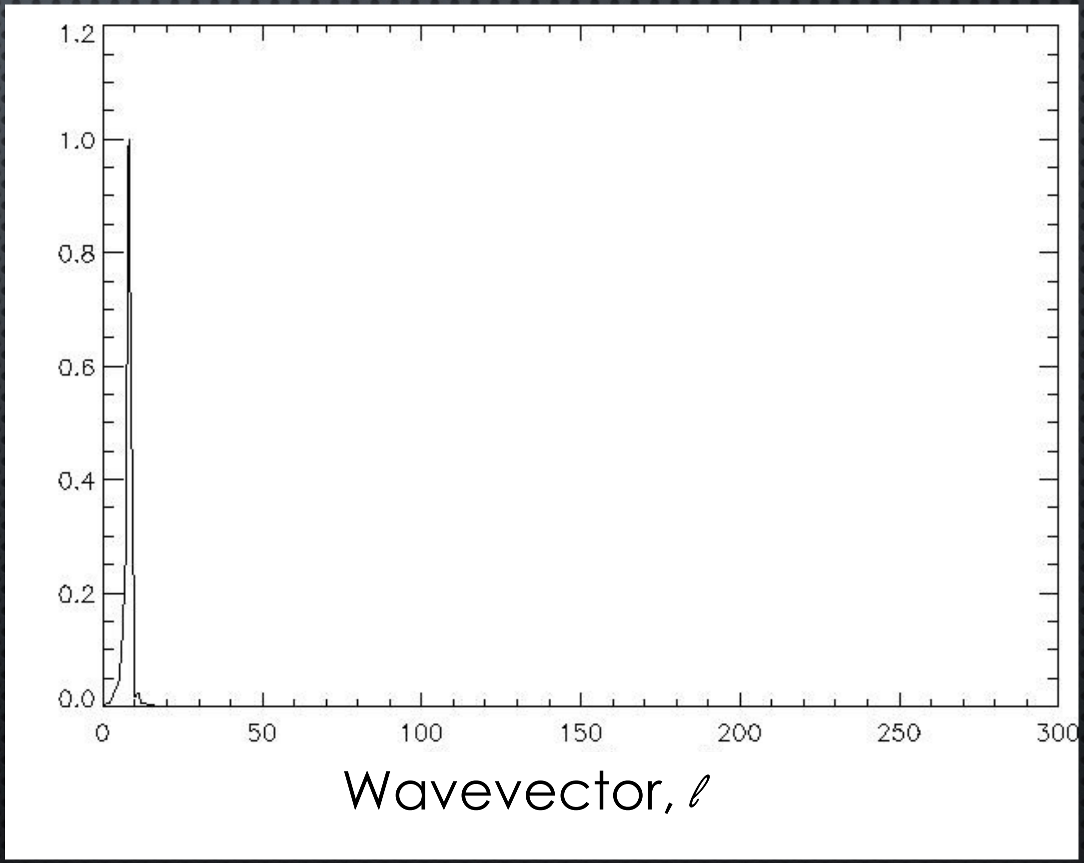
MAPS v POWER SPECTRA

real space

harmonic space



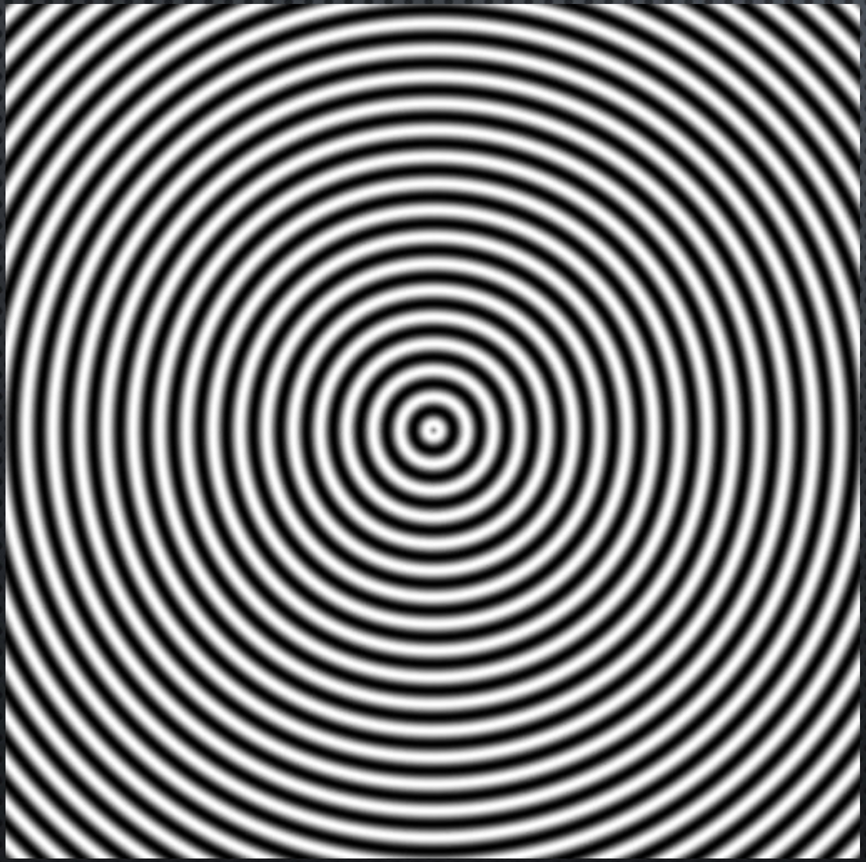
A 2d object in space: x & y

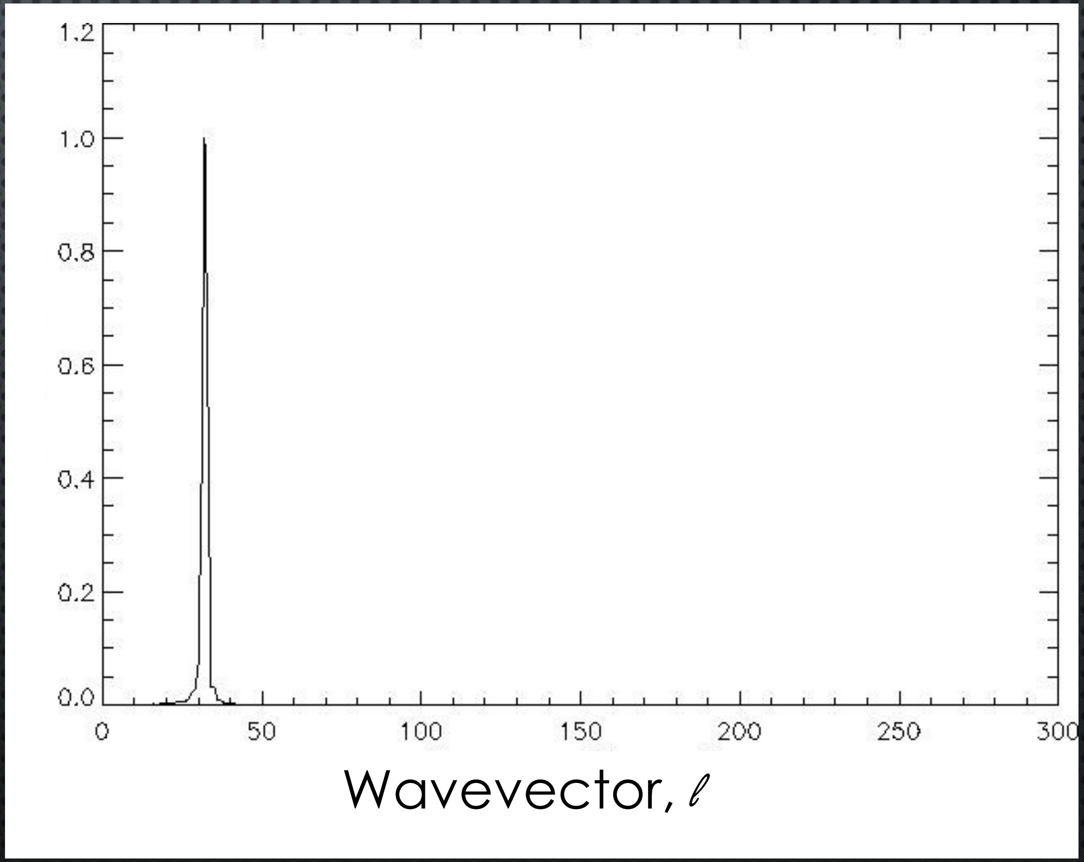
Its 1d power spectrum

MAPS v POWER SPECTRA

real space

harmonic space





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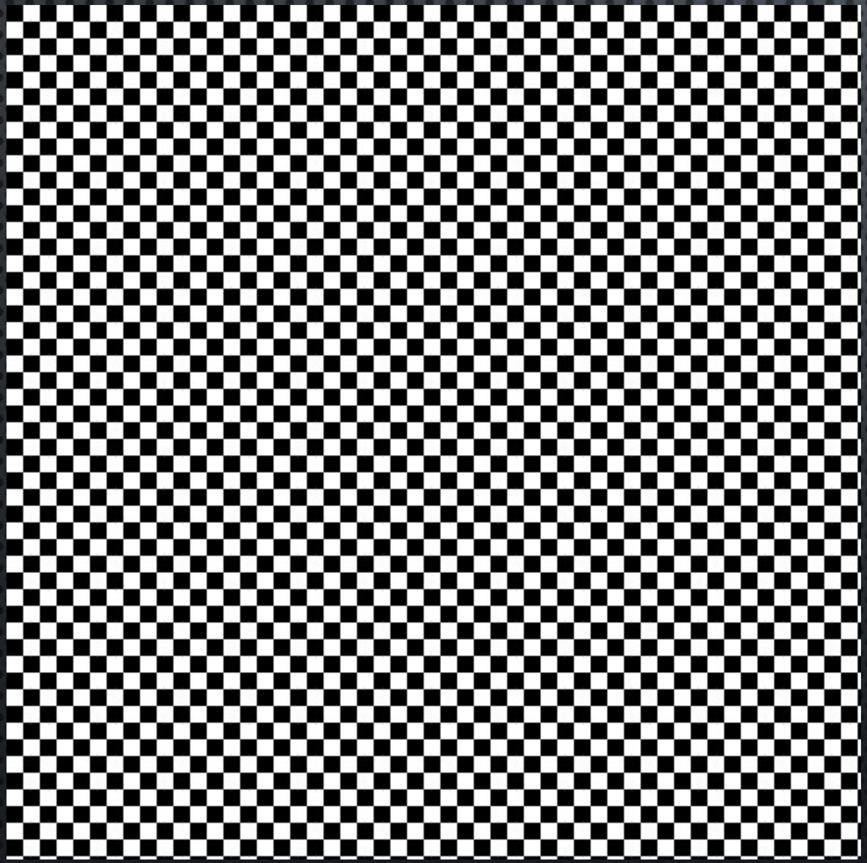

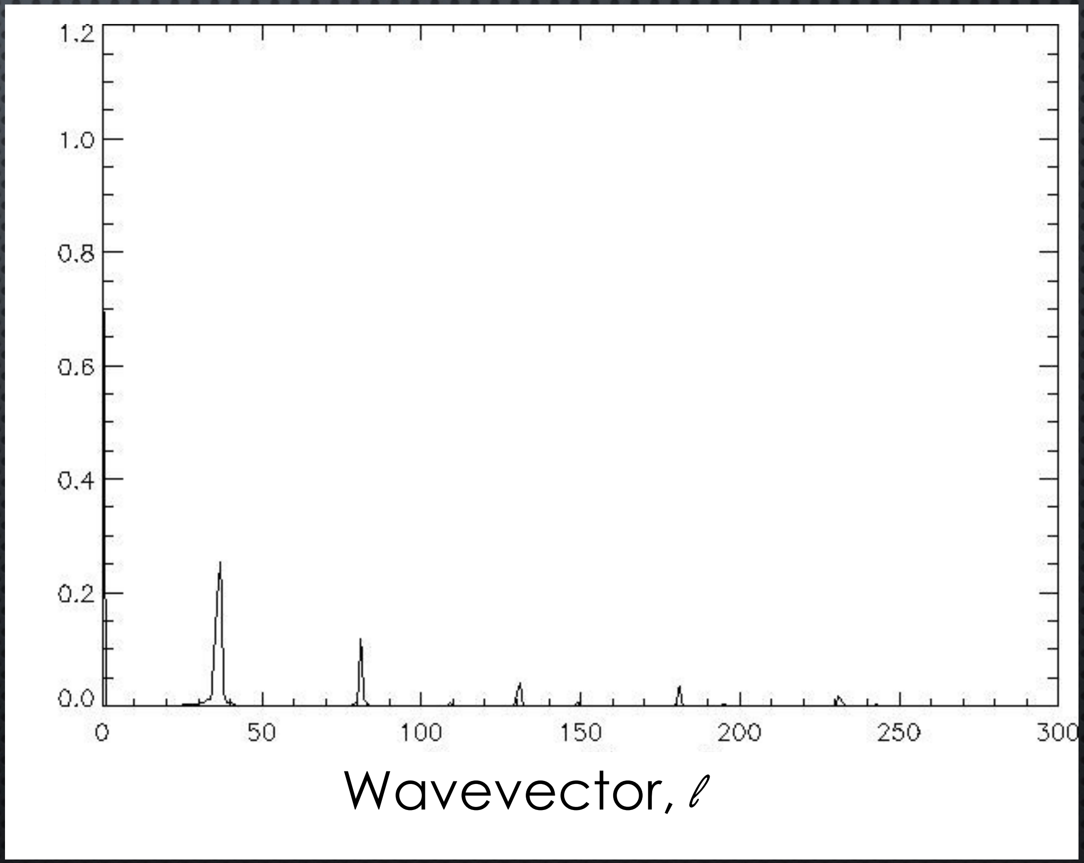

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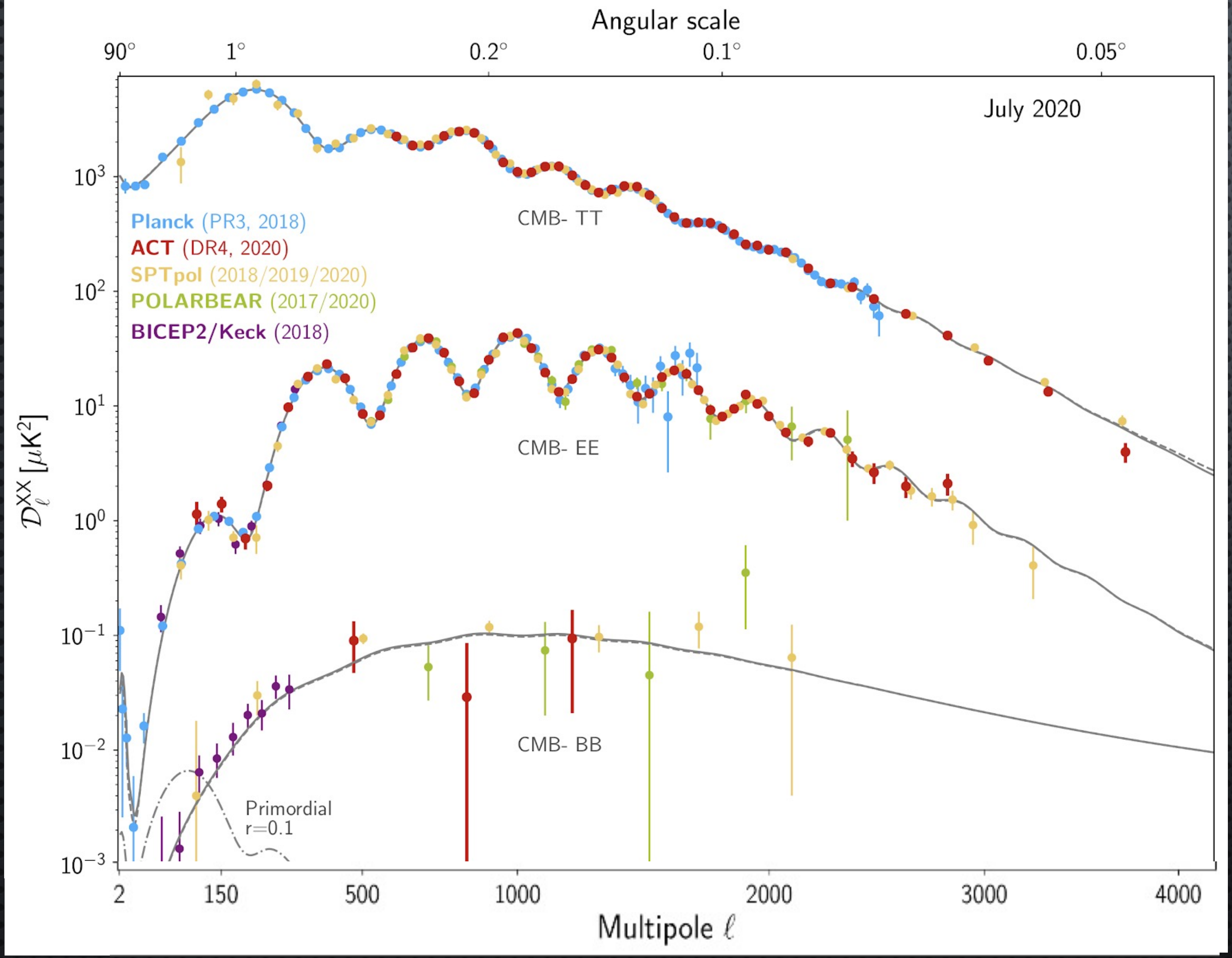
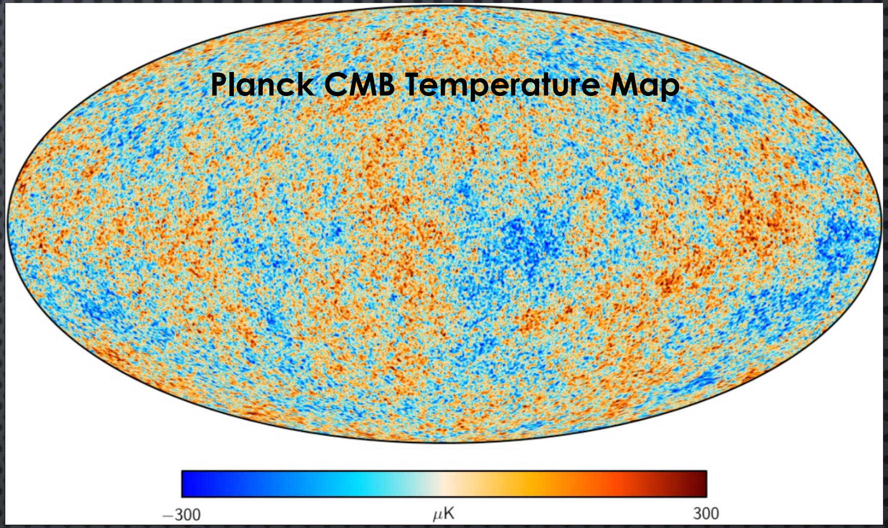
THE ALL-MIGHTY CMB POWER SPECTRA





