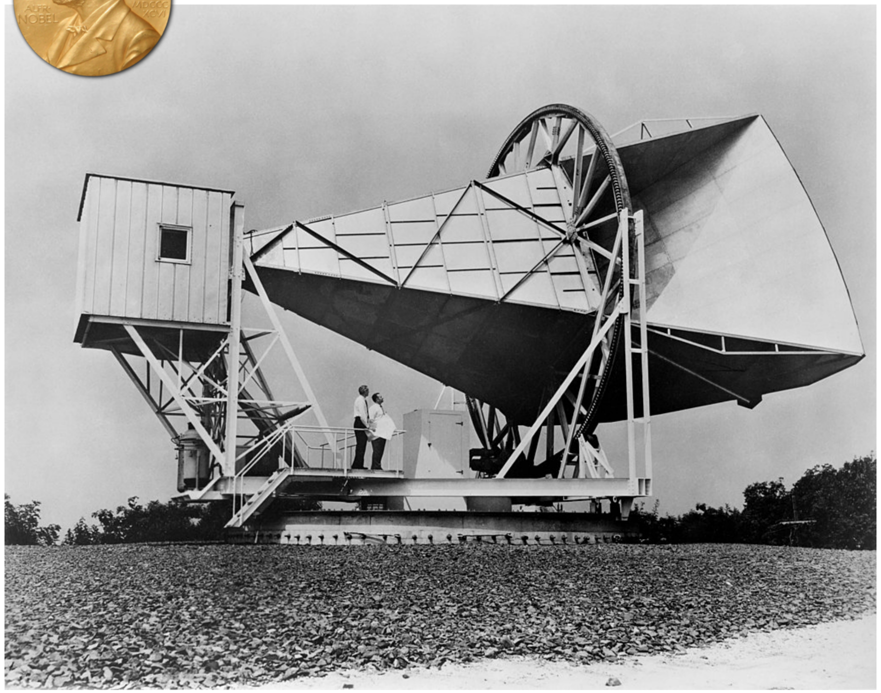
Quest of 5 questions by CMB (from space)

- What is the universe made of?
- How did it begin?
- What is its fate?
- What are the laws that govern it?
- Why do we exist in it?
- *Am I doing a good job?*

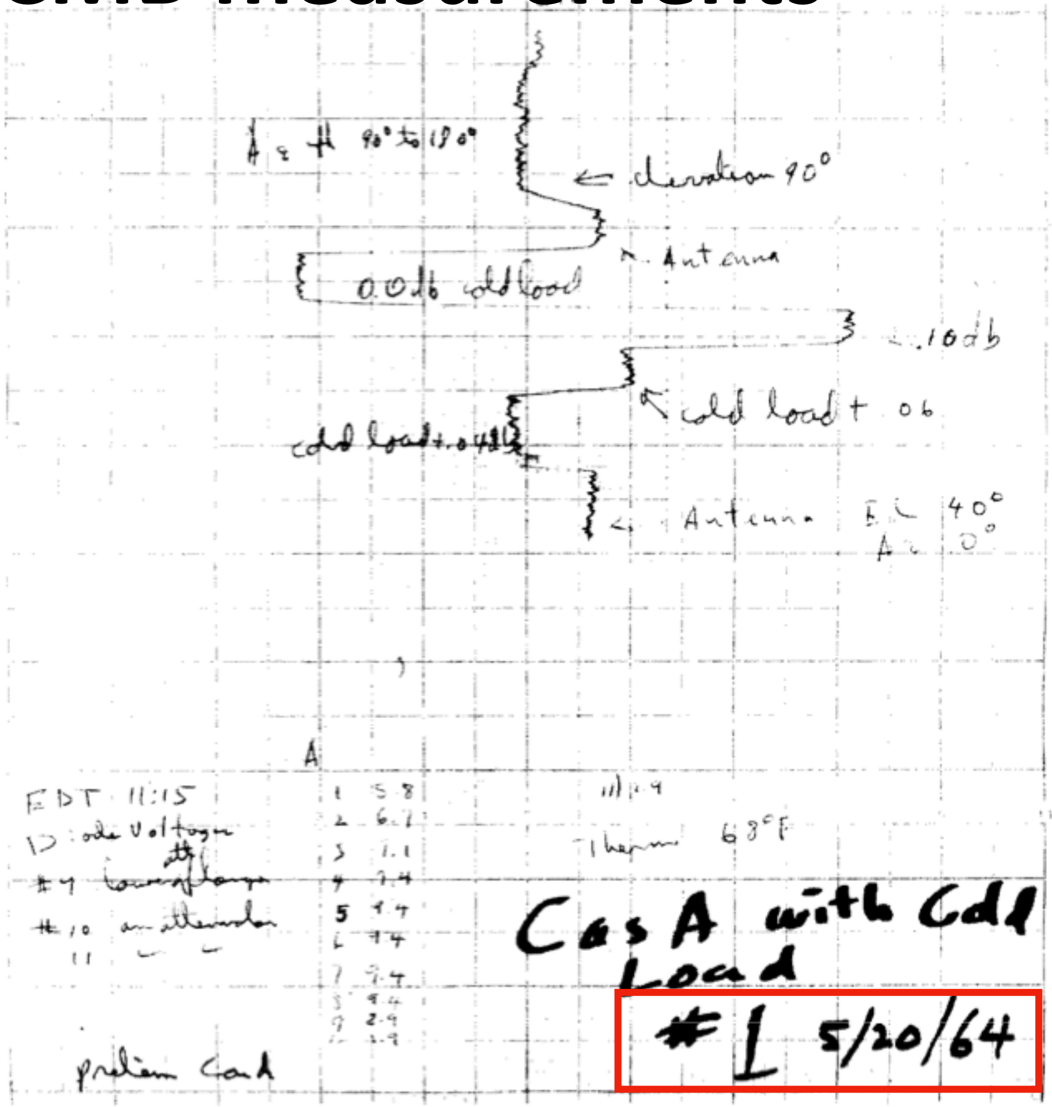
T. Matsumura, Kavli IPMU

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Very brief history of the CMB measurements

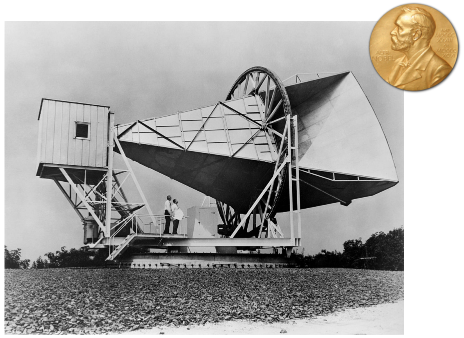


The discovery of CMB by Penzias and Wilson in 1964.



The Cosmic Microwave Background Radiation (Nobel Lecture) by Robert Wilson 8 Dec 1978.

Very brief history of CMB measurements (w/ space focus)



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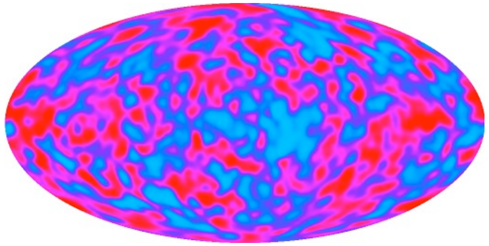
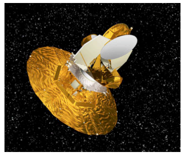
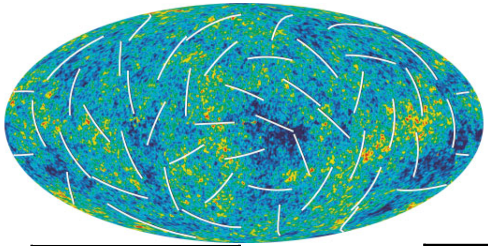
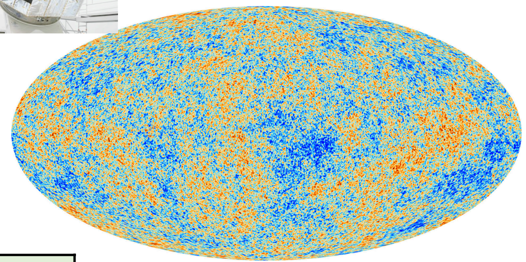


	COBE (1989)
Band	32-90 GHz
# det.	6 radiometers
Op. T	140 K
Beam	~7°
Orbit	Sun Synch.



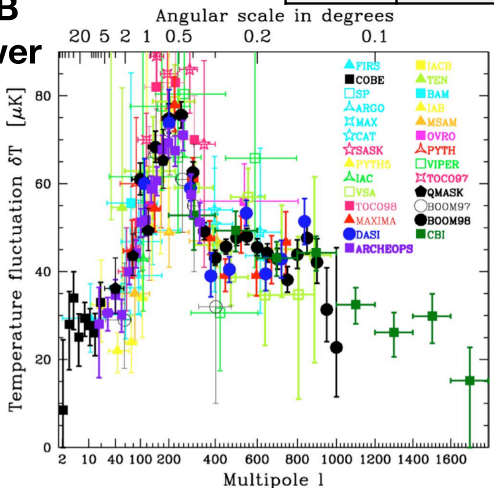


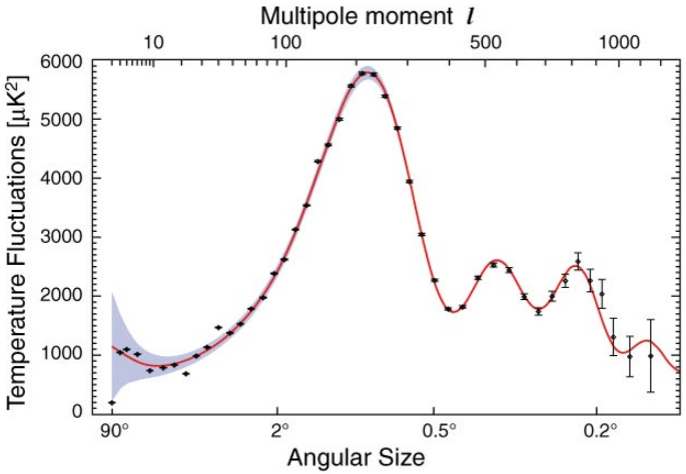
WMAP (2001)
23-94 GHz
20 radiometers
90 K
~0.22°
L2

