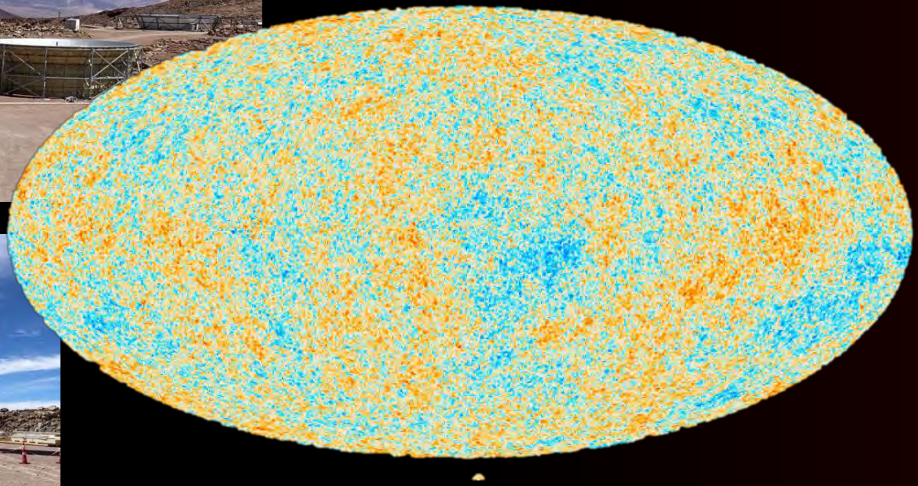
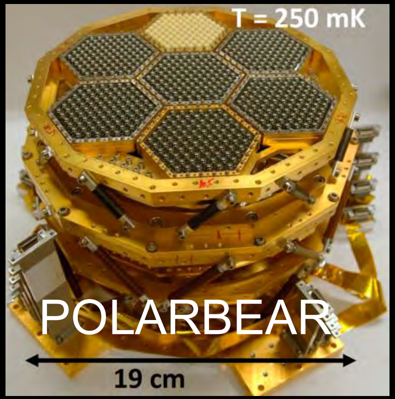
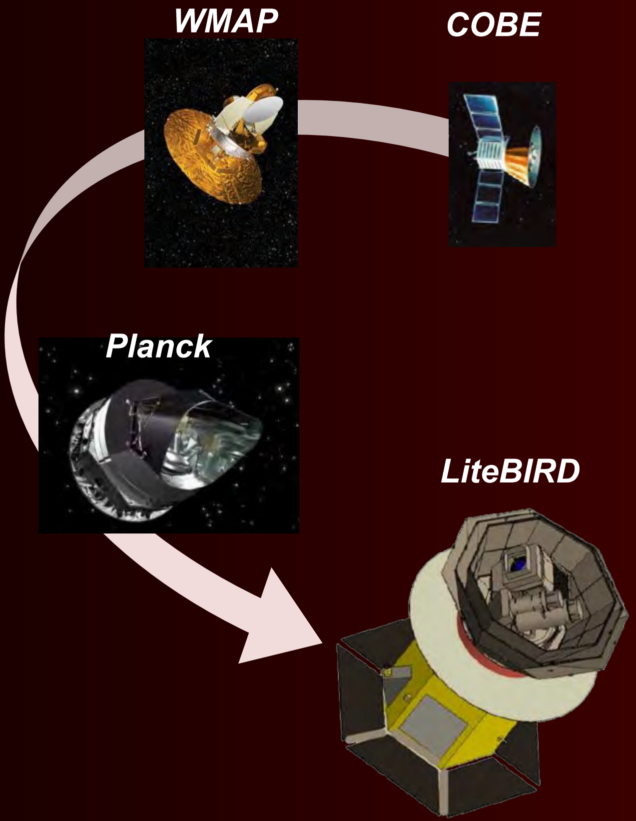
Cosmology with Cosmic Microwave Background (CMB)







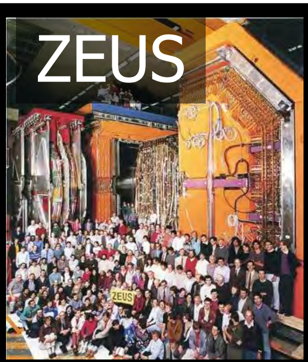
Masashi Hazumi

KEK / JAXA / Kavli IPMU / SOKENDAI

Self-Introduction

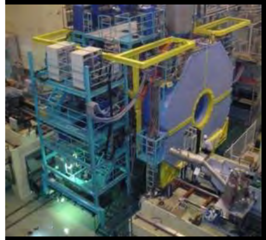
1988	1990	1992	1994	1996	1998	2000	2002	2004	2006	2008	2010	2012	2014	2016	2018	2020	2022	2024	2026

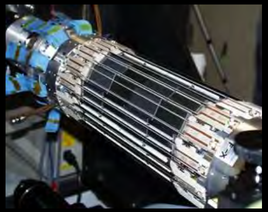
Experimental Particle Physics



PhD thesis : Search for Leptoquarks

B factory at KEK

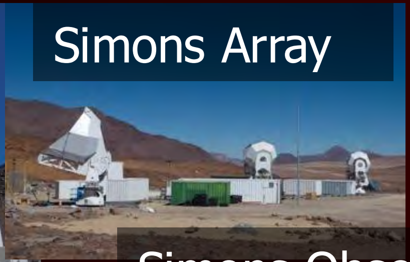




Discovery of CP violation in B meson decays

Experimental Cosmology

CMB B mode polarization to test cosmic inflation



LiteBIRD

Simons Observatory

Scintillator

Trigger

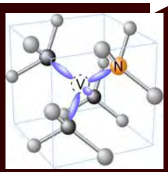
Semiconductor Detectors

Superconducting Detectors

Quantum Metrology

KTeV

Founding director of the International Center for Quantum-field measurement systems for studies of the Universe and Particles (QUP) at KEK



Measurement Methodology for Fundamental Physics (with theorists)

How did I get excited about CMB?

Three reasons

1. We could observe quantum fluctuations of space-time!
2. We could explore GUT-scale physics!
3. We have fantastic technology matching with HEP!

Outline

1. History and Key Concepts
2. Key Observations after COBE
3. CMB Polarization as the New Frontier
4. On-going and Future Projects
5. Epilogue

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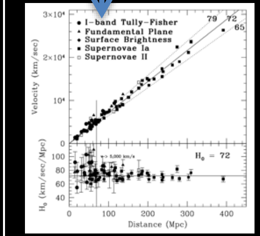
Research History on Our Expanding Universe in 20th Century

Recent meas.

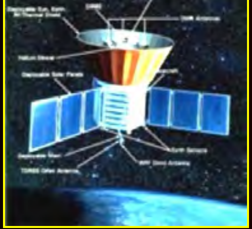


Red shift of distant galaxies (Hubble)

Our universe is expanding !

1929

COBE



Mather

Smoot

Nobel (2006)

now

- Proof of black-body radiation
- CMB anisotropy → Indication of cosmic inflation

1991

1965

Nobel (1978)

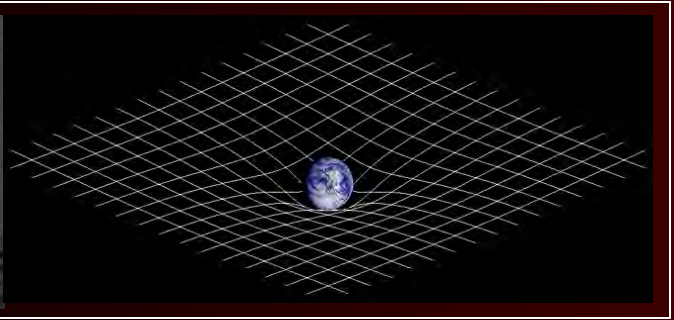
Cosmic Microwave Background (CMB)

Direct evidence for Hot Big Bang !

1915

Spacetime curvature is determined by matter and radiation.

General relativity (Einstein)



Discovery of CMB (1965)

THE COSMIC MICROWAVE BACKGROUND RADIATION

Nobel Lecture, 8 December, 1978

by
ROBERT W. WILSON
Bell Laboratories
Holmdel, N.J. U.S.A.

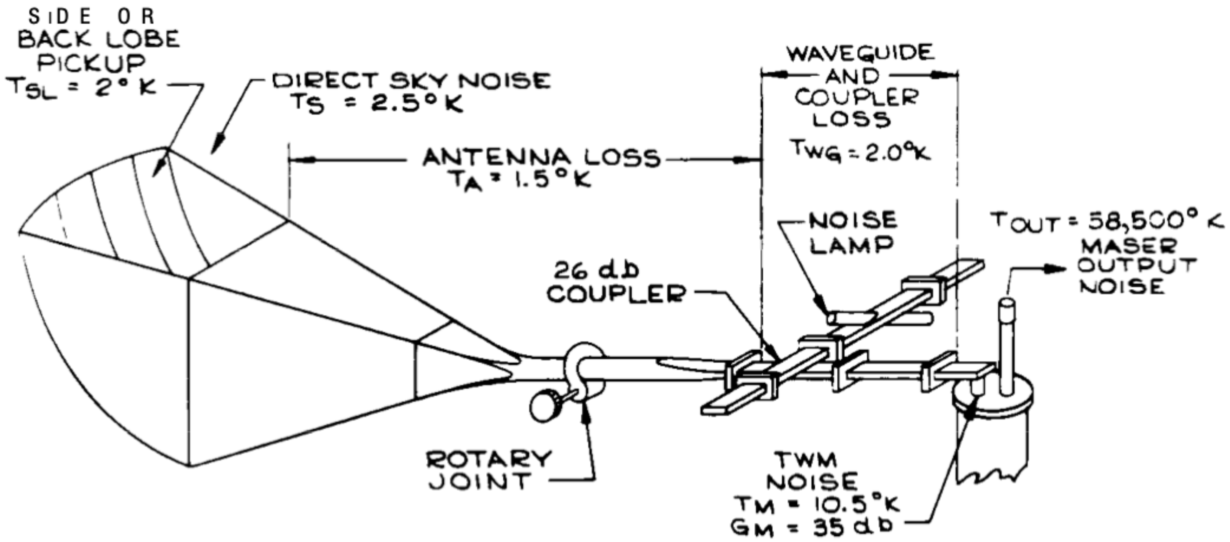


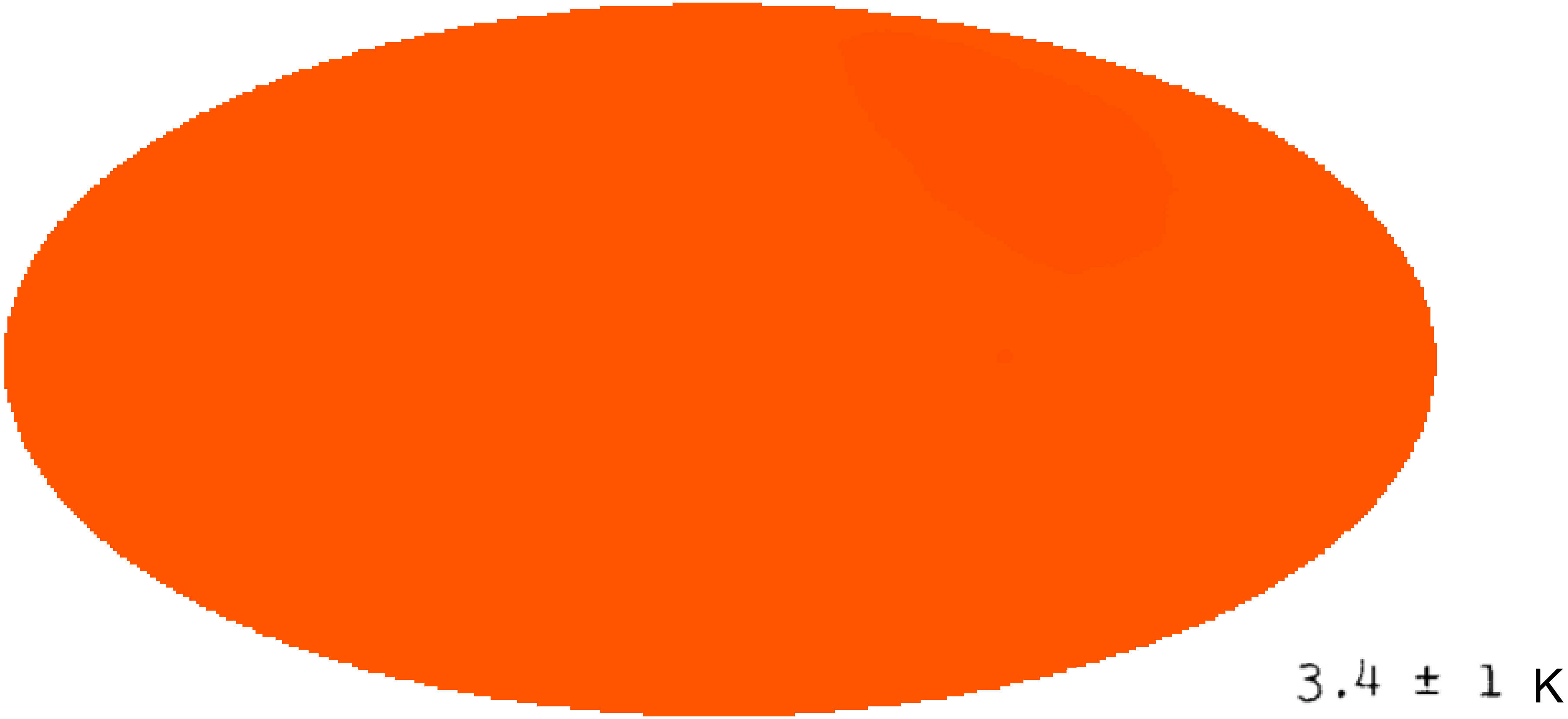
Fig. 6 A diagram of the low noise receiver used by deGrasse, Hogg, Ohm and Scovil to show that very low noise earth stations are possible. Each component is labeled with its contribution to the system noise.

	New Throat		Old Throat
He Temp.	4.22	4.22	
Calculated Contribution from Cold Load Waveguide	.38	.70 ± 0.2	
Attenuator Setting for Balance	2.73	2.40 ± 0.1	
Total C.L.	7.33	7.32 ± 0.3	6.7 ± 0.3
Atmosphere		2.3 ± 0.3	2.3 ± 0.3
Waveguide and Antenna loss		1.8 ± 0.3	.9 ± 0.3
Back lobes		.1 ± 0.1	.1 ± 0.1
Total Ant.		4.2 ± 0.7	3.3 ± 0.7
Background		3.1 ± 1	3.4 ± 1

Fig. 10 Results of our 3965 measurements of the microwave background. "Old Throat" and "New Throat" refer to the original and a replacement throat section for the 20 foot horn-reflector.

