Searching for inflation using CMB B-modes

T. Matsumura, Kavli IPMU colloquium, 2020-March-25

THE UNIVERSITY OF TOKYO
KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE
wpi World Premier International Research Center Initiative

Outline

- **Science with CMB**
- **LiteBIRD and experimental effort at IPMU**
- **Beyond LiteBIRD?**

What are the questions to be answered?

Kavli IPMU is founded as an international research institution addressing fundamental questions about the universe.

- *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?*

From IPMU HP

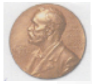
Brief history of the Universe

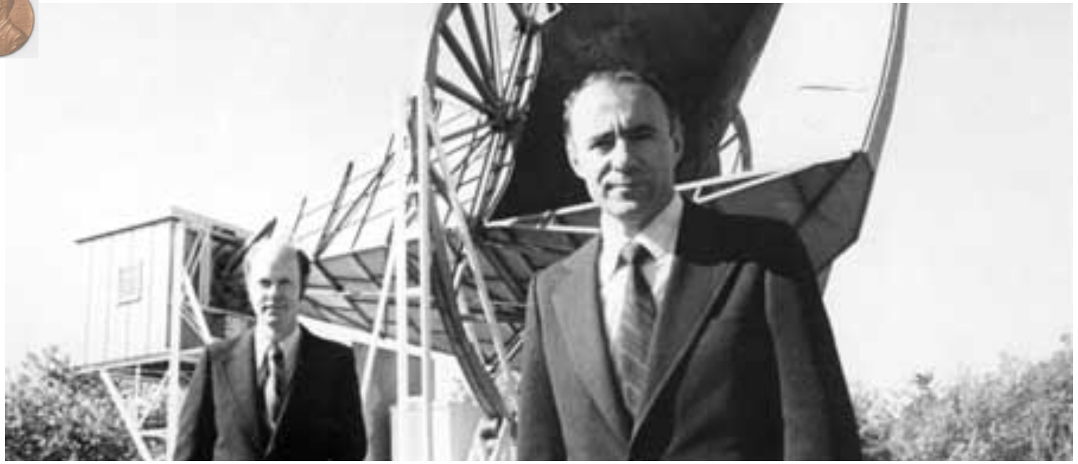
Figure from http://lambda.gsfc.nasa.gov/ (modified)

Brief history of the CMB observations

- The discovery of the expansion of the universe leads the idea of the existence of the beginning.
- From the nuclear physics, there is a prediction of 5 K thermal radiation in the early universe.

Novel prize in 1978 to Penzias and Wilson for their discovery of the cosmic microwave background in 1964.





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

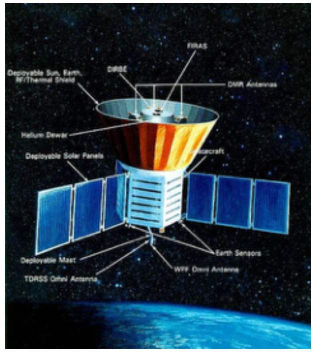
No. 1, 1965 LETTERS TO THE EDITOR 421

Note added in proof.—The highest frequency at which the background temperature of the sky had been measured previously was 404 Mc/s (Pauliny-Toth and Shakeshaft 1962), where a minimum temperature of 16° K was observed. Combining this value with our result, we find that the average spectrum of the background radiation over this frequency range can be no steeper than $\lambda^{0.7}$. This clearly eliminates the possibility that the radiation we observe is due to radio sources of types known to exist, since in this event, the spectrum would have to be very much steeper.

A. A. Penzias
R. W. Wilson

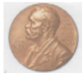
May 13, 1965
Bell Telephone Laboratories, Inc
Crawford Hill, Holmdel, New Jersey

Brief history of the CMB observations



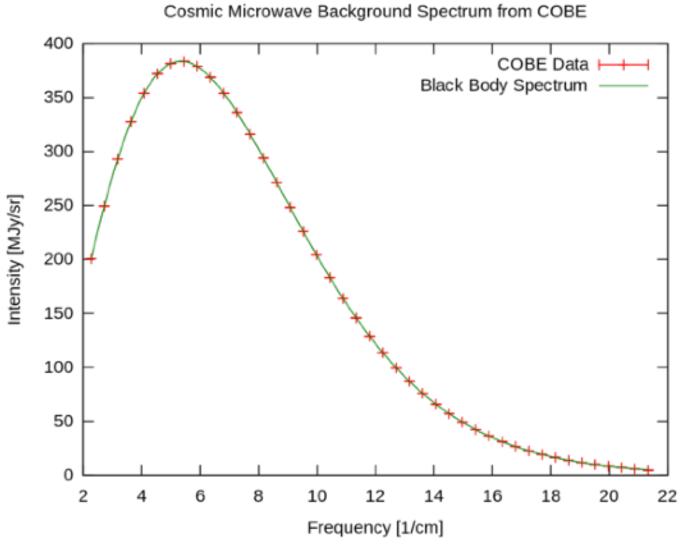
NASA COBE satellite

- **The CMB is a perfect blackbody at the temperature of T_{cmb} = 2.725 K.**

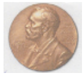



J. Mather
Far-InfraRed Absolute Spectrophotometer (FIRAS)

→**Hot big bang!**

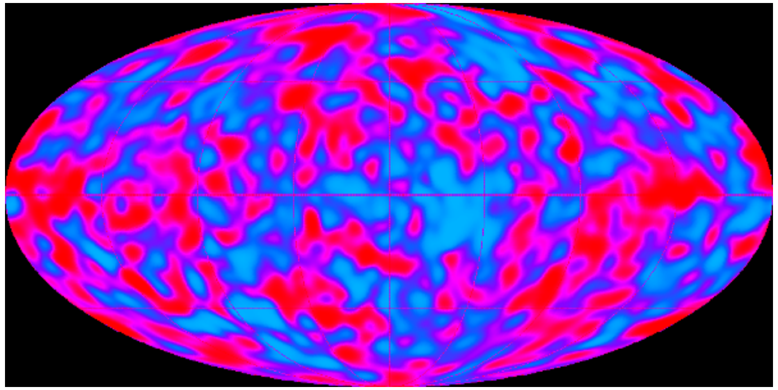


- **The CMB has a temperature fluctuation.**

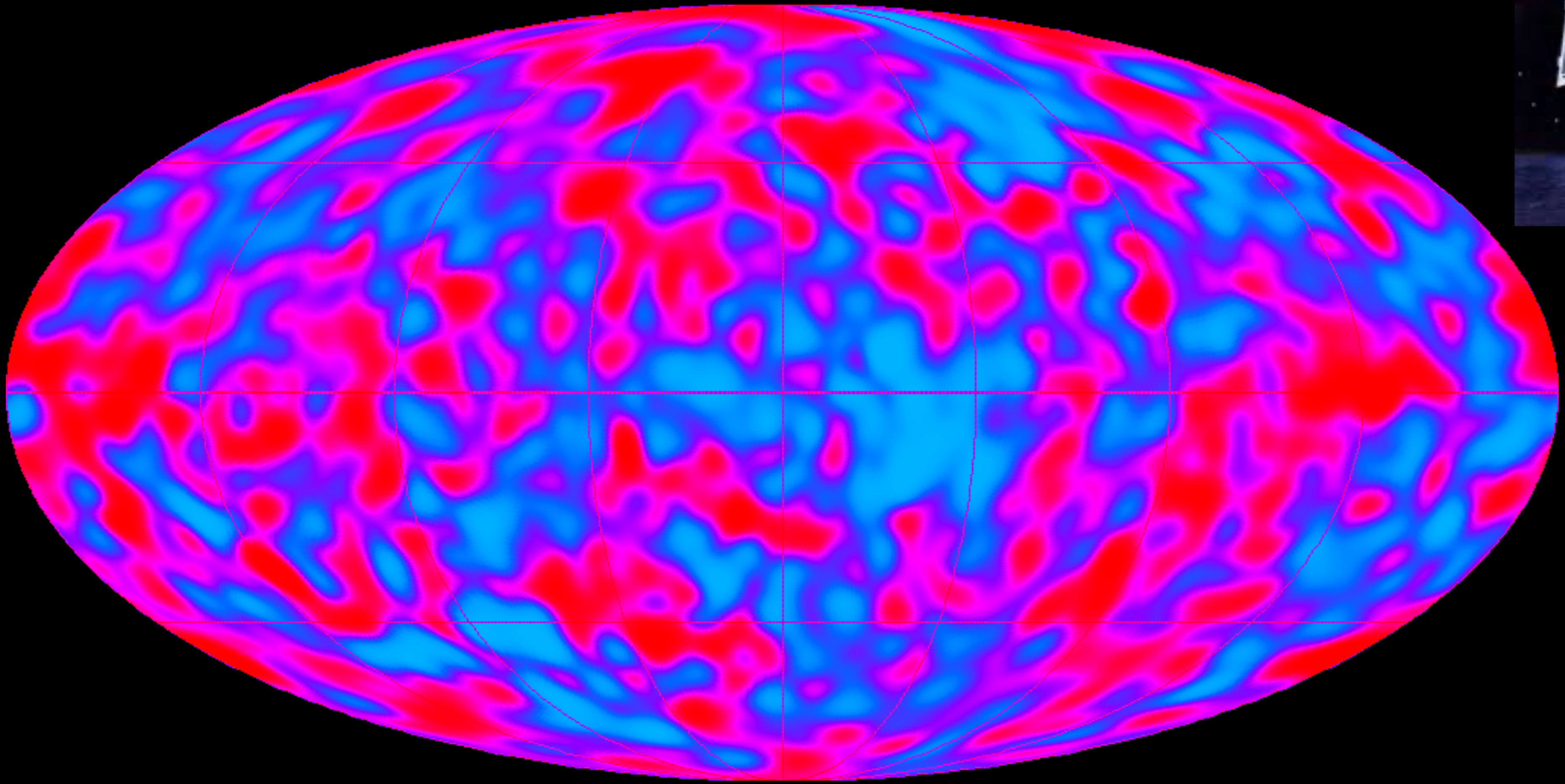



G. Smooth
Differential Microwave Radiometer (DMR)

→**Seed of the structure!**



CMB temperature map

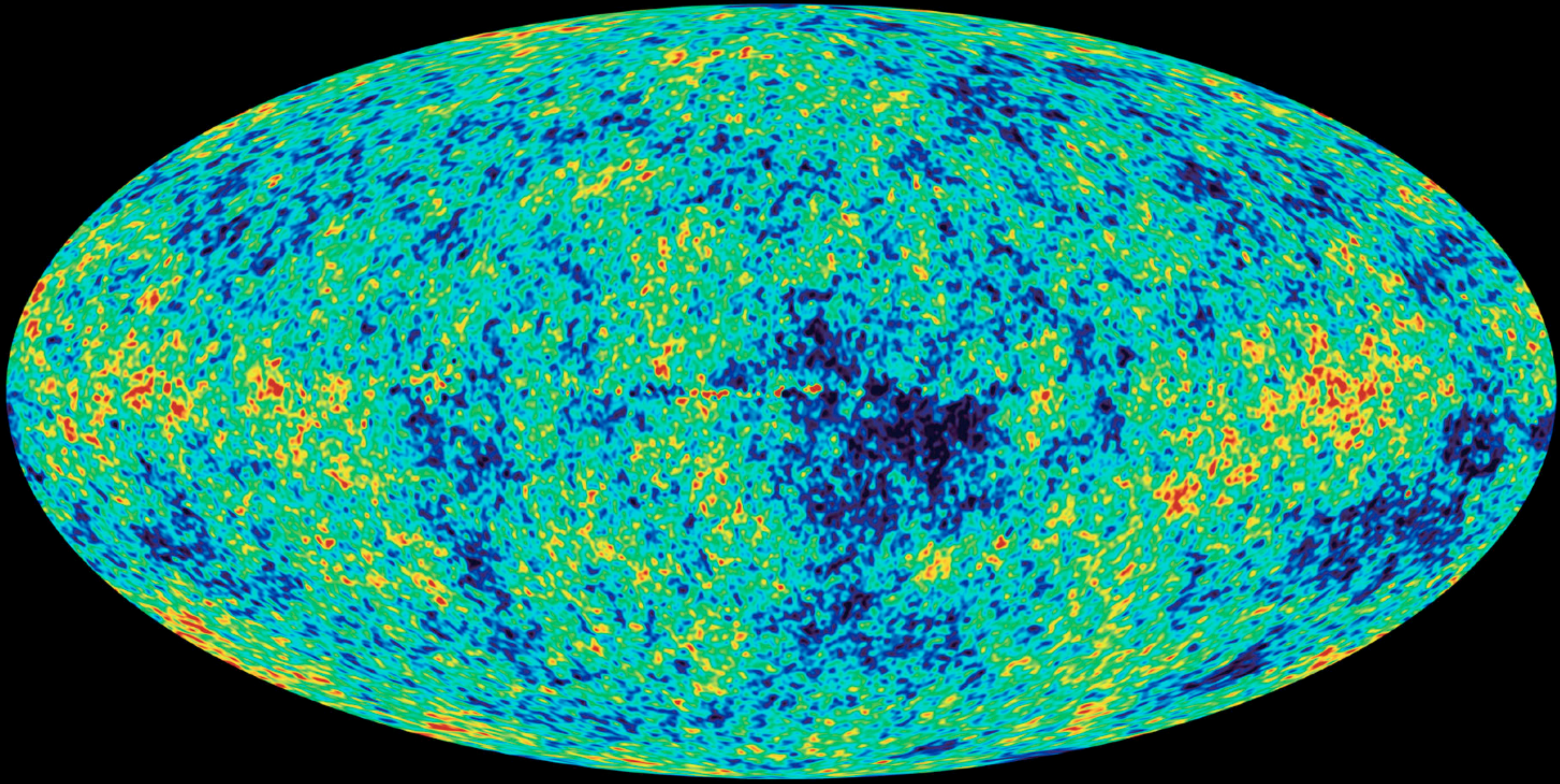


NASA COBE

Launched in 1989

The oldest light we can ever hope to observe.

CMB temperature map

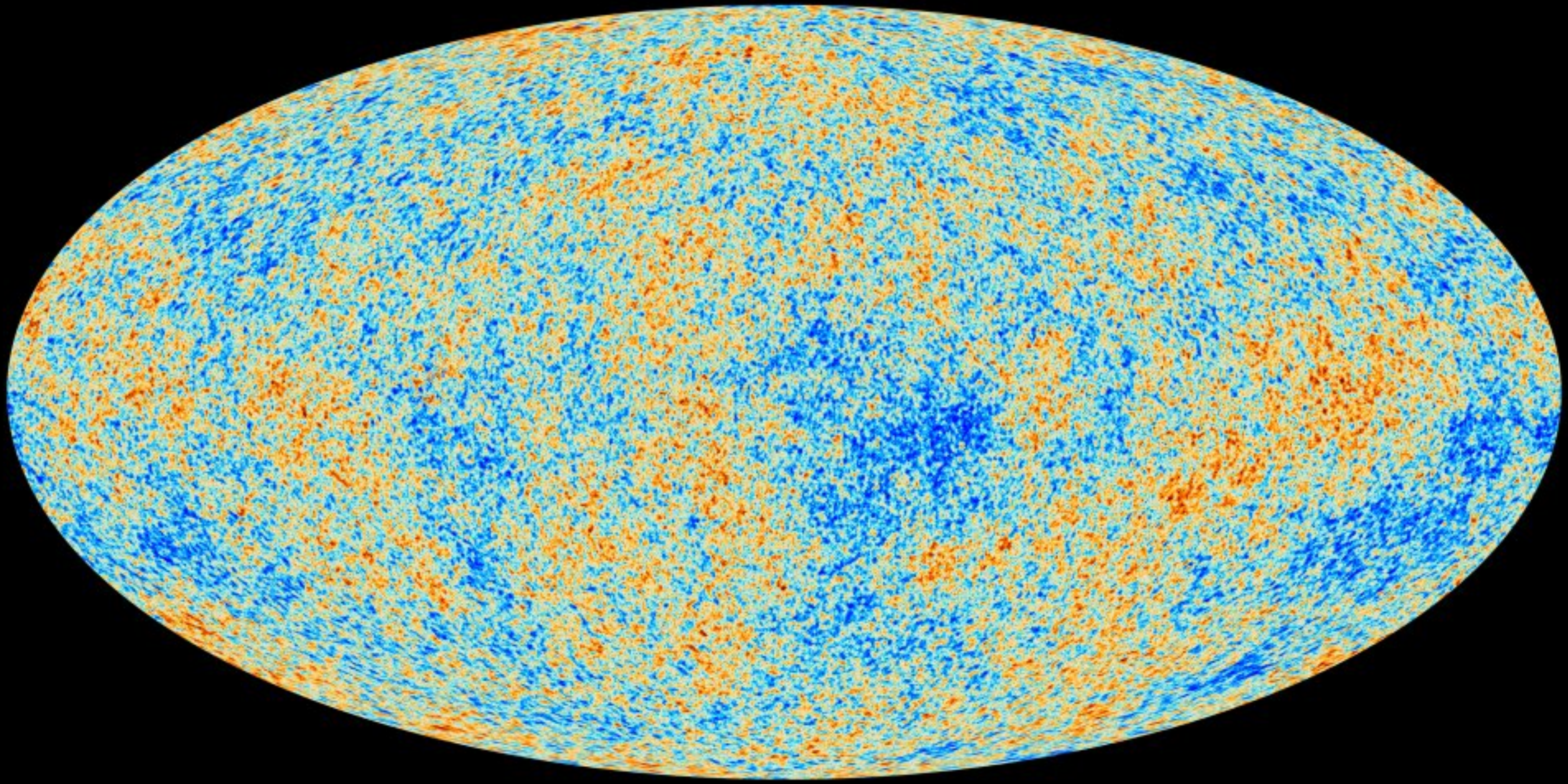


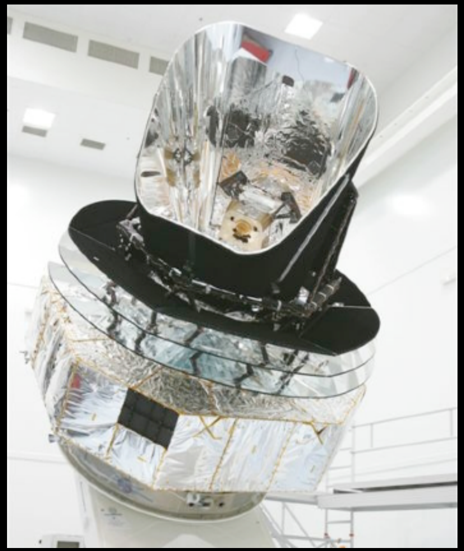
NASA WMAP

Launch in 2001

The oldest light we can ever hope to observe.

CMB temperature map

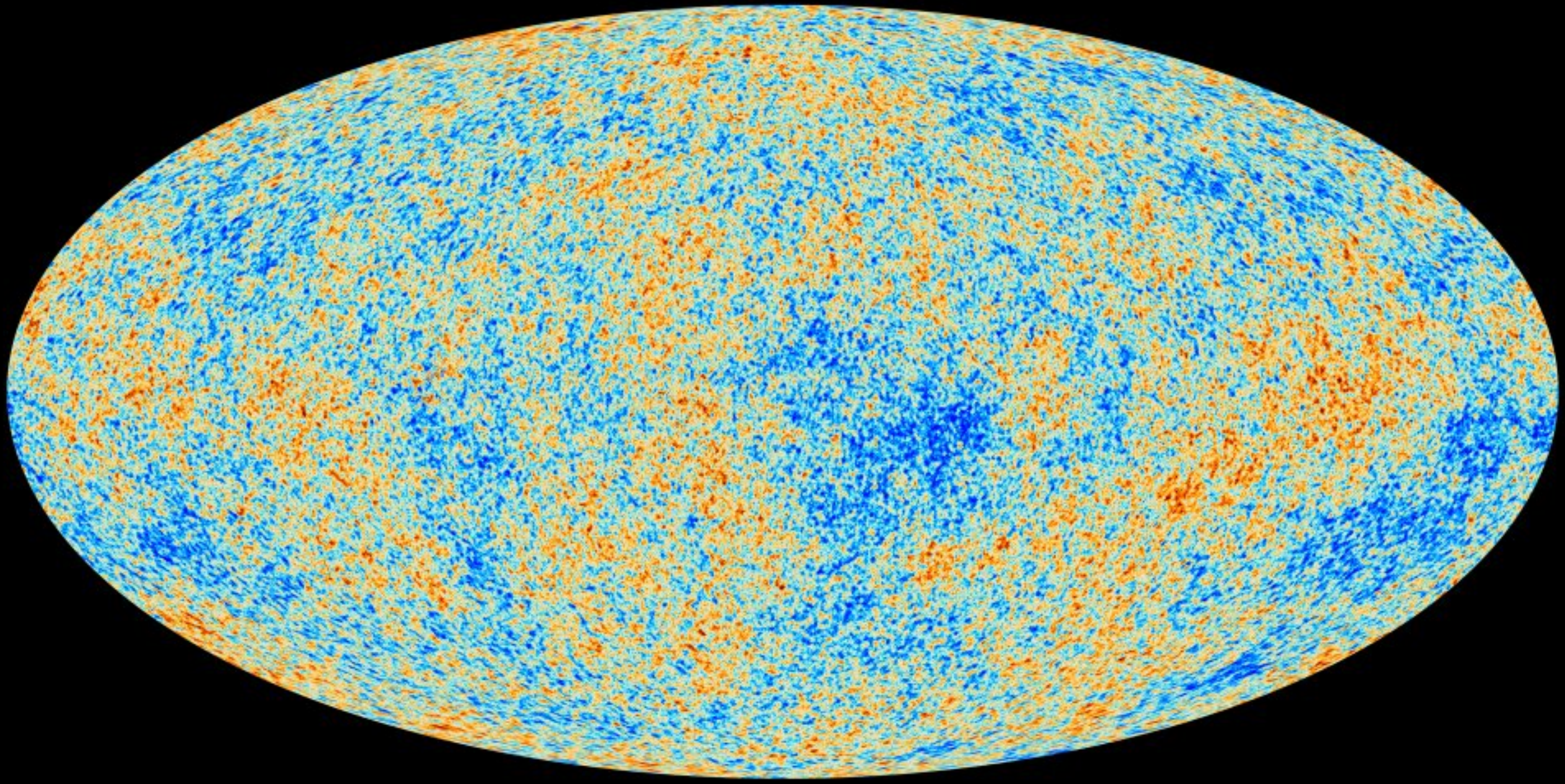


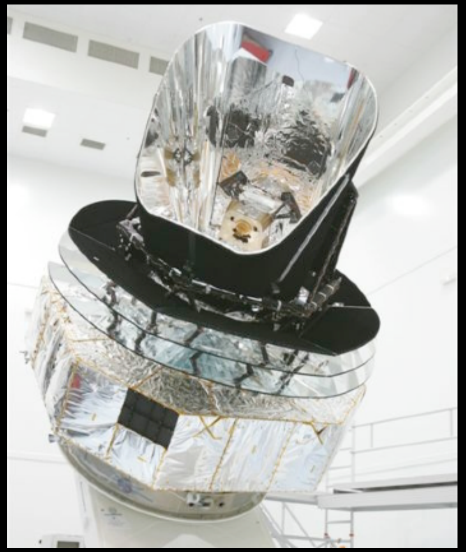


ESA Planck
Launched in 2013

The oldest light we can ever hope to observe.

CMB temperature map





ESA Planck
Launched in 2013

The red and blue spots ⇄ the higher and lower radiation flux

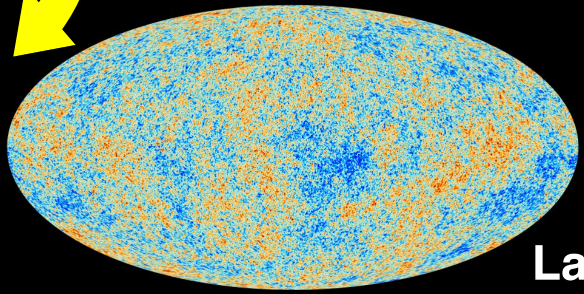
⇄ the higher and lower matter (dark matter and baryon) density

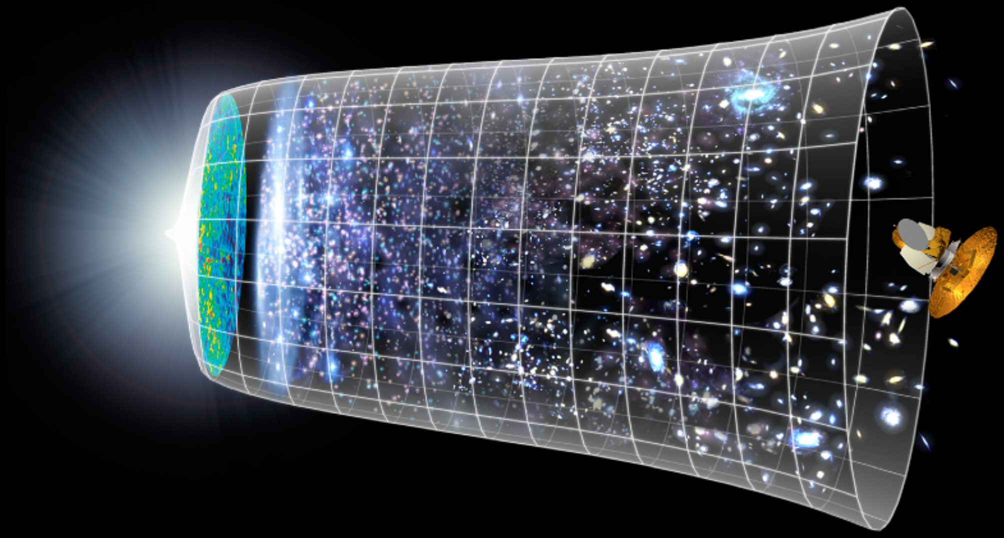
Our quest does not stop at 380,000 years!

?

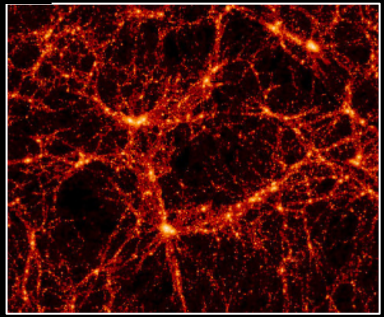
Initial condition

relic radiation CMB fluctuation



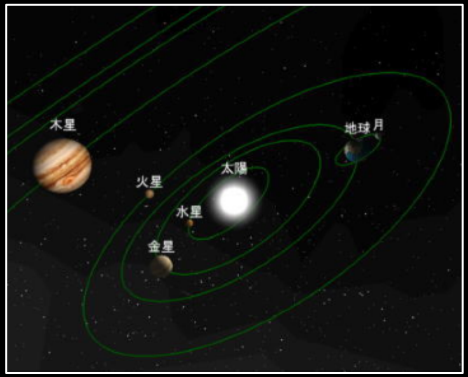


Large scale structure



Galaxy

Solar system

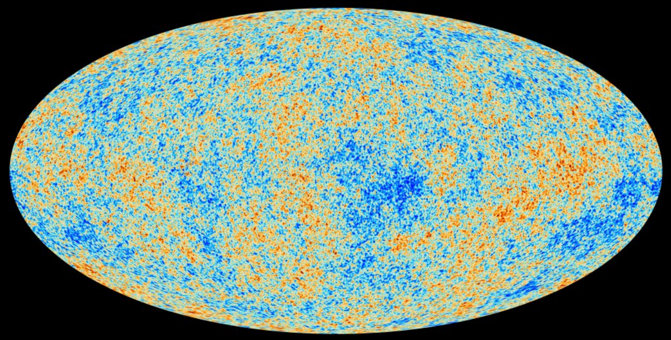


Early universe

Time

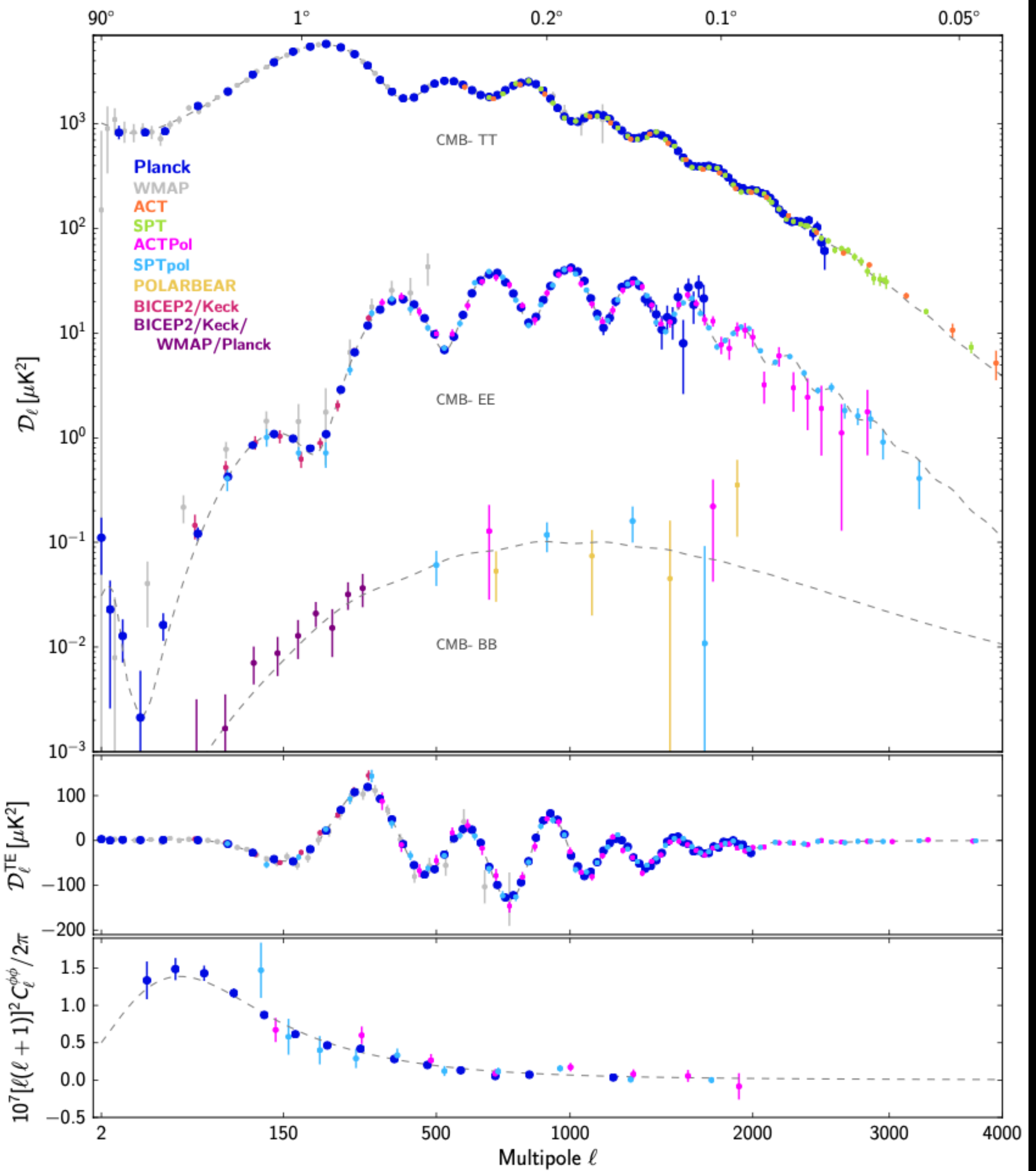
Today

What do we know about our universe today from CMB?



- Power spectrum from the temperature and polarization maps.
- This is where the data and the theory meet.

From Planck 2018 results



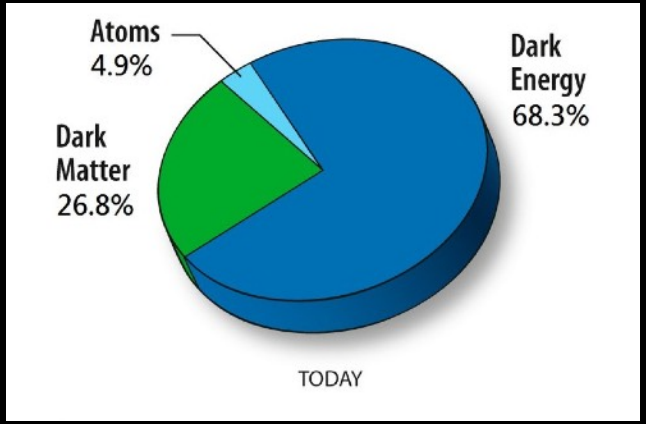
- ΛCDM cosmology with 6 parameters
  - 2 parameters for initial condition $P_R = A_s\left(\frac{k}{k_0}\right)^{n_s-1}$
  - 1 expansion rate, H_0.
  - 2 parameters for densities, $\Omega_b h^2, \Omega_c h^2$.
  - reionization, τ.

Note that no inflation is imposed at this point.

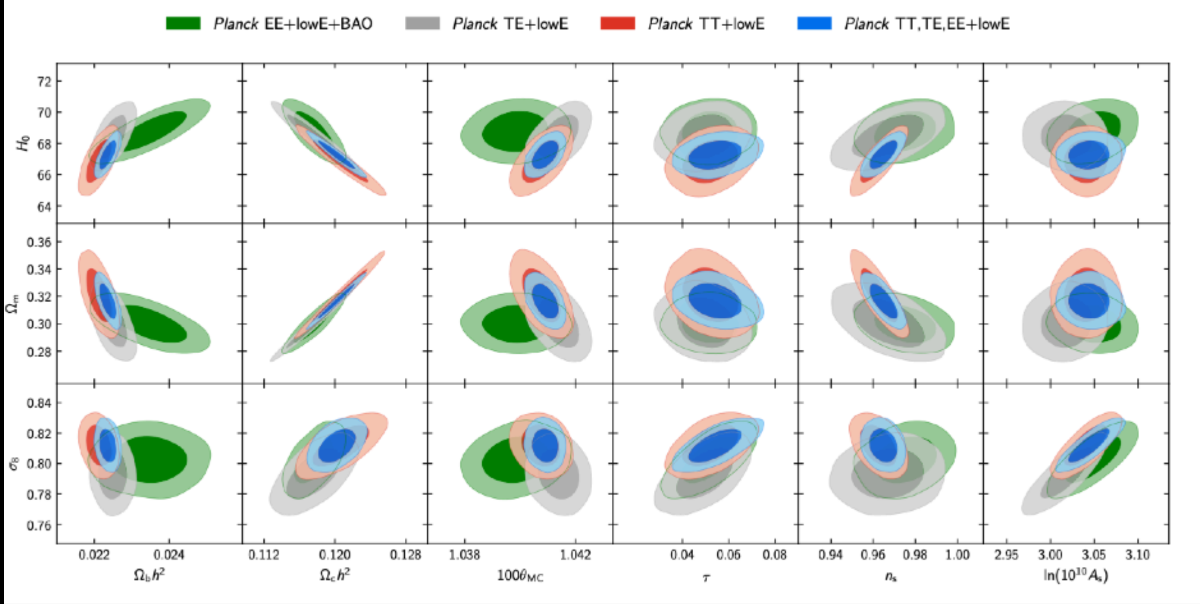
The data and the model agree to each other very well!
It is the big success to our understanding of the universe.

