Future constraints on inflation

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How I got excited about CMB B-mode

- a particle physicist's experience

1. Quantum fluctuation of the metric

$$\langle \hat{h}^{\dagger}(\vec{k},\eta)\hat{h}(\vec{k}',\eta)\rangle = |v(\vec{k},\eta)|^2(2\pi)^3\delta^3(\vec{k}-\vec{k}').$$

2. GUT-scale physics

$$V^{1/4} = 1.04 \times 10^{16} \times \left(\frac{r}{0.01}\right)^{1/4} [GeV]$$

3. Technology matching w/ HEP

Outline

1. Probes for inflation
2. Future projects
3. LiteBIRD satellite

Acknowledgments

- Jamie Bock
- Yuji Chinone
- Mark Devlin
- Olivier Dore
- Jean-Christophe Hamilton
- Shaul Hanany
- Chao-Lin Kuo
- Si-yu Li
- Jean loup Puget
- Rafael Rebolo
- Osamu Tajima
- Jan Tauber

and many others!

1. Probes for inflation

Physics of cosmic inflation

- Inflation: primordial accelerating expansion
  - Successfully solve problems of naïve big-bang model
  - Generate adiabatic & (nearly-)Gaussian initial perturbations
- Underlying physics is unknown
  - Leading hypothesis: new scalar field ϕ "Inflaton" with potential V(ϕ) → source of acceleration!
- In case of single-field slow-roll inflation (simplicity as guideline)

$$V^{1/4} = 1.04 \times 10^{16} \times \left(\frac{r}{0.01}\right)^{1/4} [GeV]$$

- r (tensor-to-scalar ratio) is a key parameter

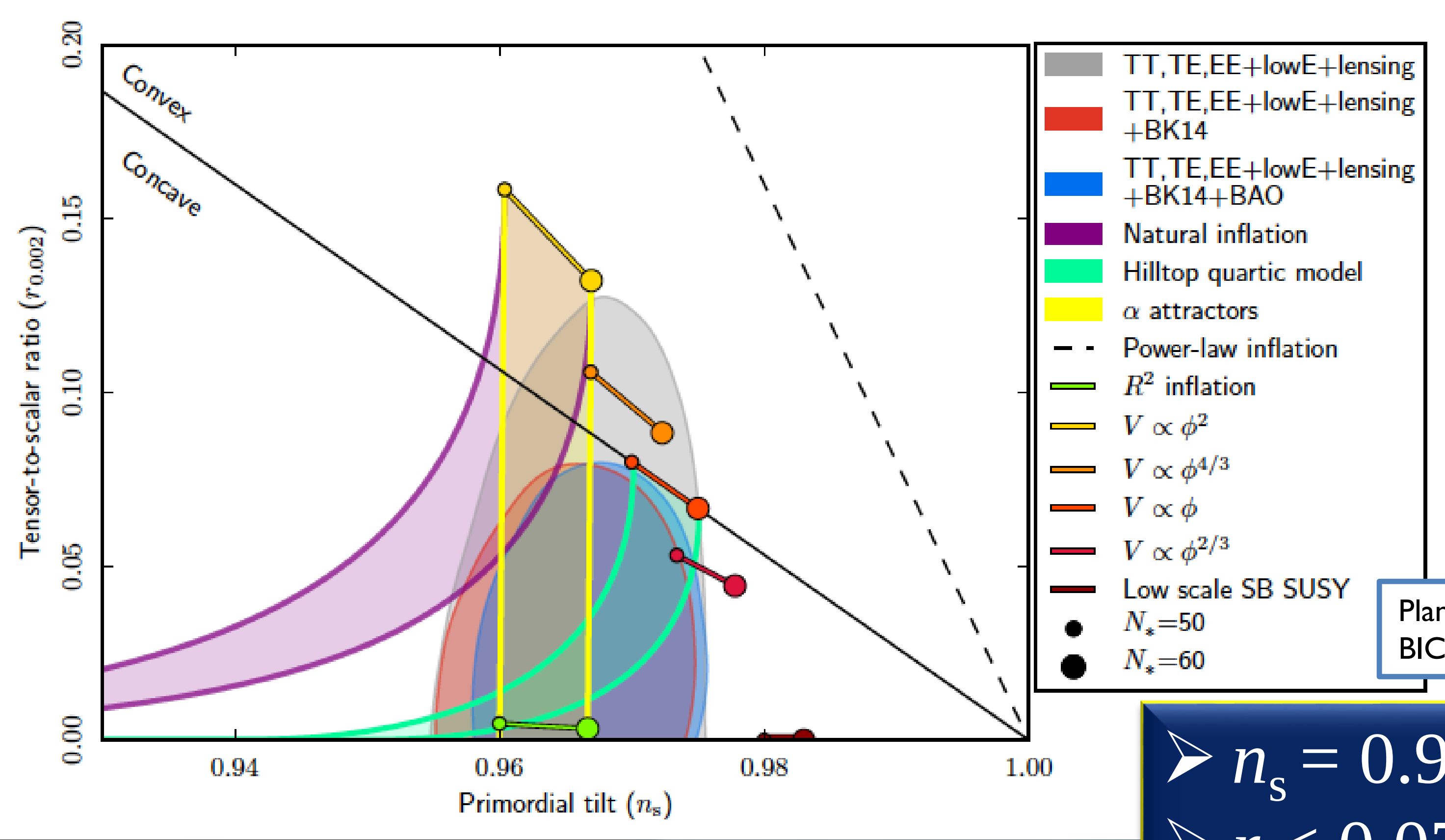
Inflation observables and future probes

Observable	**Current meas. (Planck2018)**	**Future probes**
Scalar tilt (n_s)	$n_s = 0.967(4)$	CMB E-mode
Tensor-to-scalar ratio (r) from primordial gravitational waves	r < 0.07 (95%CL)	CMB B-mode, (pulsar timing, interferometry, 21cm)
Non-Gaussianity (f_{NL})	f_{NL} < 2.5 +/– 5.7	large-scale structure

Remarks

1. Satellites (WMAP and Planck) did the great job on CMB temperature.
2. More observables exist, but measurements are more challenging. Examples include the following:
   - Tensor tilt (n_t)
   - Other non-Gaussianity parameters
   - CMB μμ, Tμ (μ: CMB spectral distortion)

Current constraints on n_s and r

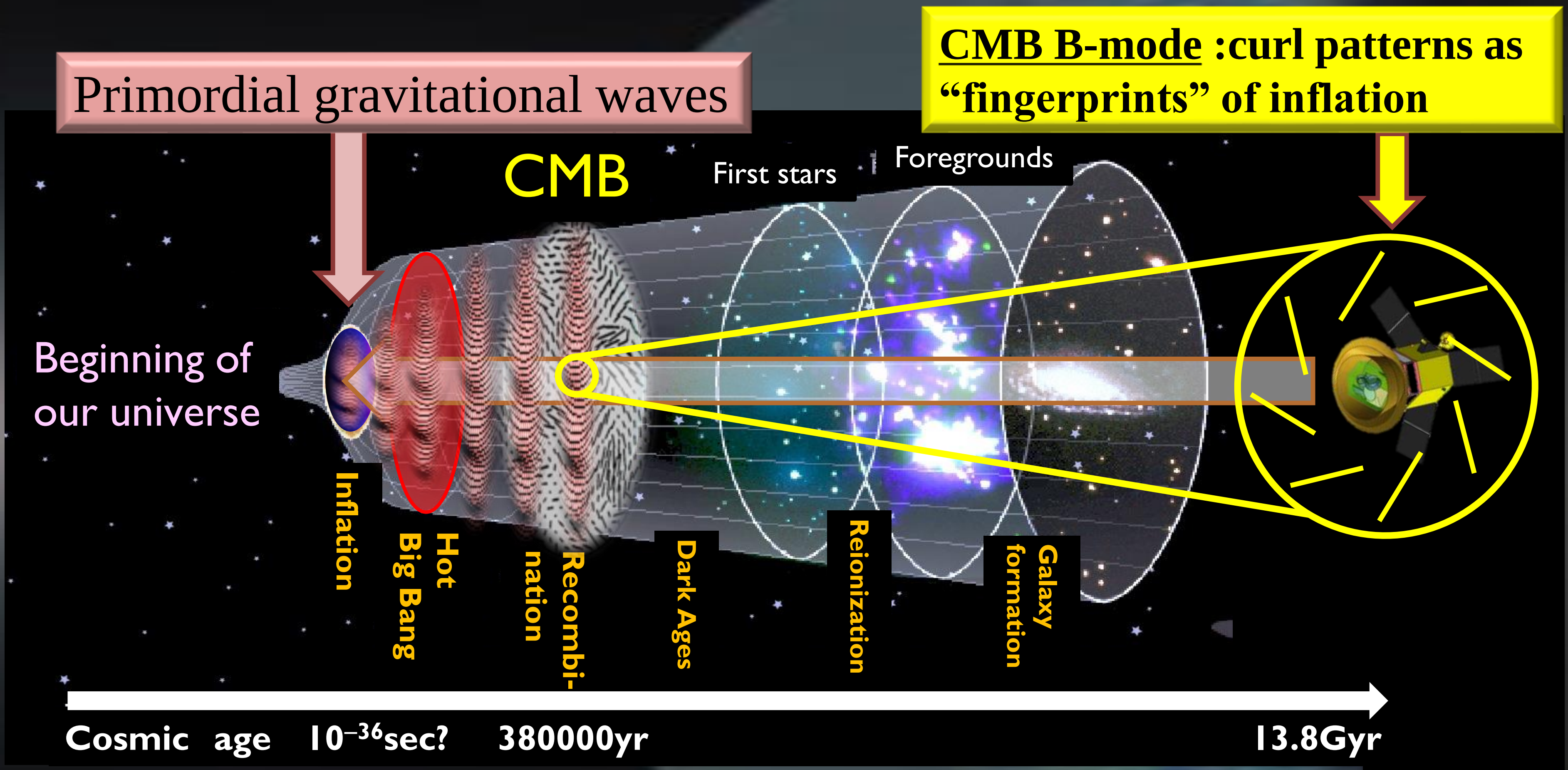


Planck 2018 I
BICEP2+KECK+Planck (BKP)

- $n_s = 0.967(4)$
- $r < 0.07$ (95%CL)

- $n_s < 1$ firmly established!
- The simplest chaotic inflation (ϕ^2) already ruled out!
- TT is limited by cosmic variance. Better meas. on r need B-mode!

