

astro8405

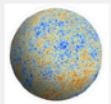
# An Introduction to the Cosmic Microwave Background

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, having you in mind 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 intervening universe (my personal favourite)
- ➡ Give you an idea on CMB data analysis: what are the tools and how different foreground emissions are handled



# Practical matters

## Lecturer:

Kaustuv Basu (AlfA room no. 1.006)  
[kbasu@uni-bonn.de](mailto:kbasu@uni-bonn.de)

## Tutors:

Subarna Chaki [s89schak@uni-bonn.de](mailto:s89schak@uni-bonn.de)  
Lynn Hansen [s88lhans@uni-bonn.de](mailto:s88lhans@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 have a **lecture script**, which is being completed 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, few more coding and plotting, all simple

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

```
def make_CMB_T_map(N,pix_size,ell,DlTT):
    "makes a realization of a simulated CMB sky map given an input DlTT as a function of ell,"
    "the pixel size (pix_size) required and the number N of pixels in the linear dimension."
    #np.random.seed(100)
    # convert Dl to Cl
    ClTT = DlTT * 2 * np.pi / (ell*(ell+1.))
    ClTT[0] = 0. # set the monopole and the dipole of the Cl spectrum to zero
    ClTT[1] = 0.

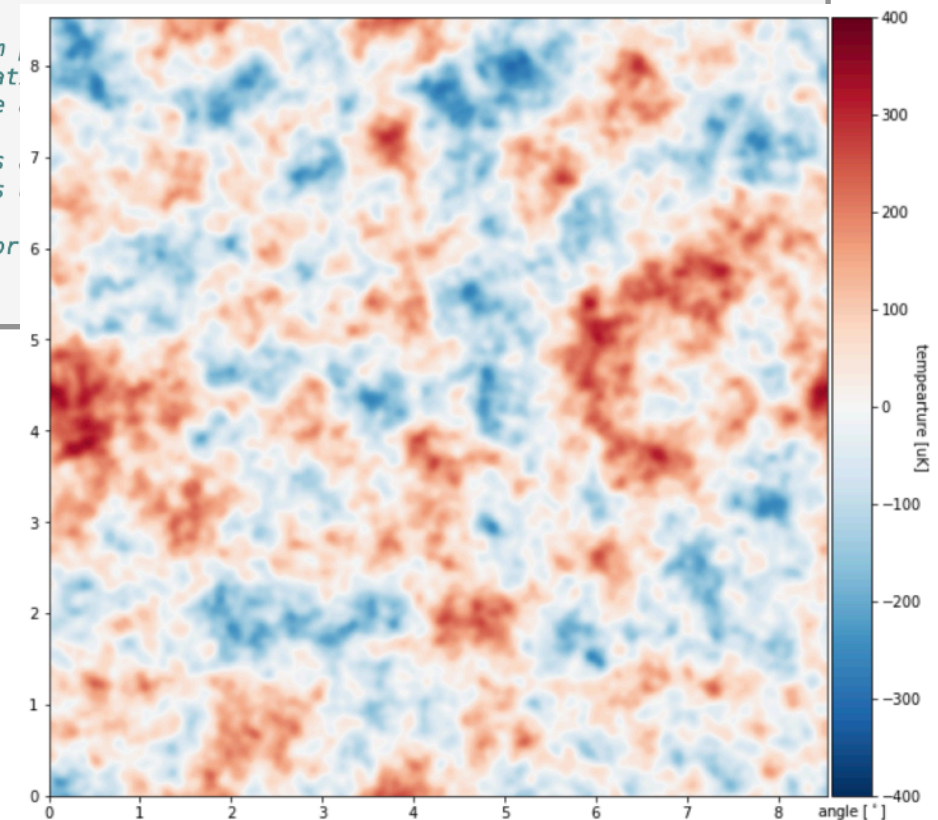
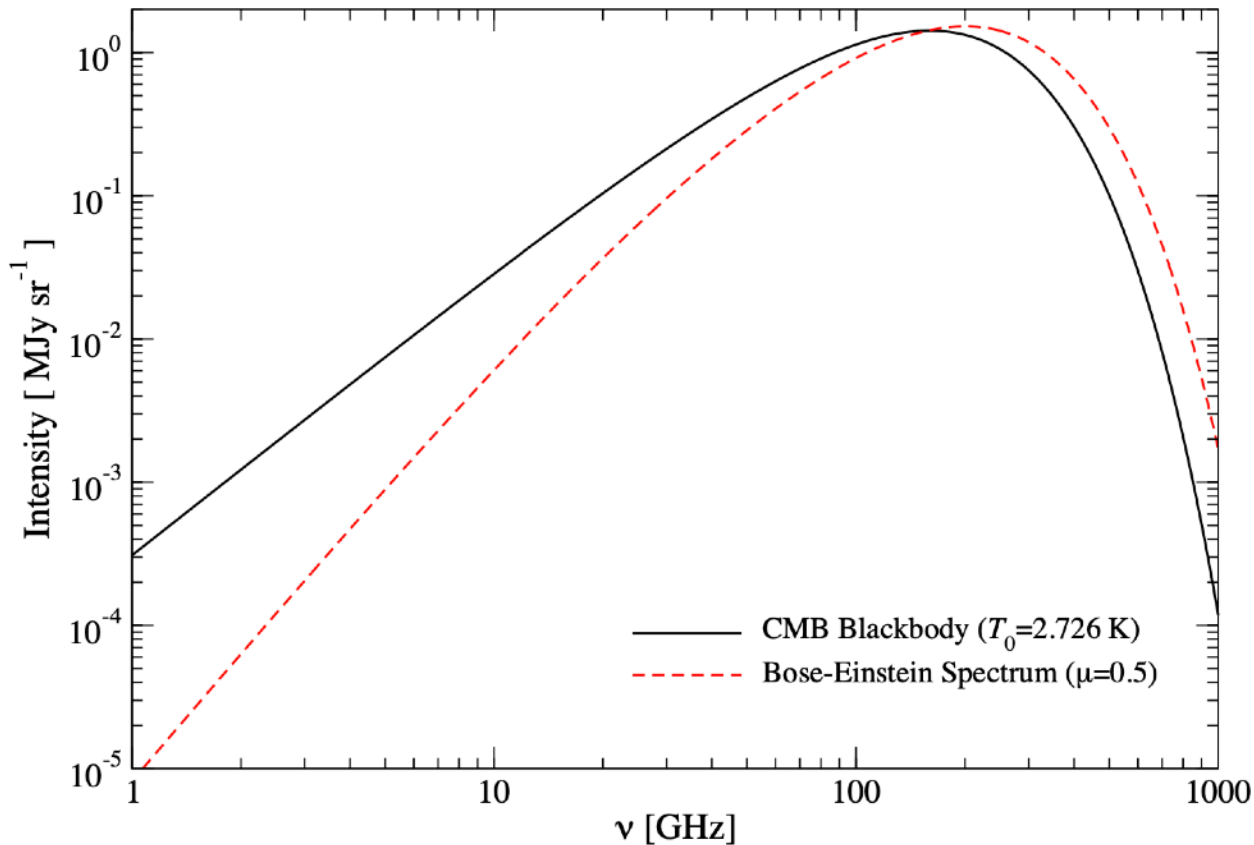
    # make a 2D real space coordinate system
    onesvec = np.ones(N)
    inds = np.linspace(-0.5, +0.5, N)

    # create an array of size N between -0.5 and +0.5
    product matrix: X[i, j] = onesvec[i] * inds[j] for i,j
    is just N rows copies of inds - for the x dimension
    inds)
    use for the y dimension

    r**2.)

    power spectrum
    ze/60. * np.pi/180.) # going from
    . * np.pi /pix_to_rad # now relat
    e_factor # making a fourier space
    eros(int(ell2d.max()+1)
    Cl spectrum (of zeros) that goes
    r.size)) = ClTT # fill in the Cls

    is defined on the multiple vector
    ed[ell2d.astype(int)]
    TT2d))
```



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

# 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  $x = (x, y, z)$

$$ds^2 = \boxed{a^2(t)}(dx^2 + dy^2 + dz^2)$$

“scale factor”

*FRW metric:*  $ds^2 = dt^2 - a^2(t) [d\chi^2 + S_k^2(\chi) d\Omega^2]$

*Hubble parameter and the Friedmann equations:*

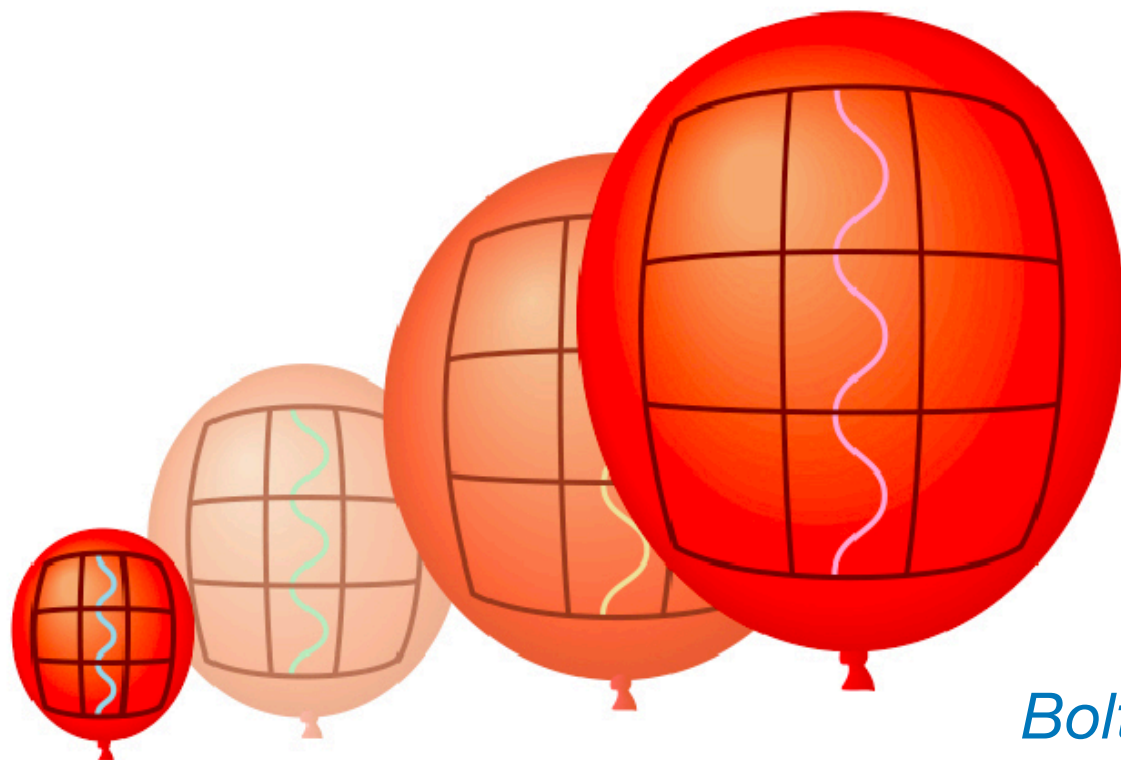
$$H(t) = \dot{a}/a$$

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

*Boltzmann equations for scalar perturbations:*

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

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



Copyright © Addison Wesley



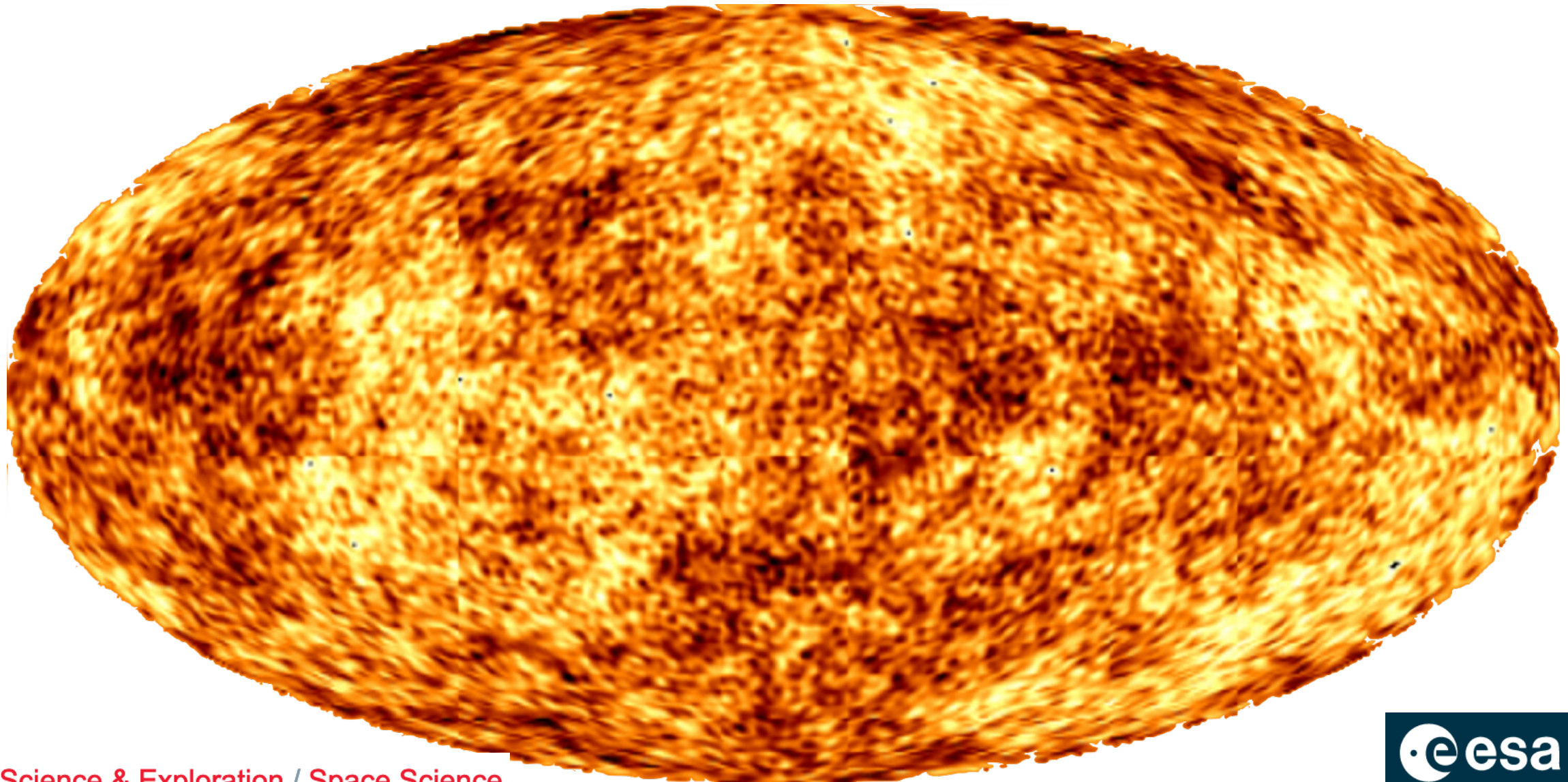
# Please ask questions at any time!



You can also email me or ask questions  
in our [eCampus Forum](#)



# What is the CMB?



ESA / Science & Exploration / Space Science

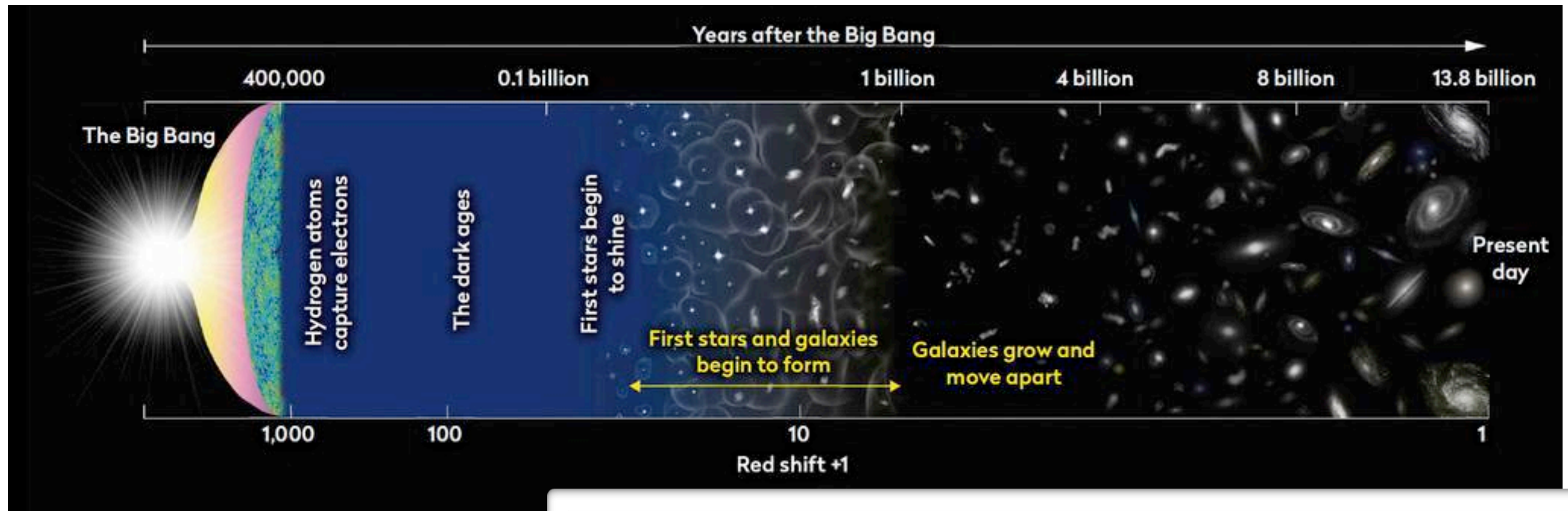


The Cosmic Microwave Background (CMB) is the cooled remnant of the first light that could ever travel freely throughout the Universe.

This 'fossil' radiation, the furthest that any telescope can see, was released soon after the 'Big Bang'.

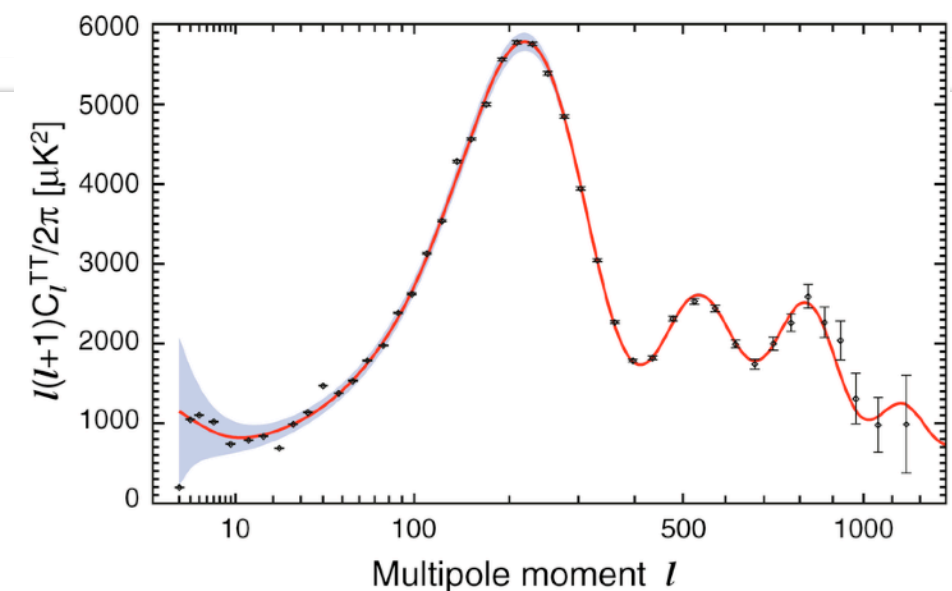


# What is the CMB?



The Cosmic Microwave Background (CMB) is the cooled remnant of the first light that could ever travel freely throughout the Universe.

This 'fossil' radiation, the furthest that any telescope can see, was released soon after the 'Big Bang'.





# Where is the CMB?

Night Sky in Optical ( $\sim 0.5\mu\text{m}$ )



courtesy University of Arizona

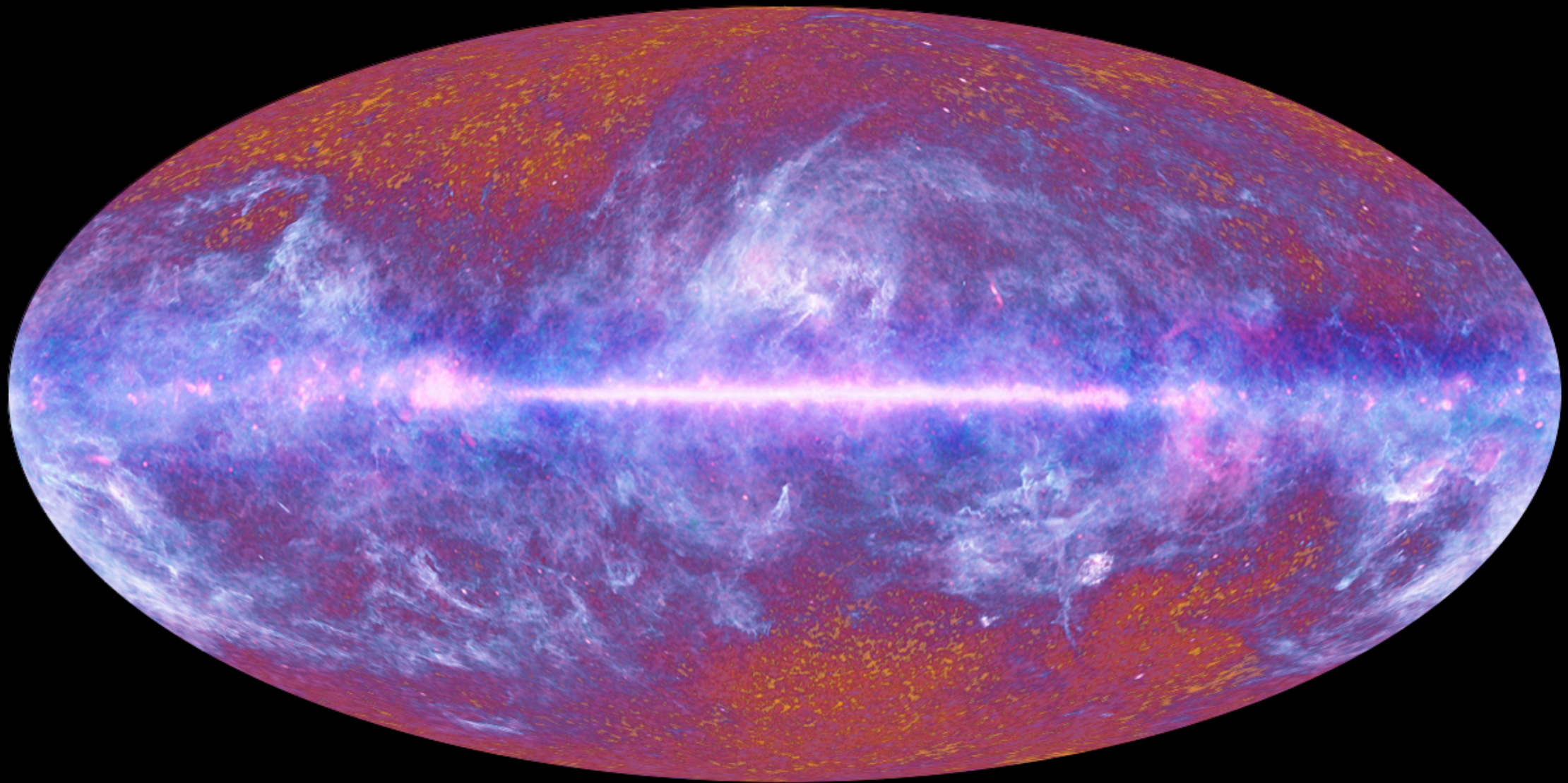


# Where is the CMB?

Night Sky in Microwave ( $\sim 1\text{mm}$ )

A large, solid orange circle is centered on a black background. The circle represents the Cosmic Microwave Background (CMB) as seen in the microwave spectrum. The text "Night Sky in Microwave (~1mm)" is written in white across the top of the circle.

