LiteBIRD

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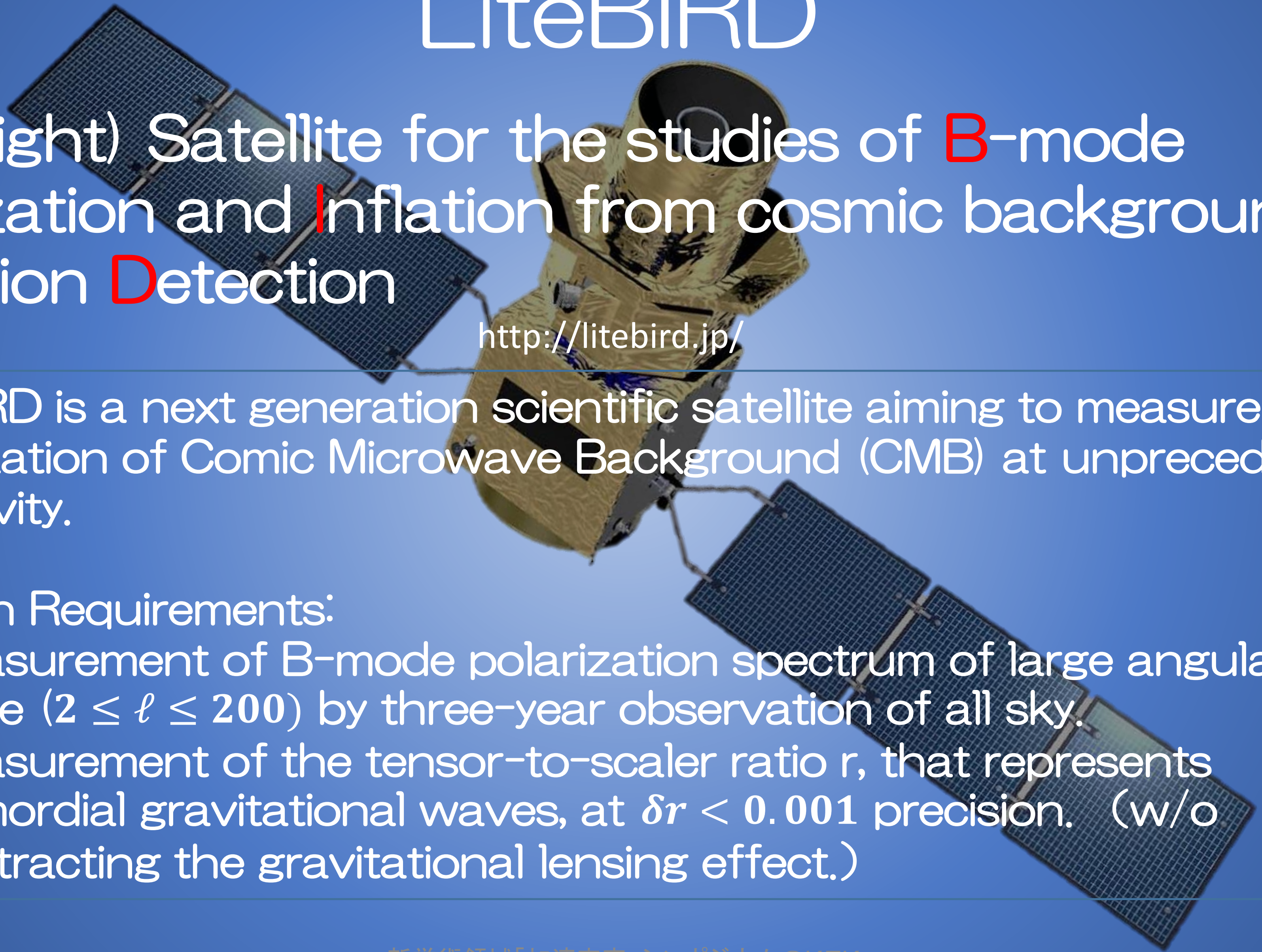
on behalf of the LiteBIRD Phase-A1 team

Mar. 8, 2017

新学術領域「加速宇宙」シンポジウム@ＫＥＫ

LiteBIRD



Lite (Light) Satellite for the studies of B-mode polarization and Inflation from cosmic background Radiation Detection

http://litebird.jp/

LiteBIRD is a next generation scientific satellite aiming to measure polarization of Comic Microwave Background (CMB) at unprecedented sensitivity.

Mission Requirements:

- Measurement of B-mode polarization spectrum of large angular scale ($2 \le \ell \le 200$) by three-year observation of all sky.
- Measurement of the tensor-to-scaler ratio r, that represents primordial gravitational waves, at $\delta r < 0.001$ precision. （w/o subtracting the gravitational lensing effect.）

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A. T. Lee (US PI)

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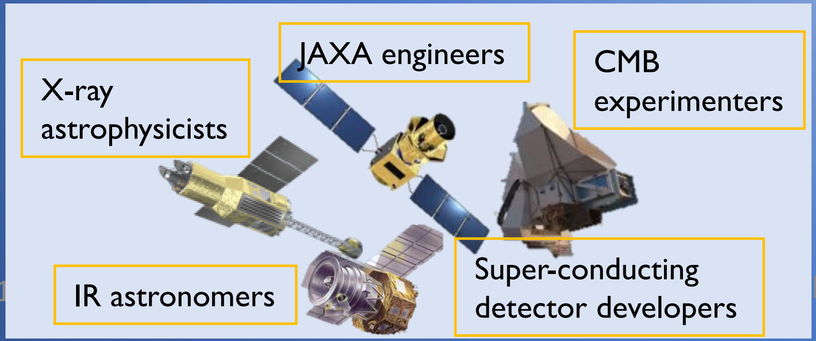
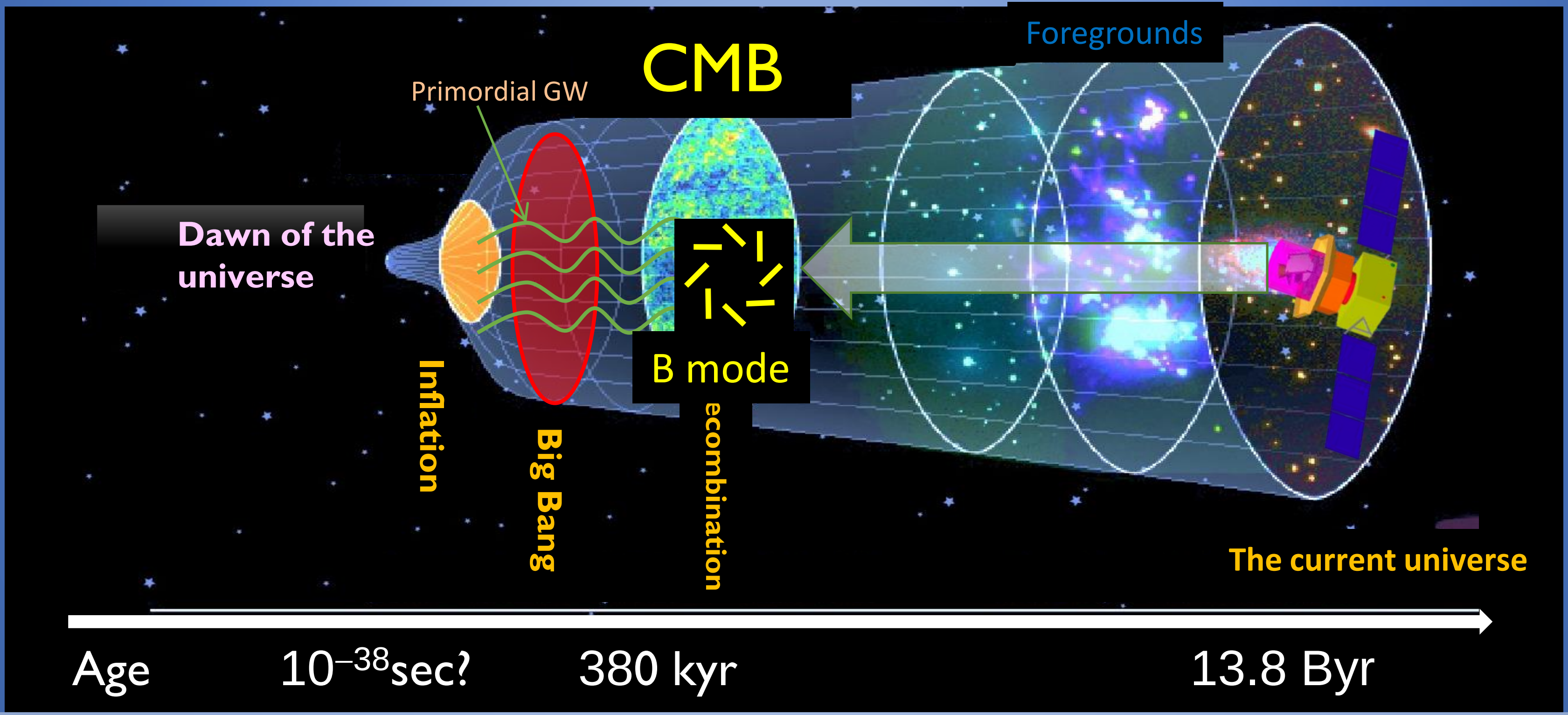


148 members, international and interdisciplinary (as of Feb 1, 2017)

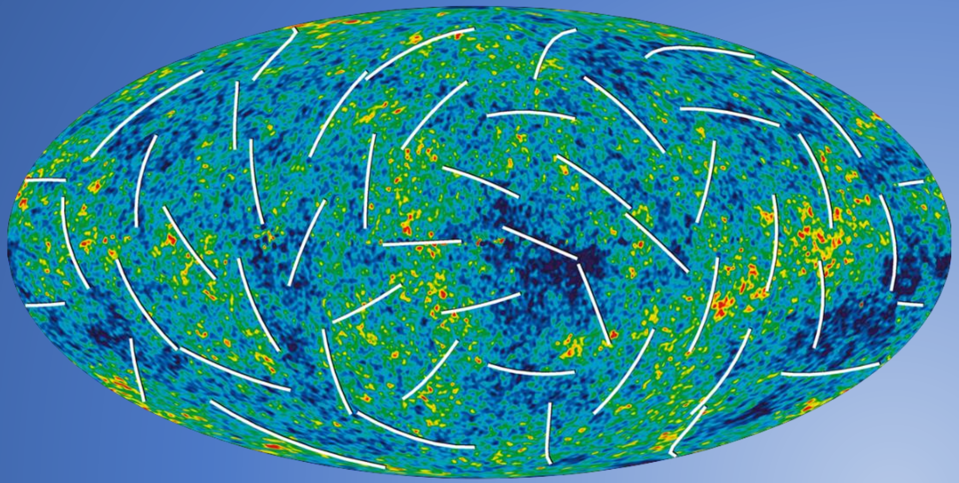
Goal： Verification of inflation using CMB

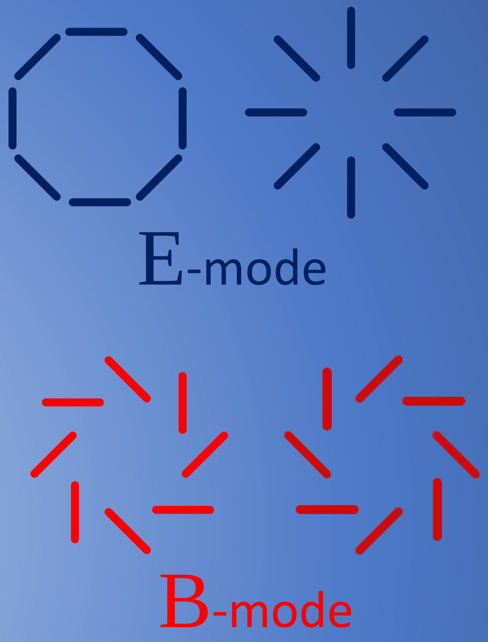
- Inflationary universe theory predicts generation of primordial gravitational waves.
- Primordial gravitational waves leave a large vortex-like patterns "inflation fingerprint" called B-mode on the CMB polarization map.
- LiteBIRD observes the CMB polarization by precisely scanning all sky from space.