CMB B-mode as probe of inflation

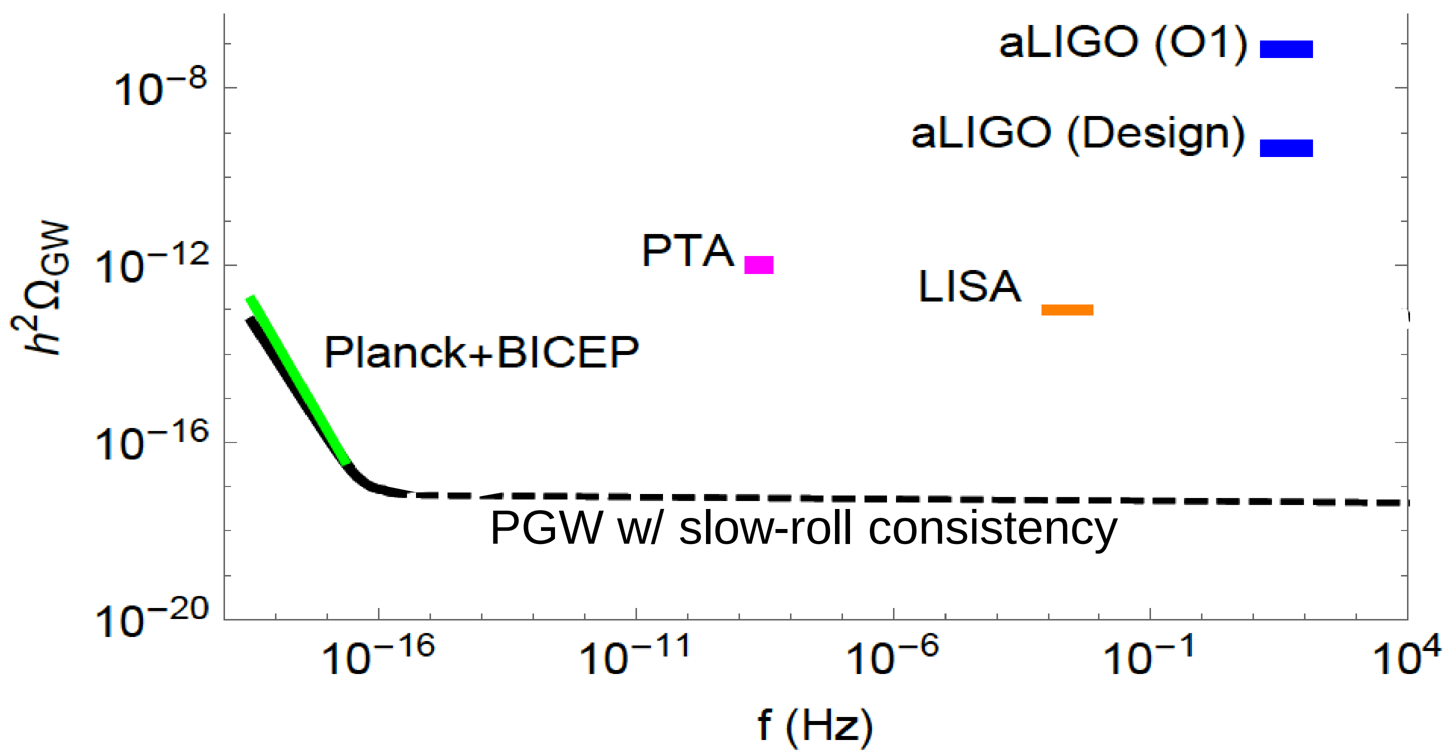


CMB B-mode is the best probe for primordial gravitational waves.
"Direct detection" of primordial GW w/ CMB as an experimental apparatus!

CMB B-mode vs. interferometer

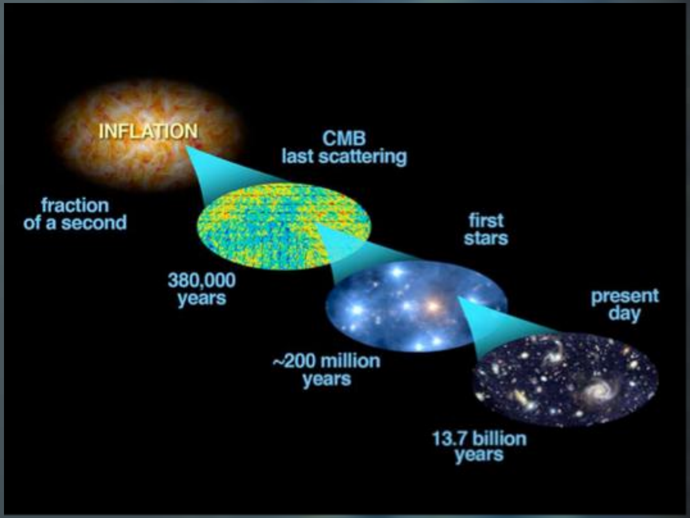
Caprini, Figueroa, arXiv1801.04268 (line w/ nt = 0.2 removed as it is irrelevant)

$$\Omega_{gw}(f) = \frac{3}{128}\Omega_{\rm rad}\, r\, A_s \left(\frac{f}{f_*}\right)^{n_t}\left[\frac{1}{2}\left(\frac{f_{\rm eq}}{f}\right)^2 + \frac{4}{9}(\sqrt{2}-1)\right]$$



Discovery with CMB B-mode will provide a clear target for a future space interferometer.

"Detecting primordial gravitational waves would be one of the most significant scientific discoveries of all time."



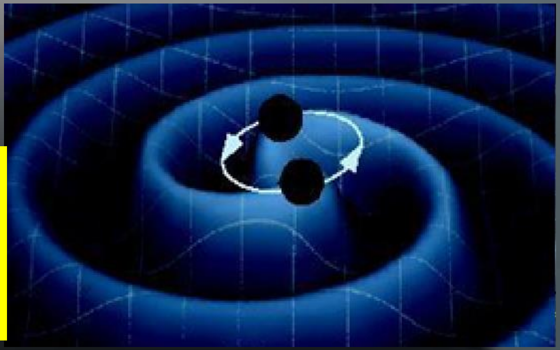
Final report of the task force on cosmic microwave background research
"Weiss committee report"
July 11, 2005, arXiv/0604101

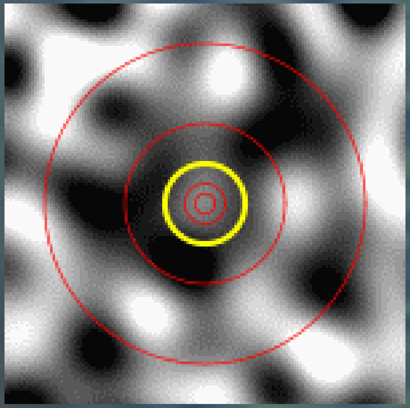
Big leap from <u>LIGO</u> to <u>CMB B-mode</u>

within Einstein's theory of general relativity

beyond Einstein

The 2017 Nobel Prize in Physics





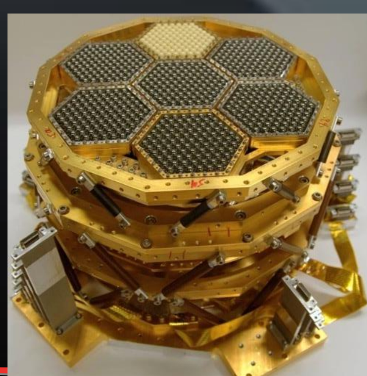
- LIGO: gravitational waves with classical origin
- CMB B-mode: gravitational waves with quantum origin

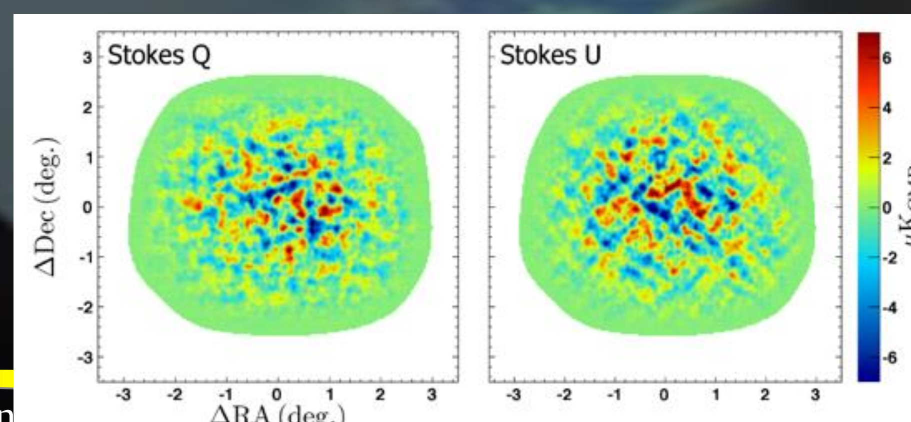
Modern CMB instrument: POLARBEAR as an example

Site:
Atacama, Chile

TES bolometer array

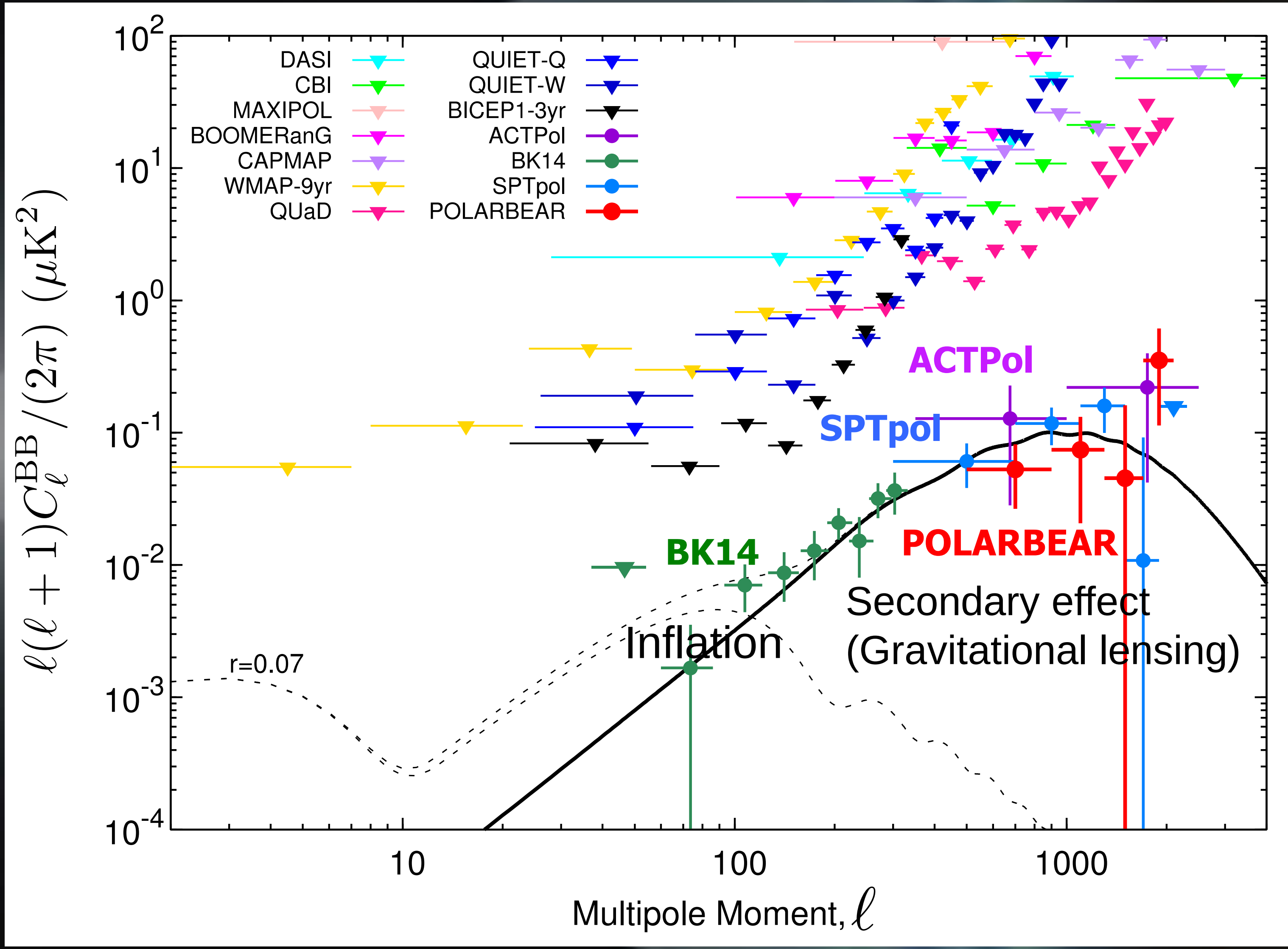
(UC Berkeley)





CMB B-mode power spectra

2017



Y. Chinone
(UC Berkeley)

About predictions on r

- Many models predict r > 0.01
- More general (less model-dependent) prediction
  - Focus on the simplest models based on Occam's razor principle → Single-field slow-roll (SFSR) models:
  - Detection of r > 0.002 establishes large-field variation (Lyth bound).
    - Significant impact on superstring theory that faces difficulty in dealing with $\Delta\phi > m_{pl}$
  - Obtaining r < 0.002 also has a significant impact on inflationary models and quantum gravity behind it.

