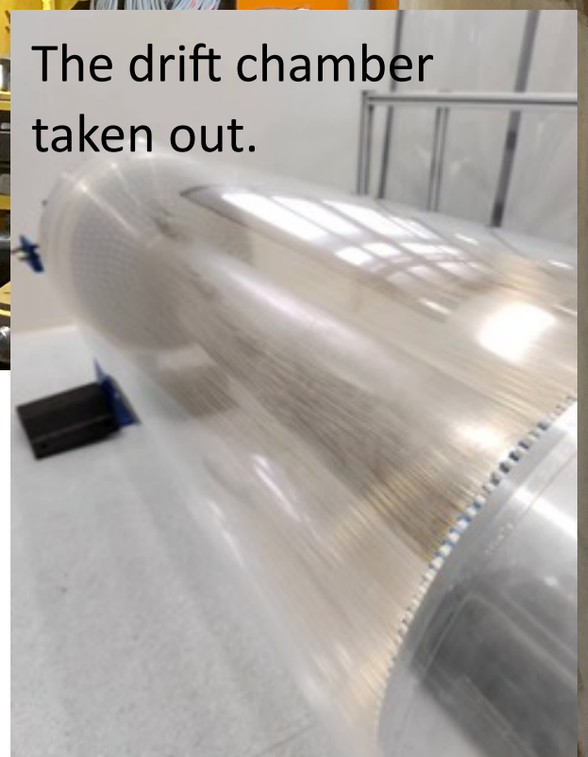



# Welcome to Korea University

- I was in IHEP on last Month
- I saw your BESIII detector !

2024. 9. 19

# Early Universe and Cosmic Microwave Background - status of GroundBIRD telescope

Background Imaging
Radiation Detector

Korea University - IHEP Workshop
October 14, 2024

Eunil Won (元, 殷溢), Department of Physics
Korea University

# Contents

- Standard Cosmology and its problems.
  - **Inflation scenario.**
- Present status of the GroundBIRD (GB) telescope.

# Cosmology

- Origin

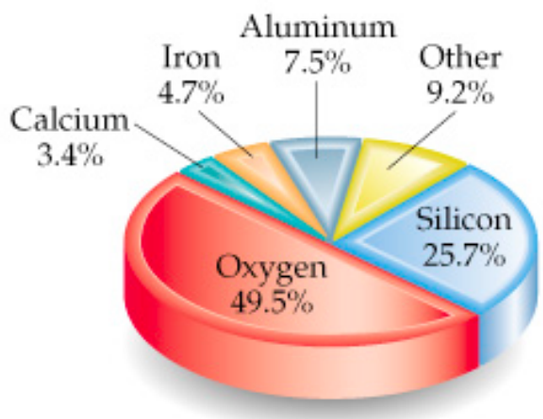
  - How was our universe born?
  - What was physics of universe at that time?

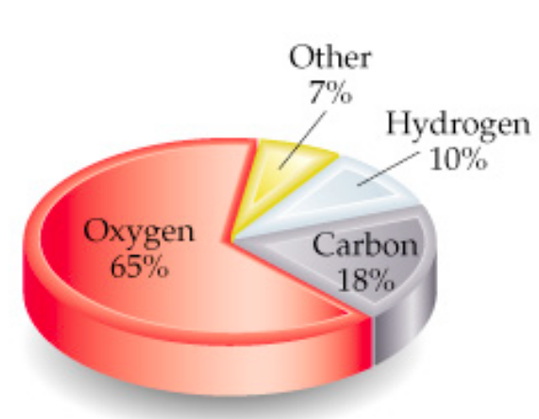

- History

  - How did our universe evolve?
  - What will happen to our universe?

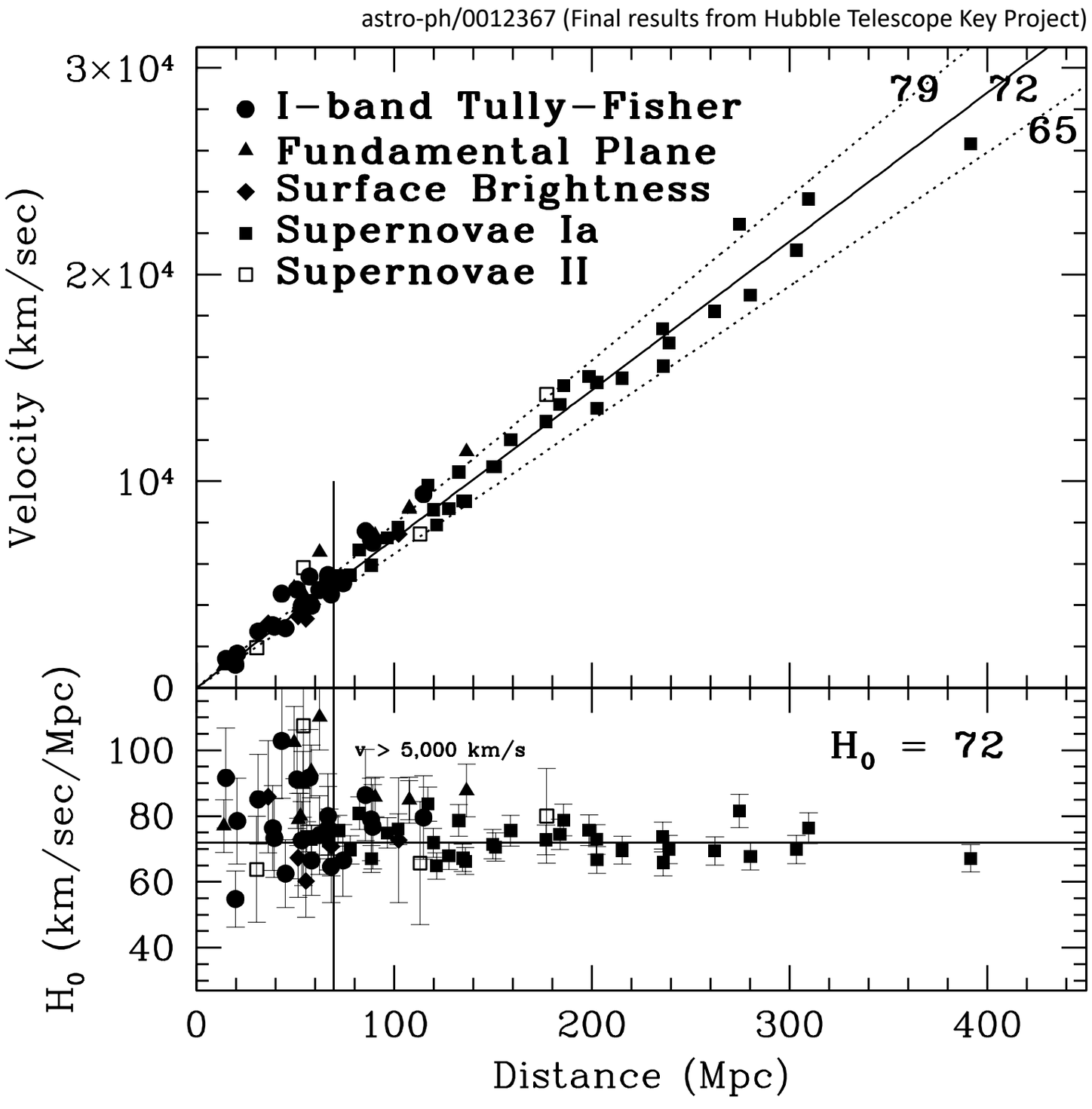
- Composition

  - What is our universe made of?
  - And why?



# Expanding Universe: observation

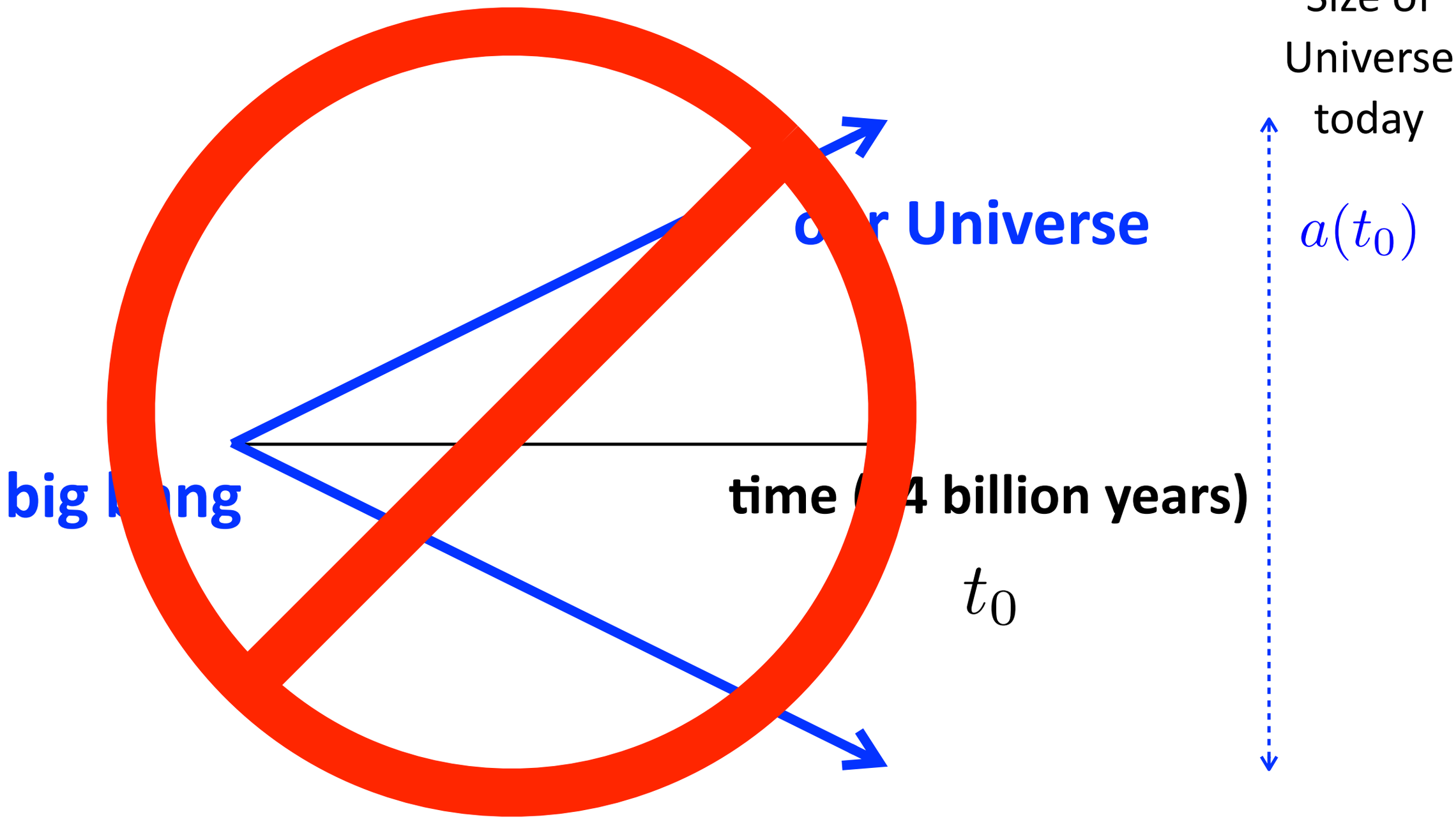



The Hubble diagram is still the most direct evidence that the universe is expanding.

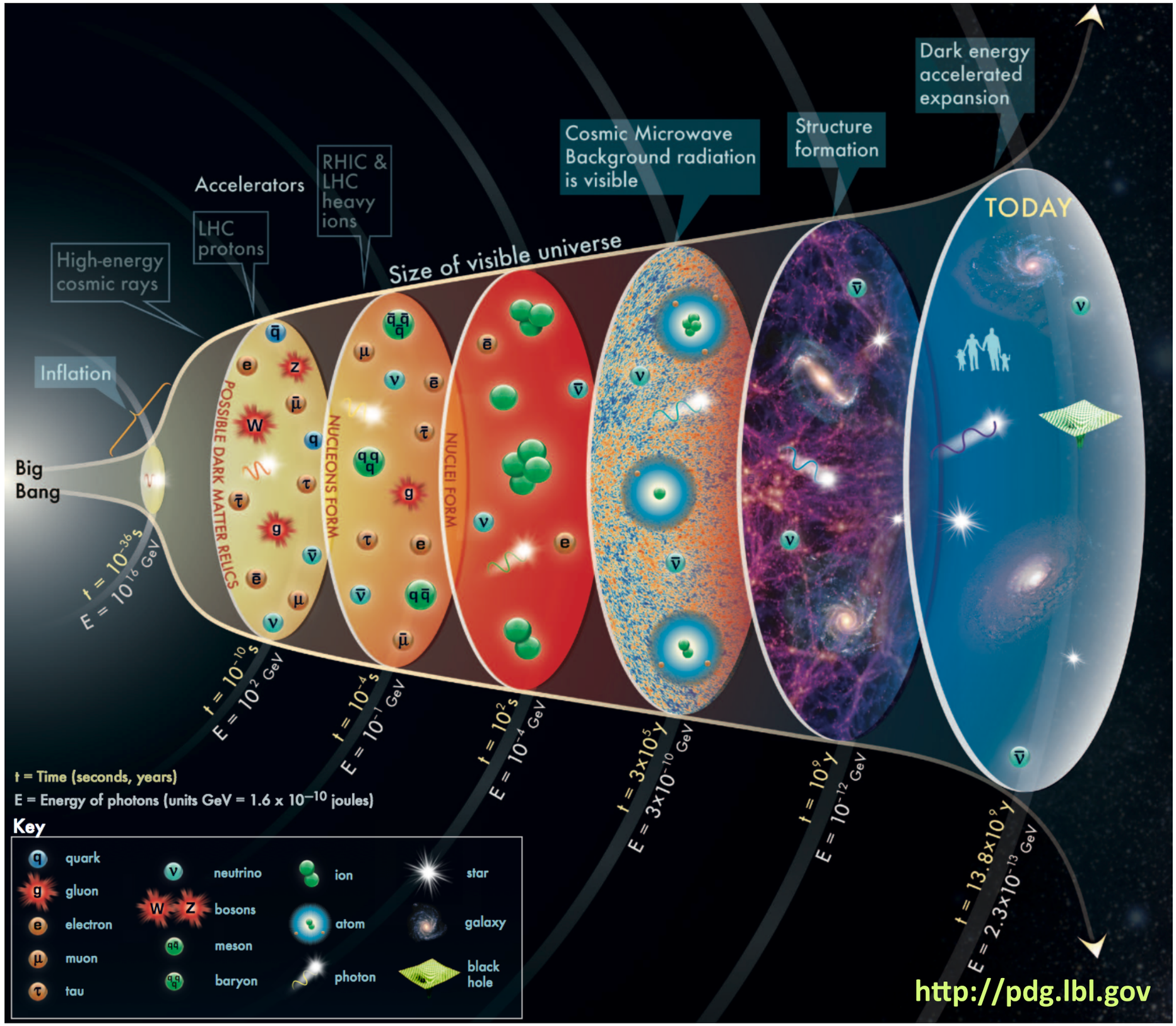
This means the universe was much hotter and denser earlier, assumed to be started from the Big Bang.

$$v = H_0 r$$

# Standard Cosmology



# A “new” proposal: rapid expansion of Universe



# Scenario at very early Universe

- **Suggested in 1980's**

$$\Delta t \sim 10^{-36}\ \mathrm{s}$$

$$\frac{a(t_\mathrm{i}+\Delta t)}{a(t_\mathrm{i})} \sim 10^{28}$$

Beginning time of inflation

- **Rapid expansion of universe = inflation**

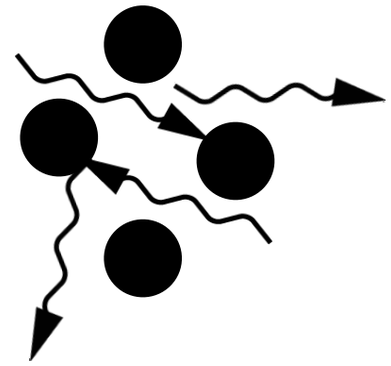
- Authors: Alan Guth (MIT), Andrei Linde (Stanford), Andreas Albrecht, (UC Davis), Paul Steinhardt (Princeton)


A. Guth, Phy. Rev. D 23, 347 (1981)
A. D. Linde, Phys. Lett. 108B, 389 (1982)
B. A. Albrecht and P. J. Steinhardt, Phys. Rev. Lett. 48 1220 (1982)

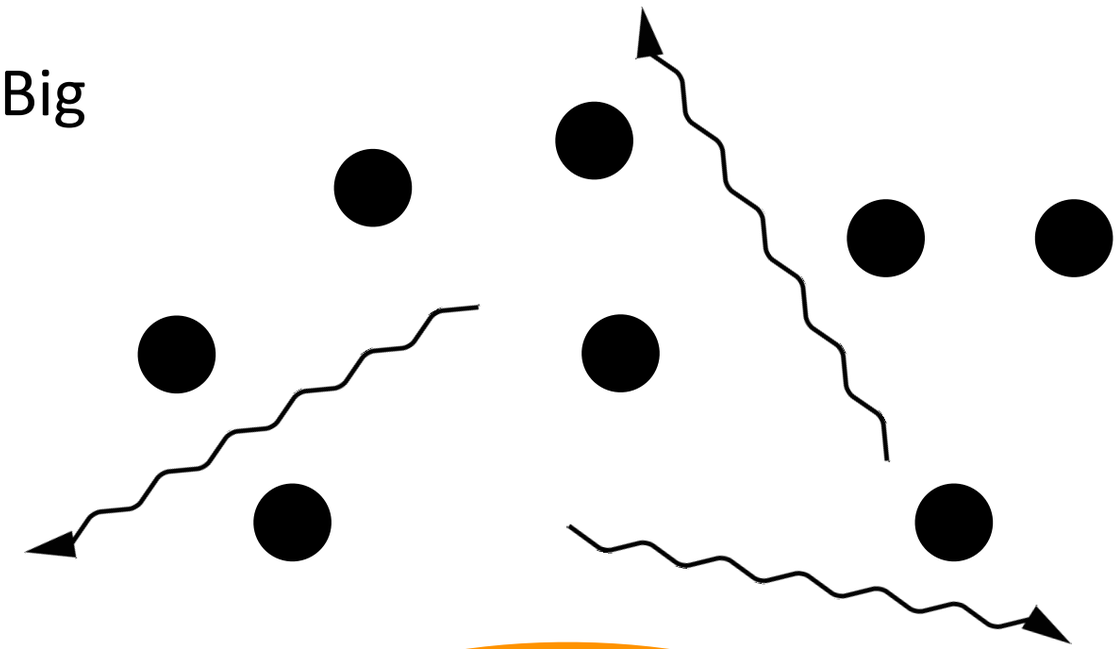
# Why do we need inflation?

# Cosmic Microwave Background

- Universe was initially in a hot dense state and it cools as it expands (initially opaque with photons)

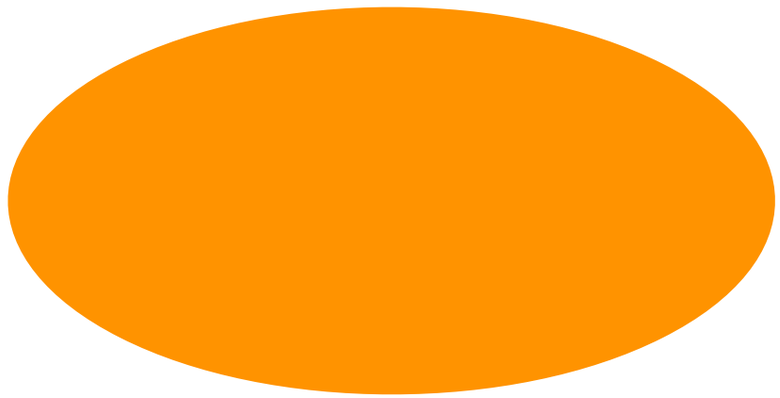


- Photons decouple ~ 400,000 years after the Big Bang (last scattering surface: LSS)



- Photon background is visible as the Cosmic Microwave Background (CMB)

- Temperature of this CMB is isotropic to few parts in $10^{-5}$ (it is a black body radiation)

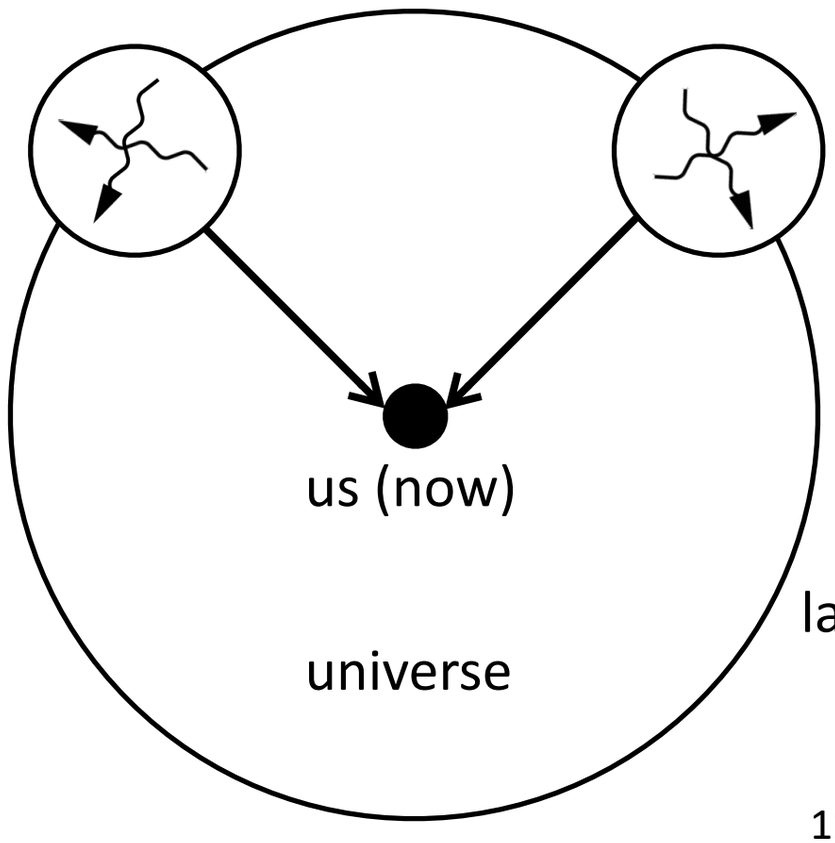


# Horizon Problem

- Observed CMB temperature is isotropic down to $10^{-5}$ level

  - Photons are not causally connected, so impossible to have same temperature (horizon problem)

(not to scale)




You can avoid this problem if

The speed of light was faster by O(100) times or

you take it as “initial condition” (you need to explain why)

# Flatness Problem

$$\rho_c \equiv \frac{H^2}{\frac{8\pi G}{3}}, \quad \Omega \equiv \frac{\rho}{\rho_c}$$

$$\rho_{c,0} \sim 6 \text{ protons/m}^3$$

$$\left(\frac{\Omega - 1}{\Omega}\right)_{t=1\text{ s}} = \left(\frac{1\text{ s}}{t_{eq}}\right)\left(\frac{t_{eq}}{t_0}\right)^{2/3}\left(\frac{\Omega - 1}{\Omega}\right)_{t=t_0}$$

