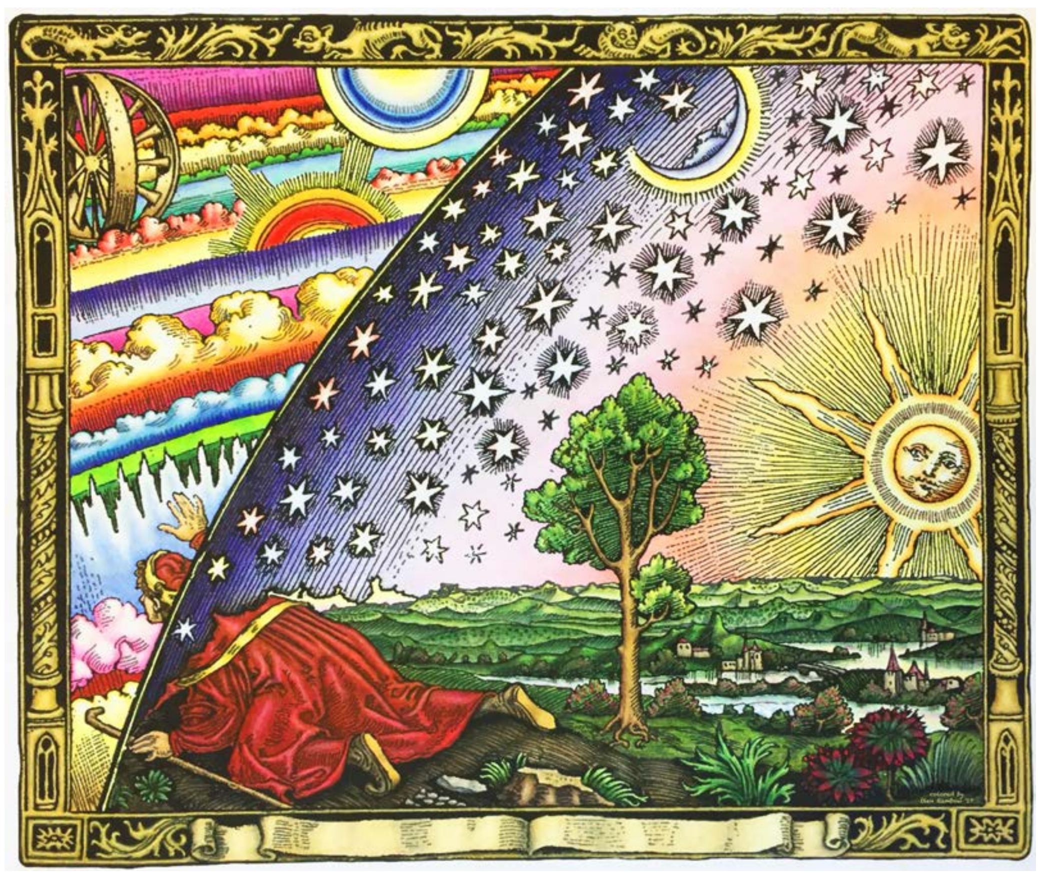
The CMB: What have we learned and what will we learn?

Adrian T. Lee
Department of Physics
Lawrence Berkeley National Laboratory

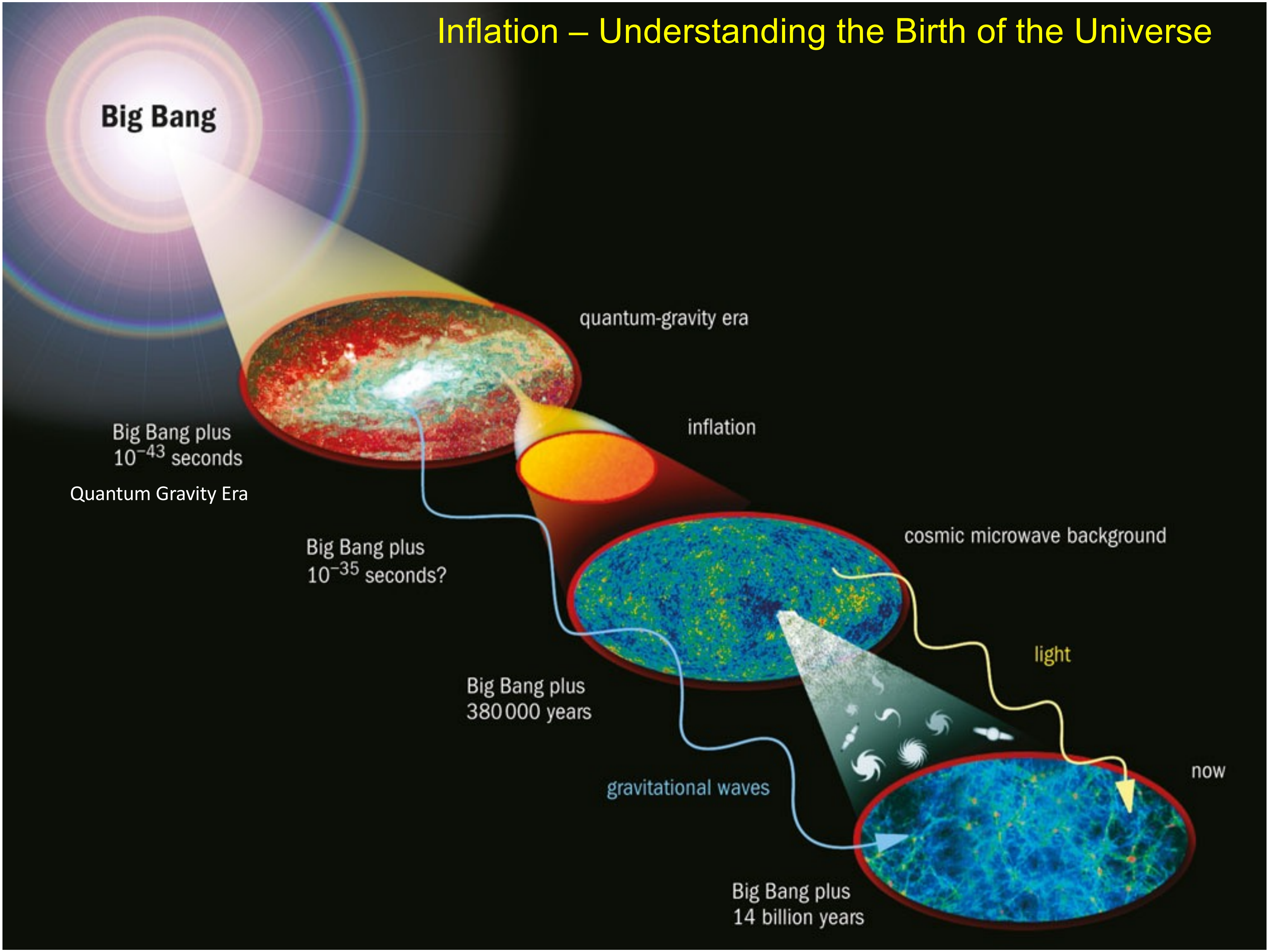


Flammarion engraving 1888

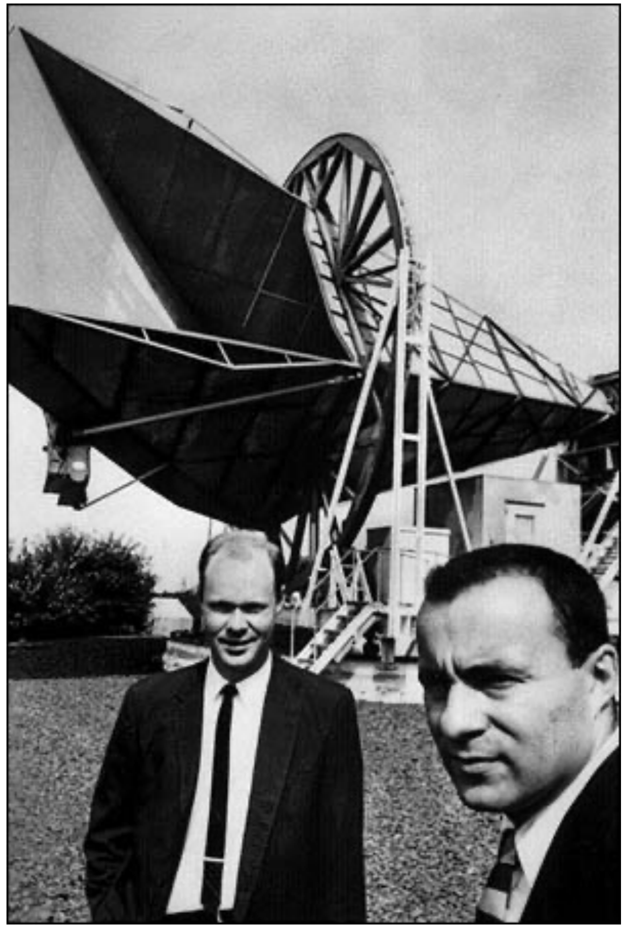
My talk

- I will talk about the past, present, and future of observations of the CMB.
- I will discuss the instrumentation built to observe the CMB.
- I will what we have learned and what we hope to learn from observing the CMB.

Inflation – Understanding the Birth of the Universe



Cosmic Microwave Background
First Discoveries



- 1948 Gamow predicts temperature of CMB
- 1965 Penzias and Wilson discover CMB

1941

PUBLICATIONS

OF THE

Dominion Astrophysical Observatory

VICTORIA, B.C.

Volume VII, No. 15

MOLECULAR LINES FROM THE LOWEST STATES OF DIATOMIC MOLECULES COMPOSED OF ATOMS PROBABLY PRESENT IN INTERSTELLAR SPACE

BY ANDREW McKELLAR

ABSTRACT.—Attention is directed to the recent spectrographic observations of W. S. Adams by which he detected in the spectrum of the early class B star, ζ *Ophiuchi*, several sharp lines from the lowest states of the CH and CN molecules. The detection of these lines of apparent interstellar origin, the presence of which was predicted by the writer on the basis of proposed molecular identifications, has provided definite evidence of the correctness of these identifications and of the presence of CH and CN in interstellar space. Comment is then made upon the possibility that other unidentified interstellar lines may be due to absorption by diatomic molecules.

In the second section of the publication a brief summary is given of the observational work and the discussions in connection with the presence of molecules in interstellar space, culminating in the results of Adams mentioned above.

The third section presents the results of a systematic examination of laboratory data for the purpose of obtaining the wave-lengths of the possible molecular interstellar lines, namely the lines arising from the lowest states, of over twenty-five of the more common diatomic molecules. These wave-lengths, obtained from some fifty articles on the analysis of band spectra, are given in tabular form.

The fourth and final section opens with a list of all the interstellar lines known at present. It is emphasized that spectrograms taken with the relatively powerful three-prism spectrograph at Victoria have barely revealed the sharp CH and CN lines under the most favourable conditions, and it is concluded that, to photograph these lines satisfactorily, a spectrograph with dispersion and resolving power comparable to the coudé instrument at the Mount Wilson Observatory is necessary.

The results of Adams, showing that only the lowest and next higher rotational states of CN are sufficiently populated to give interstellar lines, are of particular interest. They allow the determination of a "rotational" temperature for the region where the CN absorption takes place. This temperature, $2^{\circ}3K$, is compared with the temperatures estimated by Eddington for matter in interstellar space.

Evidence is put forward which indicates that, if the four as yet unidentified sharp interstellar lines* are due to absorption by diatomic molecules, these are probably hydrides. In the possible cases that the three strongest of these lines, or all four of them, are due to the same diatomic molecule, the vibrational constants of the upper electronic state concerned in the absorption by this hypothetical molecule are calculated. These constants are found to correspond reasonably closely to those of diatomic hydrides. Reasons are given for believing that, if Merrill's relatively diffuse interstellar lines in the yellow and red are due to diatomic molecules, these are probably molecules with neither very low nor very high moments of inertia, but those with intermediate values, for which the rotational constant B is around 0·5 to 1·0 cm.$^{-1}$

temperature for the region where the CN absorption takes place. This temperature, $2^{\circ}3K$, is compared with the temperatures estimated by Eddington for matter in interstellar space.

PHYSICAL REVIEW VOLUME 73, NUMBER 7 APRIL 1, 1948

Letters to the Editor

PUBLICATION of brief reports of important discoveries in physics may be secured by addressing them to this department. The closing date for this department is five weeks prior to the date of issue. No proof will be sent to the authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents. Communications should not exceed 600 words in length.

The Origin of Chemical Elements

R. A. ALPHER*
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland
AND
H. BETHE
Cornell University, Ithaca, New York
AND
G. GAMOW
The George Washington University, Washington, D. C.
February 18, 1948

AS pointed out by one of us,[1] various nuclear species must have originated not as the result of an equilibrium corresponding to a certain temperature and density, but rather as a consequence of a continuous building-up process arrested by a rapid expansion and cooling of the primordial matter. According to this picture, we must imagine the early stage of matter as a highly compressed neutron gas (overheated neutral nuclear fluid) which started decaying into protons and electrons when the gas pressure fell down as the result of universal expansion. The radiative capture of the still remaining neutrons by the newly formed protons must have led first to the formation of deuterium nuclei, and the subsequent neutron captures resulted in the building up of heavier and heavier nuclei. It must be remembered that, due to the comparatively short time allowed for this process,[1] the building up of heavier nuclei must have proceeded just above the upper fringe of the stable elements (short-lived Fermi elements), and the present frequency distribution of various atomic species was attained only somewhat later as the result of adjustment of their electric charges by β-decay.

Thus the observed slope of the abundance curve must not be related to the temperature of the original neutron gas, but rather to the time period permitted by the expansion process. Also, the individual abundances of various nuclear species must depend not so much on their intrinsic stabilities (mass defects) as on the values of their neutron capture cross sections. The equations governing such a building-up process apparently can be written in the form:

$$\frac{dn_i}{dt}=f(t)(\sigma_{i-1}n_{i-1}-\sigma_i n_i) \quad i=1,2,\cdots 238, \qquad (1)$$

where n_i and σ_i are the relative numbers and capture cross sections for the nuclei of atomic weight i, and where $f(t)$ is a factor characterizing the decrease of the density with time.

We may remark at first that the building-up process was apparently completed when the temperature of the neutron gas was still rather high, since otherwise the observed abundances would have been strongly affected by the resonances in the region of the slow neutrons. According to Hughes,[2] the neutron capture cross sections of various elements (for neutron energies of about 1 Mev) increase exponentially with atomic number halfway up the periodic system, remaining approximately constant for heavier elements.

Using these cross sections, one finds by integrating Eqs. (1) as shown in Fig. 1 that the relative abundances of various nuclear species decrease rapidly for the lighter elements and remain approximately constant for the elements heavier than silver. In order to fit the calculated curve with the observed abundances[3] it is necessary to assume the integral of $\rho_n dt$ during the building-up period is equal to 5×10^4 g sec./cm³.

On the other hand, according to the relativistic theory of the expanding universe[4] the density dependence on time is given by $\rho\cong10^6/t^2$. Since the integral of this expression diverges at $t=0$, it is necessary to assume that the building-up process began at a certain time t_0, satisfying the relation:

$$\int_{t_0}^{\infty}(10^6/t^2)dt\cong5\times10^4, \qquad (2)$$

which gives us $t_0\cong20$ sec. and $\rho_0\cong2.5\times10^5$ g sec./cm³. This result may have two meanings: (a) for the higher densities existing prior to that time the temperature of the neutron gas was so high that no aggregation was taking place, (b) the density of the universe never exceeded the value 2.5×10^5 g sec./cm³ which can possibly be understood if we

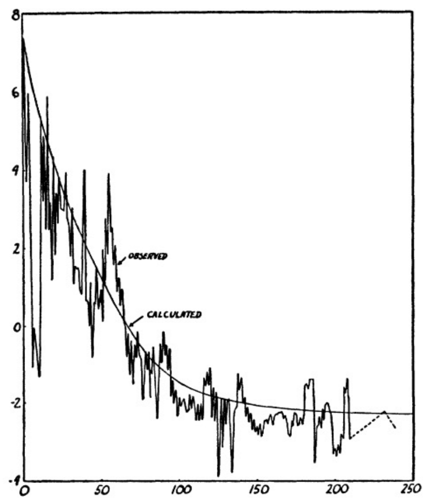


FIG. 1.
Log of relative abundance
Atomic weight

George Gamow

Alpher and Herman 1948

Osaka University,
Osaka.
July 15.

[1] Brockway and Robertson, *J. Chem. Soc.*, 1324 (1939).
[2] Pauling, *Phys. Rev.*, **36**, 430 (1930).
[3] Spaght, Thomas and Parks, *J. Amer. Chem. Soc.*, **36**, 882 (1932).
[4] Smits and Muller, *Z. phys. Chem.*, B, **36**, 140 (1938).
[5] Smits, Pollender and Kröger, *Z. phys. Chem.*, B, **41**, 215 (1938).
[6] Bridgman, "Physics of High Pressure".
[7] White and Bishop, *J. Amer. Chem. Soc.*, **62**, 16 (1940).

Nitrogen Afterglow

In a recent communication in *Nature*, L. Herman and R. Herman[1] have given an account of their spectroscopic study of the complex afterglow in nitrogen immediately after the discharge is stopped. These short-lived afterglows have also been extensively studied by Kaplan[2]. In this connexion, Herman and Herman remark that it seems difficult to explain the characteristics of the complex afterglow as recorded by them with the help of the theory of active nitrogen proposed by me[3]. It appears, however, that these authors have missed the very important point that my theory was developed for the long-lived Lewis – Rayleigh afterglow, and not for the short-lived Kaplan afterglow, which is quite a distinct phenomenon. According to my hypothesis, the Lewis – Rayleigh afterglow phenomena, for example, the long life, the rate of decay, ionization, the characteristic spectrum (selected bands from the first positive group), etc., can be very satisfactorily explained if it is assumed that the active substance in the glow is $N_2^+(X')$ ions. The Kaplan afterglows, however, contain besides $N_2^+(X')$ ions other particles

Evolution of the Universe

In checking the results presented by Gamow in his recent article on "The Evolution of the Universe" [*Nature* of October 30, p. 680], we found that his expression for matter-density suffers from the following errors: (1) an error of not taking into account the magnetic moments in Eq. (7) for the capture cross-section, (2) an error in estimating the value of α by integrating the equations for deuteron formation (the use of an electronic analogue computer leads to $\alpha = 1$), and (3) an arithmetical error in evaluating ρ_0 from Eq. (9). In addition, the coefficient in Eq. (3) is 1·52 rather than 2·14. Correcting for these errors, we find

$$\rho_{\text{mat.}} = \frac{4{\cdot}83 \times 10^{-4}}{t^{3/2}}.$$

The condensation-mass obtained from this corrected density comes out not much different from Gamow's original estimate. However, the intersection point $\rho_{\text{mat.}} = \rho_{\text{rad.}}$ occurs at $t = 8{\cdot}6 \times 10^{17}$ sec. $\cong 3 \times 10^{10}$ years (that is, about ten times the present age of the universe). This indicates that, in finding the intersection, one should not neglect the curvature term in the general equation of the expanding universe. In other words, the formation of condensations must have taken place when the expansion was becoming linear with time.

Accordingly, we have integrated analytically the exact expression[1]:

$$\frac{dl}{dt} = \left[\frac{8\pi G}{3}\left(\frac{aT^4}{c^2} + \rho_{\text{mat.}}\right)l^2 - \frac{c^2 l_0^2}{R_0^2}\right]^{1/2},$$

with $T \propto 1/l$ and $R_0 = 1{\cdot}9 \times 10^9 \sqrt{-1}$ light-years. The integrated values of $\rho_{\text{mat.}}$ and $\rho_{\text{rad.}}$ intersect at a reasonable time, namely, $3{\cdot}5 \times 10^{14}$ sec. $\cong 10^7$ years, and the masses and radii of condensations at this time become, according to the Jeans' criterion, $M_c = 3{\cdot}8 \times 10^7$ sun masses, and $R_c = 1{\cdot}1 \times 10^3$ light-years. The temperature of the gas at the time of condensation was 600° K., and the temperature in the universe at the present time is found to be about 5° K.

We hope to publish the details of these calculations in the near future.

Our thanks are due to Dr. G. Gamow for the proposal of the topic and his constant encouragement during the process of error-hunting. We wish also to thank Dr. J. W. Follin, jun., for his kindness in performing the integrations required for the determination of α, on a Reeves Analogue Computer. The work described in this letter was supported by the United States Navy, Bureau of Ordnance, under Contract NOrd-7386.

RALPH A. ALPHER
ROBERT HERMAN

Applied Physics Laboratory,
Johns Hopkins University,
Silver Spring, Maryland.
Oct. 25.

[1] Gamow, G., *Phys. Rev.*, **70**, 572 (1946).

If we take a figure of $2{\cdot}4 \times 10^9$ years as a reasonable estimate of the age of the crust, it follows that the original amount of potassium-40 would have been 2^{10}, or about 1,000 times greater than the present amount. Of this quantity, approximately two-thirds would have been transformed to argon; that is, the total quantity of argon present in the surface materials of the earth should be about 430 times the known amount of argon in the atmosphere.

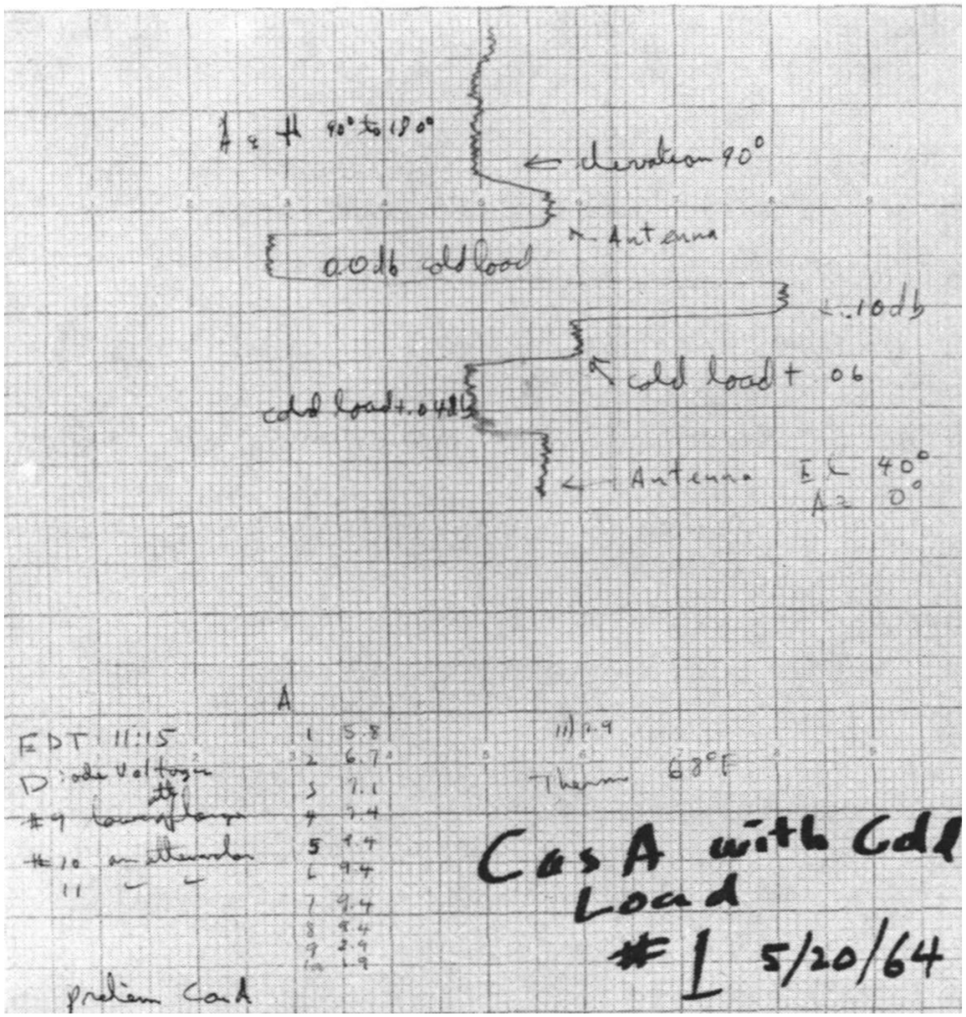
It might be assumed that the bulk of the argon generated in the solid crust was retained in the crust, but even this assumption will only reduce the discrepancy. From the quantity of sodium retained in the ocean, F. W. Clarke[5] estimates that an amount of solid material equal to about 5 per cent of the postulated shell has undergone erosion. It is hard to imagine that, if during this process the sodium was extracted from the rock, the argon would not also escape, and this process would supply a quantity of argon more than twenty times that of atmospheric argon. If, on the other hand, we assume that the argon of the atmosphere[4], which is 99·6 per cent A^{40}, is derived from the eroded layer only, we easily arrive at an age of the crust of about $1{\cdot}3 \times 10^9$ years, which differs by a factor of about 2 from the accepted estimates of geological ages. A correction to these results should be applied for the amount of argon in solution in the ocean; but it can easily be shown that this correction is of no importance.

Two other possibilities may be considered: (1) that

light-years. The temperature of the gas at the time of condensation was 600° K., and the temperature in the universe at the present time is found to be about 5° K.

We hope to publish the details of these calculations in the near future.

Penzias and Wilson



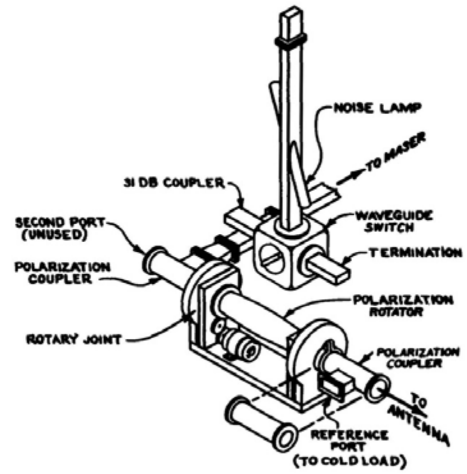


Fig. 4. Radiometer used with horn reflector.

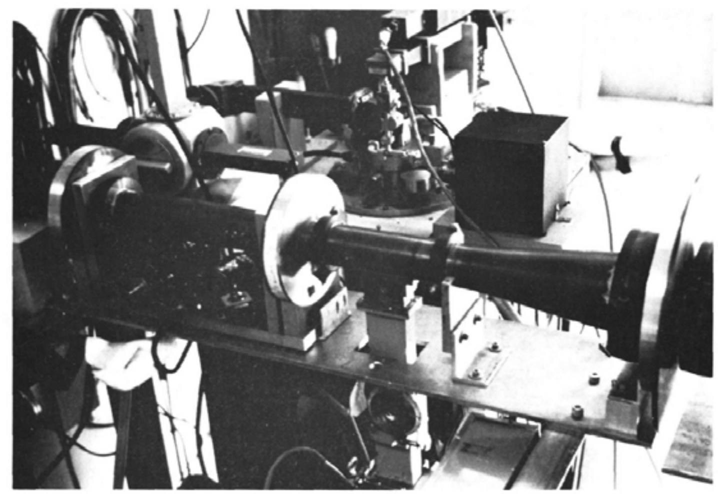


Fig. 5. Rotary Joint.