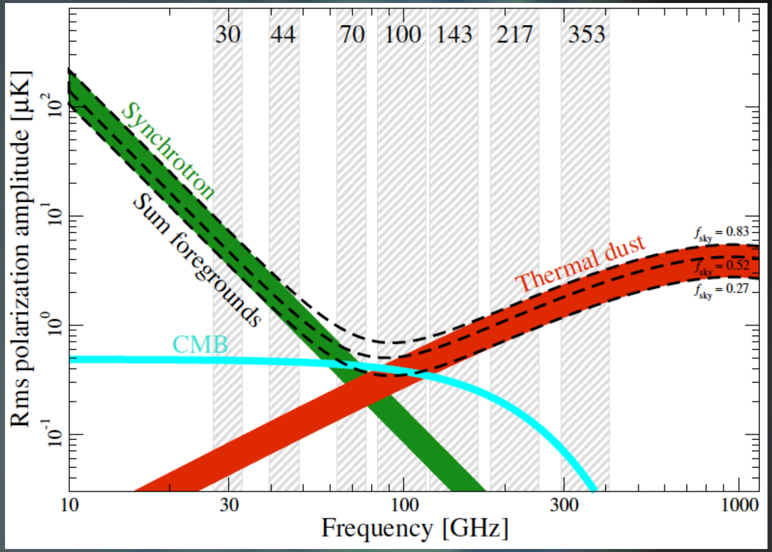
Measurements w/ $\sigma(r) < 0.001$ would provide a fairly definitive statement about the validity of large-field single-field slow-role models, which is a milestone in cosmology.

2. Future projects

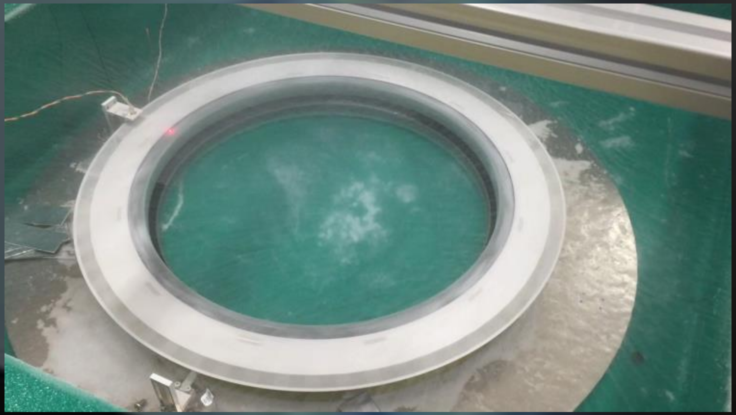
Experimental challenges

- Foreground cleaning
  - Multi-band observation
- Accuracy:
  - Excellent mitigation of systematic uncertainties
- Precision:
  - Large focal-plane array(s)

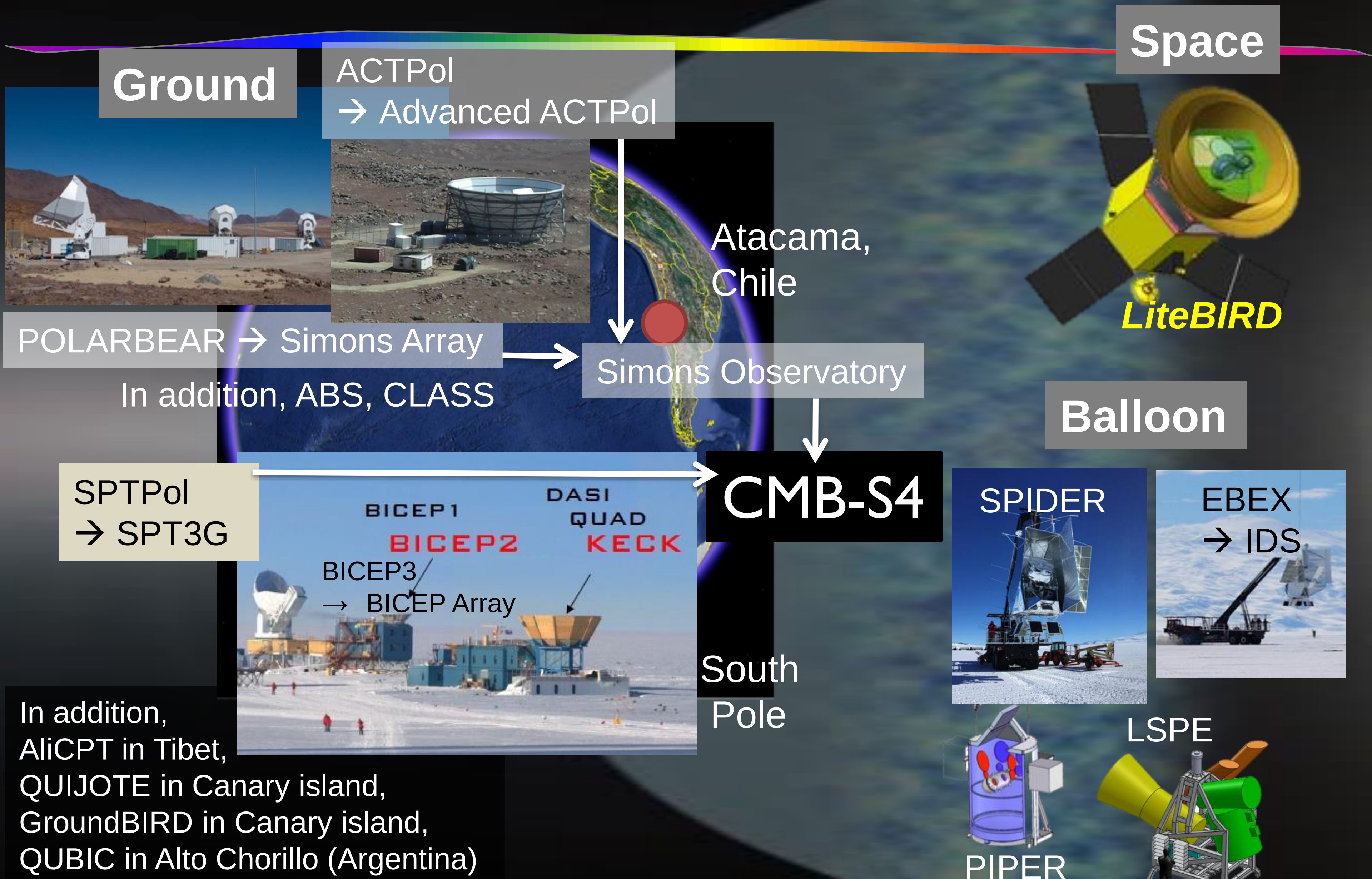
Frequency dependence of CMB and foregrounds



Polarization modulator for mitigation of systematics



On-going & future multi-frequency B-mode projects

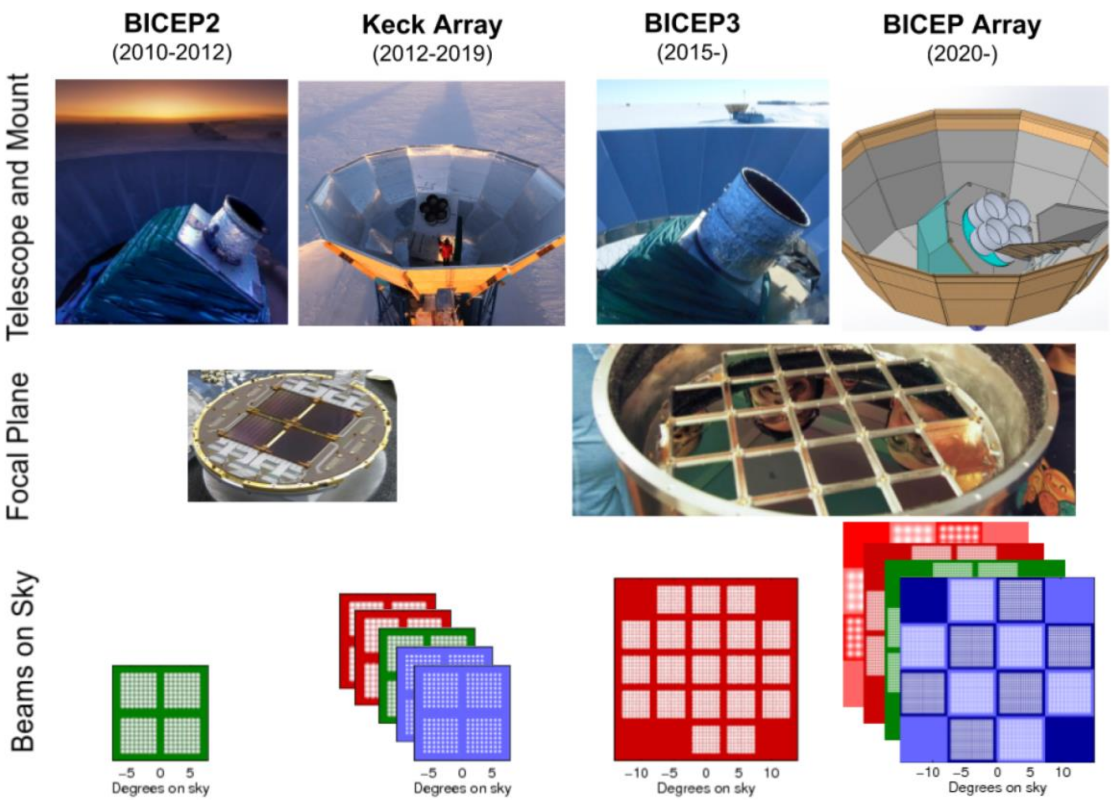


Examples

- Small aperture → BICEP-Keck
- Medium aperture → Simons Array
- Large aperture → Simons Observatory
- Balloon → IDS