The CMB appears forgettable in maps but remarkable in harmonic space

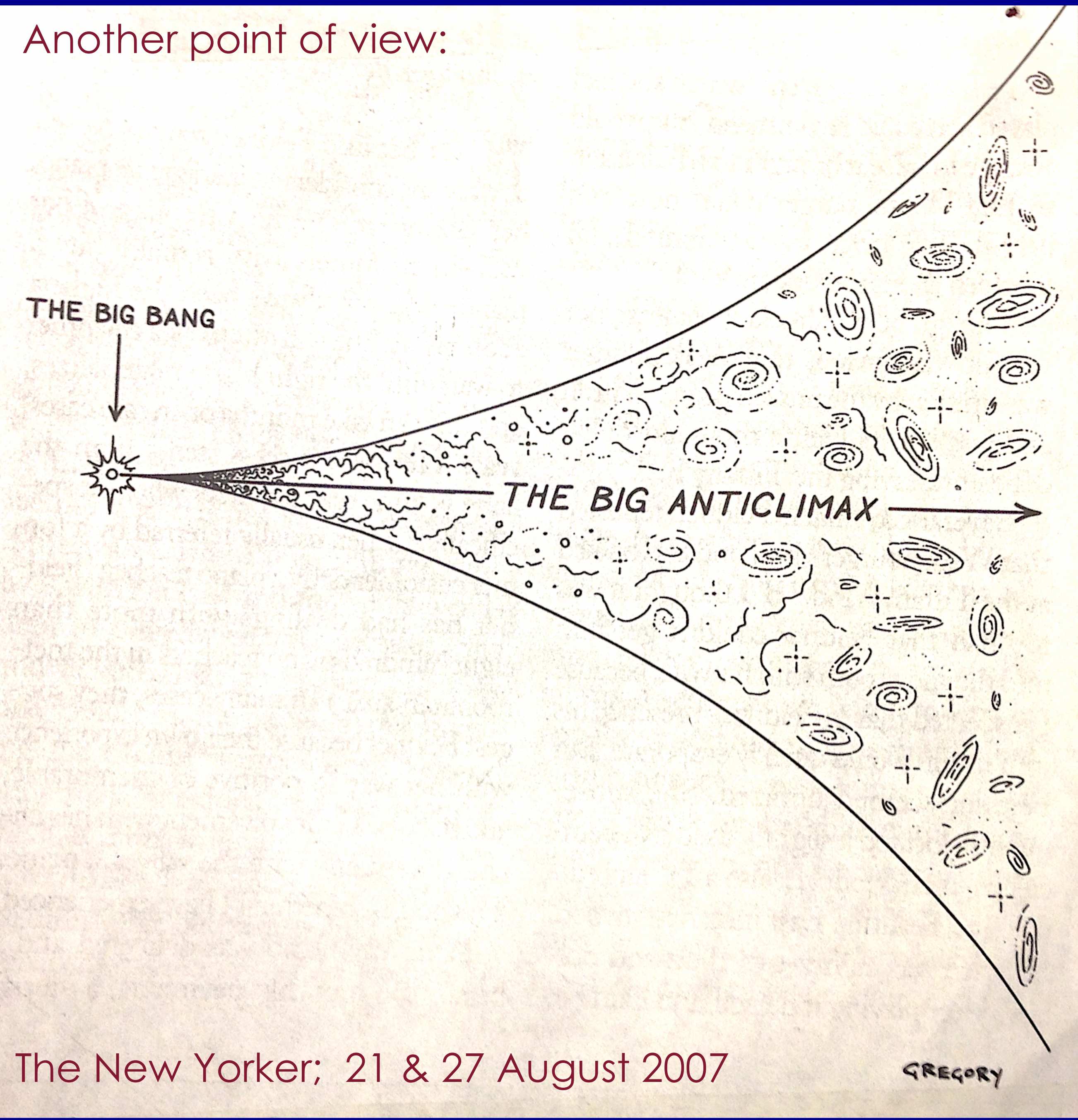
TT: intensity fluctuations
EE, BB: polarization fluctuations

Compilation from Choi et al, 2020
DOI: 10.1088/1475-7516/2020/12/045)
but already there are more data, and more coming!

ORIGIN OF COHERENT ACOUSTIC OSCILLATIONS WITHIN INFLATION FRAMEWORK

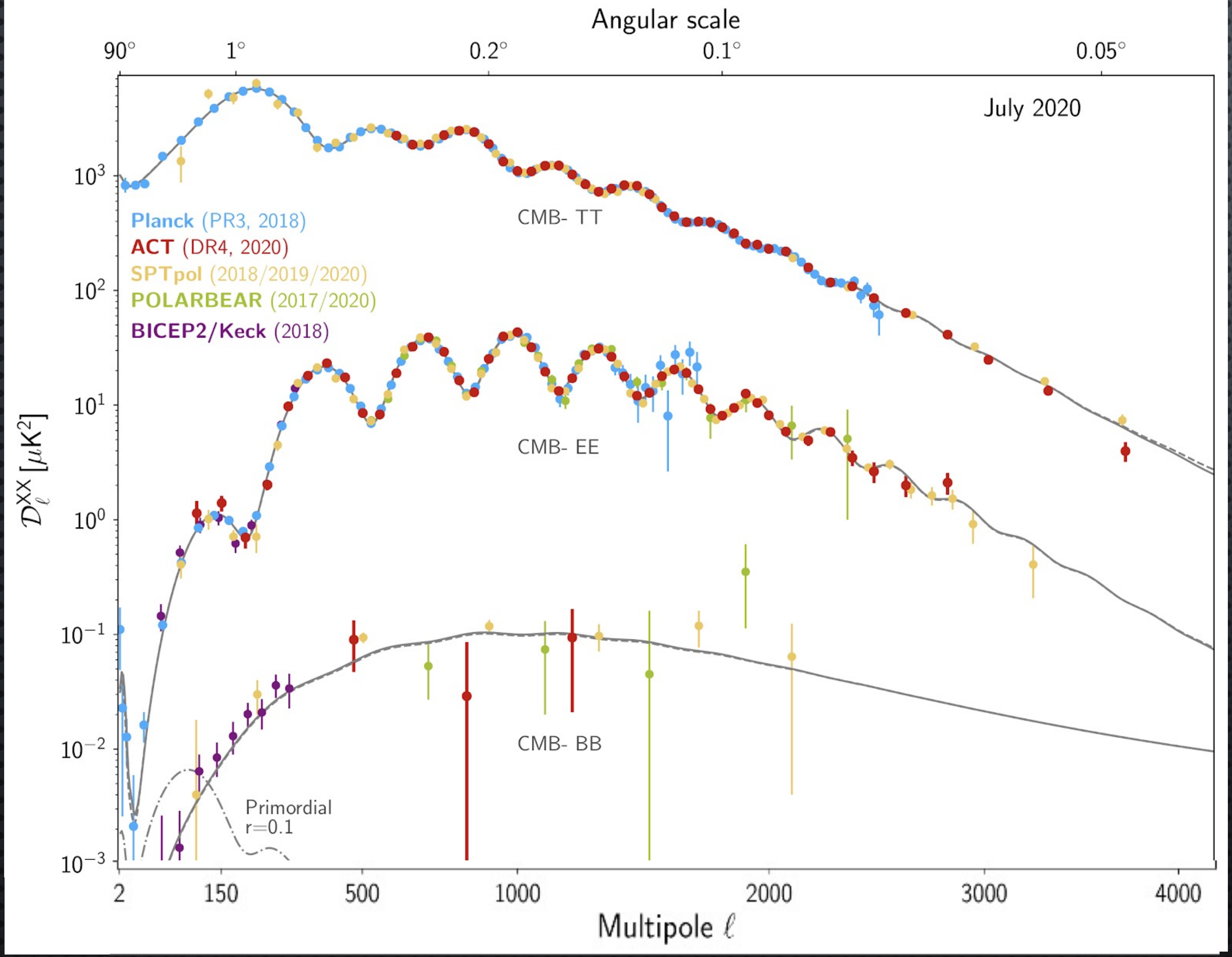
1. INFLATION ENGENDERS DARK MATTER DENSITY FLUCTUATIONS ON SUPERHORIZON SCALES.
2. TIME REVEALS THESE PREVIOUSLY SUPERHORIZON DIMPLES IN THE METRIC … AT TIME T*, A SUPERHORIZON FOURIER MODE OF K* IS REVEALED.
3. SIMPLE HARMONIC MOTION (SHM) OF THE PHOTON-BARYON FLUID ASSOCIATED WITH MODE K* ENSUES. THE PLASMA IS SUCKED INTO THE METRIC DIMPLES BY GRAVITY AND FORCED OUT BY RADIATION PRESSURE.
4. COOLING OF THE EXPANDING UNIVERSE CONGEALS THE PLASMA, RELEASING THE CMB RADIATION, BEARING PATTERNS OF THE SHM OSCILLATIONS.

Another point of view:



The New Yorker; 21 & 27 August 2007

TRANSFER FUNCTION ITSELF COMMUNICATES INITIAL CONDITIONS

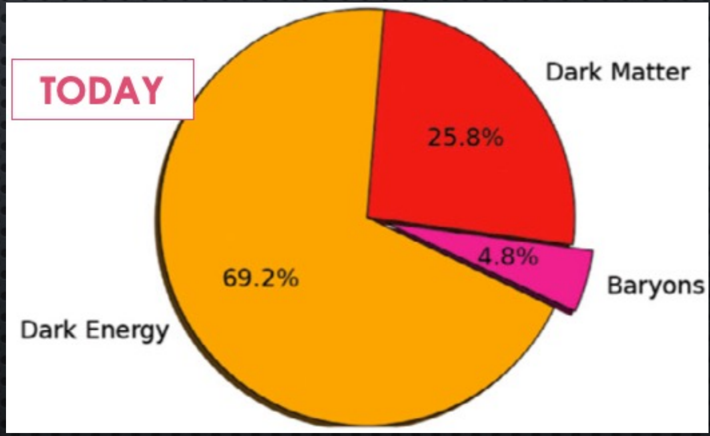


Structure in the form of transfer function assumed to act on:

$$P(k) = A_S \left(\frac{k}{k_0}\right)^{\tilde{n}_s - 1},$$

2 params

k = 3d wave-vector in the then universe



FIT WITH SIX PARAMETERS!

CMB POLARIZATION SCHEMATICALLY

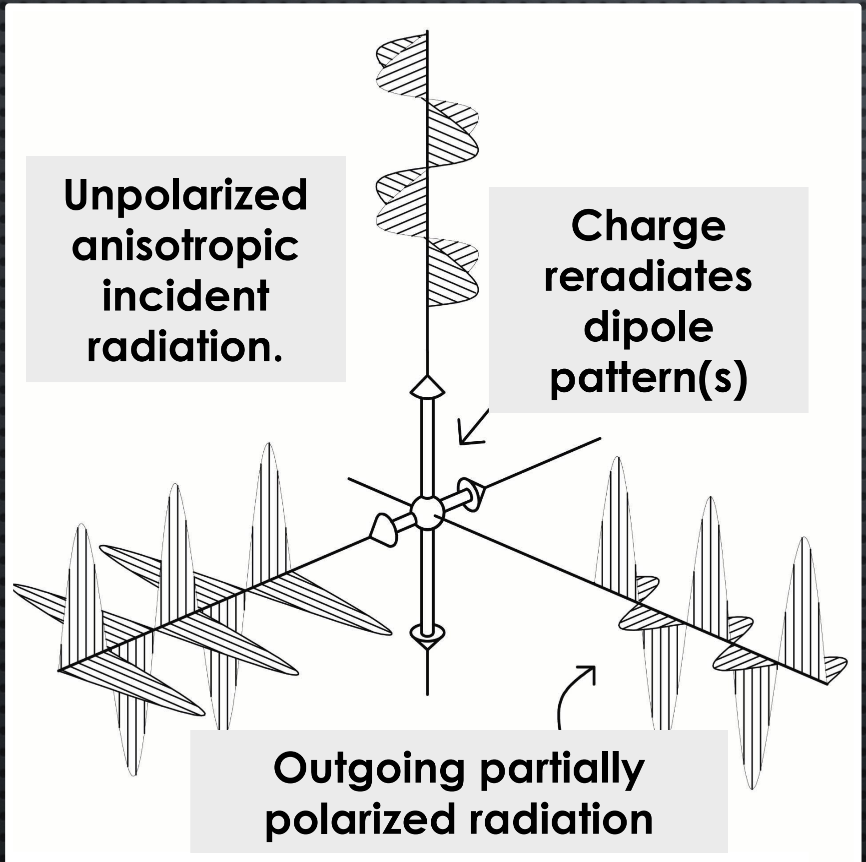
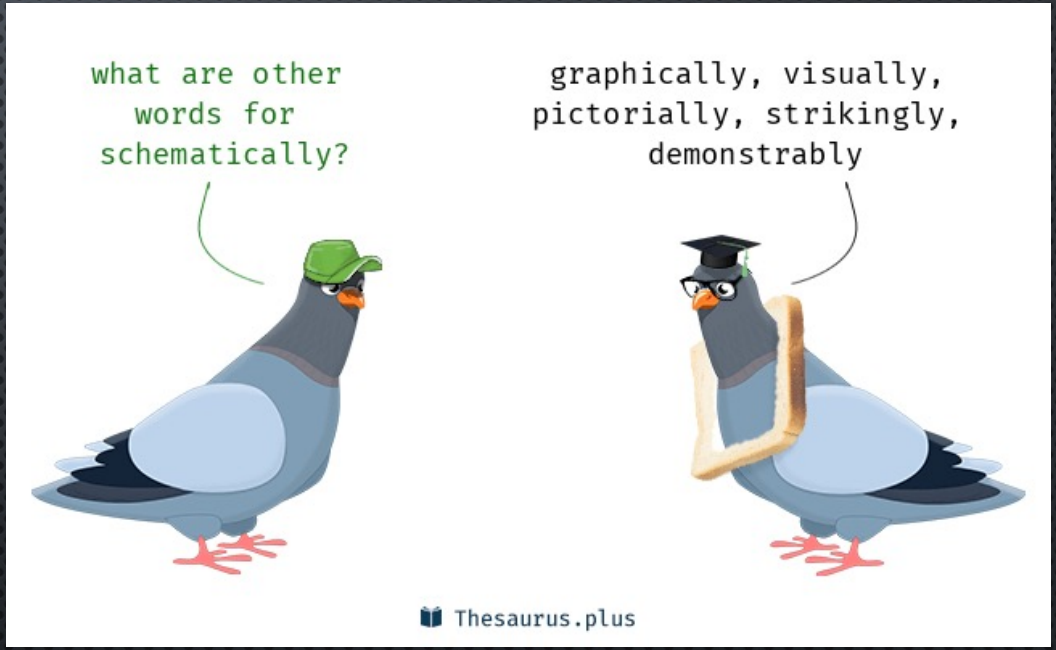


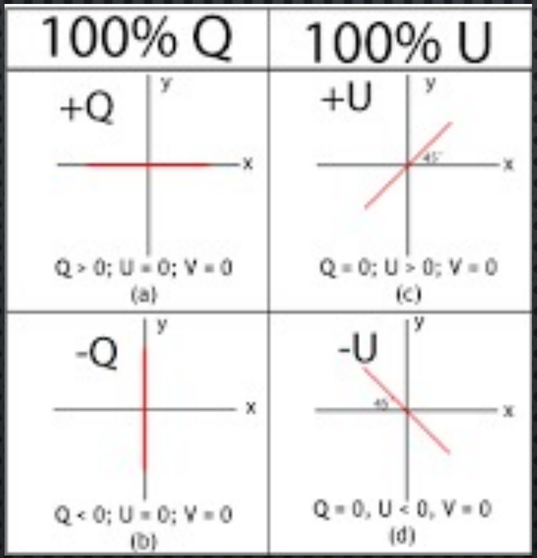
Figure courtesy of M. Hedman



Acoustic oscillations create local quadrupoles (Doppler effect)