From Planck 2018 results

What do we know about our universe today from CMB?



Parameter	TT,TE,EE+lowE+lensing 68% limits	TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$	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



- The results are consistent within the CMB data as well as among the CMB and the other tracers, e.g. BAO, BBN, SNIa.
- The cosmological parameters are determined within 1 % or less.
- The data allow to probe beyond the ΛCDM model, e.g. flatness, sum of neutrino masses and effective number, and more.

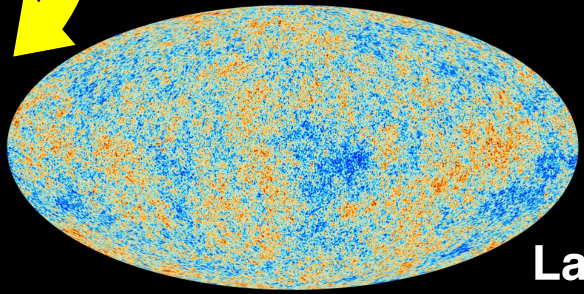
What's next?

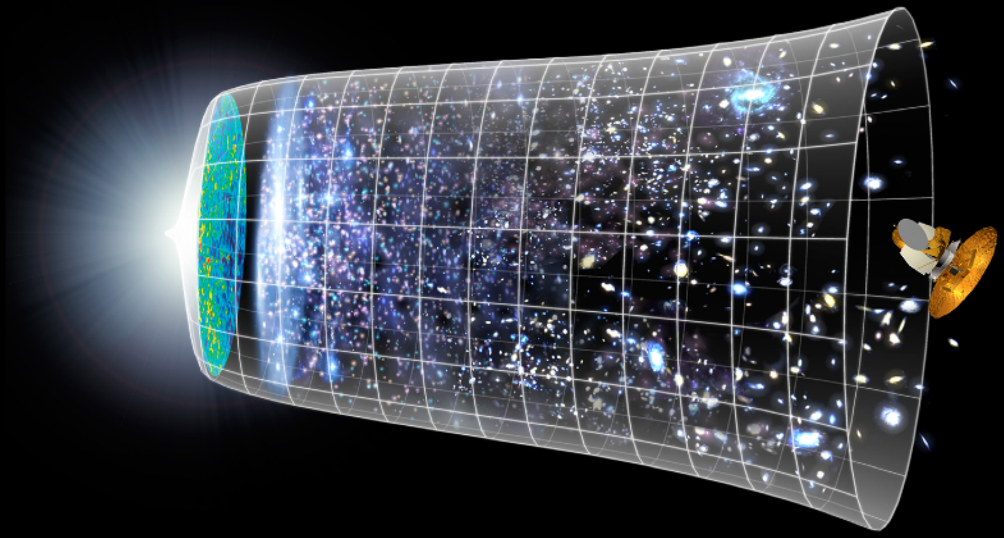
Our quest does not stop at 380,000 years!

?

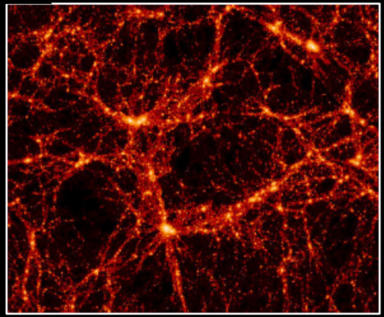
initial condition

relic radiation CMB fluctuation



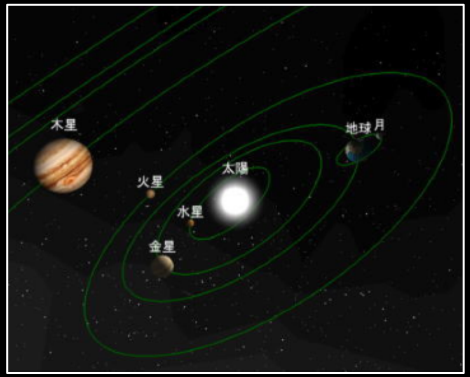


Large scale structure



Galaxy

Solar system

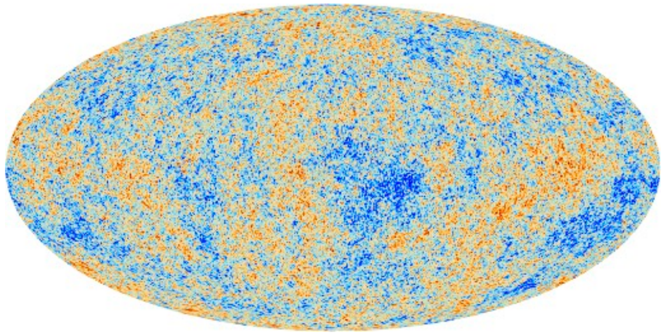


Early universe

Time

Today

Inflation



The motivation to the inflation comes from unresolved questions, e.g.

- Where does the seed of the structures come from?
- Why should the universe be flat? It requires a fine tune at early universe. (Flatness problem)
- Why do we see the same CMB between the two points that have never had a causal contact? (Horizontal problem)

introducing the idea of

Inflation

Tensor-to-scalar ratio

The amplitude of the tensor mode can be parametrized as the tensor-to-scalar ratio,

$$r = \frac{A_t}{A_s}$$

The primordial power spectrum for the scalar and tensor modes are

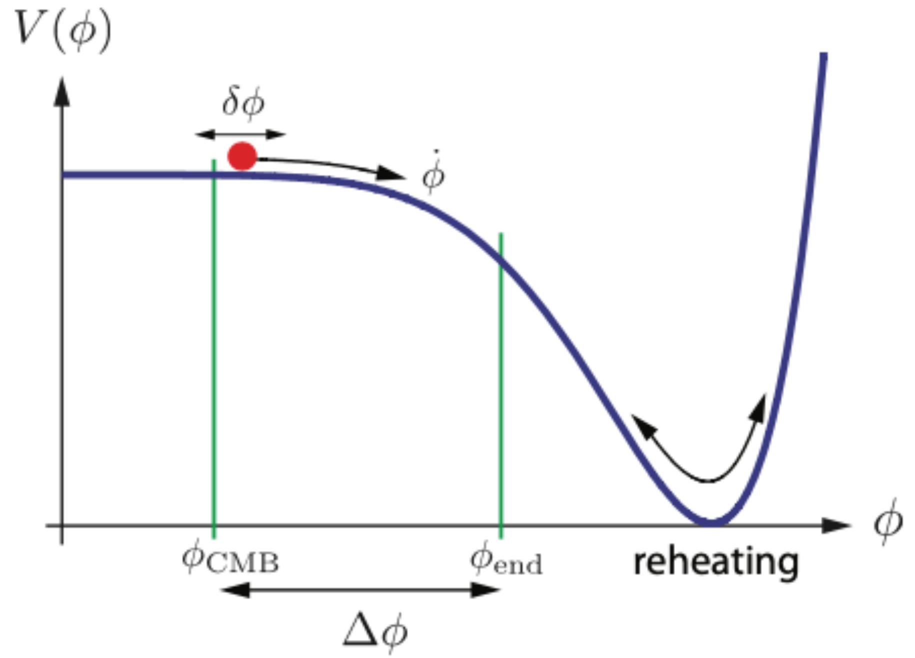
Scalar

$$P_R = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$$

Tensor

$$P_T = A_t \left(\frac{k}{k_0}\right)^{n_t}$$

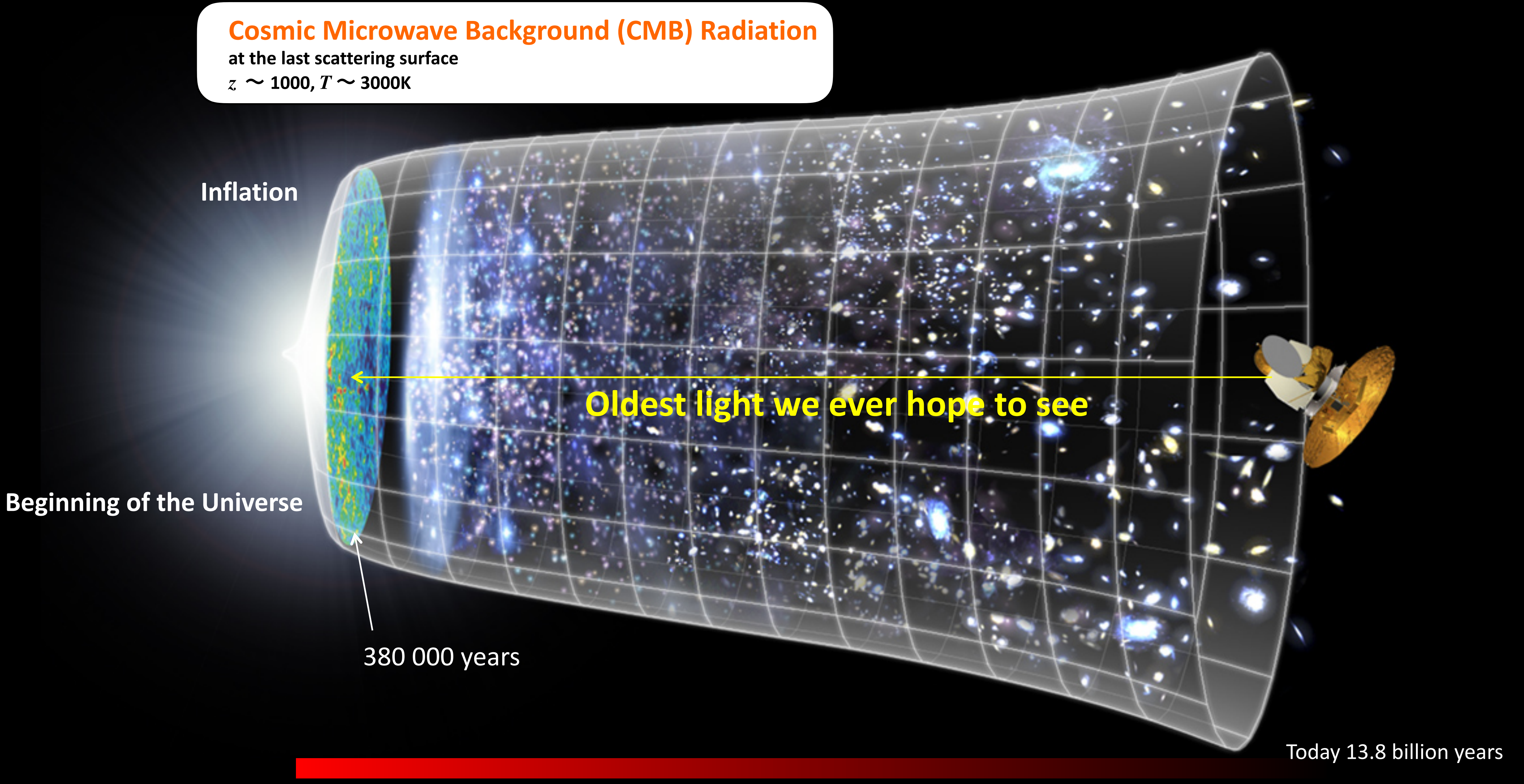
The measurement of the tensor-to-scalar ratio can provide the amplitude of the primordial gravitational wave and it gives the direct constraints on the shape fo the potential, V, V', V''.

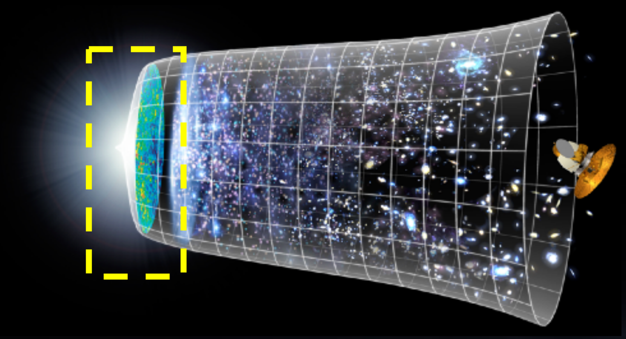


How do we observe?

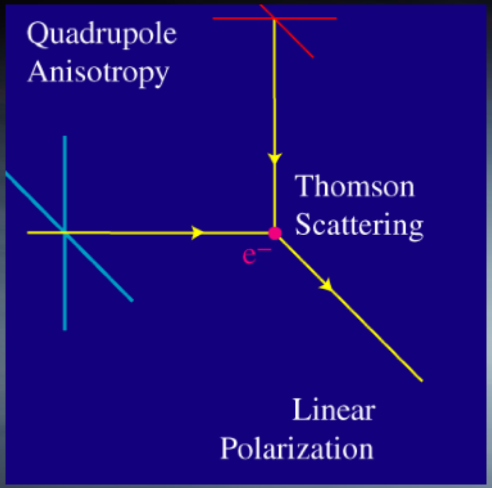
Brief history of the Universe

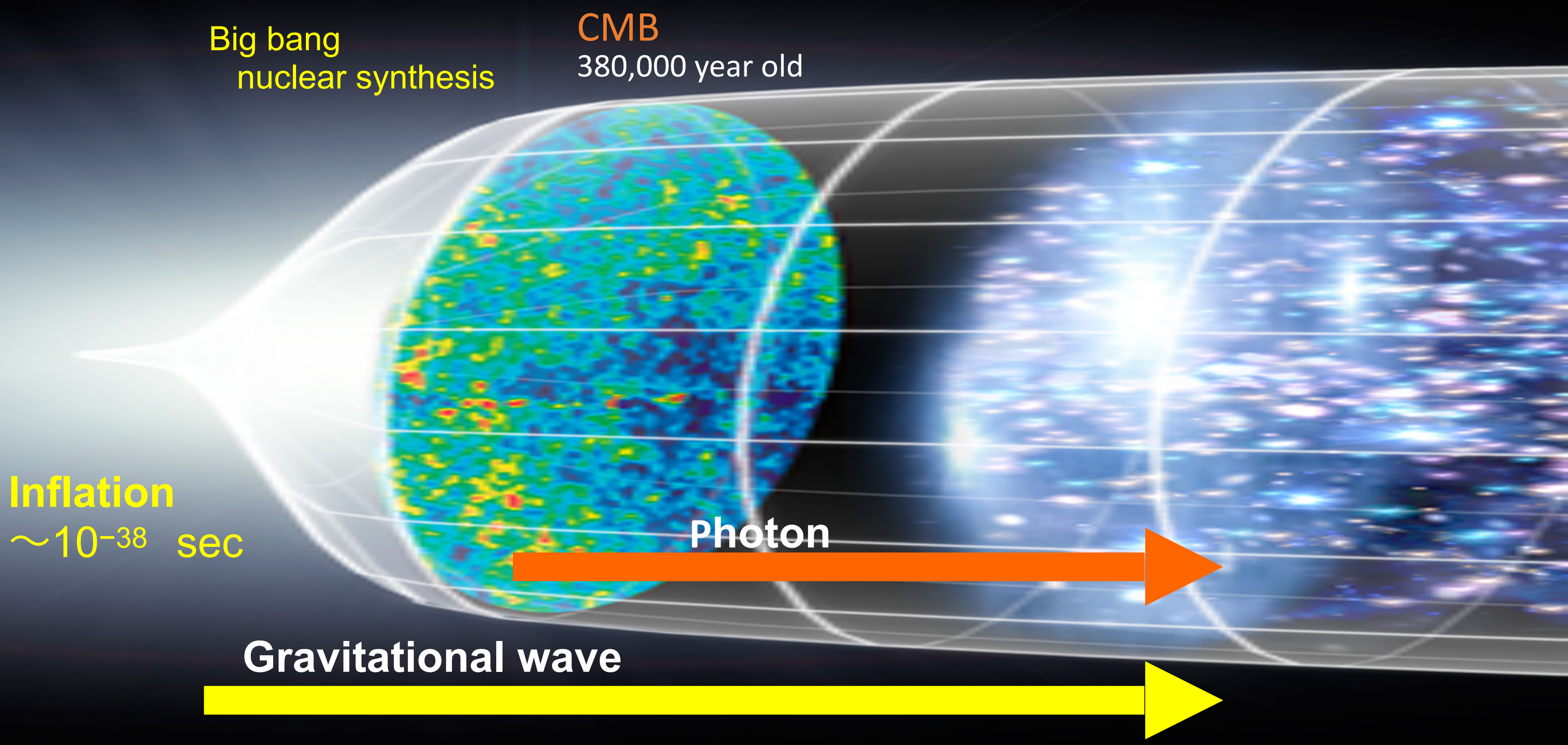
Figure from http://lambda.gsfc.nasa.gov/ (modified)

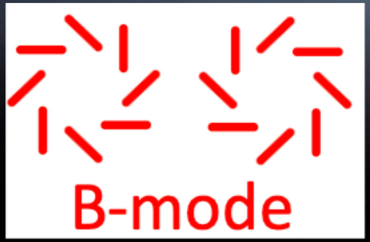




CMB to probe before the big bang



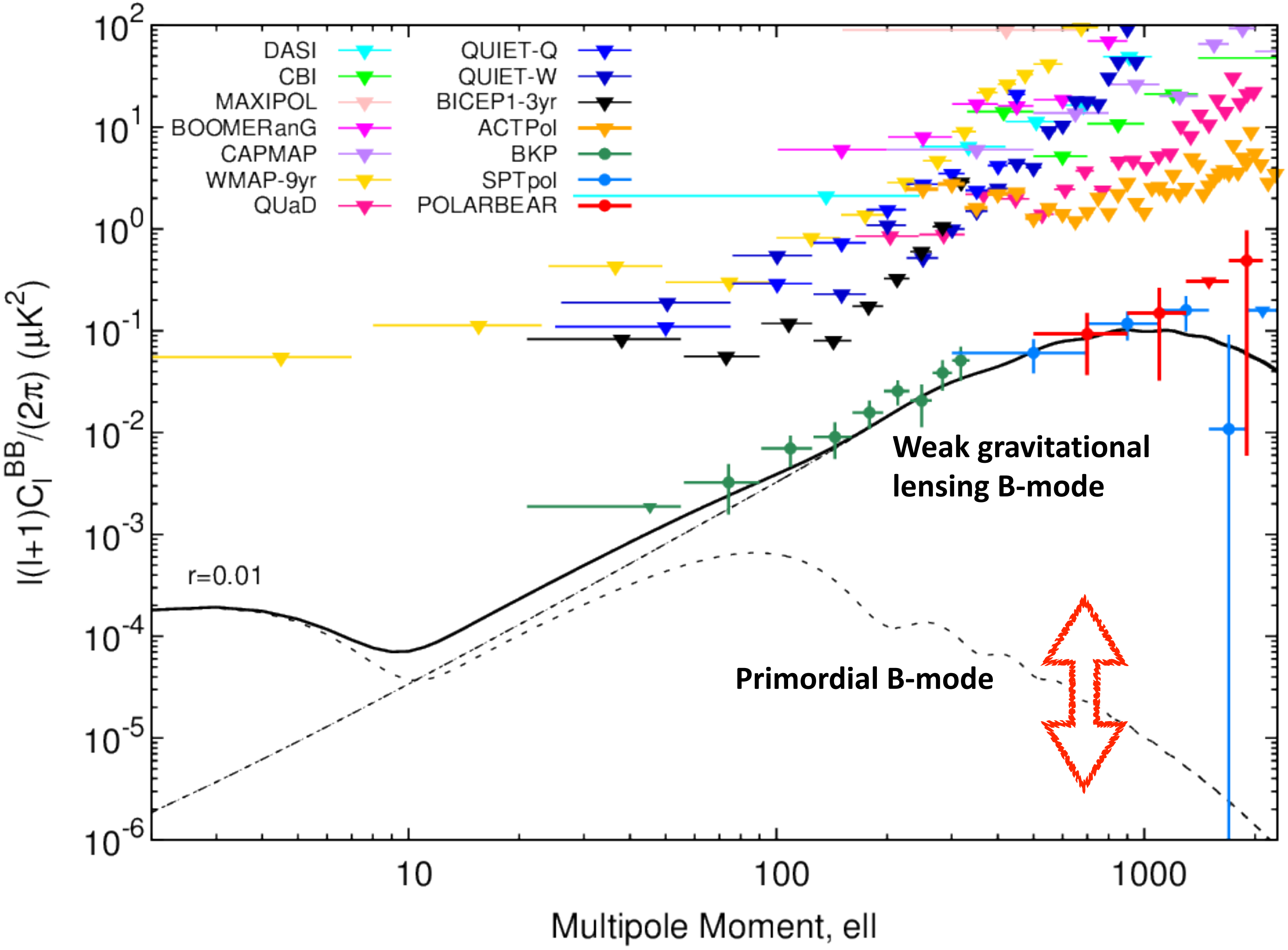




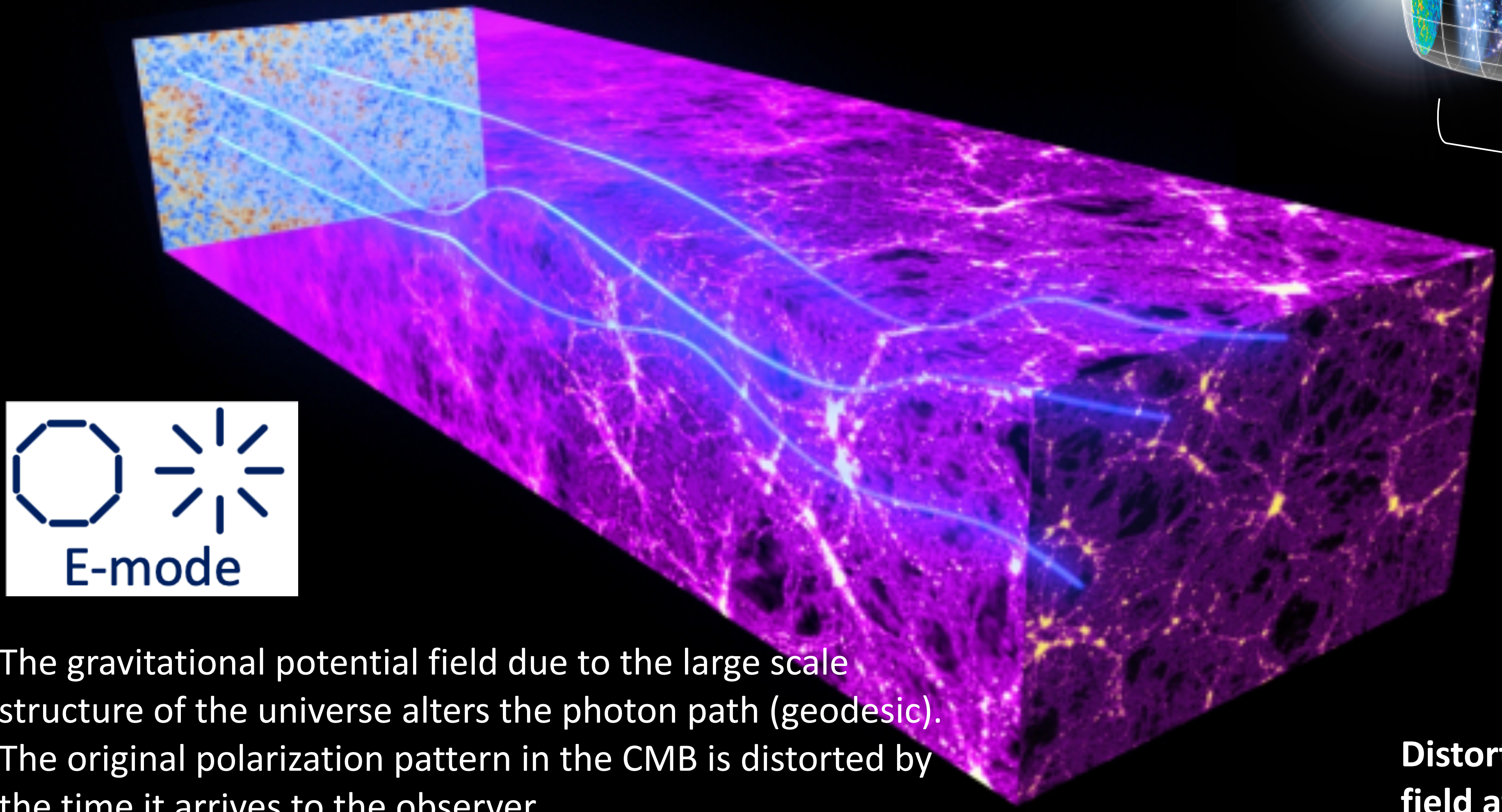
Probing inflation
If inflation exists, the primordial gravitational wave has imprinted a particular CMB polarization pattern, called B-mode.

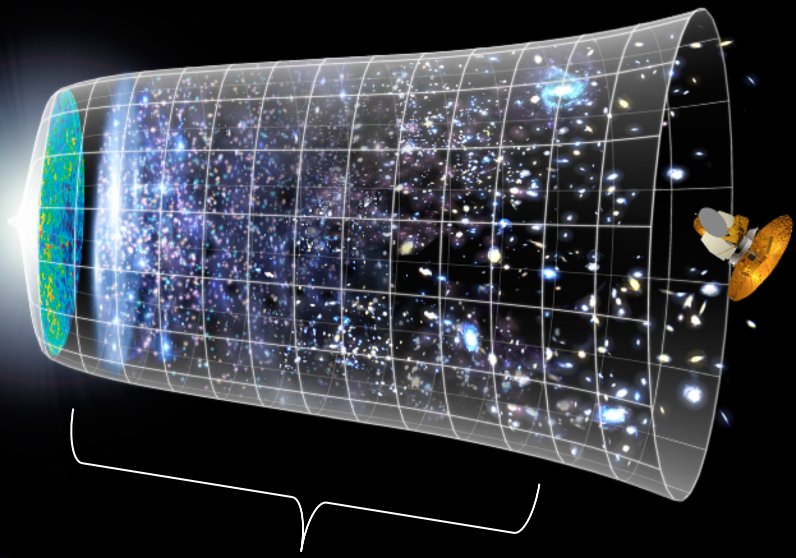
The test of inflation using the CMB polarization can probe various theories behind the inflation model, e.g. a subset or all the string theories。

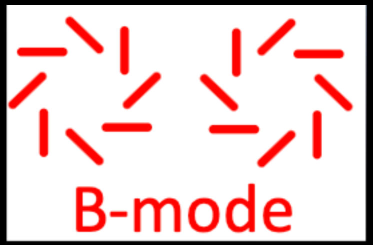
Limit of tensor-to-scalar ratio as of today



Probing the large scale structure with CMB



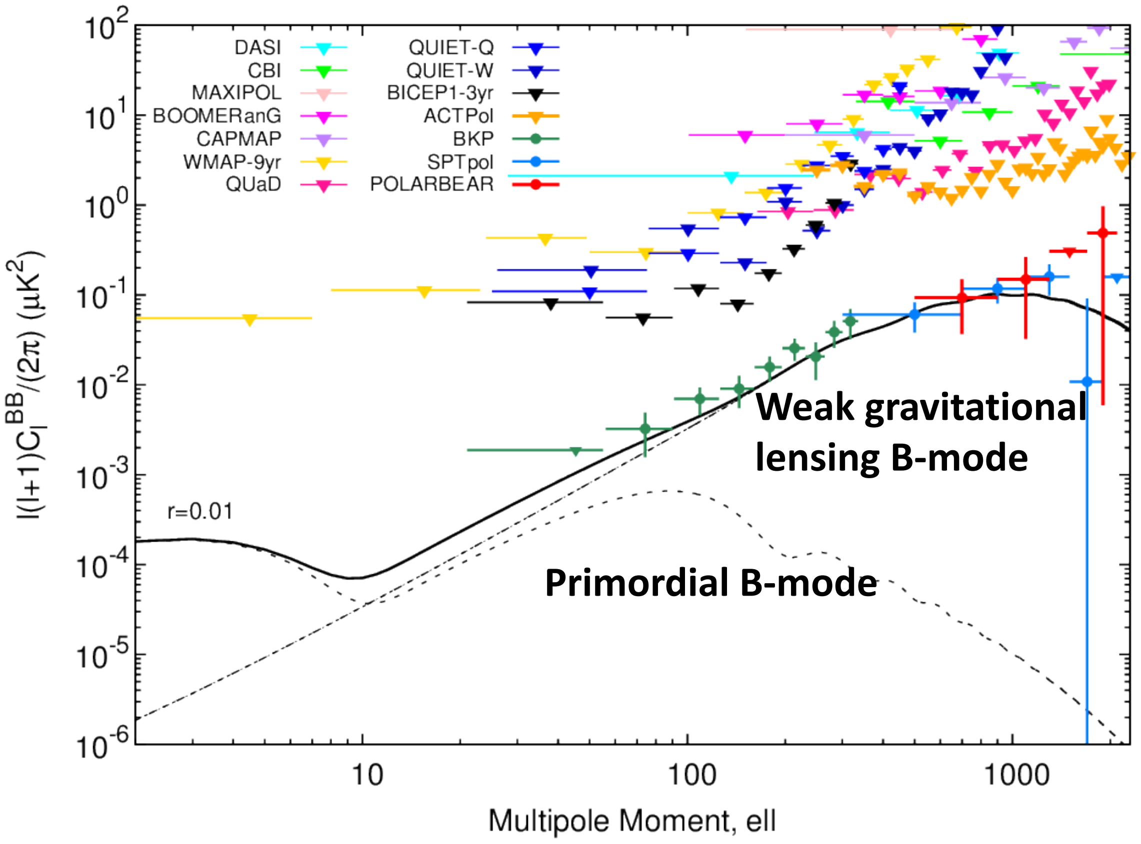




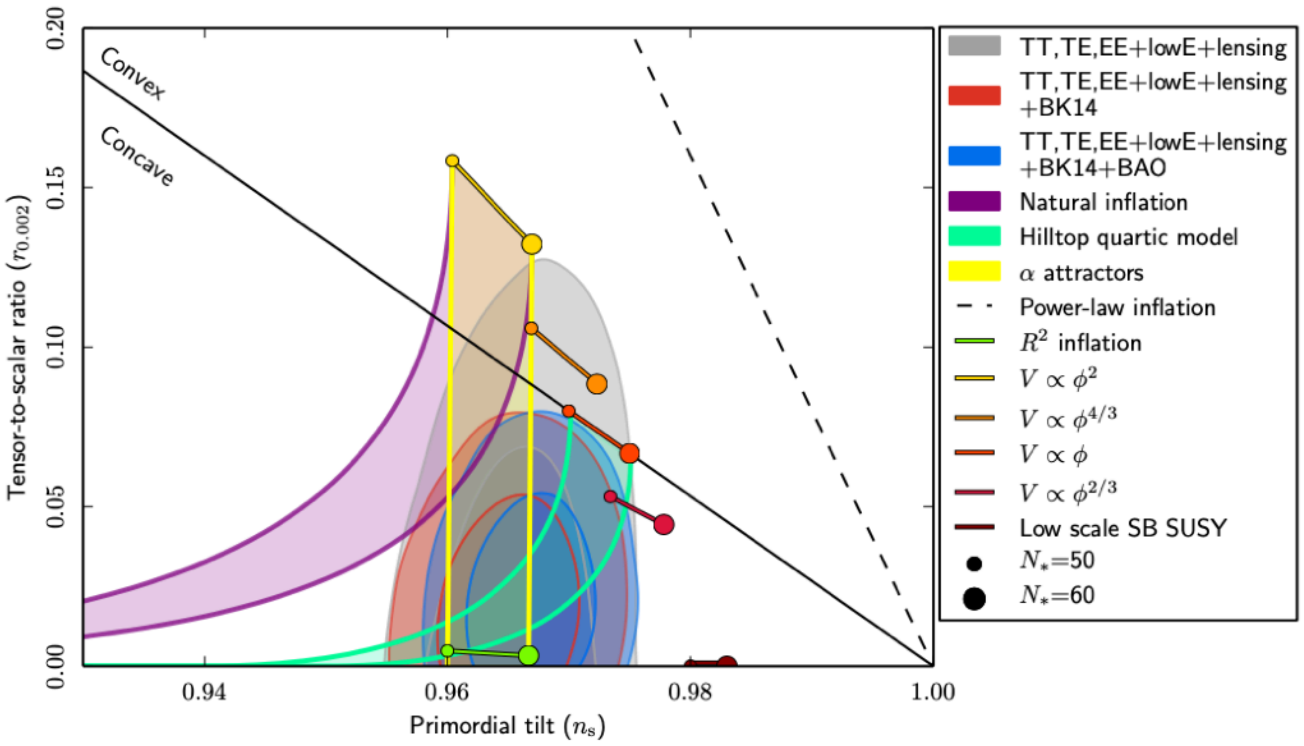
- The gravitational potential field due to the large scale structure of the universe alters the photon path (geodesic).
- The original polarization pattern in the CMB is distorted by the time it arrives to the observer.
- The measurement of the distortion contains the information of the large scale structure.

Distorted pattern of the polarization field at an observer
(The real rotation angle is about 2 arcmin.)

Limit of tensor-to-scalar ratio as of today

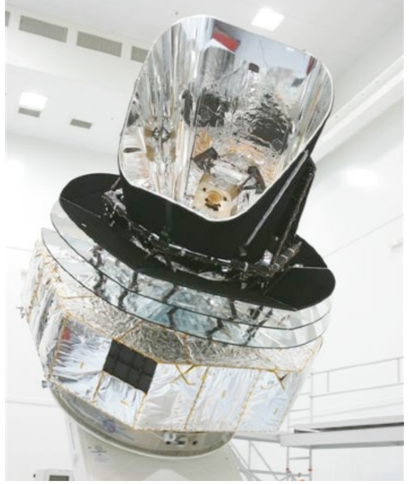


Planck2018



The current limit comes from the combination of the BICEP/KECK and Planck data.