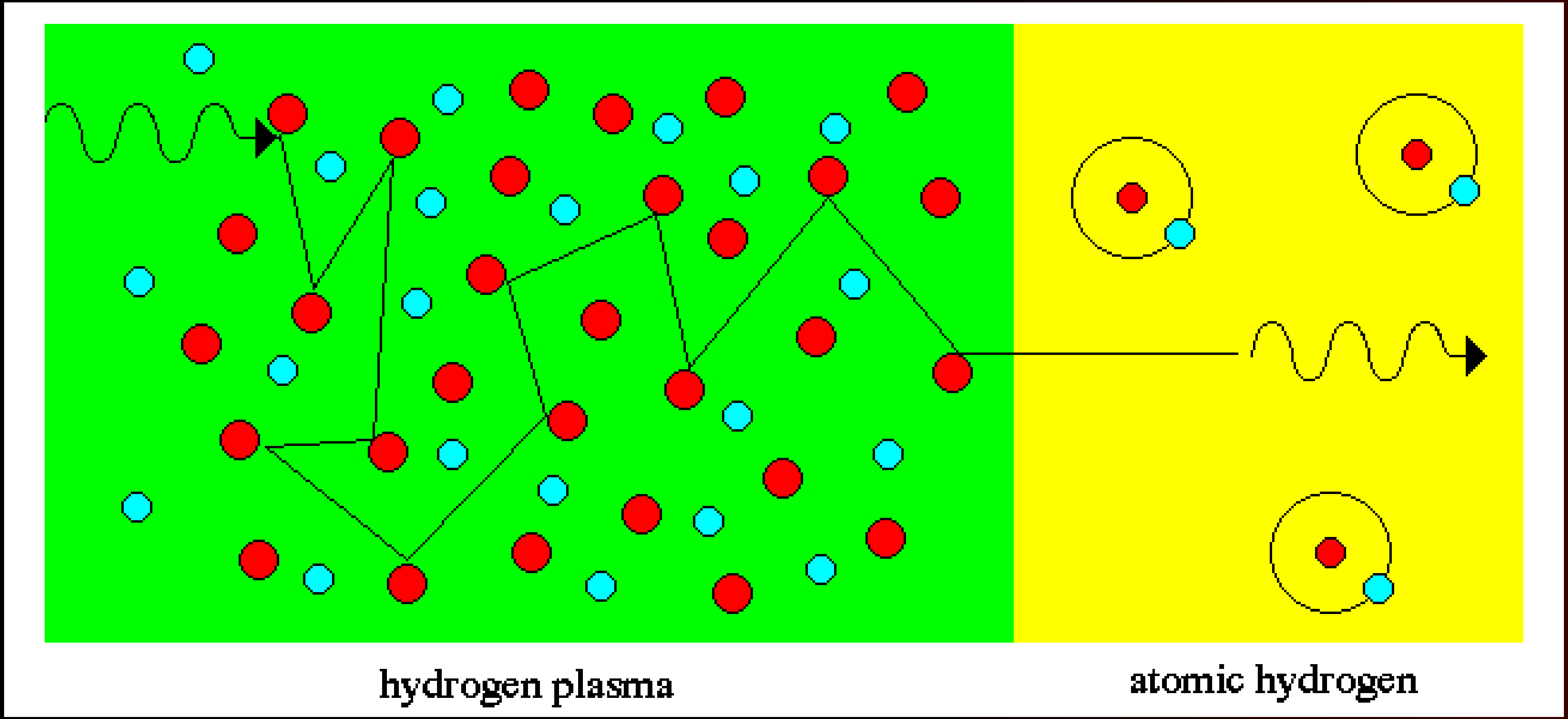
- Serendipity
- Calibration and Control of Systematics

CMB Map



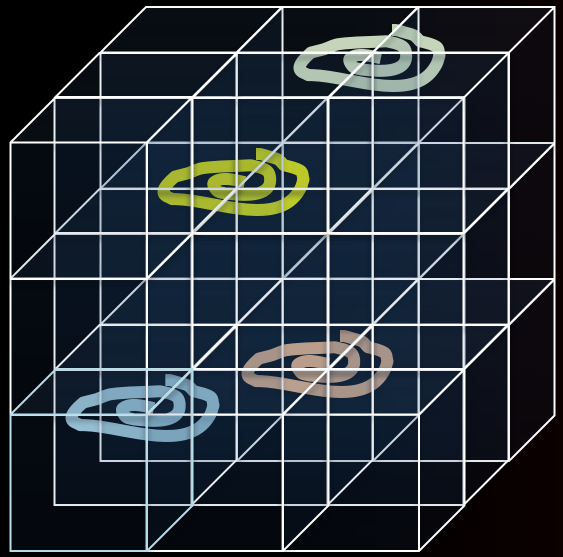
Microwaves are coming from all over the universe!

Cosmic Microwave Background (CMB)

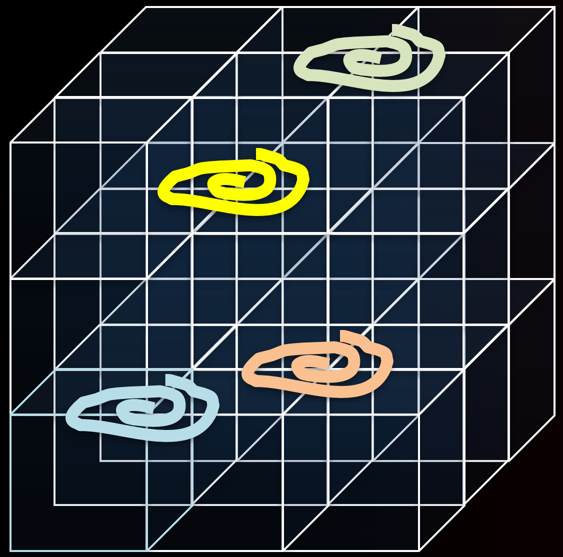


https://pages.uoregon.edu/jschombe/cosmo/lectures/lec23.html

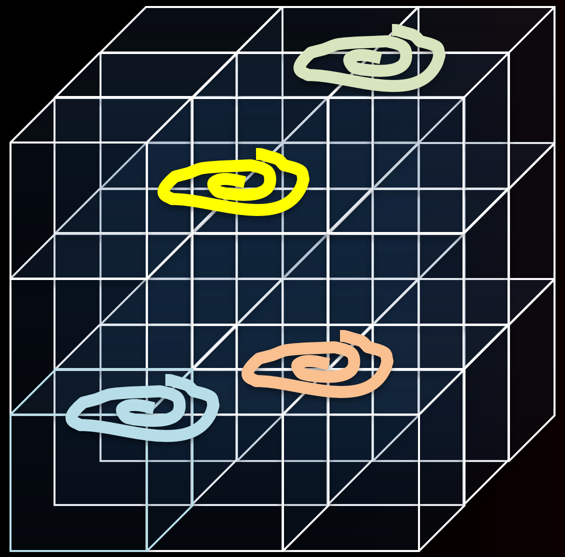
What is “expansion” of the universe?



What is “expansion” of the universe?

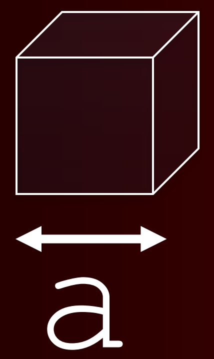


What is "expansion" of the universe?



The scale of our universe
is expressed by just one quantity,

scale factor a



What do we know about time evolution of a ?

Friedmann equation

- Einstein equation gives time evolution of metric $g_{\mu\nu}$ from first principle.

- Imposing "Cosmological principle": no special place in the universe

$$g_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & a^2(t) & 0 & 0 \\ 0 & 0 & a^2(t) & 0 \\ 0 & 0 & 0 & a^2(t) \end{pmatrix}$$

Friedmann Eq. for flat universe

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$$

→ energy density of matter and radiation

In particular, $\dot{a} > 0$ Expanding universe !

Yet another Friedmann equation

Pressure

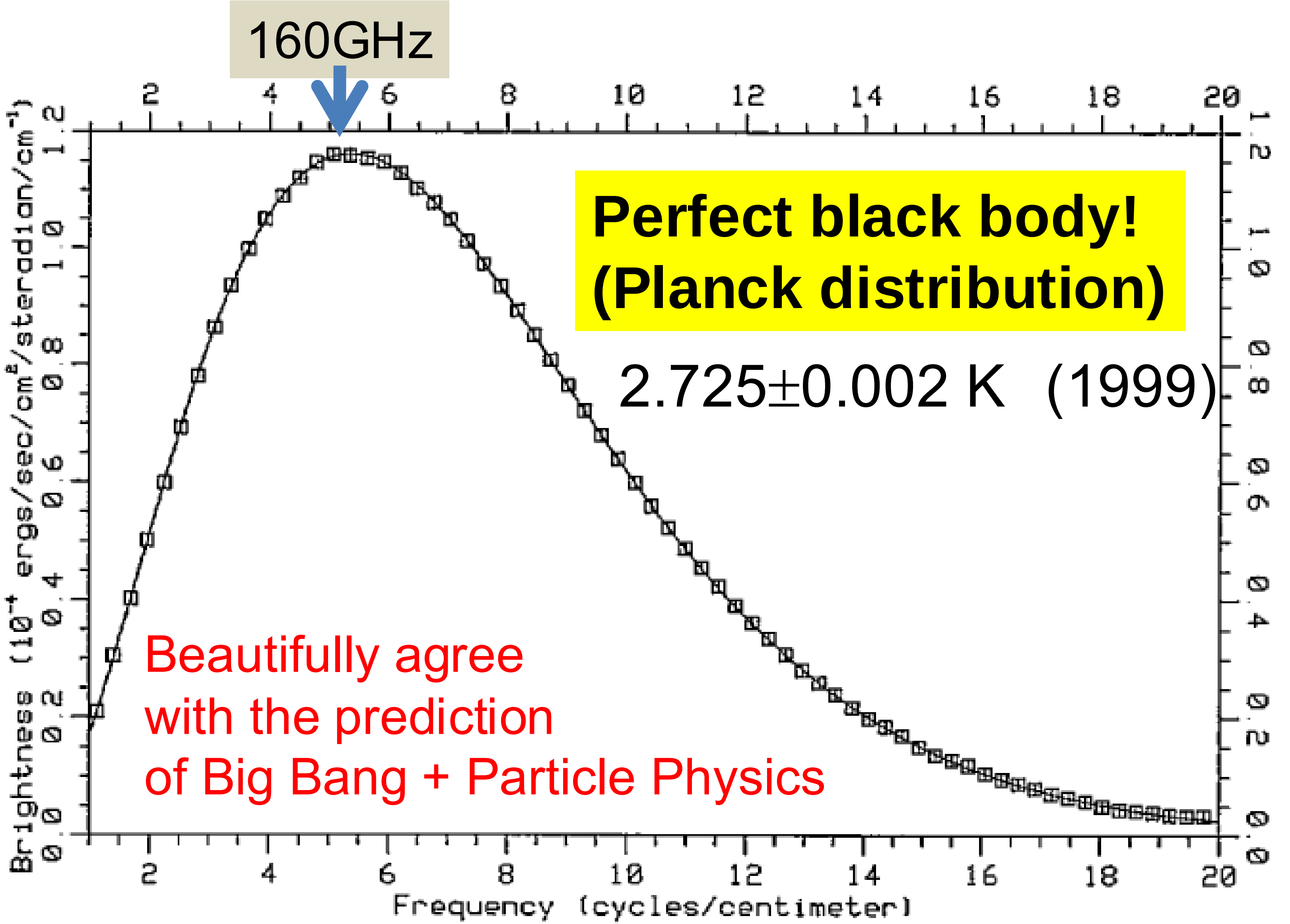
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

>0 for matter and radiation

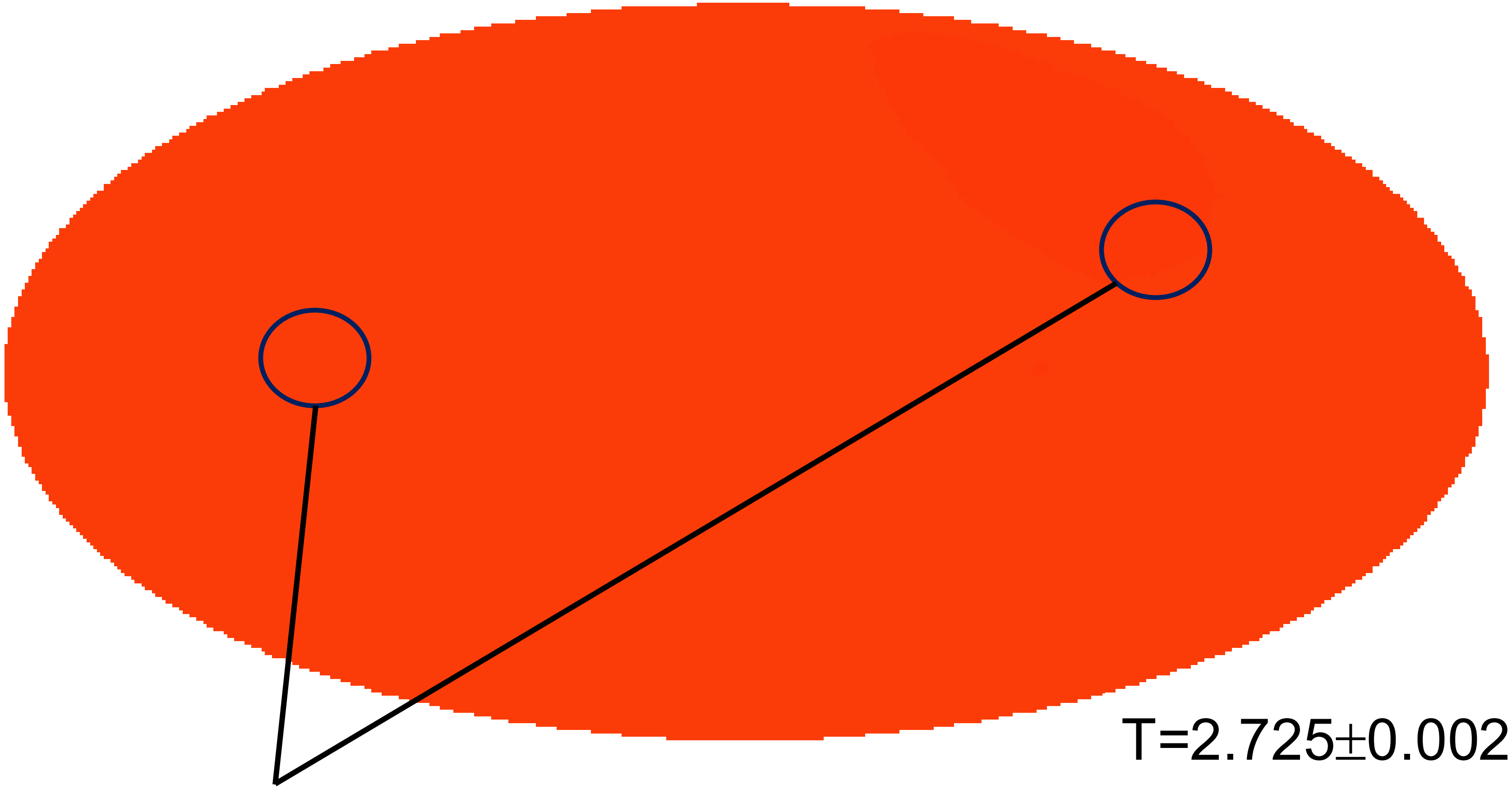
$$\ddot{a} < 0$$

With known matter and radiation,
our universe should always be decelerating

COBE Satellite



(One of) Limitations of the Big Bang Theory: The Horizon Problem



T=2.725±0.002 K

Too far apart to exchange information in the past.
Why is the temperature (intensity) of the CMB the same?