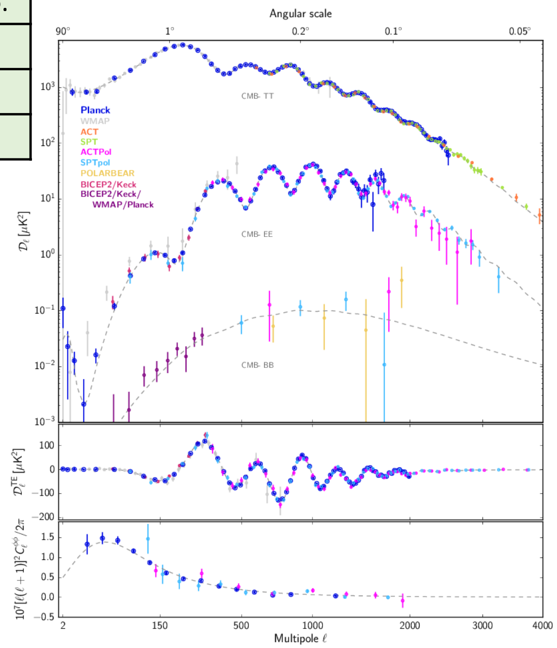


Planck (2009)
30-857GHz
11 rad. + 52 bolo.
100 mK
~0.1°
L2

Pre-WMAP CMB temperature power spectrum







Brief history of the universe

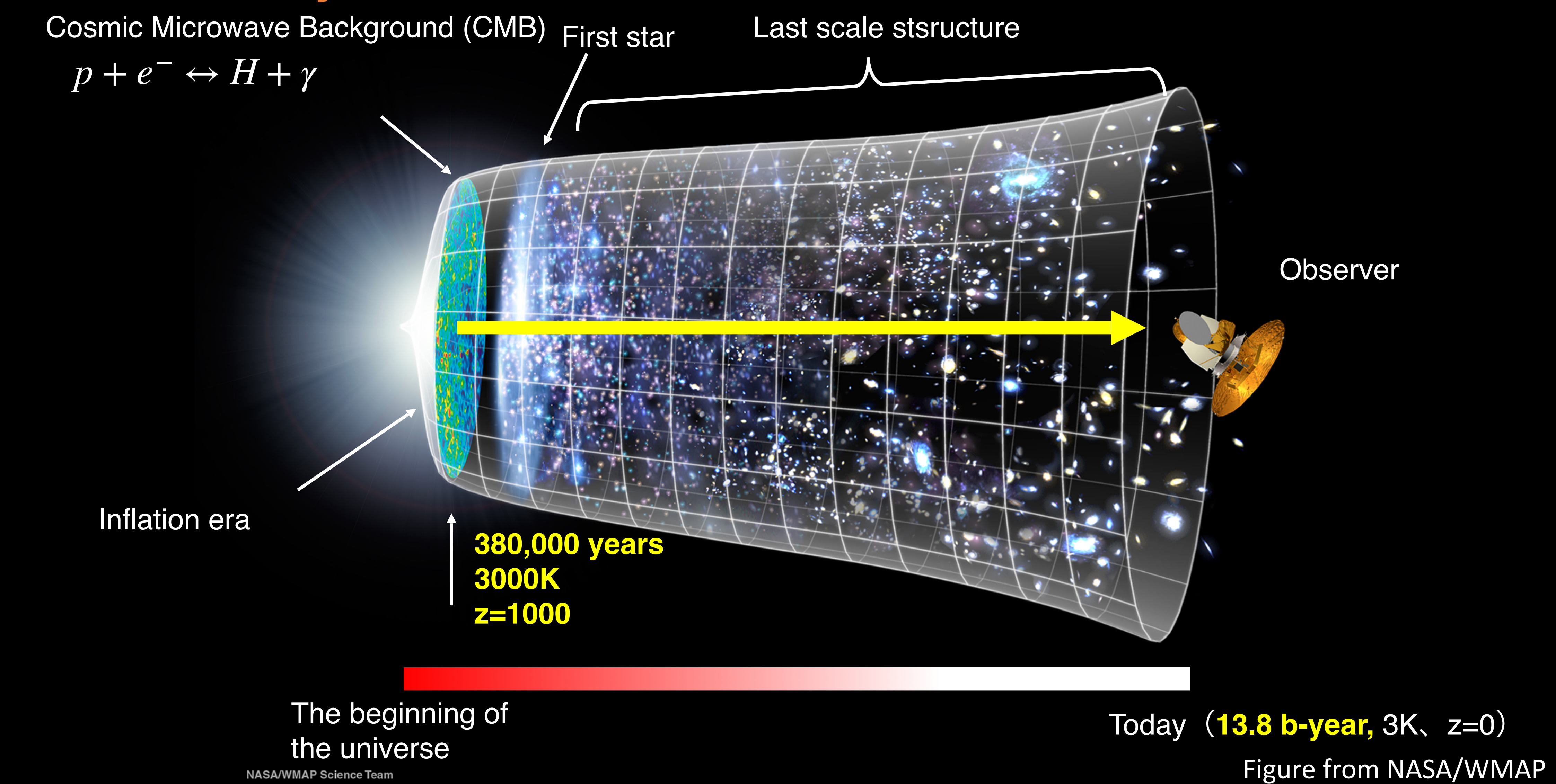
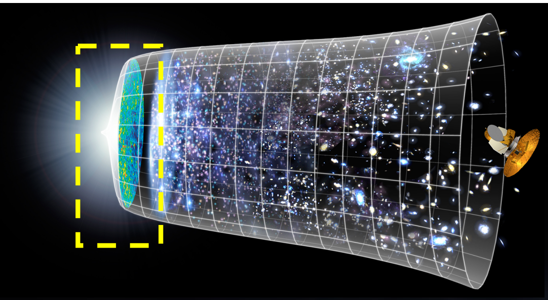
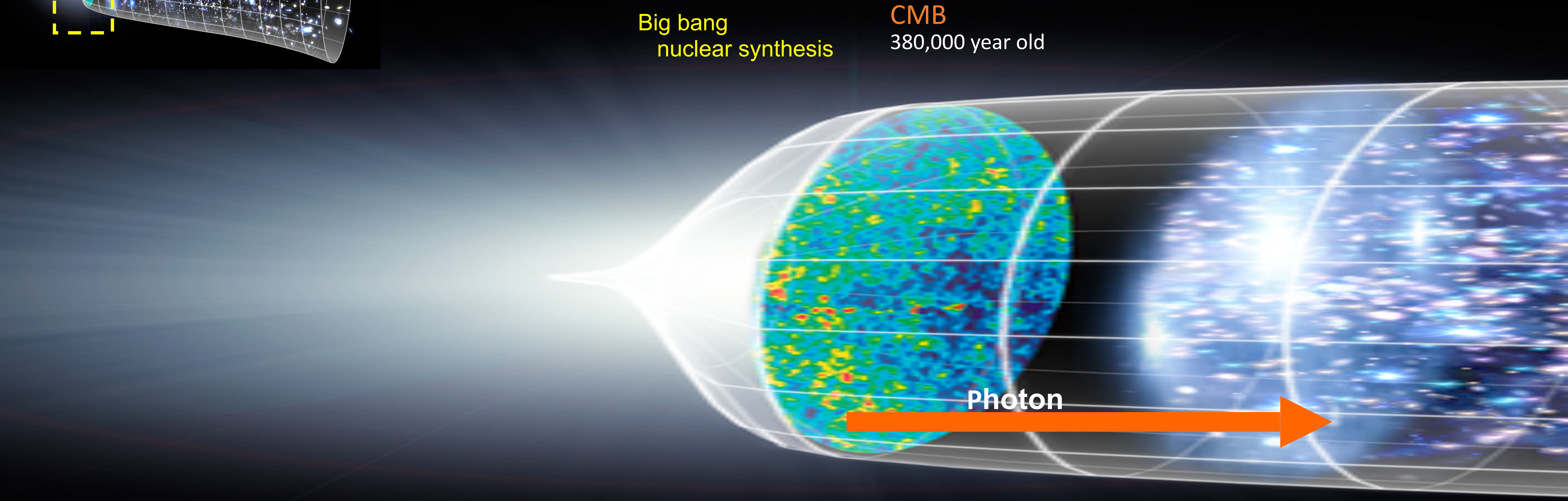


