

Cosmological Tensions seen through B-Mode Glasses

Wavy Dark Matter Conference

Carlo Baccigalupi, Astrophysics & Cosmology, SISSA

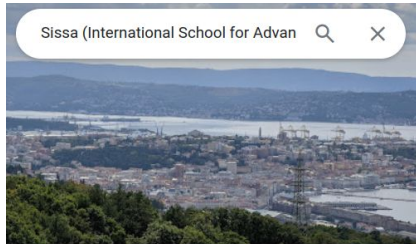


고려대학교 기초과학연구원

Korea University
The Institute of Basic Science



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Sissa (International School for Advanced Studies)

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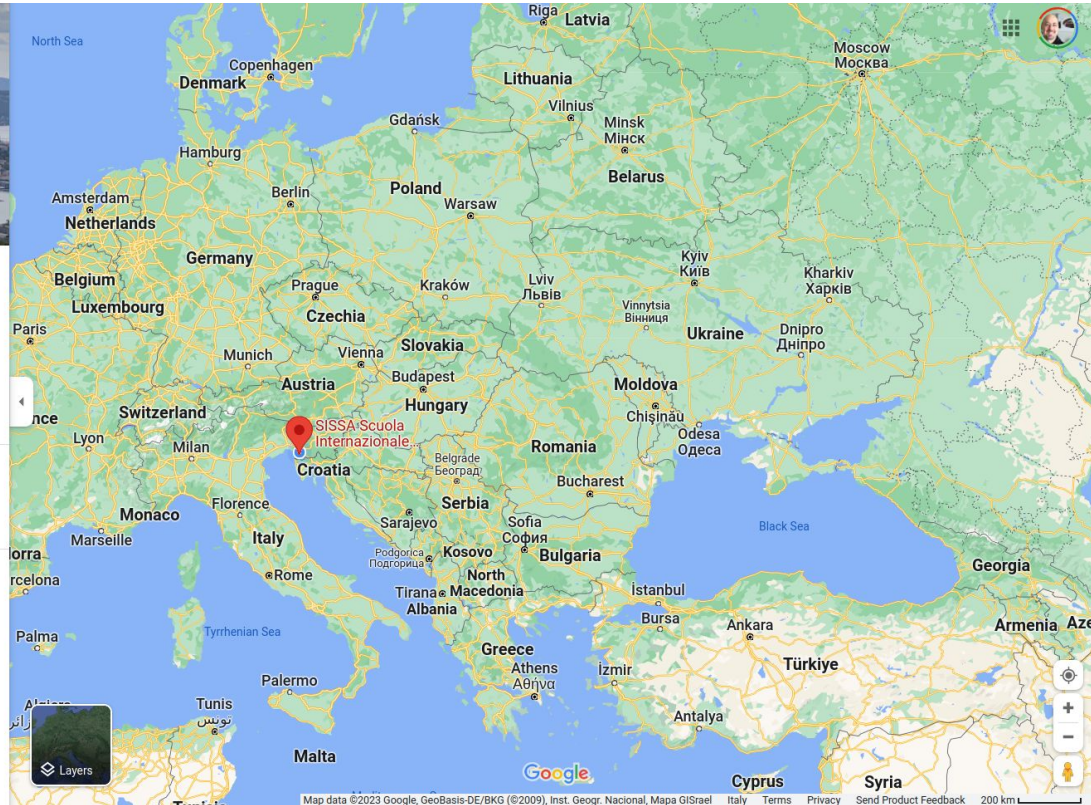
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 - Data Science,
 - Statistical and Biological Physics,
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Astrophysics & Cosmology at SISSA



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- Scientific Areas:
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 - Physics
- Computer Systems & Infrastructure for High Performance Computing: itcs.sissa.it
- Main Projects in Astrophysics & Cosmology:
 - **Euclid**
 - **Simons Array**
 - **Simons Observatory**
 - **LiteBIRD**
 - **CMB-S4**

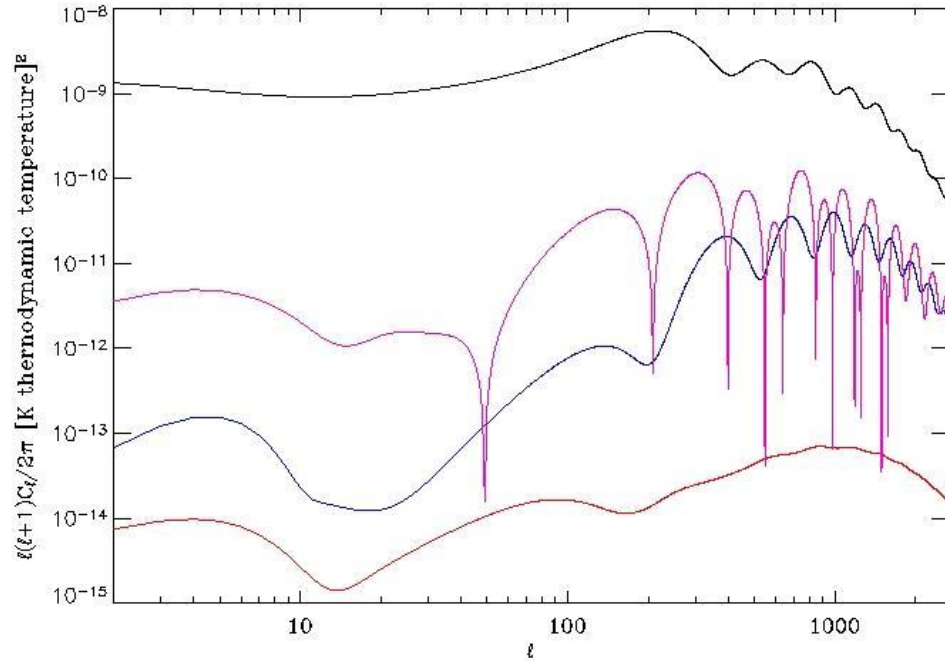


Outline

- **B-Modes, Dark Energy and Matter**
- **B-Mode Data**
- **B-Mode Constraints**
- **Future B-Mode Probes**
- **Concluding Remarks**