Inflation hypothesis (~1981)

Accelerating expansion before the hot big bang

Impossible within the Standard Model of Particle Physics !

Resolve outstanding problems of the naïve big bang model

- Horizon problem
- Flatness problem
- Structure formation
- Cosmological principle derived

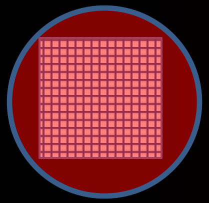
Katsuhiko Sato

Andrei Linde

Alan Guth

Alexei Starobinsky

Enormous Accelerating Expansion of Inflation



$$\ddot{a} > 0$$

New Physics required!

In 0.000000000000000000000000000000000001 second,
10000000000000000000000000 times !

Prediction of a New Particle "Inflaton"

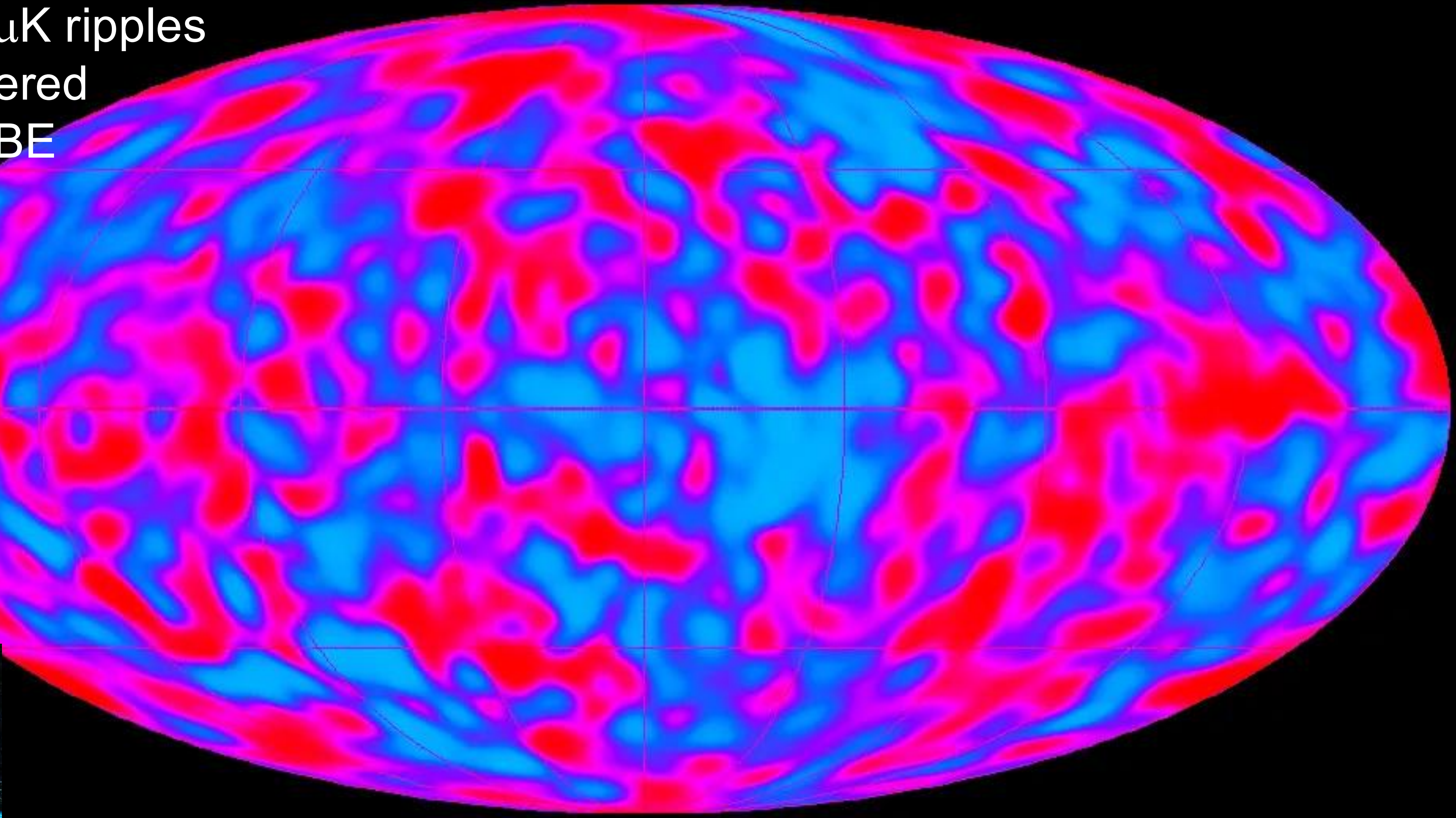
Scalar particles with the wave function ϕ and the potential $V(\phi)$ that filled the primordial Universe For a very short time

$$p = \frac{\dot{\phi}^2}{2c^2} - V(\phi)$$

No way,
negative pressure!

Inflaton is the "gas pedal" of the Universe.
It can make things happen beyond common sense.

O(10) μK ripples discovered by COBE



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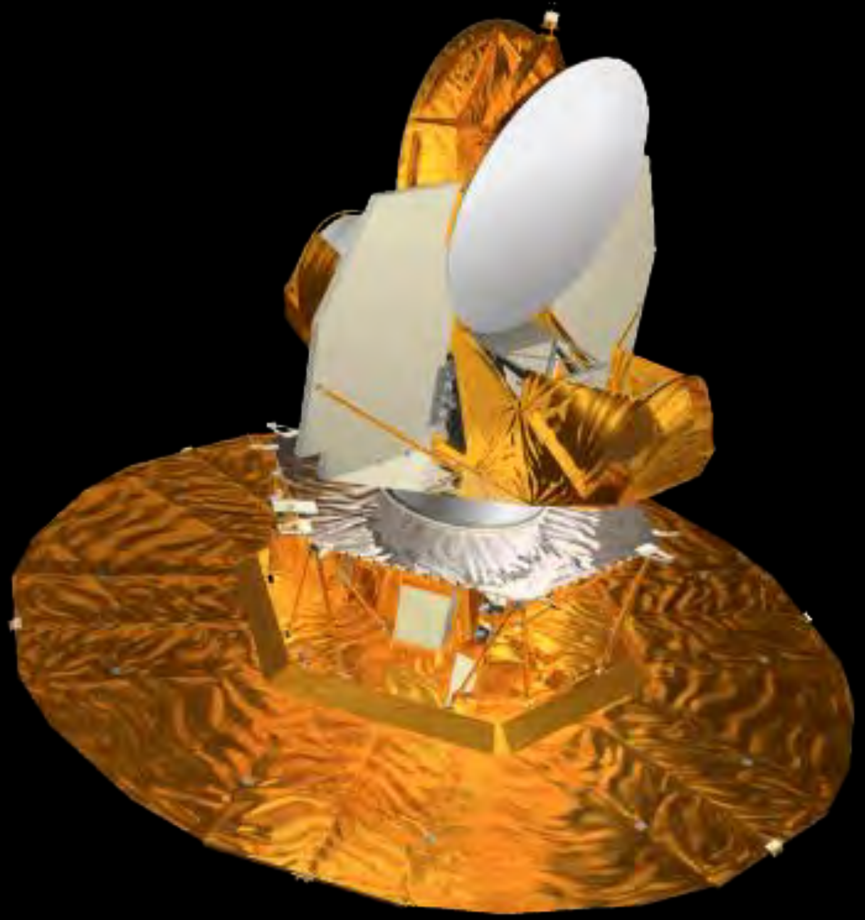
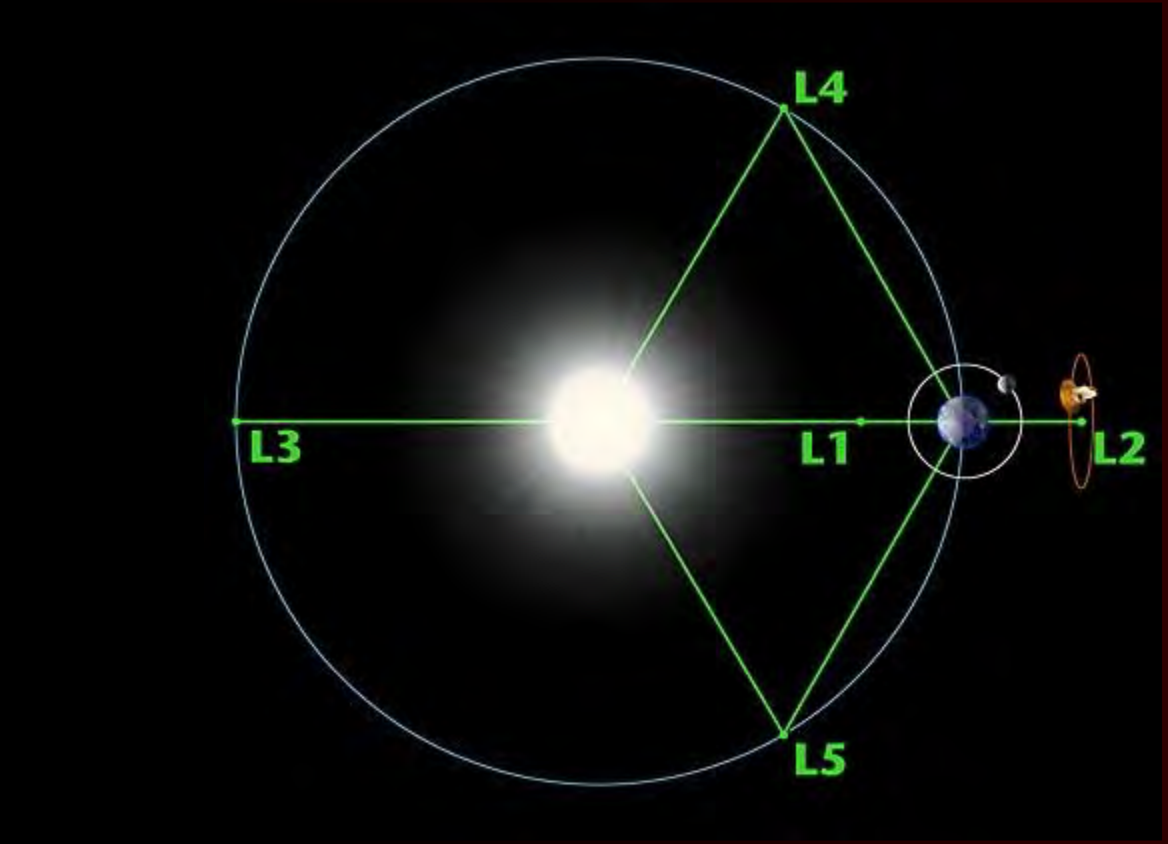
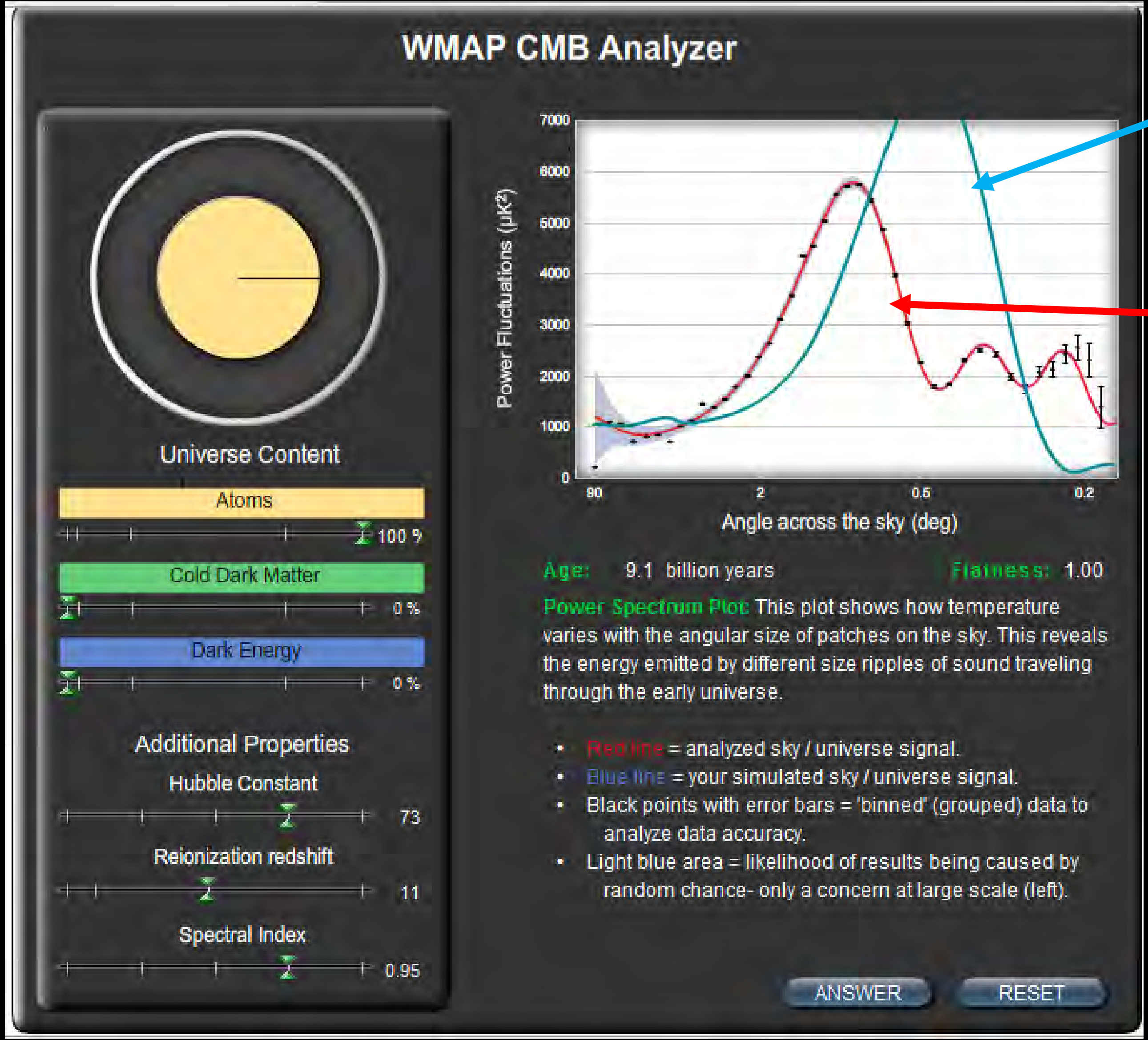
CMB Satellite in 21st Century (1): WMAP



Observations were carried out at the Sun-Earth Lagrangian point (L2), which is 1.5 million kilometers (!) away from the Earth.