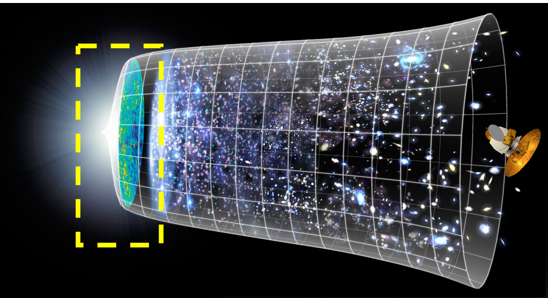
Figure from NASA/WMAP

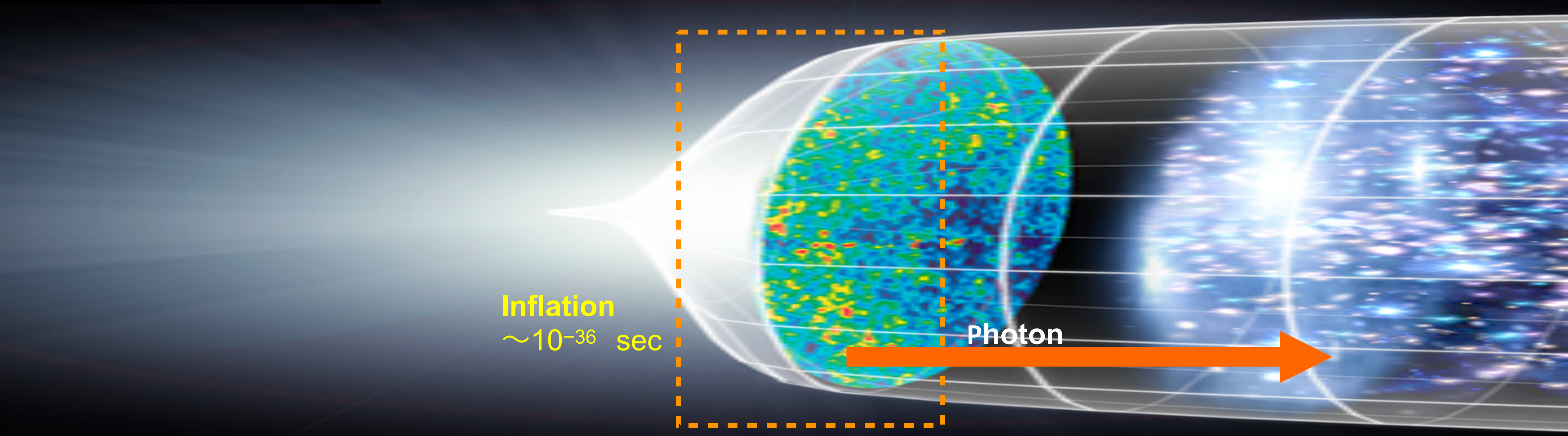
CMB to probe before the big bang





CMB to probe before the big bang

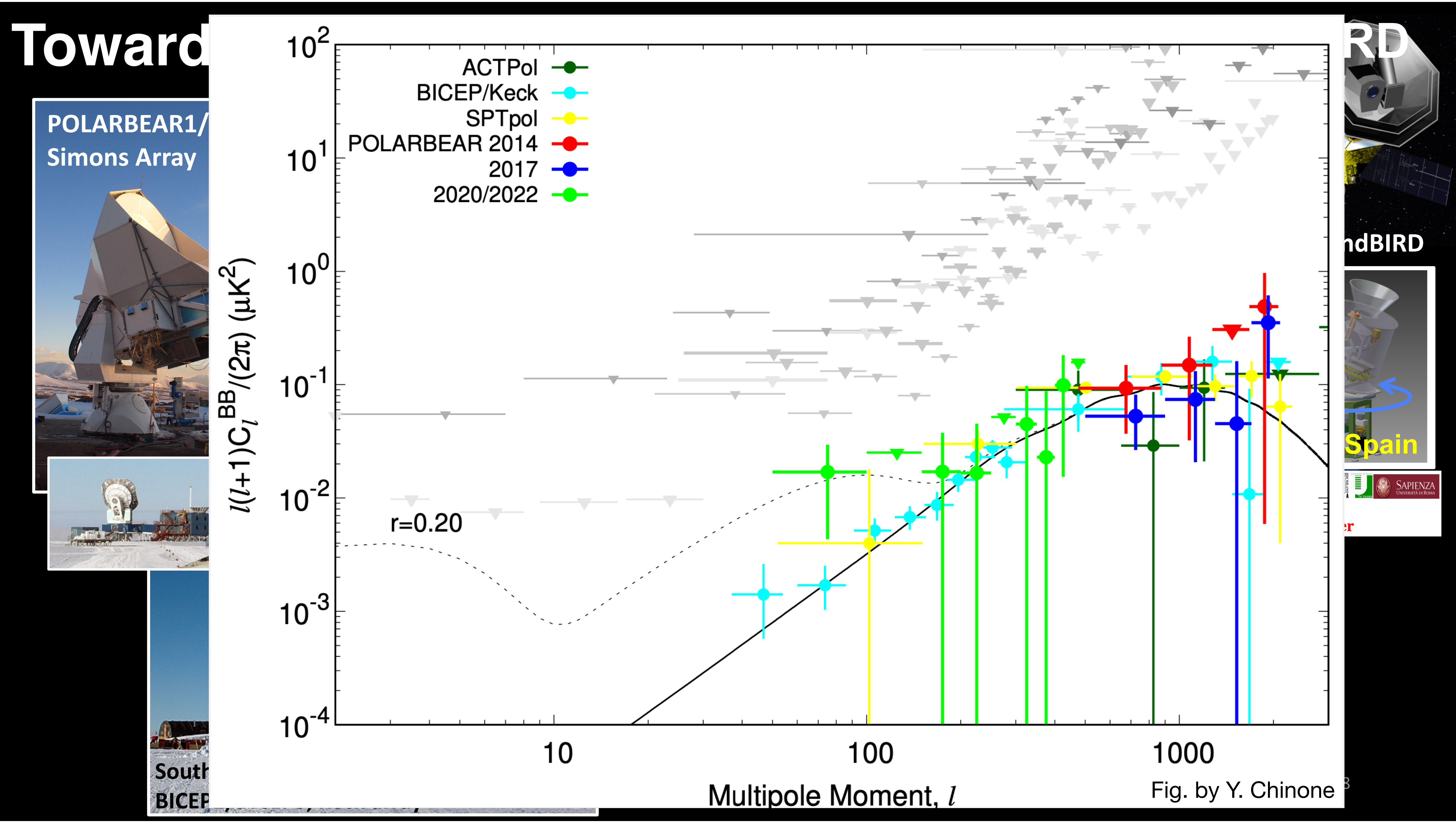




Well understood by the CMB data with the current physics framework.

Then, what's the initial condition?

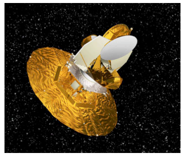
Toward primordial B modes today
Space
LiteBIRD
Planck
© JAXA
Chile
POLARBEAR1/2
Simons Array
22°57'31" SOUTH, 67°47'15"WEST ELEVATION: 17,027.6'
SIMONS
OBSERVATORY
PARQUE ASTRONÓMICO ATACAMA, CHILE
ACTpol
QUBIC
AliCPT site
Himalaya Mountains
ALICPT
Quijote
GroundBIRD
Spain
CLASS
CMB-S4
Next Generation CMB Experiment
LSPE : the Large-Scale Polarization Explorer
South pole telescope (SPTpol)
BICEP2, BICEP3, Keck array
South pole/Antarctica
Balloons: SPIDER/IDS/LSPE
7



Toward
RD
POLARBEAR1/
Simons Array
ndBIRD
Spain
South
BICEP
ACTPol
BICEP/Keck
SPTpol
POLARBEAR 2014
2017
2020/2022
r=0.20
$l(l+1)C_l^{BB}/(2\pi)$ (μK^2)
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10
100
1000
Multipole Moment, l
Fig. by Y. Chinone

Very brief history of CMB measurements (w/ space focus)

→



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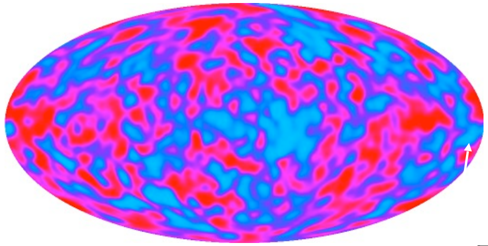
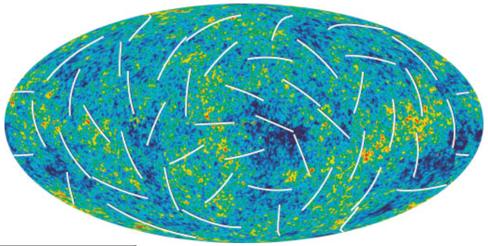
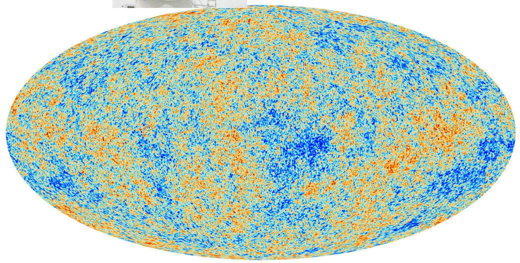
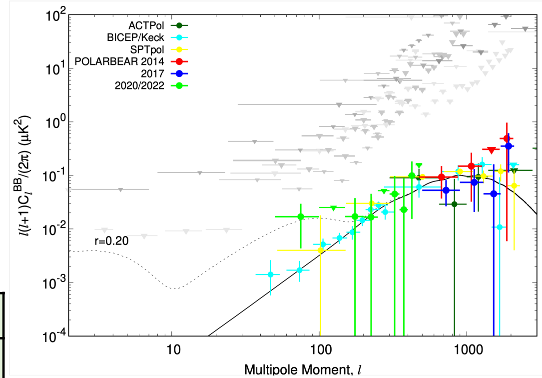
→ What's next?









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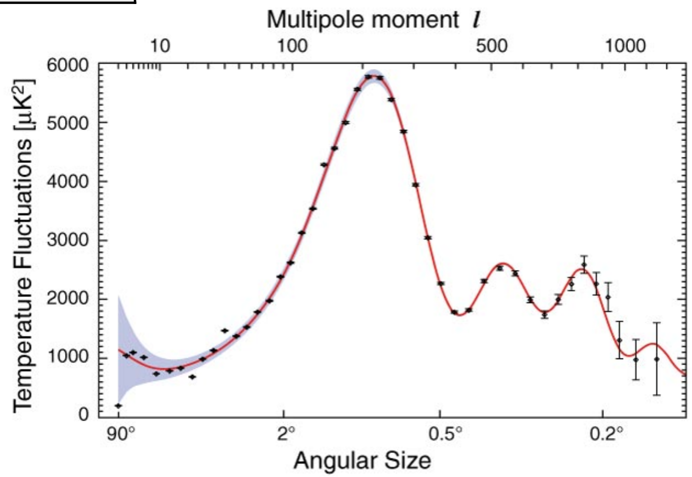

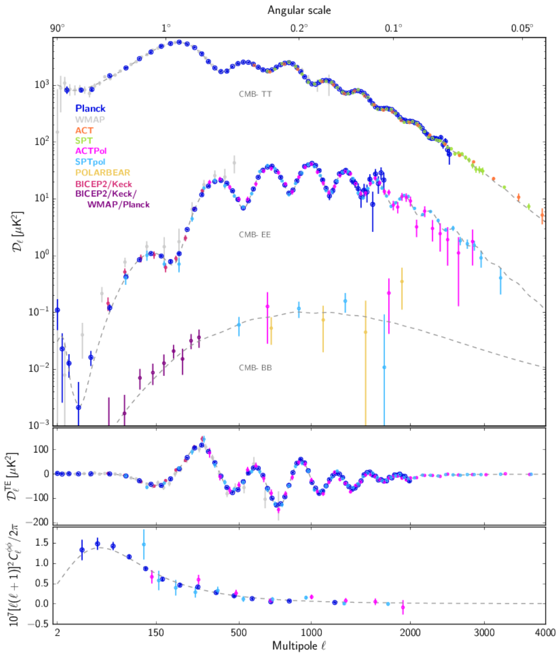

Very very brief history of the new CMB space mission

- Around 2009, **ESA Planck** was successfully launched and started its observations, and the efforts toward the next generation CMB space mission have emerged.
- In 2009, a few **CMB-pol** concept studies came out for Astro2010.
- In 2019, the probe mission concept, **PICO**, was proposed.
- Post-Planck mission concepts from the European community were proposed, e.g. **SAMPAN, B-Pol, COrE, COrE+**, and **PRISM**.
- The concept of **LiteBIRD** was first put together in 2008.
  - In 2019, JAXA ISAS selected LiteBIRD as the 2nd strategic L-class mission.
  - But there were nearly 10 years of preparations, and Hitoshi supported LiteBIRD a lot, e.g., by proposing LiteBIRD to the Science Council of Japan master plan and MEXT Roadmap from IPMU. Thank you!

Very v ssion

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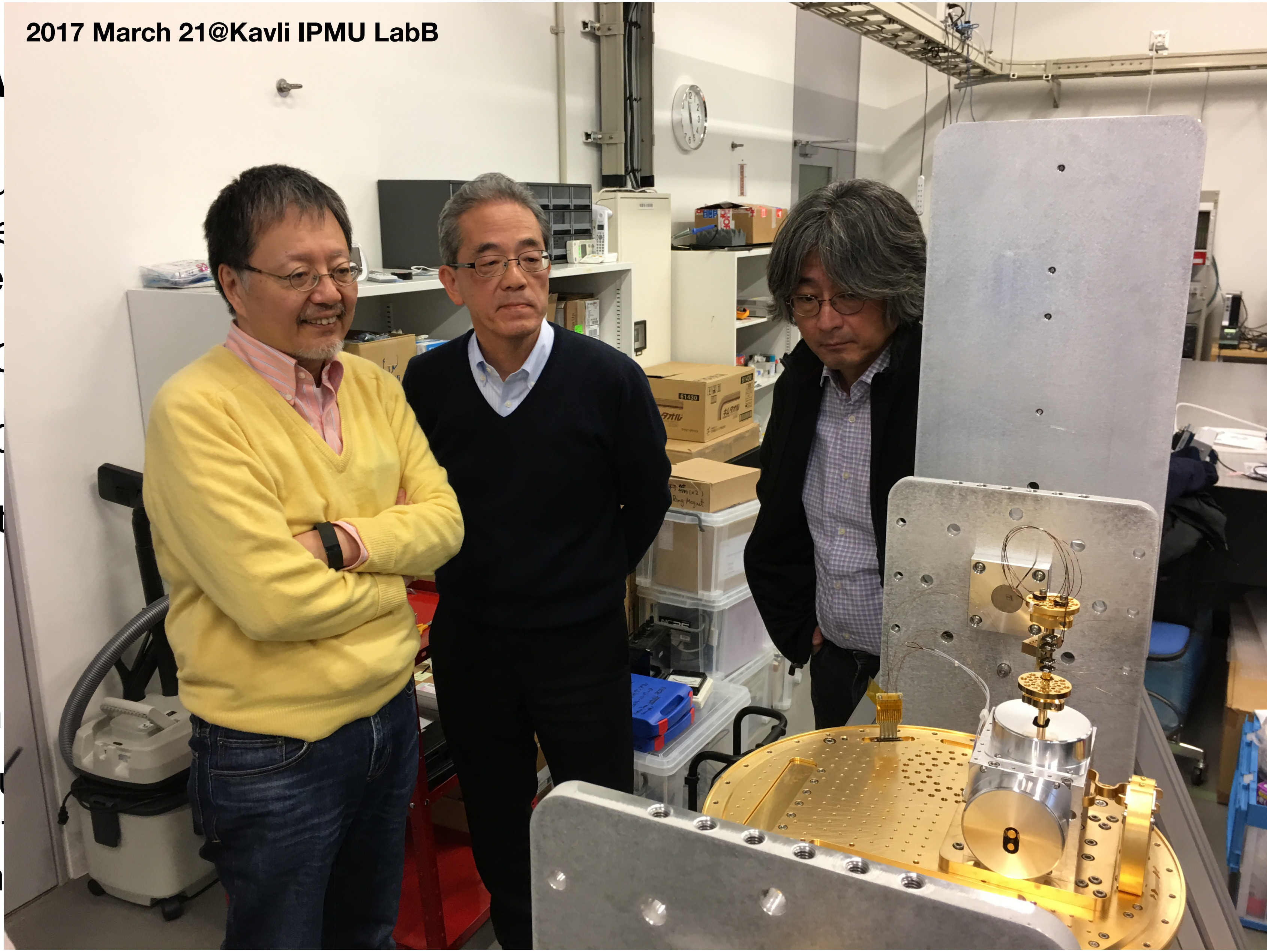