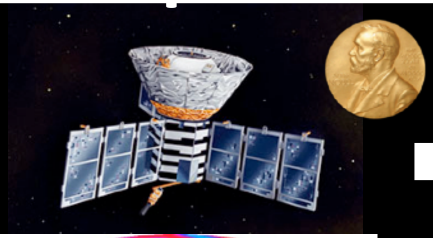
$$r < 0.06 \quad 95\% \text{ CL}$$

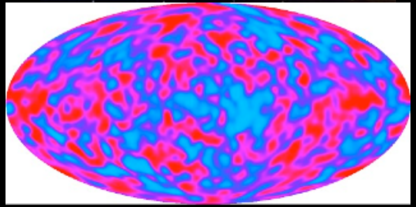


Observations

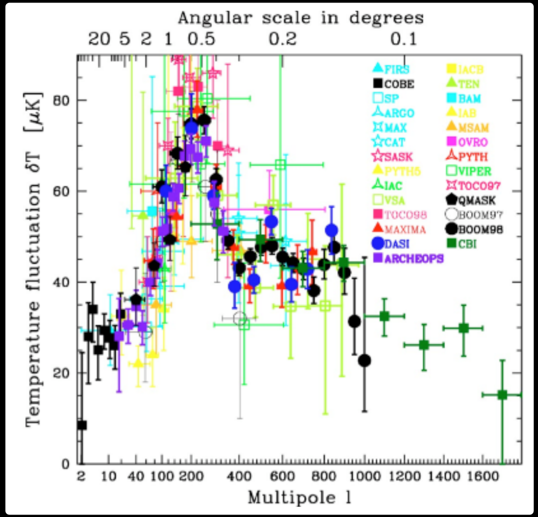
CMB polarization telescopes today

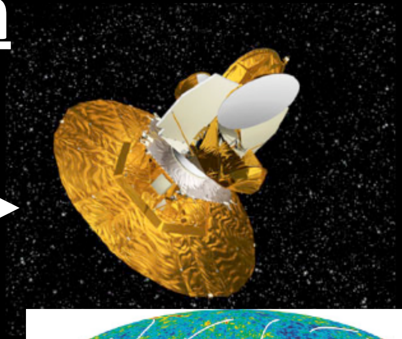
CMB space mission

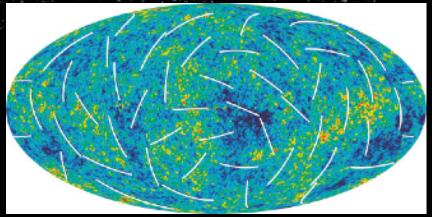




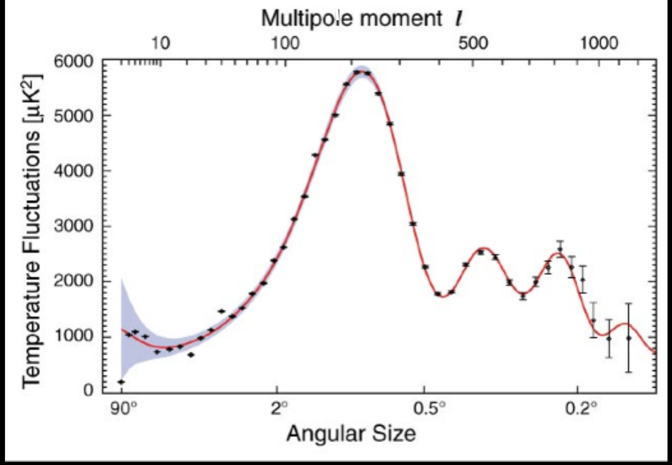
	COBE (1989)
Band	32-90GHz
# det.	6 radiometers
Op. T	140 K
Beam	～7°
Orbit	Sun Synch.

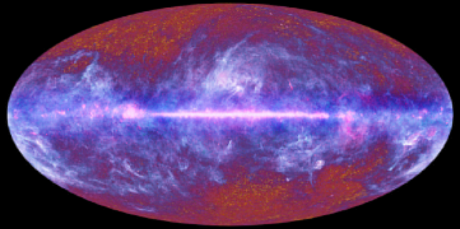




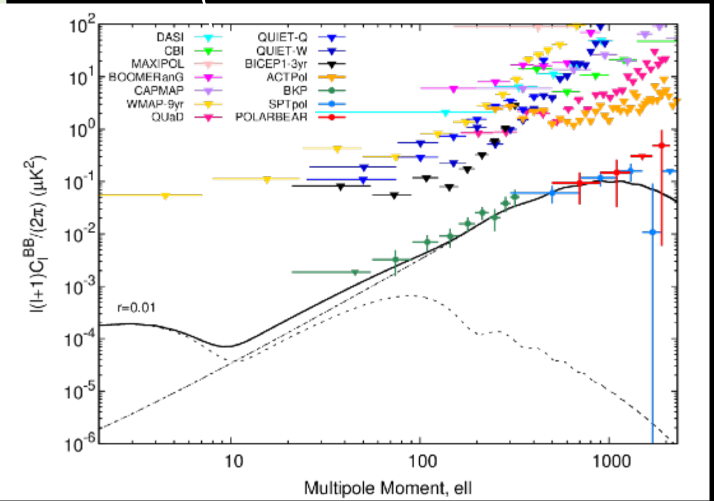


WMAP (2001)
23-94GHz
20 radiometers
90 K
～0.22°
L2





Planck (2009)
30-857GHz (pol. 353GHz)
22 radiometers + 52 bolometers
20K/100 mK
> ～0.1°
L2

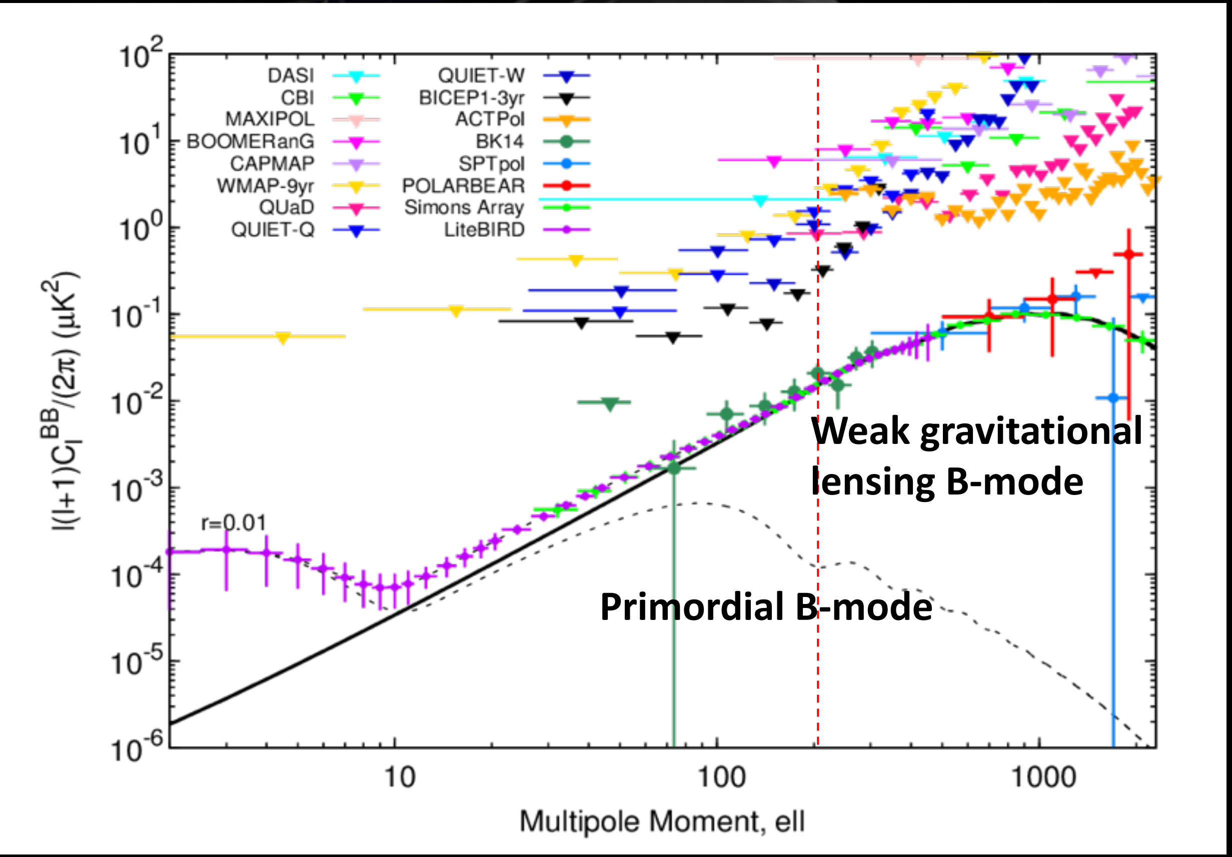


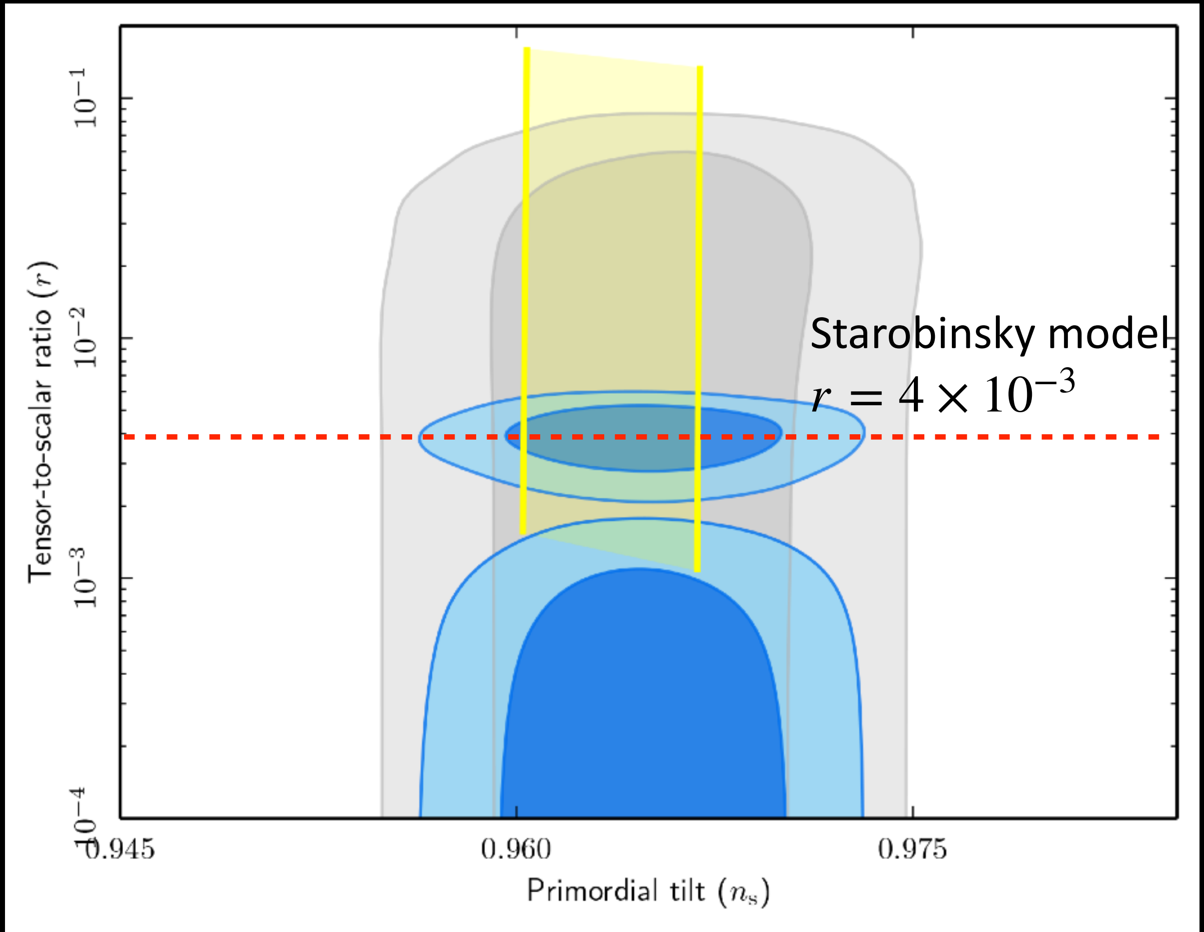
Next generation CMB satellite

One of top-priority large projects in Master plan 2017 of Science Council of Japan

LiteBIRD

is a next generation CMB polarization satellite that is dedicated to probe the inflationary B-mode. The science goal of LiteBIRD is to measure the tensor-to-scalar ratio with the sensitivity of $\sigma_r = 0.001$ for $r = 0$, and 5σ detection for $r>0.01$ for each bump. In this way, we test the major large-single-field slow-roll inflation models.





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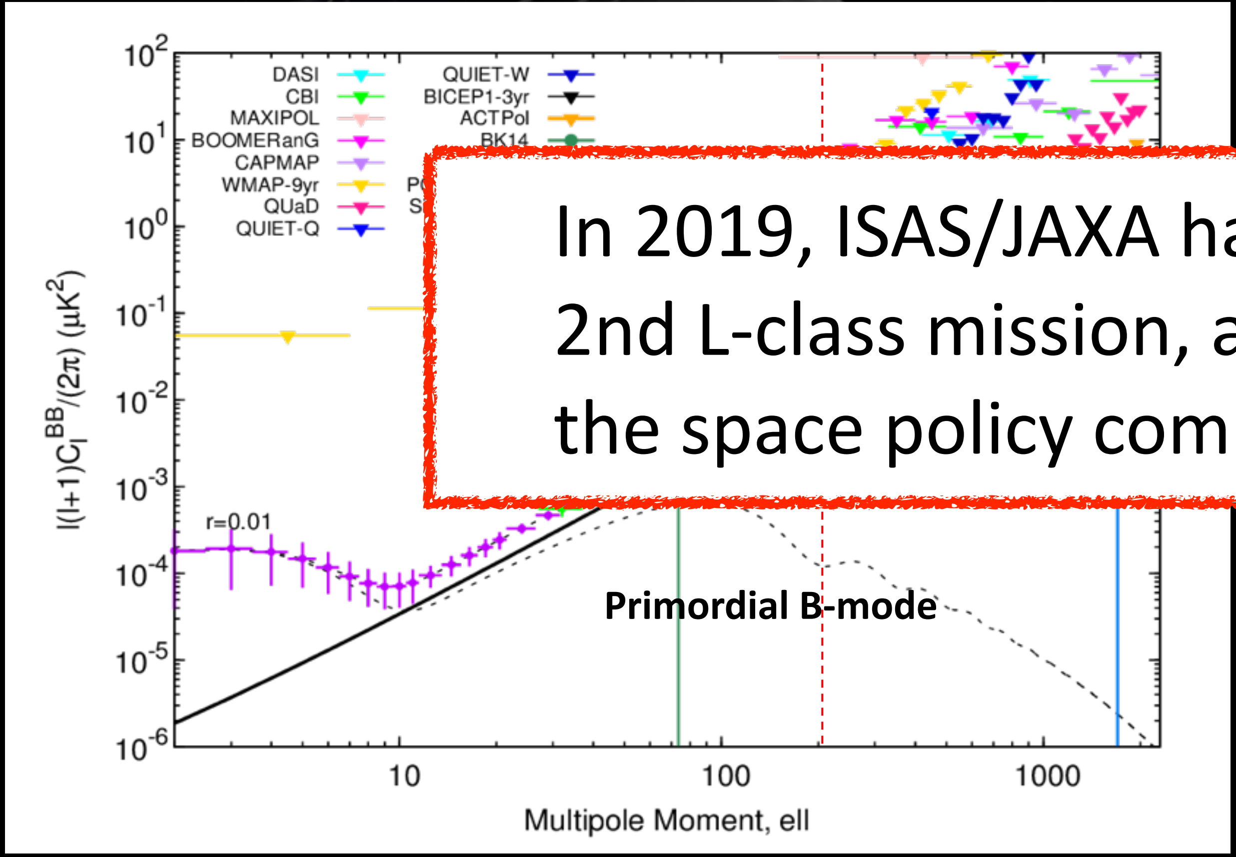
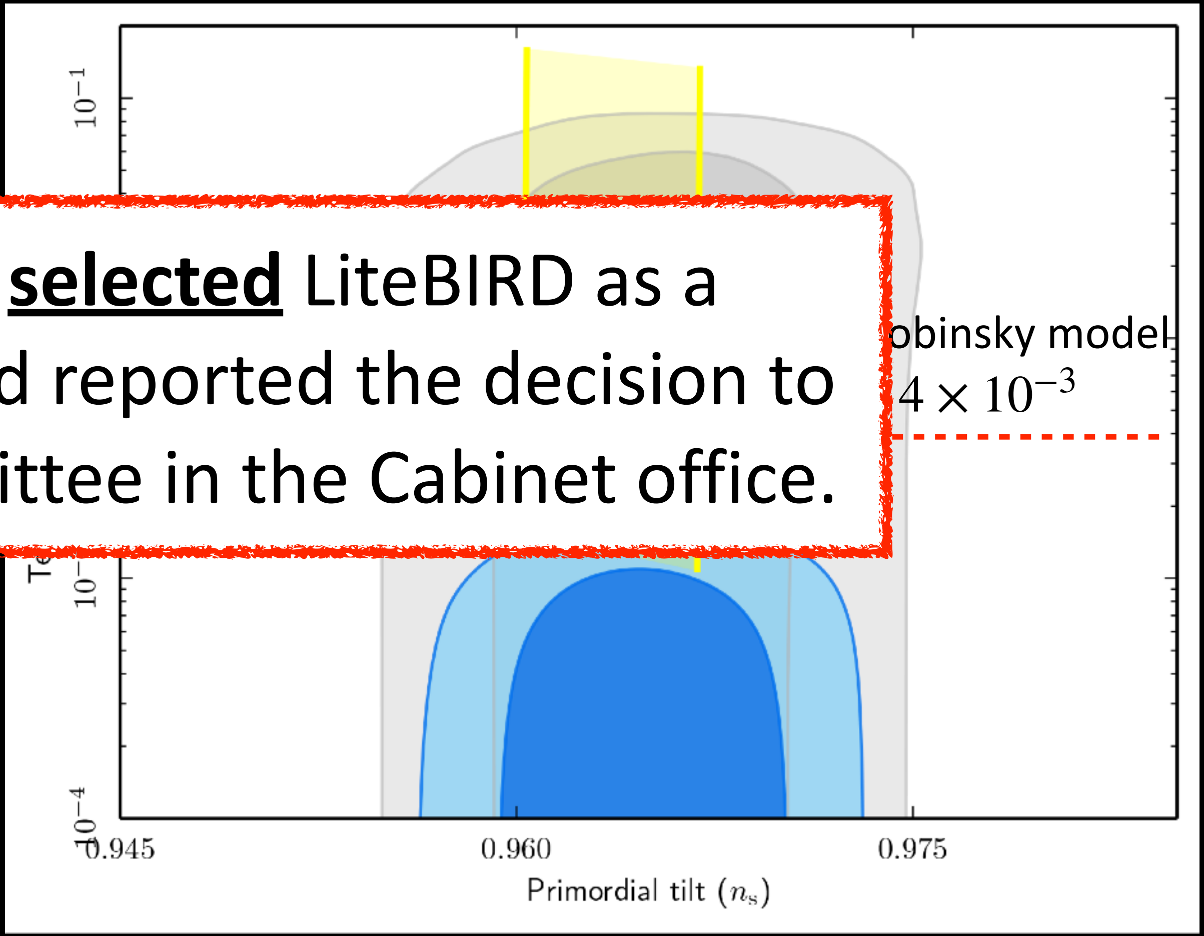
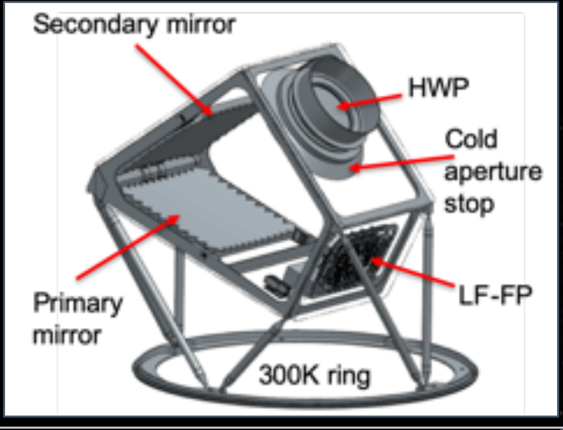




In 2019, ISAS/JAXA has **selected** LiteBIRD as a 2nd L-class mission, and reported the decision to the space policy committee in the Cabinet office.

LiteBIRD overview

LFT system



JAXA

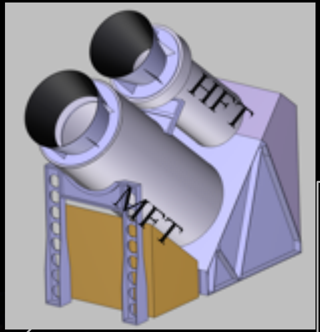
- Launch
- Satellite system incl. cryogenics
- Low frequency telescope antenna

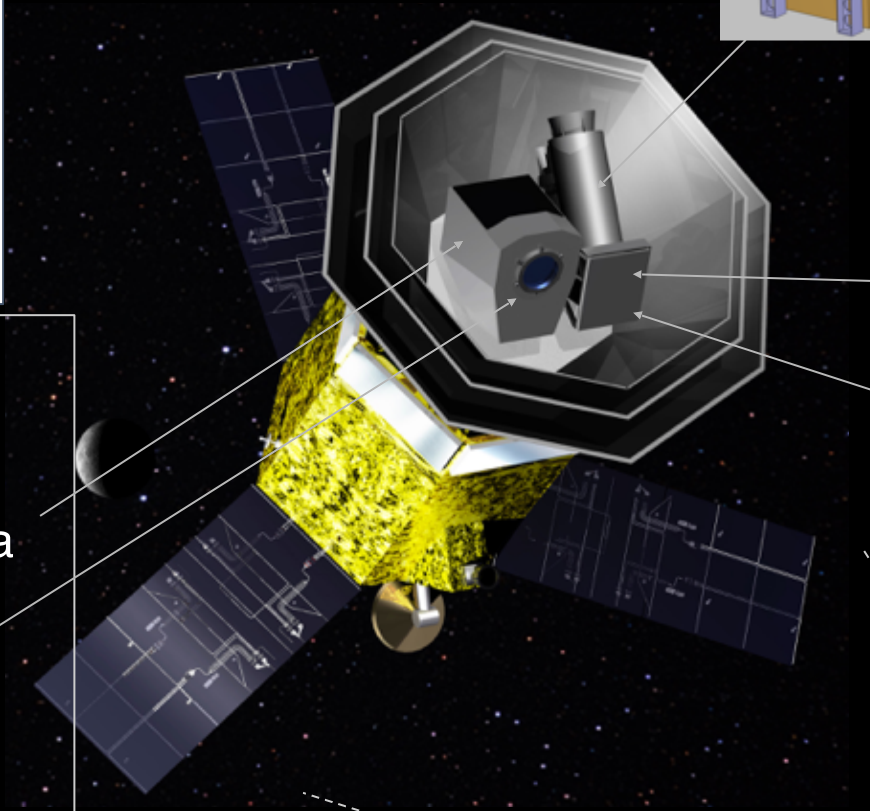
Kavli IPMU

- **Polarization modulator**
- **Data analysis**

KEK

- Ground integration/calibration





Europe

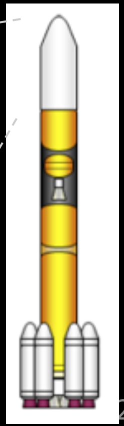
- mid/high freq. telescopes
- sub-K cooler

US

- Superconducting detector focal plane

Canada

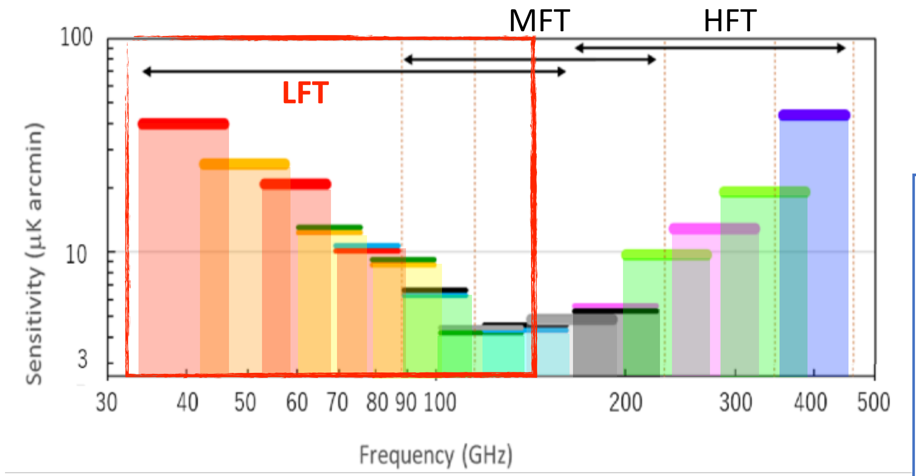
- Warm electronics



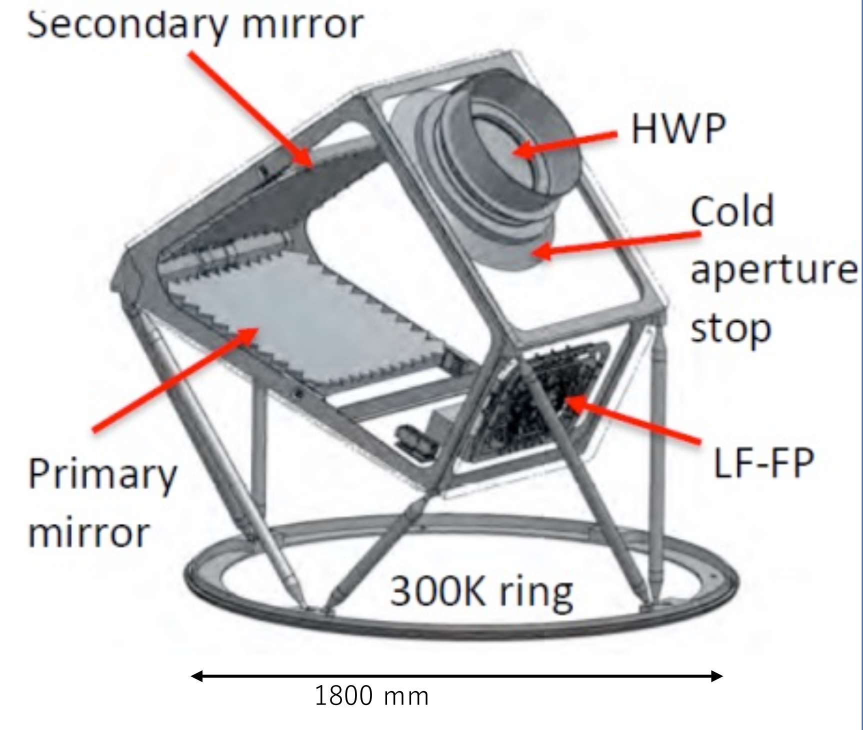
JAXA
H3 rocket

Low Frequency Telescope Unit

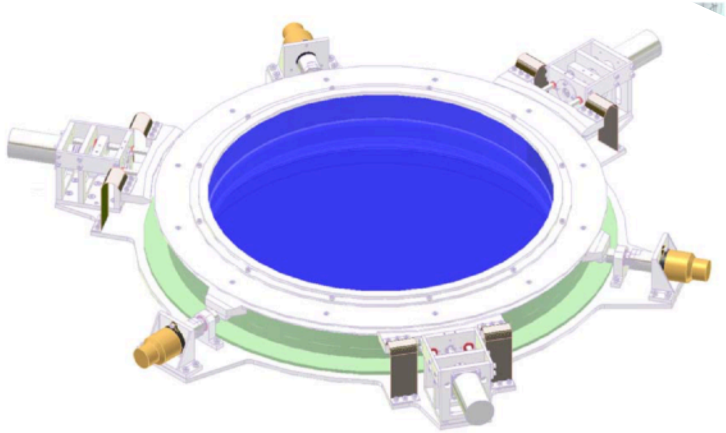
Frequency coverage (total of 15 bands)



- LFT covers the frequency range of 34-161 GHz with 9 bands.
- This corresponds to the synchrotron and the CMB channels.



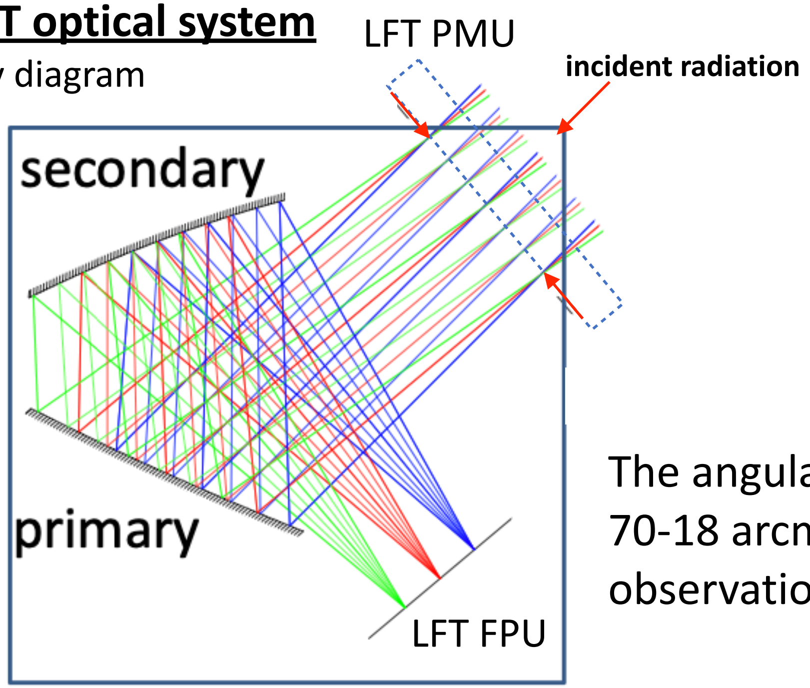
LFT polarization modulator unit (PMU)



- First optical element in the telescope.
- The details will come in a few pages.

LFT optical system

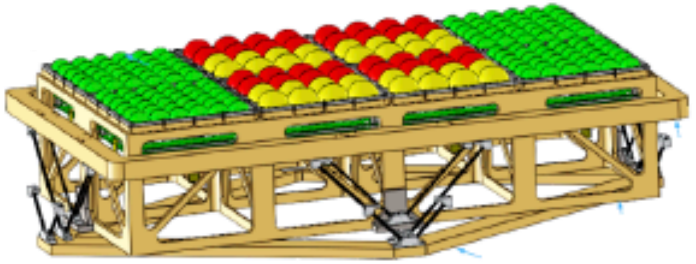
ray diagram



5 K optics enclosure + 100 mK focal plane

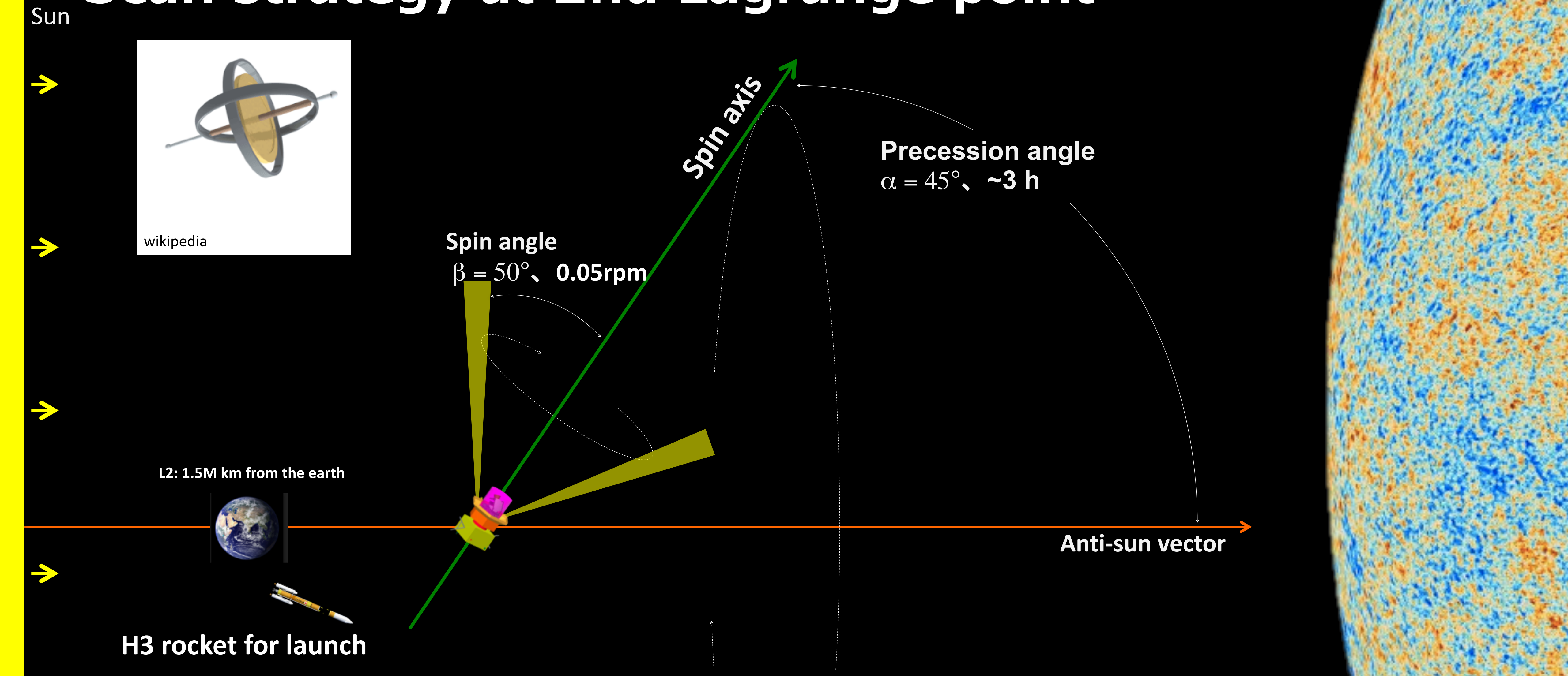
The angular resolutions are 70-18 arcmin. depending on the observational frequency band.