B-Modes, Dark Energy and Matter

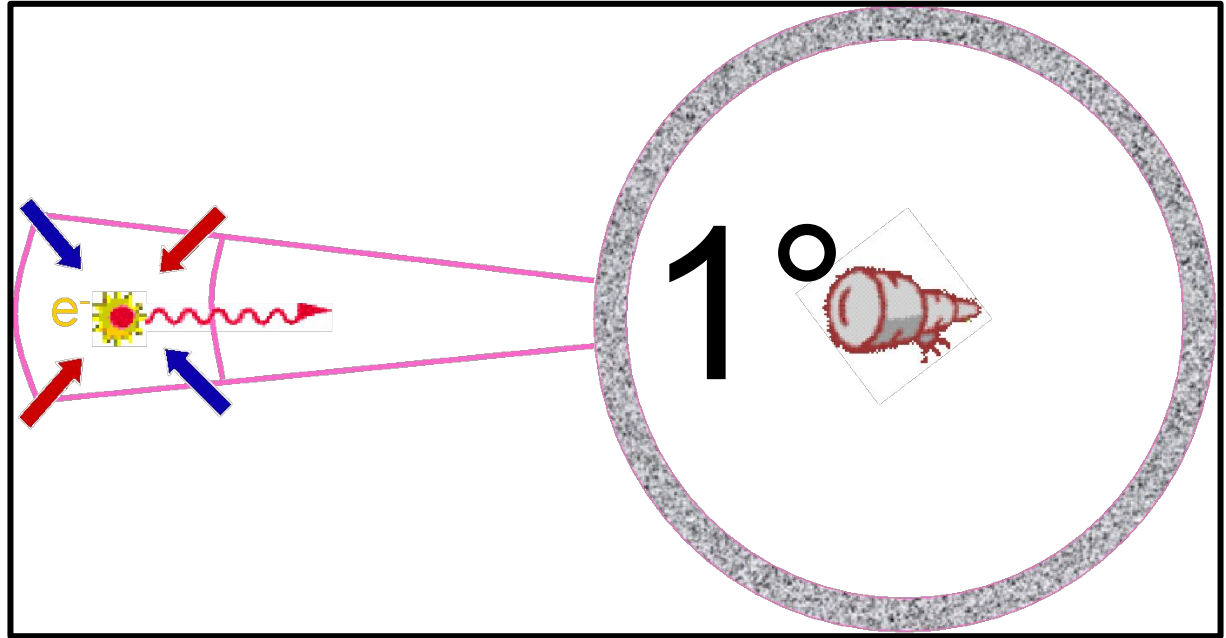
B-Modes, DE, DM



Angle $\approx 200/\ell$ degrees

B-Modes, DE, DM: Gravitational Waves

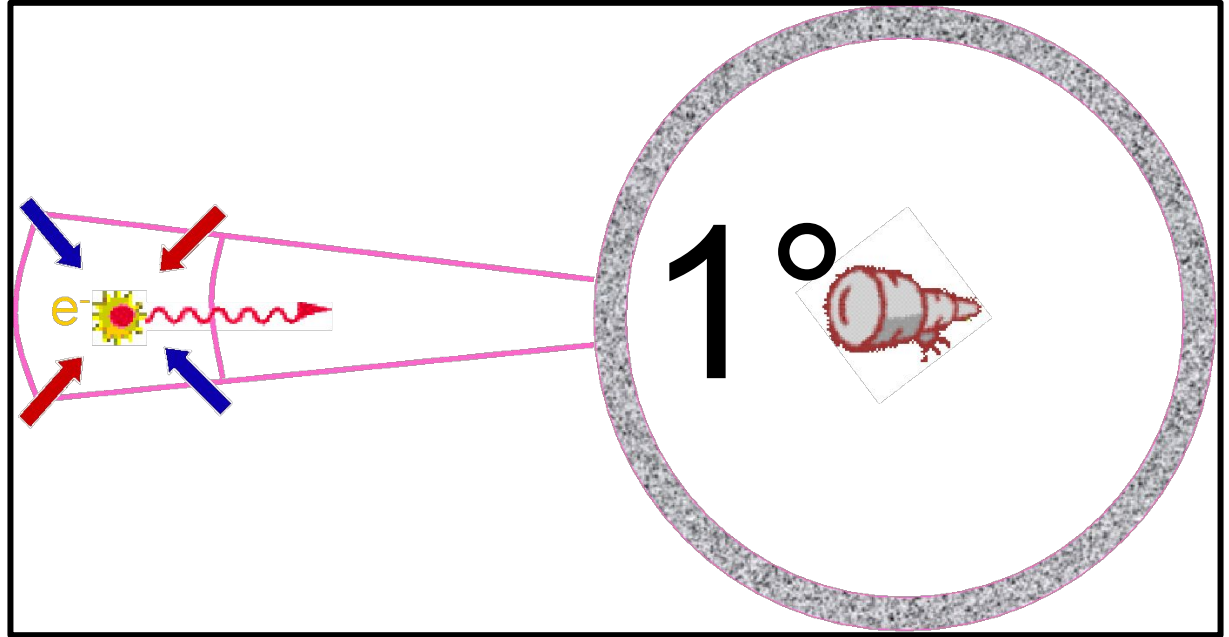
Gravitational waves not supported by sources, diffuse out rapidly below the Horizon scale, about 1 degree in the sky