APC
ASI
Berkeley UNIVERSITY OF CALIFORNIA
BERKELEY LAB
UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA
CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD
cea
Centre Pierre Binétruy CNRS • Berkeley
cnes
cnrs
CSA ASC Canada

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS
CSL CENTRE SPATIAL DE LIÈGE
ENS | PSL
erc European Research Council Established by the European Commission
EXCELENCIA MARÍA DE MAEZTU
EXCELENCIA SEVERO OCHOA
FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG
Forskningsrådet The Research Council of Norway
GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN

NASA Goddard Space Flight Center
G S S I GRAN SASSO SCIENCE INSTITUTE
INSTITUTO DE ASTROFISICA DE CANARIAS IAC
IAP
IAS Orsay
IFCA Instituto de Física de Cantabria
ifpU
IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

INFN
INAF ISTITUTO NAZIONALE DI ASTROFISICA
IPMU
IPNS 素粒子原子核研究所 Institute of Particle and Nuclear Studies
irap astrophysique & planétologie
JAXA
NASA Jet Propulsion Laboratory California Institute of Technology

NATIONAL INSTITUTE OF TECHNOLOGY KAGAWA COLLEGE 香川高専
KEK
KIPAC KAVLI INSTITUTE FOR PARTICLE ASTROPHYSICS & COSMOLOGY
KMI Kobayashi-Maskawa Institute Nagoya University
LMU
LPSC GRENOBLE | MODANE

MAX-PLANCK-INSTITUT FÜR ASTROPHYSIK
McGill
Maynooth University National University of Ireland Maynooth
名古屋大学 NAGOYA UNIVERSITY
NÉEL institut
NIST

Norwegian Directorate for Higher Education and Skills
OAC
岡山大学 OKAYAMA UNIVERSITY
QUP International Center for Quantum-field Measurement Systems for Studies of the Universe and Particles
POLITÉCNICA
idr
RWTH AACHEN UNIVERSITY

LiteBIRD

SAPIENZA UNIVERSITÀ DI ROMA
SISSA
SORBONNE UNIVERSITÉ
SRON
SSDC SPACE SCIENCE DATA CENTER
LELAND STANFORD JUNIOR UNIVERSITY 1891
Stockholm University
公立諏訪東京理科大学 Suwa University of Science
TOR VERGATA UNIVERSITÀ DEGLI STUDI DI ROMA

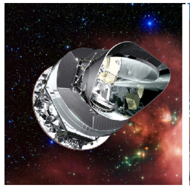
UCL
THE UNIVERSITY OF BRITISH COLUMBIA
UC UNIVERSIDAD DE CANTABRIA
Università di Catania
University of Colorado Boulder
UKRI Science and Technology Facilities Council
ULB UNIVERSITÉ LIBRE DE BRUXELLES
Universidad de La Laguna

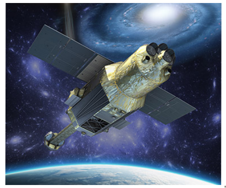
MANCHESTER 1824 The University of Manchester
UiO University of Oslo
UNIVERSITY OF OXFORD
UNIVERSITÀ DI PISA
Università degli Studi di Ferrara
UNIVERSITÀ DEGLI STUDI DI MILANO
UNIVERSITÀ DEGLI STUDI DI PADOVA
THE UNIVERSITY OF TOKYO
UNIVERSITY OF TORONTO

LiteBIRD Joint Study Group

Over 400 researchers from **Japan**, **North America** and **Europe**

Team experience in CMB experiments, X-ray satellites and other large projects (ALMA, HEP experiments, …)



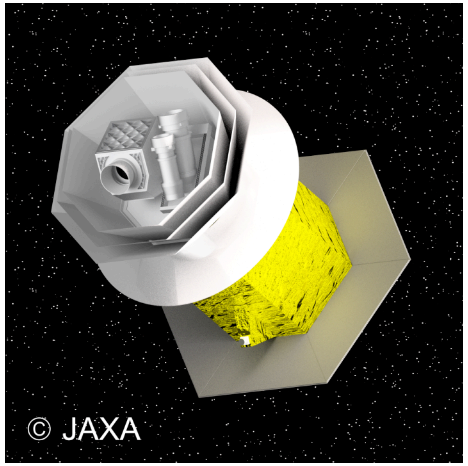


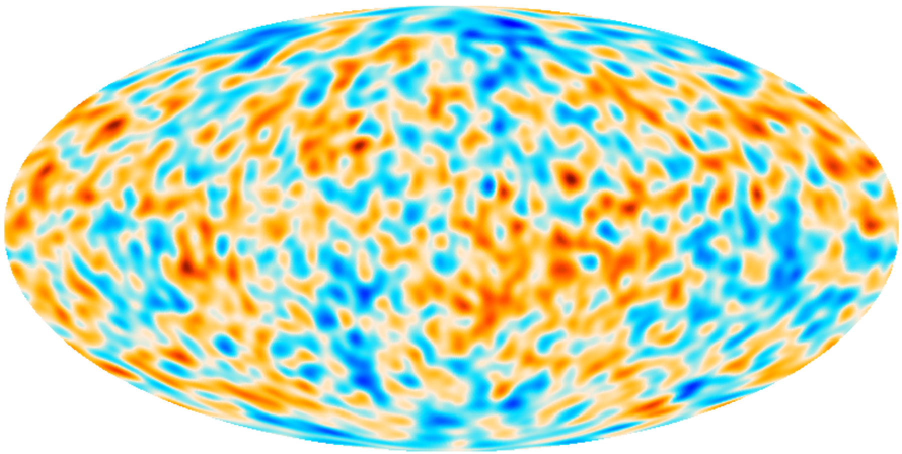
LiteBIRD Global F2F meeting
Sep 28 - Oct 1, 2023 at Elba

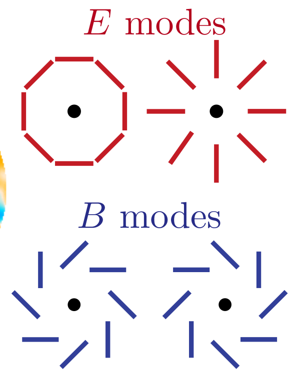
LiteBIRD overview

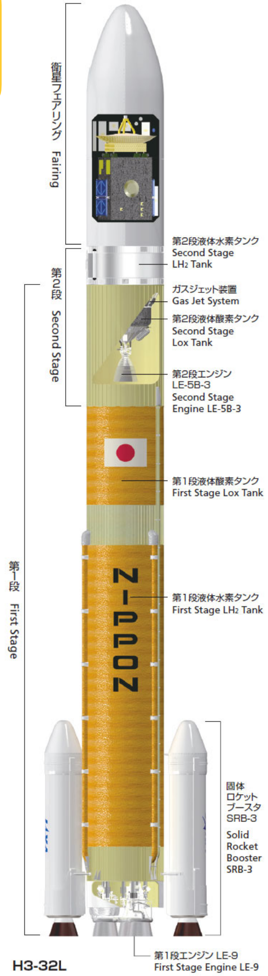
- Lite (Light) spacecraft for the study of *B*-mode polarization and Inflation from cosmic background Radiation Detection
- JAXA's L-class mission was selected in May 2019 to be launched by JAXA's H3 rocket.
- **All-sky 3-year survey**, from Sun-Earth Lagrangian point L2
- Large frequency coverage (**40–402 GHz**, 15 bands) at **70–18 arcmin** angular resolution for precision measurements of the **CMB *B*-modes**
- Final combined sensitivity: **2.2 μK·arcmin**

📖 LiteBIRD collaboration PTEP 2023







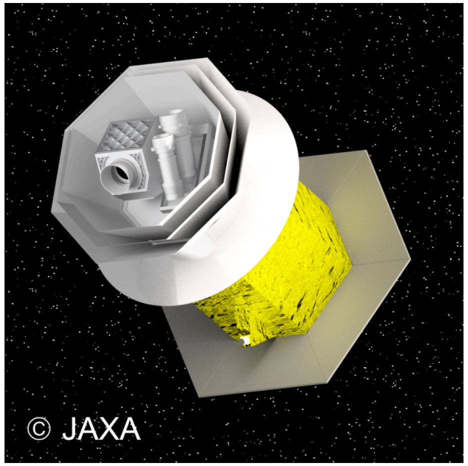


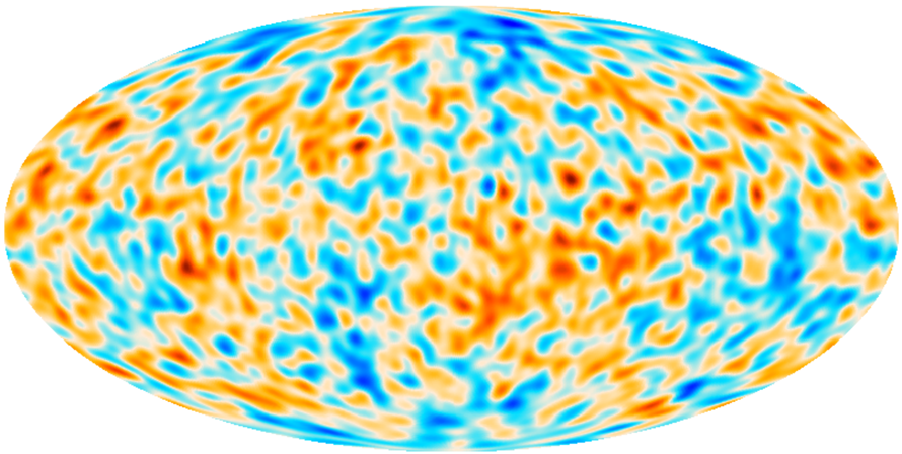
LiteBIRD overview

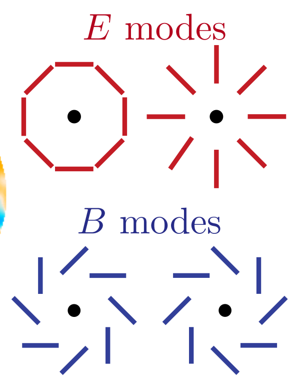
LiteBIRD reformation phase

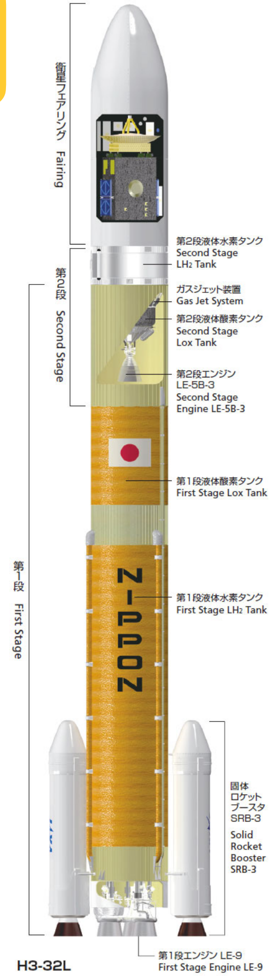
- After the ISAS/JAXA mission definition review, LiteBIRD is under rescope studies to consolidate the mission's feasibility with the same scientific objectives.
- The LiteBIRD collaboration will spend approximately one year (~ late 2025) on the studies of the reformation plan.

