astro8405

An Introduction to the
Cosmic Microwave Background

Kaustuv Basu

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eCampus | Lernplattform der Universität Bonn

astro8405: The Cosmic Microwave Background

Aktionen

This course intends to give you a modern and up-to-date introduction to the science and experimental techniques relating to the Cosmic Microwave Background. No prior knowledge of cosmology is necessary, your prerequisite are a basic understanding of electrodynamics and thermal physics and some familiarity with Python programming.

Goals of this course

➡ Present the relevance and importance of CMB research, with *you* as the future researcher who will take this field further

➡ Describe how CMB has shaped our understanding of cosmology and gave us the ‘concordance model’ (CMB temp power spectrum)

➡ Show the current frontiers of CMB research (CMB polarization and spectral distortions) and describe their scientific goals

➡ Illustrate how CMB is used as a “backlight” to learn about the in-between universe (my personal favourite)

➡ Give you an idea on CMB data analysis: what are the tools and how different foreground emissions are removed

Practical matters

Lecturer:	**Tutors:**
Kaustuv Basu (AIfA room no. 1.006) *kbasu@uni-bonn.de*	Adhishree Lahiri *s6adlahi@uni-bonn.de* Rupal Giri *s6rugiri@uni-bonn.de*

Need to decide on the day & time of the tutorial class(es)

➡ We use these lecture slides as the primary source of information, but will also do blackboard work. Slides will be posted on eCampus before the lectures (probably the night before 😉)

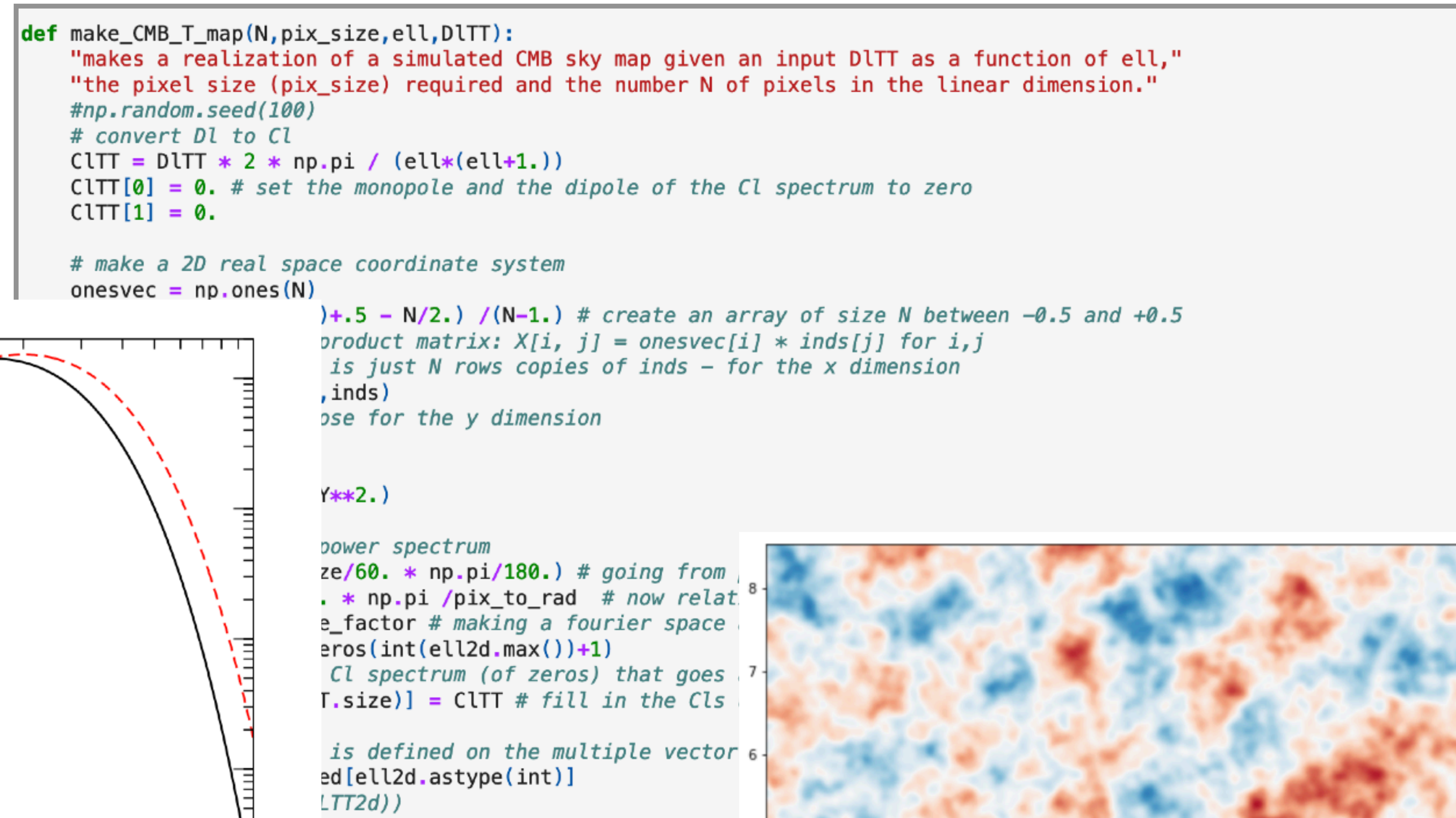
➡ We will be developing a **lecture script** as we go along. Please check the eCampus page for the latest version of this PDF script.

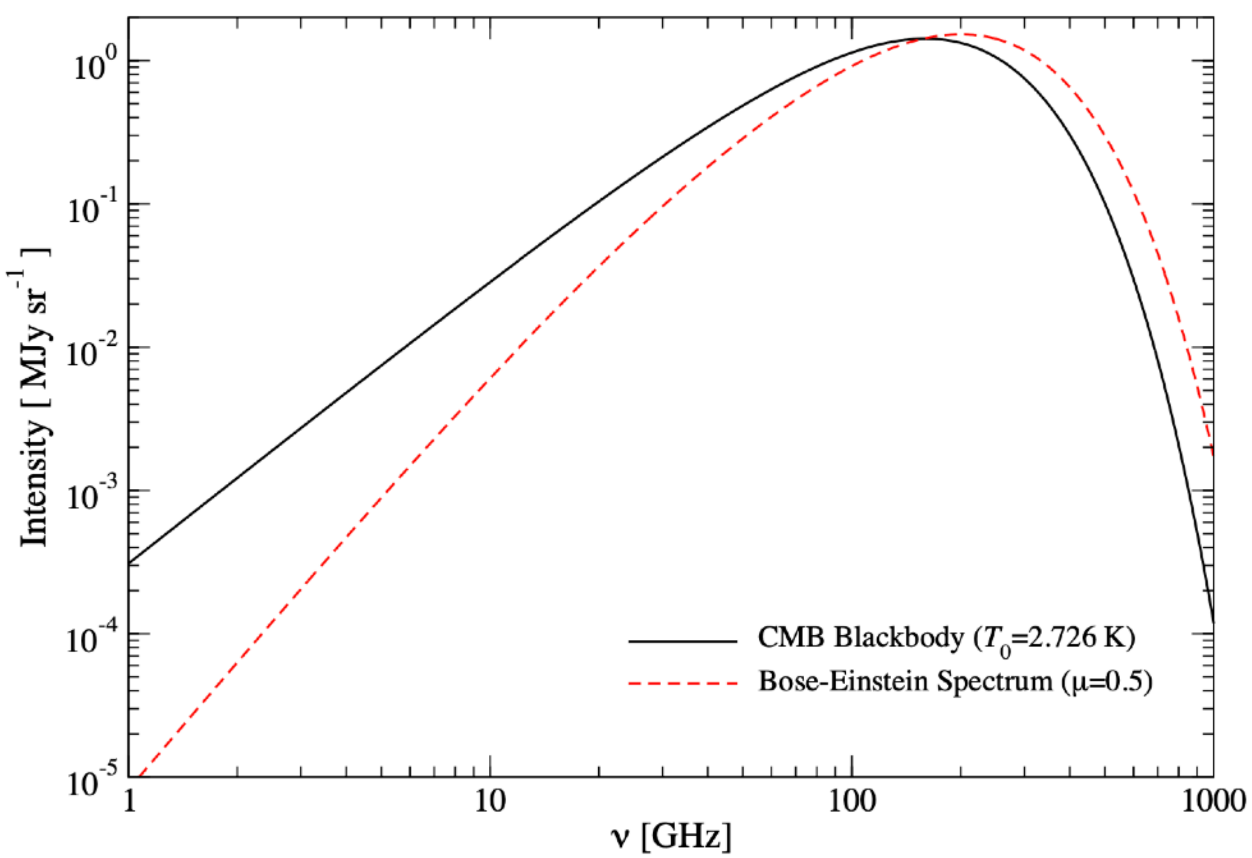
➡ We can use the eCampus forum to discuss everything related to this course (and ask questions!)

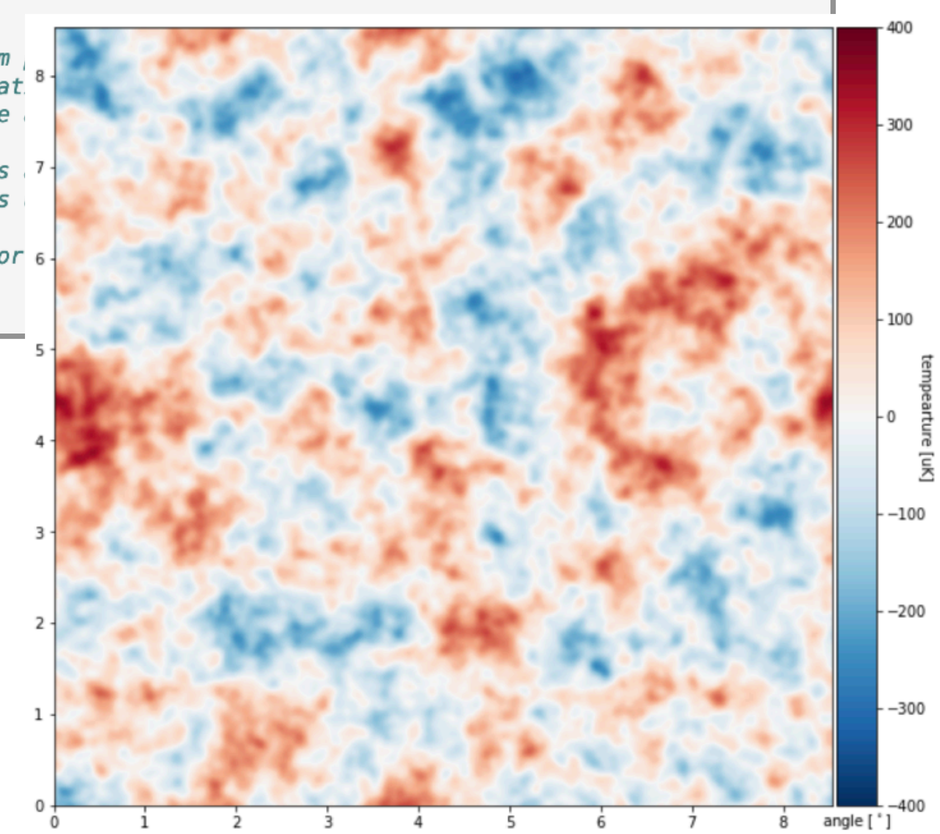
Exercises, Exercises!

A few analytic calculations, some more coding and plotting, all simple

Expect 6 or 7 exercise sheets, some will have two weeks to finish them





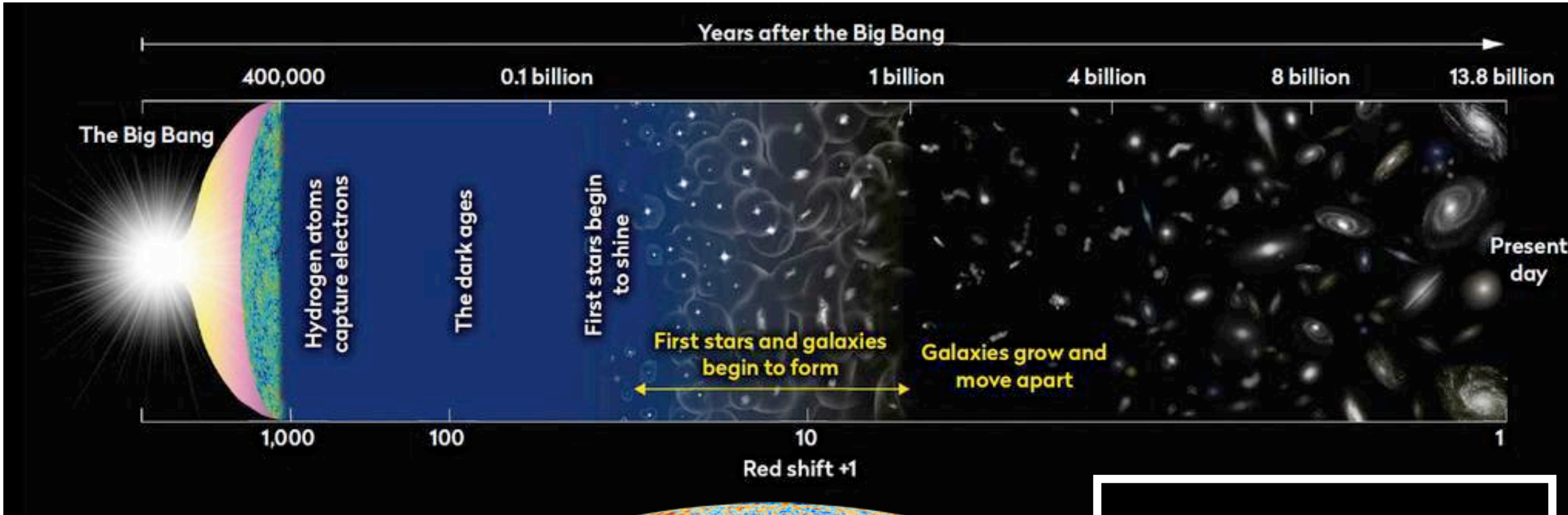


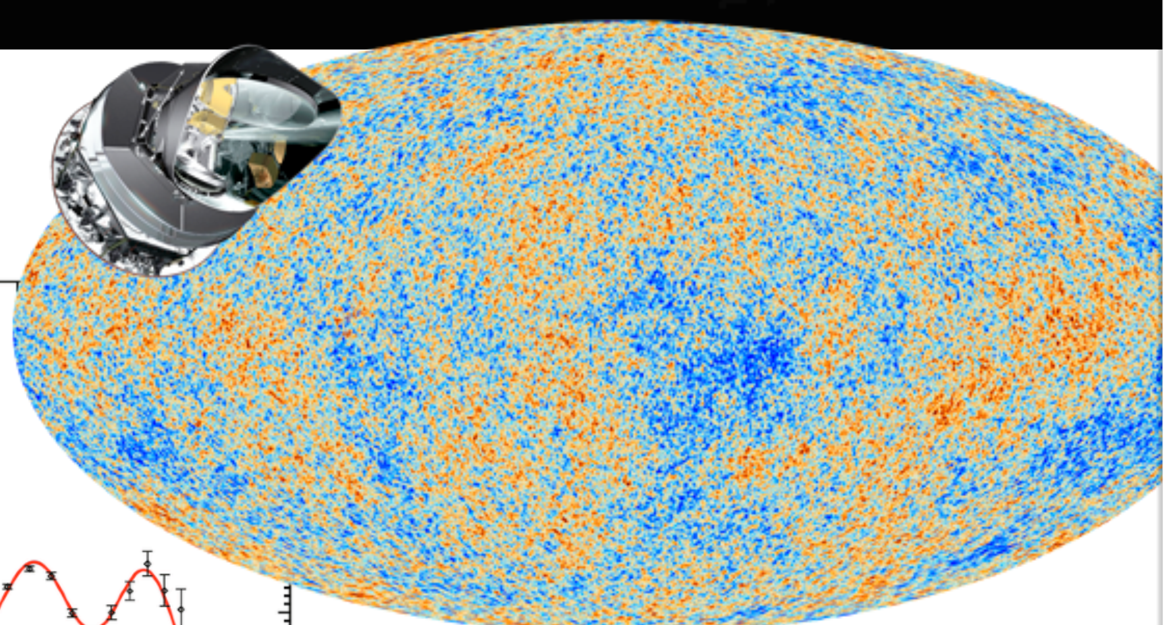
You will need to ***attempt or solve*** at least 70% of the exercises to get into the final exam.

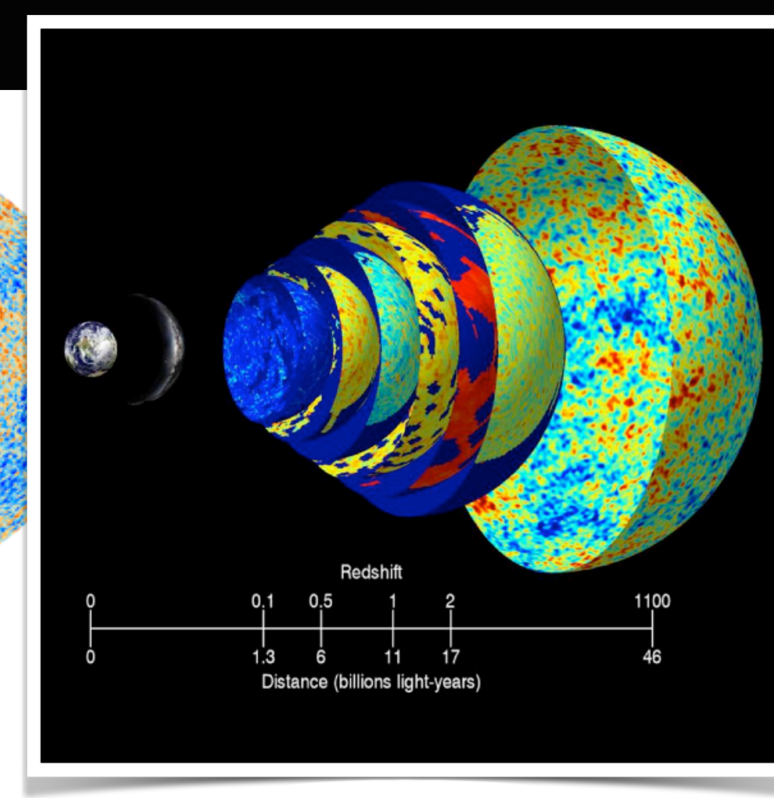
Please ask questions at any time!

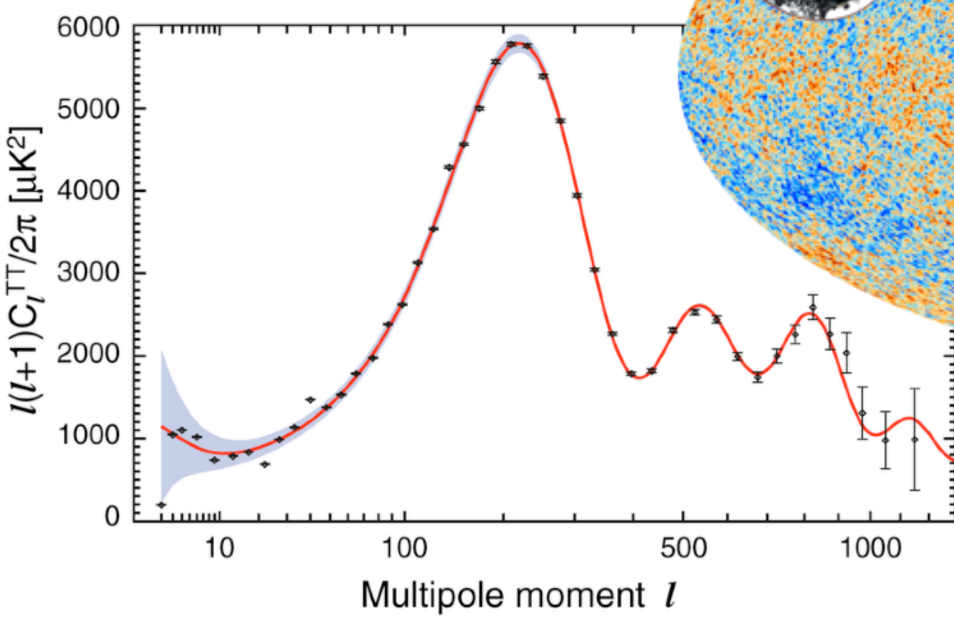
You can also email me or ask questions in our eCampus Forum

What is the CMB?



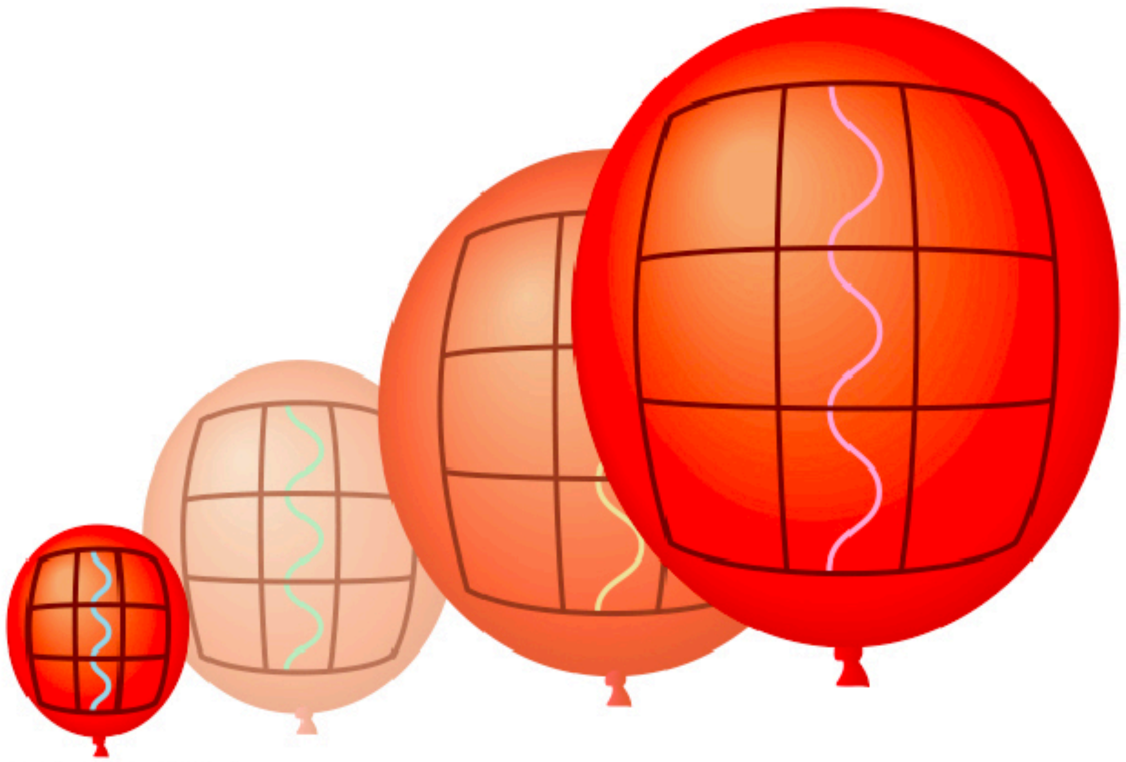






How much cosmology do we need?

$$1+z \equiv \frac{\lambda_{\text{observed}}}{\lambda_{\text{emitted}}} = \frac{a(t_{\text{obs}})}{a(t_{\text{emit}})}$$



- Homogeneously expanding Euclidean space
  - In Cartesian **comoving** coordinates $\boldsymbol{x} = (x, y, z)$

$$ds^2 = a^2(t)(dx^2 + dy^2 + dz^2)$$

"scale factor"

FRW metric: $\mathrm{d}s^2 = \mathrm{d}t^2 - a^2(t)\left[\mathrm{d}\chi^2 + S_k^2(\chi)\mathrm{d}\Omega^2\right]$

Hubble parameter and the Friedmann equations:

$$H(t) = \dot{a}/a$$

$$\frac{H^2}{H_0^2} = \Omega_r a^{-4} + \Omega_m a^{-3} + \Omega_k a^{-2} + \Omega_\Lambda$$

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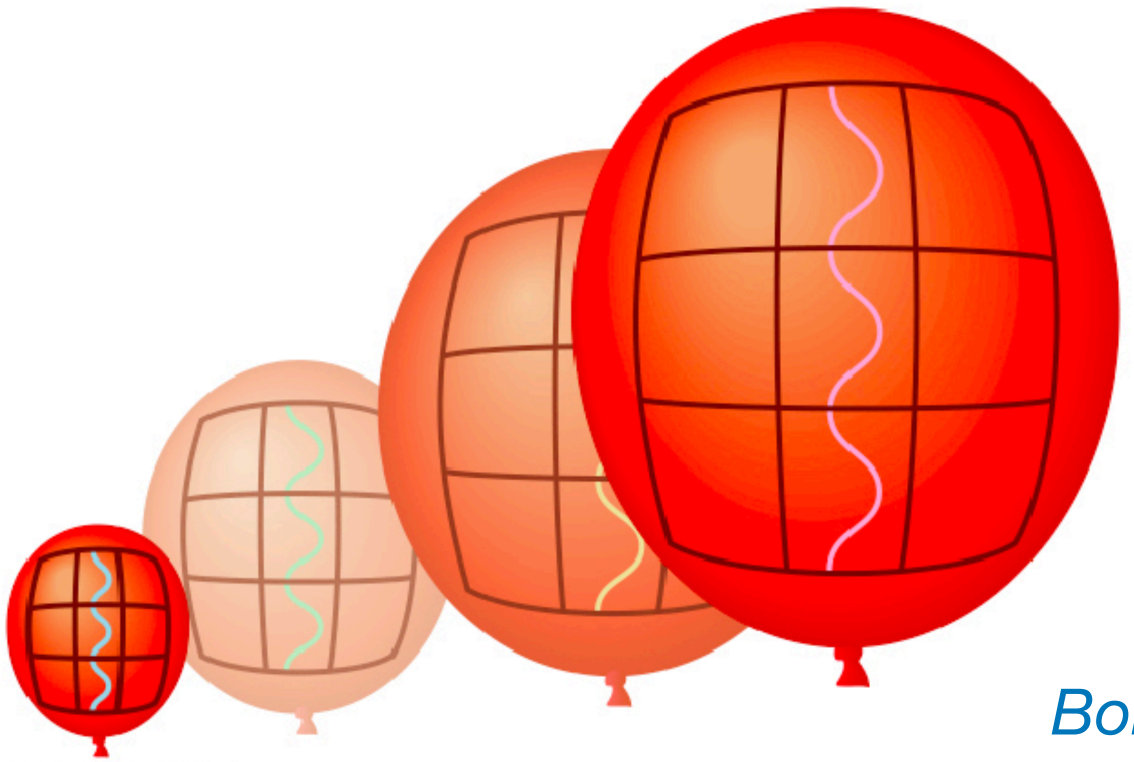

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Boltzmann equations for scalar perturbations:

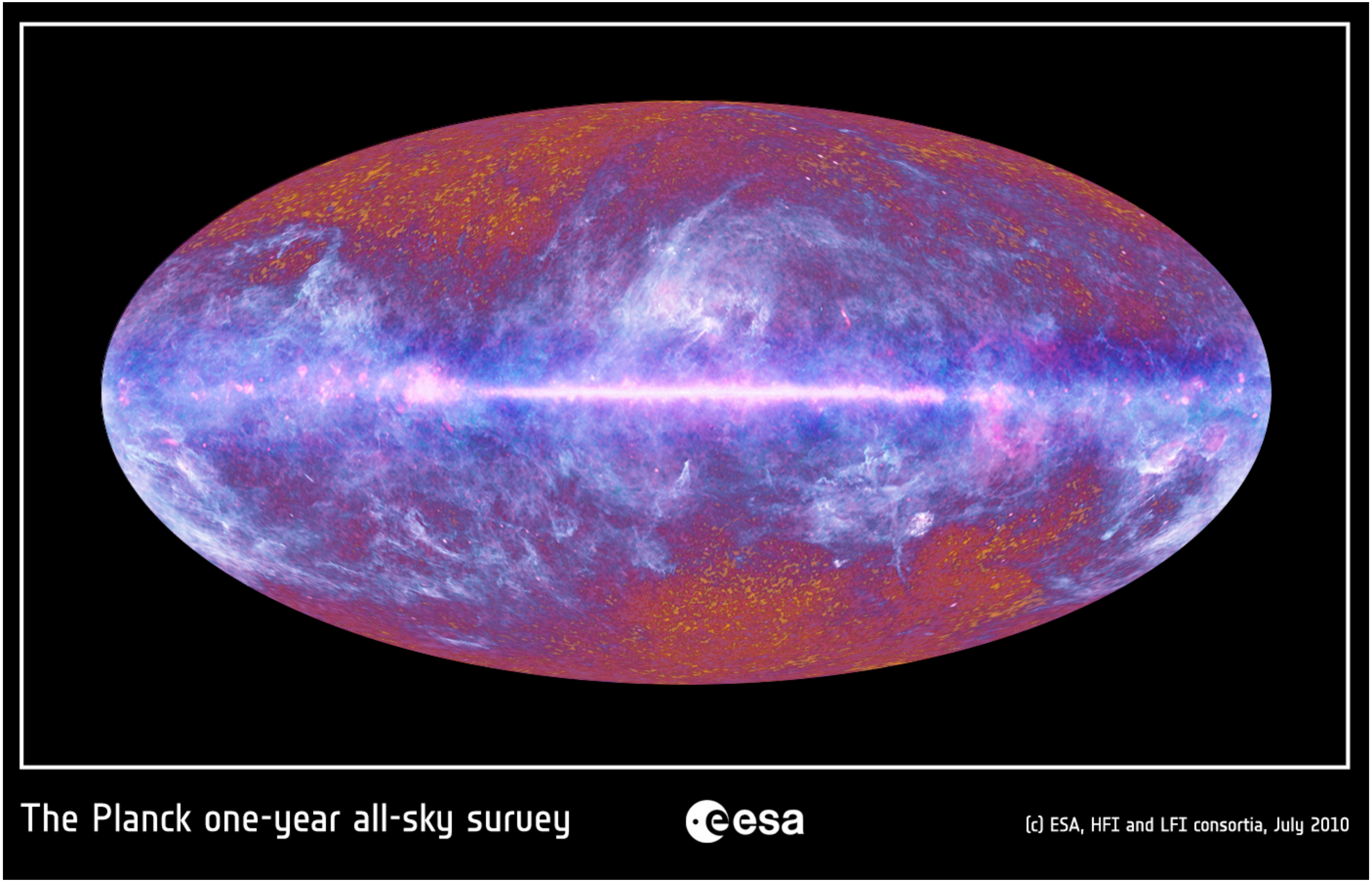
$$\dot{\Delta}_T^{(S)} + ik\mu\Delta_T^{(S)} = \dot{\phi} - ik\mu\psi + \dot{\kappa}\{-\Delta_T^{(S)} + \Delta_{T0}^{(S)} + i\mu v_b + \frac{1}{2}P_2(\mu)\Pi\}$$

$$\dot{\Delta}_P^{(S)} + ik\mu\Delta_P^{(S)} = \dot{\kappa}\{-\Delta_P^{(S)} + \frac{1}{2}[1 - P_2(\mu)]\Pi\} \quad \Pi = \Delta_{T2}^{(S)} + \Delta_{P2}^{(S)} + \Delta_{P0}^{(S)}.$$

Where is the CMB?