LIGO observes classical gravitational waves.
CMB polarization targets "gravitational waves generated by quantum fluctuations in vacuum"

Why the B-mode polarization?





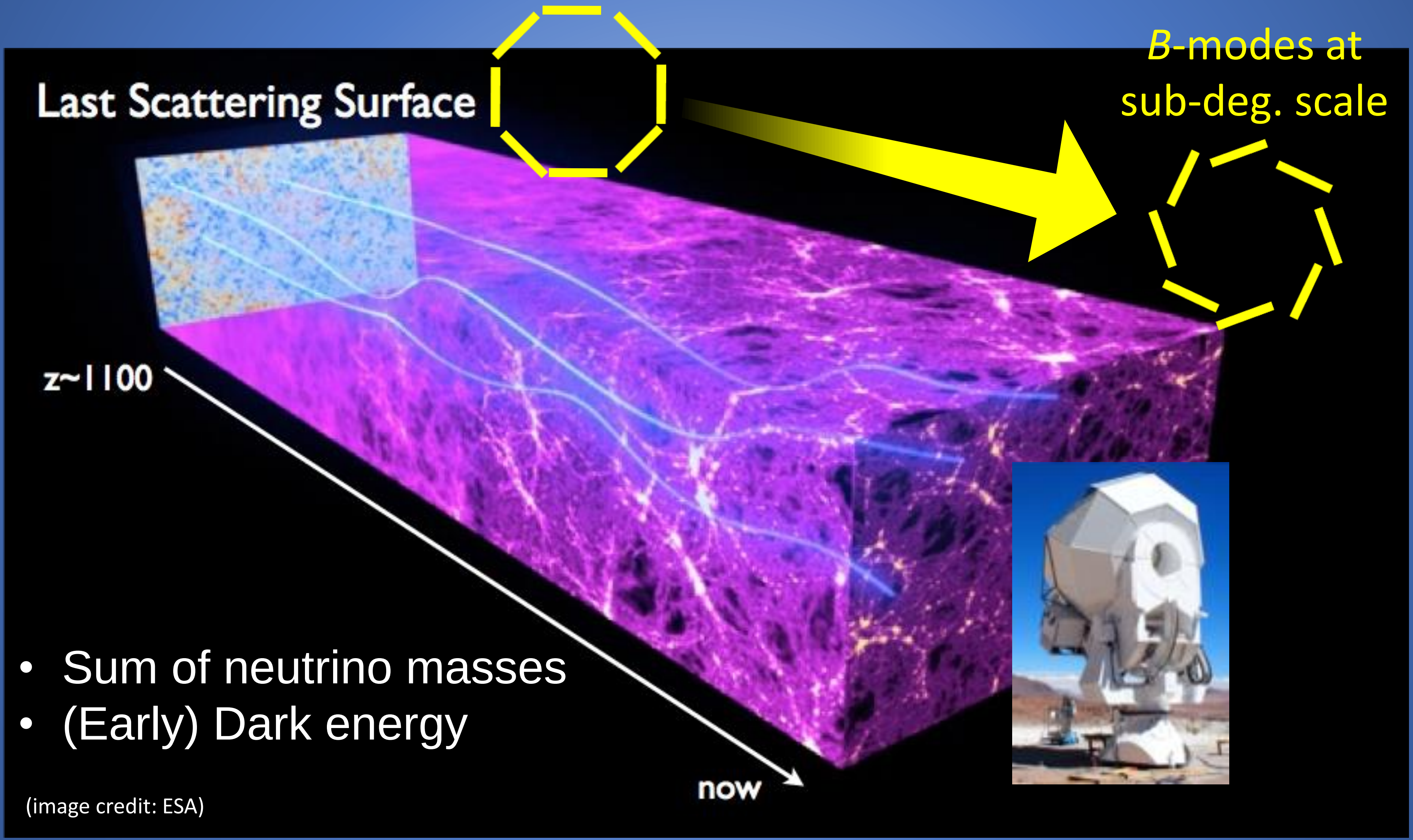
Decompose the all-sky CMB polarization into two patterns

Density Fluctuations → E-mode (Dominant, discovered)

Primordial Gravitational Waves → E-mode + B-mode (Faint, undetected)

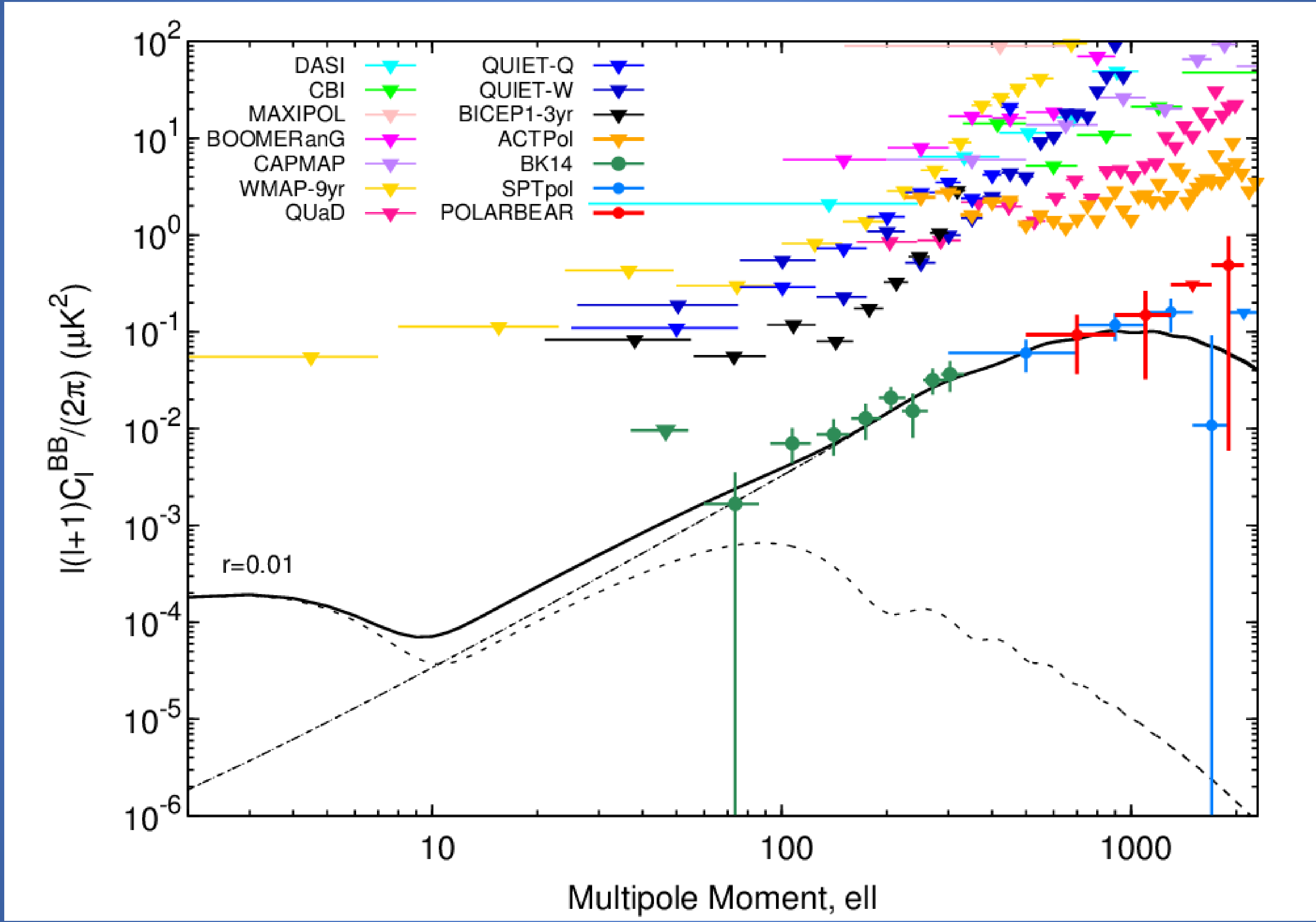
B-mode polarization makes it possible to probe primordial gravitational waves!

Lensing *B*-modes *by Weak lensing*



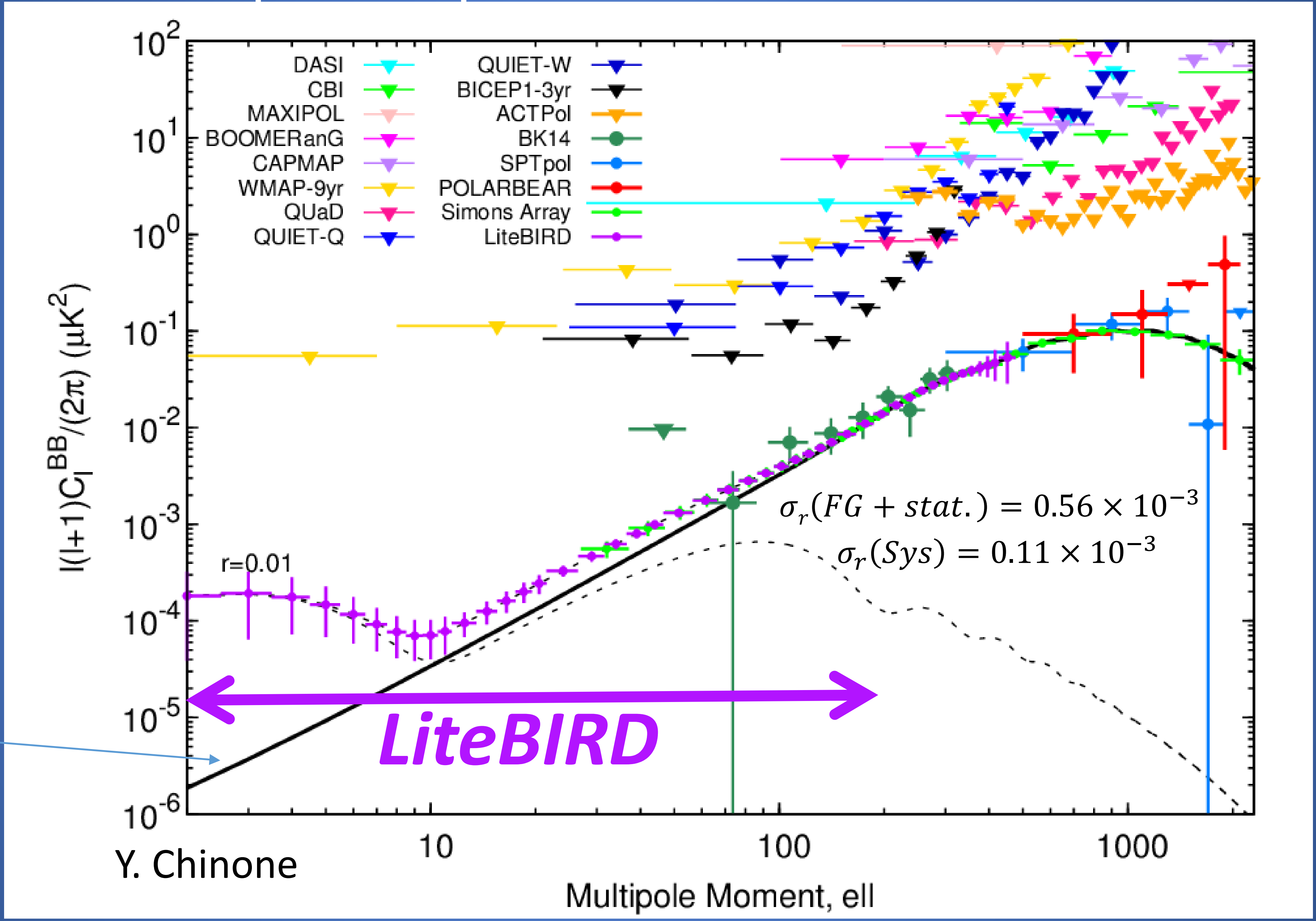
(image credit: ESA)

B-mode power spectrum measurements



Y. Chinone

B-mode power spectrum measurements



B-mode spectrum due to gravitational lensing ~5μK・arcmin

Why the $\delta r < 0.001$ goal?