📖 LiteBIRD collaboration PTEP 2023









The challenge of B-modes detection

- The *B*-mode signal is expected to have an amplitude at least 3 orders of magnitude below the CMB temperature anisotropies
- LiteBIRD is targeting a sensitivity level in polarization ~30 times better than Planck
- This extremely good statistical uncertainty must go in parallel with exquisite control of:
  1. **Instrument systematic** uncertainties
  2. **Galactic foreground** contamination
  3. **"Lensing B-mode signal"** induced by gravitational lensing
  4. Observer biases

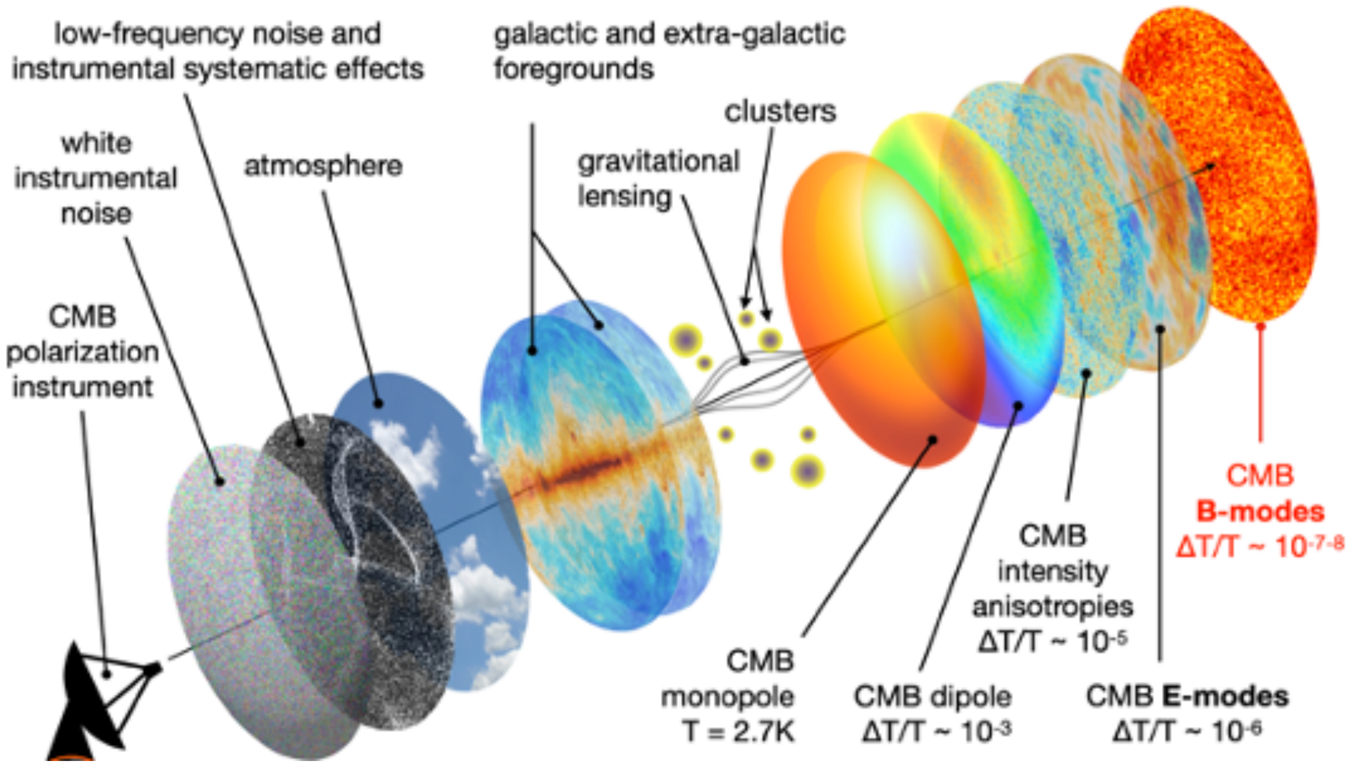
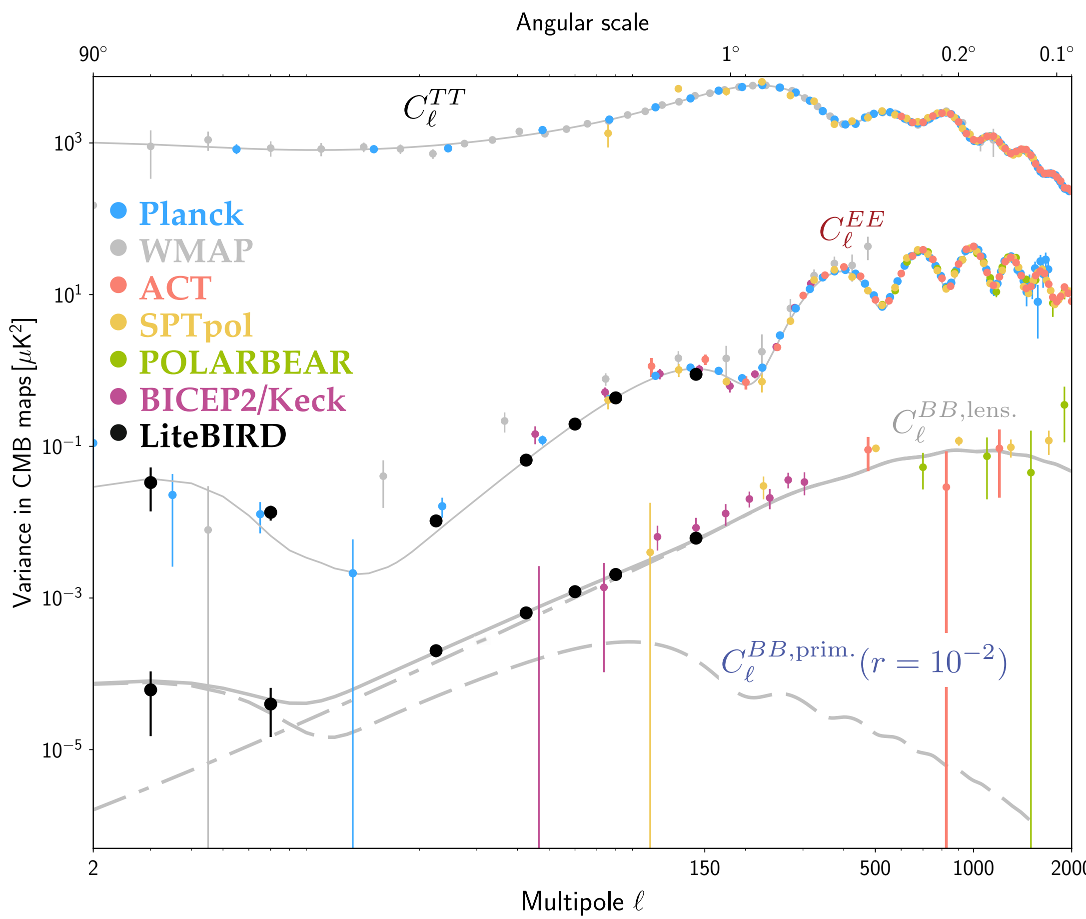


Image credit: Josquin Errard

LiteBIRD main scientific objectives

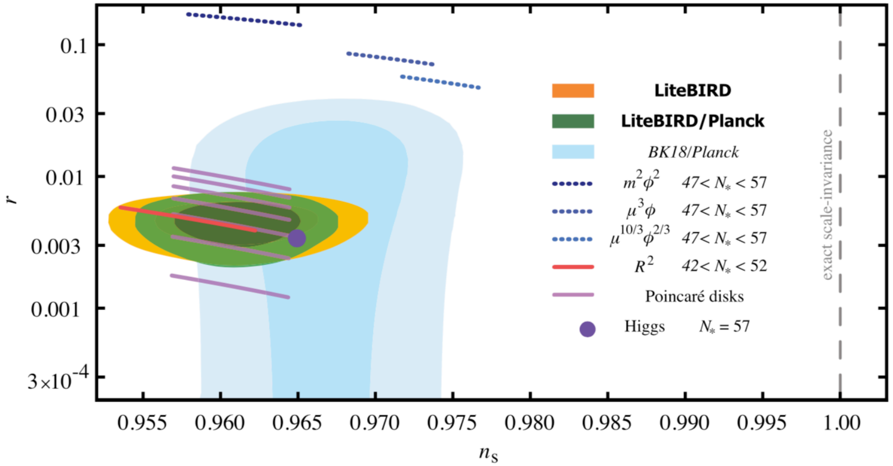
- Definitive search for the ***B*-mode signal** from **cosmic inflation** in the CMB polarization
  - Making a discovery or ruling out well-motivated inflationary models
  - Insight into the quantum nature of gravity
- The inflationary (i.e. primordial) B-mode power is proportional to the **tensor-to-scalar ratio, r**
- Current best constraint: $r < 0.032$ (95% C.L.)
  (📖 Tristram et al. 2022, combining BK18 and Planck PR4)