J. Bock

BICEP-Keck Program



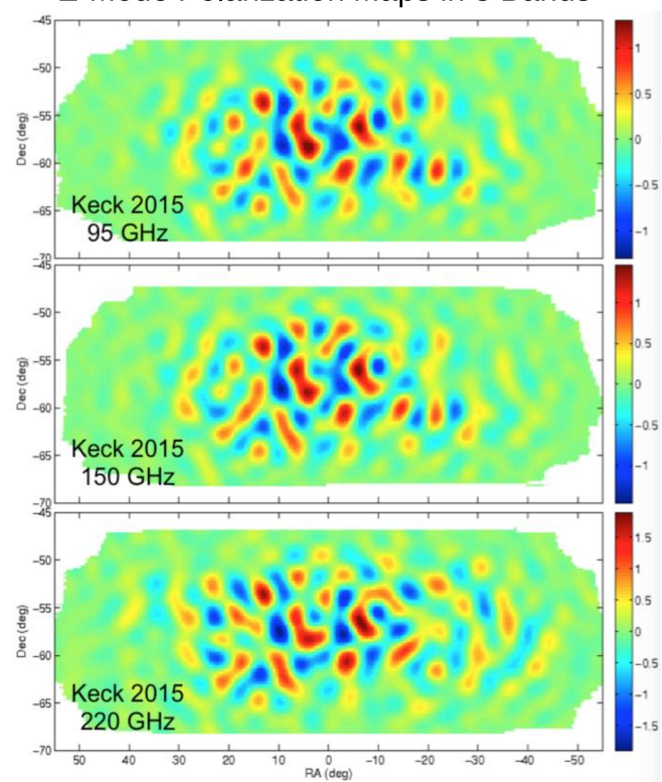
Evolutionary series of polarimeters targeting degree scales

- Small (26 & 55 cm) wide-field refracting telescopes
  - proven method to control of systematic errors
  - no active polarization modulation needed
- JPL planar antenna-coupled TES bolometer arrays
  - data in hand at 95, 150, 220 and 270 GHz
  - New arrays at 30 & 40 GHz in development
- Next-generation BICEP Array receivers in fabrication

Published B-Mode Sensitivity to r

Experiment	Year	Bands [GHz]	σ(r)
DASI	2004	26…36	7.5
BICEP1 2yr	2009	100, 150	0.28
WMAP 7yr	2010	30…60	1.1
QUIET-Q	2010	43	0.97
QUIET-W	2012	95	0.85
BICEP1 3yr	2013	100, 150	0.25
BICEP2	2014	150	0.10
BK + Planck	2015	150 + Planck	0.034
BK14	2015	95, 150 + P	0.024
ABS	2018	150	0.7
BK15	2018	95,150,220 + P	0.019

E-Mode Polarization Maps in 3 Bands



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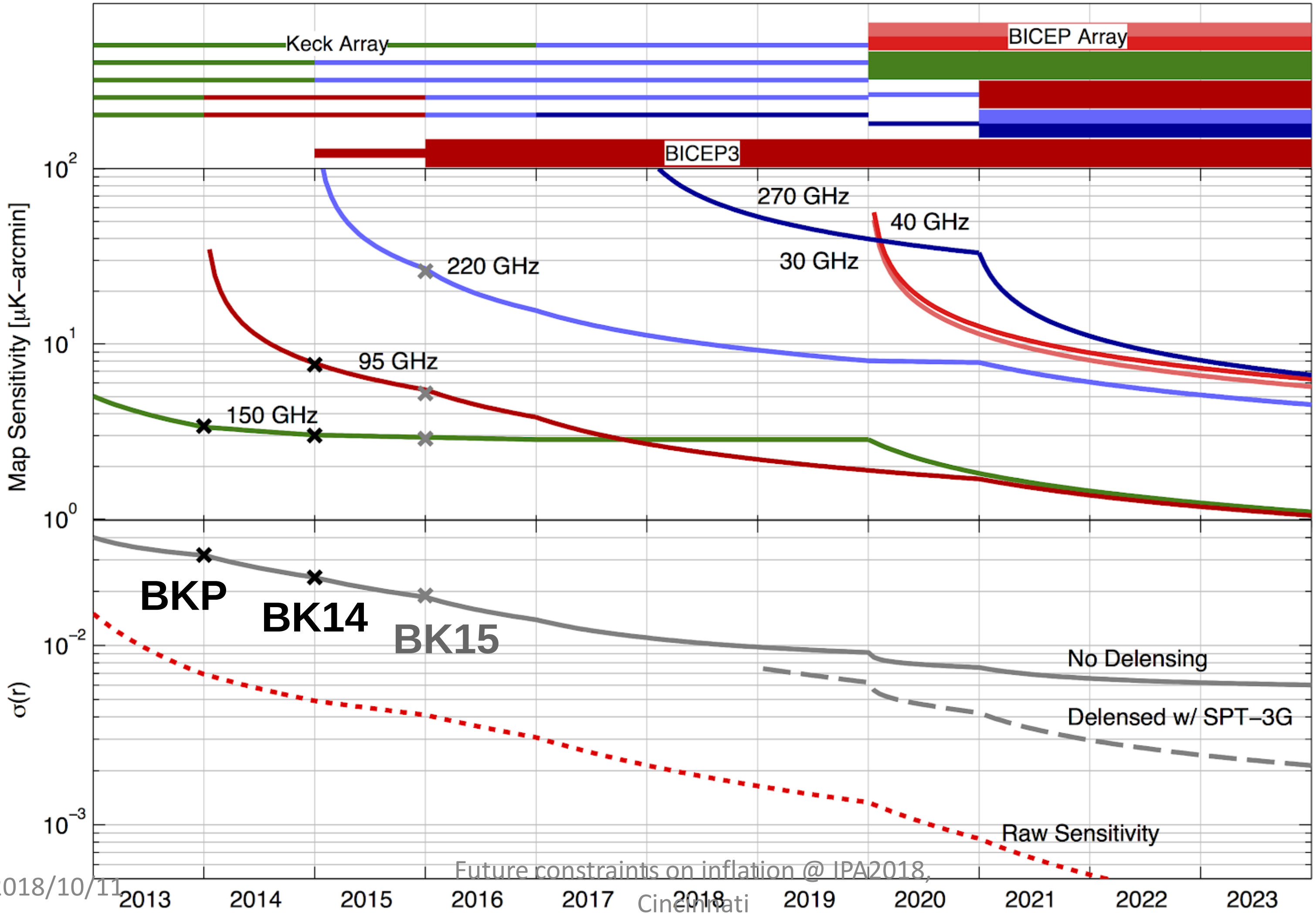
BICEP Future Forecasts

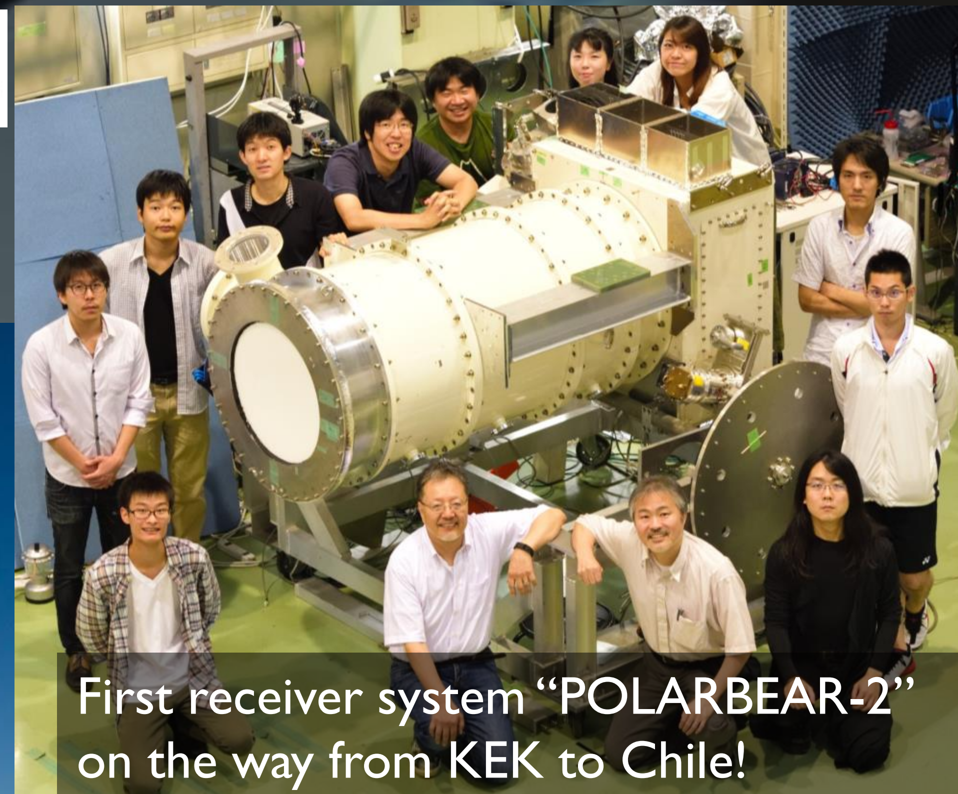
Forecasts are as realistic and complete as we can make them

- Map sensitivity scaled from on-sky *demonstrated*: NETs, yields, data cuts, observing efficiency, filtering
- r forecasts use the multi-component foreground dust and synchrotron model from BKP, BK14, BK15
- New collaboration formed with SPT for future delensing

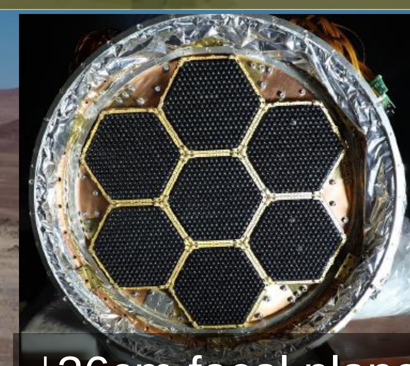


Simons Array: [σ(r) ~0.006, 4 bands]


Collaboration meeting at KEK (Mar 2017)


First receiver system "POLARBEAR-2" on the way from KEK to Chile!