- Many models predict $r > 0.01$. → Discovery at $>10\sigma$.
- In case primordial gravitational waves are not seen:
  - Focus on models with less parameters (Occam's Razor)
  - Most single field slow-roll says

$$r \simeq 0.002 \left(\frac{60}{N}\right)^2 \left(\frac{\Delta\phi}{m_{pl}}\right)^2$$

Lyth relation

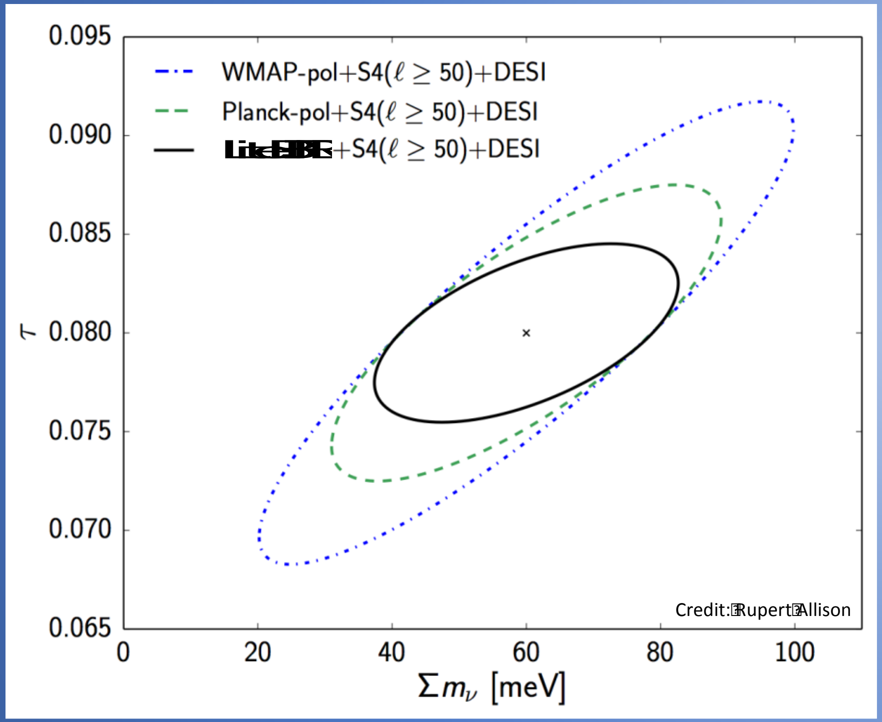
N: e-folding, m_{pl}: reduced Planck mass

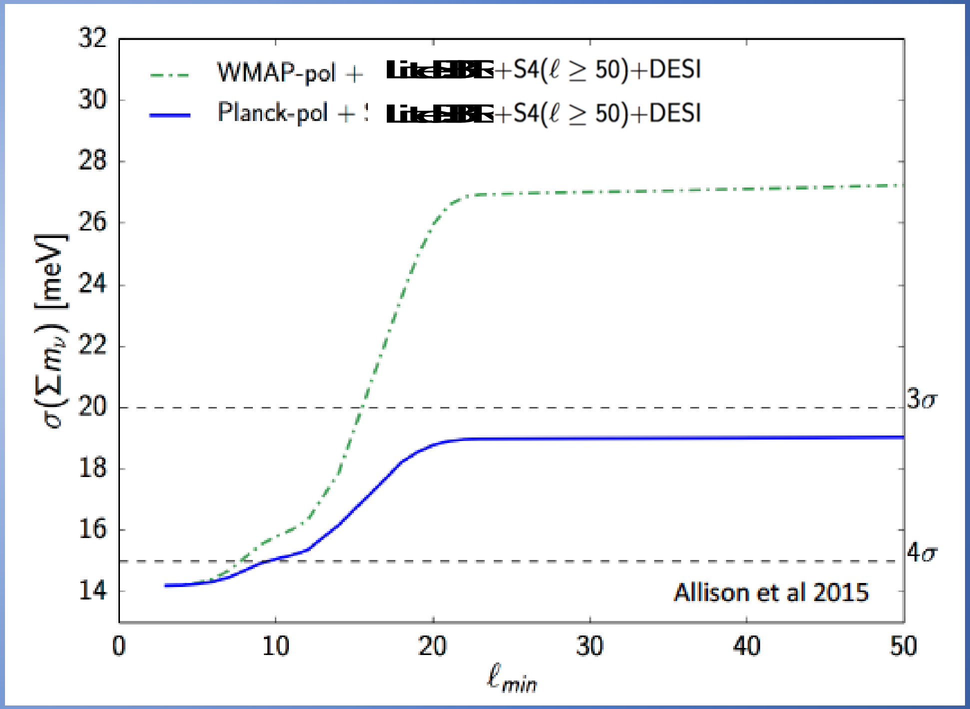
  - If LiteBIRD achieves $r < 0.002$ (95%C.L.), those that satisfy $\Delta\phi > m_{pl}$ in the typical inflation models are rejected.
    - Important milestone in the goal to identify the correct models.
    - Possible to obtain similar results in more model-dependent analyses.

τ (optical depth) and neutrino mass

- Precise τ measurement with E-mode polarization can improve the neutrino mass measurement.

arXiv:1509.07471





Better E-mode measurements in the multipole range $l < 20$ will improve τ measurement precision.

Large scale E-mode polarization measurement is needed!

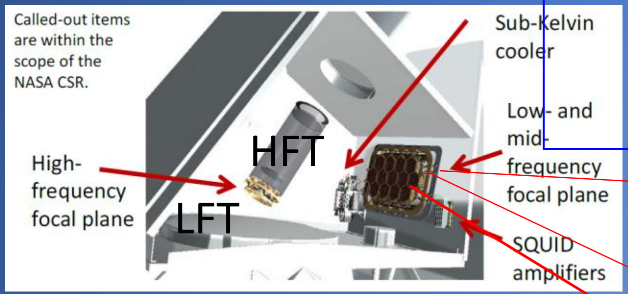
Achieving the Mission Requirements:

- All-sky survey in space
  - Observation at a large angular scale with about 30' angular resolution
  - No effects by atmosphere
- Statistical errors
  - Conduct three years of all-sky observation with 2622 superconducting sensors, and achieve 2.5 μK・arcmin.
- Foreground removal
  - Observation of 15 bands between 40～402GHz
  - Development of FG removal algorithm with models.
- Systematic errors
  - Mitigation by polarization modulation with Half Wave Plates (HWPs) and scan strategy.
  - Other effects: cosmic ray glitches and radiation tolerance.

Observation Apparatus Overview

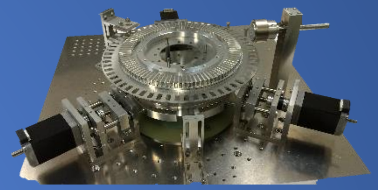
- Mission module benefits from heritages of other missions (e.g. Hitomi) and ground-based experiments (e.g. POLARBEAR). Bus module based on high TRL components