Where is the CMB?

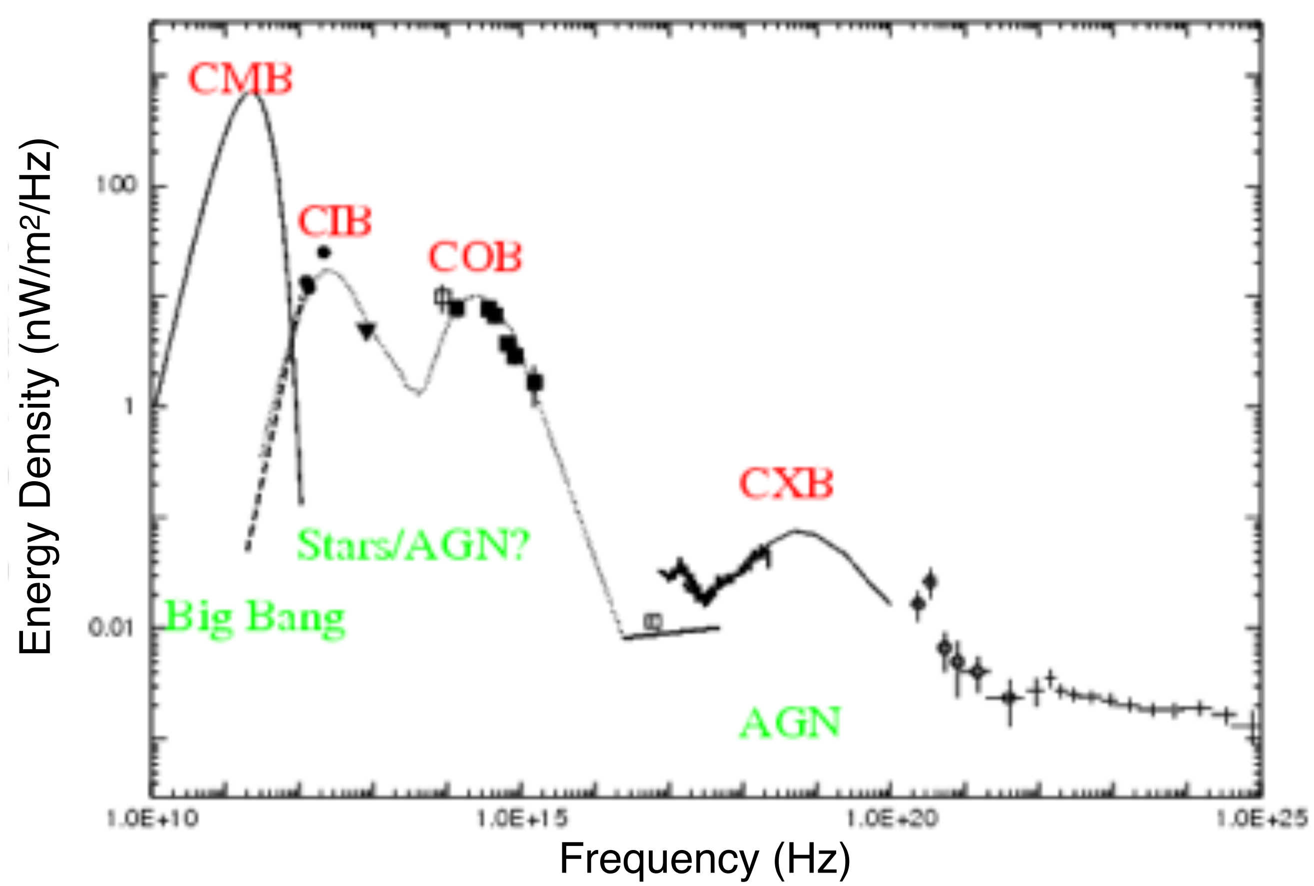
Where is the CMB?



Where is the CMB?

- CMB dominates the radiation content of the universe *by far*

- It contains nearly 93% of the radiation energy density and 99% of all the photons (410 CMB photons per cubic centimeter!)



~ 400 photons per cm^3

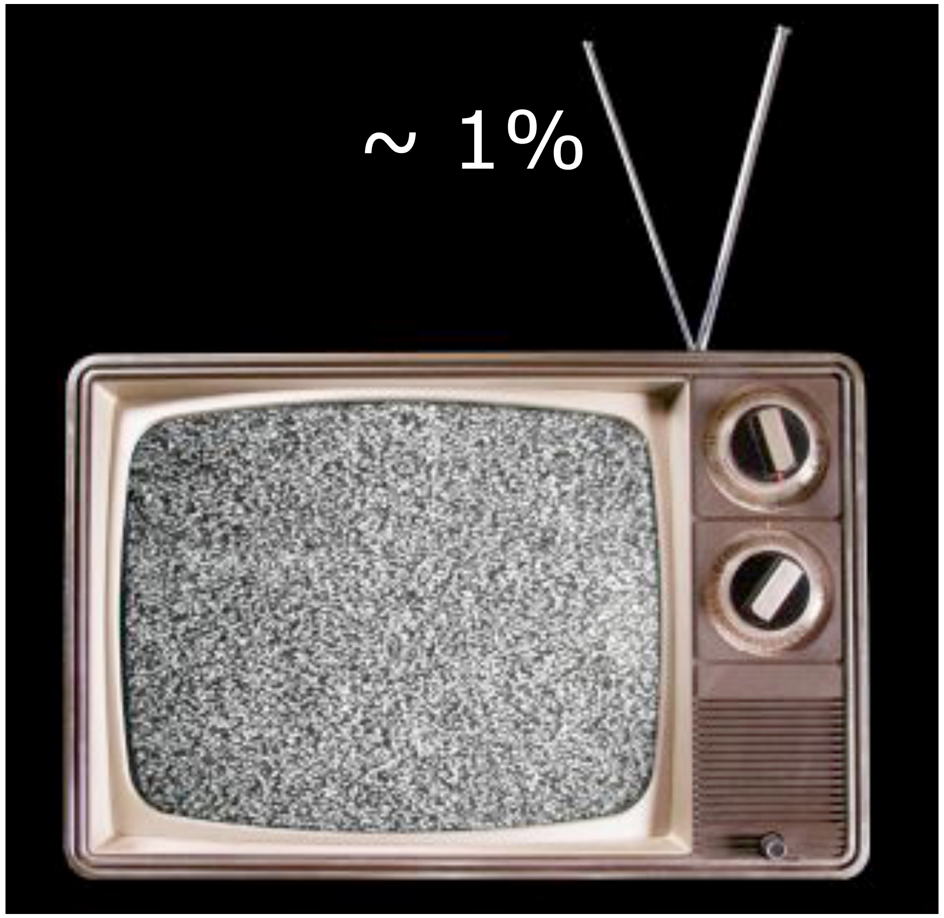
~0.3 eV/cm^3

Table 10.3: *Energy densities in the ISM*[a]

Component	(J/m^3)	(MeV/m^3)
Radiation from stars	0.7×10^{-13}	0.4
Kinetic gas motion	0.5×10^{-13}	0.3
Cosmic microwave background	0.4×10^{-13}	0.3
Cosmic rays	1.6×10^{-13}	1.0
Magnetic fields	0.4×10^{-13}	0.2

(From Bradt, Astrophysical Processes, CUP)

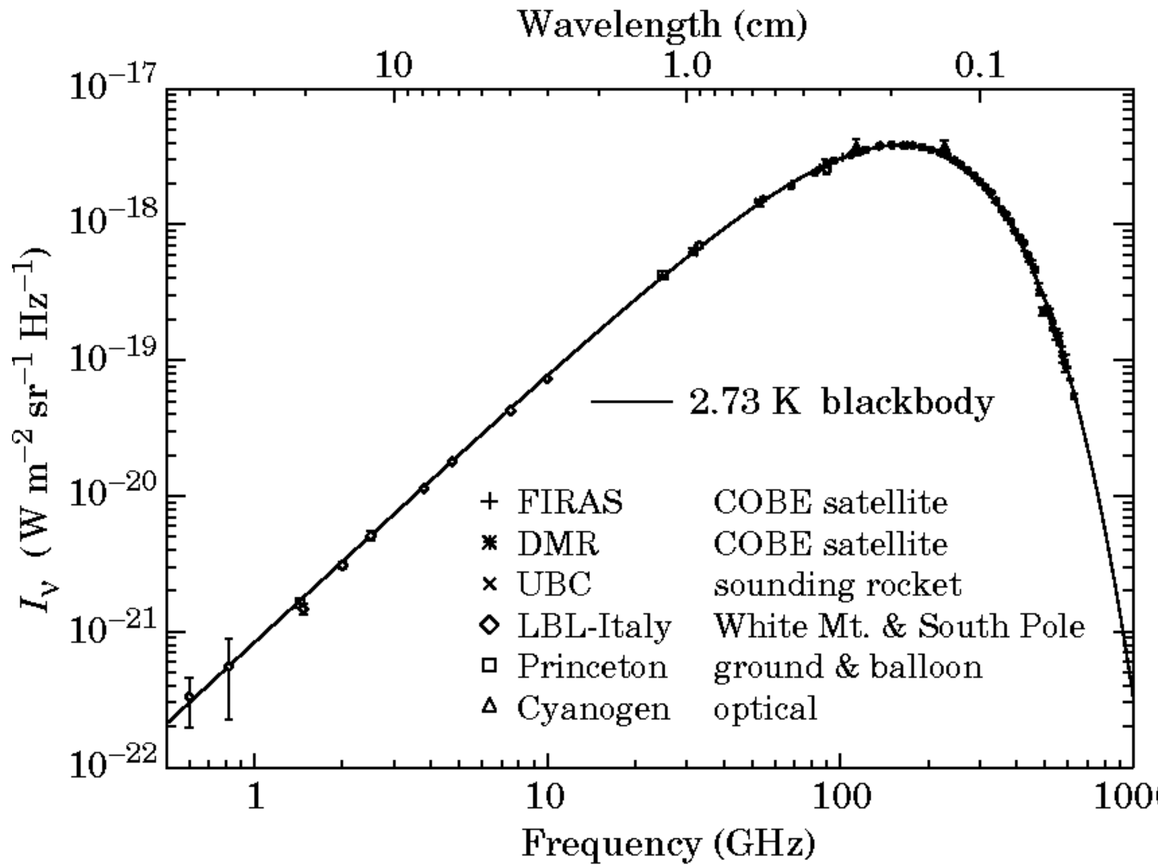
Where is the CMB?



You can "see" CMB by TV (not by a cable TV of course!).

Perhaps you can "hear" CMB by a cell phone?

The same is true for FM radio: The "hiss" you hear between switching from one station to another partly comes from the Cosmic Microwave Background!



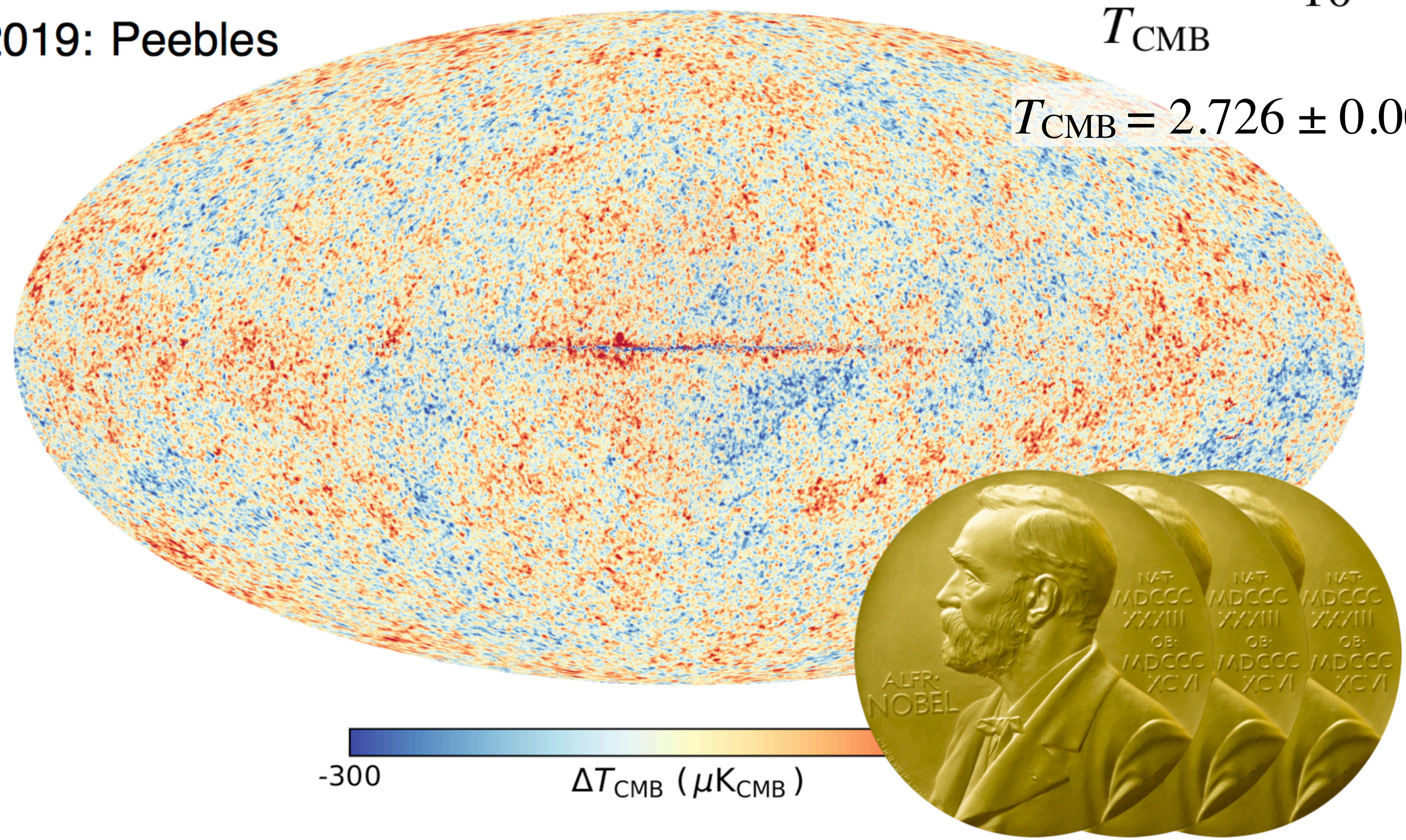
- The spectrum of CMB has a peak at 1.1mm.
- Let's compare it with…
  - –Microwave oven: 12cm
  - –Cellular phone: 20cm
  - –UHF Television: 39-64cm
  - –FM radio: 3m
  - –AM radio: 300m

Recognition for precision cosmology

1978: Penzias & Wilson
2006: Mather & Smoot
2019: Peebles

$$\frac{\Delta T_{\rm CMB}}{T_{\rm CMB}} \sim 10^{-5}$$

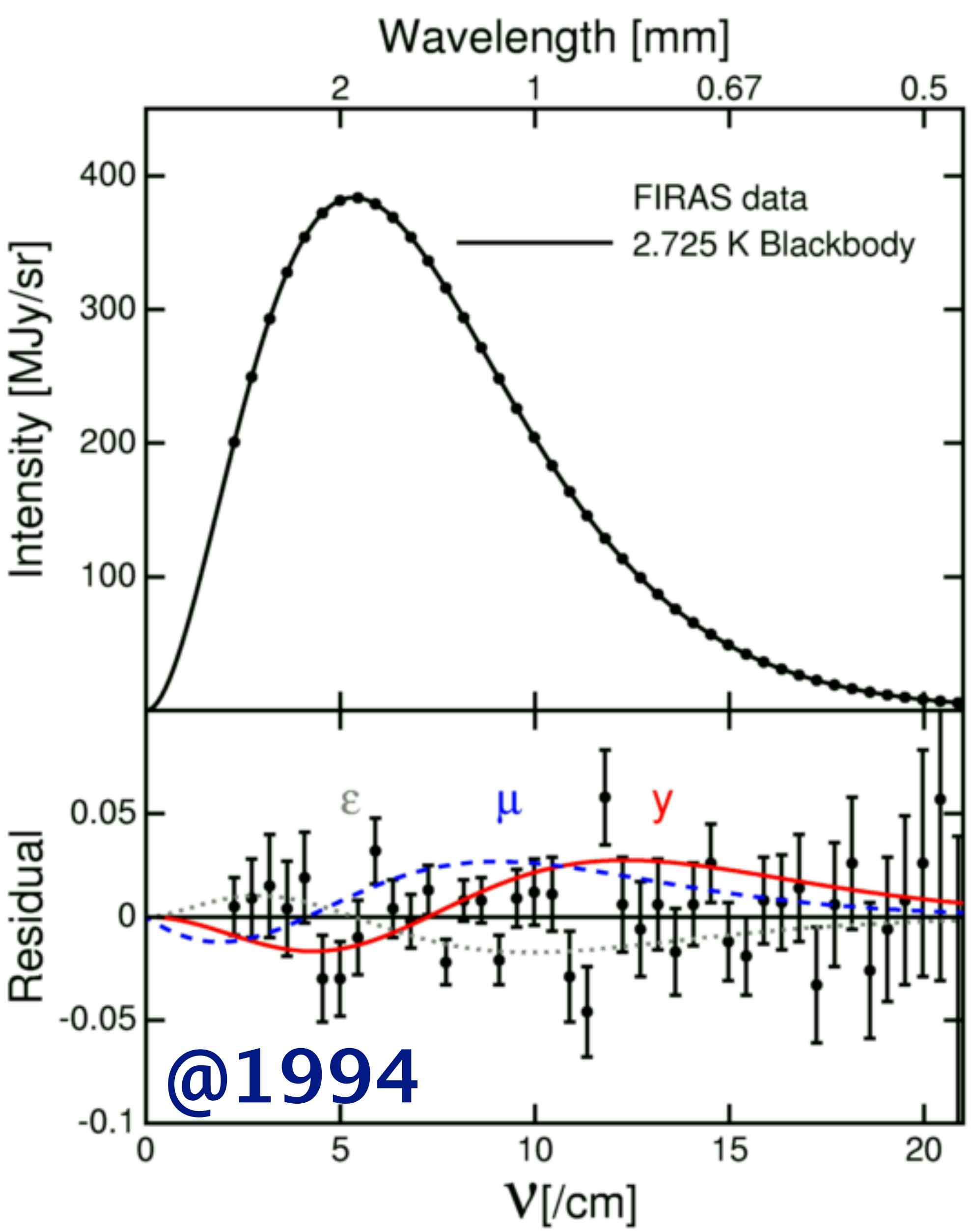
$$T_{\rm CMB} = 2.726 \pm 0.001\ {\rm K}$$

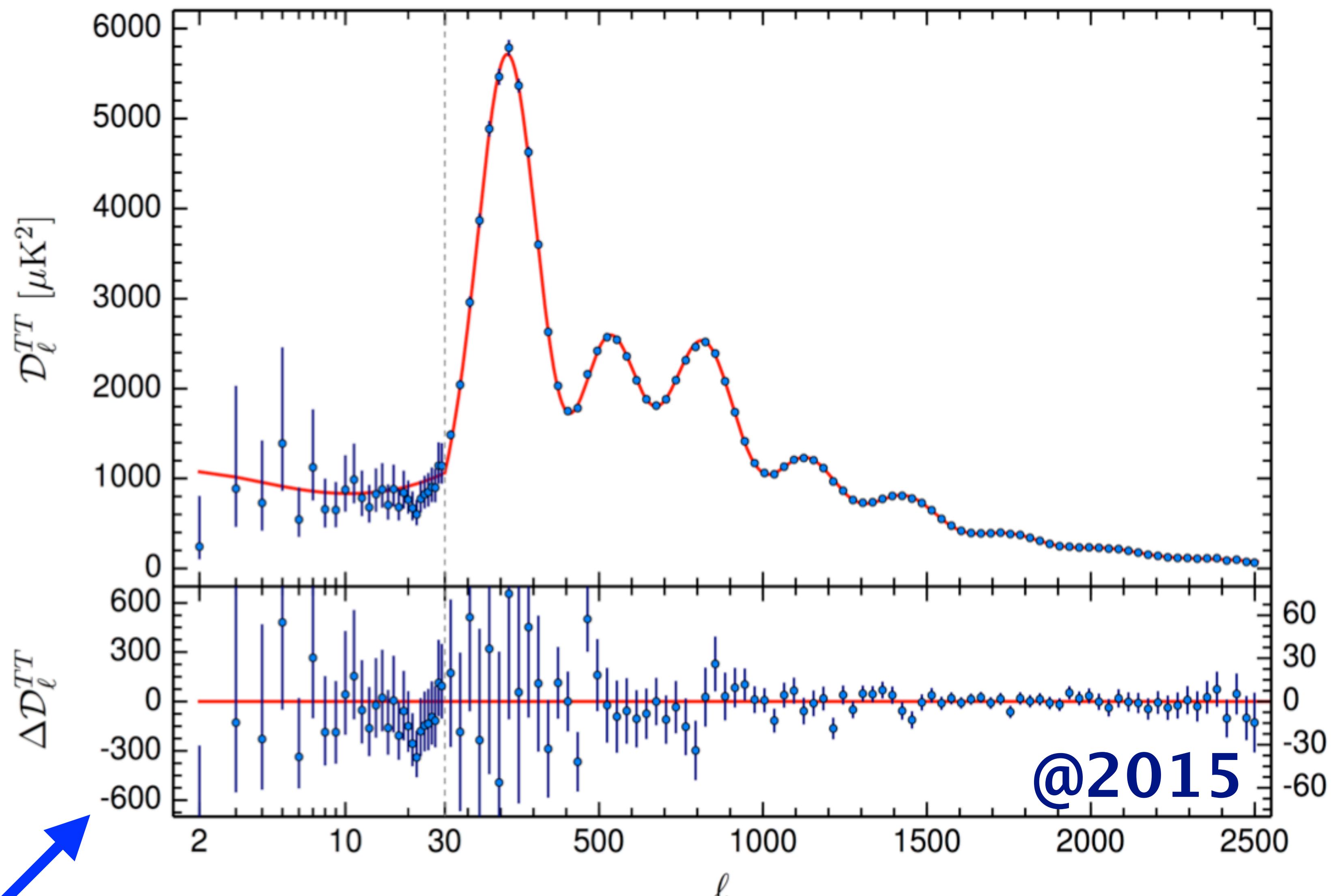


CMB temperature anisotropy map based on *Planck* data

Is CMB science dead? *Absolutely not!*

There is now widespread belief among non-cosmologists that CMB science is practically over. Indeed, CMB research has been victim of its own success!

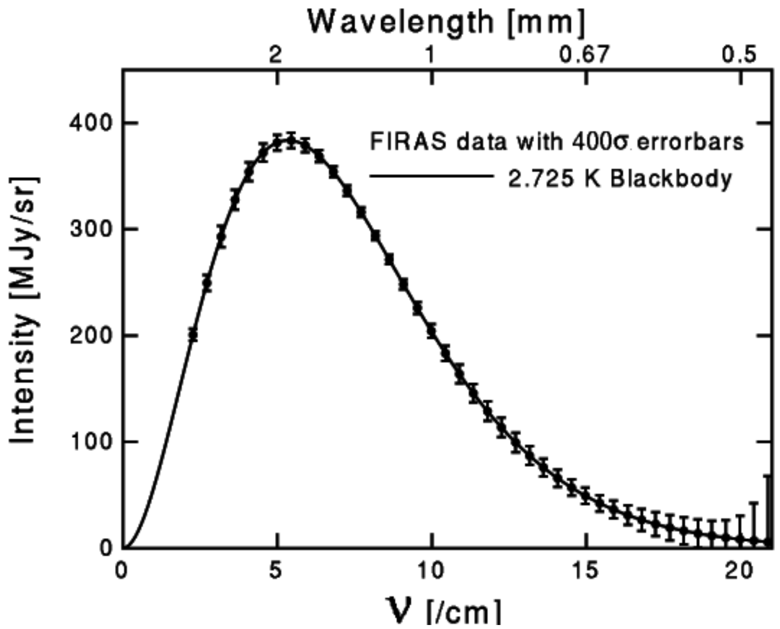




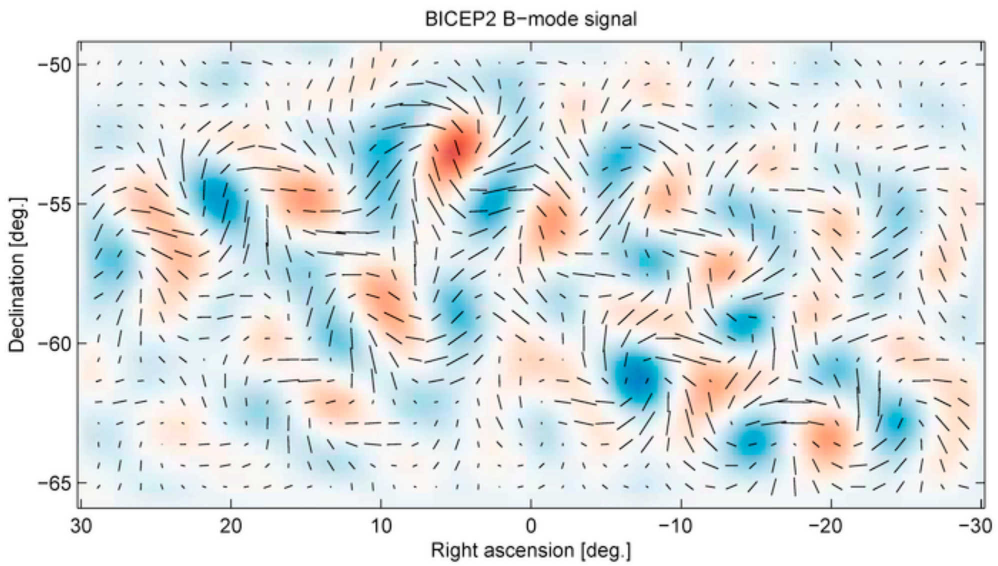
6-parameter ΛCDM cosmology is excellent fit to data

Frontiers of CMB research today

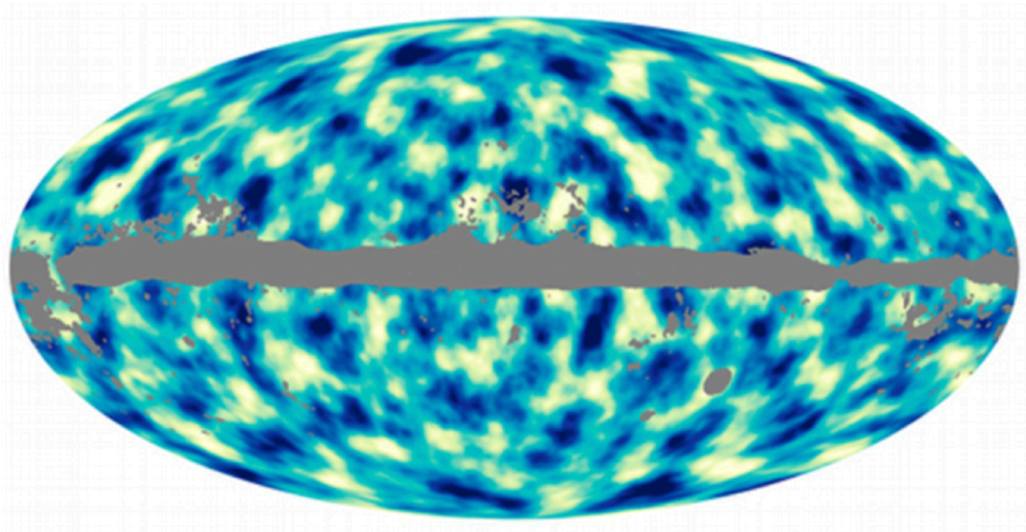
1. The thermal (blackbody) spectrum and its distortions as a cosmological probe



2. Polarization anisotropies and the search for the primordial gravitational waves



3. Secondary anisotropies and the study of the growth of large-scale structure



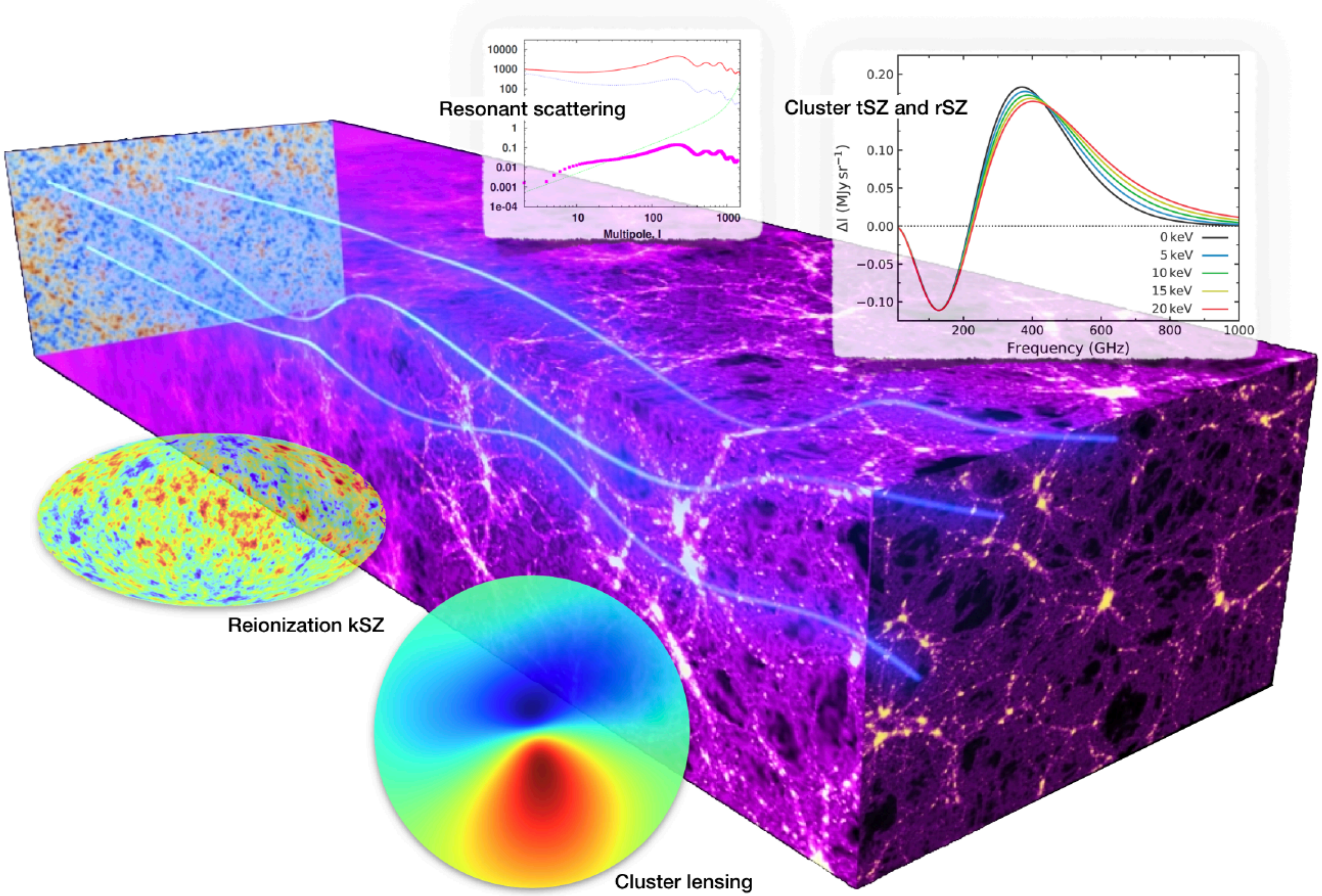
Slide from Eiichiro Komatsu

ΛCDM. Want more?