# Where is the CMB?



The Planck one-year all-sky survey



[c] ESA, HFI and LFI consortia, July 2010



# 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<sup>3</sup>

~0.3 eV/cm<sup>3</sup>

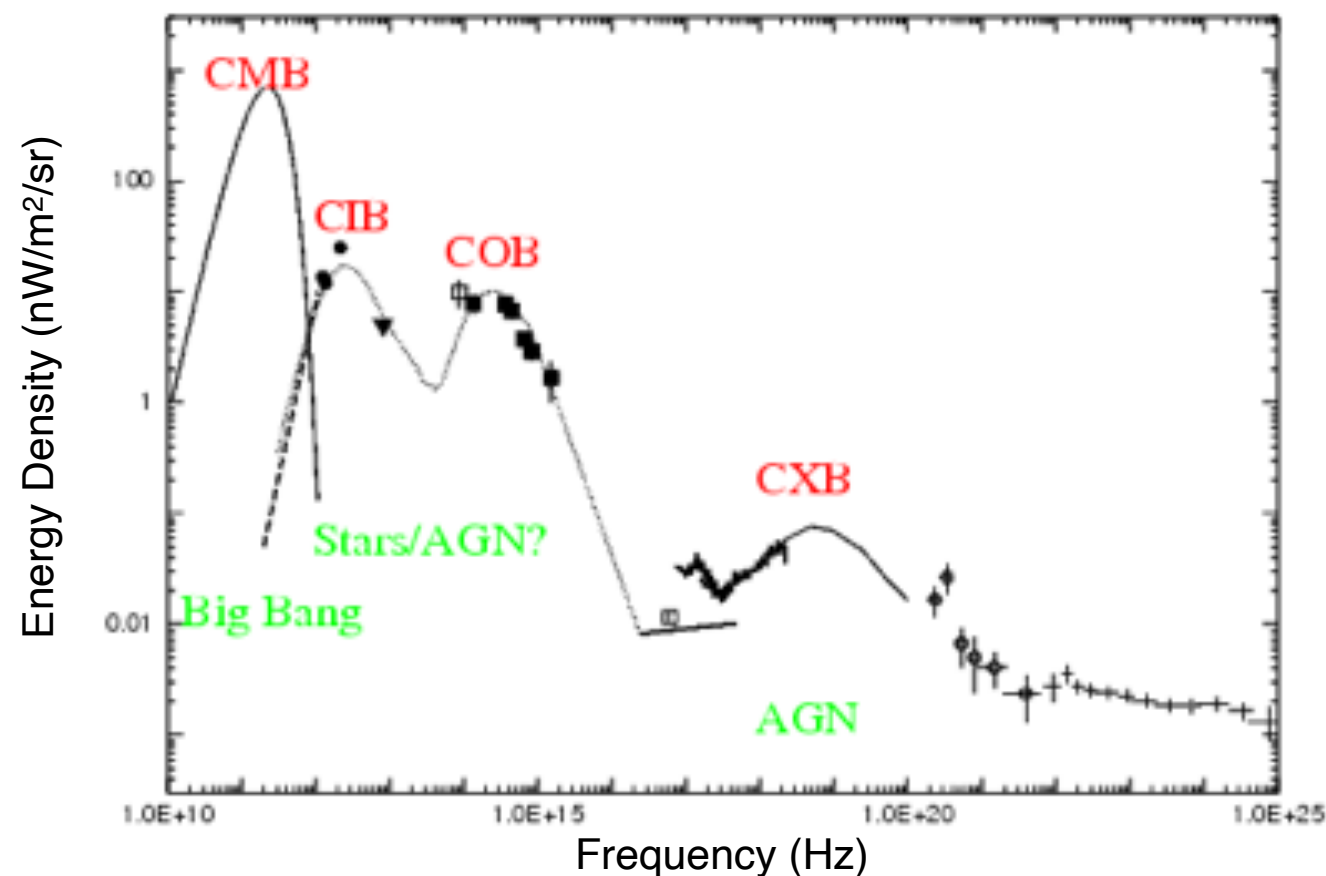
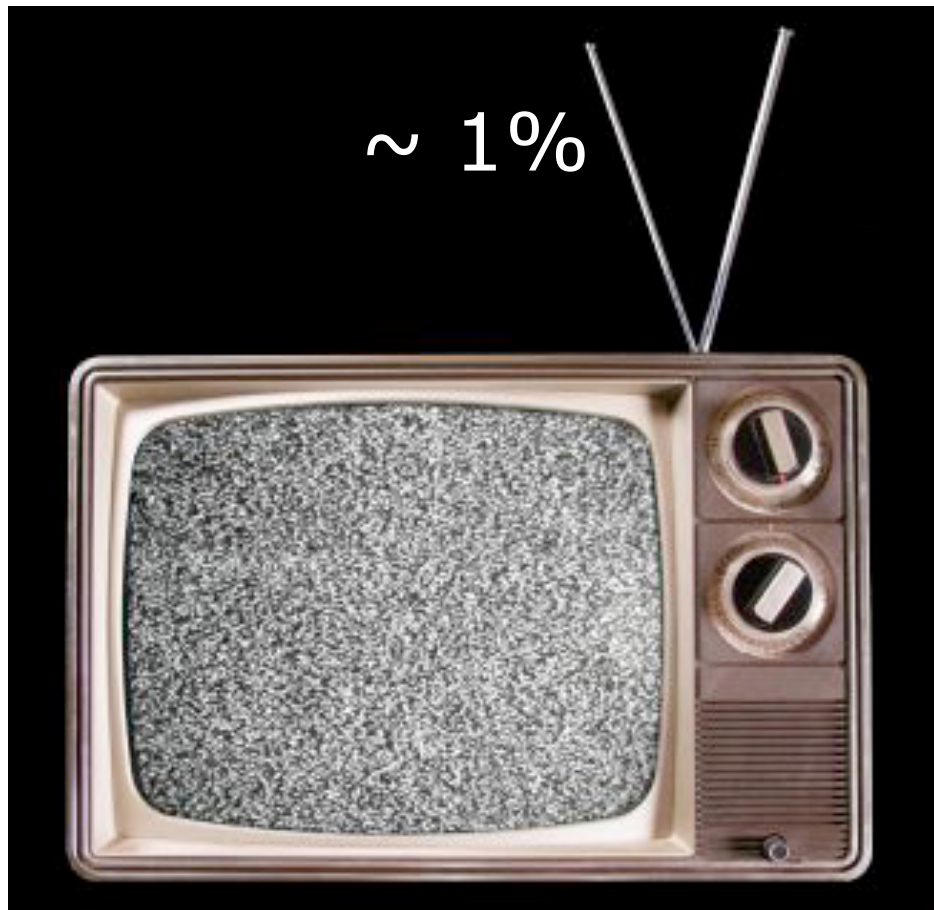


Table 10.3: *Energy densities in the ISM<sup>a</sup>*

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

(From Bradt, *Astrophysical Processes*, CUP)

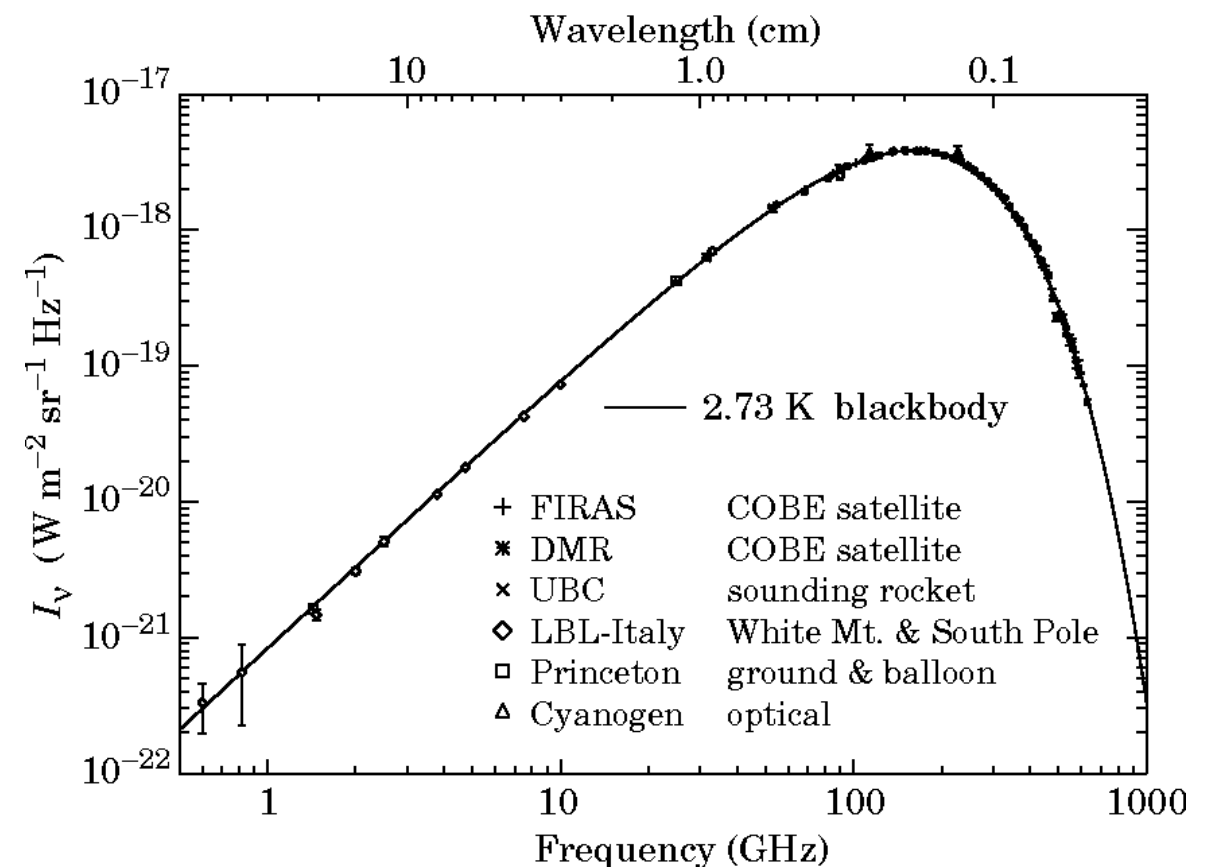
# Where is the CMB?



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

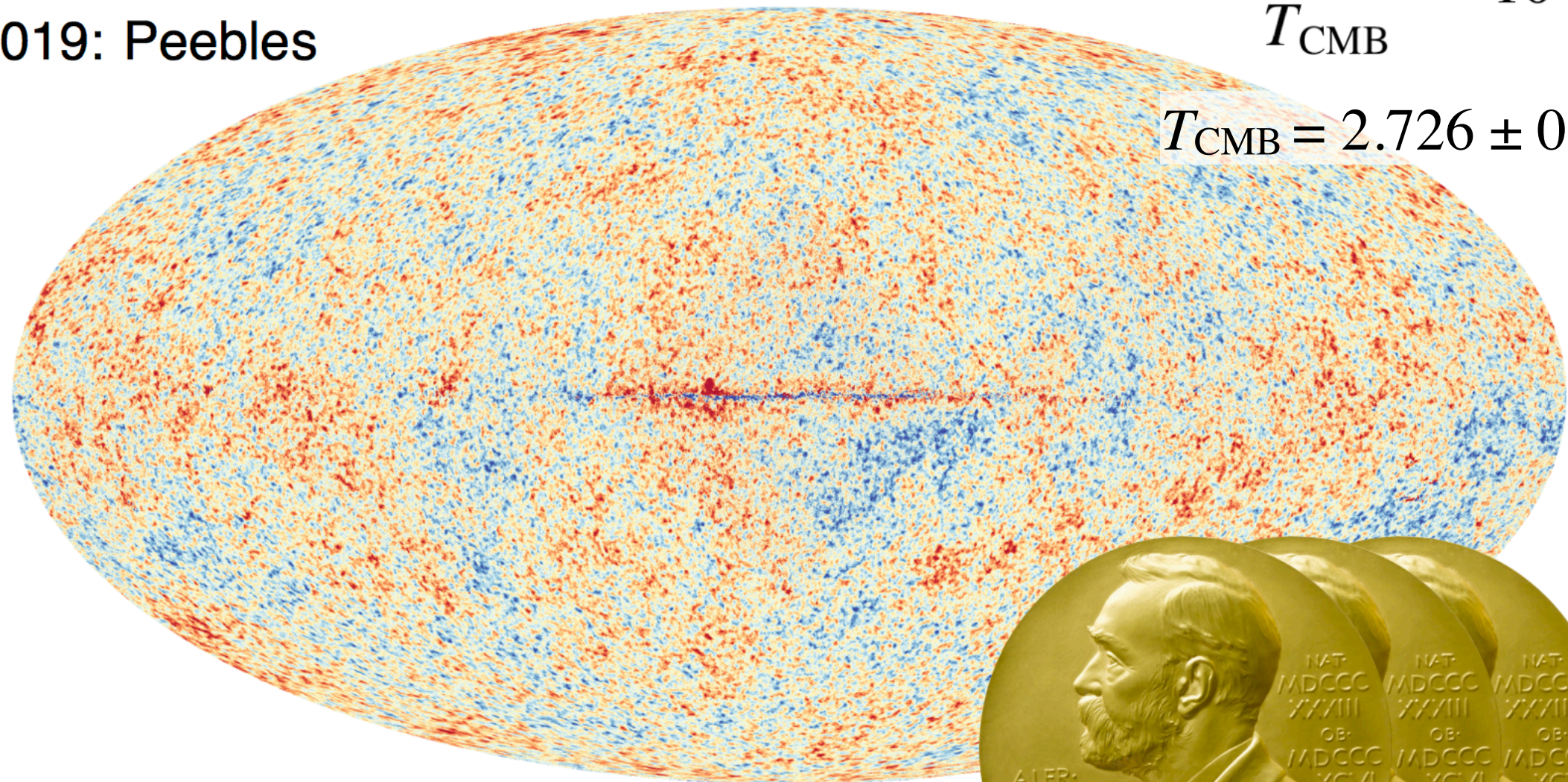
1978: Penzias & Wilson

2006: Mather & Smoot

2019: Peebles

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

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

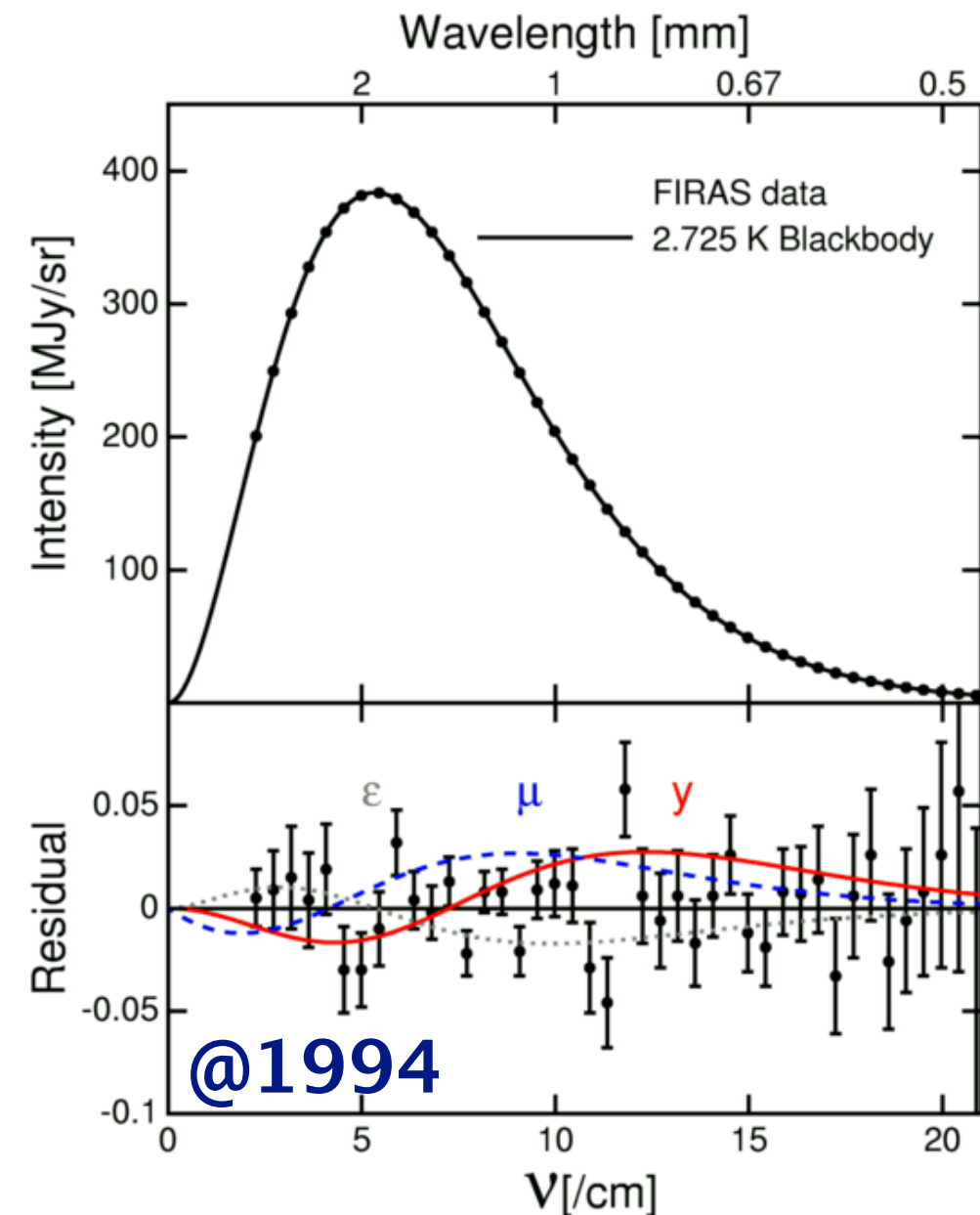


CMB temperature anisotropy map based on *Planck* data

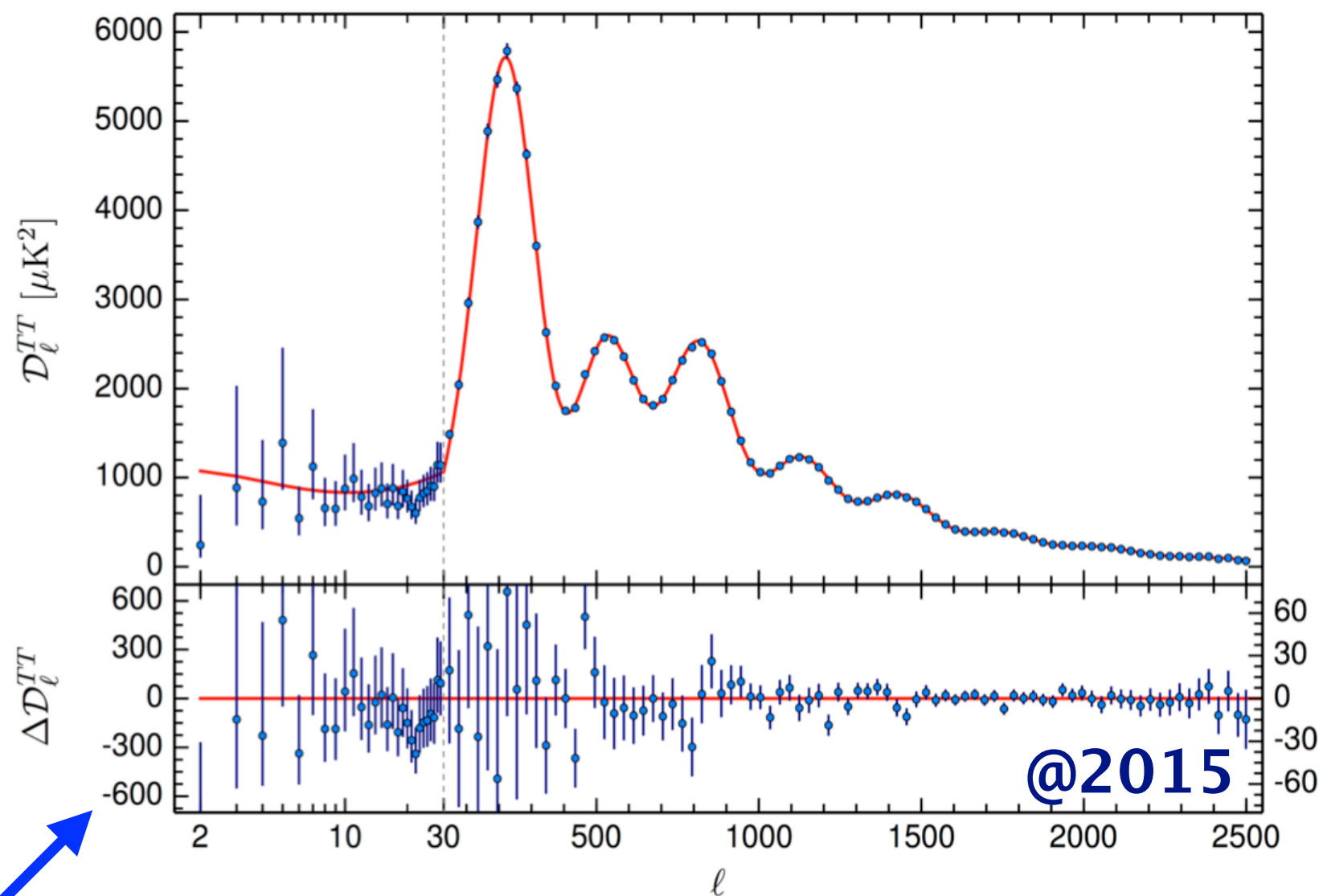


# Is CMB science dead? *Absolutely not!*

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



@1994



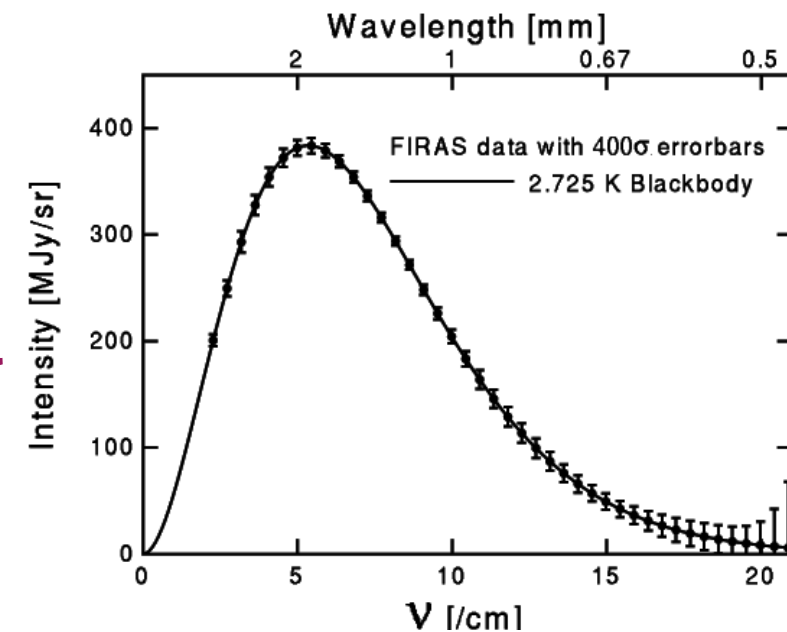
@2015

**6-parameter  $\Lambda$ CDM cosmology is excellent fit to data**

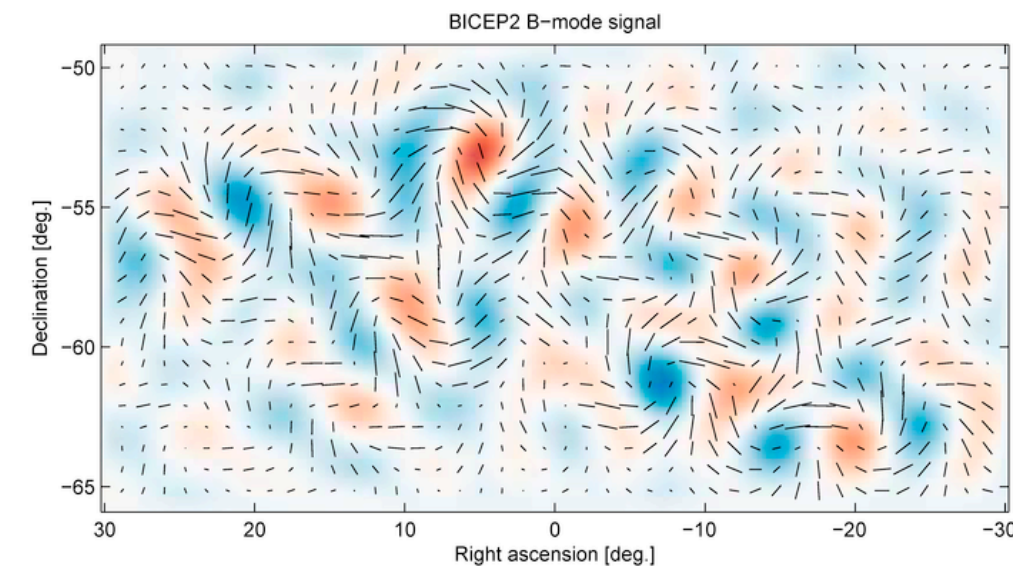


# Frontiers of CMB research today

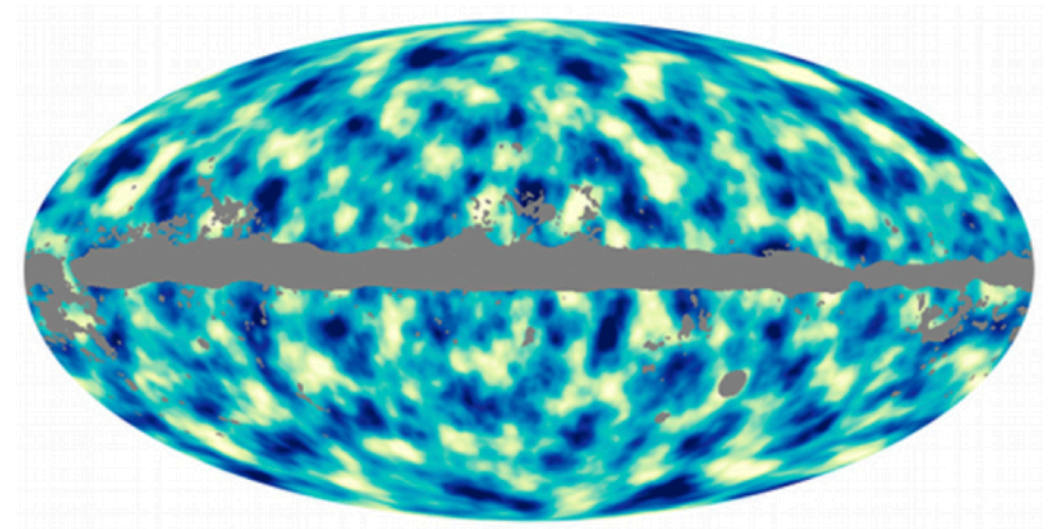
1. The thermal (blackbody) spectrum and its distortions as a cosmological probe



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



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



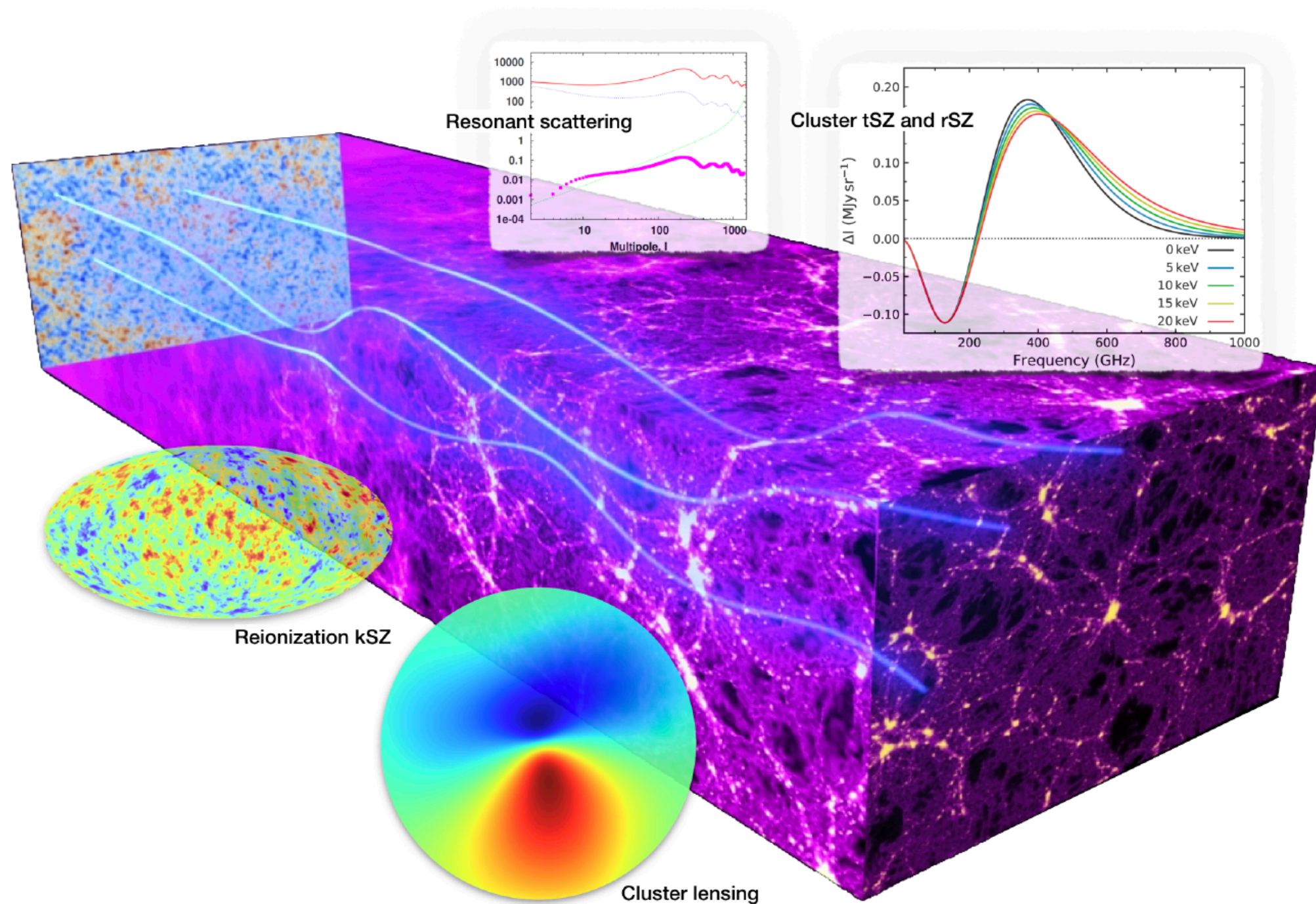
# $\Lambda$ CDM. Want more?