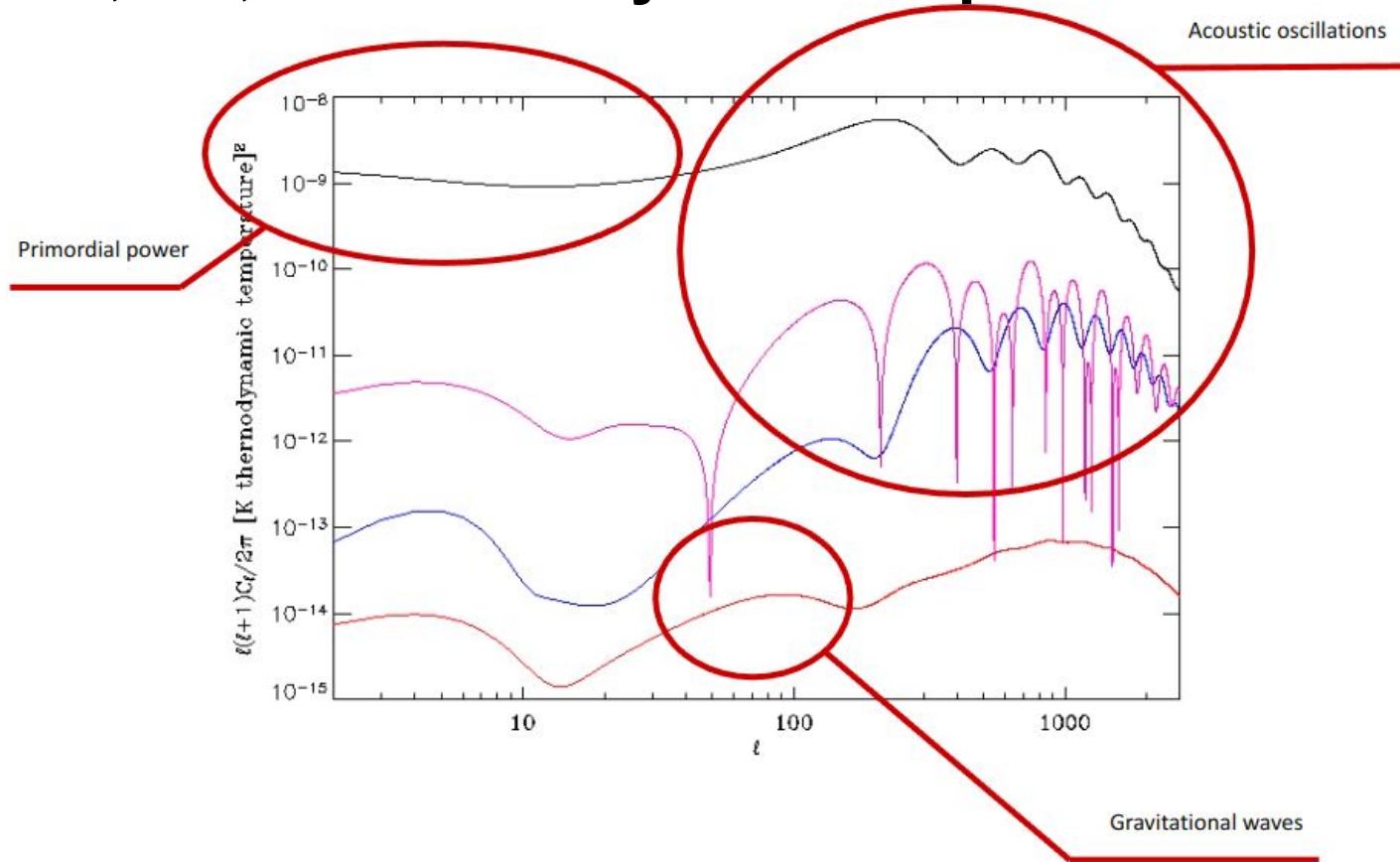
B-Modes, DE, DM: Gravitational Waves

Gravitational waves not supported by sources, diffuse out rapidly below the Horizon scale, about 1 degree in the sky

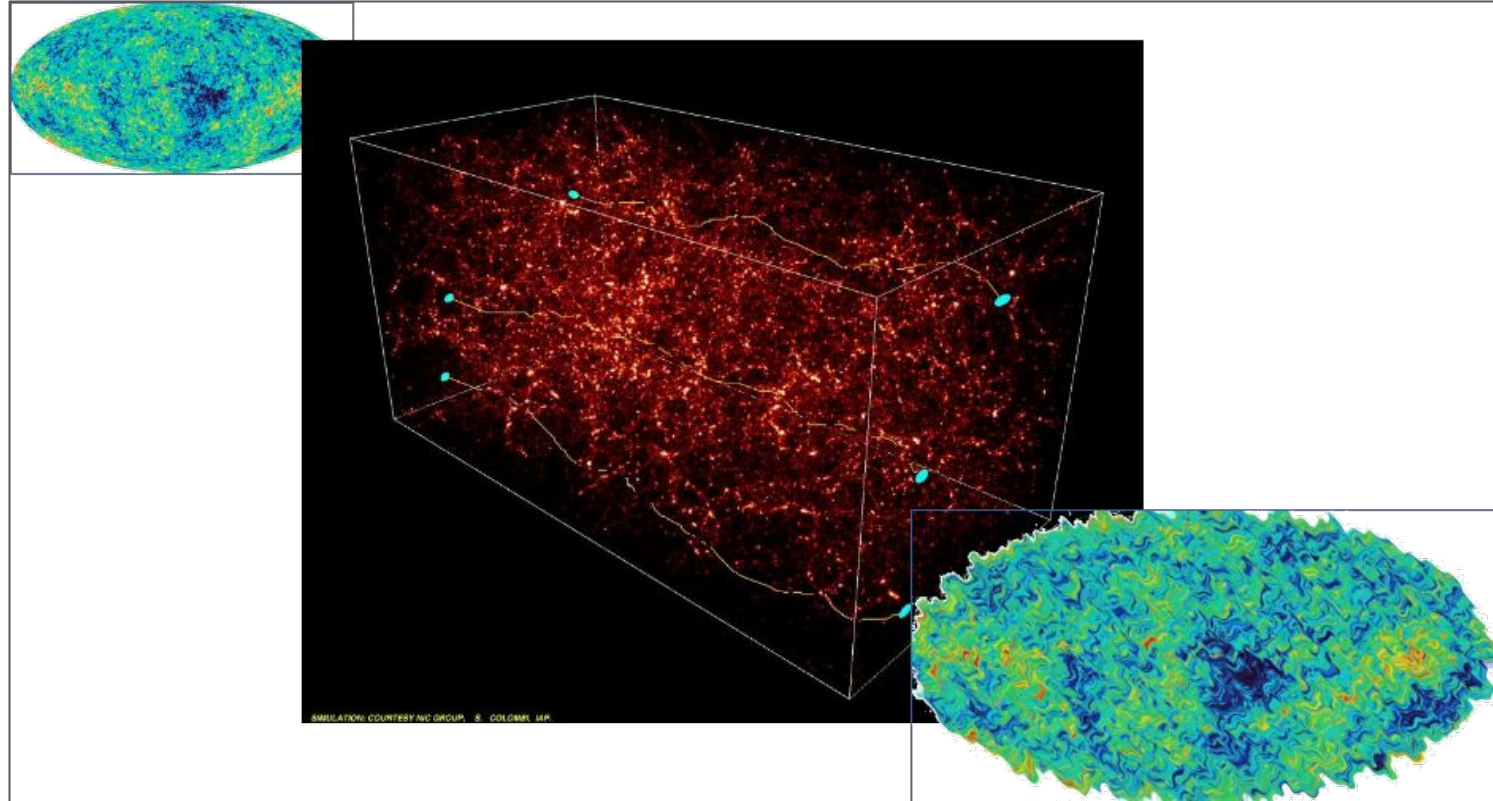
Decoupling time lasts for about 10 Mpc, no time for longer wavelengths to contribute