Spectrum 1983

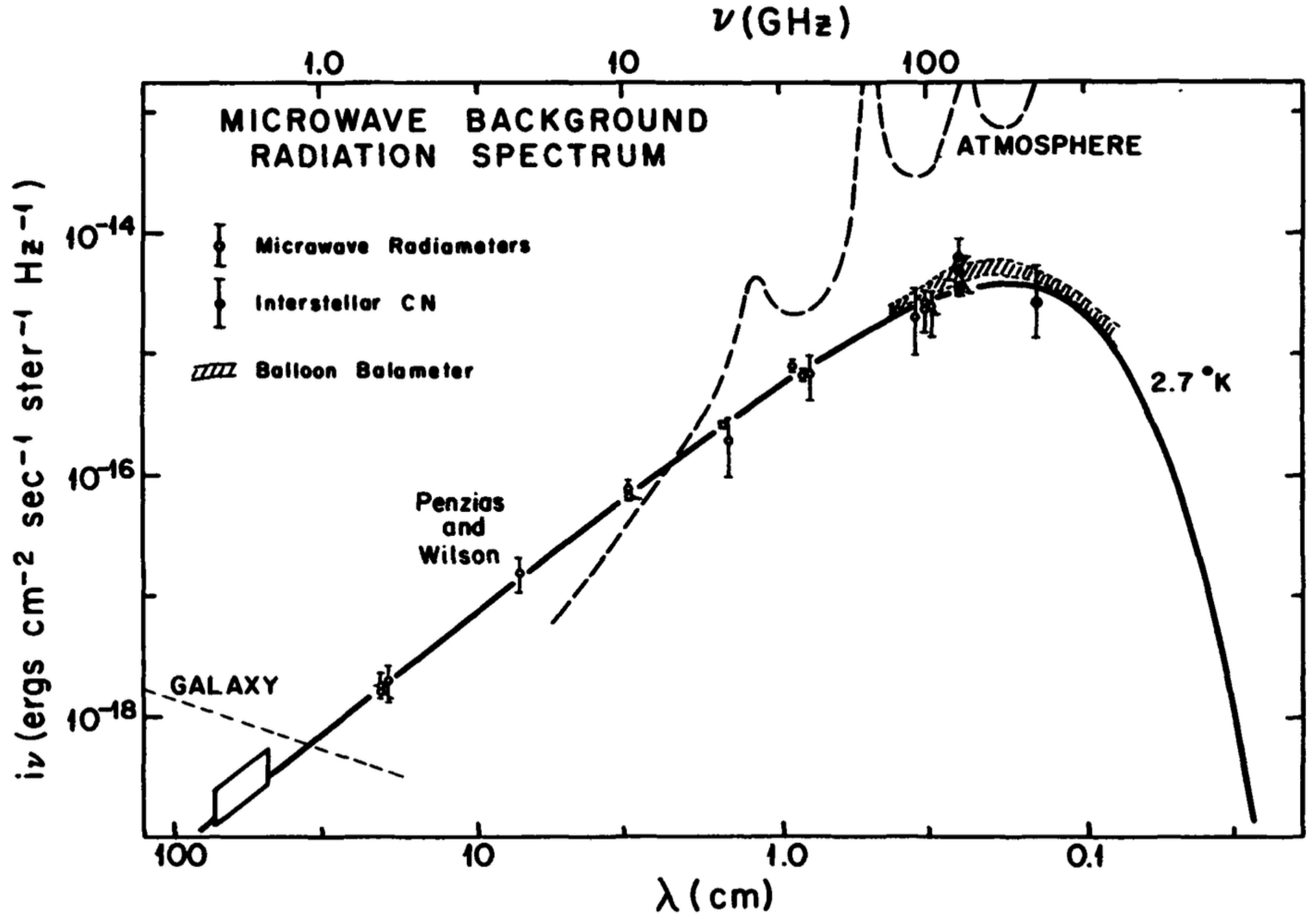


Fig. 3. Measurements of the intensity of the microwave background. Most measurements, by many groups around the world, are in reasonable agreement with the 2.7 K blackbody spectrum.

D. Wilkinson

Anisotropy 1983

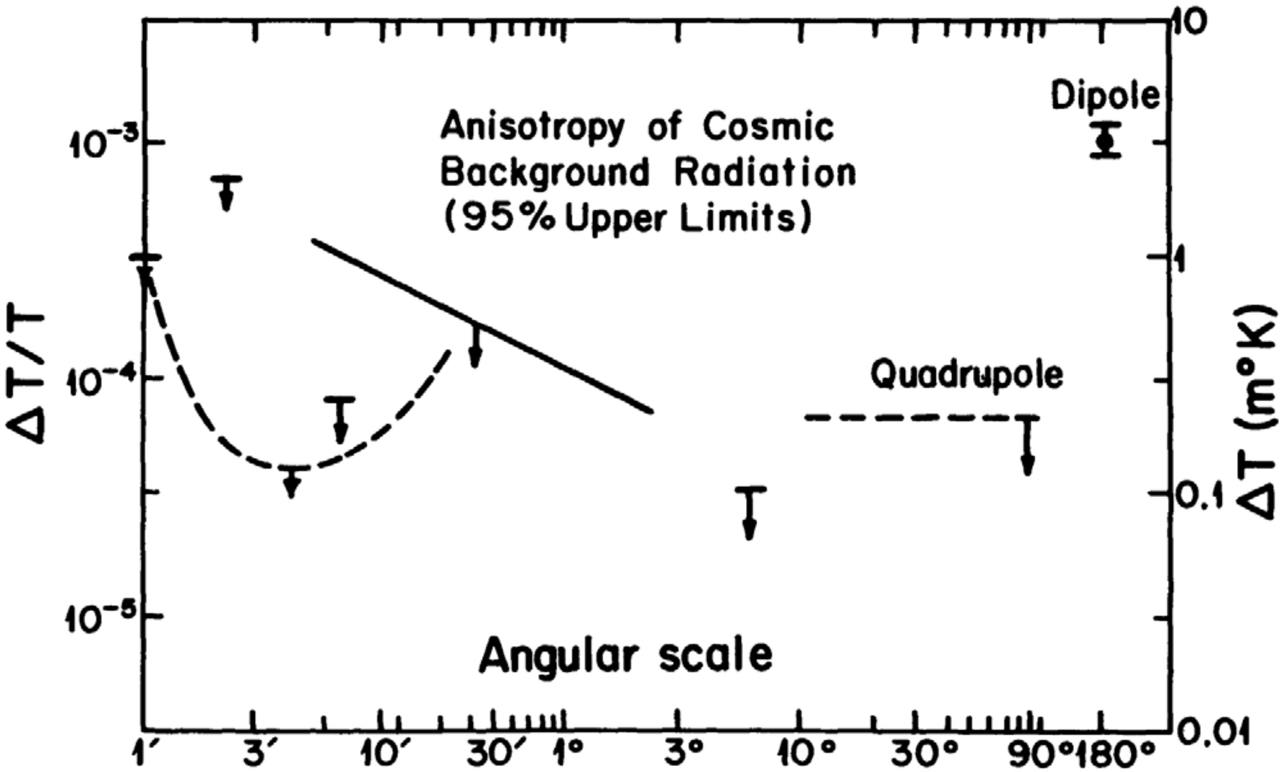


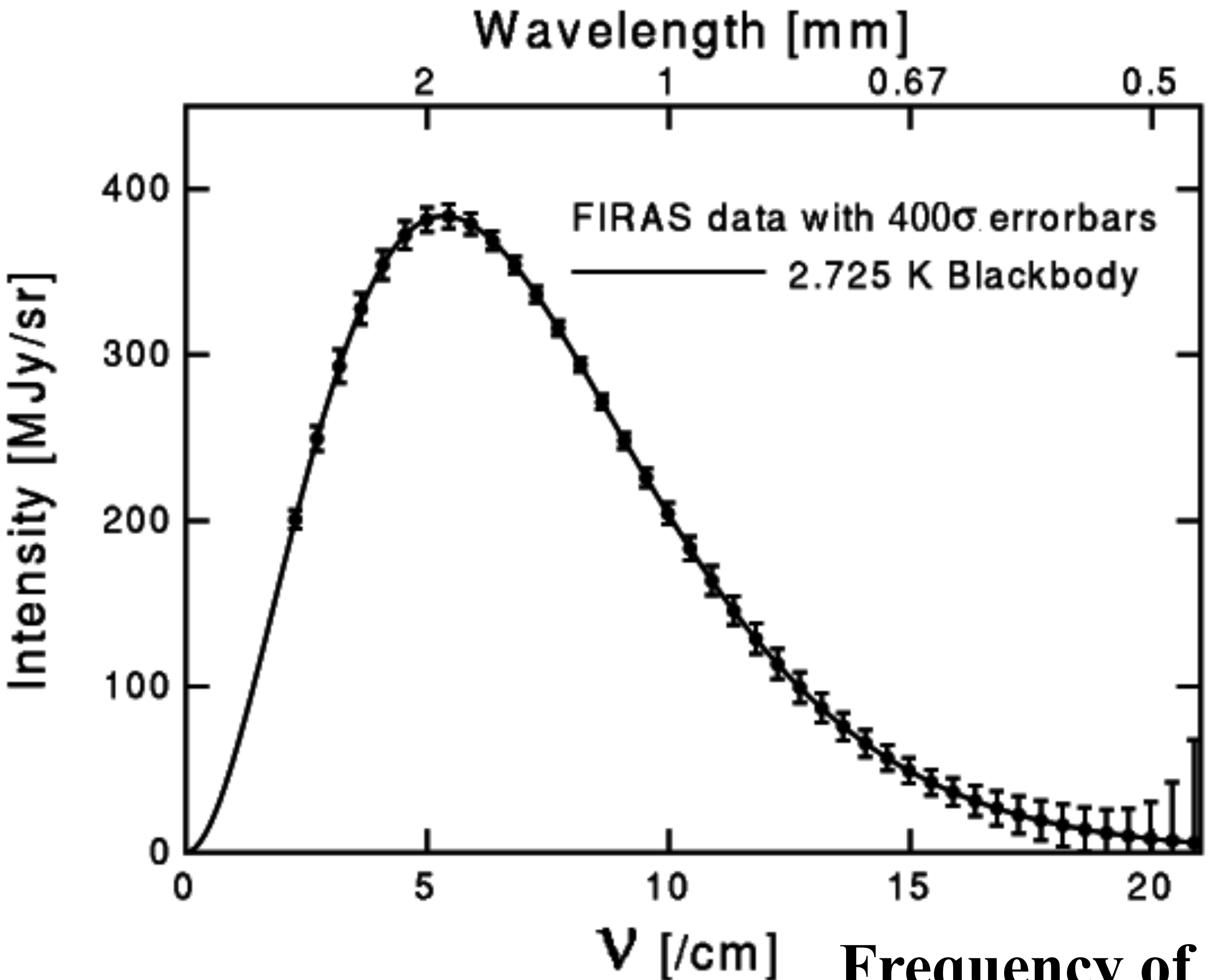
Fig. 4. Modern upper limits on spatial structure in the Fireball. The measurement at 4.5' was made at Green Bank, about 1 Km from the meeting site.

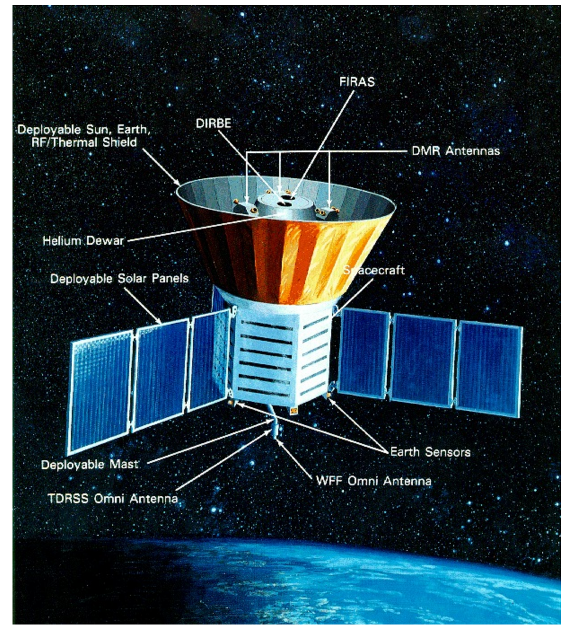
embarrassing. When the universe was about 10^6 years old, the matter started to form clumps, now seen as galaxies, galaxy clusters, etc. That process should have left bumps of magnitude $\Delta T/T \sim 10^{-4}$ to 10^{-5}, which haven't yet been seen. Incidentally, the dipole in Figure 4 is mostly due to the Sun's

D. Wilkinson

The CMB spectrum as seen by COBE/FIRAS (1992)

- **The most perfect blackbody curve ever measured**
- **Exactly what is predicted by the Big Bang**





Frequency of light

SCIENTIFIC RESULTS FROM COBE

1991

C. L. Bennett,* N. W. Boggess,* E. S. Cheng,* M. G. Hauser,* T. Kelsall,* J. C. Mather, S. H. Moseley, Jr.,* T. L. Murdock,** R. A. Shafer,* R. F. Silverberg,* G. F. Smoot,*** R. Weiss† and E. L. Wright‡

** NASA Goddard Space Flight Center, Code 685, Greenbelt, MD 20771, USA*
*** General Research Corporation, 5 Cherry Hill Drive, Danvers, MA 01923, USA*
**** Building 50-351, Lawrence Berkeley Laboratories, Berkeley, CA 94720, USA*
† MIT Department of Physics, Room 20F-001, Cambridge, MA 02139, USA
‡ Astronomy Department, UCL, Los Angeles, CA 90024, USA

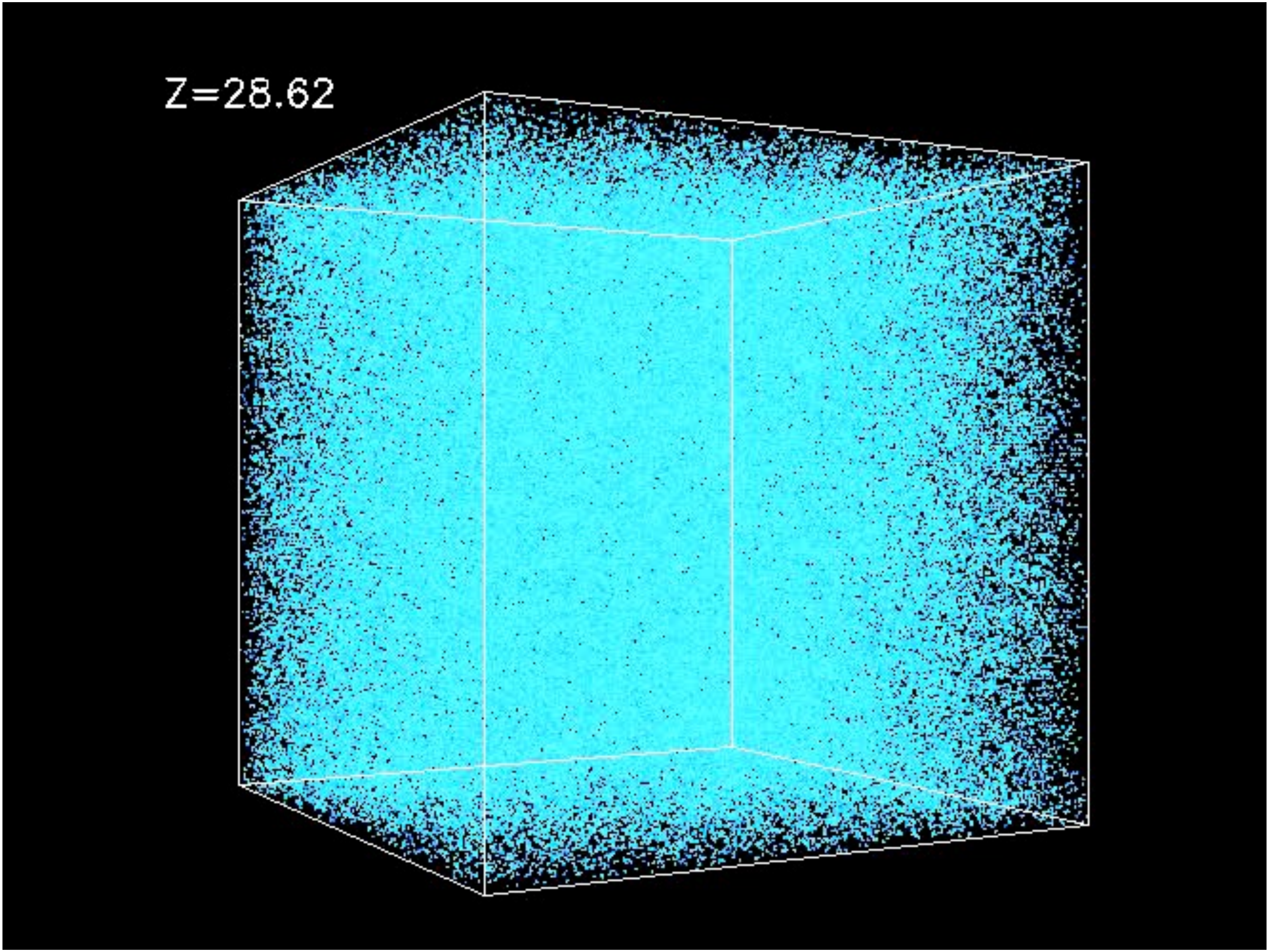
ABSTRACT

NASA's Cosmic Background Explorer (*COBE*[1]) carries three scientific instruments to make precise measurements of the spectrum and anisotropy of the cosmic microwave background (CMB) radiation on angular scales greater than 7° and to conduct a search for a diffuse cosmic infrared background (CIB) radiation with 0.7° angular resolution. Data from the Far-InfraRed Absolute Spectrophotometer (FIRAS) show that the spectrum of the CMB is that of a blackbody of temperature T=2.73±0.06 K, with no deviation from a blackbody spectrum greater than 0.25% of the peak brightness. The first year of data from the Differential Microwave Radiometers (DMR) show statistically significant CMB anisotropy. The anisotropy is consistent with a scale invariant primordial density fluctuation spectrum. Infrared sky brightness measurements from the Diffuse InfraRed Background Experiment (DIRBE) provide new conservative upper limits to the CIB. Extensive modeling of solar system and galactic infrared foregrounds is required for further improvement in the CIB limits.

Interpretation of the DMR Anisotropy

The anisotropy detected by the DMR is interpreted as being a direct result of primordial fluctuations in the gravitational potential. Assuming a power spectral density of density fluctuations of the form $P(k) = Ak^n$, the best-fit results are $n = 1.1 \pm 0.5$ with $Q_{rms-PS} = 16 \pm 4$ μK. Q_{rms-PS} is the rms quadrupole amplitude resulting from this power spectrum fit, i.e. making use of

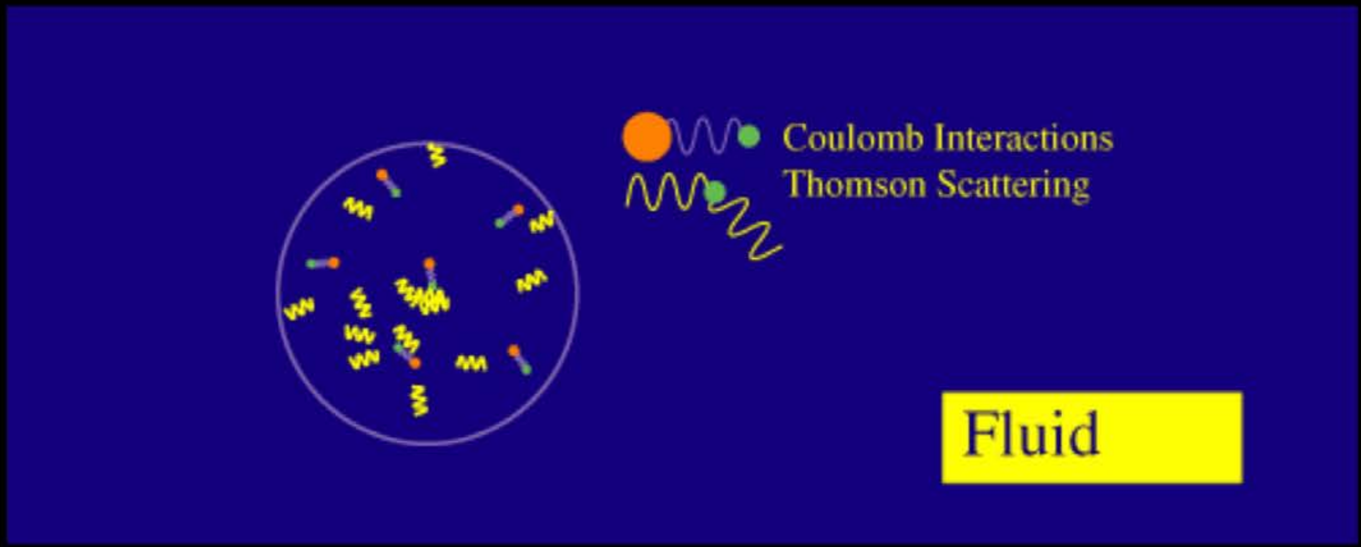
CMB Temperature Fluctuations


Z=28.62

Sound waves and acoustic oscillations

In this photon-baryon (proton) plasma

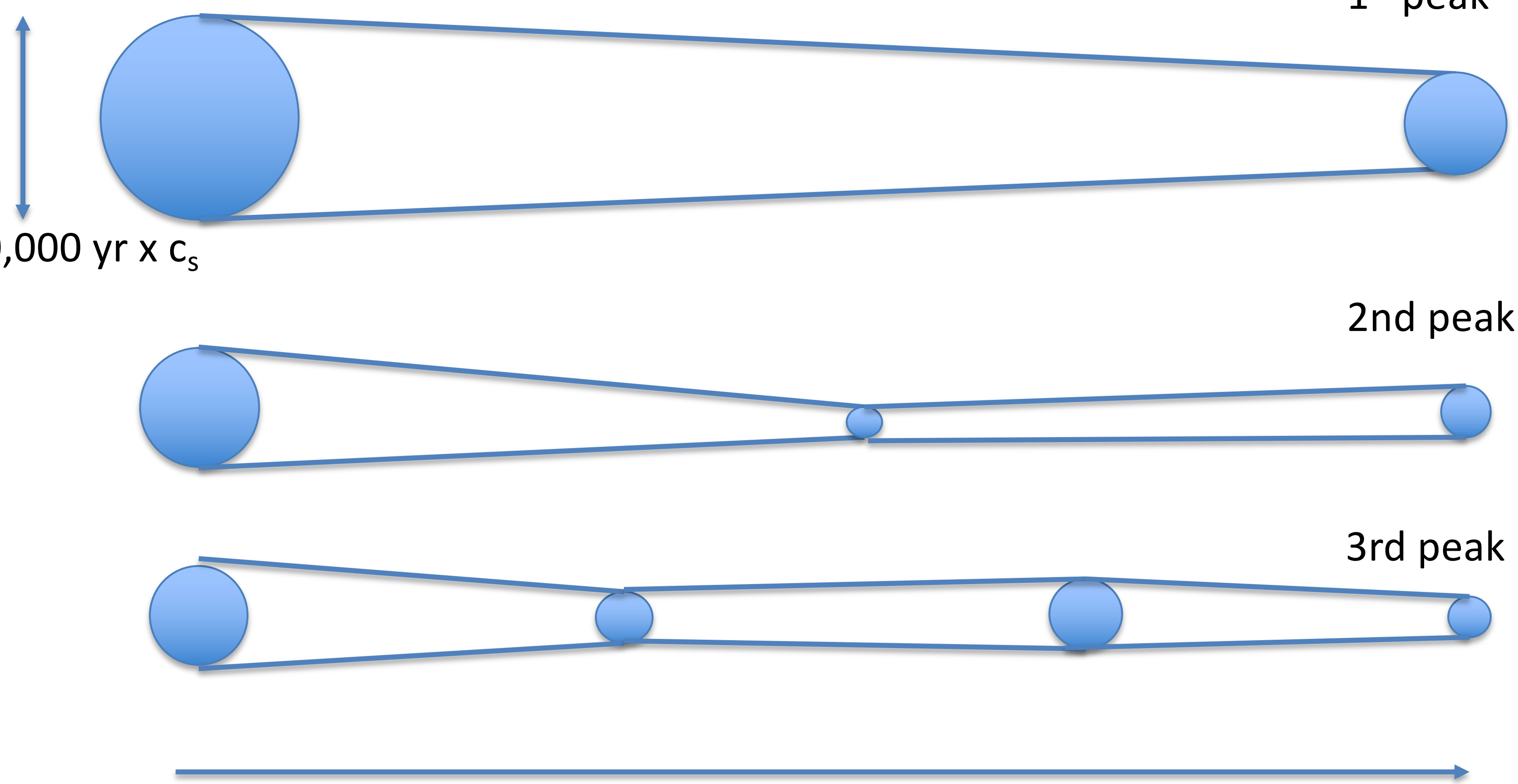
- Photons provide radiation pressure
- Pressure opposes the squeezing or compression of the fluid
- Resulting oscillations are called sound waves or acoustic oscillations



By analogy to the process in air where a travelling compressional wave is perceived as sound, we call these oscillations in the photon-baryon fluid sound waves or acoustic oscillations.

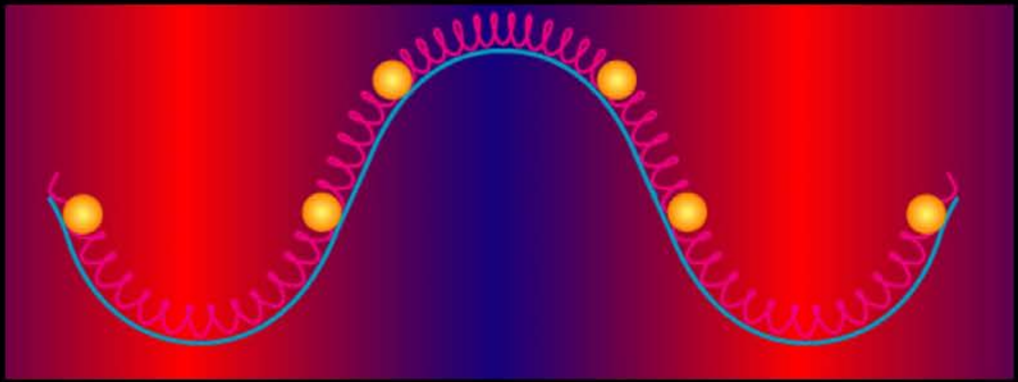
Xinyi Zhang, Wayne Hu

Acoustic Peaks in CMB



Seeing Sound

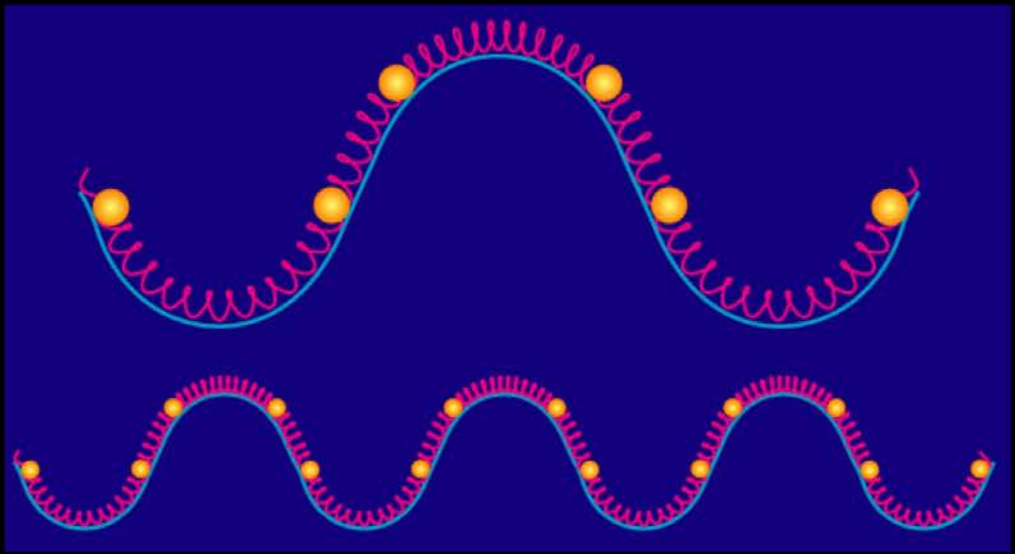
- Pattern of sound imprinted in the temperature of CMB
- Compressed regions hotter
- Rarefied regions colder