- Thanks to the CMB and other observations (large-scale structure of the Universe, supernovae, …), We now have the standard model of cosmology (ΛCDM), which can describe what we see from the early Universe to the present epoch
- What more do we want from the CMB?
- We have entered the new era: we ask deeper questions
  - **Has inflation really happened?** Did we really originate from quantum fluctuations in the early Universe?
  - **Is ΛCDM really right?** We don't understand the physical nature of Λ or CDM!

Many tests! Were there new light particles? Do DM particles annihilate? What is the mass of neutrinos? Is DE a cosmological constant? Is the distribution of hot gas and velocities consistent with ΛCDM? Etc, etc…

or use CMB as a cosmic backlight



ESA Voyage 2050 Science White Paper

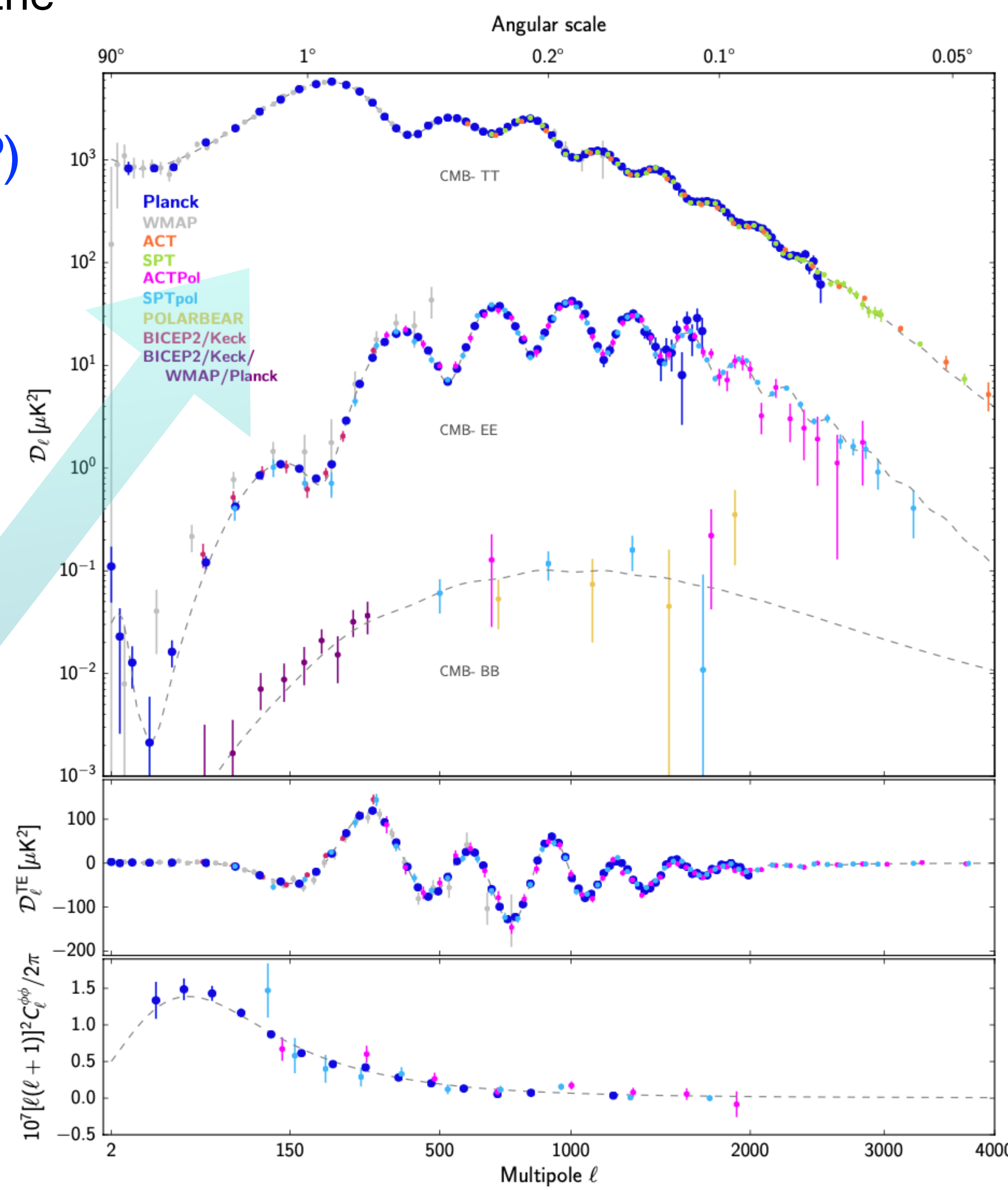
https://arxiv.org/abs/1909.01592

A Space Mission to Map the Entire Observable Universe using the CMB as a Backlight

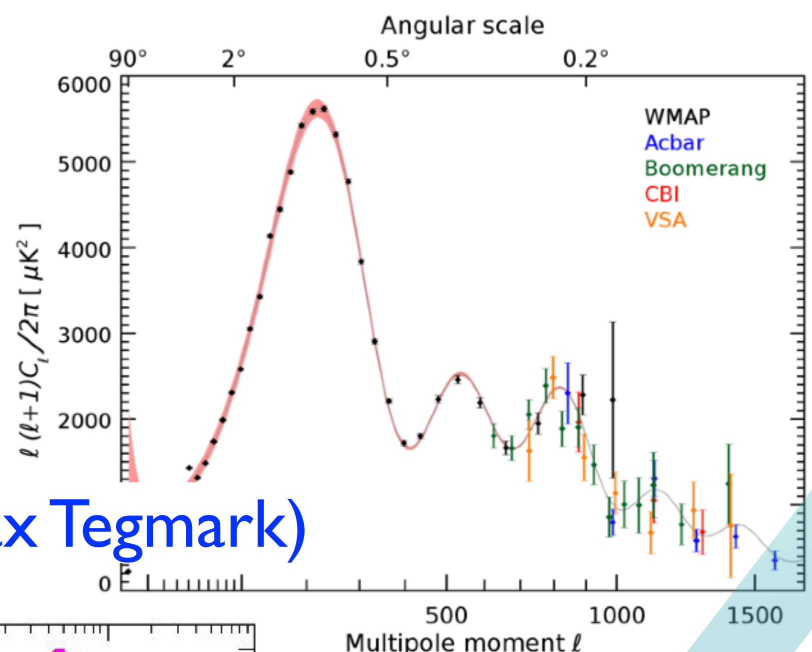
Two decades of CMB measurements

Two decades of increasingly accurate observations
From temperature to polarization, to lensing and the SZ effect, and more..

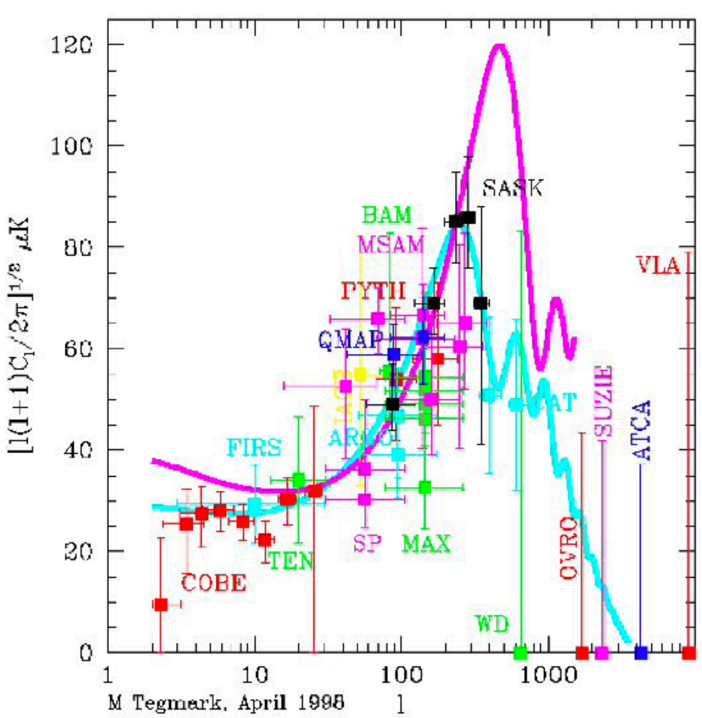
2018: Planck Legacy Results



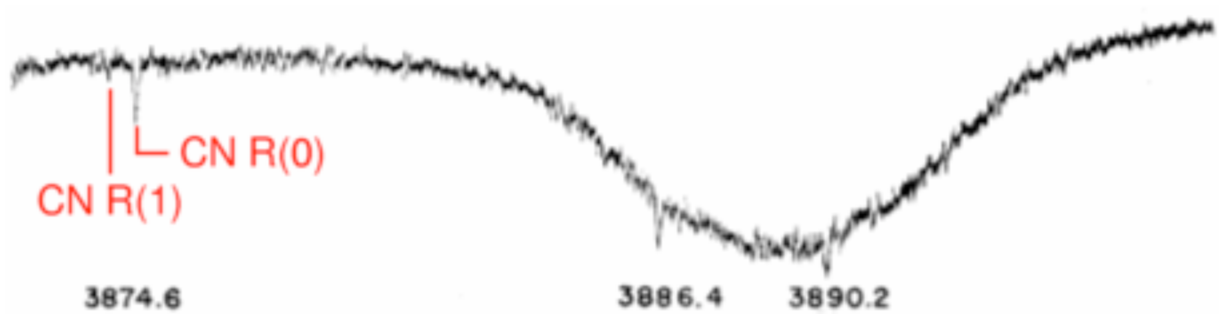
2006: Hinsaw et al. (WMAP)



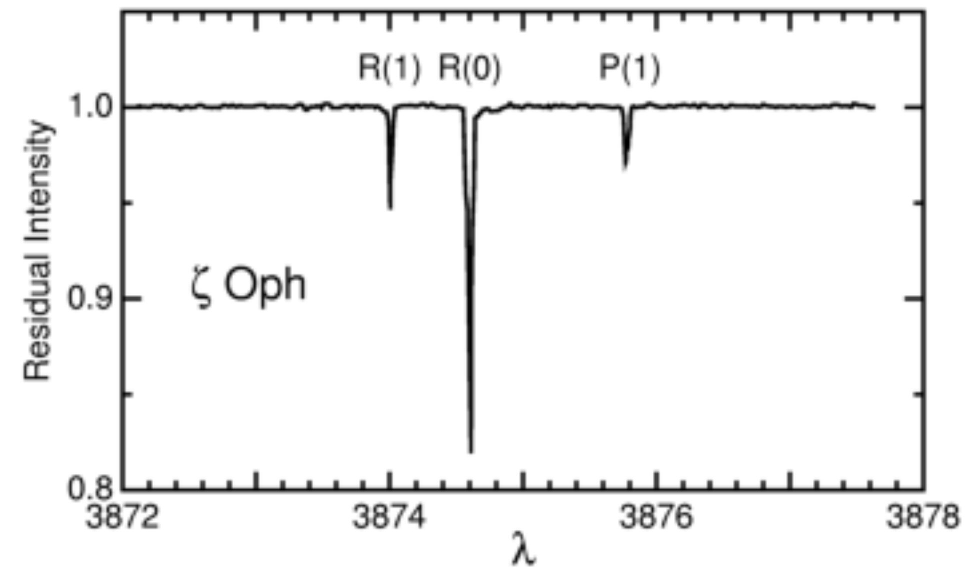
1998 (credit: Max Tegmark)



Discovery of the CMB



McKellar (1940)



- In 1940, Andrew McKellar discovers CN molecules in interstellar space from their absorption spectra (one of the first IS-molecules)

- From the CN and CH excitation line ratios, he infers the "rotational temperature of interstellar space" to be **2.3° K** (1941, PASP 53, 233)

- In his 1950 book, the Nobel prize-winning spectroscopist Gerard Herzberg remarks: "From the intensity ratio of the lines with K=0 and K=1 a rotational **temperature of 2.3° K follows, which has of course only a very restricted meaning**."

McKeller’s discovery (1940)

DEPARTMENT OF MINES AND RESOURCES, CANADA
SURVEYS AND ENGINEERING BRANCH

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

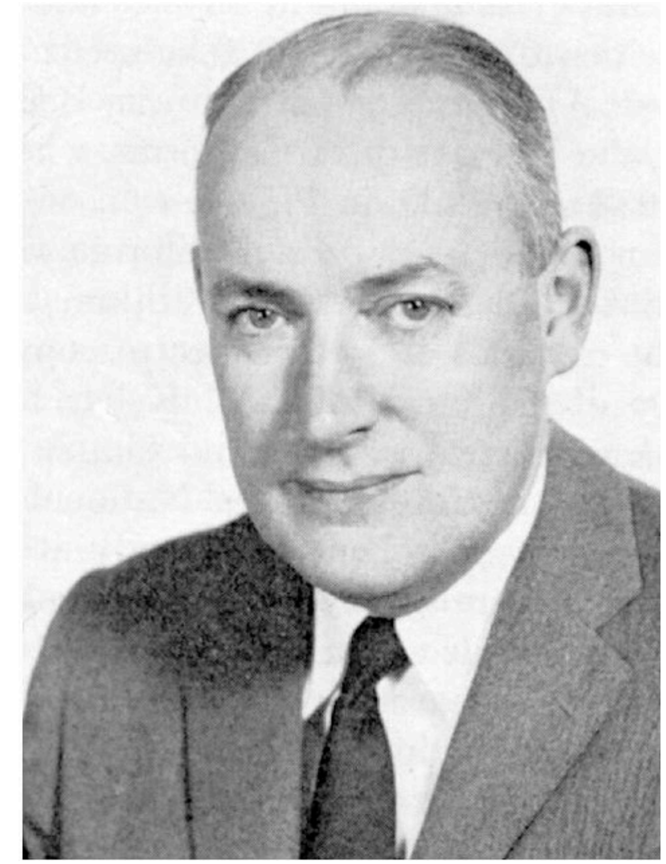
ABSTRACT.—Attention is directed to the recent spectrographic observations of W. S. Adams by which he detected in the spectrum of the early class B star, *ζ Ophiuchi*, several sharp lines from the lowest states of the CH and CN molecules. The detection of these lines of apparent interstellar origin, the 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°.3*K*, is compared with the temperatures estimated by Eddington for matter in interstellar space.



McKeller died in 1960 at the age of 50, so he did not have a chance to know the true significance of his discovery.

Discovery of the CMB

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

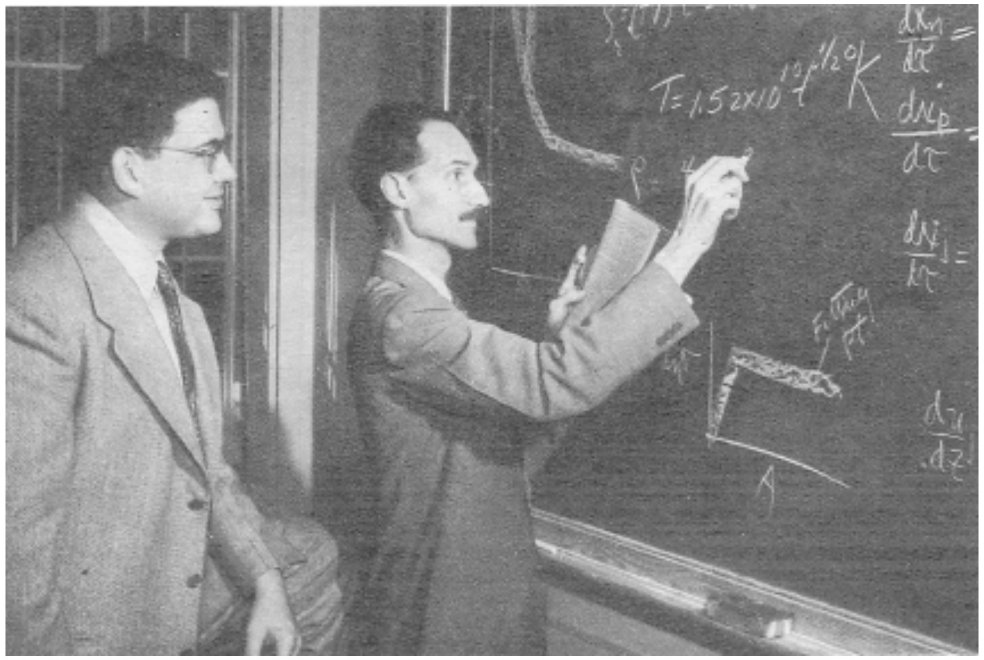
G. Gamow
The George Washington University, Washington, D. C.
February 18, 1948

- Alpher, Bethe & Gamow, in their 1948 paper, first proposed the very hot and dense early phase of the Universe (later termed derisively as "Big Bang" by Fred Hoyle). They mistakenly concluded that all elements were produced in this hot early phase.

The results of these calculations were first announced in a letter to The Physical Review, April 1, 1948. This was signed Alpher, Bethe, and Gamow, and is often referred to as the 'alphabetical article'. It seemed unfair to the Greek alphabet to have the article signed by Alpher and Gamow only, and so the name of Dr. Hans A. Bethe (in absentia) was inserted in preparing the manuscript for print. Dr. Bethe, who received a copy of the manuscript, did not object, and, as a matter of fact, was quite helpful in subsequent discussions. There was, however, a rumor that later, when the alpha, beta, gamma theory went temporarily on the rocks, Dr. Bethe seriously considered changing his name to Zacharias.

George Gamow, "The Creation of The Universe"

Discovery of the CMB



- After the "α–β–γ paper", Alpher & Herman (1948, picture on left) predict 5 K radiation background as by-product of their theory of the nucleosynthesis in the early universe (with no suggestion of its detectability).

- Shmaonov (1957) measures a uniform noise temperature of 4 ± 3 K at $\lambda=3.2$ cm.

- Doroshkevich & Novikov (1964, pictures on left) emphasize the detectability of this radiation, predict that the spectrum of the relict radiation will be a blackbody, and also mention that the twenty-foot horn reflector at the Bell Laboratories will be the best instrument for detecting it.

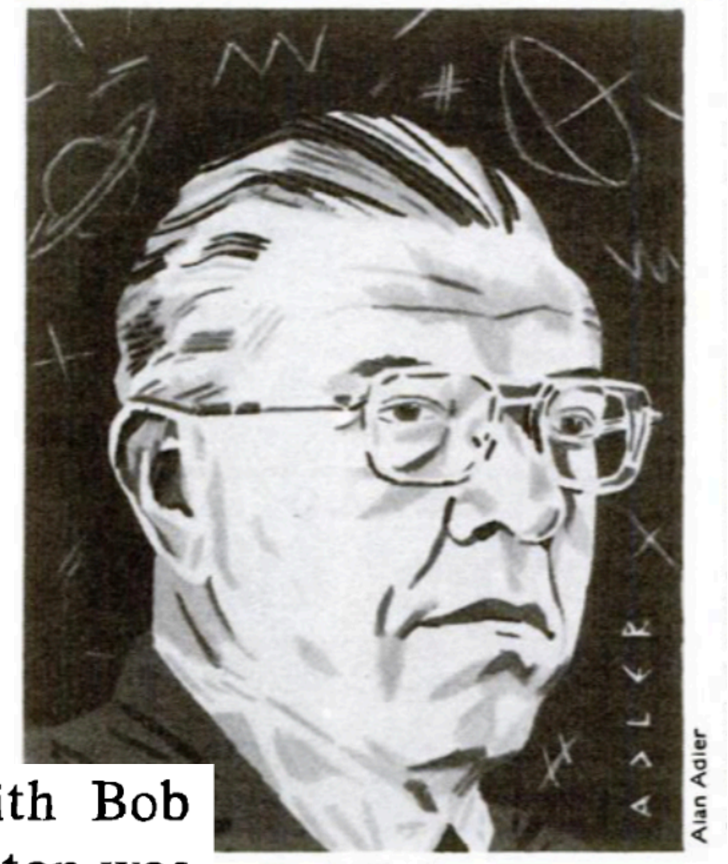
- All along this time, nobody really noticed or remembered the significance of McKeller's discovery with CN molecular line (besides Fred Hoyle..)

Discovery of the CMB

Fifty years in cosmology*

Fred Hoyle *Cockley Moor, Dockray Penrith, Cumbria, England*

*First B. M. Birla memorial lecture delivered 1987 February 27 at B. M. Birla planetarium, Hyderabad.

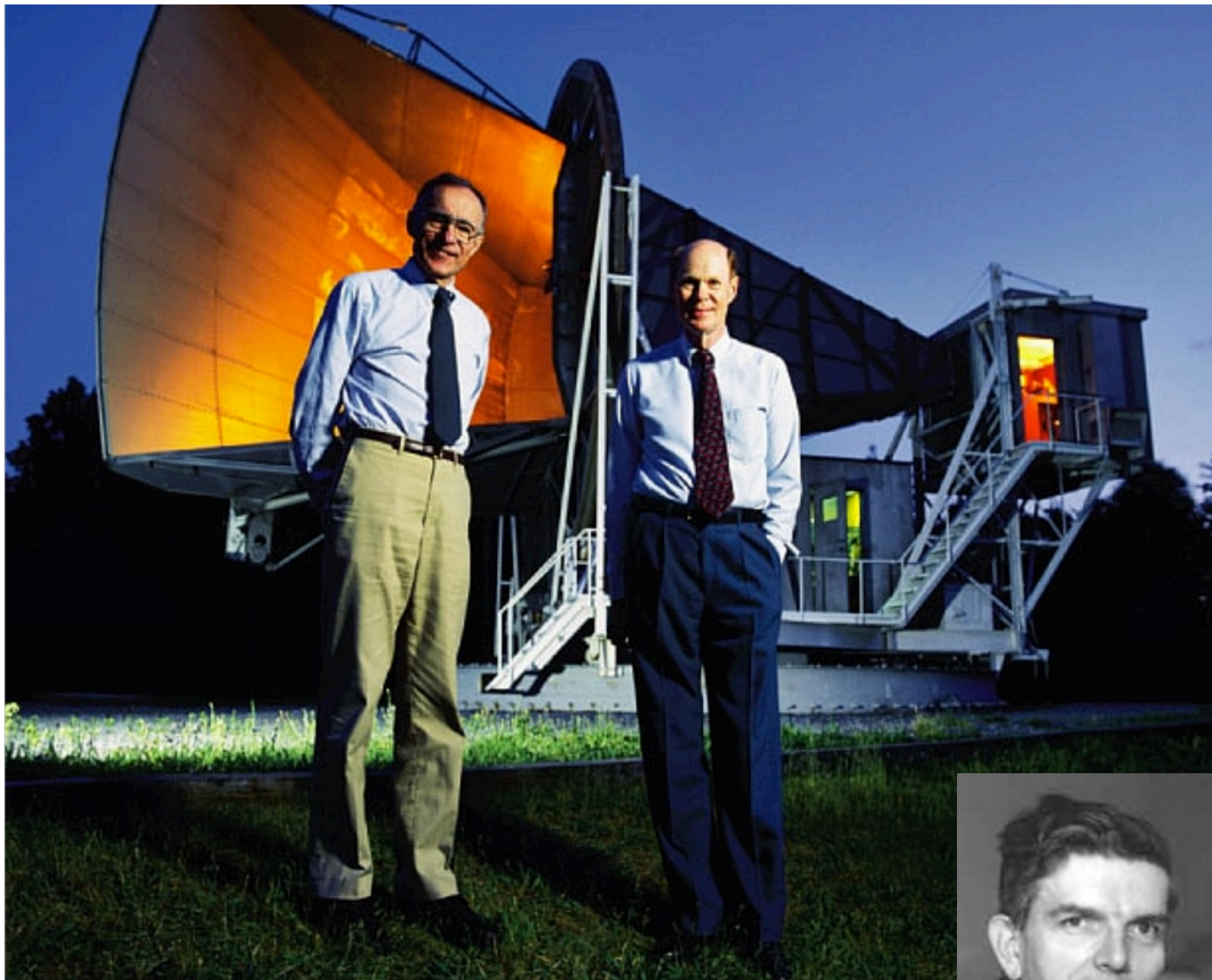


Fred Hoyle

It must have been in 1964 that I was sitting beside lake Camo in Italy, with Bob Dicke from Princeton university. Dicke told me that his group at Princeton was setting up an experiment to look for a possible microwave background, and that they were expecting a temperature of about 20K. I said this was much too high, because a background, if there was one, could not have a temperature above 3K, the excitation temperature of molecular lines of CH and CN found by Mckellar in 1940. Shortly after that the background was found at the Bell telephone laboratories by Penzias and Wilson, and it had a temperature almost exactly on Mckellar's value. The big mistake Bob Dicke and I had made was not to realize we had it there beside lake Camo, in our coffee cups. However carefully one guards against it, opportunities like this come and then slip away through one's fingers.

Discovery of the CMB

Measured Jul 1964 – Apr 1965, publ. May 1965



- Originally wanted to measure Galactic emission at λ=7.3 cm (1964–65)
- Found a direction-independent noise (3.5±1.0 K) that they could not get rid of, despite drastic measures
- So they talked with colleagues..
- Explanation of this “excess noise” was given in a companion paper by Robert Dicke and collaborators

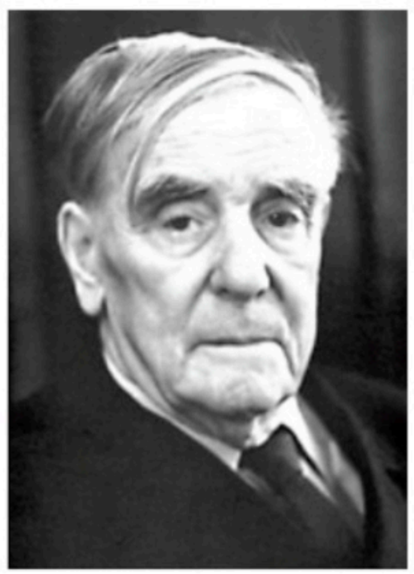
(Dicke’s famous remark after hearing about the Bell Labs result on telephone: “Well boys, we’ve been scooped”)

Discovery of the CMB

The Nobel Prize in Physics 1978

"for his basic inventions and discoveries in the area of low-temperature physics"

"For their discovery of cosmic microwave background radiation"

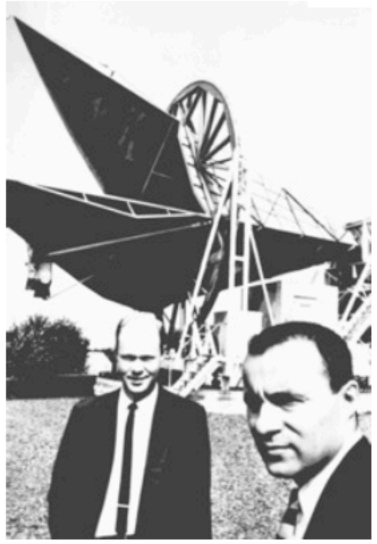


Pyotr Leonidovich Kapitsa	Arno Allan Penzias	Robert Woodrow Wilson
1/2 of the prize	1/4 of the prize	1/4 of the prize
USSR	USA	USA
Academy of Sciences Moscow, USSR	Bell Laboratories Holmdel, NJ, USA	Bell Laboratories Holmdel, NJ, USA
b. 1894 d. 1984	b. 1933 (in Munich, Germany)	b. 1936

Arno Penzias & Robert Wilson, 1965

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and free from seasonal variations (July, 1964–April, 1965). A possible explanation for the observed excess noise temperature is the one given by Dicke, Peebles, Roll, and Wilkinson (1965) in a companion letter in this issue.