Multi-chroic focal plane detectors

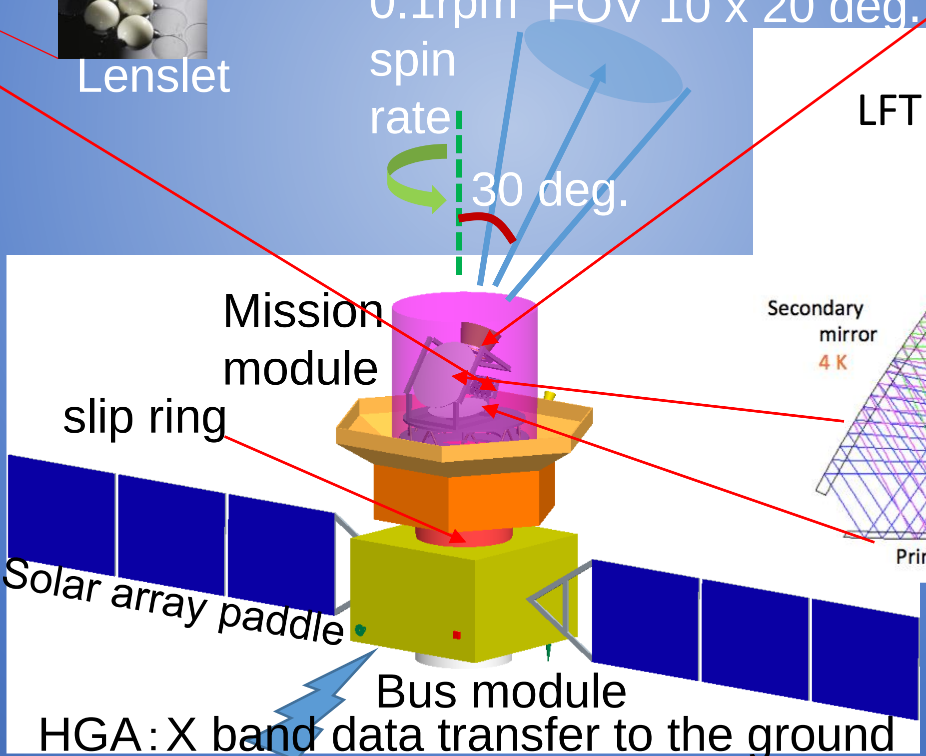


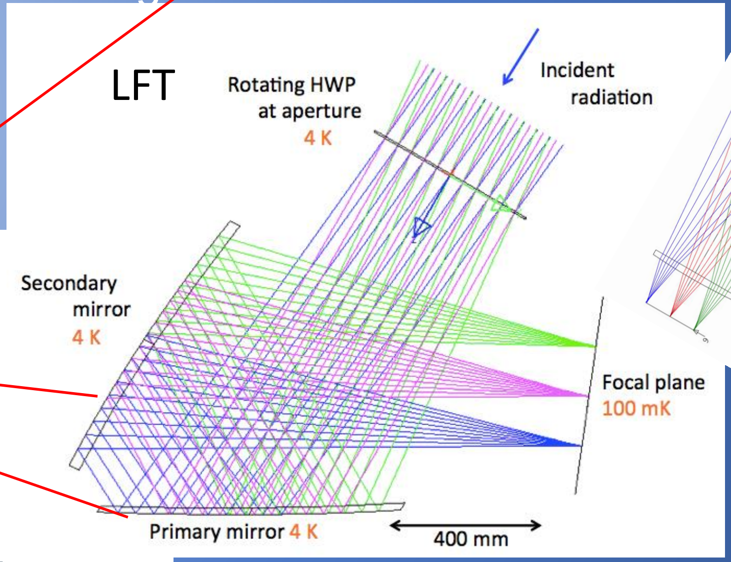
Lenslet

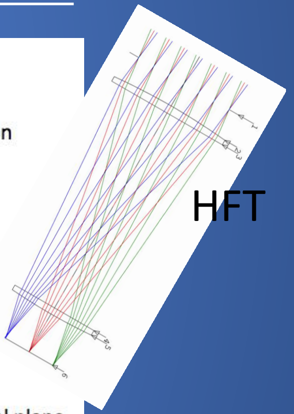
Sinuous antenna and TES



Continuously-rotating half wave plate (HWPs) for LFT and HFT



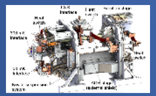


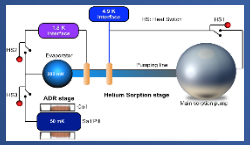


Mirrors at 4K

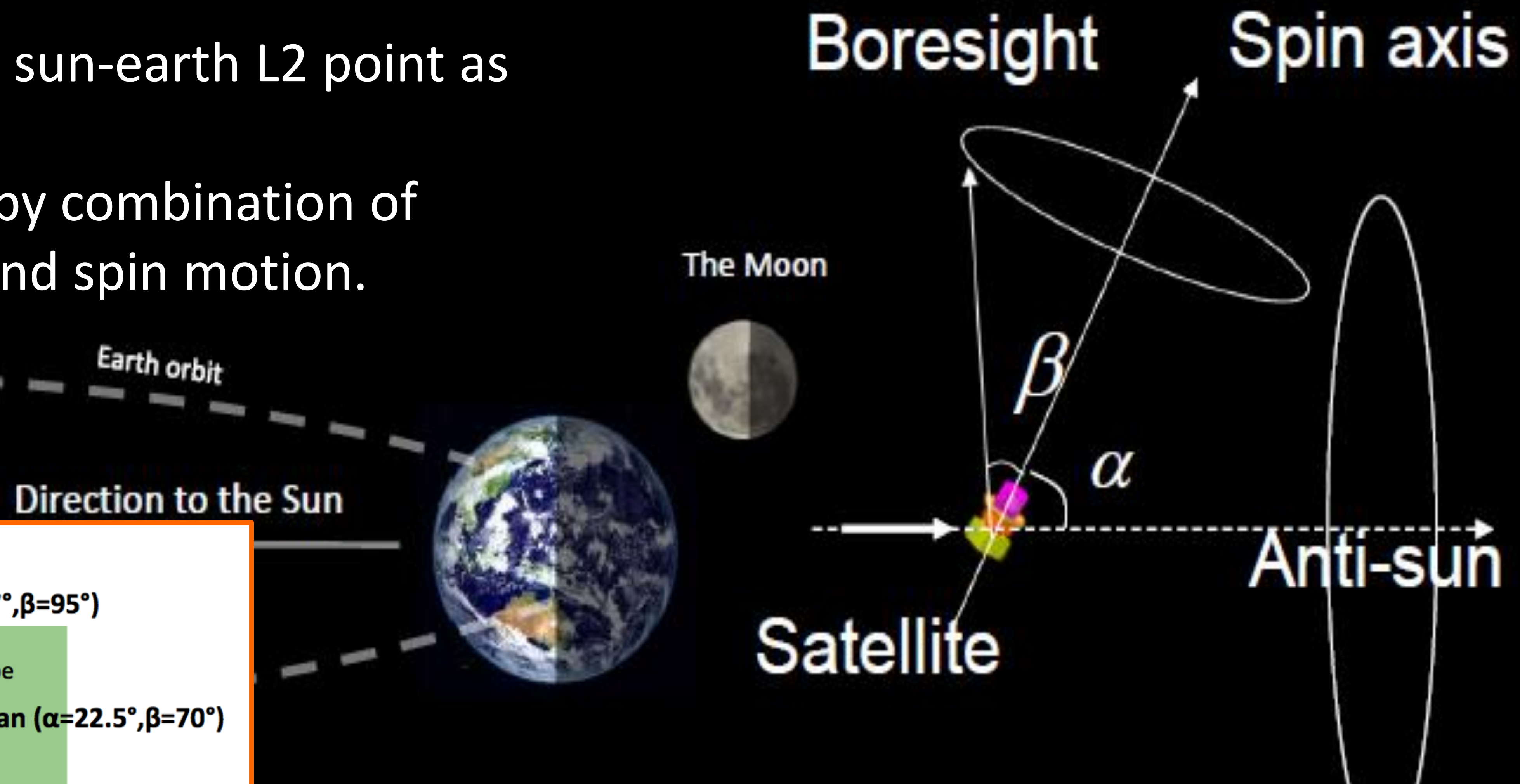
Cryogenics

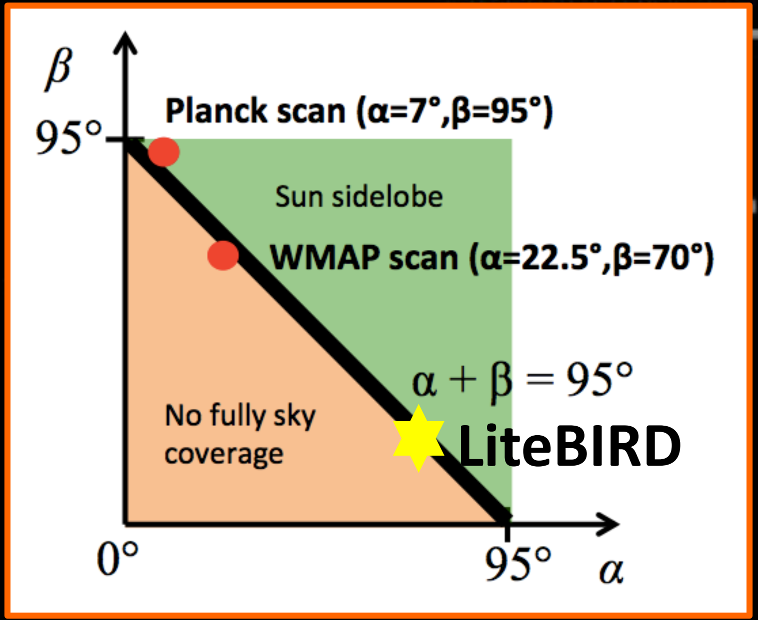
- JT/ST and ADR to generate 0.1 K





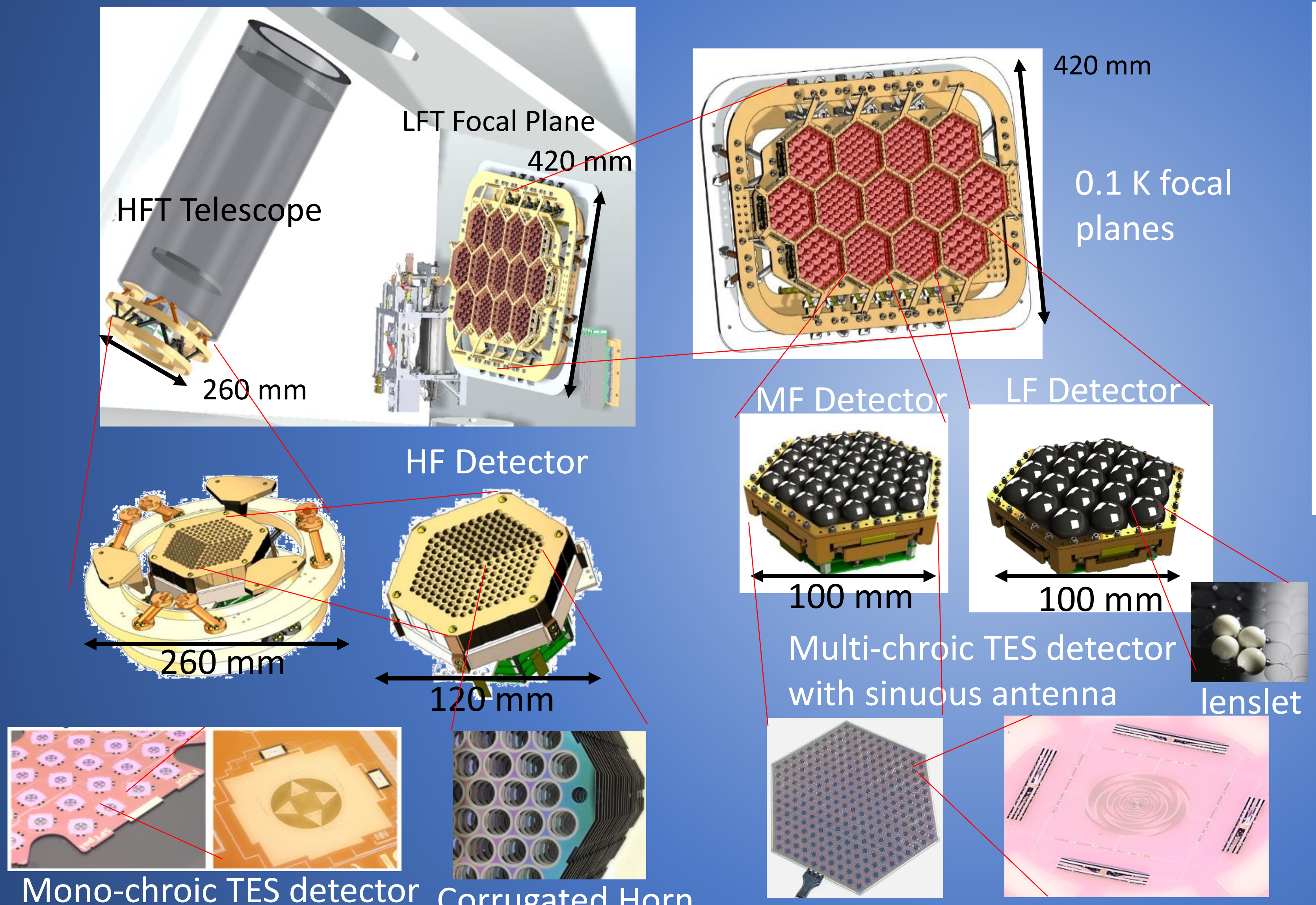
- Halo orbit at sun-earth L2 point as our baseline
- All-sky scan by combination of precession and spin motion.

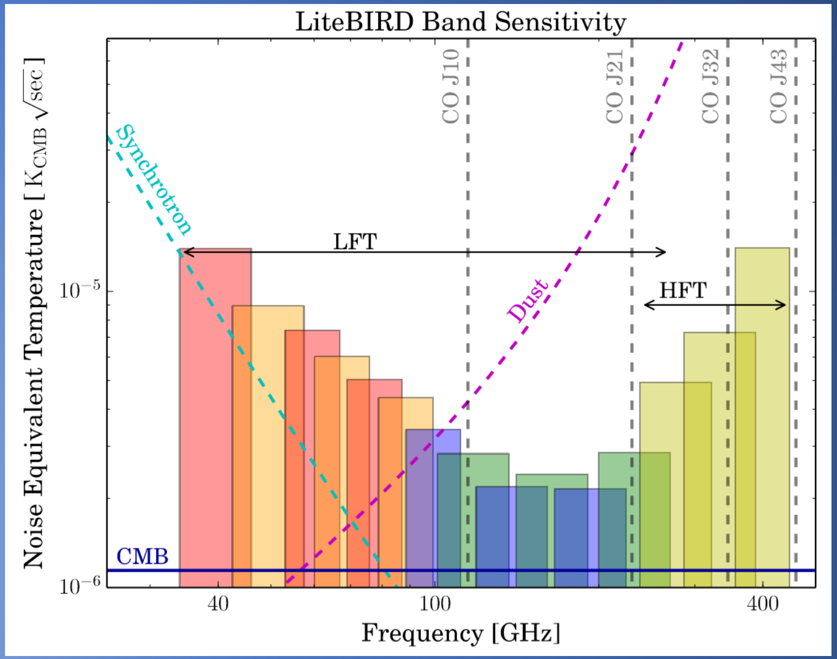




Precession angle α=65 deg. 90 min.~1day/1 rotation
Spin angle β=30 deg. ~10 min./1 rotation

Detector (Transition Edge Sensor, TES)





2622 TES bolometers cover 15 bands in the frequency range of 40 to 402 GHz.

Total sensitivity: 2.5 μK • arcmin with 3 years all sky observation with a margin factor of 1.7.