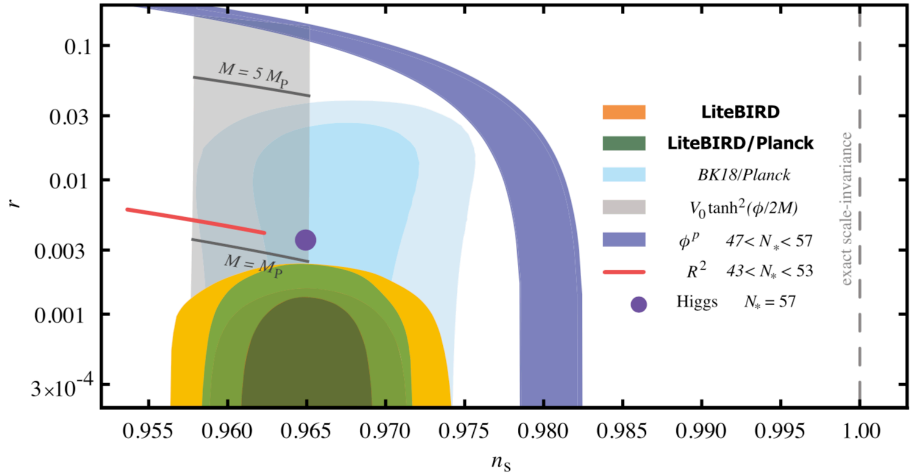
- LiteBIRD will improve current sensitivity on r by a factor ~50
- L1-requirements (no external data):
  - For $r = 0$, **total uncertainty of $\delta r < 0.001$**
  - For $r = 0.01$, 5-σ detection of the reionization ($2 < \ell < 10$) and recombination ($11 < \ell < 200$) peaks independently
- L2-requirements:
  - $\sigma_{stat} < 6\times10^{-4}$ and $\sigma_{sys} < 6\times10^{-4}$
  - Additional security margin of $\sigma_{margin} < 6\times10^{-4}$



LiteBIRD constraints on inflation

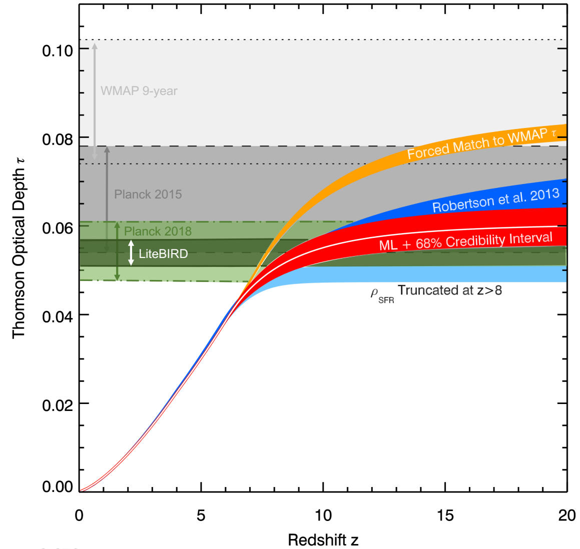
- Huge discovery impact (evidence for inflation, knowledge of its energy scale, and distance traveled by the inflaton…)
- A detection of B modes by LiteBIRD with $r > 0.01$ would imply an excursion of the inflation field that exceeds the Planck mass
  - Such a detection would **constrain theories of quantum gravity** such as superstring theories
- An upper limit from LiteBIRD would disfavour the simplest inflationary models, with $\mathcal{M} > M_p$
  - This includes the monomial models, α-attractors with a super-Planckian characteristic scale, including the **Starobinsky model** and models that invoke the Higgs field as the inflaton



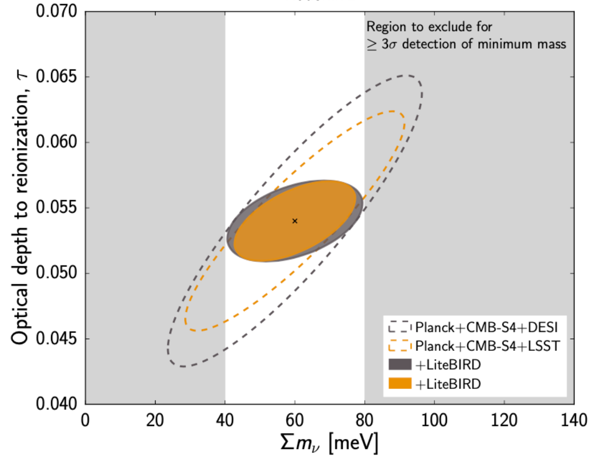


LiteBIRD other science outcomes

- The mission specifications are driven by the required sensitivity on r
- Meeting those sensitivity requirements would allow to address other important scientific topics, such as:
  1. Characterize the B-mode power spectrum and search for source fields (e.g. scale-invariance, non-Gaussianity, parity violation, …)
  2. Power spectrum features in polarization
     - Large-scale ***E*-modes**
     - **Reionization** (improve $\sigma(\tau)$ by a factor of 3)
     - **Neutrino mass** ($\sigma(\sum m_\nu) = 12$ meV)
  3. Constraints on **cosmic birefringence**
  4. **SZ effect** (thermal, diffuse, relativistic corrections)
  5. Constraints on **primordial magnetic fields**
  6. Elucidating **anomalies**
  7. **Galactic science**
     - Characterizing the foreground SED
     - Large-scale Galactic magnetic field
     - Models of dust polarization



📖 adapted from Robertson+2015

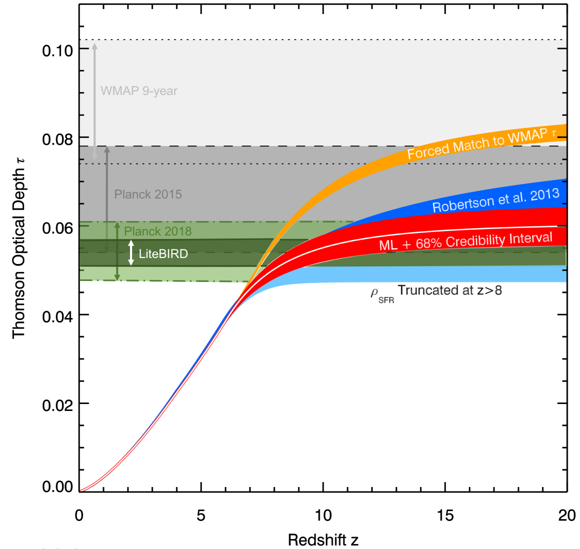


📖 adapted from Calabrese+2017

Thank you!?

Optical depth, reionization and neutrino masses

- LiteBIRD will provide a cosmic-variance limited measurement of the ***E*-mode** power spectrum at large scales ($2 < \ell < 200$)
- This will lead to improved constraints on:
  - **Reionization**
    - Cosmic-variance measurement of the **optical depth** to reionization $\Rightarrow \sigma(\tau) \approx 0.002 \Rightarrow \times 3$ improvement with respect to Planck (📖 Planck Int.Res. LVII, 2020)
    - Improved constraints on reionization history models: 35% improvement on the uncertainty of $\Delta(z_{\rm reion})$
  - **Neutrino masses**
    - $\times 2$ improvement on $\sigma(\sum m_\nu)$
    - $\sigma(\sum m_\nu) = 12$ meV $\Rightarrow 5\sigma$ detection for a minimum value of $\sum m_\nu = 60$ meV (allowed by flavour-oscillation experiments) or larger
    - Potentially allow to distinguish between the inverted neutrino mass ordering and the normal ordering



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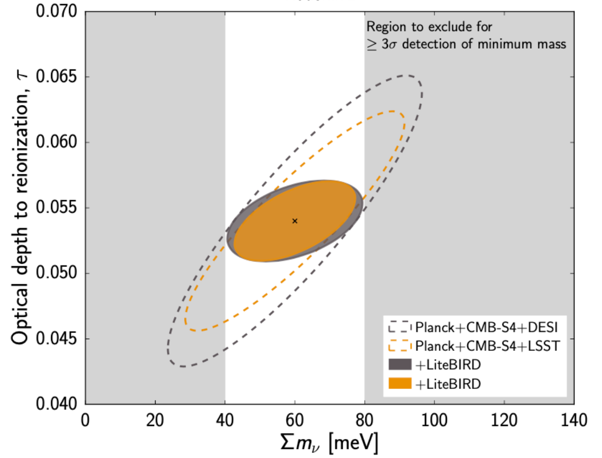
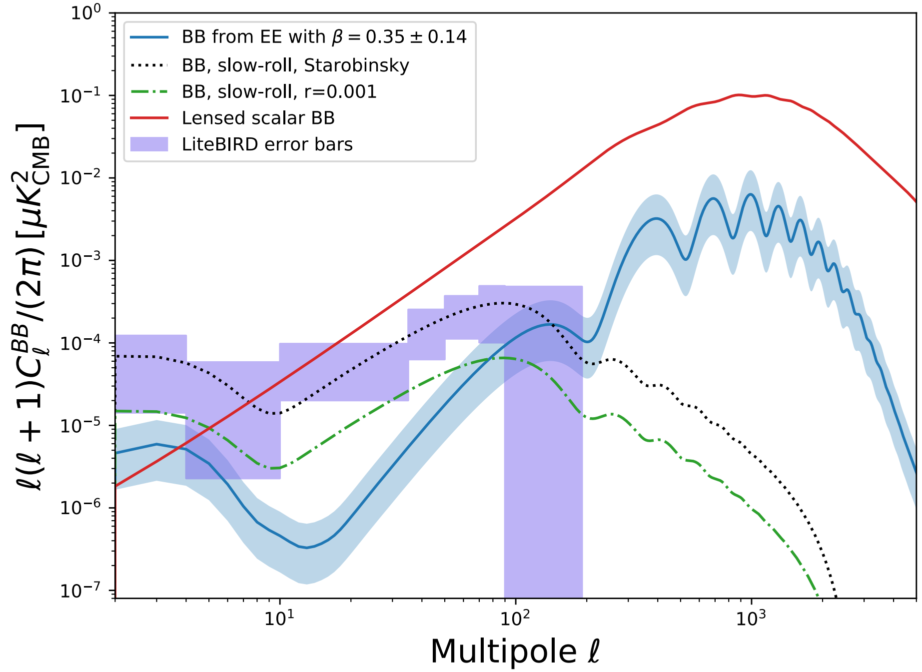


📖 adapted from Calabrese+2017

Constraints on cosmic birefringence

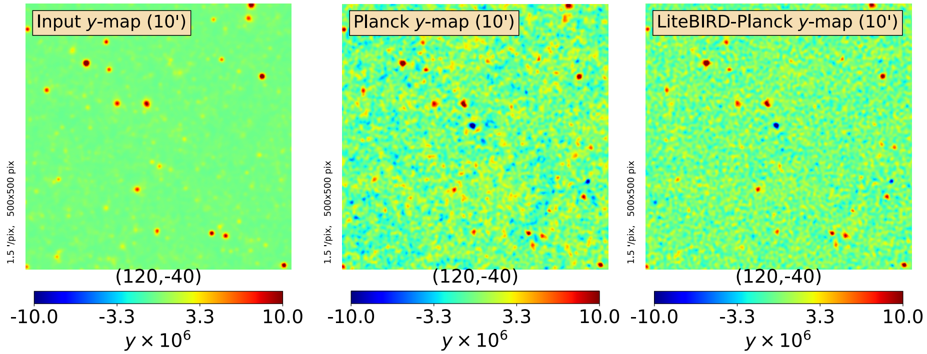
- **Cosmic birefringence** could be seeded by parity-violating processes in Universe
- Could occur if dark matter or dark energy are a pseudo-scalar field coupled to electromagnetism that changes sign under inversion of spatial coordinates
- Induces non-zero *TB* and *EB* and also a *B*-mode signal
- Constraints from the CMB must account jointly for i) a possible detector angle miscalibration (📖 Minami et al., 2019) and ii) a positive EB signal from Galactic foregrounds (📖 Diego-Palazuelos et al., 2022)
- Recent measurements show a tentative detection of a birefringence angle of **$\beta = (0.34 \pm 0.09)°$** (📖 Eskilt & Komatsu 2022, from a combination of WMAP and Planck PR4)
- LiteBIRD has the potential to:
  - Reduce the error bar on a global β leading to a **~10-sigma detection**
  - Produce a map of β to test for **cosmic-birefringence anisotropy**

