Future missions on CMB polarization : LiteBIRD

↑
Title I was given

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(KEK / Kavli IPMU / SOKENDAI)

Xith Rencontres Du Vietnam
Cosmology
50 Years After CMB Discovery

Physics of primordial CMB B-mode

- Direct evidence for cosmic inflation

- GUT-scale physics

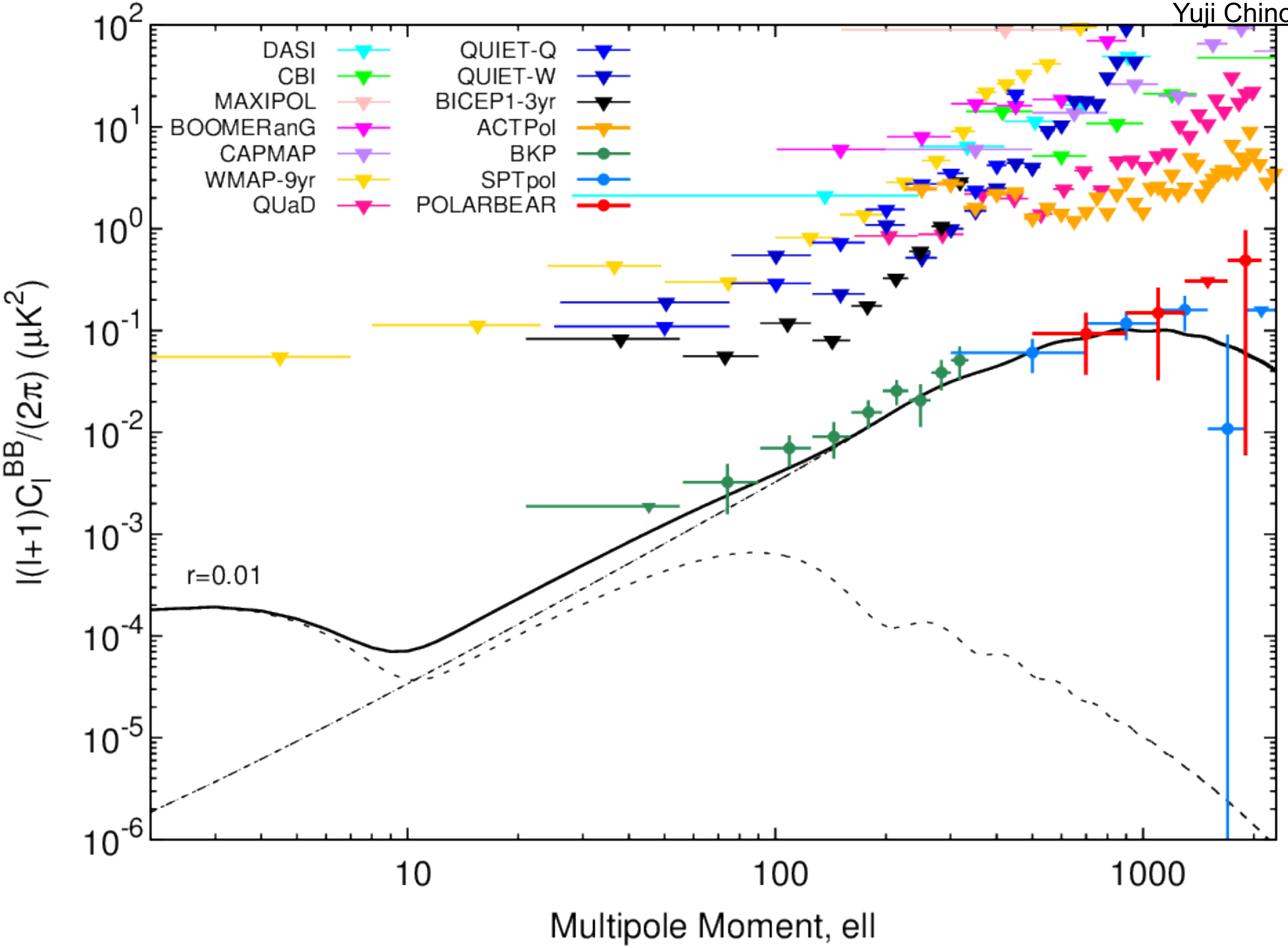
$$V^{1/4} = 1.06 \times 10^{16} \times \left(\frac{r}{0.01}\right)^{1/4} \quad [\mathrm{GeV}]$$

V: Inflaton petential, r: tensor-to-scalar ratio

- Arguably the first observation of quantum fluctuation of space-time !

Limits on r as of August 20, 2015

- Planck Temperature: $r < 0.11$ (95%C.L.)
- “BKP” Polarization: $r < 0.12$ (95%C.L.)
- Combined: $r < 0.09$ (95%C.L.)


DASI
CBI
MAXIPOL
BOOMERanG
CAPMAP
WMAP-9yr
QUaD
QUIET-Q
QUIET-W
BICEP1-3yr
ACTPol
BKP
SPTpol
POLARBEAR
r=0.01
$l(l+1)C_l^{BB}/(2\pi)$ (μK^2)
Multipole Moment, ell
10
100
1000

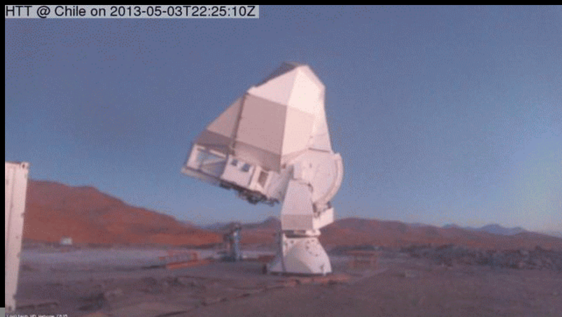
What do we need next ?

1. Larger sky area
   (BICEP2 already sample-variance limited)
2. More frequencies for foreground separation
3. More precise measurements of lensing B mode

Good News:
Powerful ground-based and balloon projects in next ~5 years
→ Error on $r \sim 0.01$ is the goal

B-mode projects in next 5 years

Ground



POLARBEAR → Simons Array

In addition, ABS, CLASS

ACTPol
→ Advanced ACTPol

Atacama, Chile

South Pole

SPTPol
→ SPT3G

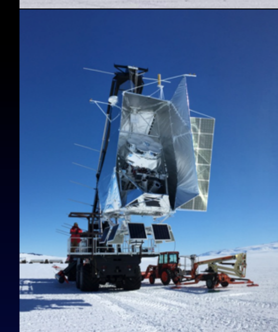
BICEP3

In addition,
QUIJOTE in Canary island,
GroundBIRD in Chile or Canary island,
AMiBA in Hawaii

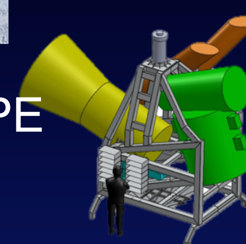
In addition,
QUBIC at Dome C

Balloon

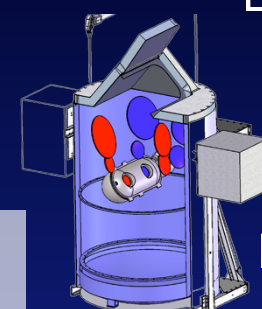
EBEX → EBEX6K



SPIDER



LSPE



PIPER

In 2020s

Space !

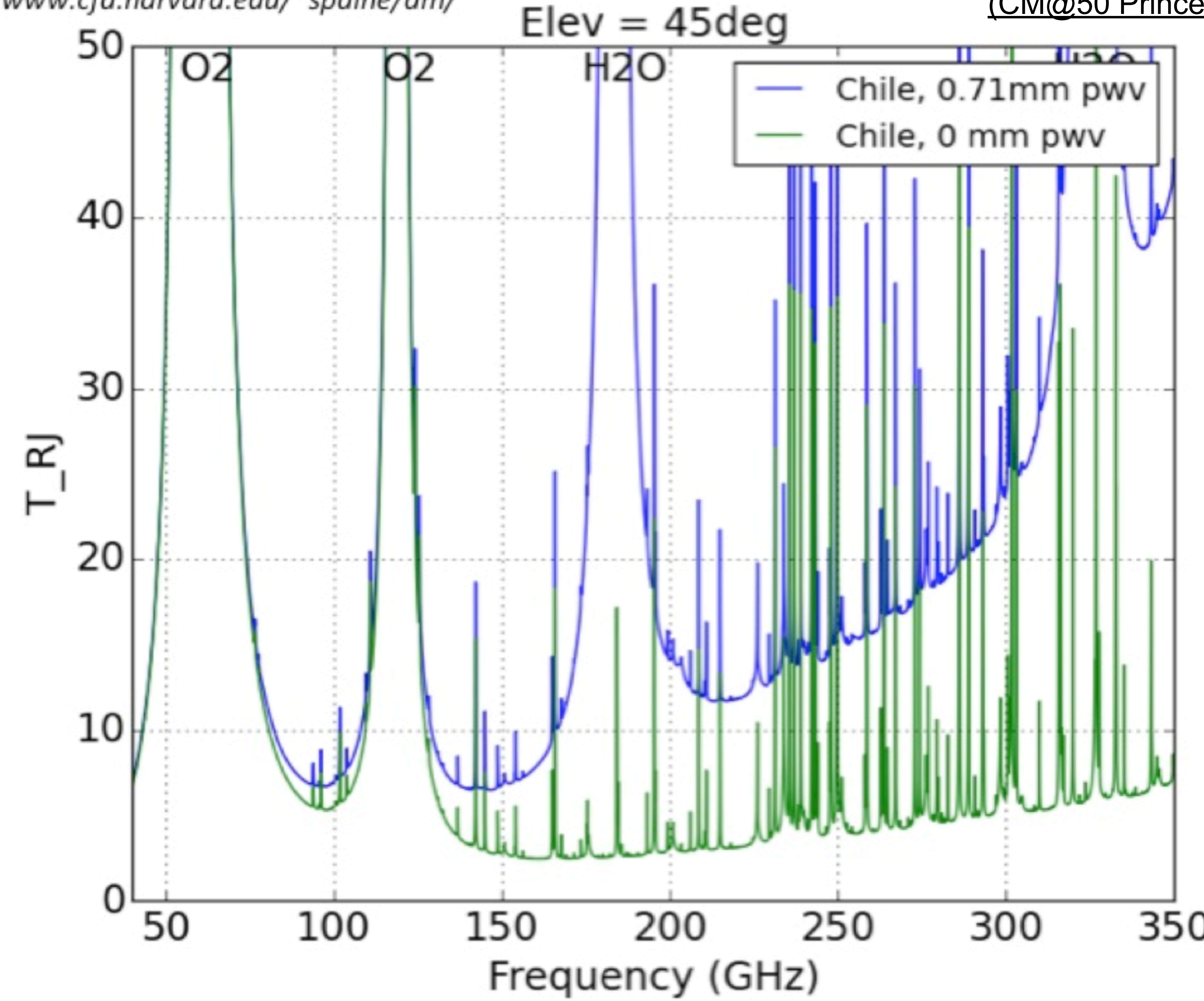
Why in space ? - Clear limitations on ground

- Frequency bands are limited → foreground rejection capability is limited
  - Lines due to O_2 and H_2O need to be avoided
  - High frequencies (e.g. 353GHz that Planck relies on for foreground removal) are hard to access
- Atmosphere is nuisance. Not only giving additional noise but may produce polarized signals at the level we want to reach.
- Hard to access very low multipoles

All the issues above do not exist in space.