Optical System

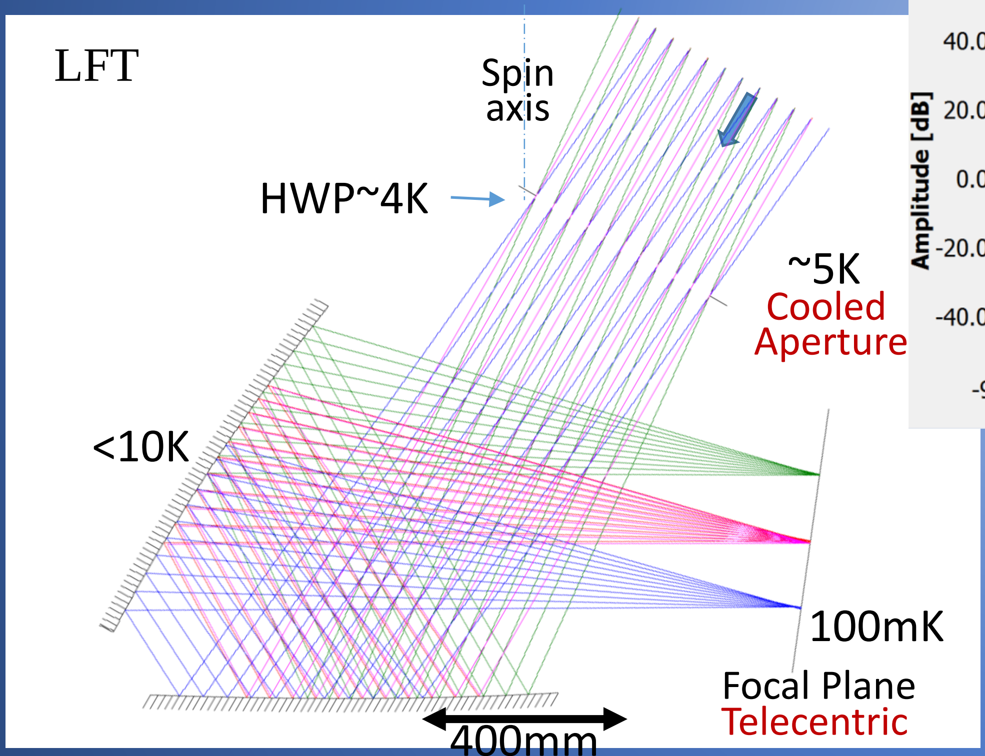
H. Imada

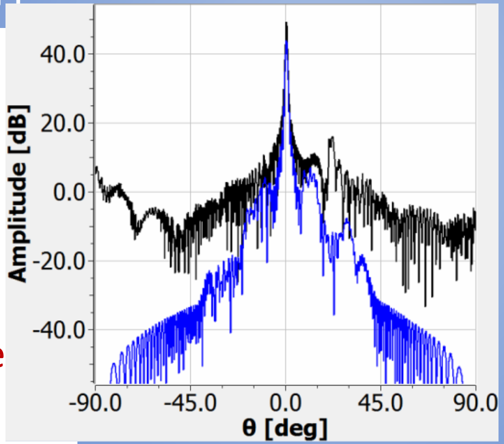
- Beam size：~< 1 deg.
- FOV: 10 x 20 degs.
- Aperture Size: 40cm

- Cold Baffle and Mirrors
- Half-wave plate to modulate polarization
- Telecentric

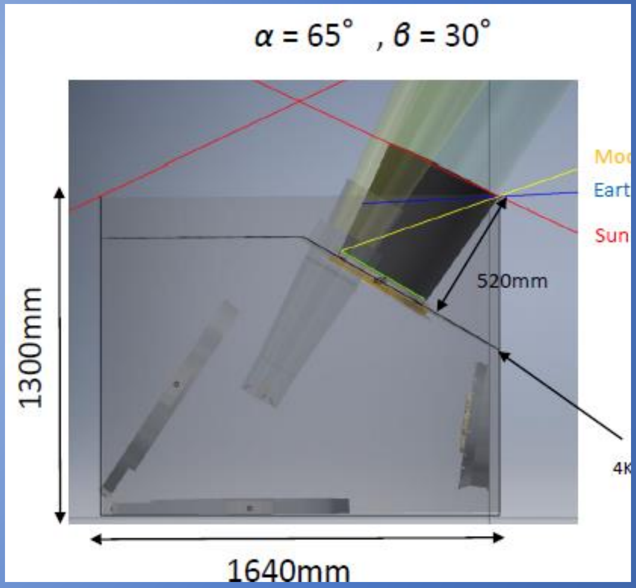
T. Hasebe

Crossed-Dragone Optical System





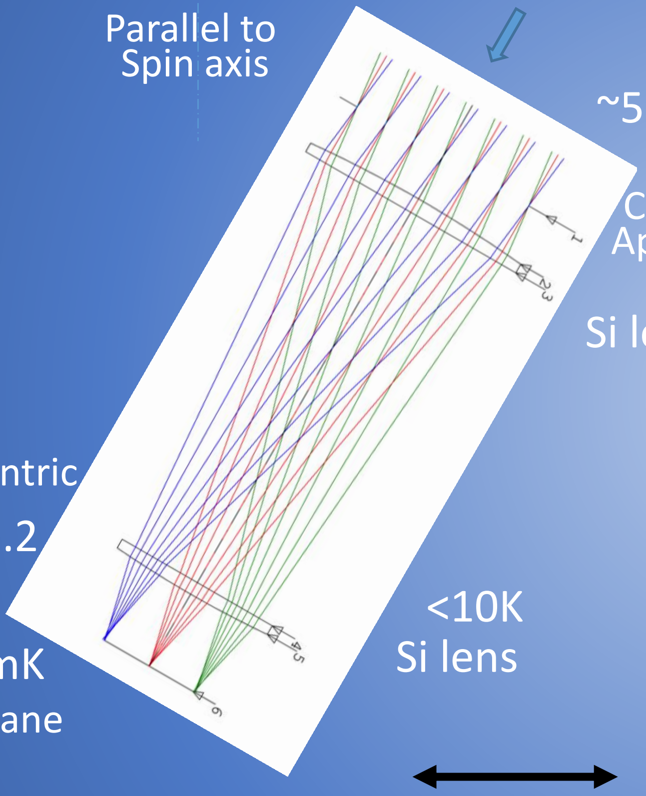
GRASP10 Simulation@60GHz, removing side-lobe w/ baffle



Thermal and structure designing, trade-off studies

Y. Sekimoto

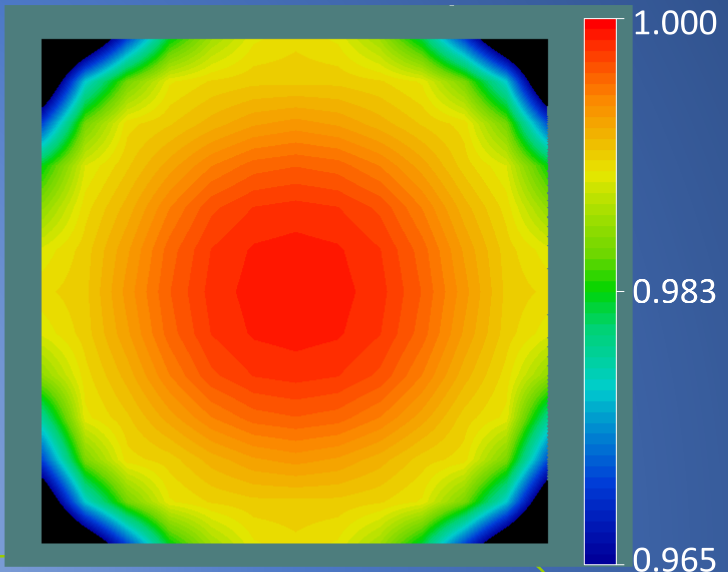
Design of high frequency telescope (HFT)

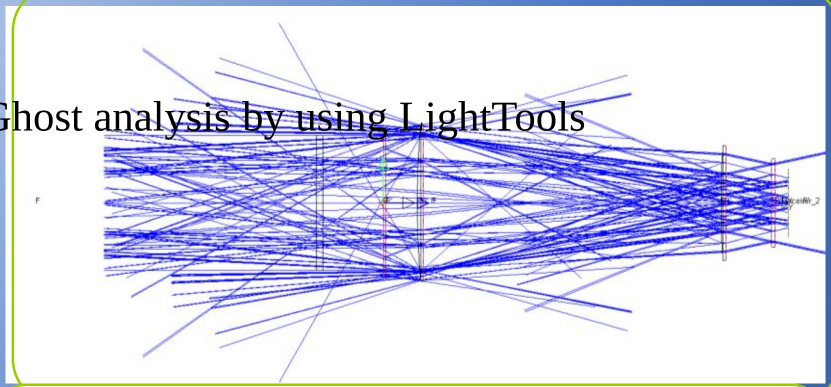


High Frequency (280-402GHz) telescope
Two plano-convex aspherical Si lenses (**φ<250mm**).

Cryogenically cooled entrance aperture to control sidelobe of feed.

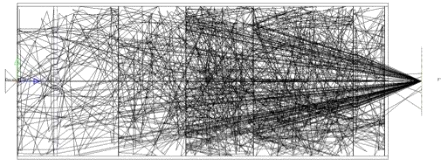
Strehl ratio @340GHz over **13x13deg^2**