- Thanks to the CMB and other observations (large-scale structure of the Universe, supernovae, ...), We now have the standard model of cosmology ( $\Lambda$ CDM), 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  $\Lambda$ CDM really right?** We don't understand the physical nature of  $\Lambda$  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  $\Lambda$ CDM? Etc, etc...



# Use the CMB as a cosmic backlight



ESA Voyage 2050 Science White Paper

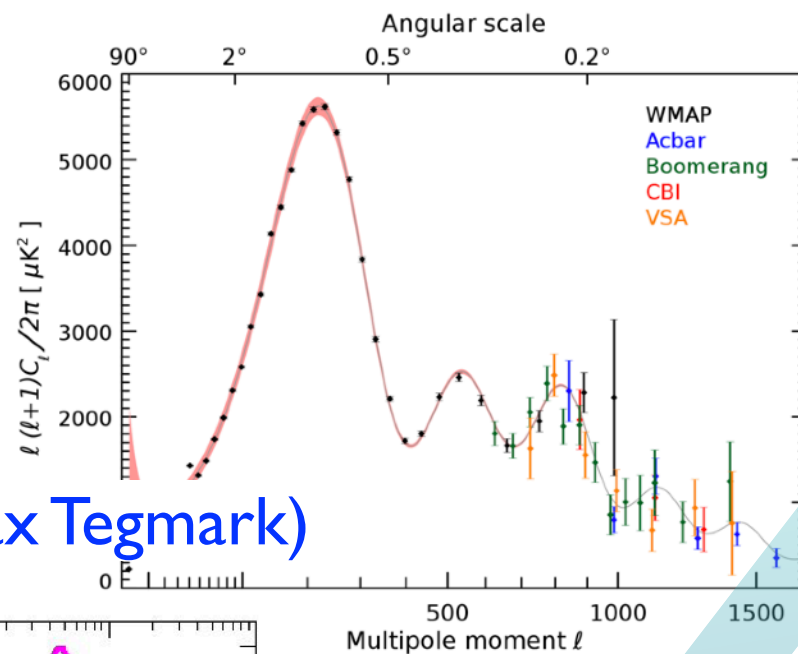
<https://arxiv.org/abs/1909.01592>

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

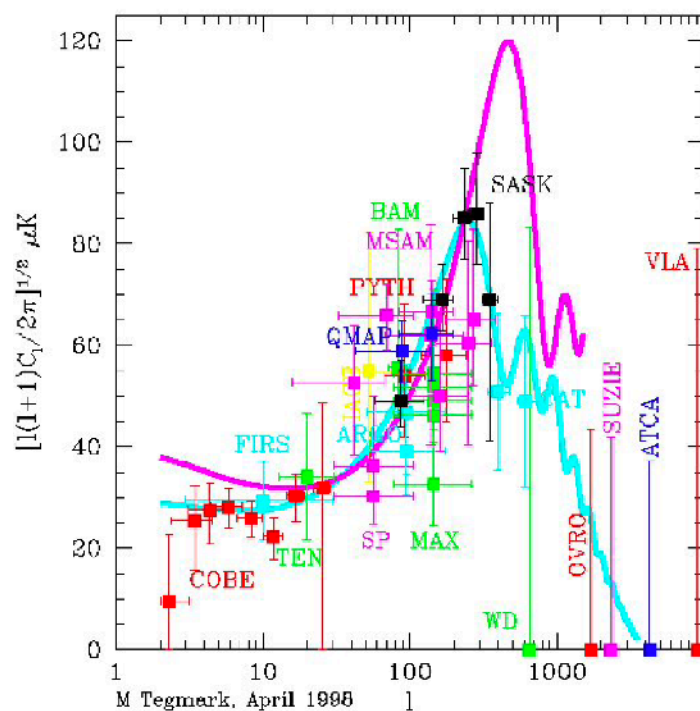
# Two decades of CMB measurements

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

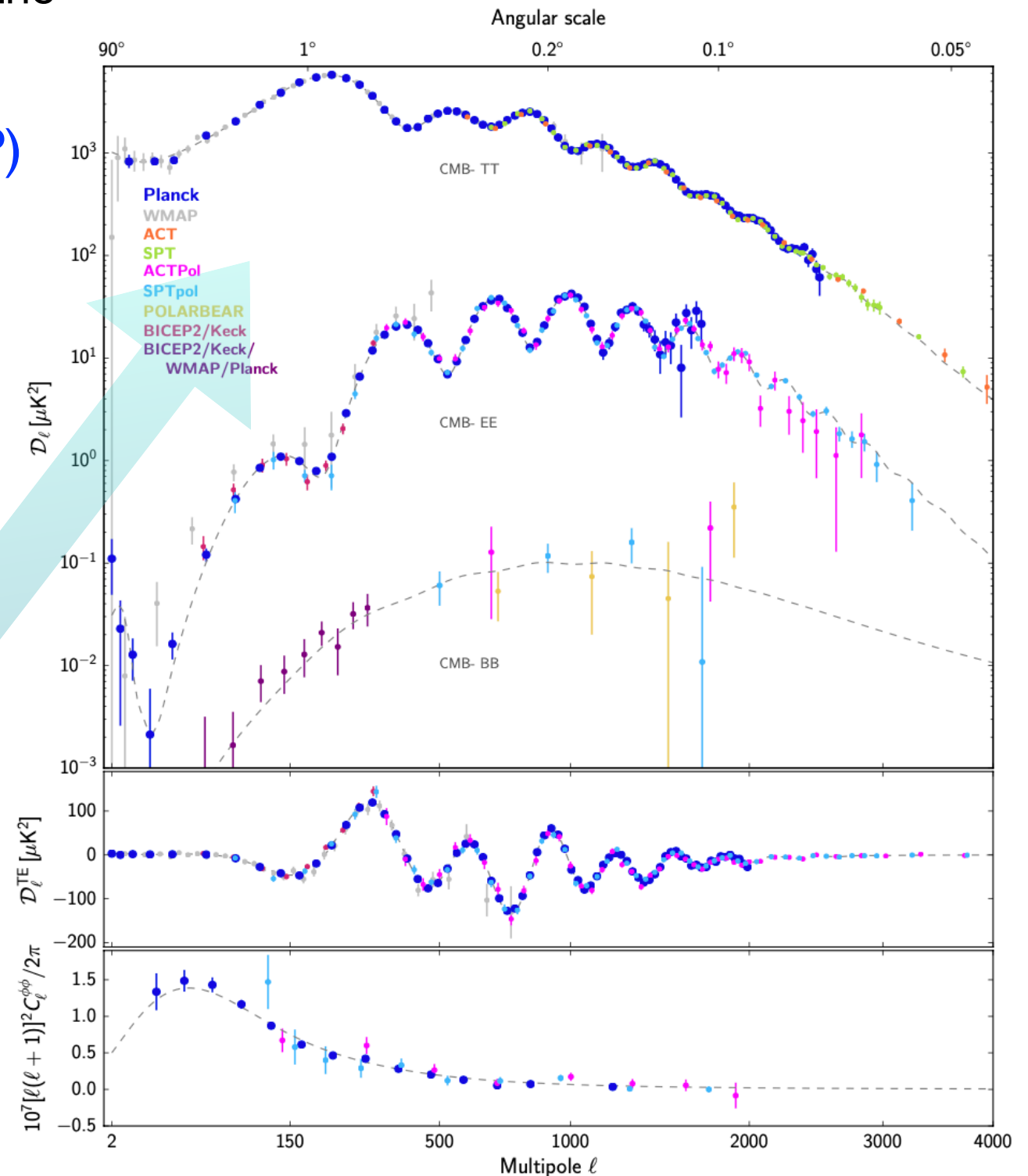
2006: Hinshaw et al. (WMAP)



1998 (credit: Max Tegmark)

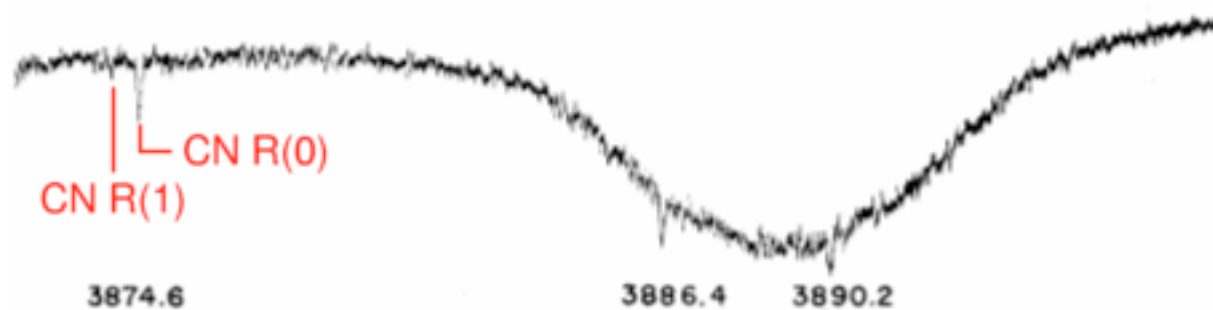


2018: Planck Legacy Results

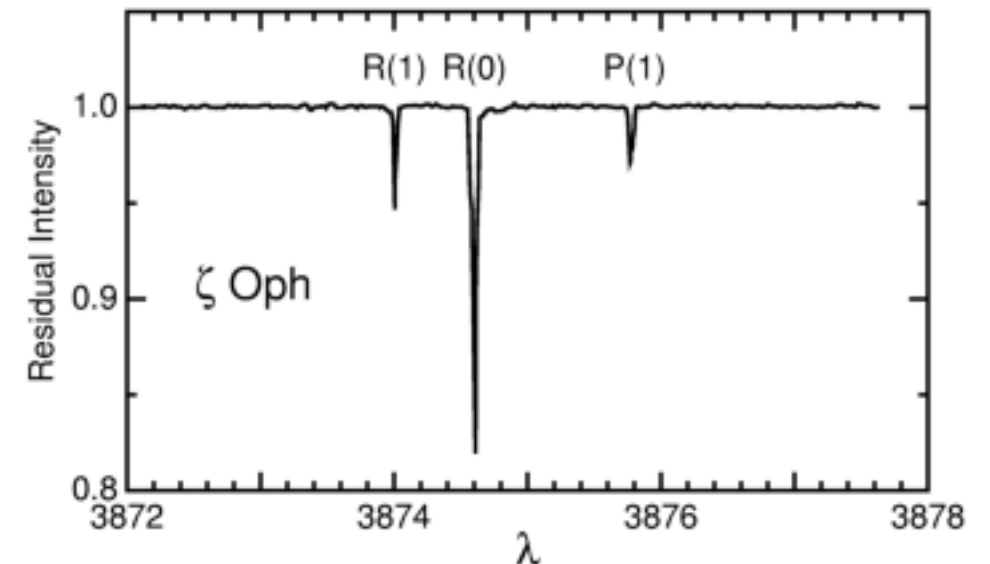




# Discovery of the CMB



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

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PUBLICATIONS  
OF THE  
**Dominion Astrophysical Observatory**  
VICTORIA, B.C.

Volume VII, No. 15

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

BY ANDREW McKELLAR

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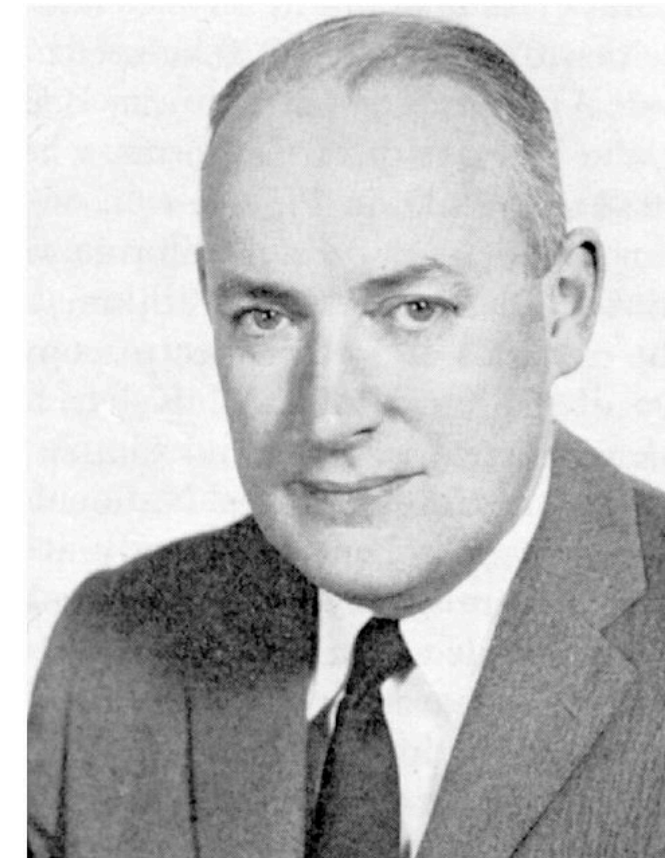
**ABSTRACT.**—Attention is directed to the recent spectrographic observations of W. S. Adams by which he detected in the spectrum of the early class B star,  $\zeta$  *Ophiuchi*, several sharp lines from the lowest states of the CH and CN molecules. The detection of these lines of apparent interstellar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



McKellar 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

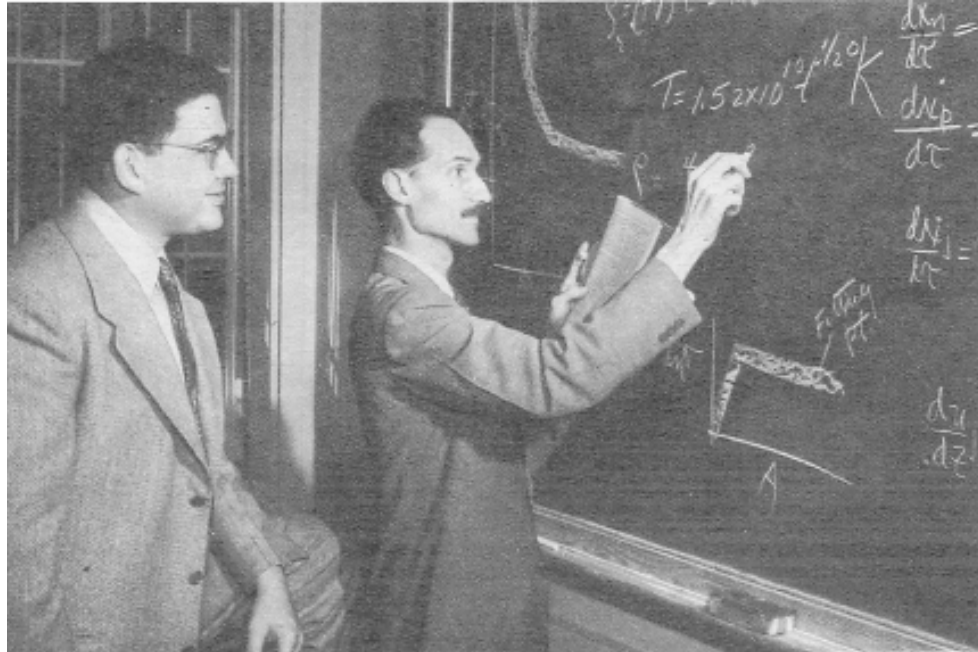
- Alpher, Bethe & Gamow, in their 1948 paper, first proposed the very hot and dense early phase of the Universe (later termed derisively as “Big Bang” by Fred Hoyle). They mistakenly concluded that all elements were produced in this hot early phase.

*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 “ $\alpha$ - $\beta$ - $\gamma$  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).

- Tigran Shmaonov (1957) reports a uniform noise temperature of  $4 \pm 3$  K at  $\lambda = 3.2$  cm in his PhD thesis.

- 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.

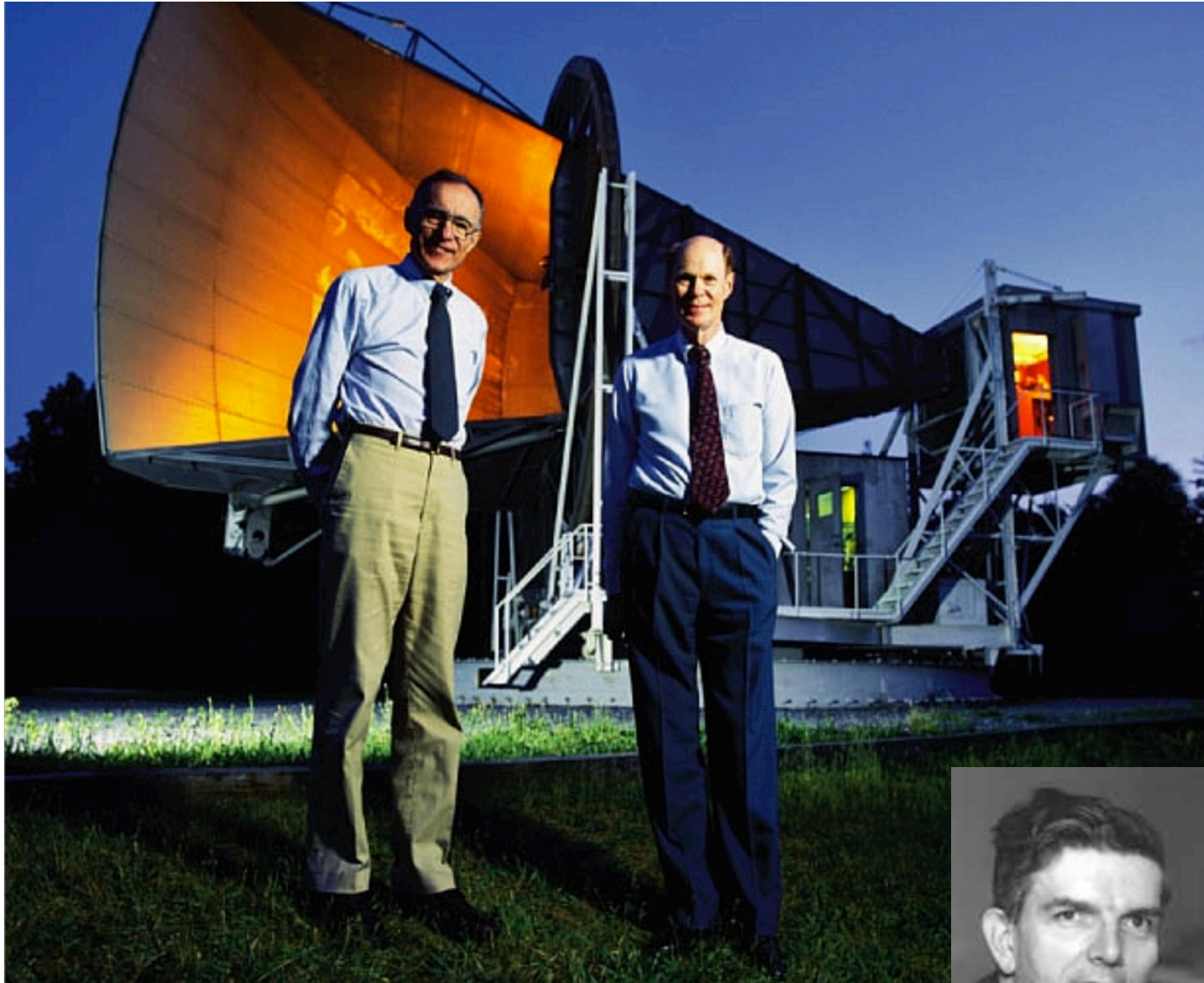


Fred Hoyle

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  $\lambda=7.3$  cm (1964–65)

- Found a direction-independent noise ( $3.5 \pm 1.0$  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**

🏆 1/2 of the prize

USSR

Academy of Sciences  
Moscow, USSR

b. 1894  
d. 1984



**Arno Allan Penzias**

🏆 1/4 of the prize

USA

Bell Laboratories  
Holmdel, NJ, USA

b. 1933  
(in Munich, Germany)



**Robert Woodrow Wilson**

🏆 1/4 of the prize

USA

Bell Laboratories  
Holmdel, NJ, USA

b. 1936

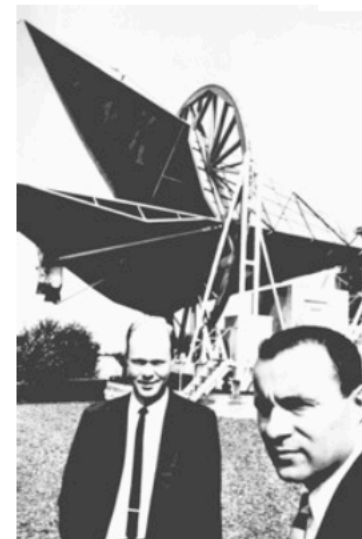
# Arno Penzias & Robert Wilson, 1965

## 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.

May 13, 1965

BELL TELEPHONE LABORATORIES, INC  
CRAWFORD HILL, HOLMDEL, NEW JERSEY



A. A. PENZIAS  
R. W. WILSON

10



1:25 model of the antenna at Bell Lab  
The 3rd floor of Deutsches Museum  
(in Munich)





# The real detector system used by Penzias & Wilson

## The 3rd floor of Deutsches Museum



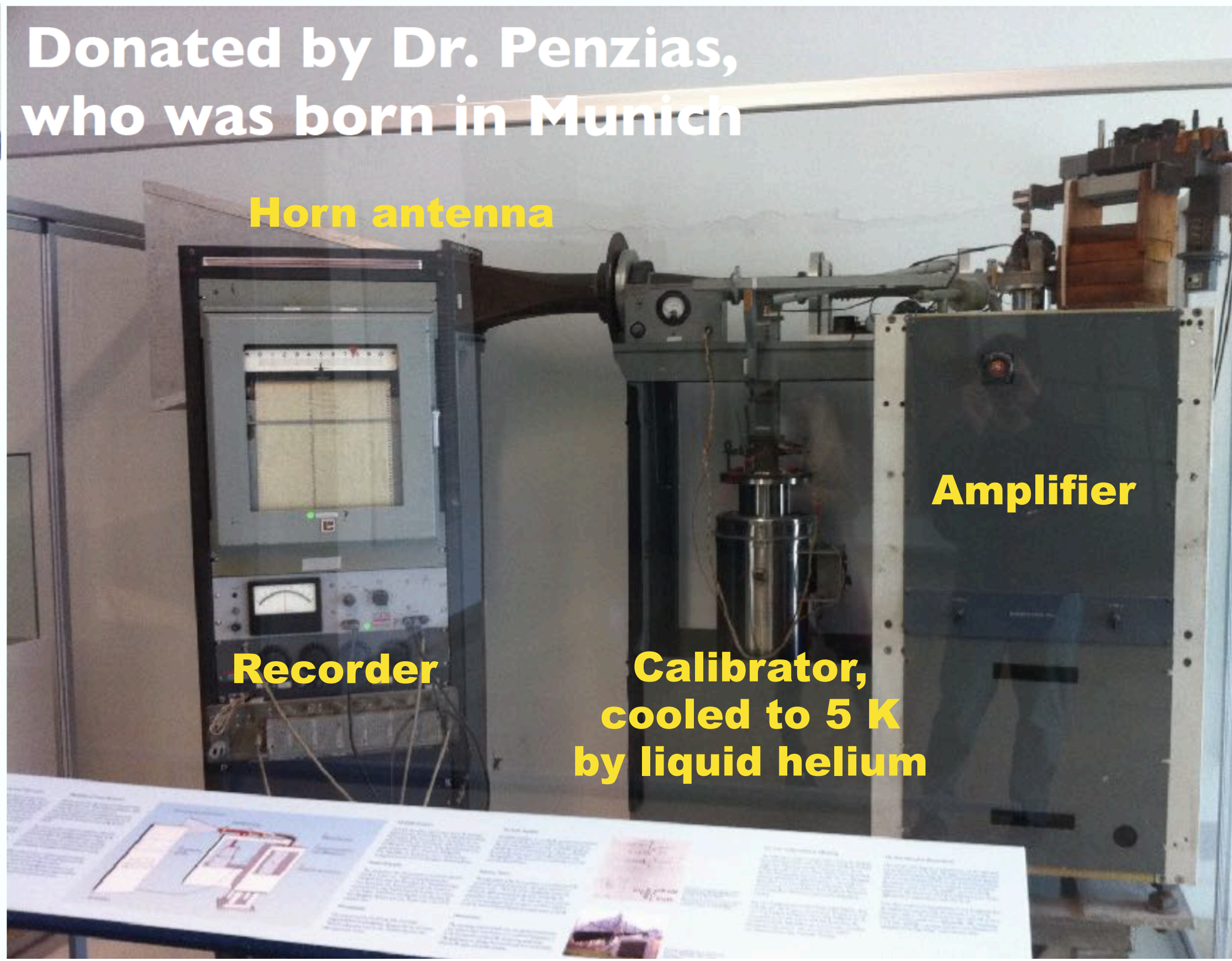
**Donated by Dr. Penzias,  
who was born in Munich**