(Atmospheric spectra from "am" model, thanks to Stevie Bergman and Bill Jones)
https://www.cfa.harvard.edu/~spaine/am/

John Ruhl
(CM@50 Princeton, June 2015)



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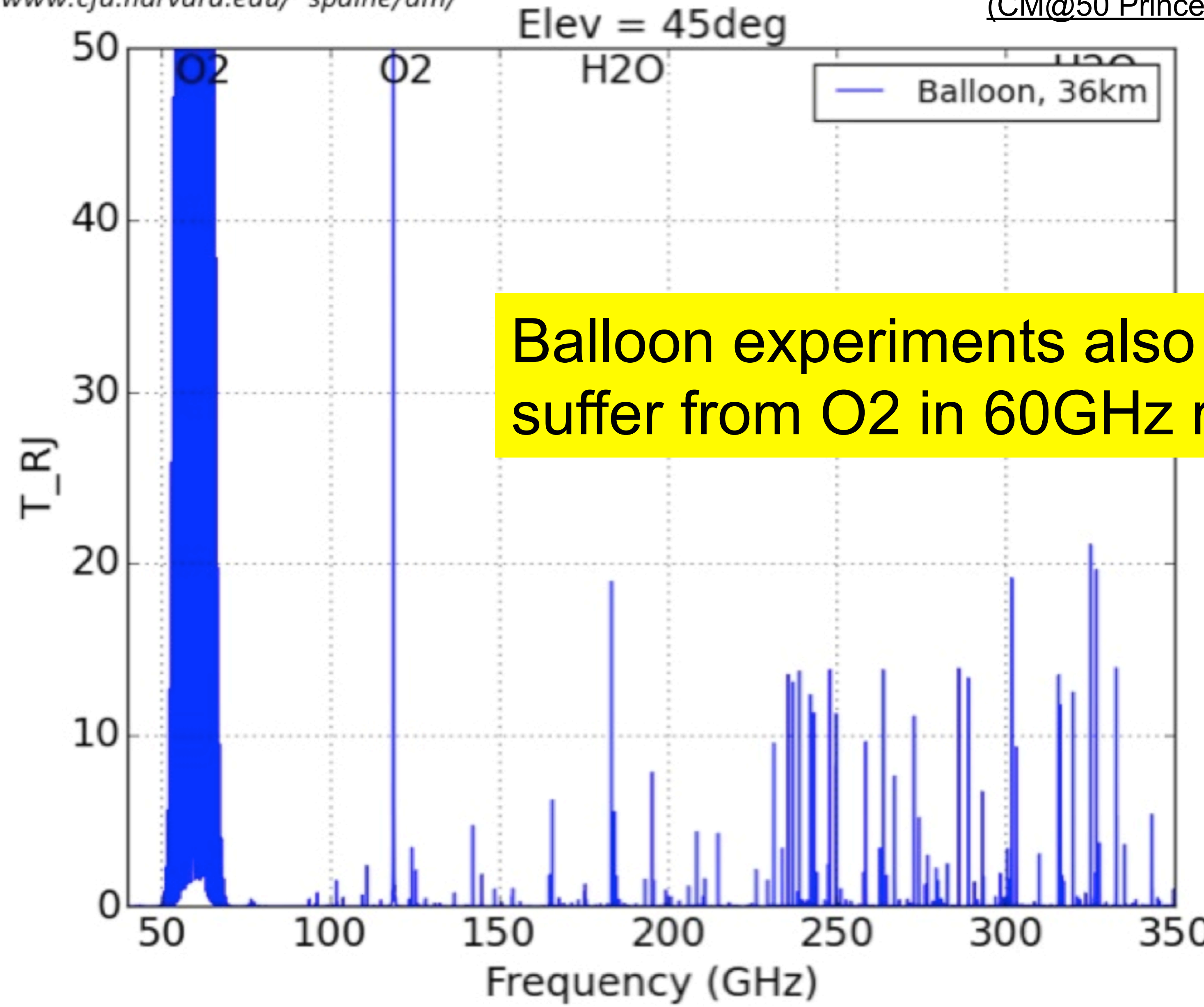


Balloon experiments also suffer from O2 in 60GHz region

Why targeting σ(r) < 0.001 ?

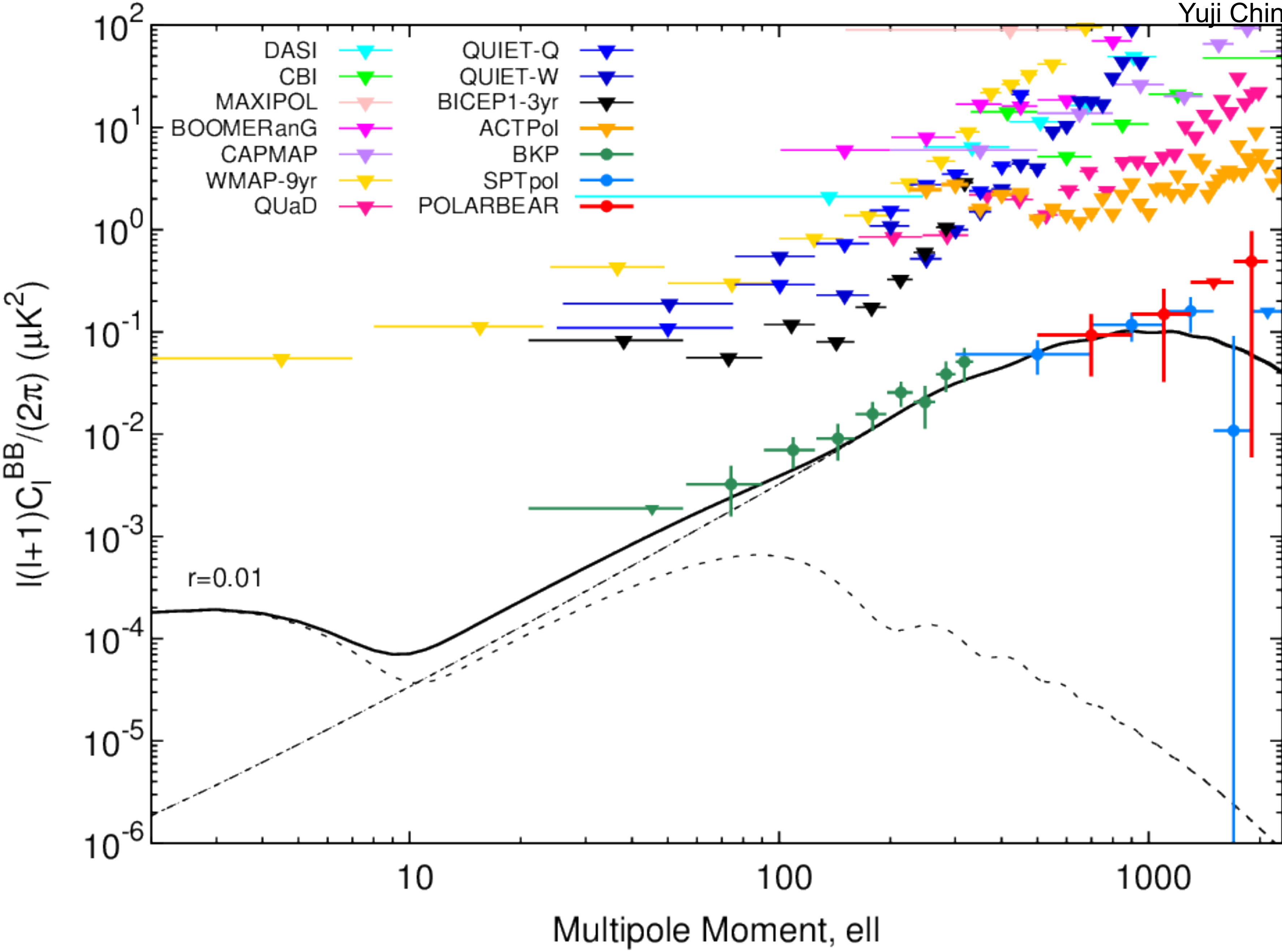
- Many models predict r>0.01 → >10σ discovery. What if we do not see the signal ?
- Single field models that satisfy slow-roll conditions give

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

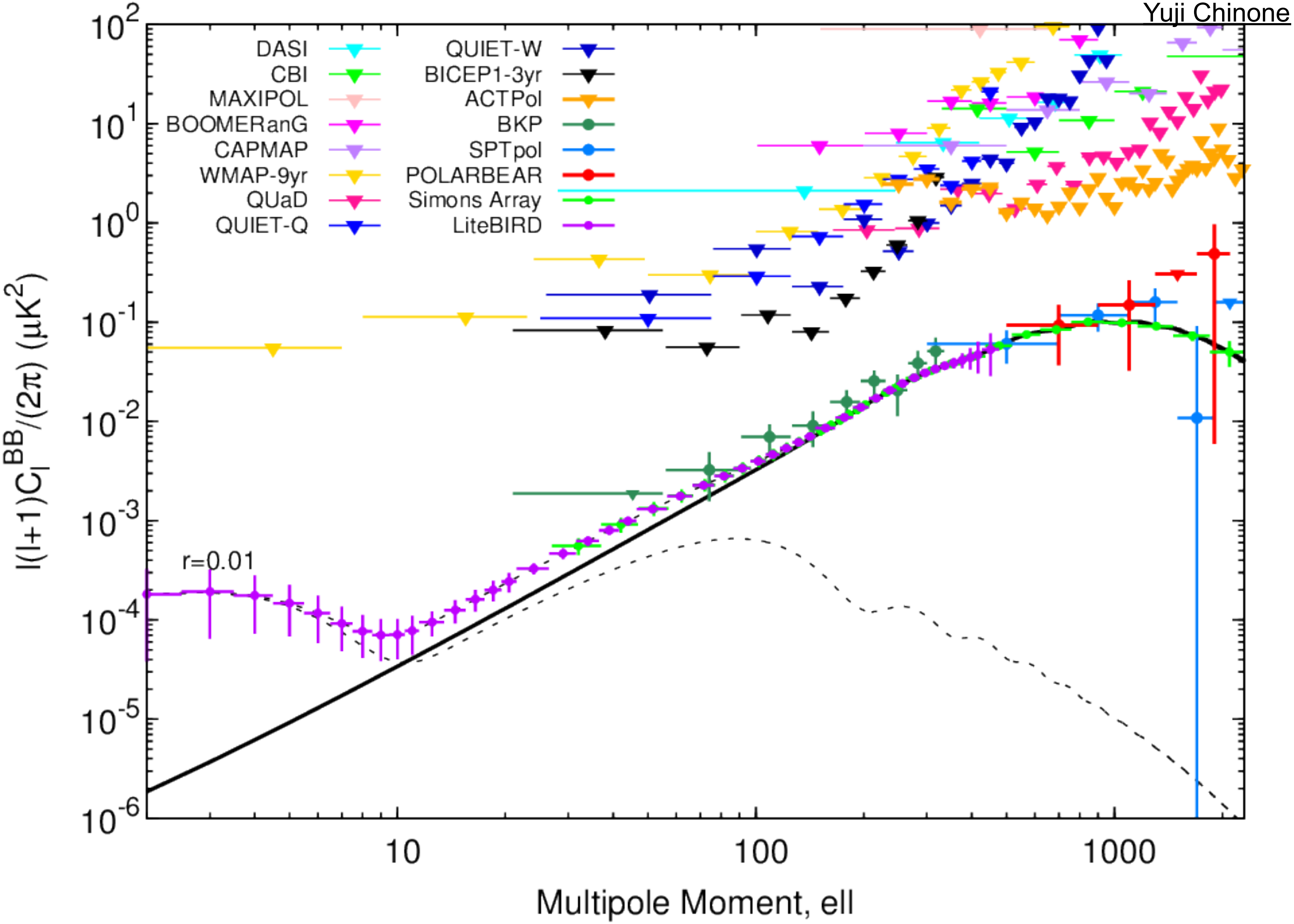
N: e-folding, m_{pl}: reduced Planck mass

- Establishing a bound r < 0.002 (95%C.L.) will rule out large field models
  - More model-dependent studies come to the same conclusion

Yuji Chinone

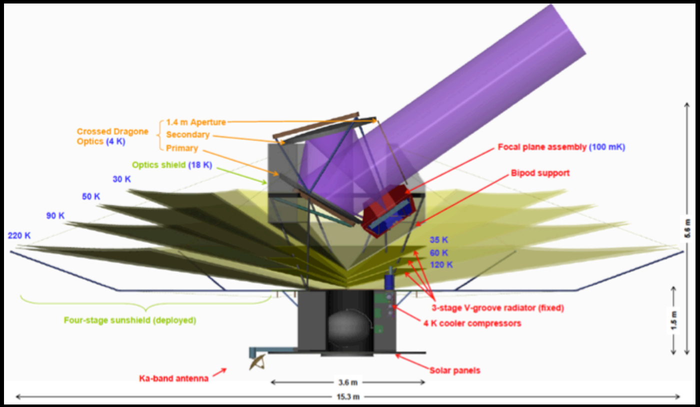


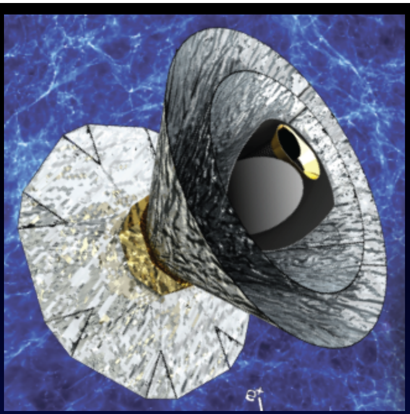
Yuji Chinone

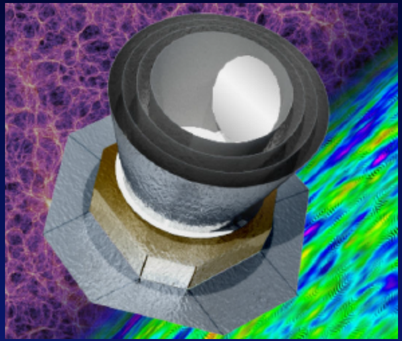


Past Proposals

- EPIC-IM (2010)
  - Proposed for Astro2010: US Astronomy and Astrophysics Decadal Survey
- PRISM (2013)
  - Proposed as an ESA L-class (L2/L3) mission
- COrE+ (2015)
  - Proposed as an ESA M-class (M4) mission



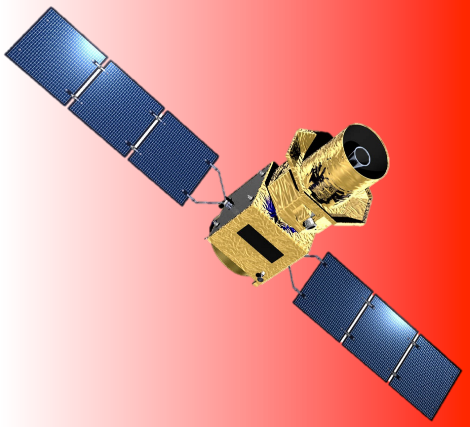




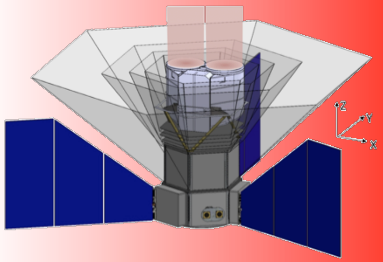
Science was rated very high. Not selected mainly from program-level considerations

Current Situation

- LiteBIRD
  - Proposal submitted to JAXA for JFY2022 launch
  - Passed initial down-selection by JAXA/ISAS (June 2015), in transition to phase-A studies
  - US participation proposal for NASA MO also passed initial down-selection (July 2015), starting phase-A studies



- PIXIE
  - NASA small PI-led mission proposal Feb 2011, not selected
  - Re-propose to next MIDEX AO (2017?)