Red - cold

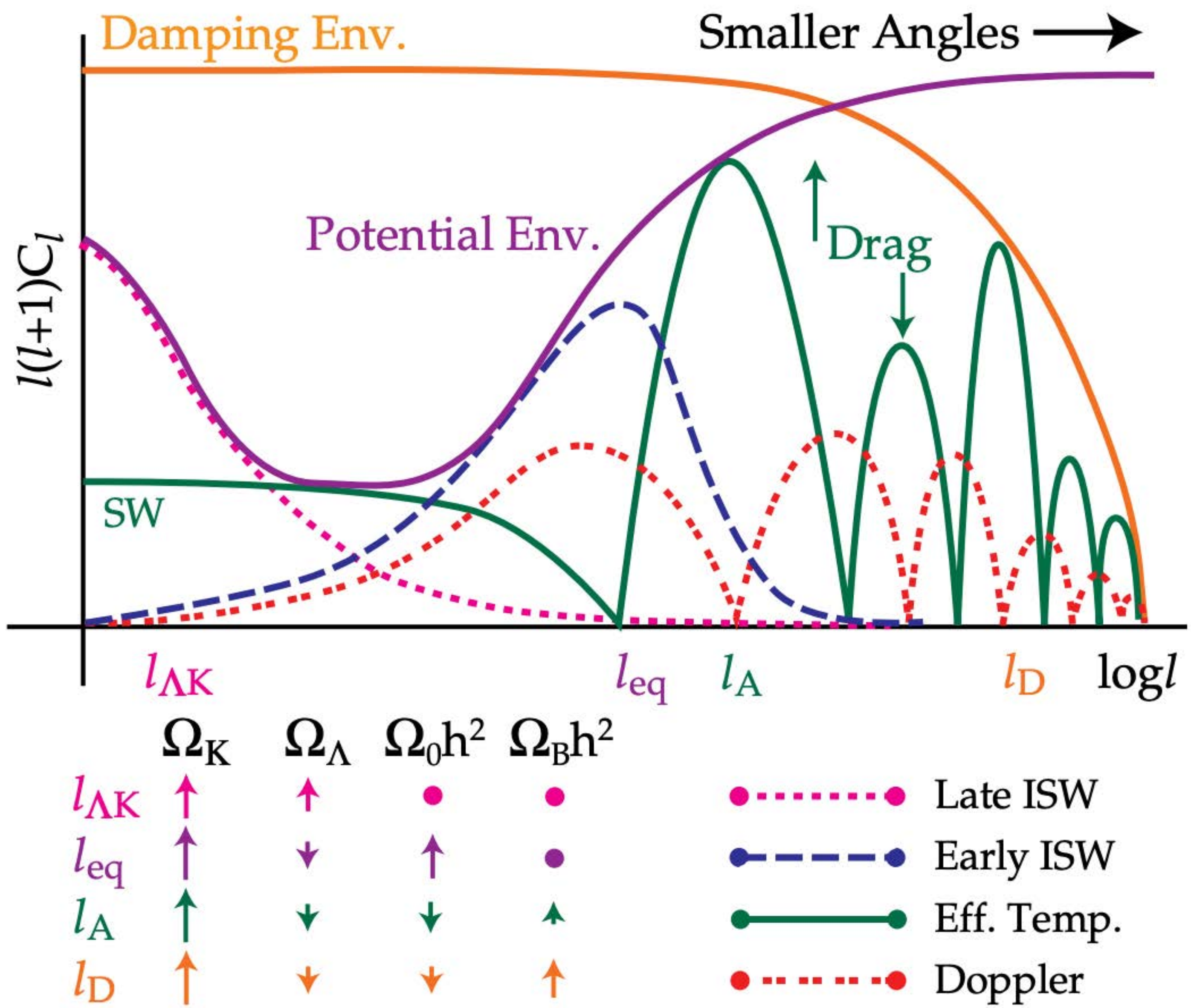
Blue - hot

- Potential fluctuations on all scales
- Each mode oscillates independently

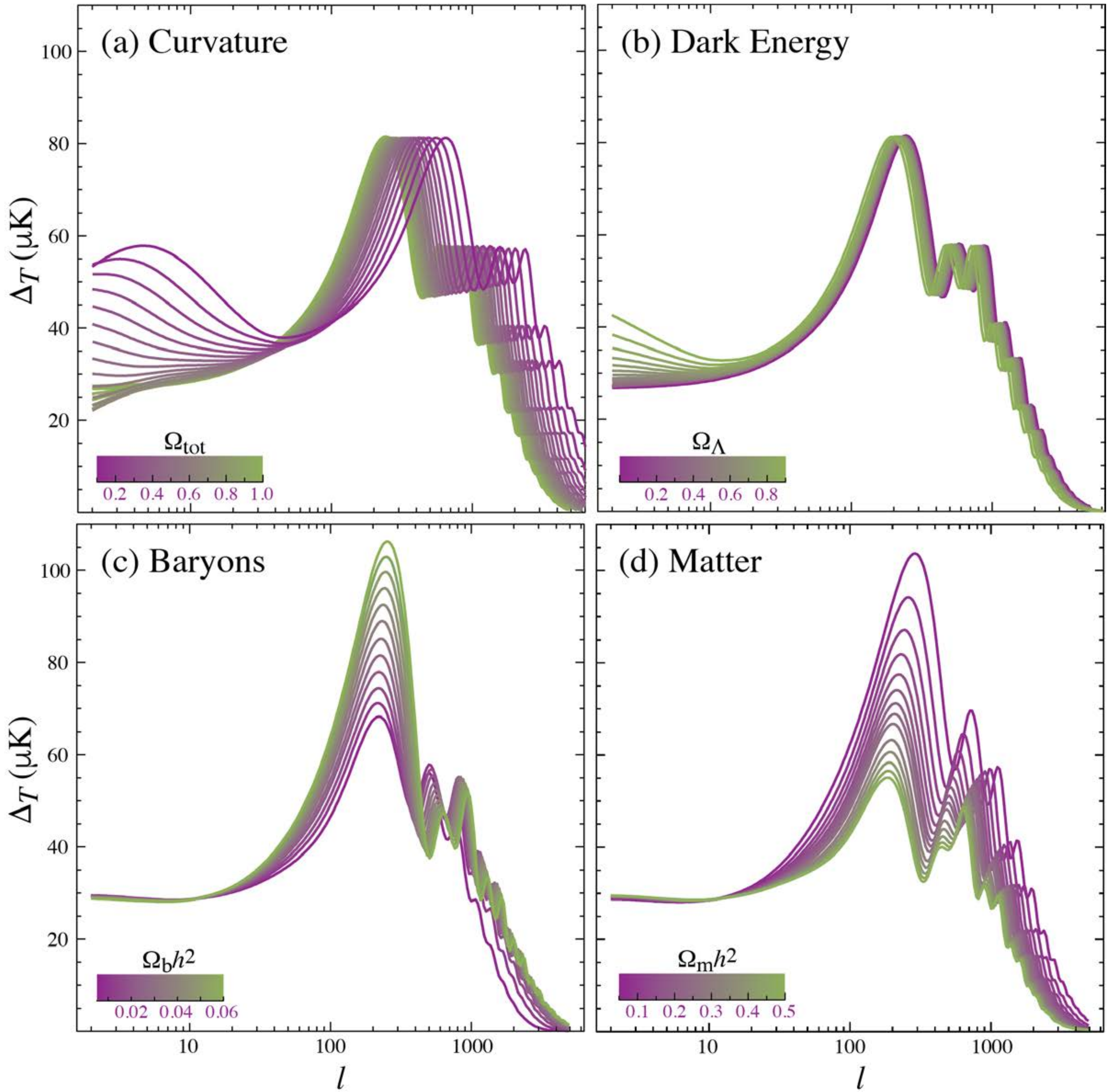


Modes that are half as long oscillate twice as fast

Contributions to CMB anisotropy

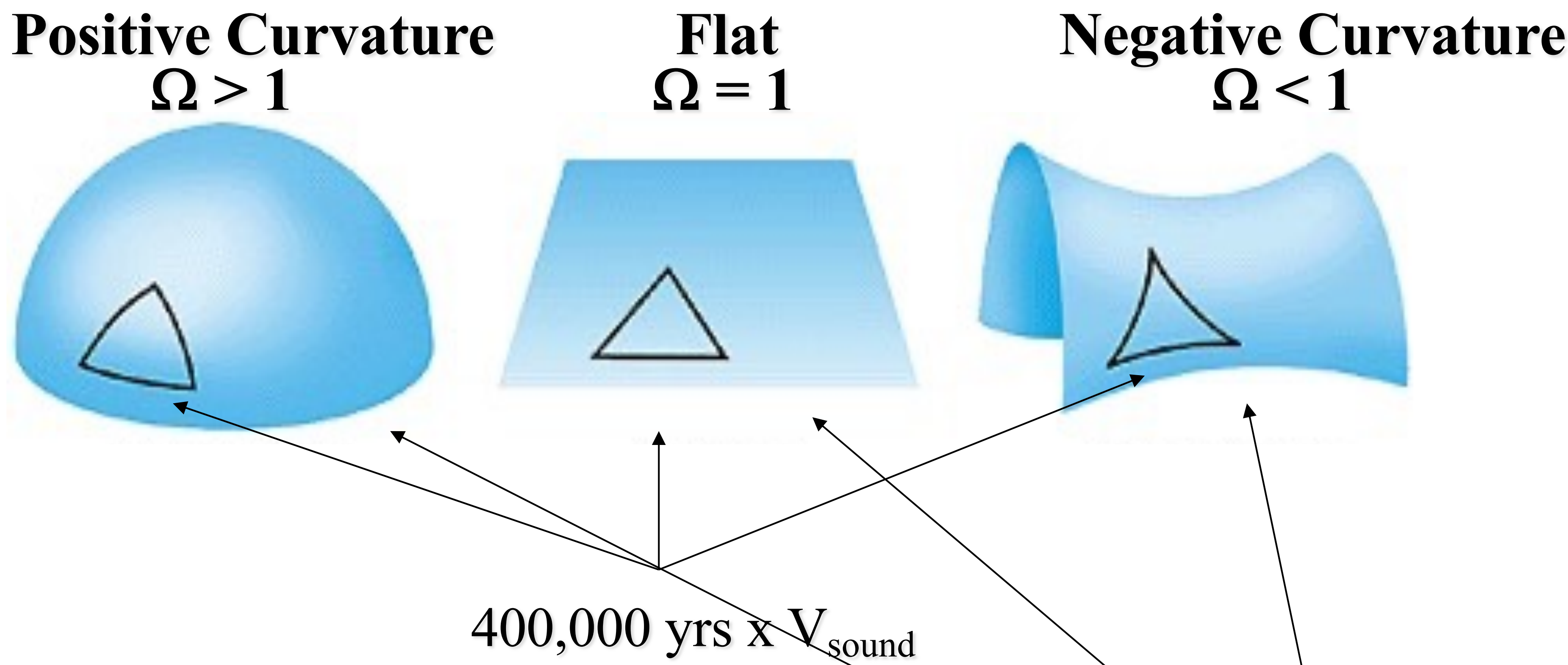


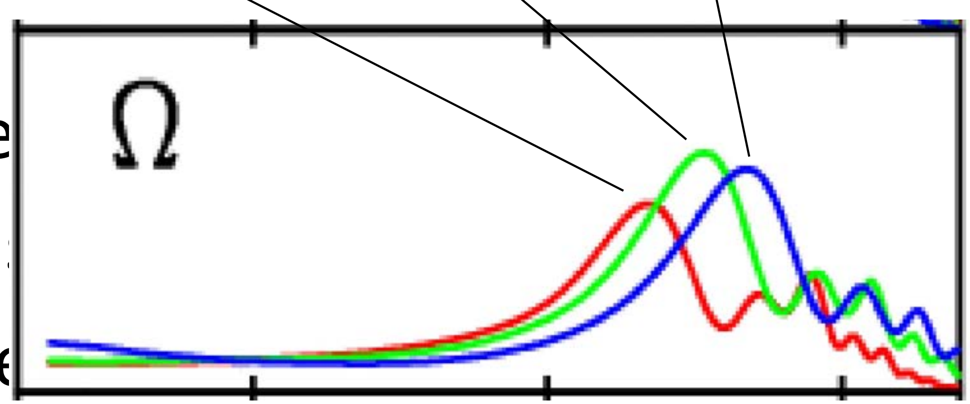
Hu, Sugiyama, and Silk 1996



(a) Curvature
(b) Dark Energy
(c) Baryons
(d) Matter
Δ_T (μK)
Ω_{tot}
0.2 0.4 0.6 0.8 1.0
Ω_Λ
0.2 0.4 0.6 0.8
$\Omega_b h^2$
0.02 0.04 0.06
$\Omega_m h^2$
0.1 0.2 0.3 0.4 0.5
20 40 60 80 100
10 100 1000
l

The curvature of space

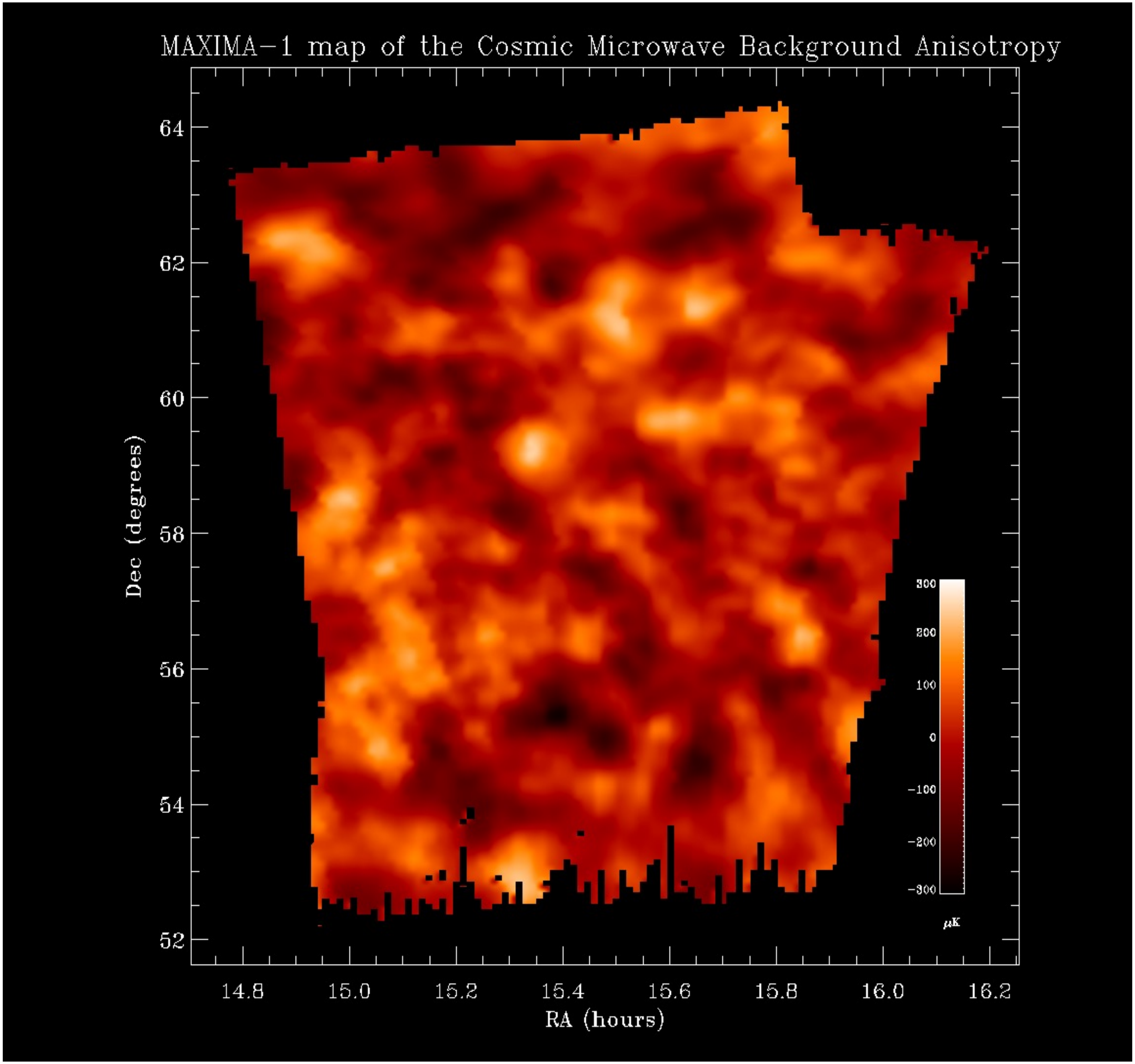




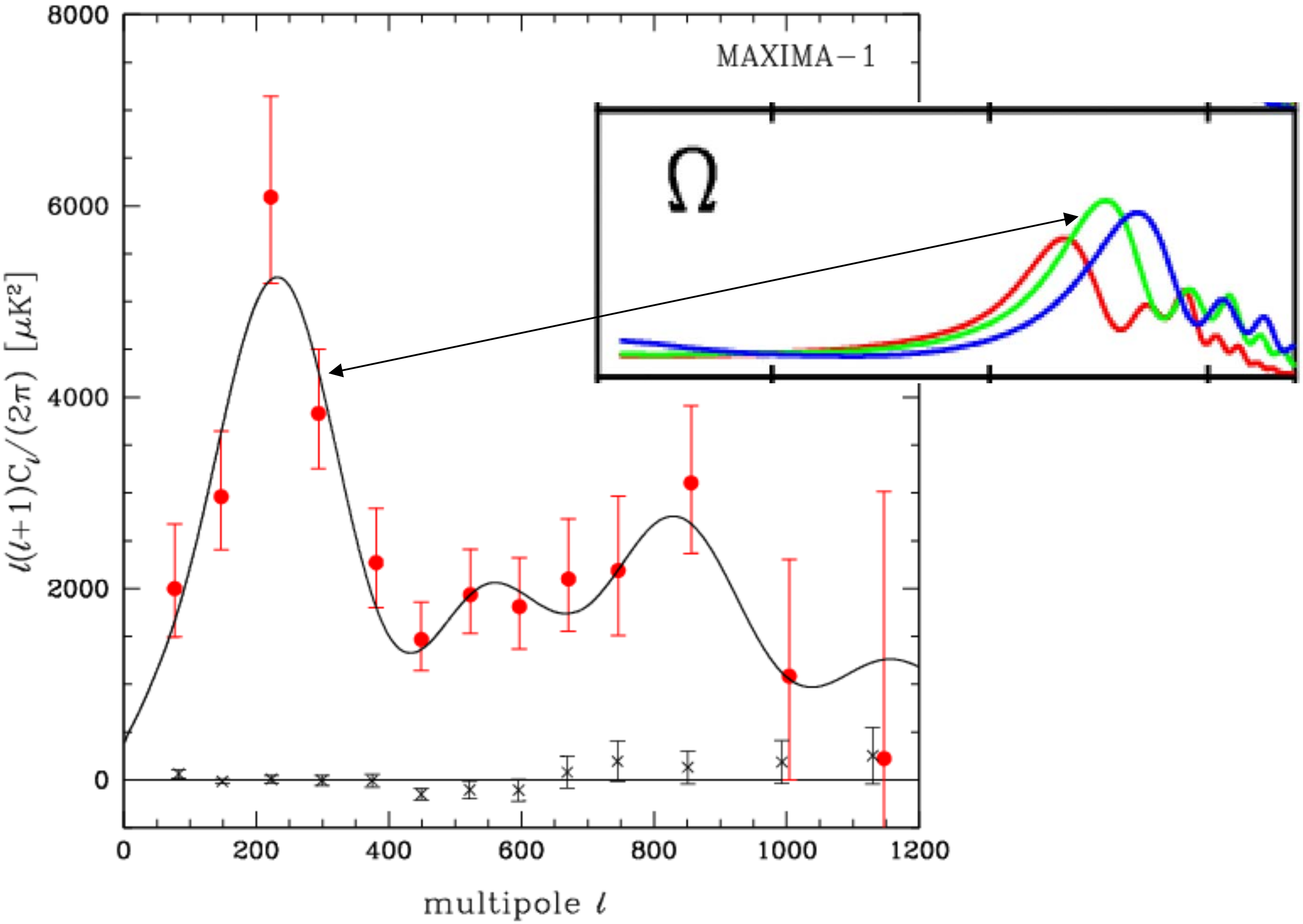
- We have a “standard rule
- Curvature changes angle
- First peak location change

MAXIMA Experiment


NATIONAL
FACILITY


MAXIMA−1 map of the Cosmic Microwave Background Anisotropy
Dec (degrees)
64
62
60
58
56
54
52
RA (hours)
14.8
15.0
15.2
15.4
15.6
15.8
16.0
16.2
300
200
100
0
−100
−200
−300
μK

MAXIMA power spectrum



November 1999

Radiation Ripples From Big Bang Illuminate Geometry of Universe

By JAMES GLANZ

Like the great navigators who first sailed around the world, establishing its size and the curvature of its surface, astronomers have made new observations that show with startling directness the large-scale geometry of the universe and the total amount of matter and energy that it contains.

The results of those observations have provided powerful support for an audacious theory, first proposed 20 years ago, that may help answer the ultimate existential question: what ignited the Big Bang explosion in which scientists believe the universe was born?

The delicate measurements relied on telescopes placed high on mountains or borne by balloons to observe slight irregularities, or ripples, in a faint glow that permeates space and is thought to have been emitted from the fading fireball of the Big Bang explosion itself.

That glow is called the cosmic microwave background radiation, and the ripples imprinted on it can be used like ticks on a ruler to measure the cosmos.

The new data also provides fresh evidence to support a finding two years ago that the expansion of the universe is accelerating under the influence of a strange form of energy that fills empty space and apparently acts against gravity.

Many researchers had assumed that the bizarre finding would eventually be disproved, but the new observations support the existence of this energy, as well as the theory of what set off the Big Bang, called inflation, which was first proposed in 1980 by Dr. Alan Guth, a physicist at the Massachusetts Institute of Technology.

"It has such tremendous implications for the universe," Dr. Rocky Kolb, a cosmologist at the University of Chicago, said of the new work. Dr. Kolb described the range of its implications as as staggering.

One set of results, released yesterday, was obtained by a team led by

Continued on Page A38

Radiation Ripples Show Geometry of Universe

Continued From Page A1

scientists at the California Institute of Technology and La Sapienza, the main campus of the University of Rome, using a balloon-borne telescope for observing microwaves. A report describing the results of this so-called Boomerang experiment was posted on a Web site maintained at the Los Alamos National Laboratory; it has not yet been subjected to peer review. The Web site is:

http://xxx.lanl.gov

Last month, scientists at Princeton University and the University of Pennsylvania, who placed a telescope on a high plateau in Chile, published similar results in Astrophysical Journal Letters. Dr. Mark Devlin, from the University of Pennsylvania and a member of the team that worked in Chile, said, "These are completely different experiments with completely different calibrations and they fall right on top of each other."

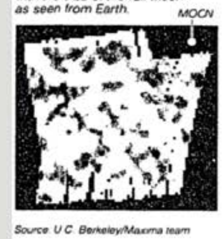
A third team, centered at the University of California at Berkeley, has also released its preliminary map of the microwave background, made with another balloon-borne telescope.

The teams' conclusions rest on measurements of the precise size of the ripples in the microwave back-

A New Yardstick For the Universe

New observations of temperature variations, or ripples, in radiation left over from the Big Bang may enable astronomers to measure the total amount of mass and energy in the universe and its geometric structure.

Image of ripples in microwave background radiation compared with the size of the full Moon as seen from Earth.



Source: U.C. Berkeley/Maxima team

The New York Times

Guth's theory.

According to the theory of inflation, a small piece of space became catastrophically stretched by the energy of fields that are predicted by advanced theories of physics. Those theories unify all known interactions between particles. No matter how curved that part of space might have been to begin with, this "inflation" would have stretched it out, like the surface of a balloon as it is blown up, in a tiny fraction of a second and created a flat universe. The tremendous well of energy in the inflated piece of space would have served as the fuel for the subsequent fireball of the Big Bang.

In the present universe, gravity does warp the relatively small regions of space close to massive objects like the Sun, neutron stars or black holes. Still, some cosmologists had suggested, on purely aesthetic grounds, that the universe in the large would be free of curvature. Inflation, with its cosmic stretching, was the first theory to explain why those suspicions might be true.

But despite that stretching, inflation would also leave telltale ripples on this exploding, Big Bang universe. The ripples occur because of principles of quantum mechanics, which impose a kind of small-scale fuzziness on all particles. The ripples in the microwave background are thought to be the legacy of that early quantum fuzziness.

The background radiation, cosmologists believe, was emitted from the fireball of the Big Bang after the inflationary expansion a few hundred thousand years after the creation event. The radiation then traveled through space for roughly 15 billion years, the present estimated age of the universe, and arrives at Earth as a sort of cosmic fossil.

"The ripples themselves were produced during inflation," Dr. Kolb said.

Because cosmologists can calculate the actual size of the ripples in the young universe, their apparent size on the sky is a measure of whether radiation from them traveled to Earth on straight or curved paths. The paths turned out to be straight, providing the main piece of evidence for the flat universe.

The Boomerang experiment measured the ripples using a telescope based on reflecting, aluminum optics and a cooled, semiconducting detector that looks like a tiny spider web, said Dr. Paolo de Bernardis, an astrophysicist at La Sapienza, who is a principal investigator of the Boomerang experiment. The microwaves heat the detector very slightly, and that change is converted into an electronic signal.

Boomerang and MAXIMA - 2001

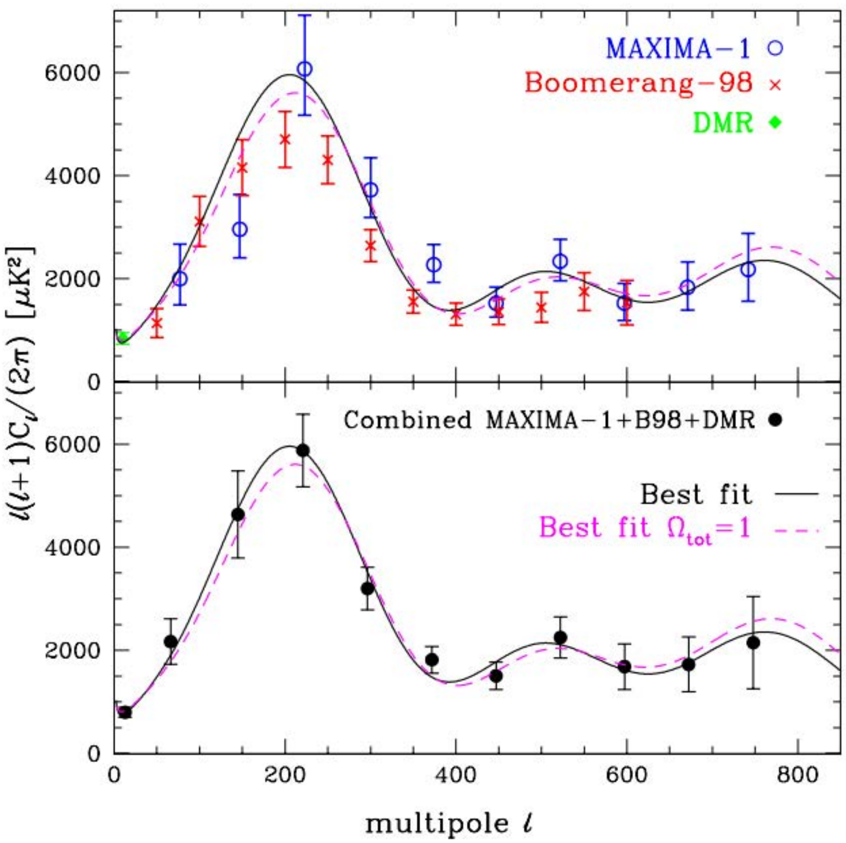
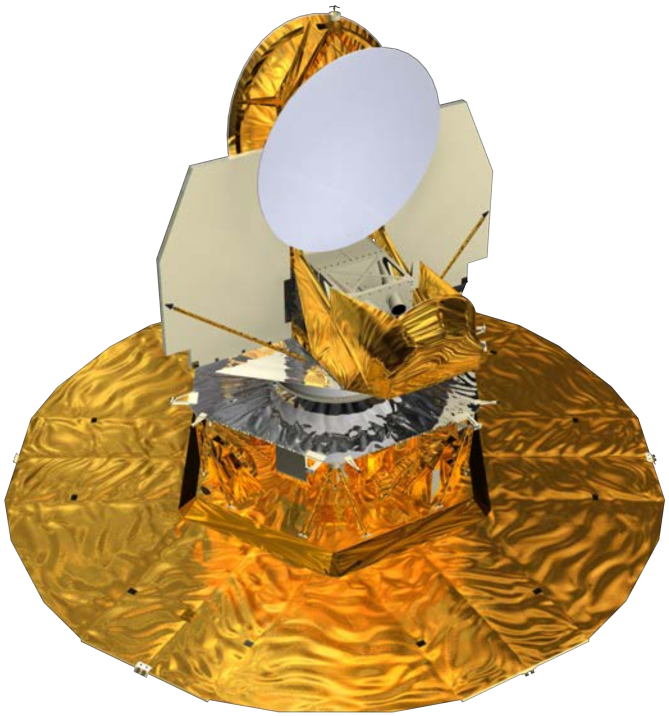
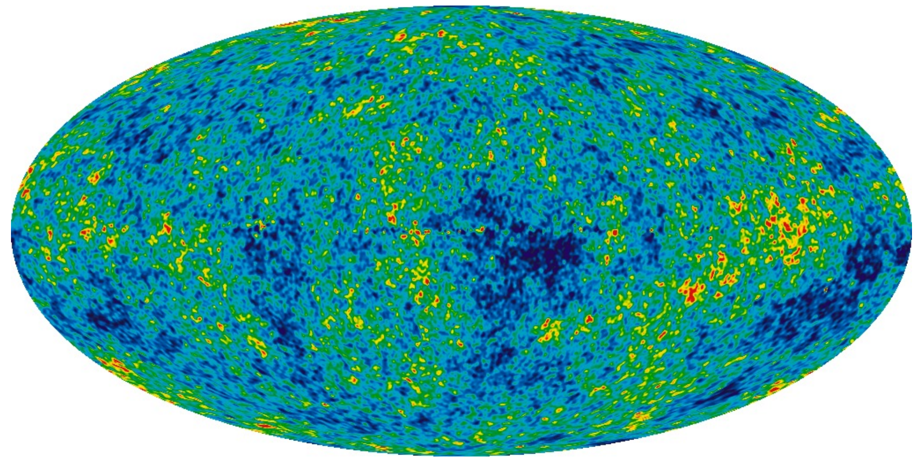


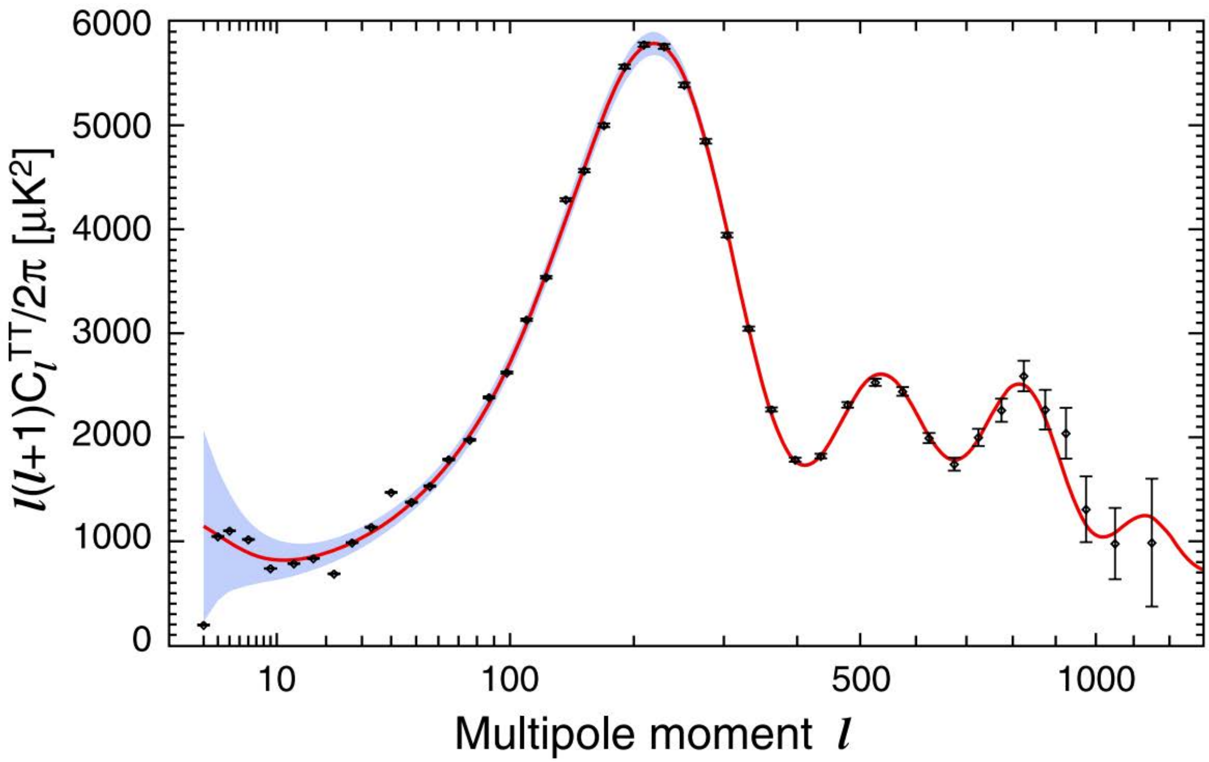
TABLE I: Parameter estimates from the two data sets [18], and the combined data, using the weak prior ($0.45 < h < 0.90$, $t_0 > 10$ Gyr, $\Omega_m > 0.1$). Below the line, we restrict the parameter space to $\Omega_{tot} = 1$ and add other cosmological information. Central values and 1σ limits are found from the 50%, 16% and 84% integrals of the marginalized likelihood. τ_C and Ω_Λ are not constrained by the data.