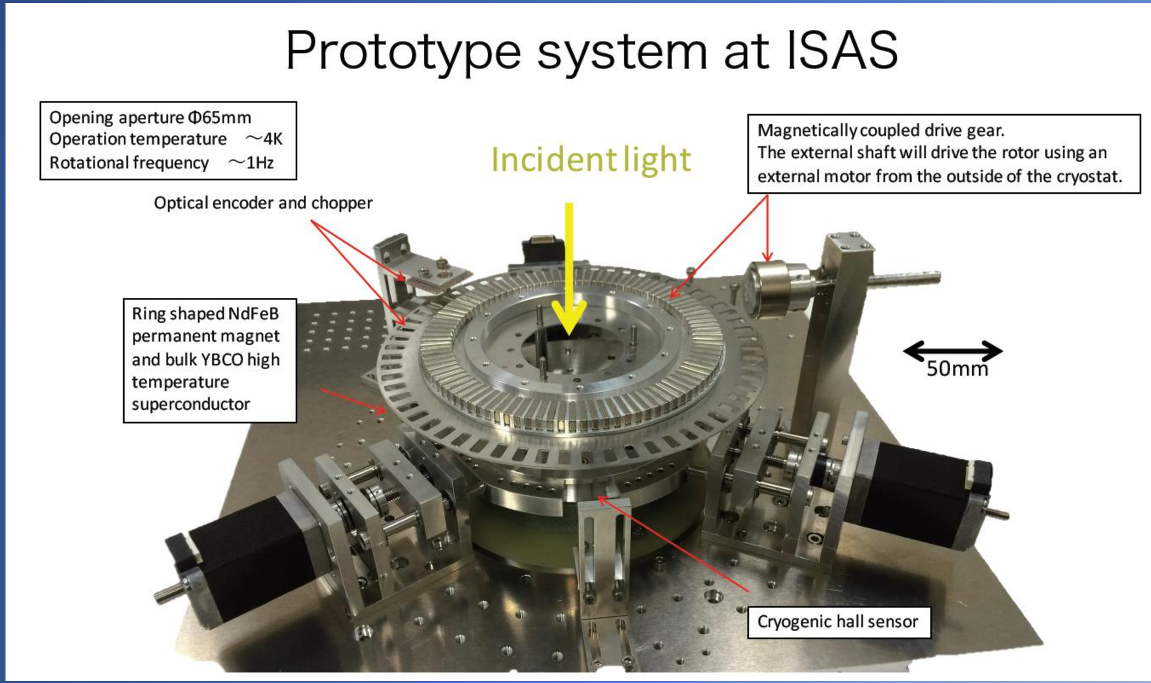


Ghost analysis by using LightTools

Stray Light analysis by using LightTools

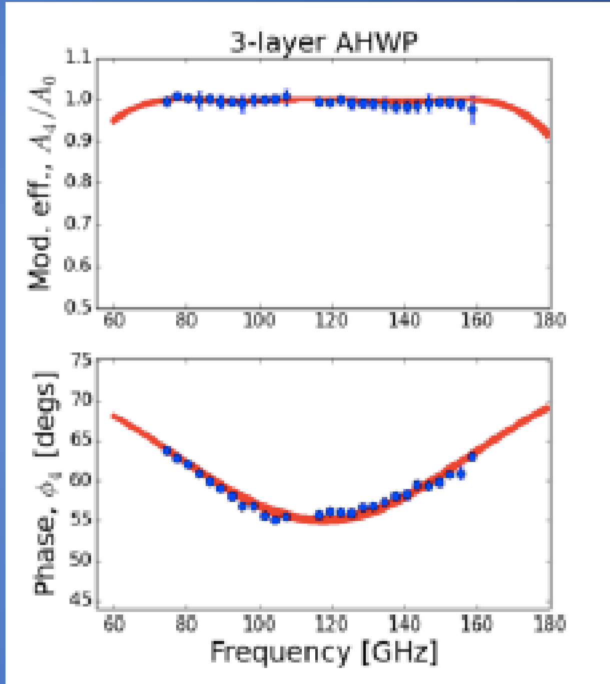


Continuous Rotating HWP

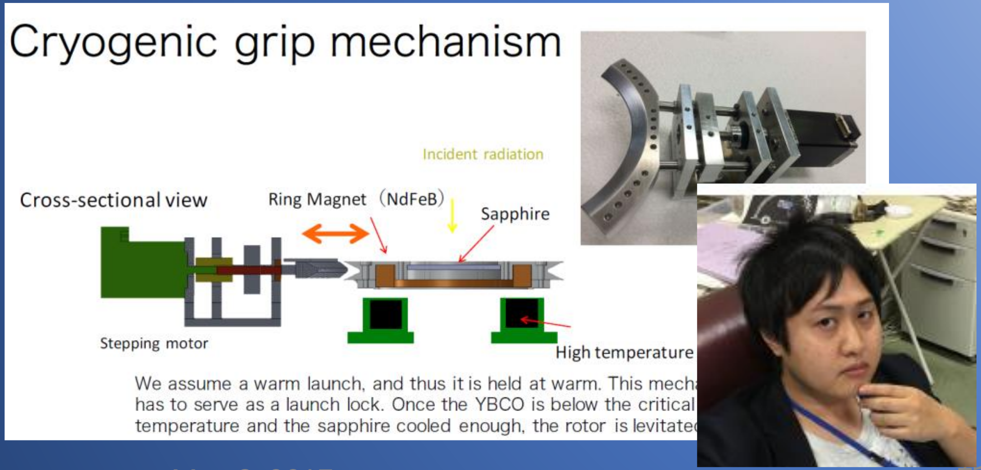


Test Cryostat to create 4K environment

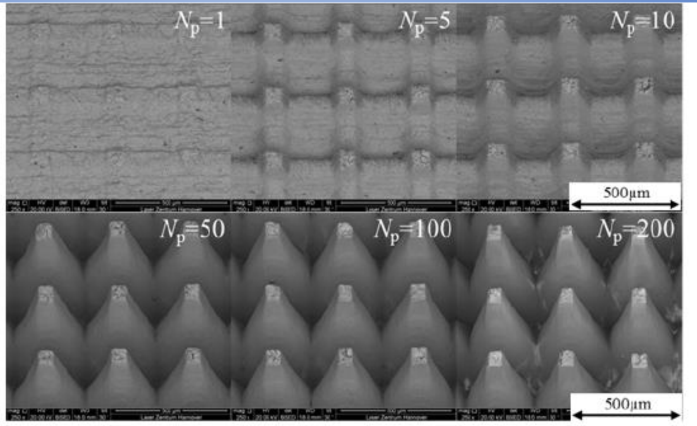
T. Matsumura et al., Appl. Opt. 55 (2016)3502



Anti-Reflection Coatings for Sapphire Substrate with Moss-eye structure



Y. Sakurai



>98% pol. modulation efficiency is required, demonstrated with three layers

Goal: Nine layer AHWP to cover the frequency range of LFT

Frequency Dependence of the Foregrounds

Foreground Radiation Model (H. Kanai et al.)

Synchrotron Radiation

$$S(\nu,\hat{\boldsymbol{n}}) = \left(\frac{\nu}{\nu_*}\right)^{\beta_S(\hat{\boldsymbol{n}})} S(\nu_*,\hat{\boldsymbol{n}})$$

Dust Radiation

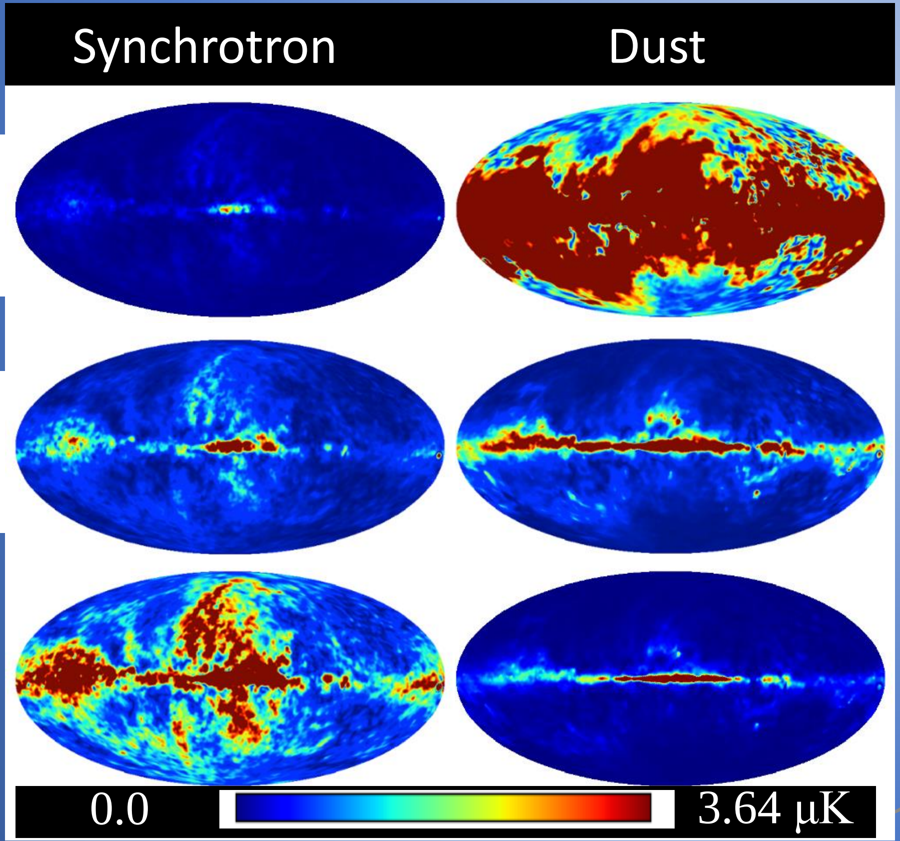
$$D(\nu,\hat{\boldsymbol{n}}) = \left(\frac{\nu}{\nu_*}\right)^{\beta_D(\hat{\boldsymbol{n}})} D(\nu_*,\hat{\boldsymbol{n}})$$

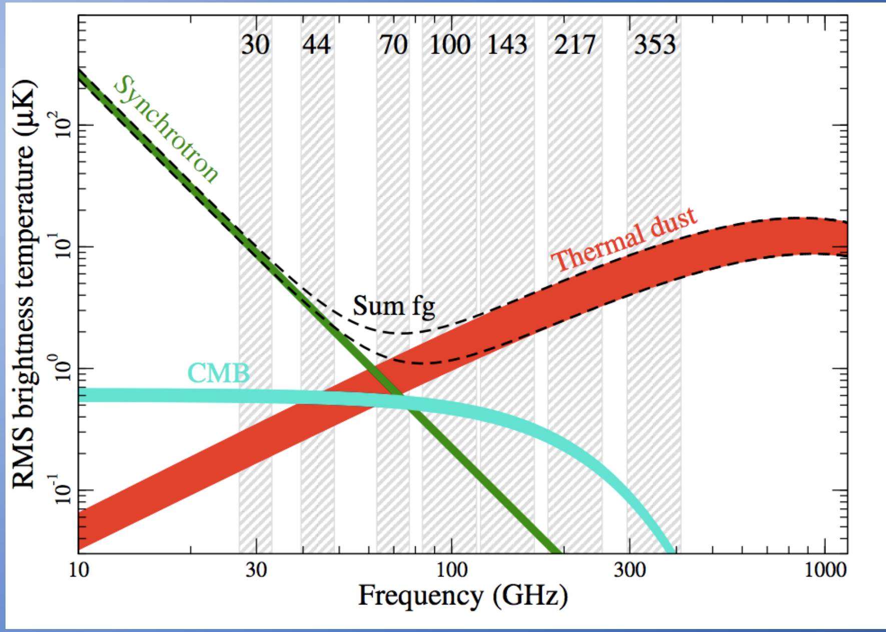
$\beta(\hat{\boldsymbol{n}})$: Spectral Index

Parameter to indicate freq. dependency of foregrounds. (different value for each direction)

280 GHz

100 GHz





↑ Difference of freq. dependencies of foregrounds and CMB polarization strength.

Planck 2015 results. I.

Improvement of Template Removal Method

Consider spatial variations of spectral index by using a "delta map", which is obtained from two observation maps for a foreground radiation, as template.

Consider dust and synchrotron

$$\mathrm{Map}(\nu,\hat{n}) = \mathrm{CMB} + g_\nu \left(\frac{\nu}{\nu_*}\right)^{\beta_\mathrm{D}(\hat{n})} \mathrm{Dust}(\nu_*,\hat{n}) + \mathrm{noise},$$

Taylor expand as $\beta = \bar{\beta} + \delta\beta(\hat{\boldsymbol{n}})$, and approximate to the primary of $\delta\beta$.

$$\mathrm{Map}(\nu,\hat{n}) \approx \mathrm{CMB} + g_\nu \left(\frac{\nu}{\nu_*}\right)^{\bar{\beta}_\mathrm{D}} [1 + \ln(\nu/\nu_*)\,\delta\beta_\mathrm{D}(\hat{n})]\mathrm{Dust}(\nu_*,\hat{n}) + \mathrm{noise},$$

Create a delta map using multiple frequency measurements.

$$\Delta\mathrm{Map}(\nu_1,\nu_2,\hat{n}) \equiv \frac{g_\nu}{\ln(\nu_2/\nu_1)} \left\{ \left(\frac{\nu}{\nu_1}\right)^{\bar{\beta}_\mathrm{D}} \frac{\mathrm{Map}(\nu_1,\hat{n})}{g_1} \ln\left(\frac{\nu_2}{\nu}\right) - \left(\frac{\nu}{\nu_2}\right)^{\bar{\beta}_\mathrm{D}} \frac{\mathrm{Map}(\nu_2,\hat{n})}{g_2} \ln\left(\frac{\nu_1}{\nu}\right) \right\}.$$

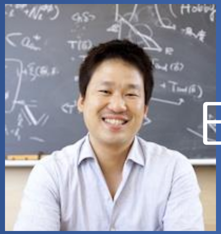
Create a map with FG removal

$$x'(\nu,\hat{n},\bar{\beta}_\mathrm{D}) = \frac{\mathrm{Map}(\nu,\hat{n}) - \Delta\mathrm{Map}(\nu_1,\nu_2,\hat{n})}{1 - \frac{g_\nu}{\ln(\nu_2/\nu_1)} \left\{ \left(\frac{\nu}{\nu_1}\right)^{\bar{\beta}_\mathrm{D}} \frac{\ln(\nu_2/\nu)}{g_1} - \left(\frac{\nu}{\nu_2}\right)^{\bar{\beta}_\mathrm{D}} \frac{\ln(\nu_1/\nu)}{g_2} \right\}}$$