- Mission for ESA M5
  - Proposal due next year
  - Planned launch date of 2029-2030

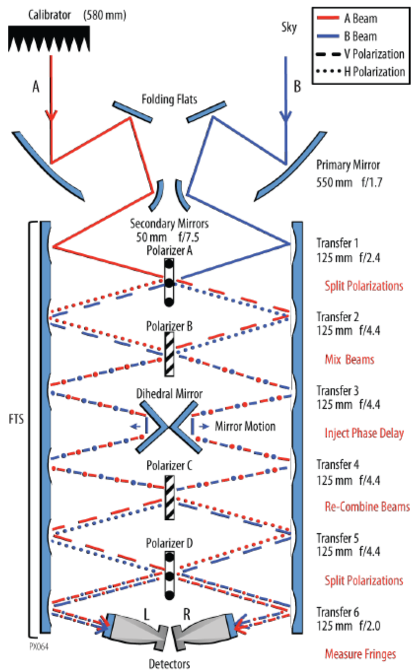
?

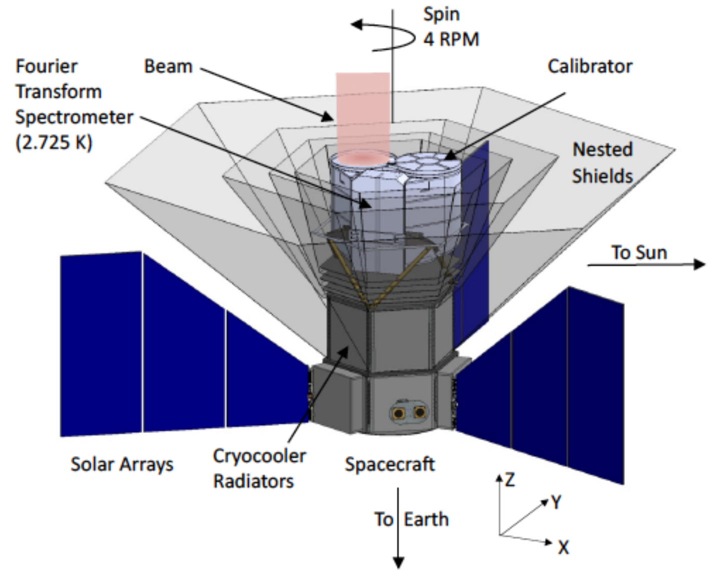
PIXIE: Primordial Inflation Explorer

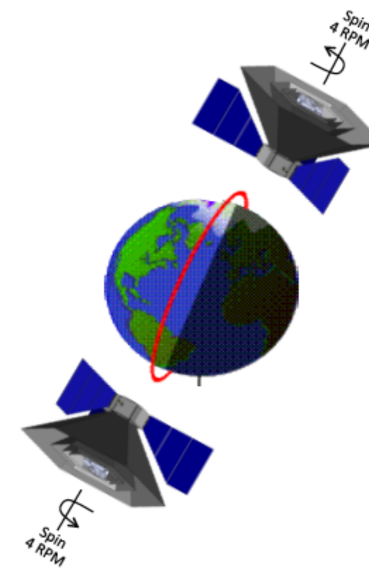
PI: Al Kogut (GSFC)

Cryogenic instrument in low-Earth orbit

- 4 multi-moded detectors
- Entire instrument at 2.725 K
- Spin at 4 RPM to sample Stokes Q/U







Full-Sky Spectro-Polarimetric Survey

- 400 frequency channels, 30 GHz to 6 THz
  - 60 – 600 GHz for CMB w/ FG removal
- Stokes I, Q, U parameters
- 49152 sky pixels each 0.9° × 0.9°
- Pixel sensitivity 6 x 10^{-26} W m^{-2} sr^{-1} Hz^{-1}
- CMB sensitivity 70 nk RMS per pixel

Scientific goals:

B-mode: $\sigma(r) < 2 \times 10^{-4}$

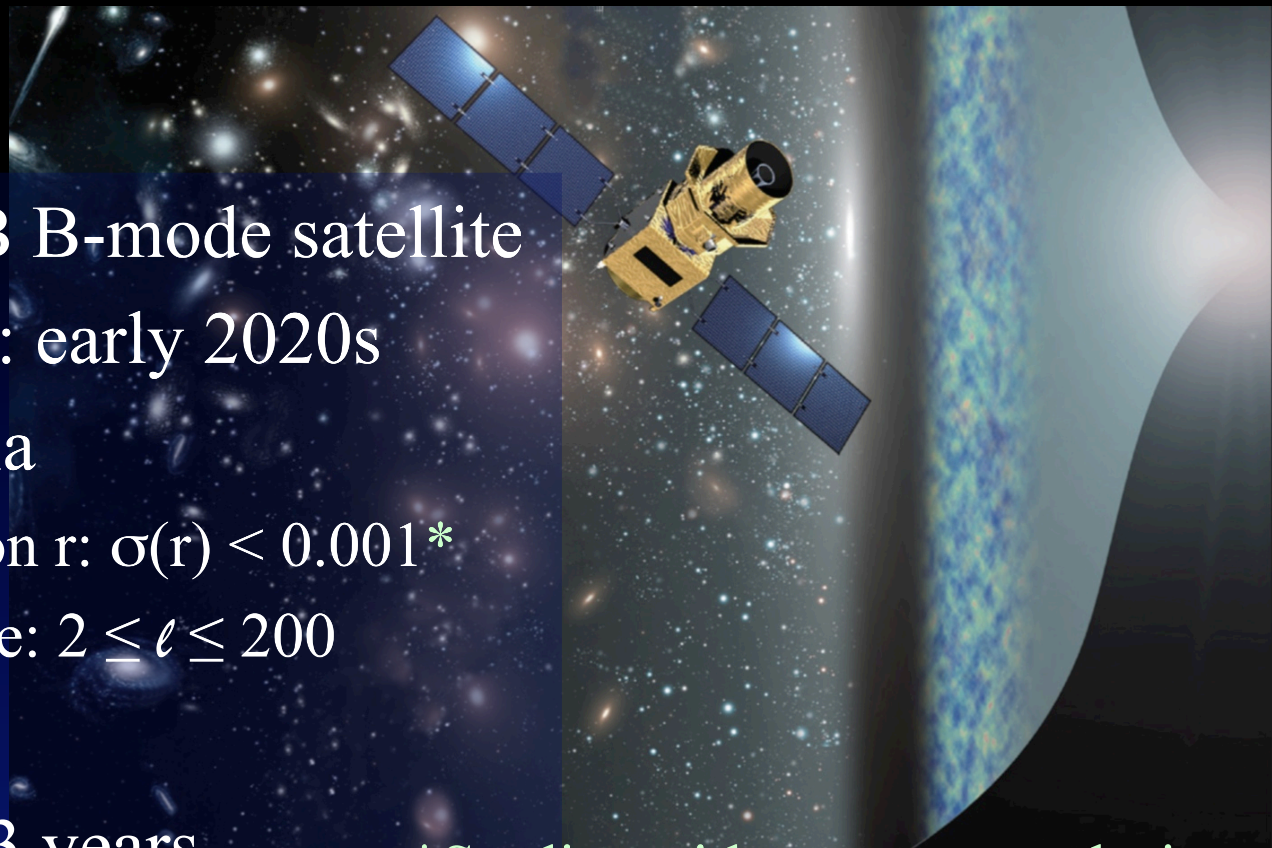
Distortion: $|\mu| < 10^{-8}$,

$|y| < 2 \times 10^{-9}$

arXiv:1105.2044

LiteBIRD

Lite (Light) Satellite for the Studies of B-mode Polarization and Inflation from Cosmic Background Radiation Detection



- JAXA-based CMB B-mode satellite
- Target launch year: early 2020s
- Full success criteria
  - Total uncertainty on r: $\sigma(r) < 0.001$*
  - Multipole coverage: $2 \leq \ell \leq 200$
- Orbit: L2
- Observing time: ≥3 years

*Studies with our current design indicate better performance

LiteBIRD working group

121 members, international and interdisciplinary (as of Ju

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A. Kusaka
A. Lee(US PI)
E. Linder
P. Richards
U. Seljak
B. Sherwin
A. Suzuki
P. Turin
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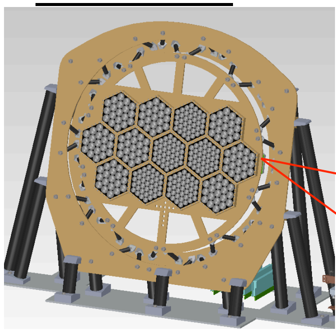
G. Rebeiz

LiteBIRD Instrument

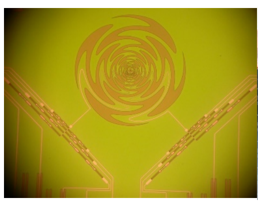
- Mission module benefits from heritages of other missions (e.g. ASTRO-H) and proof-of-principle ground-based experiments (e.g. POLARBEAR).
- Bus module based on high TRL components

Multi-chroic focal plane detectors

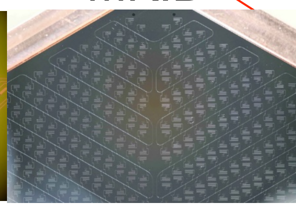


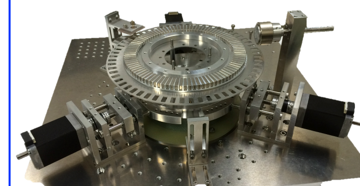
Lenslet

TES

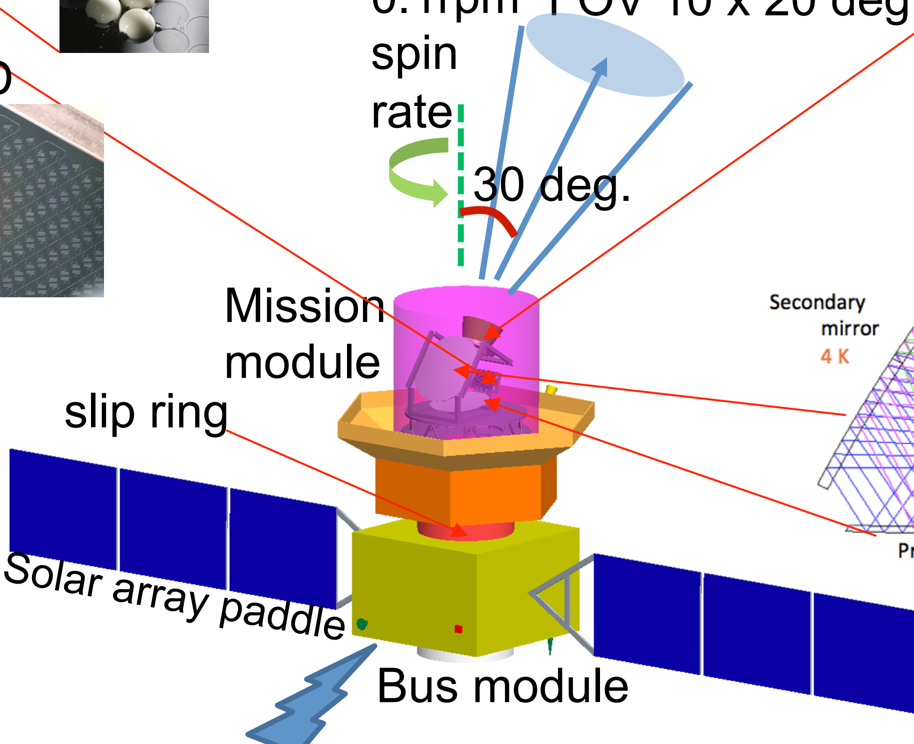


MKID

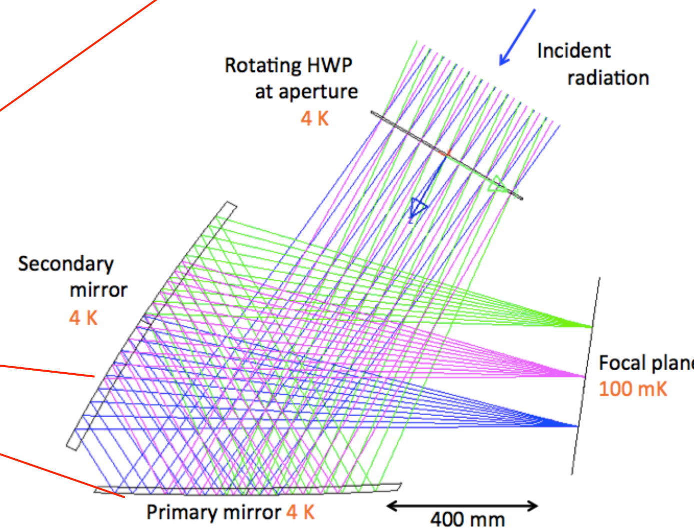




Continuously-rotating half wave plate (HWP)