**Horn antenna**

**Recorder**

**Calibrator,  
cooled to 5 K  
by liquid helium**

**Amplifier**





# You can help to protect the antenna!

As of 9. October, 2023

## SAVE HOLMDEL'S HORN ANTENNA

 HOLMDEL TOWNSHIP COMMITTEE, MONMOUTH COUNTY BOARD OF COMMISSIONERS, NJ STATE LEGISLATURE



Picture is from American Museum of Natural History/R. Mickens

9,839 Signatures Collected

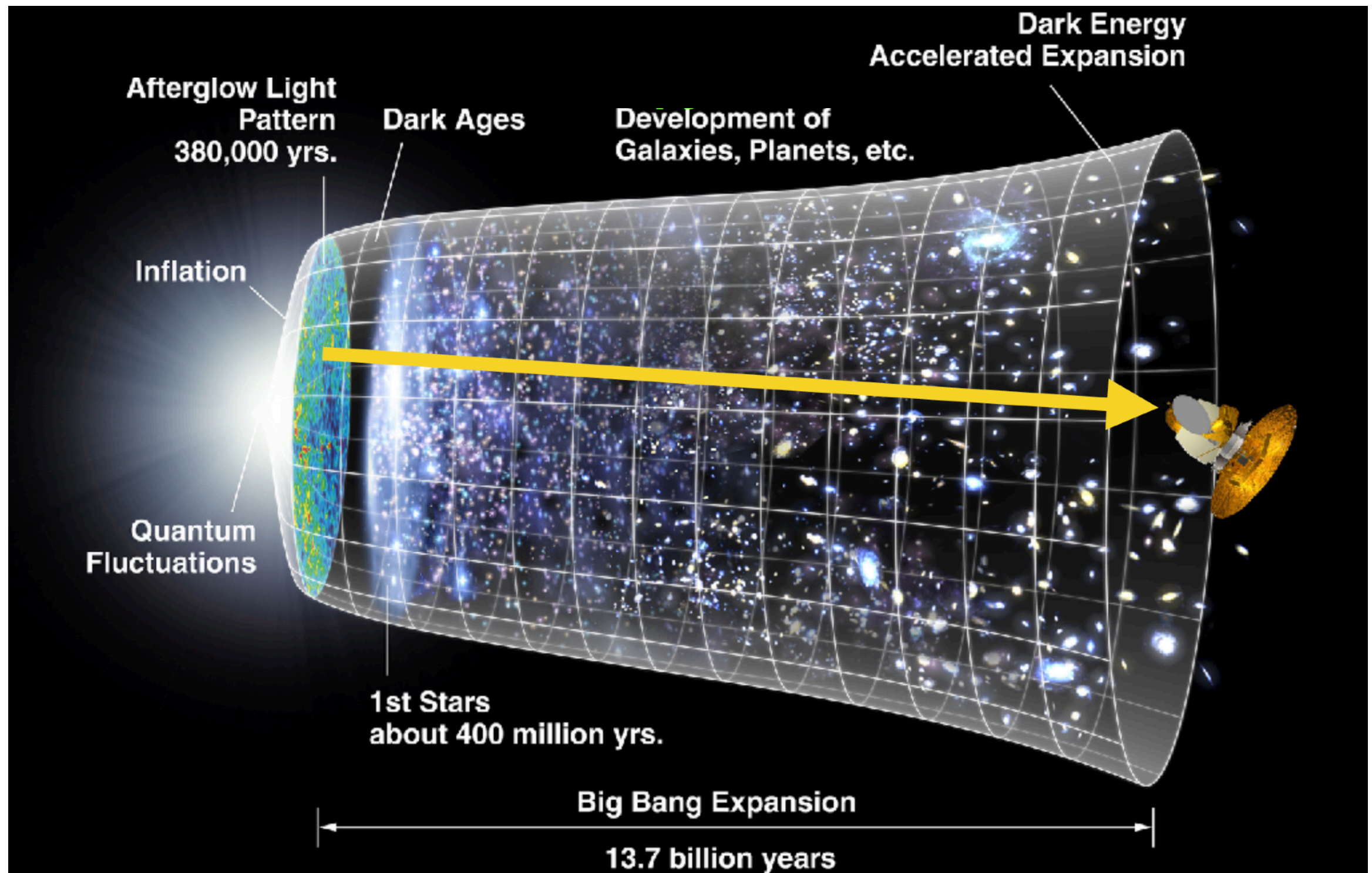
Only 2,961 more until our goal of 12,800

### SIGN THIS PETITION

Text me with updates or action needed



# The importance of learning CMB

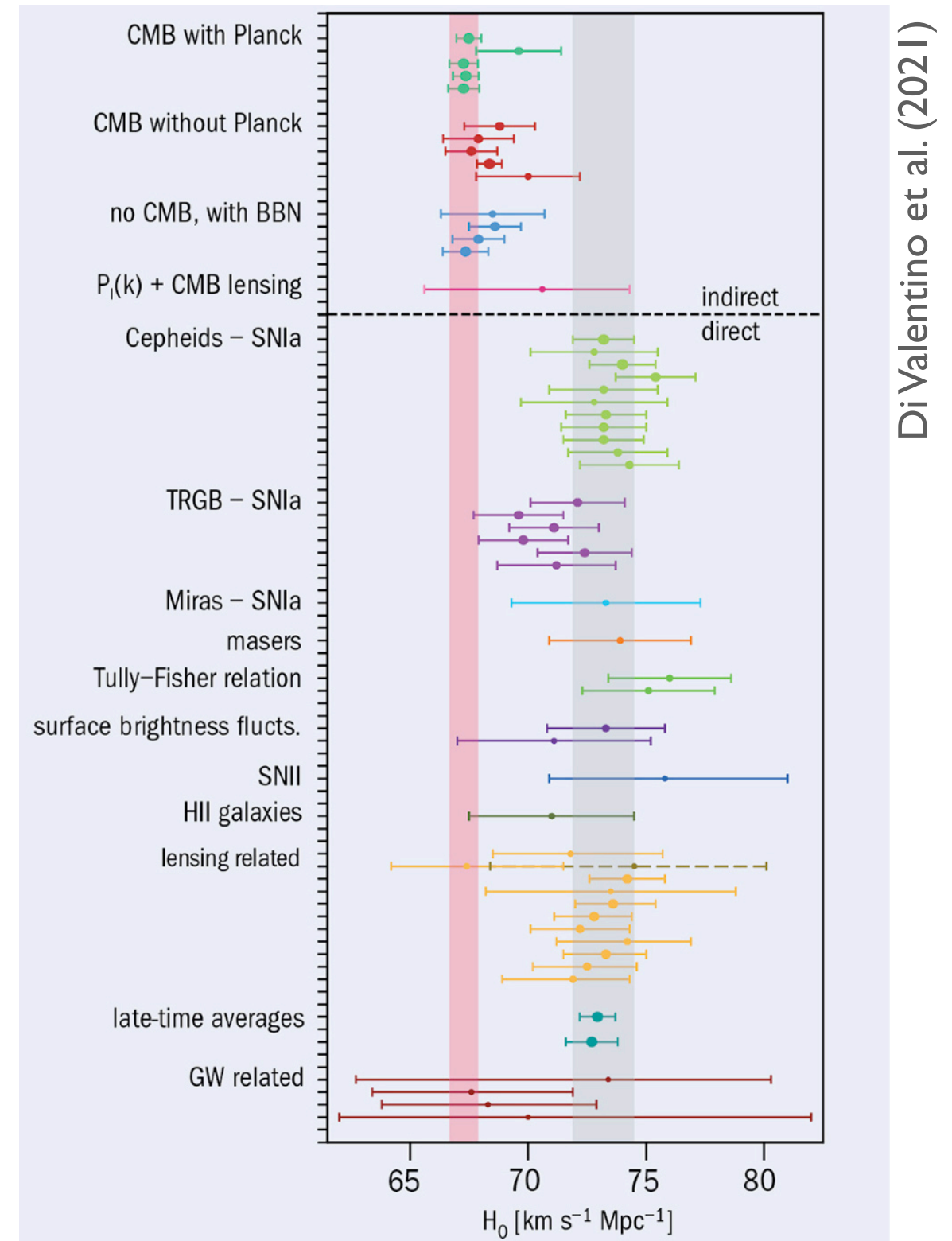
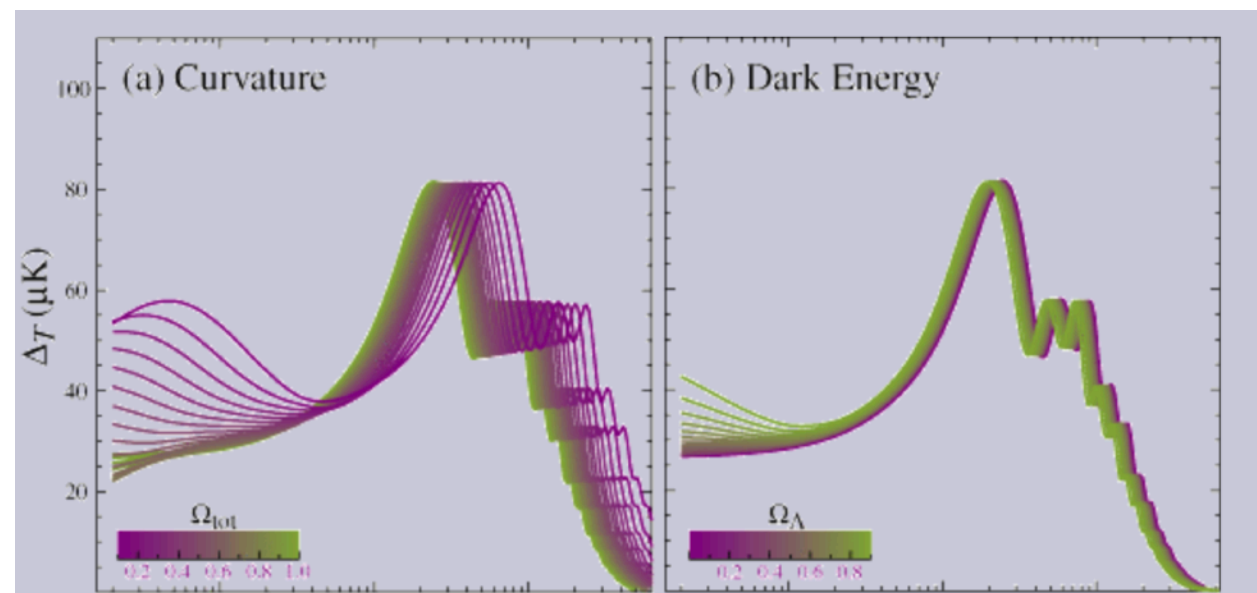
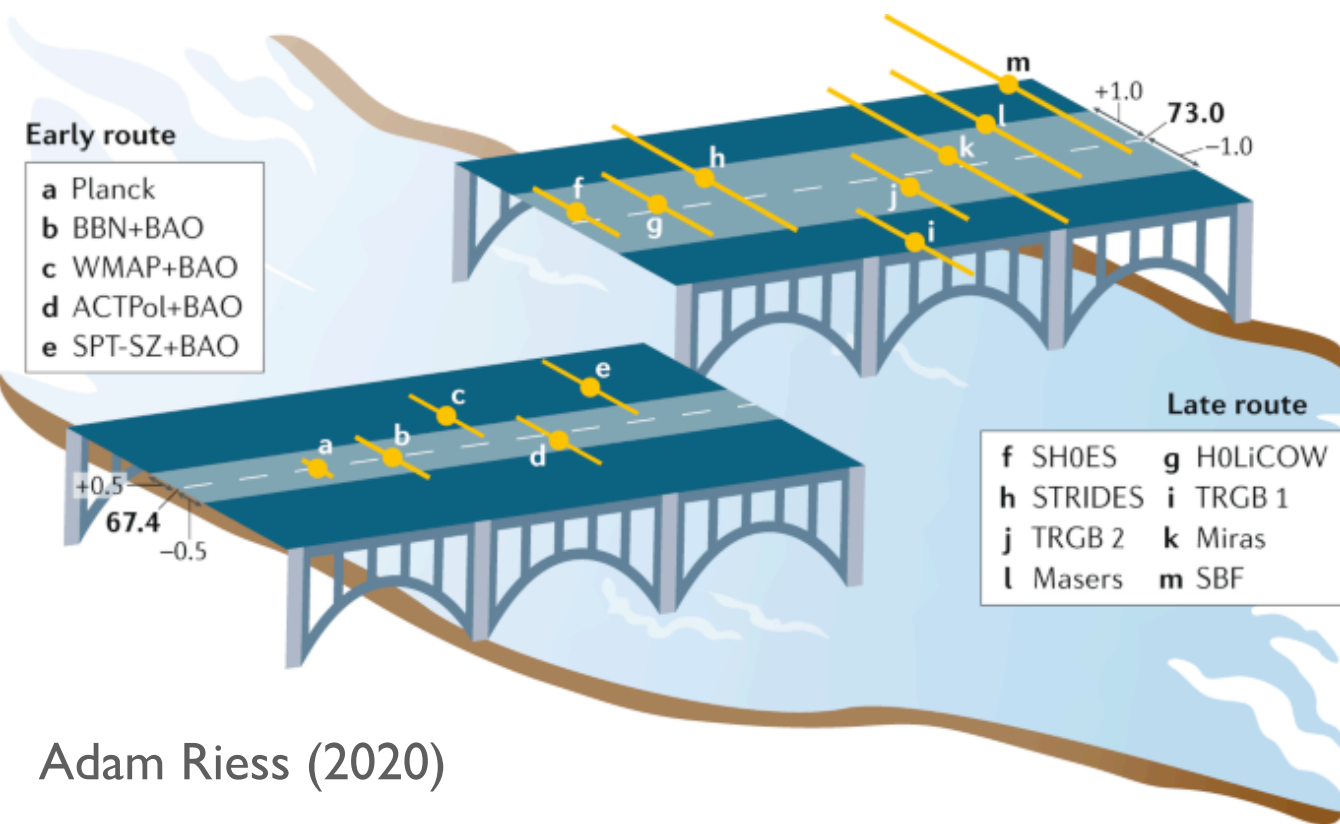


(even when it's not your main area of research)



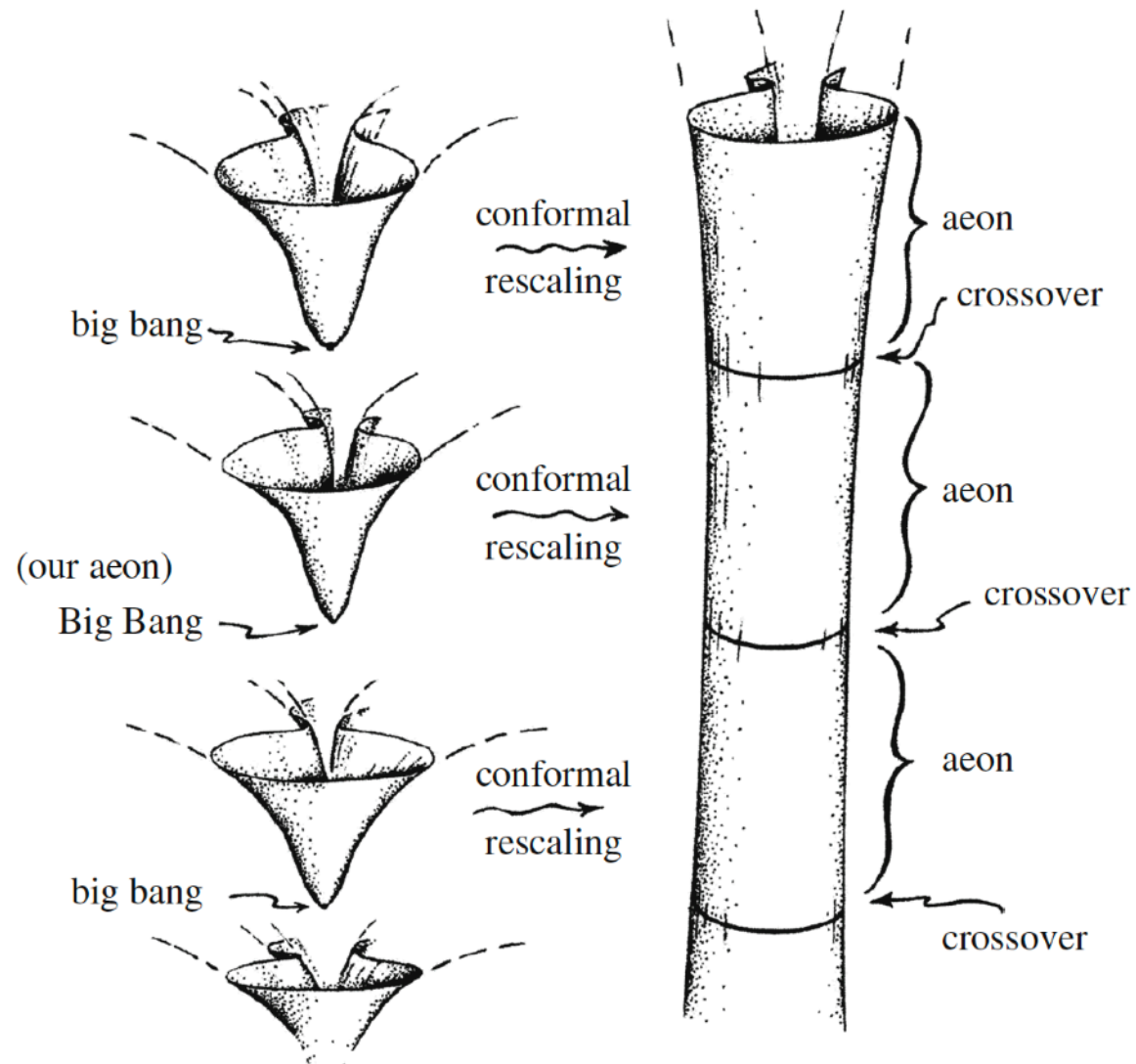
# The importance of learning CMB:

## Example 1

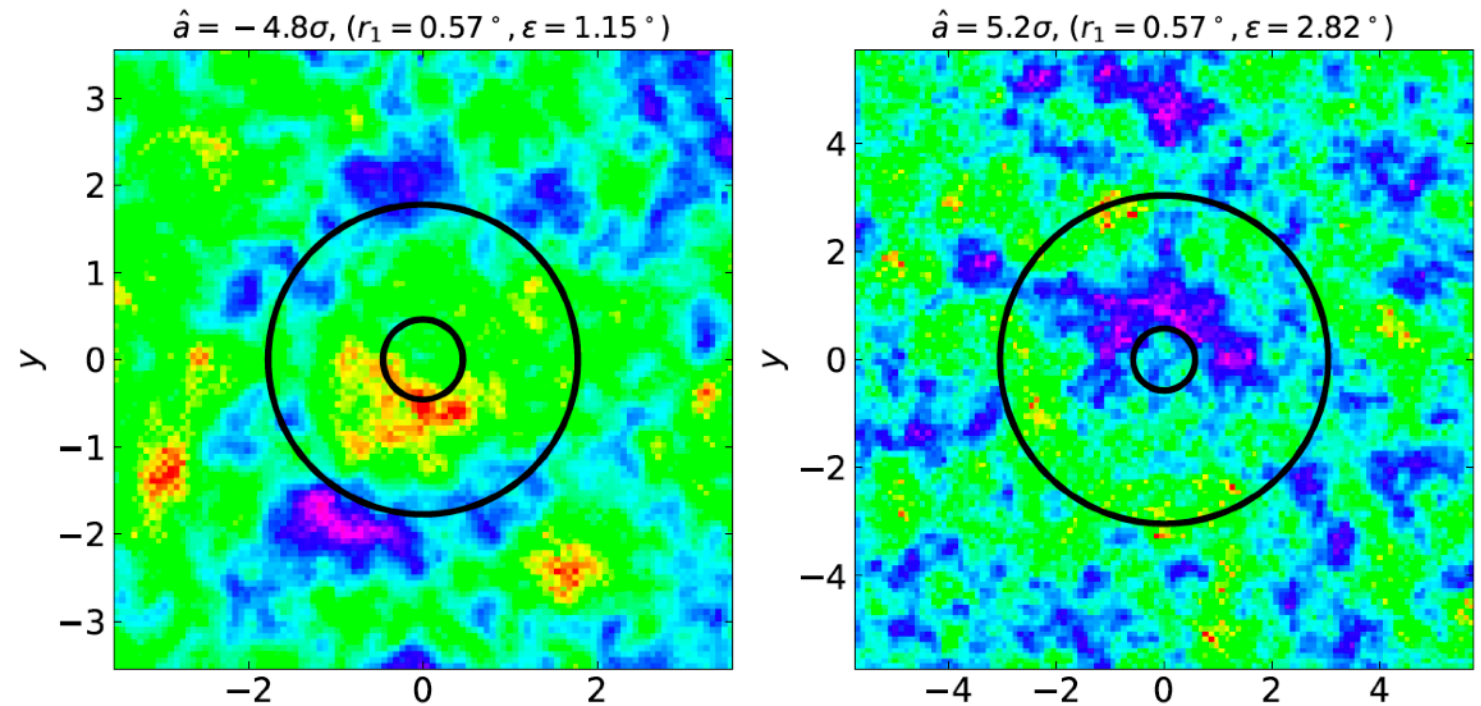


# The importance of learning CMB:

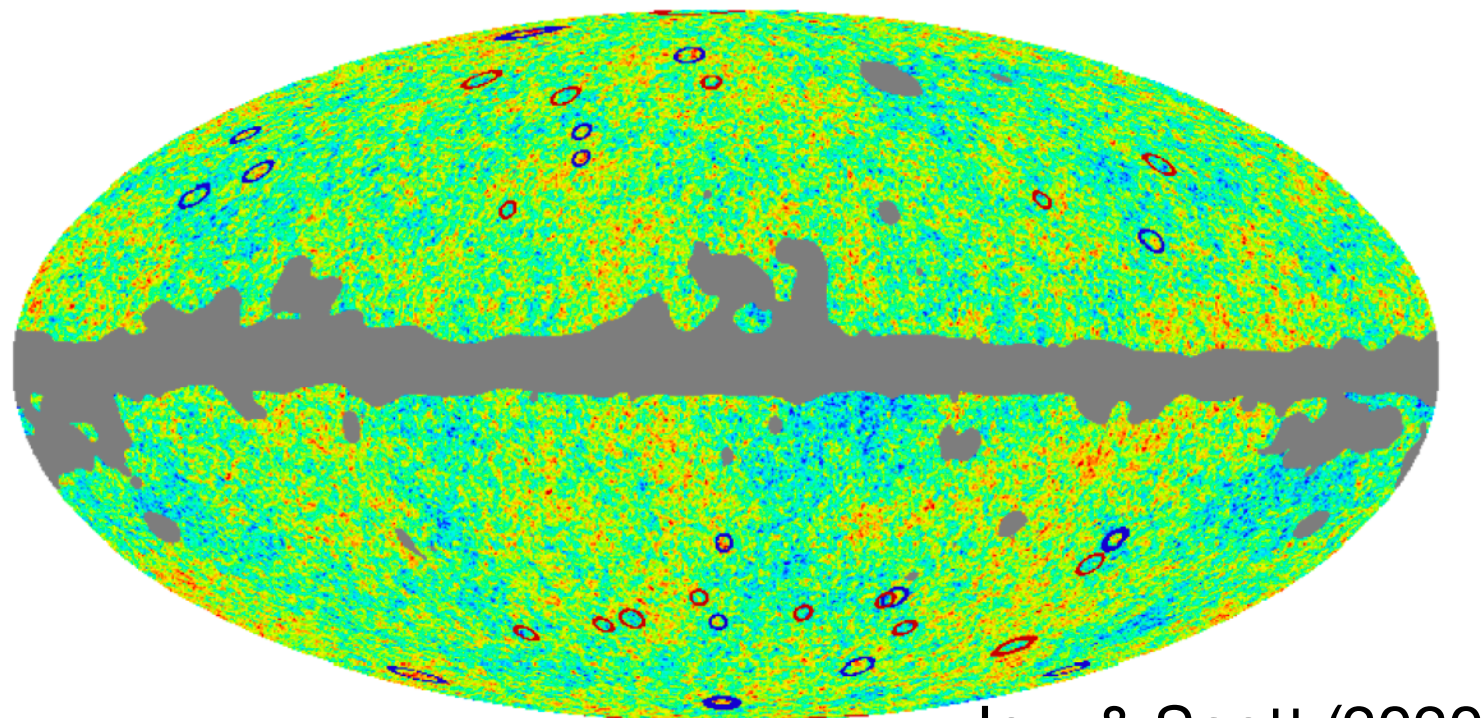
## *Example 2*



Conformal Cyclic Cosmology (CCC)  
proposed by R. Penrose



Significant Hawking points on the sky



Jow & Scott (2020)