B-Modes, DE, DM: Primary Anisotropies

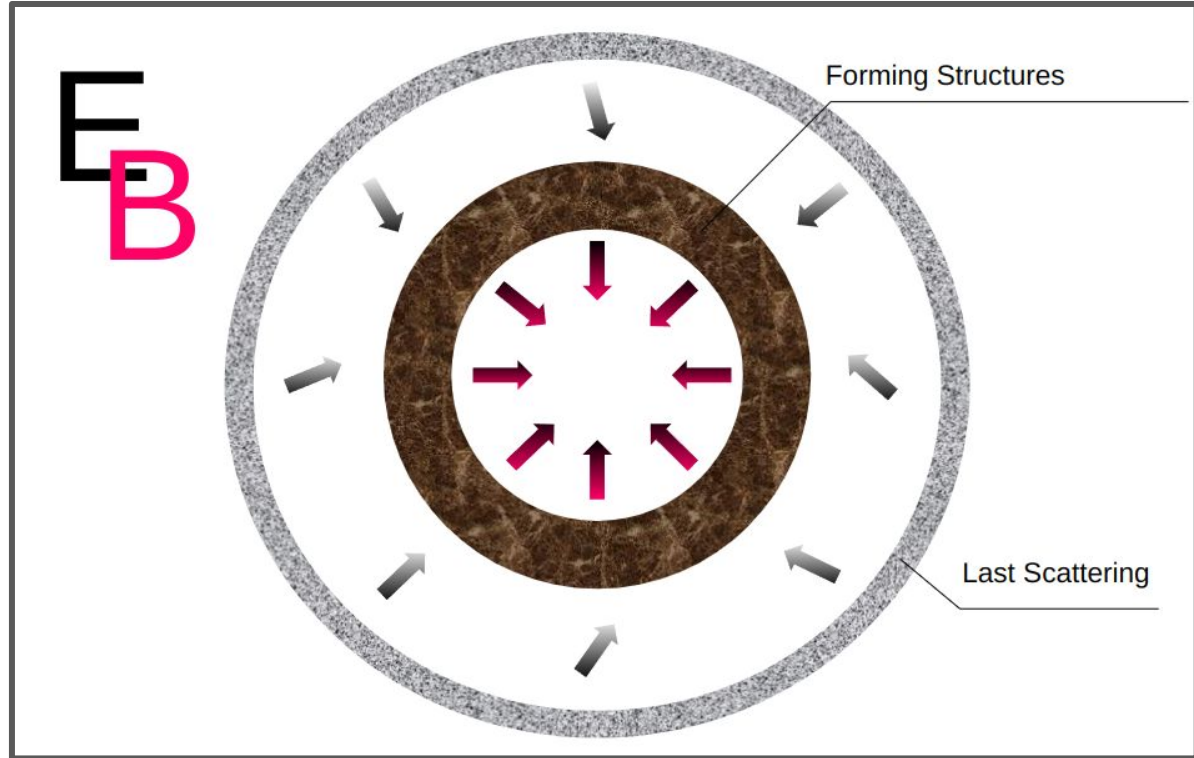


B-Modes, DE, DM: Gravitational Lensing



B-Modes, DE, DM: Gravitational Lensing

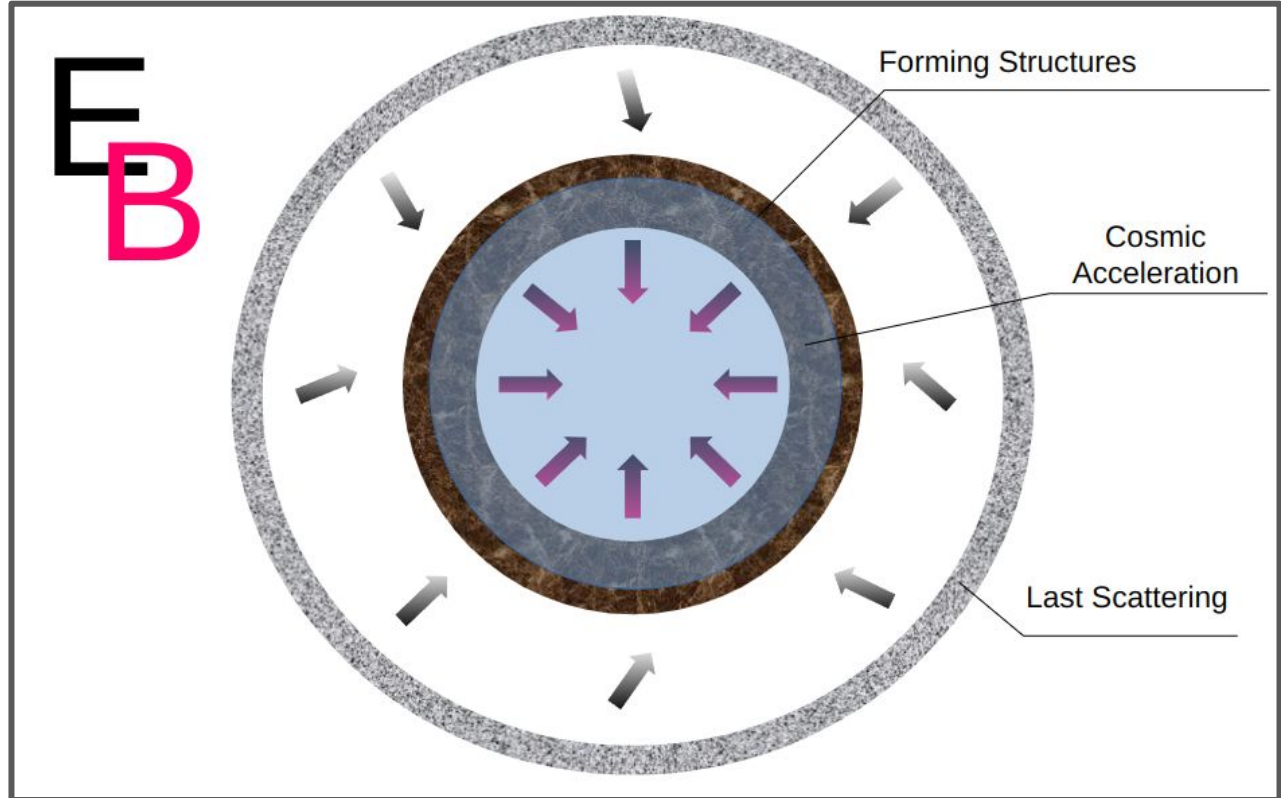
Forming Structures
act as Lenses, over a
large Redshift
Interval,
Peaking
between 1 and 3