LFT focal plane unit (FPU)



- 1248 trichroic Transition Edge Sensor (TES) bolometers cooled at 100 mK.
- Read by SQIUD + DfMUX readout system.

Scan strategy at 2nd Lagrange point



- The observational time is for three years.
- The signal modulation comes from the scan and the half-wave plate in order to mitigate the detector 1/f and the differential systematics. The 1 day of scan covers nearly a half of the sky and the 6 month covers the fully sky.

Three major challenges!

- Statistics!
- Foreground!
- Systematic error!

How to suppress the noise?

Need about 30 nK CMB equivalent noise over 1 degree scale on the sky.

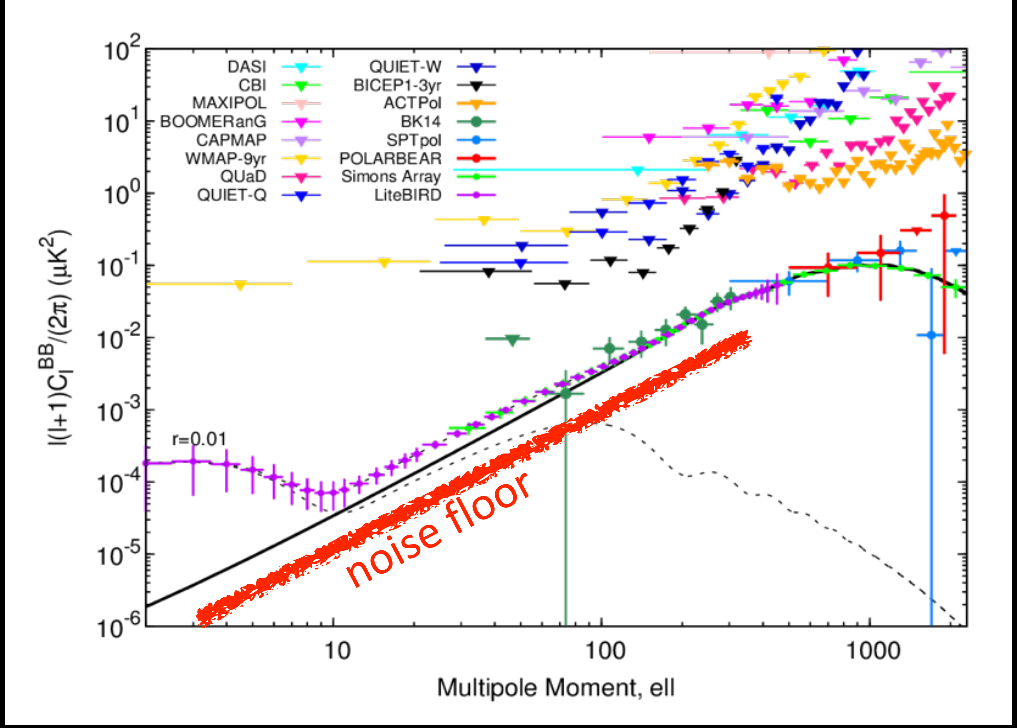
$$noise = \frac{NET_s}{\sqrt{\frac{t_{obs}}{4\pi\, f_{sky}} \times \frac{N_{det}}{2}}}$$

Single detector noise

The # of detectors

Observational time

NET_s: Given the single detector noise using a superconducting bolometric detector. **Free to choose t_{obs} and N_{det} to achieve the desired noise level.**



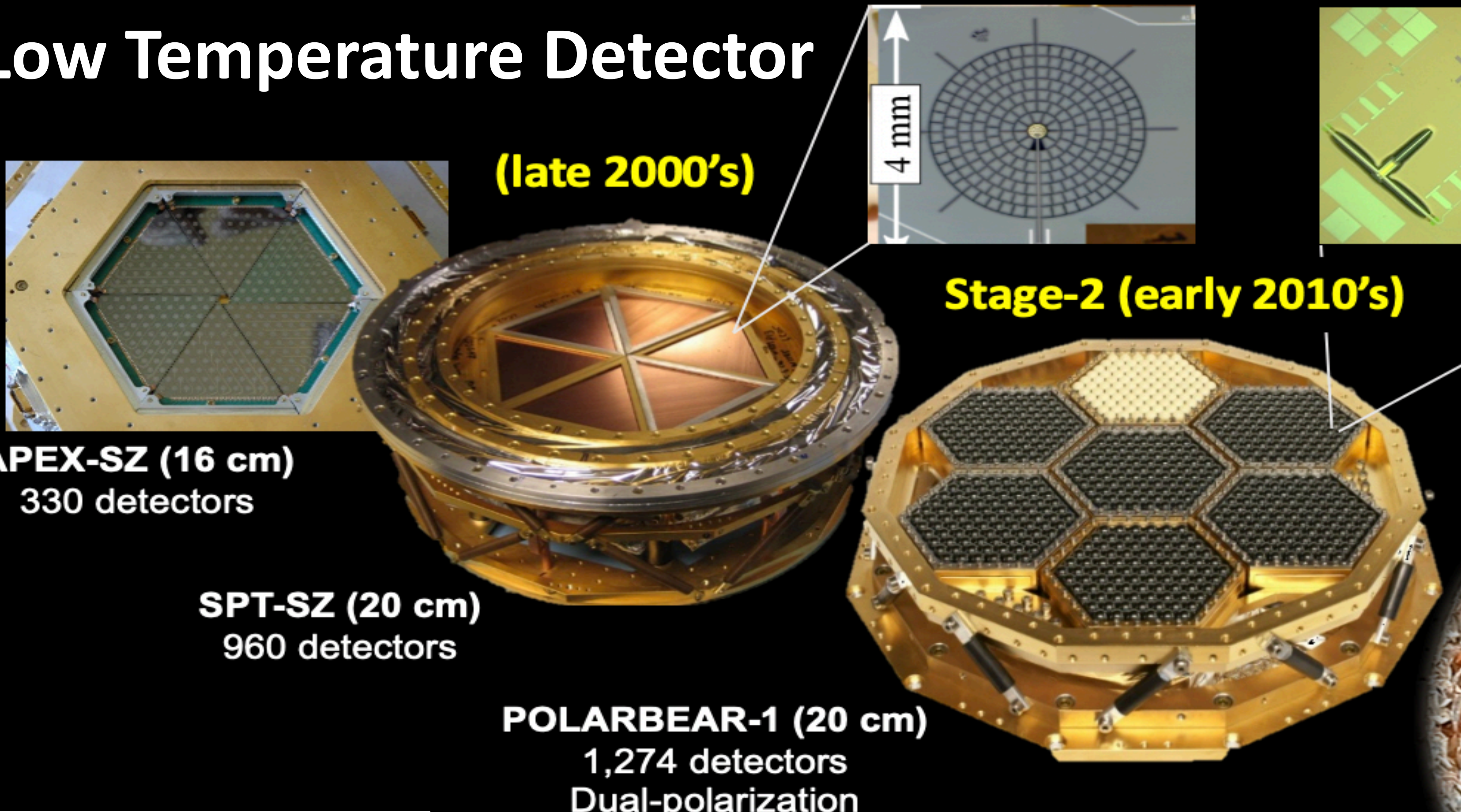
Example for a space mission:

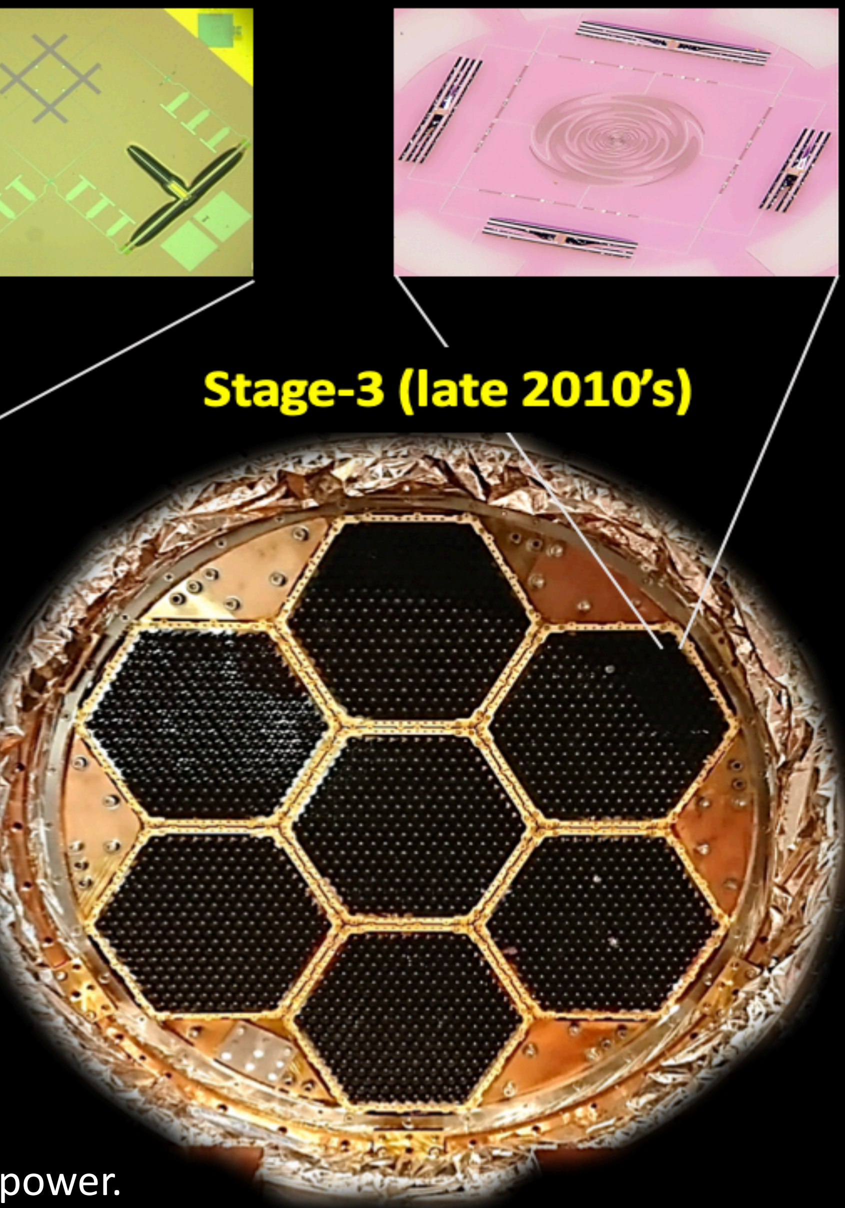
- The detector noise can be $50\ \mu K\sqrt{s}$, then $t_{obs} = 3$ years and N_{det} >~2000 detectors allow to reach the desired sensitivity over the full sky as a ball park estimate.

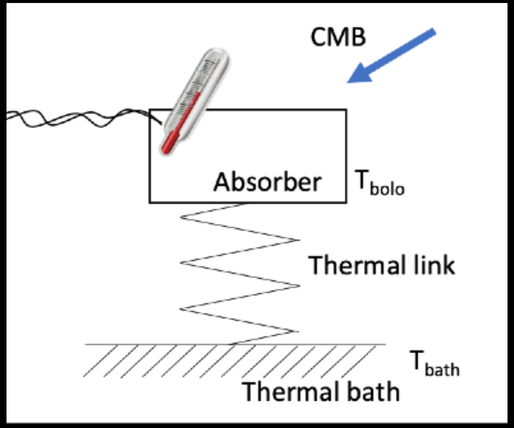
Example for a ground telescope:

- The detector noise can be $300\ \mu K\sqrt{s}$, then $t_{obs} = 3$ years and N_{det} >~40,000 detectors allow to reach the desired sensitivity over the half sky as a ball park estimate.

Low Temperature Detector



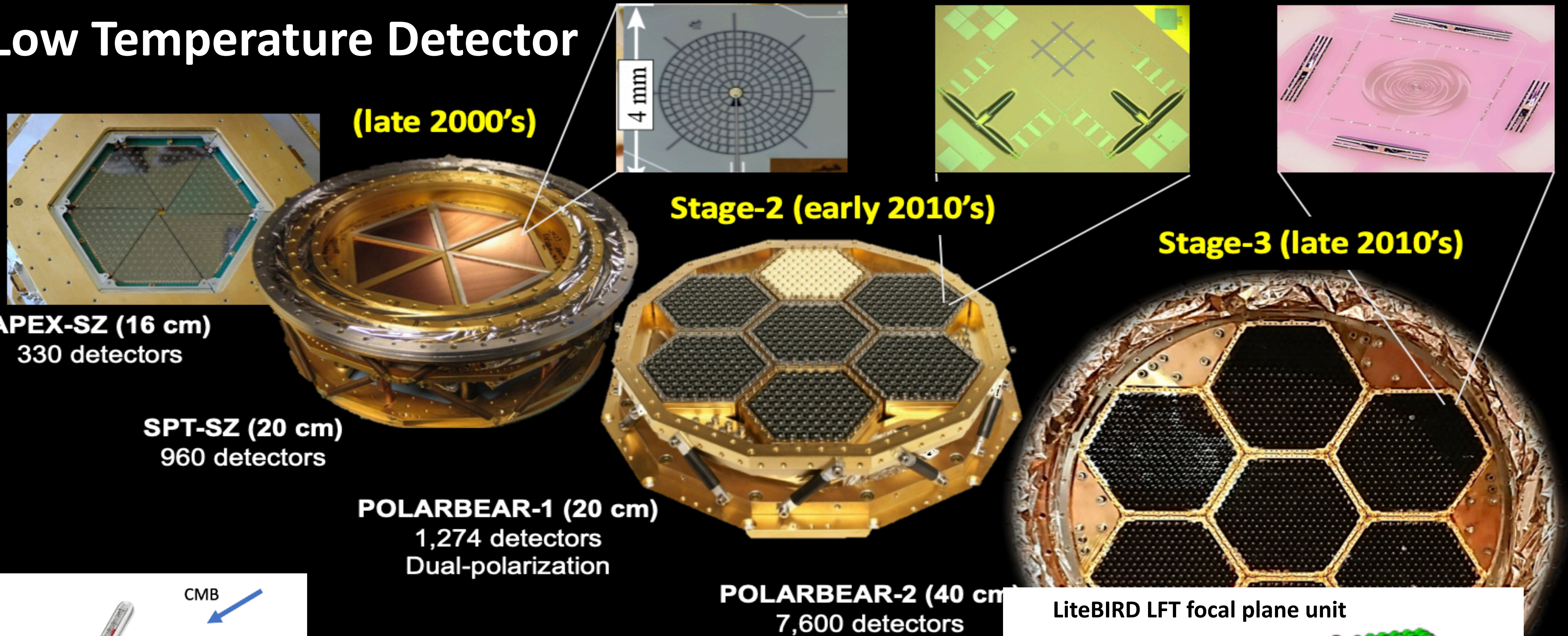


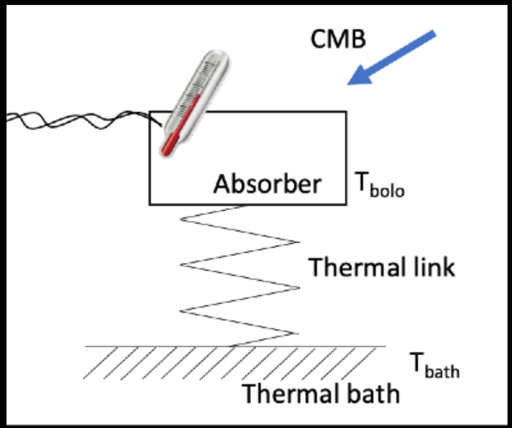


- A bolometer is very sensitive to the change of the radiative power.
- A bolometric detector that covers the radiation into a heat and measure its change using a thermometer.
- Note that Planck had the 32 semiconductor base bolometric detectors.

Slide courtesy from Toki Suzuki (LBNL)

Low Temperature Detector





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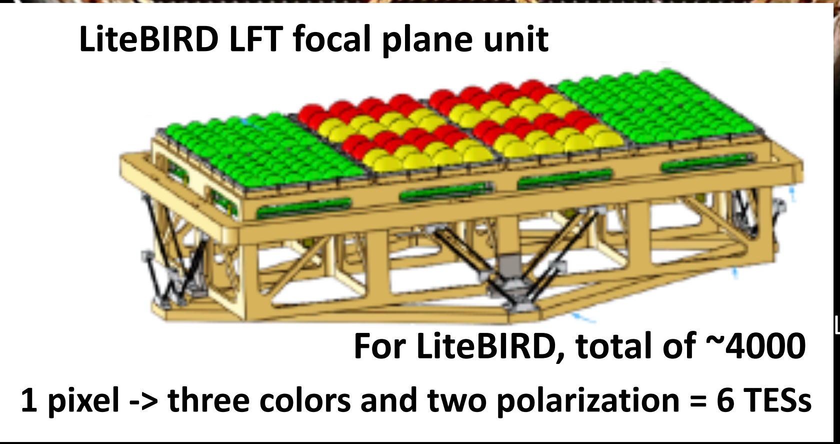
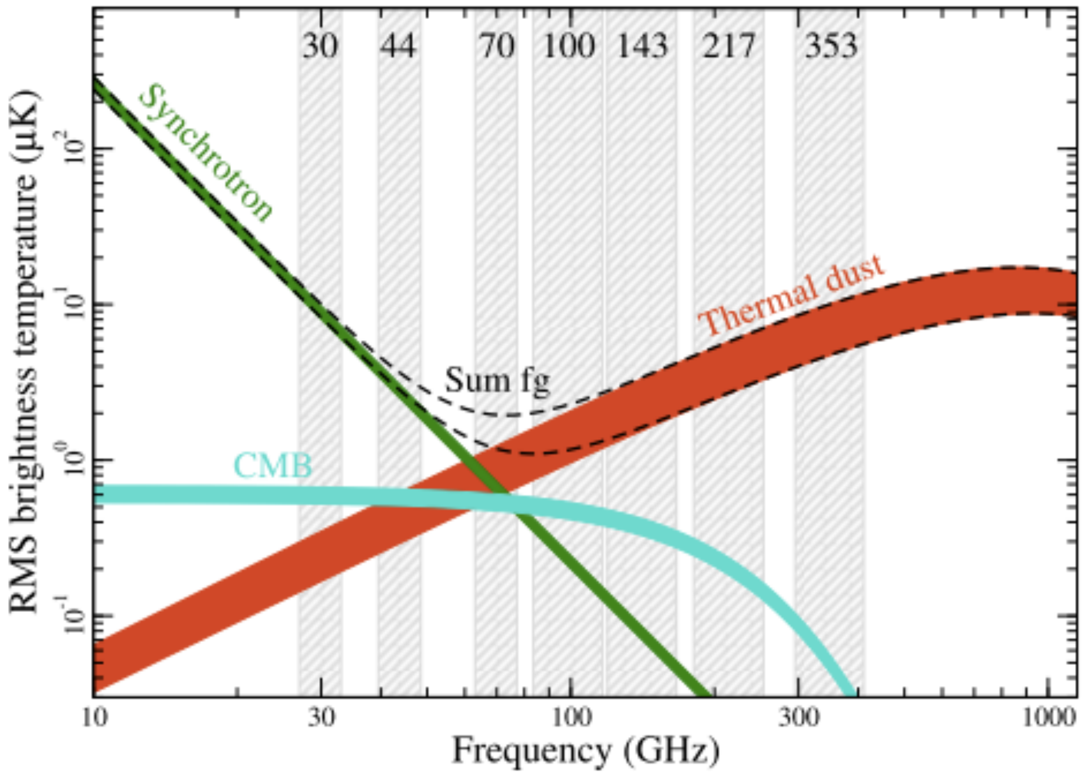
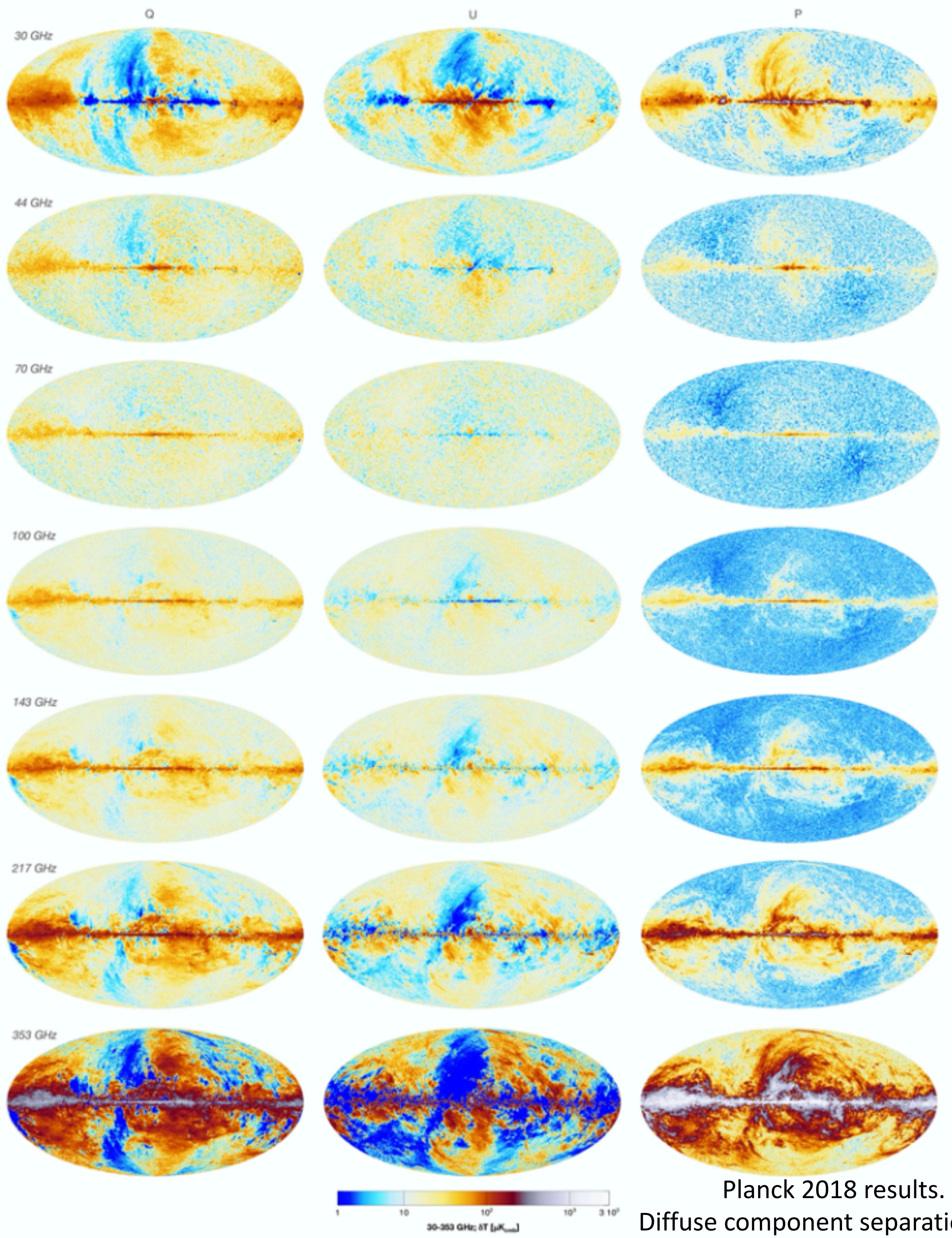


LBNL)

Polarized foreground emission

- As we live in our Galaxy, we have to observe the CMB through our polarized galactic emission.
- The main polarized foreground emissions are the synchrotron and thermal dust emissions.
- These emissions do have the difference spectral emission as compared to the CMB.





Planck 2018 results. IV.
Diffuse component separation

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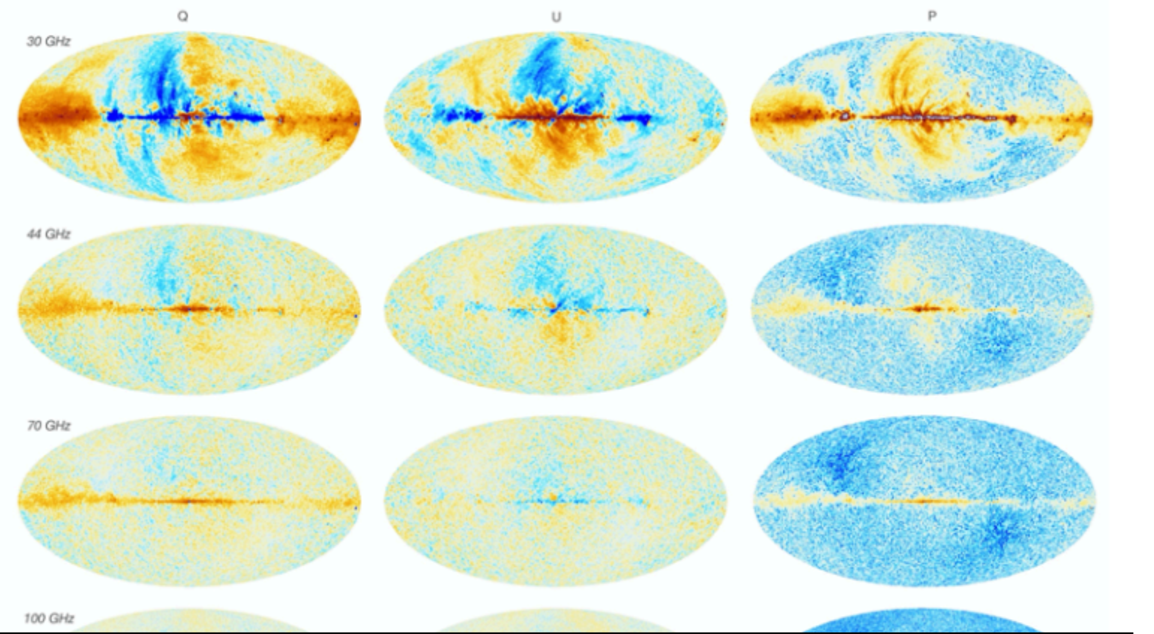
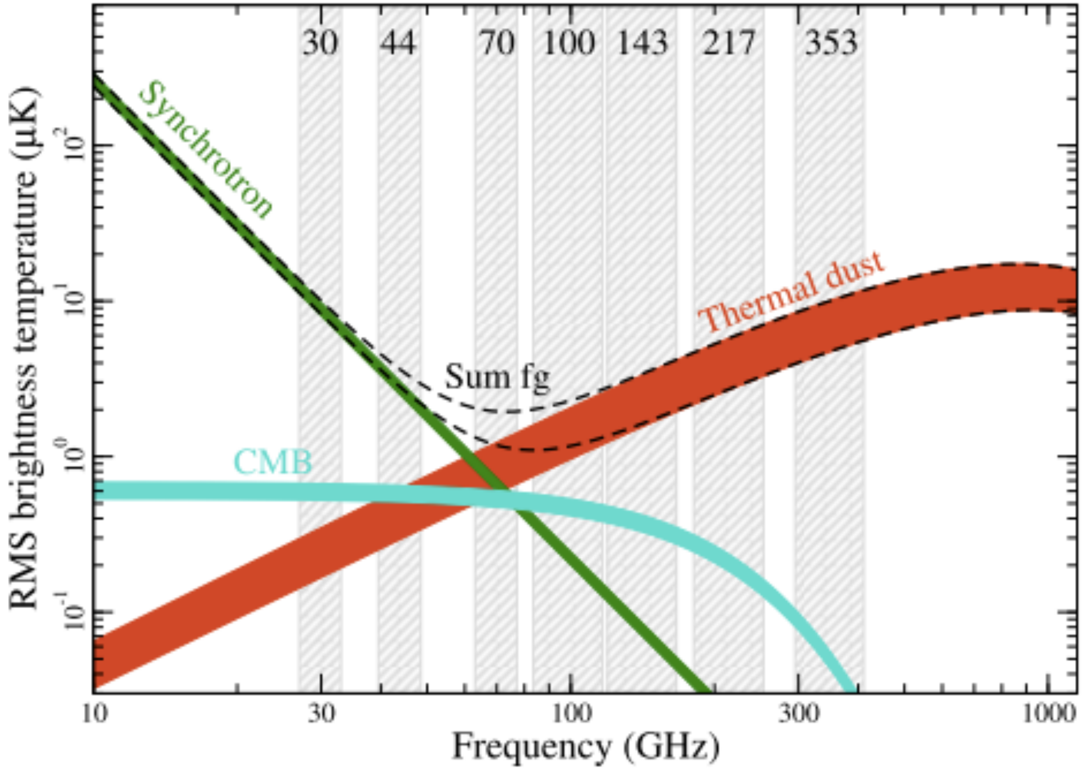
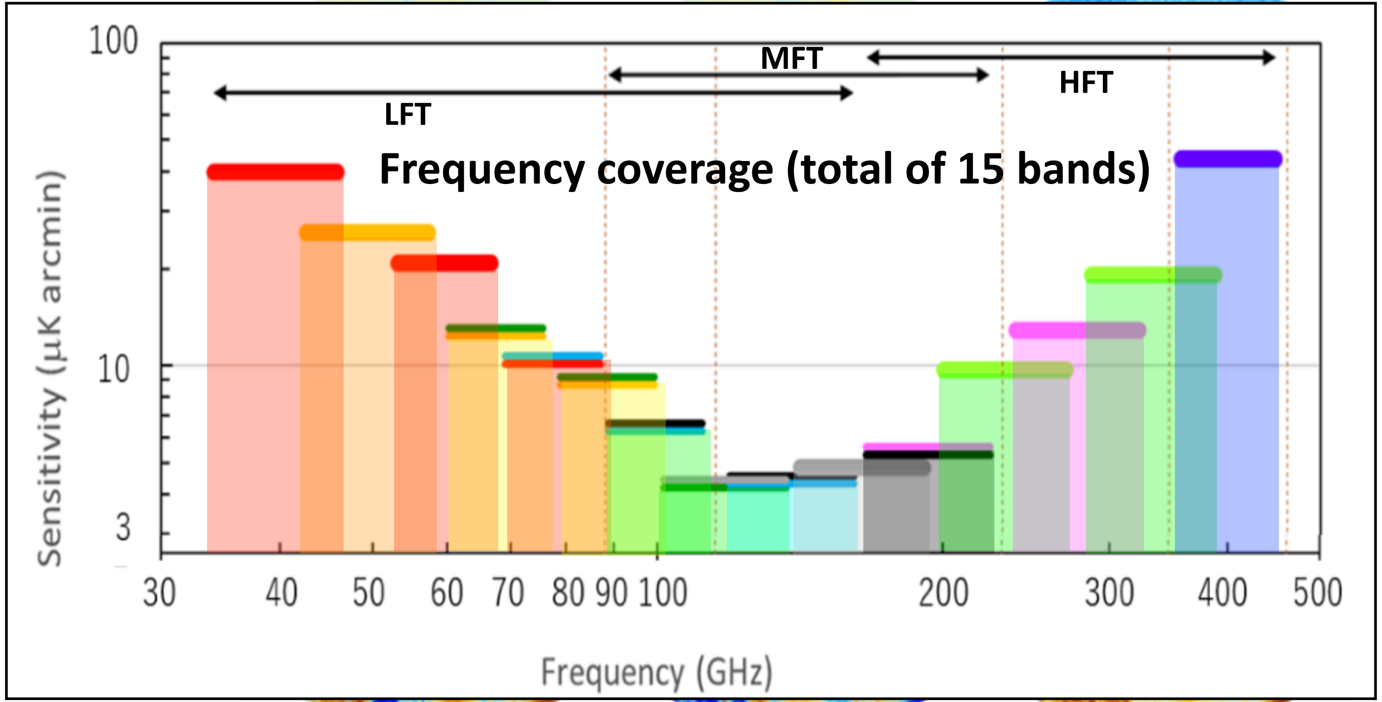


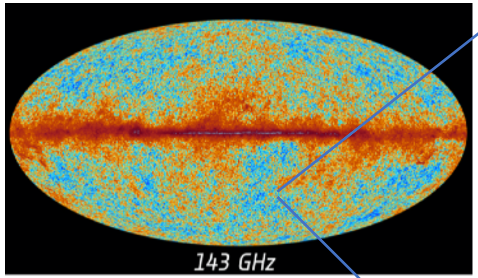




Planck 2018 results. IV.
Diffuse component separation

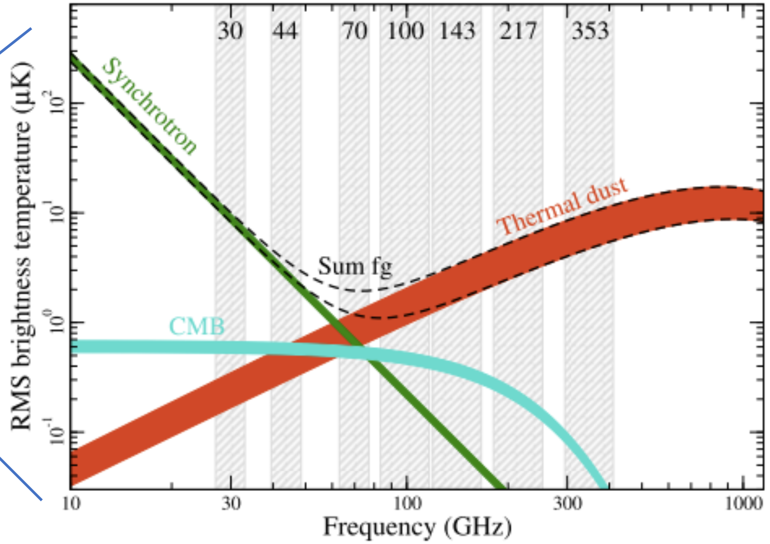
Foreground removal

Errard and Stompor, Phys.Rev. D99 (2019) no.4, 043529



Planck 143GHz map

(*this is a temperature map as an example)



Parametrizing the foreground emissions

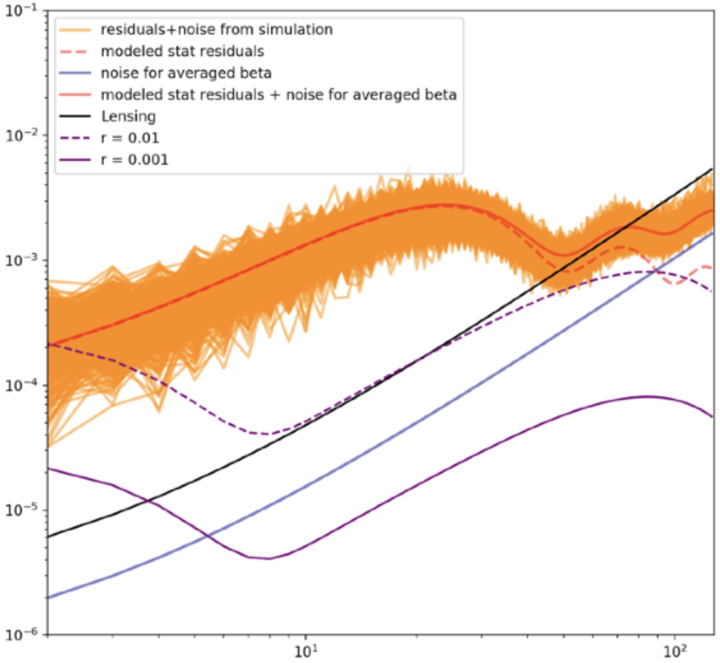
Based on the Planck data, the foreground emissions can be parametrized as

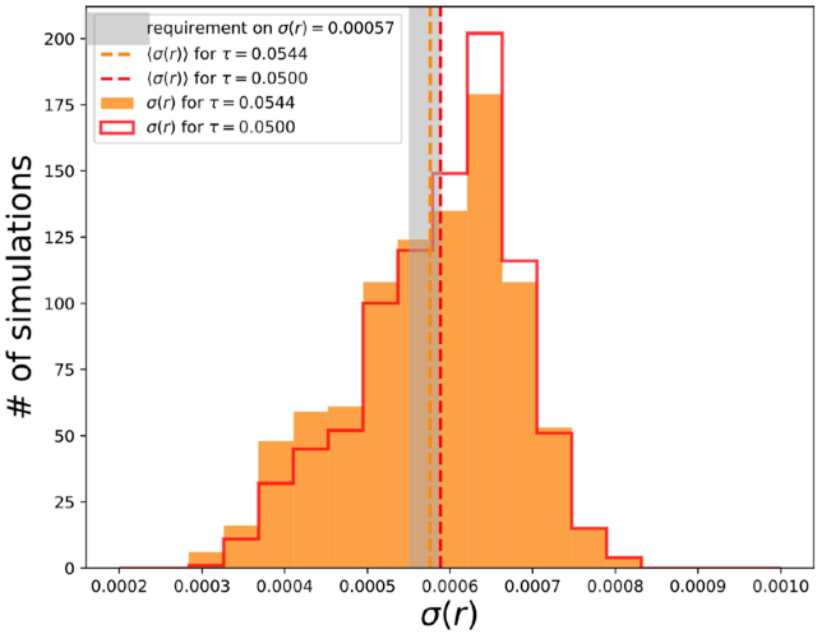
Synchrotron (incl. AME)

$$[Q_s, U_s](\hat{n},\nu) = [Q_s, U_s](\hat{n},\nu_*)\left(\frac{\nu}{\nu_*}\right)^{\beta_s(\hat{n})+C_s(\hat{n})\ln(\nu/\nu_*^C)}$$

Dust

$$[Q_d, U_d](\hat{n},\nu) = [Q_d, U_d](\hat{n},\nu_*)\left(\frac{\nu}{\nu_*}\right)^{\beta_d(\hat{n})-2}\frac{B(\nu, T_d(\hat{n}))}{B(\nu_*, T_d(\hat{n}))}$$





8 parameters to model the foreground emissions at each direction of the sky. This corresponds to

(8 parameters at each sky pixel)

× (the sky pixel number) = **6144** pars

with $N_{\mathrm{side}} = 8$

Result

$\sigma(r) = 0.0006$ for $r_{in} = 0$

The consistent results from other method too.