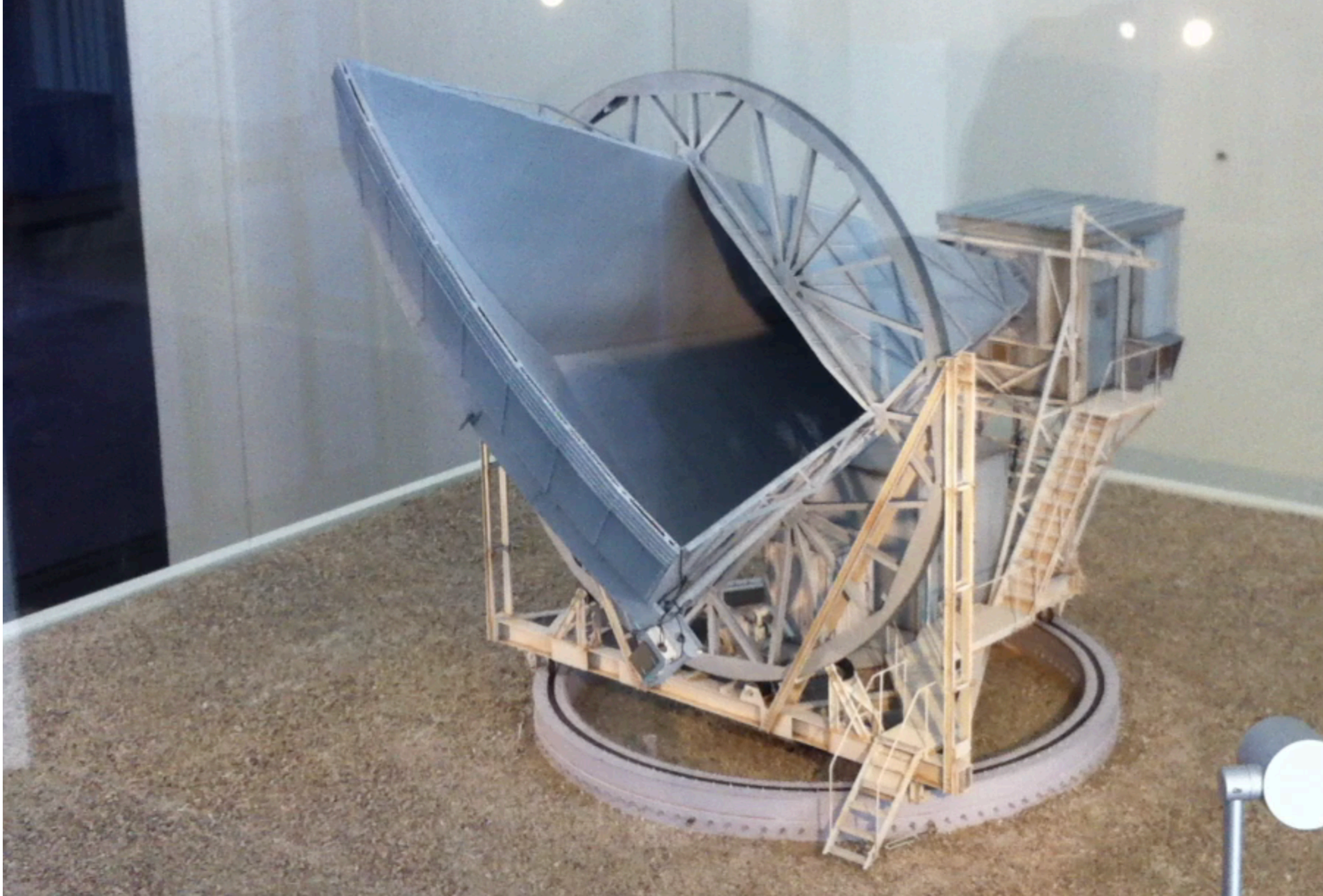
A. A. Penzias
R. W. Wilson

May 13, 1965
Bell Telephone Laboratories, Inc
Crawford Hill, Holmdel, New Jersey

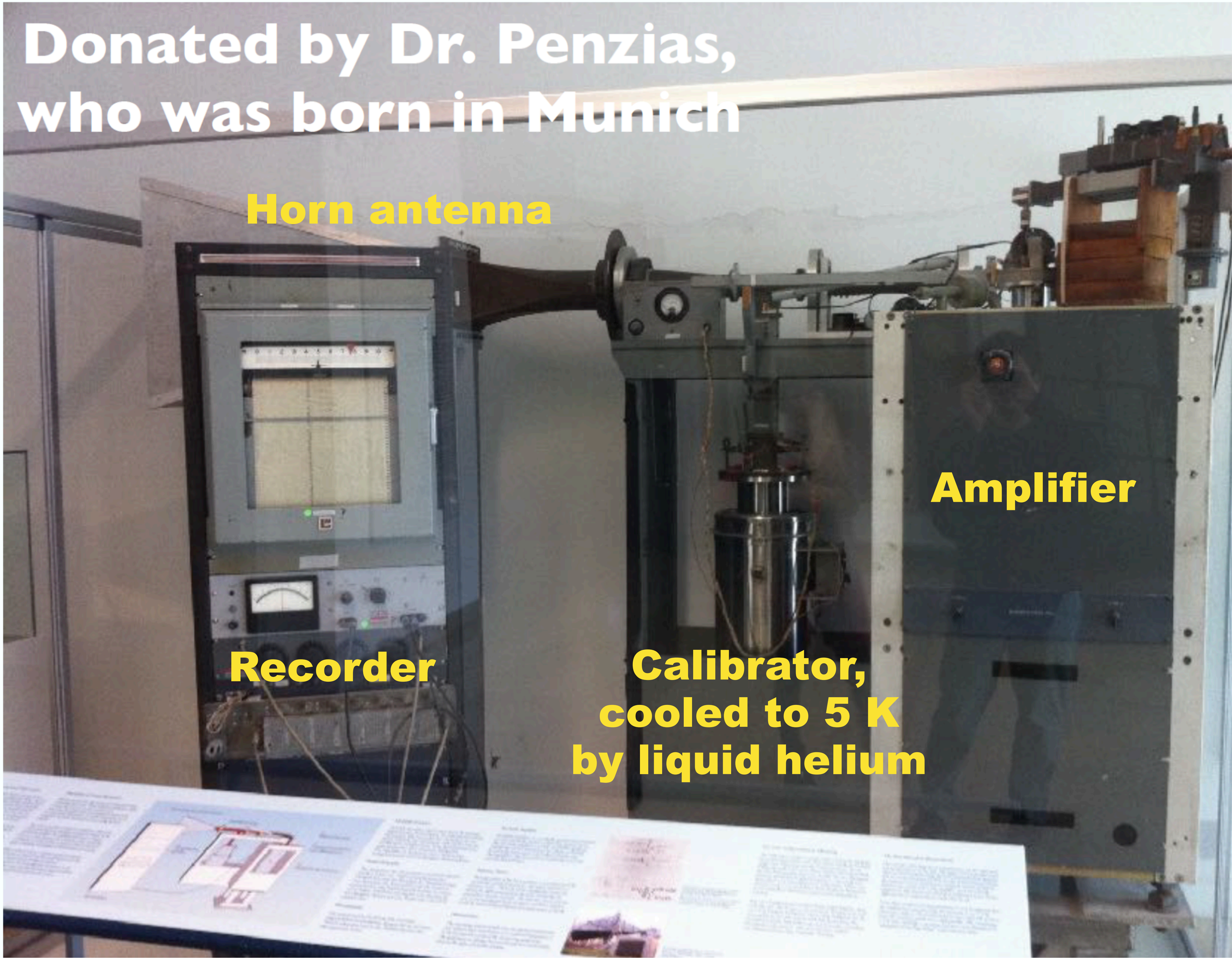
10

1:25 model of the antenna at Bell Lab

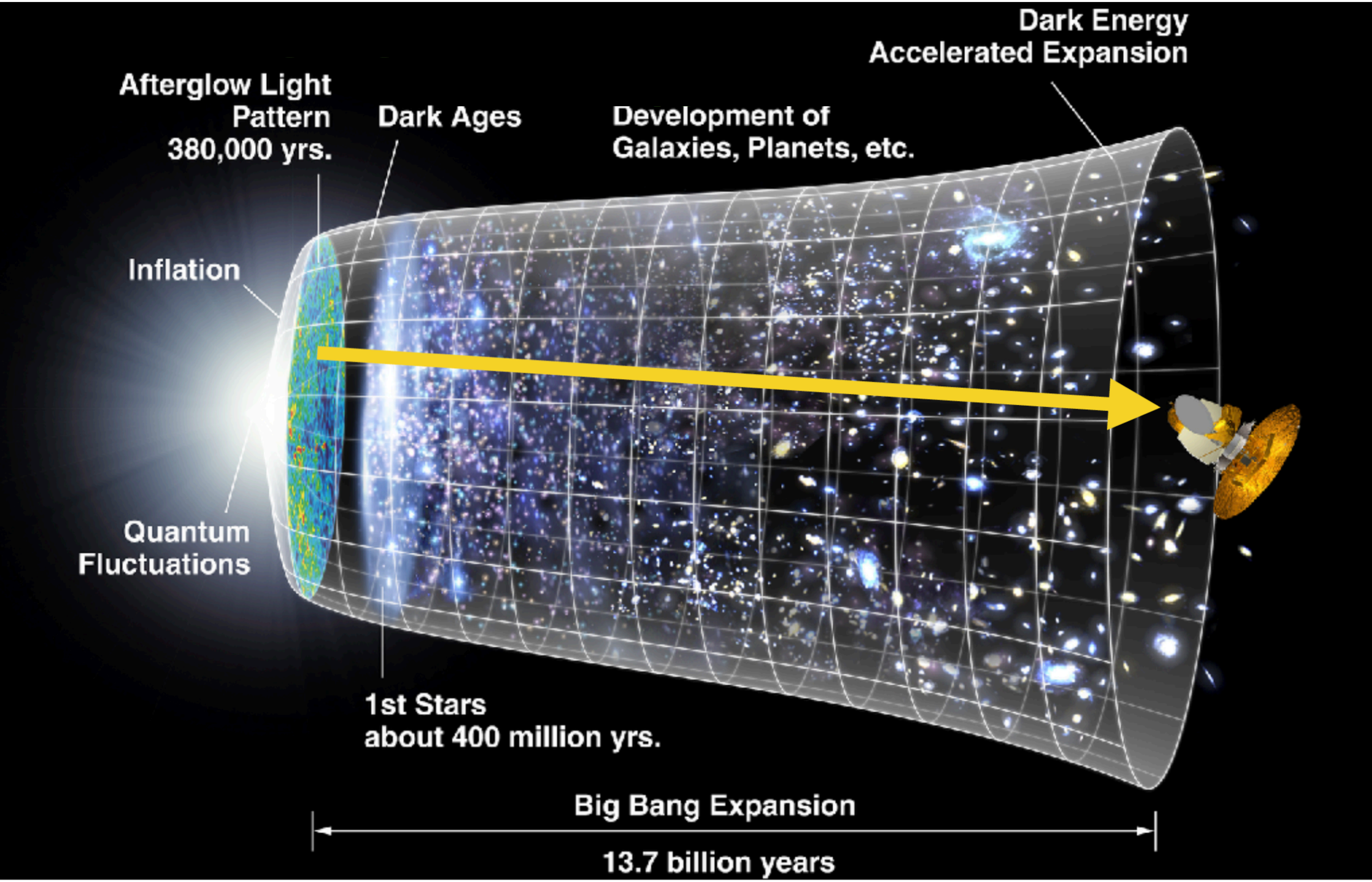
The 3rd floor of Deutsches Museum



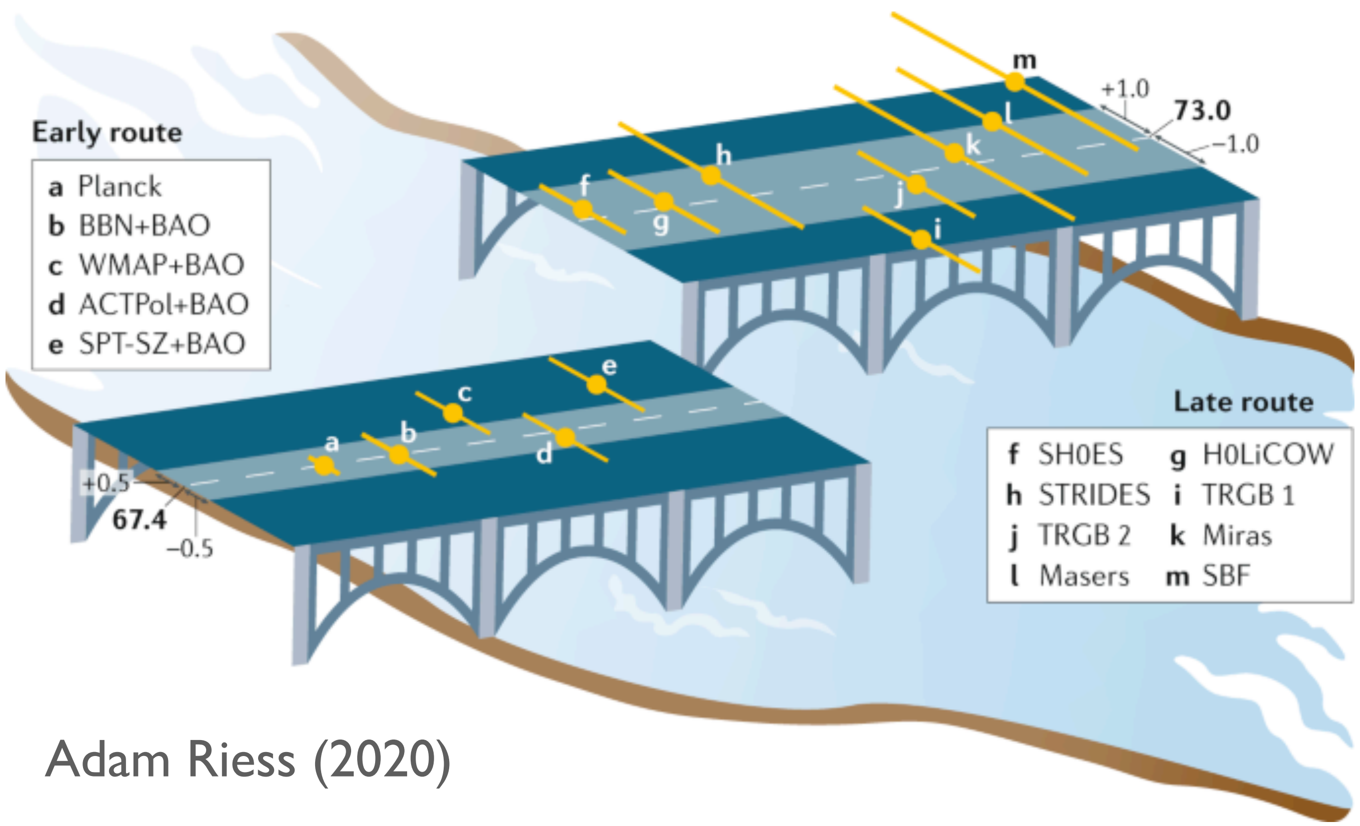
The real detector system used by Penzias & Wilson
The 3rd floor of Deutsches Museum



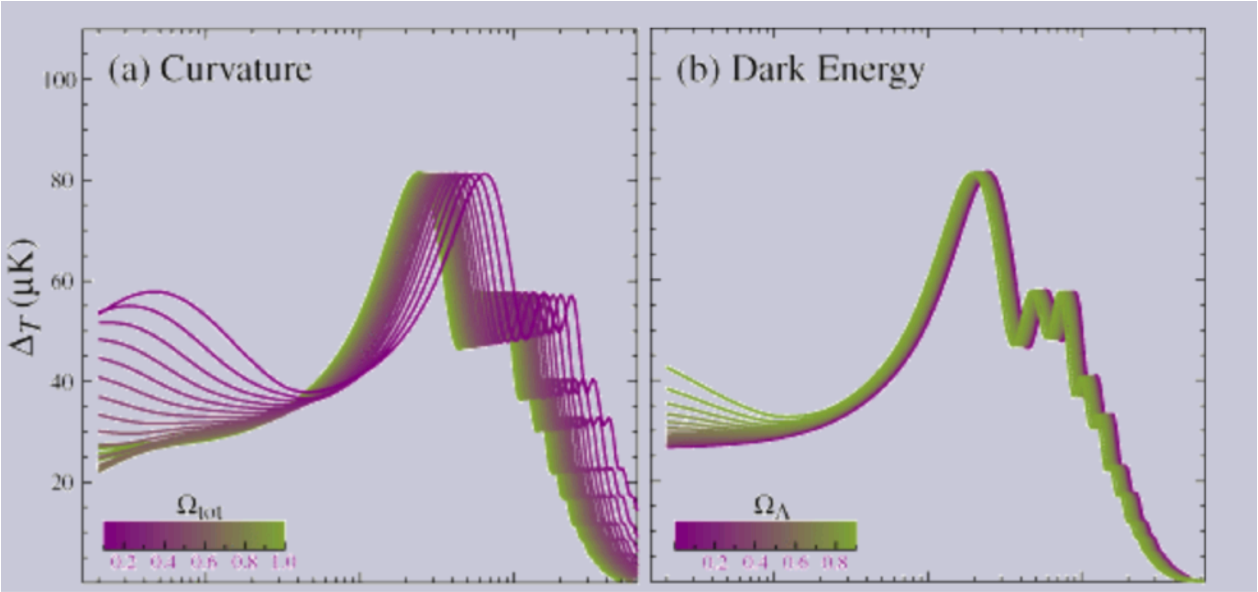
The importance of learning CMB



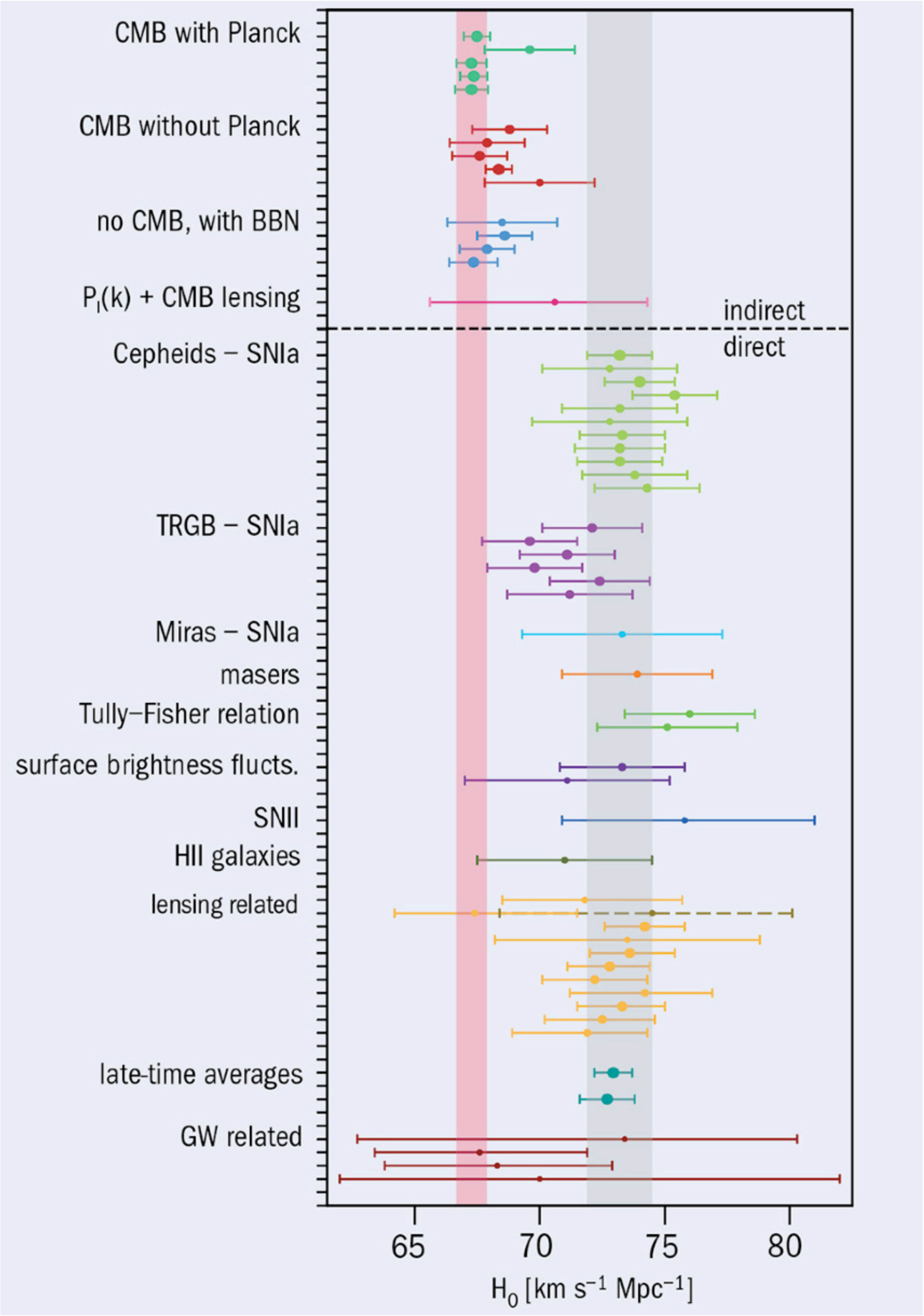
The importance of learning CMB: *Example 1*



Adam Riess (2020)

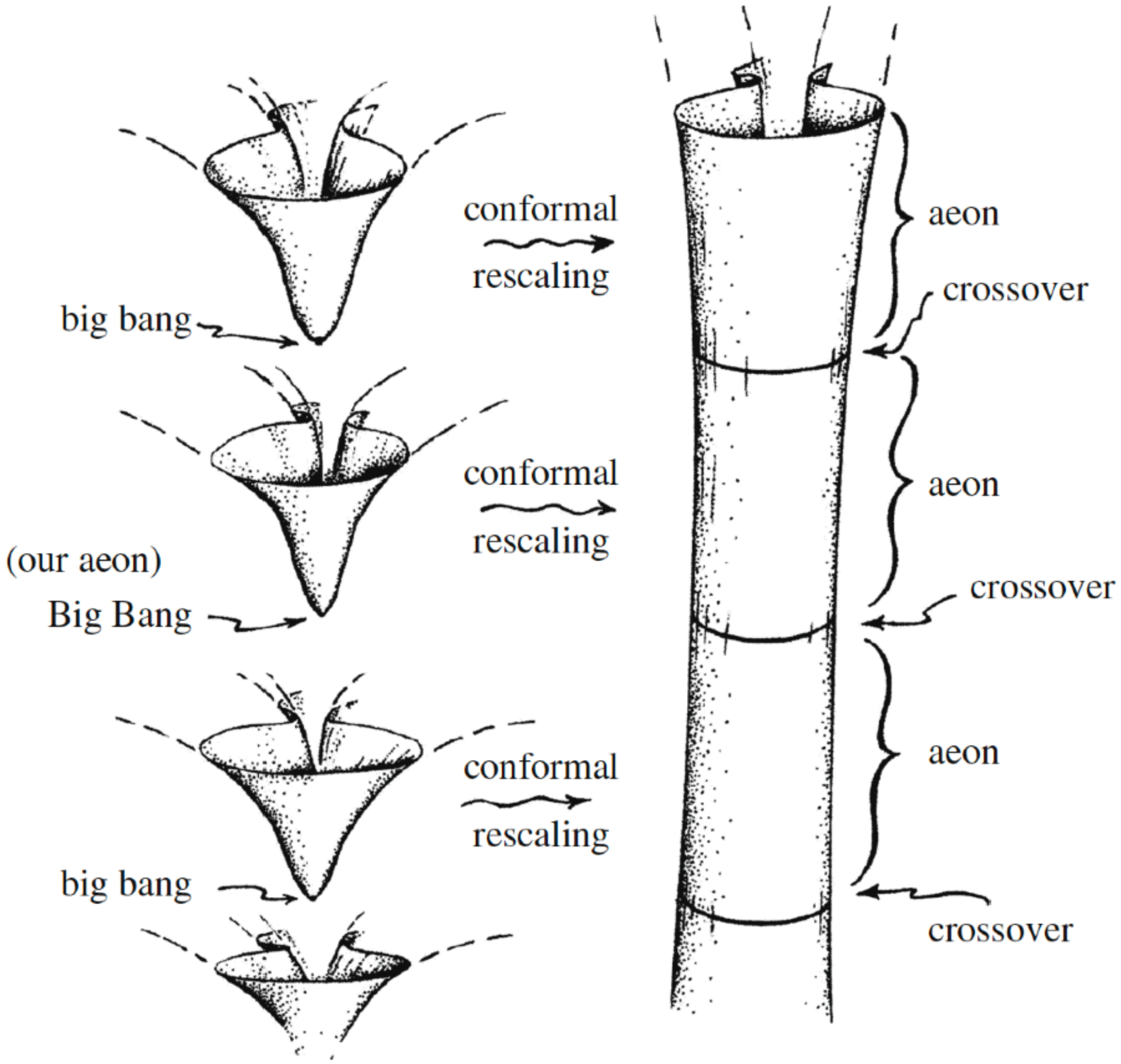


Credit: Wayne Hu

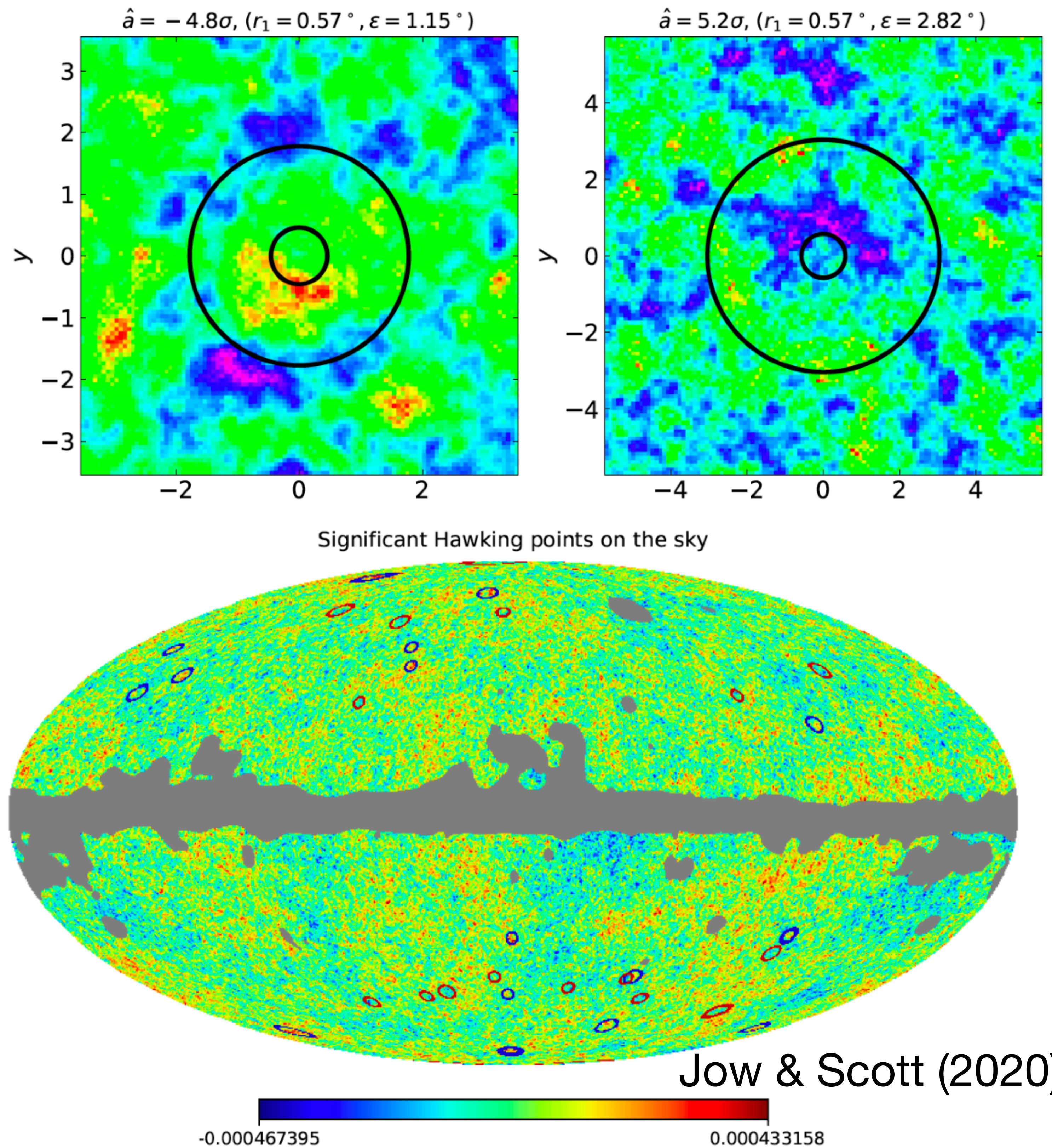


Di Valentino et al. (2021)

The importance of learning CMB: *Example 2*



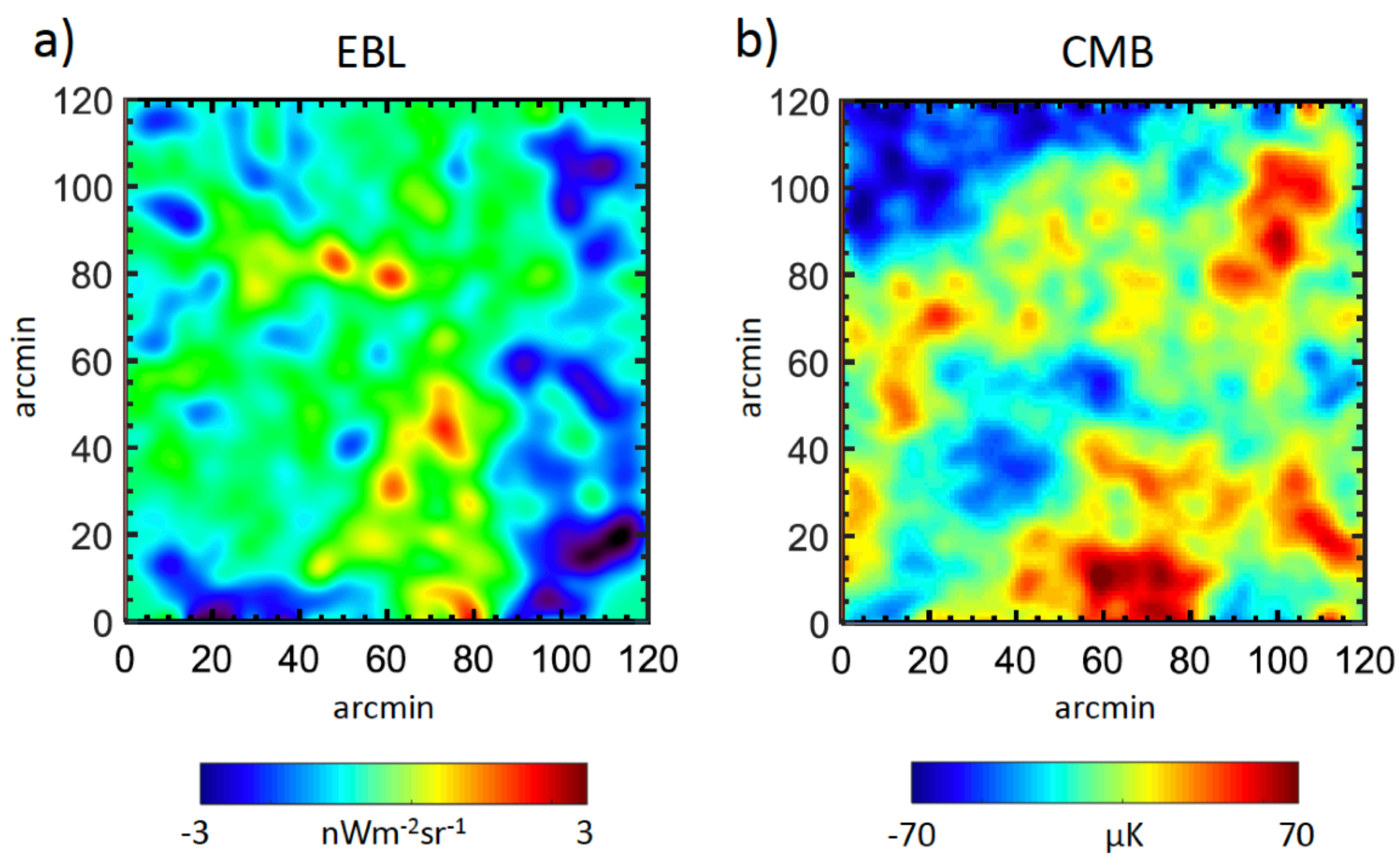
Conformal Cyclic Cosmology (CCC) proposed by R. Penrose

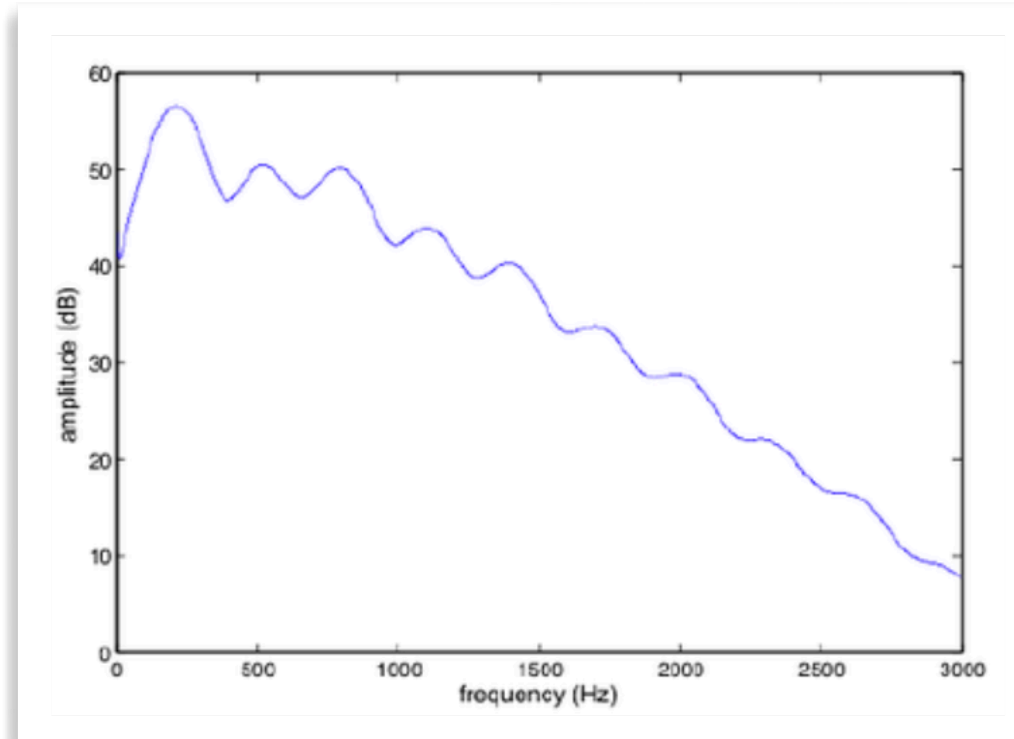


Jow & Scott (2020)

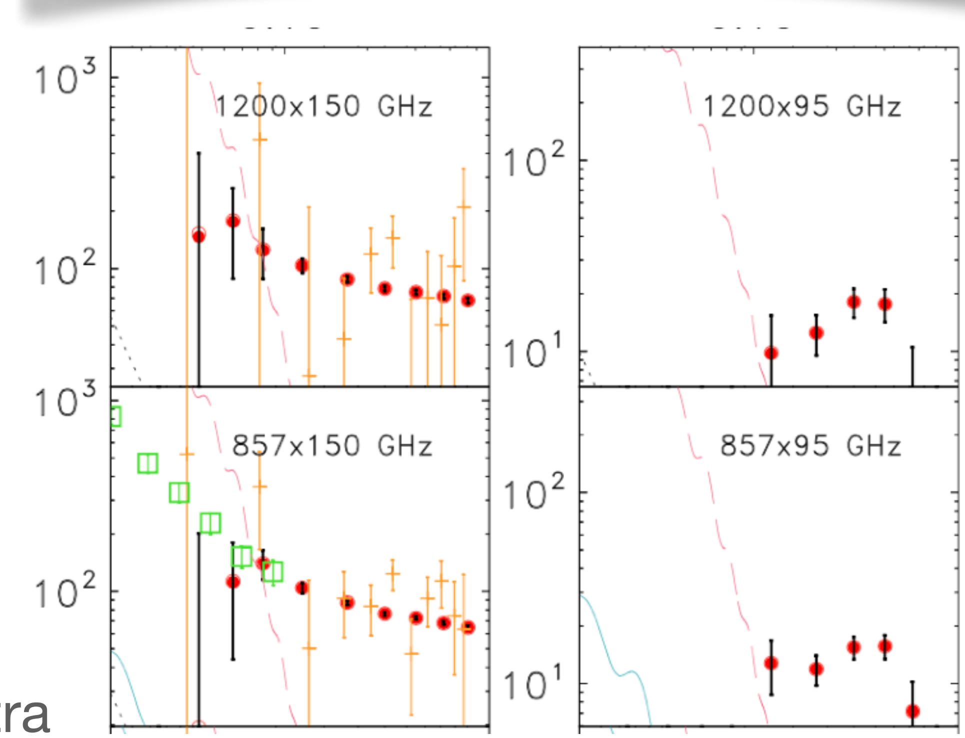
The importance of learning CMB: *Example 3*

Some people still think CMB can be explained as thermal emission from interstellar dust grains..