$t_{eq} \simeq 50,000$ years

**: time when radiation = matter in early universe**

$t_0 \simeq 13.7 \times 10^9$ years

**: the age of the universe**

Planck Satellite measurement: Ω - 1 < 0.005

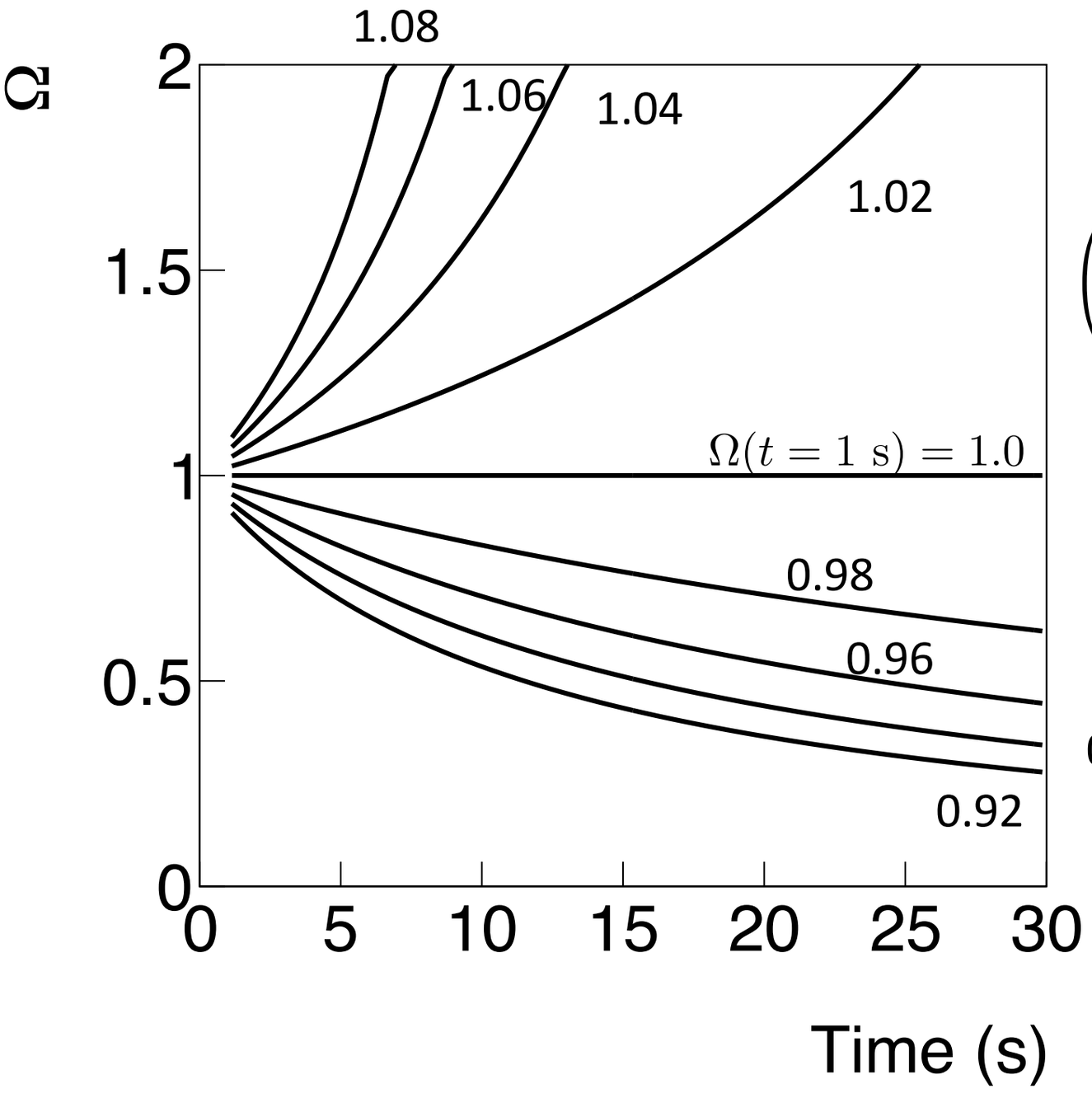
(arXiv:1502.01589, Eq. 50)

Note: Ω = 1 is unstable equilibrium.

$$\left(\frac{\Omega - 1}{\Omega}\right)_{t=1\text{ s}} \simeq 10^{-18}$$ !

# Flatness problem? It's about instability

Evolution of Ω from 1 s after Big Bang




Planck Satellite measurement: $\Omega_0 - 1 < 0.005$

(arXiv:1502.01589, Eq. 50)

$$\left(\frac{\Omega - 1}{\Omega}\right) \propto t$$

: for early radiation-dominated universe

The Ω becomes unstable very quickly:
has to be fine-tuned by $10^{-18}$ level !

: unstable equilibrium

(Zamora, Spain)

# Inflation solves,

- **Horizon Problem**

  - The entire observed universe evolves from a single coherence region.

- **Flatness Problem**

  - During inflation, the term $1/a^2$ is suppressed by ~ $10^{-56}$ naturally leading Ω=1.

$$H^2(1-\Omega) \propto \frac{1}{a^2}$$

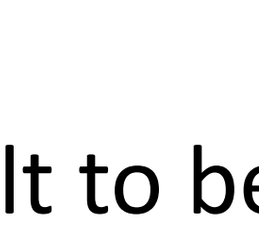
*H = (da/dt)/a*
Ω: density parameter

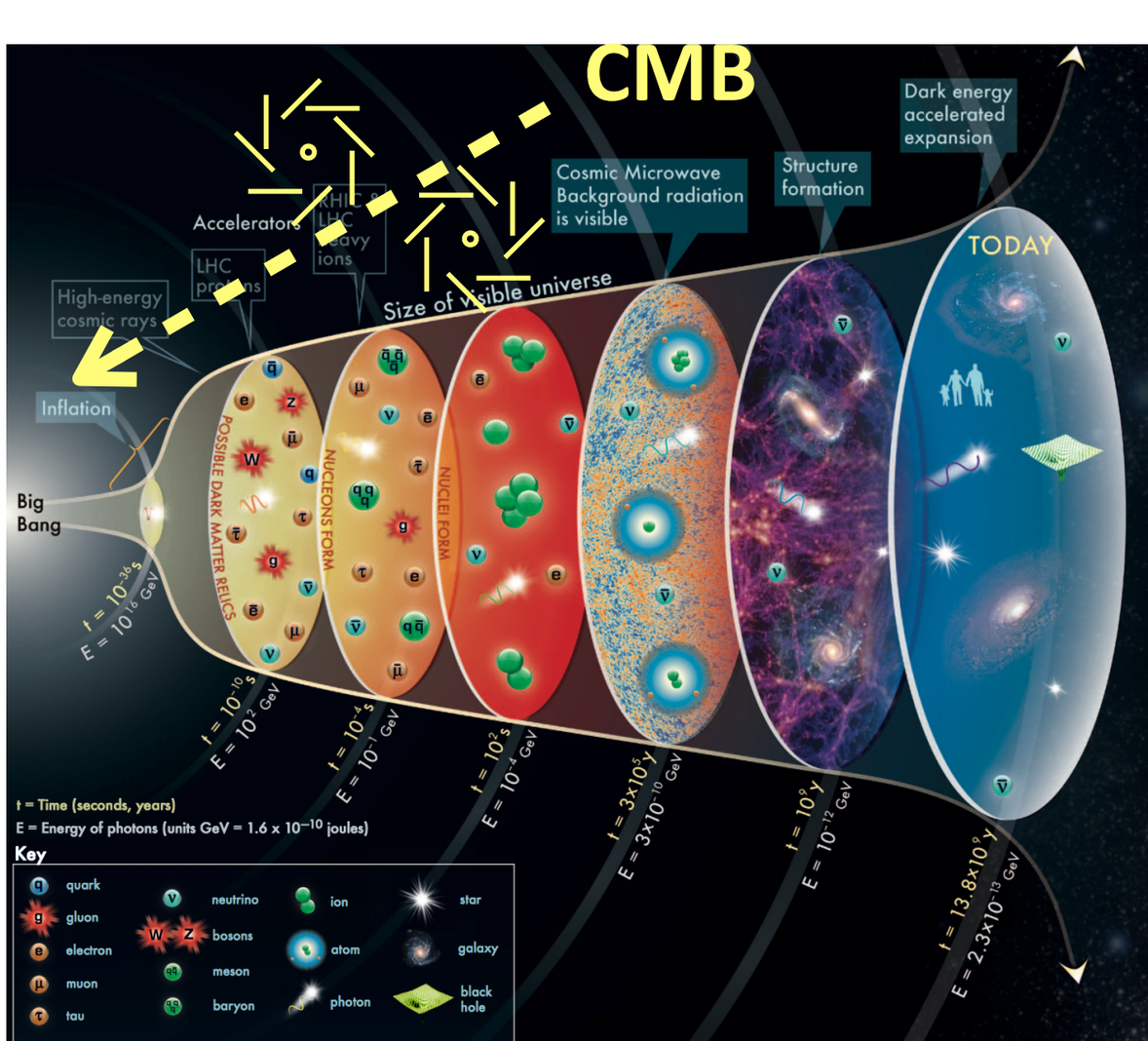
# Inflation ?

To be honest, it is difficult to believe inflation.

Inflation predicts polarizations in CMB:

- E-mode : due to density perturbation (observed)
- B-mode : due to primordial gravitational wave (**not yet observed**, tensor perturbation)





# Strength of B-mode?

- Not predicted by theory
- Has to do with energy scale of inflation

r ≡ strength of tensor / scalar

$$r = 0.008 \left( \frac{E_{\text{inflation}}}{10^{16}\ \text{GeV}} \right)^4$$

r = 0.01 indicates inflation occurred at GUT scale

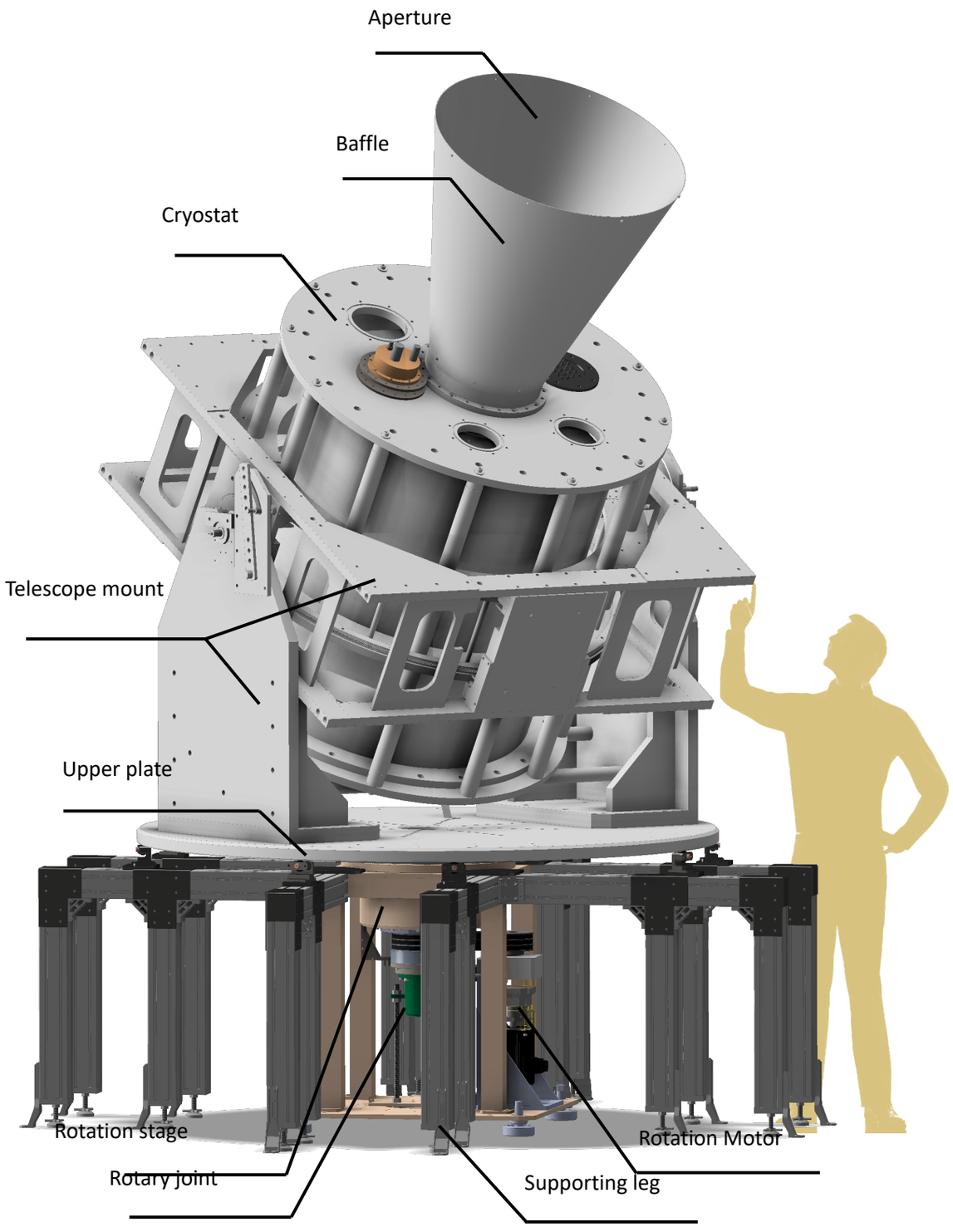
# GroundBIRD Project

GroundBIRD Collaboration (Japan, Korea, Netherlands, Spain)

- Korea
- Japan
- Spain
- Netherlands

Netherlands Institute for Space Research

# GroundBIRD Telescope



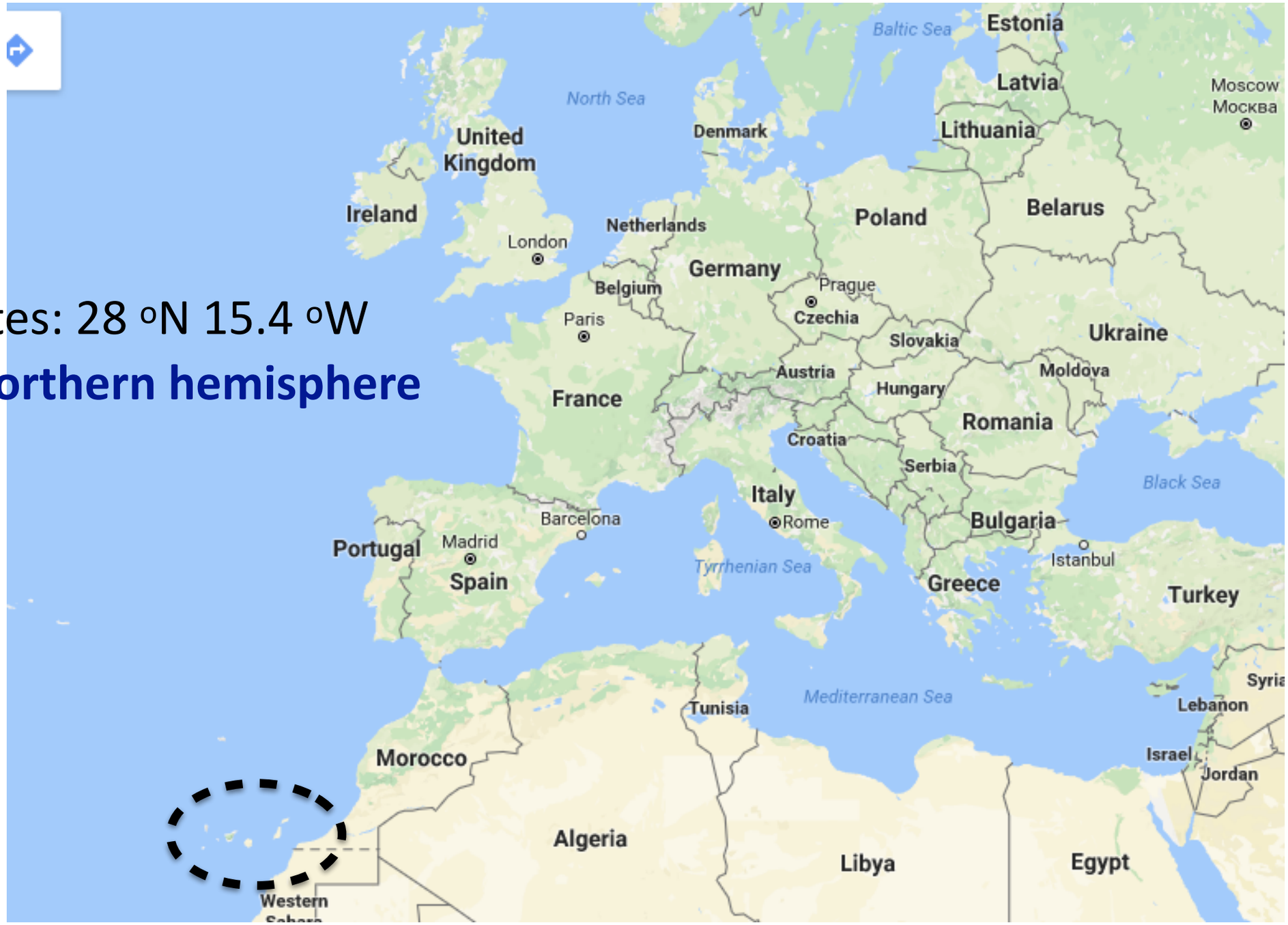

GroundBIRD (GB) is a “small” telescope constructed in KEK (Japan)

- Observation site: Tenerife Island (Spain)
- Microwave sensor: KID
- Rotating stage with 20 rpm
- IQ mix read out
- **First science: cosmological parameters**
- Ultimate goal: B-mode detection

# Canary Islands

Coordinates: 28 ºN 15.4 ºW

- In the **Northern hemisphere**




Canary Islands: Spanish Islands near to Africa

# Canary Islands





The headquarter of IAC (Instituto de Astrofisica de Canarias) is located in Tenerife island.

# The air from Europe: dried by the islands

# Observatory del Teide

A flat layer of cloud is at around 1000 m level

# Teide Mountain

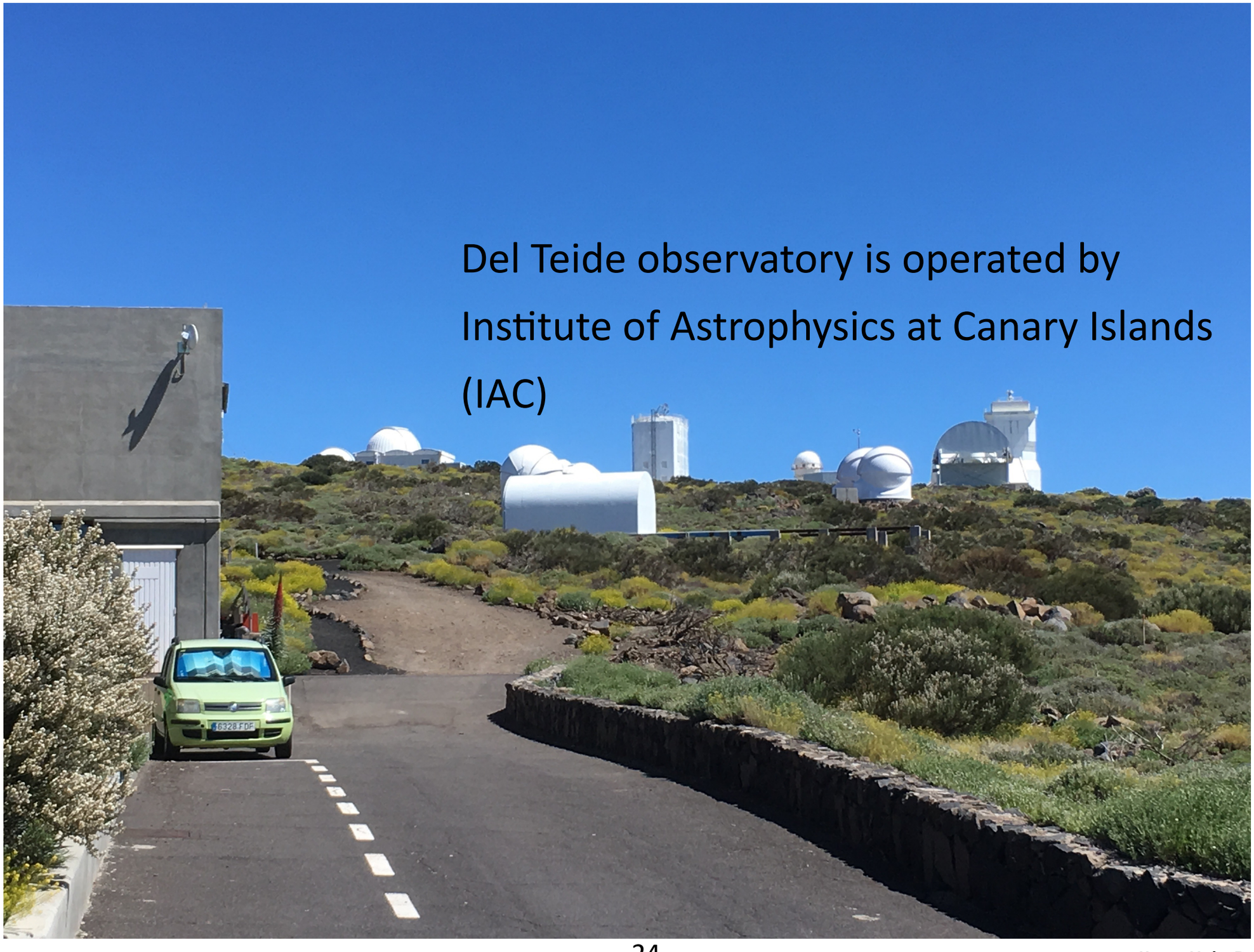
A flat layer of cloud is at around 1000 m level



2024. 8. 27

# Observatory : del Teide

Many telescopes are already here (including QUIJOTE exp.)



# History of the development

- 2015 - development of telescope
- 2017 May - Site visit
- 2018 Oct. - Dorm installation
- 2019 Sep. - Telescope installation
- 2019 Oct. - First light, moon observation
- 2020 - telescope commissioning (limited)

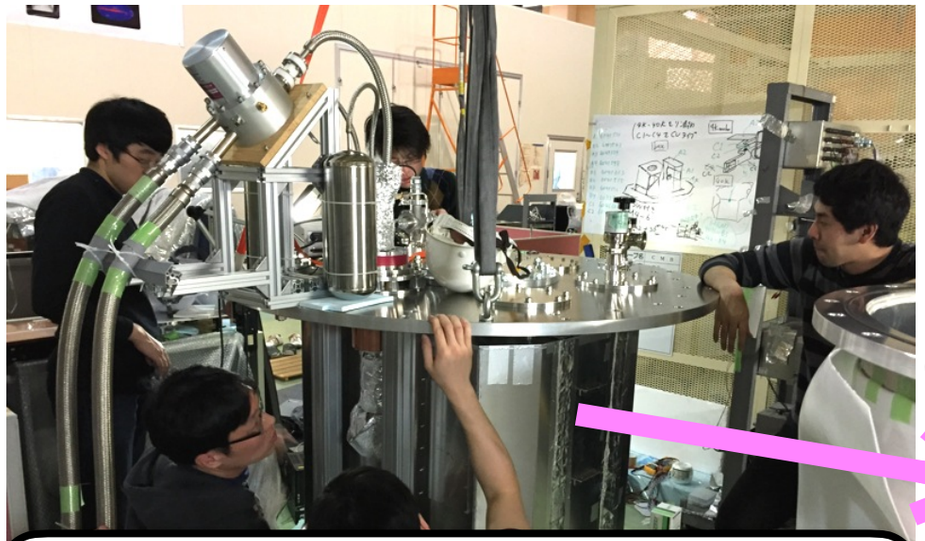
Covid-19 pandemic started here!