CMB POLARIZATION: E-MODES & B-MODES

STOKES PARAMETERS

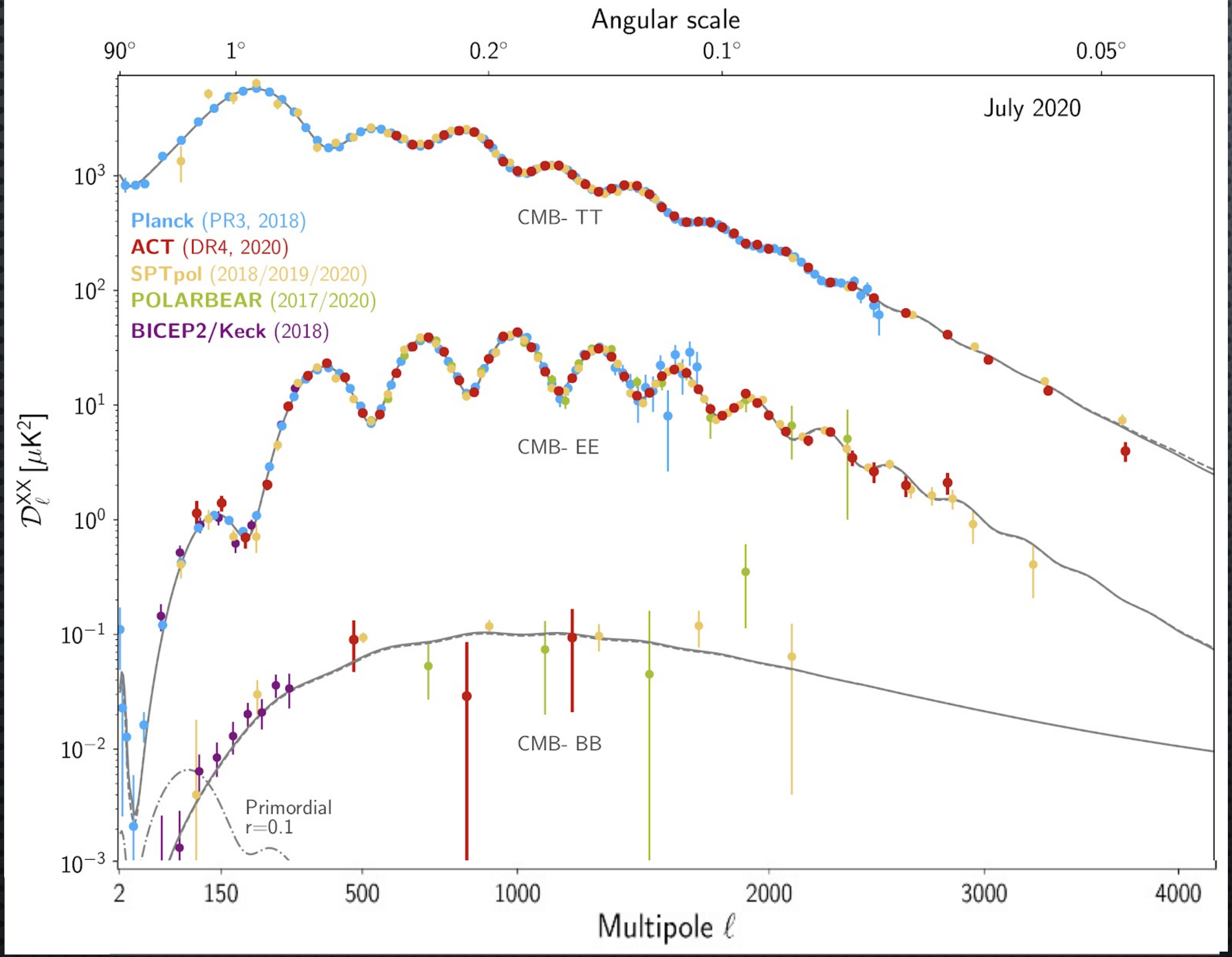


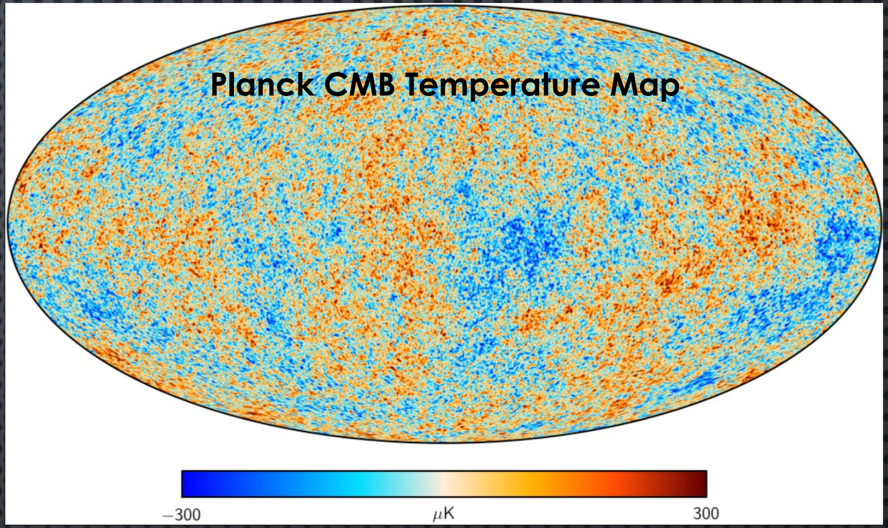
E-modes are symmetric wrt rotations around the wavevector...

B-modes are anti-symmetric wrt rotations around the wavevector...

E & B are GLOBAL not LOCAL since they are fundamentally defined in harmonic (not position) space.

THE ALL-MIGHTY CMB POWER SPECTRA





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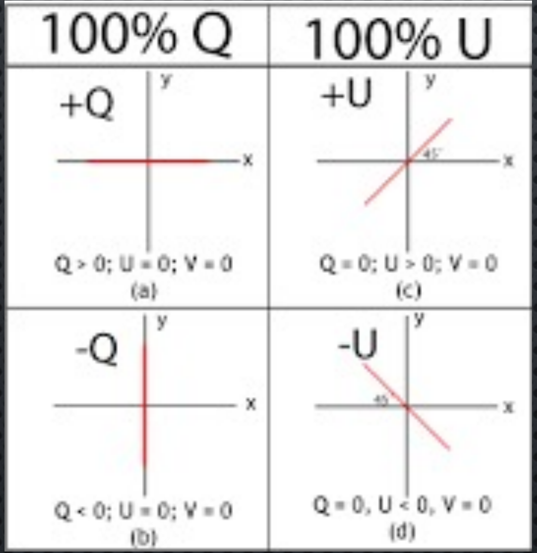

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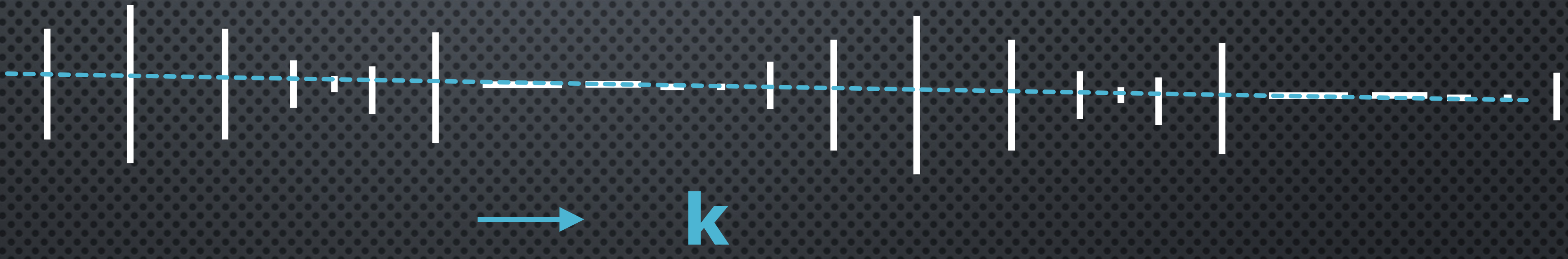

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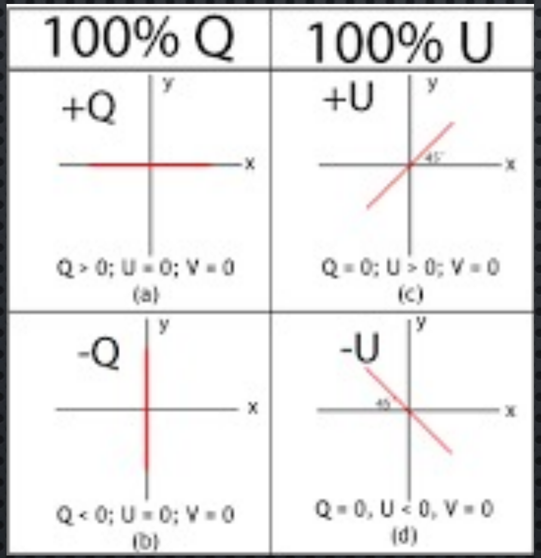

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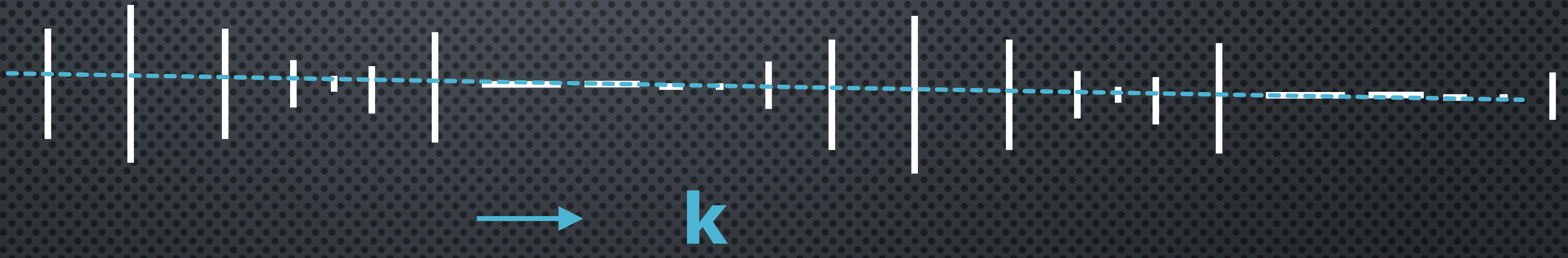

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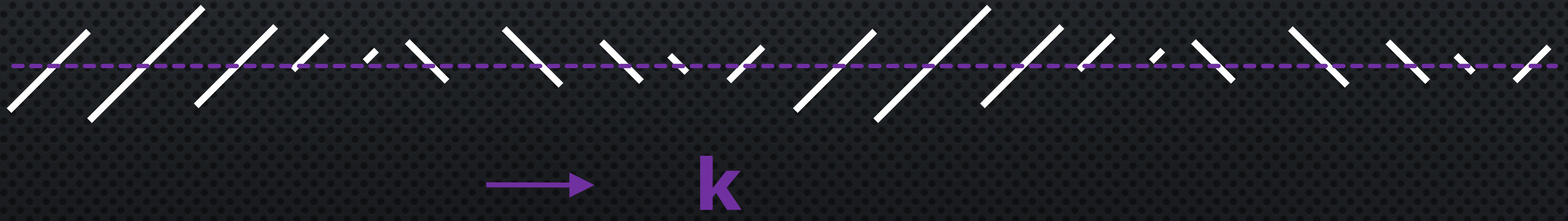

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CMB POLARIZATION: E-MODES & B-MODES

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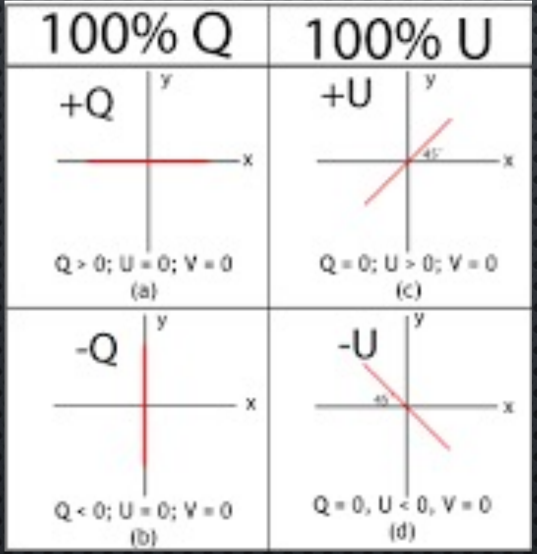
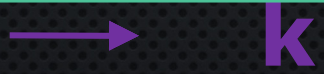


E-modes are symmetric wrt rotations around the wavevector…

ACOUSTIC OSCILLATIONS (SCALAR MODES) PRODUCE **ONLY** E-MODES!

Kamionkowski, Kosowsky & Stebbins; 1997
Seljak & Zaldarriaga 1997



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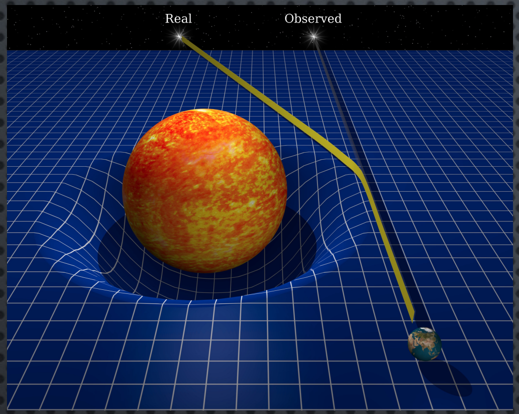
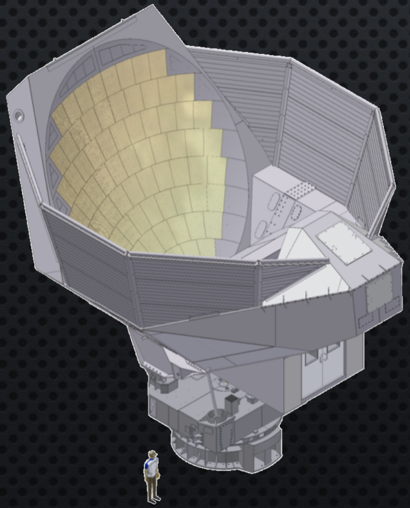
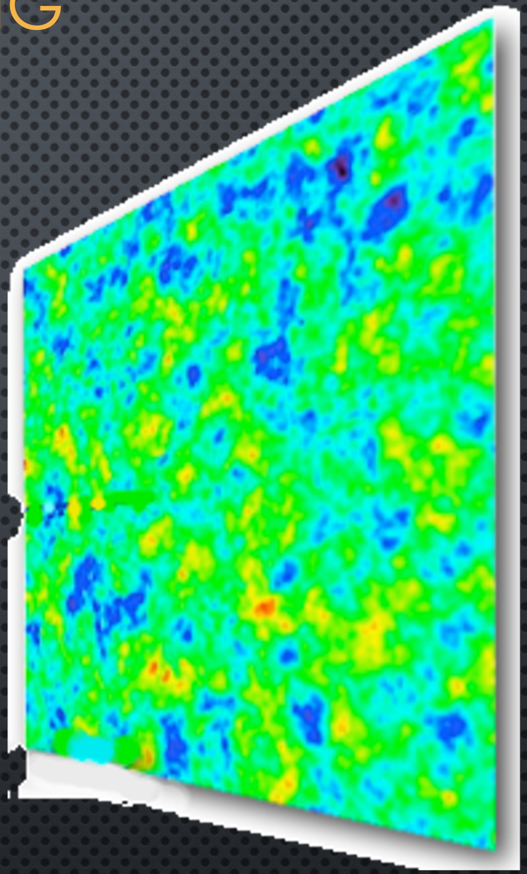
CMB PROBES: GRAVITATIONAL LENSING



Matter curves space; light traces the curvature.