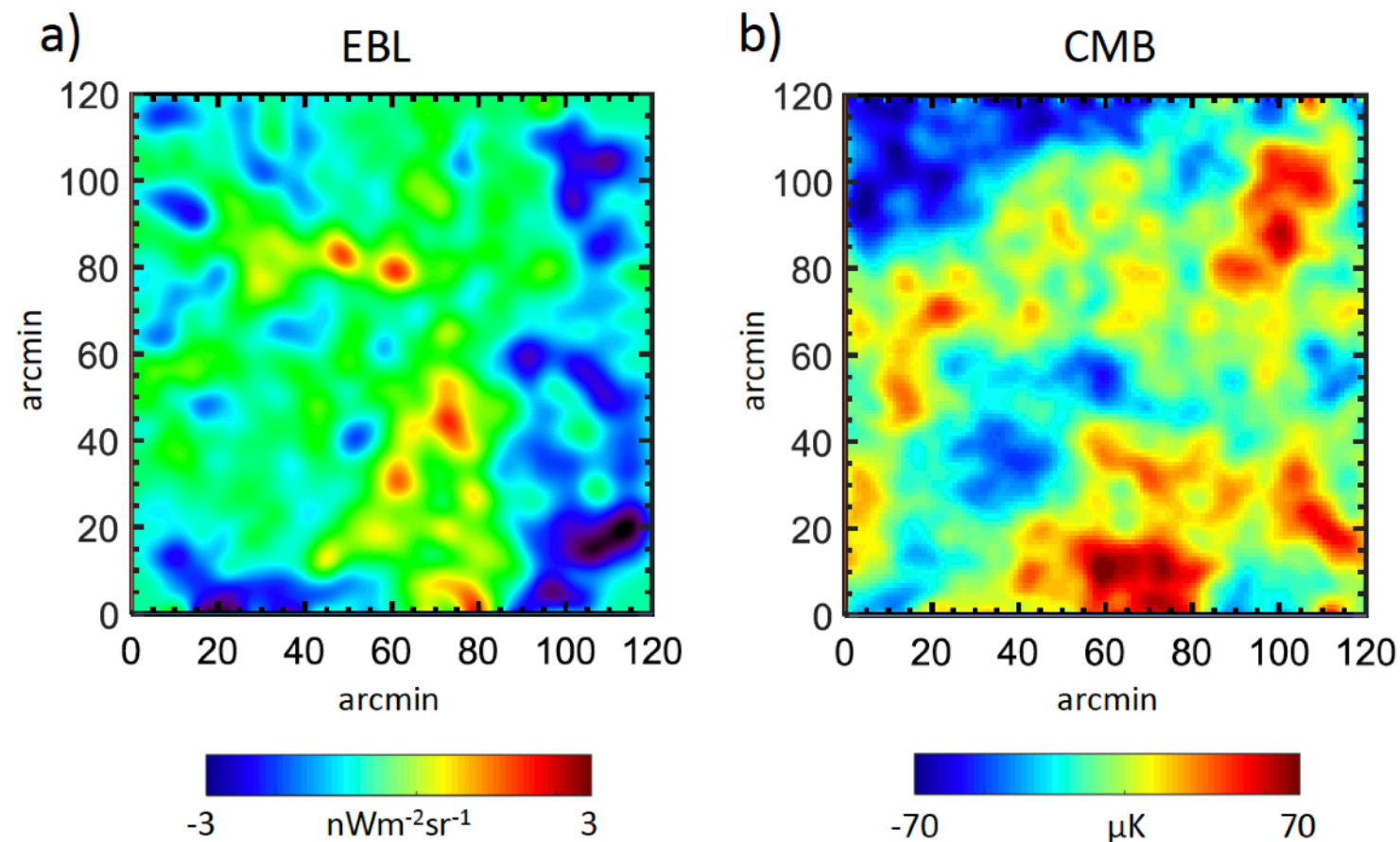




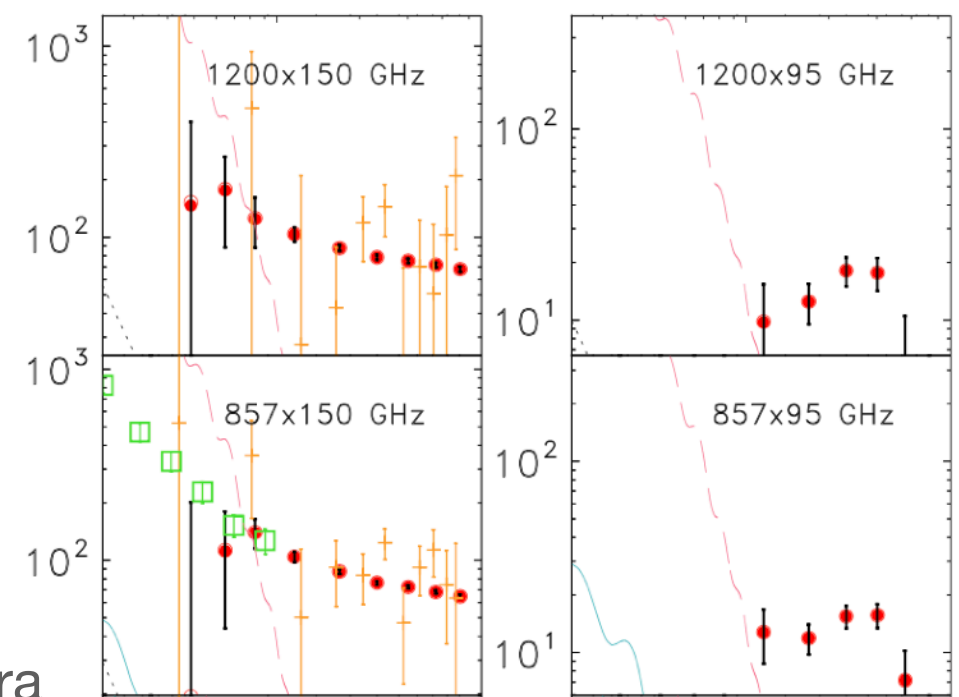
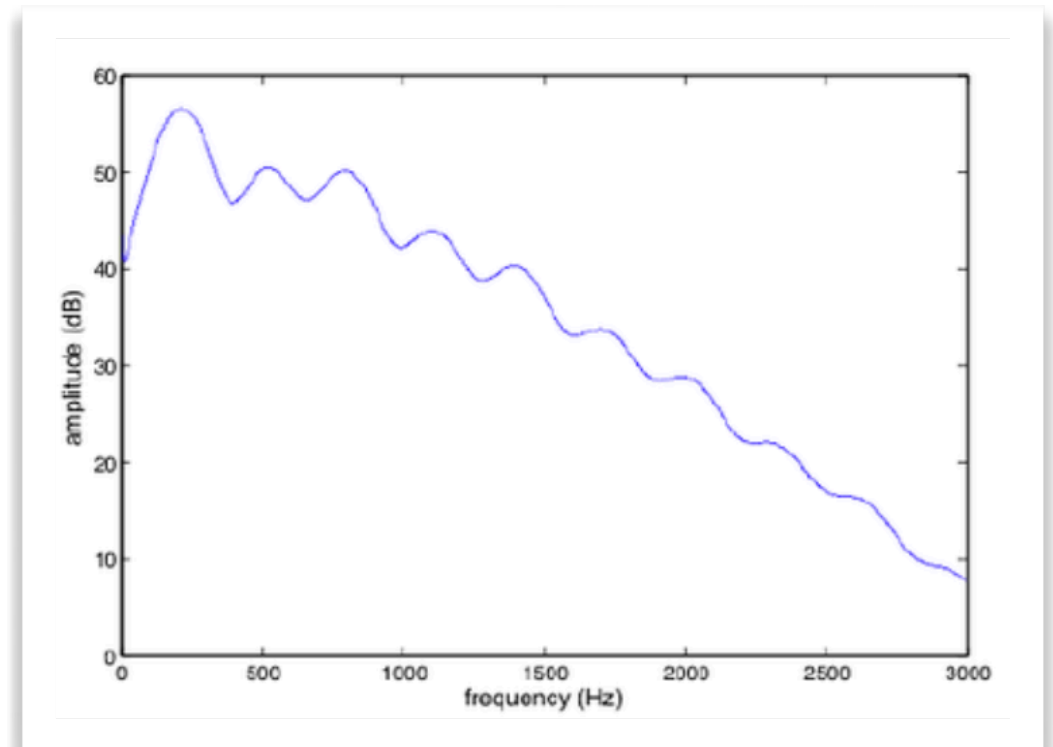
# The importance of learning CMB:

## *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

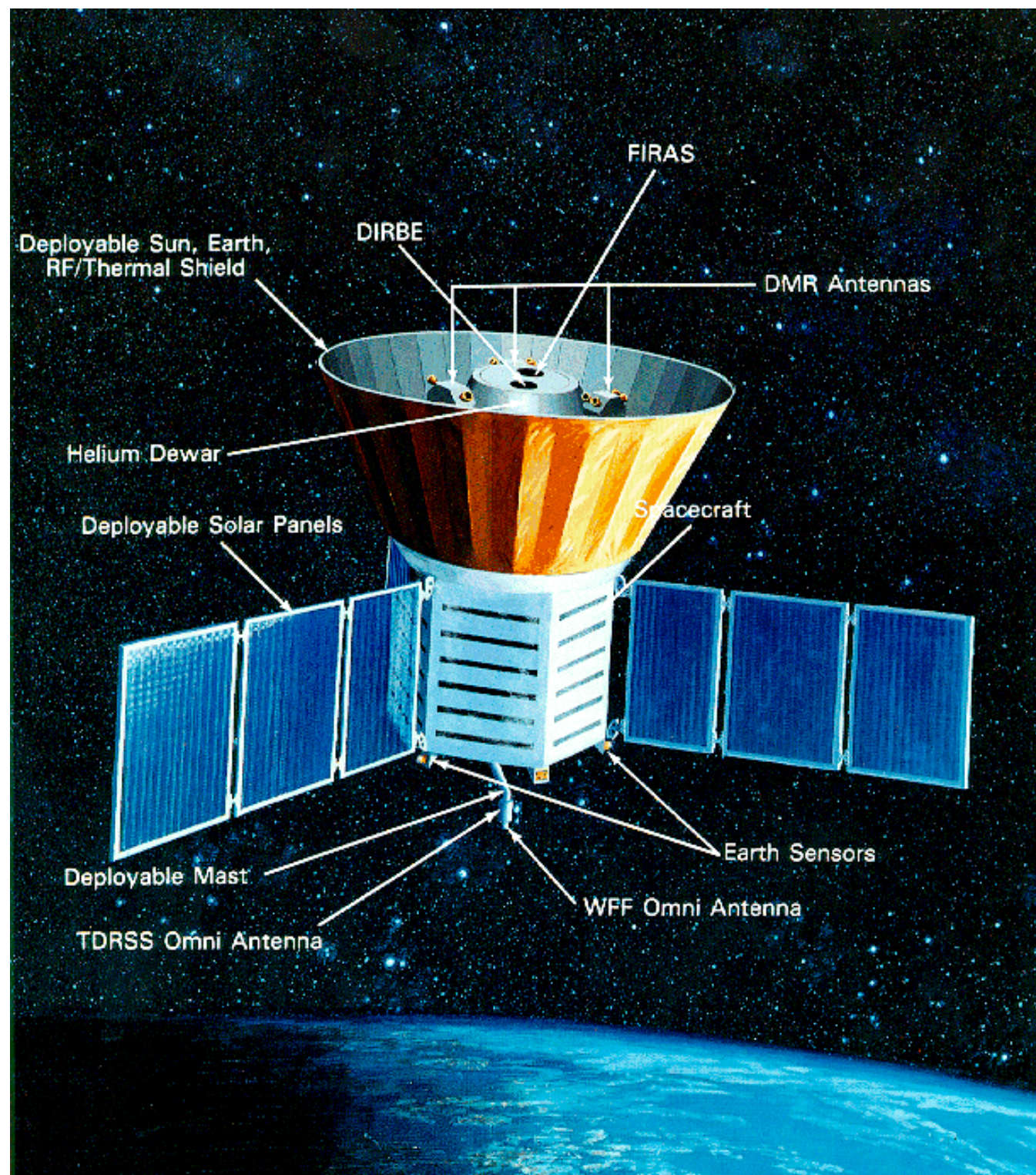
# Let's meet the experiments



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  $\mu\text{m}$  wavelength range, to search for the Infrared Background

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

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

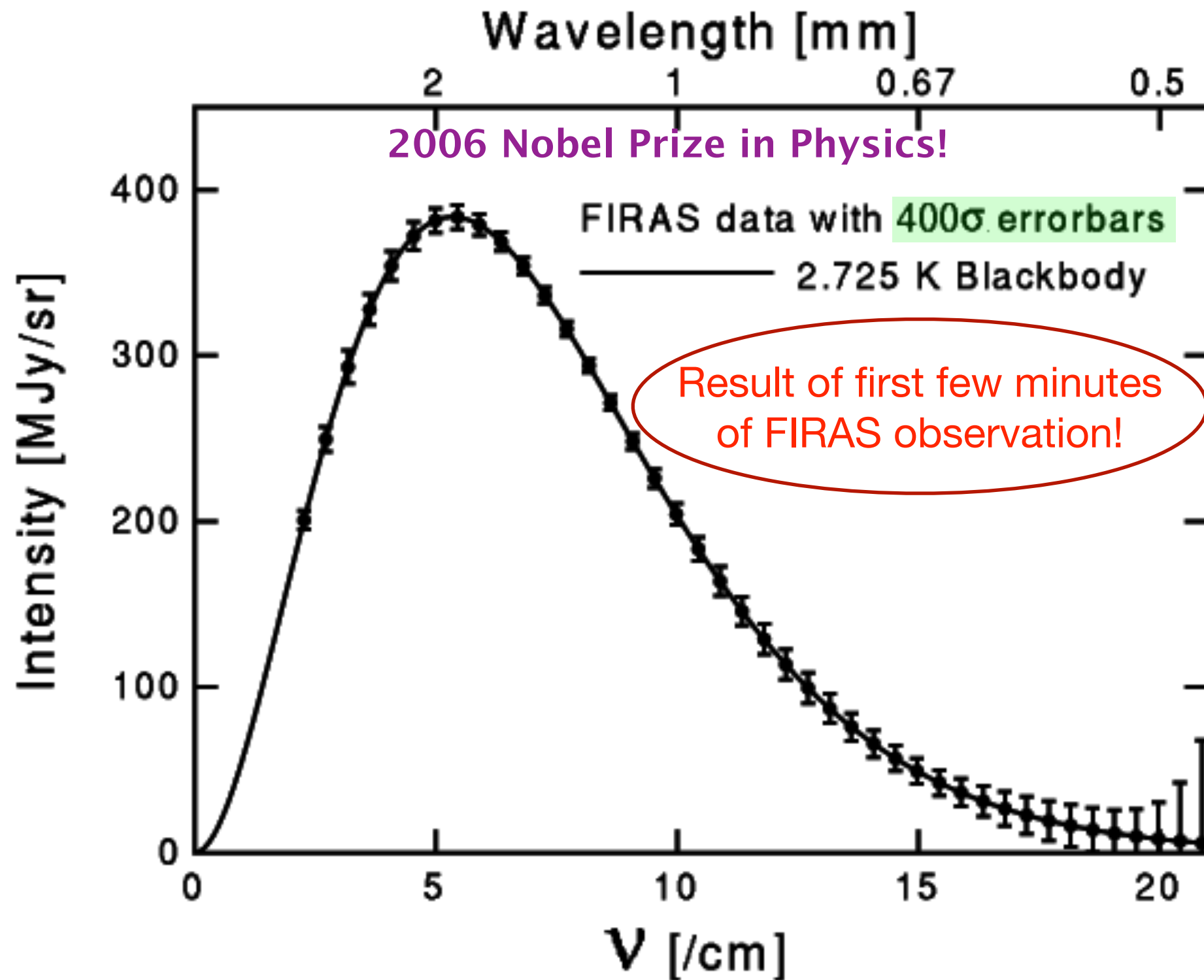


2006  
Nobel  
prize in  
physics





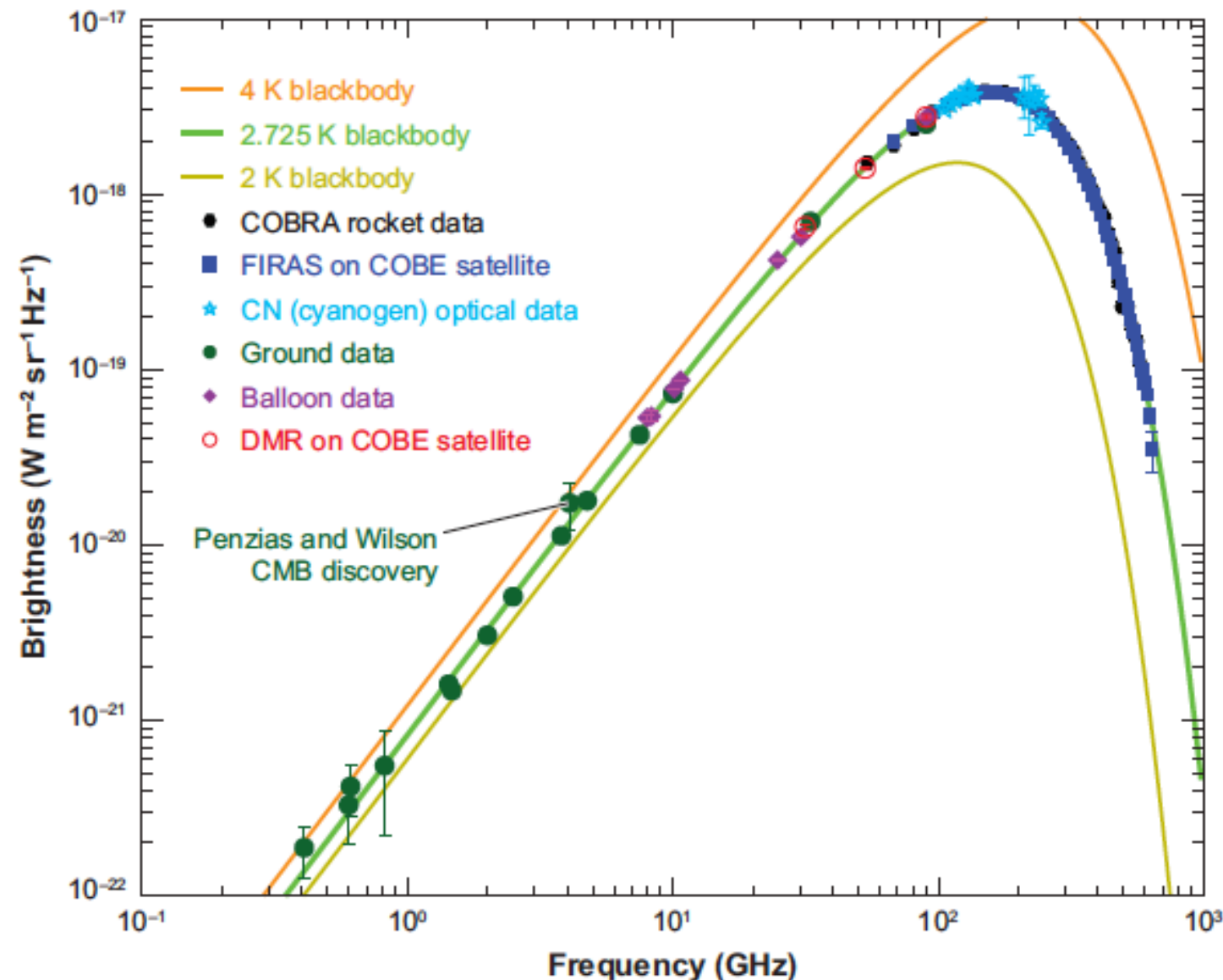
# The CMB blackbody





# Measurement of $T_{\text{CMB}}$

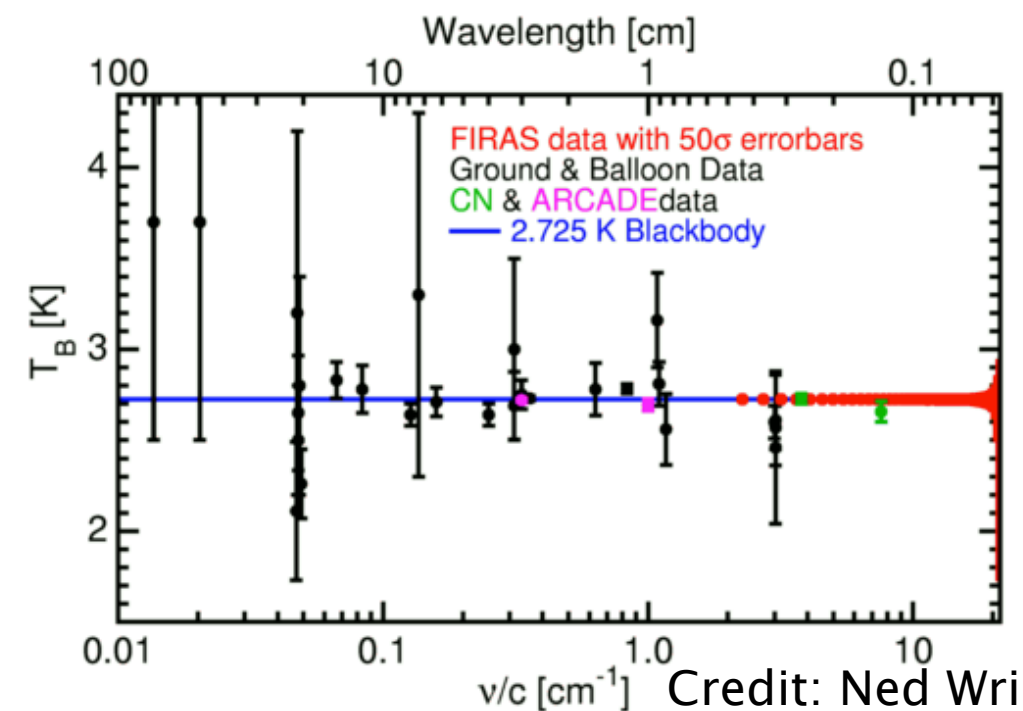
Credit: D. Samtleben



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

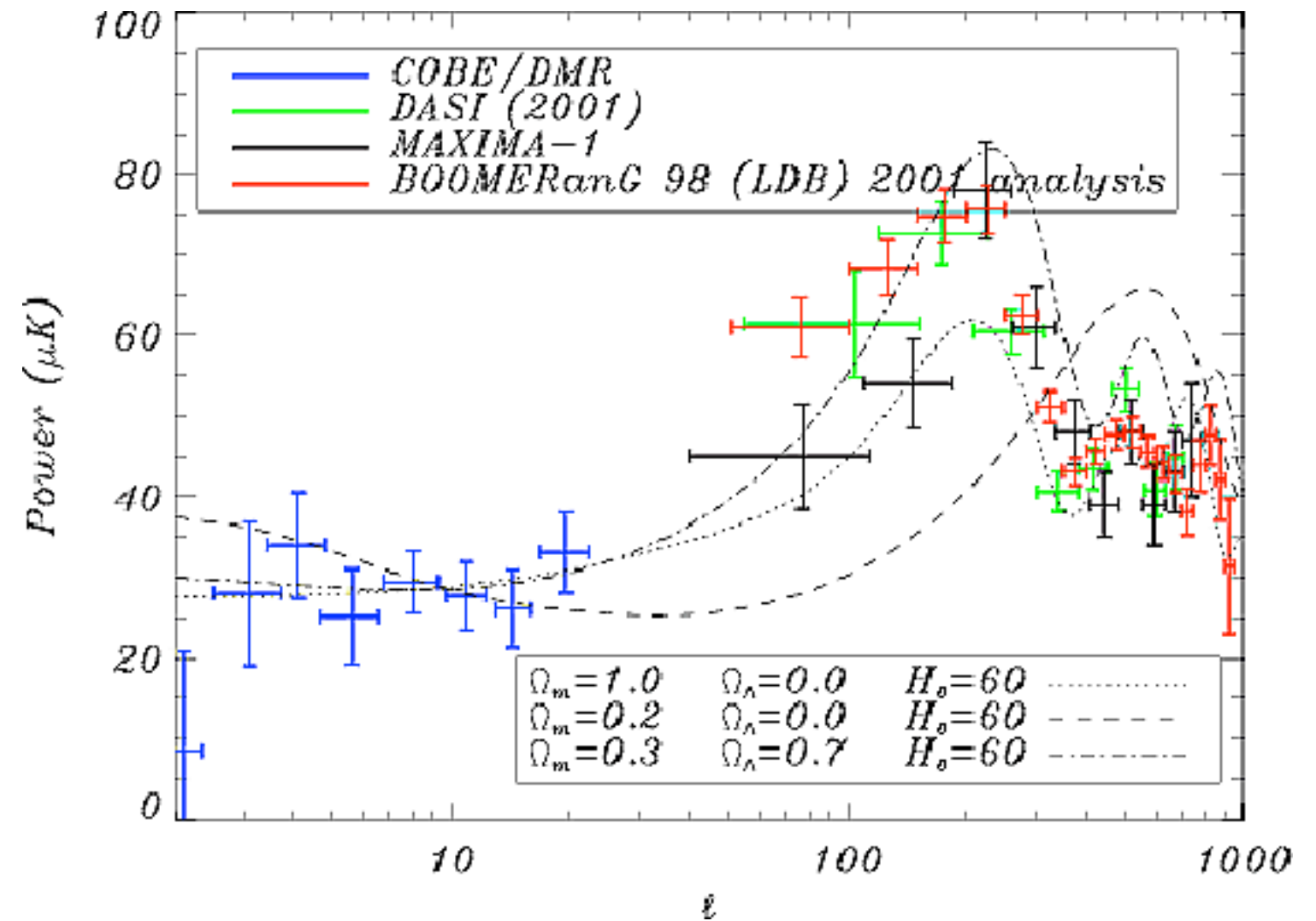
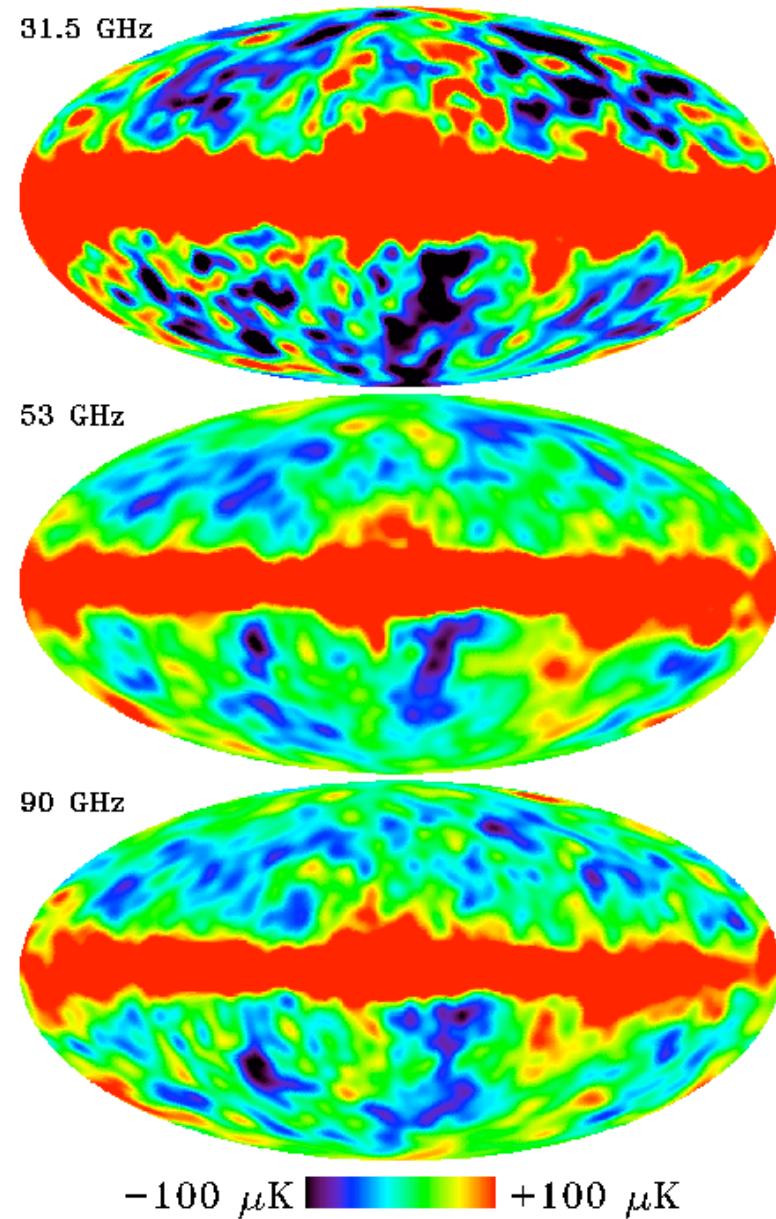
Ground and balloon based experiments have been measuring CMB temperature for decades with increasing precision