HGA : X band data transfer to the ground



Mirrors at 4K

Cryogenics

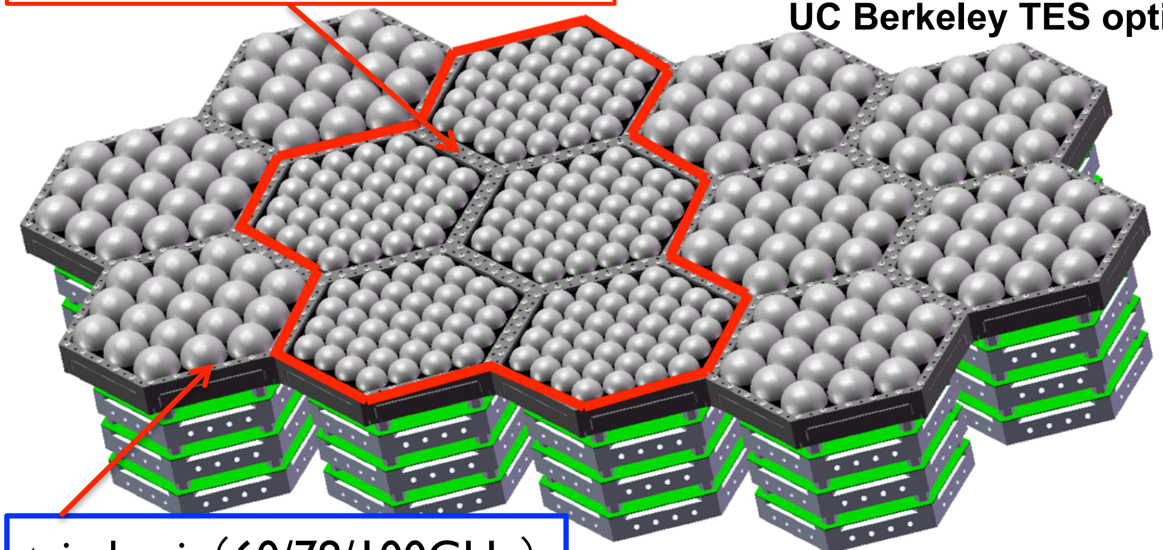
- JT/ST and ADR (Astro-H heritage)

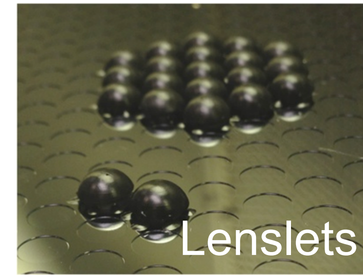
LiteBIRD focal plane baseline configuration

tri-chroic（140/195/280GHz）

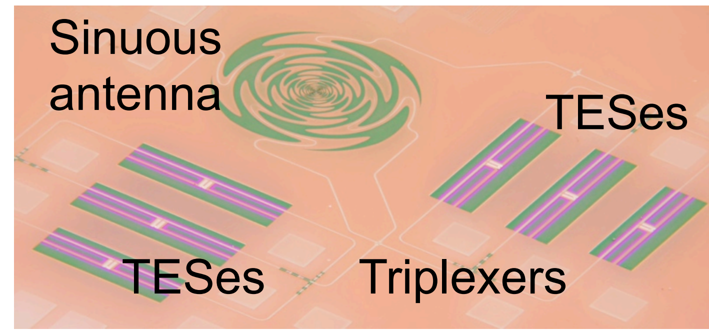
2022 TES bolometers

UC Berkeley TES option





T_{bath} = 100mK

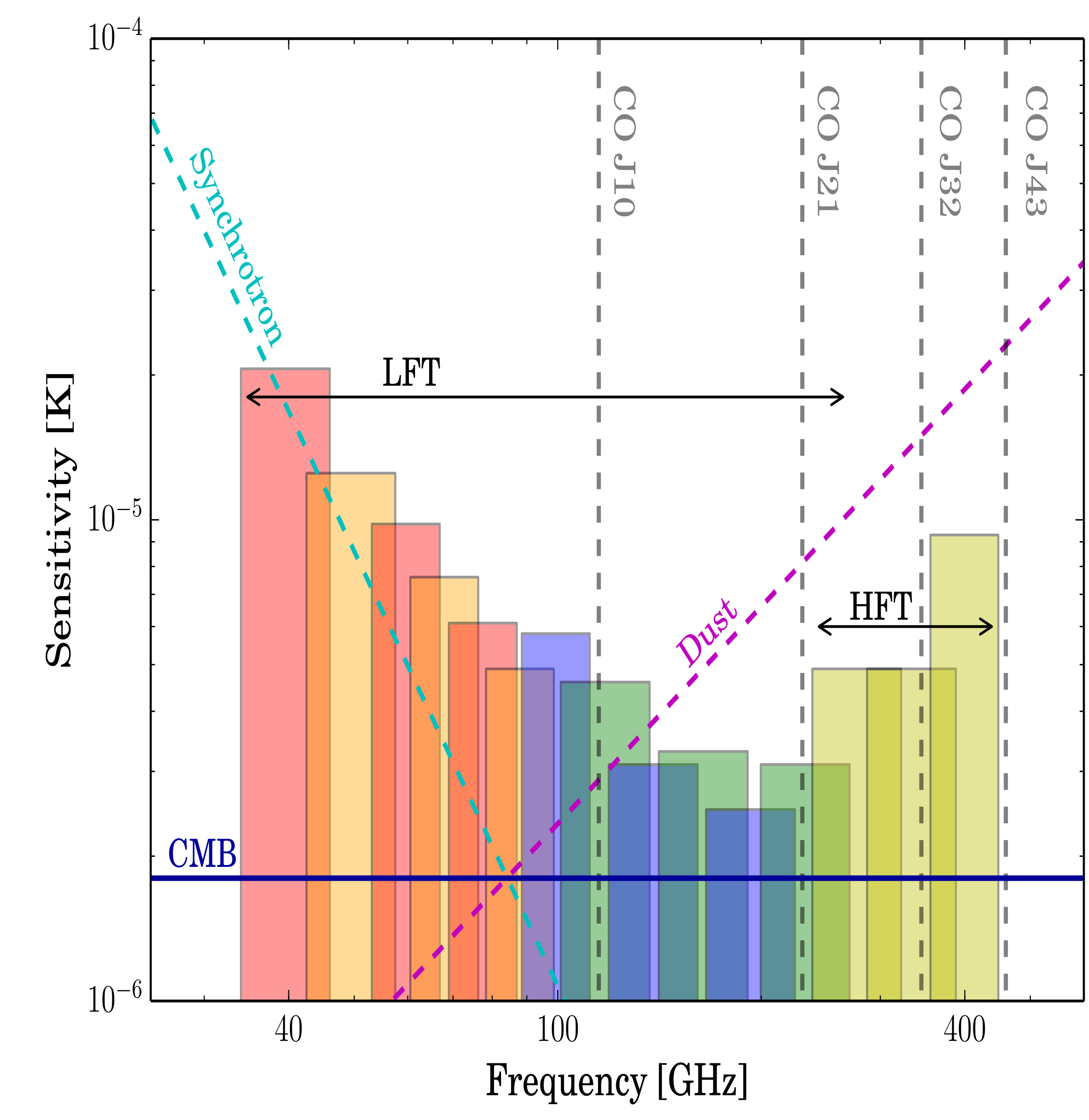


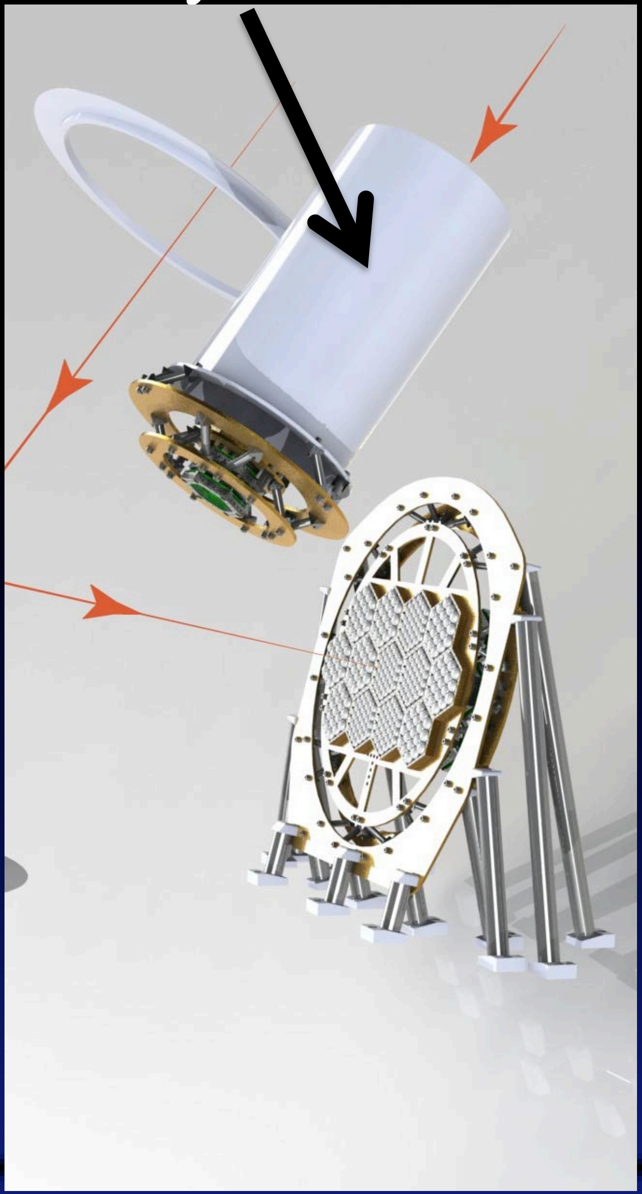
tri-chroic（60/78/100GHz）

6-band baseline design
→ 12 bands can be accommodated (with frequency overlap & w/ notch filters for CO-line rejection