	Ω_{tot}	$\Omega_b h^2$	n_s	$\Omega_c h^2$
B98+DMR	$1.15^{+0.10}_{-0.09}$	$0.036^{+0.006}_{-0.005}$	$1.04^{+0.10}_{-0.09}$	$0.24^{+0.08}_{-0.09}$
MAXIMA-1+DMR	$1.01^{+0.09}_{-0.09}$	$0.031^{+0.007}_{-0.006}$	$1.06^{+0.10}_{-0.09}$	$0.18^{+0.07}_{-0.06}$
B98+MAXIMA-1+DMR	$1.11^{+0.07}_{-0.07}$	$0.032^{+0.005}_{-0.005}$	$1.01^{+0.09}_{-0.08}$	$0.14^{+0.06}_{-0.05}$
$+(\Omega_{tot} = 1)$	1	$0.030^{+0.004}_{-0.004}$	$0.99^{+0.07}_{-0.06}$	$0.19^{+0.07}_{-0.06}$
CMB+LSS	$1.11^{+0.05}_{-0.05}$	$0.032^{+0.004}_{-0.004}$	$1.00^{+0.09}_{-0.06}$	$0.13^{+0.02}_{-0.01}$
CMB+SNIa	$1.09^{+0.06}_{-0.05}$	$0.032^{+0.005}_{-0.005}$	$1.00^{+0.09}_{-0.08}$	$0.10^{+0.04}_{-0.04}$
CMB+LSS+SNIa	$1.06^{+0.04}_{-0.04}$	$0.033^{+0.005}_{-0.004}$	$1.03^{+0.09}_{-0.07}$	$0.14^{+0.03}_{-0.02}$

WMAP (2001 launch)







- 5 frequency bands (23–94 GHz)
- Angular resolution ~13′; sensitive to polarization
- Operated for 9 years, until 2010

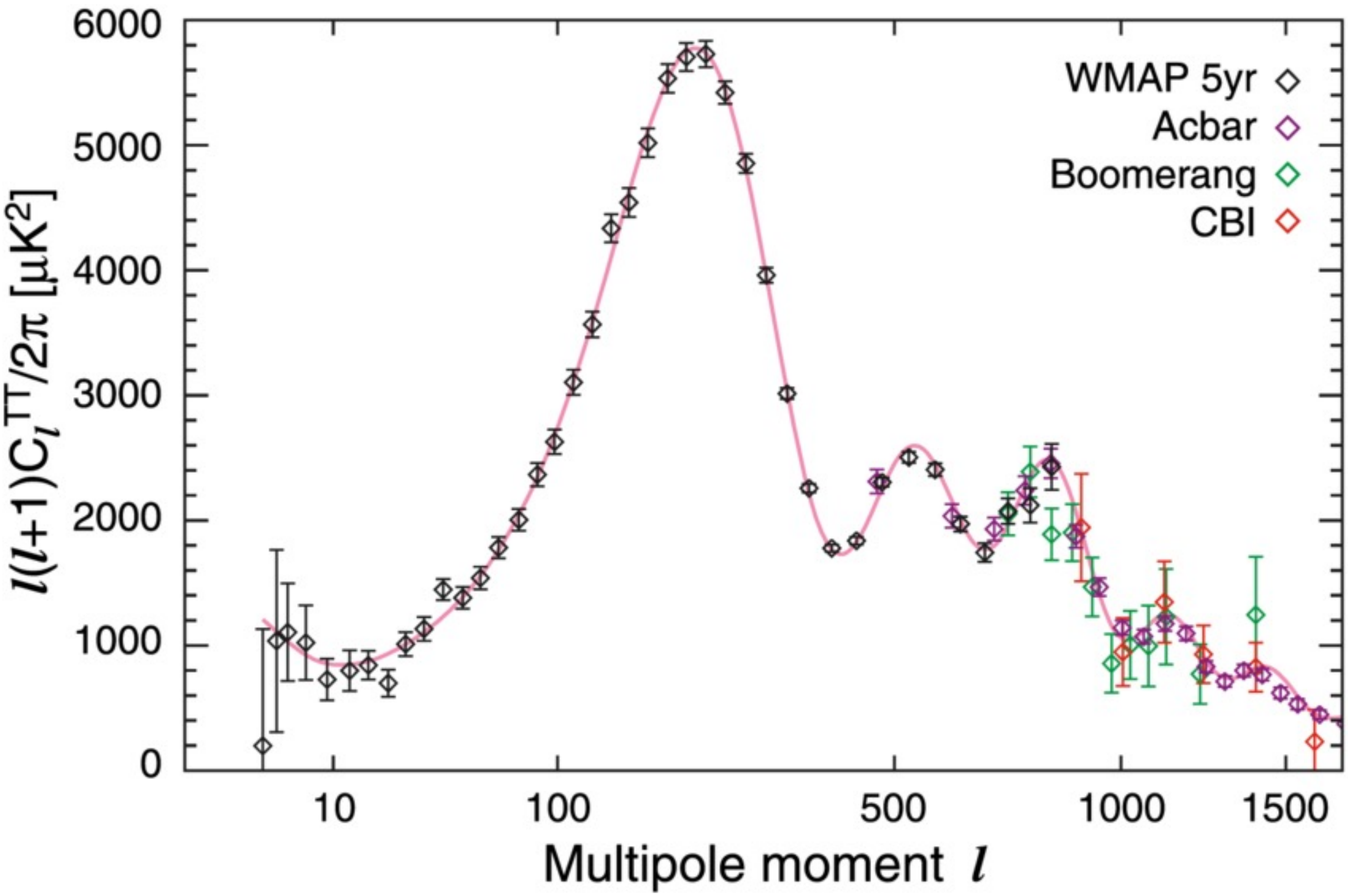
WMAP cosmological parameters

TABLE 4
Six-Parameter ΛCDM Fit; *WMAP* plus External Data[a]

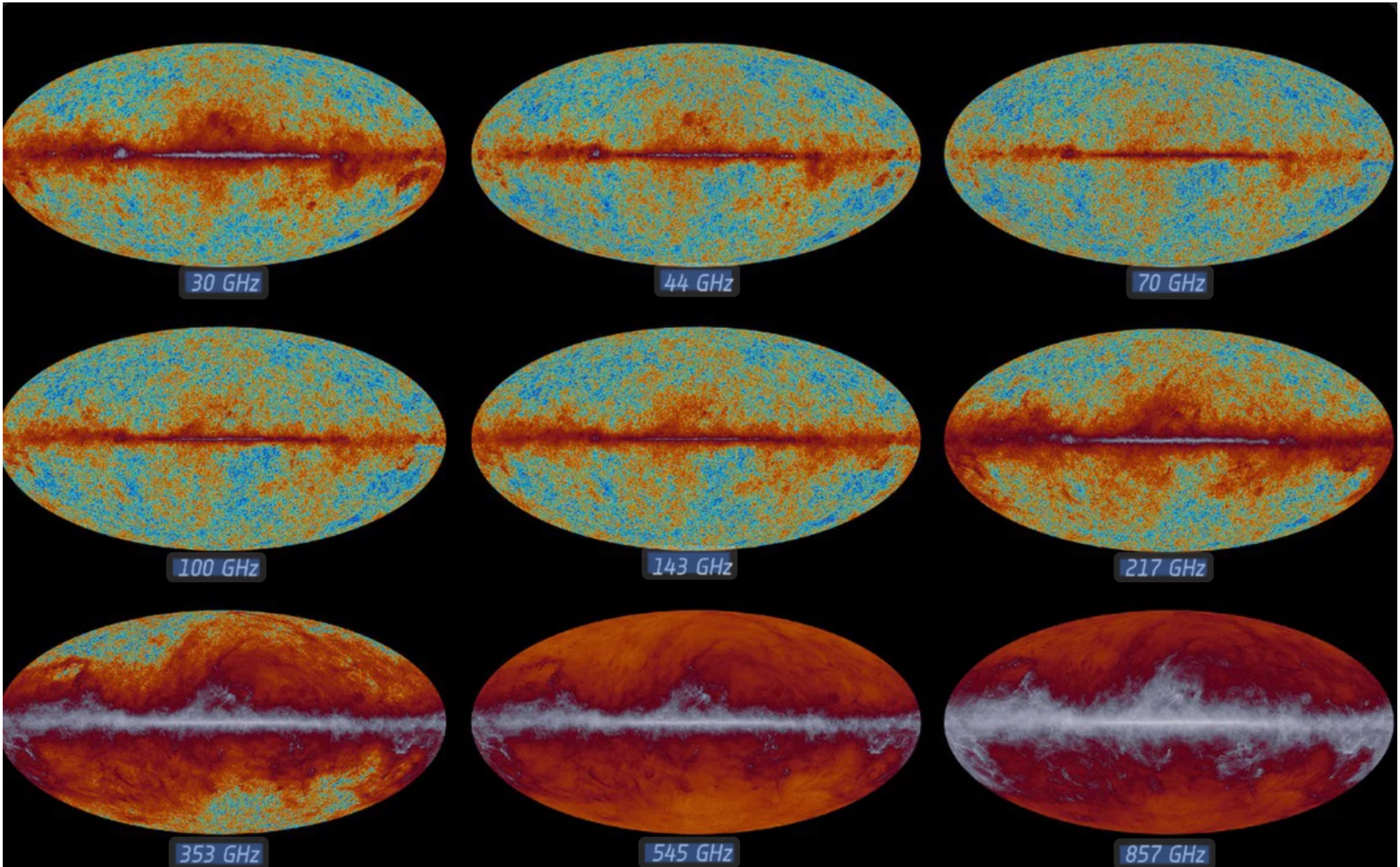
Parameter	*WMAP*	+eCMB	+eCMB+BAO	+eCMB+H_0	+eCMB+BAO+H_0
Fit parameters					
$\Omega_b h^2$	0.02264 ± 0.00050	0.02229 ± 0.00037	0.02211 ± 0.00034	0.02244 ± 0.00035	0.02223 ± 0.00033
$\Omega_c h^2$	0.1138 ± 0.0045	0.1126 ± 0.0035	0.1162 ± 0.0020	0.1106 ± 0.0030	0.1153 ± 0.0019
Ω_Λ	0.721 ± 0.025	0.728 ± 0.019	0.707 ± 0.010	0.740 ± 0.015	$0.7135^{+0.0095}_{-0.0096}$
$10^9 \Delta^2_{\mathcal{R}}$	2.41 ± 0.10	2.430 ± 0.084	$2.484^{+0.073}_{-0.072}$	$2.396^{+0.079}_{-0.078}$	2.464 ± 0.072
n_s	0.972 ± 0.013	0.9646 ± 0.0098	$0.9579^{+0.0081}_{-0.0082}$	$0.9690^{+0.0091}_{-0.0090}$	0.9608 ± 0.0080
τ	0.089 ± 0.014	0.084 ± 0.013	$0.079^{+0.011}_{-0.012}$	0.087 ± 0.013	0.081 ± 0.012
Derived parameters					
t_0 (Gyr)	13.74 ± 0.11	13.742 ± 0.077	13.800 ± 0.061	13.702 ± 0.069	13.772 ± 0.059
H_0 (km/s/Mpc)	70.0 ± 2.2	70.5 ± 1.6	68.76 ± 0.84	71.6 ± 1.4	69.32 ± 0.80
σ_8	0.821 ± 0.023	0.810 ± 0.017	$0.822^{+0.013}_{-0.014}$	0.803 ± 0.016	$0.820^{+0.013}_{-0.014}$
Ω_b	0.0463 ± 0.0024	0.0449 ± 0.0018	0.04678 ± 0.00098	0.0438 ± 0.0015	0.04628 ± 0.00093
Ω_c	0.233 ± 0.023	0.227 ± 0.017	0.2460 ± 0.0094	0.216 ± 0.014	$0.2402^{+0.0088}_{-0.0087}$
$z_{\rm eq}$	3265^{+106}_{-105}	3230 ± 81	3312 ± 48	3184 ± 70	3293 ± 47
$z_{\rm reion}$	10.6 ± 1.1	10.3 ± 1.1	10.0 ± 1.0	10.5 ± 1.1	10.1 ± 1.0

[a] ΛCDM model fit to *WMAP* nine-year data combined with a progression of external data sets. A complete list of parameter values for this model, with additional data combinations, may be found at `http://lambda.gsfc.nasa.gov/`.