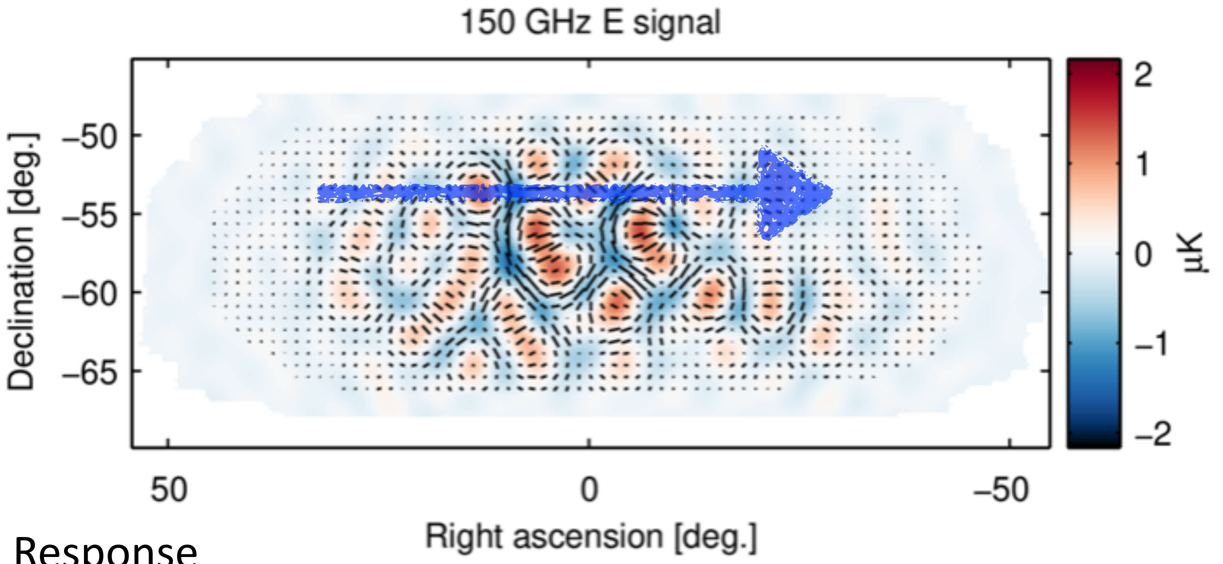
Systematics

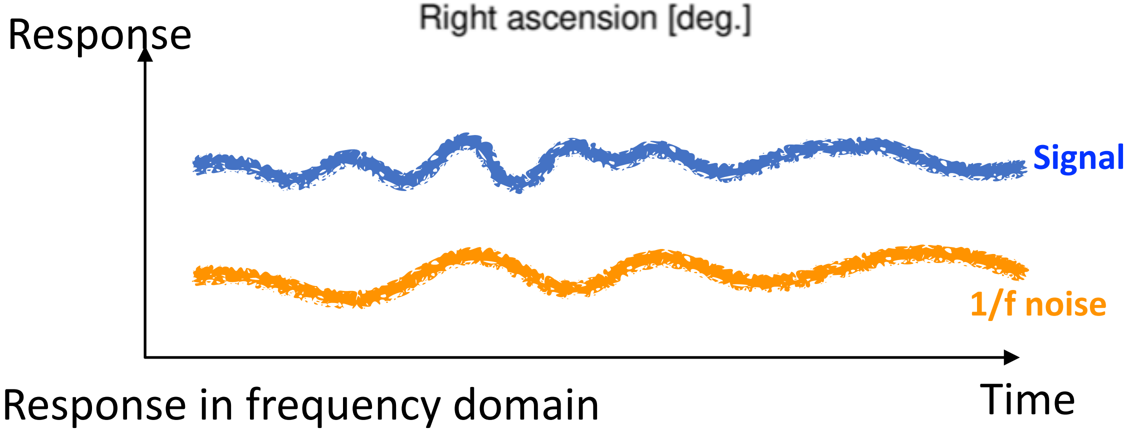
- One of the major systematics to overcome is **1/f noise**.
- The CMB is not an observation of a star nor galaxy, but rather a fluctuation.
- Our very sensitive detector is only optimized to the change of the incoming radiative power, and thus we don't take a snap shot but rather we scan the sky.

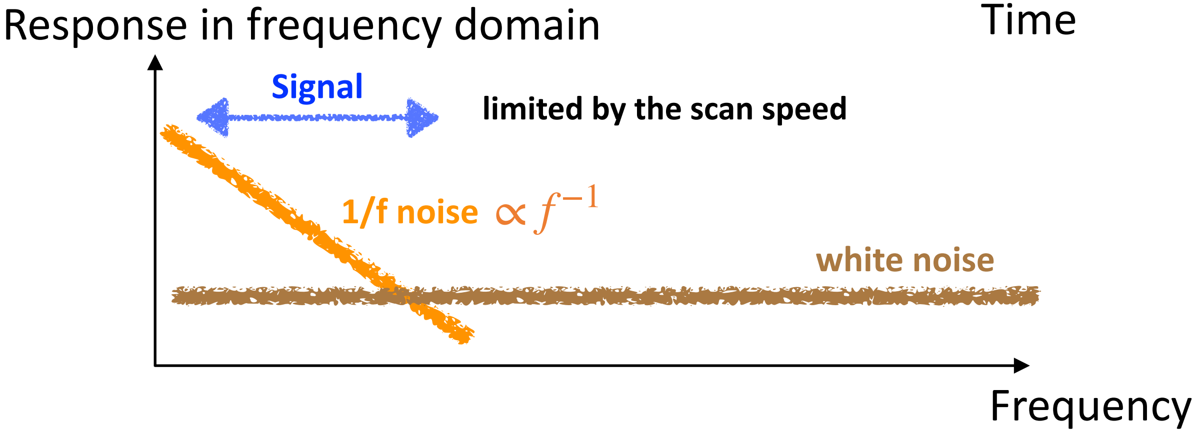
- There is no perfect instrument. Thus, the detector is subjected to various fluctuations, e.g. the thermal fluctuation of the cryogenic system. As a result, the fluctuating signal and the fluctuating "noise" degenerate. This is particularly prominent at the low frequency.

$$d = s + n_{1/f} + n_{white}$$

The Keck Array and BICEP2 Collaborations, Phys. Rev. Lett. 121, 221301, 2018







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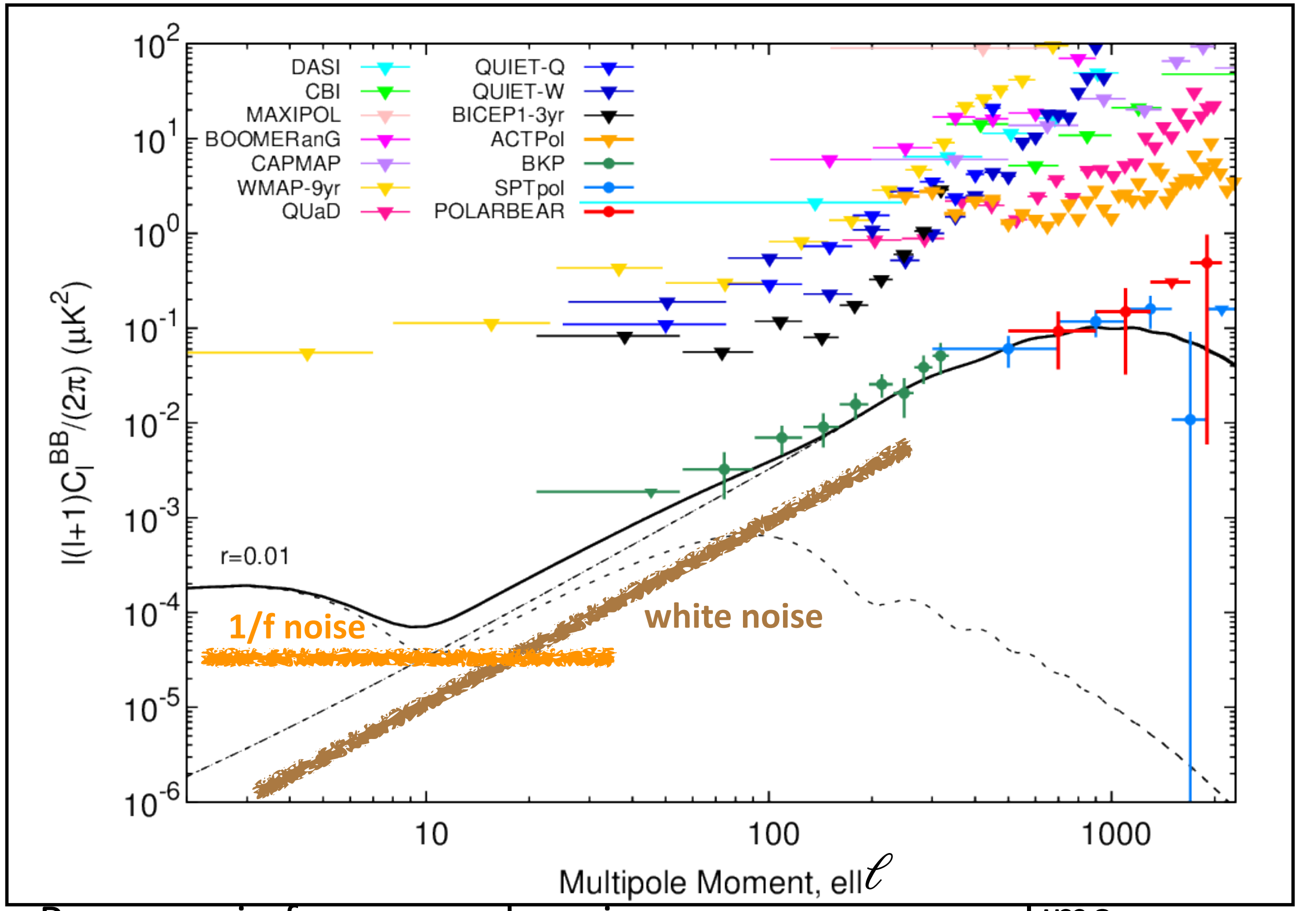

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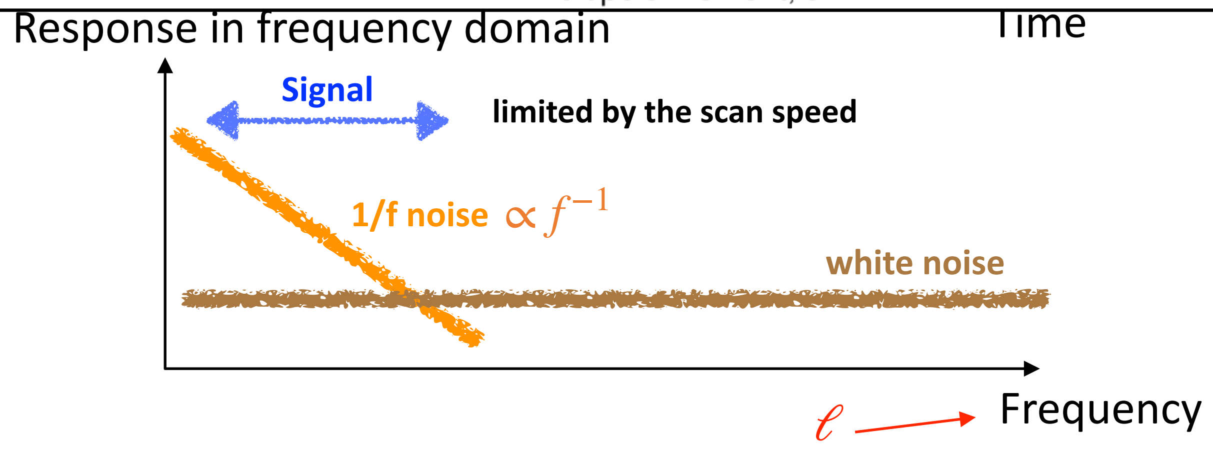

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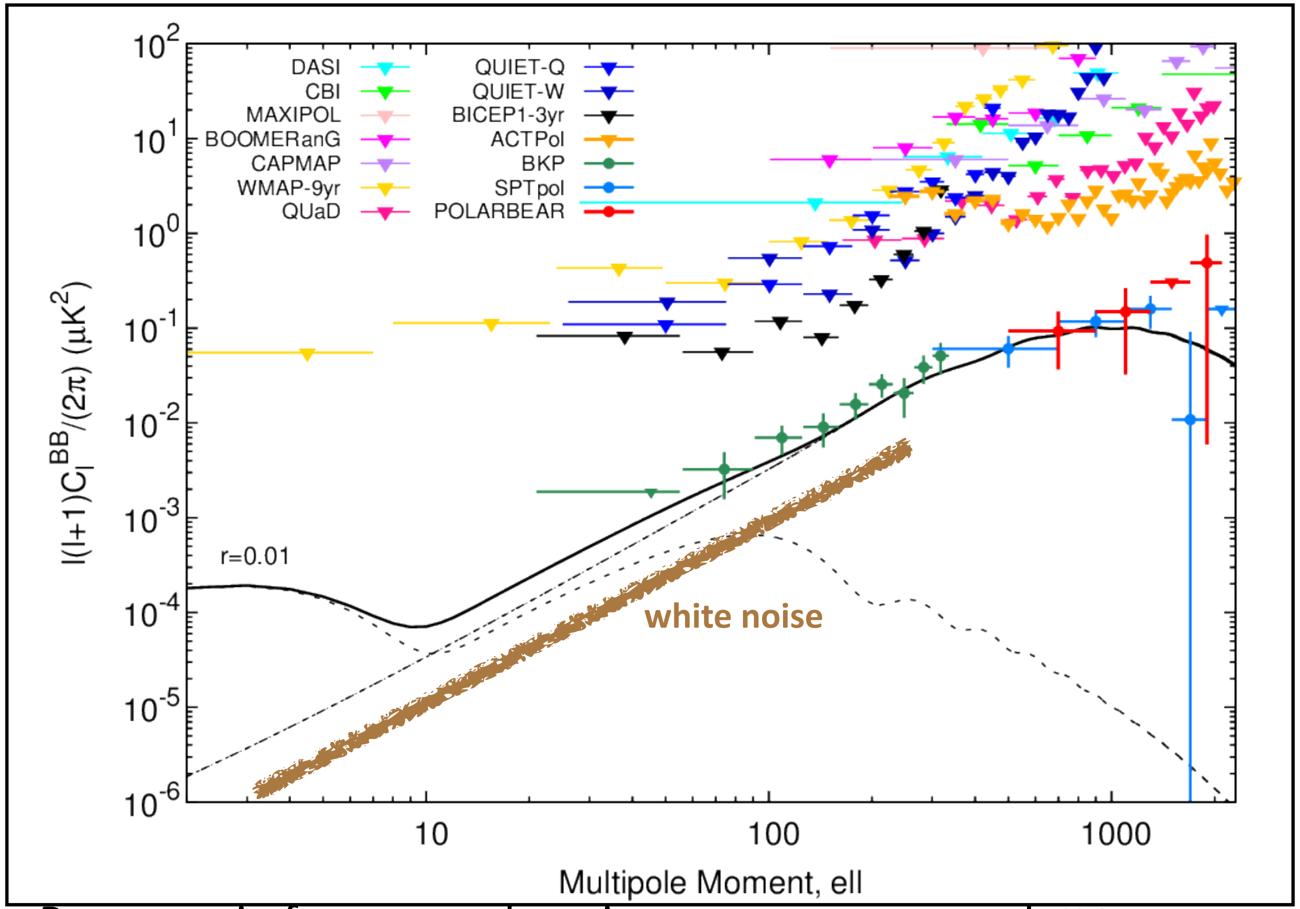
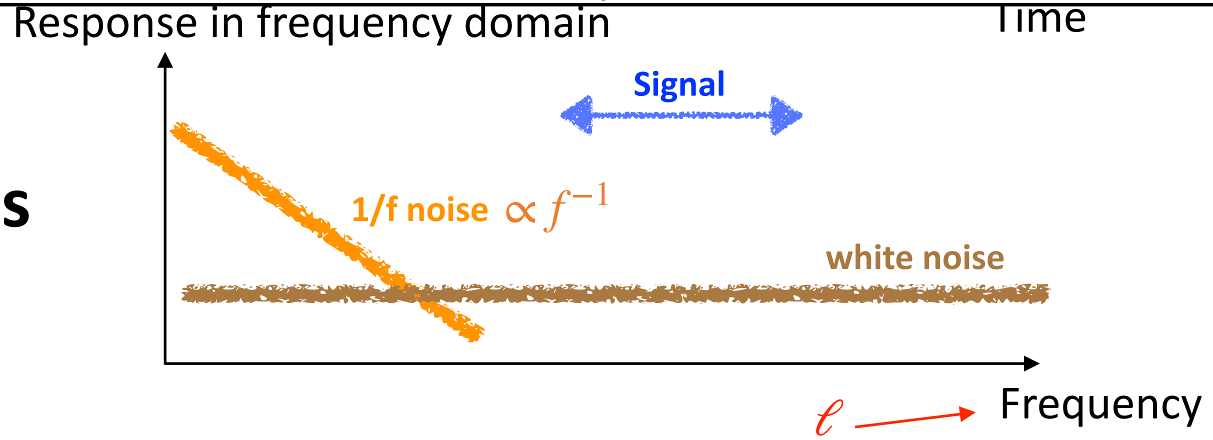
$$d = s + \cancel{n_{1/f}} + n_{white}$$

Would it be nice to be able to move this signal band to the higher frequency where the 1/f noise is free?

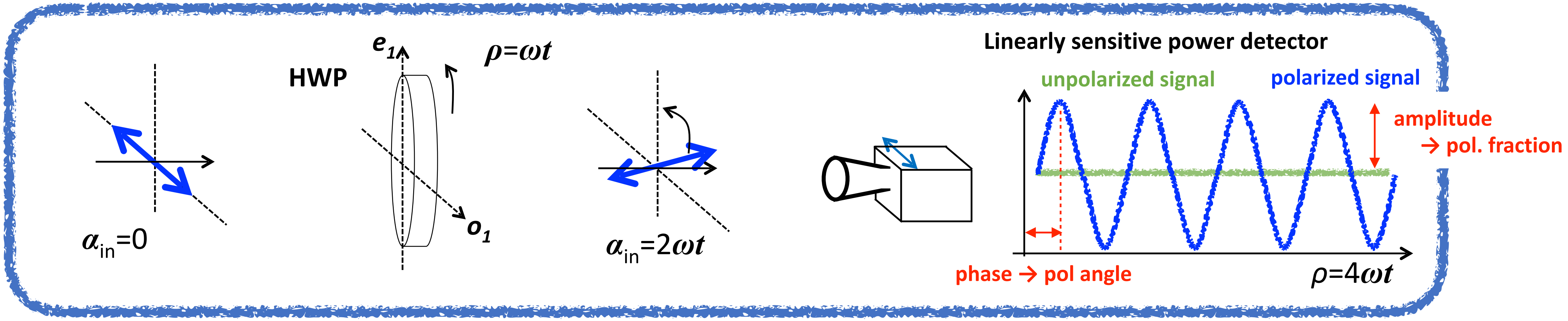
The Keck Array and BICEP2 Collaborations, Phys. Rev. Lett. 121, 221301, 2018





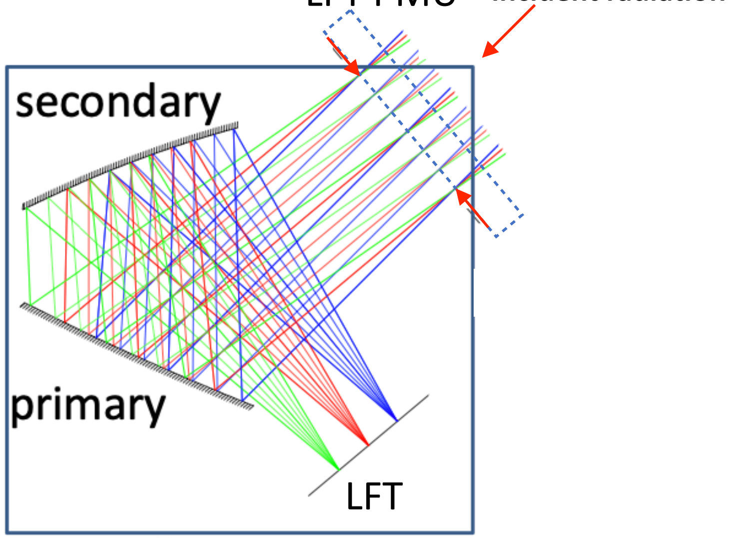
CMB polarimetry with a modulator

The common technique to introduce the modulation is to use a half-wave plate (HWP) polarization modulator.



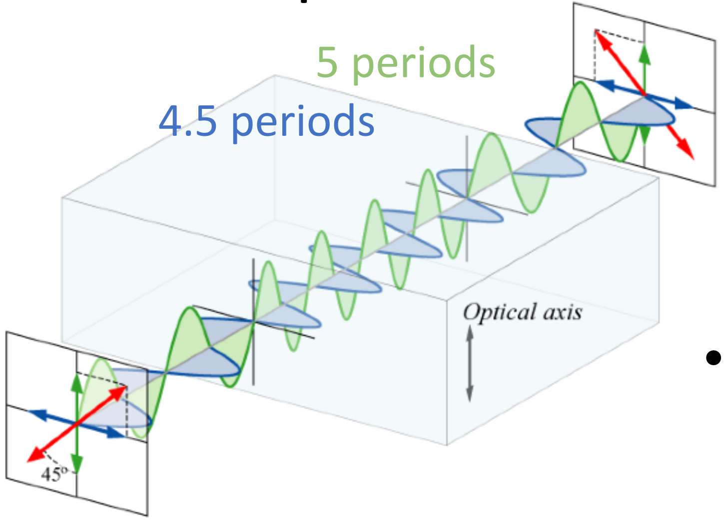
LFT optical system

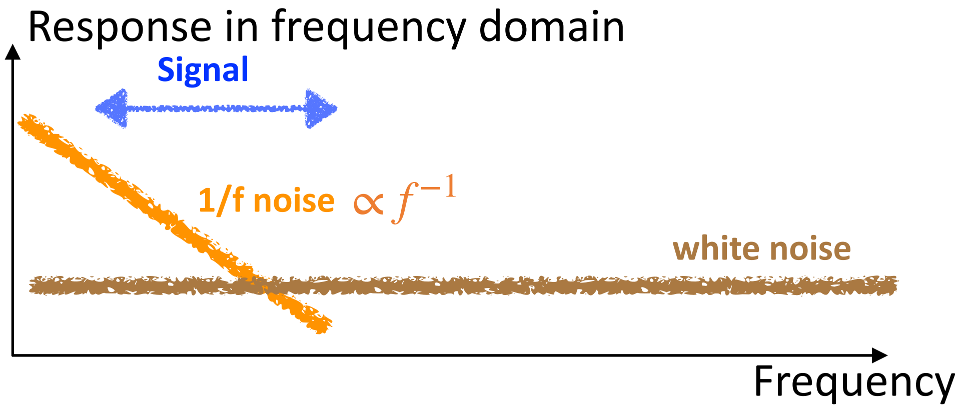
ray diagram



5 K optics enclosure + 100 mK focal plane

a birefringent material
sliced at a specific thickness





- In addition to the benefit of avoiding the 1/f noise, we can also avoid using two detector pair to remove the differential systematics.

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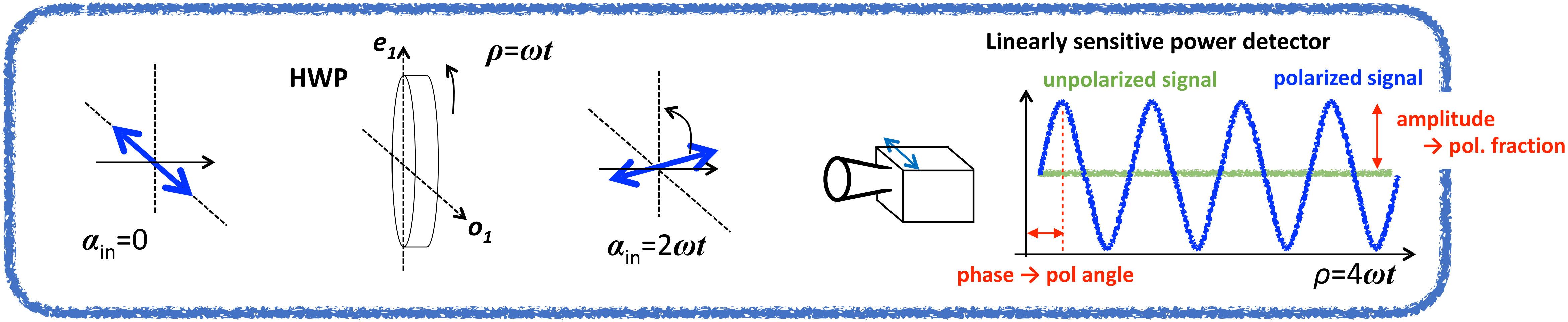

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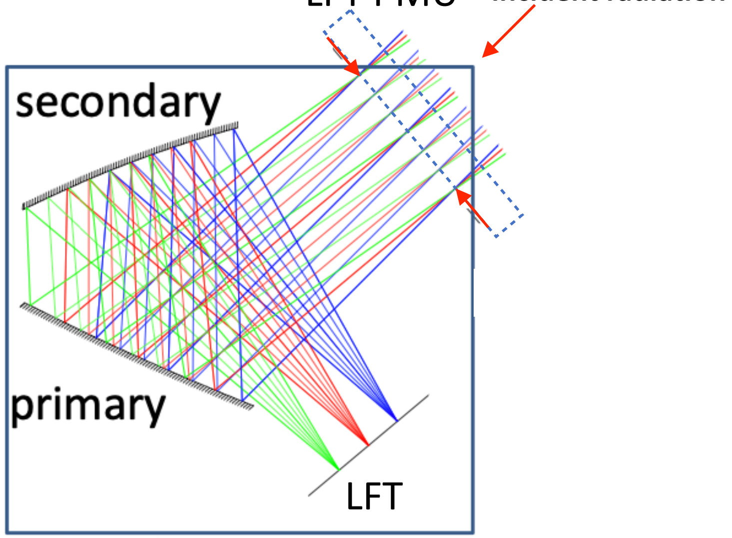

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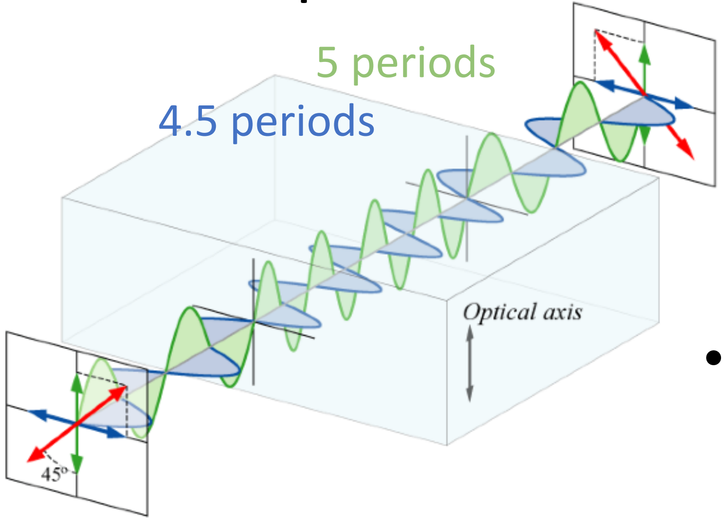
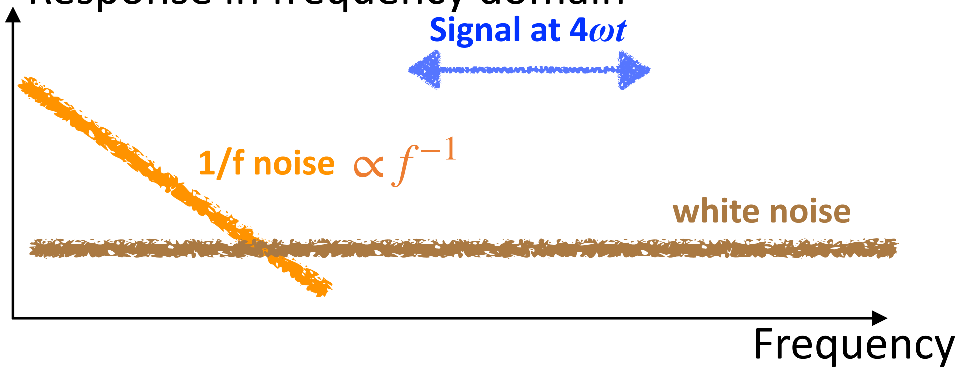


Response in frequency domain



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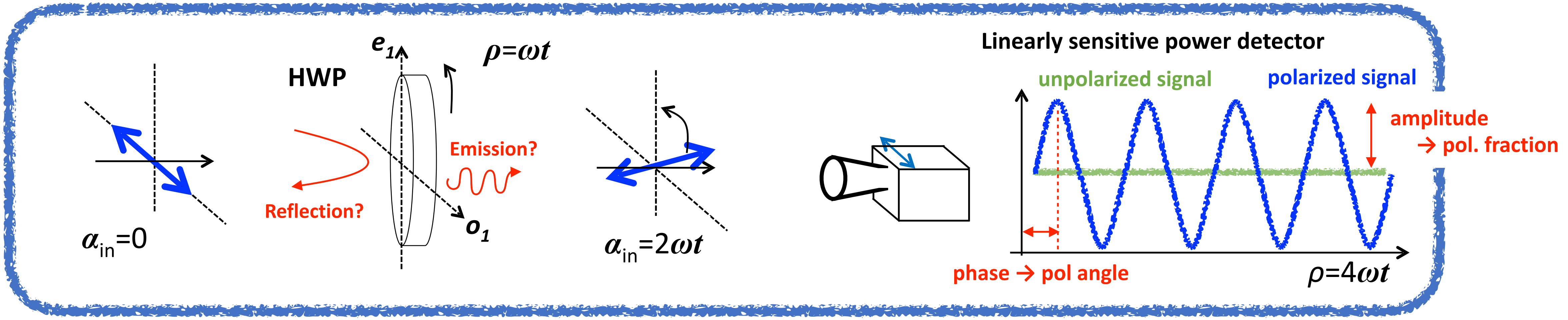

Experimental challenges!

SpaceOptCryoMechTronics

- We need to rotate the sapphire HWP at below 20 K
  to avoid the noise penalty.
- We need the CMB radiation to pass through the sapphire HWP plate over broadband
  to ensure to receive all the CMB photons.
- We need to modulate the polarization over broadband
  to ensure that we received all the polarized component of the photon.
- We need to know the angular position of the HWP
  to ensure that we can distinguish between E and B.