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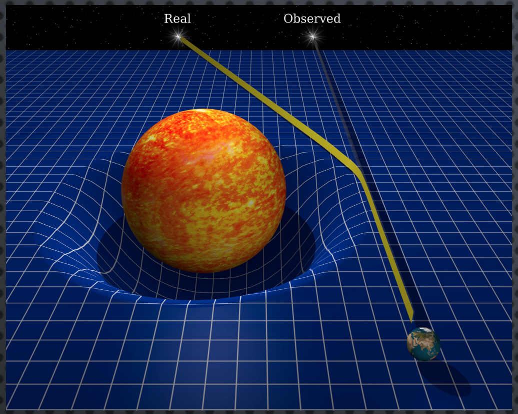

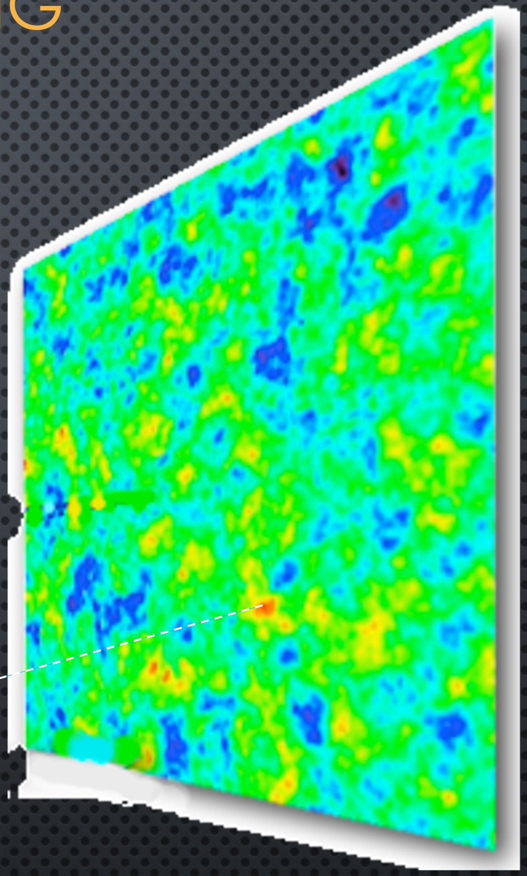

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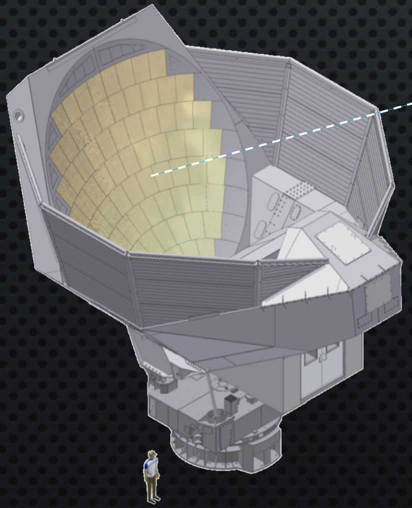

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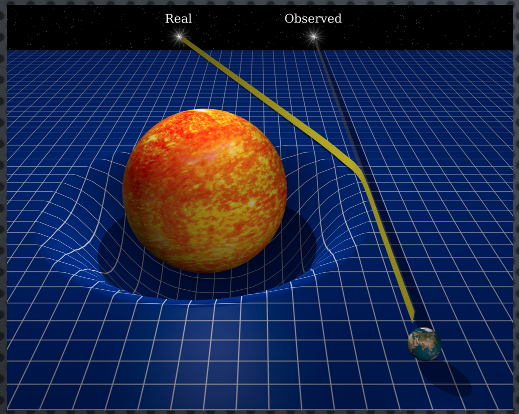

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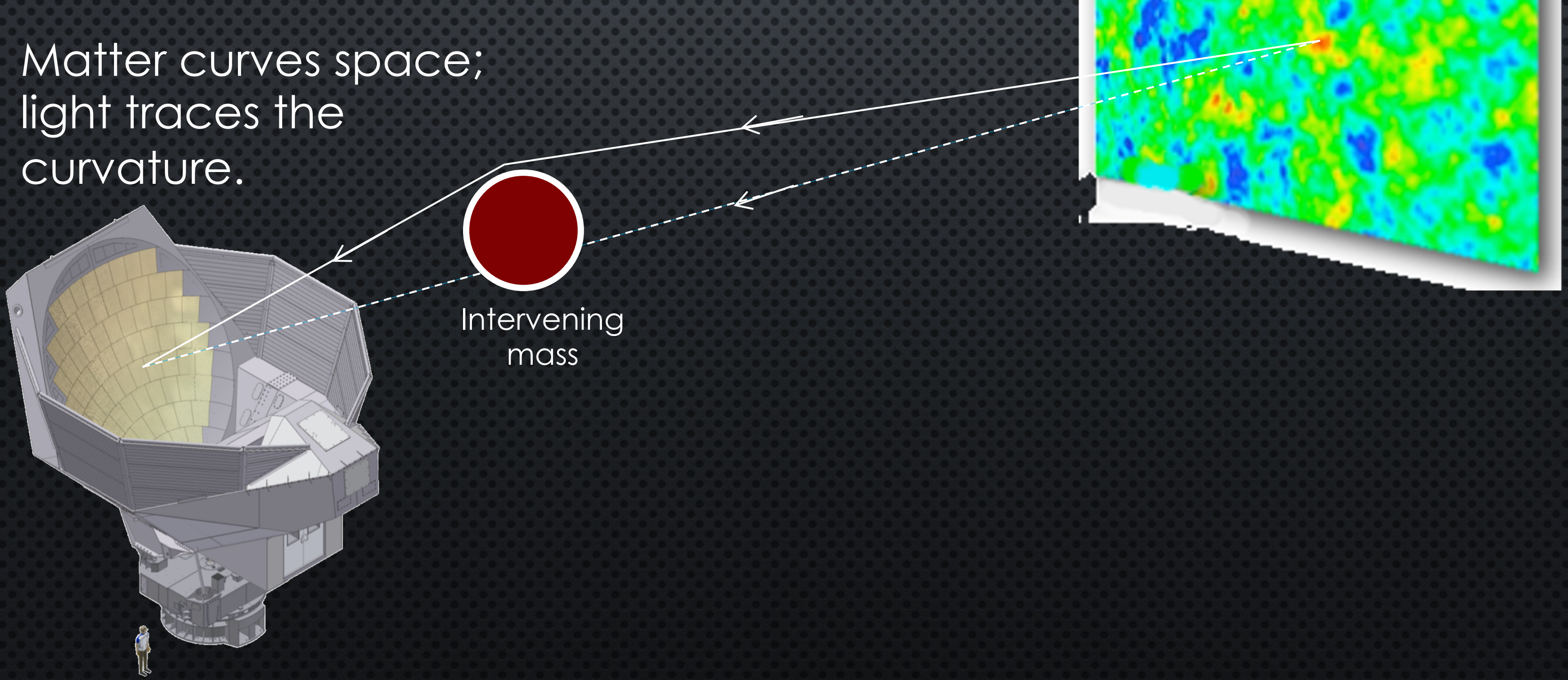

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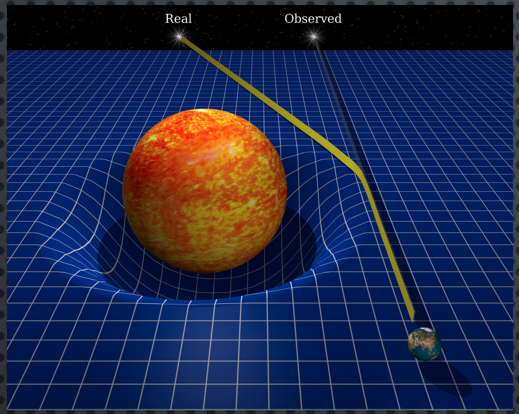

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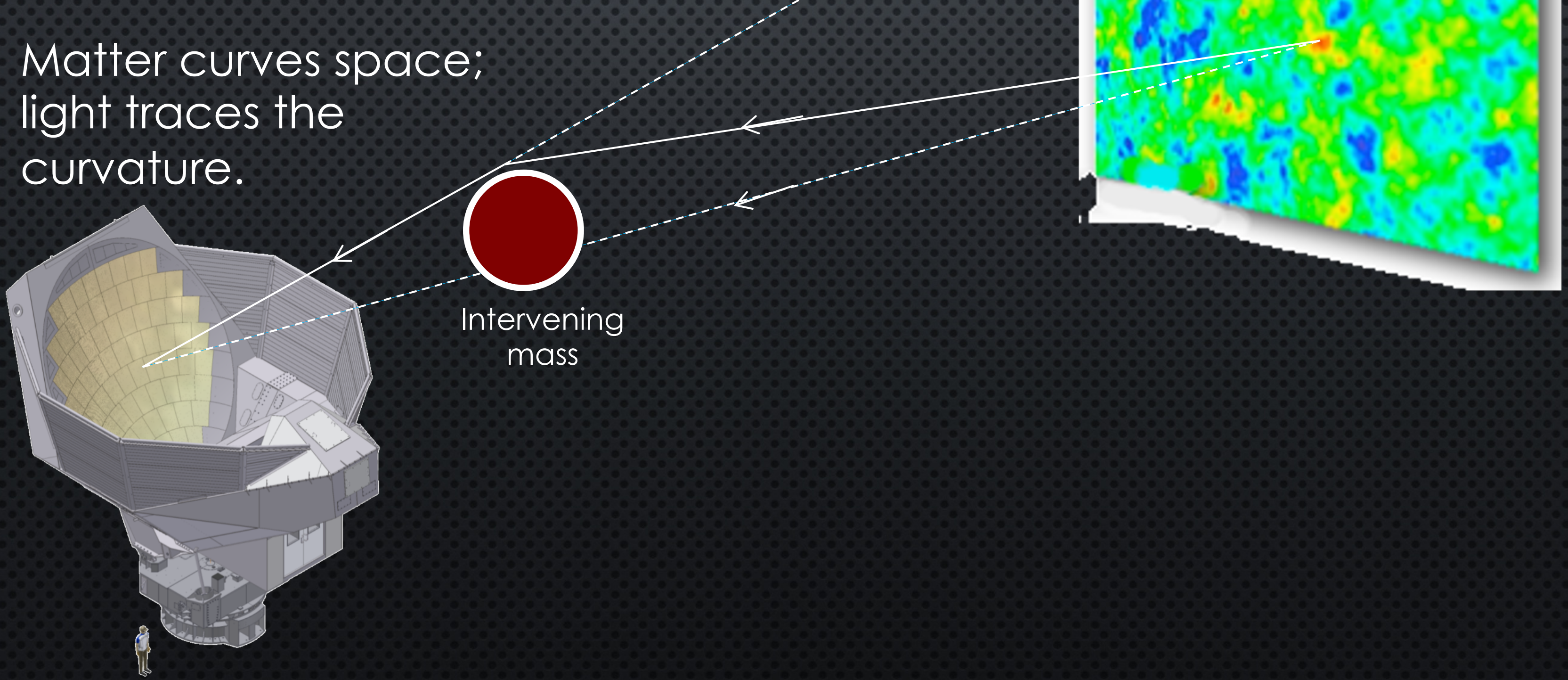

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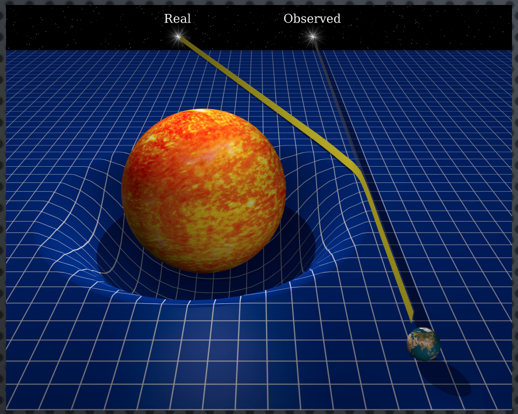
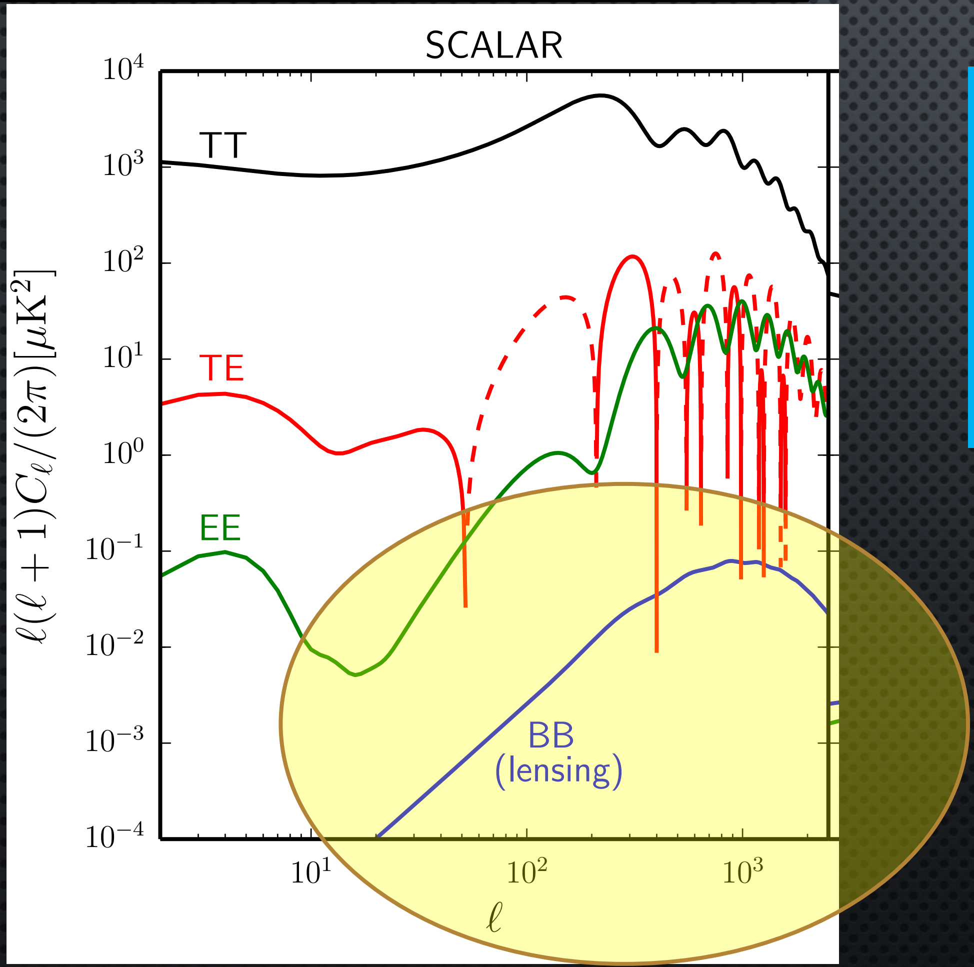


Matter curves space;
light traces the
curvature.

Rearrangement does not respect the
original polarization symmetries!

CMB POWER SPECTRA

ACOUSTIC OSCILLATIONS **ARE** SCALAR (DENSITY) FLUCTUATIONS



Lensing B modes are generated from the primordial acoustic E modes with a power spectrum of predictable shape.

GRAVITATIONAL WAVES AND B-MODES

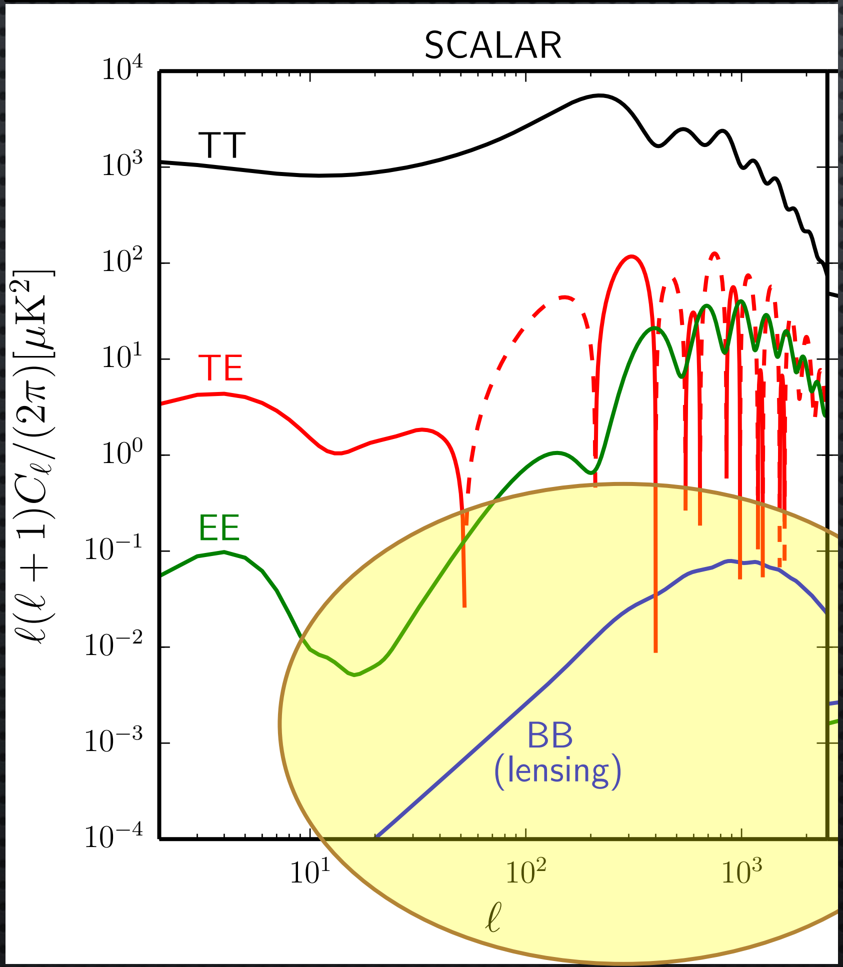
Gravitational waves distort space-time as they travel through it.

Inflation releases gravitational waves which travel through space essentially unhindered for the rest of time.