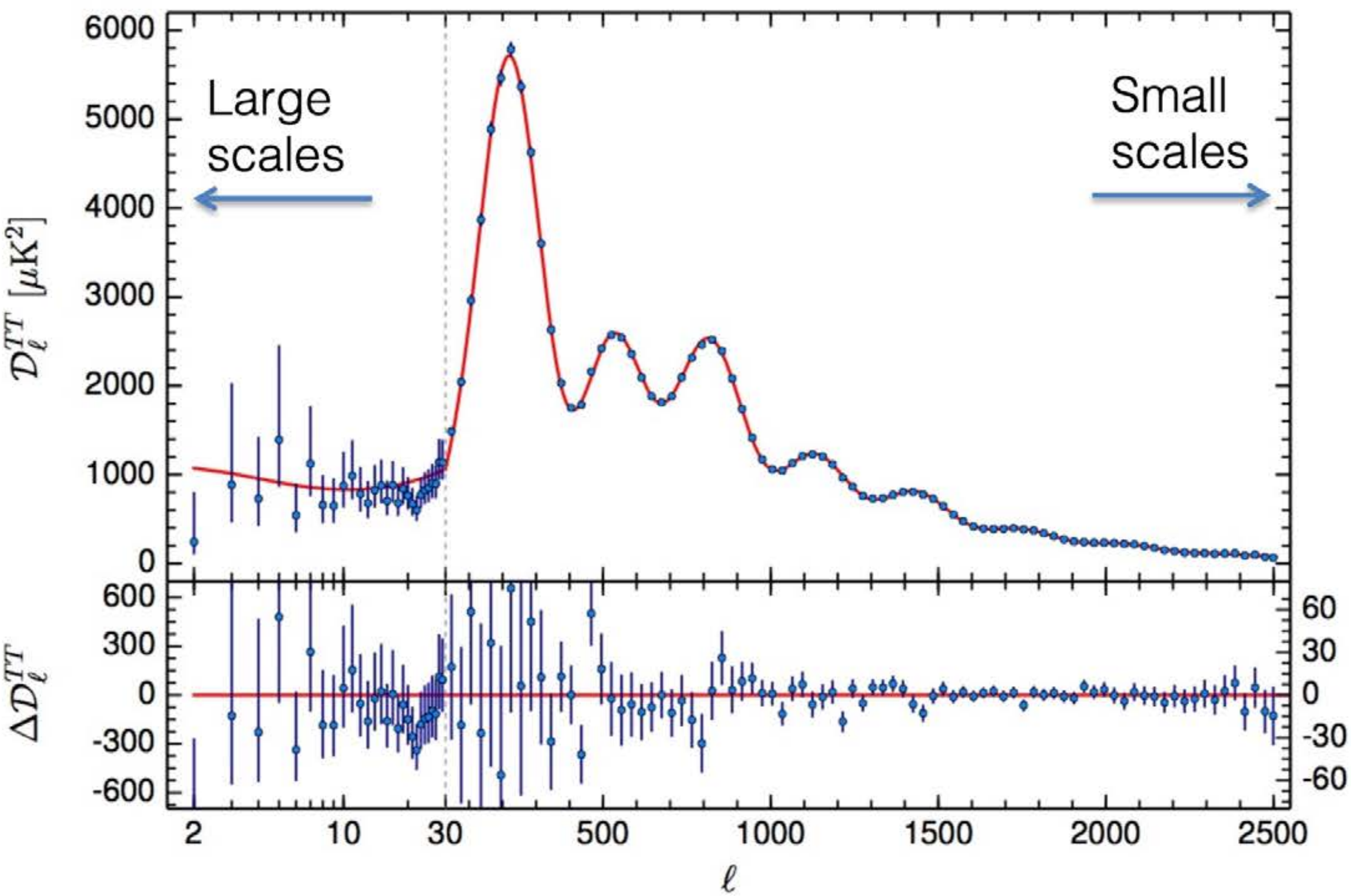
WMAP + Ground-based Experiments



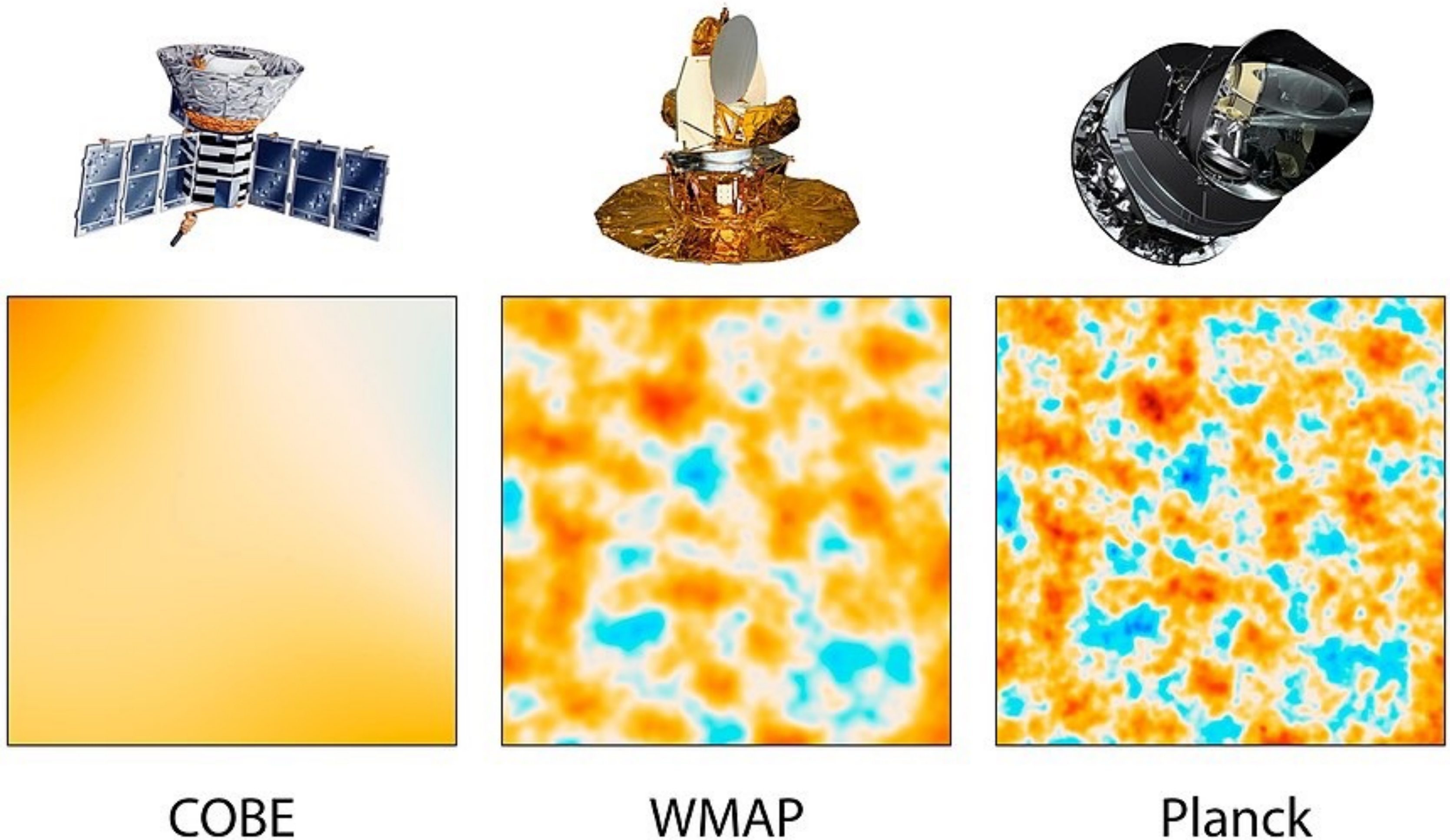
Planck Space Mission


30 GHz
44 GHz
70 GHz
100 GHz
143 GHz
217 GHz
353 GHz
545 GHz
857 GHz

Measurement: The Planck CMB Power Spectrum



$$\mathcal{D}_l \equiv l(l+1)C_l/2\pi$$

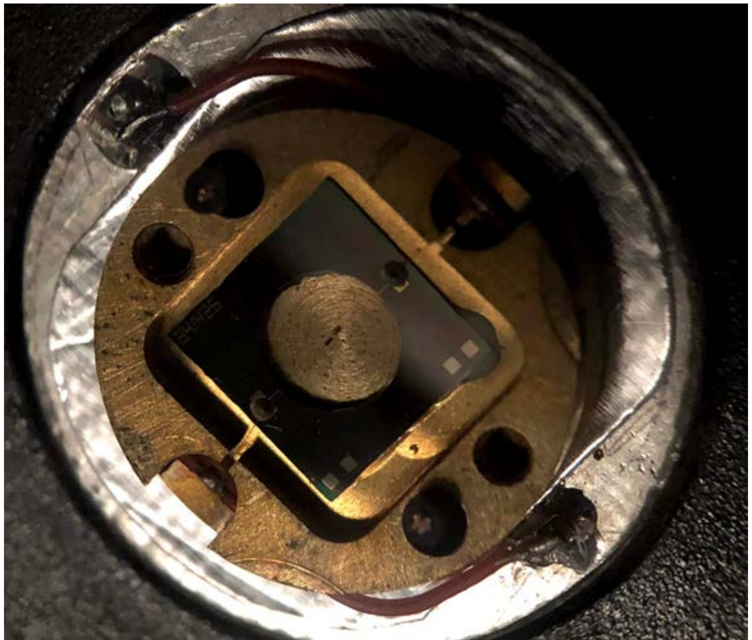

COBE
WMAP
Planck

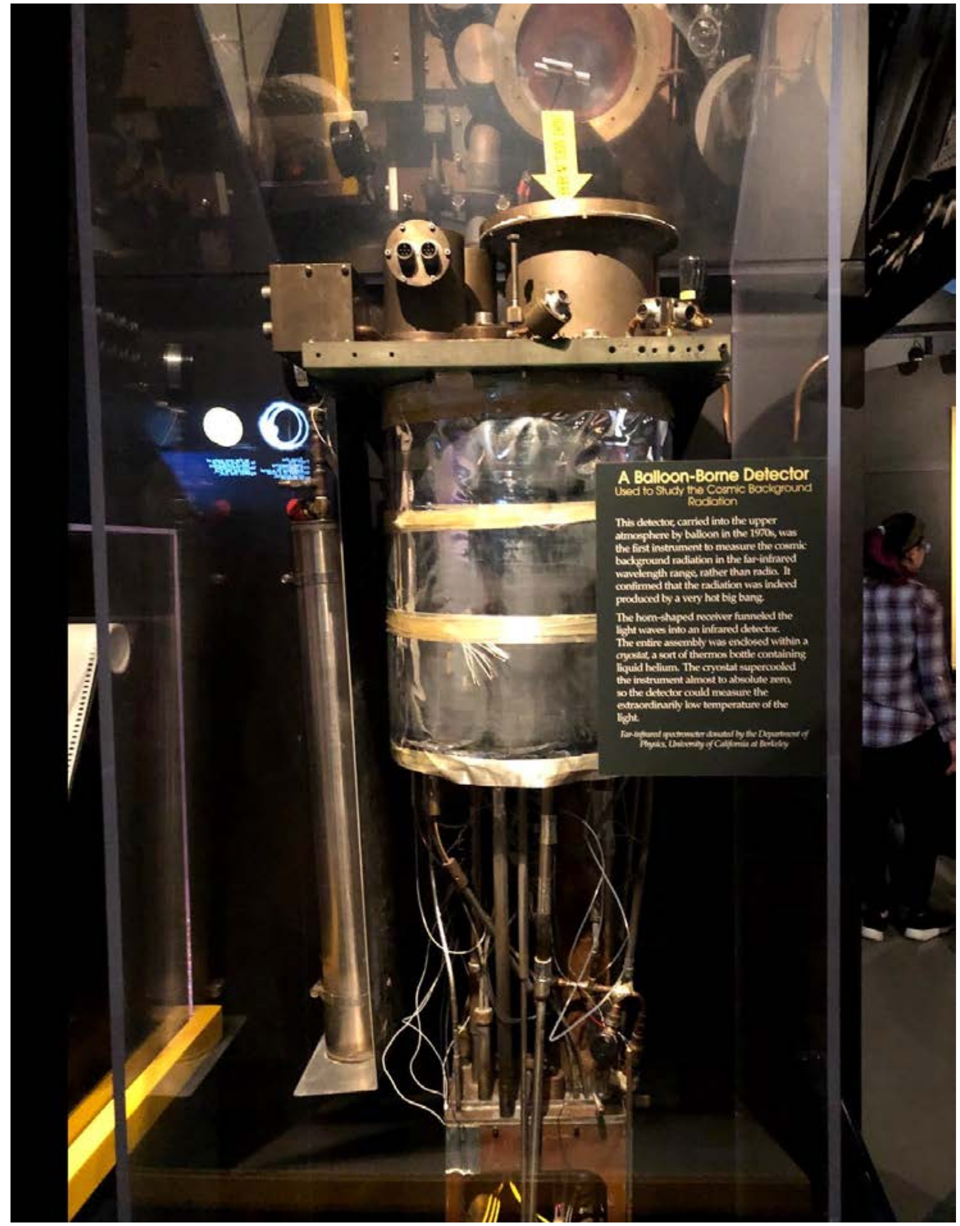
Parameter	TT+lowE 68% limits	TE+lowE 68% limits	EE+lowE 68% limits	TT,TE,EE+lowE 68% limits	TT,TE,EE+lowE+lensing 68% limits	TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$	0.02212 ± 0.00022	0.02249 ± 0.00025	0.0240 ± 0.0012	0.02236 ± 0.00015	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1206 ± 0.0021	0.1177 ± 0.0020	0.1158 ± 0.0046	0.1202 ± 0.0014	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04077 ± 0.00047	1.04139 ± 0.00049	1.03999 ± 0.00089	1.04090 ± 0.00031	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0522 ± 0.0080	0.0496 ± 0.0085	0.0527 ± 0.0090	$0.0544^{+0.0070}_{-0.0081}$	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10}A_s)$	3.040 ± 0.016	$3.018^{+0.020}_{-0.018}$	3.052 ± 0.022	3.045 ± 0.016	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9626 ± 0.0057	0.967 ± 0.011	0.980 ± 0.015	0.9649 ± 0.0044	0.9649 ± 0.0042	0.9665 ± 0.0038
H_0 [km s^{-1} Mpc^{-1}] . .	66.88 ± 0.92	68.44 ± 0.91	69.9 ± 2.7	67.27 ± 0.60	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.679 ± 0.013	0.699 ± 0.012	$0.711^{+0.033}_{-0.026}$	0.6834 ± 0.0084	0.6847 ± 0.0073	0.6889 ± 0.0056
Ω_m	0.321 ± 0.013	0.301 ± 0.012	$0.289^{+0.026}_{-0.033}$	0.3166 ± 0.0084	0.3153 ± 0.0073	0.3111 ± 0.0056
$\Omega_m h^2$	0.1434 ± 0.0020	0.1408 ± 0.0019	$0.1404^{+0.0034}_{-0.0039}$	0.1432 ± 0.0013	0.1430 ± 0.0011	0.14240 ± 0.00087
$\Omega_m h^3$	0.09589 ± 0.00046	0.09635 ± 0.00051	$0.0981^{+0.0016}_{-0.0018}$	0.09633 ± 0.00029	0.09633 ± 0.00030	0.09635 ± 0.00030
σ_8	0.8118 ± 0.0089	0.793 ± 0.011	0.796 ± 0.018	0.8120 ± 0.0073	0.8111 ± 0.0060	0.8102 ± 0.0060
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$.	0.840 ± 0.024	0.794 ± 0.024	$0.781^{+0.052}_{-0.060}$	0.834 ± 0.016	0.832 ± 0.013	0.825 ± 0.011
$\sigma_8\Omega_m^{0.25}$	0.611 ± 0.012	0.587 ± 0.012	0.583 ± 0.027	0.6090 ± 0.0081	0.6078 ± 0.0064	0.6051 ± 0.0058
z_{re}	7.50 ± 0.82	$7.11^{+0.91}_{-0.75}$	$7.10^{+0.87}_{-0.73}$	7.68 ± 0.79	7.67 ± 0.73	7.82 ± 0.71
$10^9 A_s$	2.092 ± 0.034	2.045 ± 0.041	2.116 ± 0.047	$2.101^{+0.031}_{-0.034}$	2.100 ± 0.030	2.105 ± 0.030
$10^9 A_s e^{-2\tau}$	1.884 ± 0.014	1.851 ± 0.018	1.904 ± 0.024	1.884 ± 0.012	1.883 ± 0.011	1.881 ± 0.010
Age [Gyr]	13.830 ± 0.037	13.761 ± 0.038	$13.64^{+0.16}_{-0.14}$	13.800 ± 0.024	13.797 ± 0.023	13.787 ± 0.020
z_*	1090.30 ± 0.41	1089.57 ± 0.42	$1087.8^{+1.6}_{-1.7}$	1089.95 ± 0.27	1089.92 ± 0.25	1089.80 ± 0.21
r_* [Mpc]	144.46 ± 0.48	144.95 ± 0.48	144.29 ± 0.64	144.39 ± 0.30	144.43 ± 0.26	144.57 ± 0.22
$100\theta_*$	1.04097 ± 0.00046	1.04156 ± 0.00049	1.04001 ± 0.00086	1.04109 ± 0.00030	1.04110 ± 0.00031	1.04119 ± 0.00029
z_{drag}	1059.39 ± 0.46	1060.03 ± 0.54	1063.2 ± 2.4	1059.93 ± 0.30	1059.94 ± 0.30	1060.01 ± 0.29
r_{drag} [Mpc]	147.21 ± 0.48	147.59 ± 0.49	146.46 ± 0.70	147.05 ± 0.30	147.09 ± 0.26	147.21 ± 0.23
k_D [Mpc^{-1}]	0.14054 ± 0.00052	0.14043 ± 0.00057	0.1426 ± 0.0012	0.14090 ± 0.00032	0.14087 ± 0.00030	0.14078 ± 0.00028
z_{eq}	3411 ± 48	3349 ± 46	3340^{+81}_{-92}	3407 ± 31	3402 ± 26	3387 ± 21
k_{eq} [Mpc^{-1}]	0.01041 ± 0.00014	0.01022 ± 0.00014	$0.01019^{+0.00025}_{-0.00028}$	0.010398 ± 0.000094	0.010384 ± 0.000081	0.010339 ± 0.000063
$100\theta_{s,eq}$	0.4483 ± 0.0046	0.4547 ± 0.0045	0.4562 ± 0.0092	0.4490 ± 0.0030	0.4494 ± 0.0026	0.4509 ± 0.0020
f_{2000}^{143}	31.2 ± 3.0			29.5 ± 2.7	29.6 ± 2.8	29.4 ± 2.7
$f_{2000}^{143\times217}$	33.6 ± 2.0			32.2 ± 1.9	32.3 ± 1.9	32.1 ± 1.9
f_{2000}^{217}	108.2 ± 1.9			107.0 ± 1.8	107.1 ± 1.8	106.9 ± 1.8

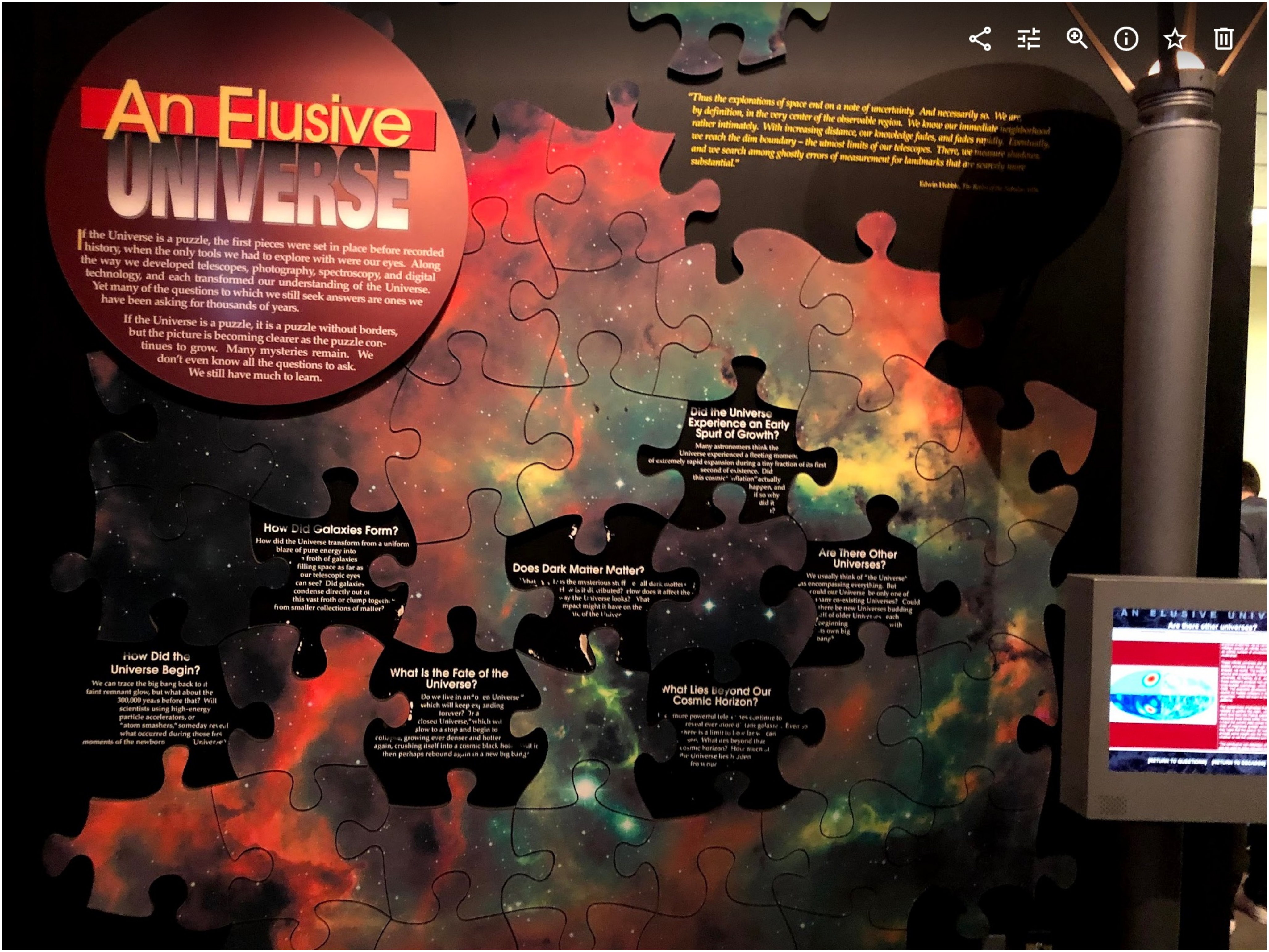
[redacted]


EXPLORE THE
UNIVERSE
What is the Universe? How big is it? How old is it? How did it begin?
Since people first gazed up at the stars,
we have searched for answers to such
questions. When our view was limited by
Universe of galaxies.
THE OBJECTS ABOVE
Armillary Sphere
Herschel 20-Foot Telescope
Gemini Observatory

Smithsonian Museum



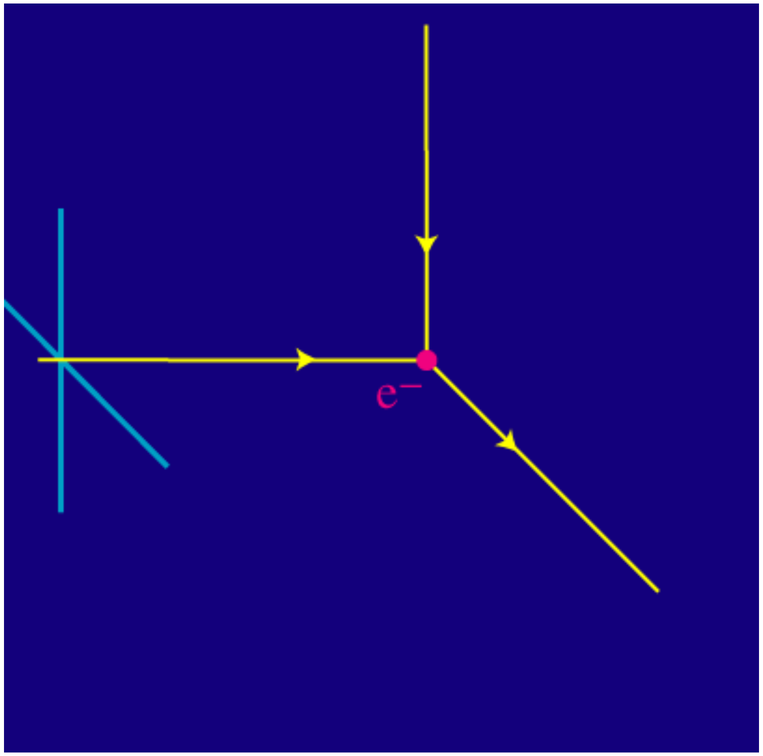




An Elusive
UNIVERSE
If the Universe is a puzzle, the first pieces were set in place before recorded history, when the only tools we had to explore with were our eyes. Along the way we developed telescopes, photography, spectroscopy, and digital technology, and each transformed our understanding of the Universe. Yet many of the questions to which we still seek answers are ones we have been asking for thousands of years.
If the Universe is a puzzle, it is a puzzle without borders, but the picture is becoming clearer as the puzzle continues to grow. Many mysteries remain. We don't even know all the questions to ask. We still have much to learn.
"Thus the explorations of space end on a note of uncertainty. And necessarily so. We are, by definition, in the very center of the observable region. We know our immediate neighborhood rather intimately. With increasing distance, our knowledge fades, and fades rapidly. Eventually, we reach the dim boundary – the utmost limits of our telescopes. There, we measure shadows, and we search among ghostly errors of measurement for landmarks that are scarcely more substantial."
Edwin Hubble
Did the Universe Experience an Early Spurt of Growth?
Many astronomers think the Universe experienced a fleeting moment of extremely rapid expansion during a tiny fraction of its first second of existence.
How Did Galaxies Form?
How did the Universe transform from a uniform blaze of pure energy into
Does Dark Matter Matter?
Are There Other Universes?
How Did the Universe Begin?
We can trace the big bang back to
300,000 years before that? Will scientists using high-energy particle accelerators, or "atom smashers," someday reveal what occurred during those first moments of the newborn
What Is the Fate of the Universe?
What Lies Beyond Our Cosmic Horizon?
AN ELUSIVE UNIV
Are there other universes?

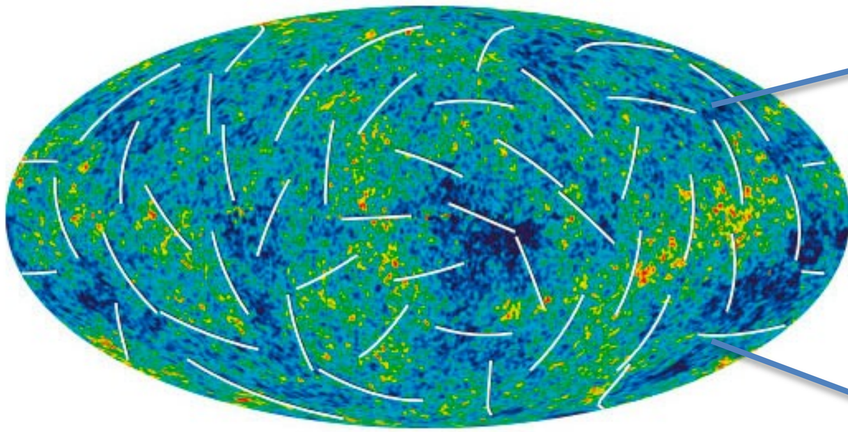
CMB Polarization Anisotropies

Polarization of CMB

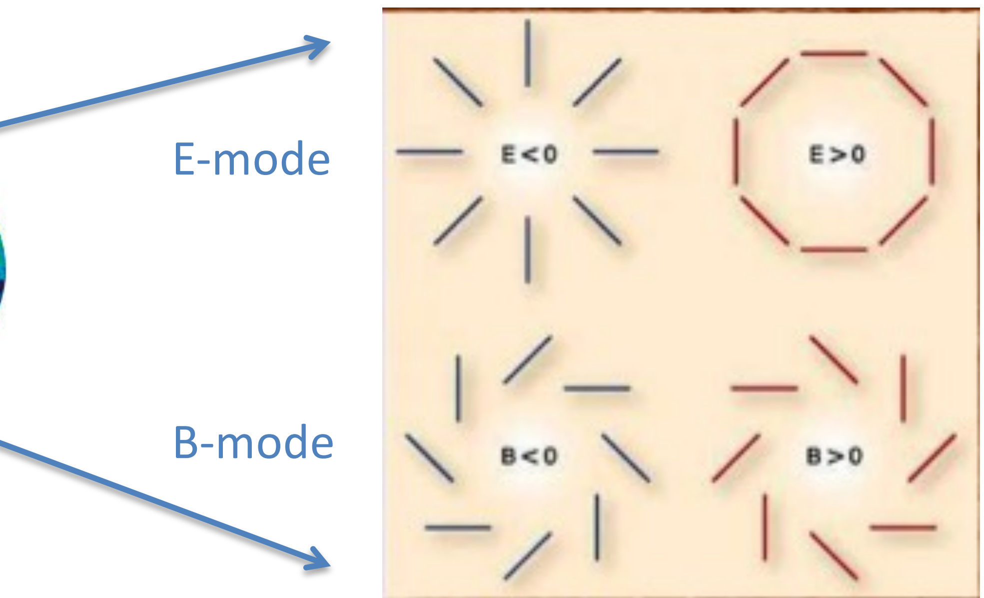


- Polarization given by direction of flux
- Anisotropic photon flux gives net polarization

CMB Polarization Anisotropies



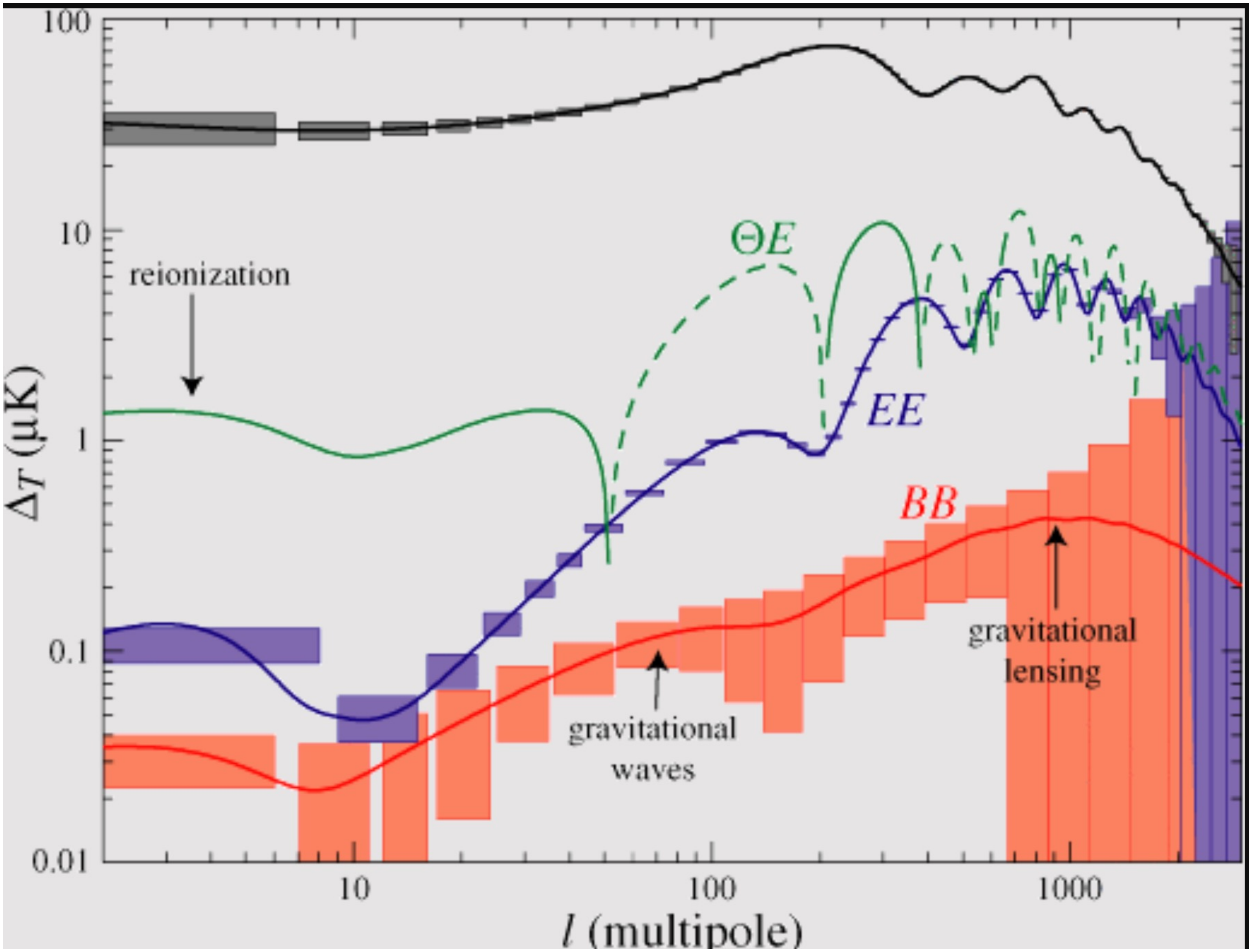
WMAP Polarization Map



- CMB Polarization map: “E-modes” and “B-modes”
- B-modes: Two sources
  - Gravitational Waves from Inflation
  - Gravitational lensing by structure in the Universe

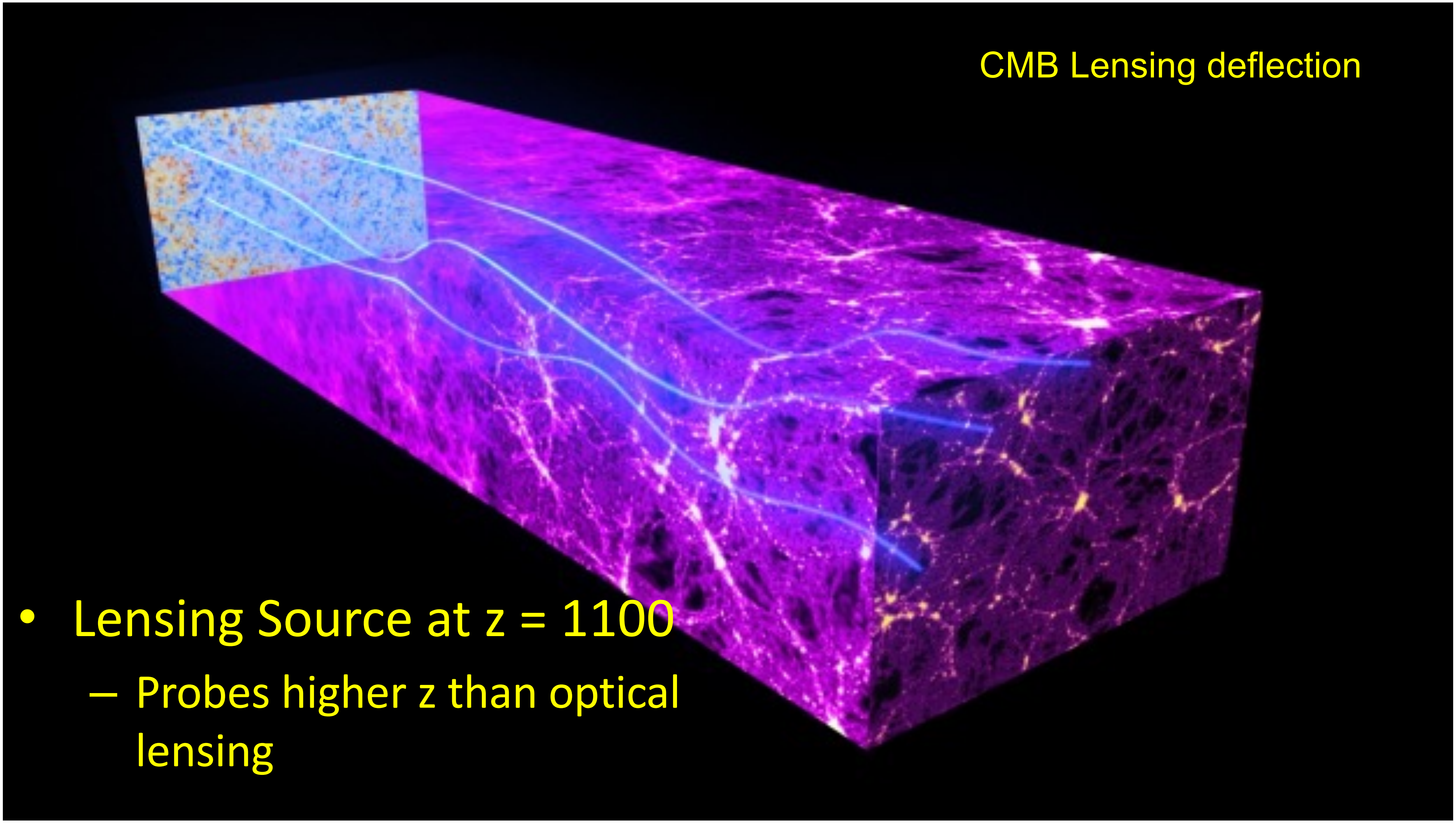
Uros Seljak and Matthias Zaldarriaga, PRL **78**, 11 (1997)

CMB Polarization Power Spectra



Gravitational Lensing

CMB Lensing

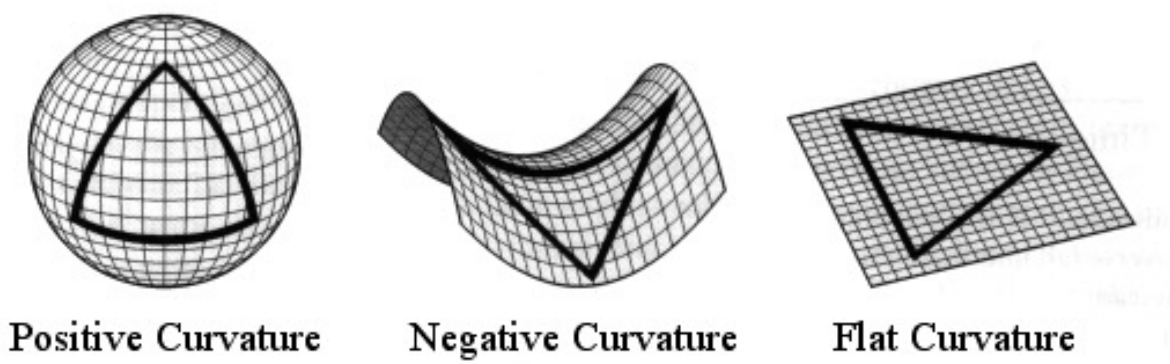


- Lensing Source at z = 1100
  - Probes higher z than optical lensing

Inflation

Inflation

- Simple Big Bang model can not explain:
  - Universe is homogeneous at one temperature
  - Geometry of Universe is close to flat



- The Inflation theory
  - Exponential expansion of space
  - Creates flat, homogeneous Universe

PHYSICAL REVIEW D VOLUME 23, NUMBER 2 15 JANUARY 1981

Inflationary universe: A possible solution to the horizon and flatness problems

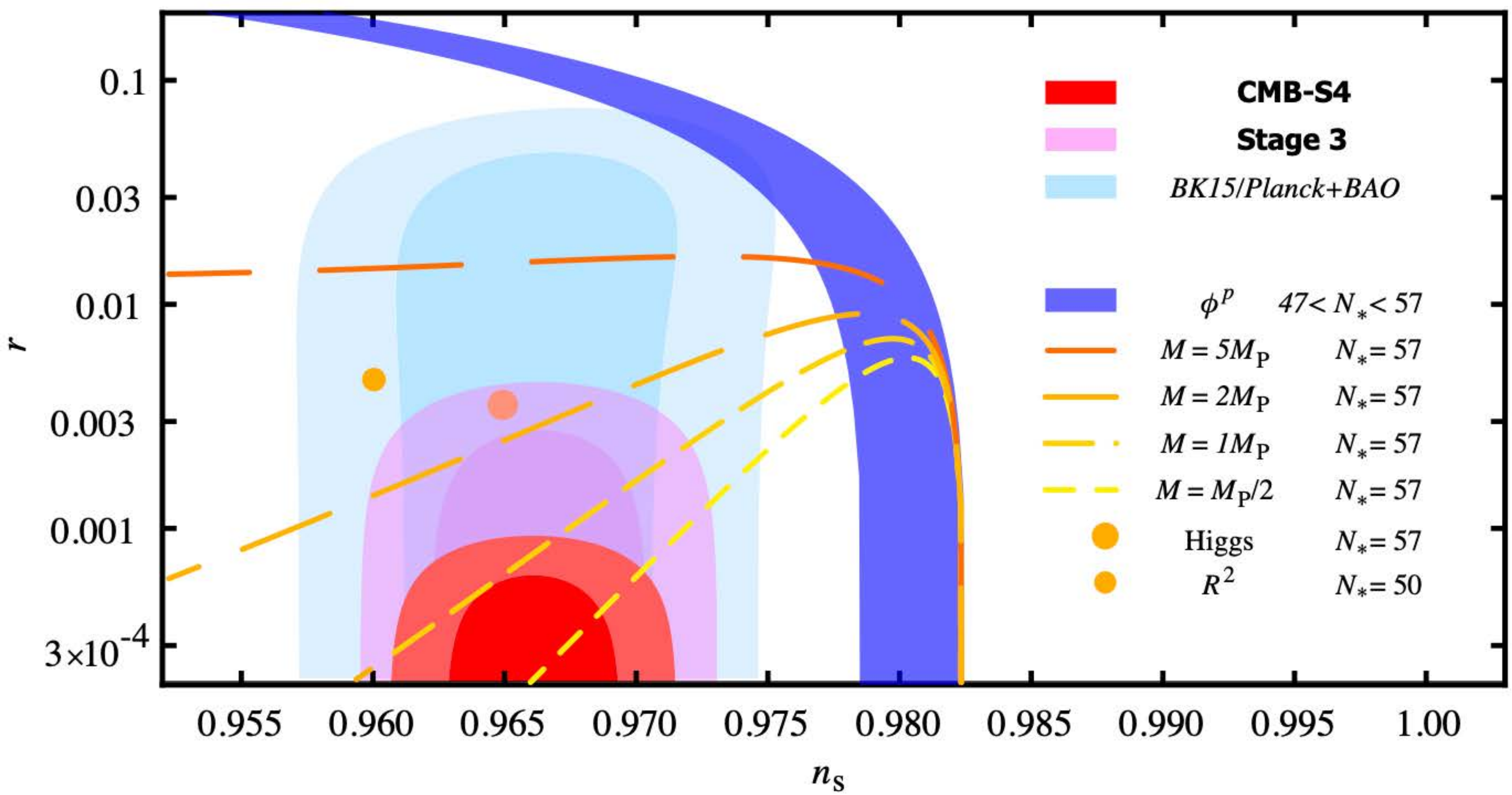
Alan H. Guth*
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 11 August 1980)