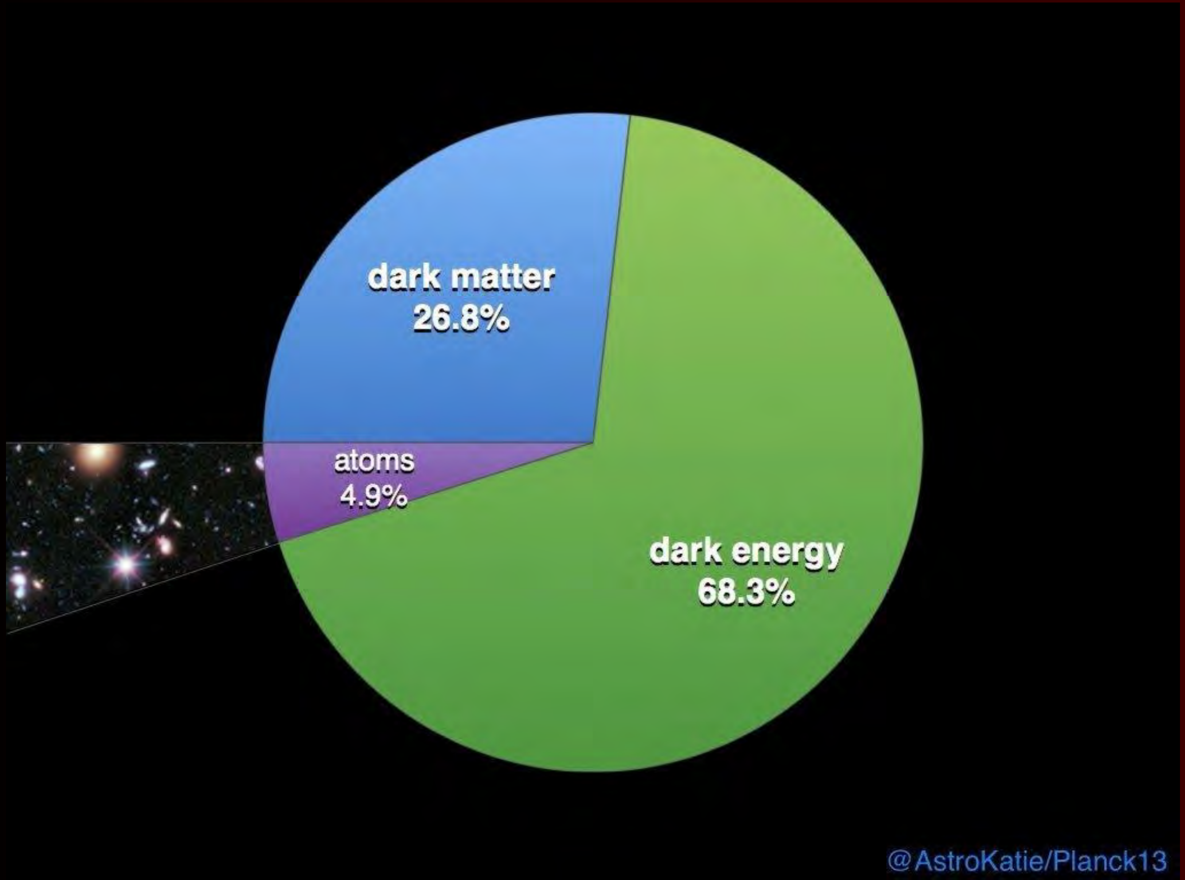


- Launch in 2001
- Observations completed in August 2010



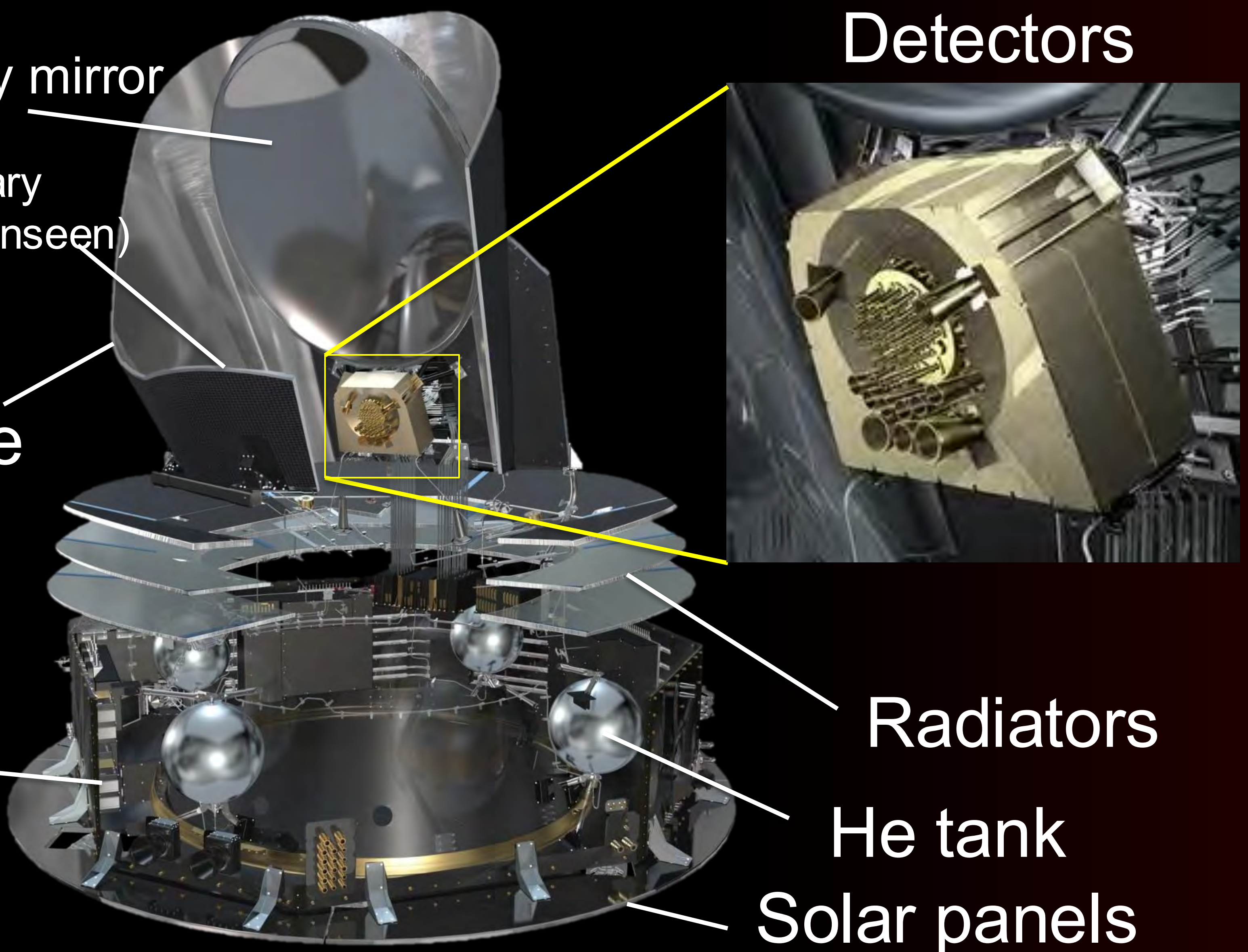
Fit with the standard model of particle physics (i.e. without dark matter, dark energy)

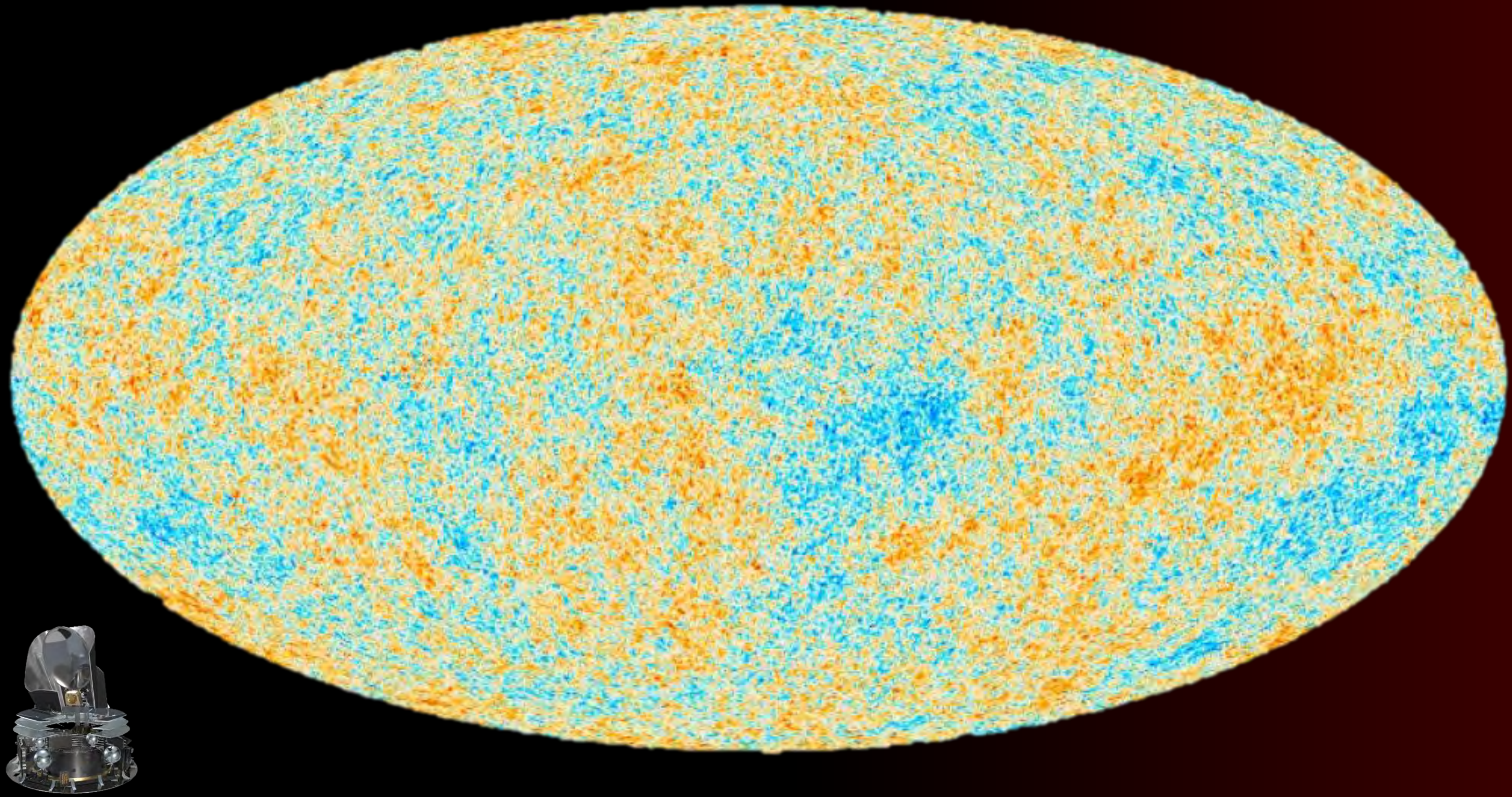
Fit with the concordance model in cosmology



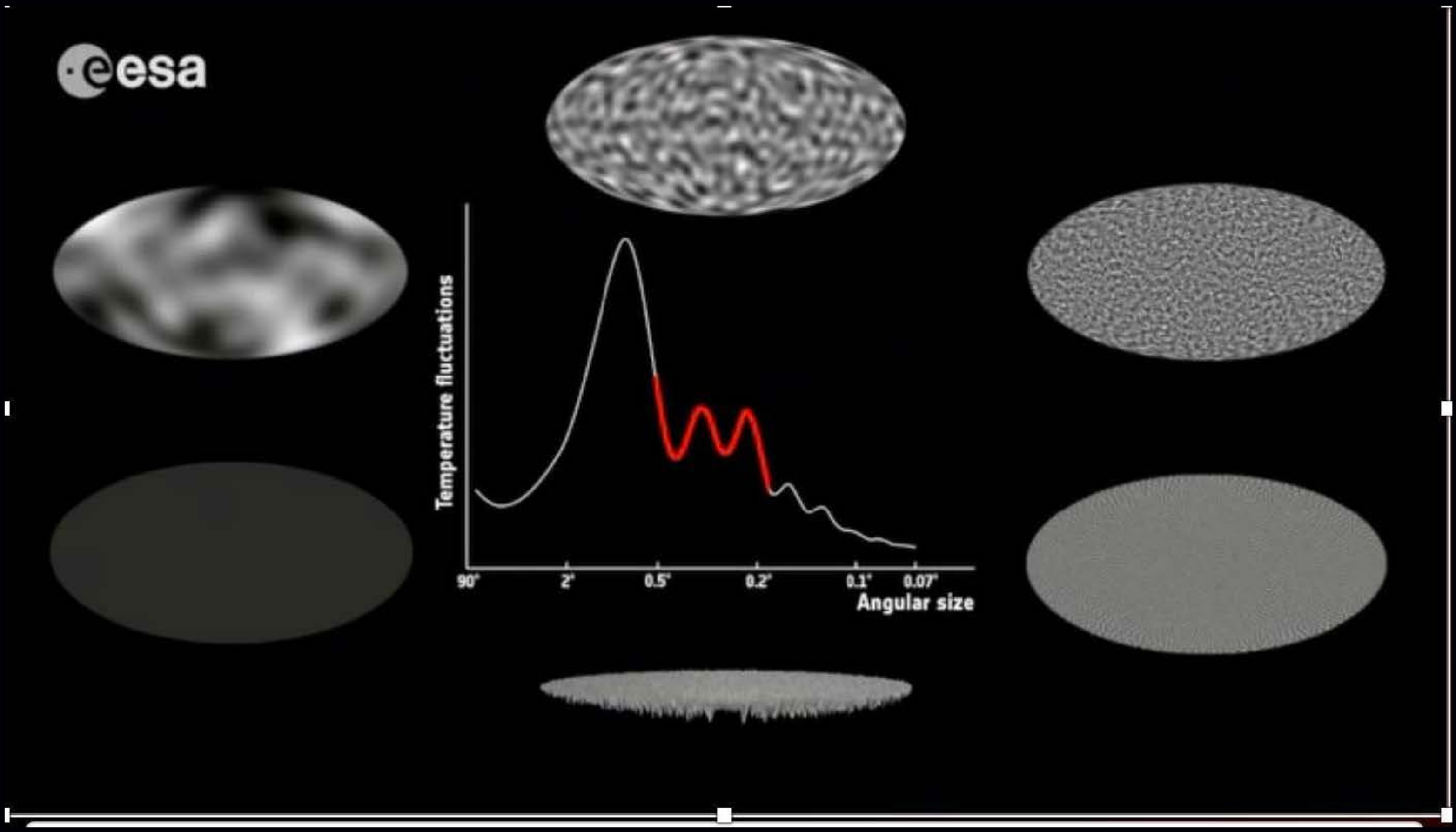
http://map.gsfc.nasa.gov/resources/camb_tool/cmb_plot.swf