T. Yamashita,
K. Ichiki,
N. Katayama,
E. Komatsu

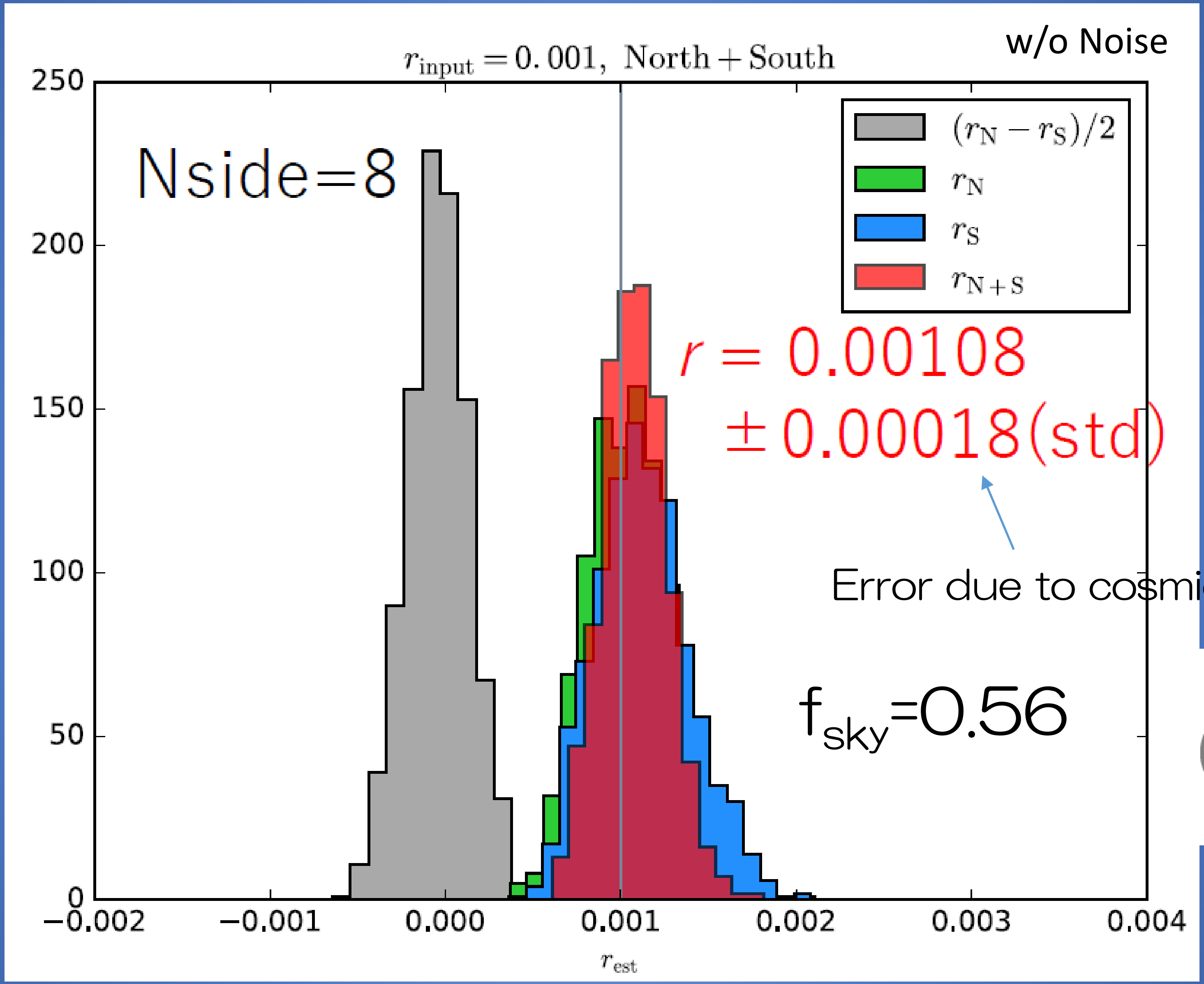
T. Yamashita

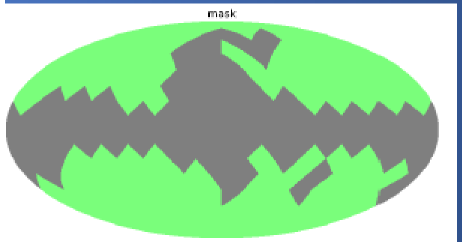
K. Ichiki



E. Komatsu

N. Katayama





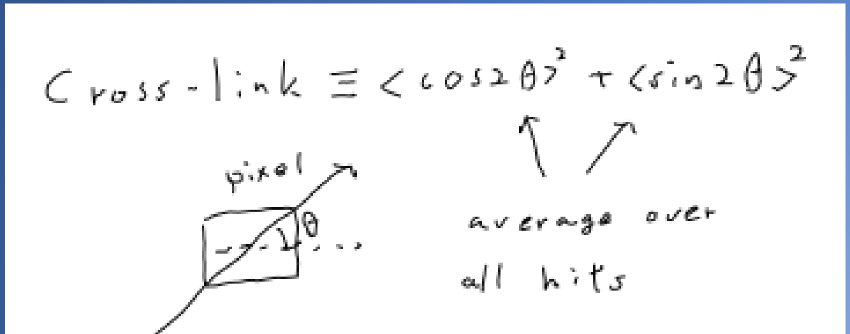
Systematic uncertainties

- The HWPs modulate the polarization of incoming light
  - allowing us to use a single pol. sensitive detector to measure Q and U
  - mitigating the leakage from temperature to polarization and the 1/f noise
- Remaining systematics:
  - The leakage from E mode to B mode
    - Polarization angle of detector
    - Pointing knowledge
  - Other systematics
    - Side-lobe
    - Cosmic ray glitches
    - HWP
  - Simulation studies are being performed for the estimation and determination of the spacecraft specification

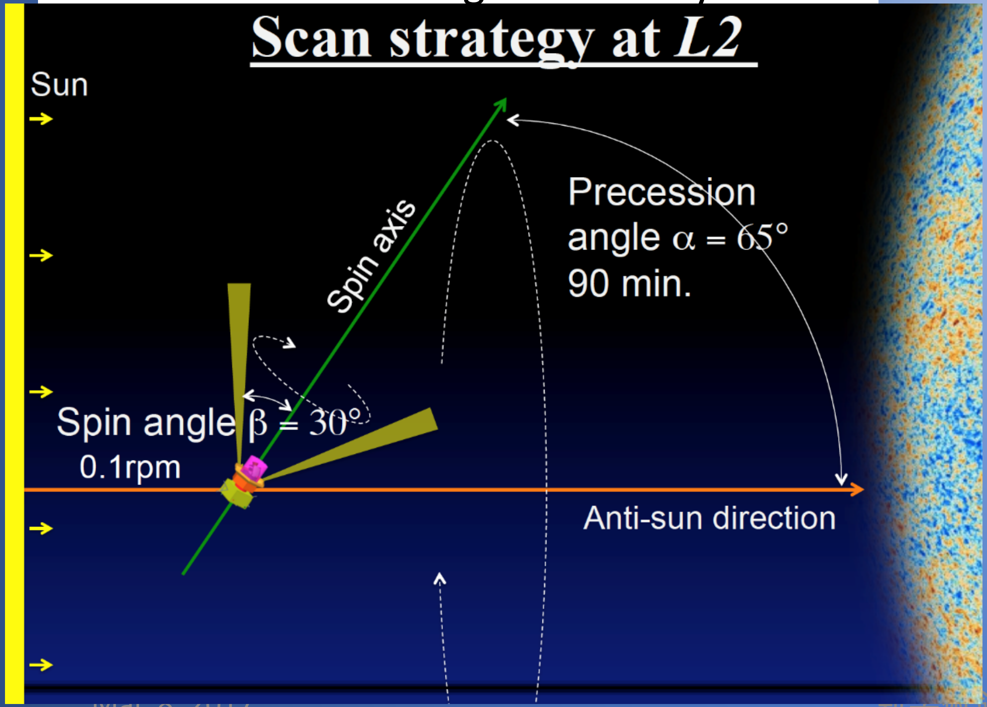
R. Nagata

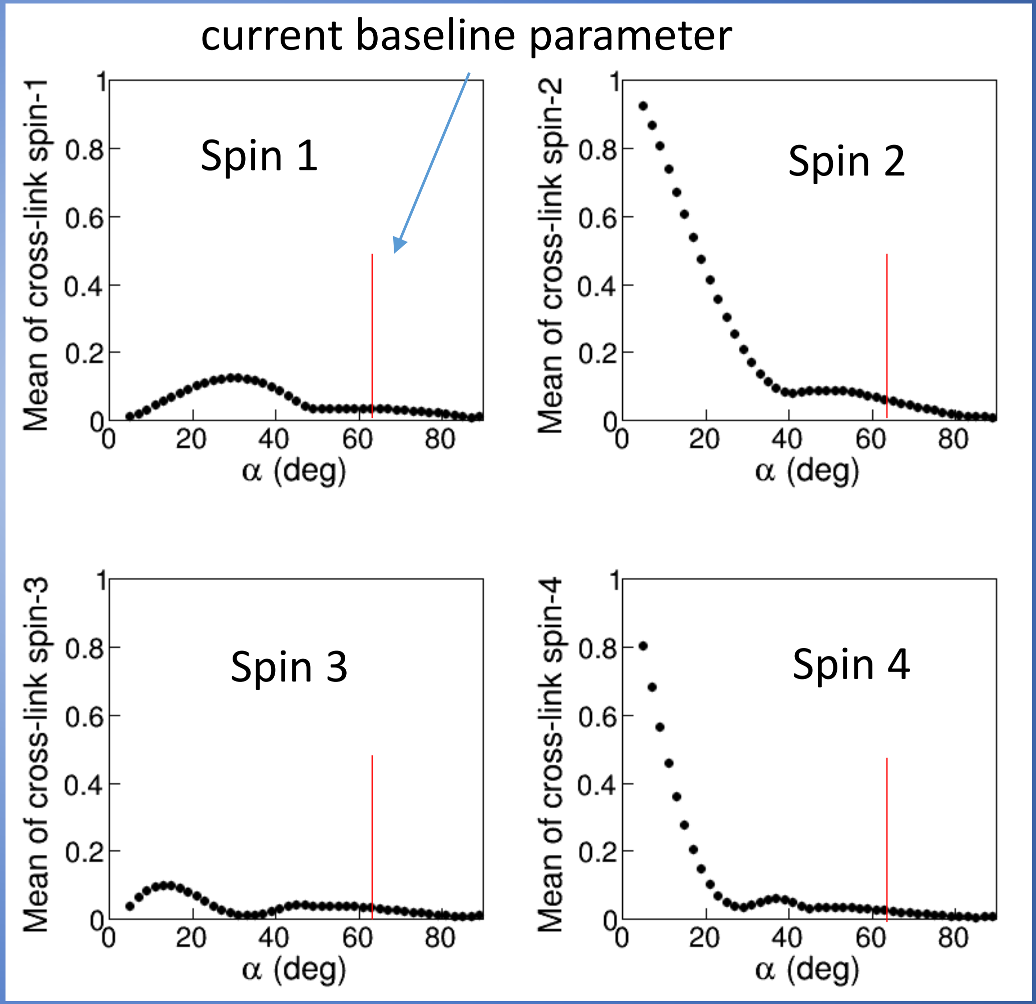
		Requirements	Exp. Meas. Error
12	Pointing knowledge of bore-sight	< 3 arcmin	0.23 arcmin
13	Abs. pol. angle	< 1 arcmin	1 arcmin

Systematic and cross-link



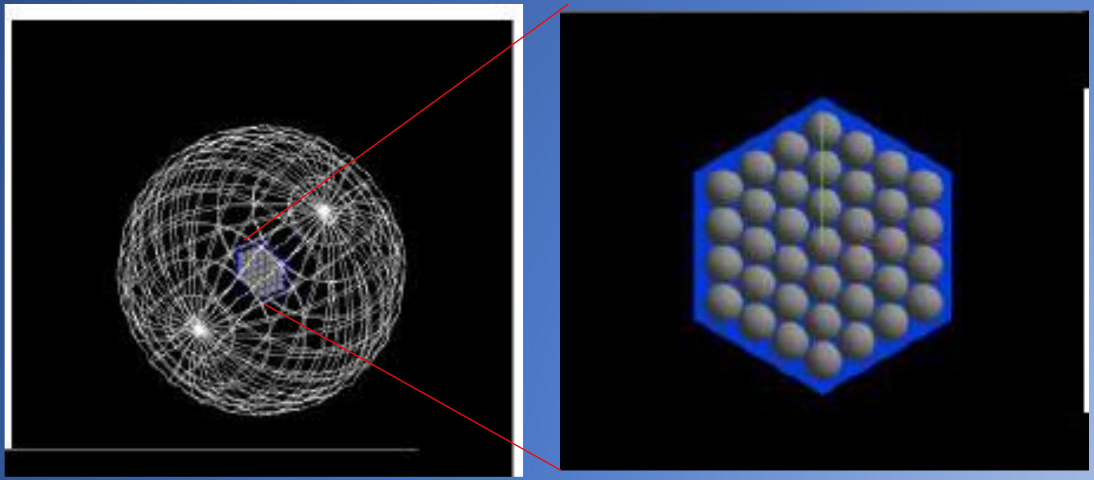
Cross-link values are directly related with the magnitude of systematics