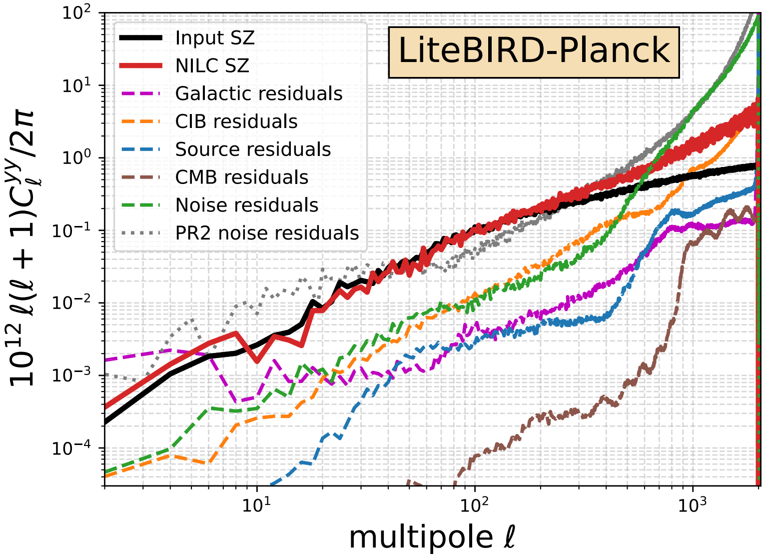


📖 LiteBIRD collaboration PTEP 2023

Mapping the hot gas in the Universe

- The **Sunyaev-Zel'dovich** effect provides a mean to map the distribution of hot electrons in the Universe
- Improved sensitivity and frequency coverage of LiteBIRD crucially contributes to improve these studies
- Combination with Planck adds the benefit of angular resolution
- LiteBIRD will **improve ×10 the noise in the SZ map** wrt Planck
- This will allow to:
  - Produce a high-fidelity SZ map over the full-sky essentially **free of contamination at $\ell < 200$**
  - Test theories of structure formation via **hot-gas tomography** from SZ × galaxy surveys correlations
  - Search form **WHIM** in filaments connecting clusters
  - Study an **inhomogeneous reionization** process via cross-correlations of SZ × CMB optical depth
  - Measure the mean gas T_e via the relativistic SZ
  - Improve constraints on $S_8 = \sigma_8(\Omega_m/0.3)^{0.5}$ by 15%

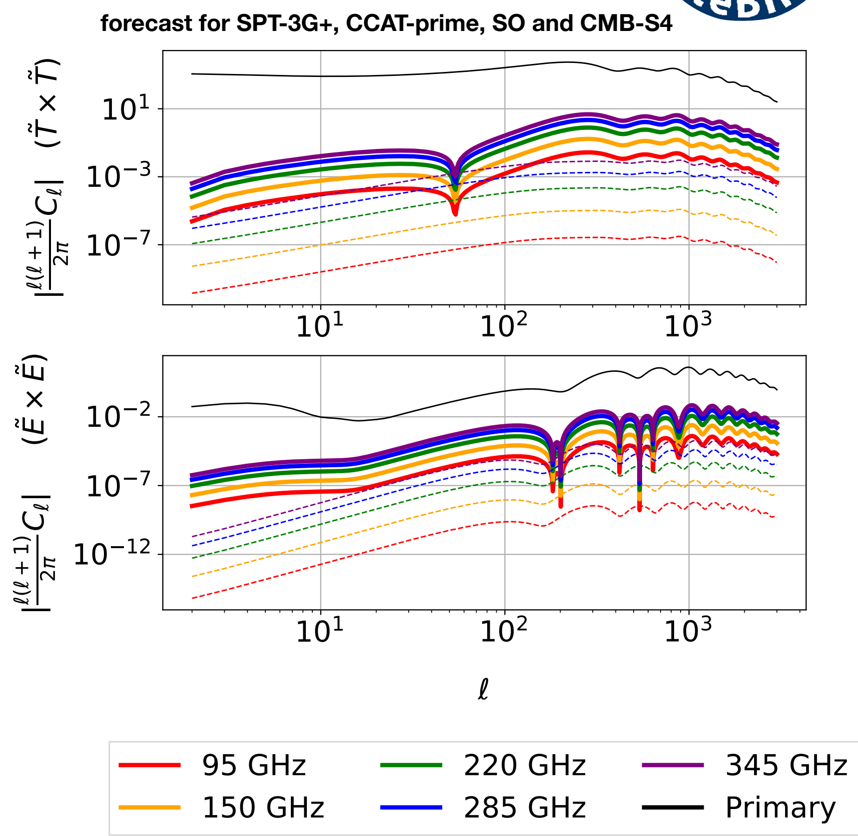




Remazeilles+ JCAP 2024

Anisotropic CMB spectral distortions

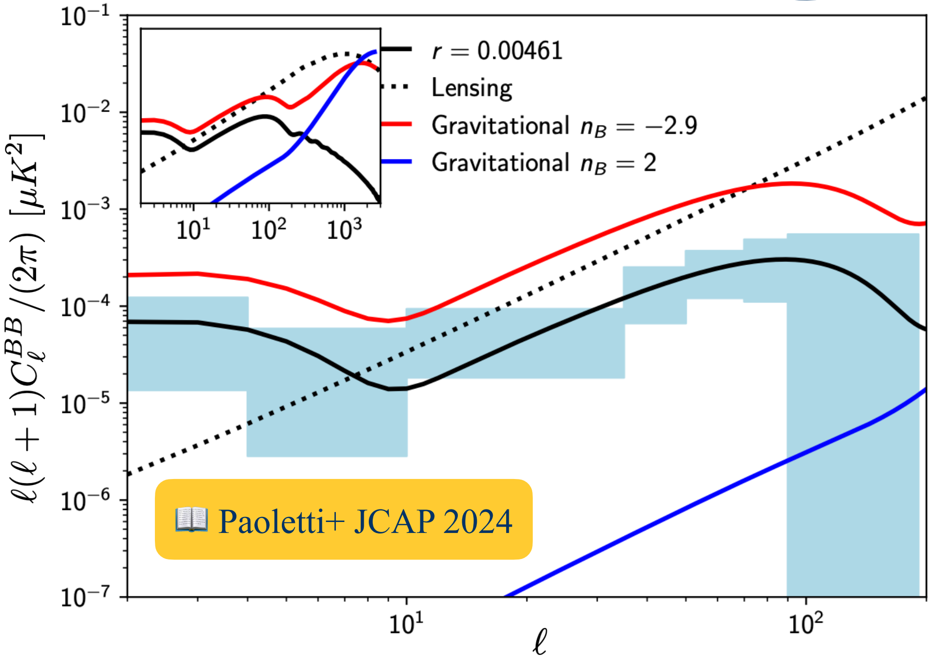
- LiteBIRD will be sensitive to any **spatially-varying CMB spectral distortion**, beyond the SZ effect
  - **Rayleigh scattering**. LiteBIRD will have sensitivity to measure at **25-sigma** (📖 Beringue et al. 2021) the frequency-dependent CMB anisotropies due to Rayleigh scattering by HI at the LSS
    - ➡ Such a detection would allow to derive improved constraints on N_{eff} and $\sum m_\nu$
  - **μ distortion**. LiteBIRD can detect an anisotropic μ distortion induced by non-Gaussian fluctuations induced during inflation
    - ➡ This would offer a power test of inflation at its onset
  - **Axion decay**. LiteBIRD can look for polarized spectral distortions produced by resonant conversion of axions into photons by the Galactic magnetic field



📖 Dibert+ PhysRevD 2022

Constraints on primordial magnetic fields

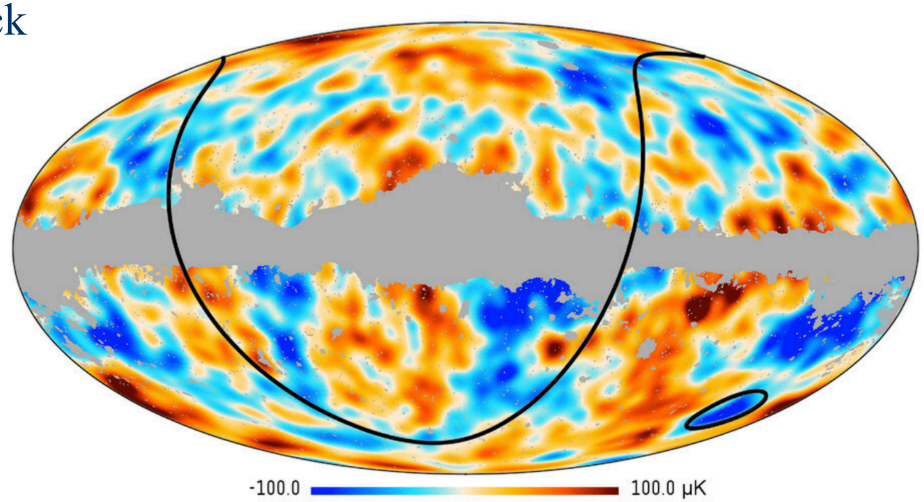
- Primordial magnetic fields (PMFs) affect the CMB via different effects:
  - **Gravitational effects** with magnetically-induced perturbations
  - Impact on the **ionization history** of the Universe due to their post-recombination dissipation
  - Induce a **Faraday rotation** of the CMB polarization
  - **Non-Gaussianity** induced in the CMB polarization anisotropies
- LiteBIRD:
  - Is a **sensitive probe** to PMFs through all these effects, thanks mainly to its remarkable sensitivity in polarization
  - Will **break the nG threshold** improving current upper limits by a factor of ~ 3
  - Will be able to **univocally identify the PFMs contribution to CMB** by joining all these effects together
  - Will allow a detection of **nG fields** with high significance



Upper limits on PMF amplitude for n_B = -2.9	
Gravitational effect	$B_{1Mpc} < 0.8$ nG
Ionization history	$\sqrt{<B^2>} < 0.7$ nG
Faraday rotation	$B_{1Mpc} < 3.2$ nG
Non-Gaussianities	$B_{1Mpc} \lesssim 1$ nG

Elucidating spatial anomalies with polarization

- Various so-called anomalies have been found in WMAP and Planck temperature data that exert a mild tension against the ΛCDM cosmological model:
  - a lack of power on large angular scales
  - the alignment of the quadrupole and octopole moments
  - a hemispherical asymmetry in power on the sky
  - a lack of correlation at large angular scales
  - parity asymmetry in the power associated with even/odd mode
  - an anomalous "Cold Spot" on a scale of ~ 10°
  - anomalously low temperature variance