CMB Satellite in 21st Century (2): Planck

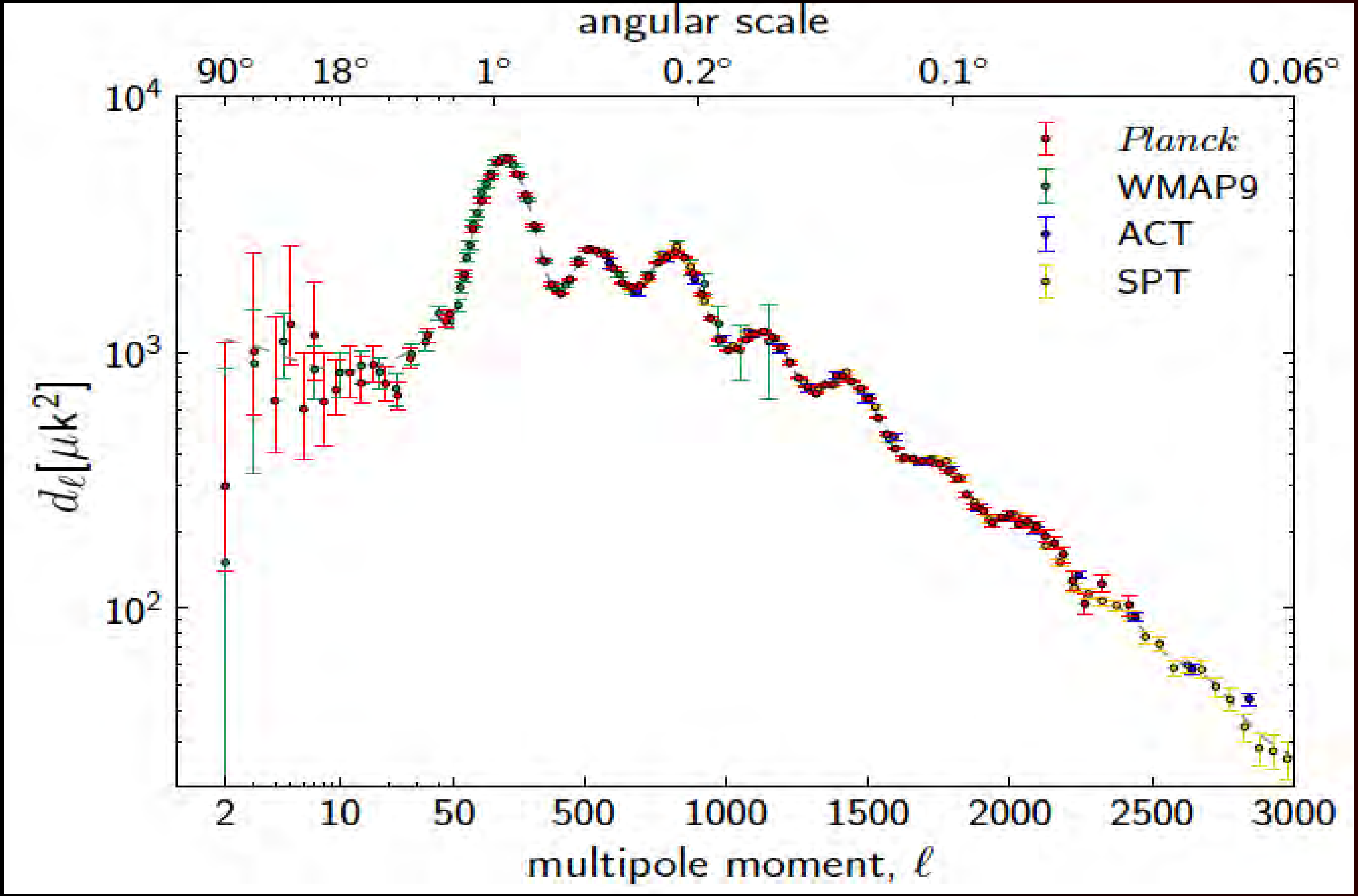




Spectral analysis



CMB Temperature Anisotropy Today



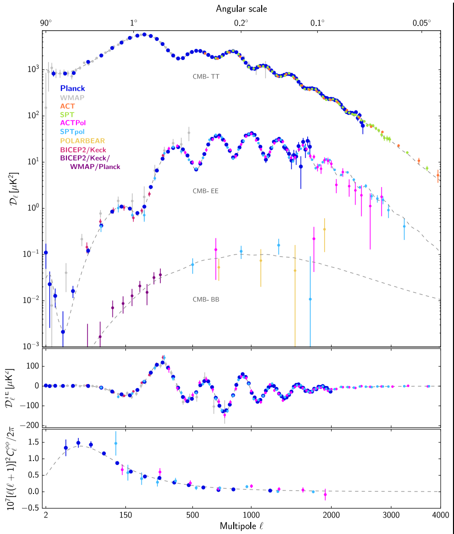
Concordance Model of Cosmology (ΛCDM)

In a nutshell

- General relativity + cosmological principle
  - Physical existence of space is expressed by the scale "*a*" alone
  - Friedmann equation for the time evolution of flat universe →

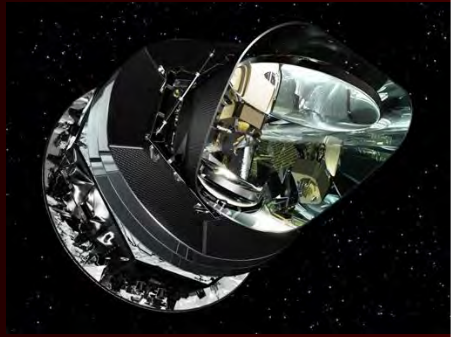
$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3}$$

- Initial adiabatic, Gaussian perturbation (consistent with inflation hypothesis)
- Only six fit parameters are sufficient to describe the current set of precision data!



Parameter	*Planck* alone	*Planck* + BAO
$\Omega_b h^2$	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9649 ± 0.0042	0.9665 ± 0.0038

Planck 2018



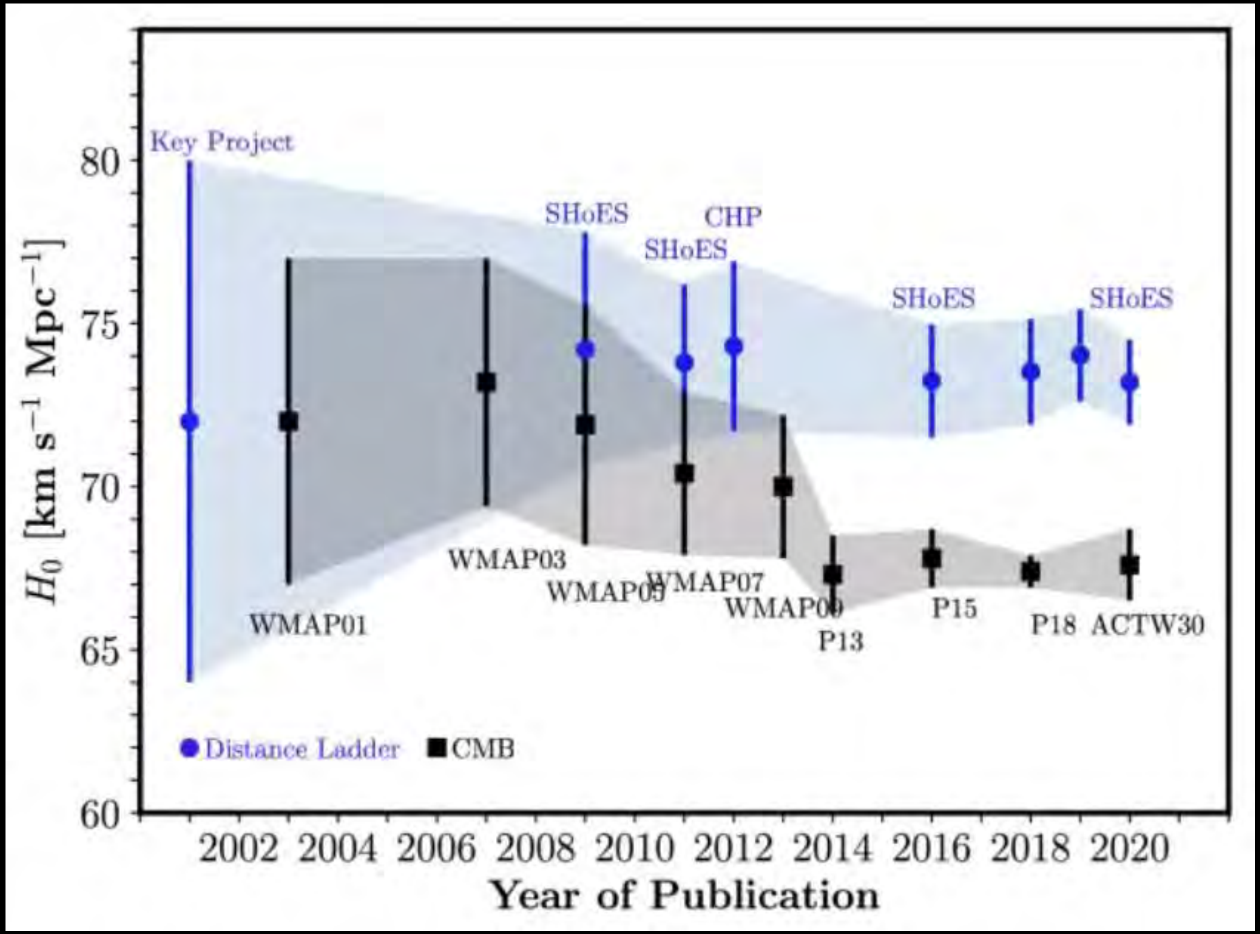
Other parameters (e.g. Ω_Λ, t_0) are derived.

Dark Energy (69%) | Dark Matter (26%) | 5 %

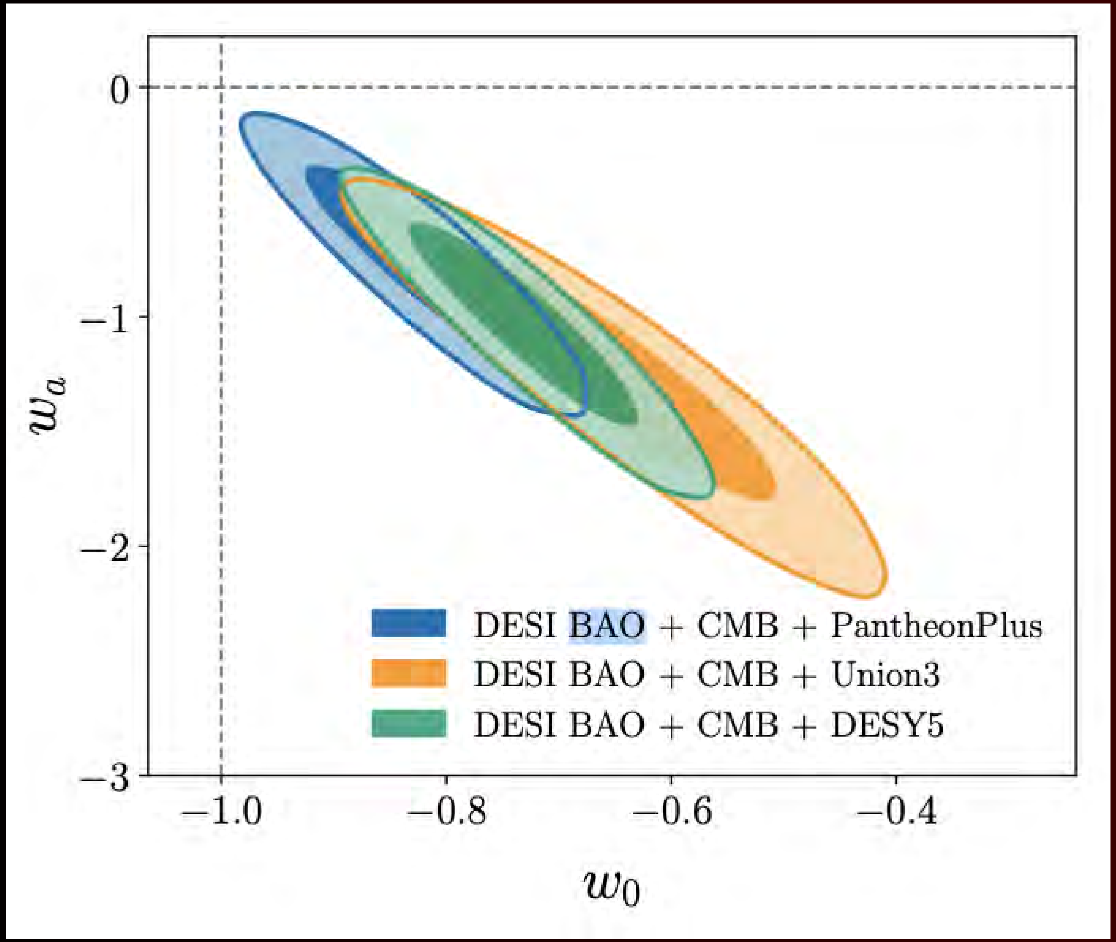
← Baryon

Tantalizing hints of beyond-ΛCDM anomalies

Hubble Tension



Deviation from Λ



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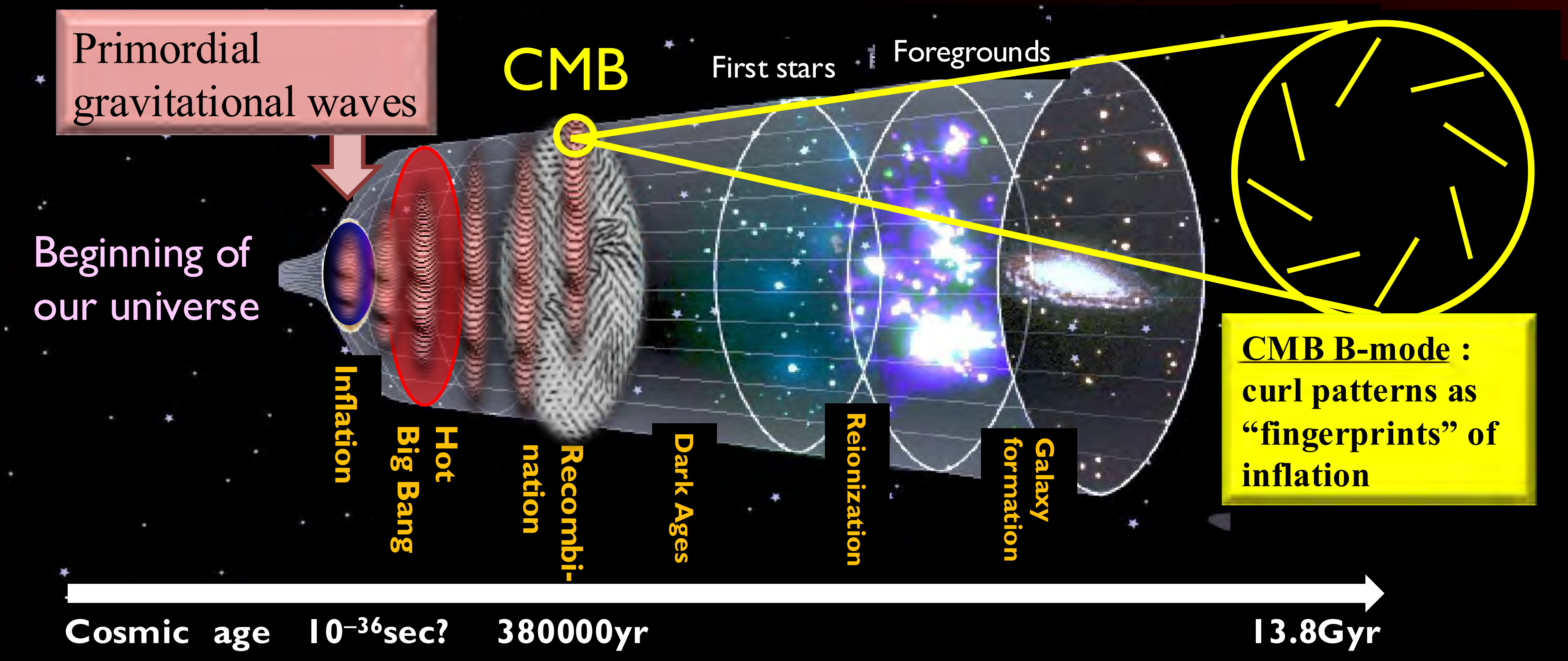
Testing cosmic inflation and quantum gravity with polarization of cosmic microwave background (CMB)



- By far, the most sensitive probe of the primordial gravitational waves!
- The B-mode signal is proportional to the inflaton potential V.