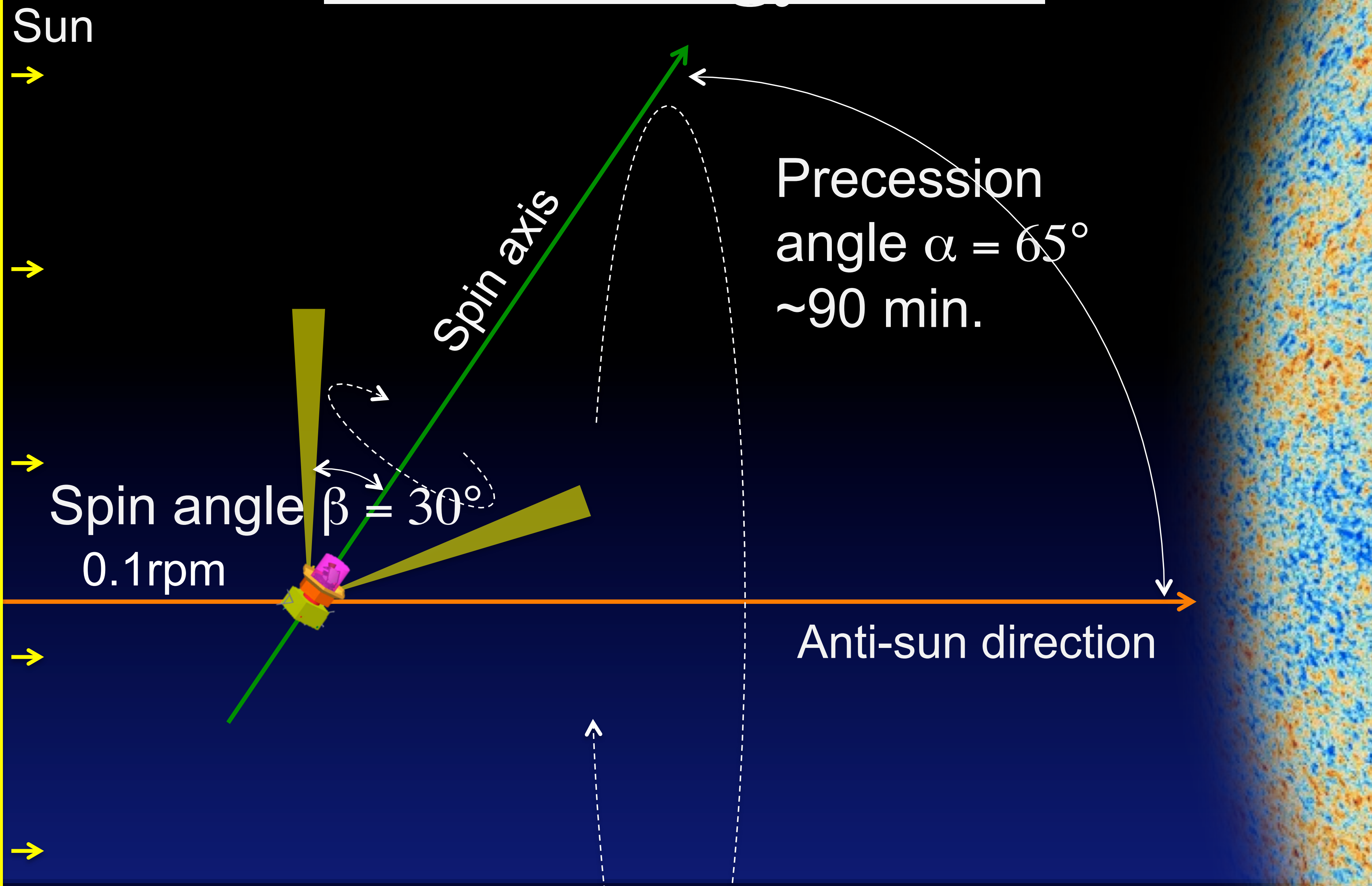
Band (GHz)	Beam (ar-cmin)	NET ($\mu K\sqrt{s}$)	Pixels per wafer	N_{wf}	N_{bolo}	NET_{arr} ($\mu K\sqrt{s}$)	Sens. ($\mu K{\cdot}arcmin$)	Sens. with margin ($\mu K{\cdot}arcmin$)	Band
60	54.1	94	19	8	304	5.4	9.6	15.7	X
78	55.5	59	19	8	304	3.4	6.0	9.9	X
100	56.8	42	19	8	304	2.4	4.3	7.1	Y
140	40.5	37	37	5	370	1.9	3.4	5.6	Y
195	38.4	31	37	5	370	1.6	2.9	4.7	Z
280	37.7	38	37	5	370	2.0	3.5	5.7	Z
total					2022		1.6	2.6	

15 frequency bands can be accommodated with an additional horn-coupled array

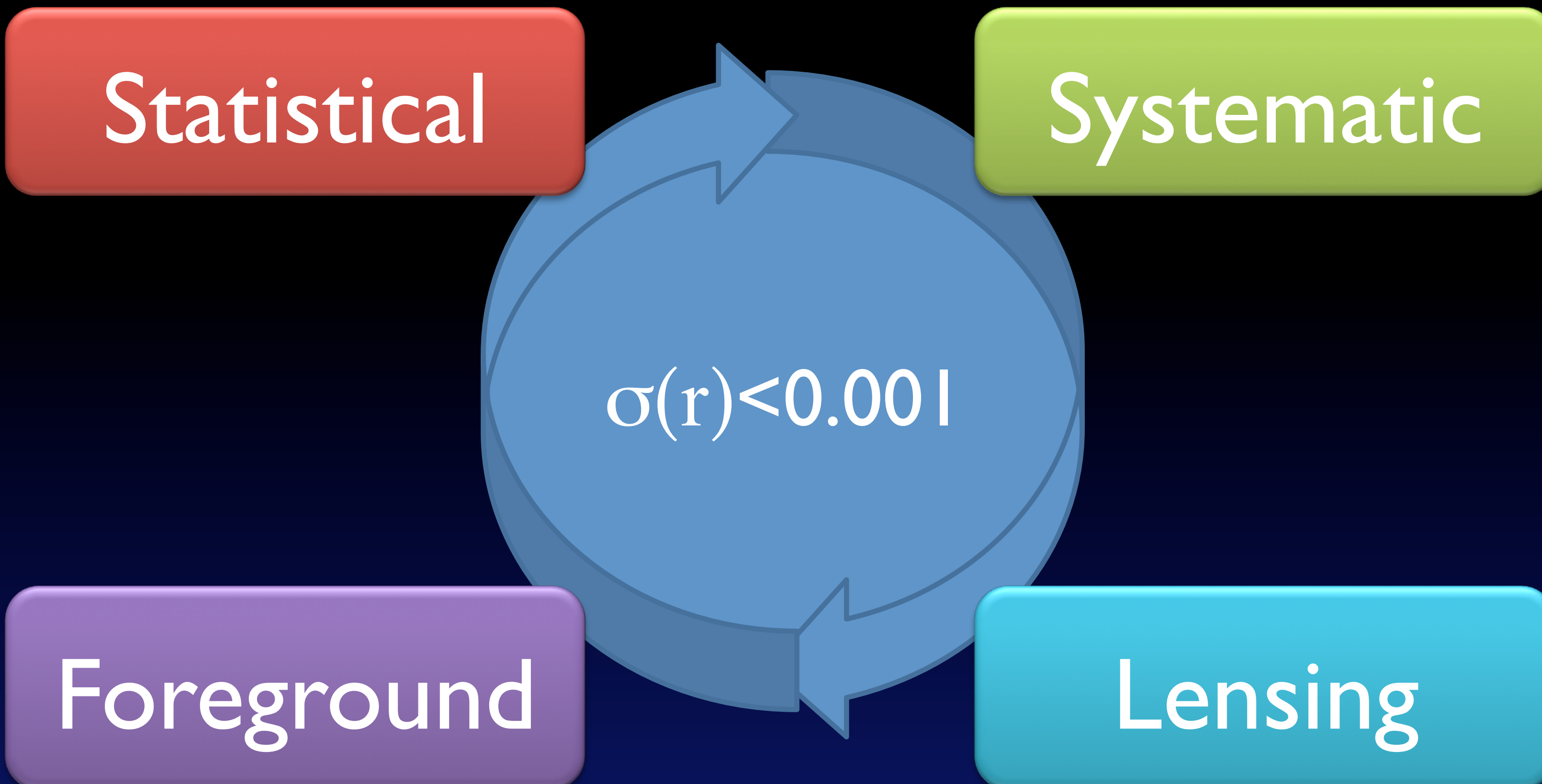




Scan strategy at *L2*



Road to achieve the full success



Observer bias as the 5th element → mitigation by e.g. blind analyses

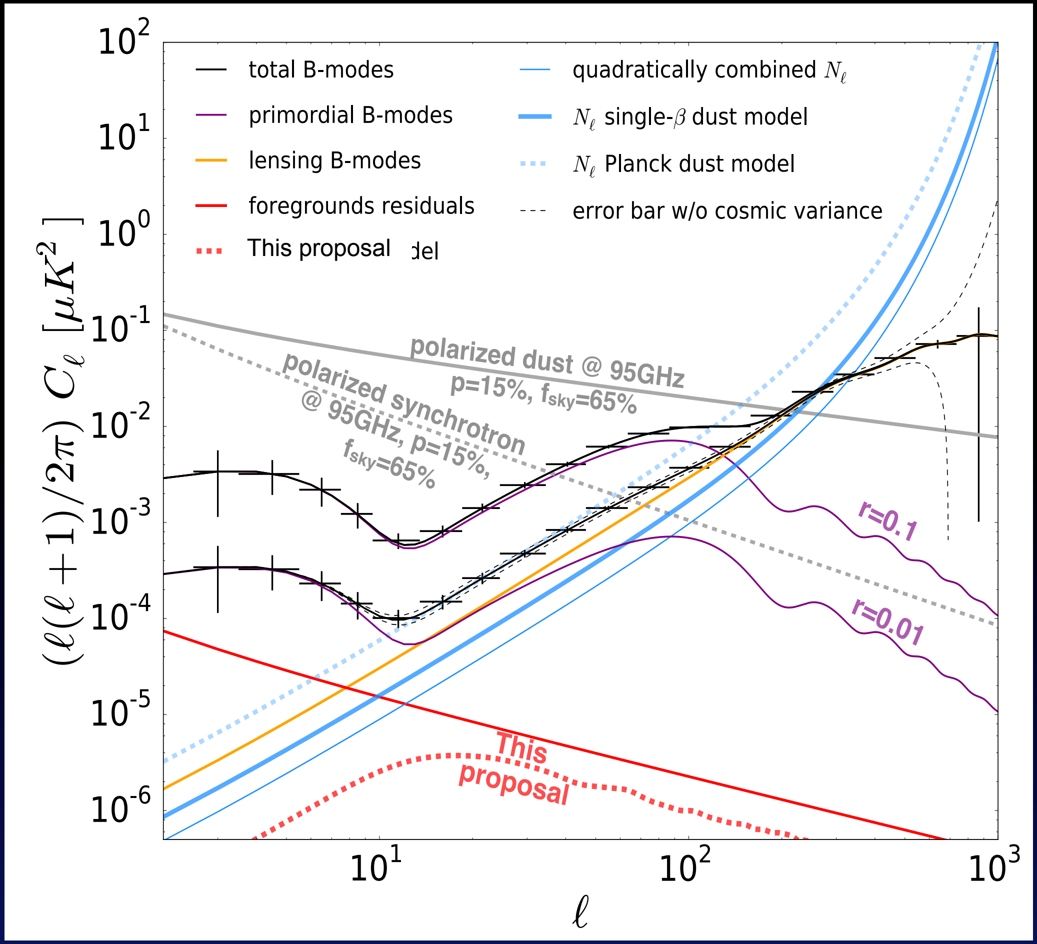
LiteBIRD systematic uncertainties

Requirements on major sources of uncertainties

	Diff. gain calibration	Diff. beam width	Diff. beam pointing	Diff. beam ellipticity	Pointing knowledge	Angle calibration
$\ell = 4$	0.003 %	0.8 %	$4''$	3 %	$8'$	$1'$
$\ell = 80$	0.03 %	0.6 %	$3''$	0.1 %	$30'$	$10'$

- L2 provides superior conditions for measuring faint B-mode fluctuations.
- HWP mitigates differential systematics greatly.
  - ABS experience → LiteBIRD requirements on systematic leakage are met except monopole. A constant and small monopole leakage can be compensated for during map making.
- E to B leakage due to satellite pointing is not mitigated by HWP, but it is not a problem. Expected pointing accuracy of 0.7’ is much better than the requirement.
- Absolute polarization angle is calibrated with E-B correlations with an expected accuracy of 1’.