In the presence of gravitational waves, the CMB polarization develops BOTH parity-even E-mode AND parity-odd B mode polarization

PRIMORDIAL GRAVITATIONAL WAVES

ACOUSTIC OSCILLATIONS **ARE** SCALAR (DENSITY) FLUCTUATIONS



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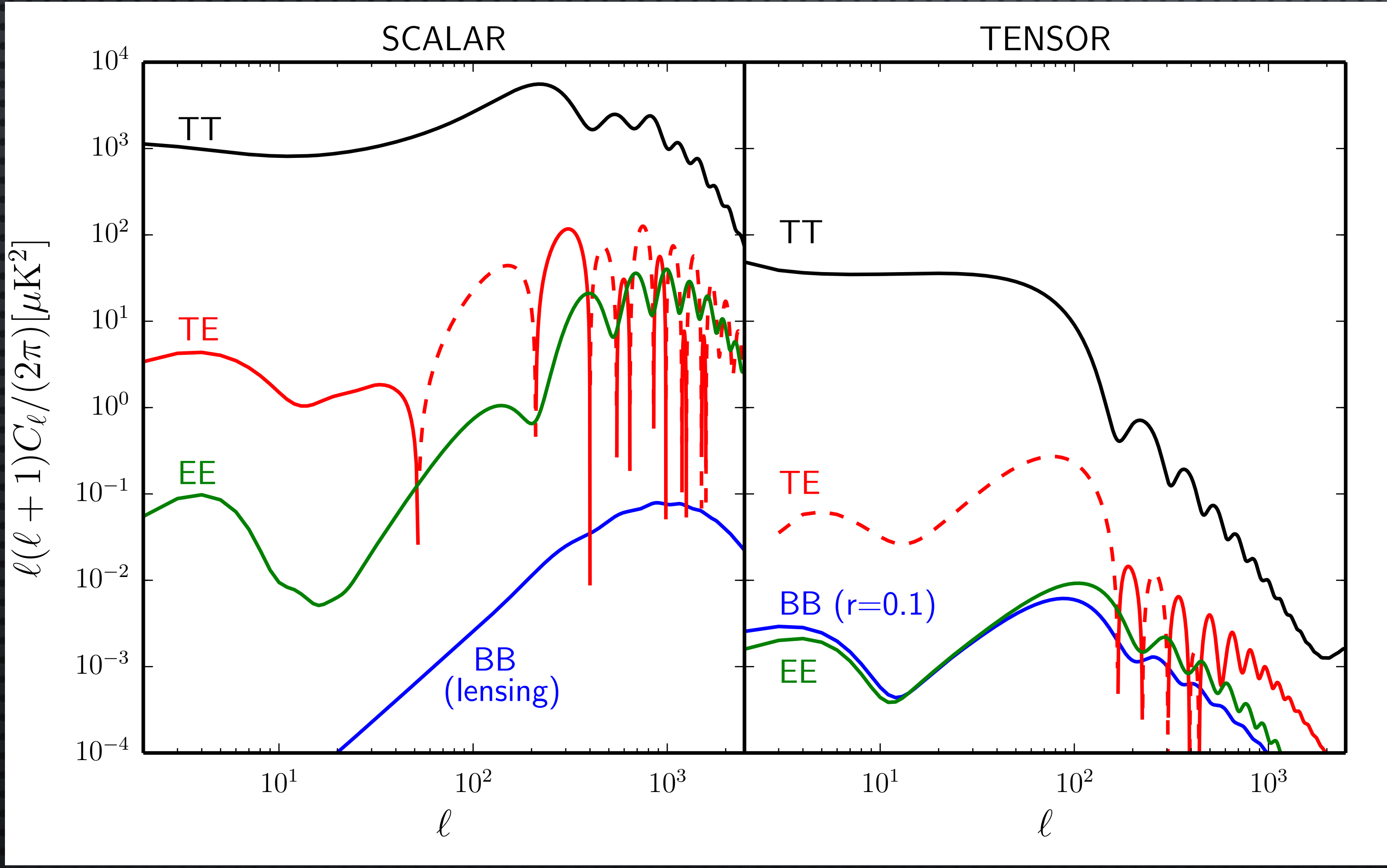
PRIMORDIAL GRAVITATIONAL WAVES

ACOUSTIC OSCILLATIONS **ARE** SCALAR (DENSITY) FLUCTUATIONS	GRAVITATIONAL WAVES **ARE** TENSOR FLUCTUATIONS IN THE METRIC



PGWs IMPACT TT, TE & EE SOMEWHAT.

…. but BB OPENS UP A NEW FUNDAMENTAL OBSERVABLE!

INFLATIONARY MODELS GENERICALLY PREDICT PGWs

VERIFIICATION OF INFLATION?
QUANTUM NATURE OF GRAVITY?
GRAND UNIFICATION SCALE?

PRIMORDIAL GRAVITATIONAL WAVES

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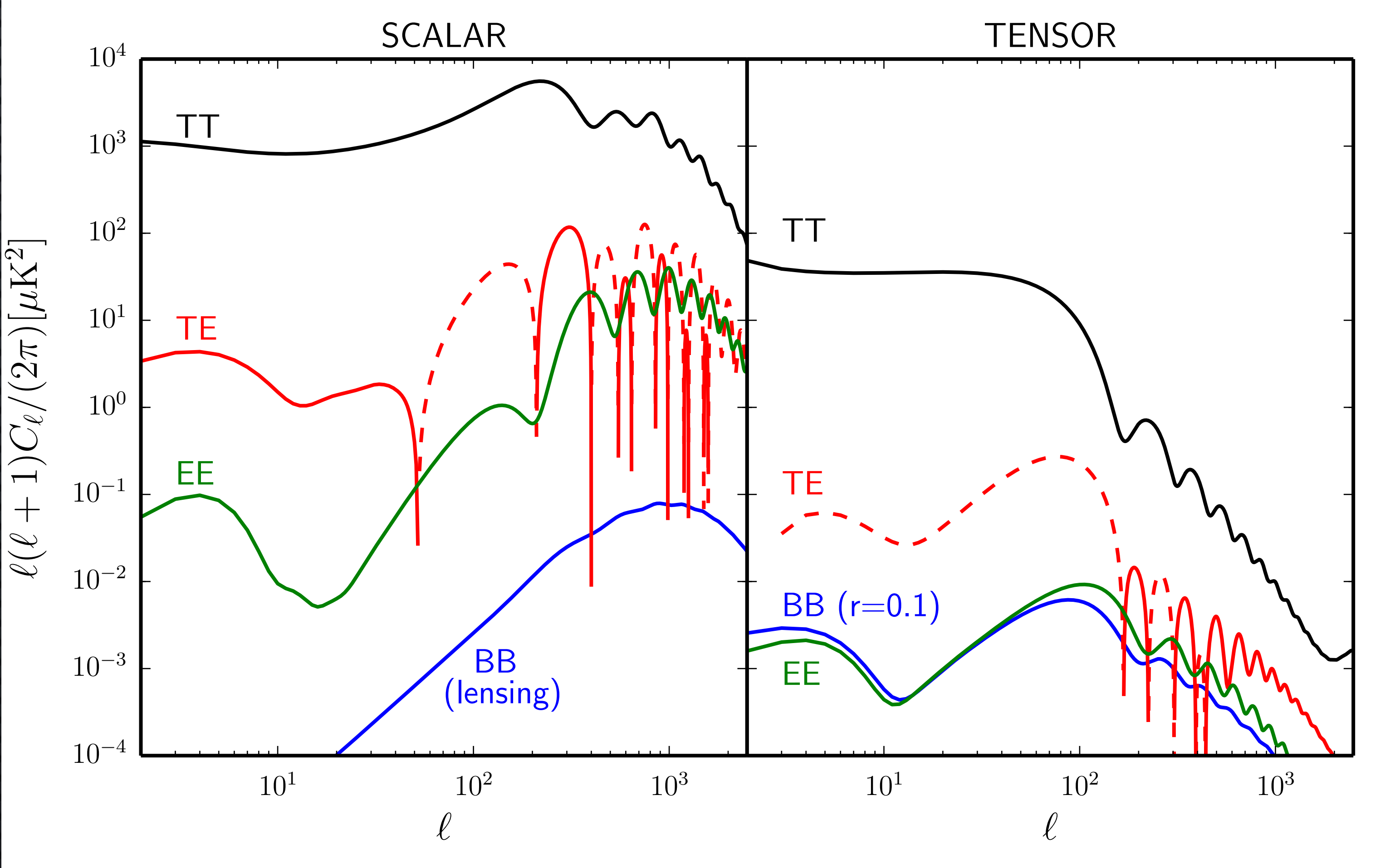

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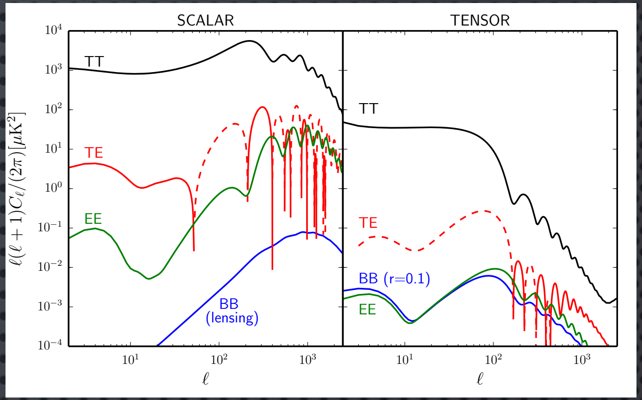
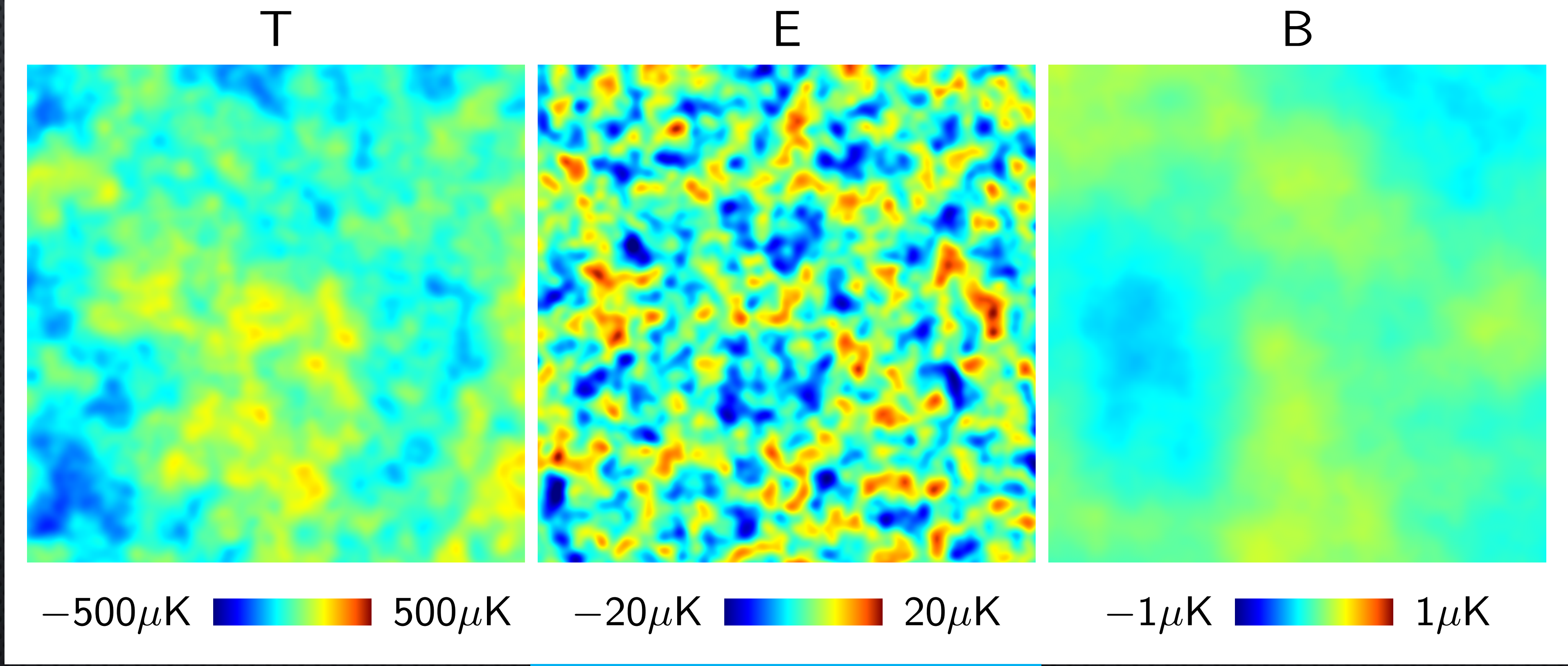
CURRENT STATUS:
r < 0.036 (95% CL),
BICEP/Keck, 2021
PRL **127**, 151301

SIMULATION OF PRIMORDIAL B-MODES FROM INFLATION



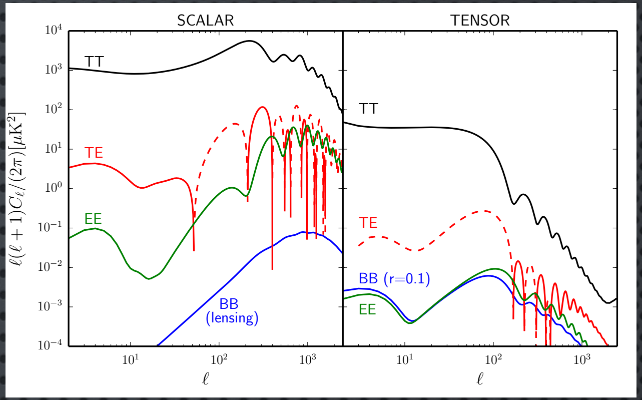
PRIMORDIAL MAPS (simulated)



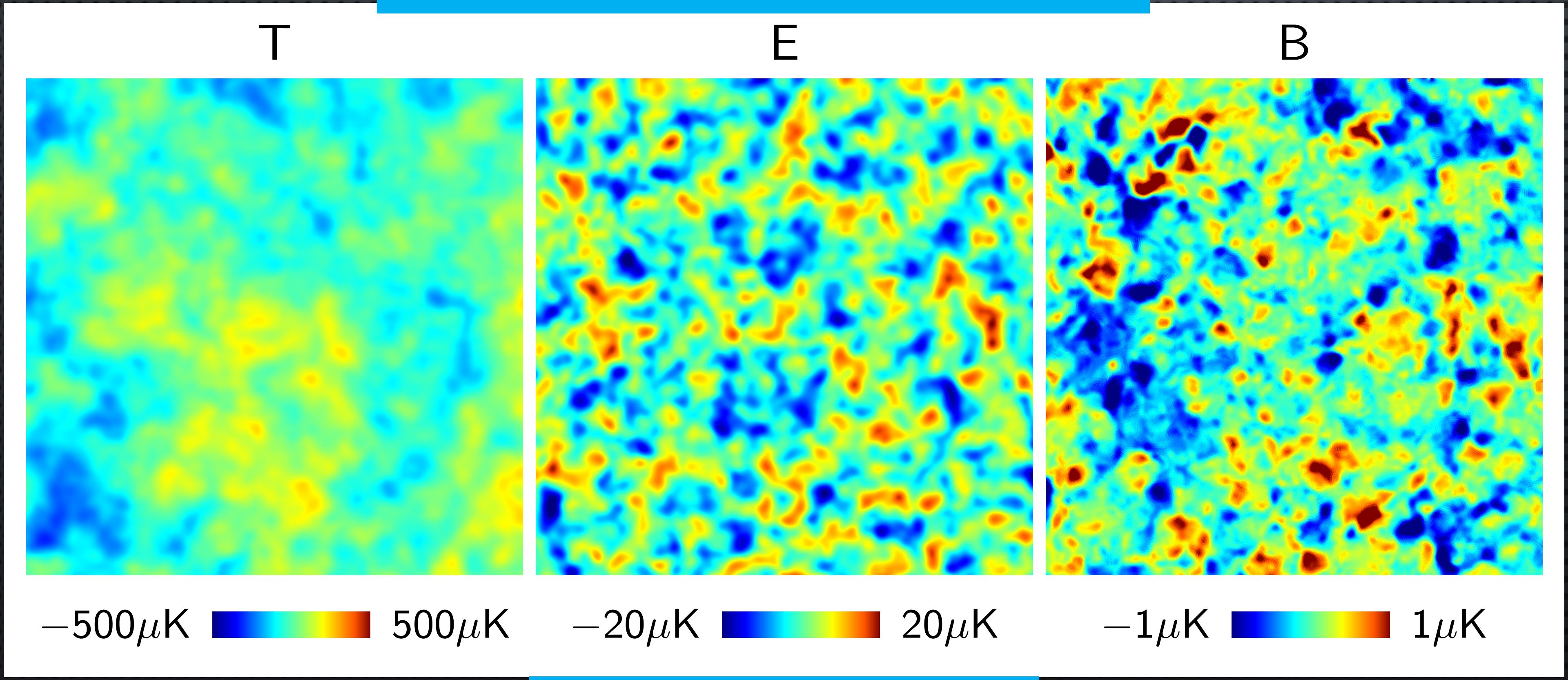
Figures courtesy of Sigurd Naess

Color bar scales for panels In triptych vary!

SIMULATION OF PRIMORDIAL B-MODES FROM INFLATION



LENSED PRIMORDIAL MAPS (simulated)



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Color bar scales for panels In triptych vary!