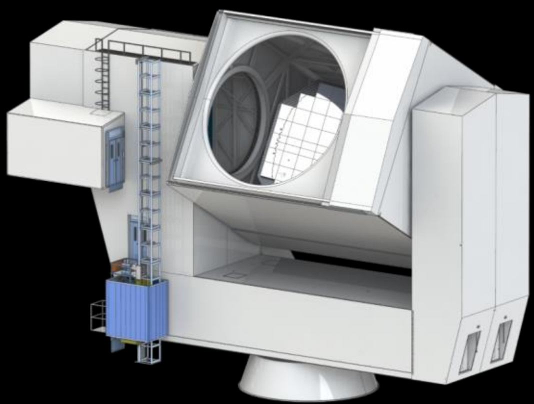

First light expected in 2018


ϕ36cm focal plane

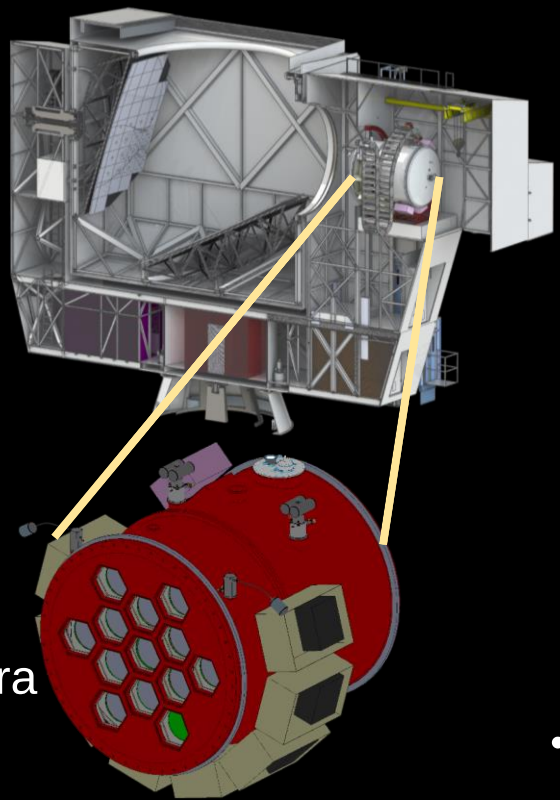
M. Devlin

Simons Observatory

Full operations in 2021

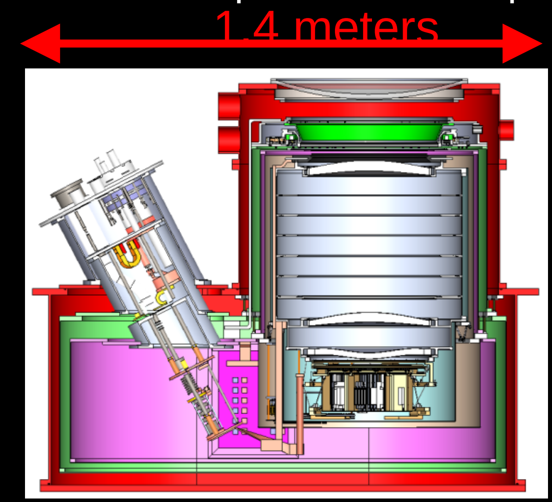


Large Aperture Telescope



Large Aperture Telescope Camera

Small Aperture Telescopes



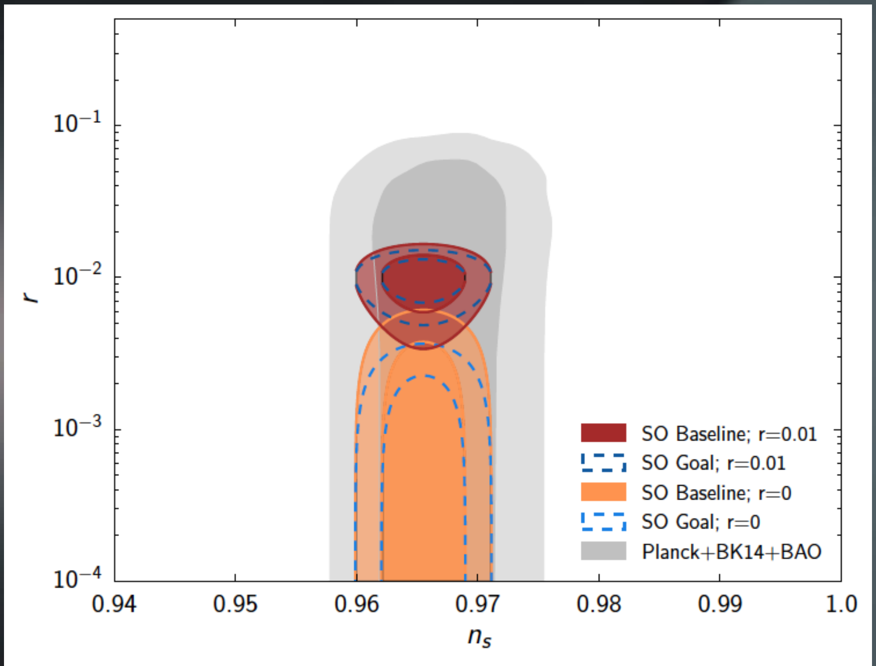
- Three telescopes each with a 50 cm aperture.
- A total of 30,000 detectors

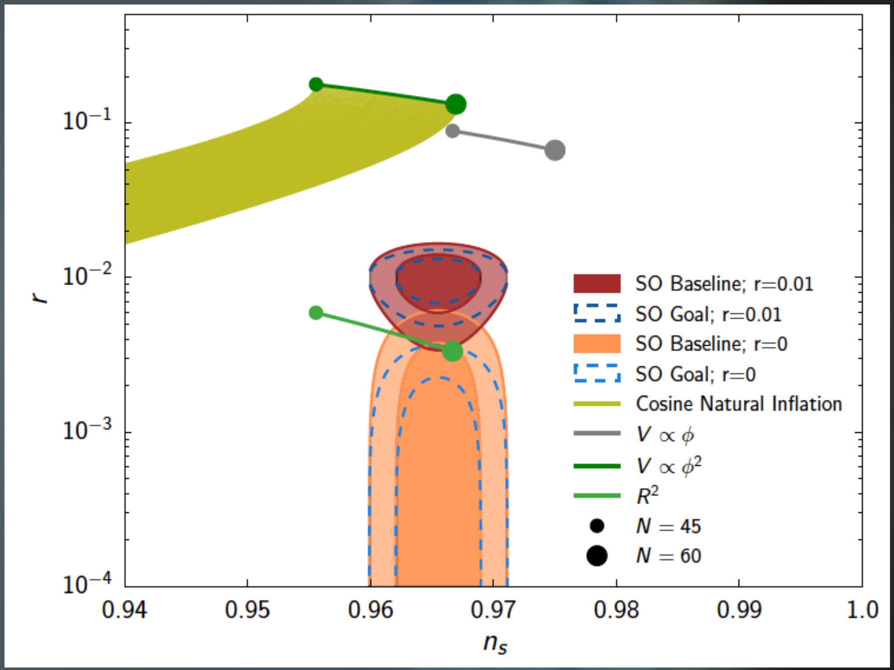
- 6 meter off-axis Cross Dragone design
- 9 degree field of view – 9 times the throughput of ACT
- 1.7 arcmin resolution at 150 GHz
- Up to 70,000 detectors can be accommodated (30,000 planned)

- Extensive site infrastructure in Chile
- Data pipeline and analysis development

Simons Observatory forecasts

arXiv:1808.07445



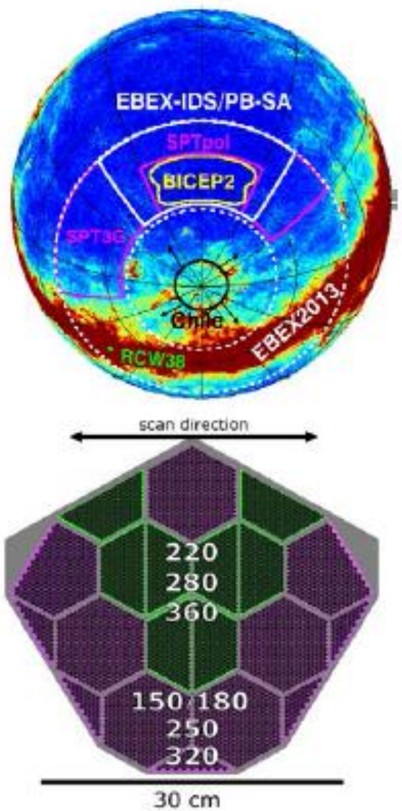


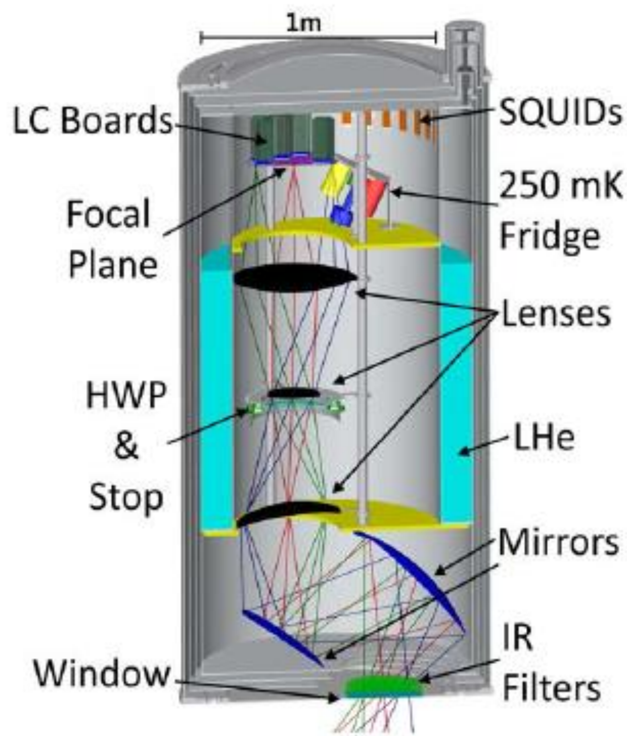
$\delta r = 0.003$

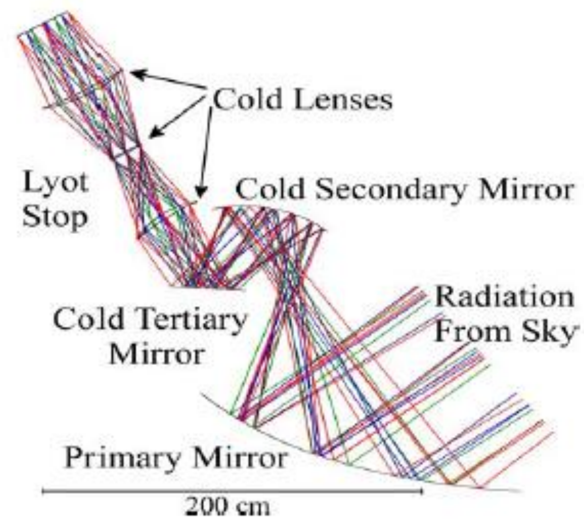
Inflation and Dust Surveyor - IDS

S. Hanany

- 20,562 detectors with 3,966 multi-chroic, polarization sensitive pixels
- 7 frequency bands (150, 180, 220, 250, 280, 320, 360 GHz)
- Resolution between 3.2 and 7.2 arcmin
- 20 days proposed Antarctic flight in 2022,
- 1500 sq deg. overlapping with BICEP-Keck (BK, SA)
- r<0.003 (95%) including data from BK+SA; r<0.008 (95%) IDS alone
- Progress in detector development reported in Aubin et al. ??







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Yet another inflationary probe: non-Gaussianity