- 2021 Jun. - **IR camera installation**
- 2021 Jul. - Installation of new sensors (partial)
- 2021 Jul. - **A forecast paper published**! (ApJ **915**, 88, 2021)
- 2021. Oct. - **Debugging of IR camera**
- 2023. Oct. - **beginning of full observation.**

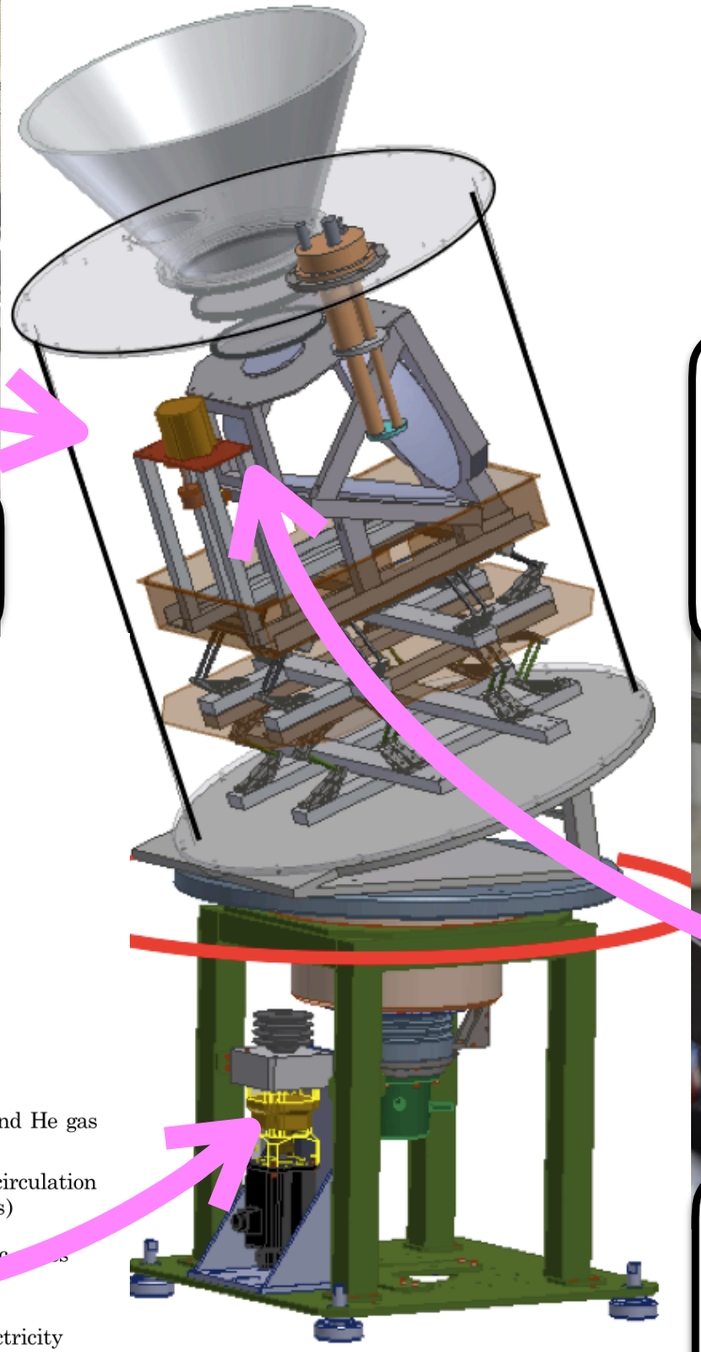
# The GroundBIRD Telescope Instrument

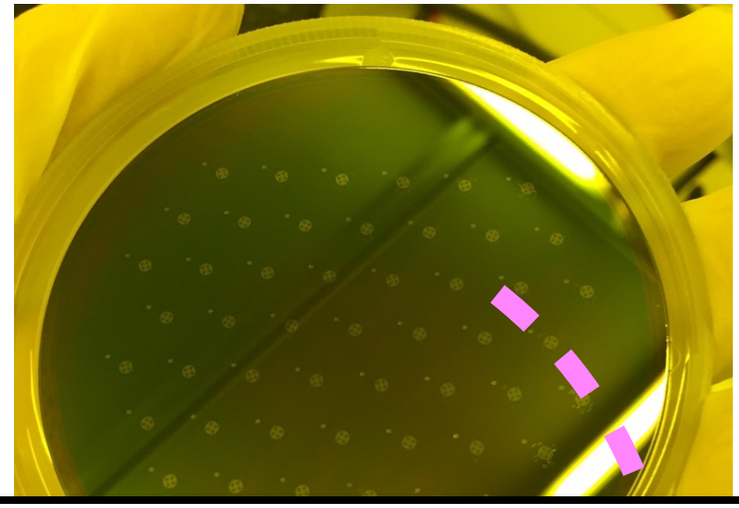
Details in Low Temp. phys. 176 691 (2014)

Communication: PLC

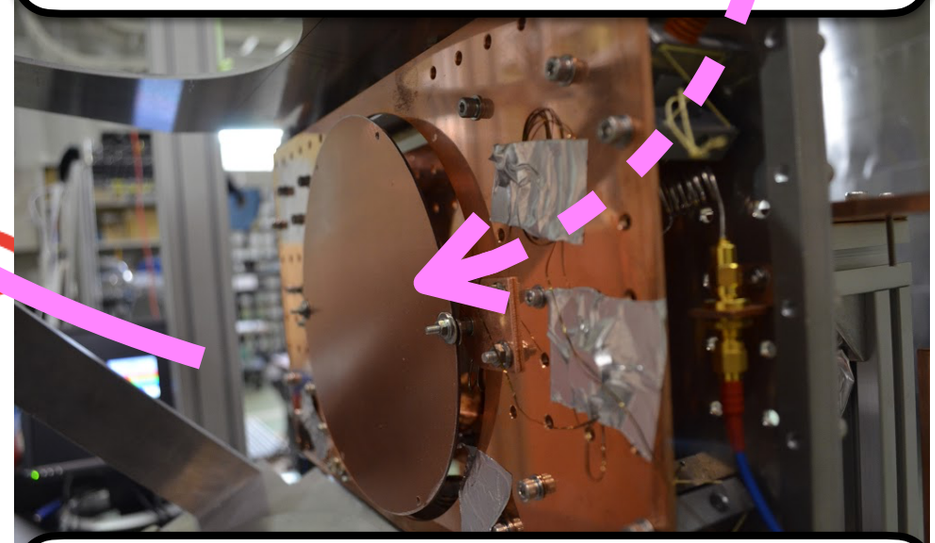


Cooled by PTC + He-4/3

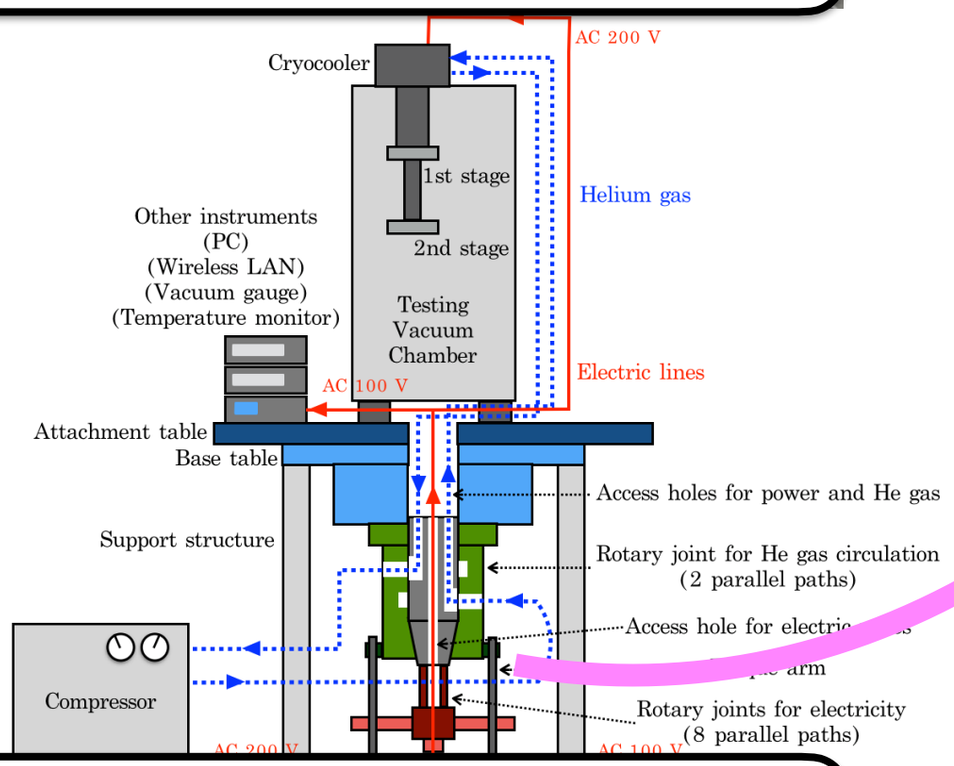




MKID array: @ 250 mK
138 ch for 145 GHz,
23 ch for 220 GHz.



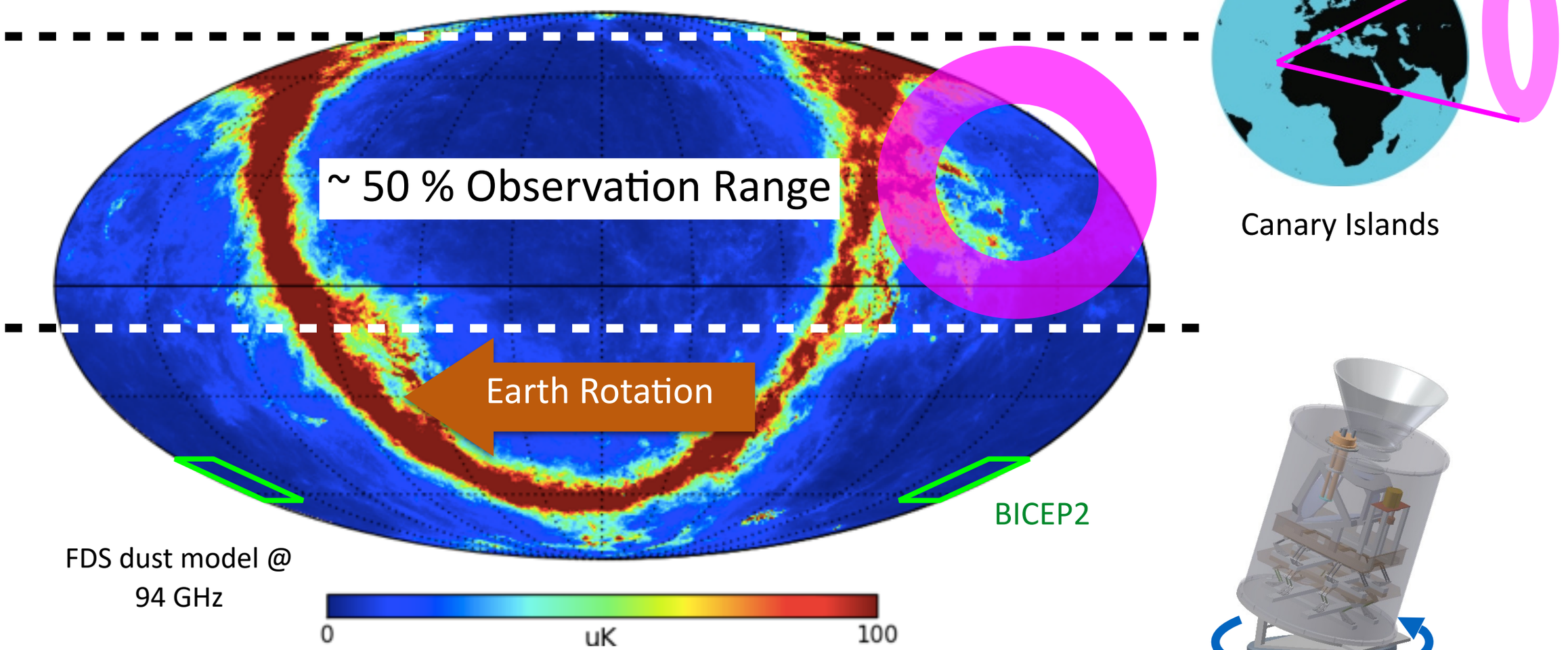
Cold optics: @ 4 K dual reflector, 20° FoV. angular resolution of 0.6° @ 145 GHz




High speed rotation: 120°/s

# Continuous Rotation of the GB Telescope

1. Mitigation of 1/f noise
2. A large sky coverage (> 10 x current ground based)



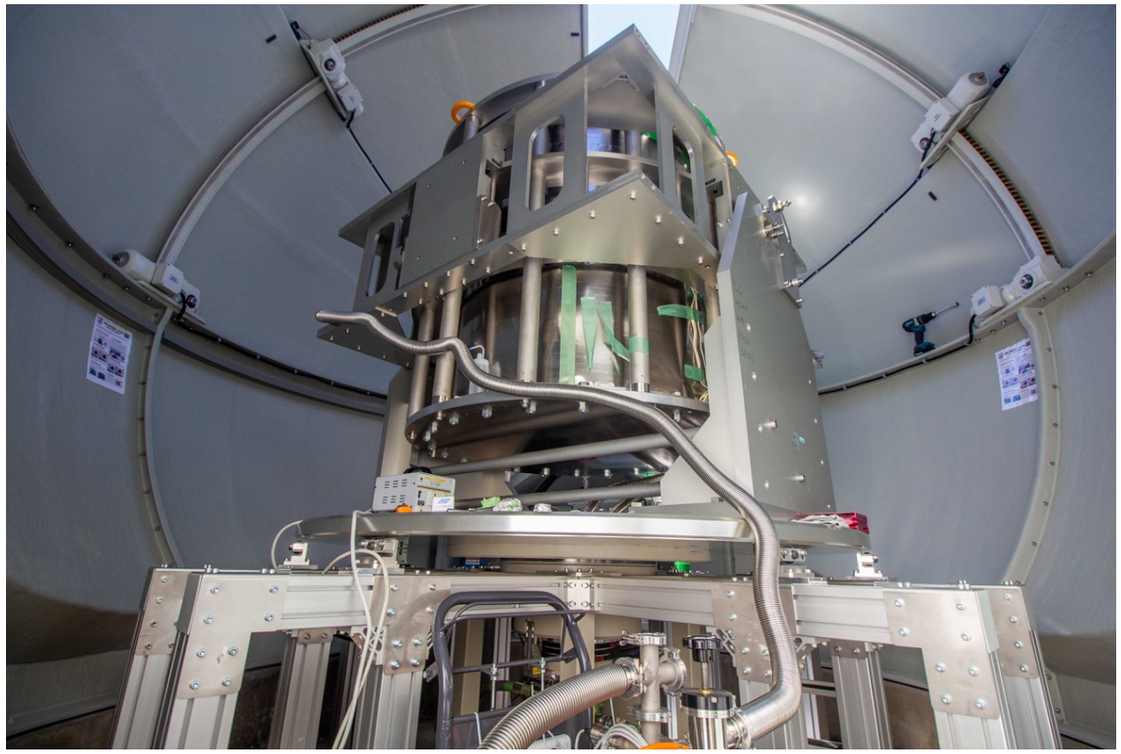


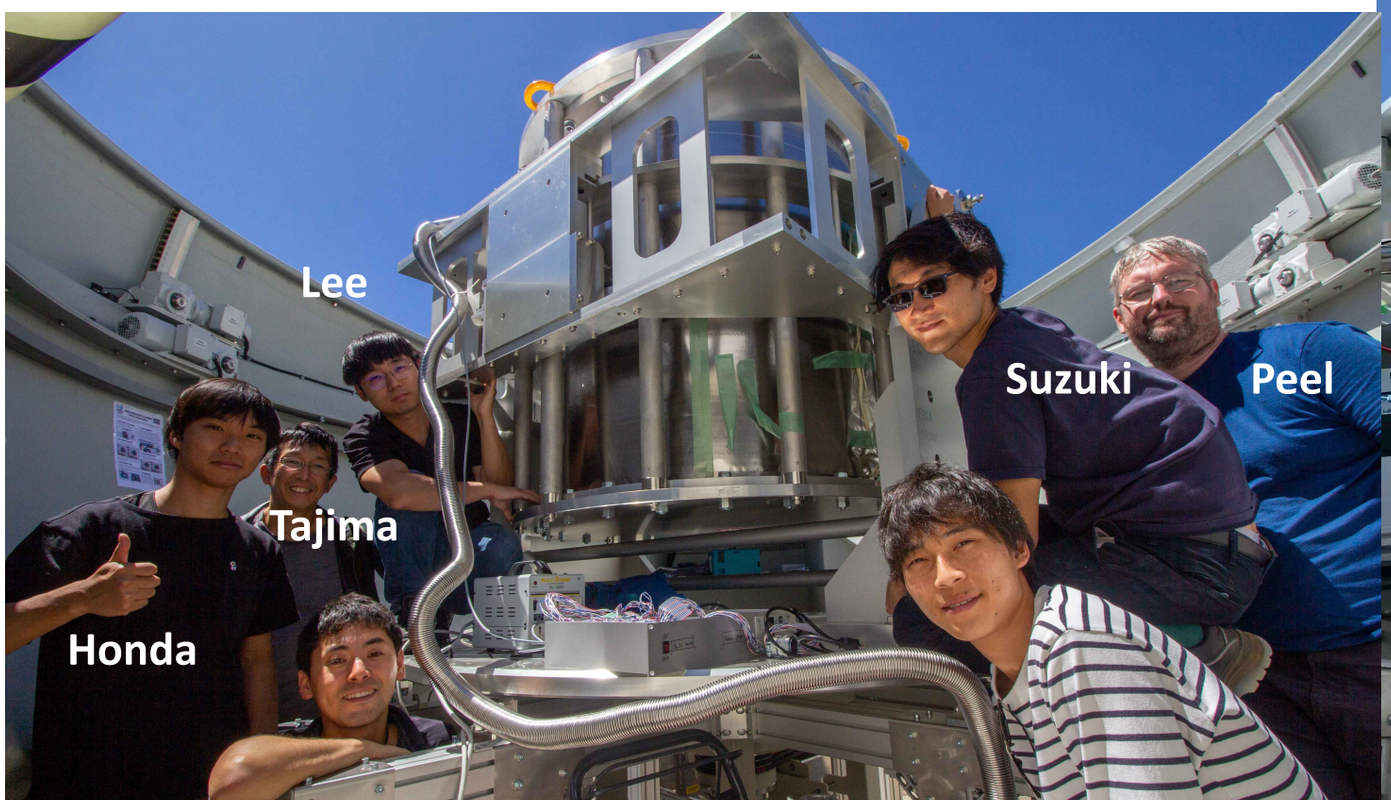

GB CMB observation at 145/220 GHz

# The GB assembly in action (KEK)

# Dorm Installation (2018) - 3 days


# GB Installation (2019)

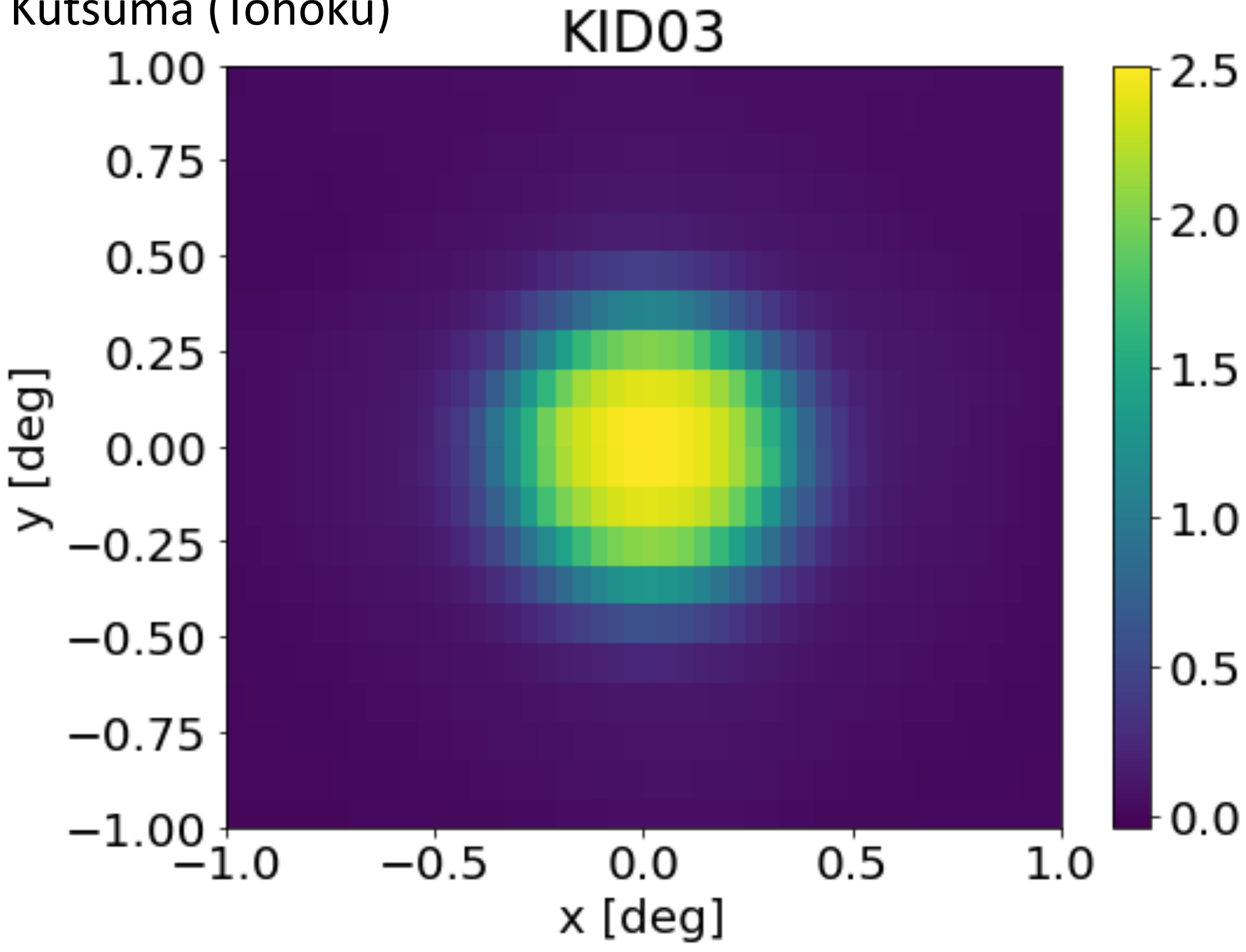




**2019. 9. 20, 1 am GMT : Ready for observation!**

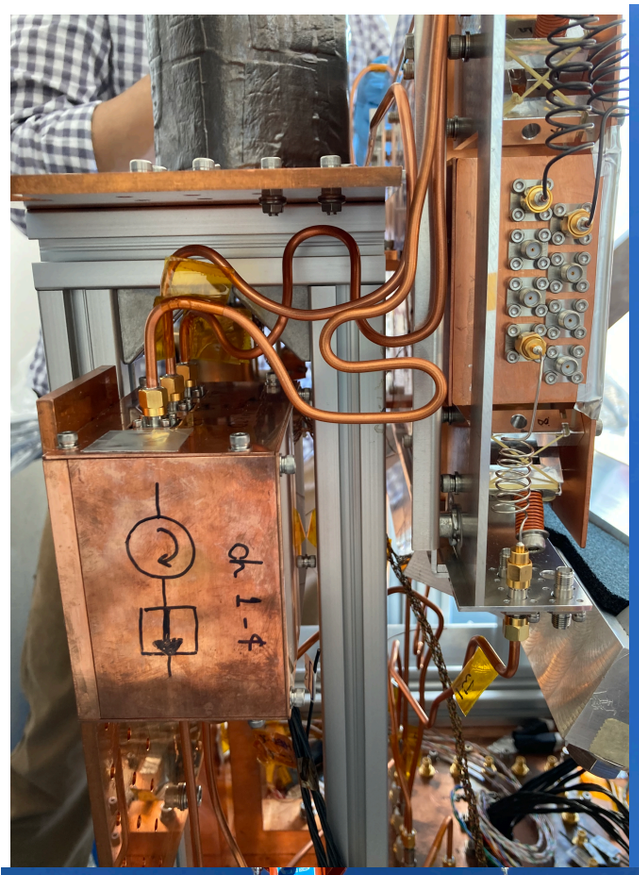
# The First Light : Moon Observation

Hiroki Kutsuma (Tohoku)