Development at Kavli IPMU

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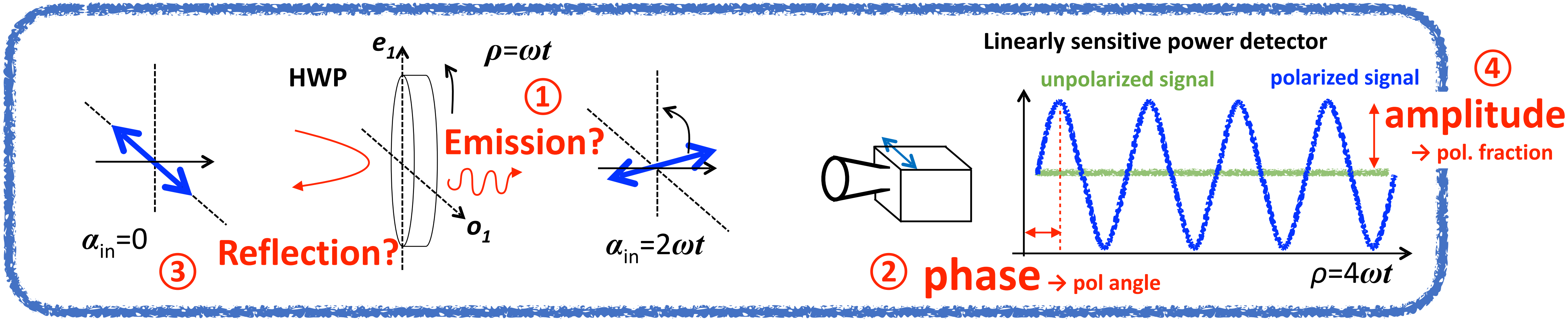

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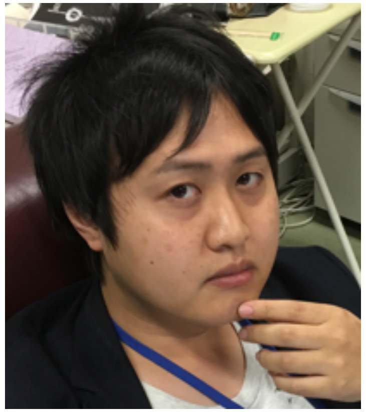
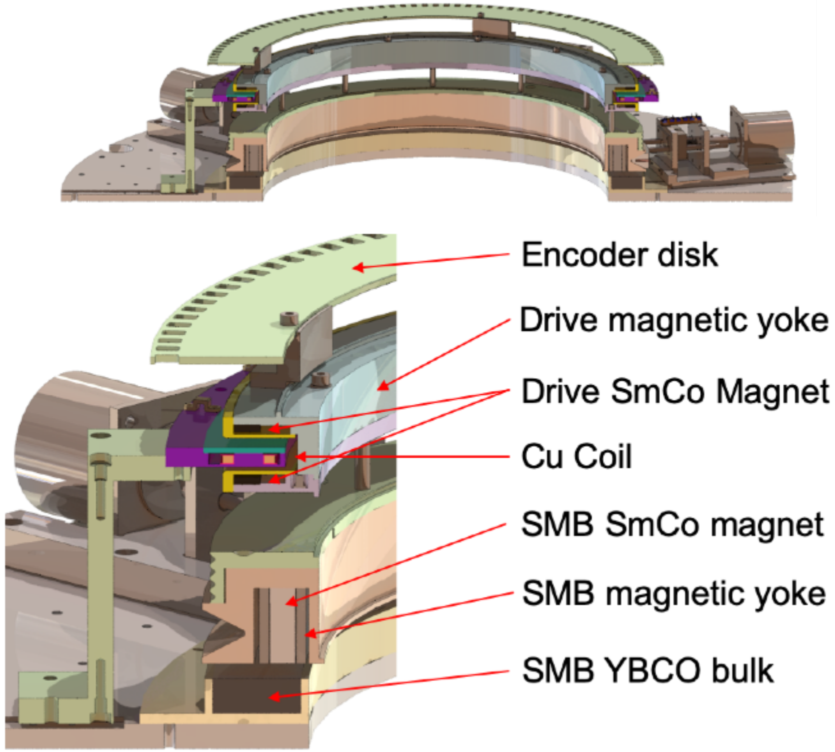
SpaceOptCryoMechTronics

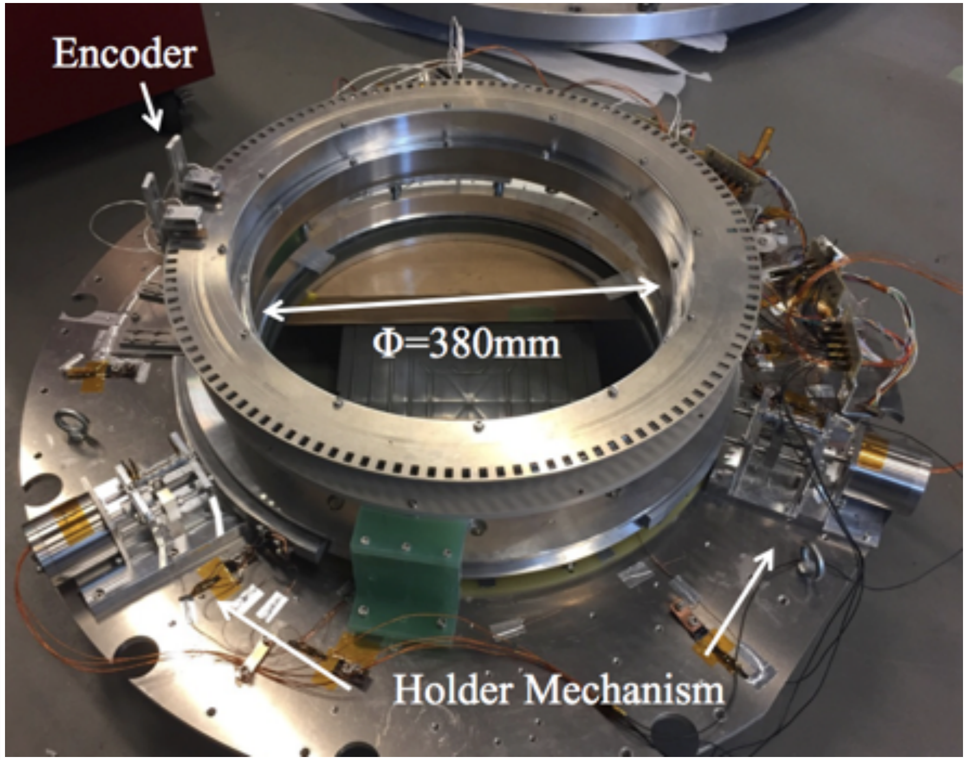
Zero contact. rot. mechanism

Y. Sakurai IPMU PD

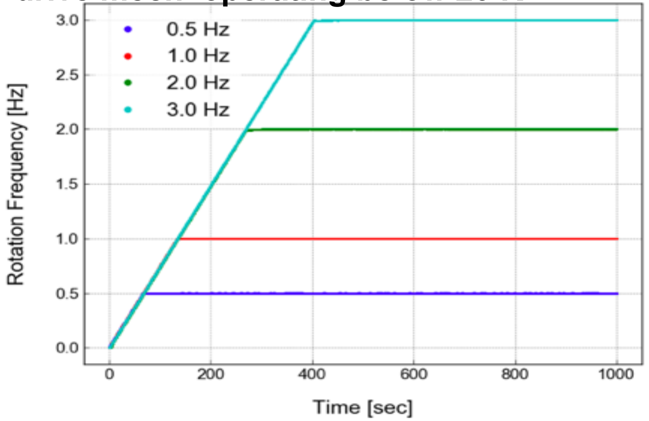


The world first demonstration of the cryogenic (<10K) contact free rotational mechanism with this size.



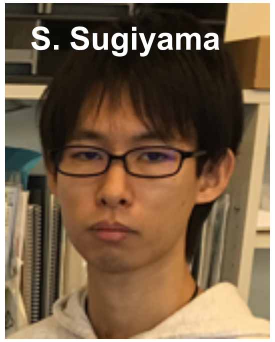


Rotational performance using the cryo. drive mech. operating below 20 K

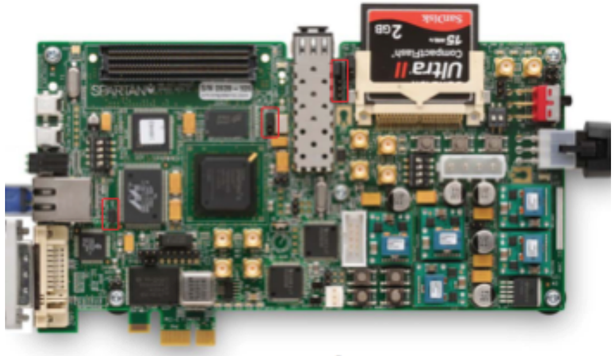


Y. Sakurai et al. in prep.

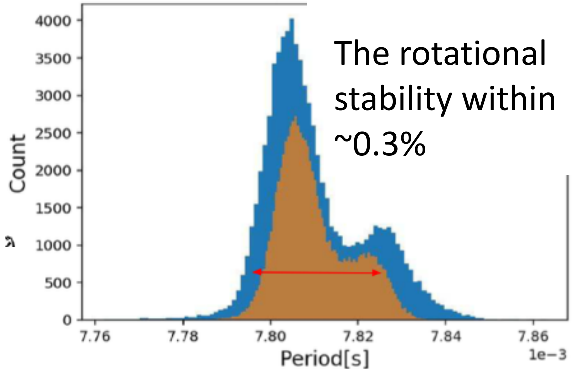
BBM PMU for a lab demonstration



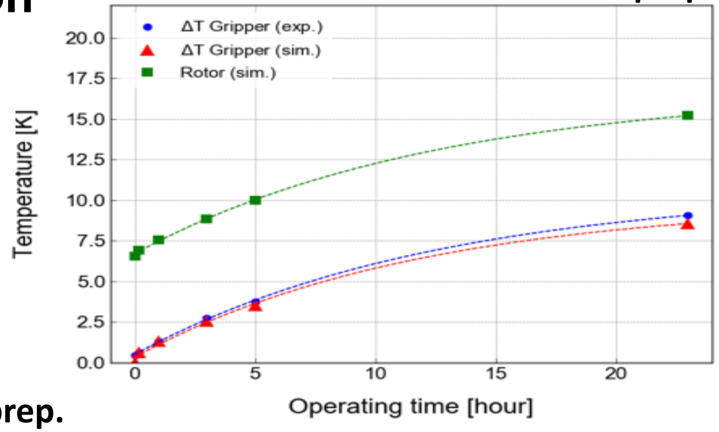
Saitama Univ.



FPGA

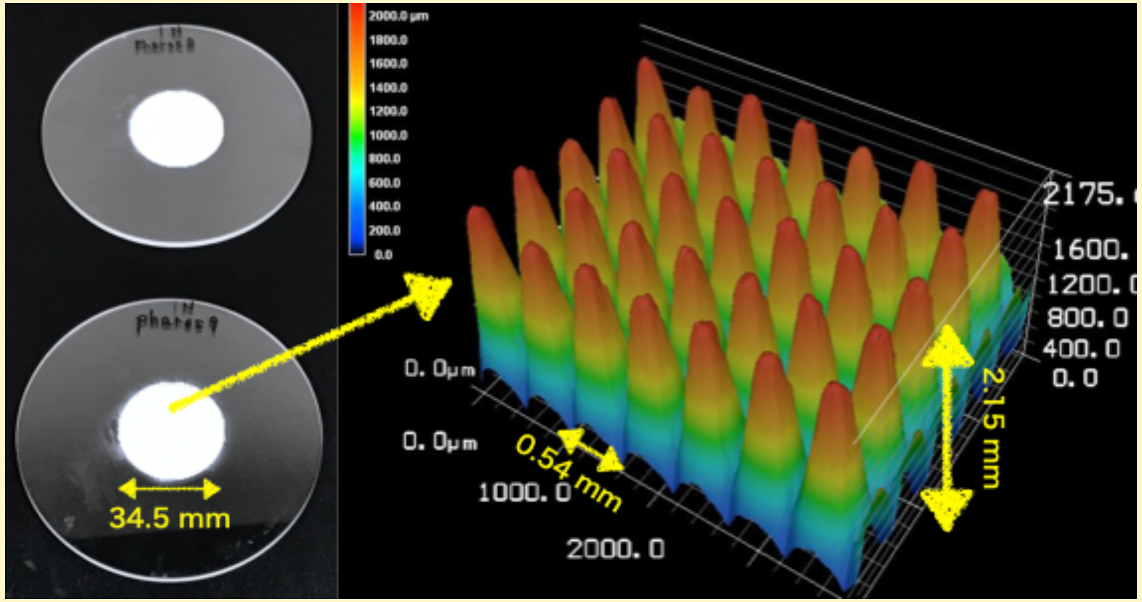


S. Sugiyama et al. in prep.



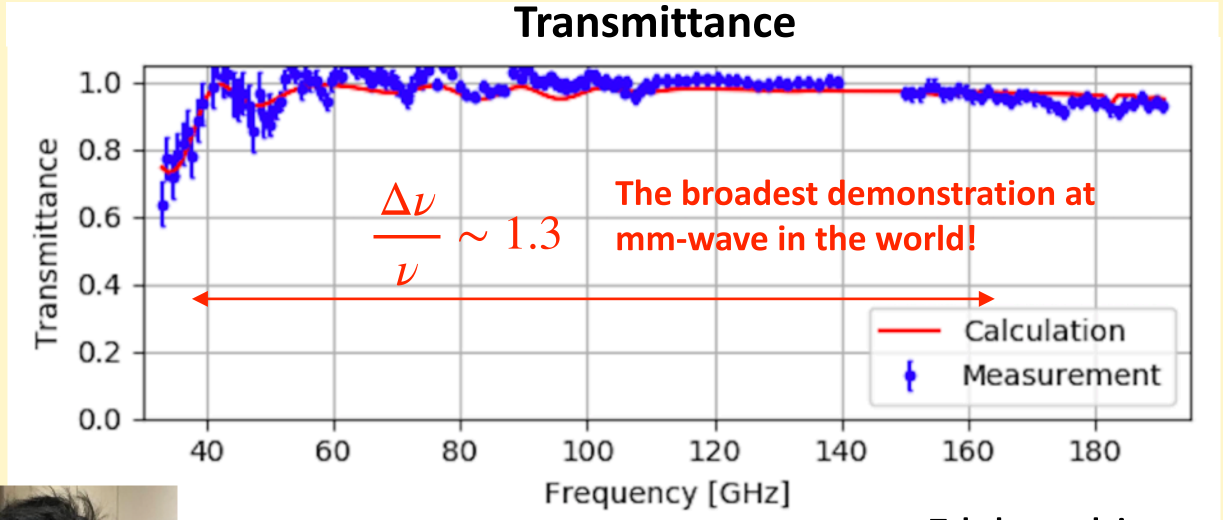
Development results

Broadest AR and achromatic HWP using sapphire

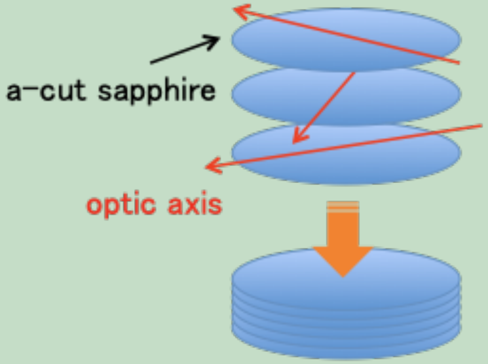


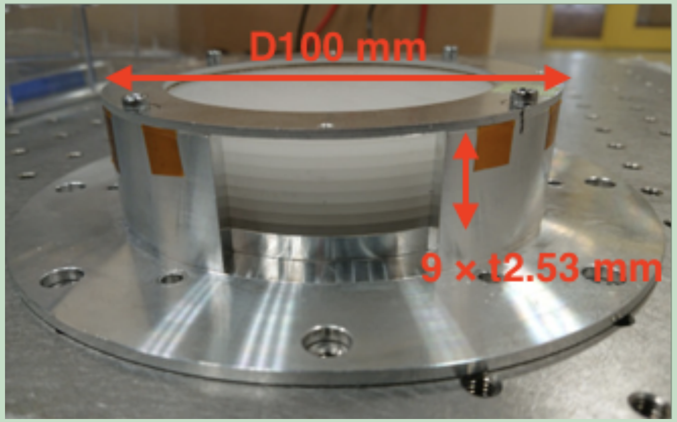
Univ. of Tokyo

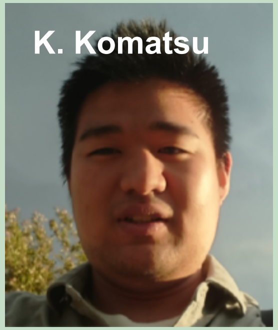
Transmittance



Takaku et al. in prep.

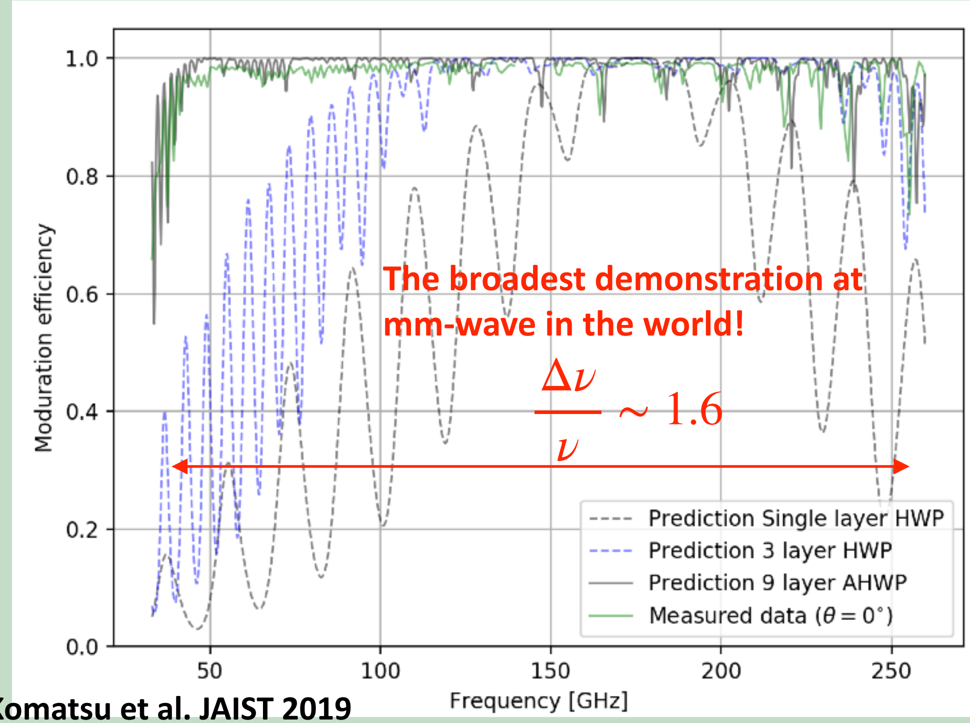






Okayama Univ.

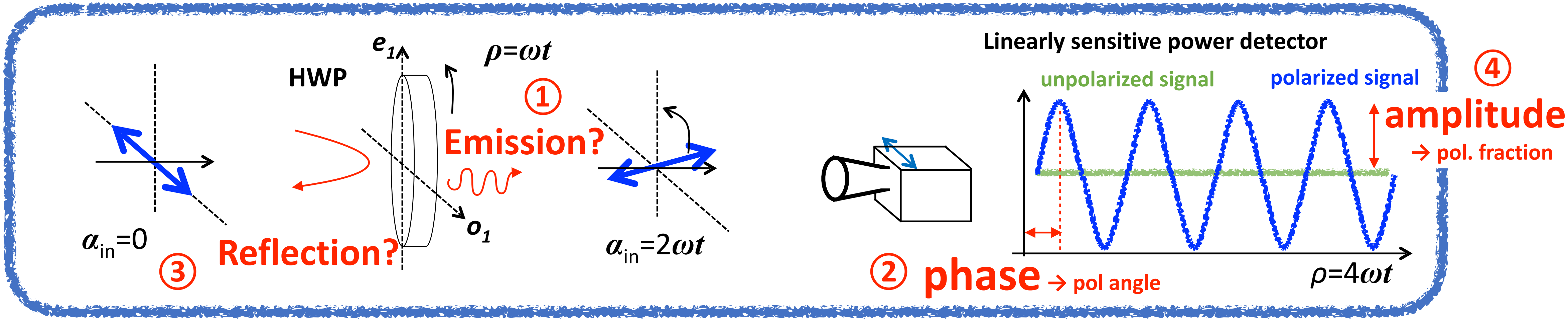
Polarization modulation efficiency



Komatsu et al. JAIST 2019

CMB polarimetry with a modulator

The common technique to introduce the modulation is to use a half-wave plate (HWP) polarization modulator.



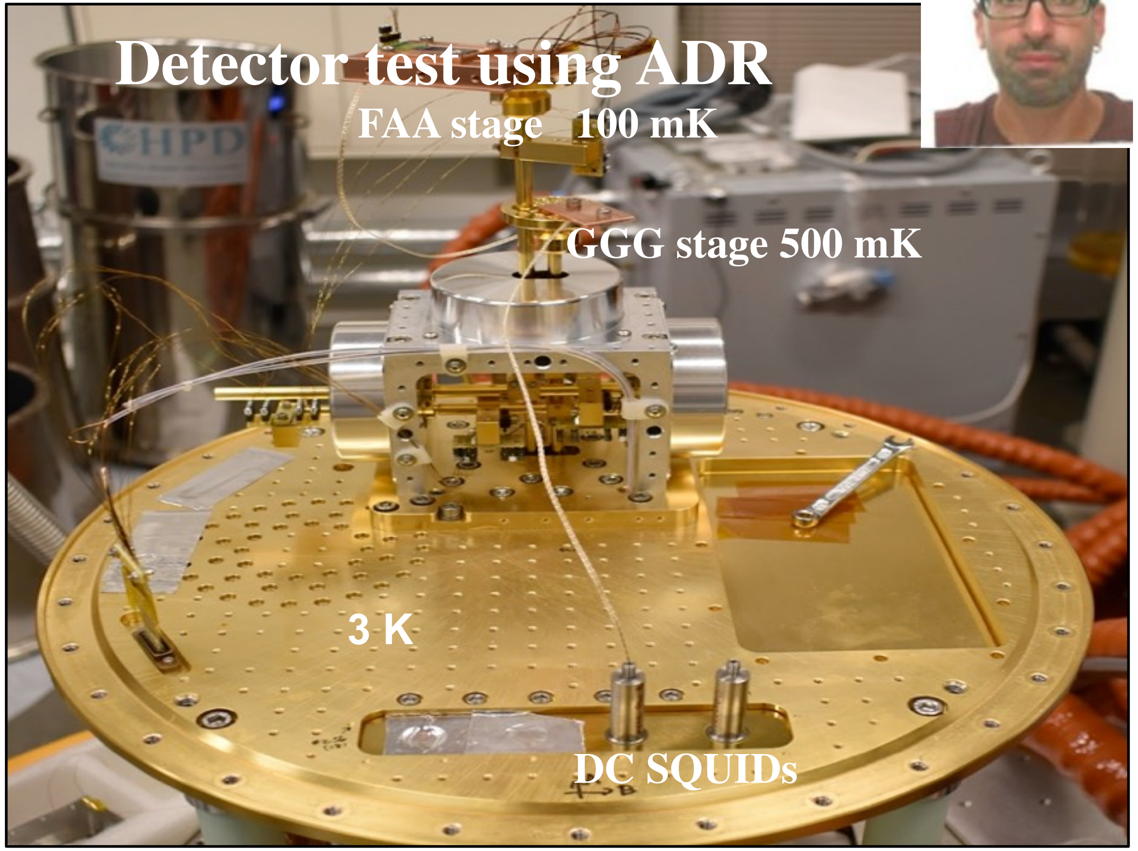
Experimental challenges!

1. We need to rotate the sapphire HWP at below 20 K
   to avoid the noise penalty.
2. We need to know the angular position of the HWP
   to ensure that we can distinguish between E and B.
3. We need the CMB radiation to pass through the sapphire HWP plate over broadband
   to ensure to receive all the CMB photons.
4. We need to modulate the polarization over broadband
   to ensure that we received all the polarized component of the photon.

The development and the lab demonstration using a BBM are in progress!

Detector test

IPMU/Oxford



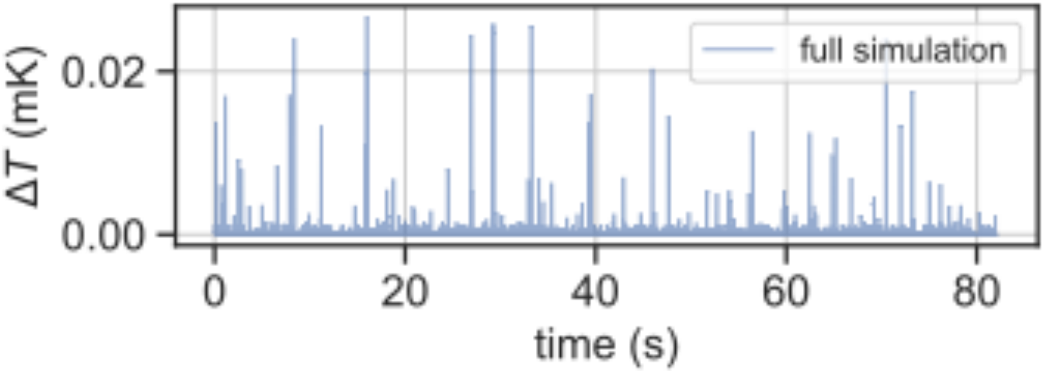
The aims of the study is to address

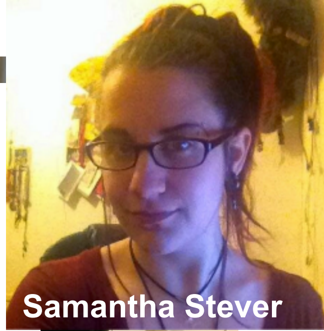
- Present: Detector parameters, noise, time response, etc.
- Future: Check possible interference between detector/readout with
  - HWP magnetic bearing.
  - Cosmic ray testing at 100 mK with radioactive source.

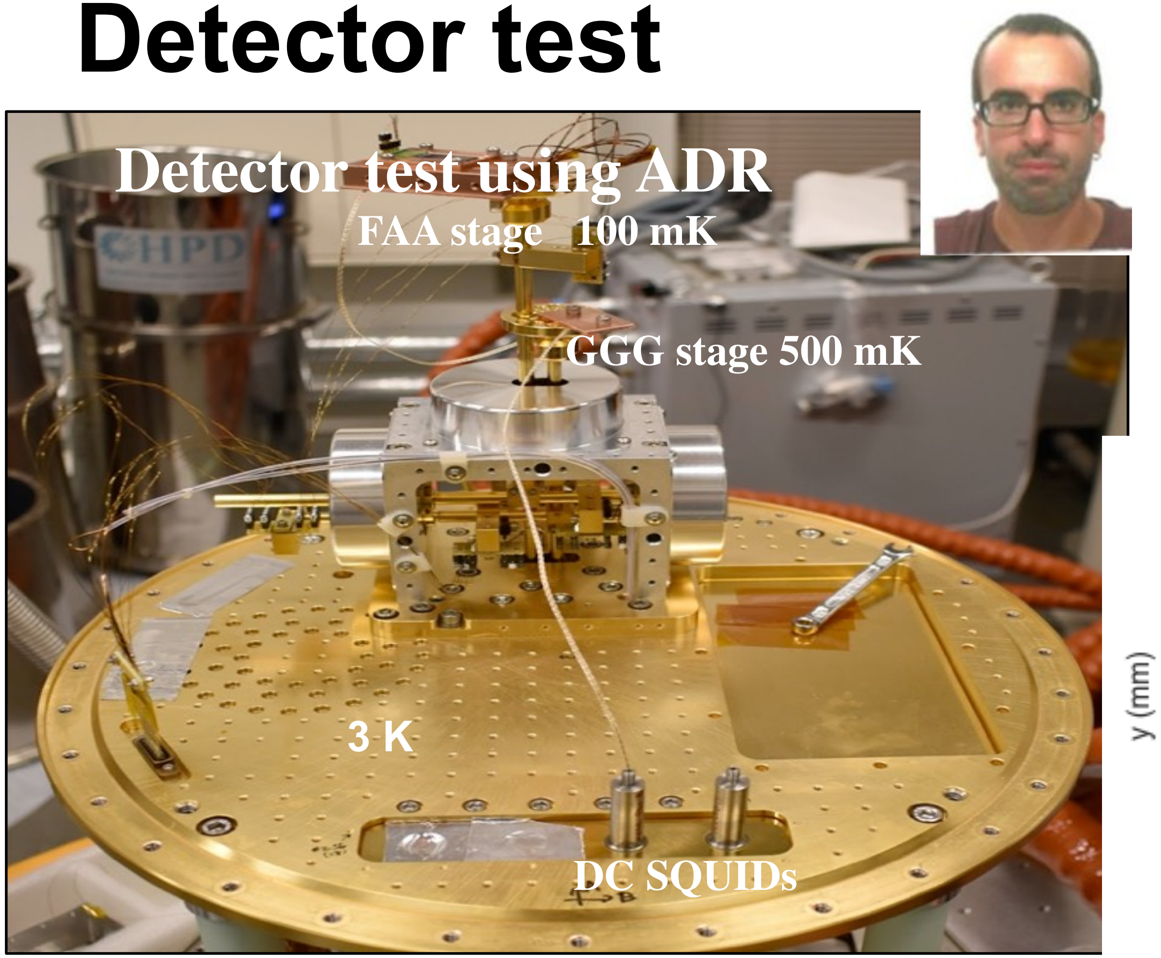
Detector test

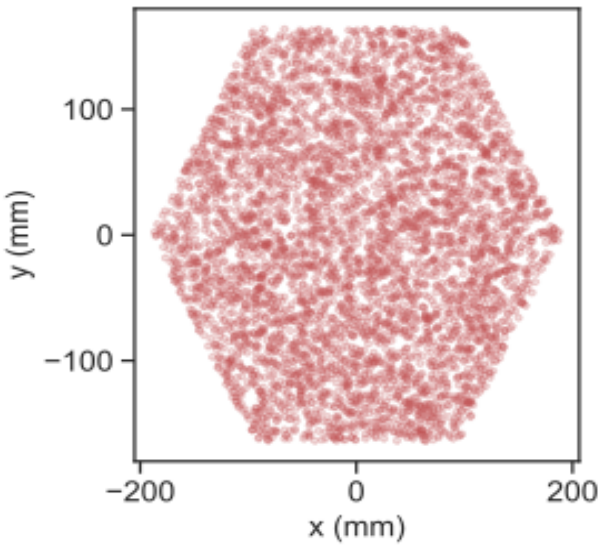
IPMU/Oxford

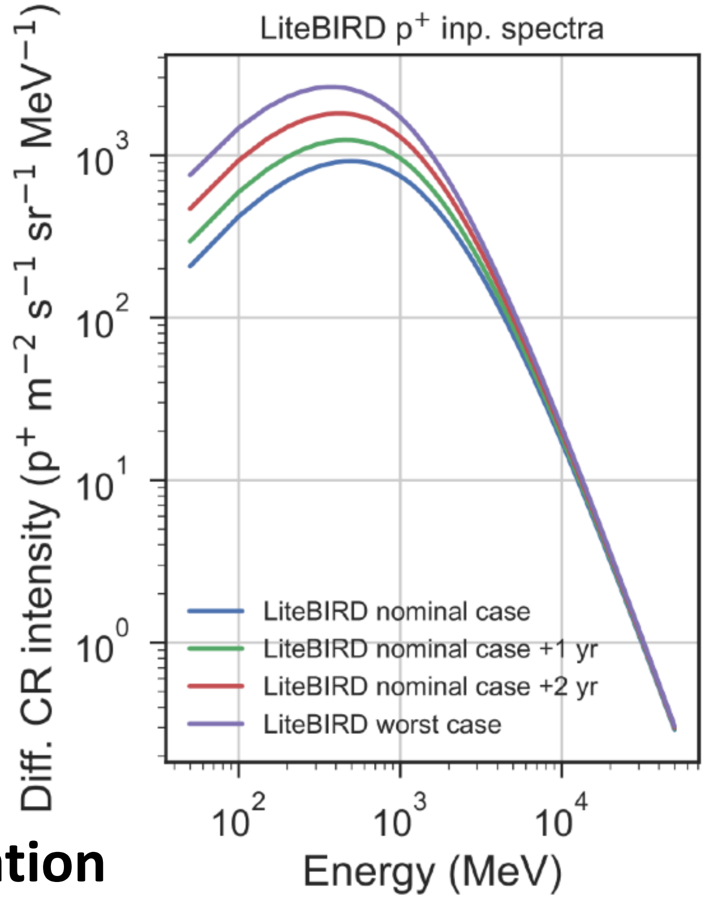
simulated cosmic ray temperature fluctuation on wafer