- **Non-Gaussianity (f_{NL})** – Sensitive to **Inflaton field**, single- or multi-field

$$\phi = \phi_{linear} + f_{NL}\,\phi^2_{linear}$$

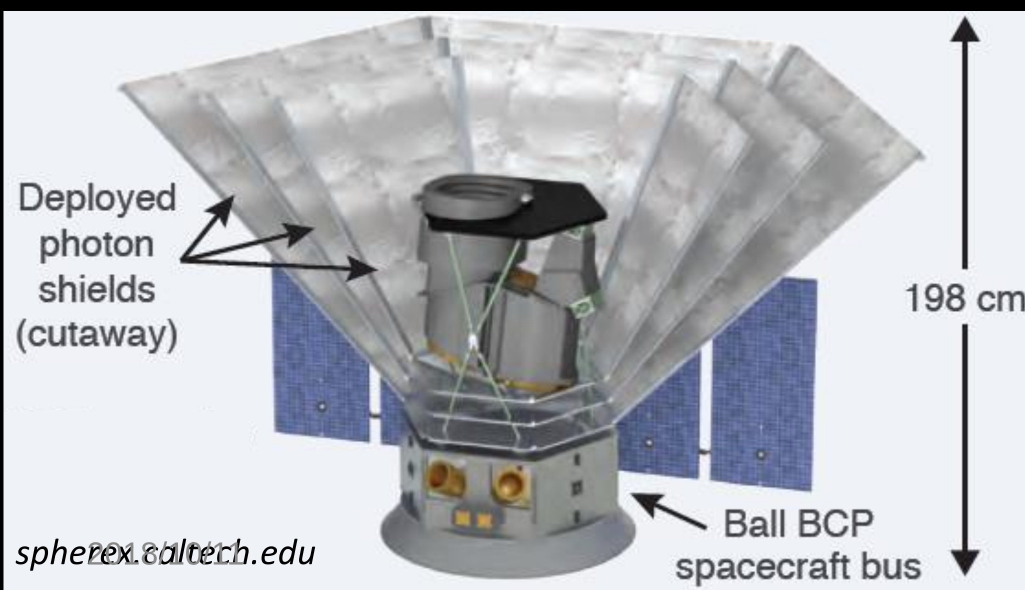
$$CMB:\ f_{NL} < 10.8\ (2\sigma)$$

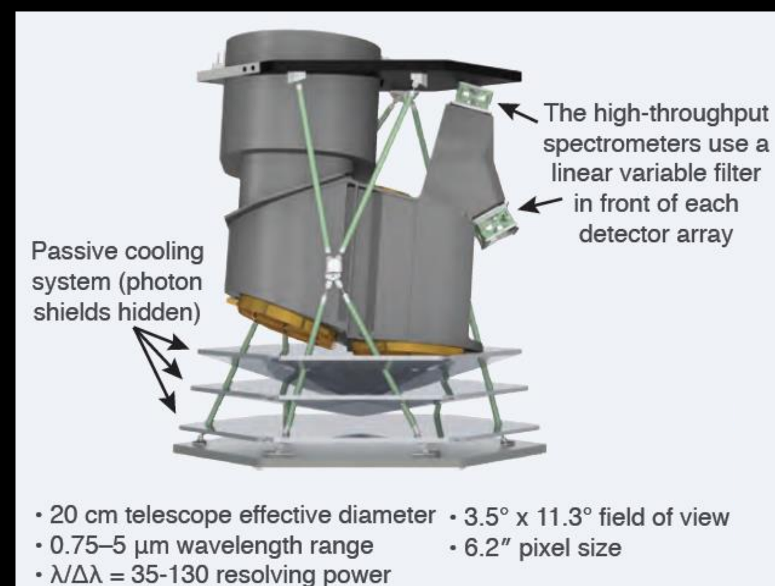
CMB near cosmic limits – use large-scale structure!

Local f_{NL}; Planck 2015 results

SPHEREx: Near-Infrared All-Sky Spectral Survey

- NASA MIDEX in competitive Phase A (selection early 2019, launch 2023)
- Large-volume galaxy redshift survey designed for large spatial scales
- Broad science includes studies of extragalactic background and interstellar ices





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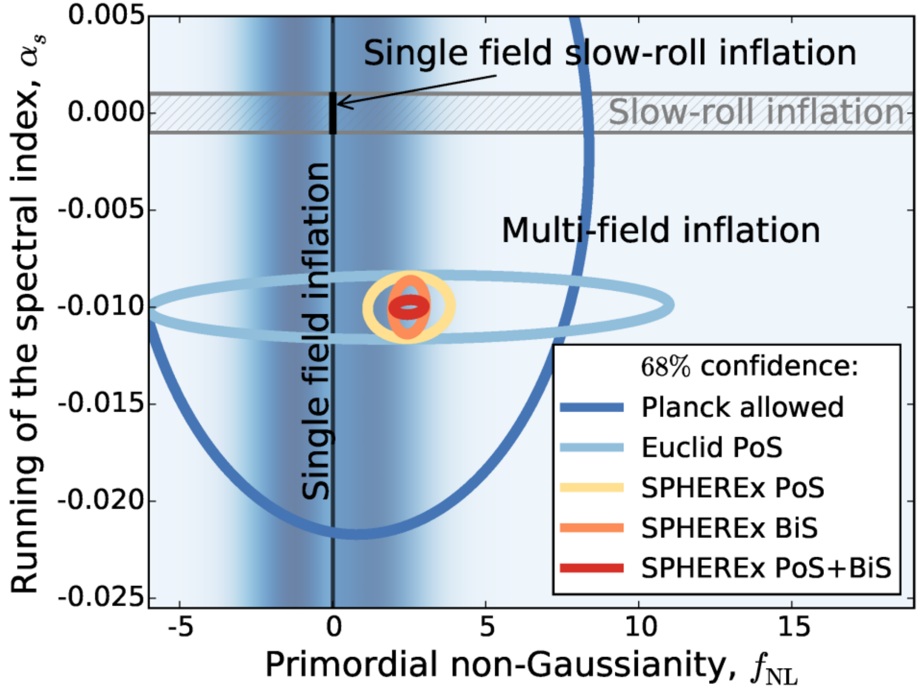
SPHEREx Tests Inflationary Non-Gaussianity

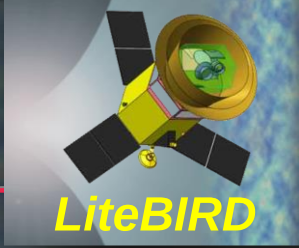


1σ errors statistical (systematics)	SPHEREx (MEV)			Euclid PoS	Planck & BOSS
	PoS	BiS	PoS+BiS		
SPHEREx f_{NL} Req't	1.15	0.55	0.5	N/A	N/A
f_{NL}	0.89 (0.53)	0.35 (0.22)	0.32 (0.21)	5.6	5.0
Spectral Index n_s ($\times 10^{-3}$)	2.7	1.9	1.1	2.6	4.0
Running α_s ($\times 10^{-3}$)	1.0	0.9	0.25	1.1	13
Curvature Ω_k ($\times 10^{-4}$)	7.7	8.1	4.4	7.0	40
Dark Energy figure of merit (bigger is better)	371			309	14

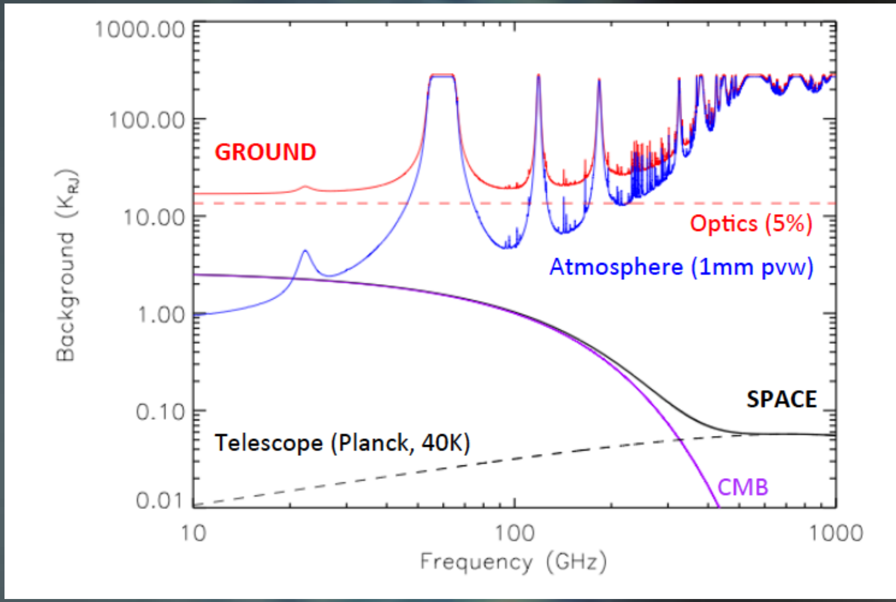
- Non-Gaussianity discriminates between multi- and single-field models
- Projected SPHEREx sensitivity is $\Delta f_{NL} < 0.5$ (1σ)
  - Two independent tests via power spectrum and bispectrum
- Competitively tests running of the spectral index
- SPHEREx low-redshift catalog is complementary for dark energy

3. LiteBIRD satellite

Why measurements in space ?



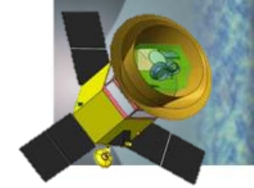
- Superb Environment !
  - No statistical/systematic uncertainty due to atmosphere
  - No limitation for the choice of observing bands
  - No ground pickup



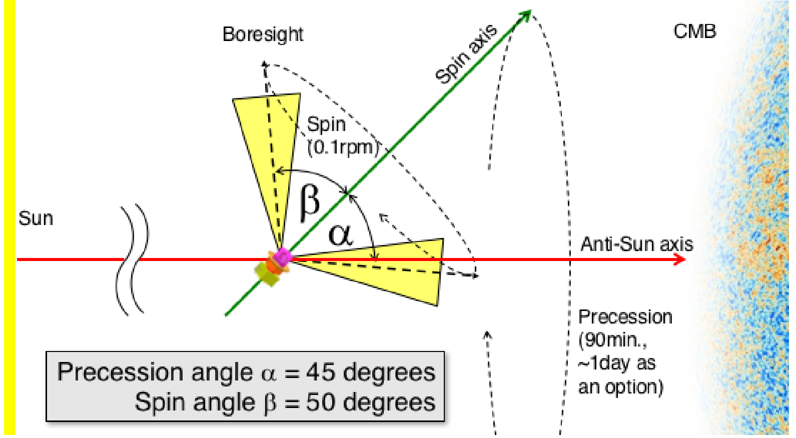
Rule of thumb: 1,000 detectors in space ~ 100,000 detectors on ground

- Only way to access lowest multipoles w/ precision/accuracy
  - Both bumps need to be observed for the firm confirmation of cosmic inflation → We need measurements in space.