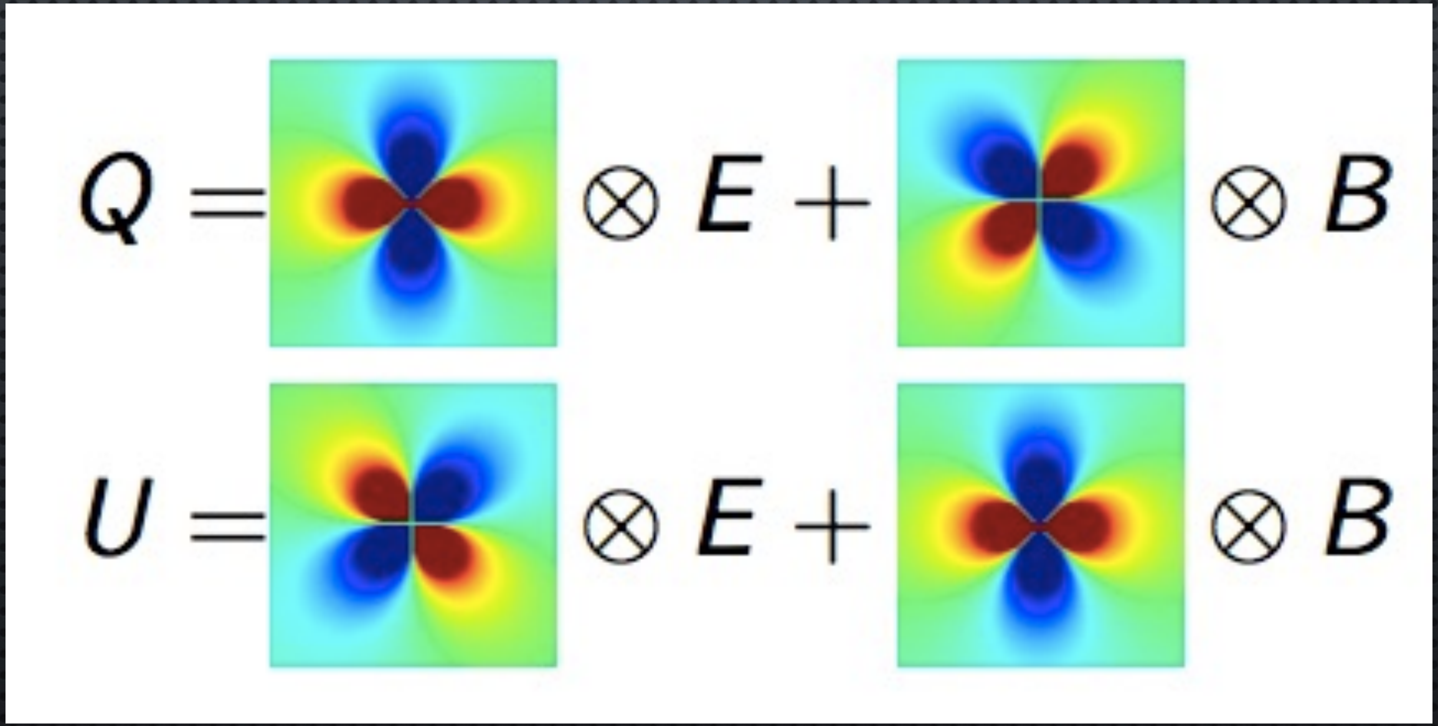
HOW Q & U ARE RELATED TO E & B

(Geeky aside to explain something that might have been bugging you.)

HOW Q & U ARE RELATED TO E & B

(Geeky aside to explain something that might have been bugging you.)

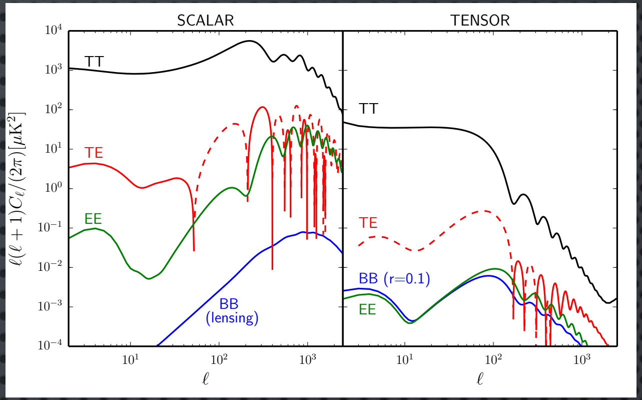
Convolutions with quadrupoles!
Keep in mind that E >> B.



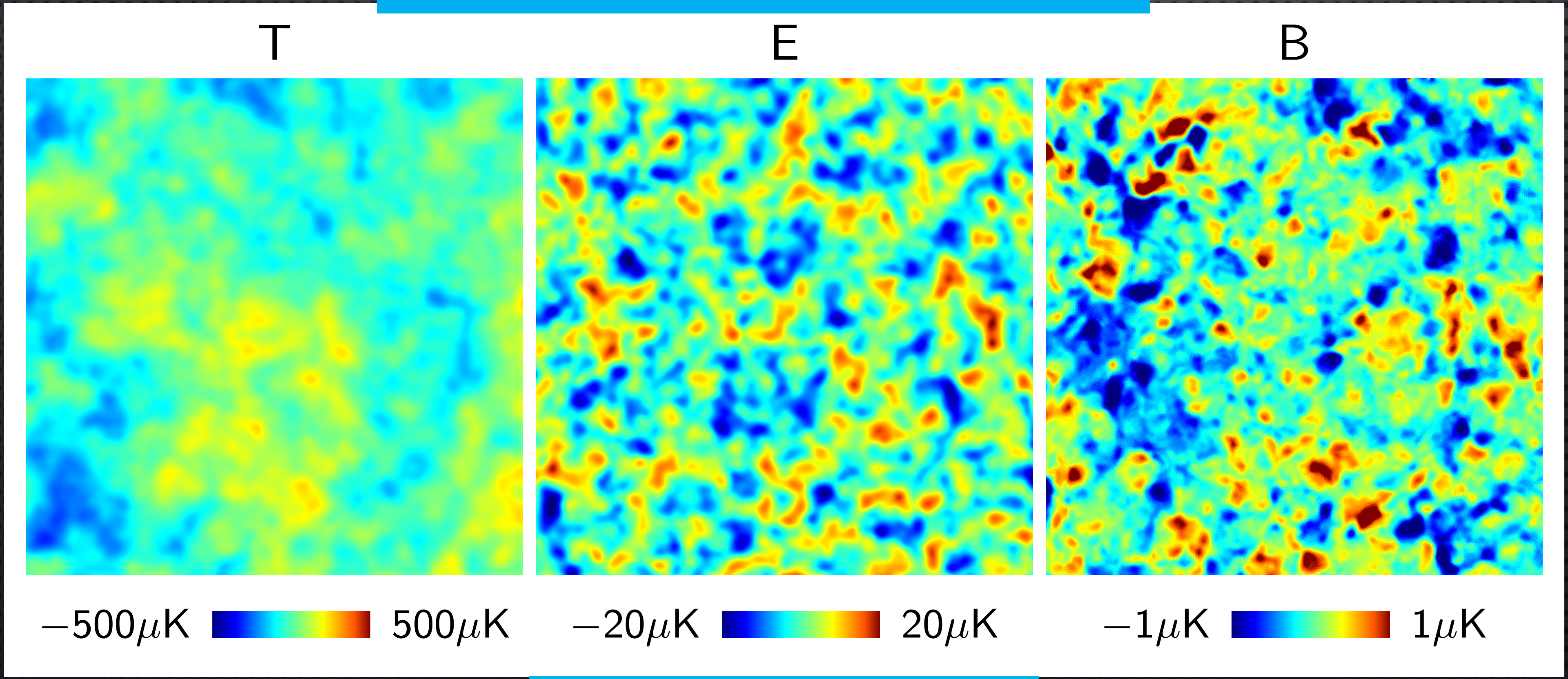
Figures courtesy of Sigurd Naess

(Back to former slide.)

SIMULATION OF PRIMORDIAL B-MODES FROM INFLATION



LENSED PRIMORDIAL MAPS (simulated)



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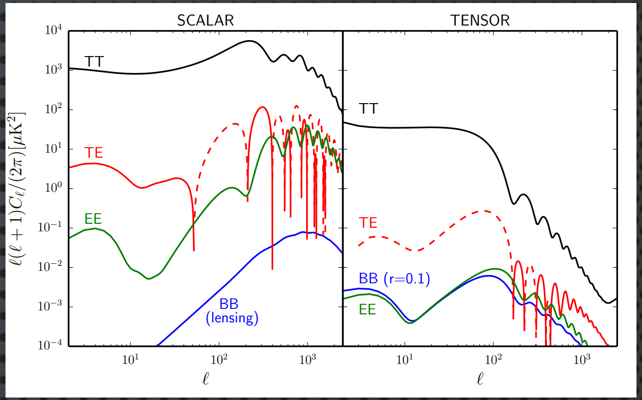
Color bar scales for panels In triptych vary!

Now Q & U are displayed!

SIMULATION OF PRIMORDIAL B-MODES FROM INFLATION



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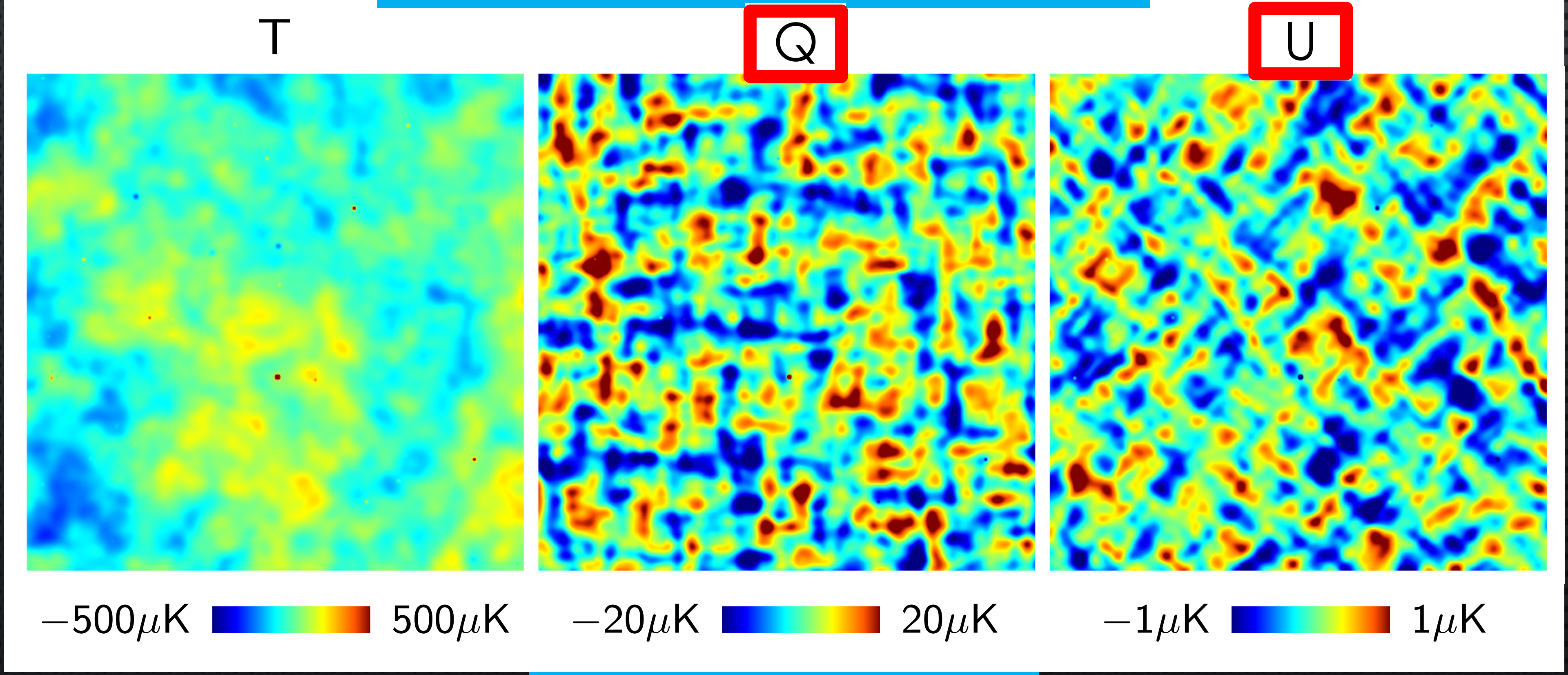

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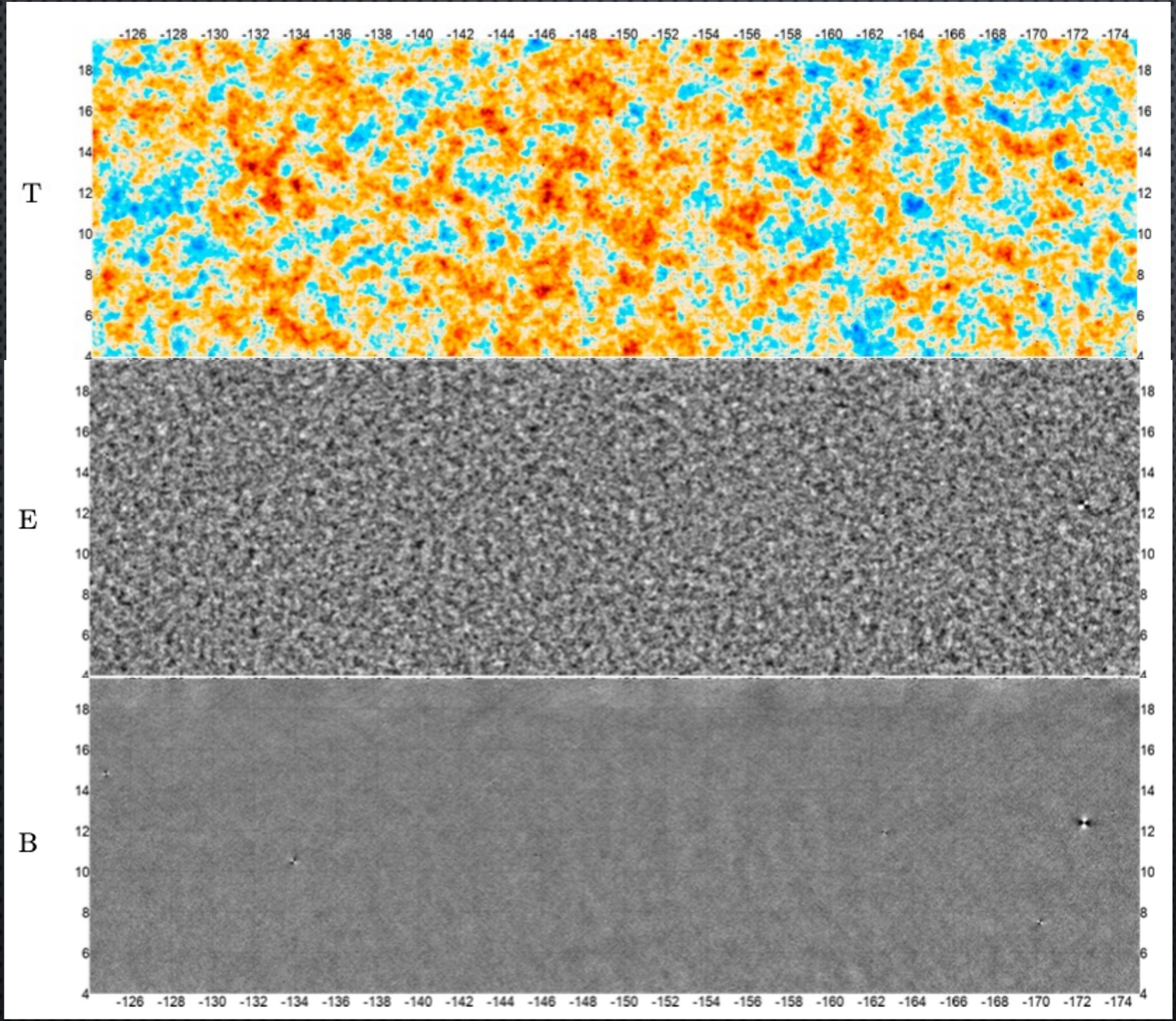
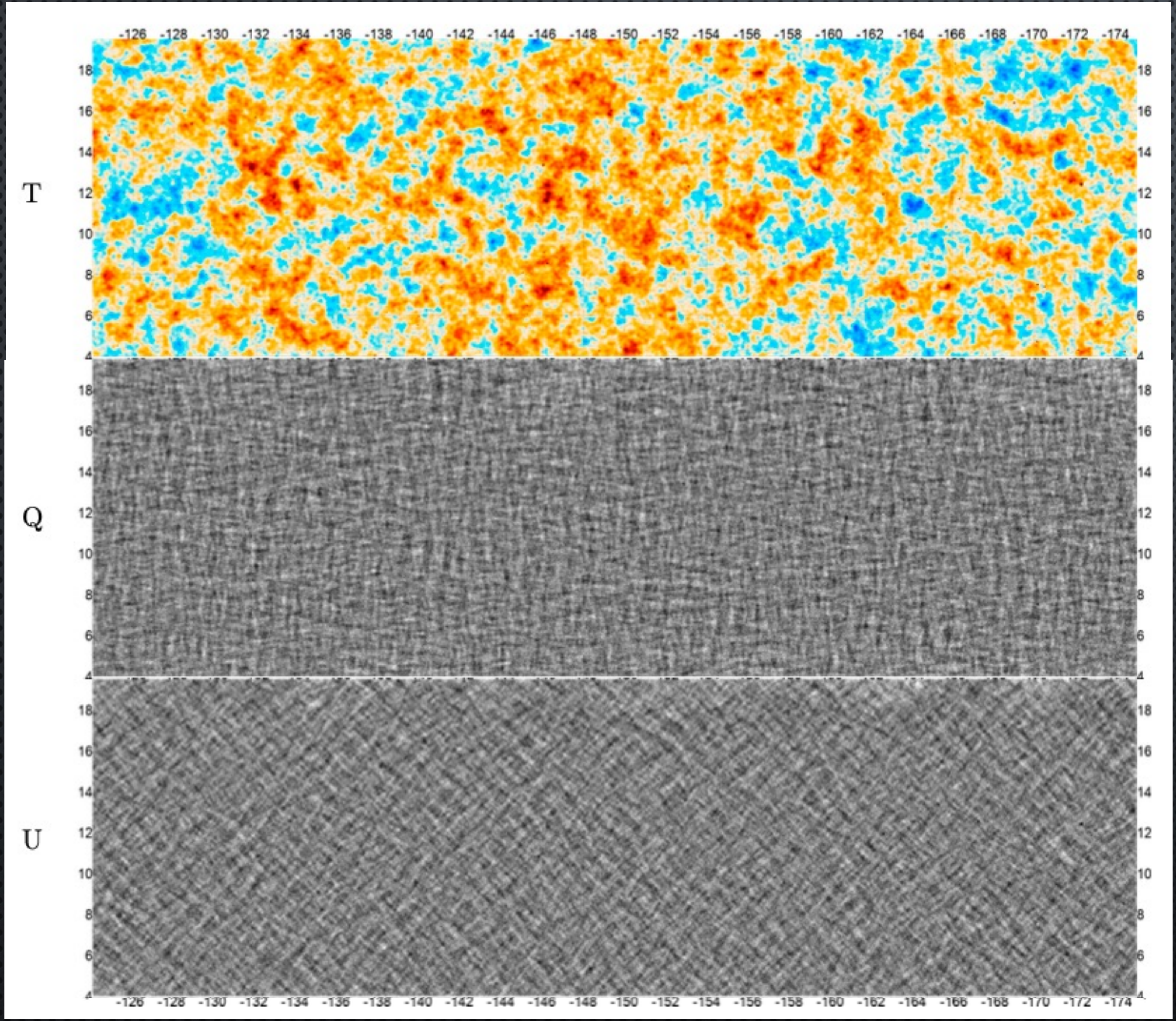