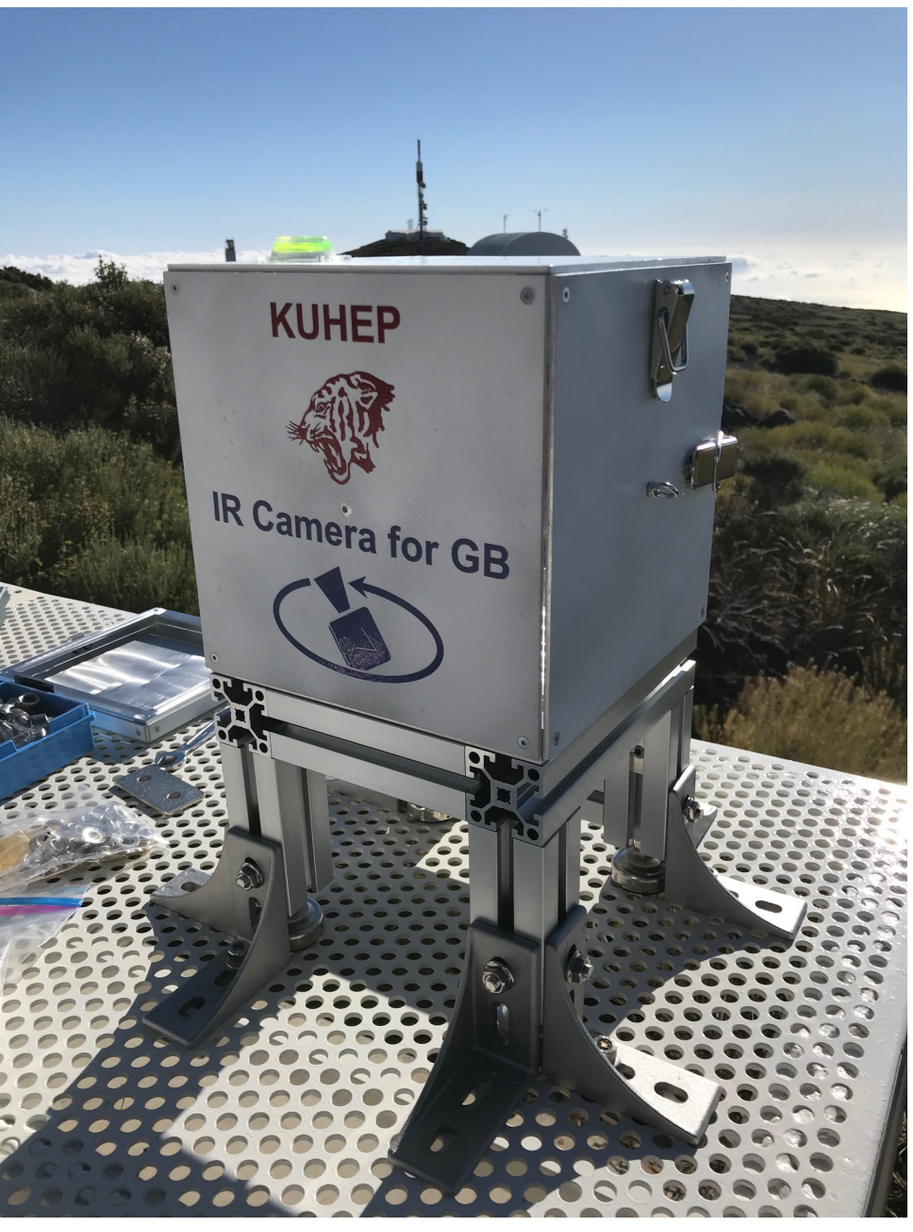
# COVID-19 - beginning of 2020

# New sens mer 2021)



9 am - 6 pm
No lunch...
(due to limited people/time)

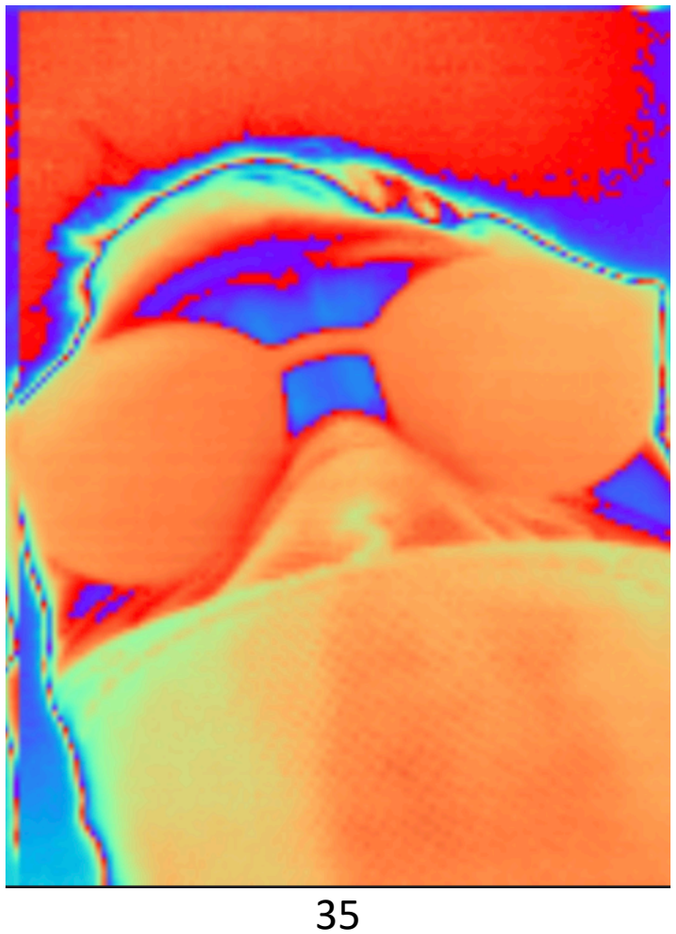
# IR camera Installation (summer 2021)

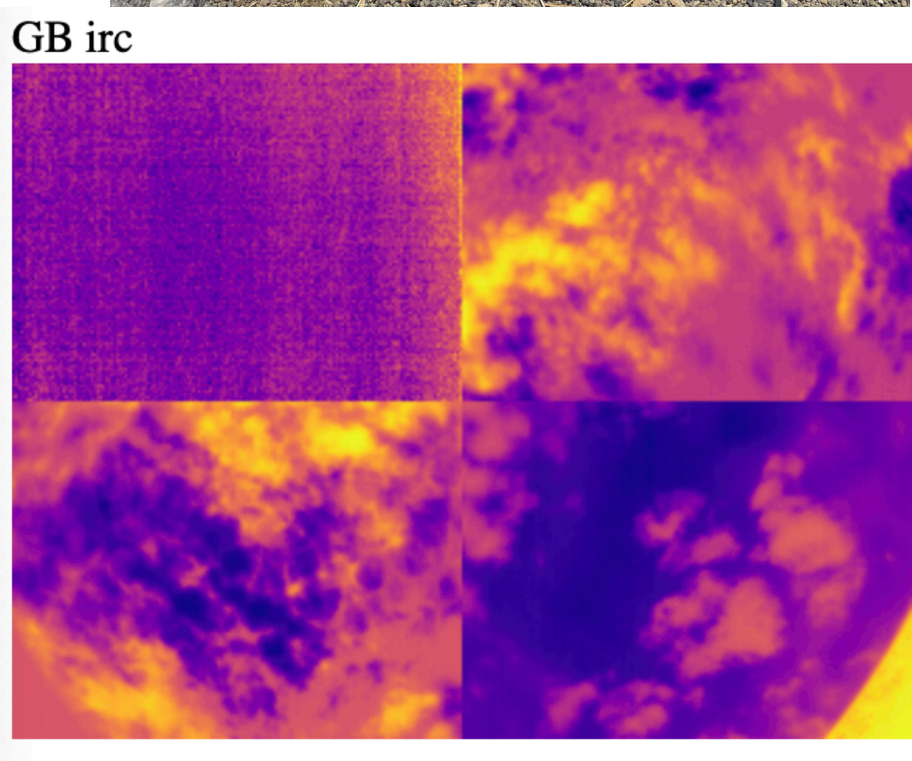



- Cloud monitoring
- KU contribution
- PoE enabled SBC (running linux) has 4 IR cams.
- Very comfortable debugging in this field office!

My face w/ IR cam.

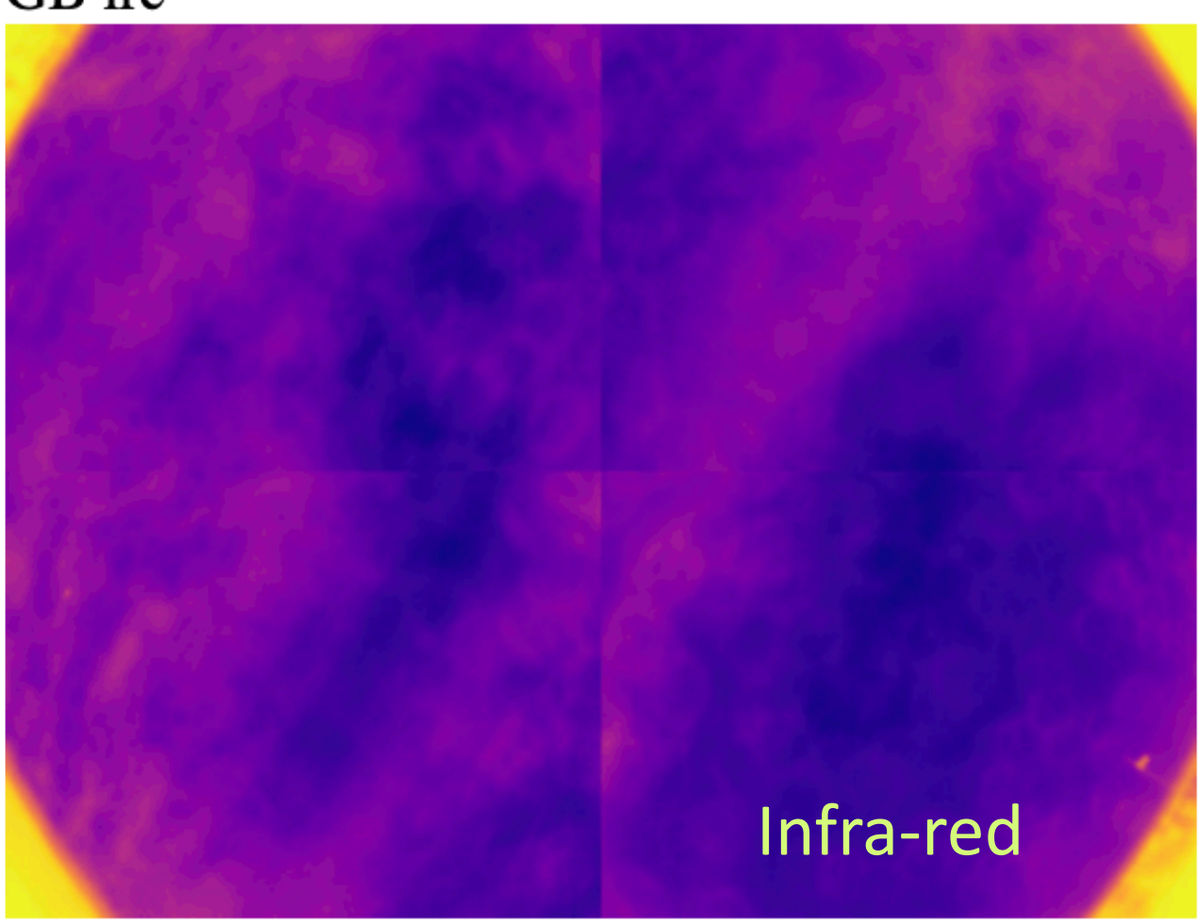
Can you see the mask I am wearing?

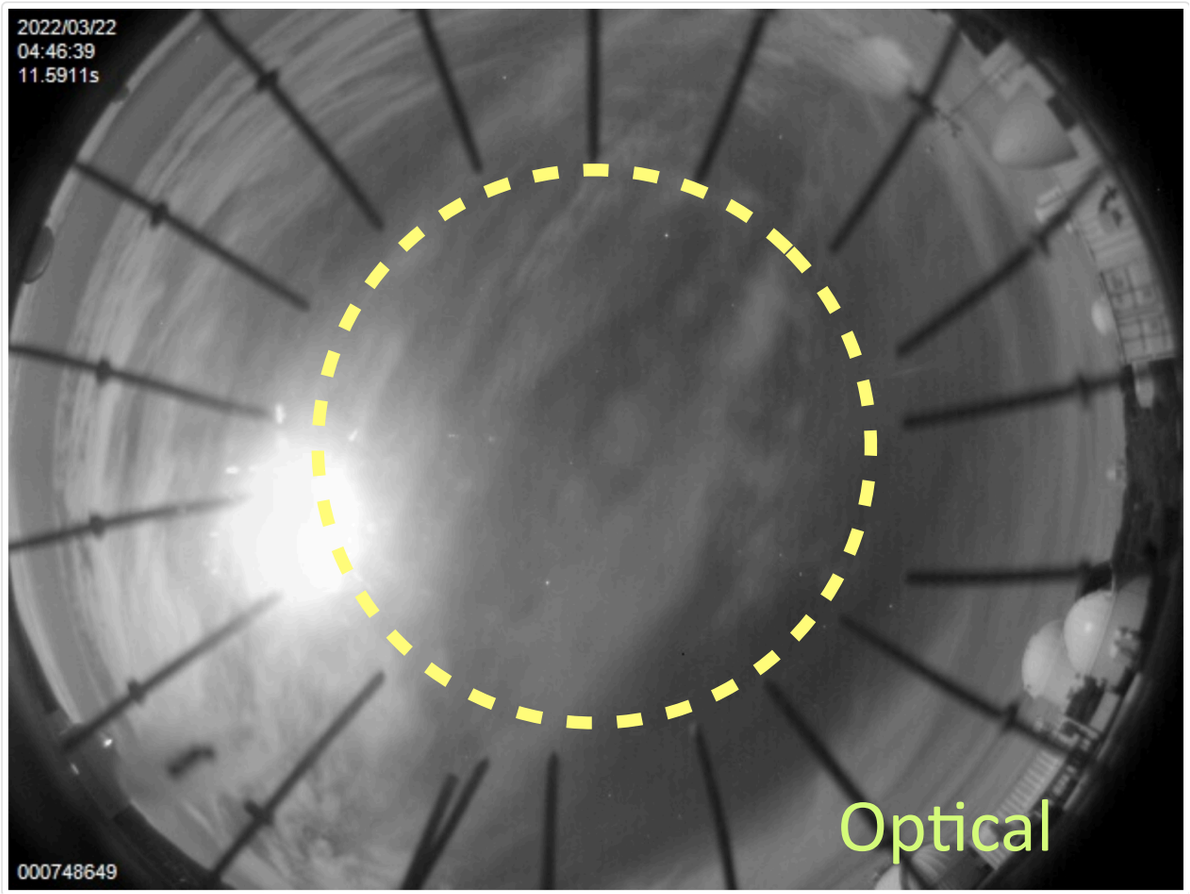




# IR camera debug (Feb. 2022)

- There was electric contact problem between shutter and the camera module.
- This was temporarily fixed in Feb. 2022.



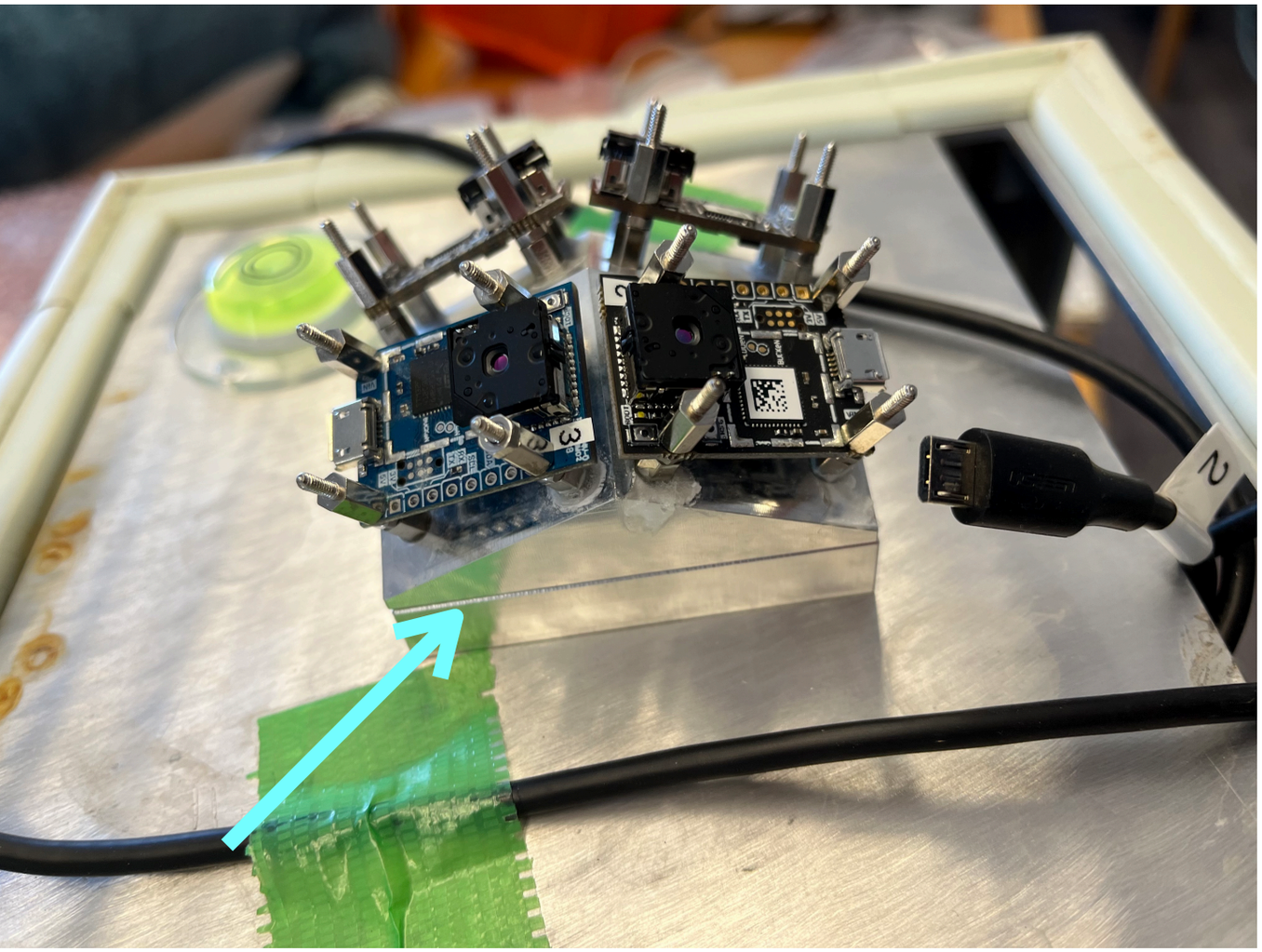



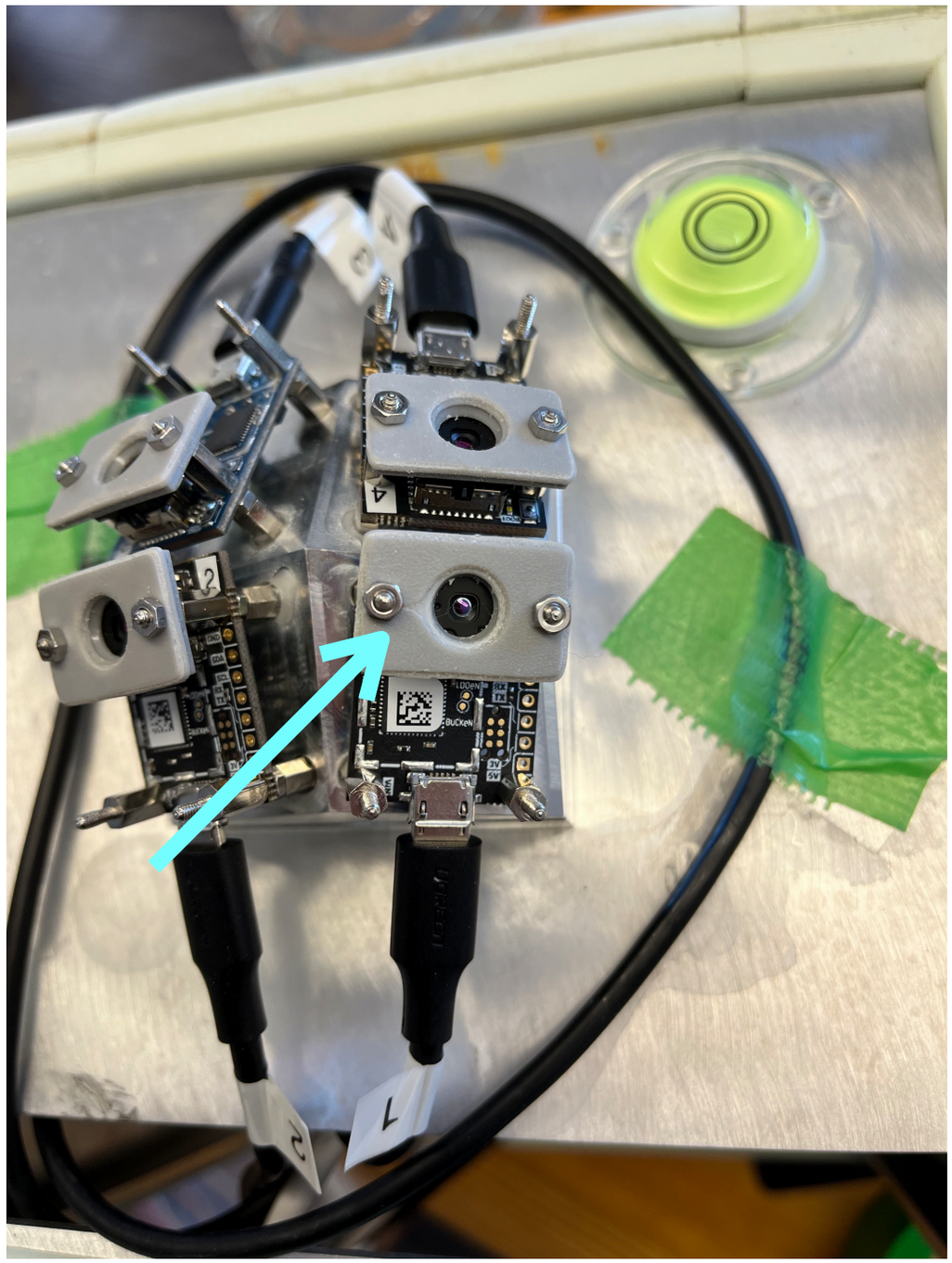

```
2022-03-22T04:49:31.583270 Cam 1 TR
2022-03-22T04:49:32.383298 Cam 2 TL
2022-03-22T04:49:32.511303 Cam 3 BL
2022-03-22T04:49:31.743276 Cam 4 BR
```

Note: this is fish-eye view (2π coverage).