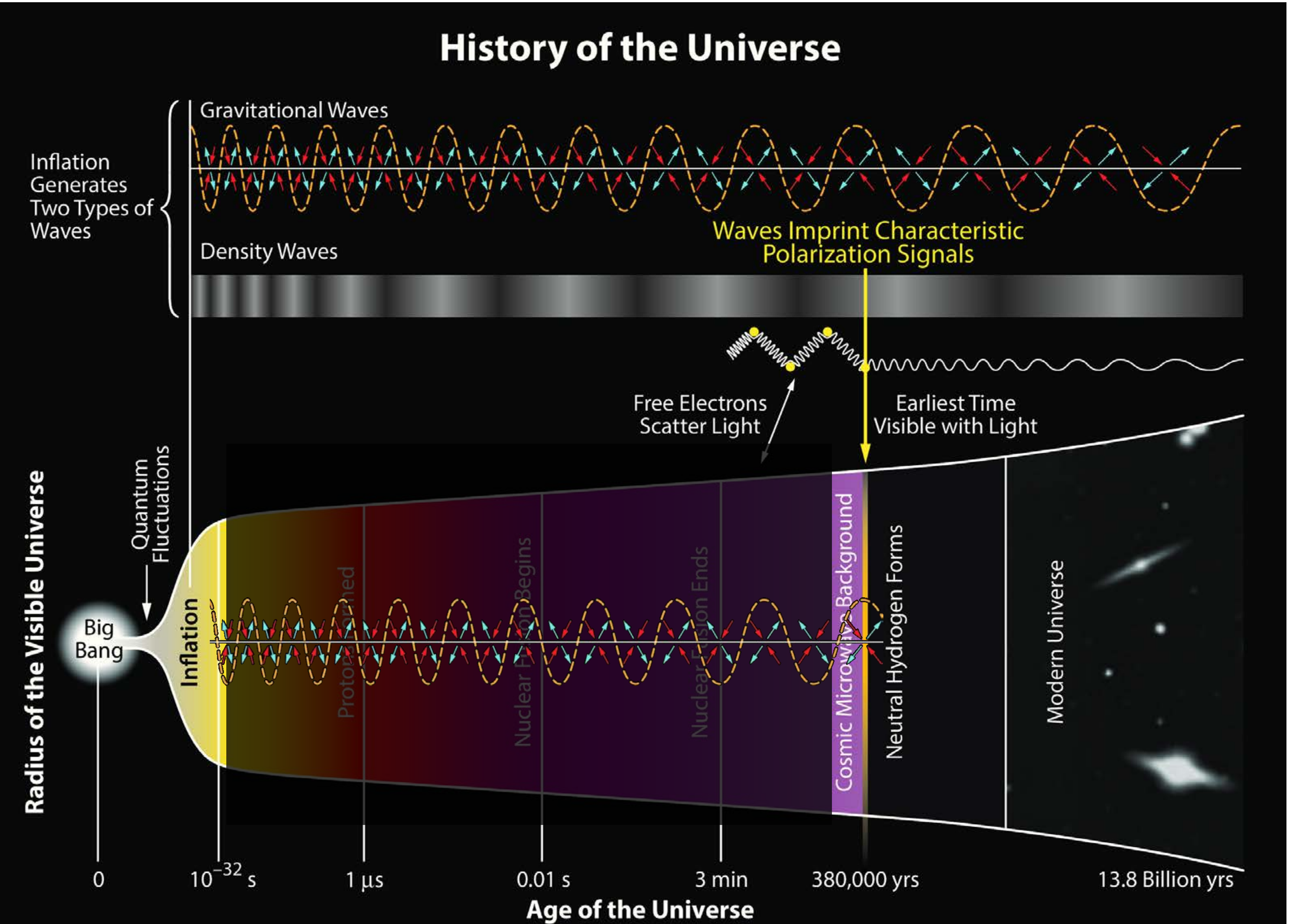
The standard model of hot big-bang cosmology requires initial conditions which are problematic in two ways: (1) The early universe is assumed to be highly homogeneous, in spite of the fact that separated regions were causally disconnected (horizon problem); and (2) the initial value of the Hubble constant must be fine tuned to extraordinary accuracy to produce a universe as flat (i.e., near critical mass density) as the one we see today (flatness problem). These problems would disappear if, in its early history, the universe supercooled to temperatures 28 or more orders of magnitude below the critical temperature for some phase transition. A huge expansion factor would then result from a period of exponential growth, and the entropy of the universe would be multiplied by a huge factor when the latent heat is released. Such a scenario is completely natural in the context of grand unified models of elementary-particle interactions. In such models, the supercooling is also relevant to the problem of monopole suppression. Unfortunately, the scenario seems to lead to some unacceptable consequences, so modifications must be sought.

Inflation Science

- Our question: How did the universe begin?
  - What is the origin of structure in the universe?
- Present: Much data support Inflation
- Future: CMB has potential to see a direct signature of Inflation

CMB Inflation Constraints



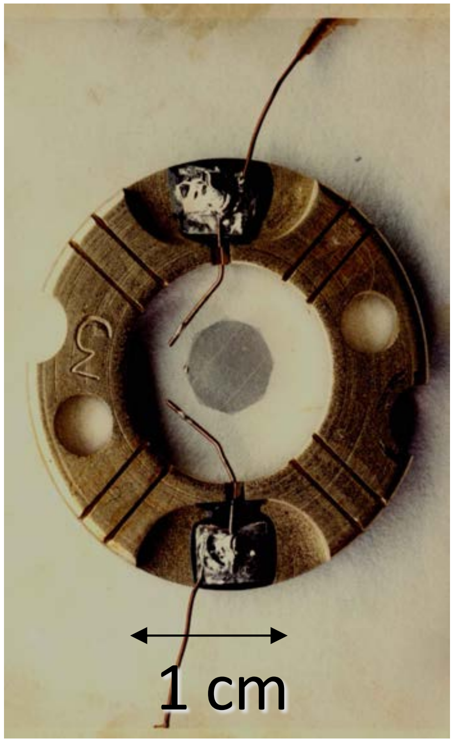


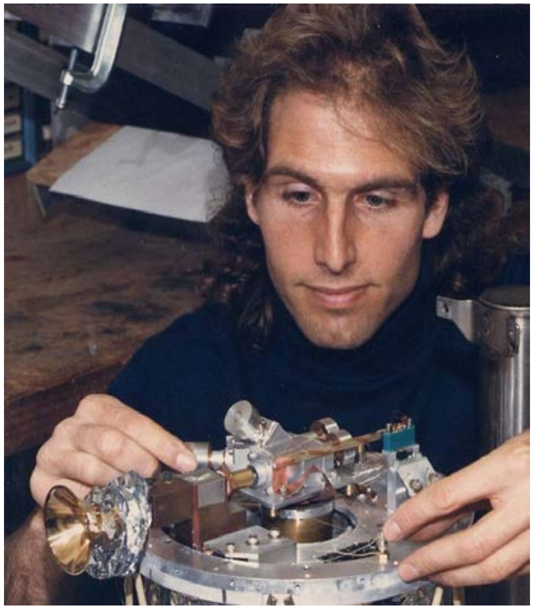
BICEP2 Collaboration

If we make a detection

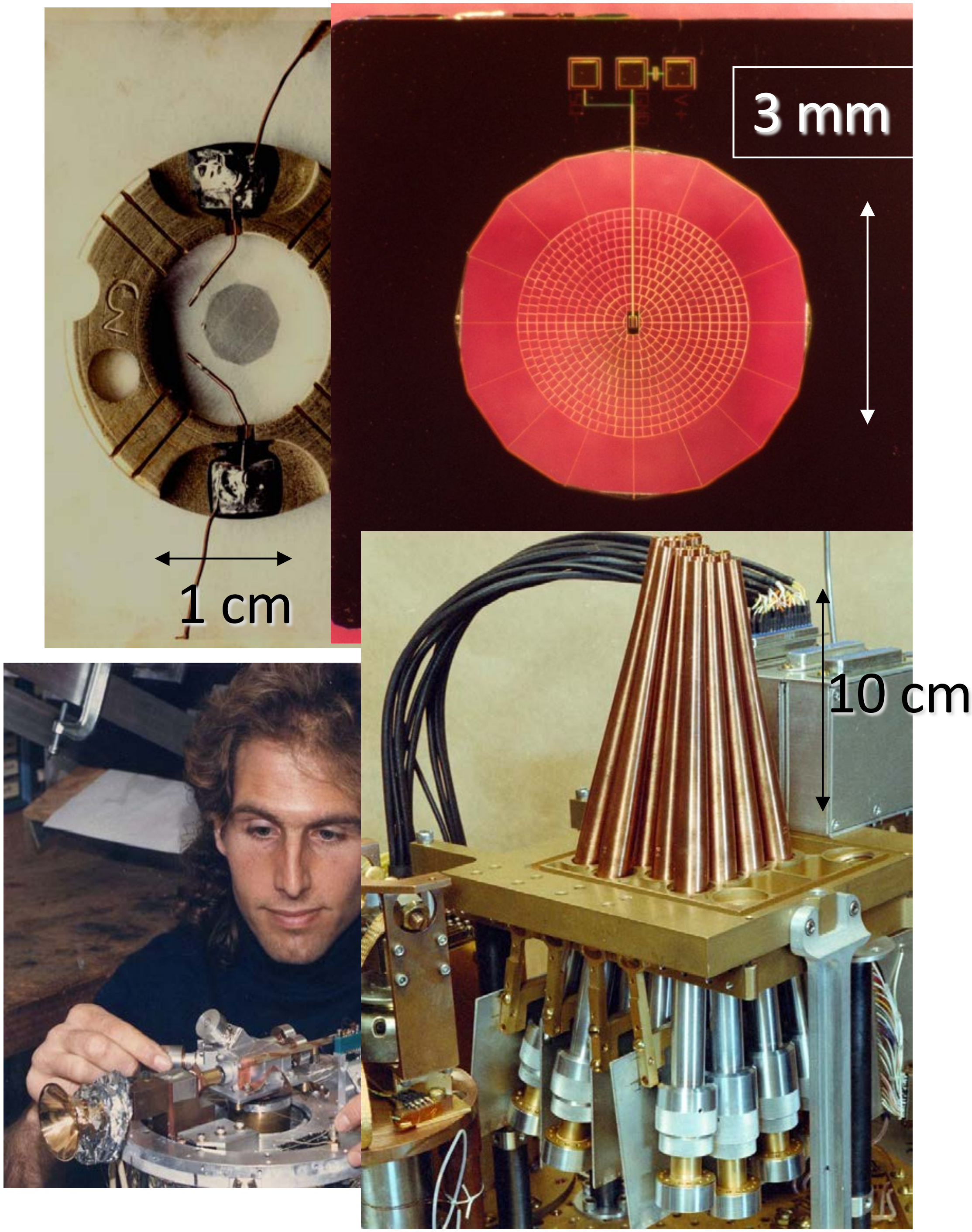
- Prove that inflation occurred
  - Measure Energy Scale
- Test Inflation models including string-motivated
- Opens a new window on Ultra-High Energy physics
  - 12 orders of magnitude higher Energy than CERN LHC!
  - QM fluctuations of the gravitational field
  - First experimental clue to quantum gravity
  - Large potential for discovery