LiteBIRD Sensitivity



$\sigma(r) = 0.45 \times 10^{-3}$

for r = 0.01, including foreground removal*, cosmic variance and delensing w/ CIB**

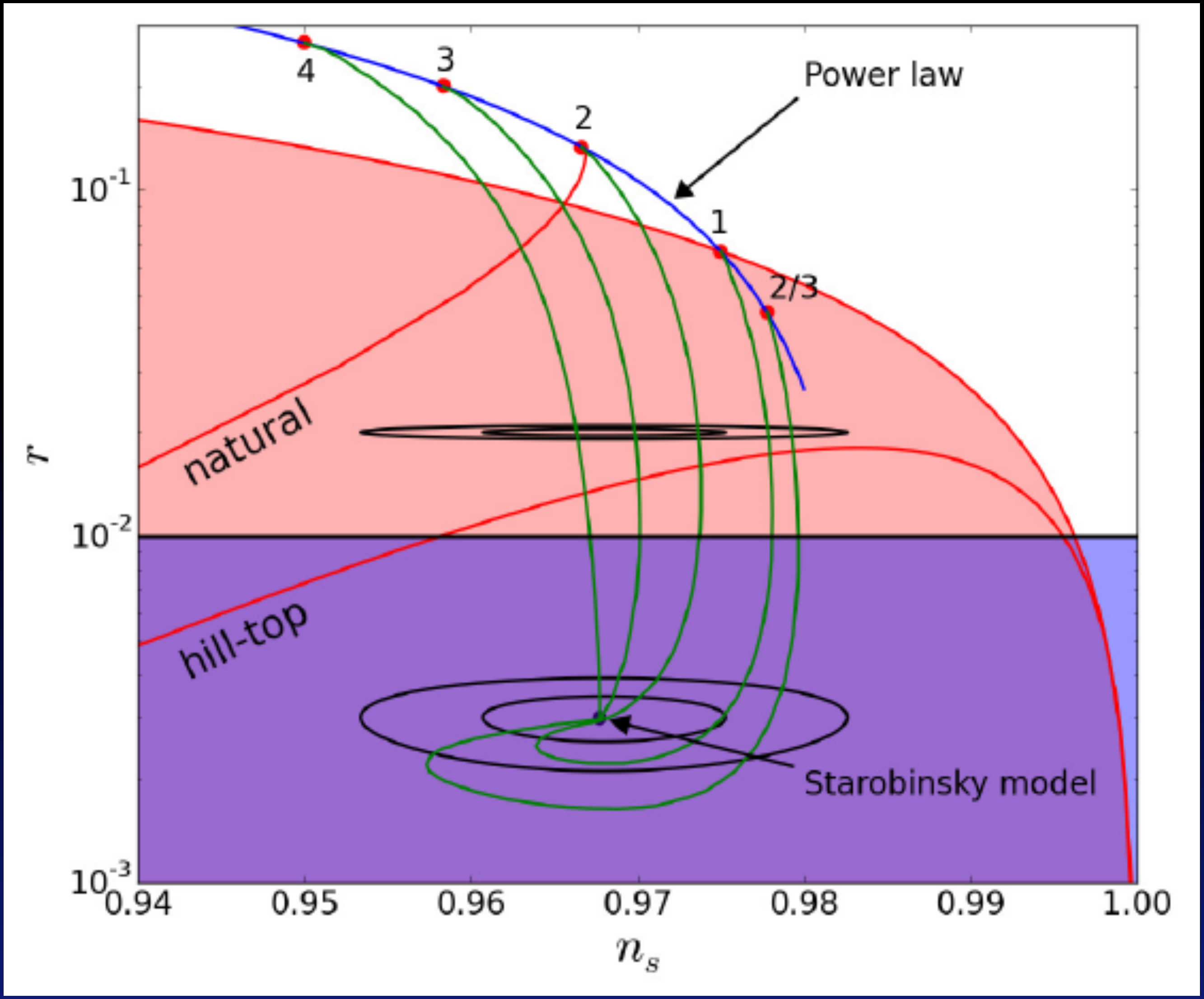
$r < 0.4 \times 10^{-3}$ (95% C.L.)

for undetectably small r

* Foreground residual estimation with Errard et al. 2011, Phys. Rev. D 84, 063005 plus a new method (this proposal, another paper in preparation)

** "Delensing the CMB with the Cosmic Infrared Background", B. D. Sherwin, M. Schmittfull arXiv:1502.05356

LiteBIRD constraints on r vs. n_s plane



Three additional comments

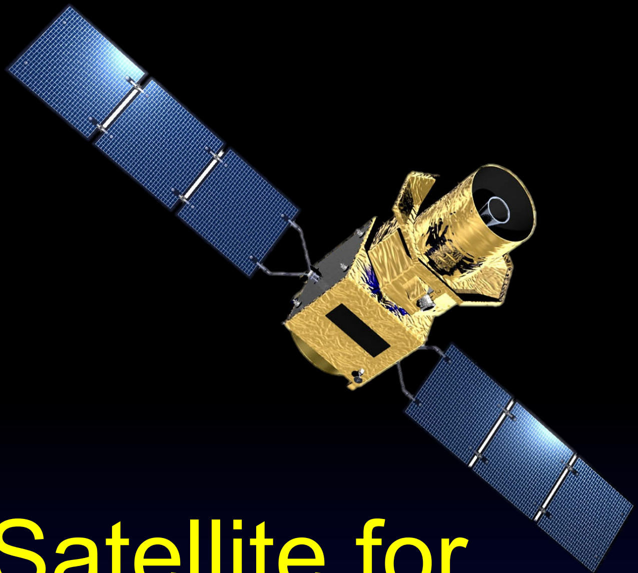
(1) If evidence is found before launch

- r is fairly large !
- Much more precise measurement of r from LiteBIRD will play a vital role in identifying the correct inflationary model.
- LiteBIRD will measure the B-mode power spectrum w/ high significance for each bump !
  - Deeper level of fundamental physics

$\sigma(r) < 0.001$ is what we need to achieve in any case to set the future course of cosmology

No-Lose Theorem of LiteBIRD

(2) Synergy



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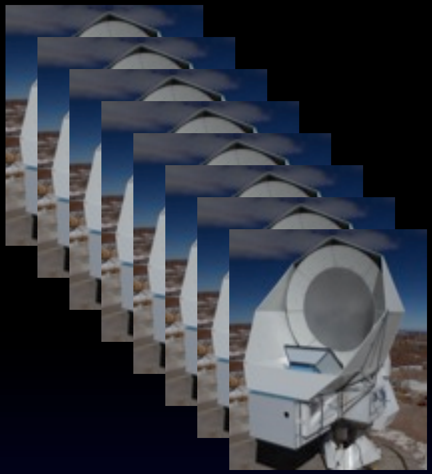
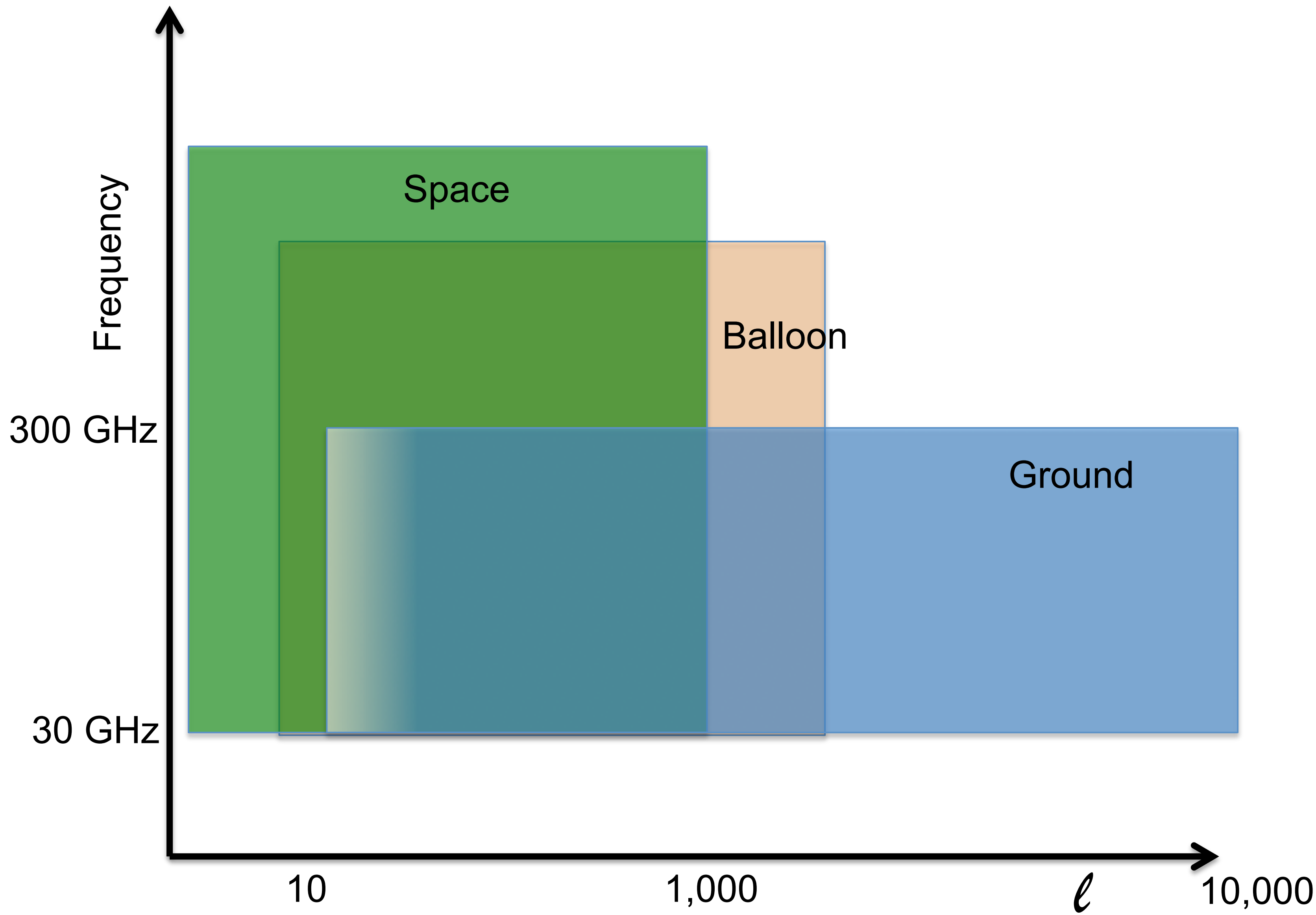


Satellite for ultimate r meas.
$\sigma(r)<0.001$
$2 \leq \ell \leq 200$

Telescope arrays on ground
$30 \leq \ell \leq \sim 3000$ e.g. CMB-S4

Powerful Duo

Complementarity of Observations



(3) Beyond inflation

- LiteBIRD will provide the most precise whole-sky maps of B-mode and E-mode.
  - C_l^{BB}, r, n_t, ..
  - C_l^{EE}, bi-spectrum, tri-spectrum, ..
  - Deviations from standard power spectra (incl. C_l^{EB})
  - Non-standard patterns (e.g. bubbles) in the maps
  - etc.

Bounce, Multiverse, Universe from Nothing

Bold ideas from theorists are welcome !

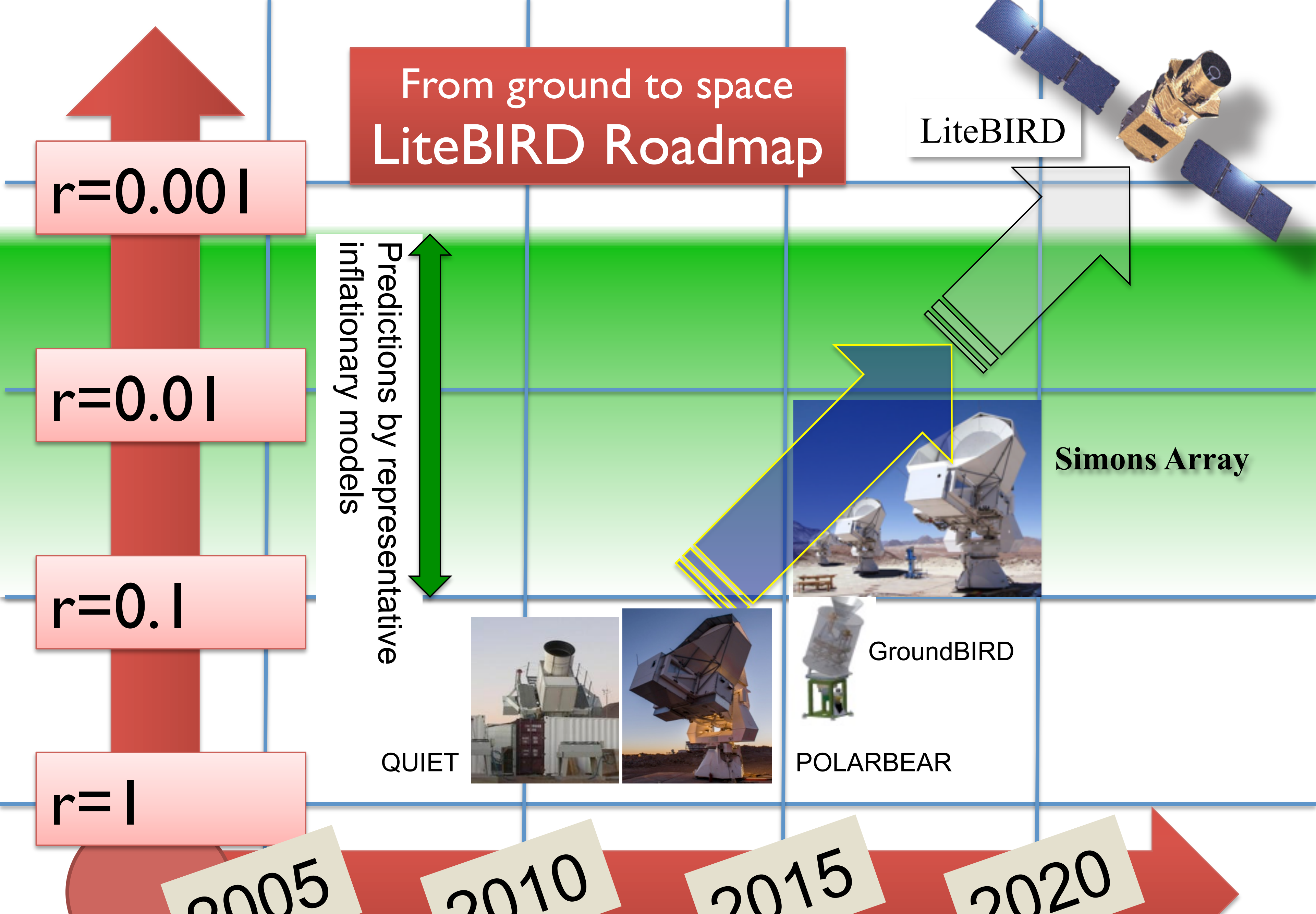
Summary

- CMB B-mode is the key to the direct confirmation of cosmic inflation and will shed light on quantum gravity
- Missions in 2020s are designed to achieve $\sigma(r) < 0.001$, 100 times better than the present limit.
- LiteBIRD passed initial down-selections of both JAXA and NASA, targeting launch in early 2020s.
- PIXIE proposal anticipated in 2017
- ESA M5 call is in consideration

Stay tuned !