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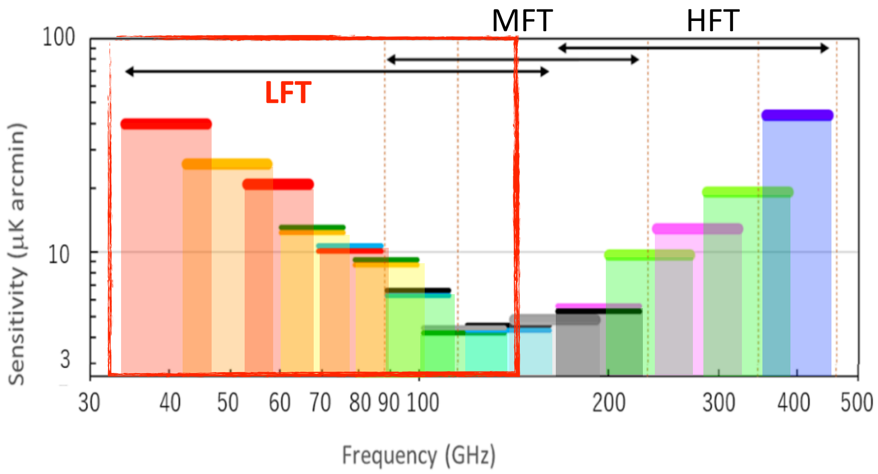
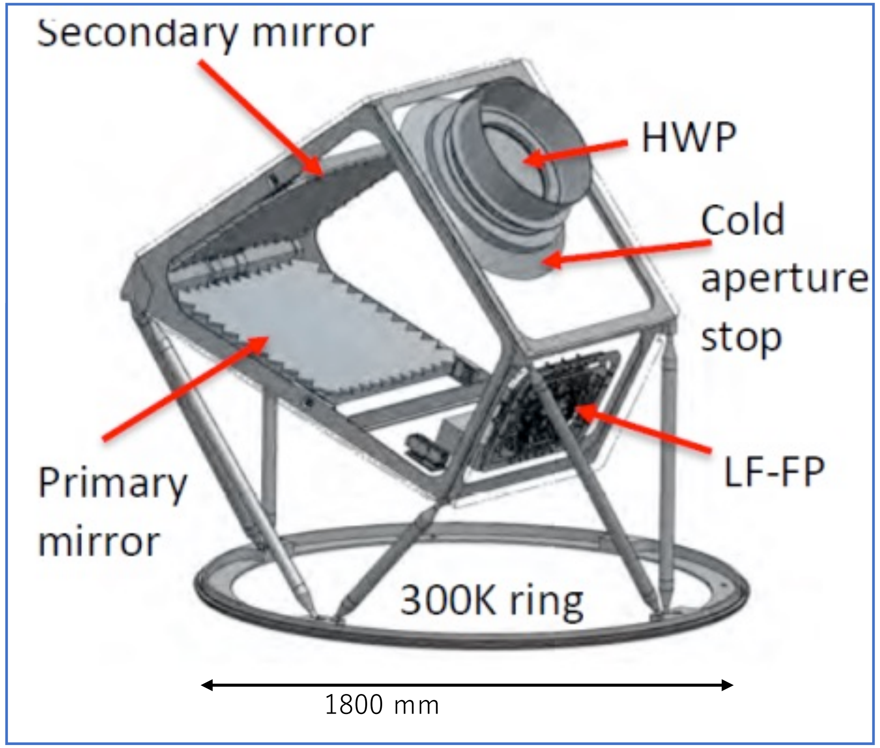
Experiment ⇄ Simulation including the foreground removal ⇄ Calibration

Low Frequency Telescope Unit

Frequency coverage (total of 15 bands)

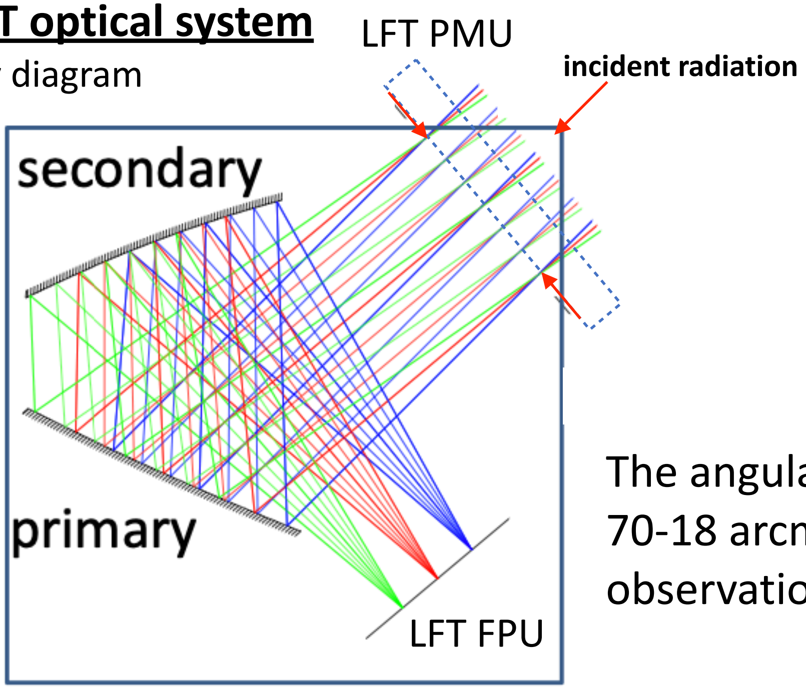


- **LFT covers the frequency range of 34-161 GHz with 9 bands.**
- **This corresponds to the synchrotron and the CMB channels.**



LFT optical system

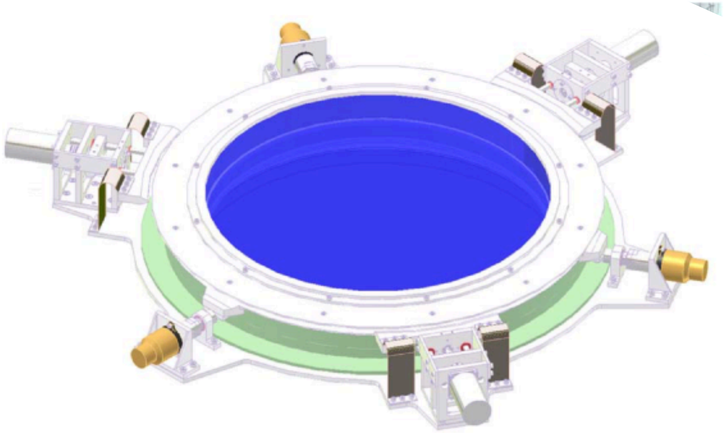
ray diagram



5 K optics enclosure + 100 mK focal plane

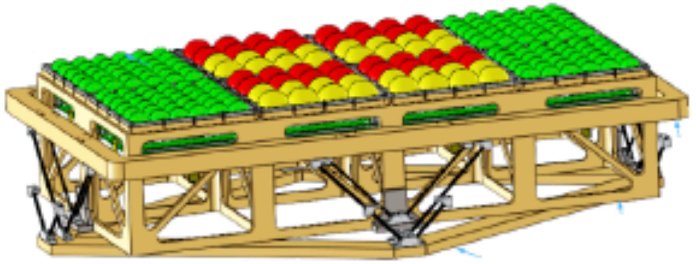
The angular resolutions are 70-18 arcmin. depending on the observational frequency band.

LFT polarization modulator unit (PMU)



- First optical element in the telescope.
- The details will come in a few pages.

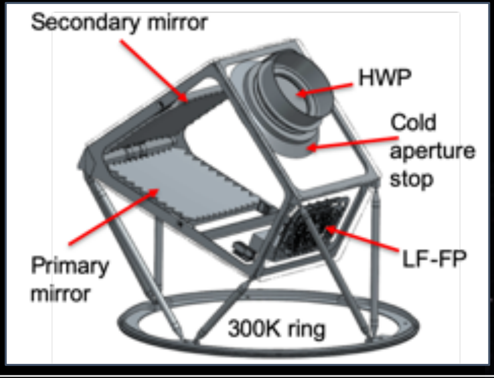
LFT focal plane unit (FPU)

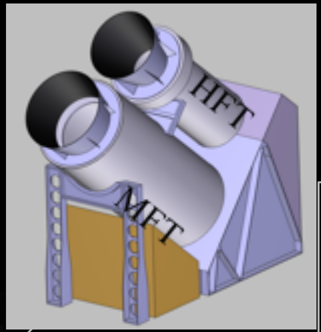


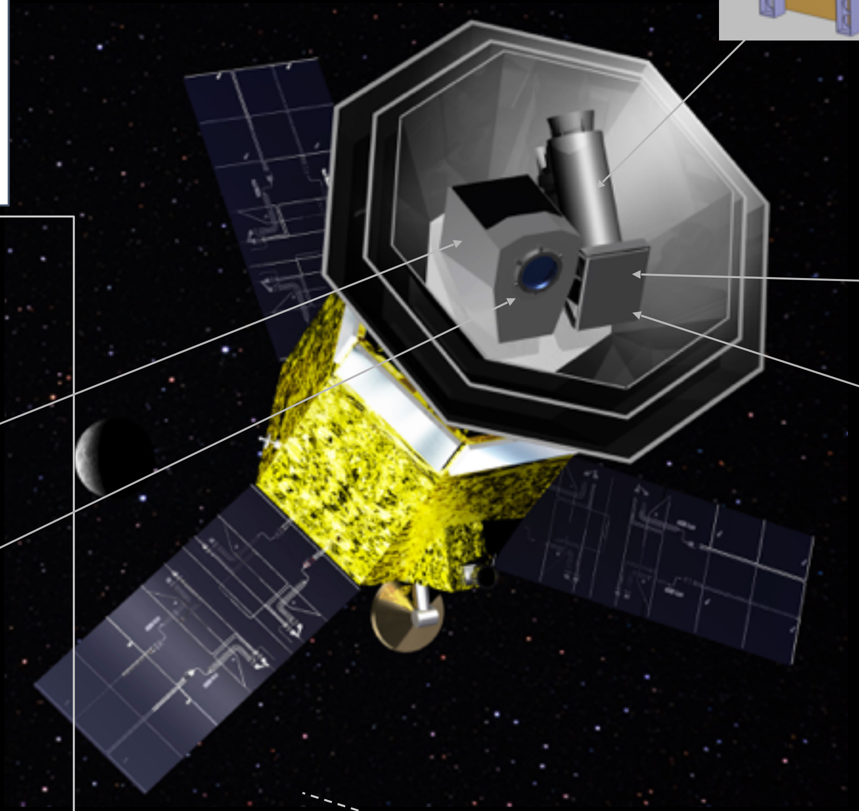
- 1248 trichroic Transition Edge Sensor (TES) bolometers cooled at 100 mK.
- Read by SQIUD + DfMUX readout system.

LiteBIRD overview

LFT







JAXA
- Launch
- Satellite system incl. cryogenics
- Low frequency telescope

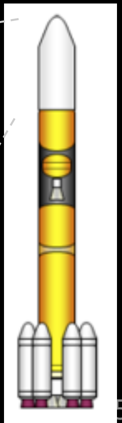
Kavli IPMU
- **Polarization modulator**
- **Data analysis**

KEK
- Ground integration/calibration

Europe
- mid/high freq. telescopes
- sub-K cooler

US
- Superconducting detector focal plane

Canada
- Warm electronics



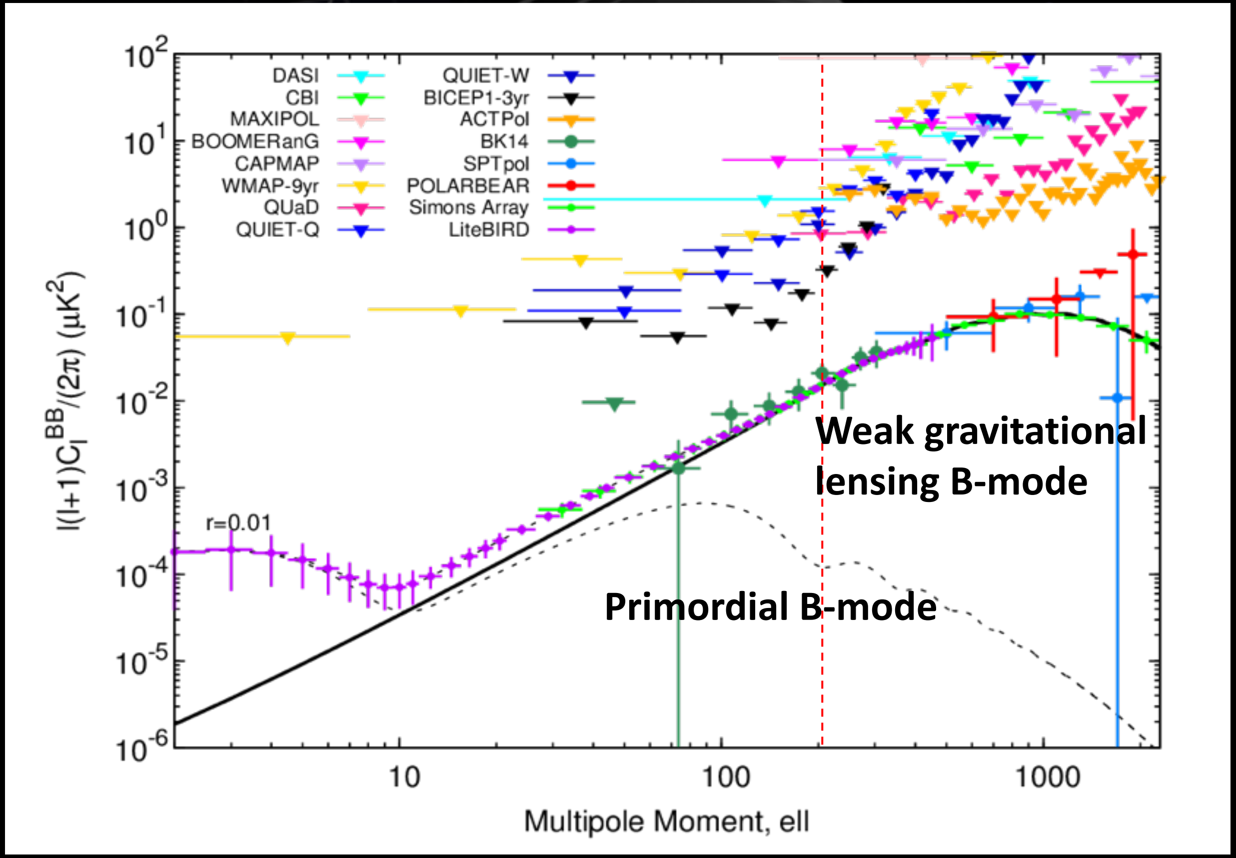
JAXA H3 rocket

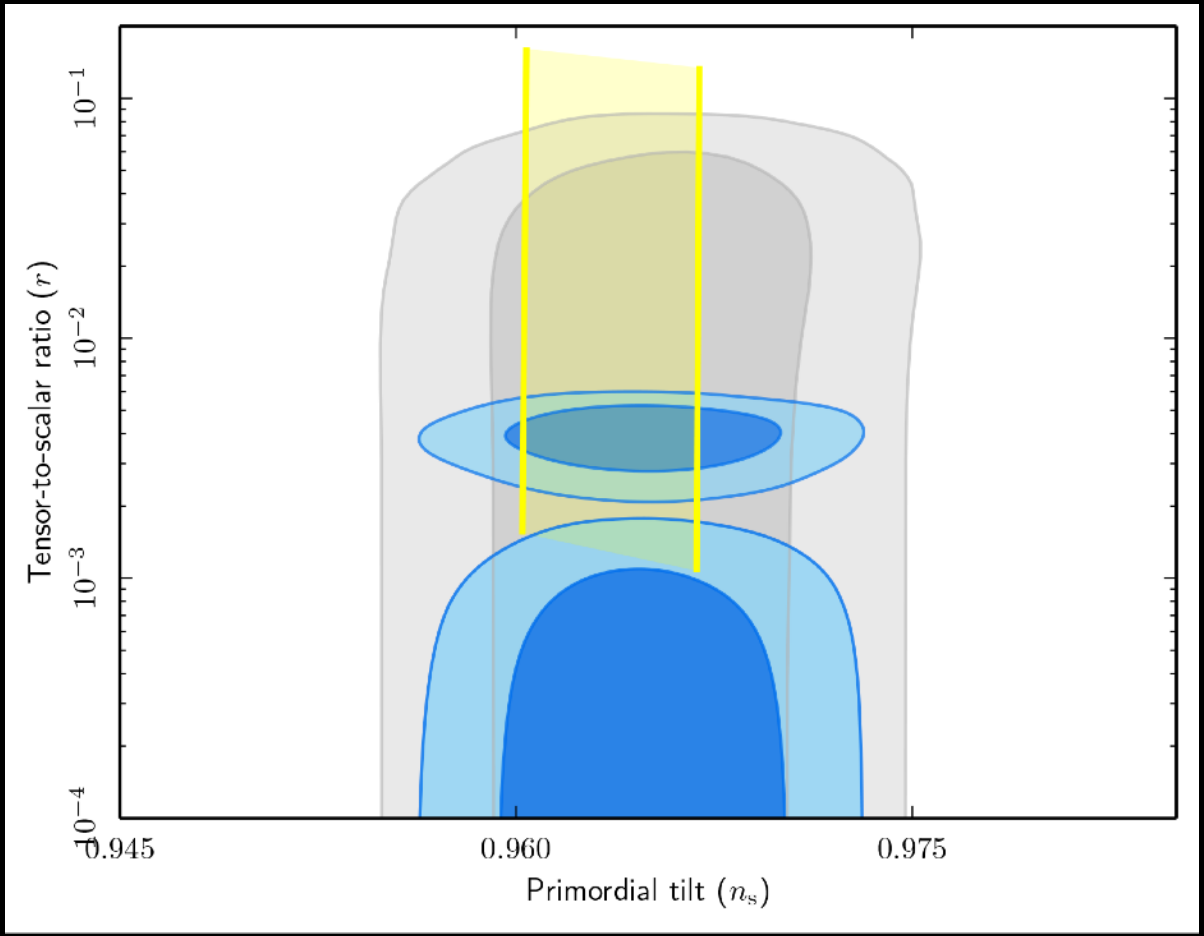
What can we learn from LiteBIRD in the end?

One of top-priority large projects in Master plan 2017 of Science Council of Japan

LiteBIRD

is a next generation CMB polarization satellite that is dedicated to probe the inflationary B-mode. The science goal of LiteBIRD is to measure the tensor-to-scalar ratio with the sensitivity of σ_r = 0.001 for r = 0, and 5σ detection for r>0.01 for each bump. In this way, we test the major large-single-field slow-roll inflation models.

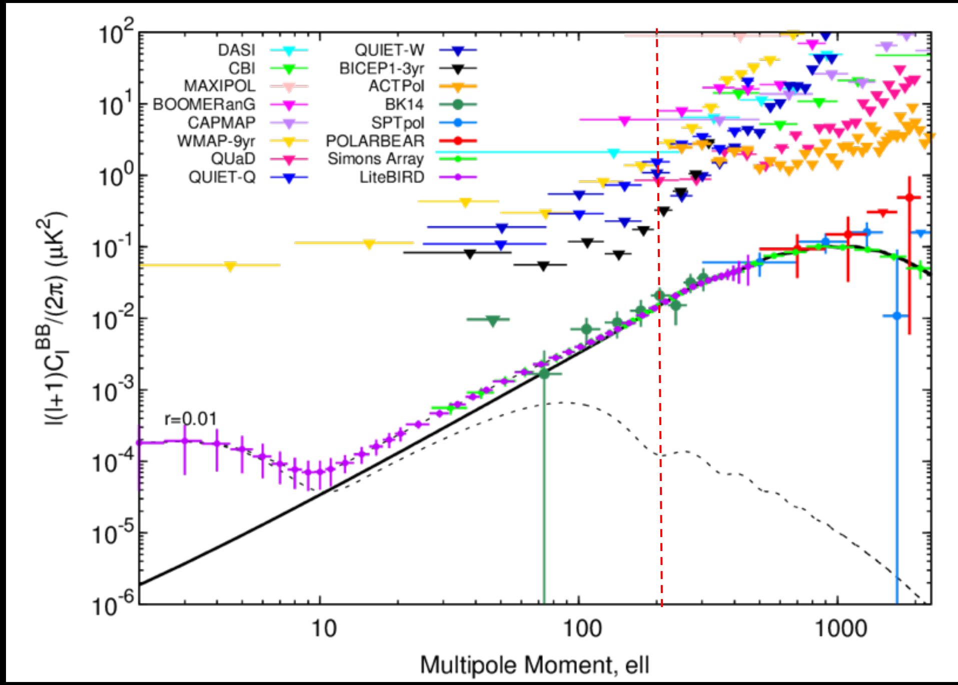




Science from LiteBIRD

While the design of LiteBIRD is purely driven by the inflationary B-mode signal, LiteBIRD can deliver a number of rich by-products from its measurement.

- Characterization of B-mode, e.g. non-Gaussianity
- Reionization history from E-mode and the neutrino mass
- Cosmic birefringence
- Galactic magnetic field
- CMB polarization power spectrum shape
- SZ effect
- Anomaly
- Cross-correlation science
- Galactic science



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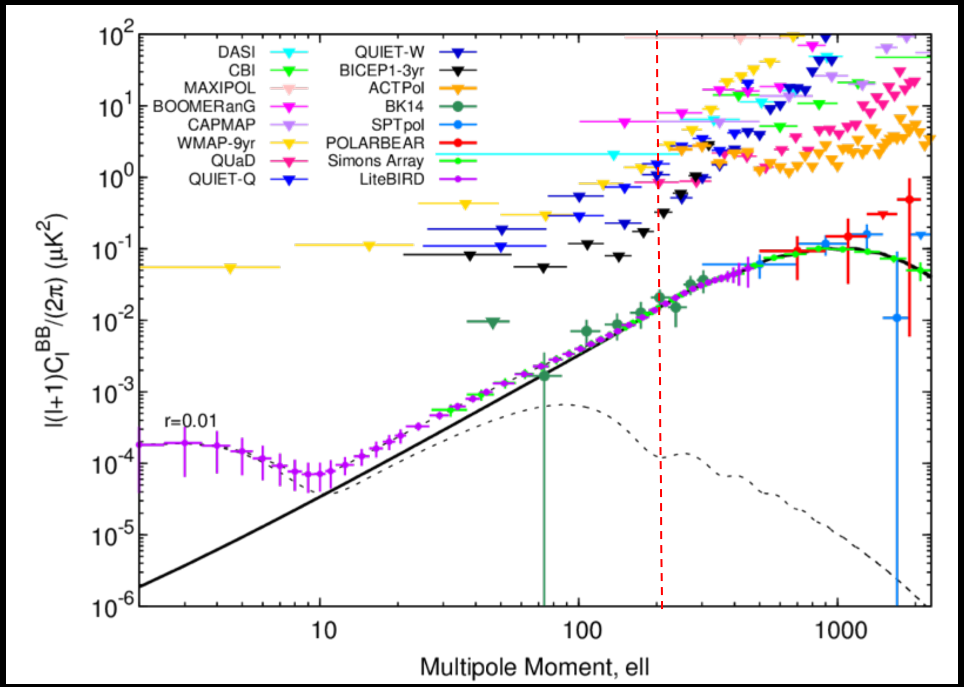

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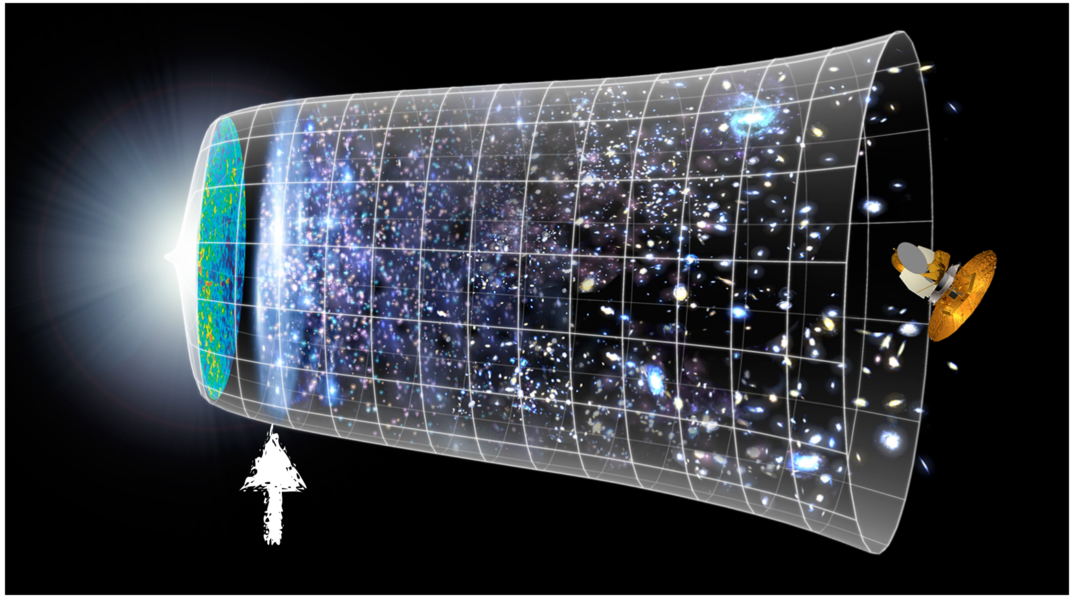
H. Ochi
Yokohama
National University

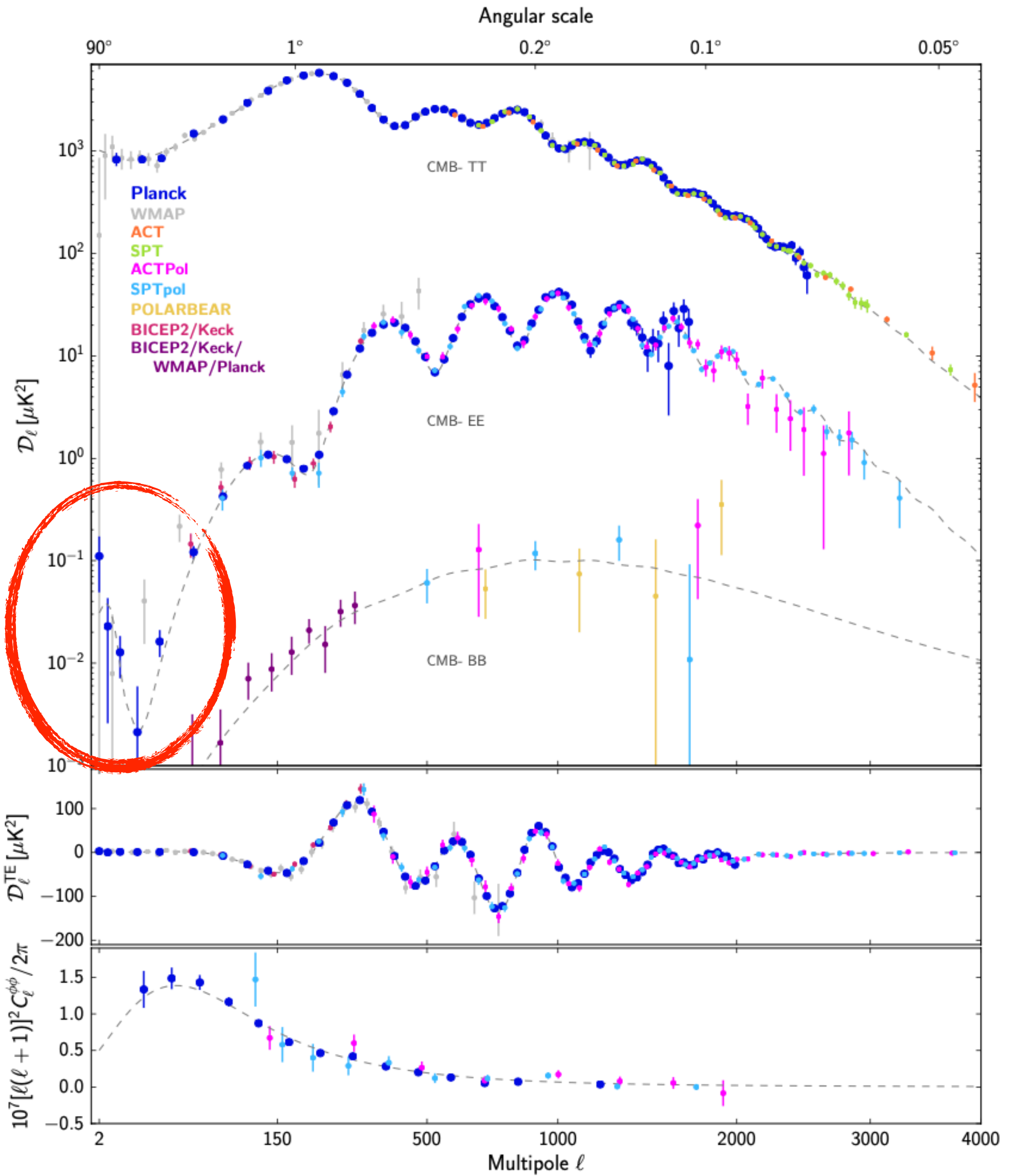
Large-scale E-mode



- The CMB can be polarized by the plasma from the reionization.
- Planck is sensitive to the feature originated from reionization.
- The sensitivity of Planck is not sufficient enough to carry out the cosmic variance limited measurement.

$$\tau = 0.0544^{+0.0070}_{-0.0081}$$ 68%, TT, TE, EE+lowE

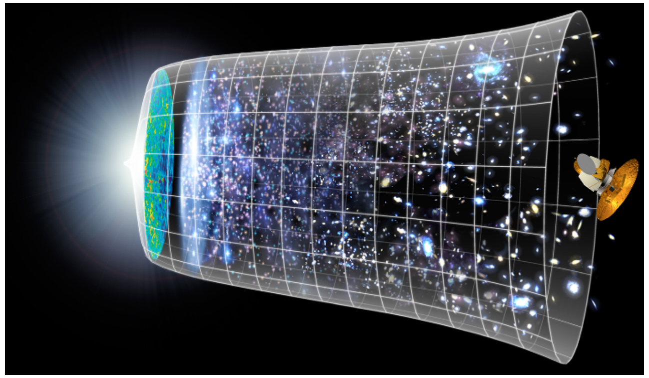
From Planck2018

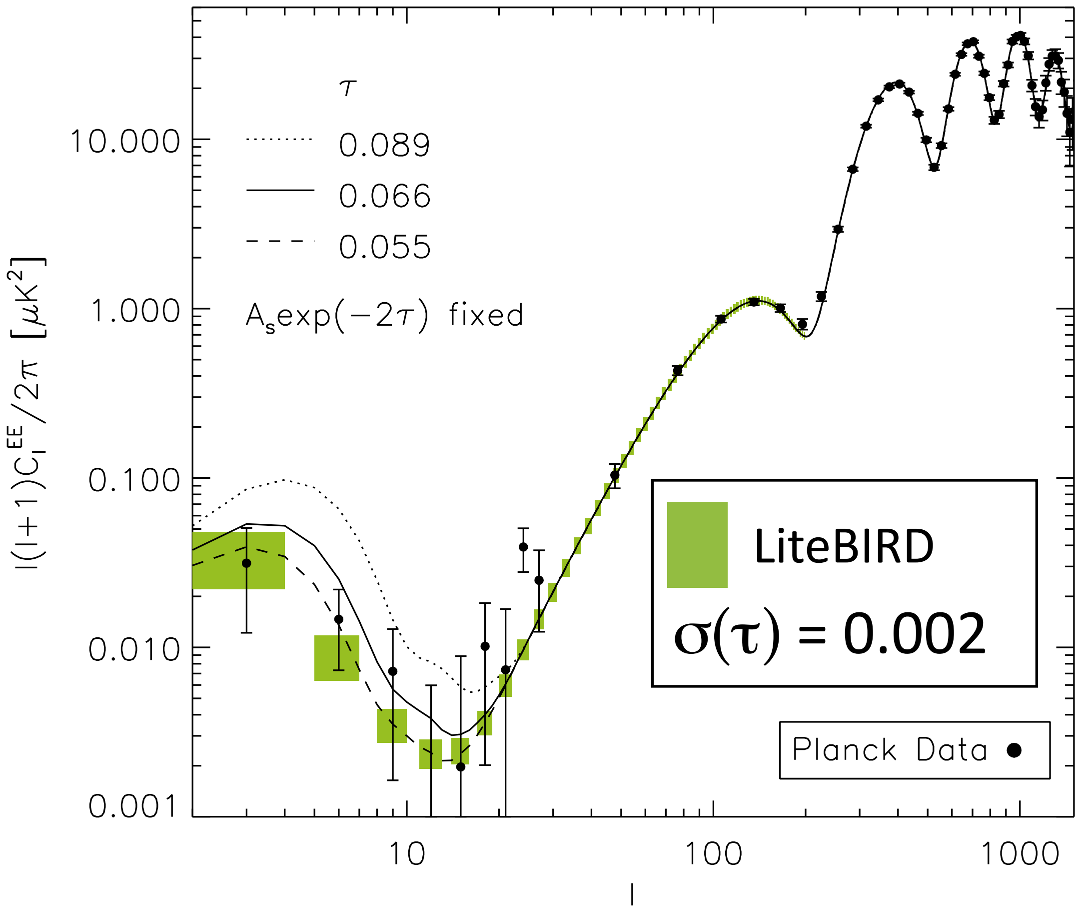


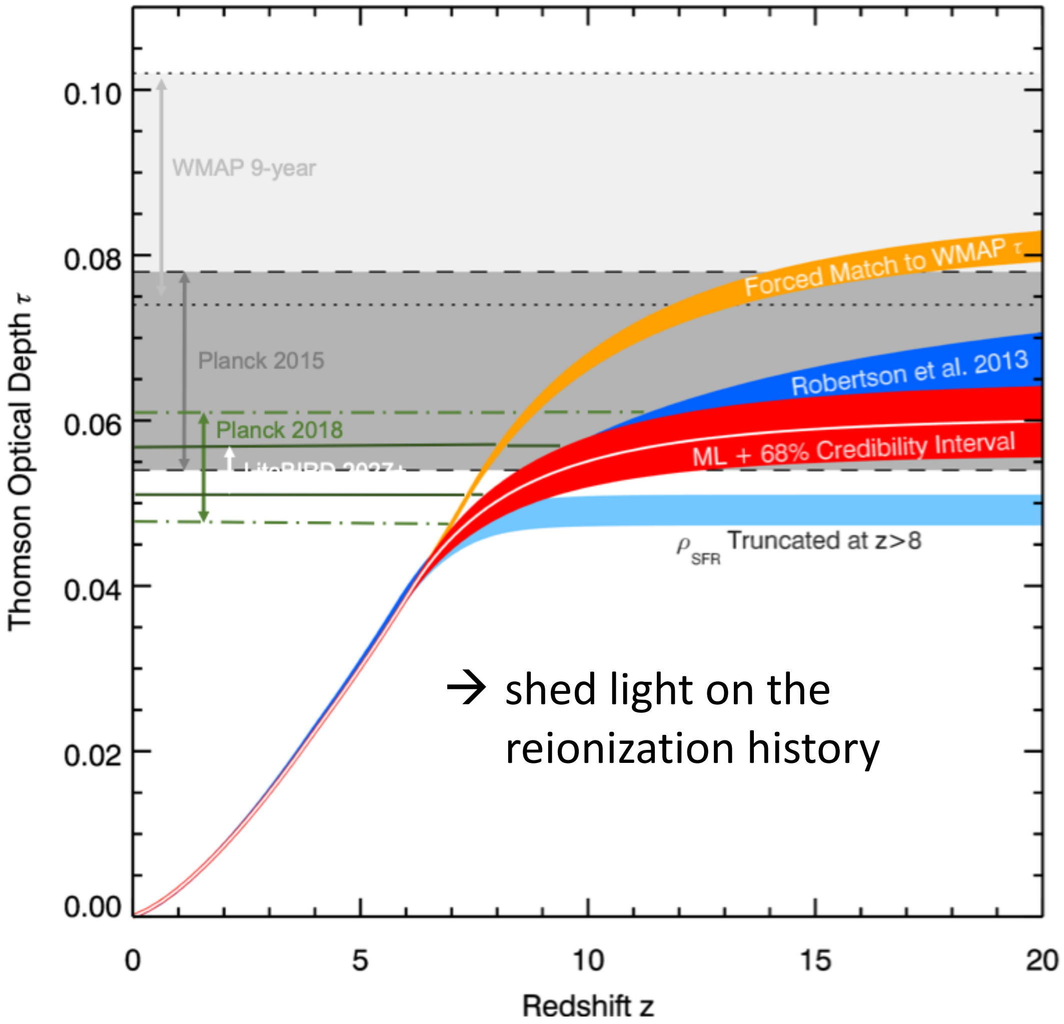
Why do we care?