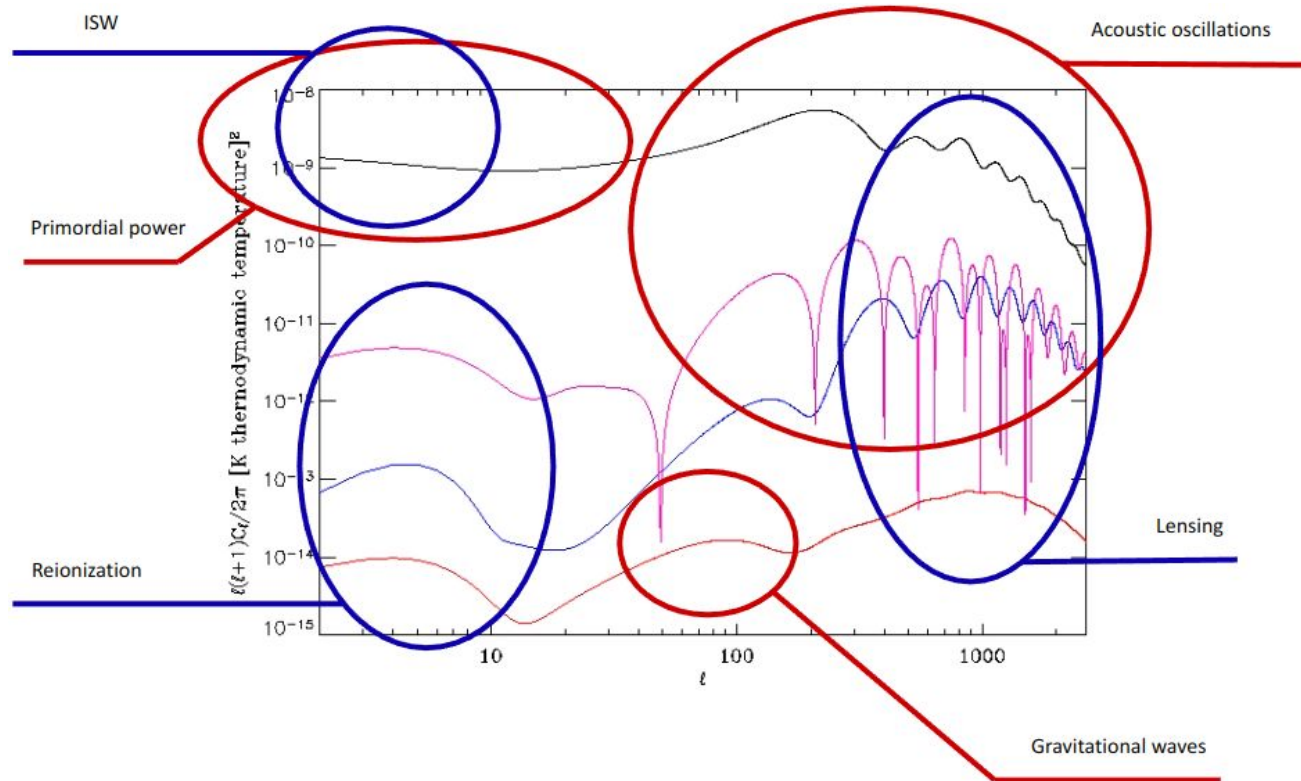
B-Modes, DE, DM: Gravitational Lensing

Forming Structures act as Lenses, over a large Redshift Interval, Peaking between 1 and 3

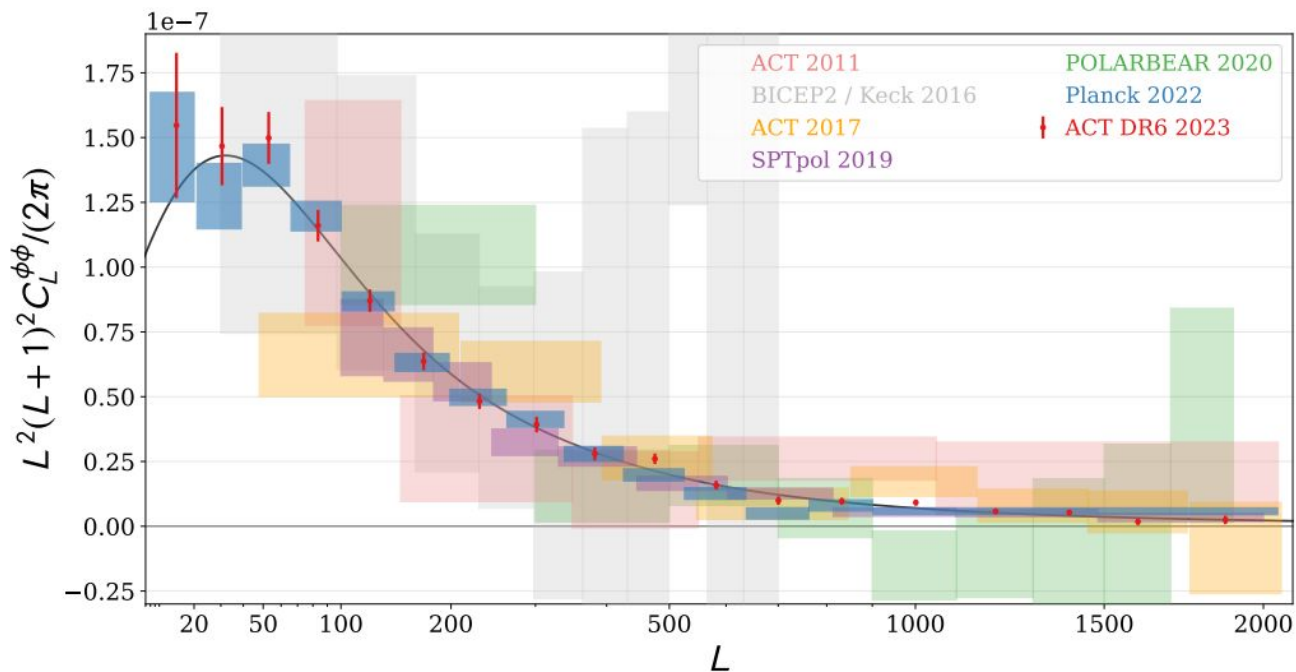
The CMB Lensing is a Probe for Dark Energy, by itself and in Cross-Correlation with LSS Probes



B-Modes, DE, DM: Secondary Anisotropies



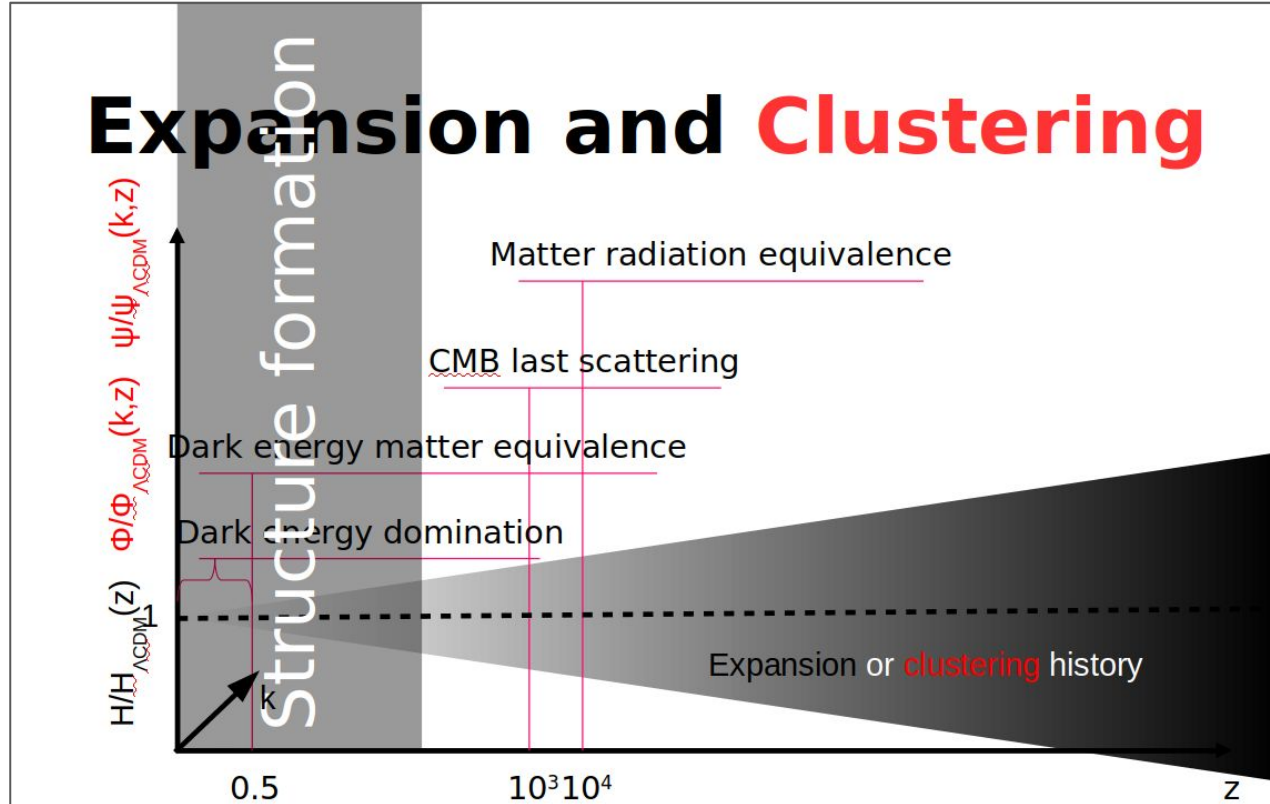
B-Modes, DE, DM: Gravitational Lensing Data