Detectors

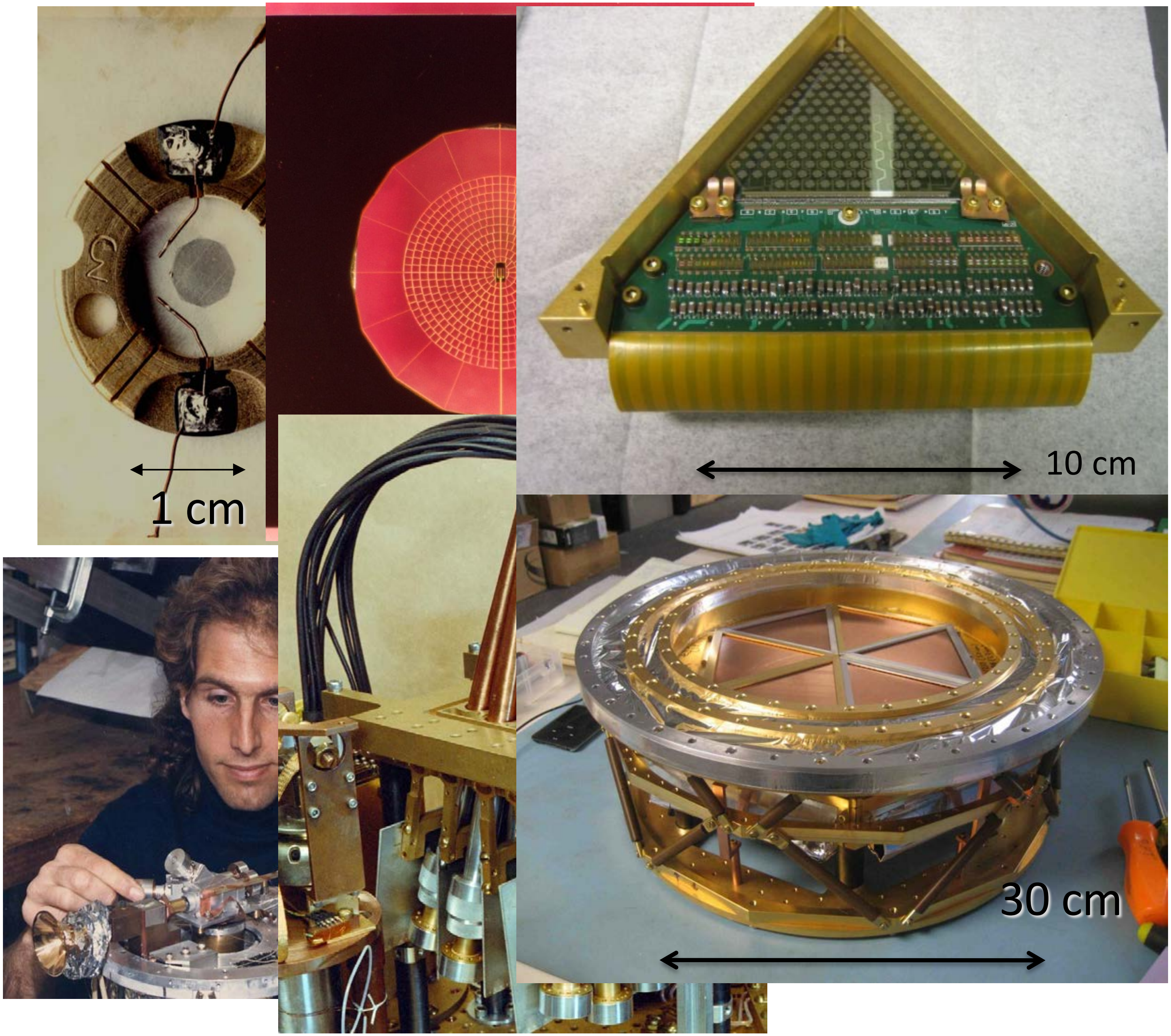




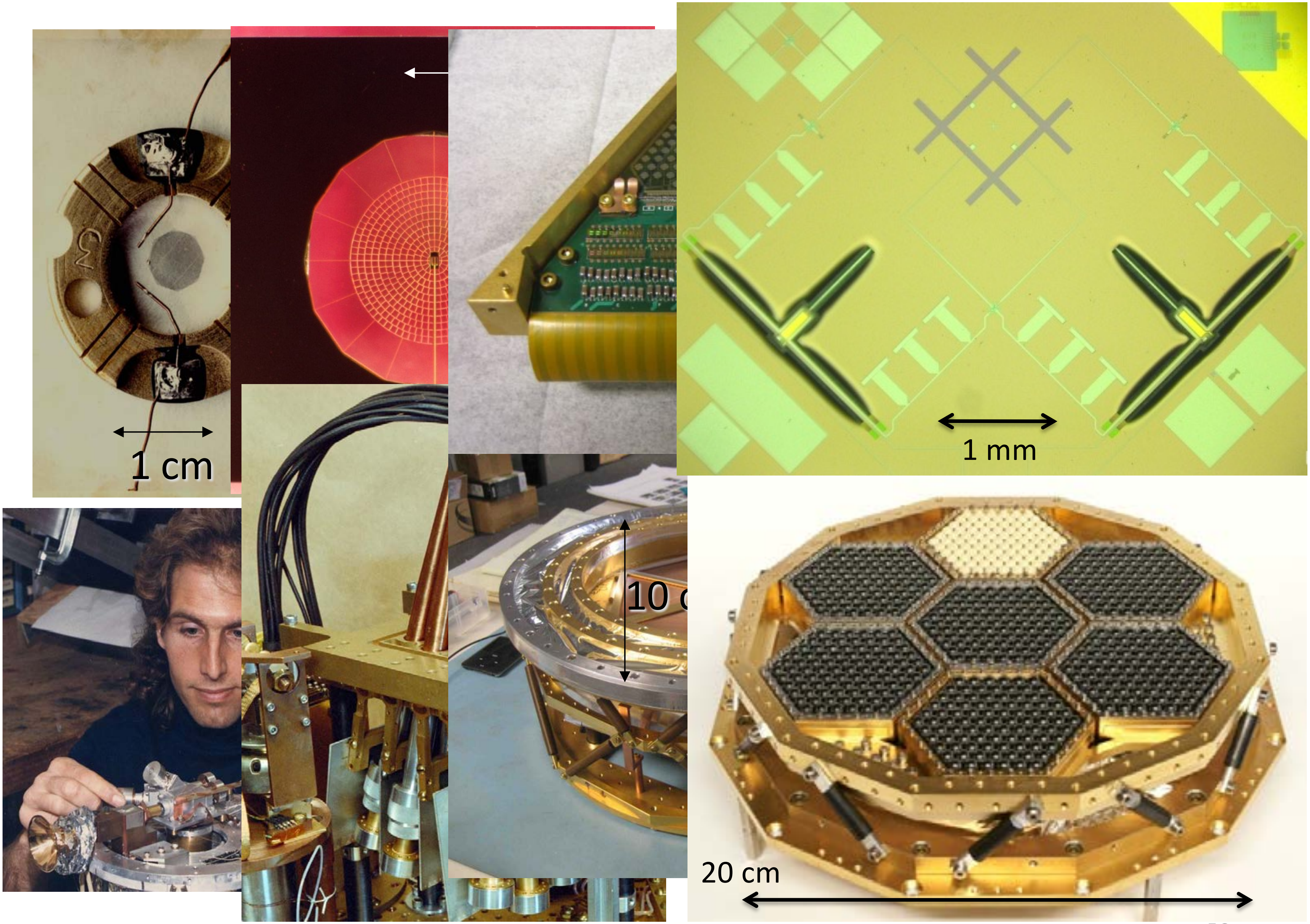
1980's



1980’s 1990’s



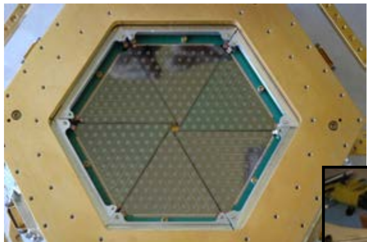
1980's 1990's 2000's



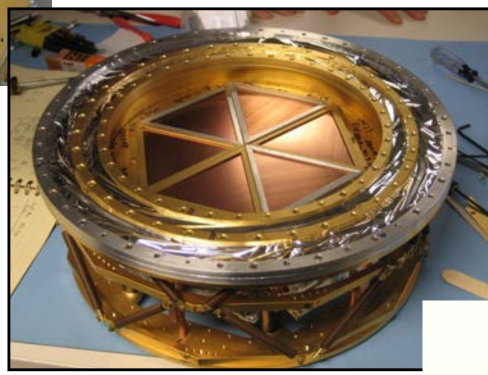
1980's 1990's 2000's 2010's

Experimental Evolution

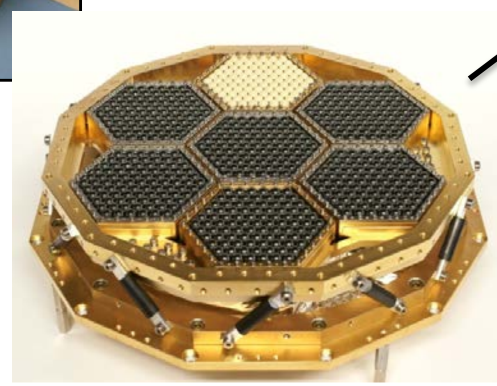
16 cm



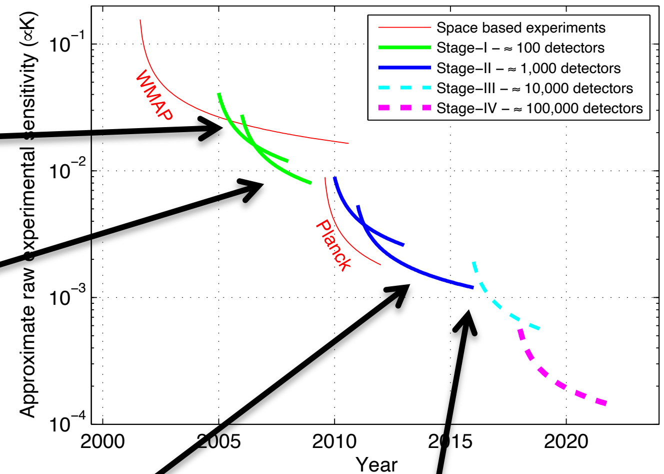
APEX-SZ
330 detectors



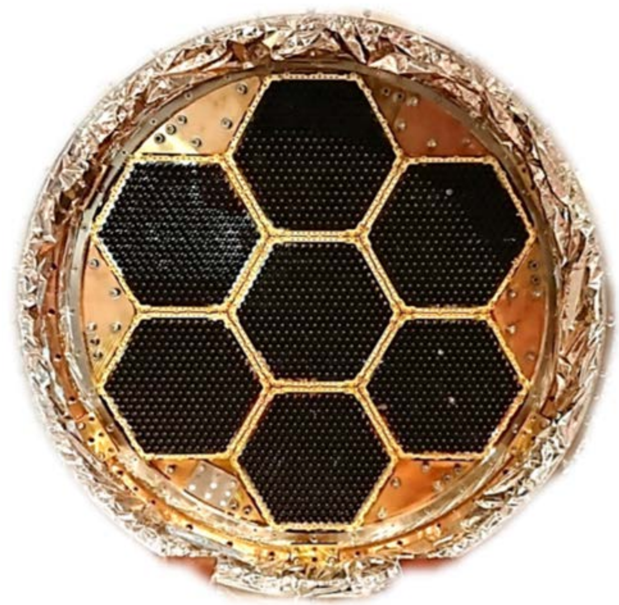
SPT-SZ
960 detectors



POLARBEAR-1
1274 detectors
Dual-Polarization



400 mm

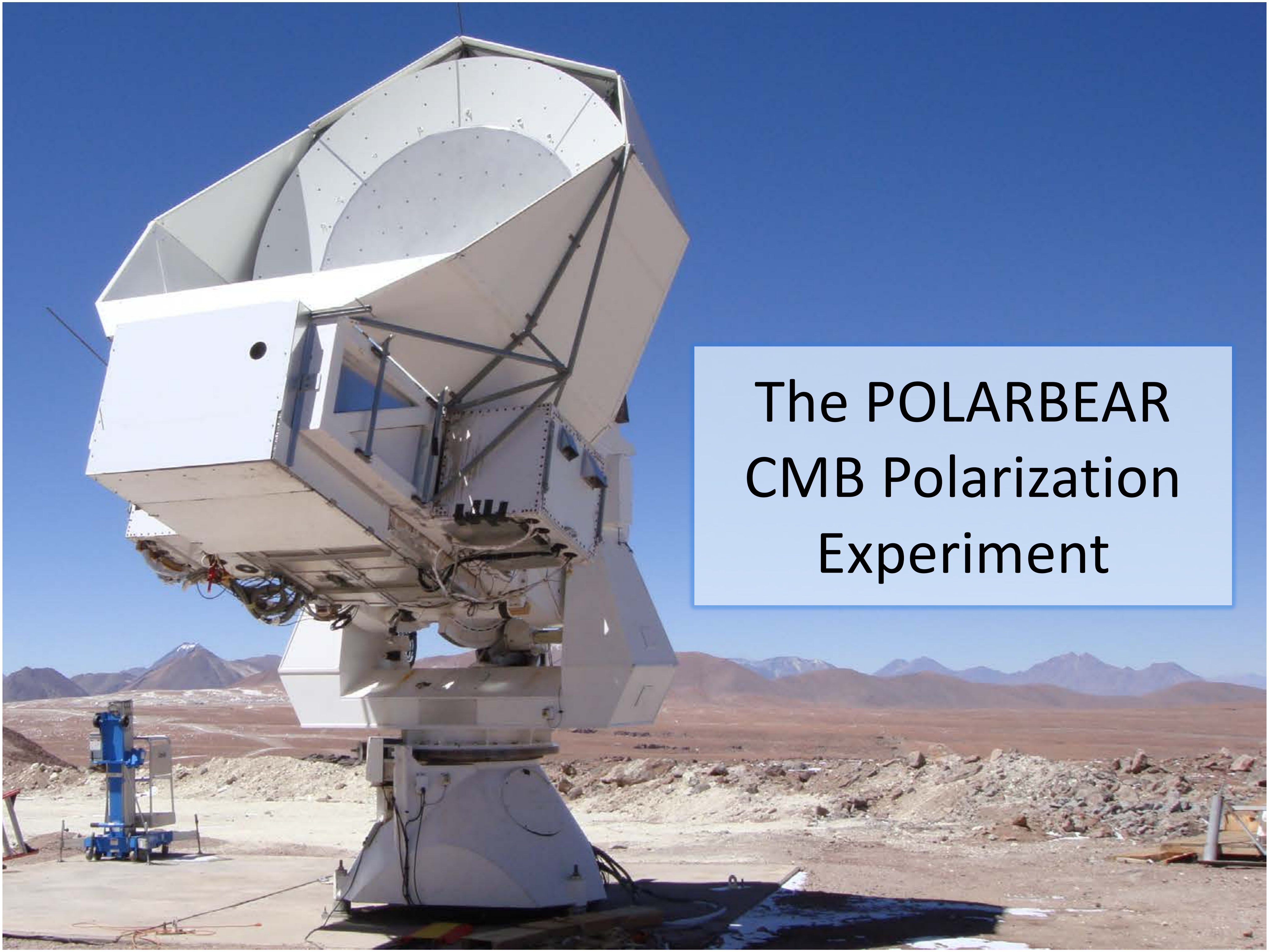


POLARBEAR-2/SPT-3G
8,000/15,000 detectors
Dual-Polarization
2/3 Color/pixel

Marvell Nanofabrication Facility – U.C. Berkeley

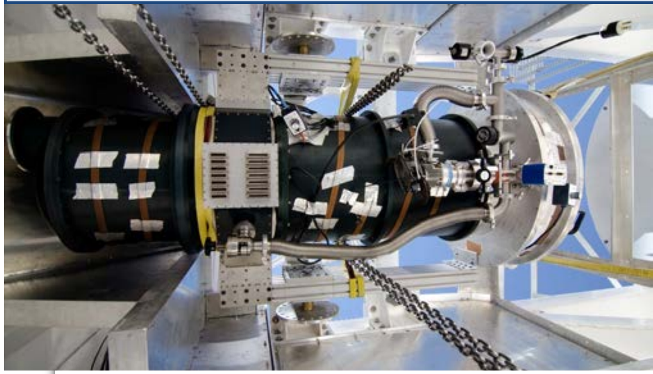
Complete bolometer fab facility

- Silicon Nitride
- Superconducting Niobium

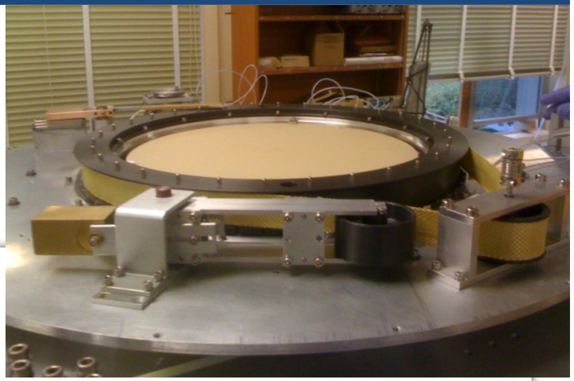


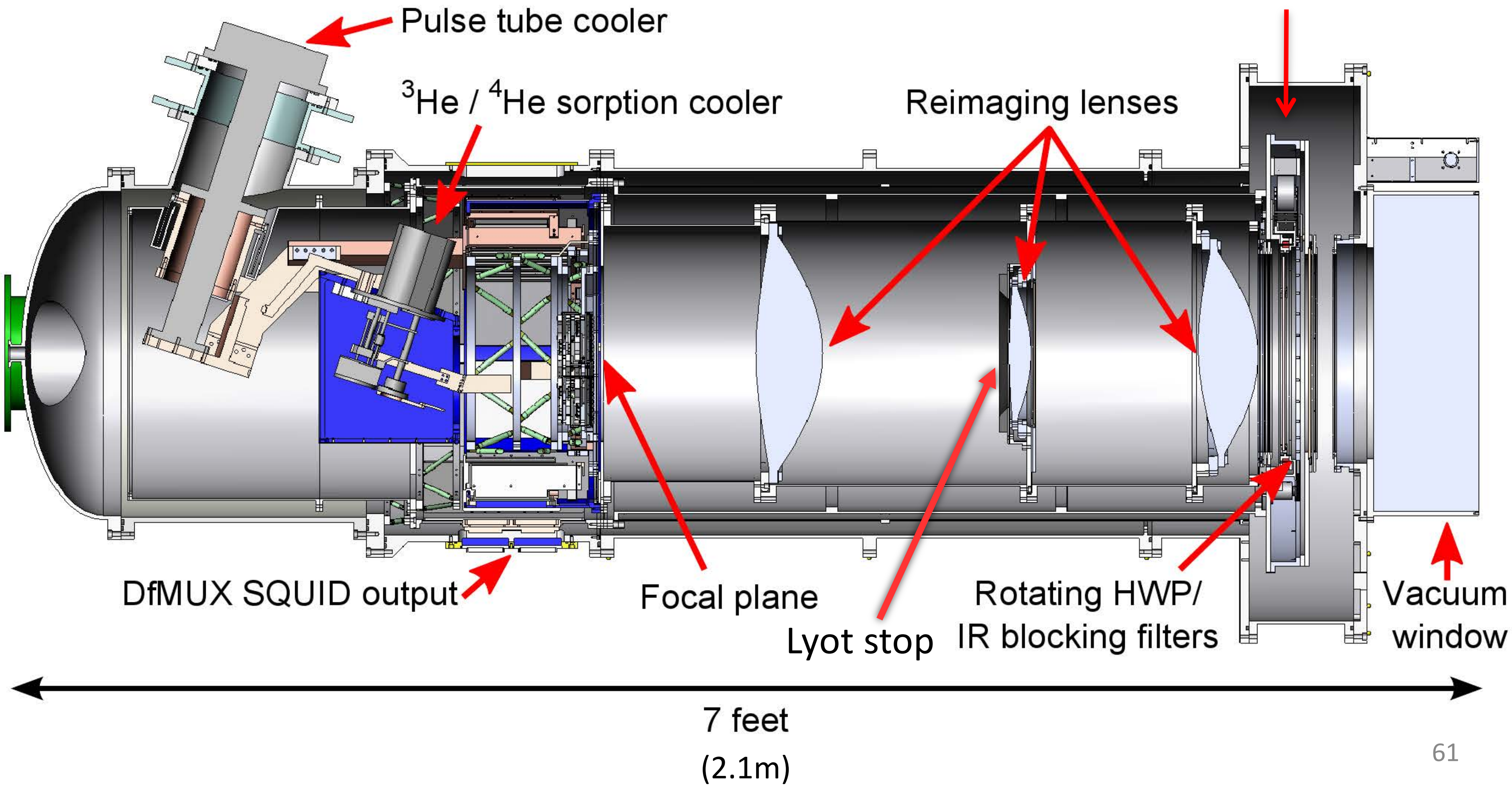
The POLARBEAR CMB Polarization Experiment

POLARBEAR-I Receiver



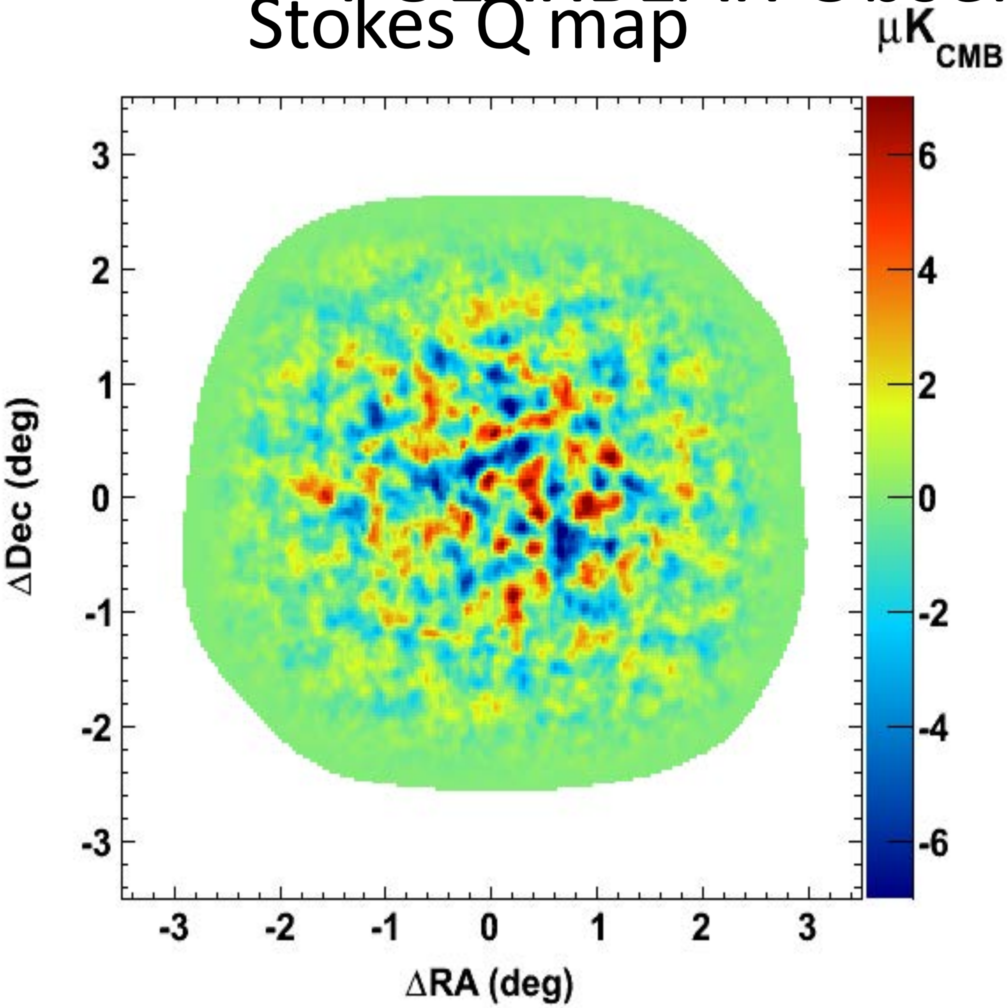
HWP



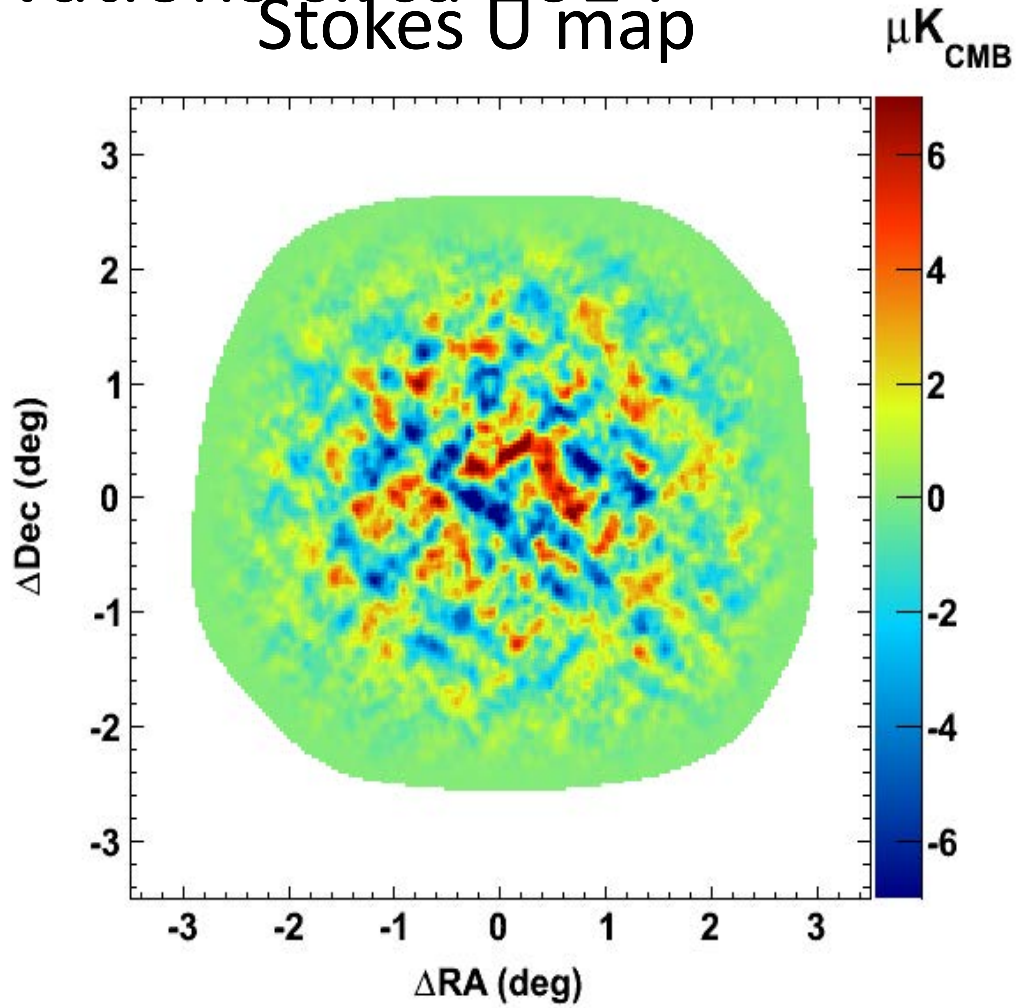


POLARBEAR Observations circa 2014

Stokes Q map

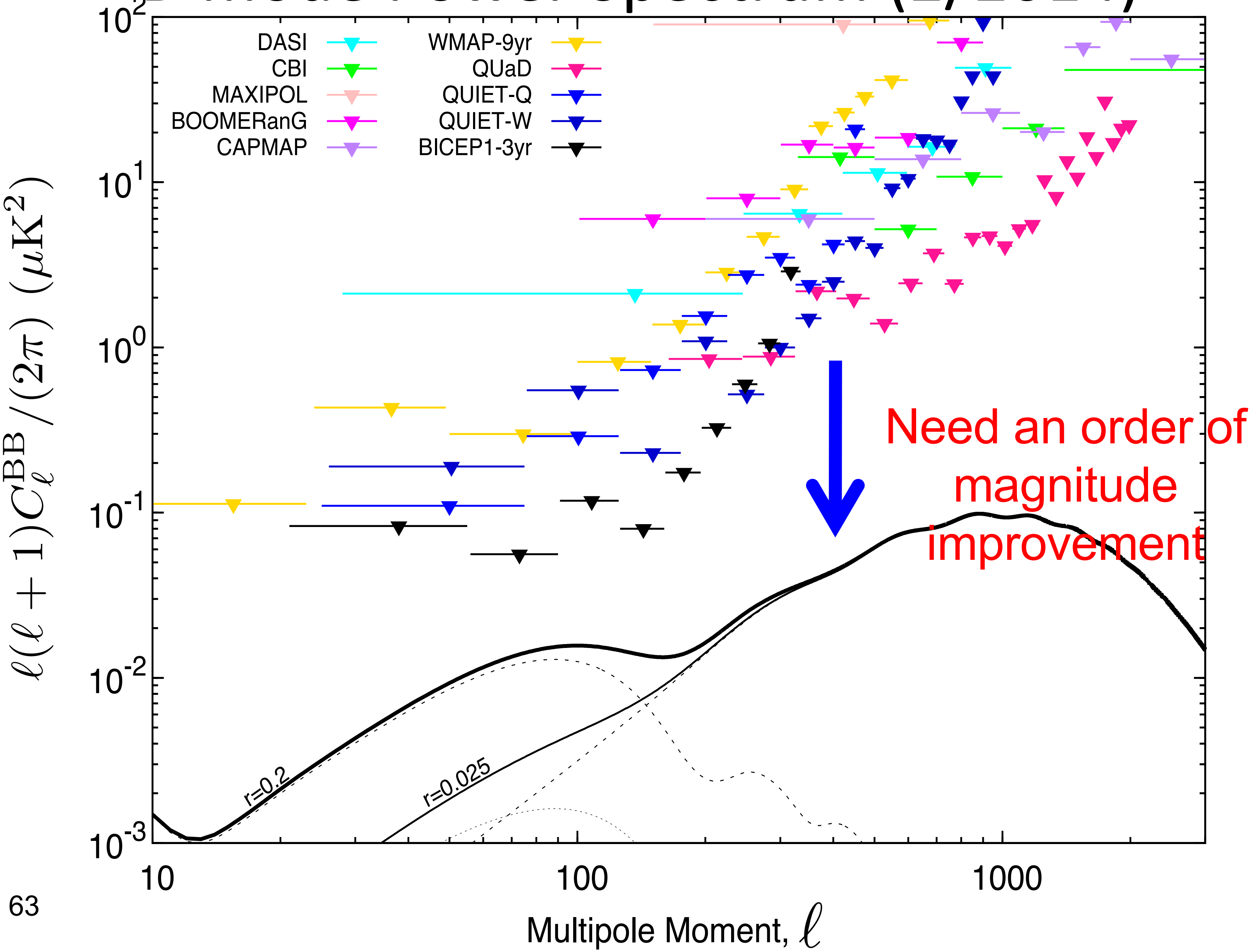


Stokes U map

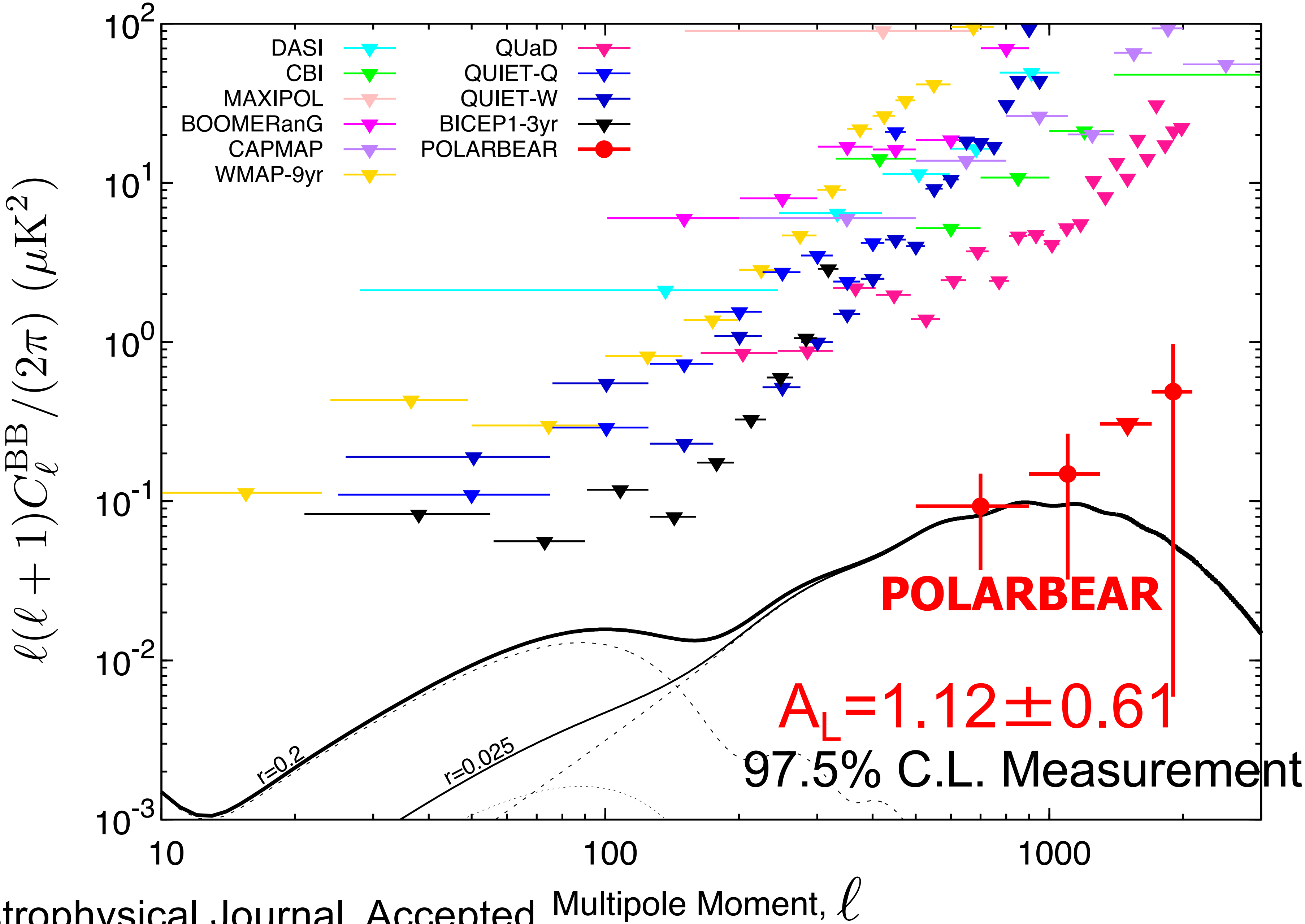


- Roughly 10 times deeper than PLANCK
- Most sensitive polarization maps @ sub-degree scales
  - in experiments which have released data (~6 uK-amin)

B-mode Power Spectrum (2/2014)