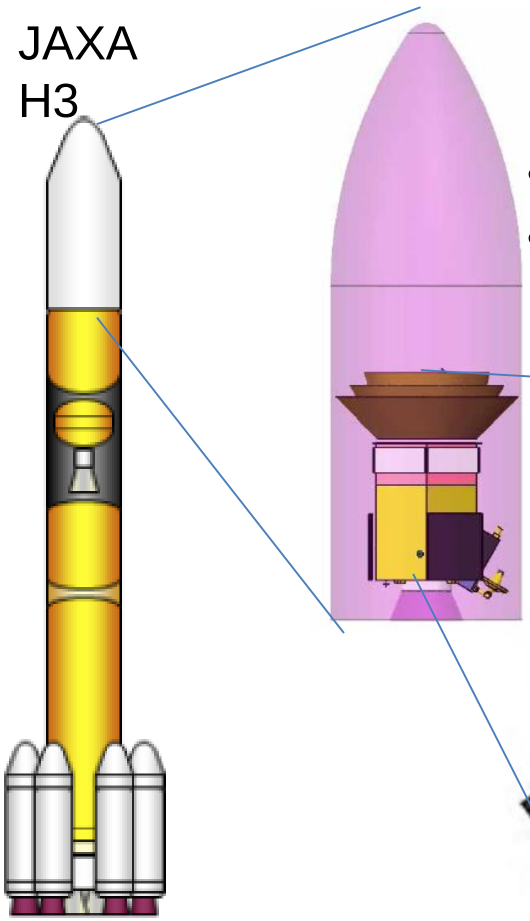
LiteBIRD



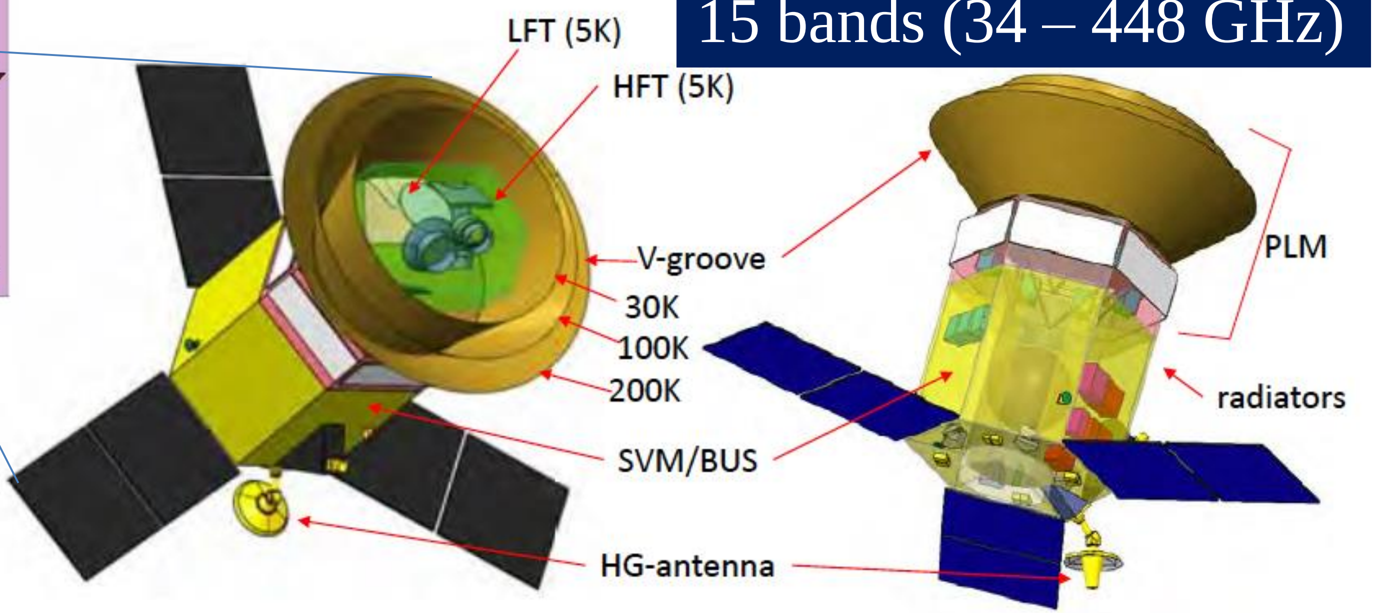
- JAXA-led international mission proposal (12 countries)
- Status: Phase A (concept development)
- 3yr observations at L2



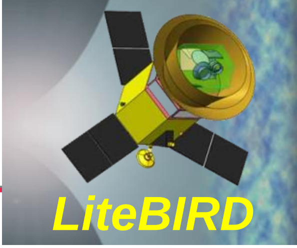
- The only space mission proposal in Phase A in the world
- Final selection in 2019
- Launch in 2027

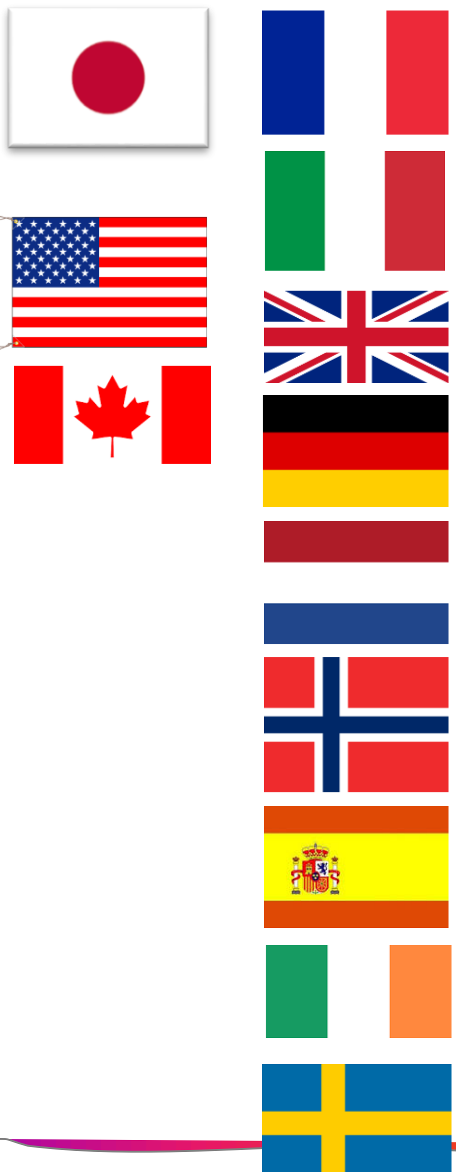


15 bands (34 – 448 GHz)