Huge discovery impacts

- Direct evidence for inflation
- Knowledge on the inflation energy scale
- First evidence for quantum fluctuation of space-time

Insight on quantum gravity, including String Theory

"Detecting primordial gravitational waves would be one of the most significant scientific discoveries of all time."

Final report of the task force on cosmic microwave background research "Weiss committee report" July 11, 2005, arXiv/0604101

Physics of cosmic inflation

- Cosmic inflation is the accelerating expansion before the hot Big Bang, the leading hypothesis.
- New scalar field ϕ called "Inflaton" with potential V(ϕ) as a source of acceleration.
- In case of single-field slow-roll inflation (simplicity as the guideline), two important relations exist:

1) $$V^{1/4} = 1.04 \times 10^{16} \times \left(\frac{r}{0.01}\right)^{1/4} [GeV]$$

r (tensor-to-scalar ratio) is a key parameter

2) $$r \simeq 2 \times 10^{-3} \left(\frac{60}{N}\right)^2 \left(\frac{\Delta\phi}{m_{pl}}\right)^2$$

$\Delta\phi$: characteristic scale of inflaton field in which inflaton potential changes significantly. (A. Linde JCAP 2017)

Measurements with $\sigma(r) < 0.001$ would provide a fairly definitive statement about the validity of the most important class of inflationary models, i.e. , single-field slow-roll models with $\Delta\phi$ exceeding the Planck scale, which would constitute a milestone in cosmology.

CMB polarization power spectra today

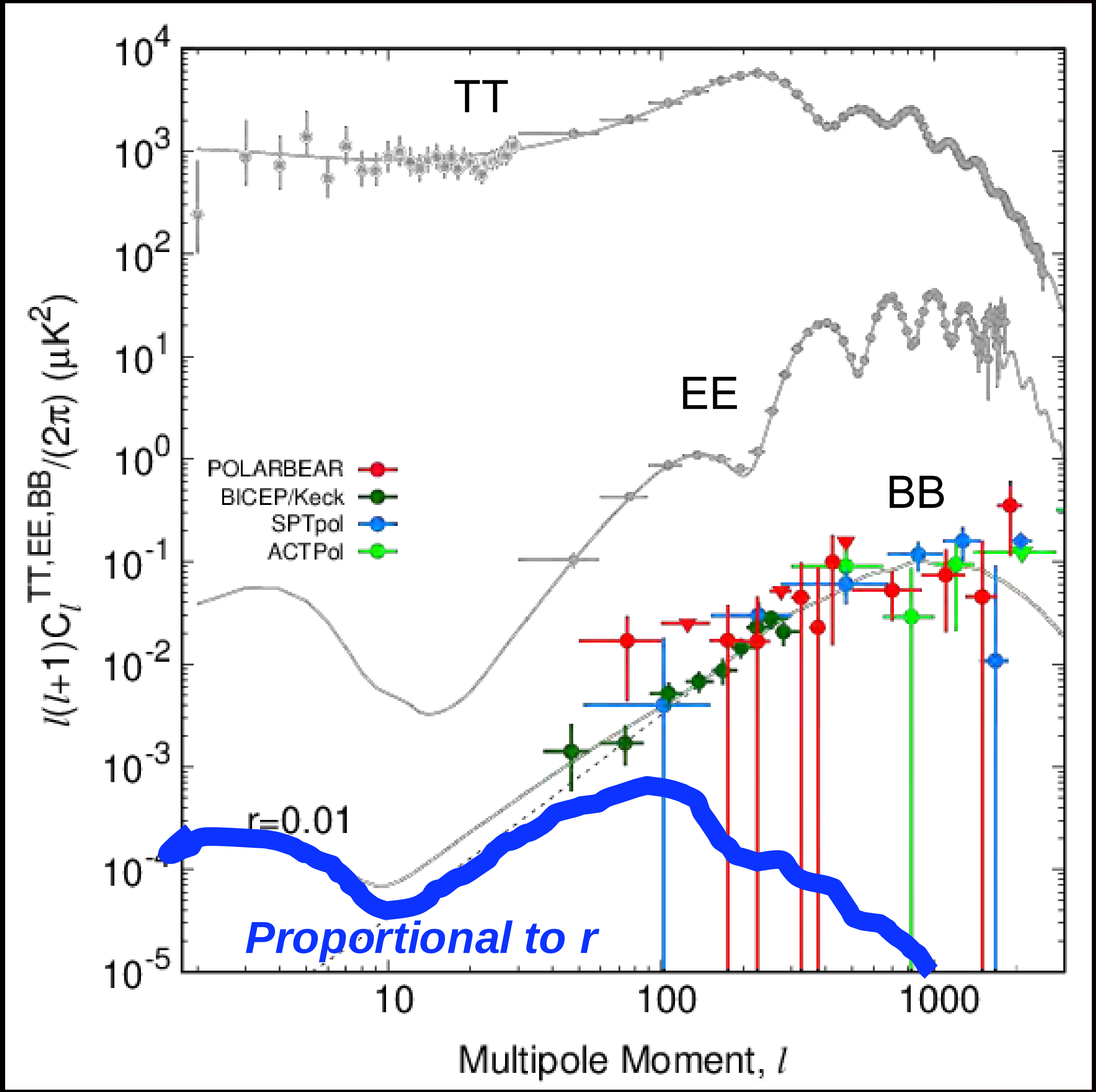
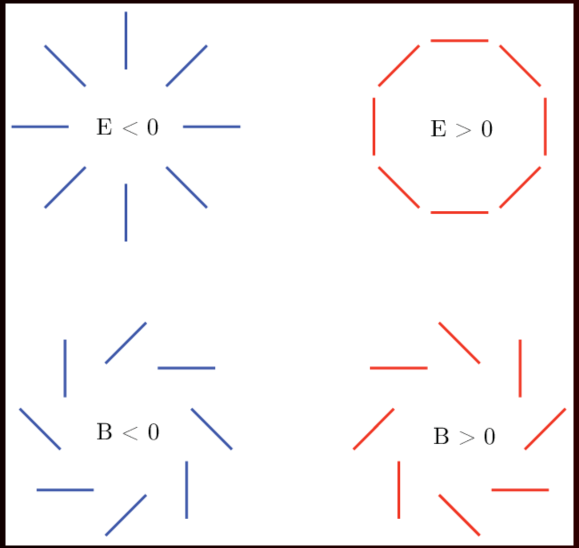
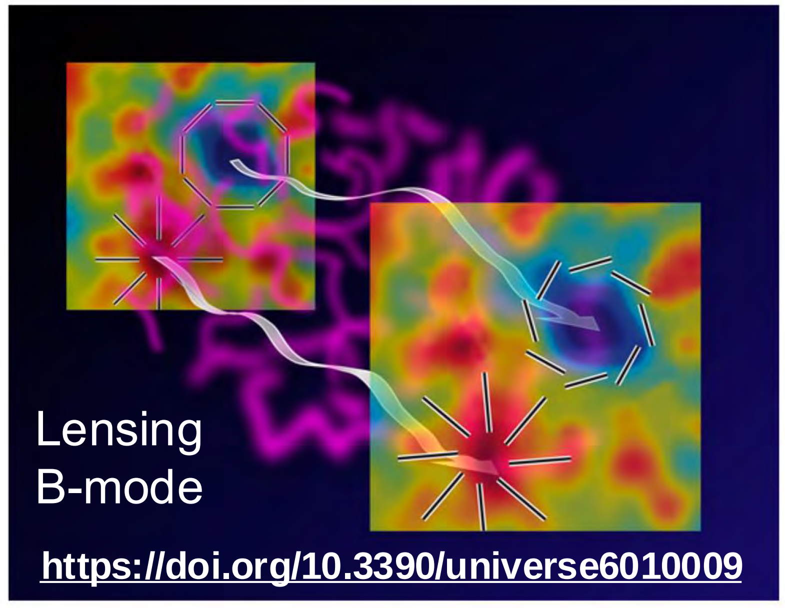


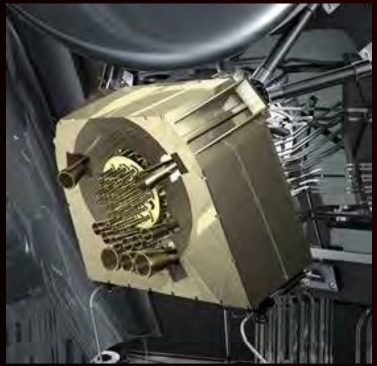
Figure by
Yuji Chinone
(QUP)

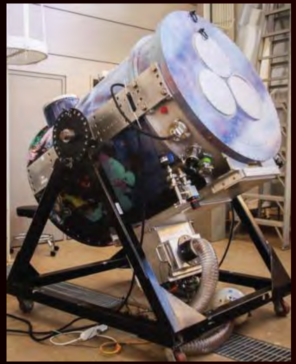
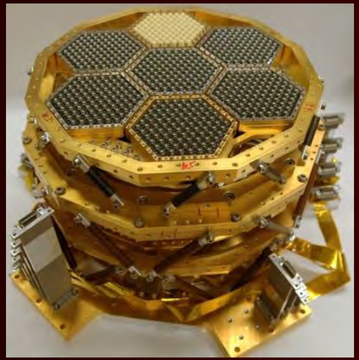




Why CMB measurements so good?

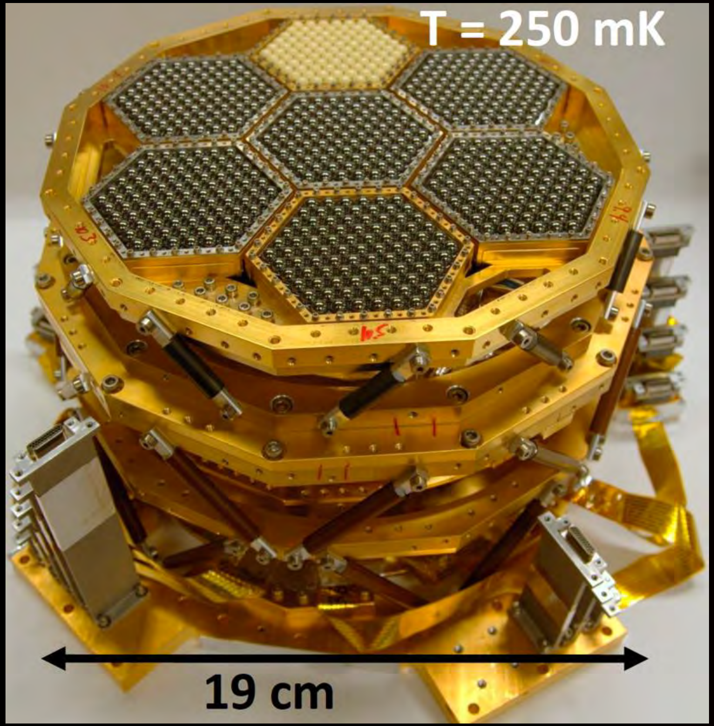
- Linear evolution from initial state to CMB emission
- CMB well preserved until today
- Precision inversely proportional to observing time!
- Remarkable development of observational instruments, in particular low temperature detectors!

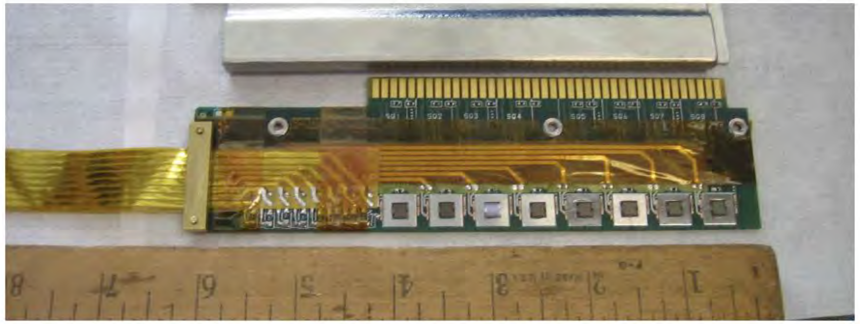


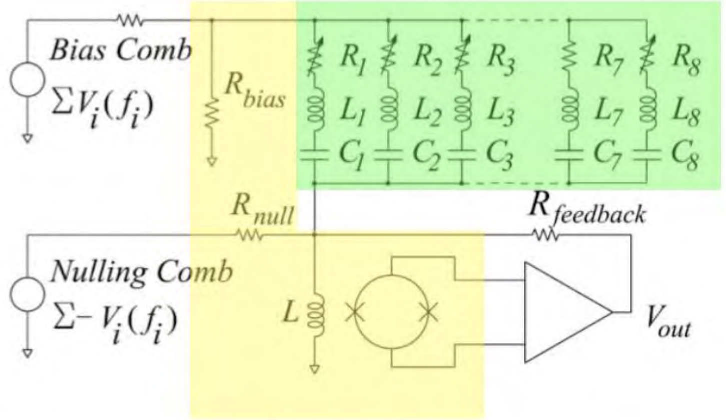
POLARBEAR as an example

- Dedicated CMB polarization experiment
- Located at 5200 meters in Atacama, Chile
- First light Jan. 2012, expanded to Simons Array from 2018
- Powerful TES array with 3.5arcmin beam for 150GHz

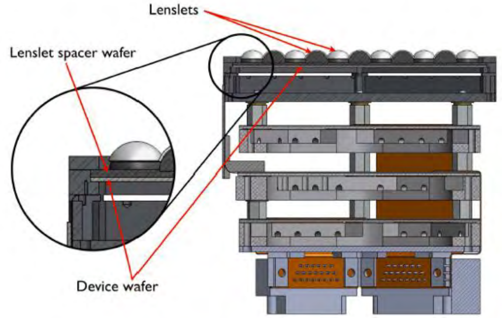




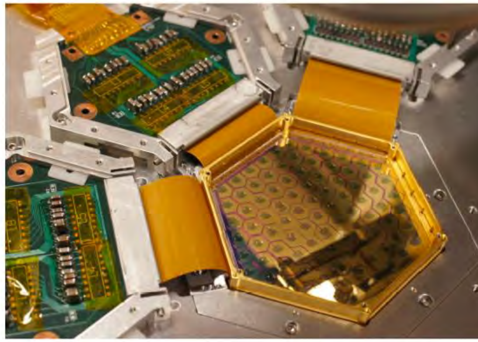
(a) Photo of an assembled squid amplifier readout card



(b) Schematic of the frequency multiplexed readout scheme developed at Berkeley.



(a) CAD rendering of a wafer holder



(b) An unfolded wafer module.