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



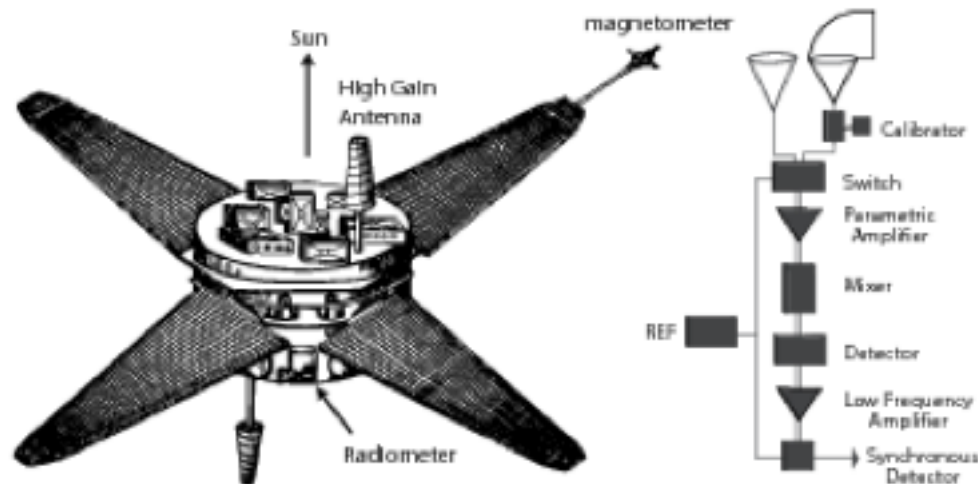
Credit: Archeops team

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

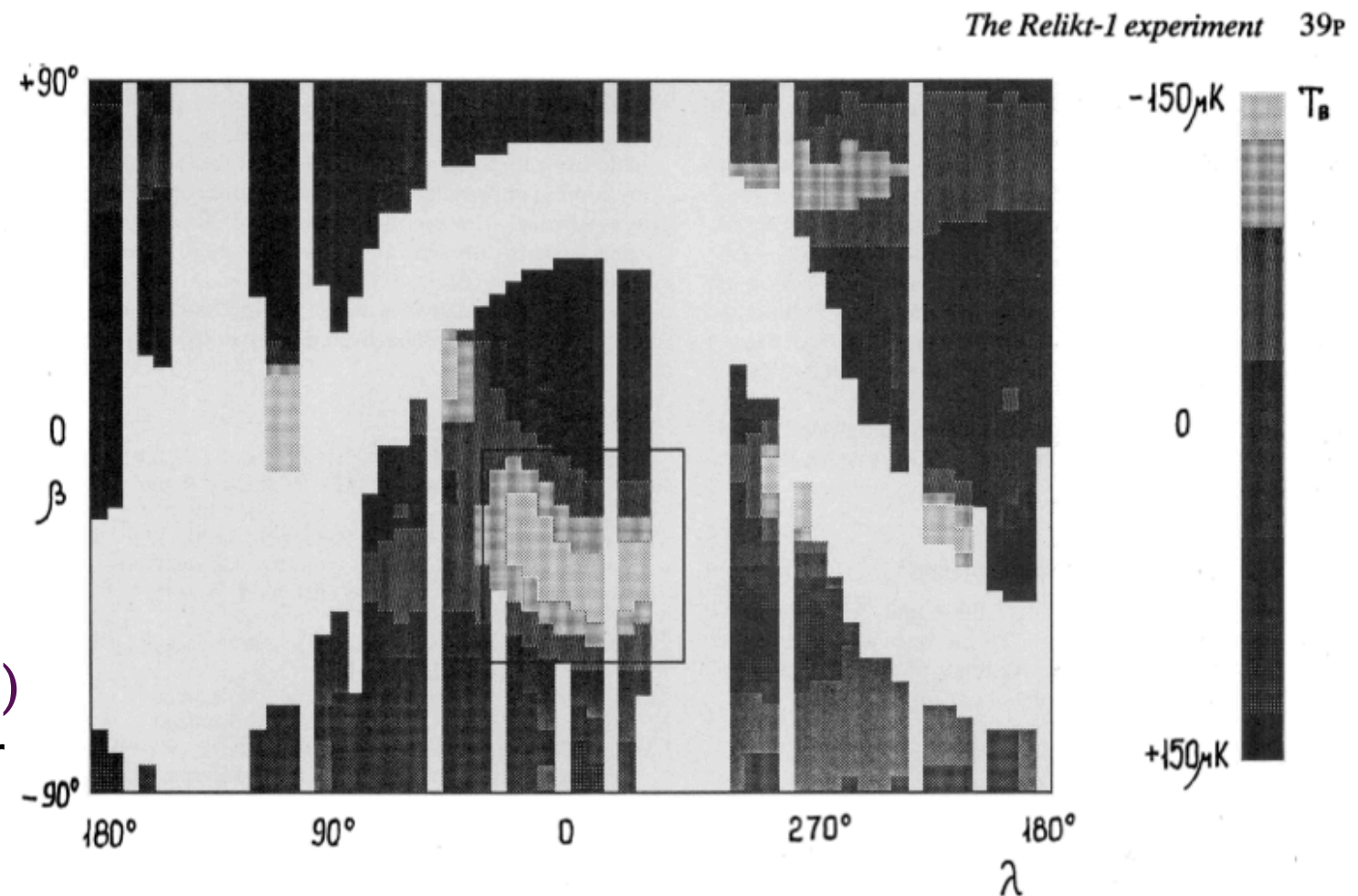
2006 Nobel Prize in Physics  
for George Smoot



# 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  
 $-71 \pm 43 \mu K$  at large angles at 90% confidence,  
including systematics.

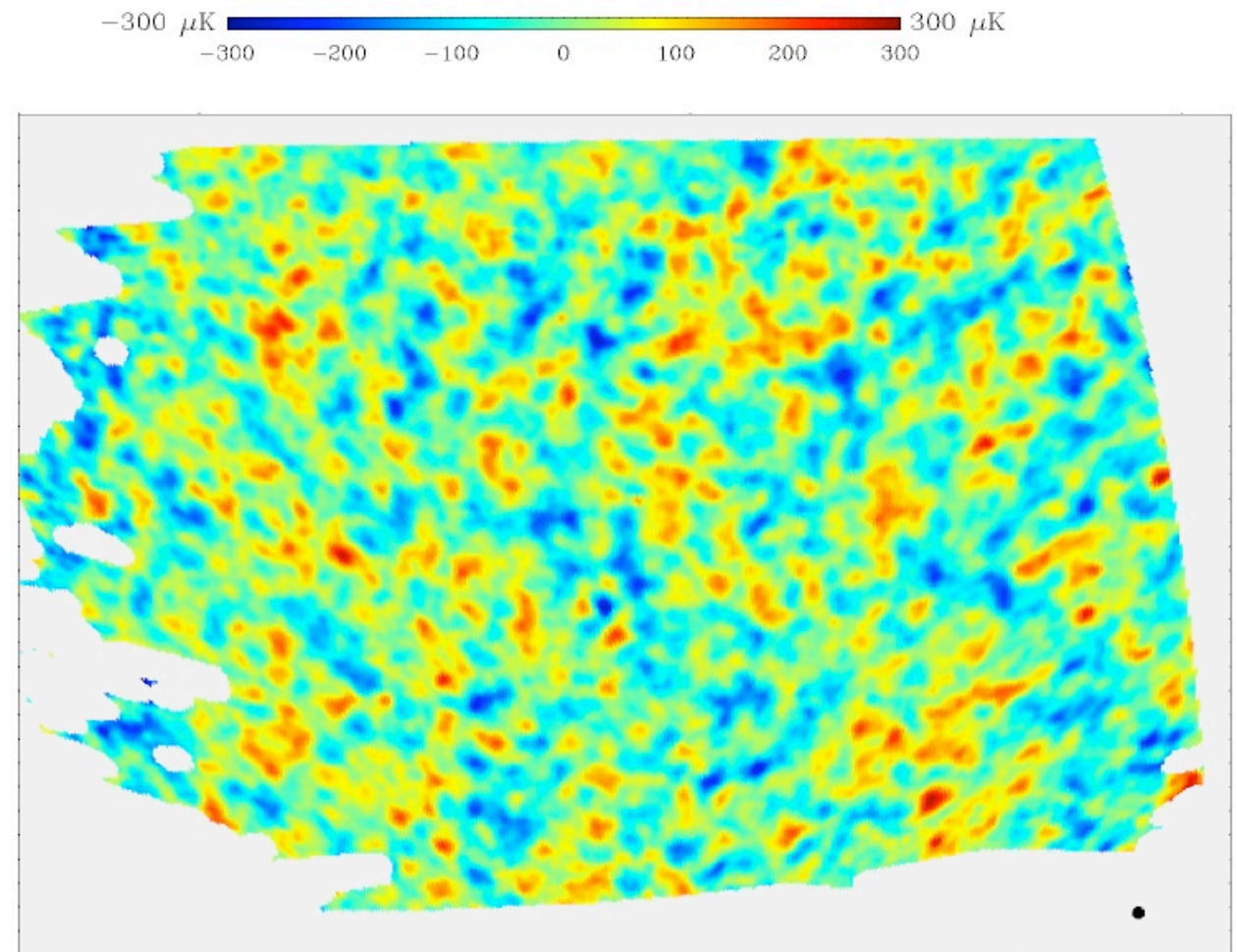


# Anisotropies seen by BOOMERANG



## Boomerang launch Dec 1998

(Balloon Observations Of Millimetric  
Extragalactic Radiation AND Geophysics)



Flight: 10 days  
1800  $\text{deg}^2$   
3 % of the Sky  
Resolution  $0.2^\circ$



# WMAP: 2001–2010



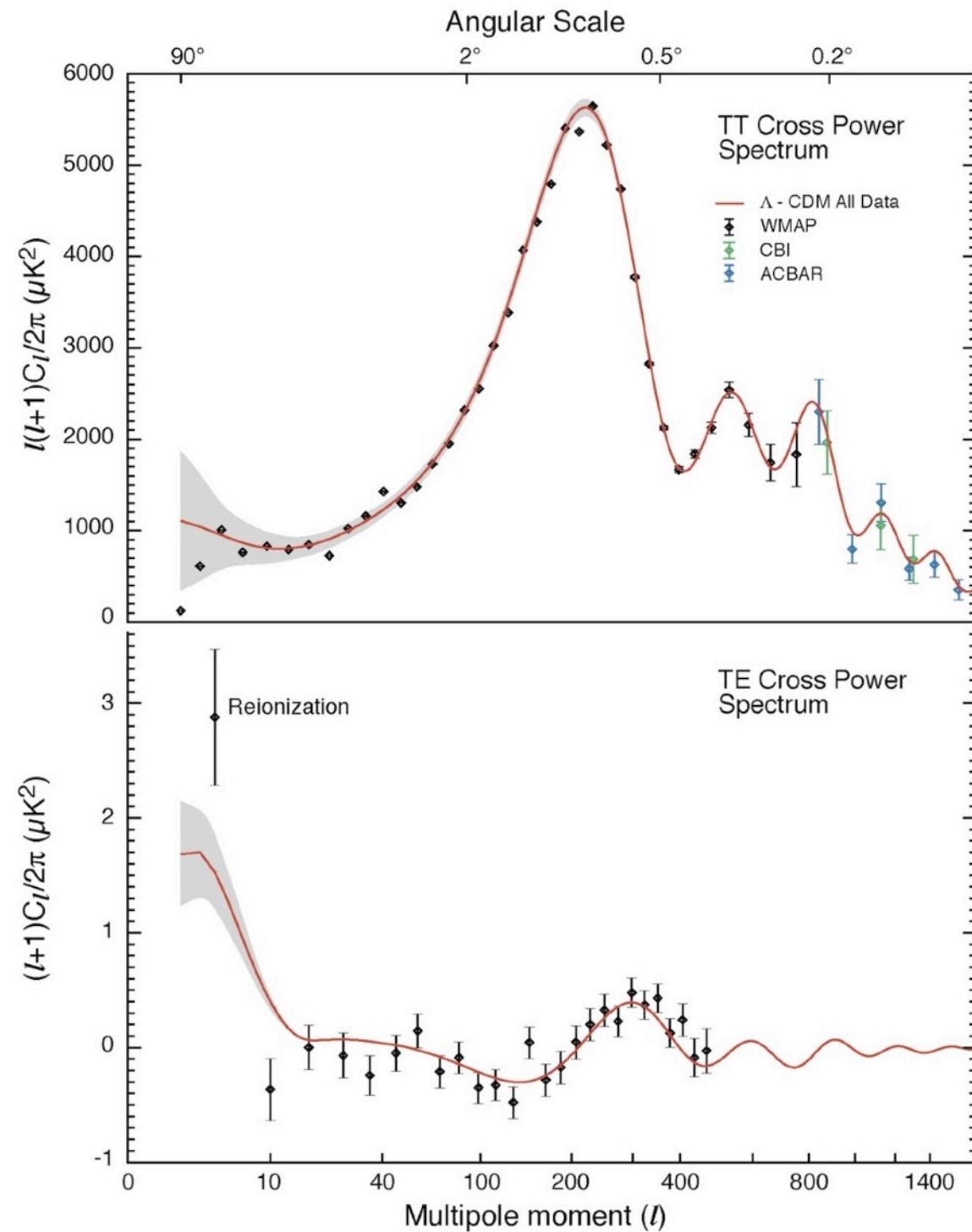
Credit: NASA



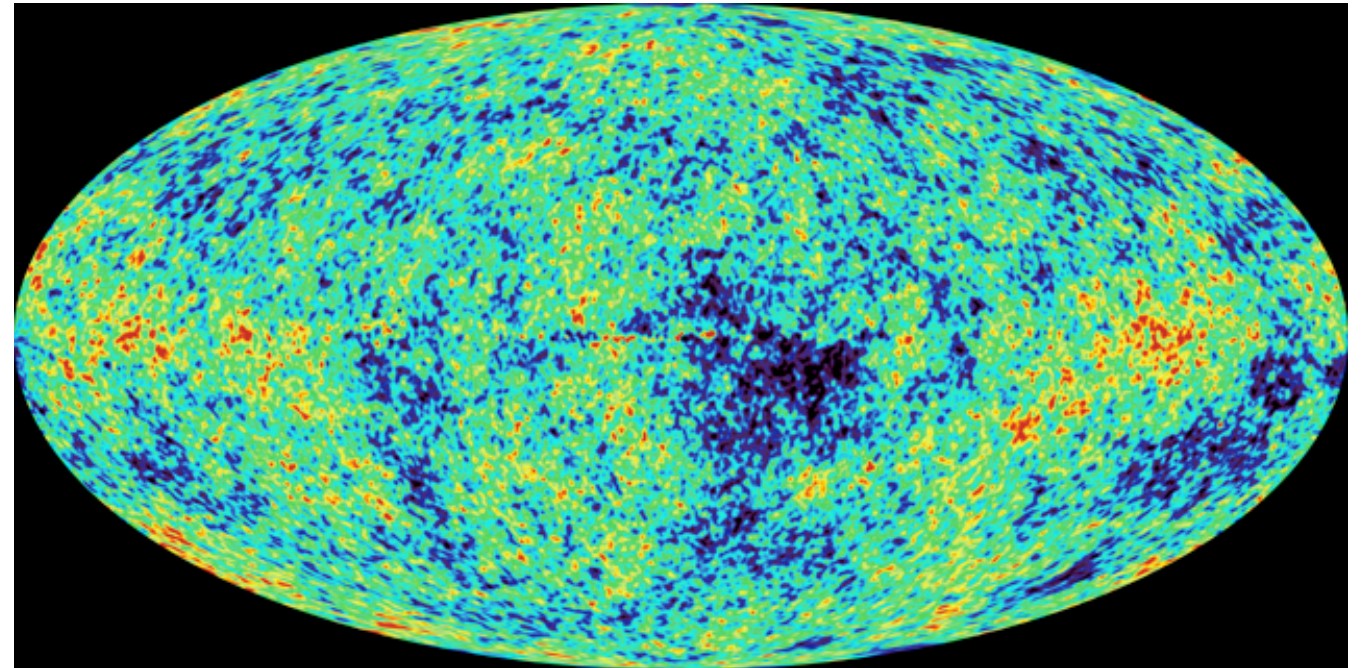
Note the same dual receivers as COBE. This design, plus the very stable conditions at the L2, minimizes the “ $1/f$  noise” in amplifiers and receivers.

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

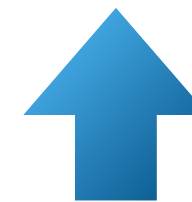
# WMAP results after 1st year



(Credit: WMAP Science Team)



Internal Linear Combination map



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



# Planck satellite (2009–2013)

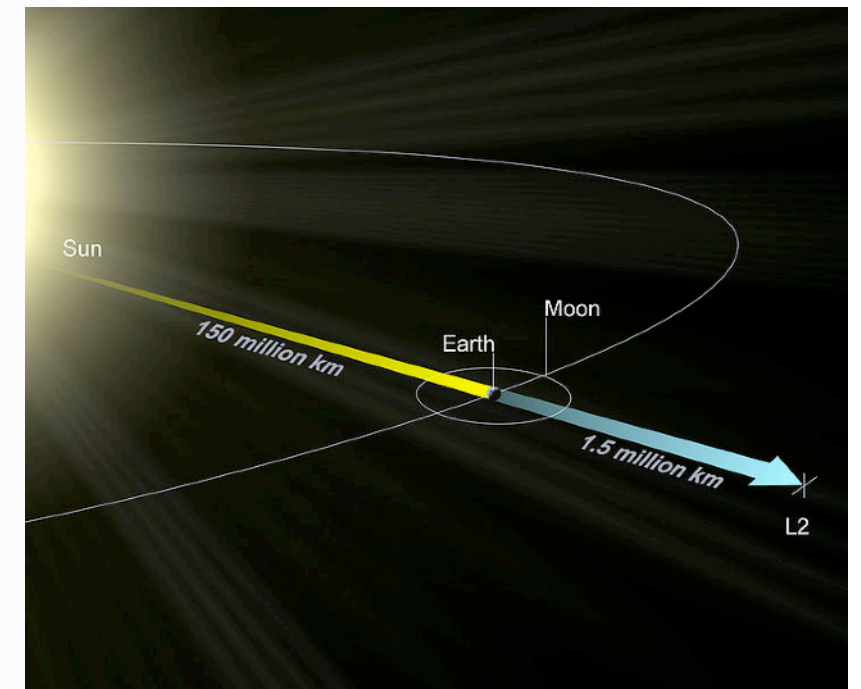


Credit: ESA

# PLANCK launch: May 2009



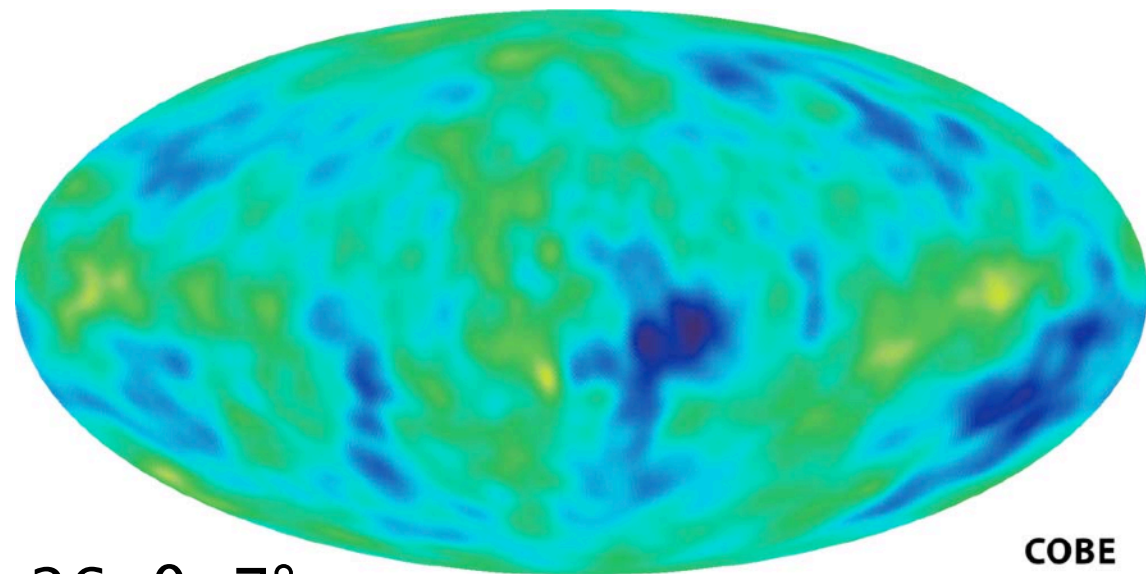
Credit: ESA



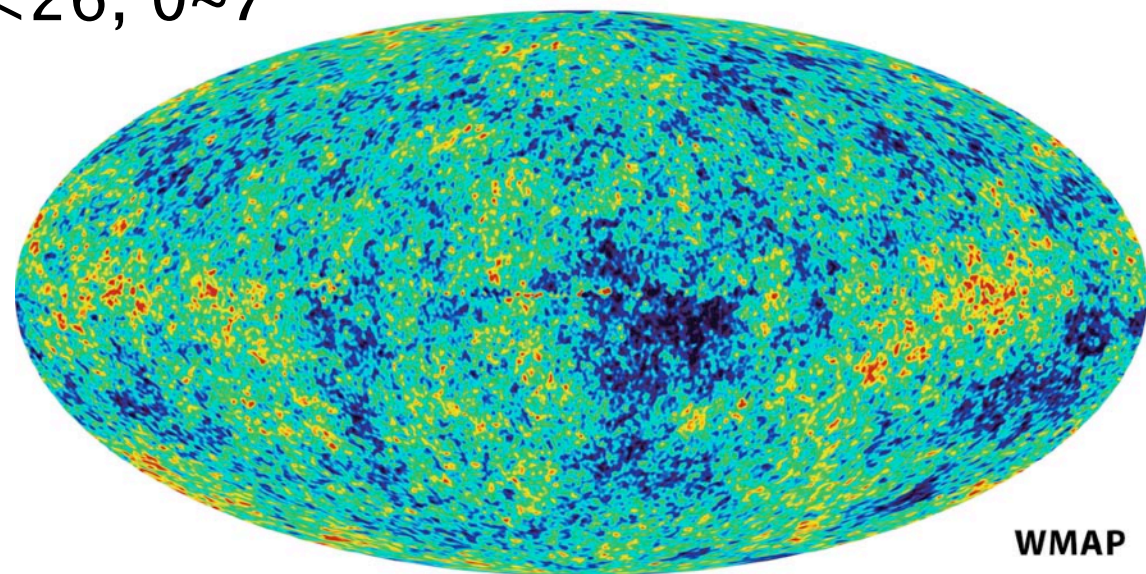
Destination L2:  
The second  
Lagrangian point