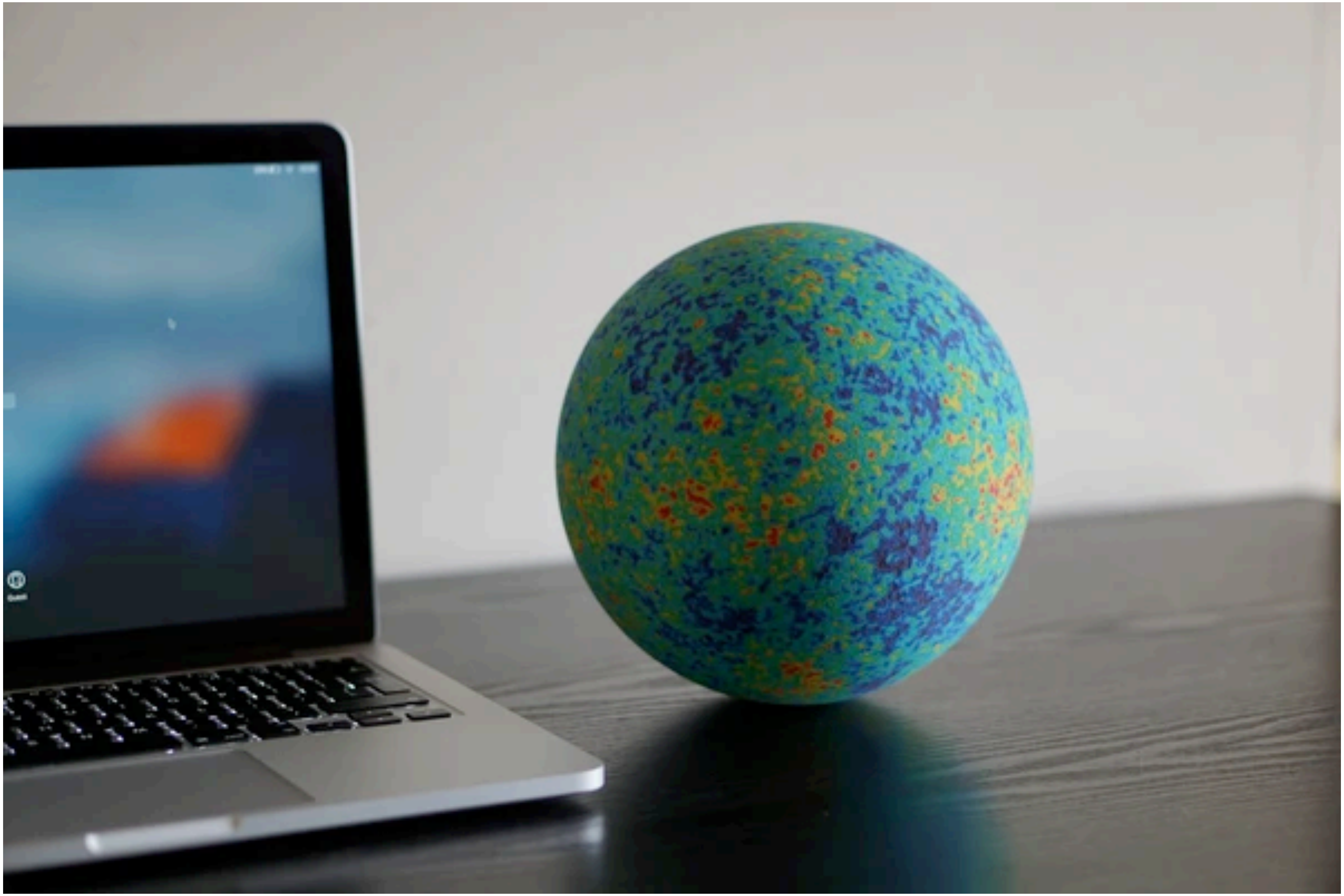


(a certain Vavryčuk, published in the MNRAS)



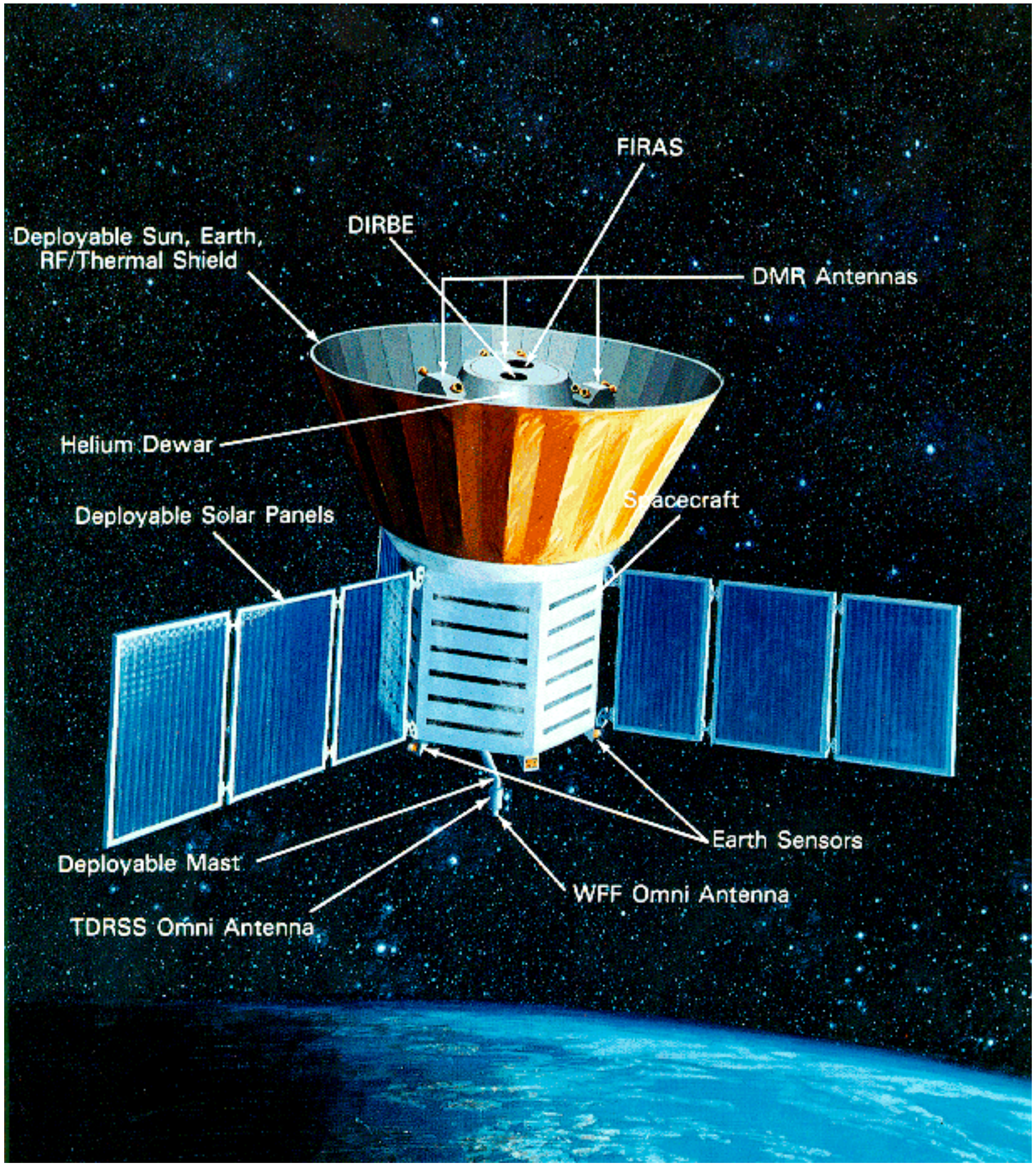
Viero et al. (2019), CMB-CIB cross spectra

Let's meet the experiments



Credit: TheLittlePlanetFactory / WMAP globe (£45)

COBE satellite



Credit: NASA

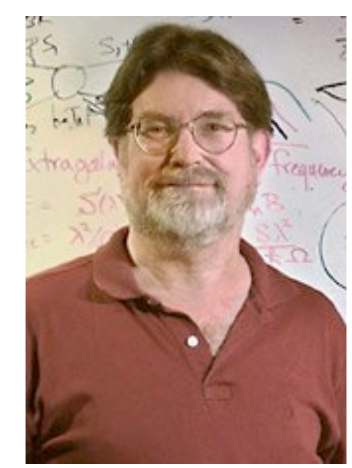
Launched on Nov. 1989 on a Delta rocket.

DIRBE: Measured the absolute sky brightness in the 1–240 μm wavelength range, to search for the Infrared Background

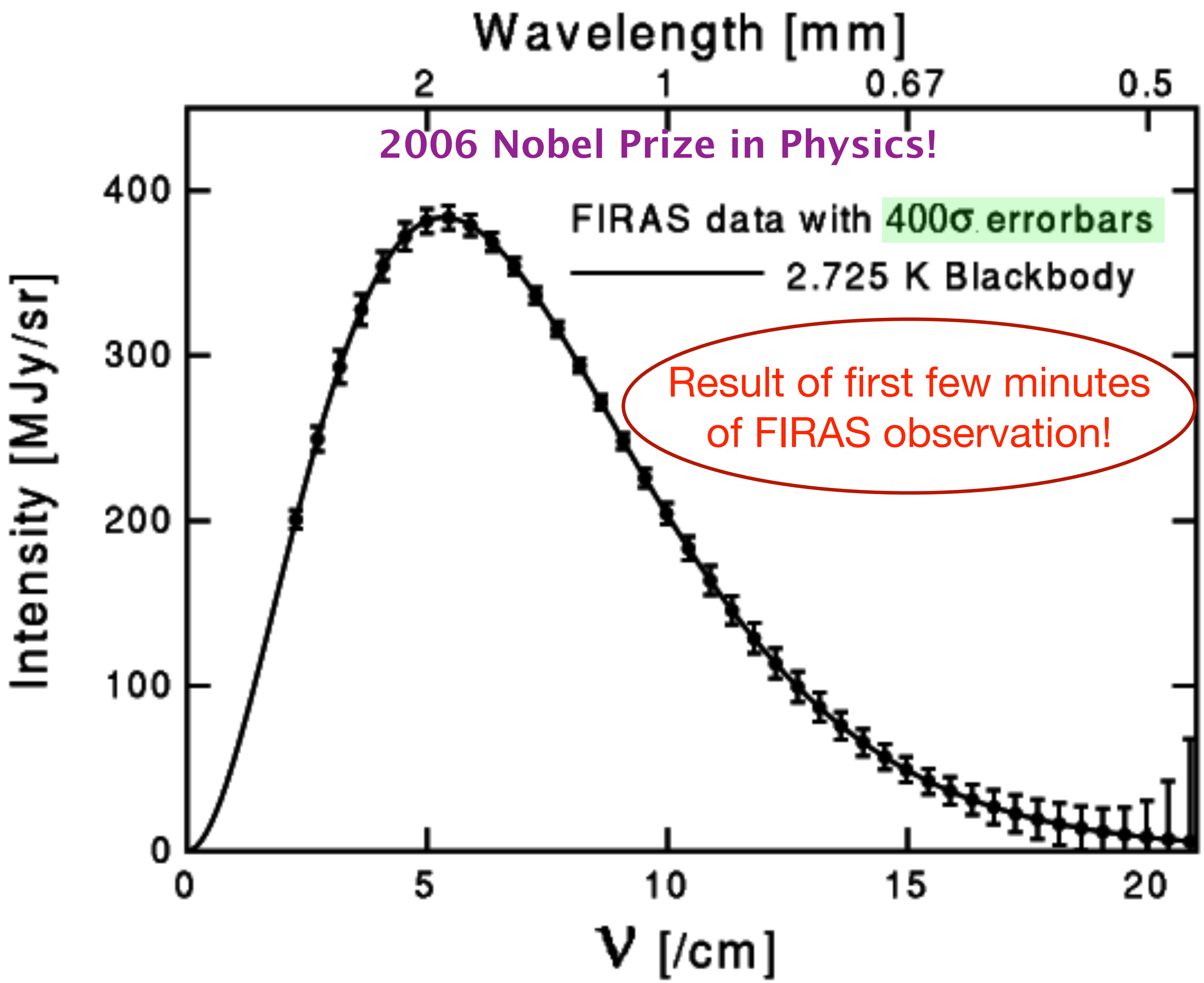
FIRAS: Measured the spectrum of the CMB, finding it to be an almost perfect blackbody with $T_0 = 2.725 \pm 0.002$ K

DMR: Found "anisotropies" in the CMB for the first time, at a level of 1 part in 10^5

2006 Nobel prize in physics

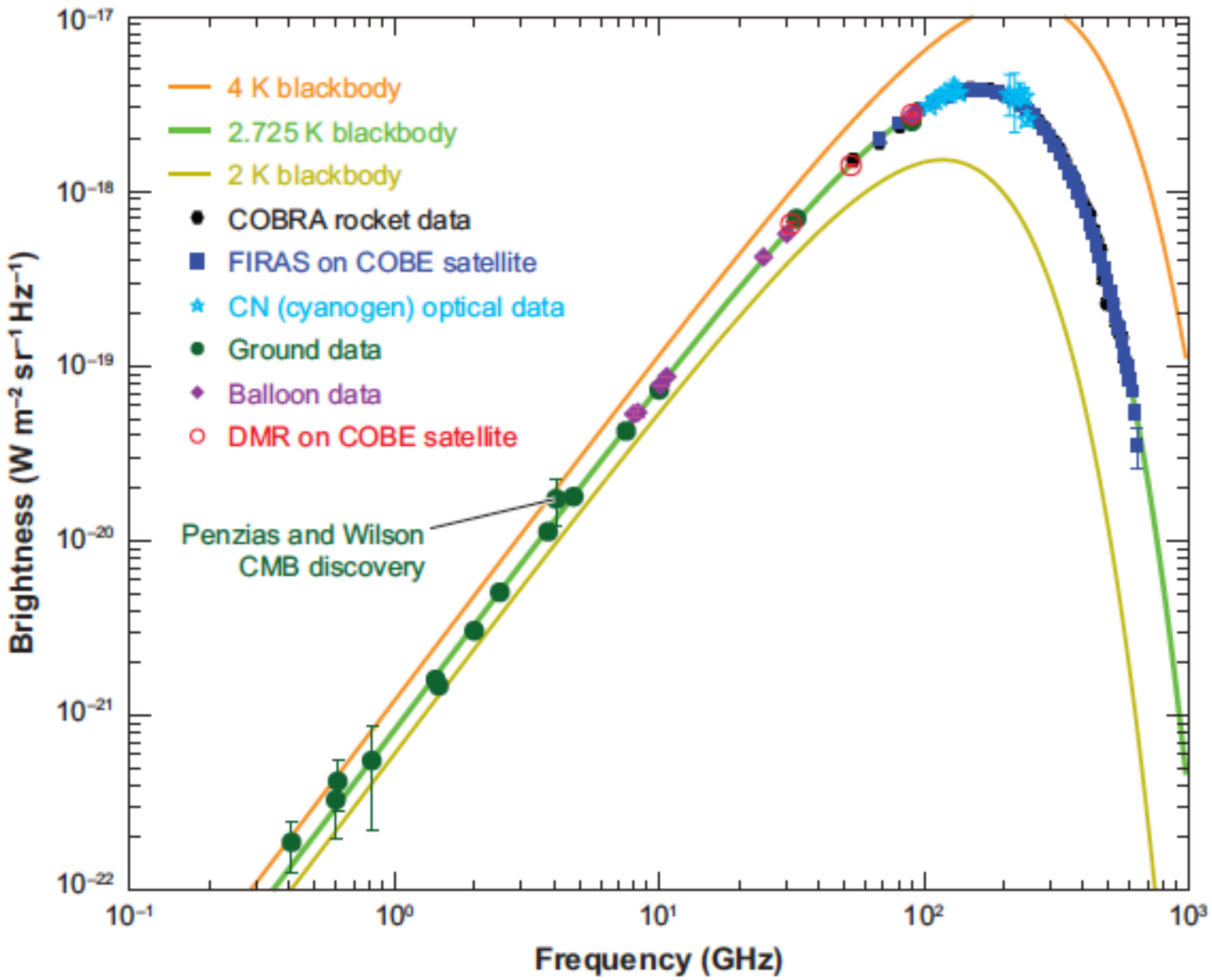


The CMB blackbody



Measurement of T_{CMB}

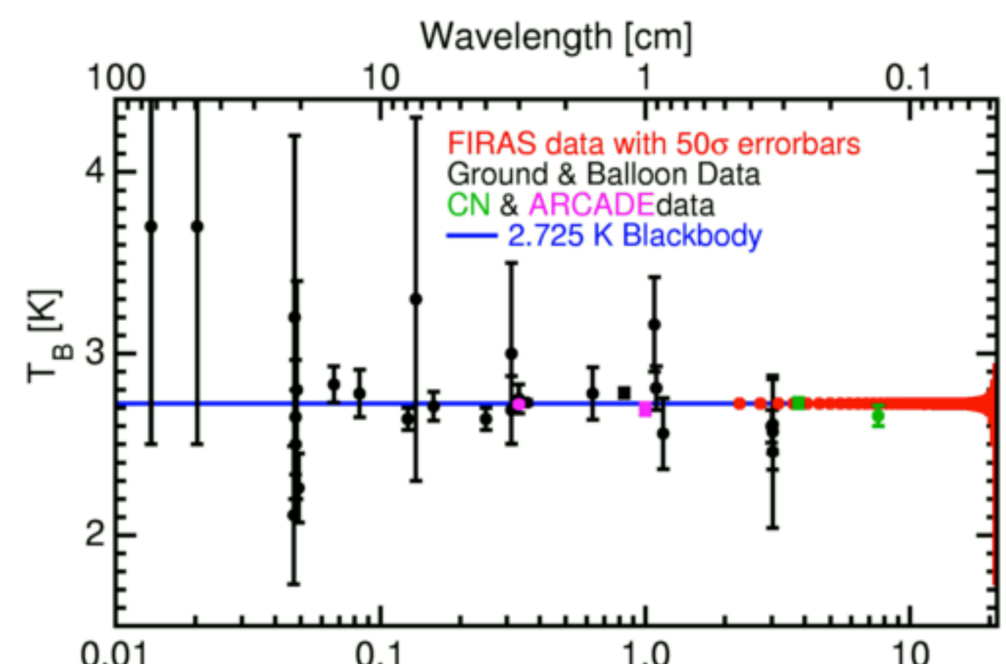
Credit: D. Samtleben



Measured blackbody spectrum of the CMB, with fit to various data

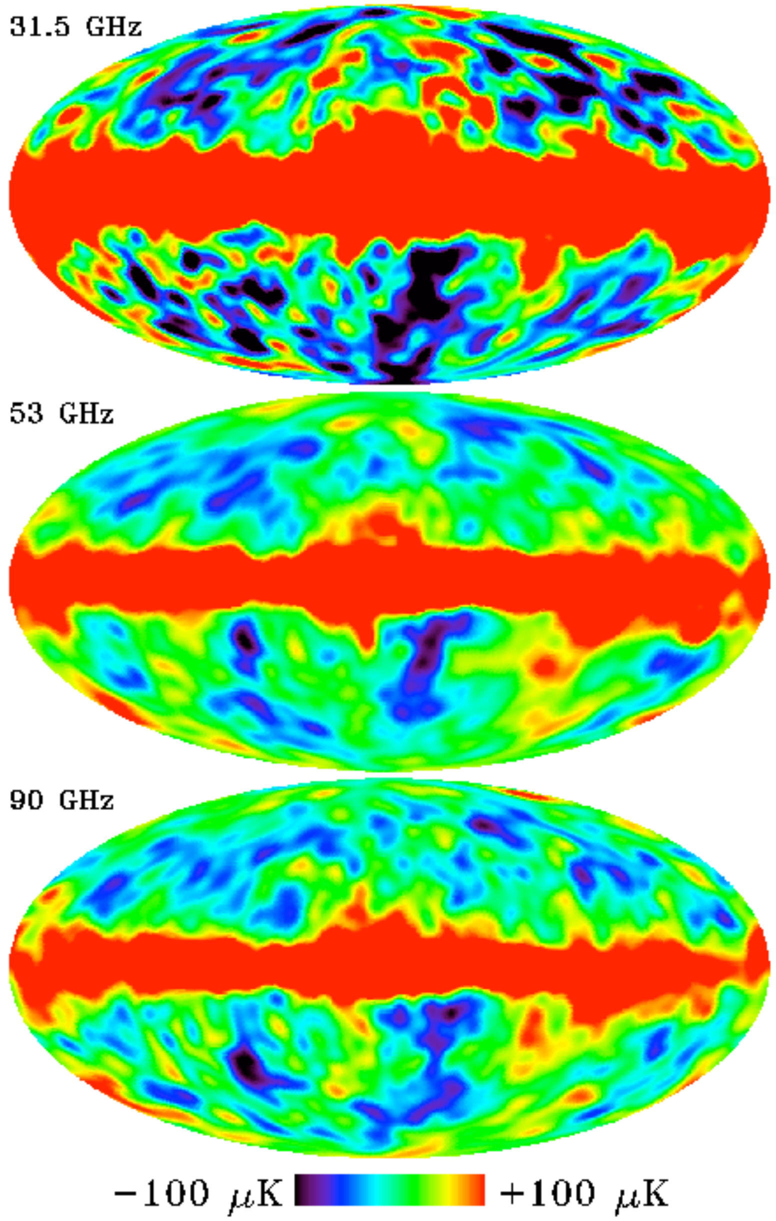
Ground and balloon based experiments have been measuring CMB temperature for decades with increasing precision

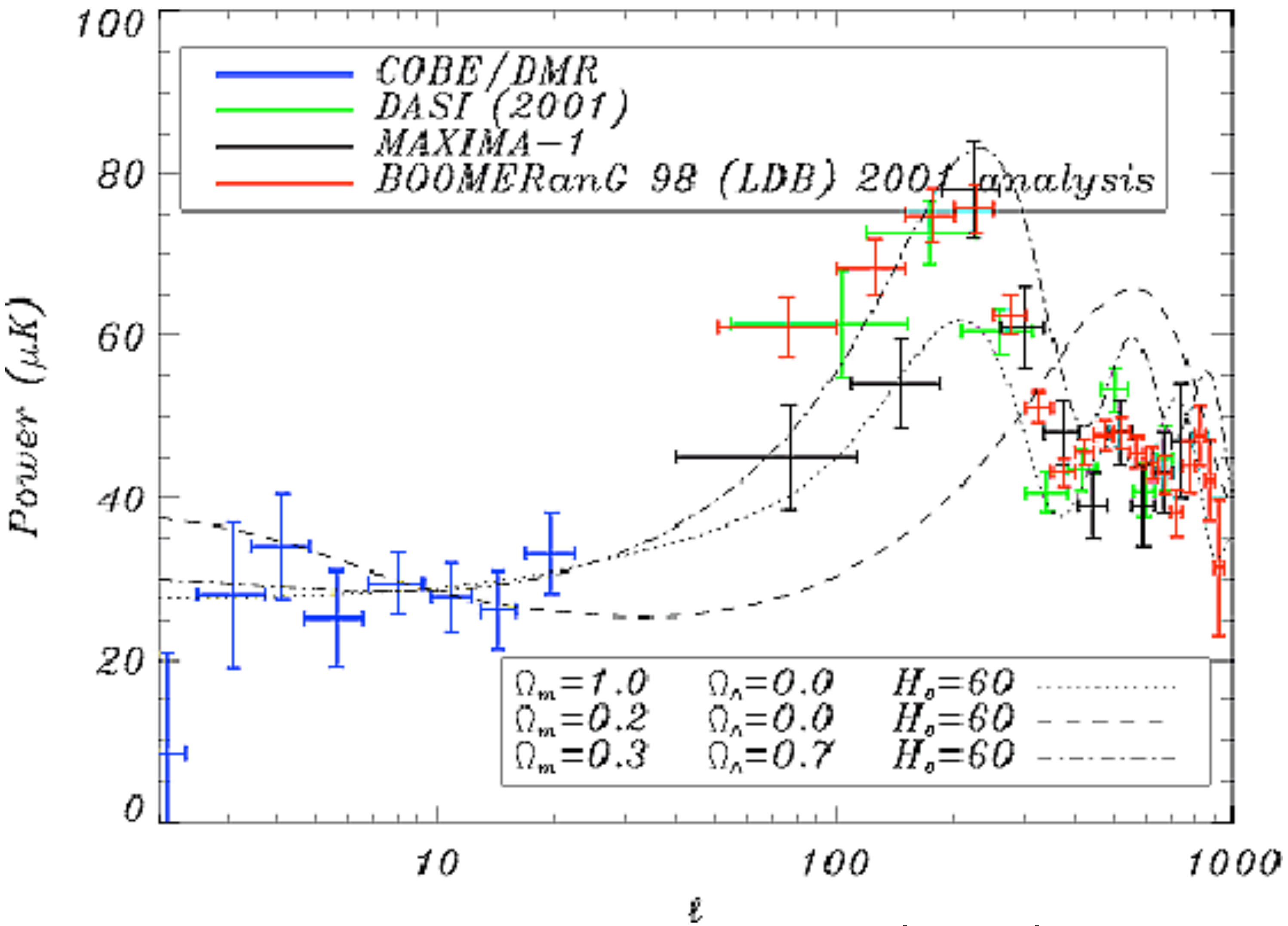
but it was realized that one has to go to the stable thermal environment of outer space to get a really accurate measurement (and observe in the Wien part).