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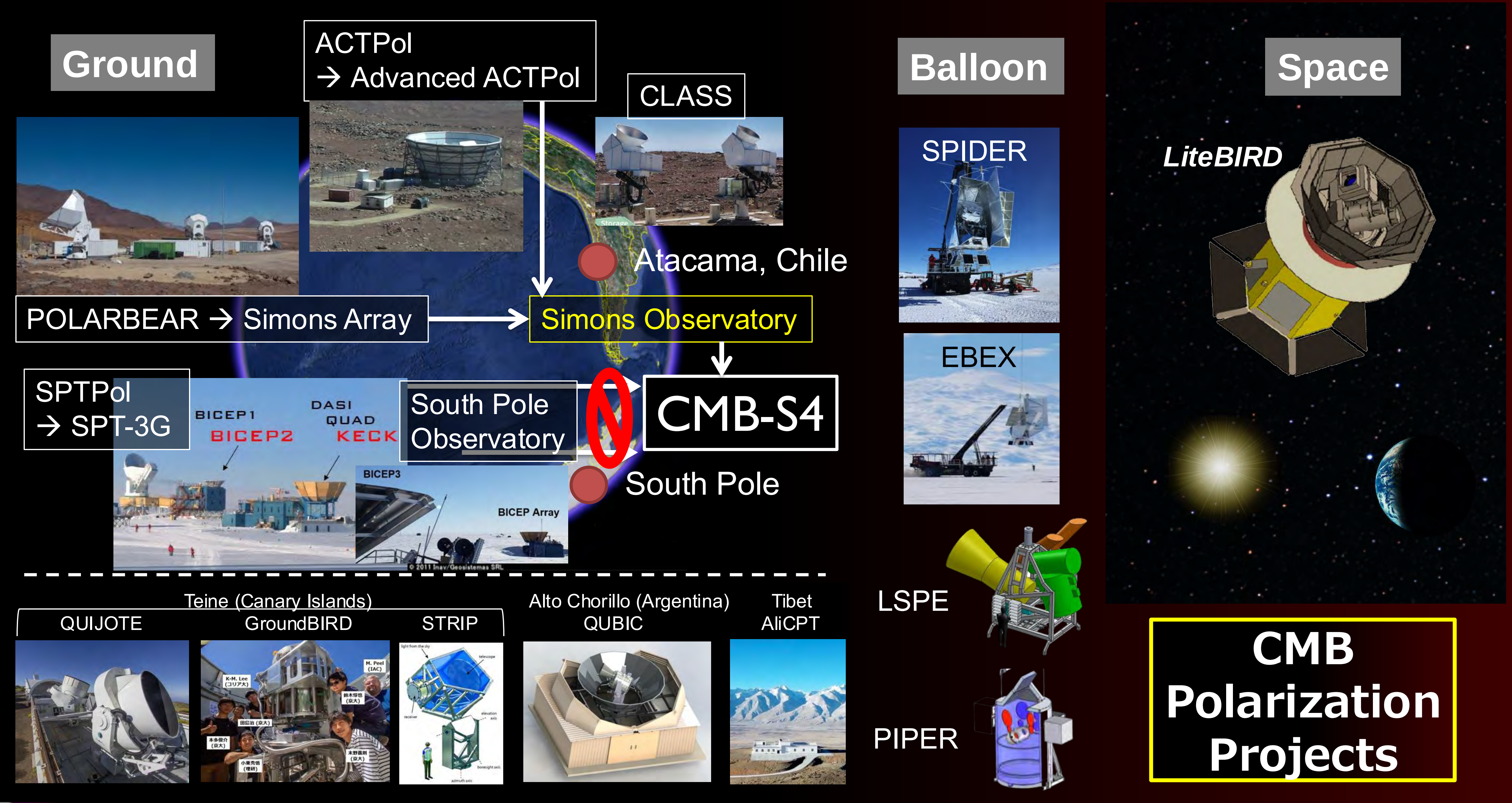
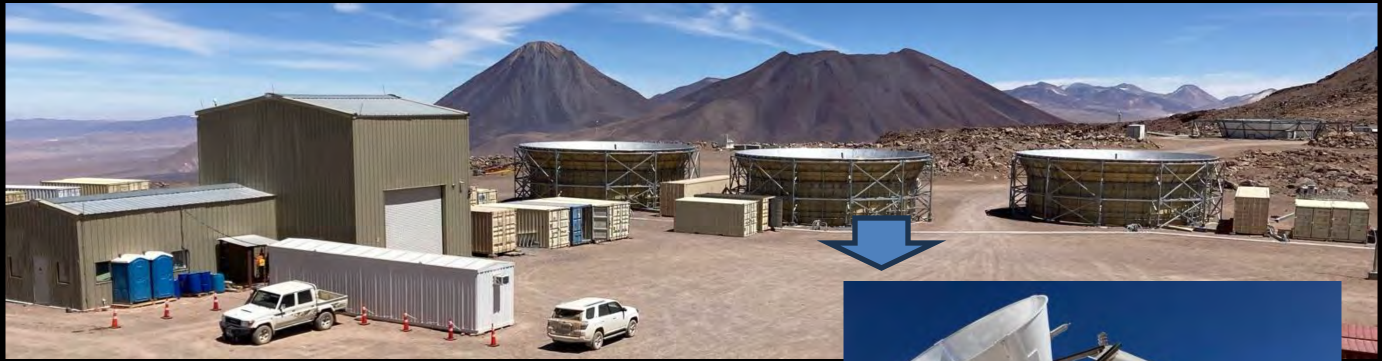


Ground
ACTPol
→ Advanced ACTPol
CLASS
Atacama, Chile
POLARBEAR → Simons Array
Simons Observatory
SPTPol
→ SPT-3G
BICEP1
DASI
QUAD
BICEP2
KECK
South Pole
Observatory
CMB-S4
BICEP3
BICEP Array
South Pole
Teine (Canary Islands)
QUIJOTE
GroundBIRD
STRIP
Alto Chorillo (Argentina)
QUBIC
Tibet
AliCPT
Balloon
SPIDER
EBEX
LSPE
PIPER
Space
LiteBIRD
CMB
Polarization
Projects

Simons Observatory (SO)



Photos in Dec 2024

Small Aperture Telescopes (SATs) started taking data in 2024.

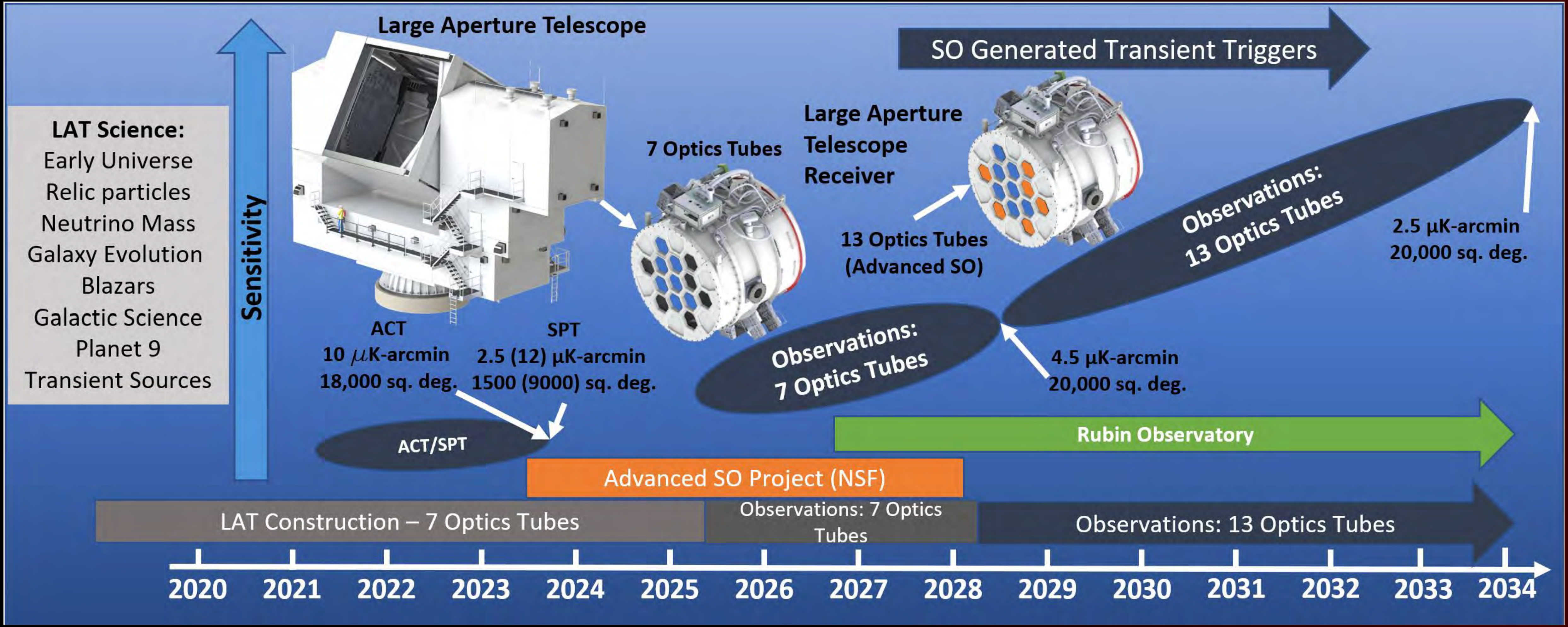
Large Aperture Telescope (LAT) Commissioning in 2025

Target sensitivity: $\sigma(r) = 0.003$

Current limit is $r < 0.032$ (95% C.L.) (M. Tristram et al. 2021, combining Bicep2/Keck 2018 and Planck PR4 data set)

Rich science (next page)

Simons Observatory (SO) Large Aperture Telescope (LAT)