Large-scale E-mode

A cosmic variance limited measurement of EE on large angular scales will be an important, and guaranteed, legacy for LiteBIRD!





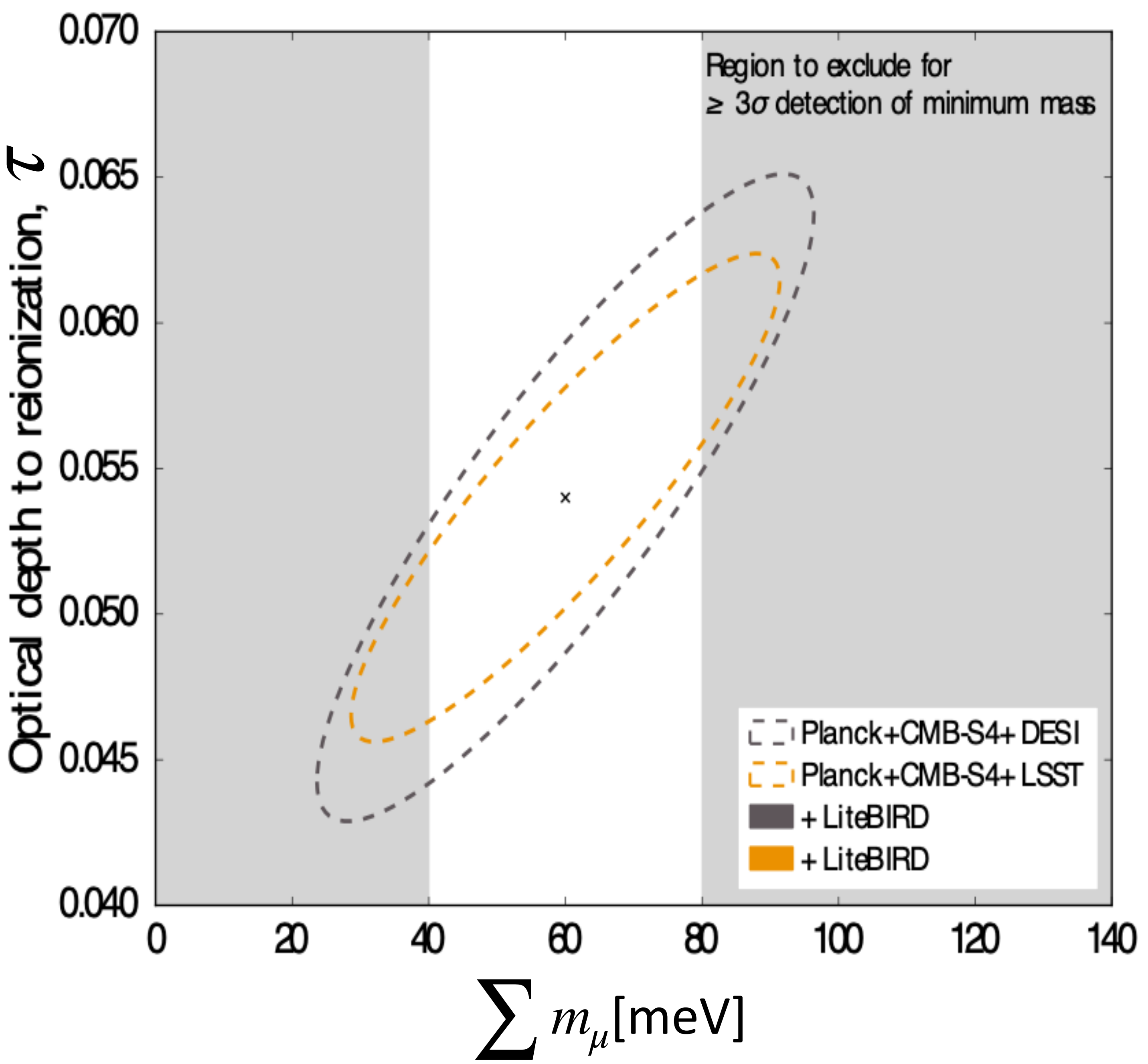


Σm_ν w/ improved τ

The determination of tau helps break the degeneracy in the lensing B-mode between the overall amplitude and the smearing by the neutrino mass.

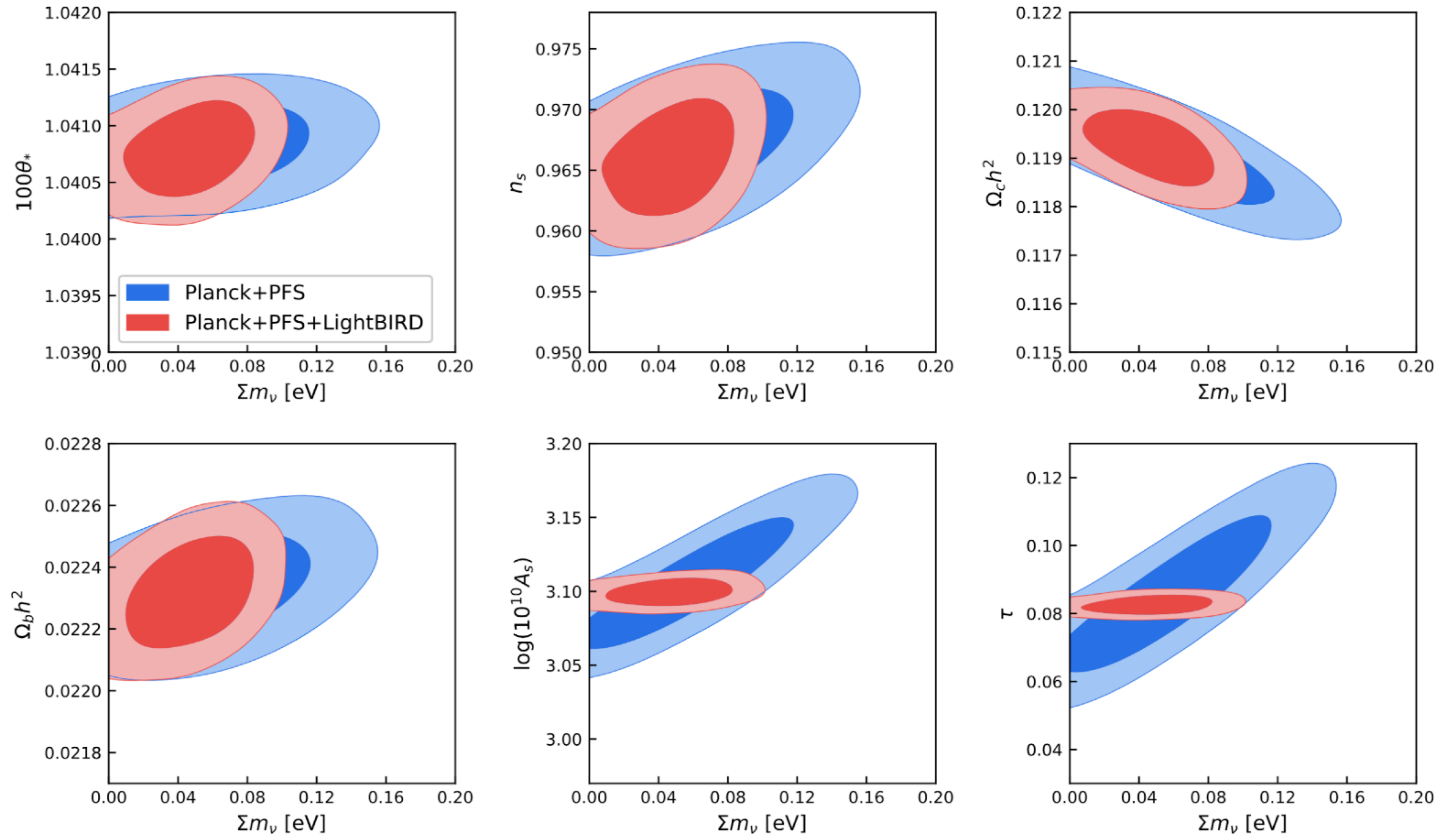
- $\sigma(\Sigma m_\nu) = 15$ meV
- $\geq 3\sigma$ detection of minimum mass for normal hierarchy
- $\geq 5\sigma$ detection of minimum mass for inverted hierarchy

Caveat:
No systematic error included yet.



Synergy beyond CMB

Given the measurement of the reionization history, τ, by LiteBIRD, what PFS can do for the parameter constraints.



Courtesy from R. Makiya(IPMU)

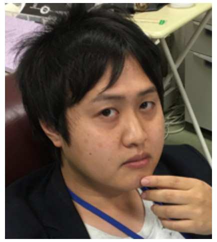
CMB telescopes in Chile

POLARBEAR, POLARBEAR2/Simons Array

Simons Observatory

Nobu

- **PB, PB2/SA**
  - Gain calibrator Analysis on CMB and atmospheric dust
- **Simons Observatory**
  - Optics design
  - Optics tube delivery
  - Gain calibrator



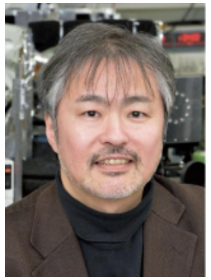
Yuki

Fred

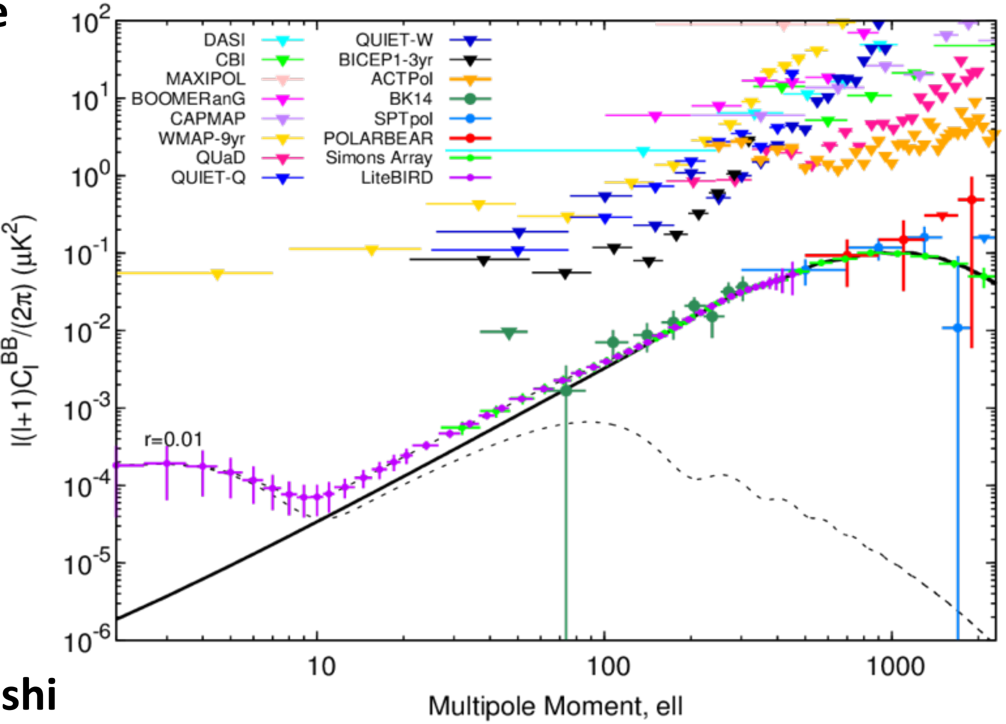
Keigo

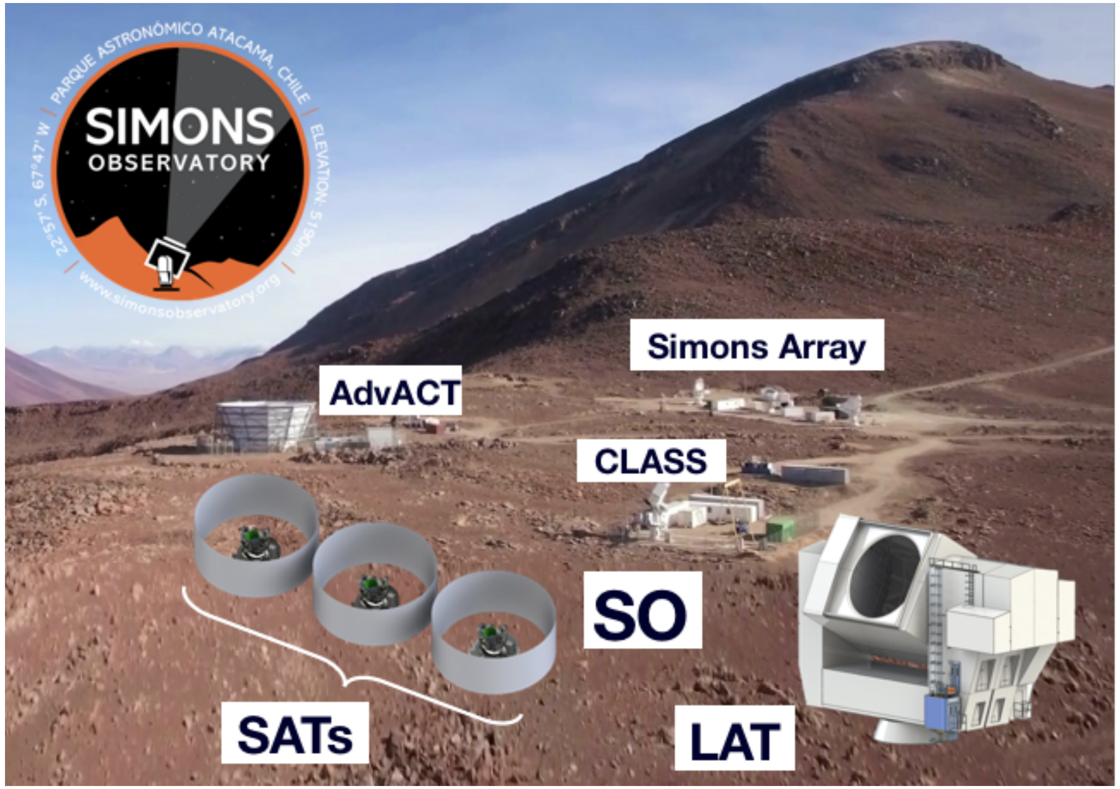
Daisuke

Satoru



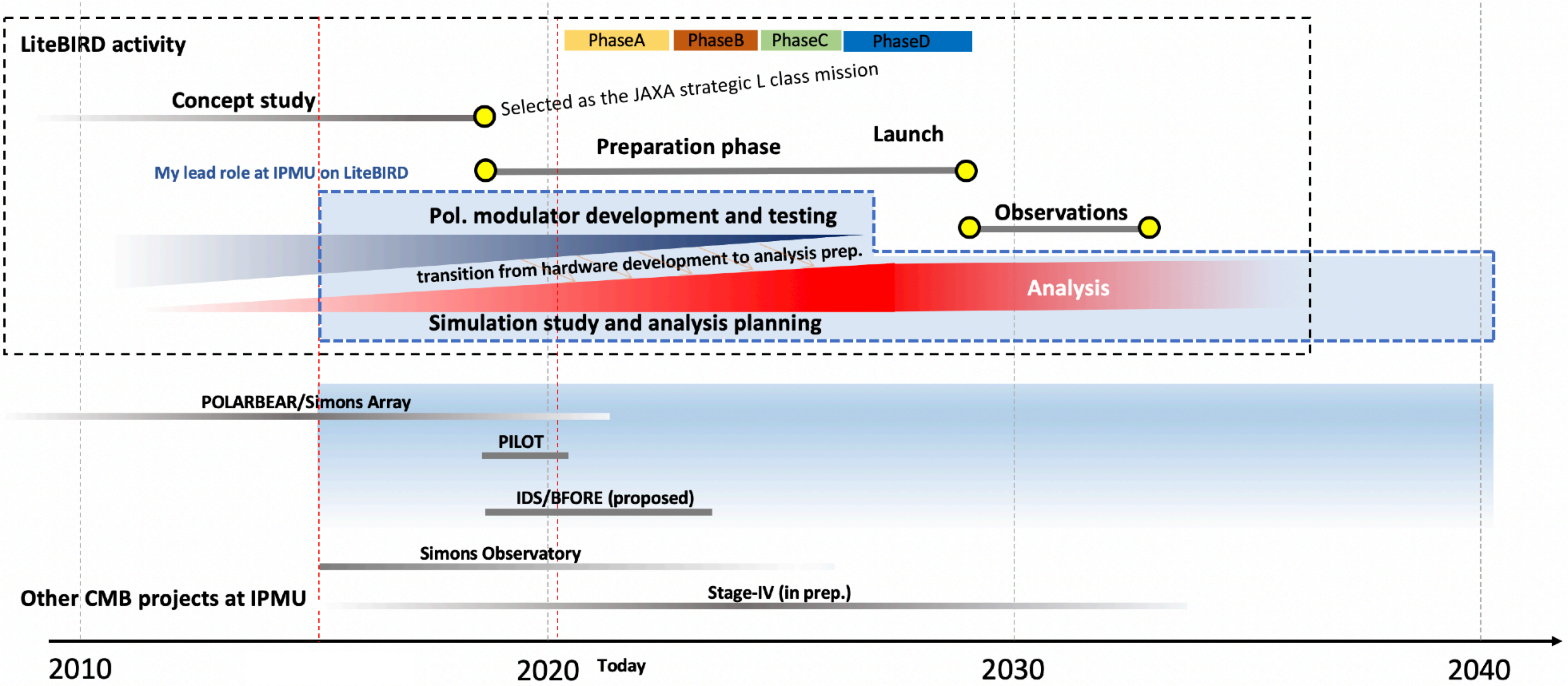
Masashi





Next 10+ years

CMB experiments in next 10+ years



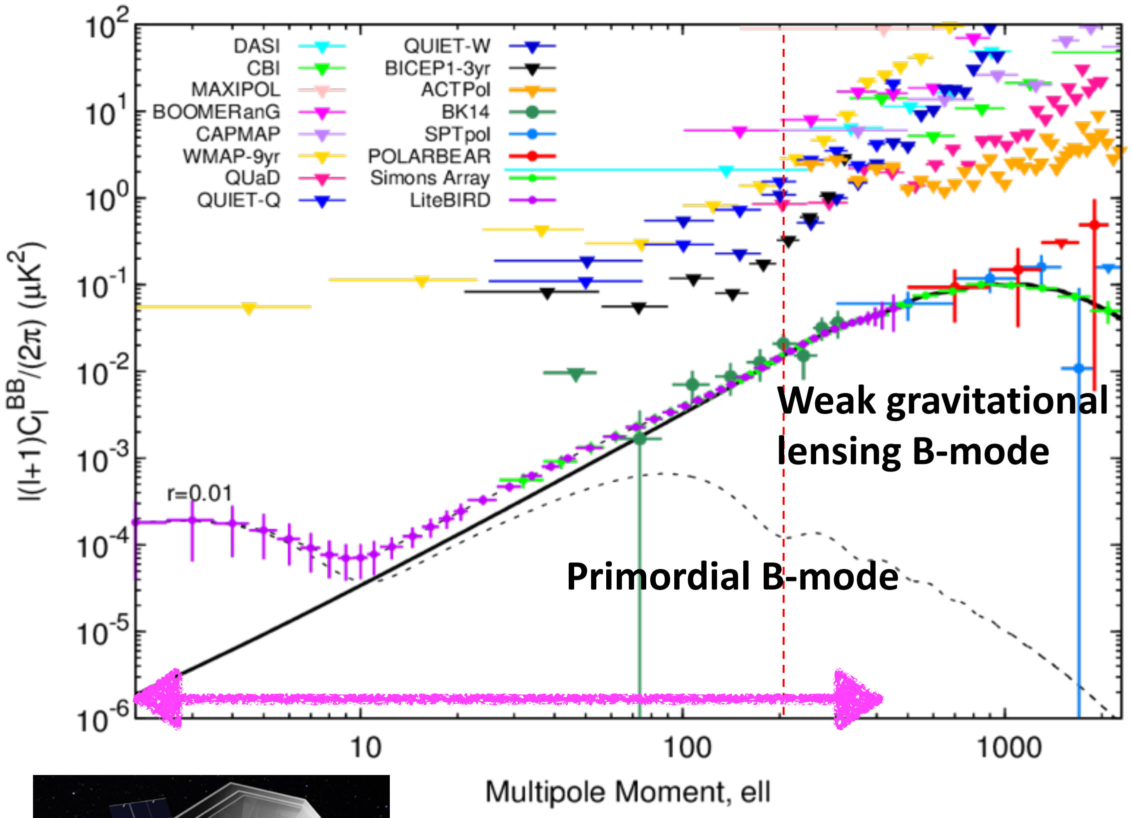
Beyond 10+ years

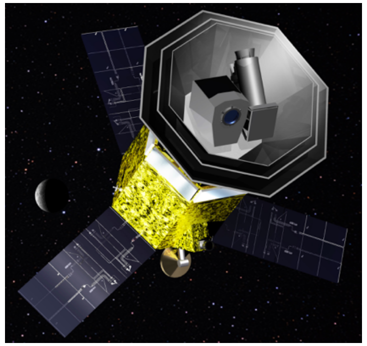
Beyond 10+ years

- The synergetic analysis with the LiteBIRD data and the data using the ground telescopes, e.g. Stage-IV.

- The combination of the low-ℓ data and the high-ℓ data can allow to remove the lensing B-mode contribution as the cosmic noise, so called delensing.

- This gives the opportunity to probe the sensitivity beyond $r < 10^{-3}$ w/ some factor. Also increasing the broader ℓ range increases the sensitivity to the non-Gaussianity.



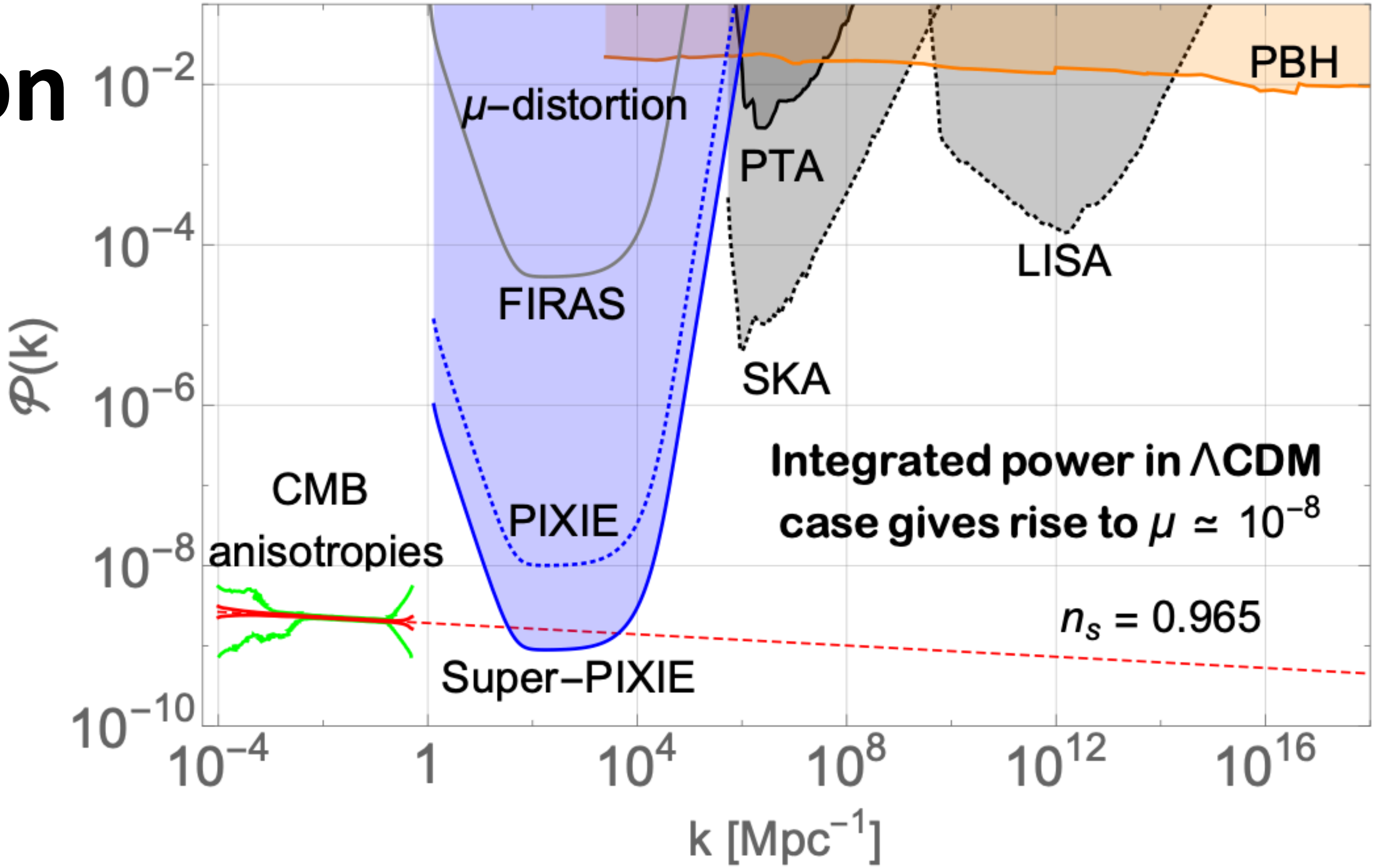


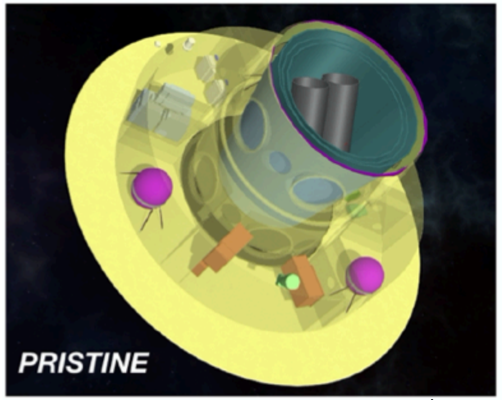
CMB Spectral distortion

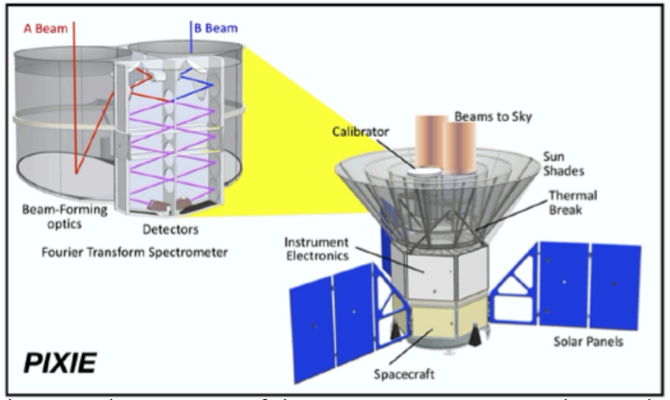
- The CMB spectrum measured by COBE was often called as the perfect black body.

- But with a close look into the thermal history of the universe, any energy injection well before the last scattering surface can distort the CMB black body spectrum. Within ΛCMD, the CMB spectrum is expected to be distorted $\mu = 1.6 \times 10^{-8}$.

- No experiment has been funded, but many researchers started to think about the path forward for its measurement from the ground and balloon (path-finder) and space.





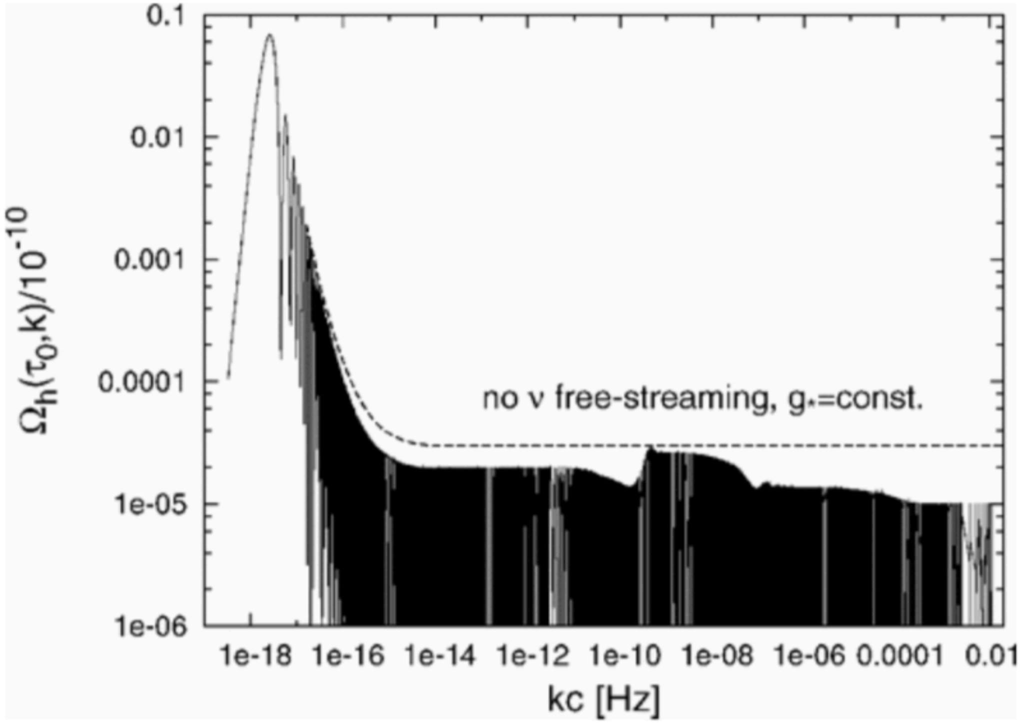


New Horizons in Cosmology with Spectral Distortions of the Cosmic Microwave Background
ESA Voyage 2050 Science White Paper

Primordial GW spectrum

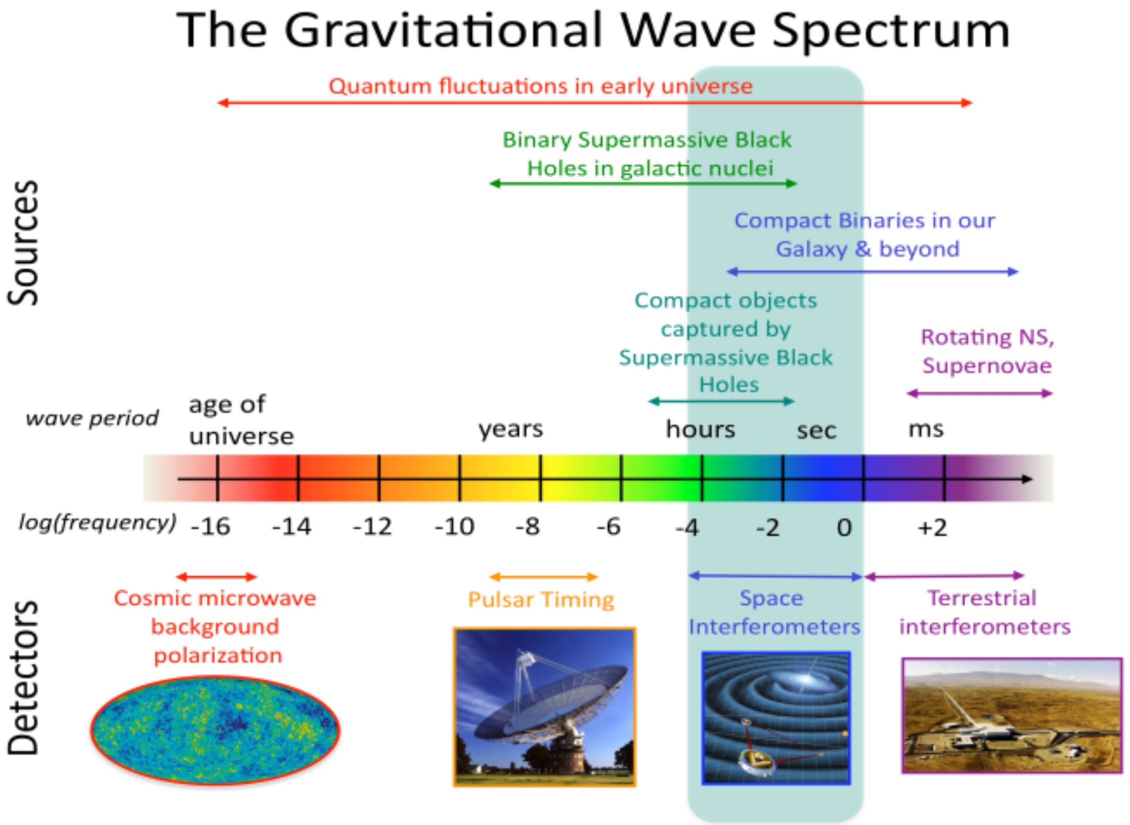
- The CMB B-mode measurement is to constrain the amplitude of the primordial gravitational wave (PGW).

- The PGW does has a spectral shape which is well predicted by the frame work of ΛCMD.



Yuki Watanabe and Eiichiro Komatsu
Phys. Rev. D 73, 123515, 2006

Figure from http://lambda.gsfc.nasa.gov/



- Any experimental constraint with the 2-3 data points is already a great step forward.

- Yet, the feasibility is highly depending on the amplitude of the spectrum, which comes from the CMB B-mode search.

Summary

- CMB lab has started in 2017.
- A big efforts are taken to test the theory of inflation through the CMB B-mode search.
- Among many experimental efforts from the ground and the balloon, a long waited CMB B-mode satellite proposal is now selected and that is LiteBIRD. Kavli IPMU is taking a lead on this effort through design, development, simulation, and we will host as the data center for LiteBIRD.
- Also, the ground base effort is in progress with POLARBEAR, POLARBEAR2/ Simons Array, and Simons Observatory.
- You know where the lab is now, and so visit us!