POLARIZATION
E & B
IRL

ACT maps
772 deg^2
(T map includes Planck)
Naess *et al*, 2020; JCAP 12, 046



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ANTICIPATED LIMITATIONS TO OVERCOME TO PURSUE PRIMORDIAL GRAVITATIONAL WAVE DETECTION

Signals are small

Instrumental systematics are not

(e.g. due to beams, I—>P & other polarization effects)

Celestial foregrounds are not

(direct contamination, masking impacts, onus on understanding bandpasses)

Local environmental contaminations are not

(e.g atmosphere, ground, Starlink)

Numbers of detectors and receivers needed are not

(use dilution fridges, high multiplexing factors, automated assembly)

Data sets are not

(simulations, rerunning analyses , keeping track of metadata & products are tough)

CHALLENGES
IN PURSUING PGWs
(A SUBSET)

Atmosphere

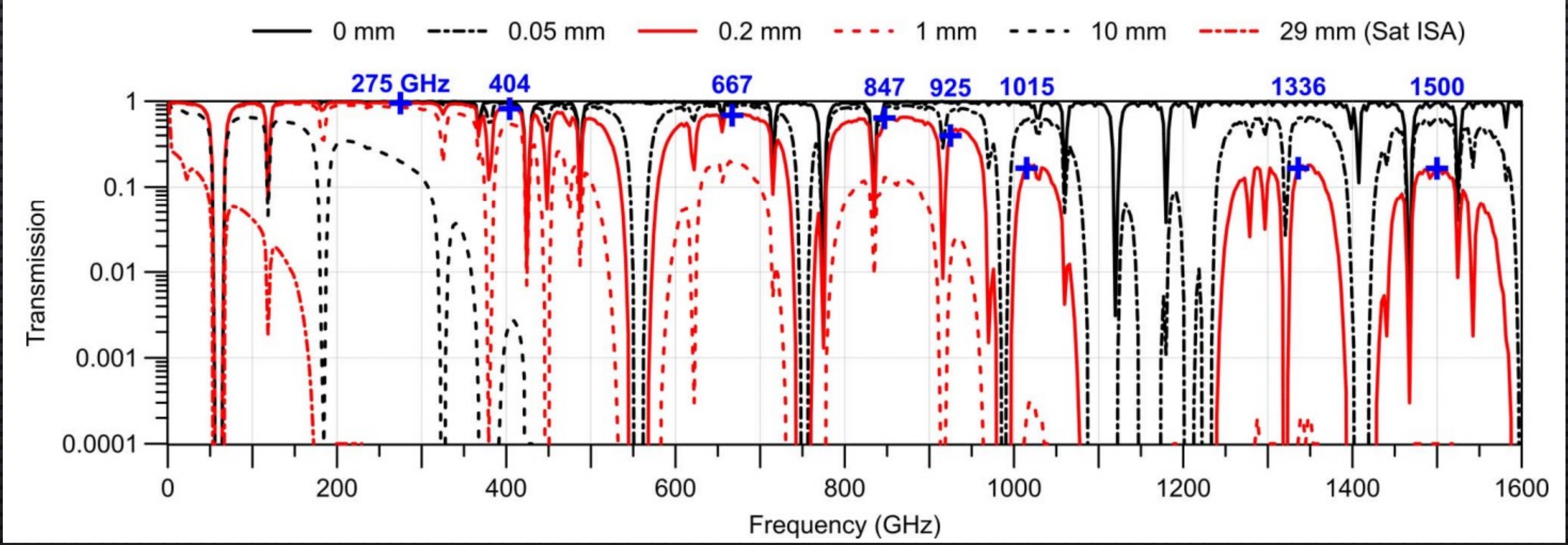
Production Capacity

Access

Problems Not Yet Dreamt Of

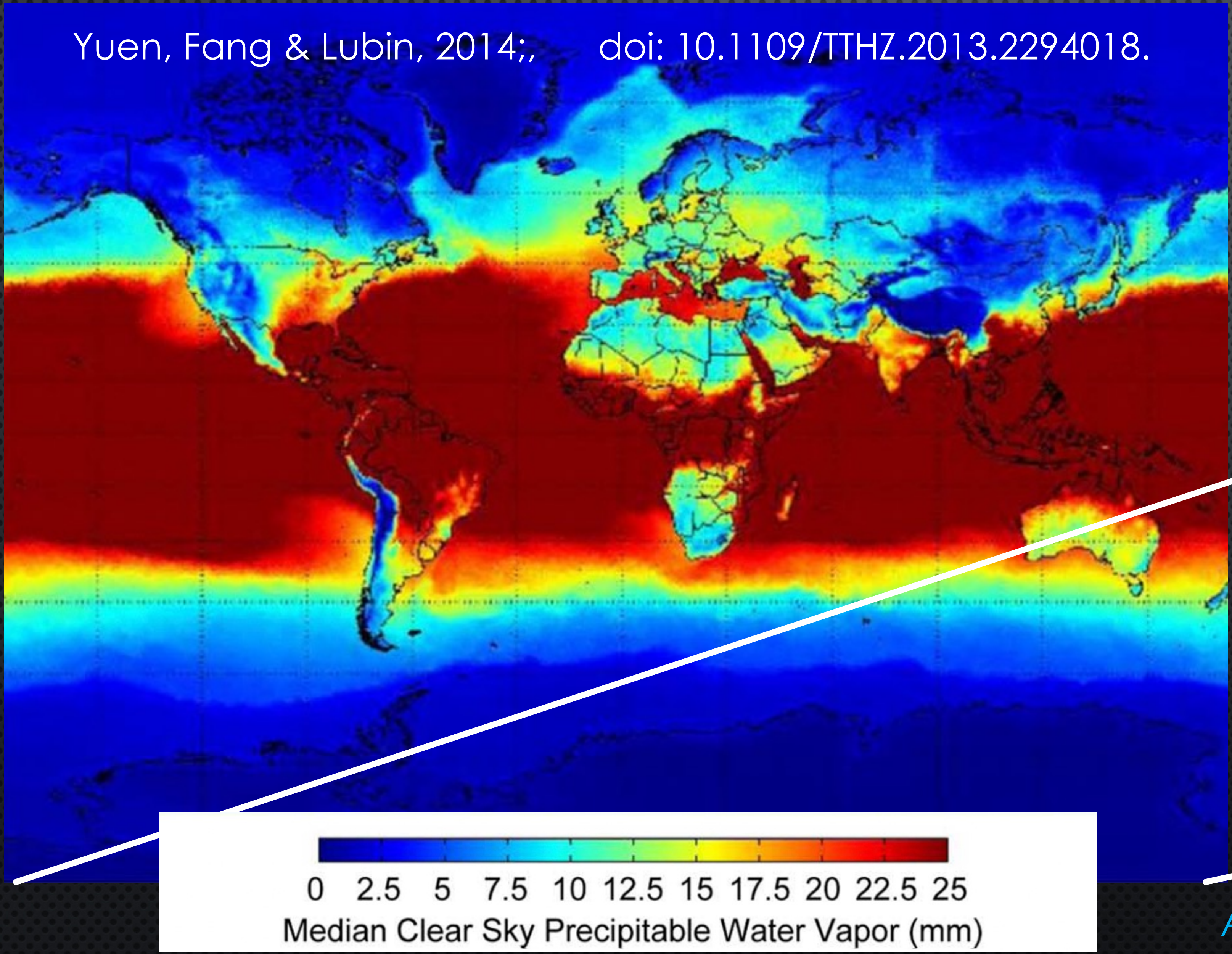
ATMOSPHERE. ATMOSPHERE. ATMOSPHERE. ATMOSPHERE.

It gets in the way.



Suen, Fang & Lubin, 2014;, doi: 10.1109/TTHZ.2013.2294018 (caveat regarding 0 mm model)

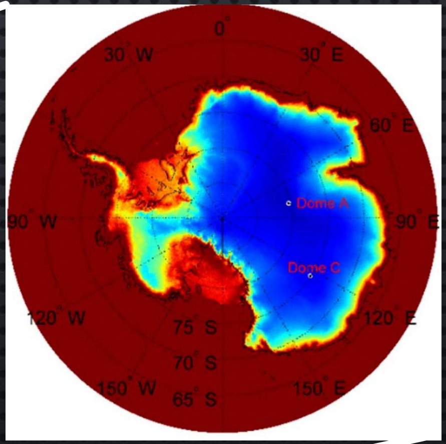
ATMOSPHERE. ATMOSPHERE. ATMOSPHERE. ATMOSPHERE.



It gets in the way.

Go dry or go home!

Except for f < 20 GHz



Atacama Desert

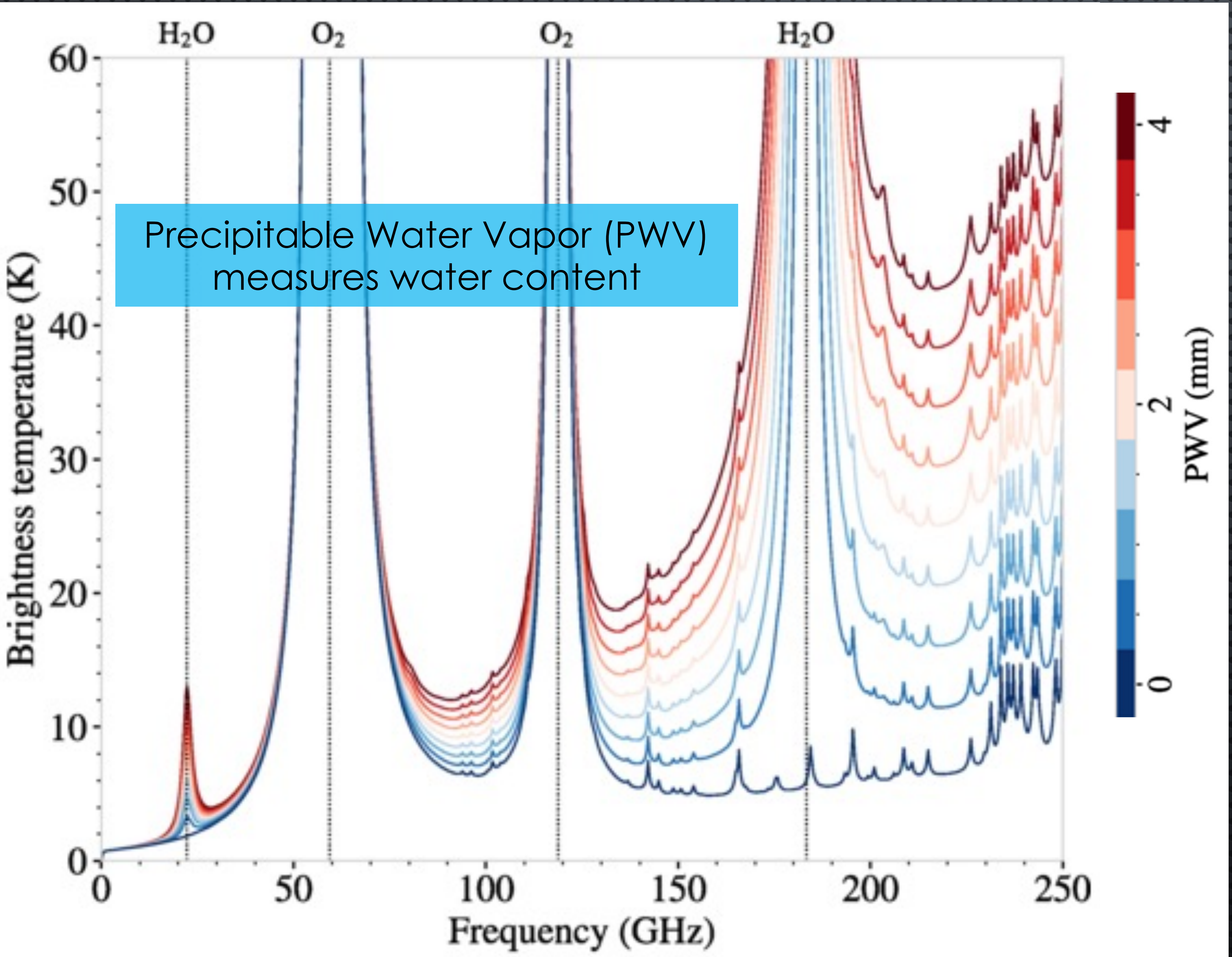
Antarctica

Tibetan Plateau

Greenland

Also see work by Denis Barkats +

ATMOSPHERE. ATMOSPHERE. ATMOSPHERE. ATMOSPHERE.



It gets in the way.

And it adds spurious signal.

Extra signal = extra loading.

The signal varies with elevation,

The signal is not constant.

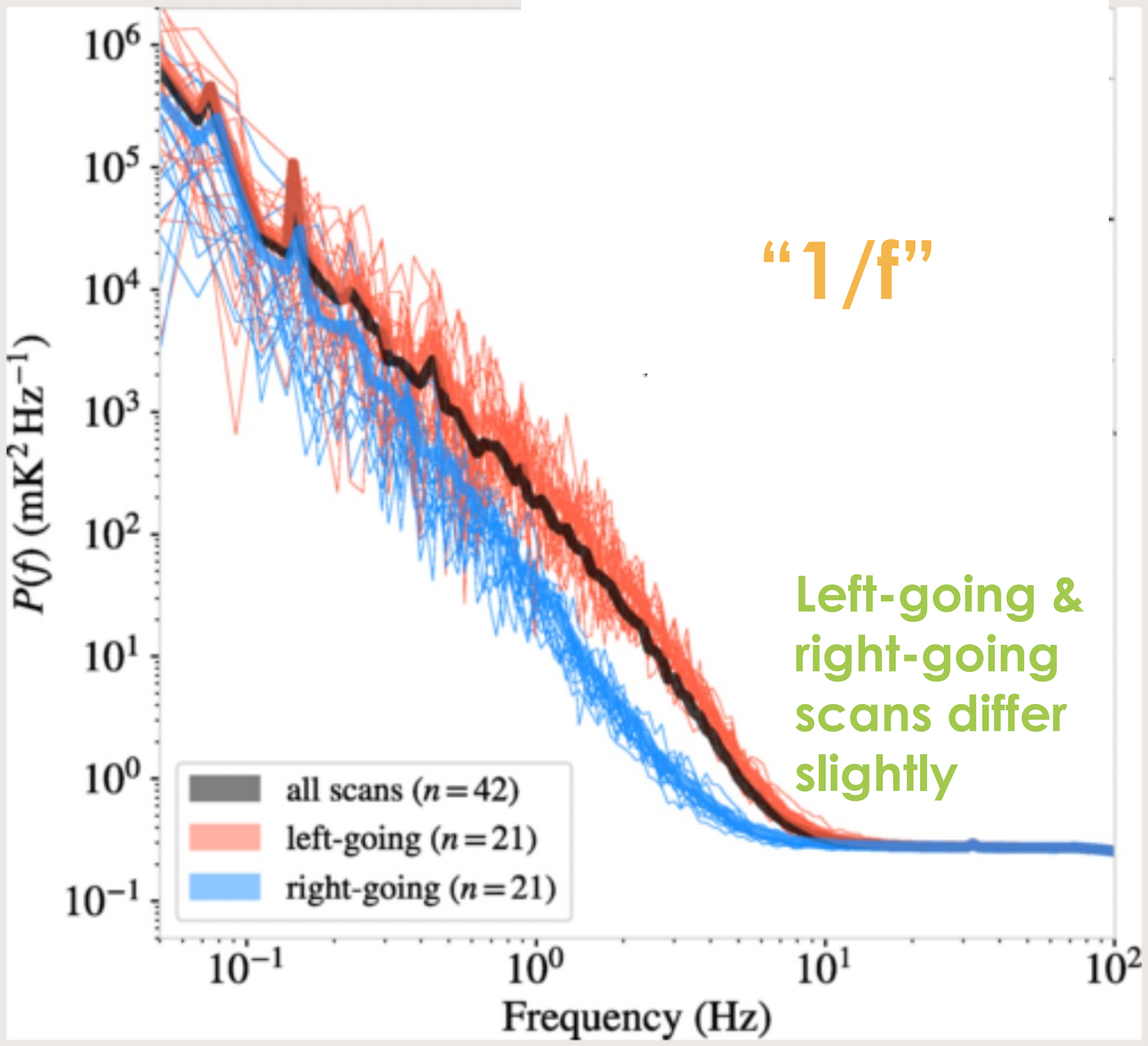
PWV varies with time.