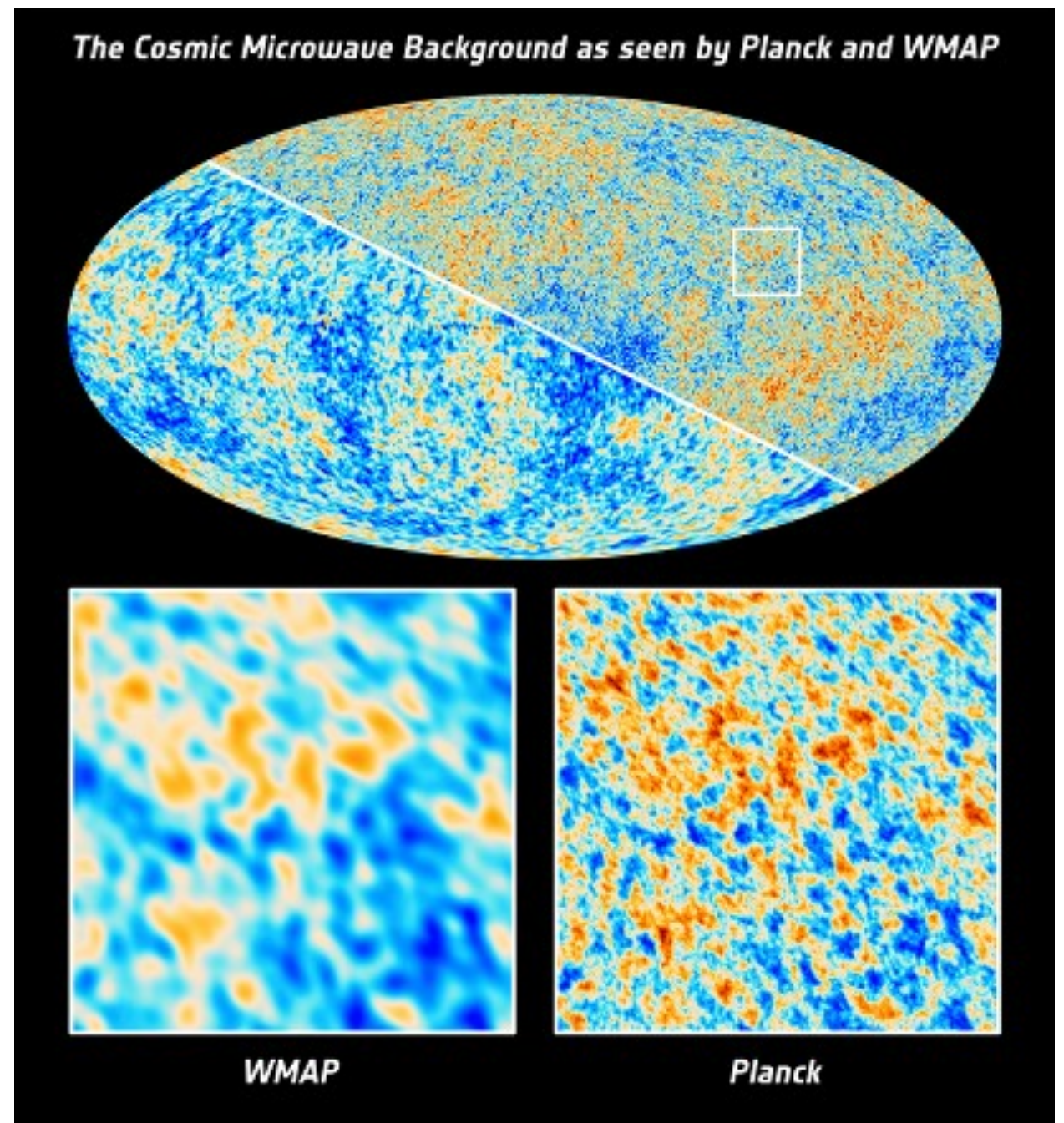
# Planck transformed the CMB science



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



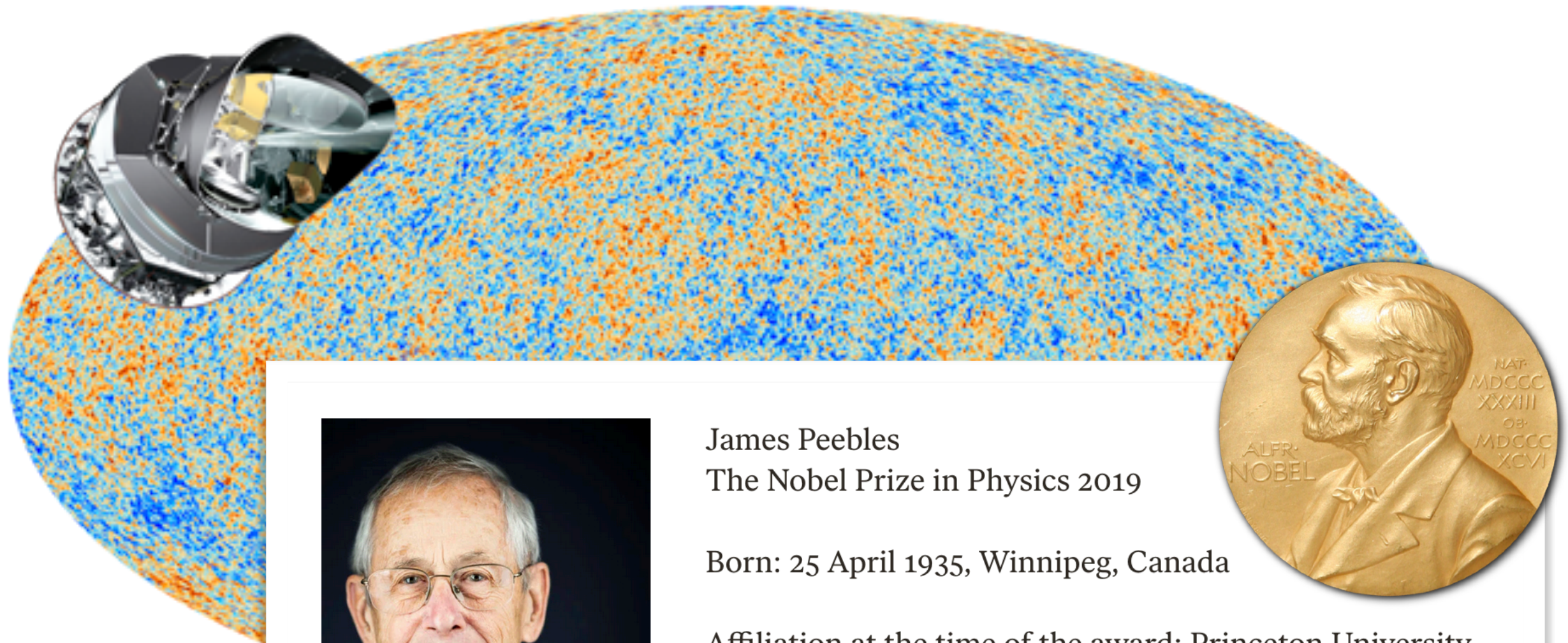
$l < 780, \theta \sim 0.2^\circ$



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



# CMB sky seen from Planck



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

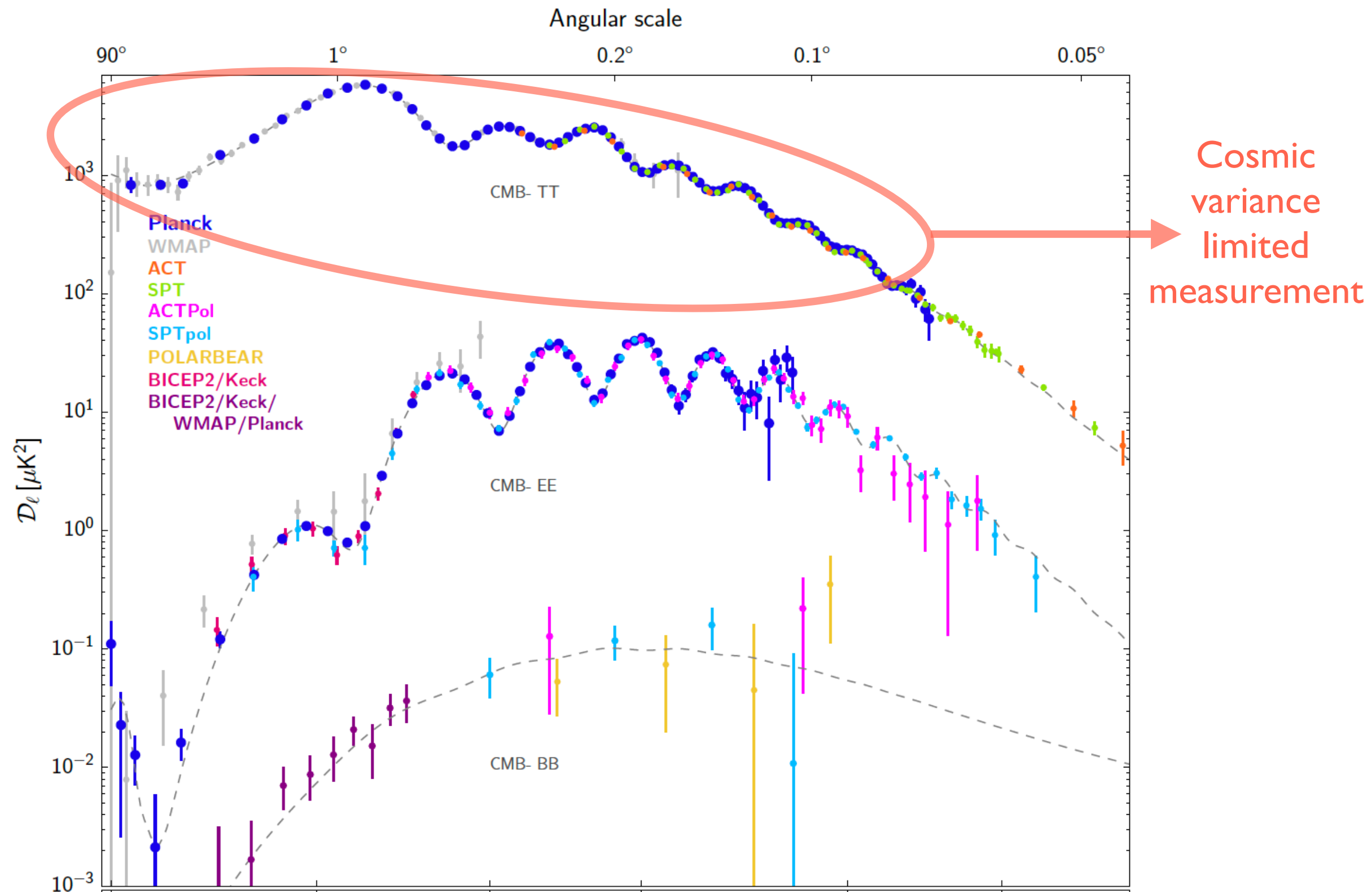
Prize motivation: “for theoretical discoveries in physical  
cosmology”

Prize share: 1/2





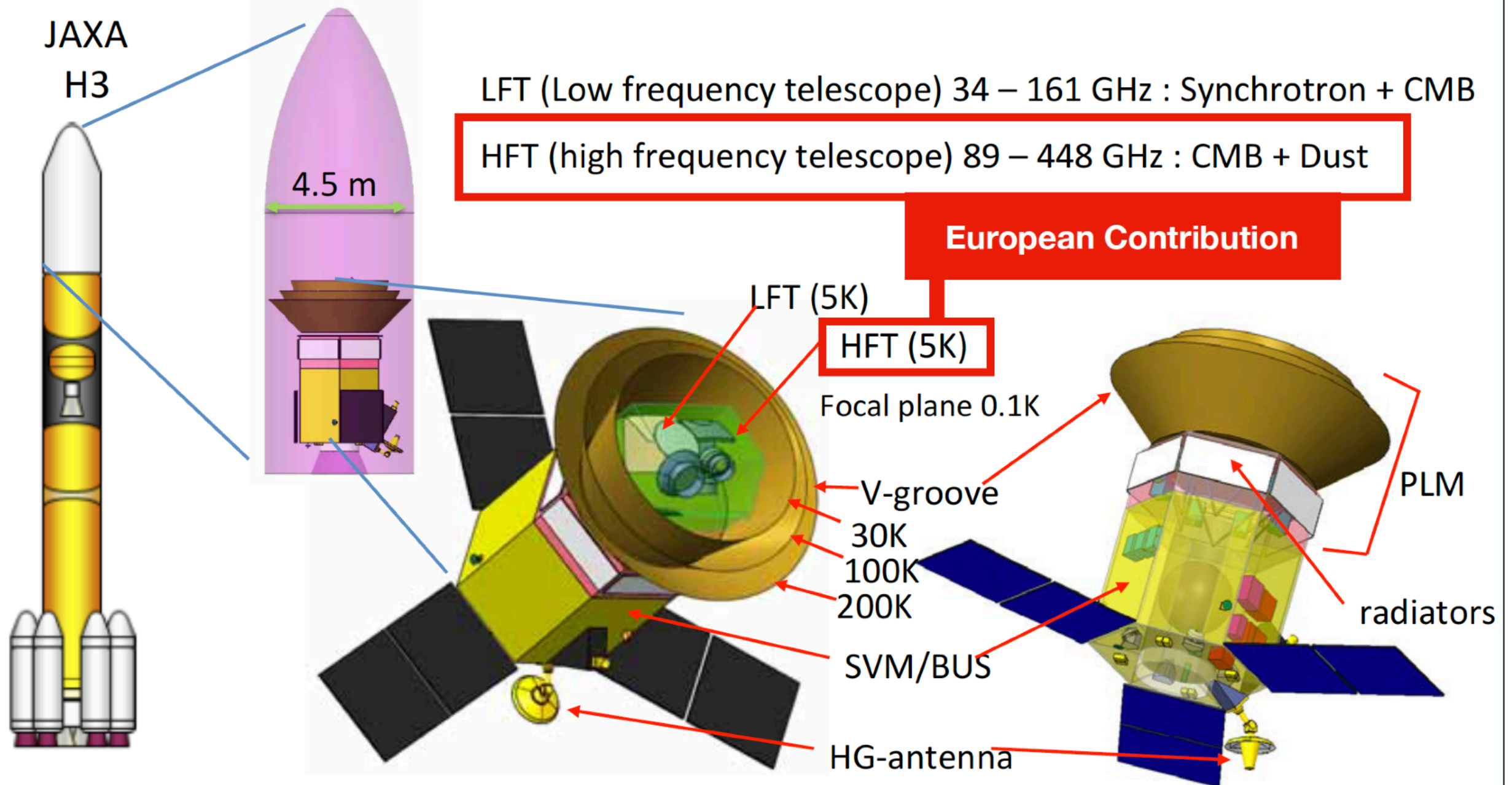
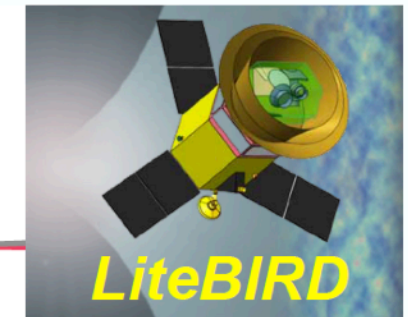
# CMB state-of-the-art (mid-2018)



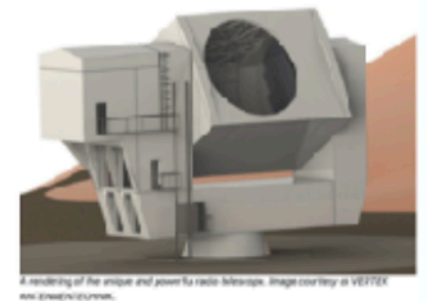
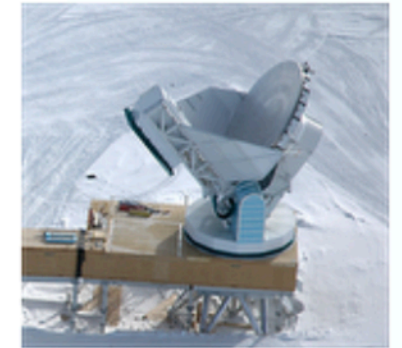
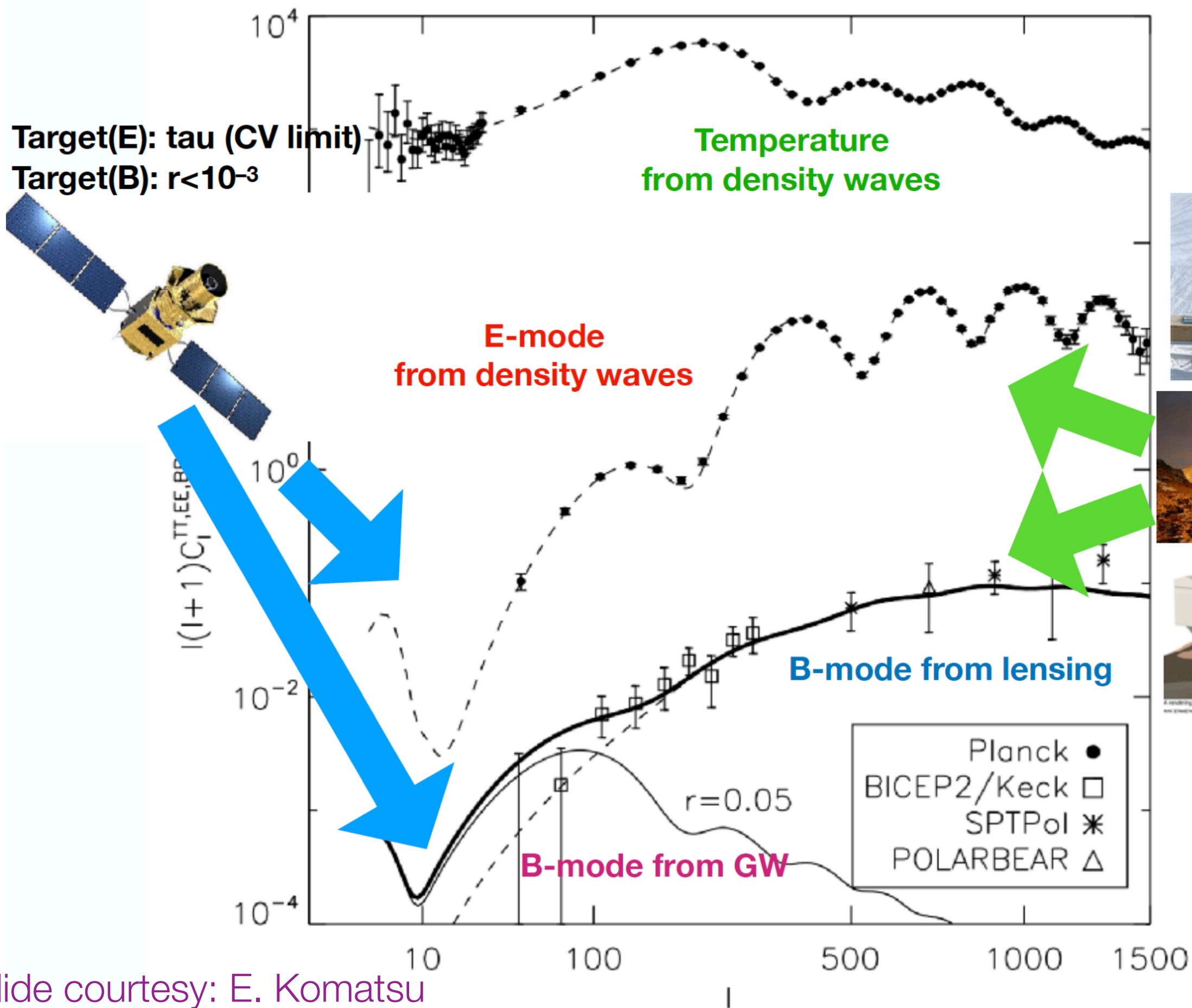
Slide courtesy Yutaro Sekimoto (ISAS/JAXA)

# LiteBIRD Spacecraft

## Launch 2027





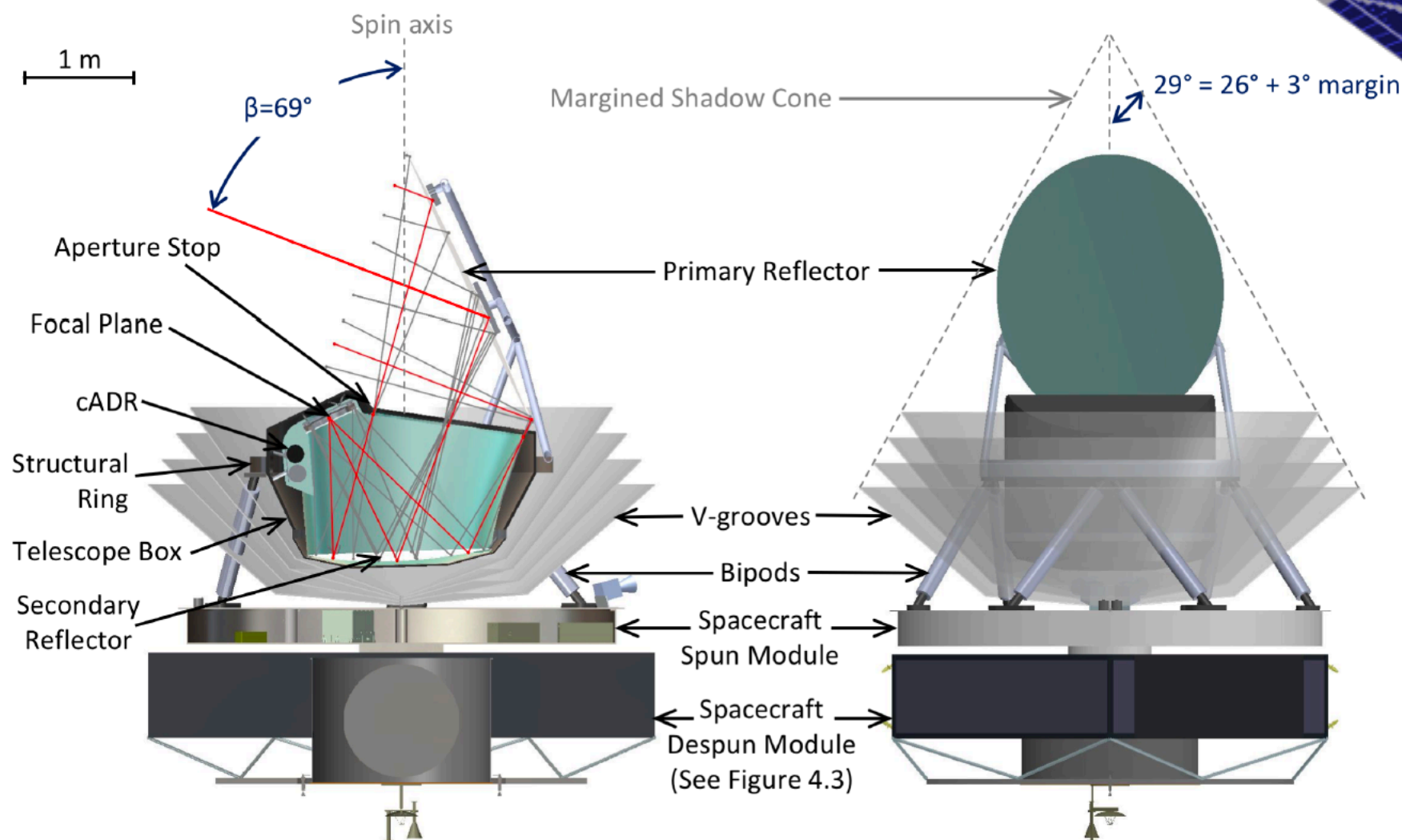
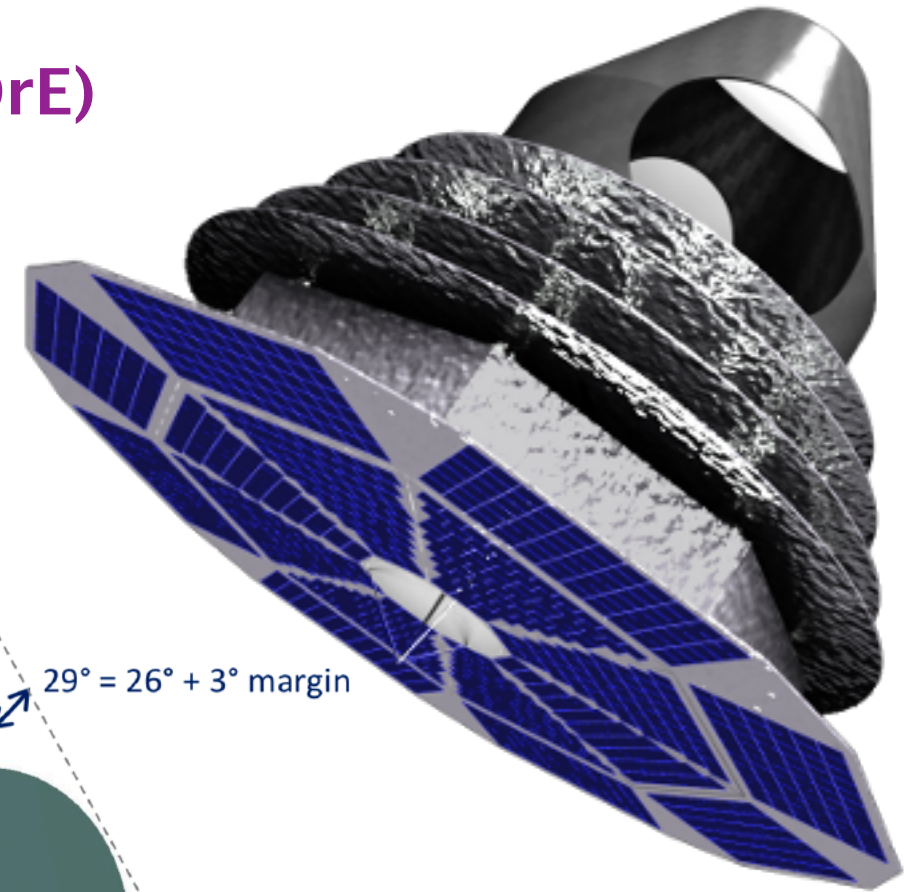


Slide courtesy: E. Komatsu

# Future space-missions/concepts

## Cosmic Origins Explorer (CORe)

## Voyage-2050 Mission Concept



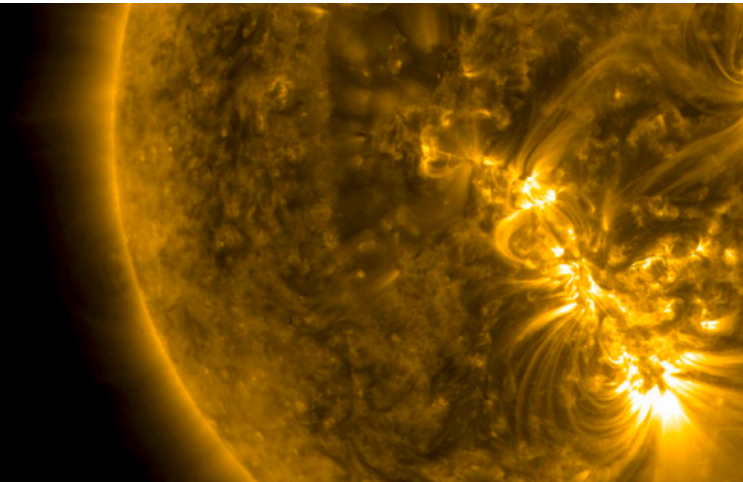


# Selection of CMB science for *Voyage 2050*

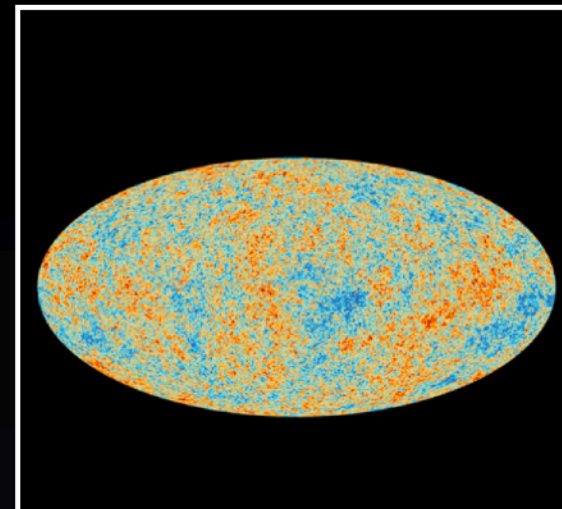
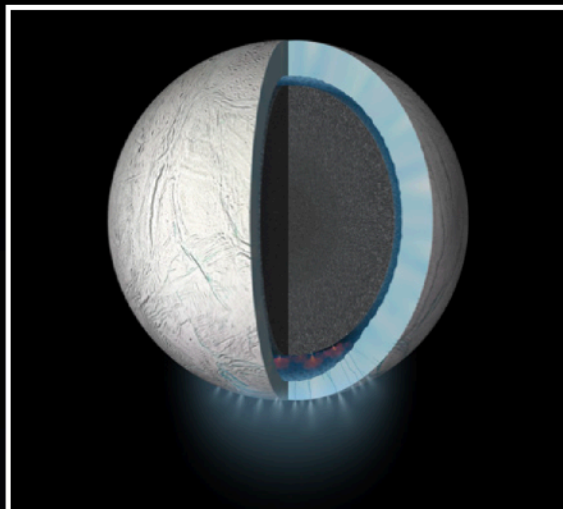
[https://www.esa.int/Science\\_Exploration/Space\\_Science/Voyage\\_2050\\_sets\\_sail\\_ESA\\_chooses\\_future\\_science\\_mission\\_themes](https://www.esa.int/Science_Exploration/Space_Science/Voyage_2050_sets_sail_ESA_chooses_future_science_mission_themes)

## Voyage 2050

Final recommendations from  
the Voyage 2050 Senior Committee



- **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*.