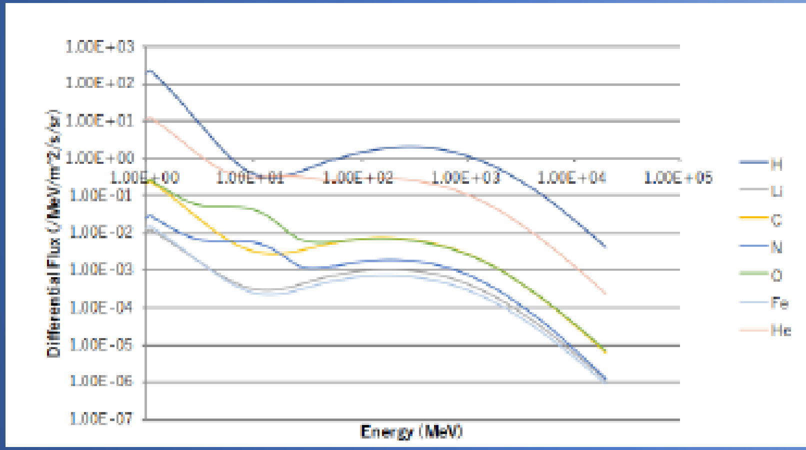




S. Uozumi

Cosmic ray glitch studies



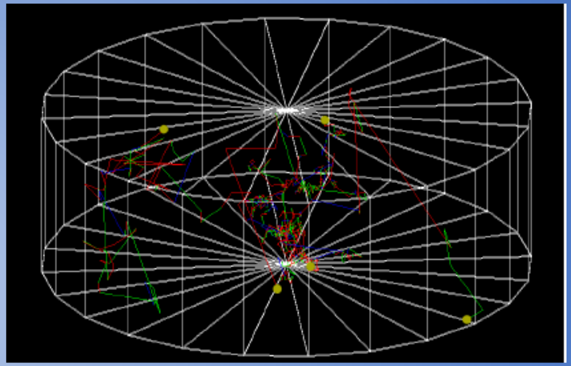


SPENVIS + Geant 4

Cosmic ray rate: ~1.3/cm^2/s

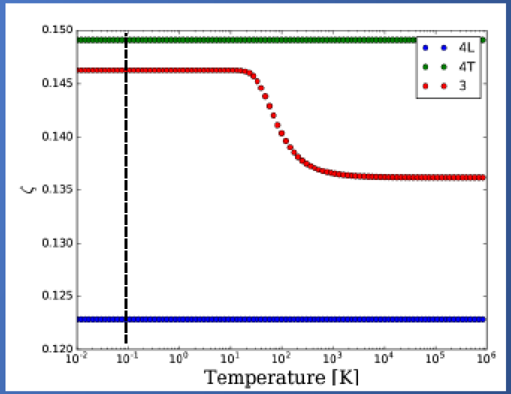
A. Kibayashi

Development of a simulation for the ballistic phonon propagation in Si with the boundaries based on G4CMP



Y. Minami

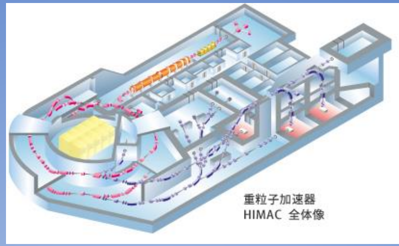
Calculation of phonon transmission probability between Au and Si based on dispersion models



Comparison with a real detector will be performed and mitigation of glitches will be studies

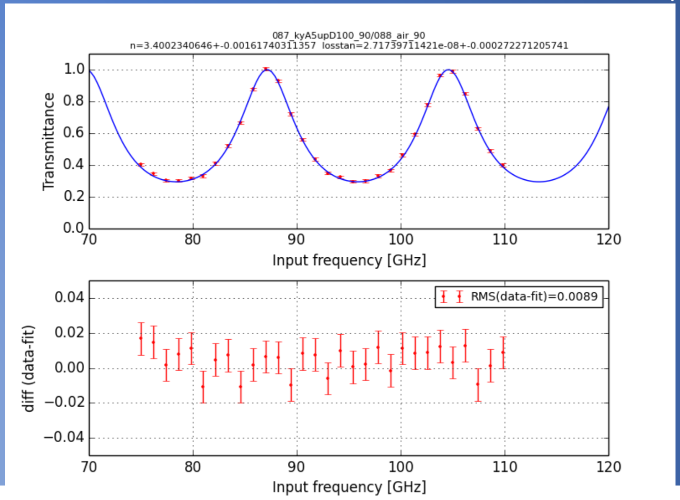
Proton Beam Irradiation Test

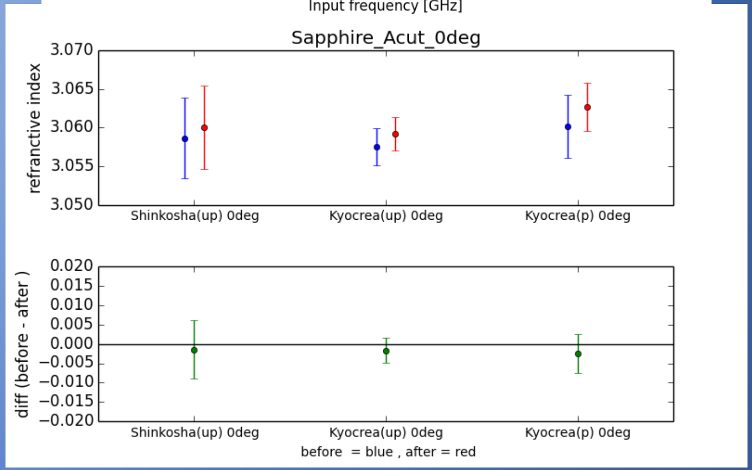
160MeV proton beam ~ 10krad irradiation @ NIRS

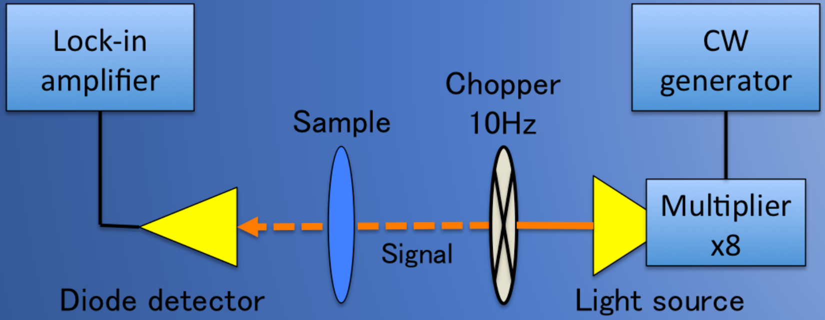


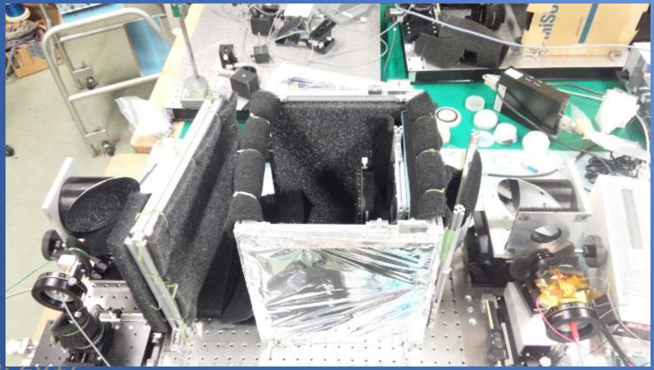
http://www.nirs.go.jp/rd/collaboration/himac/outline.shtml

Example: Measurement of refractive index before and after irradiation on sapphire









Millimeter wave transmittance measuring device @ Kavli IPMU

K. Komatsu

Irradiation test done also for AR, superconducting detector, magnets, etc.

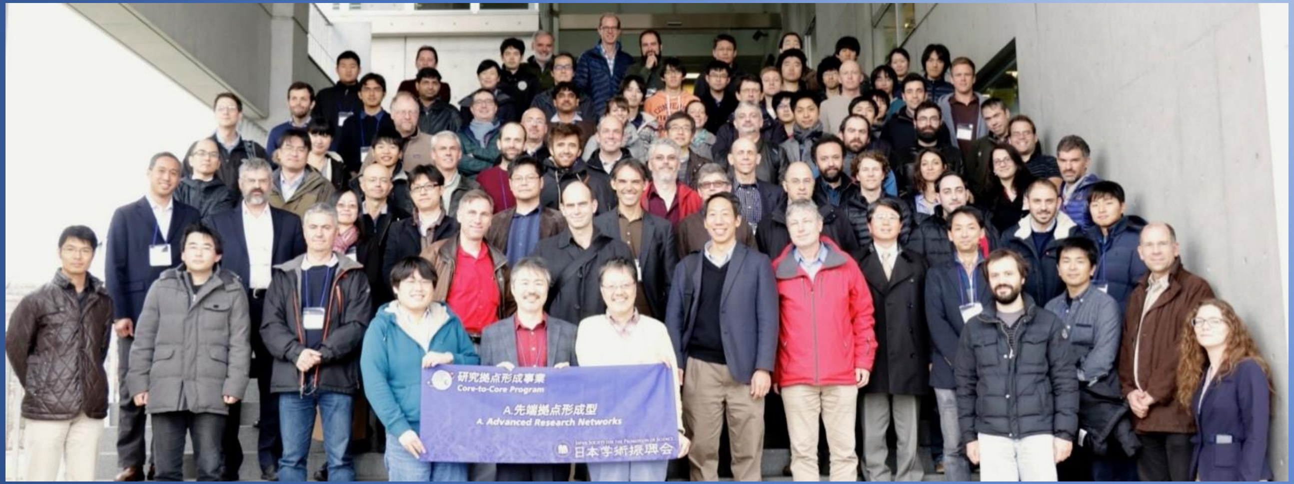
T. Matsumura, K. Komatsu, H.I, et al.

The status of LiteBIRD

- A candidate of JAXA's next strategic large missions, aiming to launch in mid of 2020's
- LiteBIRD selected as one of the top-priority projects in Master Plan 2014 and 2017 by Science Council of Japan.
- LiteBIRD chosen as one of ten new projects in MEXT Roadmap 2014 for Large-scale Research Projects.
- Formal proposal submitted to the ISAS, JAXA in Feb., 2015. First evaluation is passed. Starting the conceptual design phase-A1 in Sep. 2016.
- The US LiteBIRD team has submitted a proposal to NASA's missions of opportunity in Dec. 2014 to supply the focal plane detectors and a sub-Kelvin refrigerator system. It passed the first evaluation, and conceptual study (Phase A) is ongoing.

T. Dotani, Phase-A1 team leader

JSPS Core to Core meeting "B mode from Space" at Kavli IPMU, Dec. 2015



Second meeting "B mode from Space" at McGill University, Jan. 2017

International collaboration for LiteBIRD R&D

Summary

- LiteBIRD is a satellite designed to measure the gravitational wave strength at $\delta r<0.001$ by precisely observing the CMB B-mode polarization.
- It measures B-mode power spectrum in the range of $2 \leq \ell \leq 200$ at $2.5\,\mu$K • arcmin sensitivity by observing all-sky with 2622 superconducting detector sensors for three years.
  - Remove foreground radiation in observation frequency range of 40～402GHz with 15 bands.
  - Estimation of systematic errors/calibration accuracy using simulation and requirements of the satellite specifications currently under evaluation.

Backup slides

Summary of the systematics

Category	Effect	Mitigation
Diff. gain	T -> B	Pol. Modulation
Diff. pointing	dT -> B	Pol. Modulation
Diff. beam width	dT -> B	Pol. Modulation
Diff. beam ellip.	dT -> B	Pol. Modulation
Pointing knowledge	E -> B	Star Tracker
Gain drift	E -> B	Gain calibration
Beam width drift	E -> B	Beam calibration
Pol. angle	E -> B	Cl_EB
1/f noise	Det. -> B	Pol. Mod. or Fast scan
Bandpass mismatch	T -> B	Pol. Modulation
Cosmic ray glitches	Det. -> B	Template subtraction
Time constant	Det. -> B	Calibration
Side-lobe	T -> B	Beam calibration
Half Wave Plate	T -> B, E -> B	Calibration

T: CMB 2.7K monopole, dT: CMB temp. anisotropies, E: E-mode pol, B: B-mode pol., Det.: Detector