PWV varies with position.

Atmospheric emission at world-class site (Atacama).

Figure adapted from Morris et al, 2022, PRD 105, 042004; using the am software (S. Paine, 10.5281/ zenodo.5794521)

ATMOSPHERE. ATMOSPHERE. ATMOSPHERE. ATMOSPHERE.



"1/f"

Left-going & right-going scans differ slightly

It gets in the way.

And it adds spurious signal.

Extra signal = extra loading.

The signal varies with elevation,

The signal is not constant.

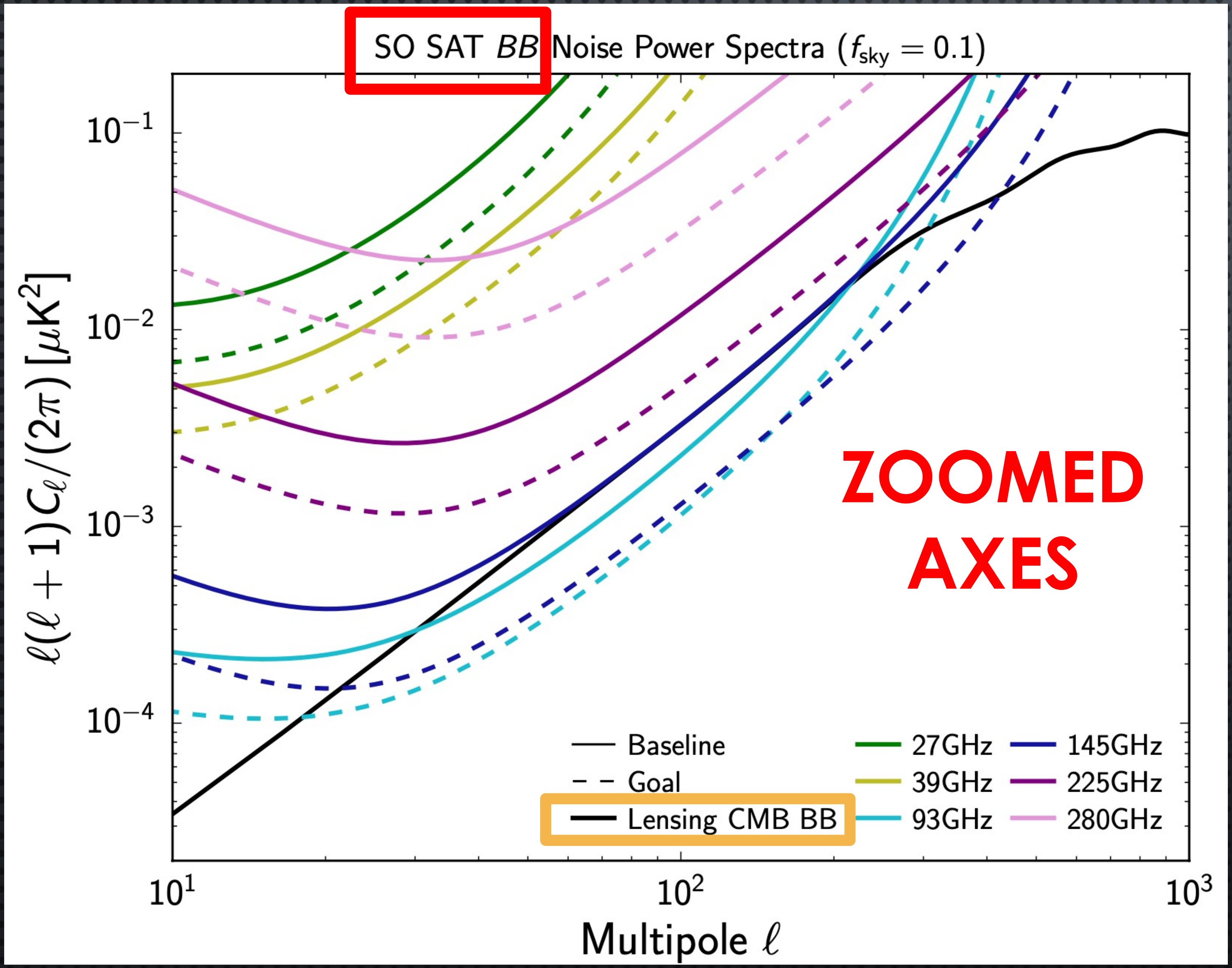
PWV varies with time.

PWV varies with position.

Data taken at 150 GHz with ACT scanning.

Morris et al, 2022, PRD 105, 042004;

PWV VARIATIONS LEAD TO EXTRA LOW-ELL NOISE



Polarization (BB)

Focus on solid dark blue 150 GHz curve

Simons Observatory (SO) includes telescopes (SATs) designed to look for PGWs.

This SO SAT noise model is based on multiple small aperture instruments. But; needs confirmation!

The beam is apparent at high ℓ and the atmosphere at low ℓ.

From SO Collaboration,'The Simons Observatory: Science Goals and Forecasts,' 2019 JCAP02(2019) 056.

CHALLENGES
IN PURSUING PGWs
(A SUBSET)

Atmosphere

Production Capacity

Access

Problems Not Yet Dreamt Of

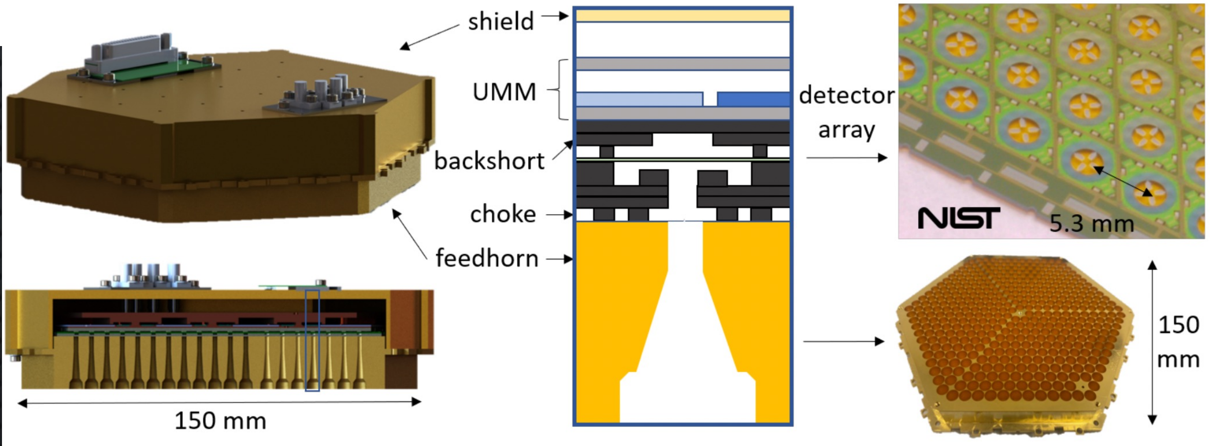
CHALLENGE OF ATMOSPHERE → MORE DETECTORS

SO, BICEP Array, CMB-S4, Ali-CPT & others:
detector modules based on 150 mm detector wafers

Then, 100,000 detectors ~ 50-100 modules.

PARACHIAL EXAMPLE of SO:

PLAN: deploy 49 modules in the next 2 yrs.



McCarrick, Healy et al, 2021, for JLTP, arXiv:2112.01458

Each module has:
1 detector wafer
4 optical coupling wafers, aligned & glued
1 multi-layer interface ("routing") wafer
28 multiplexing chips

1 feedhorn array
1 high-precision mounting tray

1 lid
1 magnetic shield
2 PCBs, one with imbedded flex & MDM
4 coax connections
Pogo pins, tripod springs, washers, screws

Each module requires:
Precision gluing of parts (CTE alignments)
~ 12,000 aluminum wire bonds
~ 100 gold wire bods
Pre-assembly screening of most parts
Two stages of testing at 100 mK

CHALLENGE OF ATMOSPHERE → MORE DETECTORS

Aphorism: Detectors define the critical path for CMB experiments.

Hypothesis: Detector R&D defines the critical path for CMB experiments
Aim: Get past the R&D and move into production mode

Context for Production rates including R&D:
ACT: 10 O(1000) detector modules produced over 15 yrs [0.7/ yr]
SO: 39 O(2000) detector modules (+ 10 O(200) modules) over 5 yrs [8/ yr]

Punchline: Hypothesis looks good so far! CMB-S4 will be the next test.

MORE DETECTORS → HUGE RECEIVERS + HIGH THROUGHPUT PRODUCTION OF OPTICS

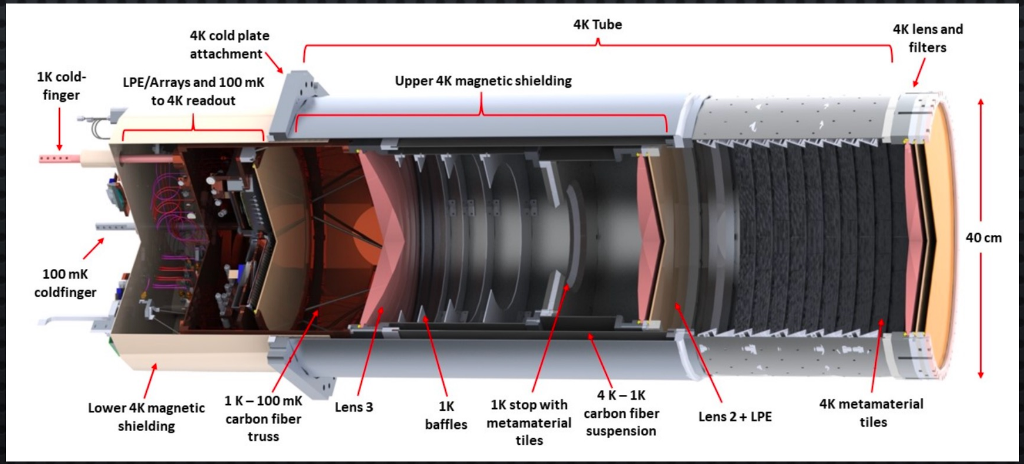
SO LAT Receiver
2.4 m dia

SO LAT holds 13 optics tubes (36-cm)

Each has: 3 AR-coated silicon lenses, 1 AR-coated window, 1 AR-coated alumina filter, and free-space filters

Each SO SAT (42 cm stop) has the same elements + an extra AR-coated alumina filter and an AR-coated sapphire HWP

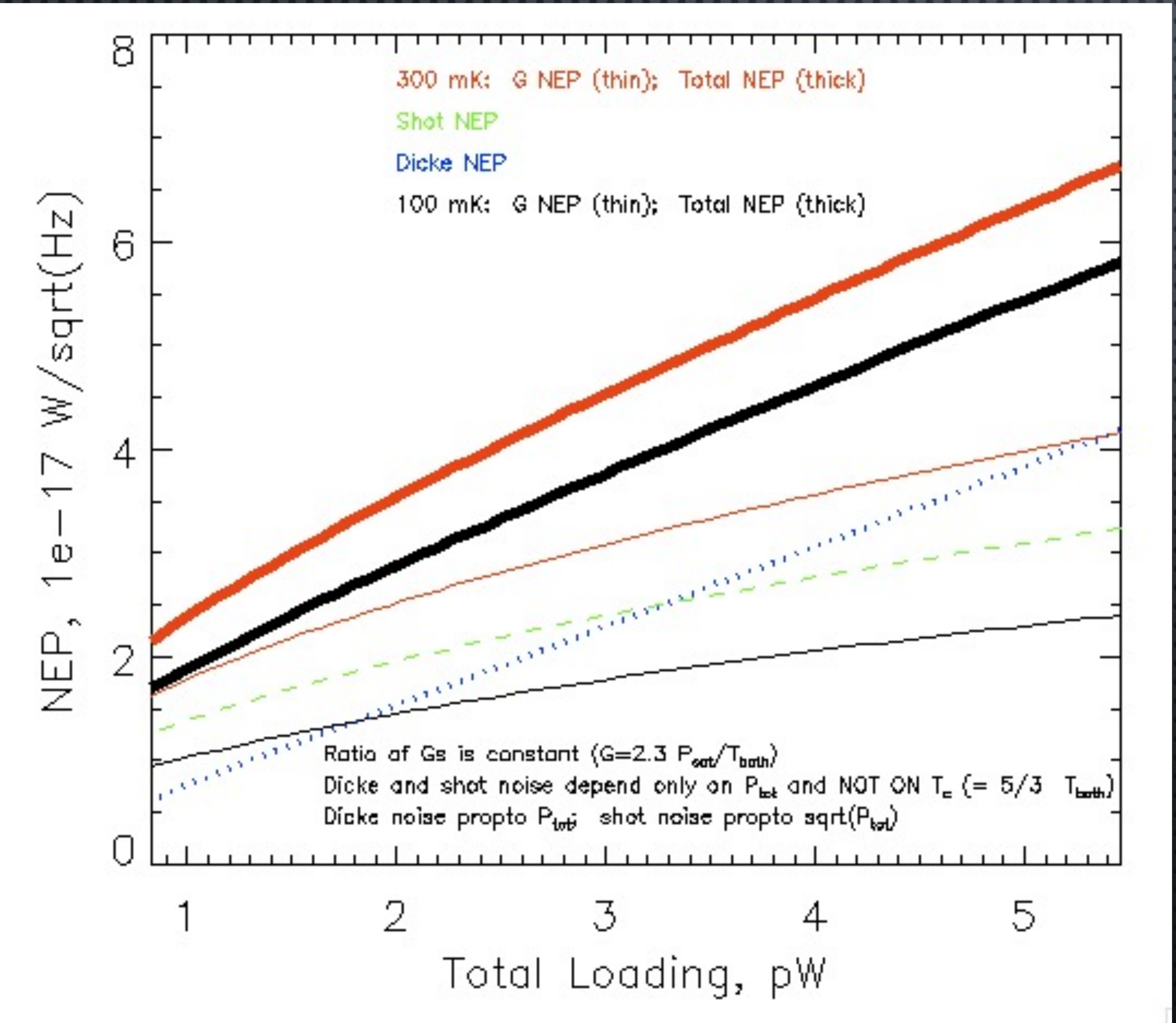
BICEP ARRAY & CMB-S4 also need many AR-coated optical elements!



It could be worse
if not for DRs!

Xu et al, 2020; SPIE 11453, doi:10.1117/12.2576151.

DETECTOR SENSITIVITIES: 100 mK & "BACKGROUND LIMITED"



MODERN PULSE-TUBE BACKED DILUTION FRIDGES ARE EASIER TO USE THAN 3He SYSTEMS (more cooling power – 100-300 uW typical at 100 mK)

We've been running one at 17kft in Chile since 2012.

CHALLENGES

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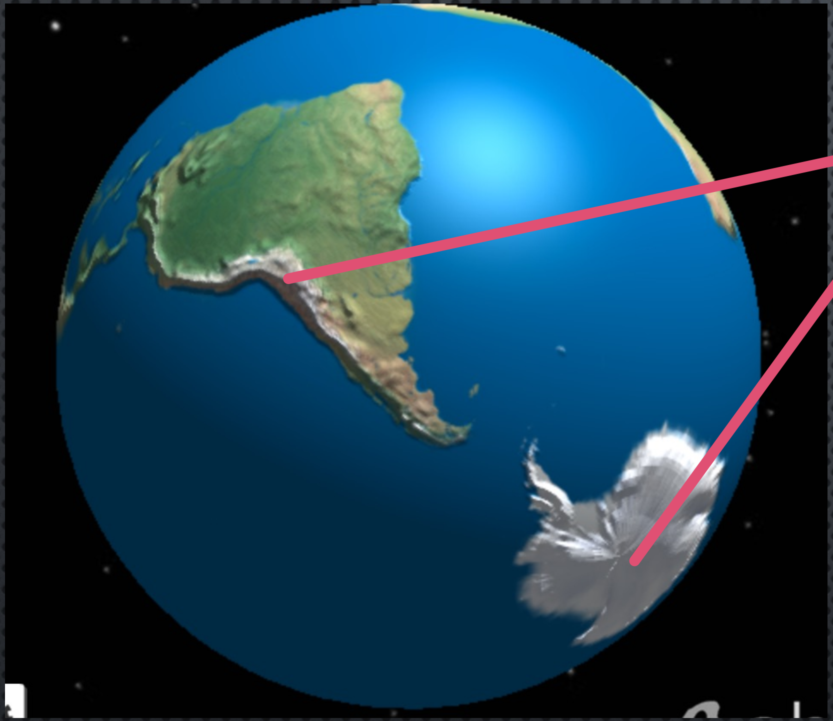
CHALLENGE OF ATMOSPHERE → SPECIFIC SITES



Great for observations but remote and with complicated stakeholder situations

- Remote → off the grid
  - Diesel is not cheap nor particularly green
  - Expanding power supply requires civil construction not just $$ to the electric company
- Access for personnel
  - South Pole – (only a) small on-site team has good year-round access to instrument
  - Chile – easy year-round access for entire team, but the instrument site itself is not always accessible

Distributed workforce

- Safety, communications, hiring, shipping

Challenge: a difficult or demanding task, esp. one seen as a test of one's abilities or character

CHALLENGES

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END SLIDE
STAGGS LAB AUGUST 2022


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