Credit ESA/Planck Collaboration

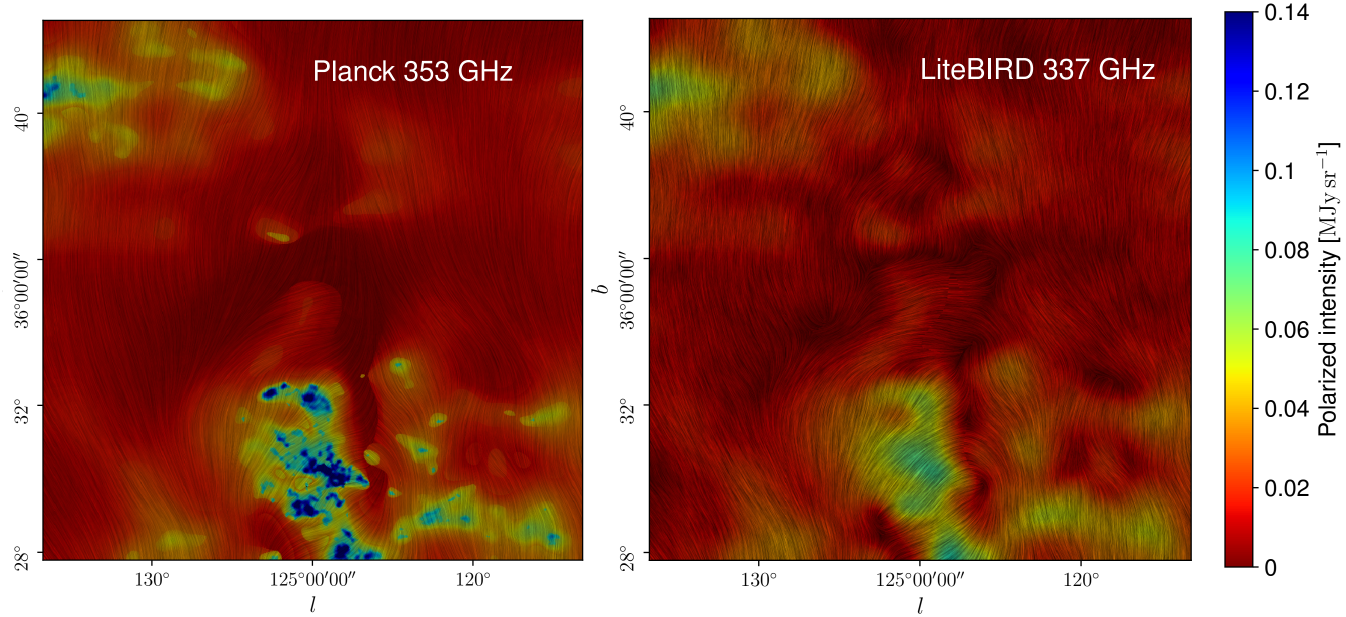
- Given their modest statistical significance, these could simply be statistical flukes
- However, they may also be hints of **new physics** beyond the standard model

- Polarized CMB anisotropies provide independent information on the fluctuations that source the temperature anisotropy
- **LiteBIRD E-mode polarization sky maps will allow further tests** on the nature of these spatial anomalies at close to the cosmic-variance level of sensitivity

Galactic astrophysics

- LiteBIRD will provide 15 high-sensitivity polarization full-sky maps from 40 to 402 GHz
- Sensitivity improved by a factor of 5 at 40 GHz and 10 at 402, with respect to Planck
- Gain in spectral resolution

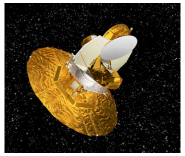
- **Wealth of Galactic science possible**:
  - Geometry of the Galactic magnetic field
  - Interstellar turbulence
  - Dust composition
  - Grain alignment
  - Cold clumps
  - Geometry of synchrotron-bright loops
  - SED of the synchrotron emission
  - Nature of AME and spectral variations...
  - … and many others!

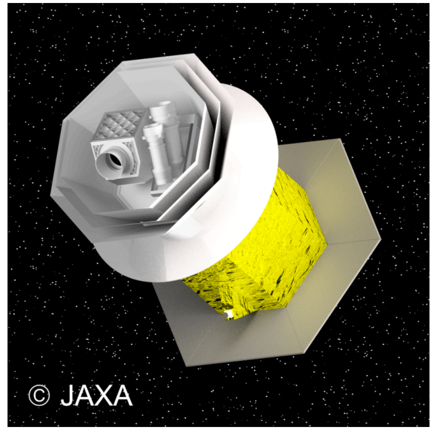


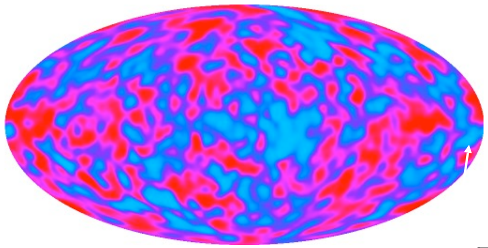
Summary

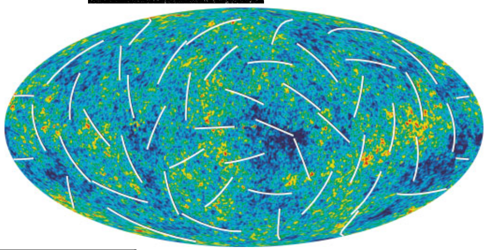
- LiteBIRD is the selected JAXA/ISAS strategic L-class mission with international partners.
- The team is currently undergoing the reformation design phase, and we plan to conclude this by late summer.
- LiteBIRD may be known as the tensor-to-scalar ratio. It is true, but it is also essential to stress that broad science outcomes exist.
- We didn’t cover this in this talk, but even broader scientific outcomes exist by combining the data from the CMB ground telescopes, e.g. Simons Observatory, SPO, and CMB-S4.

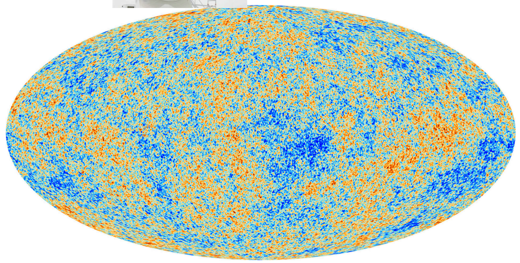
Very brief history of CMB measurements (w/ space focus)







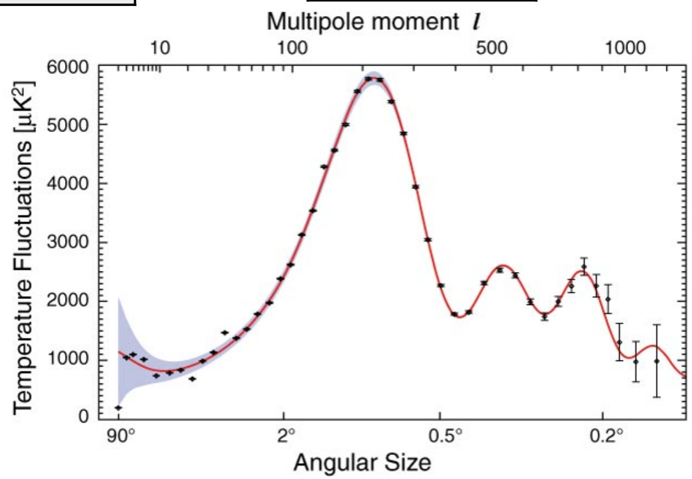


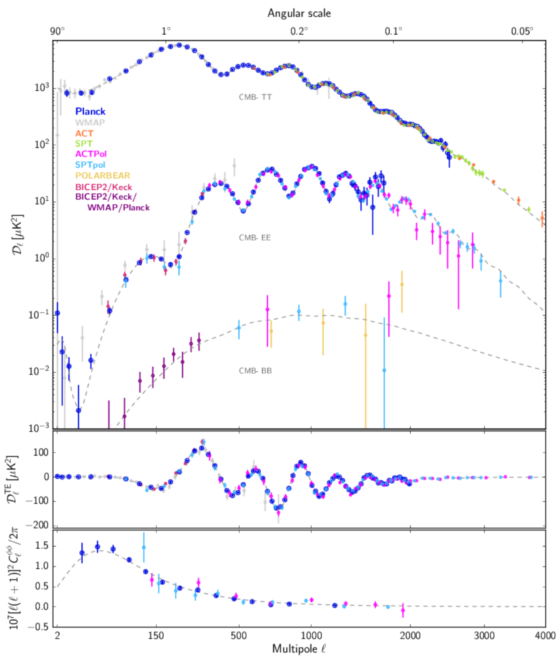


	COBE (1989)
Band	32-90 GHz
# det.	6 radiometers
Op. T	140 K
Beam	～7°
Orbit	Sun Synch.

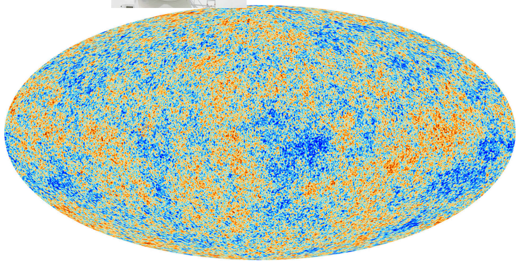
WMAP (2001)
23-94 GHz
20 radiometers
90 K
～0.22°
L2

Planck (2009)
30-857GHz
11 rad. + 52 bolo.
100 mK
～0.1°
L2





Very brief history of CMB measurements (w/ space focus)



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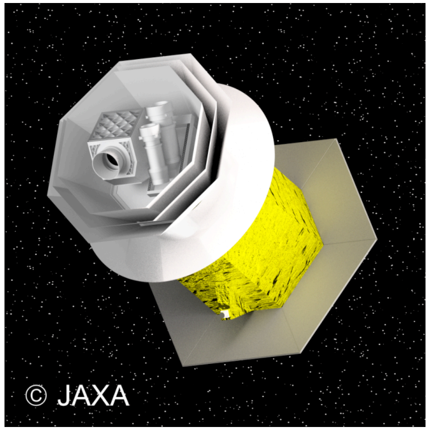

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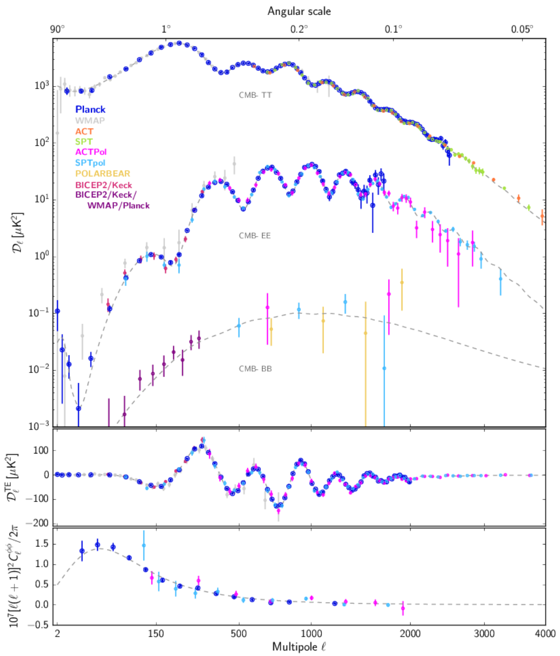
- **CMB Probe mission for more comprehensive science outcomes.**
- **Spectral distortion (monopole)**



Planck (2009)
30-857GHz
11 rad. + 52 bolo.
100 mK
∼0.1°
L2

↕

Ground telescopes
SO, SPO, CMB-S4 and more

SIMONS OBSERVATORY

CMB S4

Thank you!