Credit: Ned Wright

COBE DMR Measurements



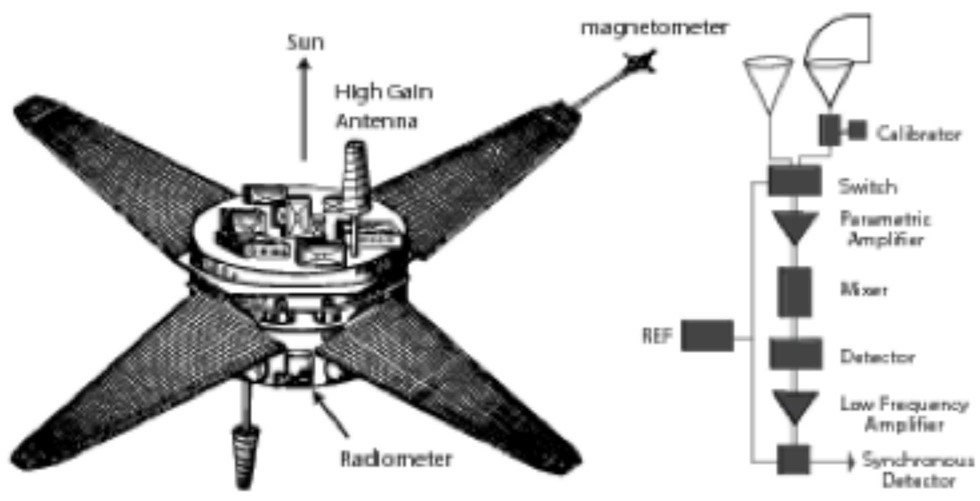


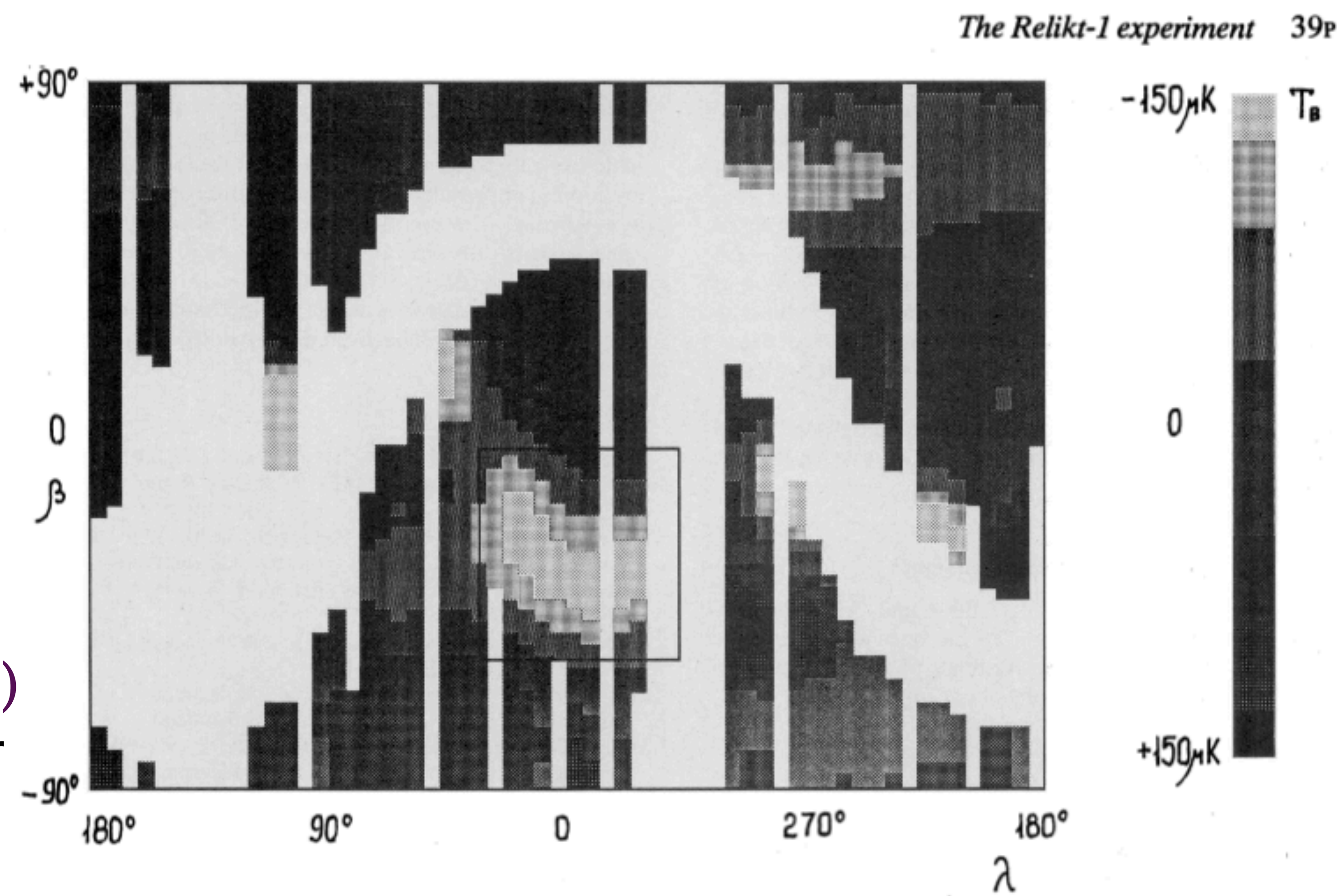
Credit: Archeops team

COBE DMR results
First announced in Smoot et al. (1992)

2006 Nobel Prize in Physics for George Smoot

Relikt-1





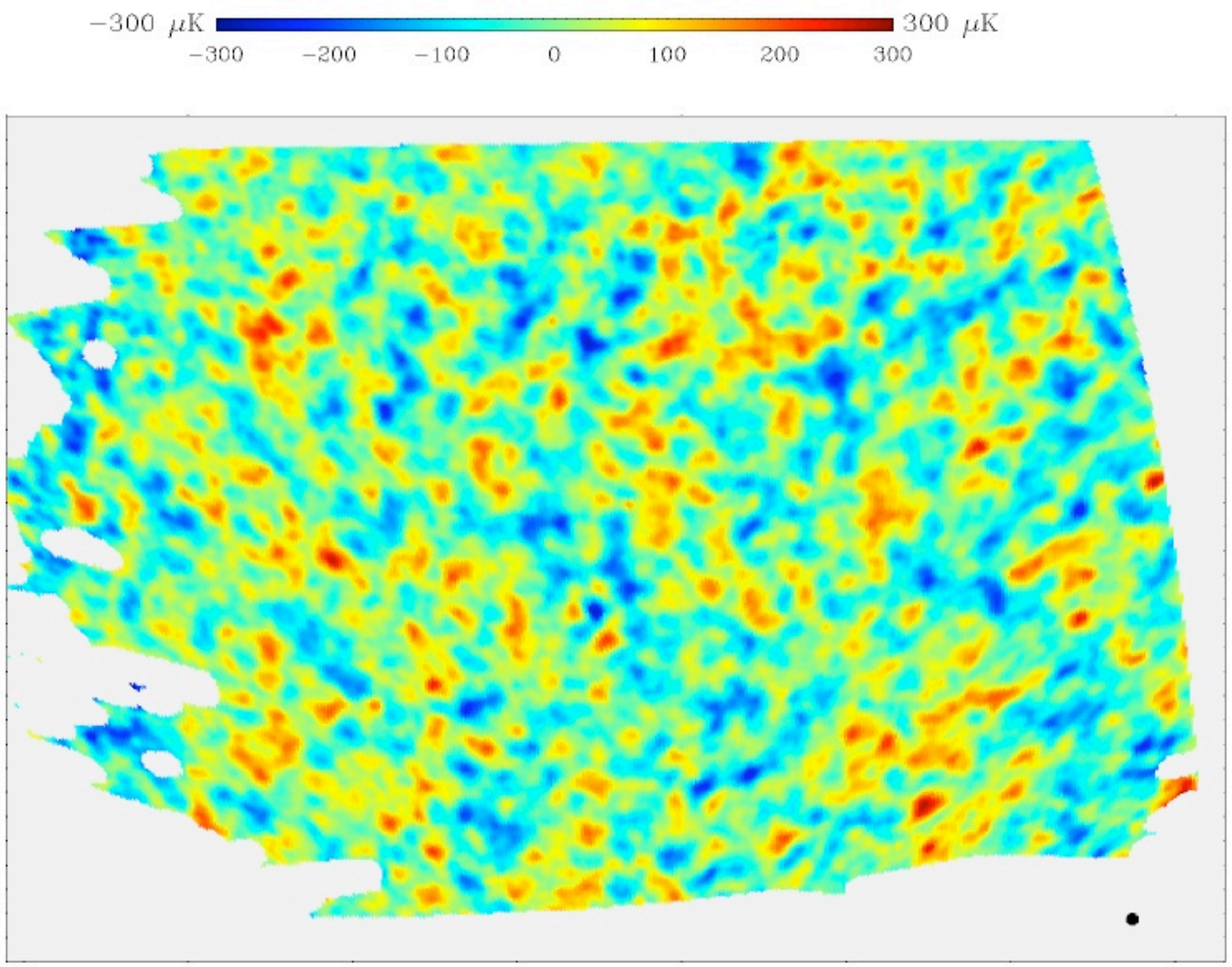
Launched July 1983 (6 yr before COBE)
Single frequency (37 GHz) radiometer

Strukov et al. (1992)

Analysis seriously delayed by the breakup of the USSR..

A 1992 paper reported a temperature decrement of
−71 ± 43 μK at large angles at 90% confidence,
including systematics.

Anisotropies seen by BOOMERANG



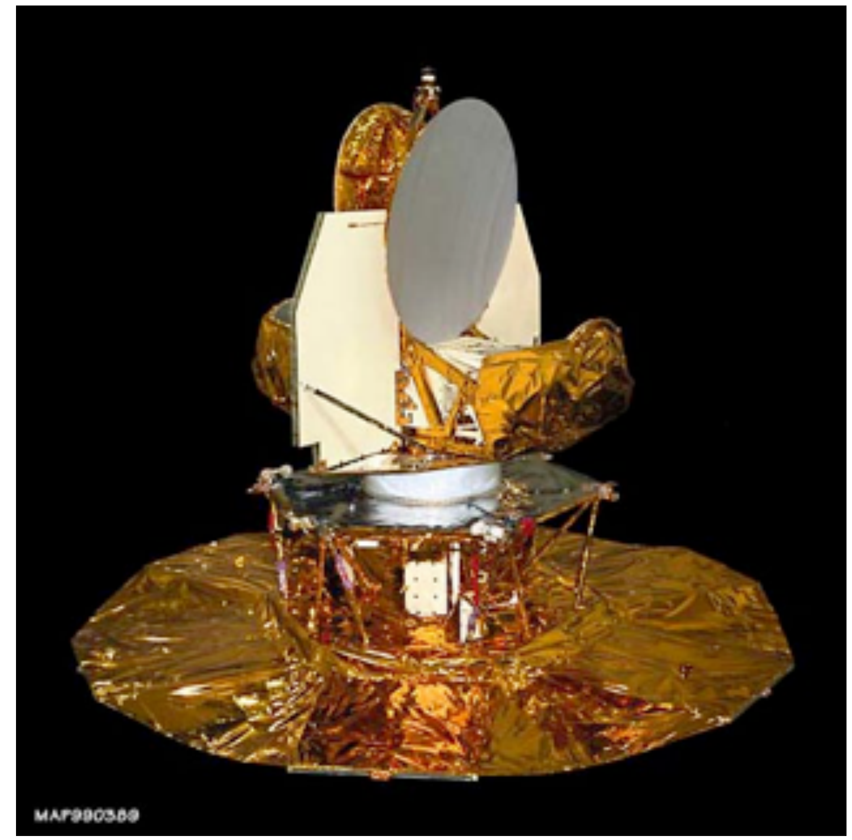
Boomerang launch Dec 1998

(Balloon Observations Of Millimetric Extragalactic Radiation ANd Geophysics)

Flight: 10 days
1800 deg^2
3 % of the Sky
Resolution 0.2^o

WMAP: 2001–2010

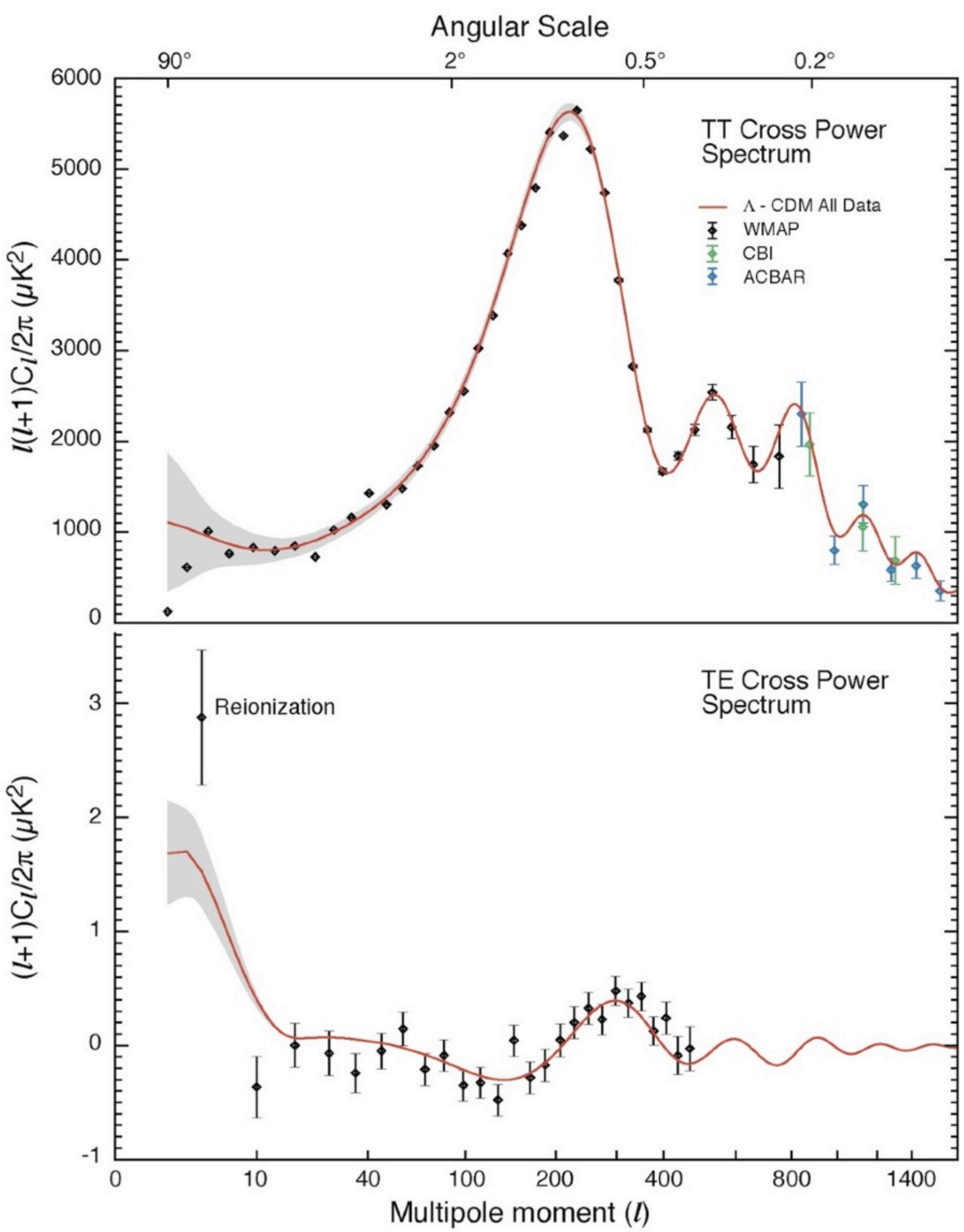
Credit: NASA



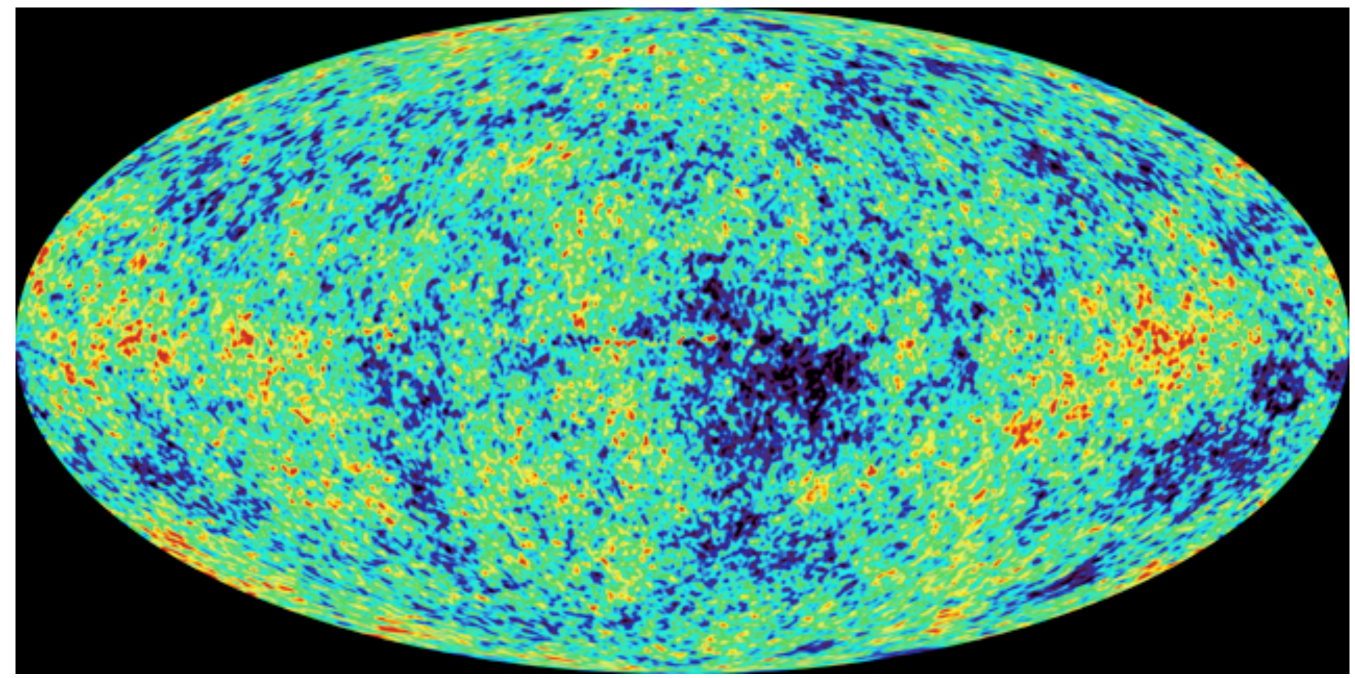
Note the same dual receivers as COBE. This design, plus the very stable conditions at the L2, minimizes the “1/f noise” in amplifiers and receivers.

Thus after 7 years, the data could still be added and noise lowered (of course, the improvement gradually diminishes).

WMAP results after 1st year



(Credit: WMAP Science Team)



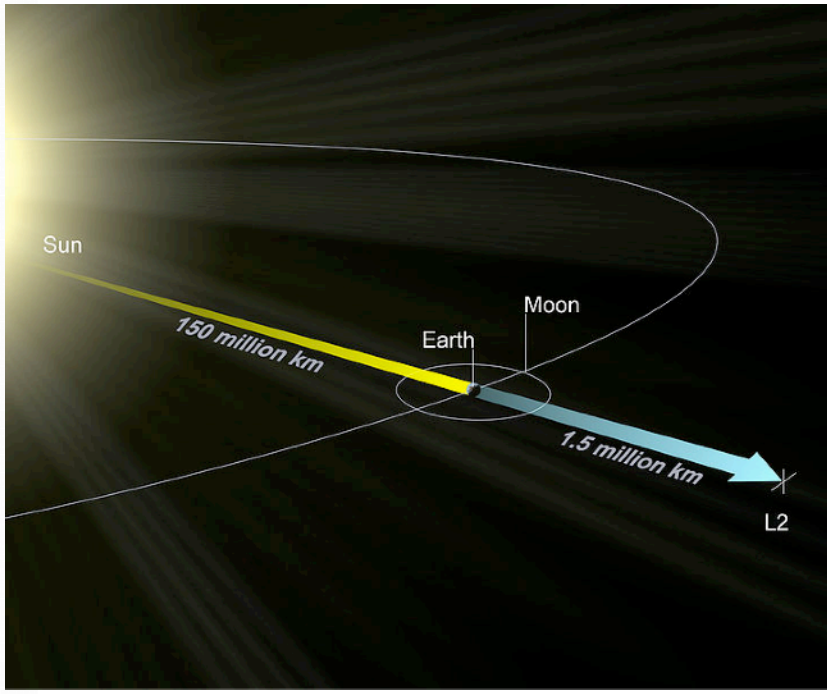
Internal Linear Combination map

Obtaining this map will be one of the exercises later in our course!

Planck satellite (2009–2013)

Credit: ESA

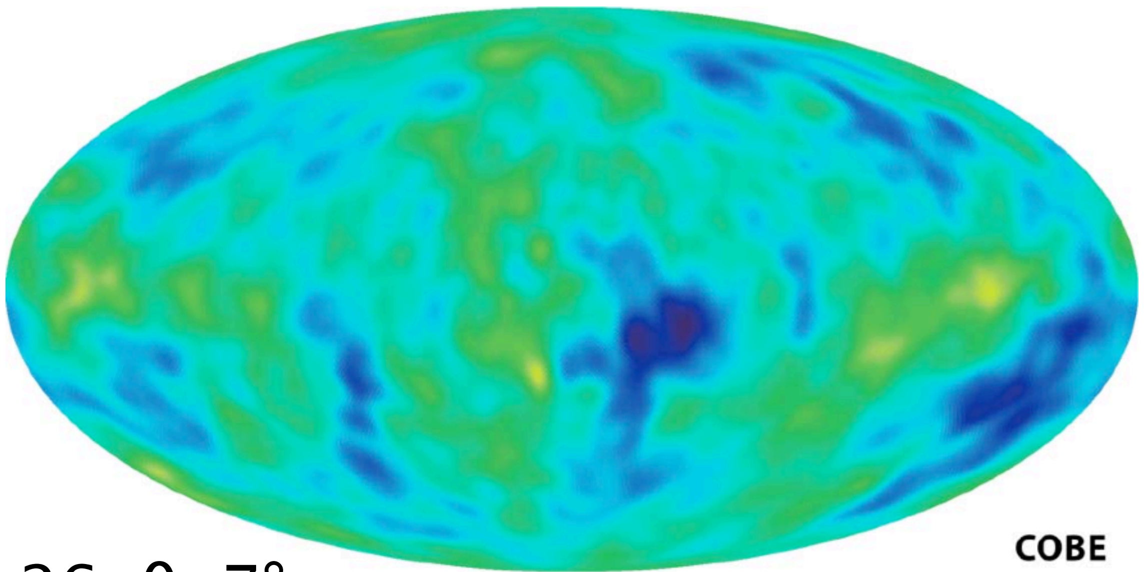
PLANCK launch: May 2009



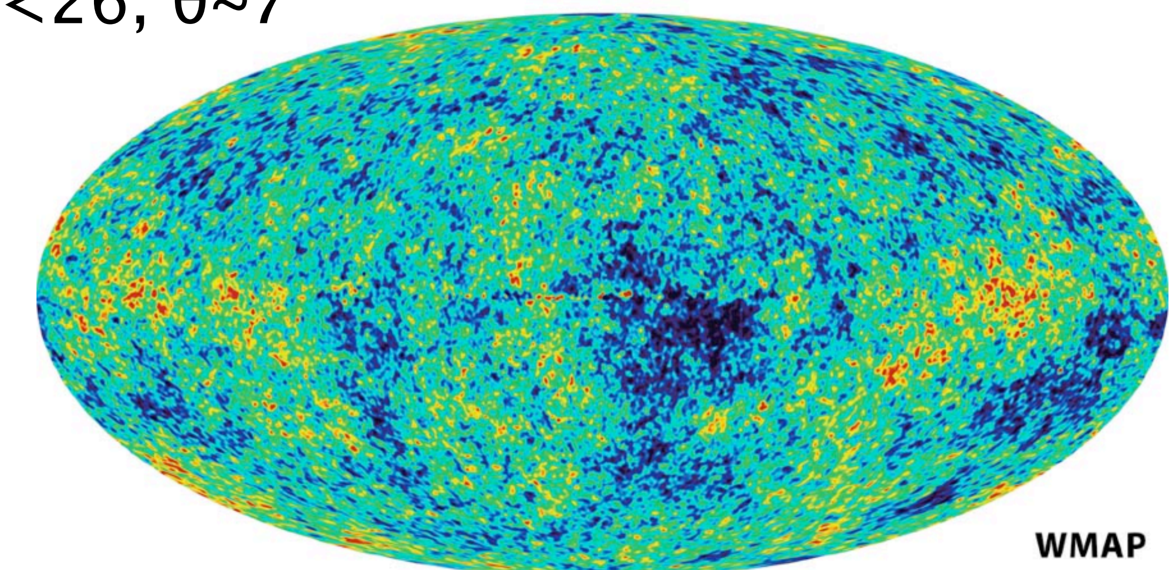
Destination L2:
The second
Lagrangian point

Credit: ESA

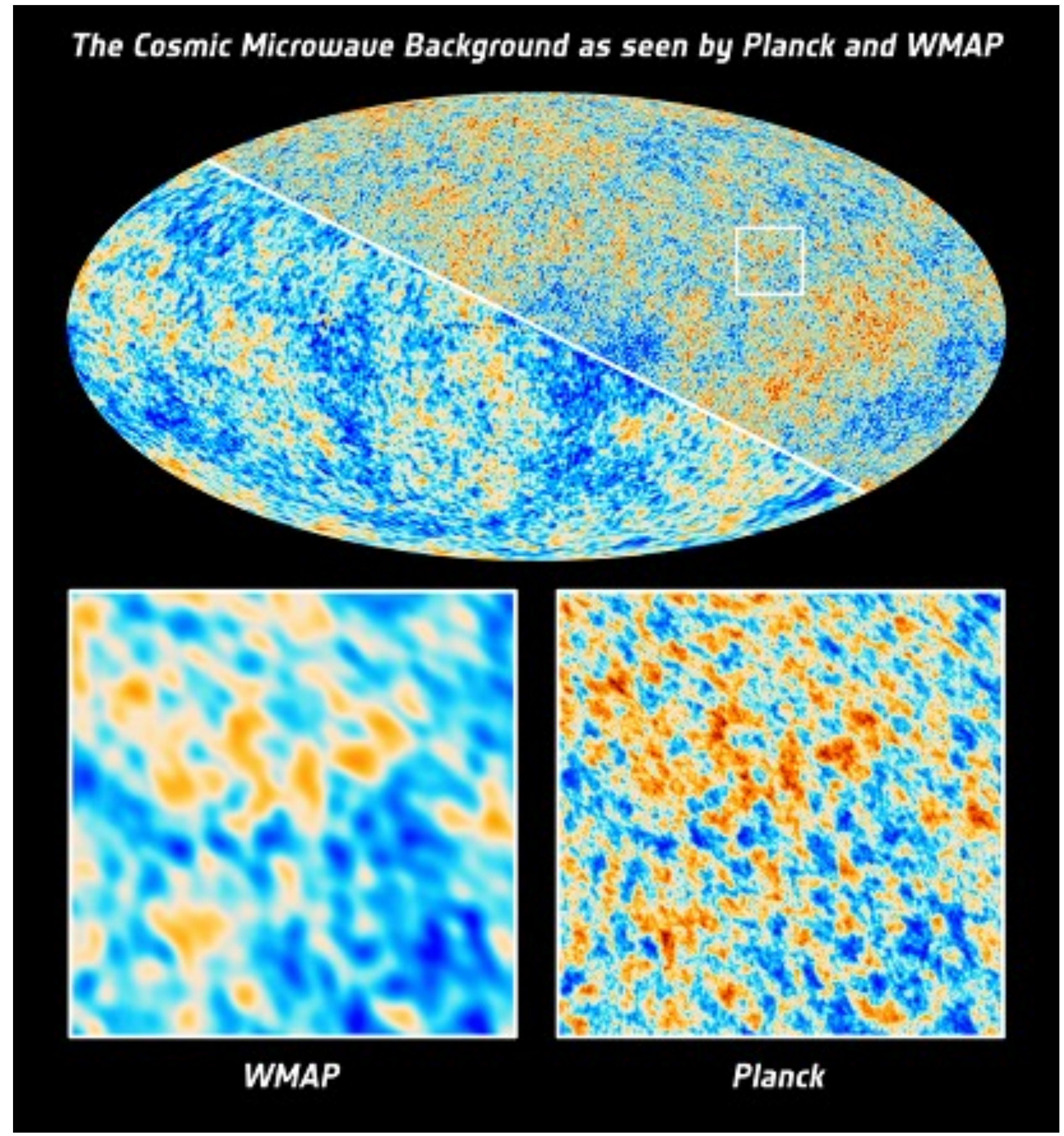
Planck transforming the CMB science



$l<26$, $\theta \sim 7^\circ$

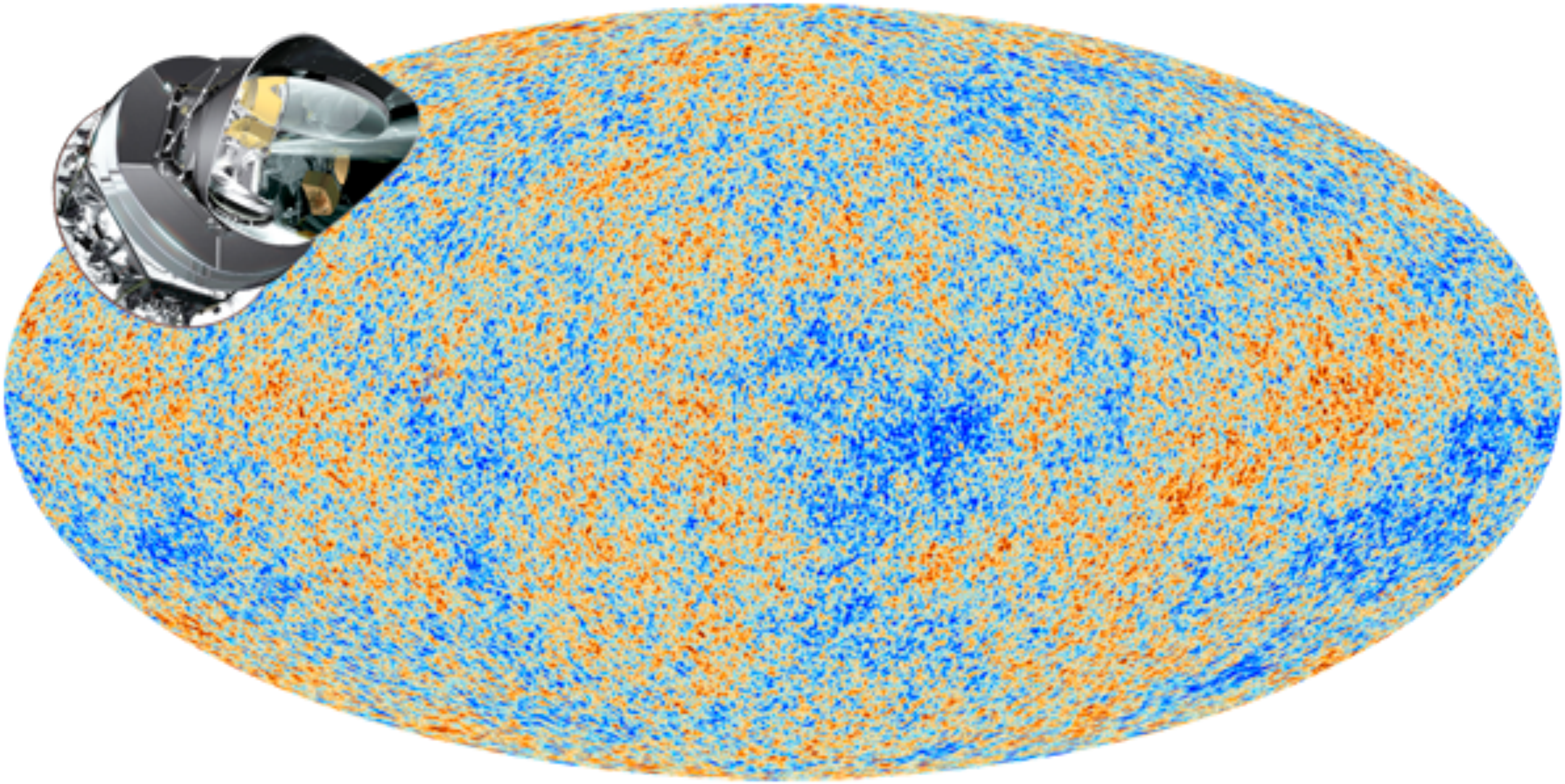


$l<780$, $\theta \sim 0.2^\circ$



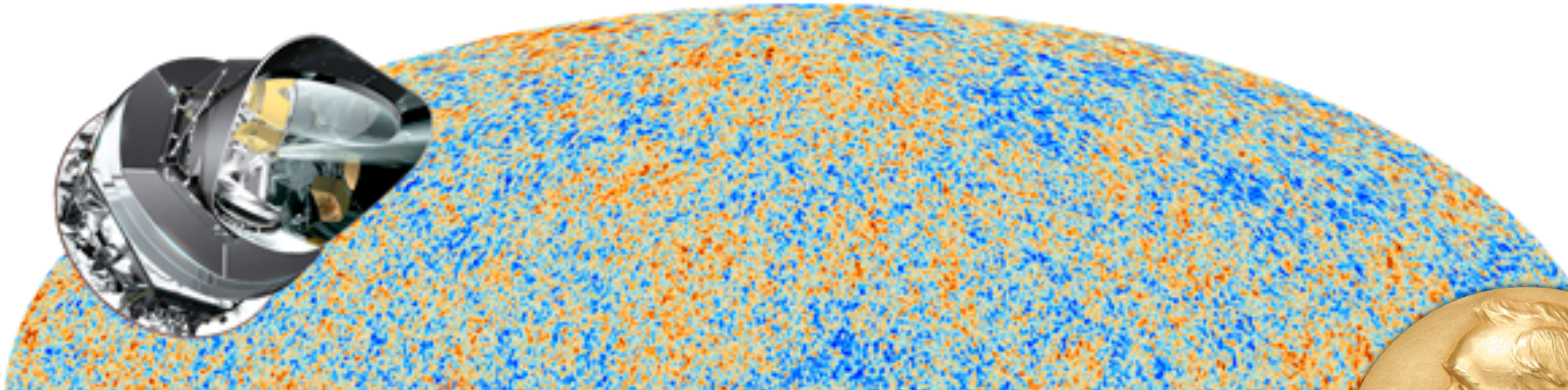
$l<2160$, $\theta \sim 0.1^\circ$

CMB sky seen from Planck

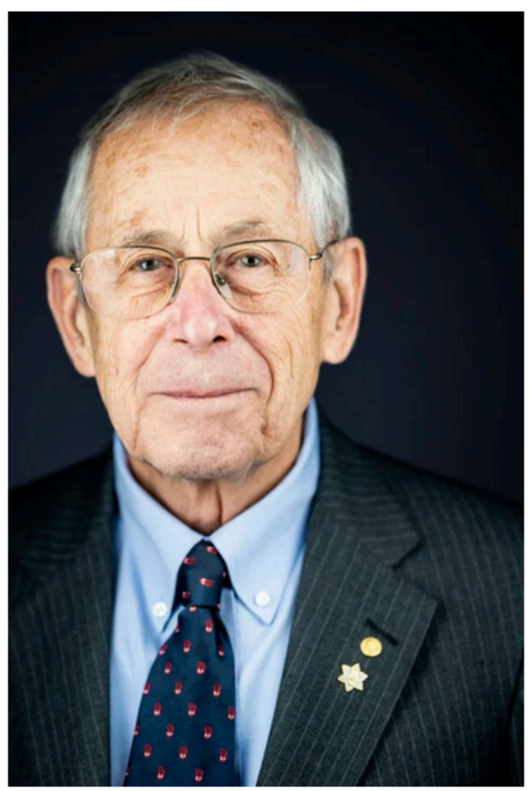


Temperature measurement from Planck, dipole and Galaxy subtracted.