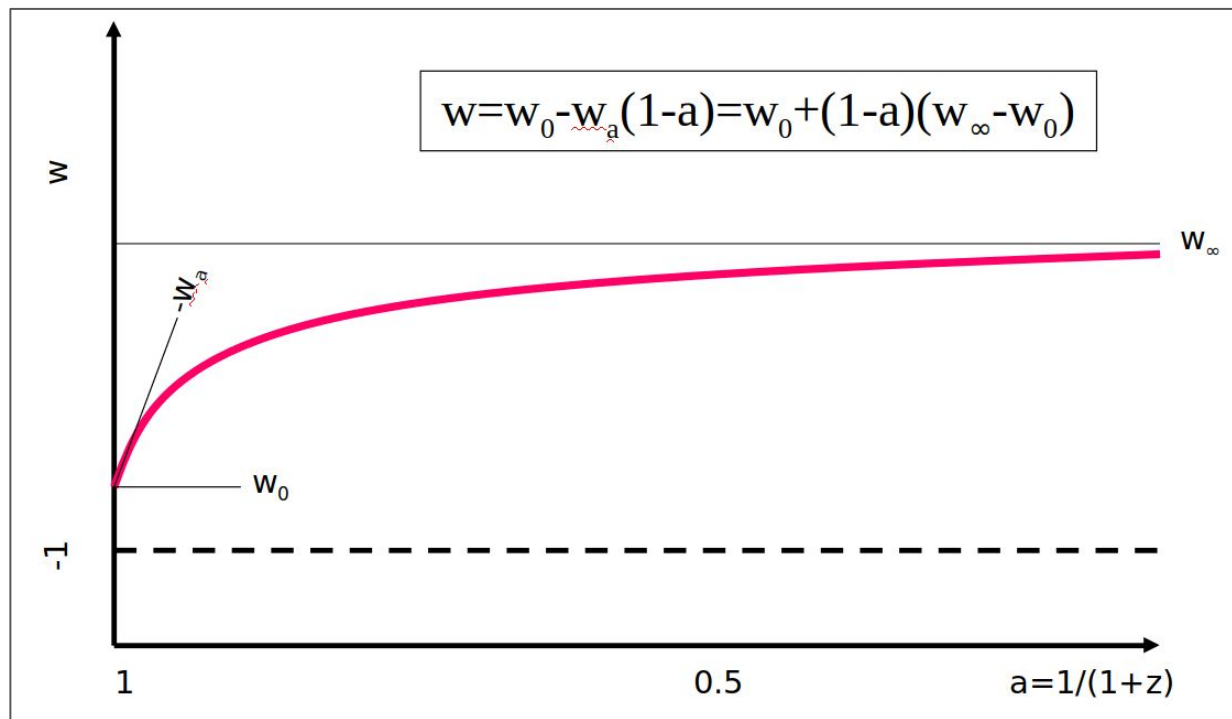
ACT Collaboration 2023

ui.adsabs.harvard.edu/link_gateway/2023arXiv230405202Q/arxiv:2304.05202

B-Modes, DE, DM: Where and When



B-Modes, DE, DM: Dark Energy & Modified Gravity



Dark Energy

Modified Gravity

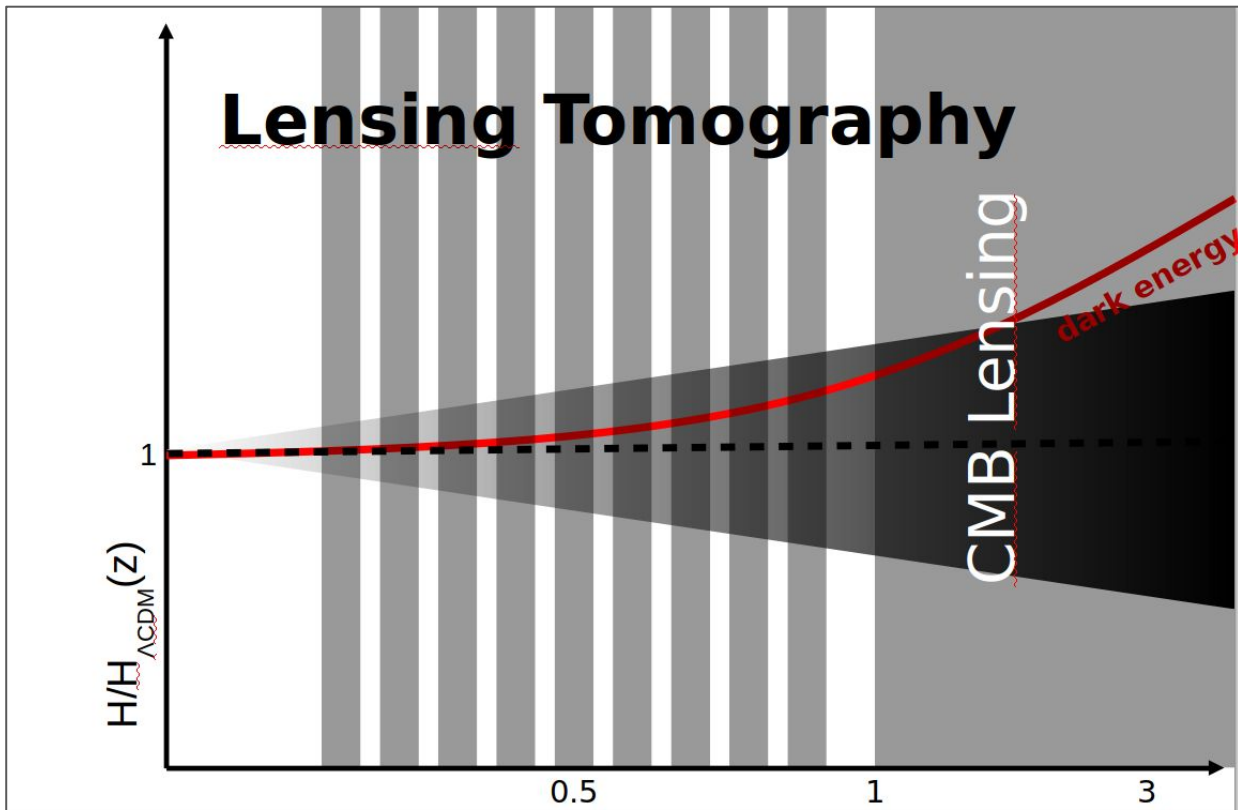
$$\eta(a, k) \equiv \Phi/\Psi.$$

$$-k^2 \Phi \equiv 4\pi G a^2 \mu(a, k) \rho \Delta$$

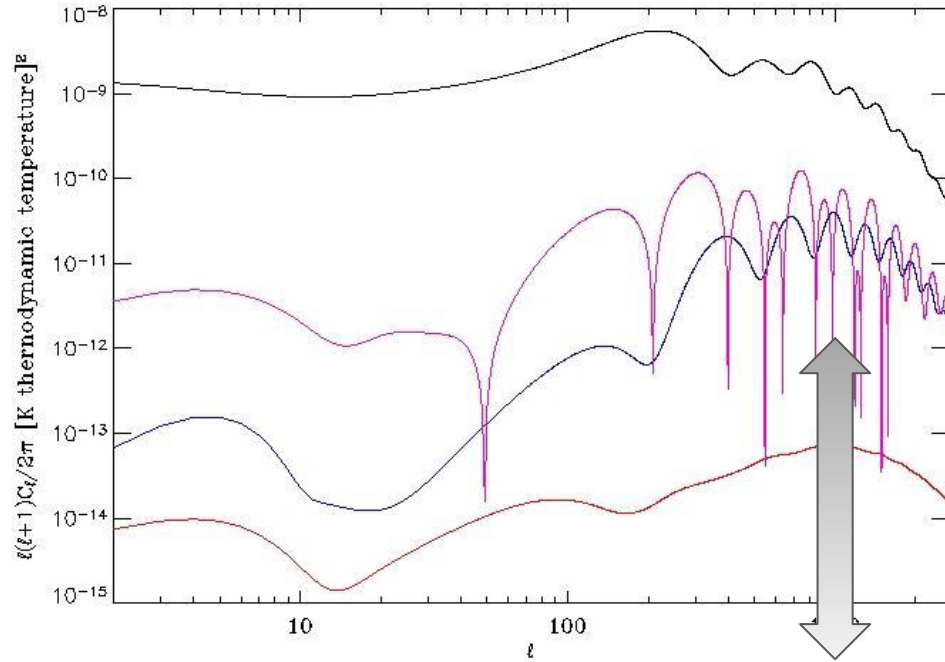
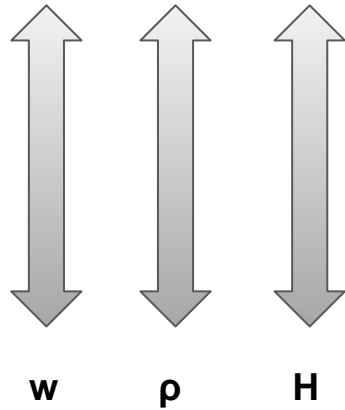
$$-k^2 \Psi \equiv 4\pi G a^2 \eta(a, k) \rho \Delta$$