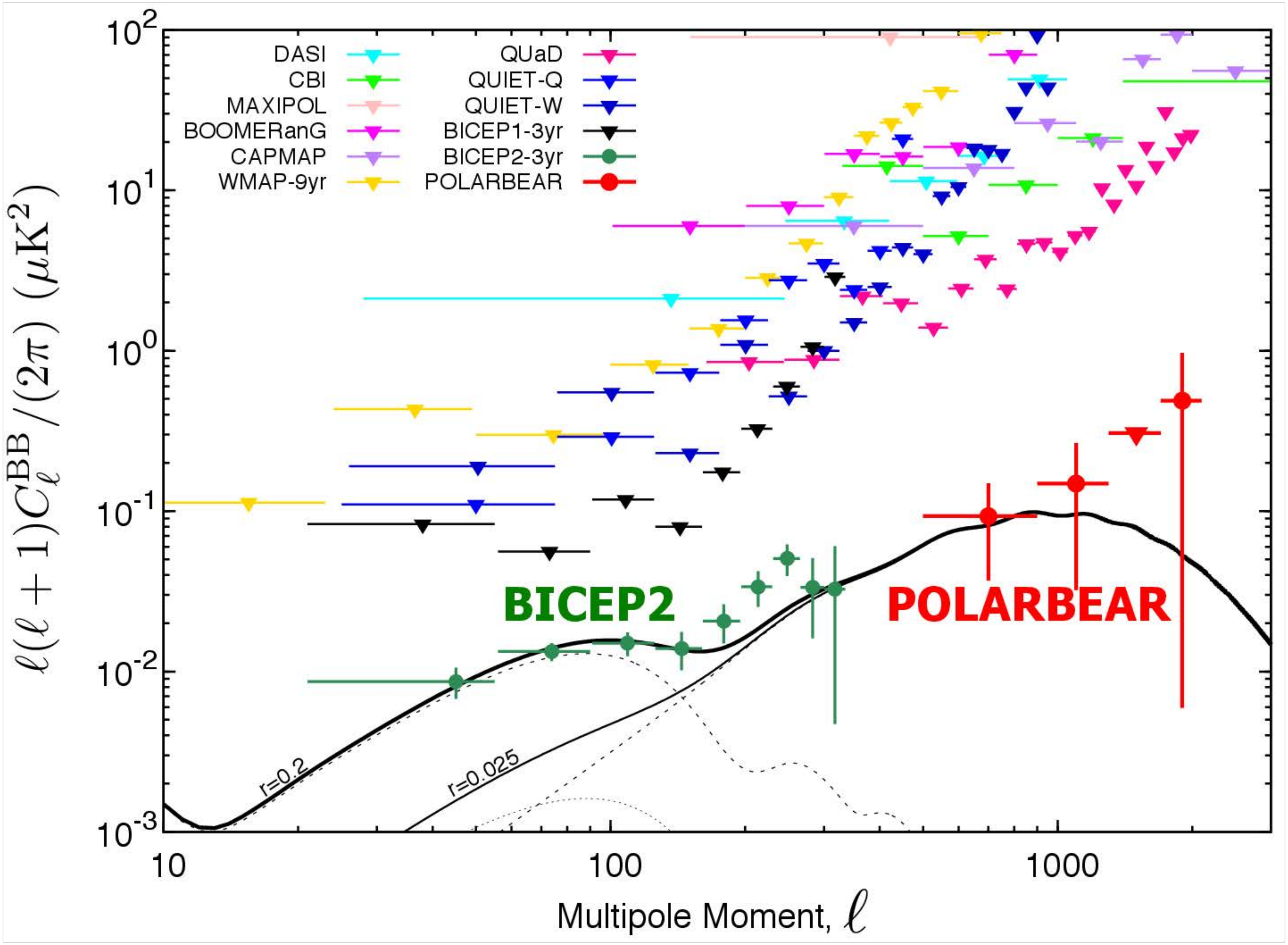


New POLARBEAR B-mode Spectrum

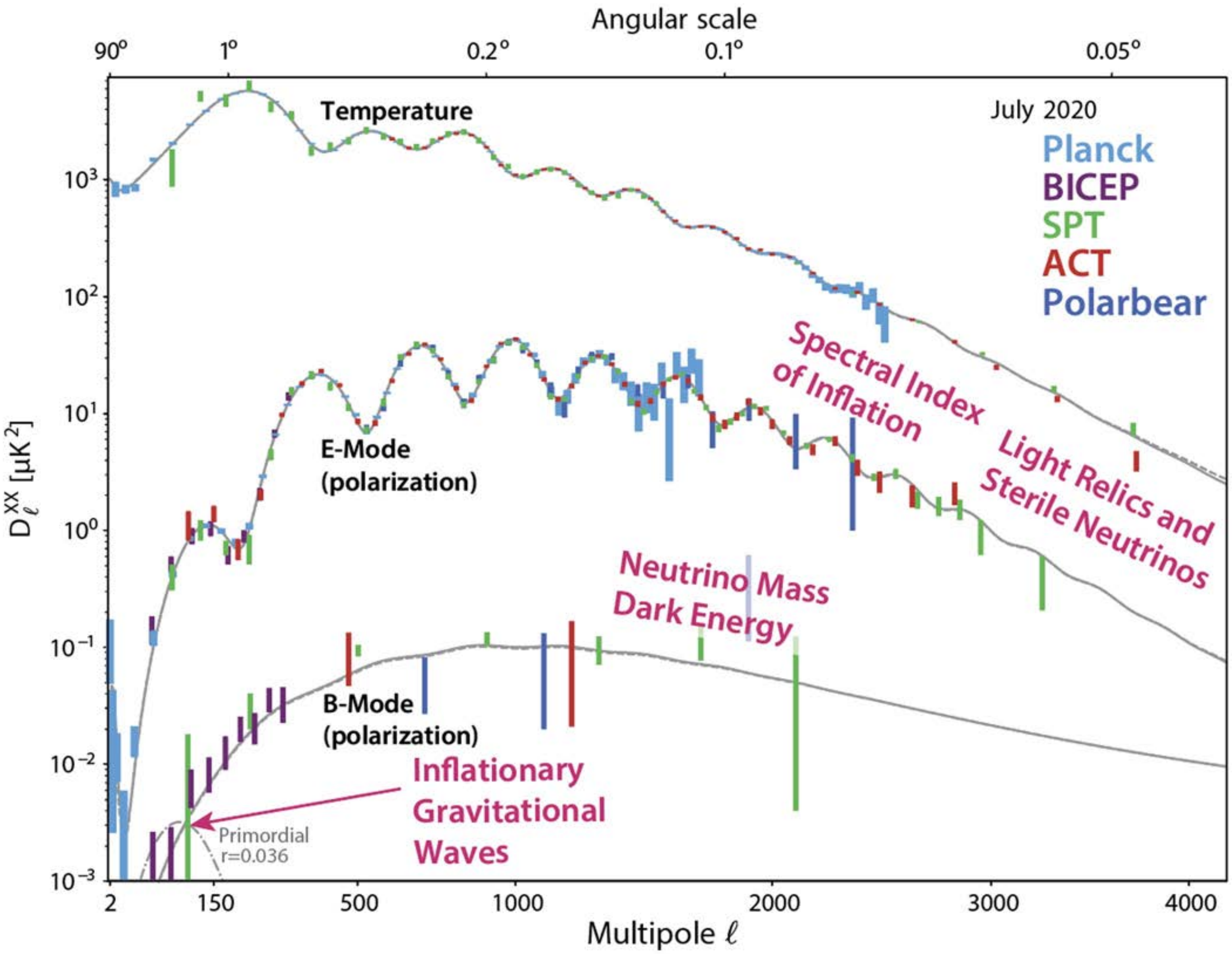


Astrophysical Journal, Accepted

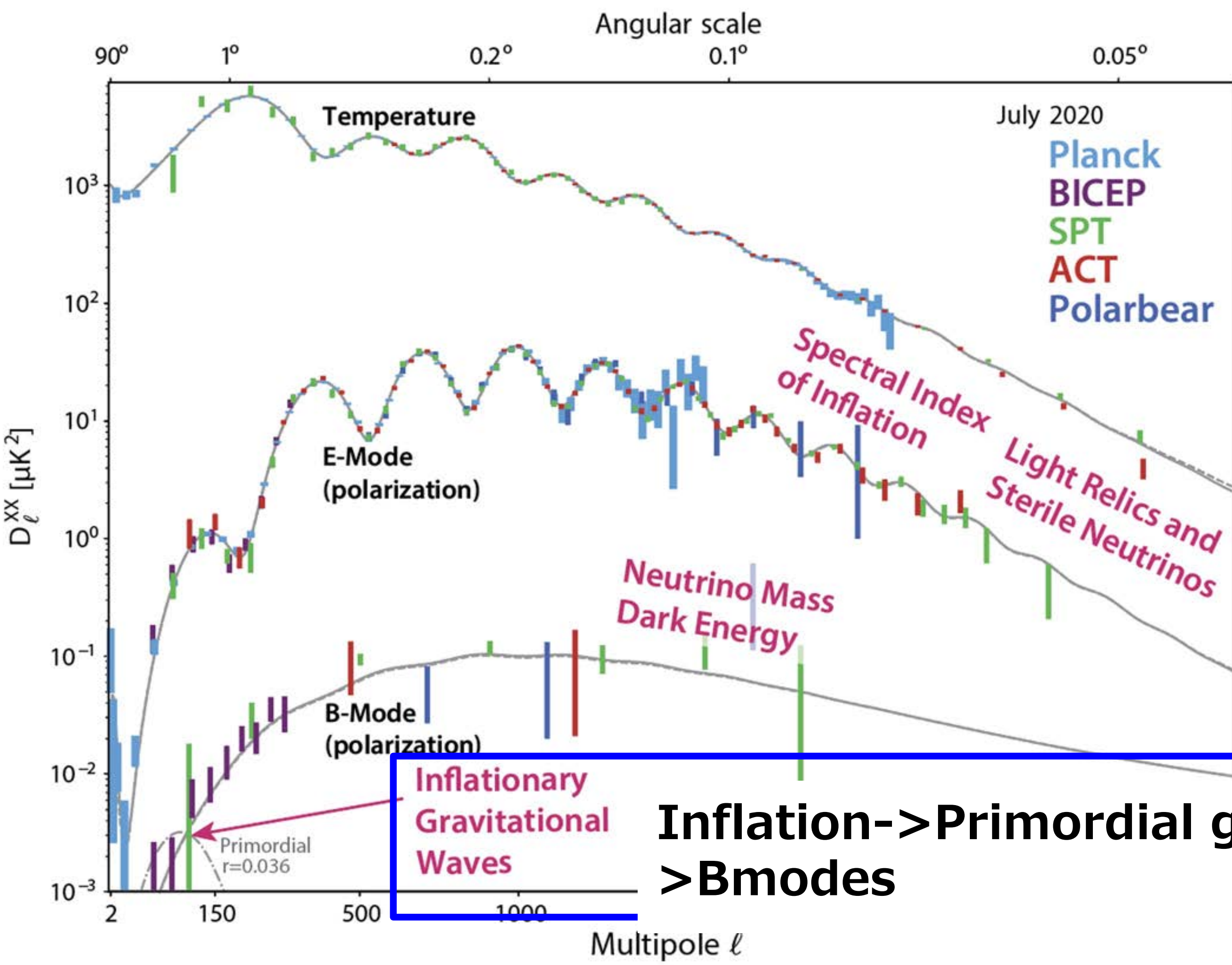
BICEP2 results



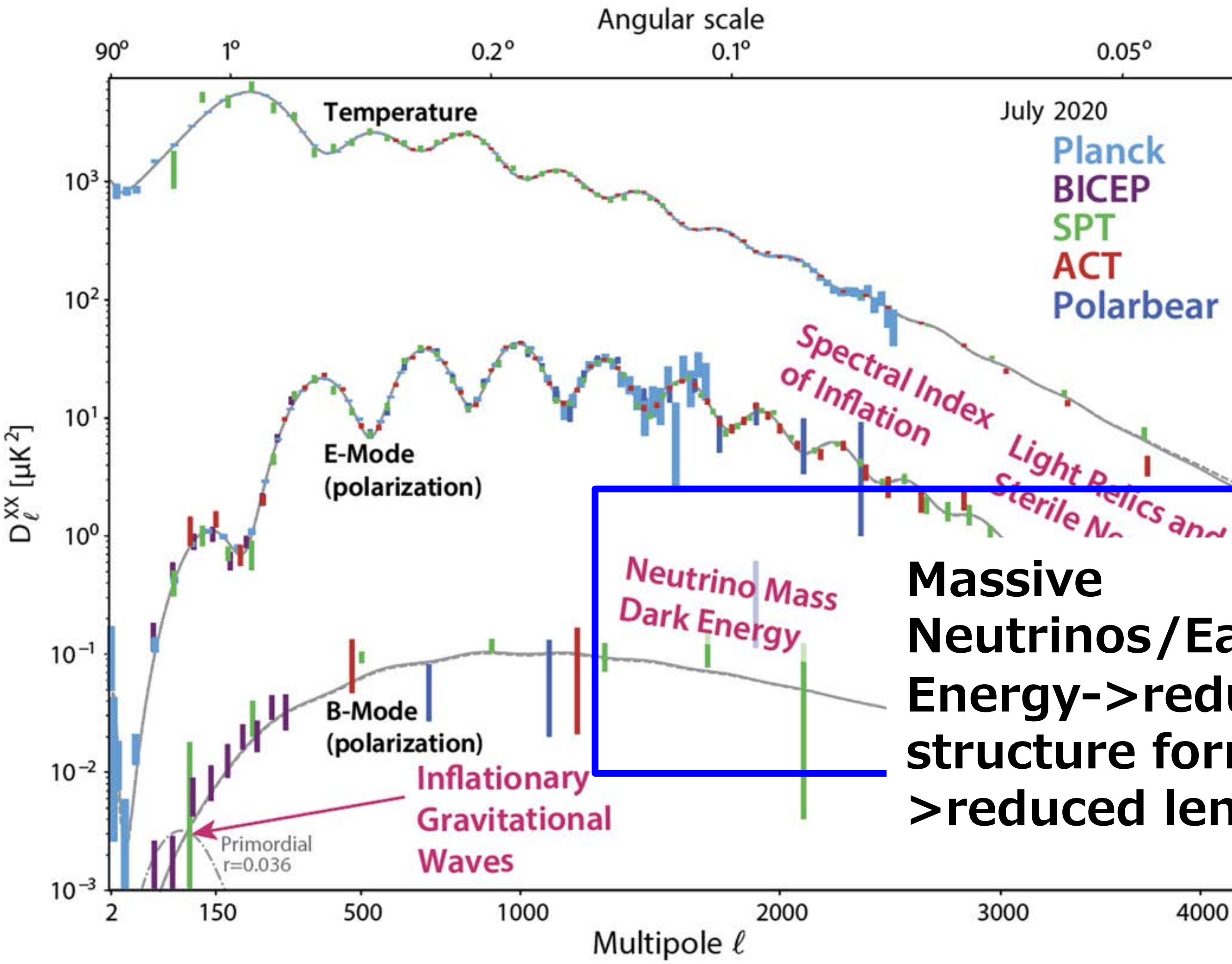
Simons Array



Angular scale
90°
1°
0.2°
0.1°
0.05°
Temperature
July 2020
Planck
BICEP
SPT
ACT
Polarbear
E-Mode
(polarization)
B-Mode
(polarization)
Spectral Index
of Inflation
Light Relics and
Sterile Neutrinos
Neutrino Mass
Dark Energy
Inflationary
Gravitational
Waves
Primordial
r=0.036
D_ℓ^{XX} [μK^2]
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
2
150
500
1000
2000
3000
4000
Multipole ℓ

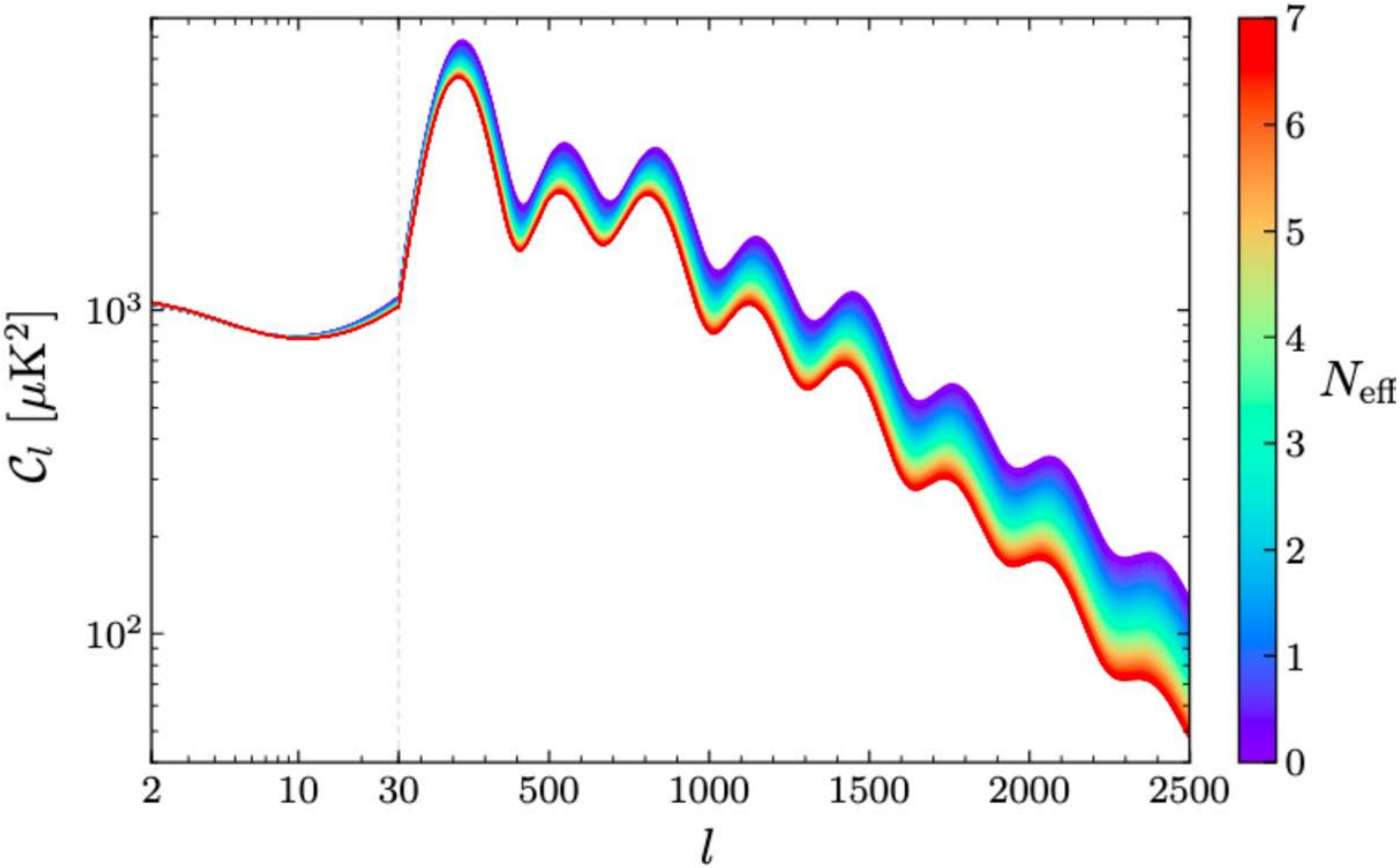


Inflation->Primordial grav waves->Bmodes



Massive Neutrinos/Early Dark Energy->reduced structure formation->reduced lensing

Neff and CMB dampling tail



D. Baumann

Effective relativistic species, N_{eff}

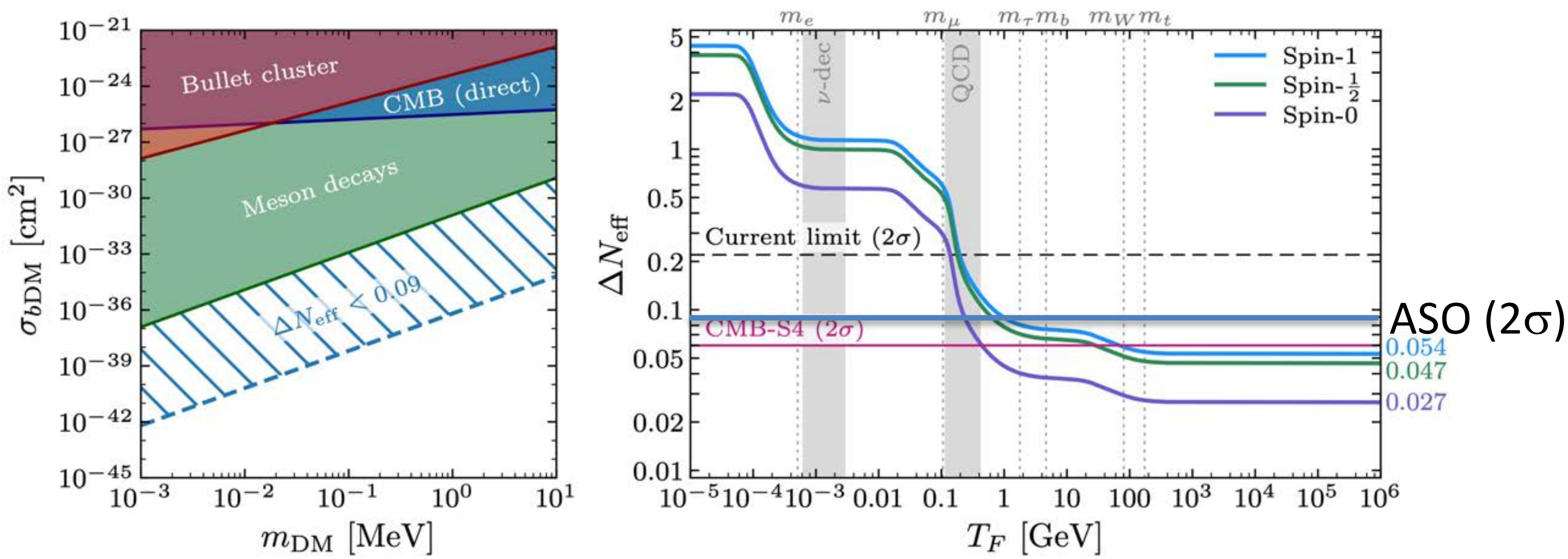
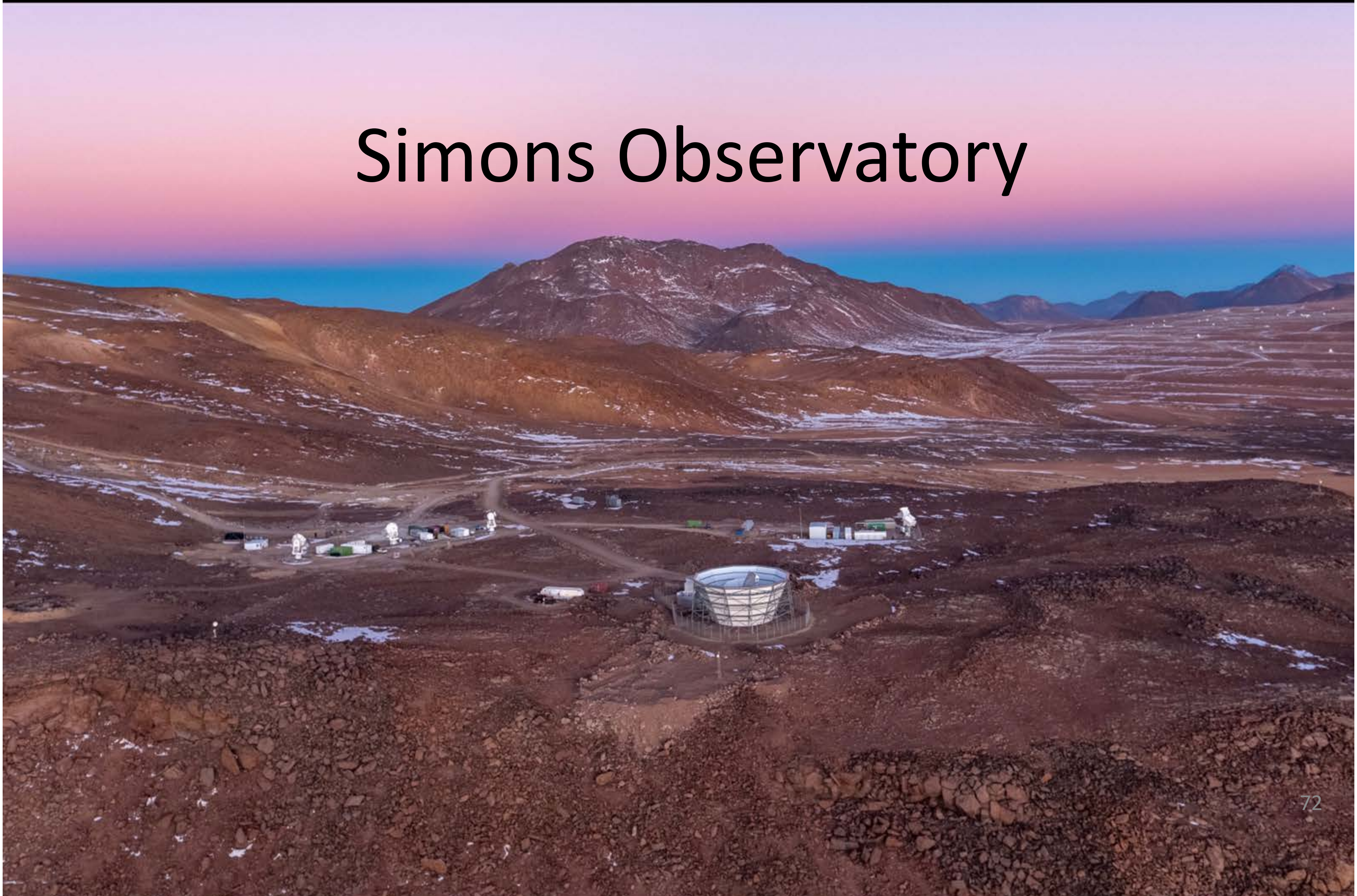


Figure 10. *Left: Limits on the dark-matter-baryon cross-section $\sigma_{b\rm DM}$ for a Yukawa potential. Future cosmological constraints will restrict $\Delta N_{\rm eff} < 0.09$ and, therefore, exclude cross-sections large enough to thermalize the (200 keV-mass) particle mediating the force [196]. This limit is compared to the direct bound on baryon-dark-matter scattering from the CMB [198] and to the constraints on dark forces from the Bullet Cluster [199]. The strongest current constraint is from the absence of meson decays to the mediator [200]. Right: Contributions of a single massless particle, which decoupled from the SM at temperature T_F, to the effective number of relativistic species, $N_{\rm eff} = N_{\rm eff}^{\rm SM} + \Delta N_{\rm eff}$, with the SM expectation $N_{\rm eff}^{\rm SM} = 3.045$ from neutrinos. The dashed line shows the 2σ limit from a combination of current CMB, BAO, and Big Bang nucleosynthesis (BBN) observations [127]. The purple line shows the projected sensitivity of CMB-S4 and illustrates its power to constrain light thermal relics. The displayed values on the right are the observational thresholds for particles with different spins and arbitrarily large decoupling temperatures.*

Simons Observatory



Simons Observatory

Atacama Chile

17,000 ft

SIMONS FOUNDATION

HEISING-SIMONS FOUNDATION

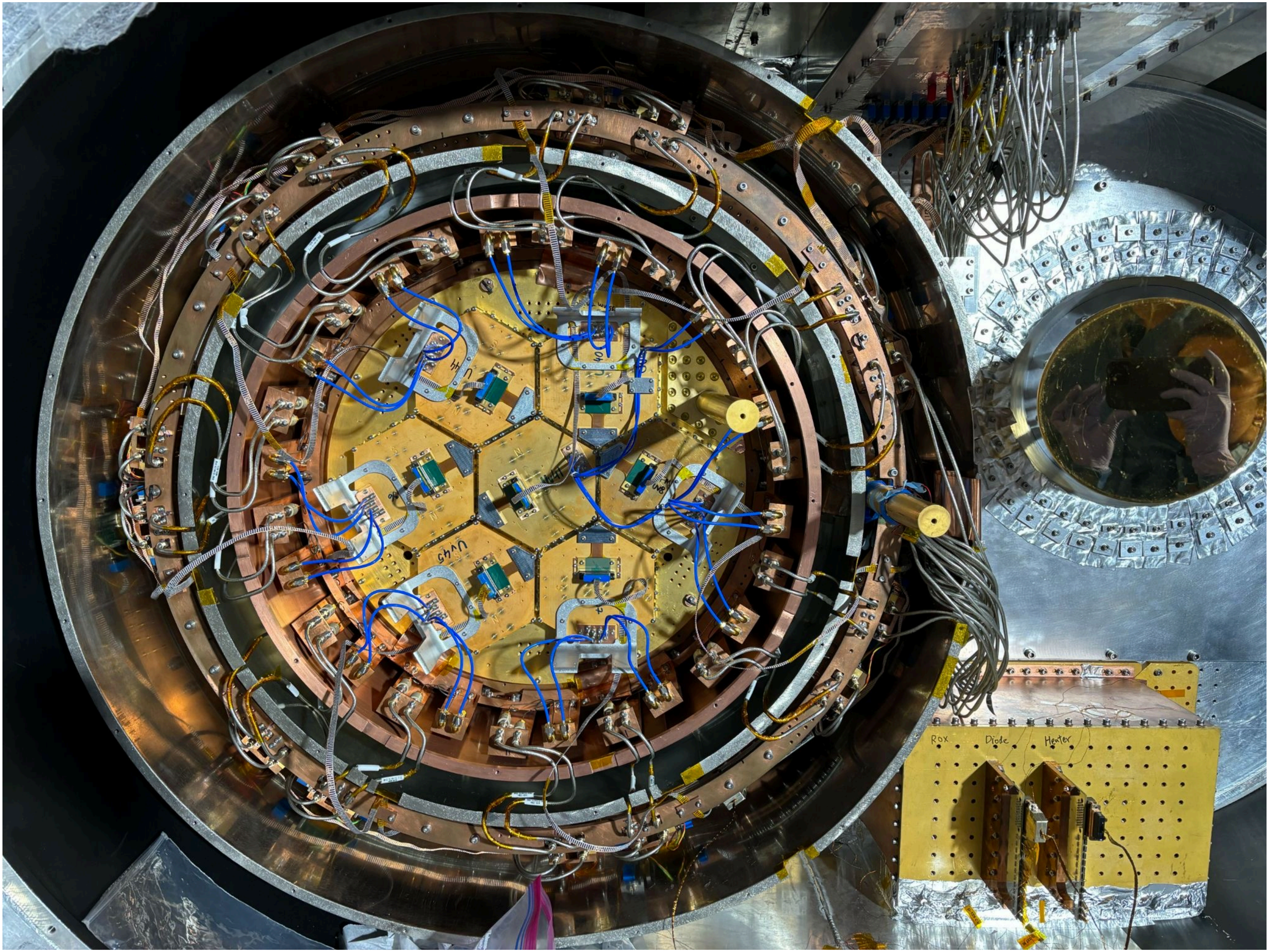
The Simons Observatory

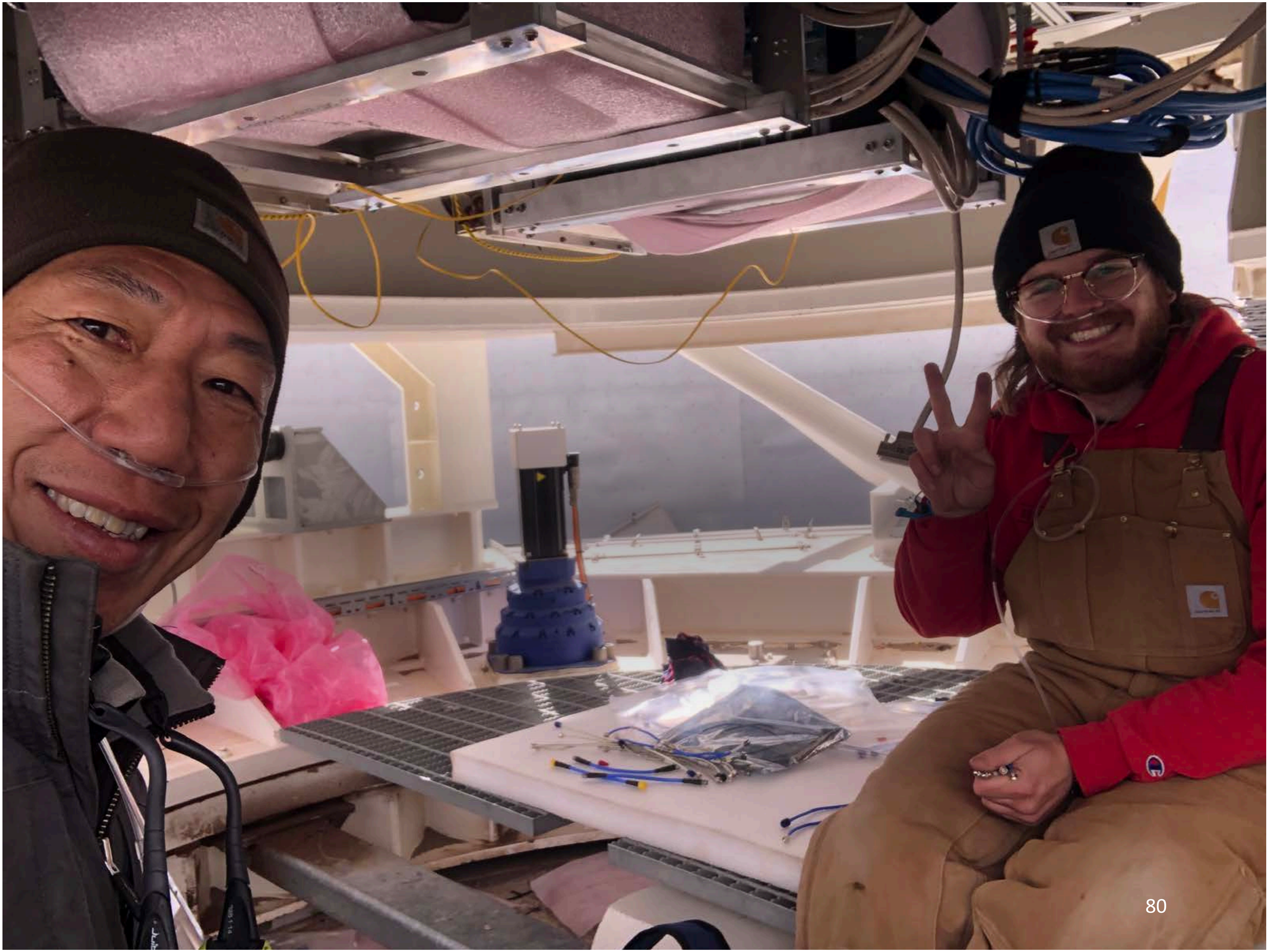
Large Aperture Telescope (LAT)

- 6 m primary mirror
    - Just had first light!
- 6 bands 27-280 GHz
- 2’ FWHM beam at 93 GHz
- 30k detectors
- Upgrade to 60k in 2028

Small Aperture Telescopes (SATs)

- 3 telescopes
- 0.4 m primary lens
- **Spinning half-wave plate modulates polarization to recover low-l B**
- 6 bands: 27-280 GHz
- 30' FWHM @ 93 GHz
- 30k detectors (total: ~10k each)
- First light Oct 2023
- Upgrade to 6 telescopes ~2028


Rox
Diode
Heater



	Parameter	SO-Baseline[a] (no syst)	**SO-Baseline[b]**	SO-Goal[c]	Current[d] (2018-19)	Method	Sec.	**Advanced-SO (2024-2032)**
Primordial	r	0.0024	**0.003**	0.002	0.03	BB + ext delens	3.4	**0.0012**
perturbations	$e^{-2\tau}\mathcal{P}(k=0.2/\mathrm{Mpc})$	0.4%	**0.5%**	0.4%	3%	$TT/TE/EE$	4.2	**0.4%**
	$f_{\mathrm{NL}}^{\mathrm{local}}$	1.8	**3**	1	5	$\kappa\kappa \times$ LSST-LSS + 3-pt	5.3	**1**
		1	**2**	1		kSZ + LSST-LSS	7.5	
Relativistic species	N_{eff}	0.055	**0.07**	0.05	0.2	$TT/TE/EE + \kappa\kappa$	4.1	**0.045**
Neutrino mass	Σm_ν	0.033	**0.04**	0.03	0.1	$\kappa\kappa$ + DESI-BAO	5.2	**0.03**
		0.035	**0.04**	0.03		tSZ-N $\times$ LSST-WL	7.1	
		0.036	**0.05**	0.04		tSZ-Y + DESI-BAO	7.2	
Deviations from Λ	$\sigma_8(z=1-2)$	1.2%	**2%**	1%	7%	$\kappa\kappa$ + LSST-LSS	5.3	**1%**
		1.2%	**2%**	1%		tSZ-N $\times$ LSST-WL	7.1	
	H_0 (ΛCDM)	0.3	**0.4**	0.3	0.5	$TT/TE/EE + \kappa\kappa$	4.3	
Galaxy evolution	η_{feedback}	2%	**3%**	2%	50-100%	kSZ + tSZ + DESI	7.3	**2%**
	p_{nt}	6%	**8%**	5%	50-100%	kSZ + tSZ + DESI	7.3	**4%**
Reionization	Δz	0.4	**0.6**	0.3	1.4	TT (kSZ)	7.6	**0.3%**

[a] This column reports forecasts from earlier sections (in some cases using 2 s.f.) and applies no additional systematic error.

[b] This is the nominal forecast, increases the column (a) uncertainties by 25% as a proxy for instrument systematics, and rounds up to 1 s.f.

[c] This is the goal forecast, has negligible additional systematic uncertainties, and rounds to 1 s.f.

[d] Primarily from [44] and [287].

[44] BICEP2 and Planck collaborations, Joint Analysis of BICEP2/Keck Array and Planck Data, Phys. Rev. Lett. 114 (2015) 101301
[287] Planck collaboration, Planck 2018 results. VI. Cosmological parameters

Table 9. Summary of SO key science goals. All of our SO forecasts assume that SO is combined with *Planck* data.

From: The Simons Observatory: science goals and forecasts
Peter Ade et al., JCAP02 (2019) 056
https://ui.adsabs.harvard.edu/abs/2019JCAP...02..056A/abstract

Summary

- Hunt for Inflation is on!
  - Early Universe = ultra-high energies
- Large step in power spectrum measurements
  - Neff: possible clues for Dark Matter
  - Lensing: probe of Dark Matter and Dark Energy
- Simons Observatory – Moving to science data
- Future: More experiments at/in South Pole, Chile, and Space