# IR camera debug (Apr. 2022)

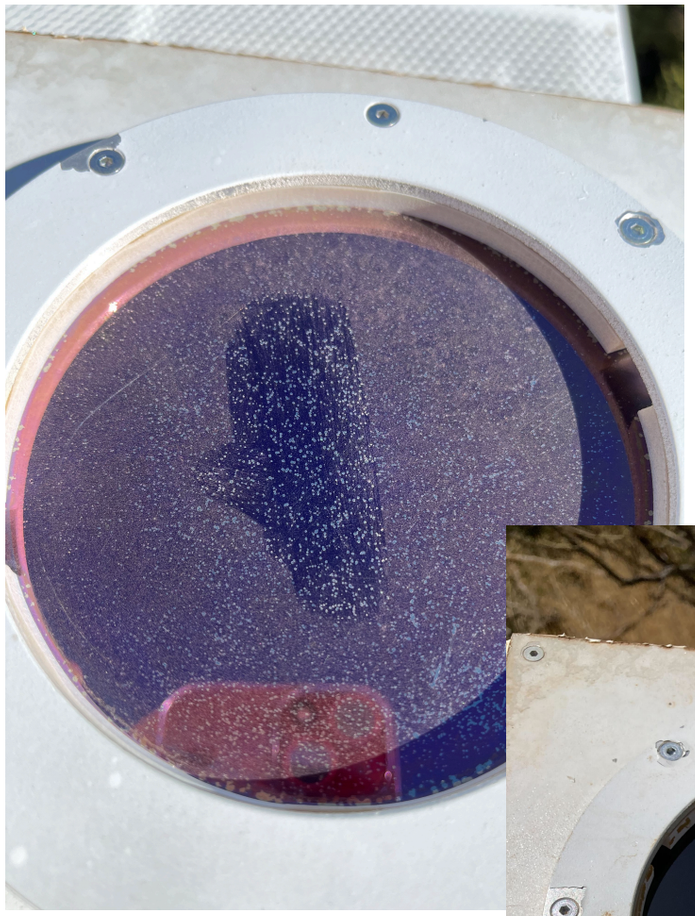
- New aluminum base mount (better rigidity)
- We installed extra structure to hold the module tight (3D printed).





# IR camera debug (Apr. 2022)

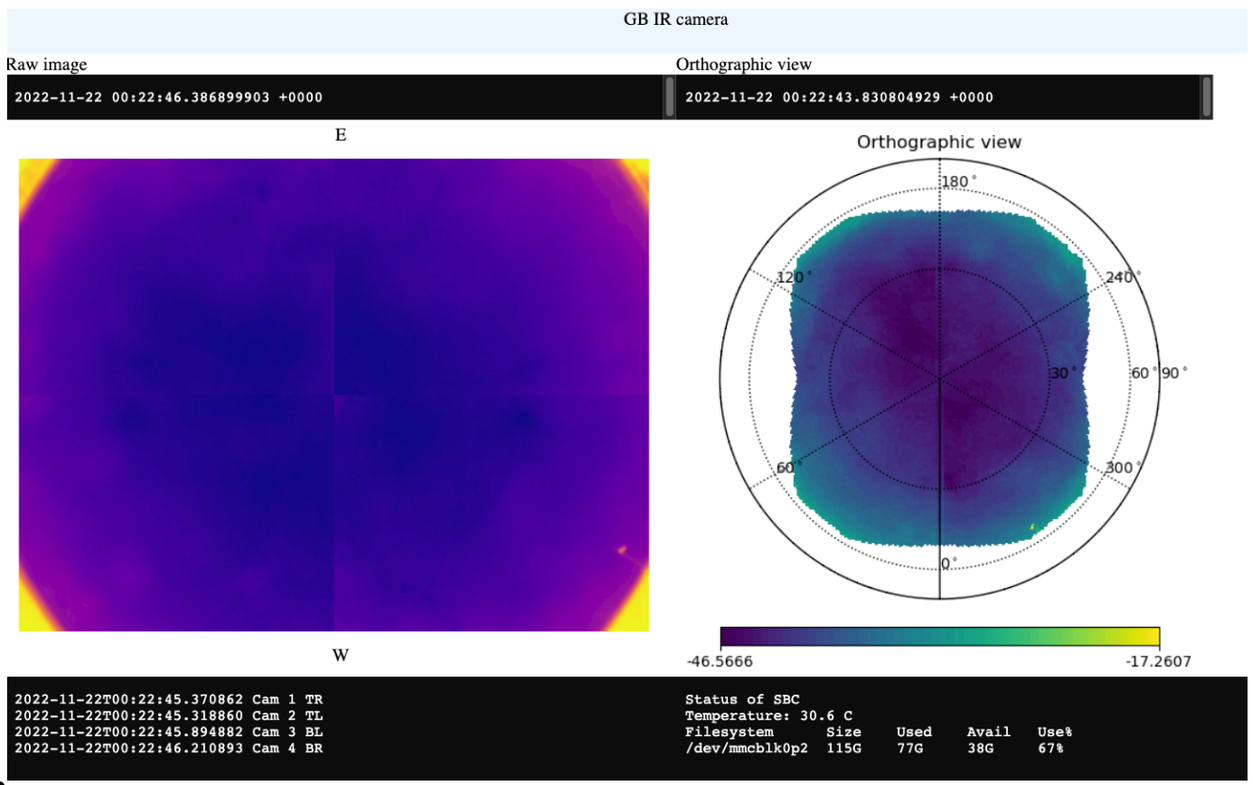
- New problem: germanium window coating was damaged (pilled off)



- Sunlight, rain, snow, temperature change… ($\Delta T \sim 40$°C )

- We installed new diamond-coated germanium window.

- We also put “calibrated map” and improved interface.



# Full detector array! (May 2023)

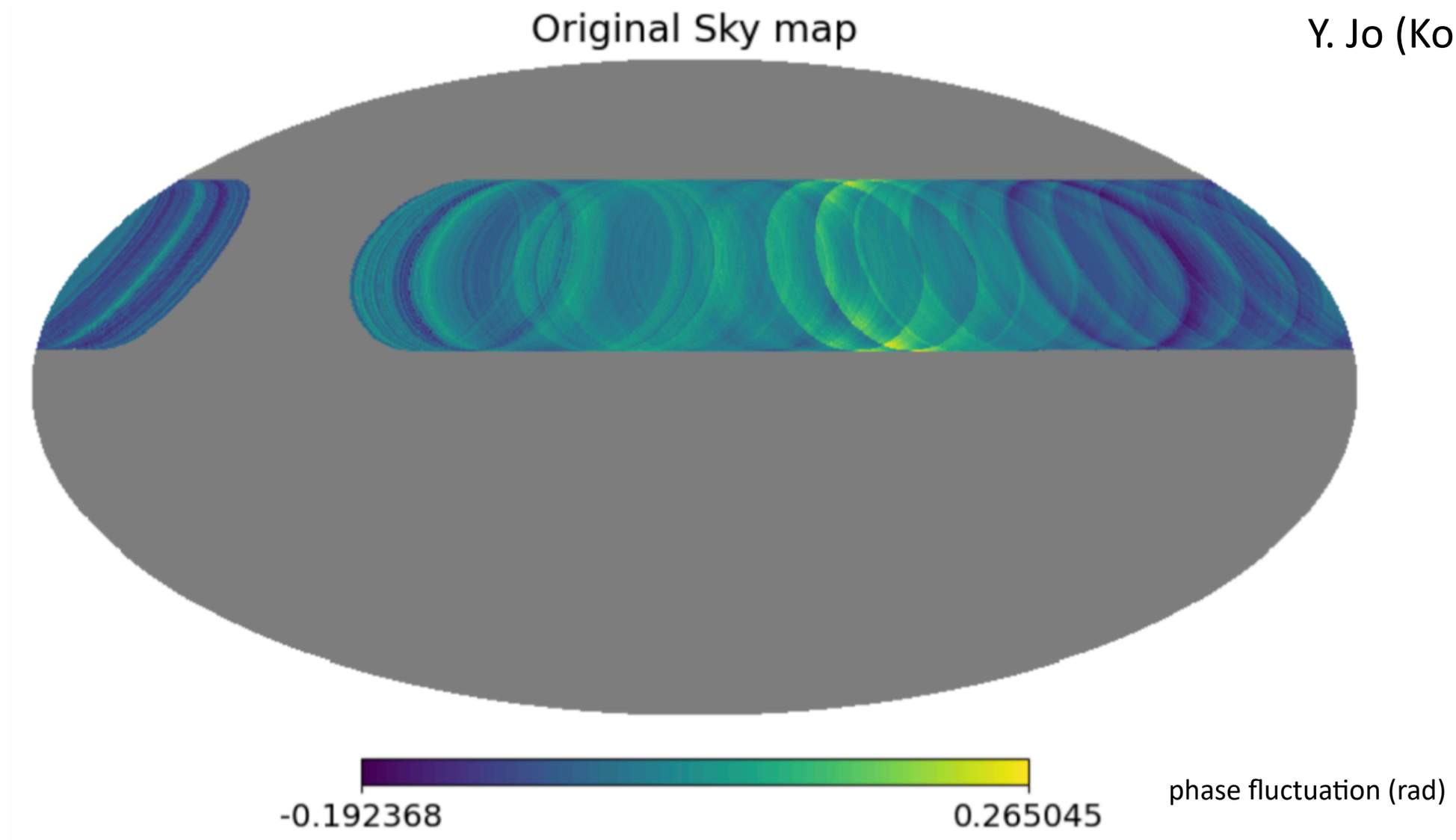
- GB now has full KID arrays (161 channels)

# **Real Data!** (summer 2024)

- GB sky map reconstruction: goal is to see the **dipole** due to solar movement.

  - Only one detector (no relative calibration over multiple channels)
  - Approximately one-day data

Y. Jo (Korea U)



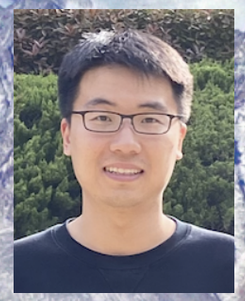
# Summary

- Detector: polarisation antenna coupled KID
  - Wide band (30%) low cross-talk (<0.01%) in simulation stage
- Readout with commercial FPGA
  - IQ mixing technique
- **Infra-red camera installed in 2021.**
  - Installed in 2021 and is under debugging.
- **Full detector** installed in summer of 2023**.**
- **We are working on understanding the real data.**

# Ali CMB Polarization Telescope (AliCPT)

- A ground CMB polarization telescope led by IHEP in Tibet plateau.

I had a lengthy discussion (Sep. 19) with
Xinmin Zhang (IHEP)
Shibo Shu (IHEP)

- **I wish IHEP's great success of AliCPT !**

- **Liang Zhan** (IHEP) will come to Korea on Nov. for a sterile $\nu$ workshop that I am organizing.

https://indico.ibs.re.kr/event/709/

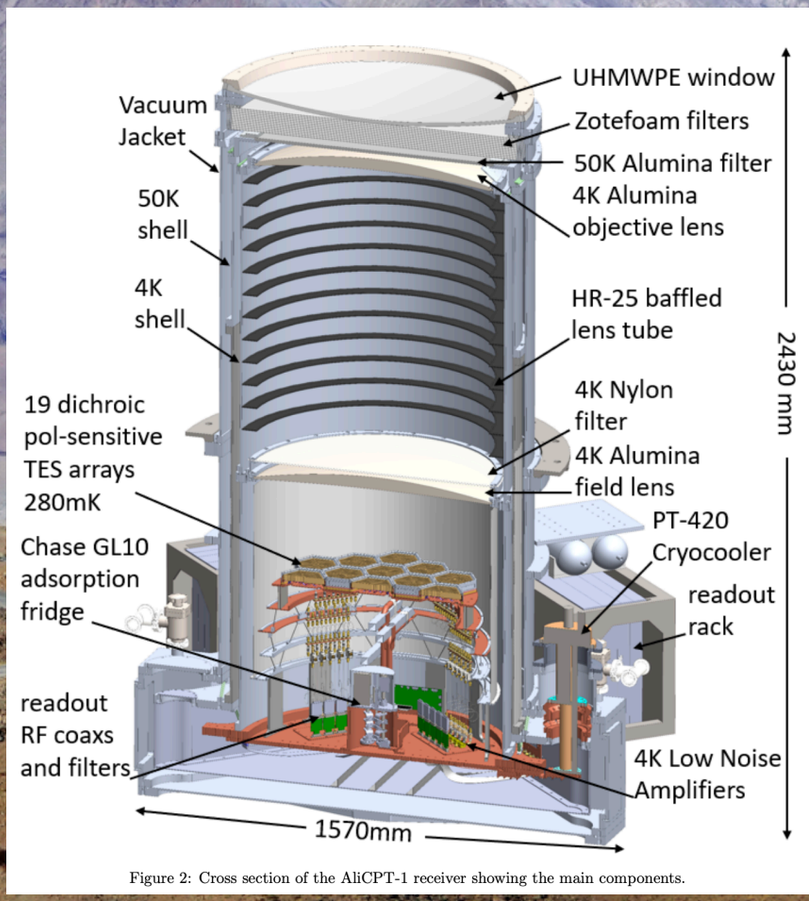
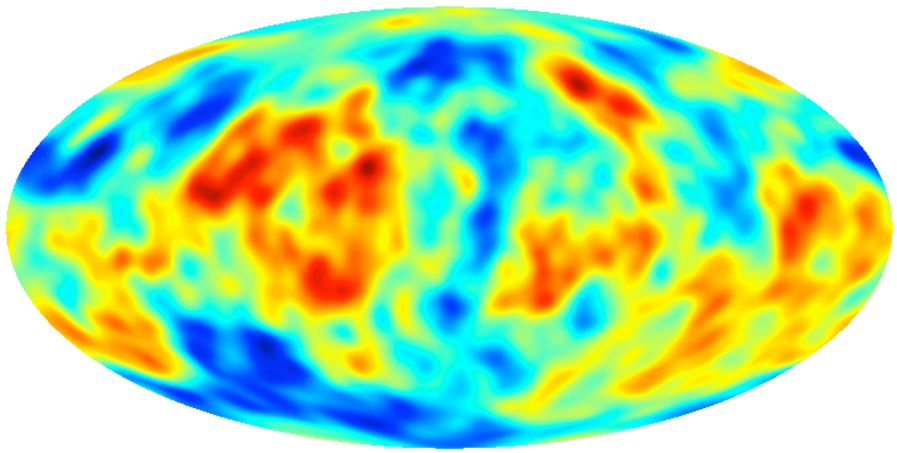


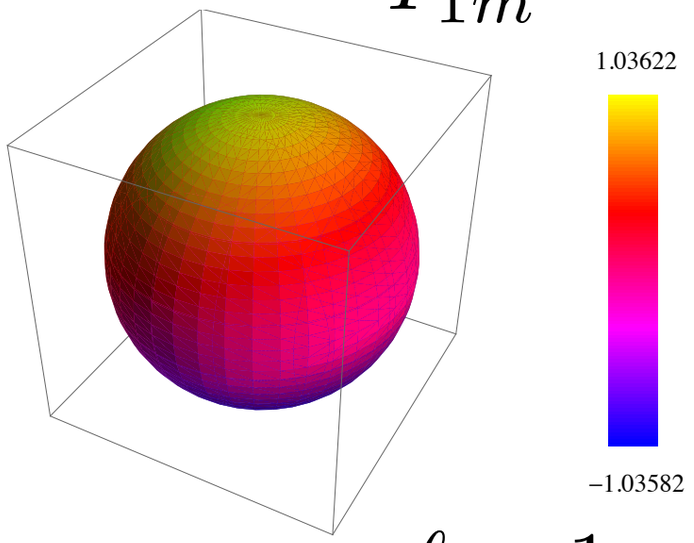

Figure 2: Cross section of the AliCPT-1 receiver showing the main components.

# Power Spectrum of $\Delta T(\theta, \phi)/\langle T \rangle$



$= a_{1m}$

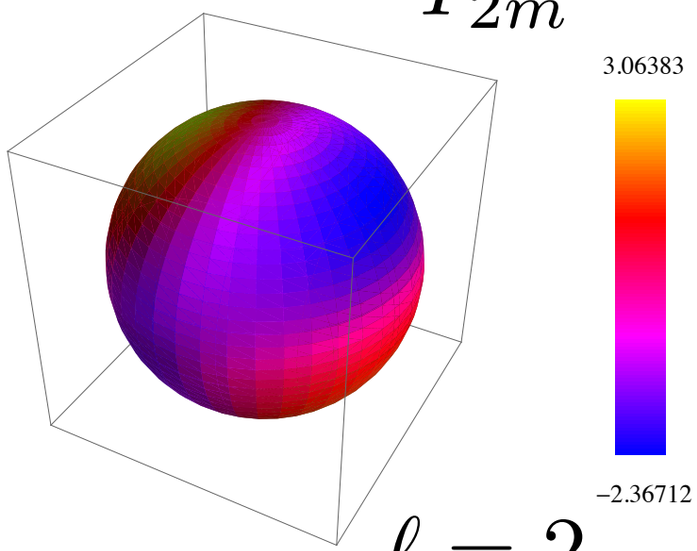
$Y_{1m}$




$\ell = 1$

$+ \; a_{2m}$

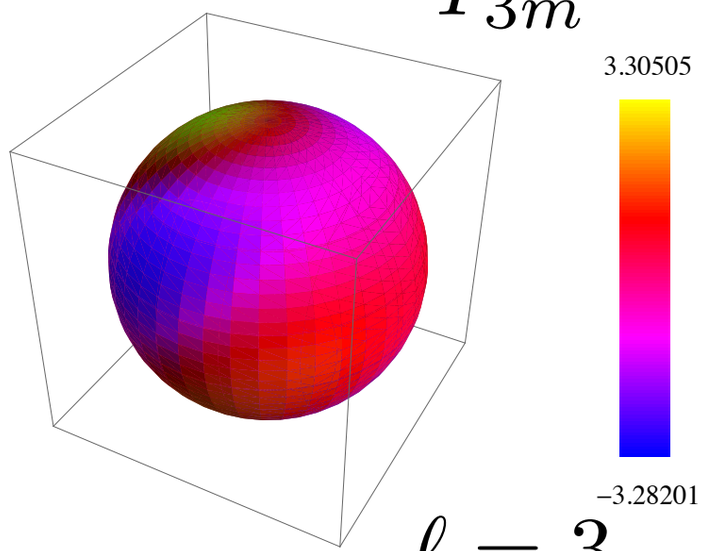
$Y_{2m}$




$\ell = 2$

$+ \; a_{3m}$

$Y_{3m}$




$\ell = 3$

• •

# Tensor perturbation seen by BICEP2?

## March 17, 2014 (Nature)

The BICEP2 instrument (foreground) at the South Pole has detected signs of ripples from the Universe's first moments.

COSMOLOGY

# Telescope captures view of gravitational waves

*Images of the infant Universe reveal evidence for rapid inflation after the Big Bang.*

**If it is true, this is the smoking gun evidence of inflation cosmology !**

underwent a spurt of wrenching, exponential growth called inflation during the first tiny fraction of a second of its existence.

waves as they continued to ripple through the Universe some 380,000 years later, when stars had not yet formed and matter was still

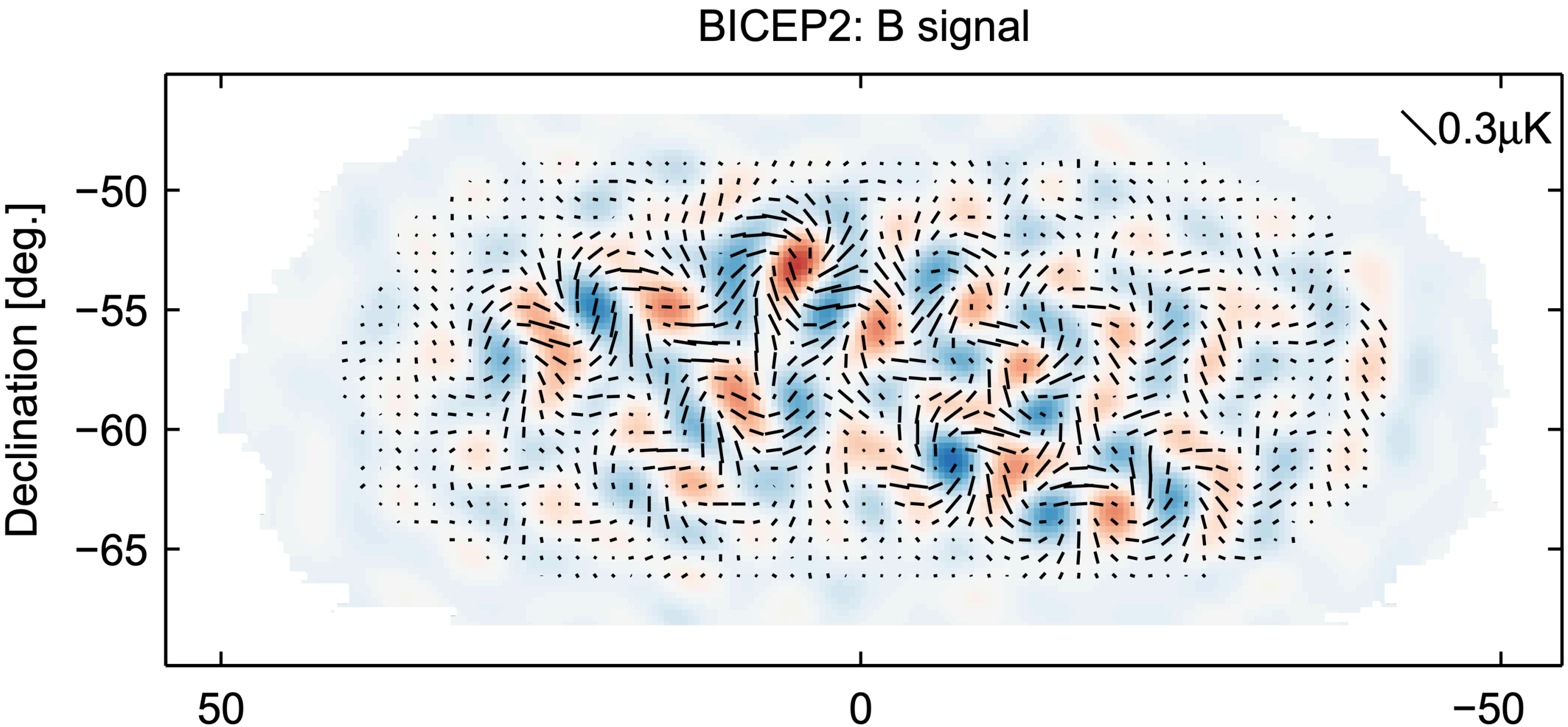
ripples from the Big Bang:
go.nature.com/cjjh5y

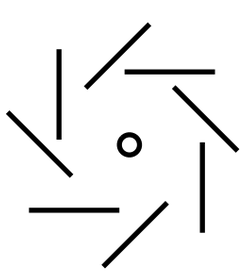
energies.