$$-k^2 (\Phi + \Psi) \equiv 8\pi G a^2 \Sigma(a, k) \rho \Pi$$

B-Modes, DE, DM: Gravitational Lensing Tomography



B-Modes, DE, DM: Gravitational Lensing Anisotropy Peak



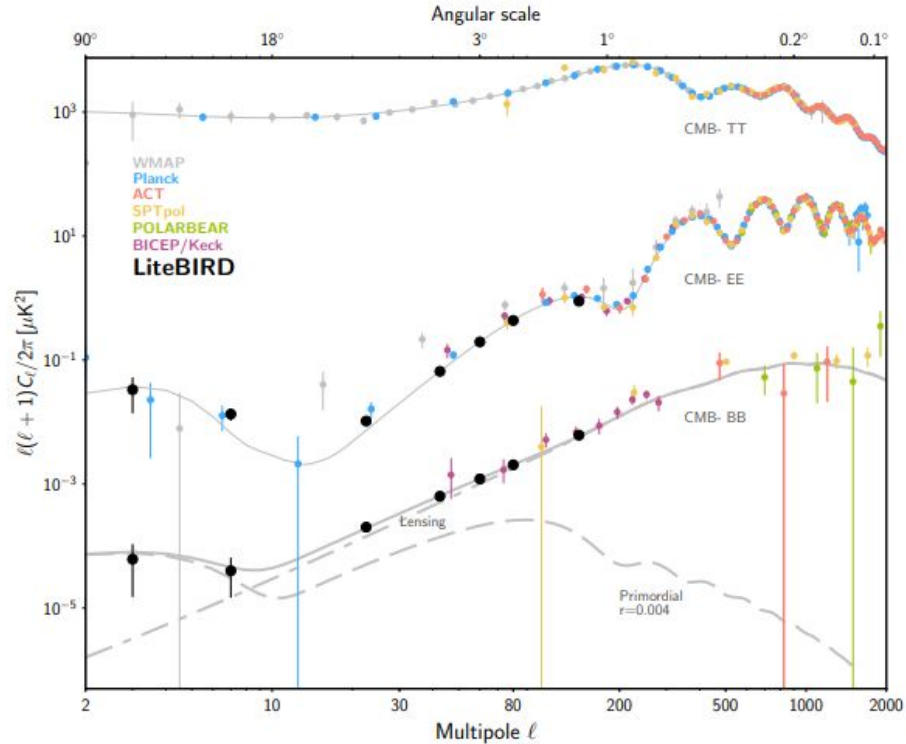
Angle $\approx 200/\ell$ degrees

Acquaviva & Baccigalupi 2006

ui.adsabs.harvard.edu/link_gateway/2006PhRvD..74j3510A/arxiv:astro-ph/0507644