LiteBIRD Joint Study Group



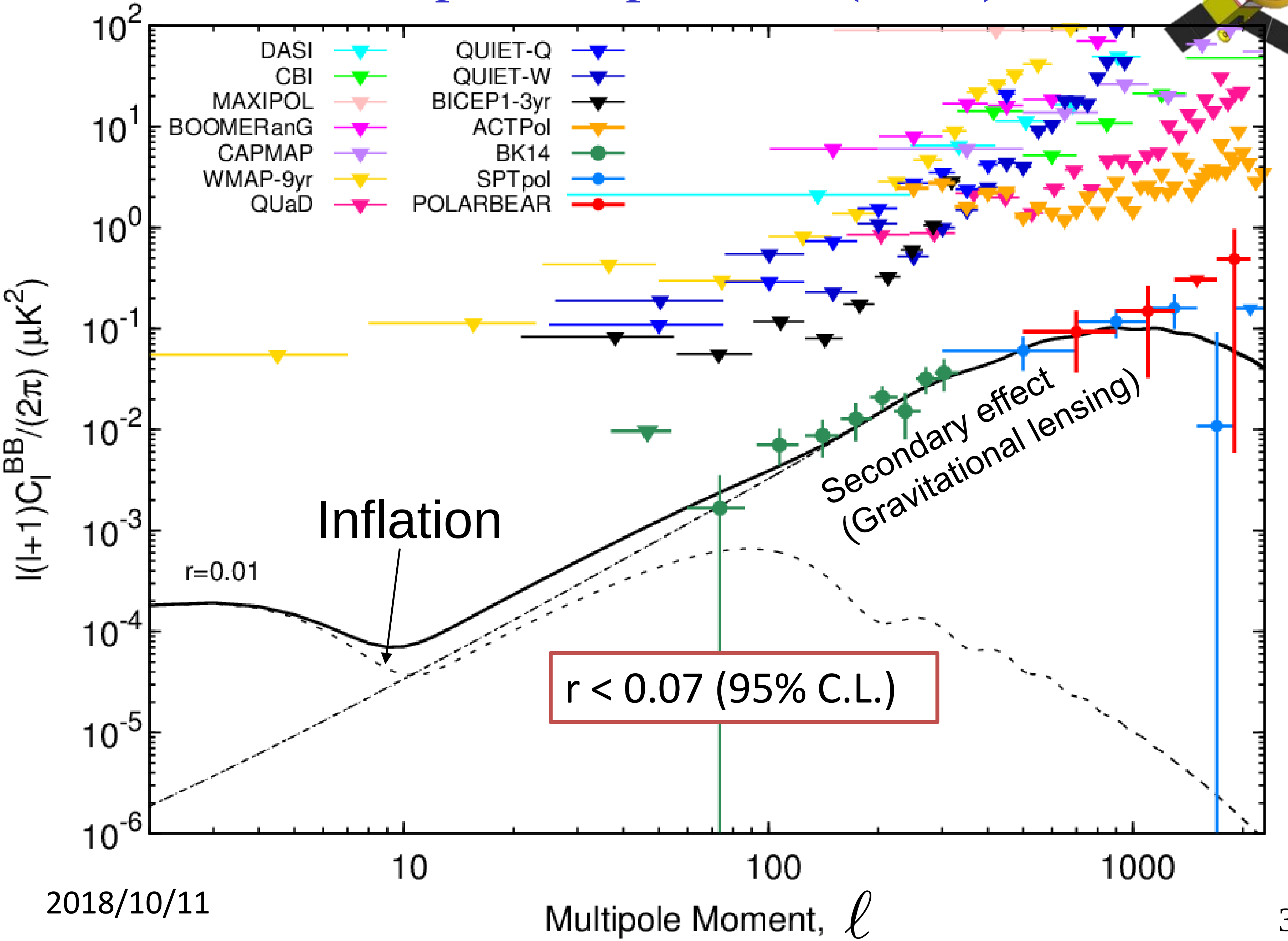


About 180 researchers from all over the world

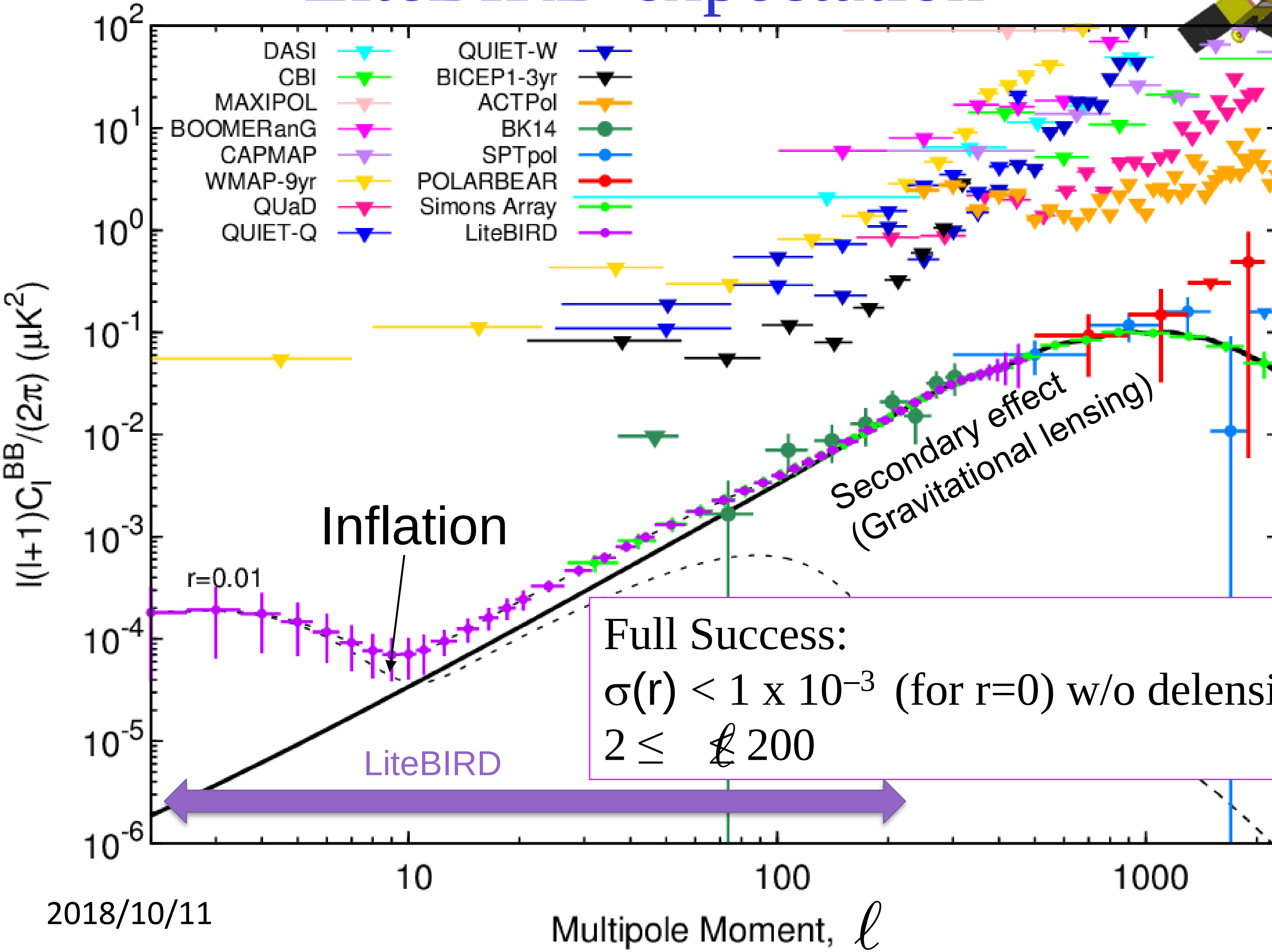
Y. Sekimoto[14,37], P. Ade[2], K. Arnold[49], J. Aumont[12], J. Austermann[29], C. Baccigalupi[11], A. Banday[12], R. Banerji[56], S. Basak[7,11], S. Beckman[49], M. Bersanelli[44], J. Borrill[20], F. Boulanger[4], M.L. Brown[53], M. Bucher[1], E. Calabrese[2], F.J. Casas[10], A. Challinor[50,60,64], Y. Chinone[16,47], F. Columbro[46], A. Cukierman[47,36], D. Curtis[47], P. de Bernardis[46], M. de Petris[46], M. Dobbs[23], T. Dotani[14,37], L. Duband[3], JM. Duval[3], A. Ducout[16], K. Ebisawa[14], T. Elleflot[49], H. Eriksen[56], J. Errard[1], R. Flauger[49], C. Franceschet[54], U. Fuskeland[56], K. Ganga[1], J.R. Gao[35], T. Ghigna[16,57], J. Grain[9], A. Gruppuso[6], N. Halverson[51], P. Hargrave[2], T. Hasebe[14], M. Hasegawa[5,37], M. Hattori[42], M. Hazumi[5,14,16,37], S. Henrot-Versille[19], C. Hill[21,47], Y. Hirota[38], E. Hivon[61], D.T. Hoang[1,63], J. Hubmayr[29], K. Ichiki[24], H. Imada[19], H. Ishino[30], G. Jaehnig[51], H. Kanai[59], S. Kashima[25], K. Kataoka[30], N. Katayama[16], T. Kawasaki[17], R. Keskitalo[20,48], A. Kibayashi[30], T. Kikuchi[14], K. Kimura[31], T. Kisner[20,48], Y. Kobayashi[39], N. Kogiso[31], K. Kohri[5], E. Komatsu[22], K. Komatsu[30], K. Konishi[39], N. Krachmalnicoff[11], C.L. Kuo[34,36], N. Kurinsky[34,36], A. Kushino[18], L. Lamagna[46], A.T. Lee[21,47], E. Linder[21,48], B. Maffei[9], M. Maki[5], A. Mangilli[12], E. Martinez-Gonzalez[10], S. Masi[46], T. Matsumura[16], A. Mennella[54], Y. Minami[5], K. Mistuda[14], D. Molinari[52,6], L. Montier[12], G. Morgante[6], B. Mot[12], Y. Murata[14], A. Murphy[28], M. Nagai[25], R. Nagata[5], S. Nakamura[59], T. Namikawa[27], P. Natoli[52], T. Nishibori[15], H. Nishino[5], C. O'Sullivan[28], H. Ochi[59], H. Ogawa[31], H. Ogawa[14], H. Ohsaki[38], I. Ohta[58], N. Okada[31], G. Patanchon[1], F. Piacentini[46], G. Pisano[2], G. Polenta[13], D. Poletti[11], G. Puglisi[36], C. Raum[47], S. Realini[54], M. Remazeilles[53], H. Sakurai[38], Y. Sakurai[16], G. Savini[43], B. Sherwin[50,65,21], K. Shinozaki[15], M. Shiraishi[26], G. Signorelli[8], G. Smecher[41], R. Stompor[1], H. Sugai[16], S. Sugiyama[32], A. Suzuki[21], J. Suzuki[5], R. Takaku[14,40], H. Takakura[14,39], S. Takakura[16], E. Taylor[48], Y. Terao[38], K.L. Thompson[34,36], B. Thorne[57], M. Tomasi[44], H. Tomida[14], N. Trappe[28], M. Tristram[19], M. Tsuji[26], M. Tsujimoto[14], S. Uozumi[30], S. Utsunomiya[16], N. Vittorio[45], N. Watanabe[17], I. Wehus[56], B. Westbrook[47], B. Winter[62], R. Yamamoto[14], N.Y. Yamasaki[14], M. Yanagisawa[30], T. Yoshida[14], J. Yumoto[38], M. Zannoni[55], A. Zonca[33],

- ISAS/JAXA Phase A1 (Sep. 2016 – Aug. 2016)
- US technology development (NASA)
- Science contribution studies and science maturity studies (CSA)
- Studies at Concurrent Design Facility (ESA) with LiteBIRD European Consortium
- Phase A commitment by ASI
- Phase A commitment by CNES

B-mode power spectrum (2016)



LiteBIRD expectation



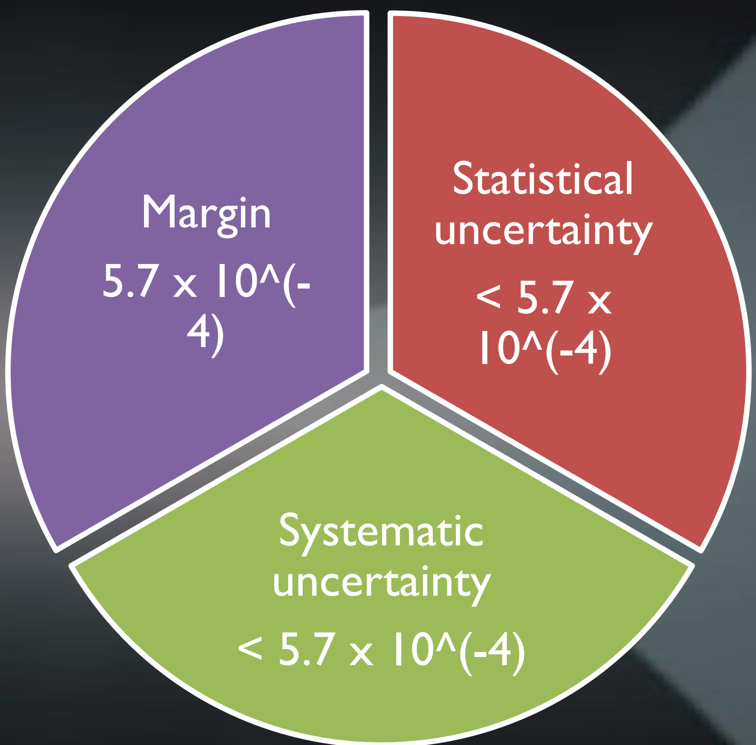
Full Success:

$\sigma(r) < 1 \times 10^{-3}$ (for r=0) w/o delensing

$2 \leq \ell \leq 200$

Design drivers

$\delta r < 1 \times 10^{-3}$



Our simulations tell that both criteria are satisfied!

Statistical uncertainty includes
- foreground subtraction
- lensing B-mode
- 1/f noise

Broadband 34 – 448 GHz (15 bands)

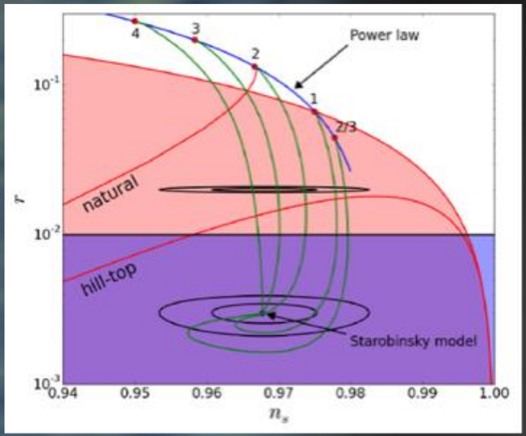
Systematic uncertainty includes
- 1/f noise
- Polarization efficiency and its knowledge
- Disturbance to instrument
- Off-boresight pick up
- Calibration accuracy

Polarization Modulation

Impacts of discovery

- Direct evidence for cosmic inflation in case power spectrum agrees w/ prediction
  - Many models predict $0.003 < r < 0.05$
  - Narrowing down models in r vs. n_s plane
- Shed light on GUT-scale physics

$$V^{1/4} = 1.04 \times 10^{16} \times \left(\frac{r}{0.01}\right)^{1/4} [GeV]$$



- New era of physics w/ experimental tests of quantum gravity
  - First observation of quantum fluctuation of space-time
  - Studies on top-down constraints in string theory in progress
    - $r > 0.01$ not easy (super-Planckian field excursions)
- Unexpected discovery (e.g. non-standard power spectrum) may rule out standard inflation paradigm
- Sense of wonder beyond science!

Summary

- Three important observables (r, n_s, f_{NL}) to test inflation.
- Measurements of r w/ CMB B-mode are particularly important.
- Ambitious projects have been proposed or in preparation for improvements by 1~2 order of magnitude on r and f_{NL}.
- Discoveries may even constrain quantum gravity theory, including superstring theory!

Backup slides

ΛCDM with six fit parameters

Baryon

Dark Energy (69%)	DM (26%)	5 %

--- *Planck* 2015 6-parameter fit to flat ΛCDM cosmology ---		Planck results in PDG2018
baryon density of the Universe	$\Omega_b = \rho_b/\rho_{crit}$	$^\ddagger 0.02226(23)\,h^{-2} = {}^\dagger 0.0484(10)$
cold dark matter density of the Universe	$\Omega_c = \rho_c/\rho_{crit}$	$^\ddagger 0.1186(20)\,h^{-2} = {}^\dagger 0.258(11)$
100 × approx to r_*/D_A	$100 \times \theta_{MC}$	$^\ddagger 1.0410(5)$
reionization optical depth	τ	$^\ddagger 0.066(16)$
scalar spectral index	n_s	$^\ddagger 0.968(6)$
ln power prim. curv. pert. (k_0=0.05 Mpc^{-1})	$\ln(10^{10}\Delta_R^2)$	$^\ddagger 3.062(29)$

2 parameters for initial conditions

- Other parameters (e.g. Ω_Λ, t_0) are derived.

Standard Cosmology (ΛCDM)

Precision measurements support a remarkably simple picture!

- GR + cosmological principle
  - Physical existence of space is expressed by the scale "*a*" alone
  - Friedmann equation for time evolution of flat universe $$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3}$$
- Initial adiabatic, Gaussian perturbation
  - **Consistent with inflation hypothesis**
- Only six fit parameters are sufficient to describe the current set of precision data !
  - Flat universe assumption works fine.

Modern cosmology is a precision science like HEP!

Why are CMB measurements so precise/accurate?

- Linear evolution from initial state to CMB emission
- CMB well preserved until today
- Precision inversely proportional to observing time!
- Remarkable development of observational instruments!

Other probes (e.g. 3D galaxy maps) are also very useful, complementary and/or unique (with careful treatments of biases and other non-linear effects)

If evidence is found before launch

LiteBIRD

- r is fairly large → Comprehensive studies by LiteBIRD !
- 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 if r>0.01.
  - Deeper level of fundamental physics

No-Lose Theorem of LiteBIRD