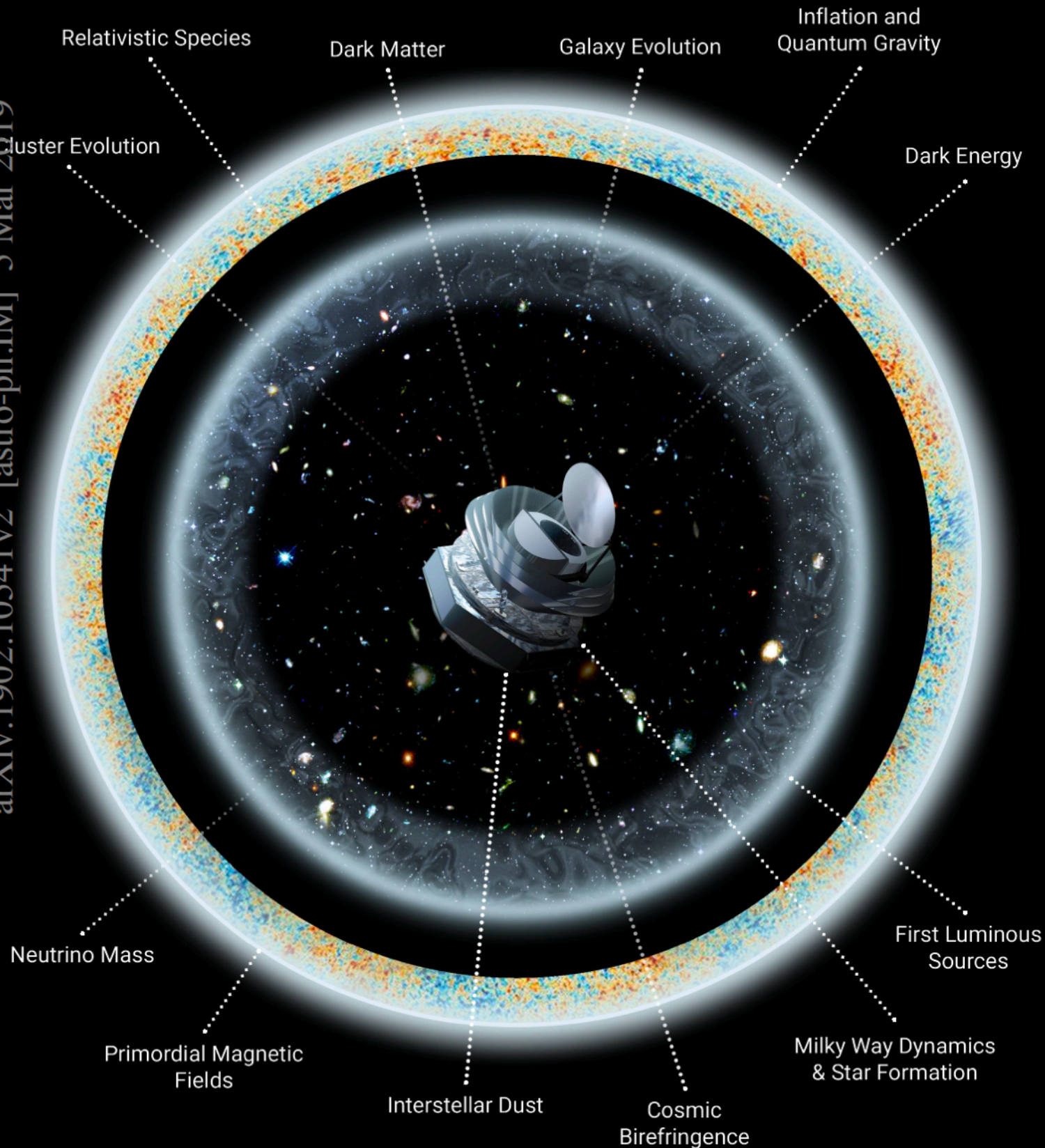
July 2021



# PICO

PROBE OF INFLATION  
AND COSMIC ORIGINS

arXiv:1902.10541v2 [astro-ph.IM] 5 Mar 2019



## 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  $5 \times 10^{15}$  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 $N_{\text{eff}}$*

**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)

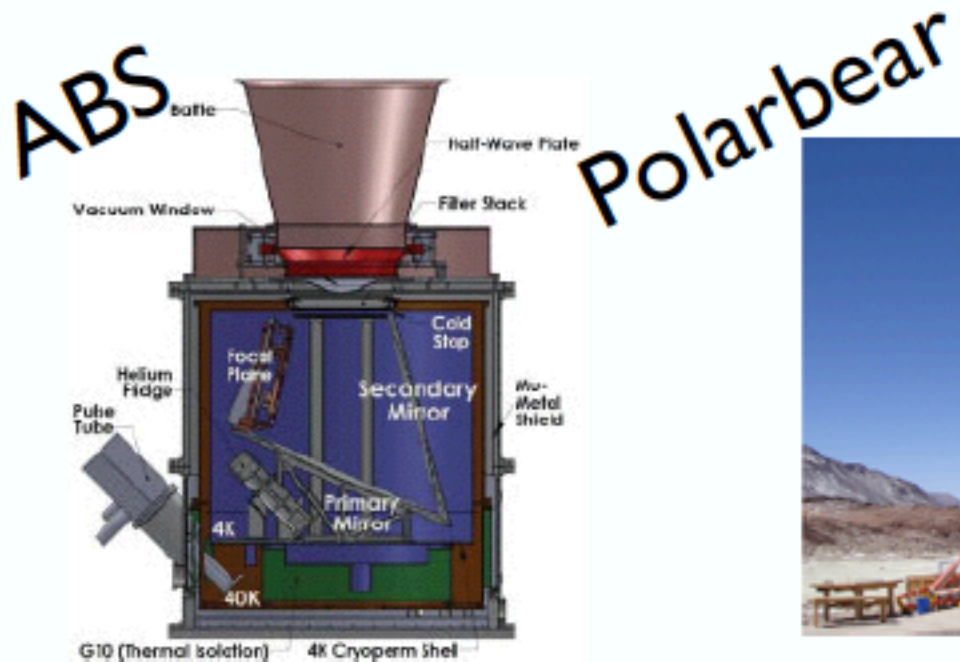
**SO7.** Determine if magnetic fields are the dominant cause of low Galactic star-formation efficiency (§ 2.5.2)



# Current/recently concluded ground-based experiments



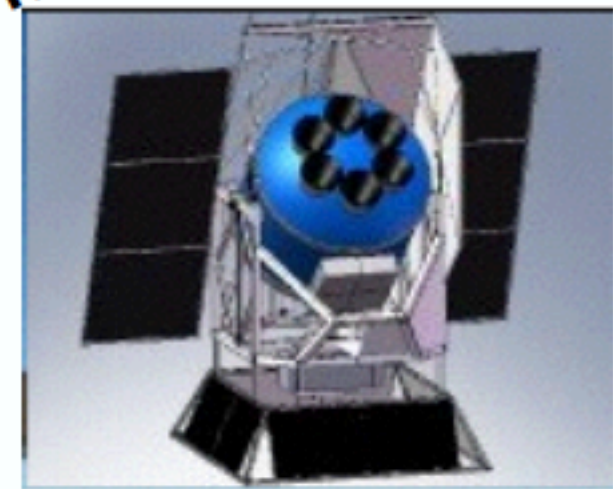
Have broad science range



Polarbear



SPIDER

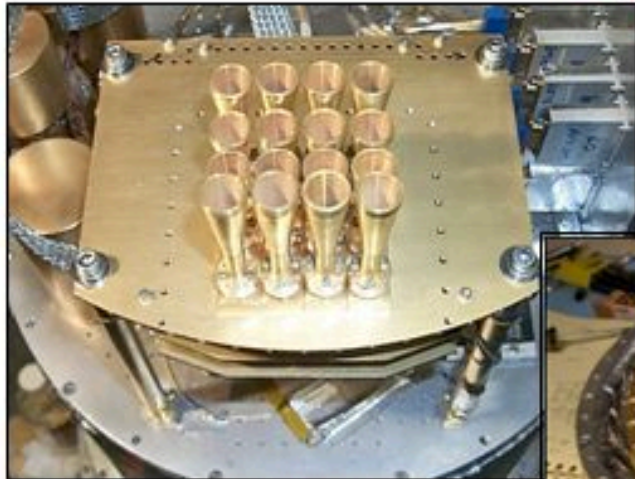


Dedicated to r



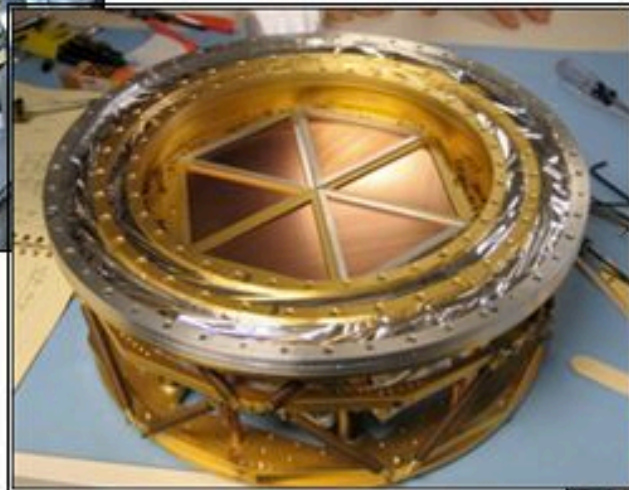
# Evolution of CMB detector assembly (bolometer arrays)

2001: ACBAR  
16 detectors



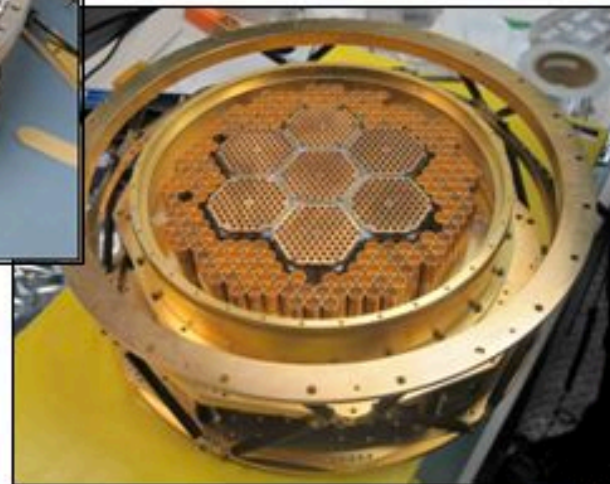
**50x improvement**

2007: SPT  
960 detectors



**Add polarization**

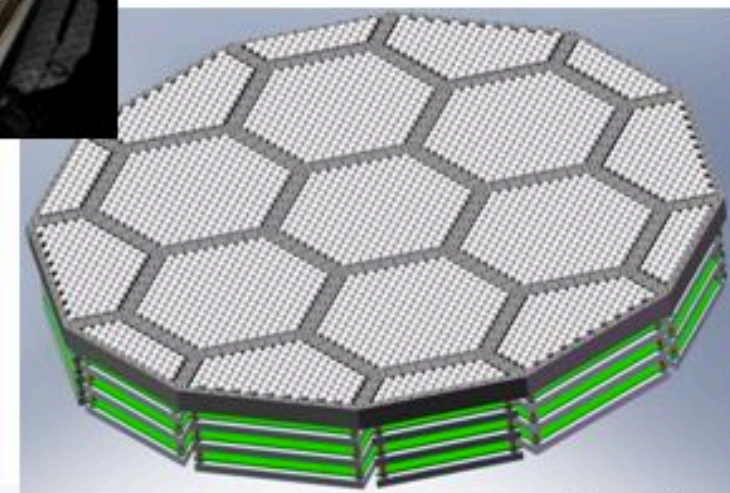
2012: SPTpol  
~1600 detectors



(Credit: SPT collaboration)

**10x improvement**

2016: SPT-3G  
~15,200 detectors

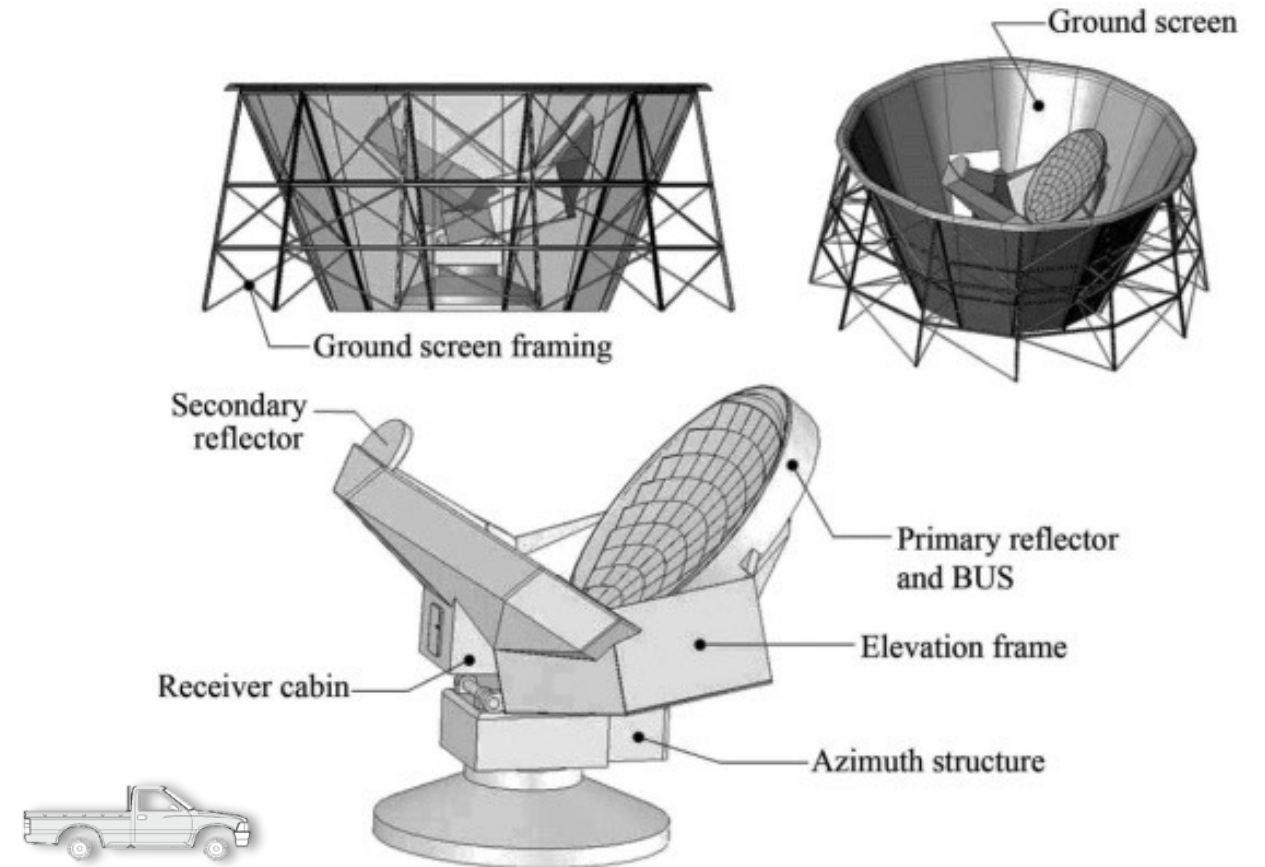
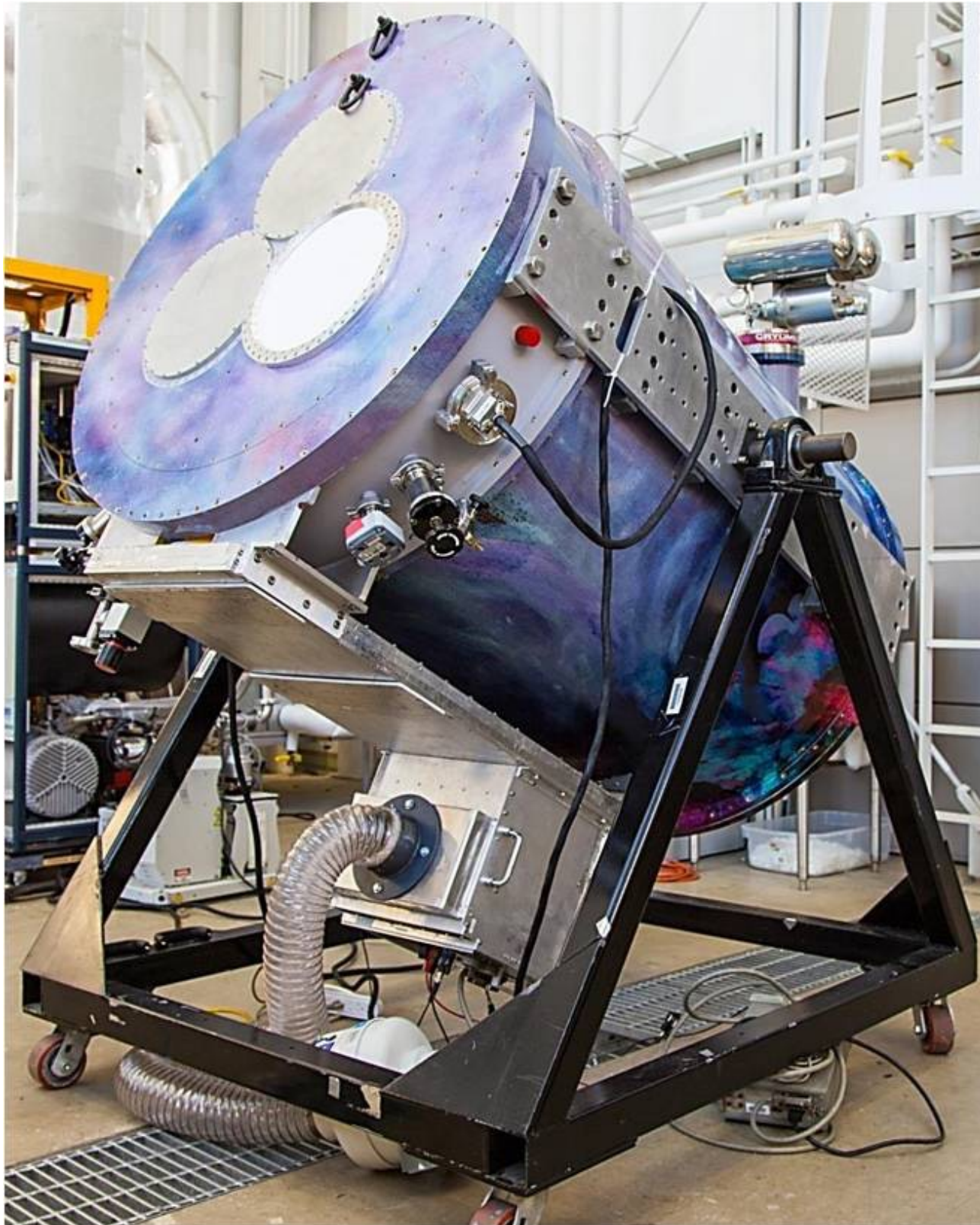


Novosad, et al.

Evolution of the SPT detector assembly



# 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

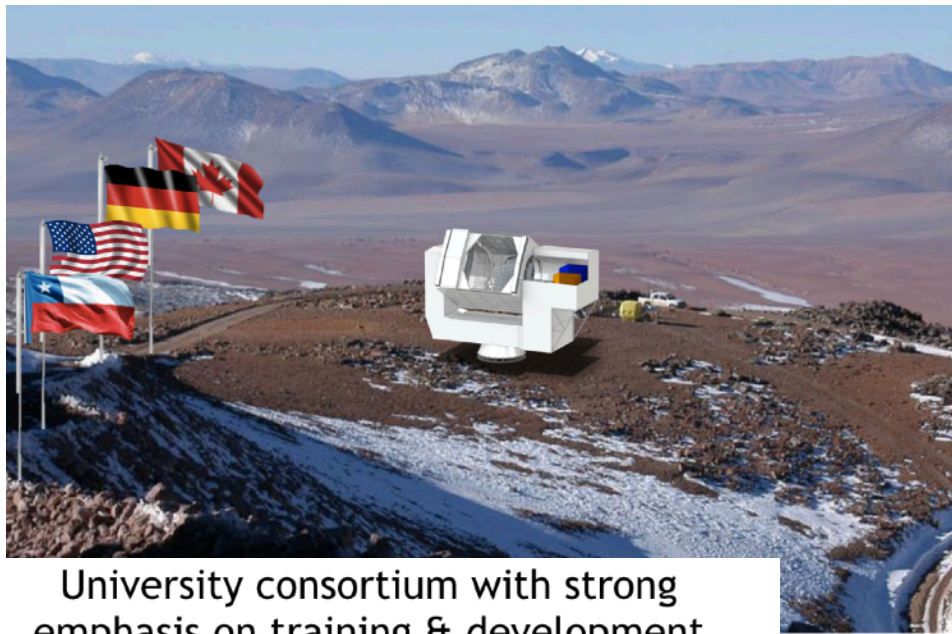


<https://www.simonsfoundation.org/series/the-eternal-sky/>





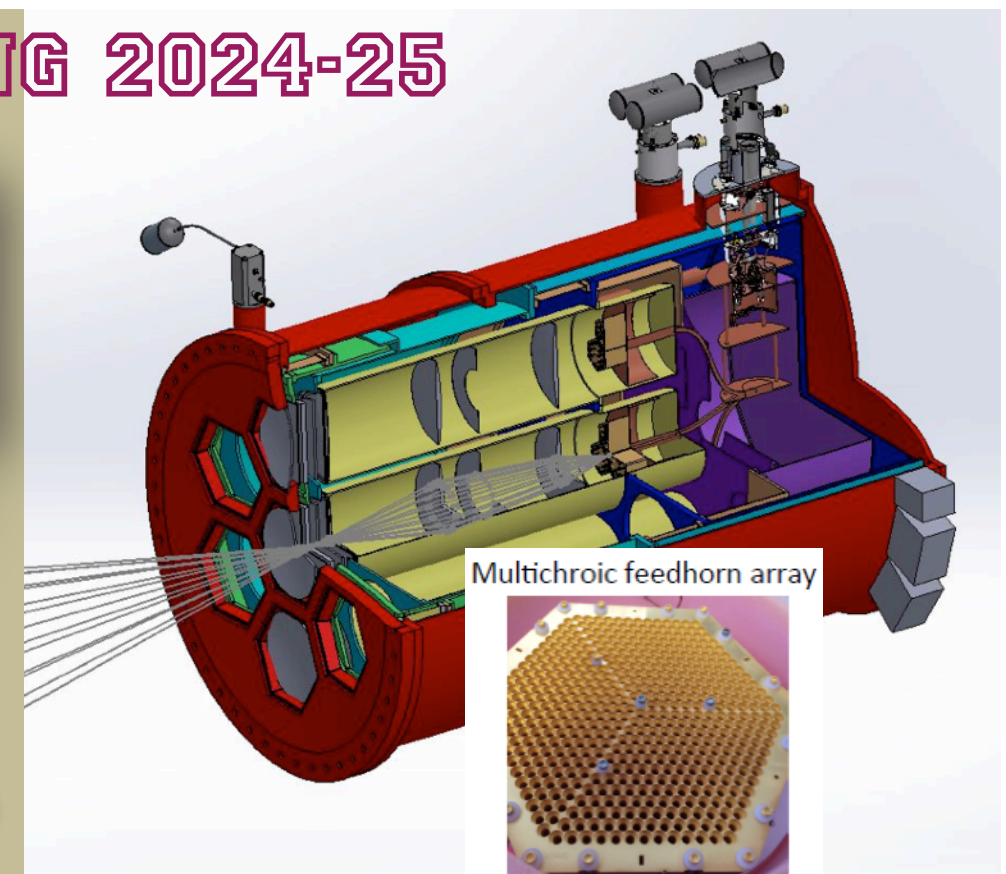
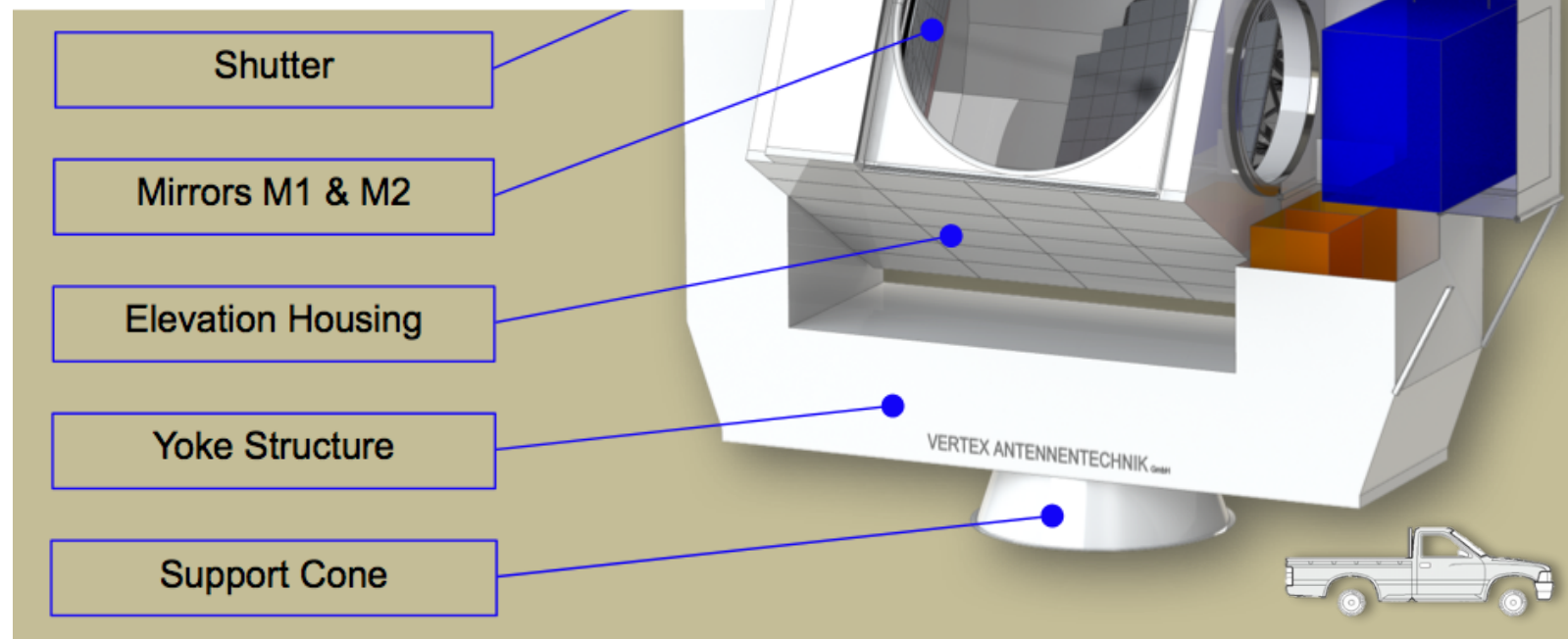
# CCAT-prime: A submillimeter CMB experiment with Bonn University as partner



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%**





# Questions?



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