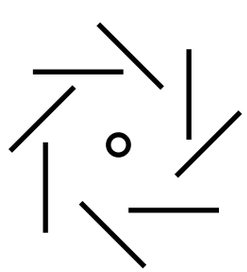
The fact that infla-

tion, a quantum ▶

# BICEP2 PRL B-mode "signal" plot

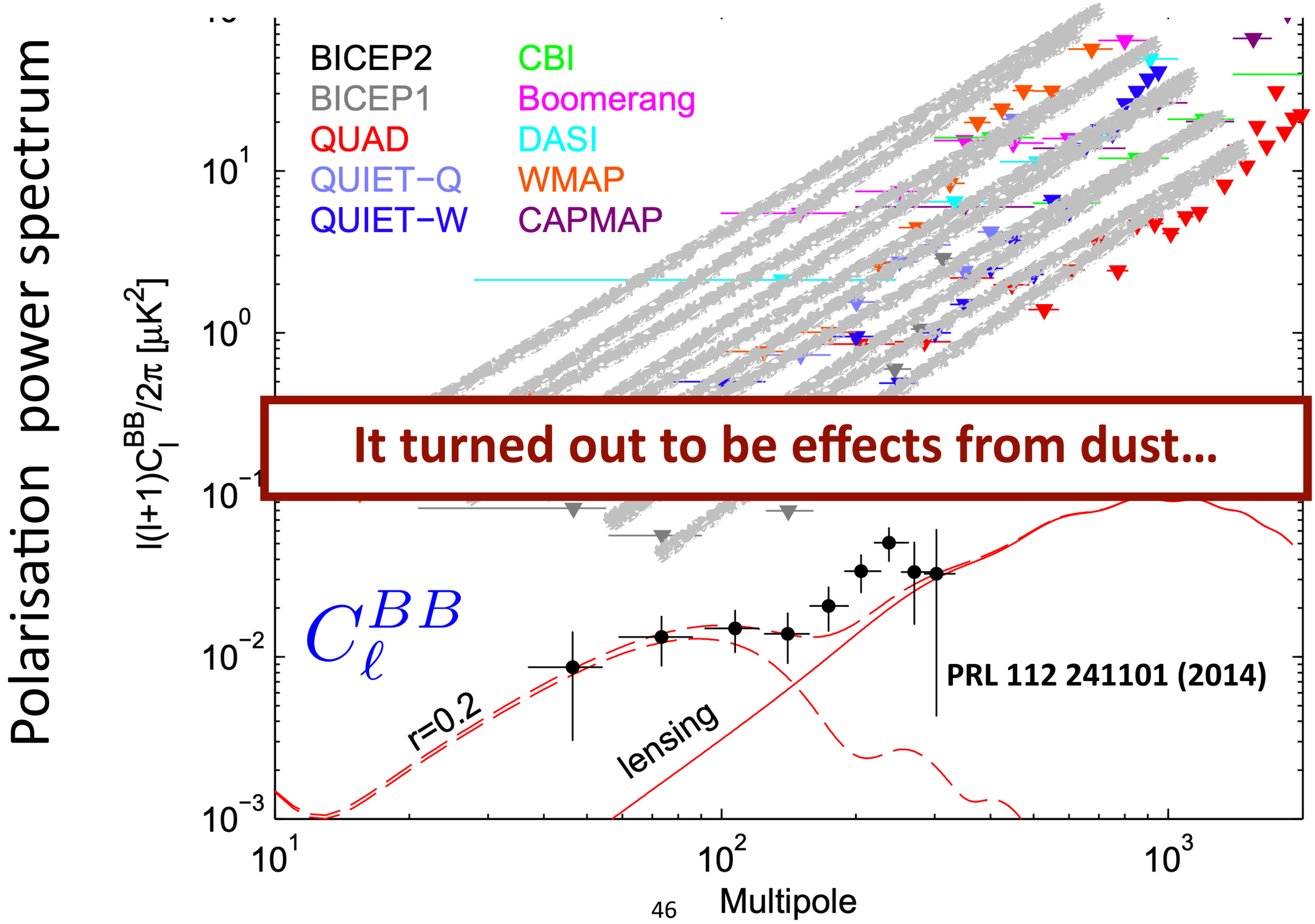




?

# BICEP2 claimed to see B-mode?

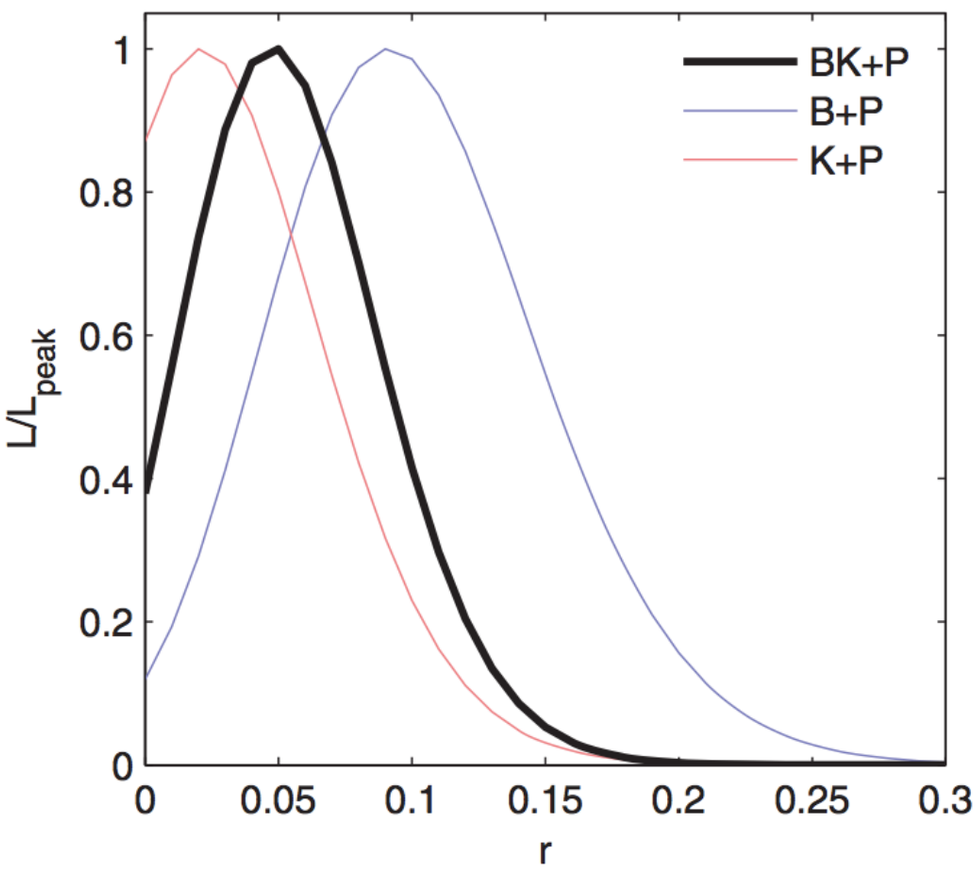



**It turned out to be effects from dust…**

# Is BICEP2 right?

**Joint study of BICEP2 and Planck data:PRL 114, 101301 (2015)**

***… We find strong evidence for dust and no statistically significant evidence for tensor modes…***

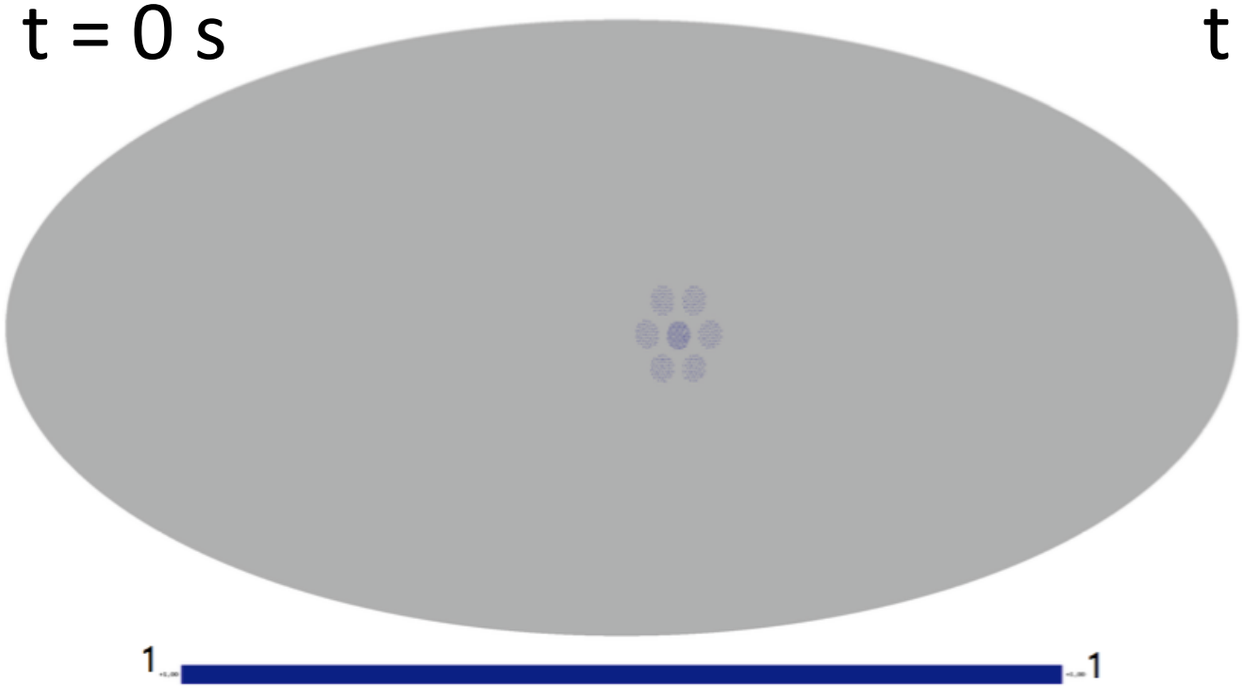



# r < 0.12 @ 95% C.L.

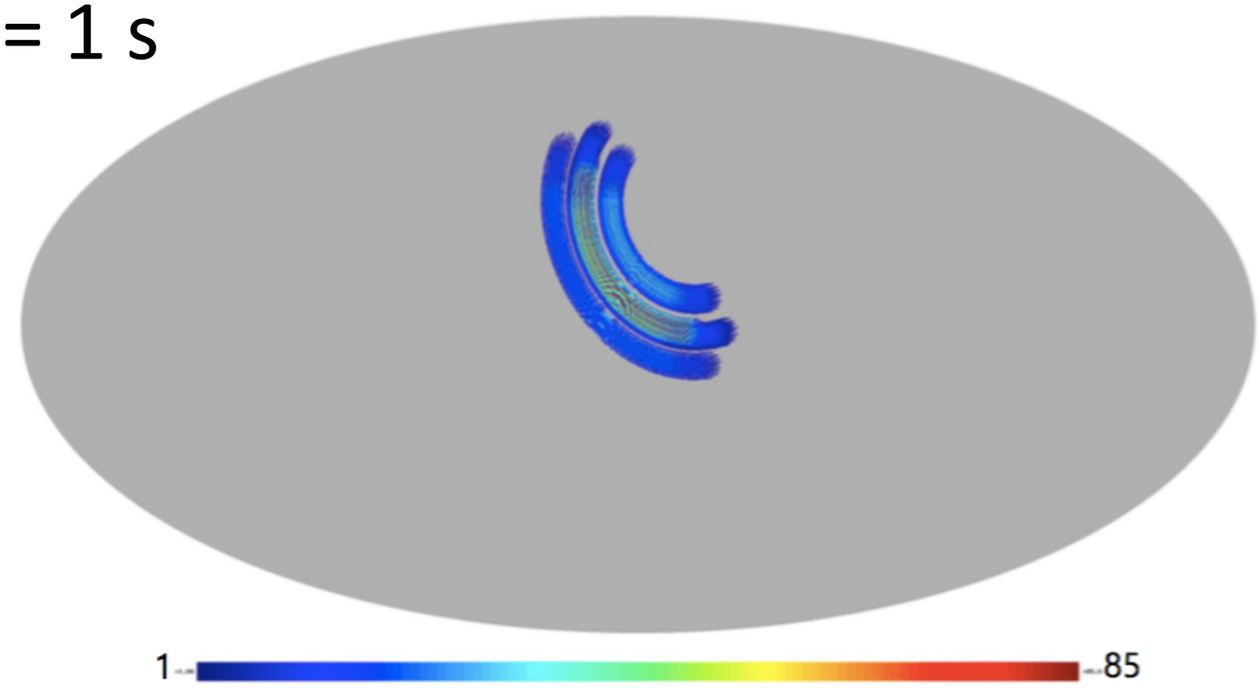
# GB rotation and the hit-map

K. Lee (Korea U)

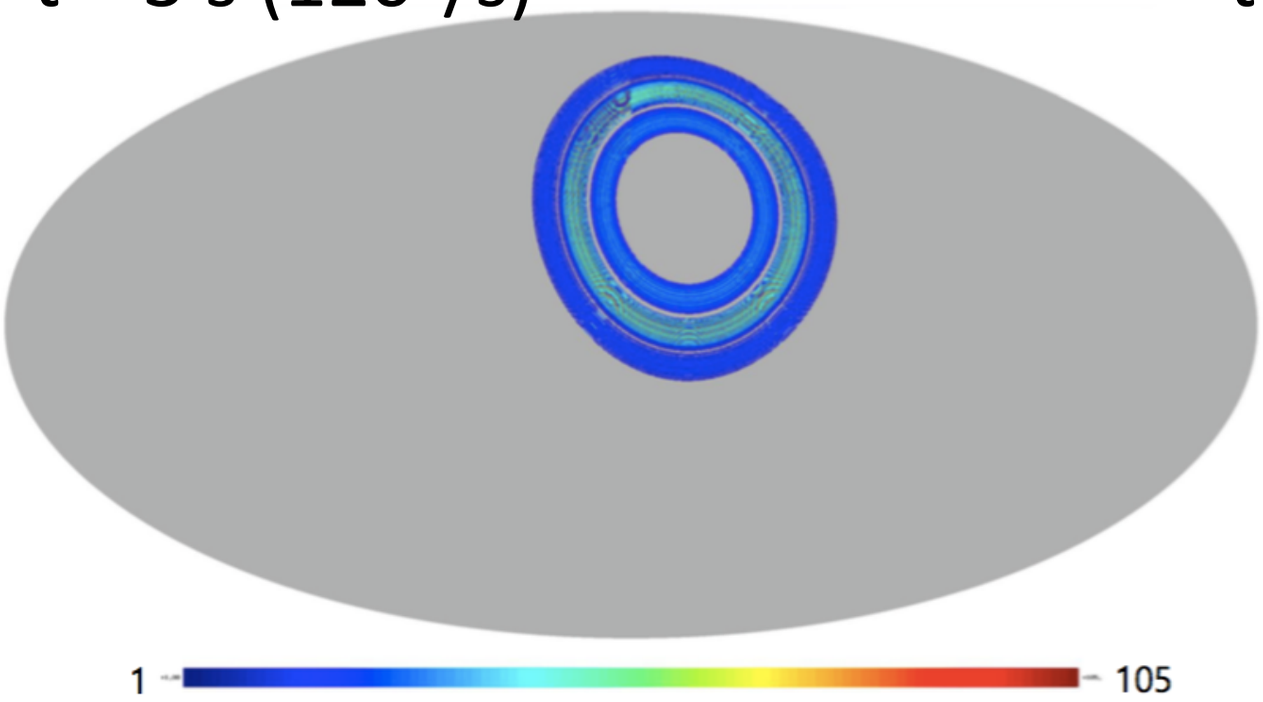
t = 0 s



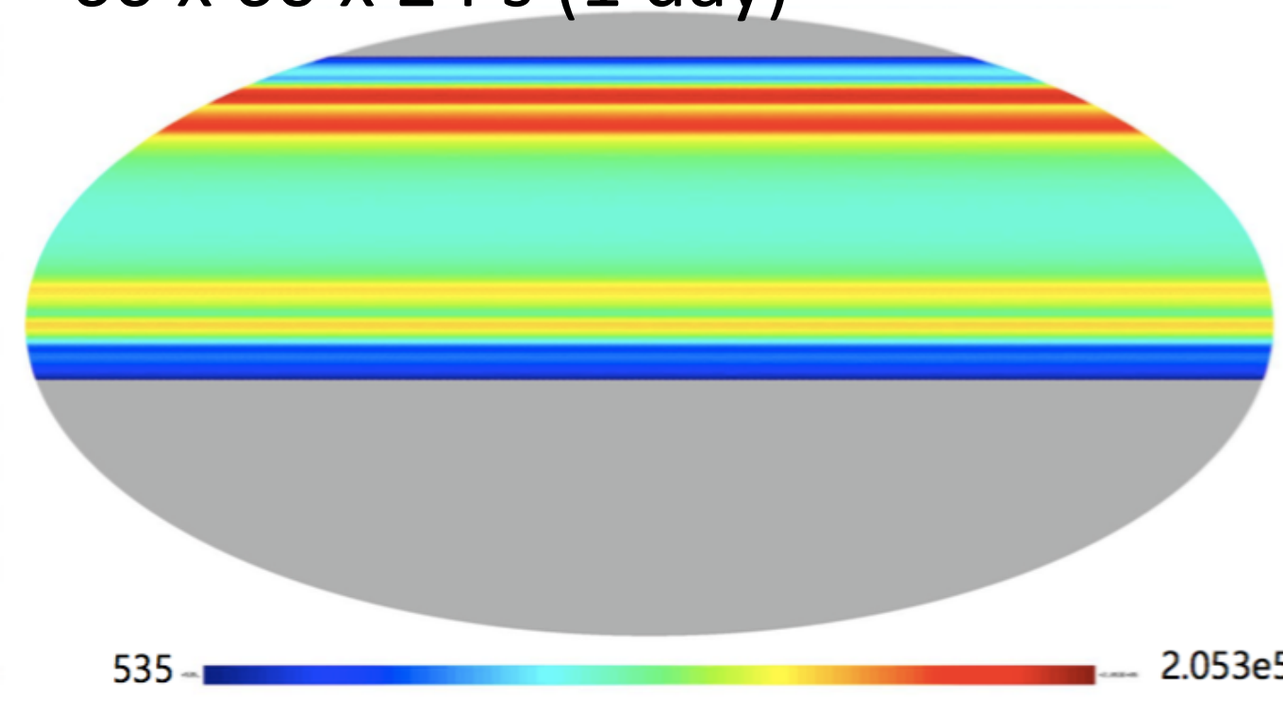

t = 1 s




t = 3 s (120°/s)




t = 60 x 60 x 24 s (1 day)



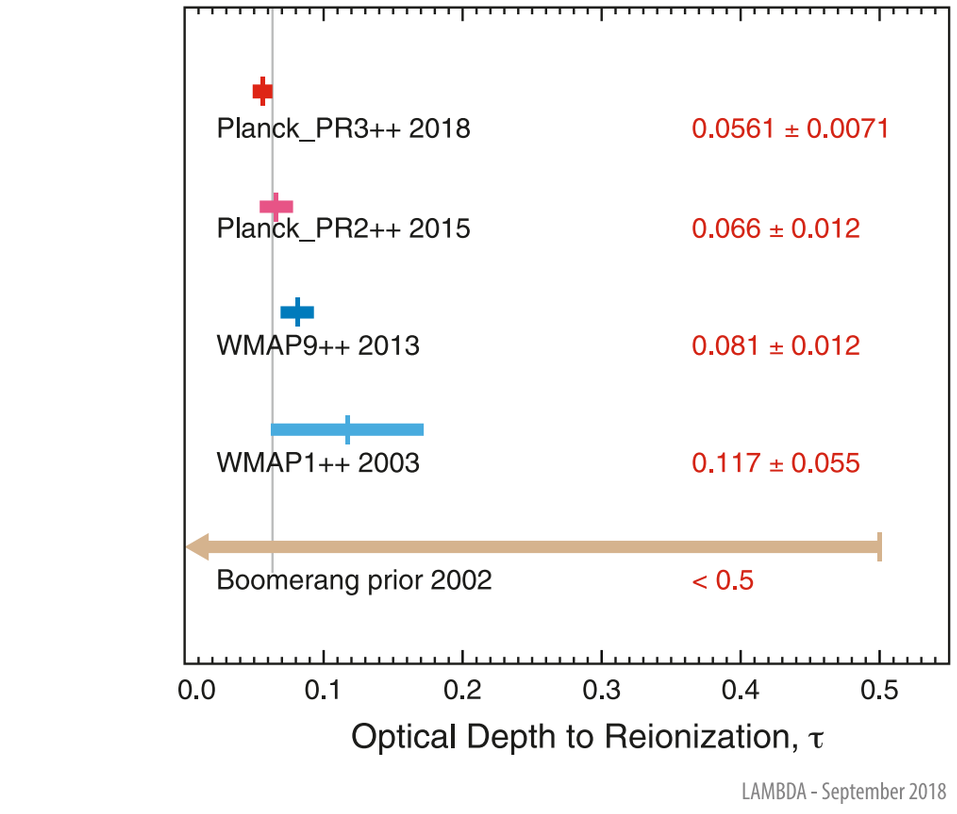
# More on physics at CMB decoupling

Optical depth (τ): a measure of the line-of-sight free-electron opacity to CMB radiation.

$\Gamma(t)$ : scattering rate of CMB with electrons.

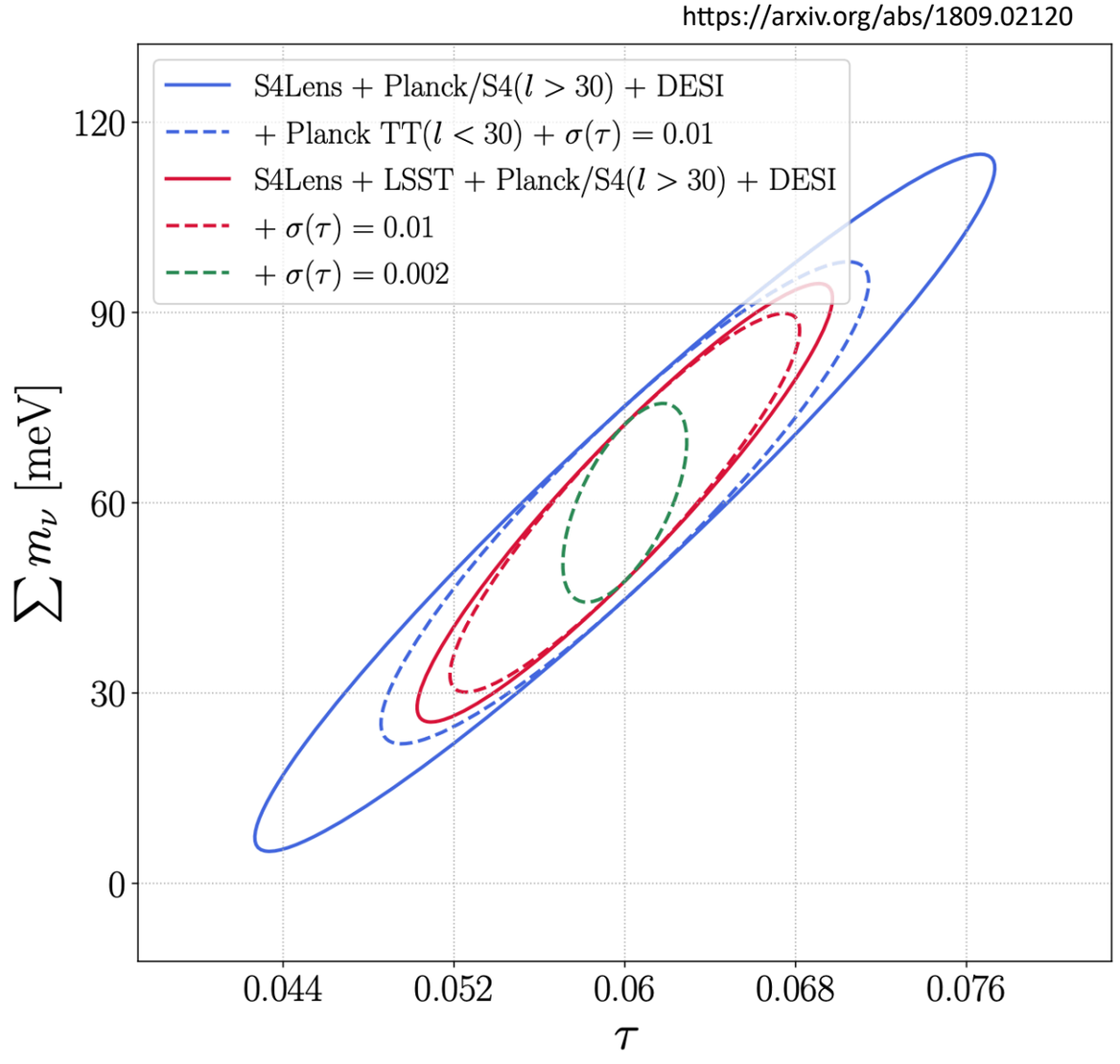
$$\tau(t) = \int_t^{t_0} \Gamma(t)\ dt$$

https://lambda.gsfc.nasa.gov/education/graphic_history/taureionzation.html




A clear systematic tendency for recent space-measurements

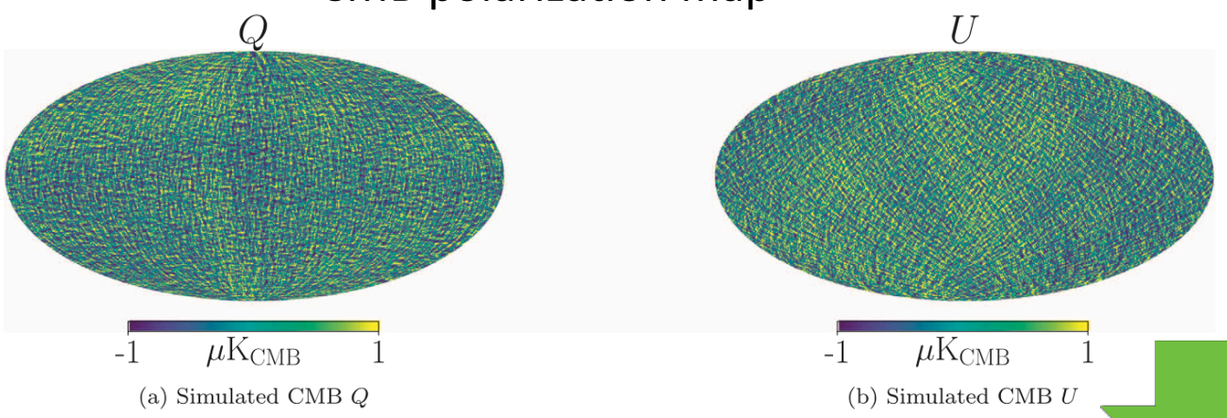
https://arxiv.org/abs/1809.02120




τ constrains sum of neutrino mass cosmologically.