CMB sky seen from Planck



Temperatur



© Nobel Media. Photo: A. Mahmoud

James Peebles
The Nobel Prize in Physics 2019

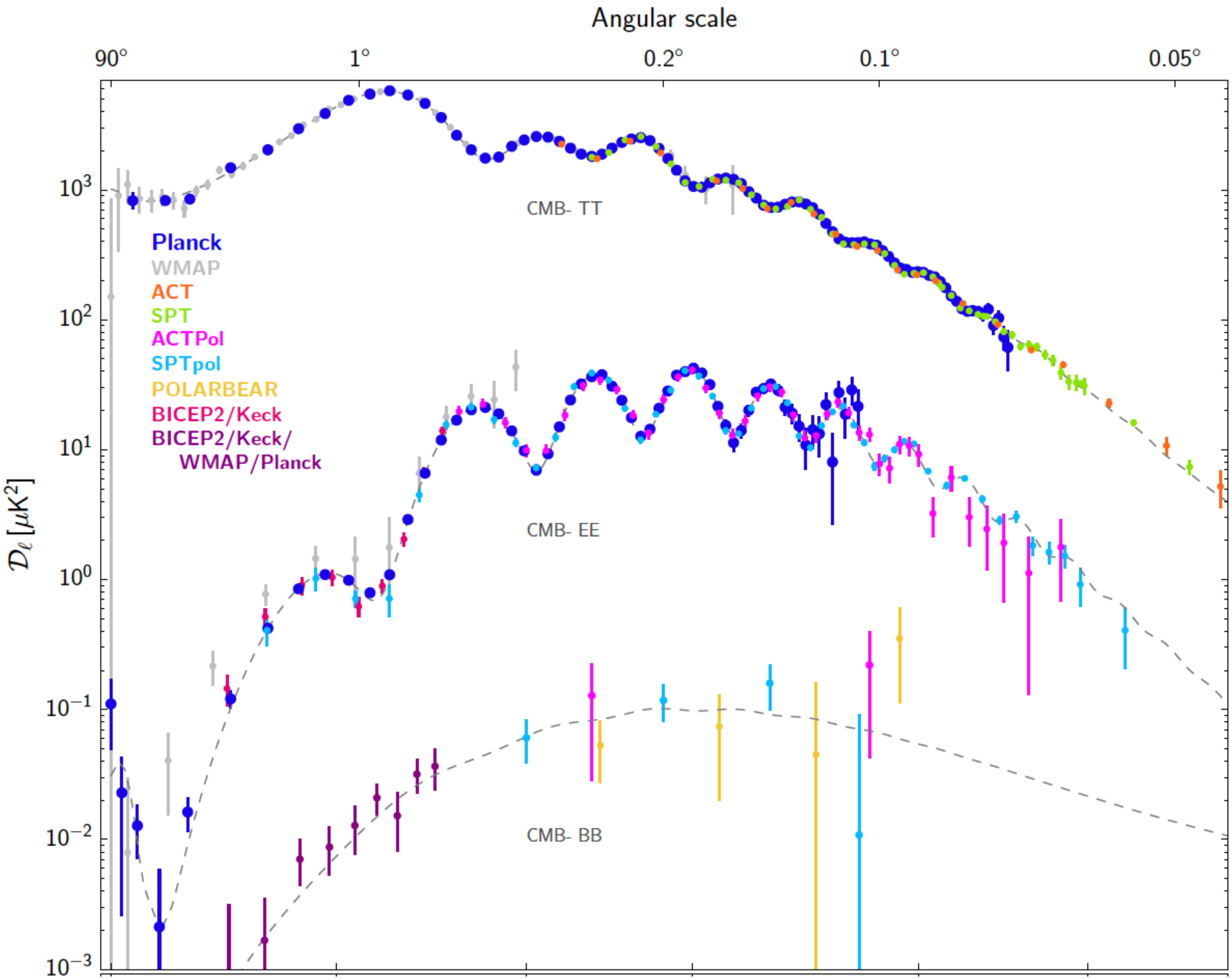
Born: 25 April 1935, Winnipeg, Canada

Affiliation at the time of the award: Princeton University, Princeton, NJ, USA

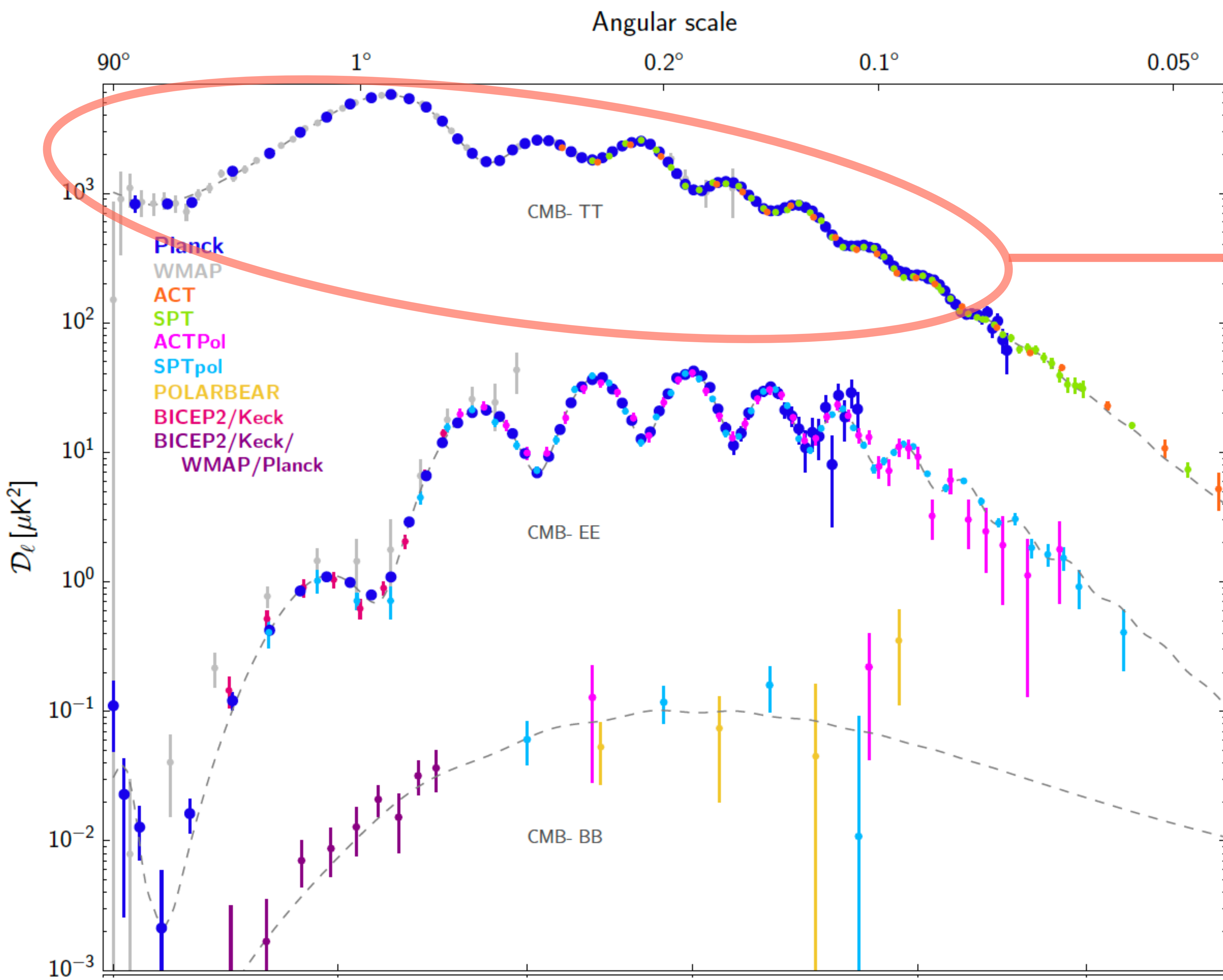
Prize motivation: “for theoretical discoveries in physical cosmology”

Prize share: 1/2

CMB state-of-the-art (mid-2018)



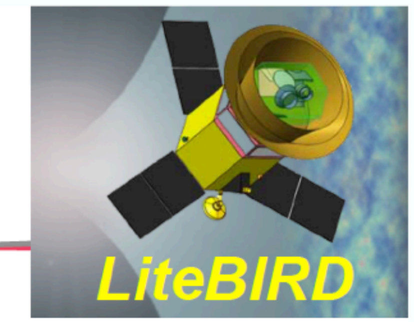
CMB state-of-the-art (mid-2018)



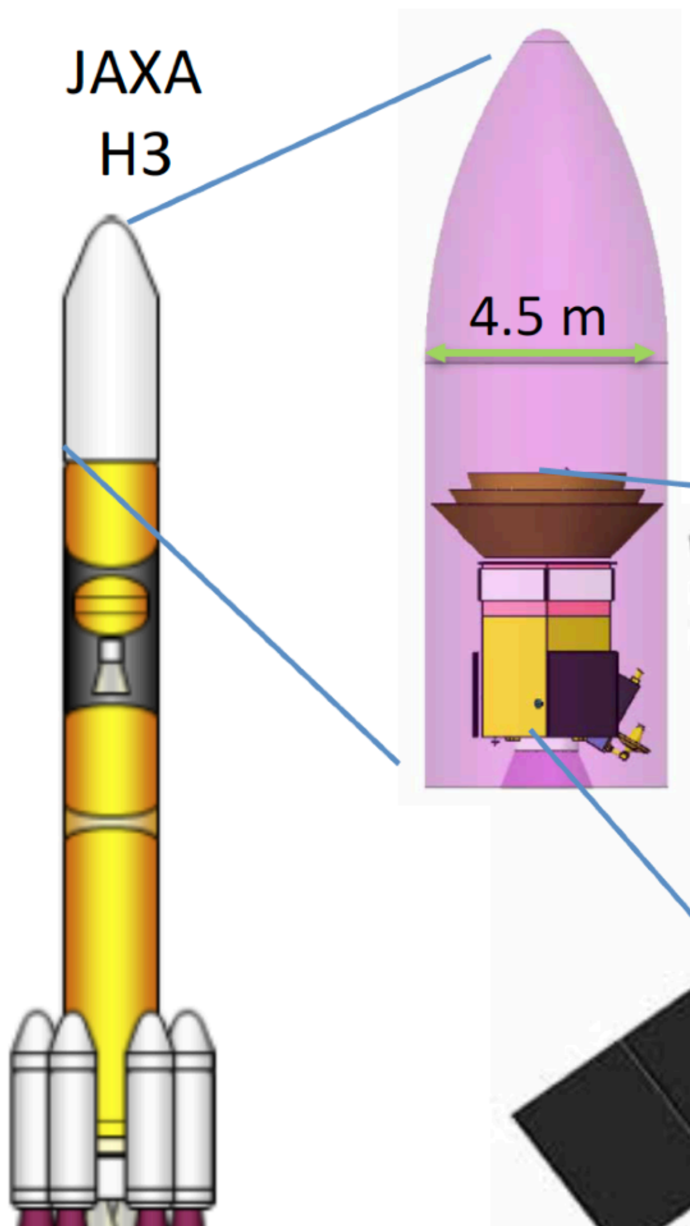
Cosmic variance limited measurement

Slide courtesy Yutaro Sekimoto (ISAS/JAXA)

LiteBIRD Spacecraft



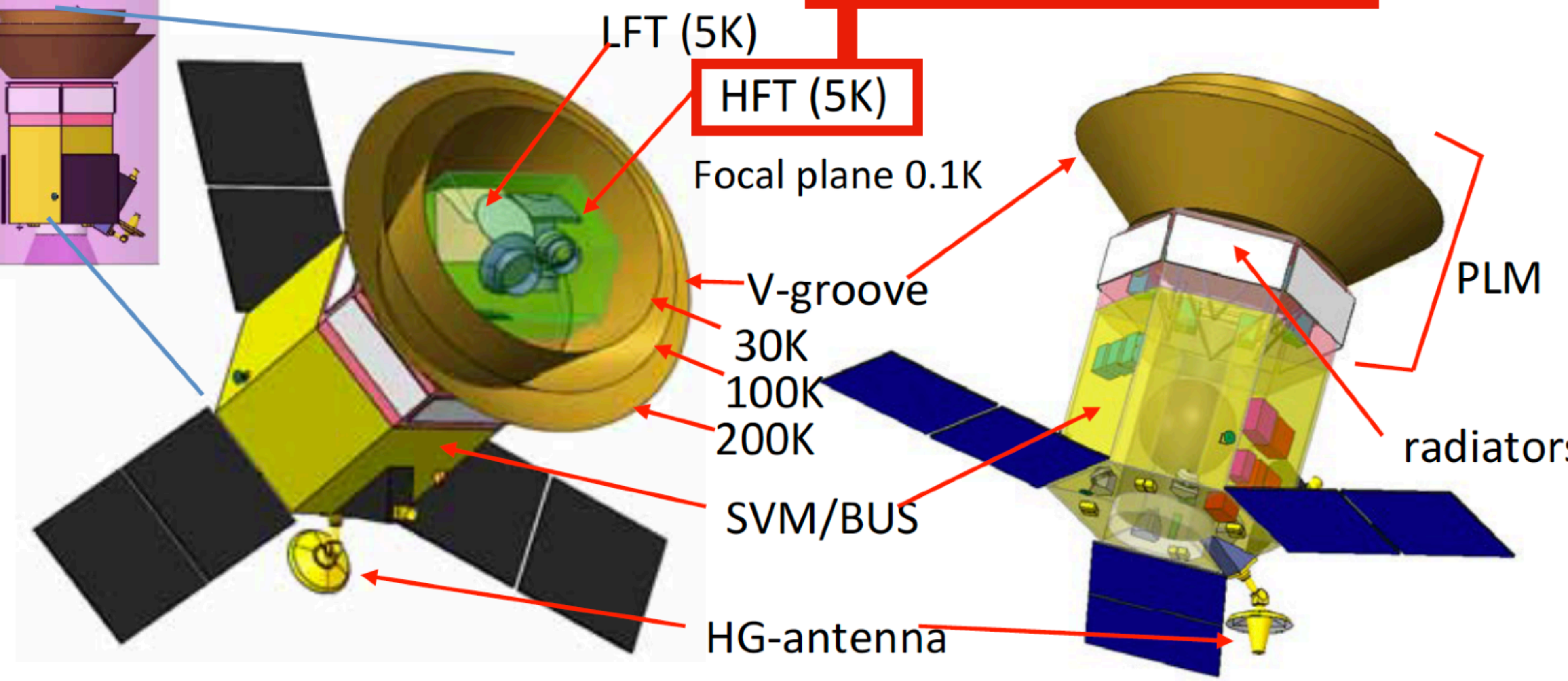
Launch 2027

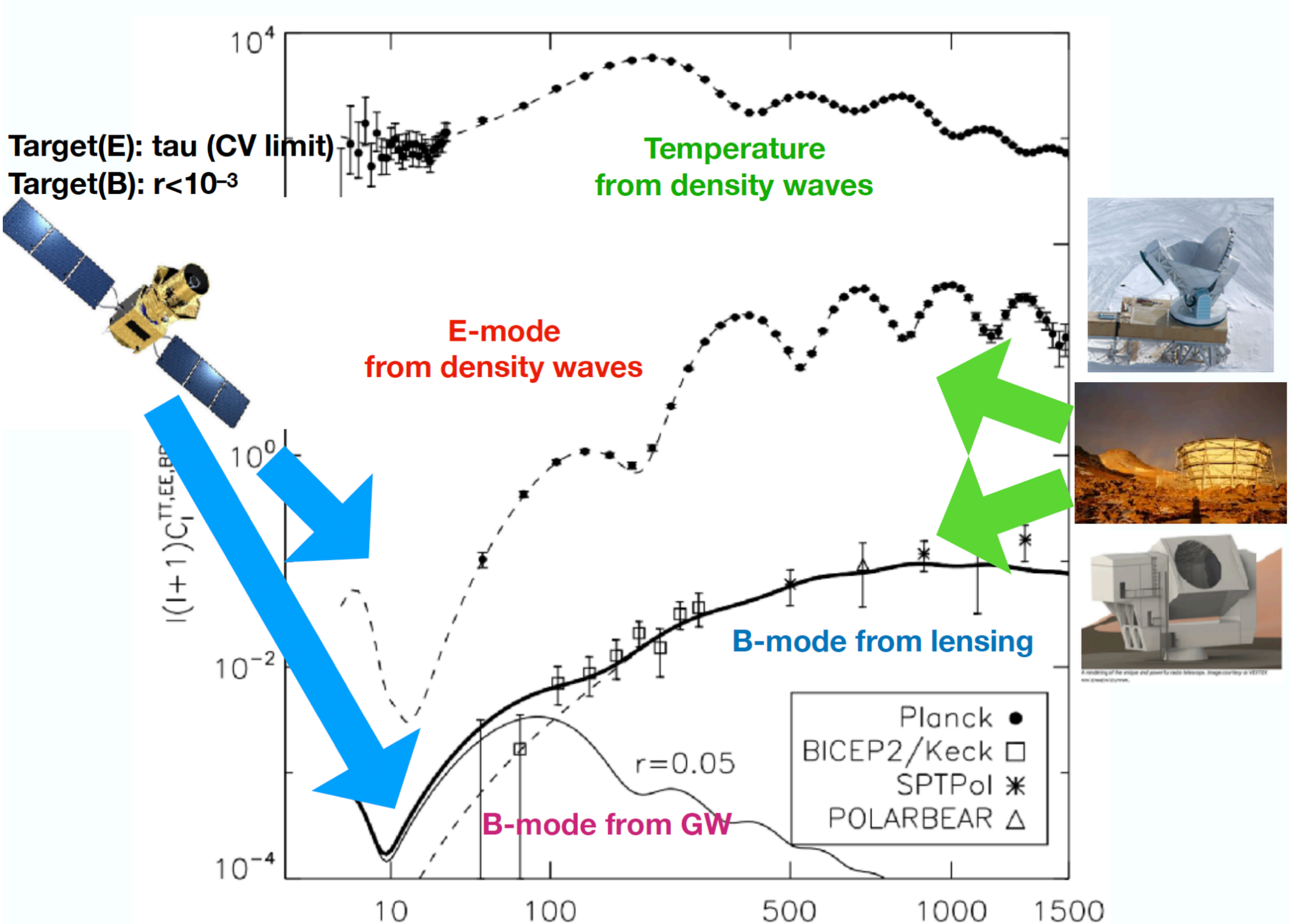


LFT (Low frequency telescope) 34 – 161 GHz : Synchrotron + CMB

HFT (high frequency telescope) 89 – 448 GHz : CMB + Dust

European Contribution

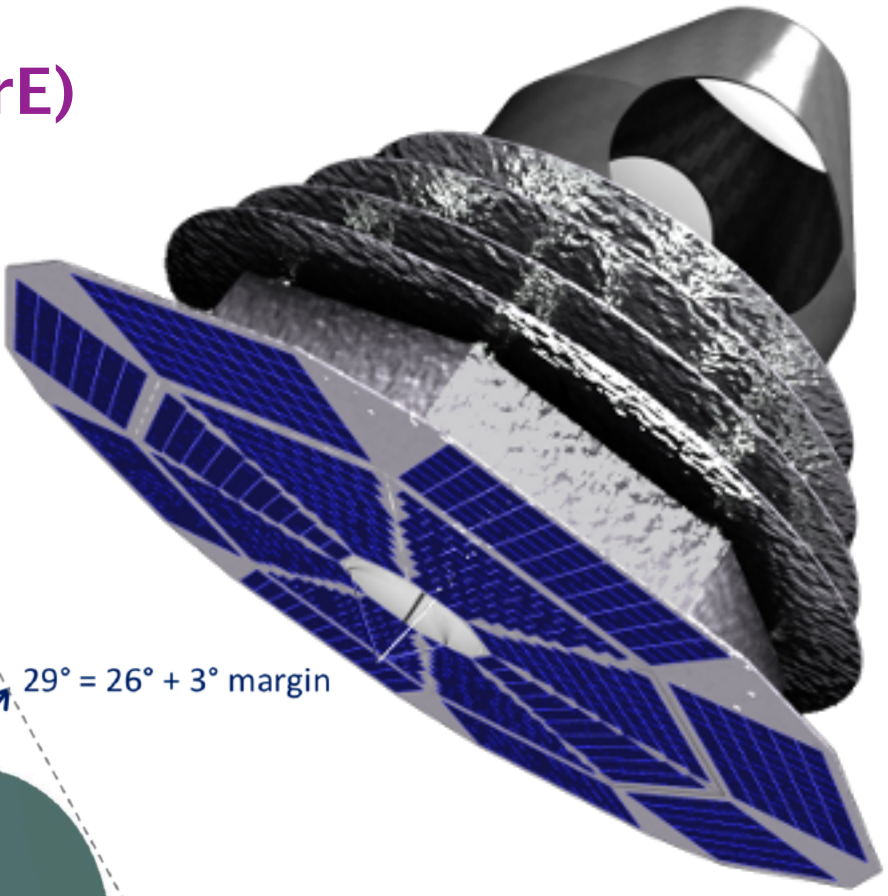




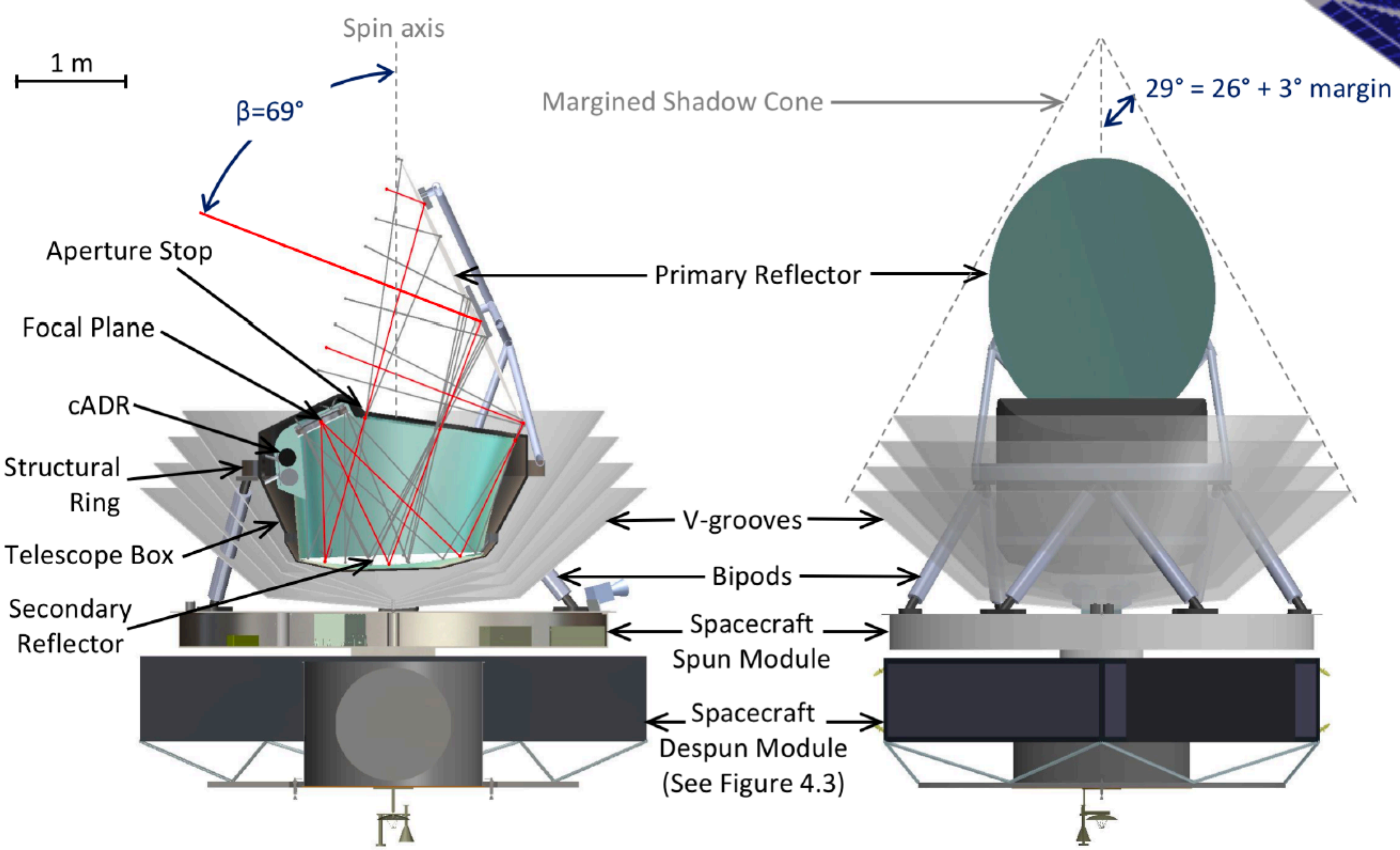
Slide courtesy: E. Komatsu

Future space-missions/concepts

Cosmic Origins Explorer (COrE)



Voyage-2050 Mission Concept

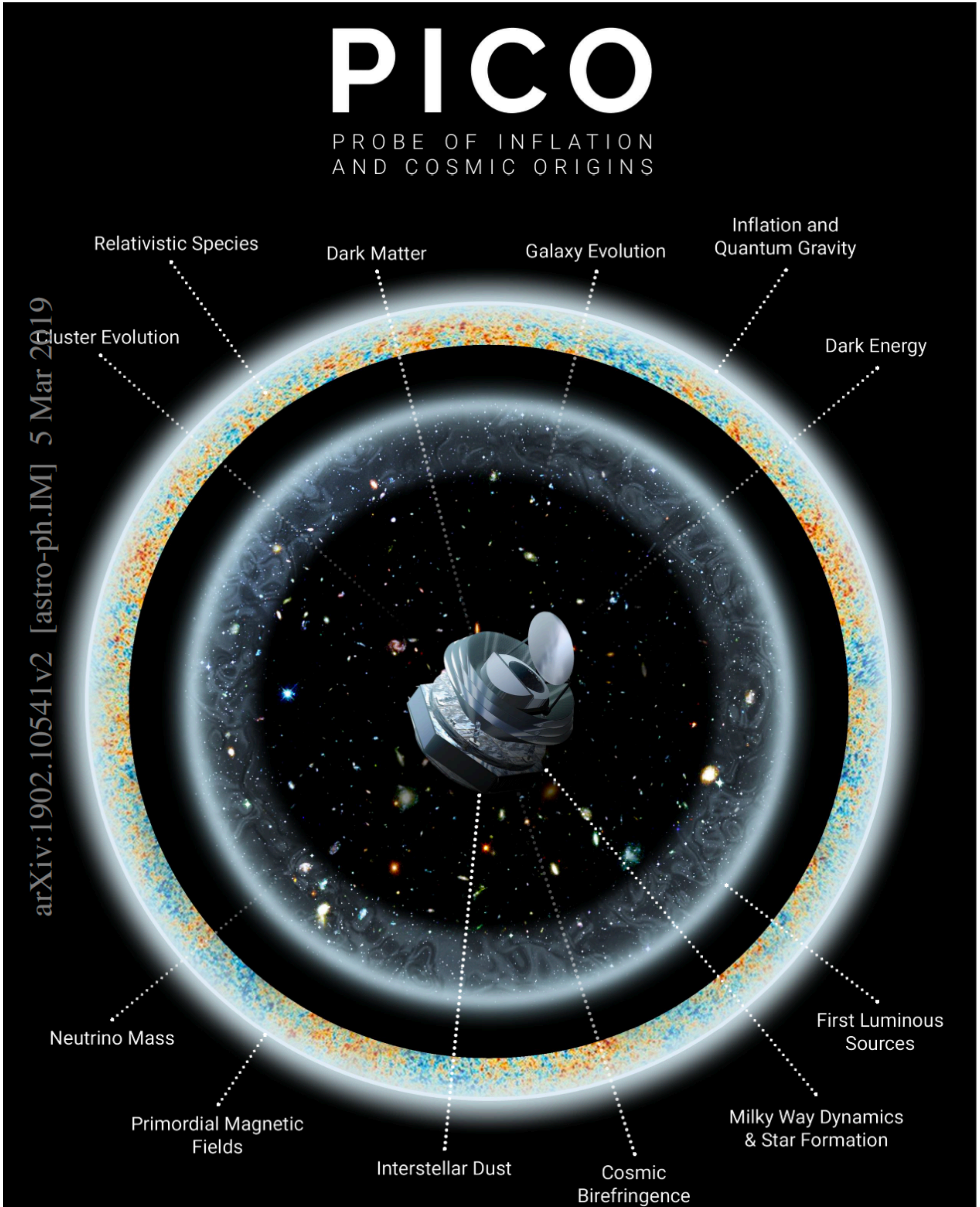


Selection of CMB science for *Voyage 2050*

https://www.esa.int/Science_Exploration/Space_Science/Voyage_2050_sets_sail_ESA_chooses_future_science_mission_themes

- **New Physical Probes of the Early Universe.** How did the Universe begin? How did the first cosmic structures and black holes form and evolve? These are outstanding questions in fundamental physics and astrophysics, and we now have new astronomical messengers that can address them. Our recommendation is for a Large mission deploying gravitational wave detectors or precision microwave spectrometers to explore the early Universe at large redshifts. This theme follows the breakthrough science from *Planck* and the expected scientific return from *LISA*.