Backup slides

From ground to space
LiteBIRD Roadmap



ISAS/JAXA mission categories

Space Policy Commission under cabinet office intends to guarantee predetermined ***steady annual budget*** for space science and exploration for ISAS/JAXA to maintain its excellent scientific activities

Strategic Large Missions (300M$ class) for JAXA-led flagship science mission with HIIA vehicle (3 in ten years)

ASTRO-H

2016

✔ LiteBIRD

~2022

Competitively-chosen medium-sized focused missions (<150M$ class) with Epsilon rocket (every 2 year)

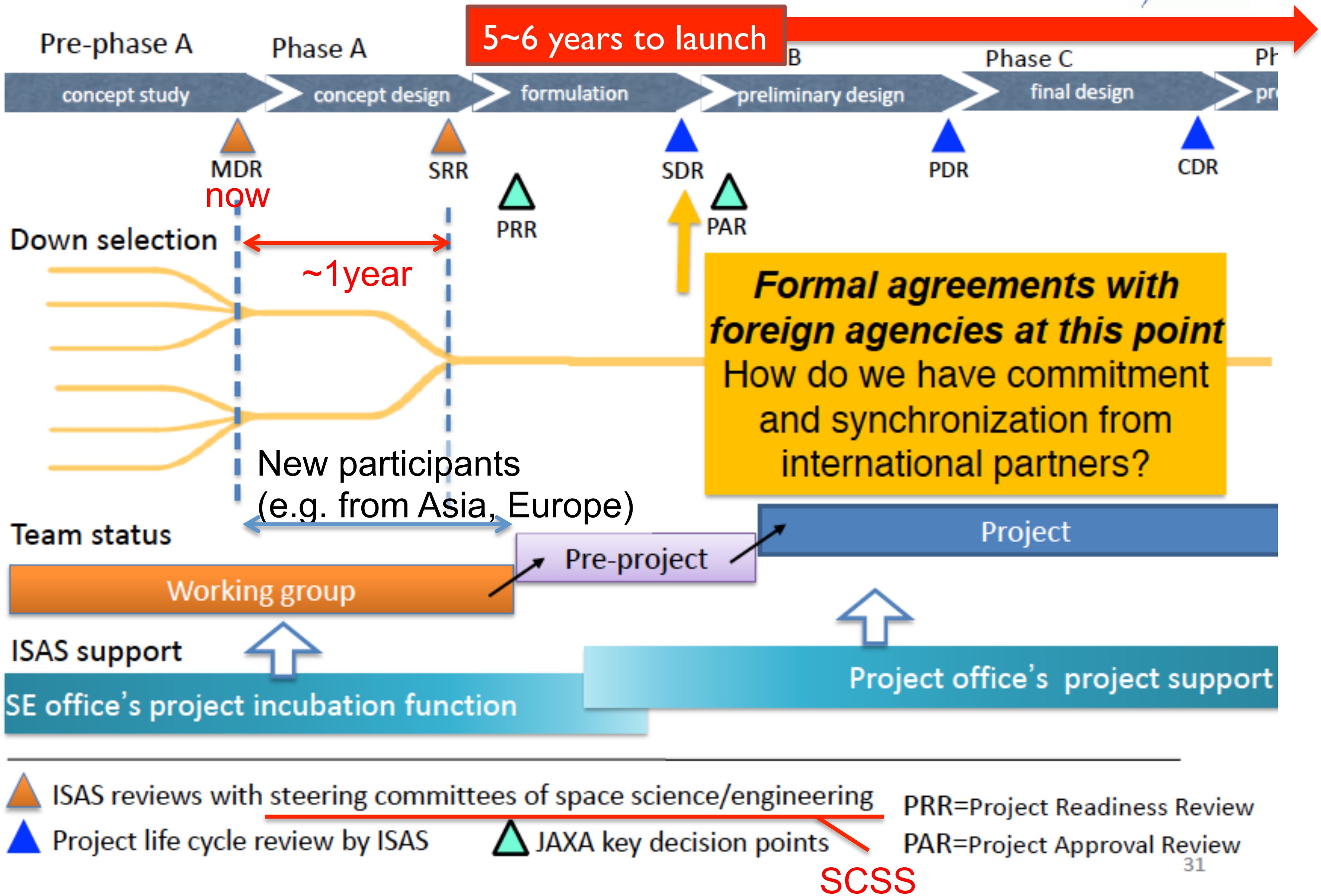
ERG

#3 Under selection

Missions of opportunity (10M$ per year) for foreign agency-led mission, sounding rocket, ISS

JUICE

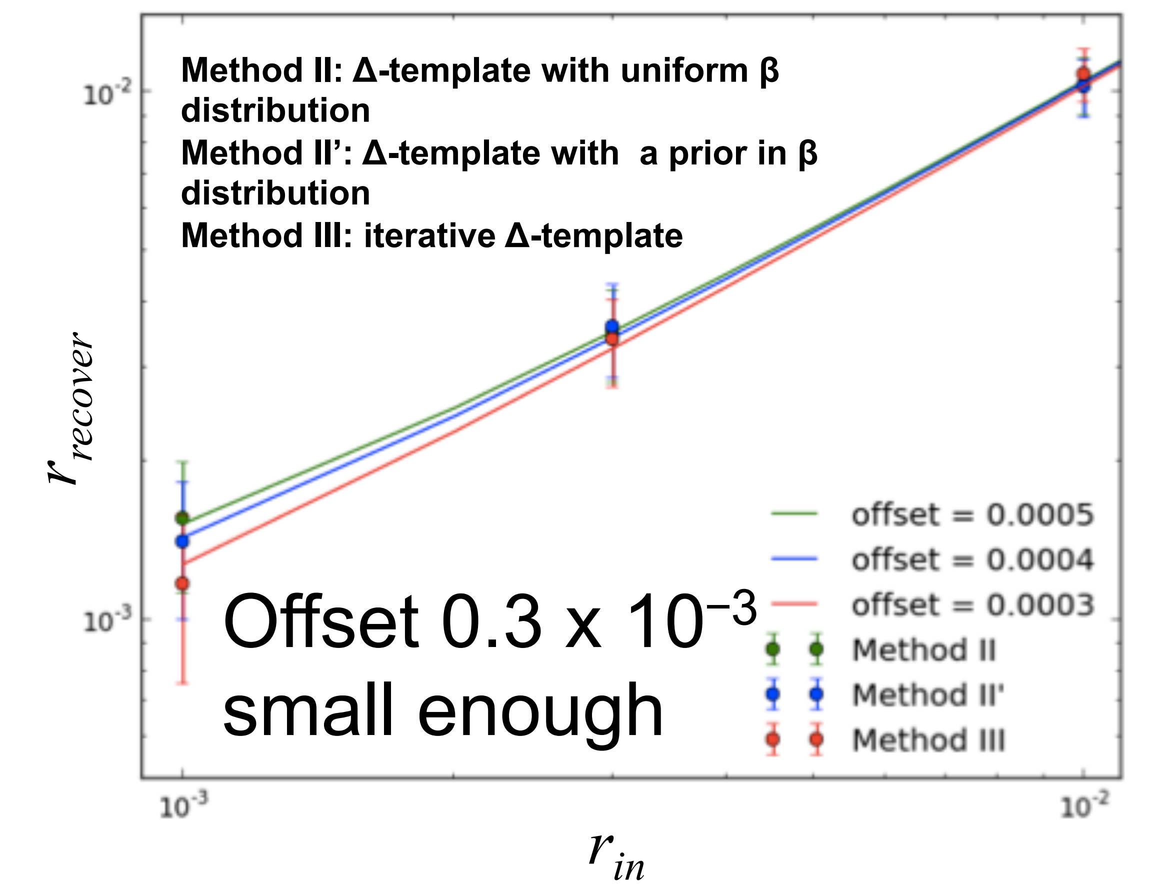
Project Timeline after MDR



LiteBIRD foreground subtraction exercise using a template method with 6 bands

We apply the template method to the pre-launch Planck sky model (Dust polarization fraction is set to be ×3) using the 6 bands, and test the recovery of tensor-to-scalar ratio, r. Use l <47 and f_{sky} of 50%.

Band (GHz)	Sensitivity (μK arcmin)
60	10.3
78	6.5
100	4.7
140	3.7
195	3.1
280	3.8
Total	1.8 (2.9[b])

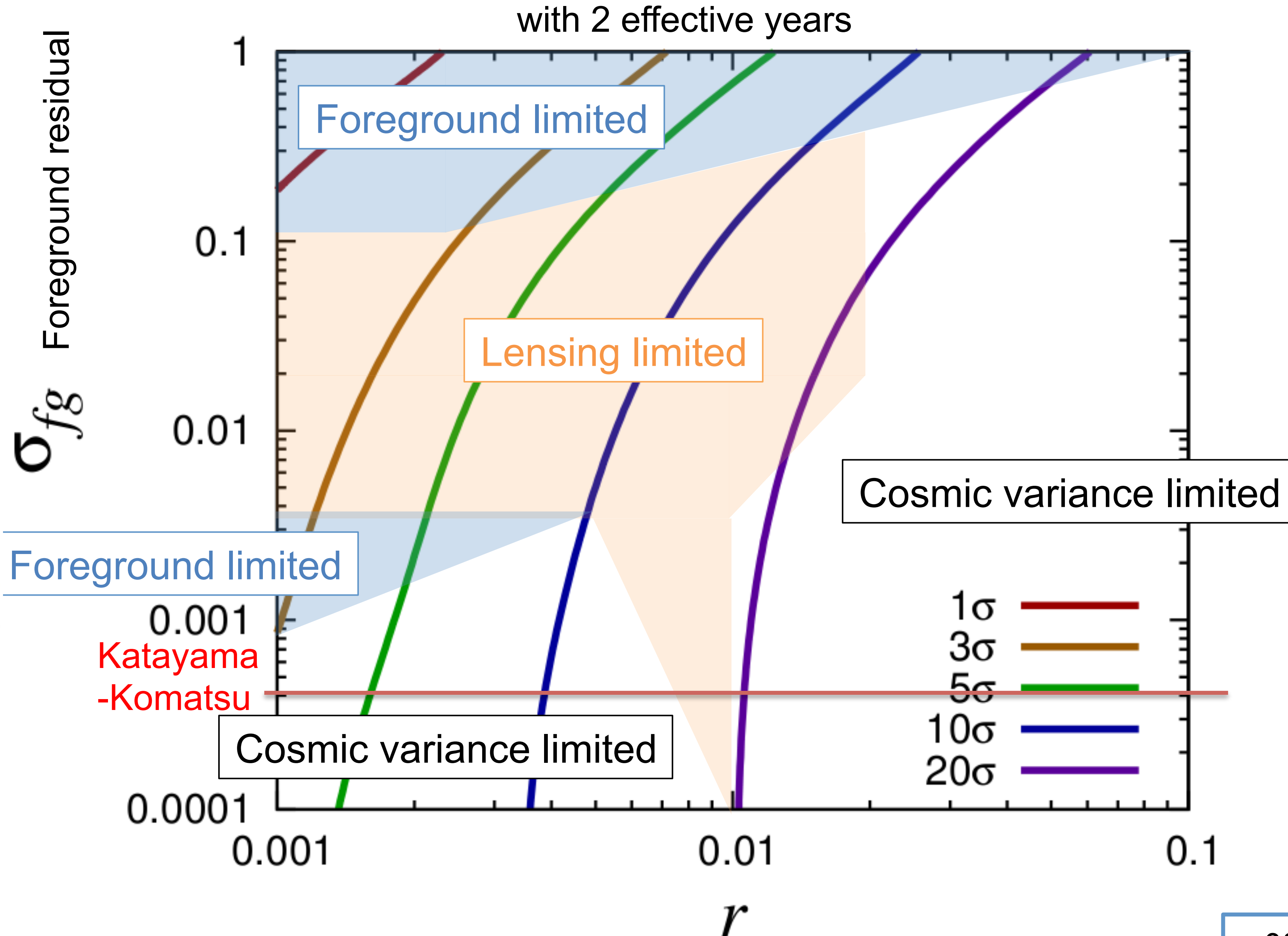


Katayama, Komatsu et al. in pre

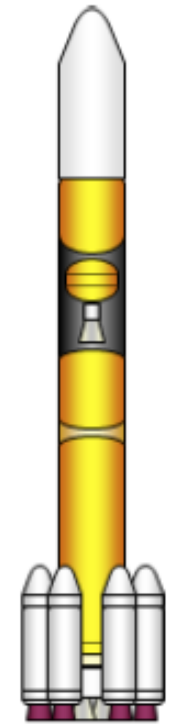
Expected sensitivity on r

R. Nagata

$$F_\ell^{XY}(\nu) = \sum_{fg=S,D} \left[C_\ell^{fg,XY}(\nu)\, \sigma^{fg,XY} + N_\ell^{fg,XY}(\nu;\nu_{tp}) \right]$$