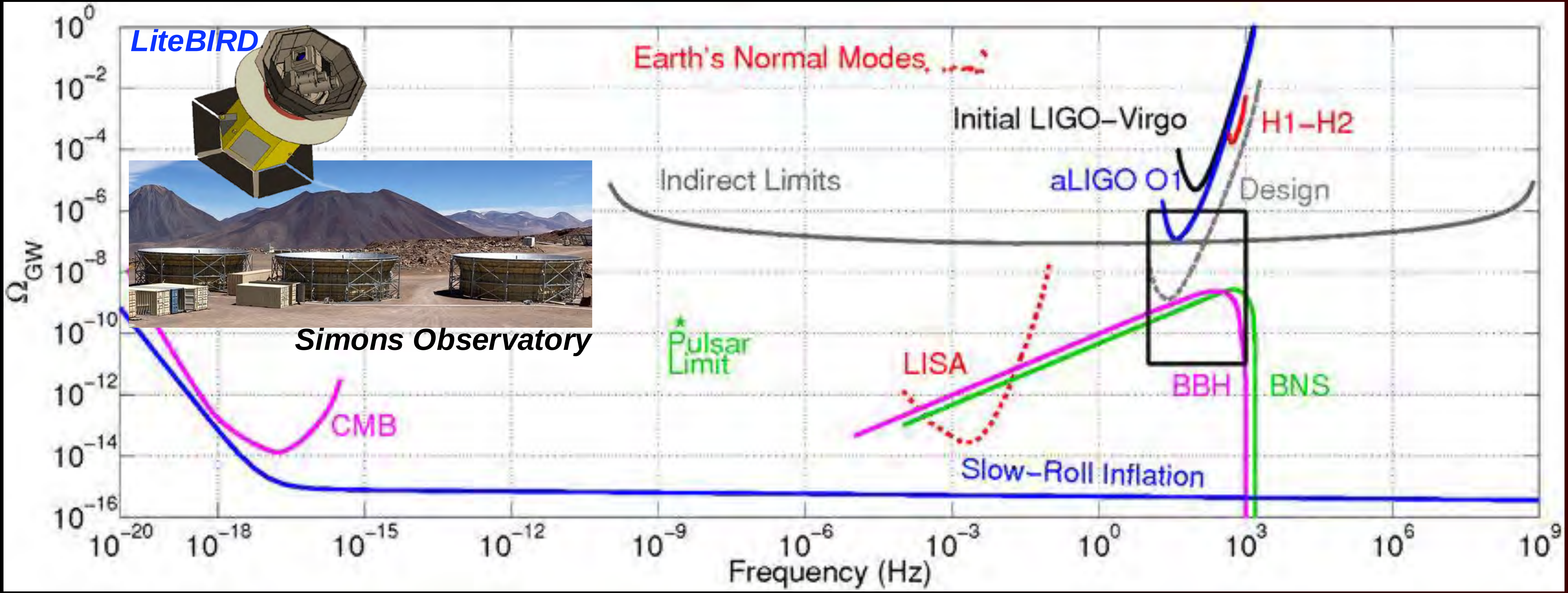
arXiv:2503.00636

Science Goals from SO LAT Survey

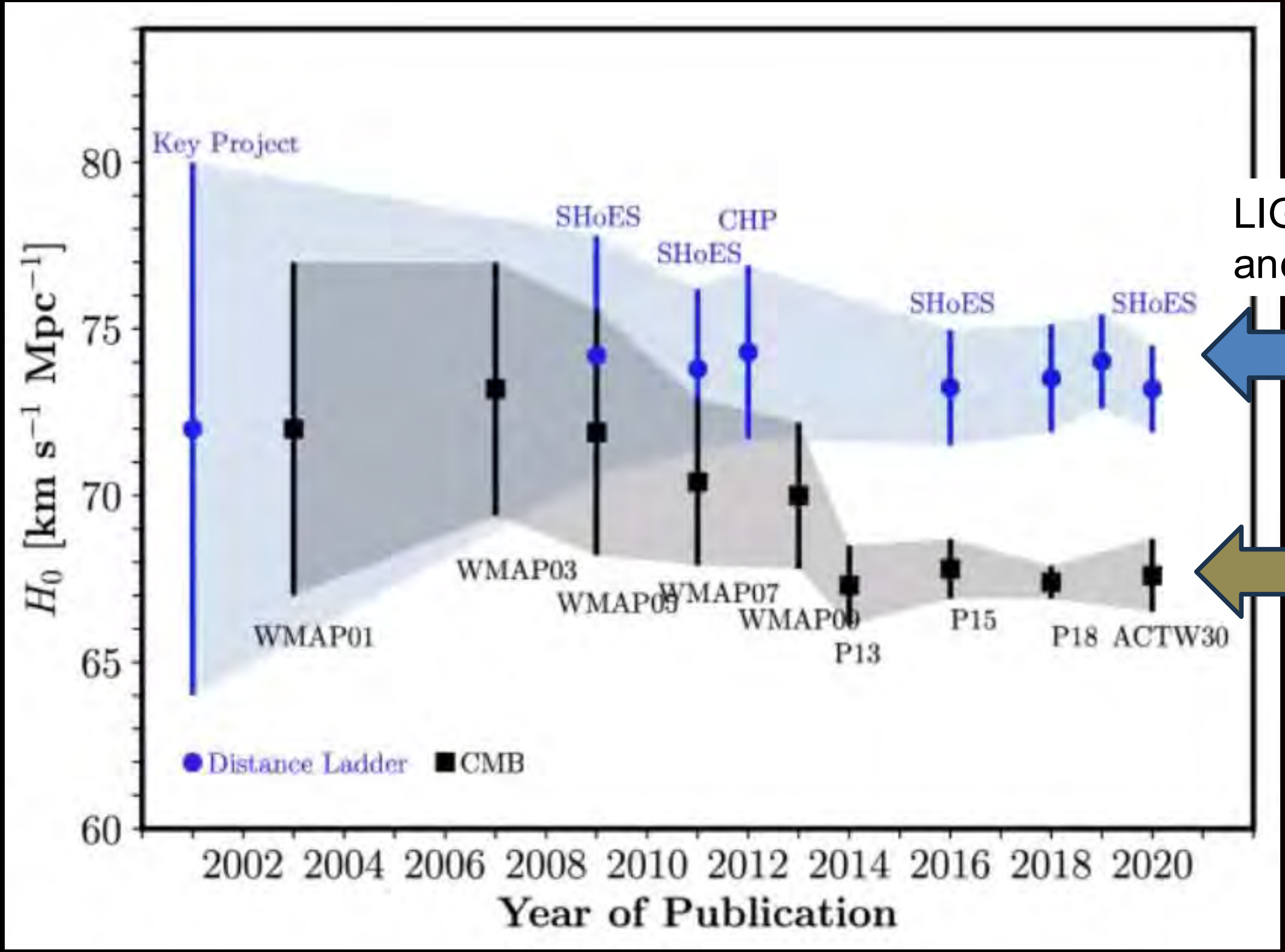
arXiv:2503.00636

	Current[b]	SO 2025–2034	Using Rubin, DESI, or *Euclid*
Primordial perturbations			
n_s	0.004	0.002	-
$e^{-2\tau}\mathcal{P}(k = 0.2\,\mathrm{Mpc}^{-1})$	3%	0.4%	-
$f_{\mathrm{NL}}^{\mathrm{local}}$	5	1	✓
Relativistic species			
N_{eff}	0.2	0.045	-
Neutrino mass[c]			
$\sum m_\nu$ (eV, $\sigma(\tau) = 0.01$)	0.1	0.03	✓
$\sum m_\nu$ (eV, $\sigma(\tau) = 0.002$)		0.015	✓
Accelerated expansion			
$\sigma_8(z = 1 - 2)$	7%	1%	✓
Galaxy evolution			
η_{feedback}	50–100%	2%	✓
p_{nt}	50–100%	4%	✓
Reionization			
Δz	1.4	0.3	-
τ	0.007	0.0035	-
Cluster catalog	4000	33,000	✓
AGN catalog	2000	96,000	-
Galactic science			
Molecular cloud B-fields	10s	> 860	-
$\sigma(\beta_{\mathrm{dust}})$	0.02	0.005	-
Solar System Science			
Distance limit for 5 $M_\oplus$ Planet 9	500 AU	900 AU	✓
Asteroid detections		$\sim 10,000$	
Transient detection distance			
Long GRBs, on-axis		1300 Mpc	-
Low-luminosity GRBs		70–210 Mpc	-
TDEs, on-axis		670 Mpc	-

Synergy between GW and CMB



Synergy between GW and CMB



LIGO/Virgo/Kagra
and beyond

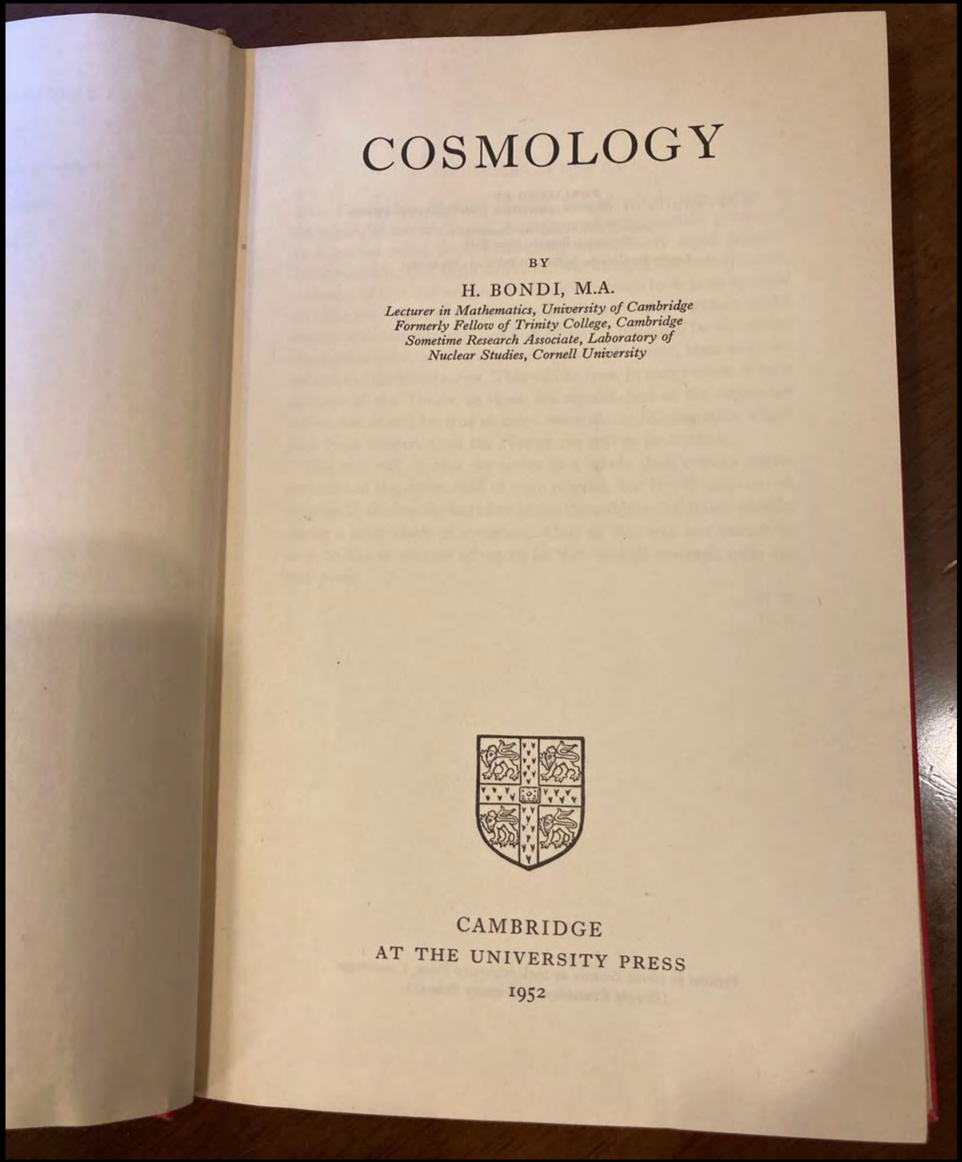
SO LAT
E-mode

My CMB talks in Taiwan this week

Date/Time	Place	Event	Title	Contents
Mar. 12 (Wed) 14:00-15:30	AS IoP	AS IoP Special Colloquium	"Cosmology with Cosmic Microwave Background"	Past and Present
Mar. 13 (Thu) 10:20-11:00	NCU	Mini-workshop "The New World of Spin Zero - New trends in particle cosmology"	"Ongoing CMB Projects"	Project-oriented
Mar. 13 (Thu) 14:00-15:00	NCU	CHiP Special Talk	"The New World of Spin Zero - Fundamental mysteries of nature and CMB polarization"	Big Picture and Future

Outline

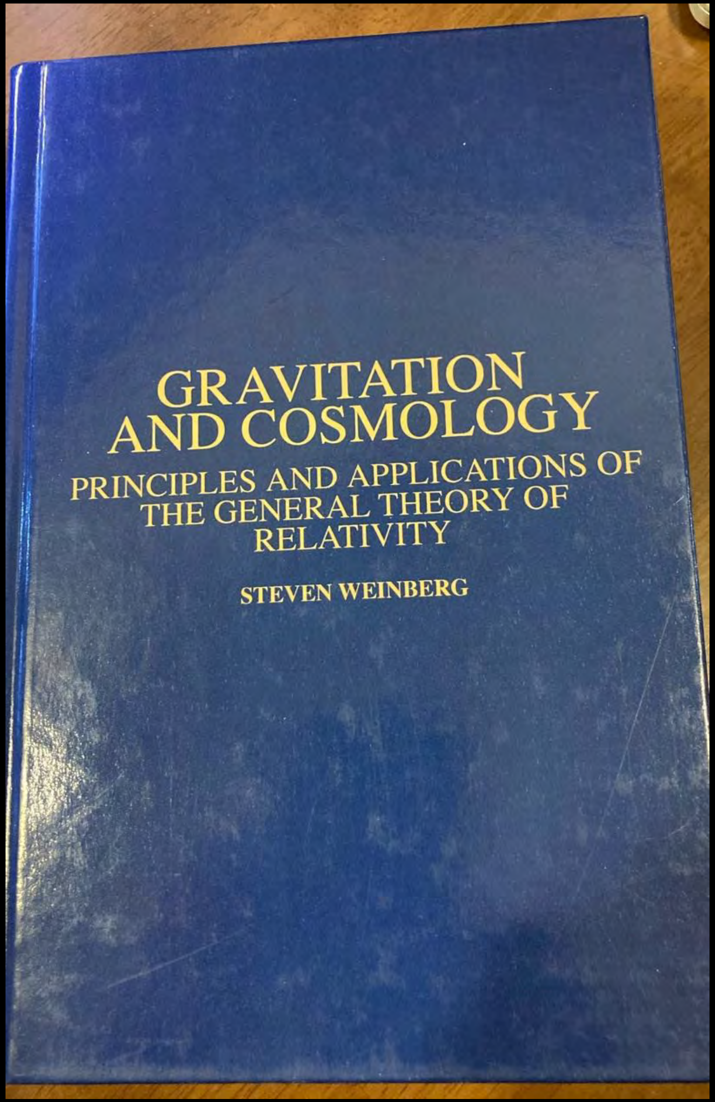
“Cosmology” by H. Bondi (1952)



Chapter XIV
THE PRESENT POSITION IN COSMOLOGY

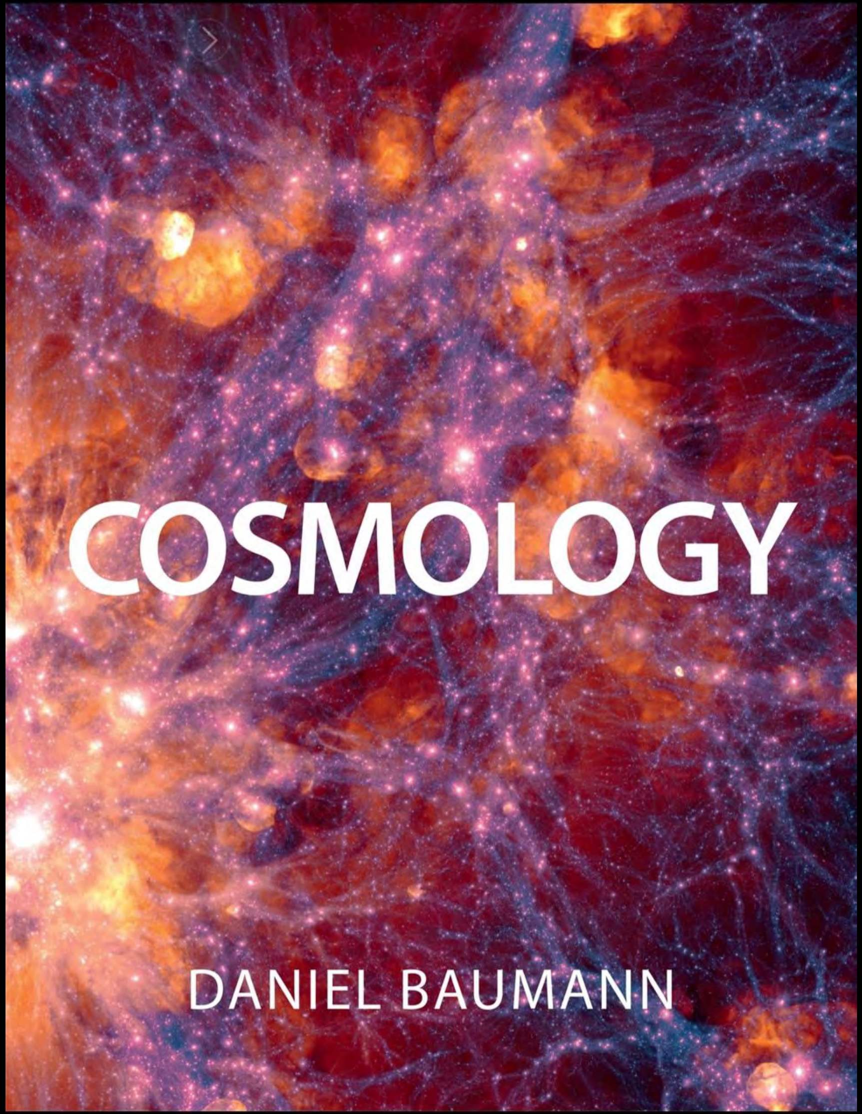
- The multiplicity of existing theories…
- …the reciprocal of Hubble’s constant…is appreciably shorter time than the age of the Earth…
- The situation is entirely different in a theory with continual creation such as the steady-state theory.
- …an observational decision between them should be possible.

“Gravitation and Cosmology” by S. Weinberg (1972)



- Chap.15. THE STANDARD MODEL
  - The Einstein field equations require that the scale factor must have been extremely small at some finite time in the past. …As the universe subsequently expanded, both radiation and matter cooled. Eventually, when the temperature had dropped to about 4000K, the free electrons joined atoms,…breaking the thermal contact between matter and radiation…It is widely, though not unanimously, believed, that the microwave radiation background discovered in 1965 is just this left-over radiation,…
- Chap. 16. COSMOLOGY: OTHER MODELS
  - … 2 Models with a Cosmological Constant / 3. The Steady State Model Revisited / 4 Models with a Varying Constant of Gravitation

“Cosmology” by D. Baumann (2022)



This book has been a first introduction to the basic principles of cosmology. We have learned how a combination of theoretical advances and precision observations have transformed cosmology into a quantitative science. Questions about the age of the universe, its composition and its evolution now have very precise answers. Although cosmology has become part of mainstream science, it is a special type of historical science. The cosmological experiment cannot be repeated, since the Big Bang only happened once. Nevertheless, cosmologists have been able to reconstruct much of the history of the universe from a limited amount of observational clues. This culminated in the ΛCDM model which describes the cosmological evolution from 1 second after the Big Bang until today, 13.8 billion years later. The details of cosmological structure formation, through the gravitational clustering of small density variations in the primordial universe, are well understood. There is now even evidence for the rather spectacular proposal that quantum fluctuations during a period of exponential expansion about 10^{-34} seconds after the Big Bang provided the seed fluctuations for the large-scale structure of the universe.

At the same time, many fundamental questions in cosmology remain unanswered. We do not know what drove the inflationary expansion, what kind of matter filled the universe after inflation, and how the asymmetry between matter and antimatter was created. The nature of dark matter remains unknown and how dark energy fits into quantum field theory is still a complete mystery. Finally, we do not know what happened at the Big Bang singularity, and if there was any time (and space) before that moment. We hope that future observations of the polarization of the CMB and of the large-scale structure of the universe will help to unlock these mysteries. In addition, we will need new theoretical ideas. Maybe one of these ideas will come from a reader of this book. That would be wonderful.

“Cosmology” by XXX (2102)

Viewer discretion is advised

- *Precise measurements of tensor-to-scalar ratio yield r = 0.00XX +/- 0.0000XX, where…*
- *According to the latest measurements with quantum sensors, axions are responsible for XX% of dark matter, and …*
- *We know that dark energy’s dynamics allowed our Universe to be…*
- *…We have now seen sufficient evidence for the multiverse model and …*

The best way to predict the future is to invent it.

Thank You!