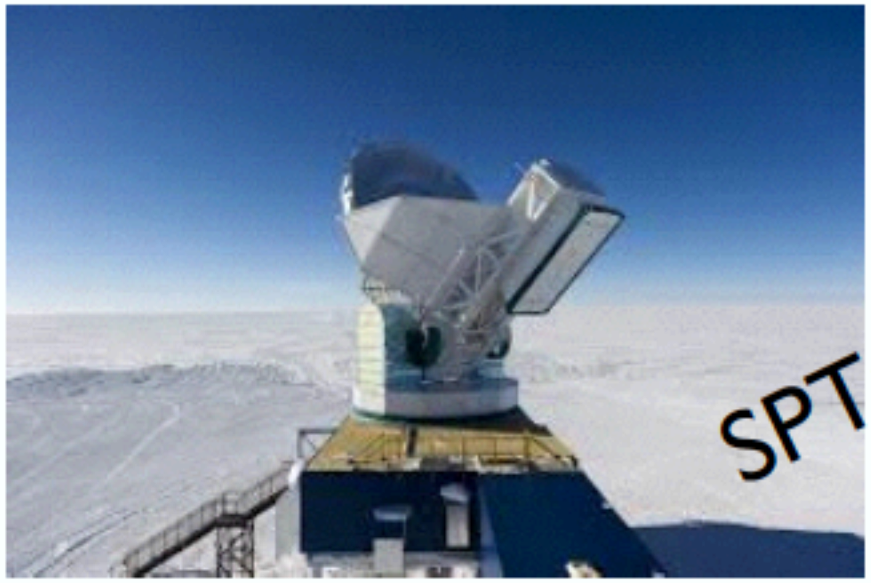
July 2021



Science Goals (from NASA Science Plan)	Science Objectives
Explore how the Universe began: Inflation	**SO1**. Probe the physics of the big bang by detecting the energy scale at which inflation occurred if it is above 5×10^{15} GeV, or place an upper limit if it is below (§ 2.2.1, Fig. 2.1)
	SO2. Probe the physics of the big bang by excluding classes of potentials as the driving force of inflation (§ 2.2.1, Fig. 2.2)
Discover how the Universe works: neutrino mass and $N_{\rm eff}$	**SO3**. Determine the sum of neutrino masses. (§ 2.2.2, Fig. 2.5)
	SO4. Tightly constrain the thermalized fundamental particle content of the early Universe (§ 2.2.2, Fig. 2.4)
Explore how the Universe evolved: reionization	**SO5**. Distinguish between models that describe the formation of the earliest luminous sources in the Universe (§ 2.3, Fig. 2.6)
Explore how the Universe evolved: Galactic structure and dynamics	**SO6**. Test models of the composition of Galactic interstellar dust (§ 2.5.1)
	SO7. Determine if magnetic fields are the dominant cause of low Galactic star-formation efficiency (§ 2.5.2)

Current/recently concluded ground-based experiments

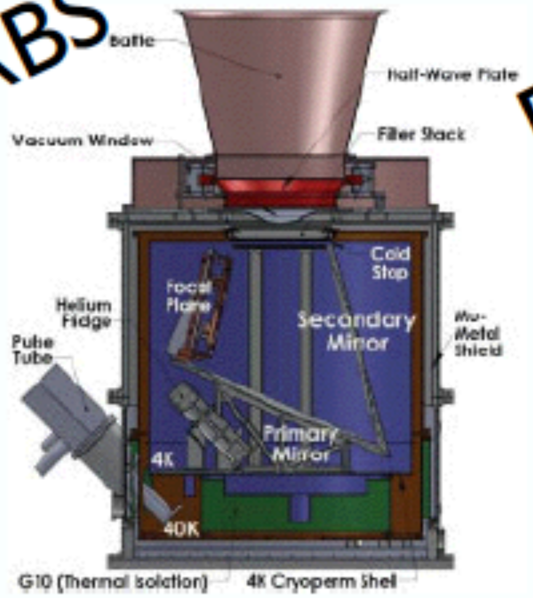
ACTpol



SPTpol

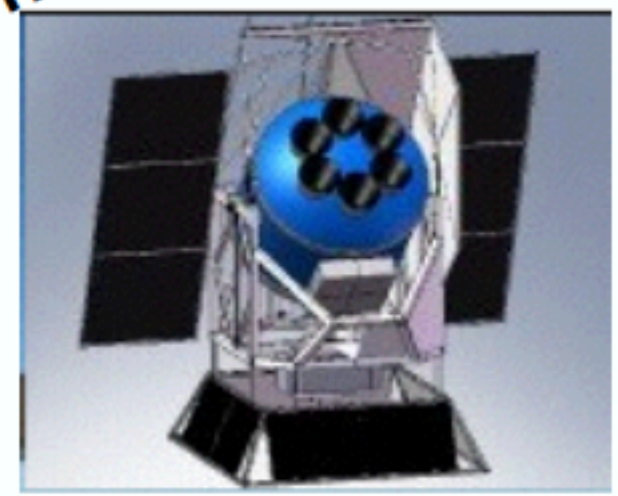
Have broad science range

ABS



Polarbear

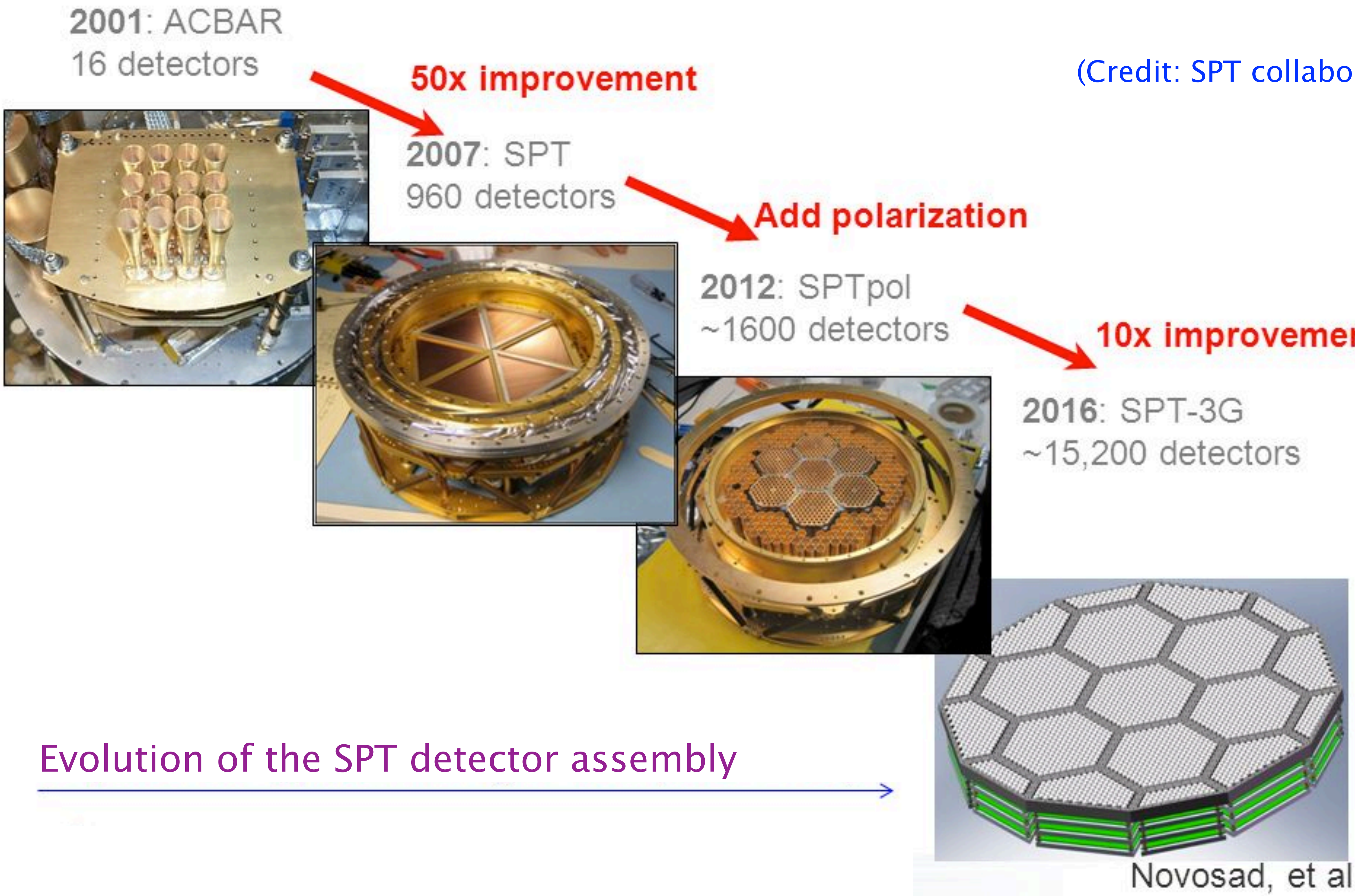
SPIDER



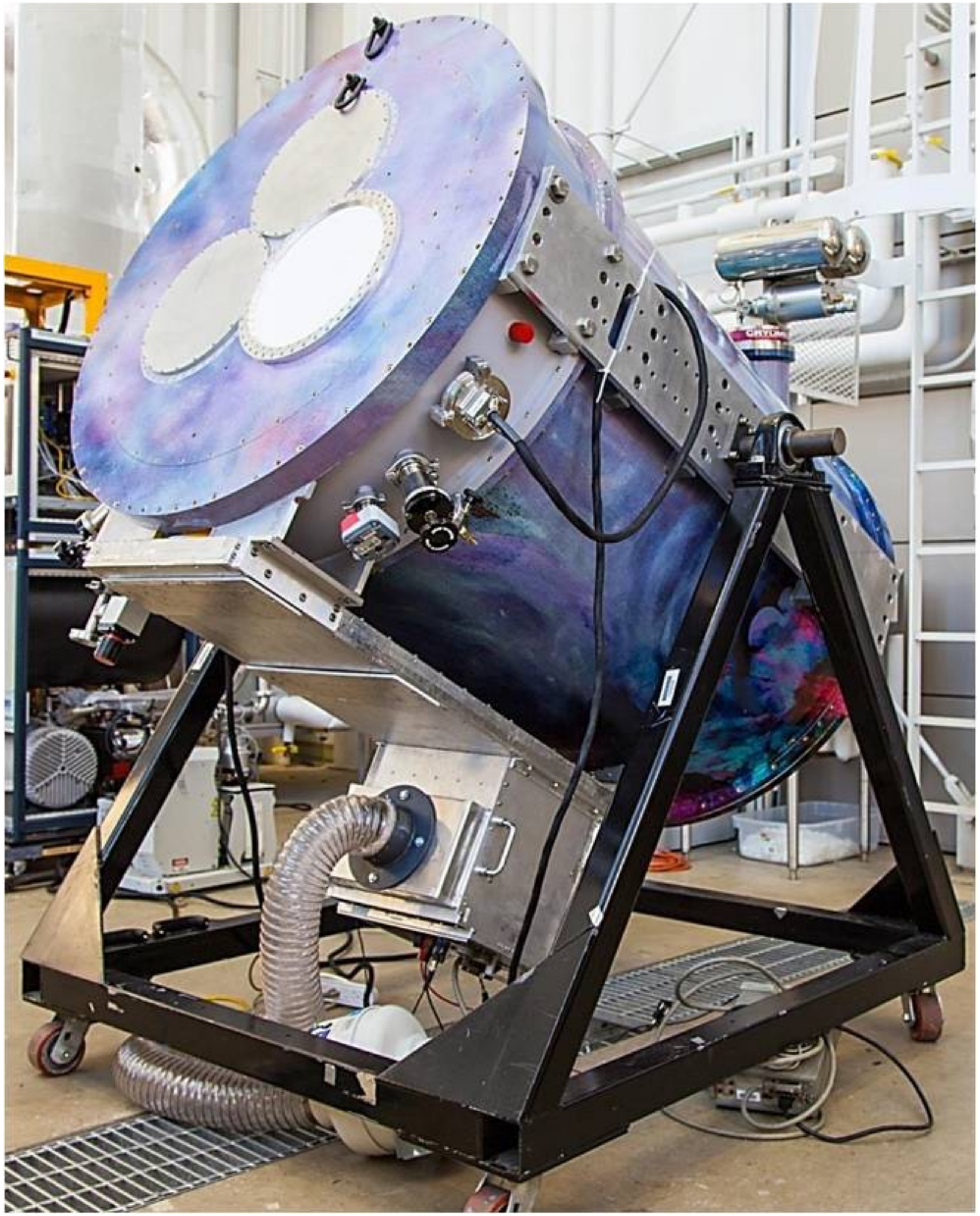
Dedicated to r

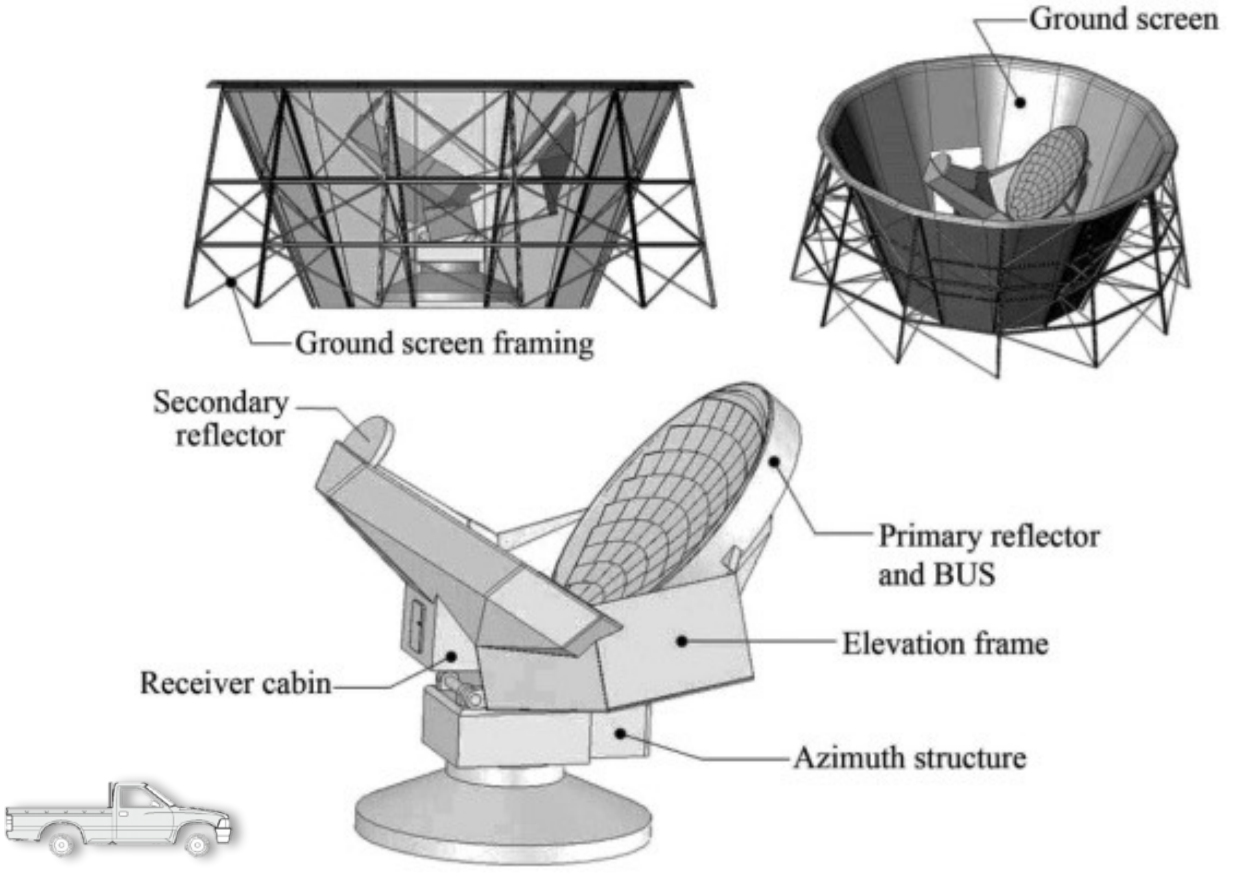
Evolution of CMB detector assembly (bolometer arrays)

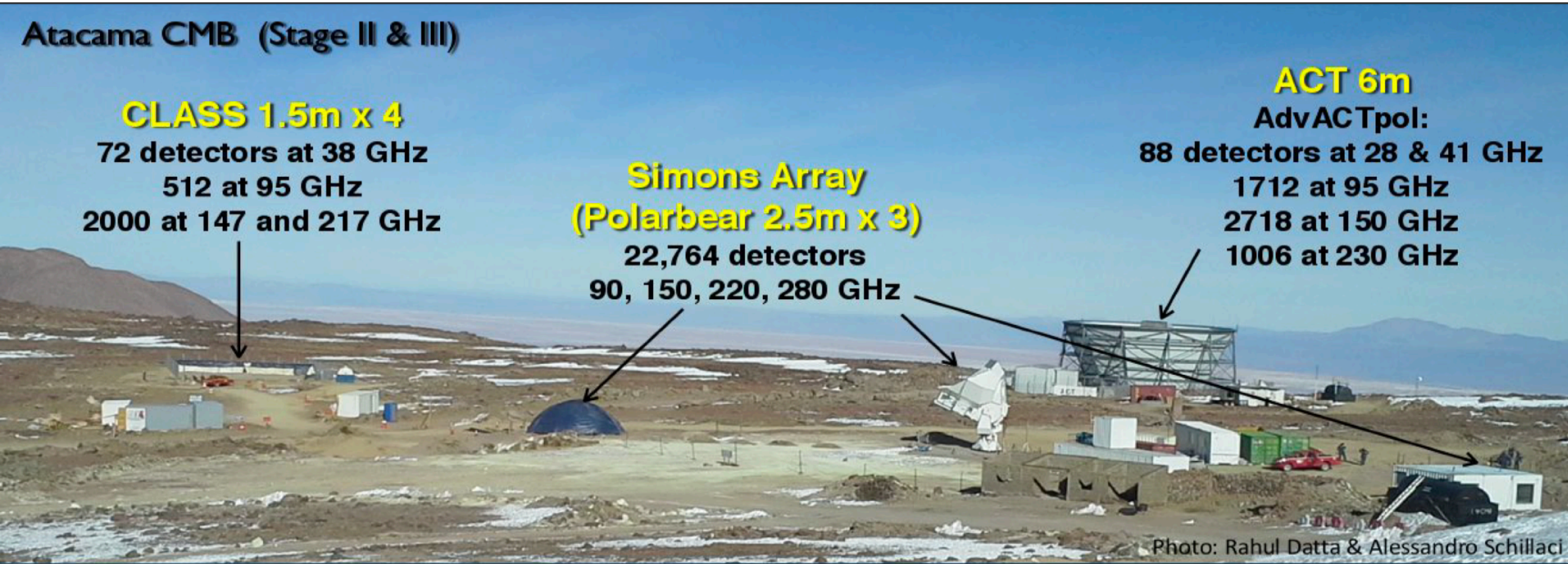
(Credit: SPT collaboration)

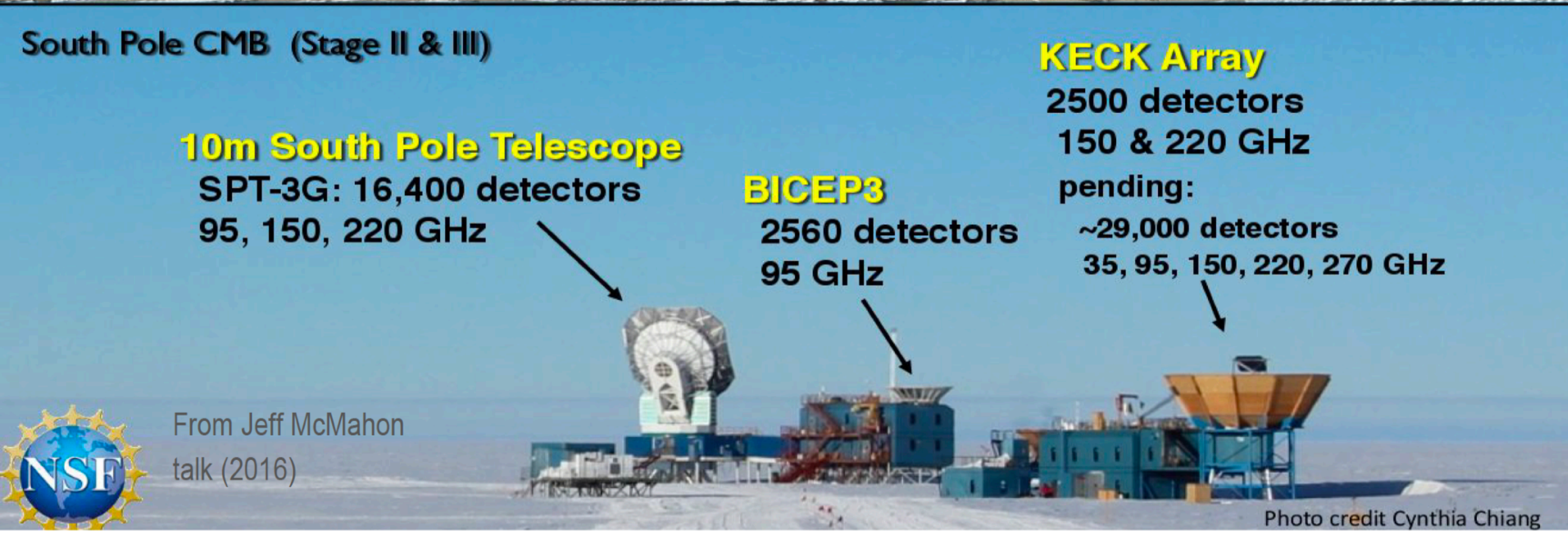


Example of a modern CMB telescope (ACT)






Atacama CMB (Stage II & III)
CLASS 1.5m x 4
72 detectors at 38 GHz
512 at 95 GHz
2000 at 147 and 217 GHz
Simons Array
(Polarbear 2.5m x 3)
22,764 detectors
90, 150, 220, 280 GHz
ACT 6m
AdvACTpol:
88 detectors at 28 & 41 GHz
1712 at 95 GHz
2718 at 150 GHz
1006 at 230 GHz
Photo: Rahul Datta & Alessandro Schillaci


South Pole CMB (Stage II & III)
10m South Pole Telescope
SPT-3G: 16,400 detectors
95, 150, 220 GHz
BICEP3
2560 detectors
95 GHz
KECK Array
2500 detectors
150 & 220 GHz
pending:
~29,000 detectors
35, 95, 150, 220, 270 GHz
From Jeff McMahon
talk (2016)
Photo credit Cynthia Chiang

Upcoming ground-based experiments

Starting in 2023

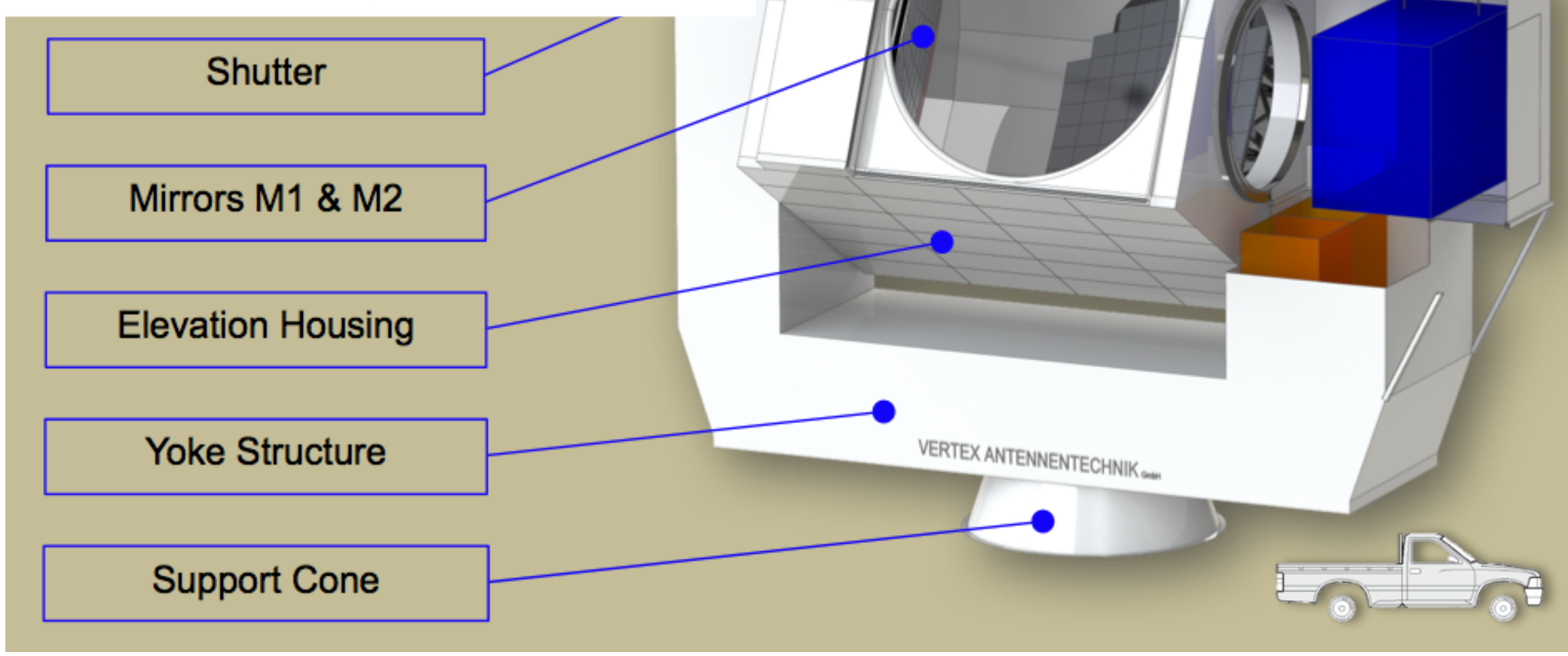
https://www.simonsfoundation.org/series/the-eternal-sky/

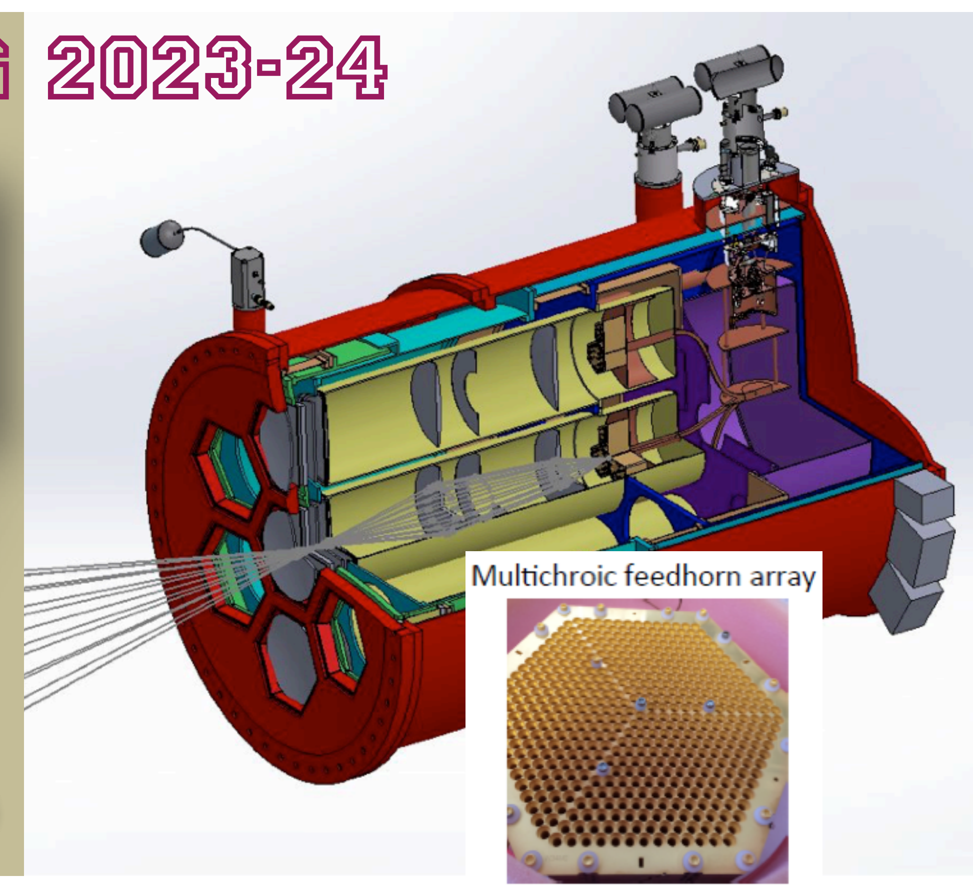
CCAT-prime: A submillimeter CMB experiment with Bonn University as partner

University consortium with strong emphasis on training & development

- **Cornell University, Director 70%**
- **Univ. Cologne & Univ. Bonn 25%**
  - joining: LMU (Mohr), MPA (Komatsu)
- **Canadian University consortium 5%**

STARTING 2023-24





Questions?

Feel free to email me or ask questions in our eCampus Forum