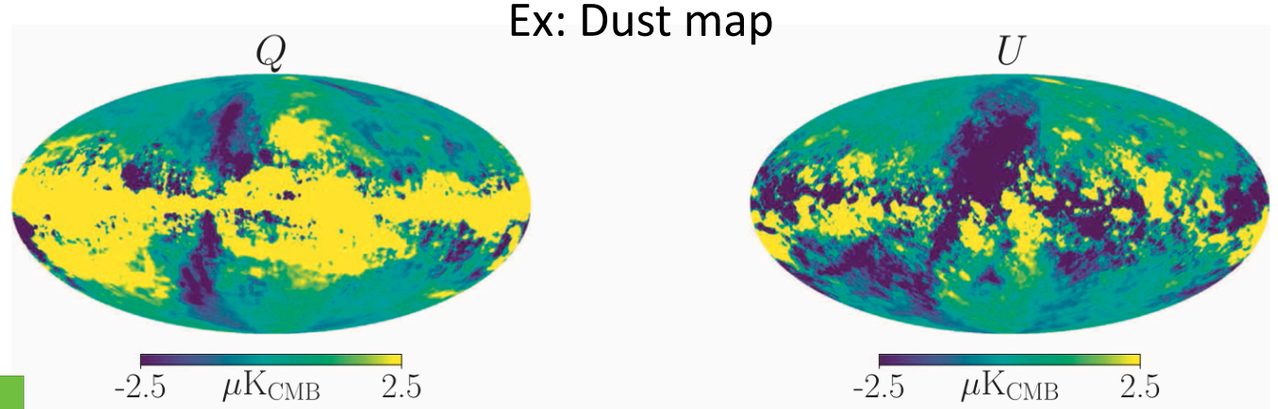
# A forecast of the optical depth

CMB polarization map




(a) Simulated CMB $Q$ (b) Simulated CMB $U$

Ex: Dust map

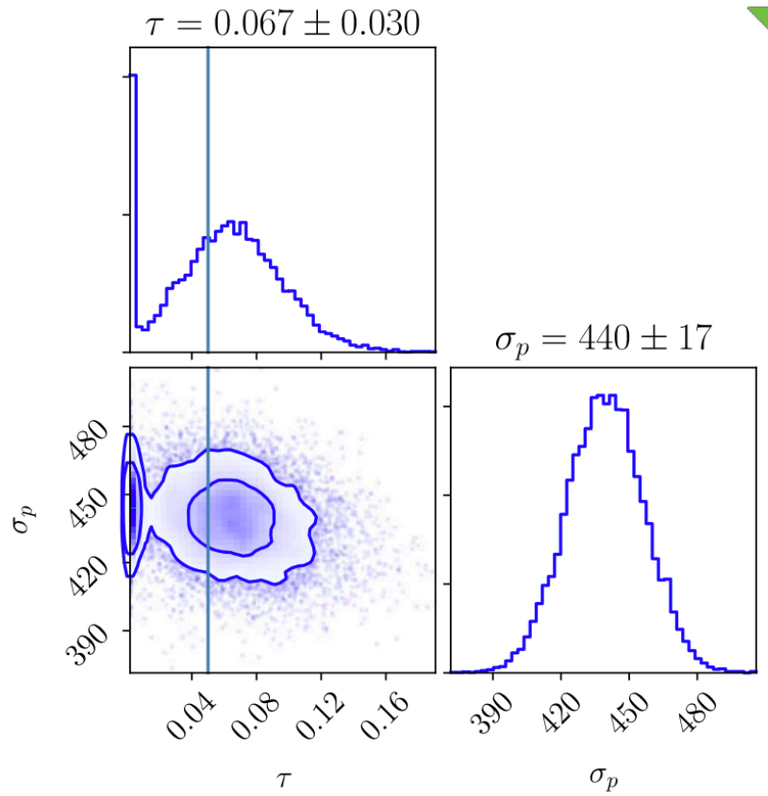



(c) Dust at 145 GHz, $Q$ (d) Dust at 145 GHz, $U$

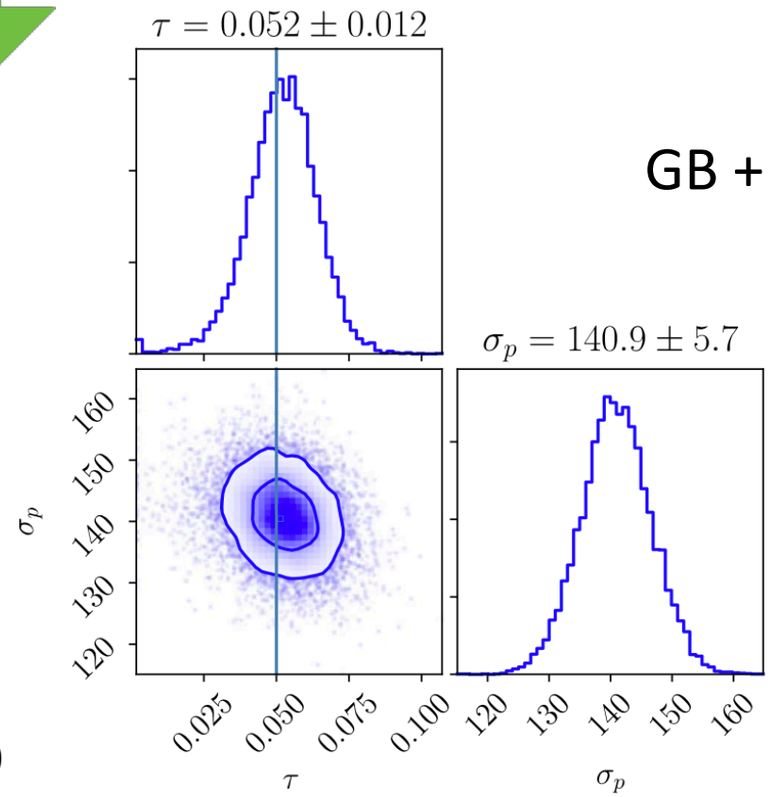
$$\mathcal{L}(C_\ell) = \frac{1}{|2\pi\mathbf{M}|^{1/2}} \exp\left( -\frac{1}{2}\mathbf{m}^T\mathbf{M}^{-1}\mathbf{m} \right)$$

: likelihood fit

GB only




GB + QUIJOTE joint



# A forecast of the optical depth published!

The Astrophysical Journal, 915:88 (10pp) 2021 July 10 **July 10, 2021.**

https://doi.org/10.3847/1538-4357/ac024b



CrossMark

## A Forecast of the Sensitivity on the Measurement of the Optical Depth to Reionization with the GroundBIRD Experiment

K. Lee[1], R. T. Génova-Santos[2,3], M. Hazumi[4,5,6,7], S. Honda[8], H. Kutsuma[9,10], S. Oguri[5], C. Otani[9,10], M. W. Peel[2,3], Y. Sueno[8], J. Suzuki[8], O. Tajima[8], and E. Won[1]

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[3] Departamento de Astrofísica, Universidad de La Laguna, E38206 La Laguna, Tenerife, Canary Islands, Spain
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[6] Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI), UTIAS, The University of Tokyo, Kashiwa, Chiba 277-8583, Japan
[7] The Graduate University for Advanced Studies (SOKENDAI), Miura District, Kanagawa 240-0115, Hayama, Japan
[8] Physics Department, Kyoto University, Kyoto, 606-8502, Japan
[9] Department of Physics, Tohoku University, 6-3 Aramaki-Aoba, Aoba-ku, Sendai, Miyagi 980-8578, Japan
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*Received 2021 February 5; revised 2021 May 6; accepted 2021 May 14; published 2021 July 12*

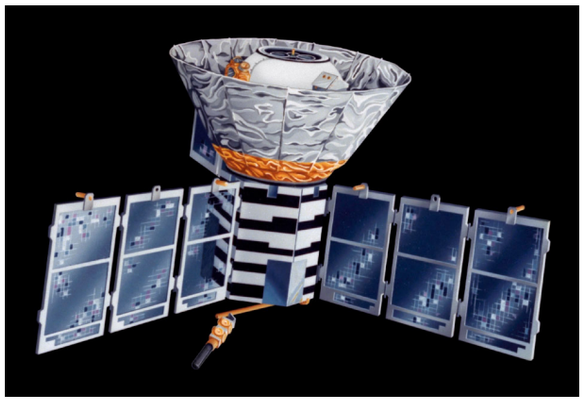
$$\sigma_\tau = 0.03 \text{ for GB only}, \ \sigma_\tau = 0.01 \text{ for GB + QUIJOTE}$$

✓ **First cosmology paper from our group (took 4 years!).**

# Density fluctuation exists!

- **Galaxy and star formation? It's a quantum mechanical fluctuation by inflation.**

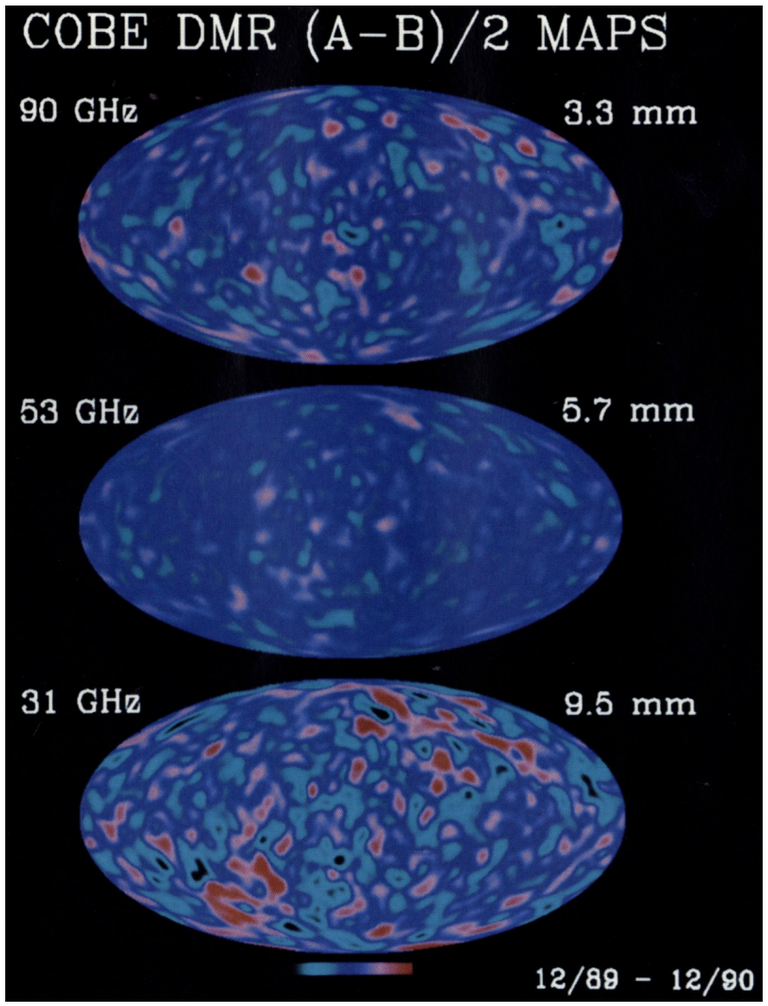
**In APS meeting of April 23, 1992:**



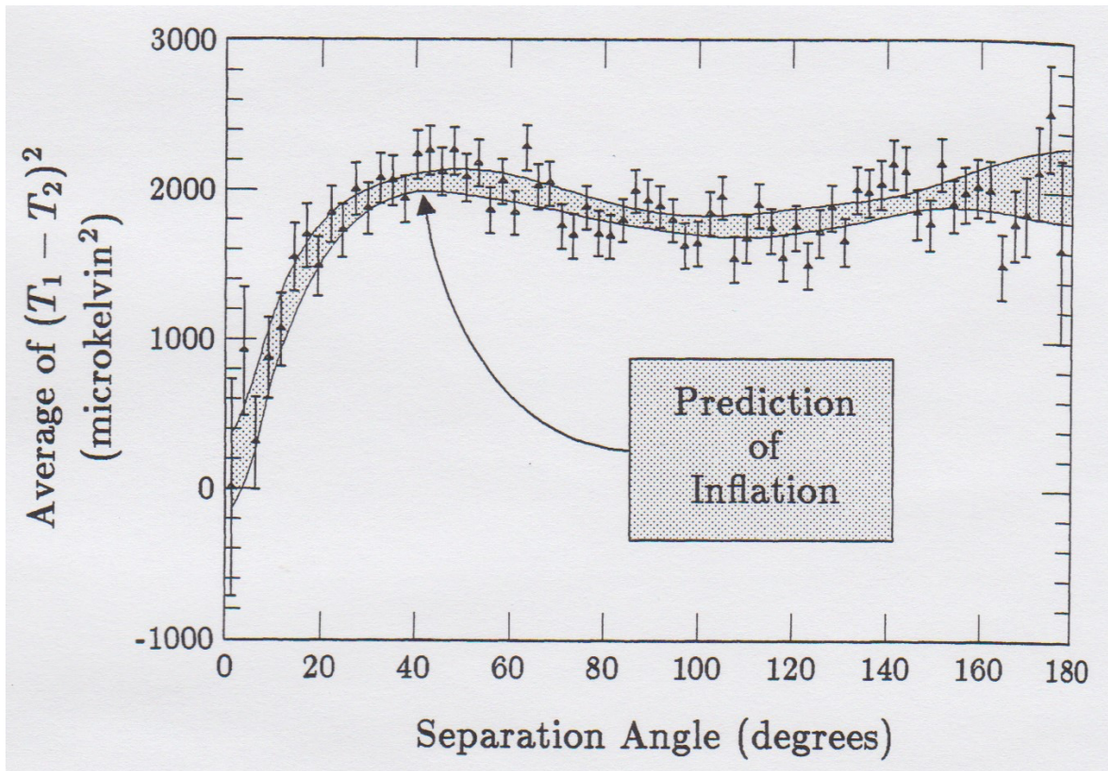
http://map.gsfc.nasa.gov/media/081000/index.html

COBE: COsmic Background Explorer

G. Smoot et al, Astro. Jour. Lett. 396 L1-5 (1992)



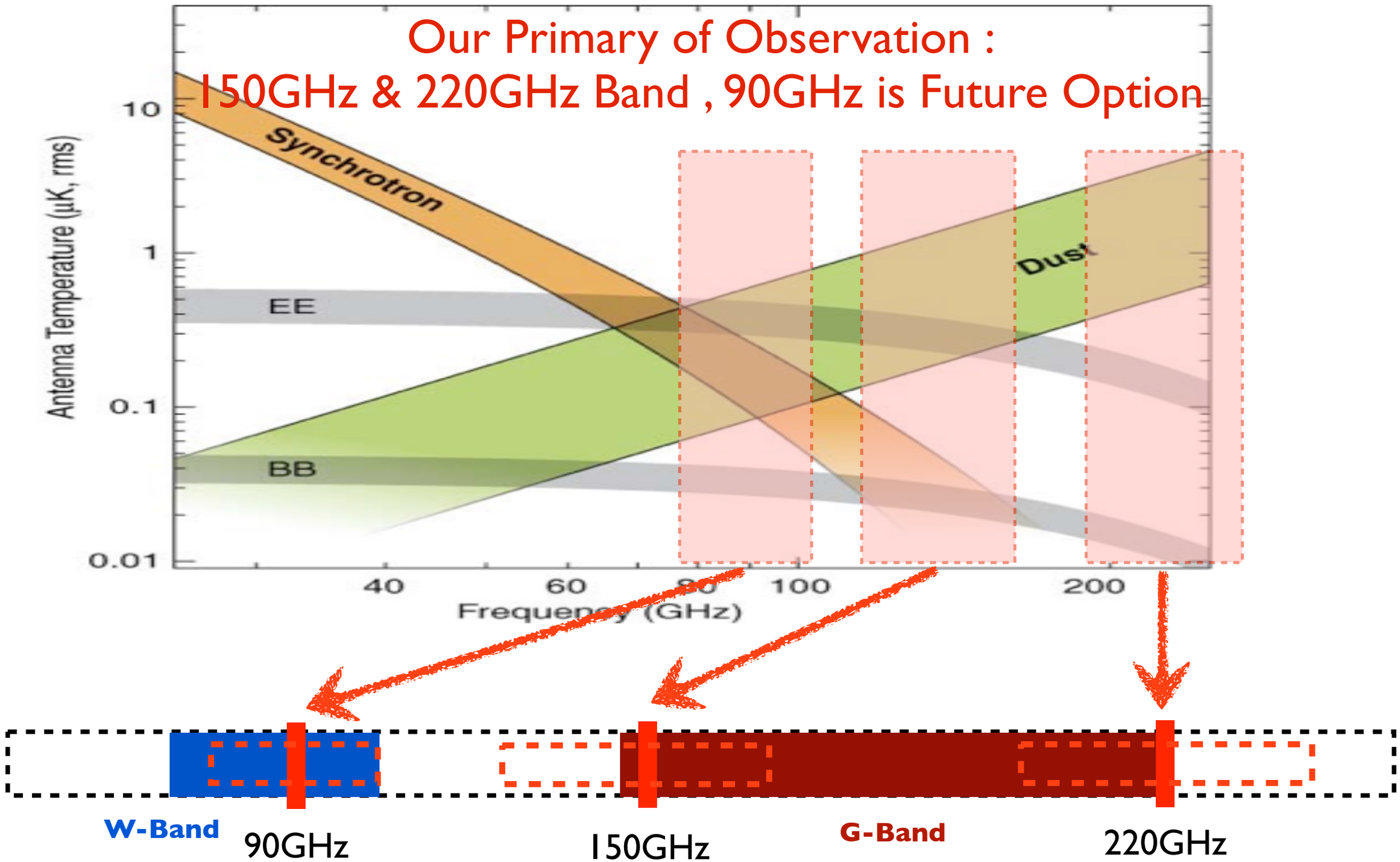

A. Guth, The Inflationary Universe (1997)




**Primordial "seeds" have been found (CMB anisotropy) : Nobel prize in 2006**

# GroundBird Observation Freq.

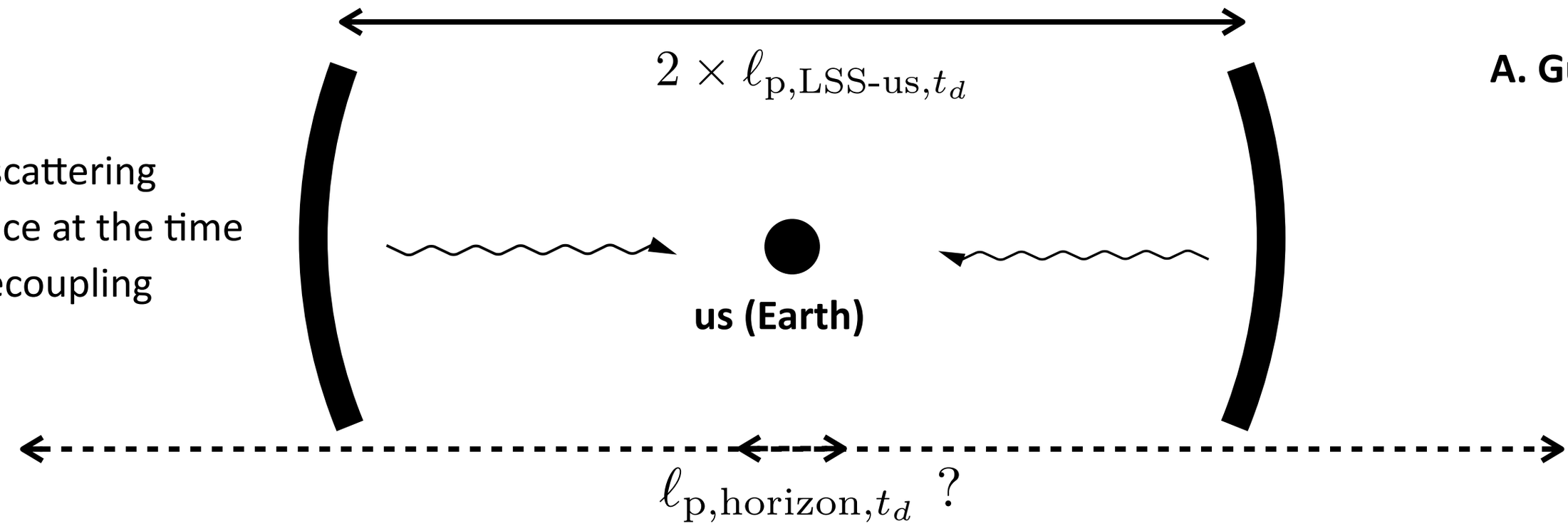
Our Primary of Observation :
150GHz & 220GHz Band , 90GHz is Future Option



# Horizon Problem

**A. Guth**

last scattering surface at the time of decoupling




$$2 \times \frac{\ell_{\mathrm{p,LSS\text{-}us},t_d}}{\ell_{\mathrm{p,horizon},t_d}} < 1 \ (?)$$

**:isotropy of CMB temperature expects it to be less than 1.**

$$\ell_{\mathrm{p}} = 2cH_0^{-1}\left[1 - \frac{1}{\sqrt{1+z}}\right]$$

$$\ell_{\mathrm{p,LSS\text{-}us},t_d} \simeq \frac{2.7\ \mathrm{K}}{3,000\ \mathrm{K}}\ell_{\mathrm{p,LSS\text{-}us},t_0}$$

$$\ell_{\mathrm{p,horizon},t_d} = 3ct_d$$

(flat, matter-dominant universe approximation)

- Cosmology: It was back in 2009 in KEK for the Belle general meeting...

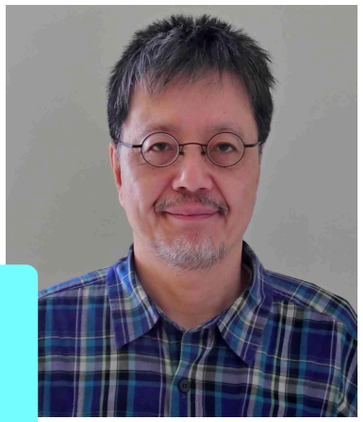
The meeting was **boring**, so I started working on calculating $K^0$ regeneration in layers of silicon detectors.