Launch Vehicle



H-II A

- First Flight in 2001
- **23** successful launches/24
- Latest one: GPM
- GTO 4-6 ton class capability

H-II B

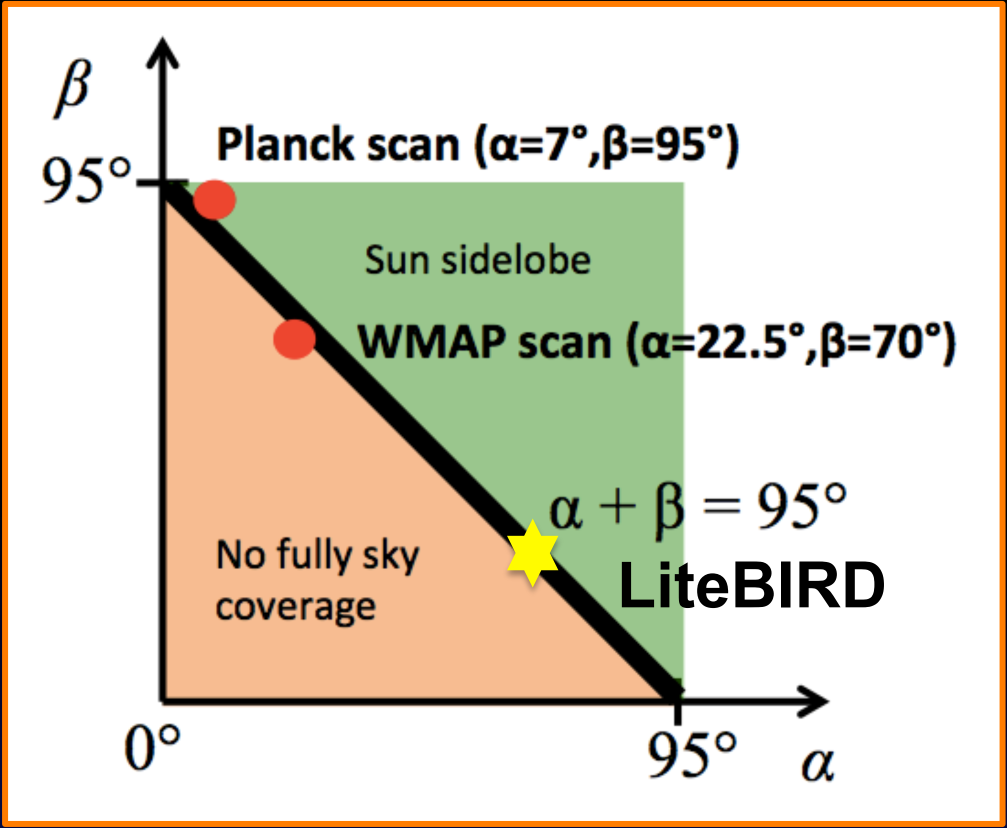
- First Flight in 2009
- **4** successful flights/4 of 16.5 ton HTV to ISS
- GTO 8 ton class capability

H3

- will be ready in 2020
- ½ cost w/ same capability (comparison w/ H-II B)

LiteBIRD's target launch year = 2021-2022

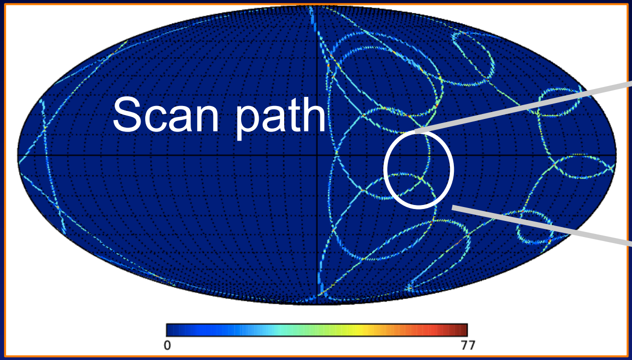
Scan strategy

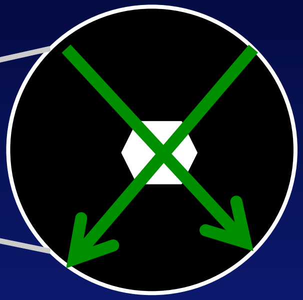


α+β ≥ 90° for full sky

α+β ≤ 95° from thermal/ optical requirements

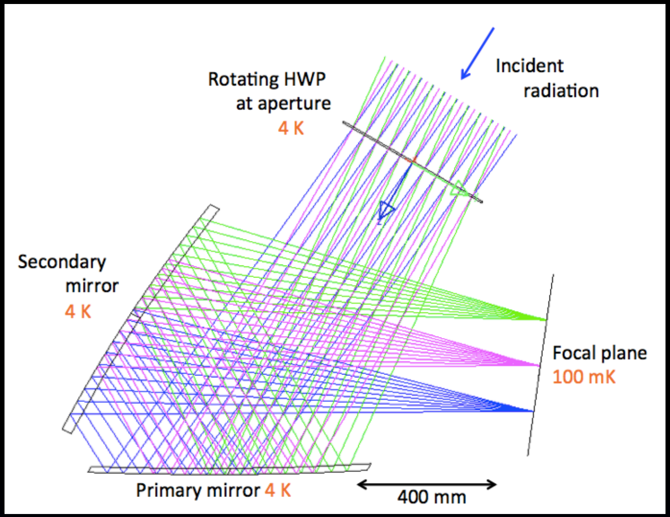
(α、β)=(65°,30°) chosen to minimize the effect of E to B leakage due to pointing bias





Good crosslink reduces pointing bias w/ multiple measurements

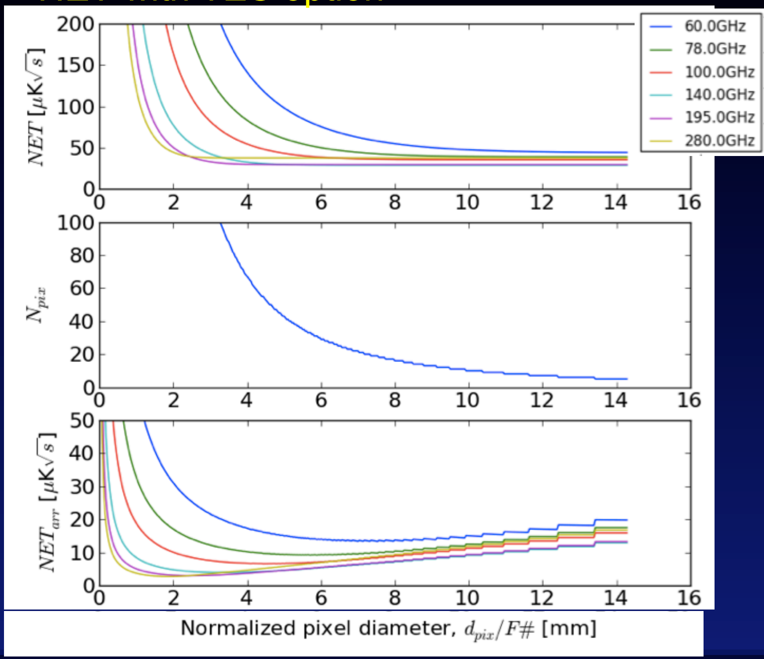
Baseline instrument model and sensitivity



Source	Temperature [K]	Emissivity	Efficiency
CMB	2.725	1	1
Achromatic half-wave plate	4	0.1	0.98 (AR)
Aperture	4	1	$1-\epsilon_s$
Primary and secondary mirrors	4	0.005	1
Infrared filter	1	0.1	0.95
Lens	0.1	0	0.99 (AR)
Antenna and micro-strip related	0.1	N.A.	0.73

The cross-Dragone telescope provides the diffraction limited focal plane size of D=300mm.
We employed the tri-chroic pixel using TES to optimize the focal plane configurations.

NET with TES option



Band [GHz]	N_{det}	P_{load} [pW]	G_{ave} [pW/K]	*NEP* [aW/√Hz]	*NET* [μK√s]	w^{-1} [μK.arcmin]
60	304	0.296	6.49	8.28	94.07	15.72
78	304	0.301	6.61	8.61	58.97	9.86
100	304	0.286	6.27	8.72	42.26	7.06
140	370	0.361	7.92	10.56	36.89	5.59
195	370	0.243	5.32	9.45	31.00	4.70
280	370	0.123	2.70	7.57	37.54	5.69
Combined	2022					2.65

Note: The sensitivity w^{-1} is computed with the following assumptions:
1. Observational time of 3 years with the efficiency of 72%.
2. The detector yield is 80 %.
3. NET has a margin of 1.25.

Detector and readout

- Sensitivity : Optical NEP = 2×10^{-18} W/√Hz
- Broad frequency coverage : ~50 – 320 GHz
- Multi-pixel array: ~2000
- Low power consumption (< 100W total)
- Controlled sidelobe at a feed

Band (GHz)	Sensitivity (μK arcmin)
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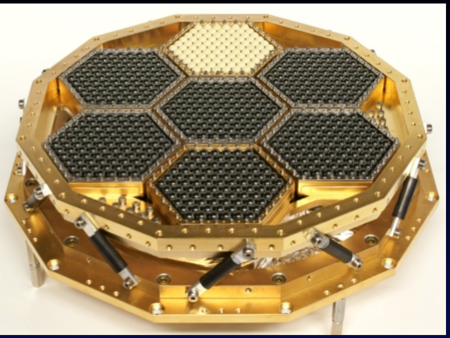
Transition edge sensor (TES) bolometer

Example from POLARBEAR focal plane



Z. Kermish Ph.D. thesis
UC Berkeley

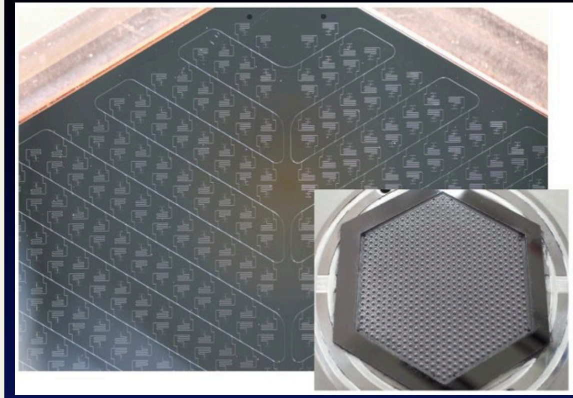
PB-1
1274 TESs with 80% yield.
NET per array: 23 μK√s

PB-2
2 bands/pixel (95,150GHz)
7588 TESs (1897×2pol×2band)
Readout is DfMUX with MUX=40
by McGill Univ.

High TRL by the use in various CMB experiments.
Need space qualified low loading TES and low power consumption readout.

Microwave kinetic inductance detector (MKI

Example of MKID from NAOJ.



K. Karatsu et al. 2013

NEP ~ 6×10^{-18} W/√Hz
Single band at 200GHz
MUX=600

More examples from JPL, SRON and others.

Attractive features and rapid progress in the MKID development. Potential candidate for a future mission in a few years.

Both TES and MKID are exposed to the proton beams (10 years eq. at L2). They are in the process of measuring the effect.