This was a very lengthy calculation and I was doing hand-written elaboration in several pages…

$$\alpha_{\rm L}(t) = e^{-i\Sigma\cdot t}\left[\alpha_{\rm L}^0\cos\left(\frac{\Delta\lambda}{2}\sqrt{1+4r^2}t\right) - i\frac{\alpha_{\rm L}^0+2r\alpha_{\rm S}^0}{\sqrt{1+4r^2}}\sin\left(\frac{\Delta\lambda}{2}\sqrt{1+4r^2}t\right)\right],$$

$$\alpha_{\rm S}(t) = e^{-i\Sigma\cdot t}\left[\alpha_{\rm S}^0\cos\left(\frac{\Delta\lambda}{2}\sqrt{1+4r^2}t\right) + i\frac{\alpha_{\rm S}^0-2r\alpha_{\rm L}^0}{\sqrt{1+4r^2}}\sin\left(\frac{\Delta\lambda}{2}\sqrt{1+4r^2}t\right)\right]$$

Suddenly, Nobu Katayama approached me and



Hey, Won san, don't you want to do something cool?

(I was really tired of calculating this) Hey, what is it? I'll take anything other than this...

It is inflation cosmology, isn't it a cool thing to do?

Hey, let's do it.

Eventually, that work was published in 2011. **But I had no idea on what I was getting into, with "yes" to Nobu...**

PHYSICAL REVIEW D **84,** 111501(R) (2011)

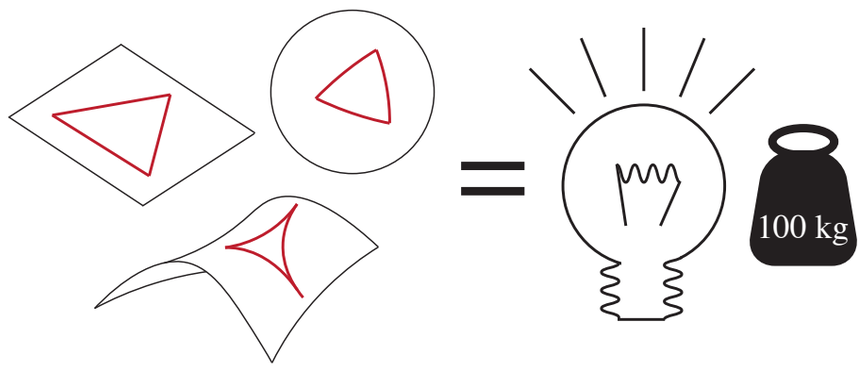
**Effect of nuclear interactions of neutral kaons on *CP* asymmetry measurements**

B. R. Ko,[1] E. Won,[1,*] B. Golob,[2,3] and P. Pakhlov[4]
[1]*Korea University, Seoul*
[2]*Faculty of Mathematics and Physics, University of Ljubljana, Ljubljana*
[3]*J. Stefan Institute, Ljubljana*
[4]*Institute for Theoretical and Experimental Physics, Moscow*
(Received 9 June 2010; revised manuscript received 27 October 2011; published 21 December 2011)

- It turns out that...

One has to know the dynamics of the curved spacetime: **general theory of relativity**
and and of course Einstein's field equations!

$$R_{\alpha\beta} - \frac{1}{2}Rg_{\alpha\beta} = \frac{8\pi G}{c^4}T_{\alpha\beta}$$




Applying them to Universe: has a solution of that is dynamic (expanding or contracting).

: this is called the **Friedmann equation** ($a(t) \propto$ size of space at time t, or called the scale factor)

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

Introduce a (extremely fast) **expansion of Universe right after the Big Bang** - to solve
**Horizon problem**
**Flatness problem**

To see if inflationary Universe is realized in nature,
we look tiny **CMB polarization** signals:

Superconducting detector technology, cold electronics.
Frequency domain readout, I/Q mixing.
RF telescope.

To even partially understand all steps, it took 10 years for myself.

- Another big problem was : the CMB that I was aware of 10 years ago…

- One slide introduction to myself: I'm

Top Quark Production in Multi - Jet Final States

Eunil Won (Rochester U.)
1996

**D0/Fermilab/US**

Observation of $D^+ \to K^+\eta^{(\prime)}$ and Search for $CP$ Violation in $D^+ \to \pi^+\eta^{(\prime)}$ Decays

**Belle/KEK/Japan**

E. Won *et al.* (Belle Collaboration)
Phys. Rev. Lett. **107**, 221801 – Published 21 November 2011

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chester U. (1996)
1422813
: FERMILAB-THESIS-1996-23, UMI-97-19960-MC, RX-1588 (ROCHESTER)
NAL-E-0740

PHYSICAL REVIEW D **84,** 111501(R) (2011)

**Effect of nuclear interactions of neutral kaons on $CP$ asymmetry measurements**

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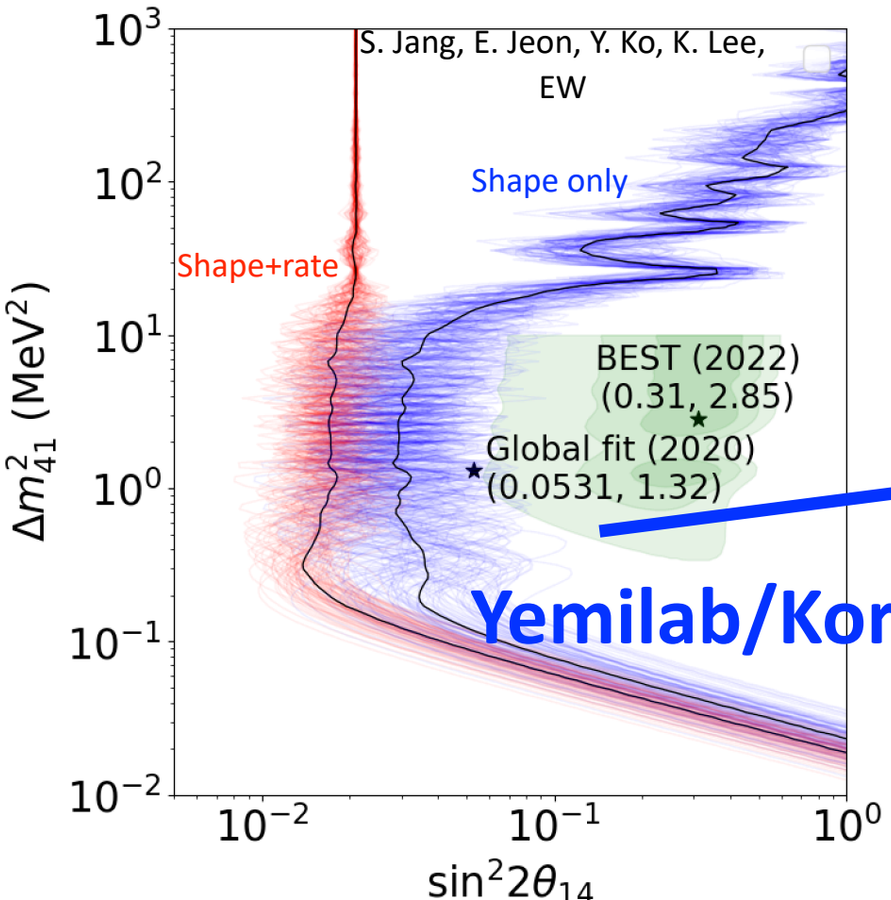
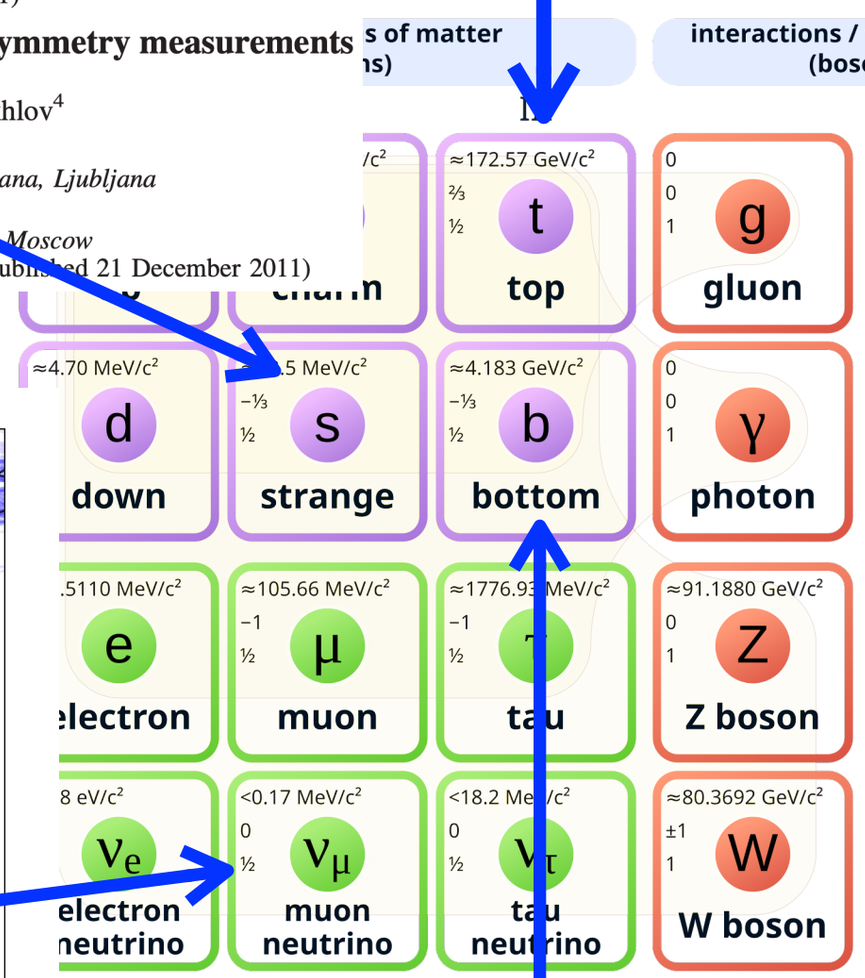
[3]*J. Stefan Institute, Ljubljana*
[4]*Institute for Theoretical and Experimental Physics, Moscow*
(Received 9 June 2010; revised manuscript received 27 October 2011; published 21 December 2011)

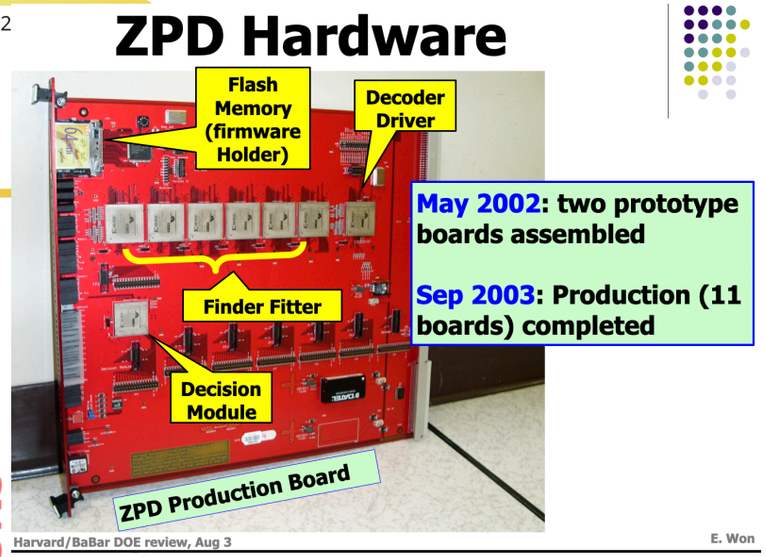
**KEK and Korea**




**Yemilab/Korea**




**Harvard/US**




**Belle/KEK/Japan**

PHYSICAL REVIEW D **83,** 071101(R) (2011)

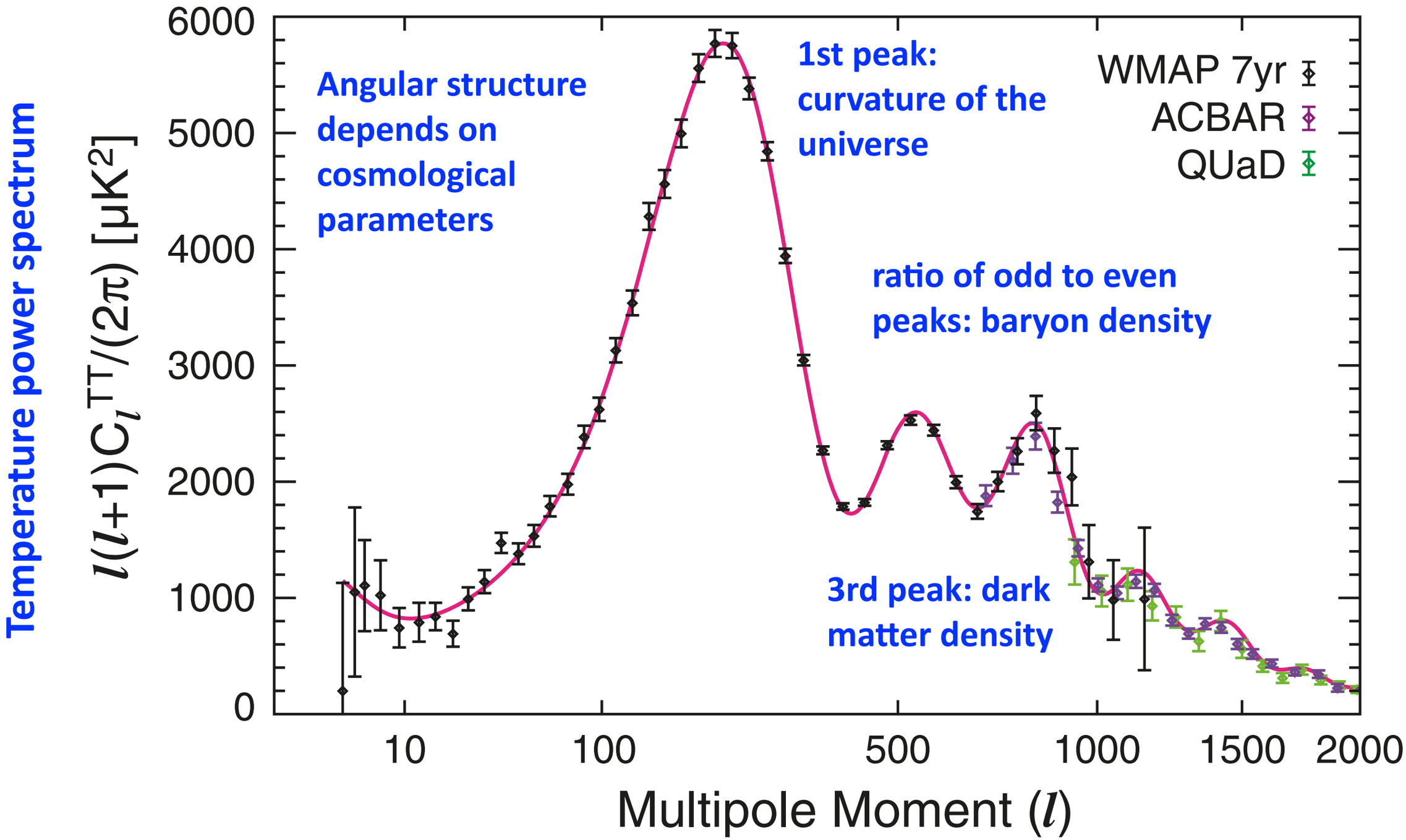
**Measurement of the decay $B^0 \to \pi^-\ell^+\nu$ and determination of $|V_{ub}|$**

H. Ha,[20] E. Won,[20] I. Adachi,[8] H. Aihara,[48] T. Aziz,[43] A. M. Bakich,[42] V. Balagura,[15] E. Barberio,[26] A. B

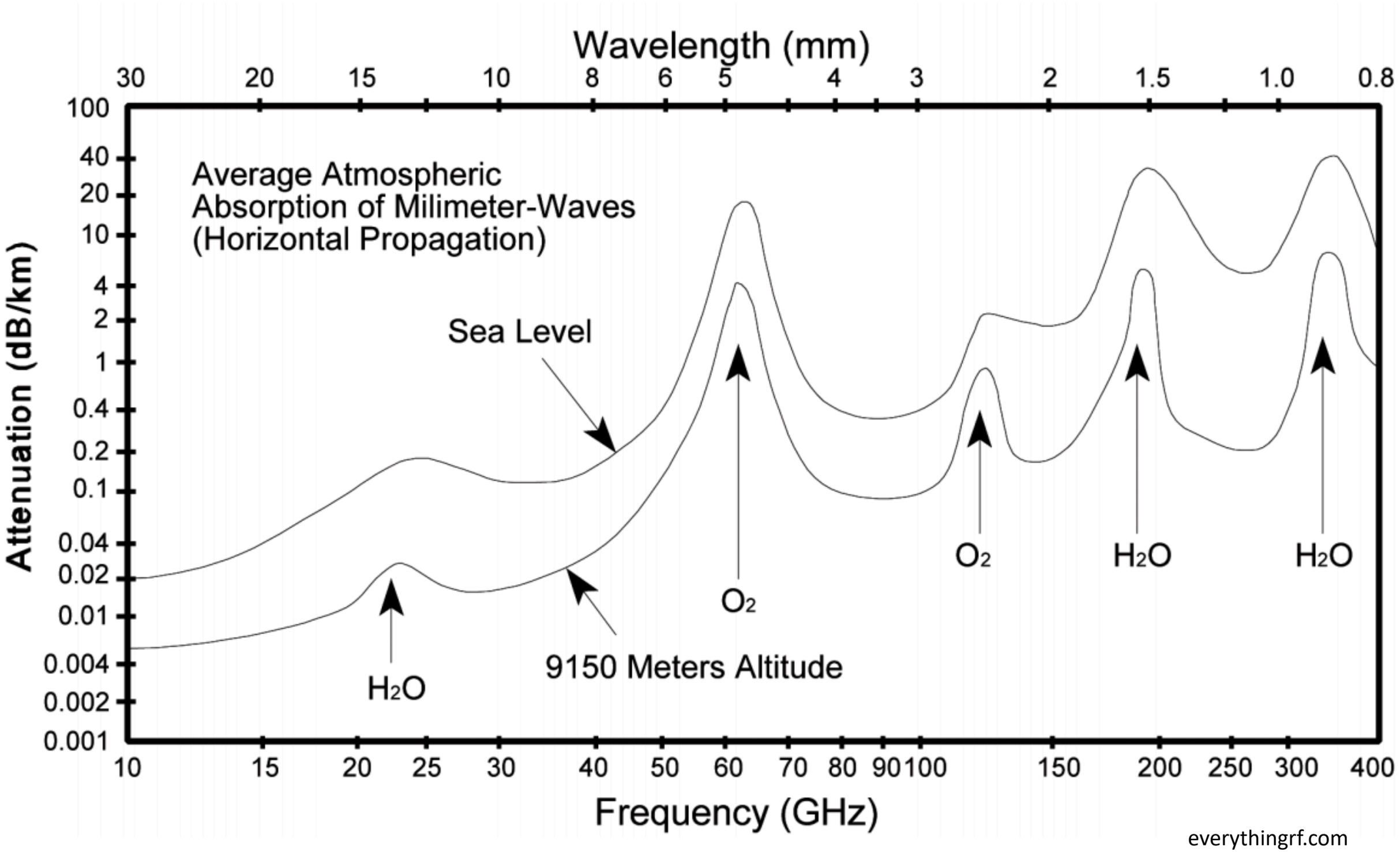
# Power Spectrum

**Theoretical prediction (with parameters) matches data extremely well**

E. Komatsu et al, APJ 192:18 1 (2011)



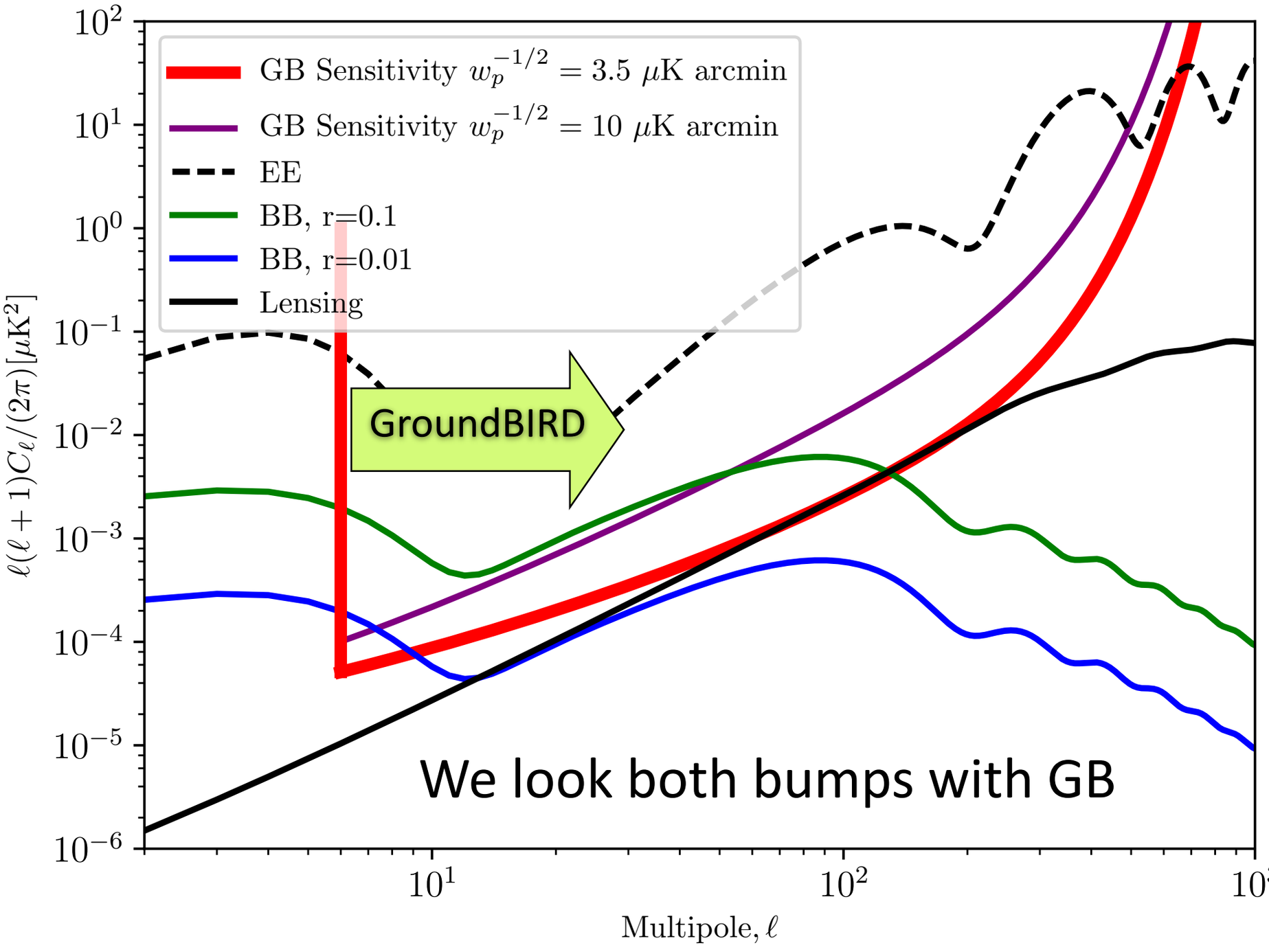
# Why dry air? : CMB is absorbed by water.




everythingrf.com

# The GroundBIRD Sensitivity

Noise power spectrum: $N_\ell^{BB} = \left( \frac{\pi}{10800} \frac{w_p^{-1/2}}{\mu\mathrm{K\ arcmin}} \right)^2 \mu\mathrm{K}^2\ \mathrm{str}$




$w_p^{-1/2}$
: noise in Stokes parameters Q/U per pixel of solid angle with $\sqrt{\Omega_{\mathrm{pixel}}} = 1$ arcmin