B-Mode Data

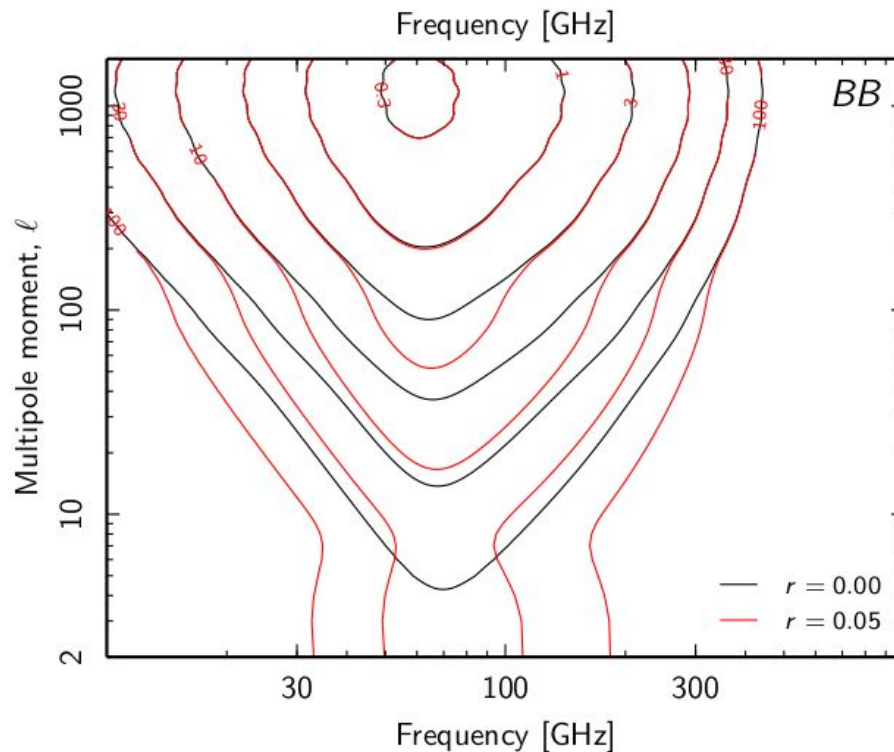
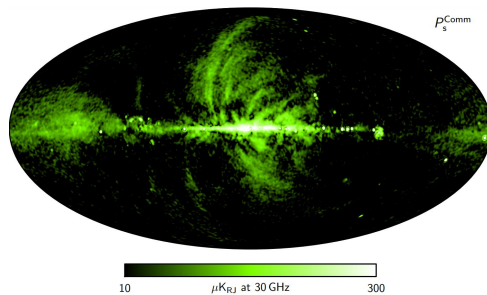
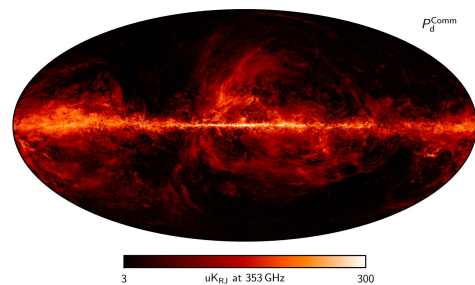
B-Mode Data



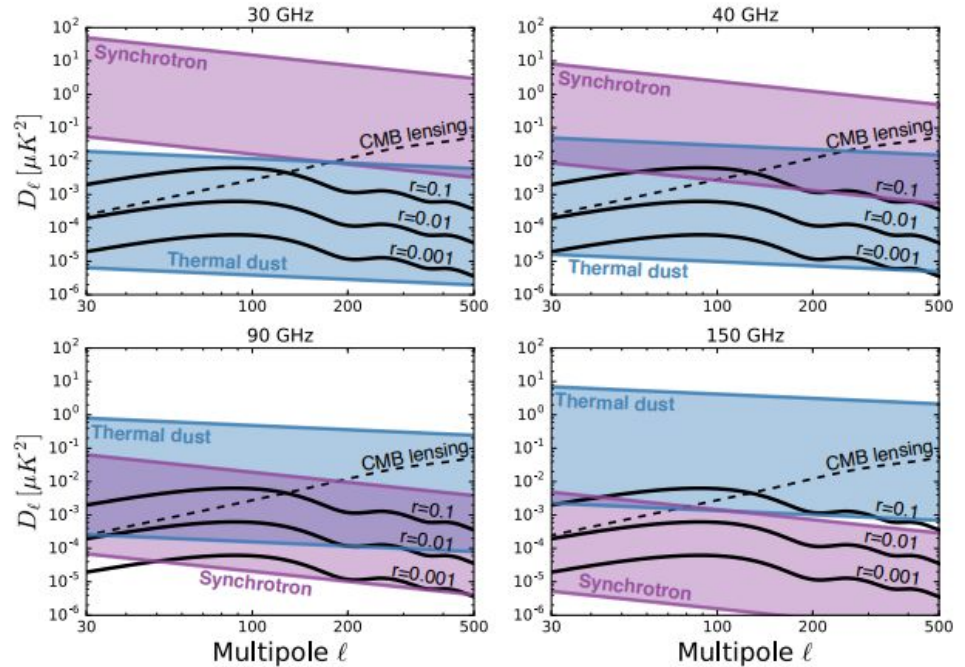
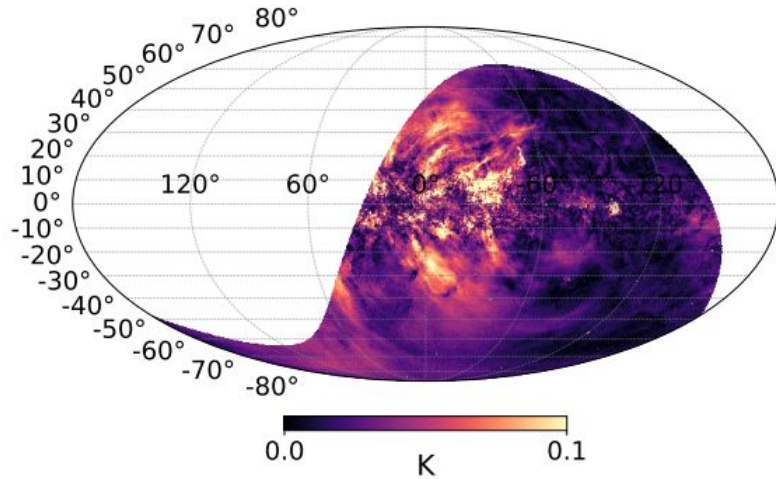
LiteBIRD Collaboration, PTEP 2022

ui.adsabs.harvard.edu/abs/arXiv:2202.02773

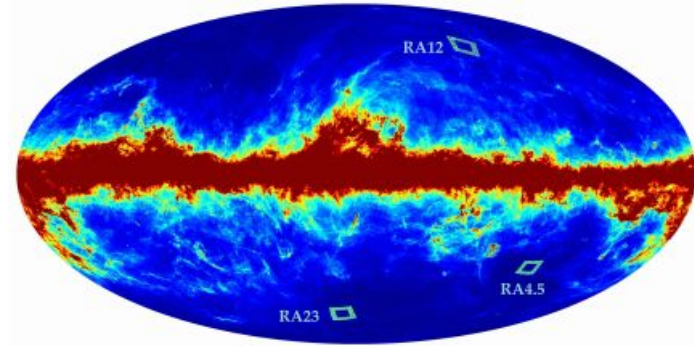
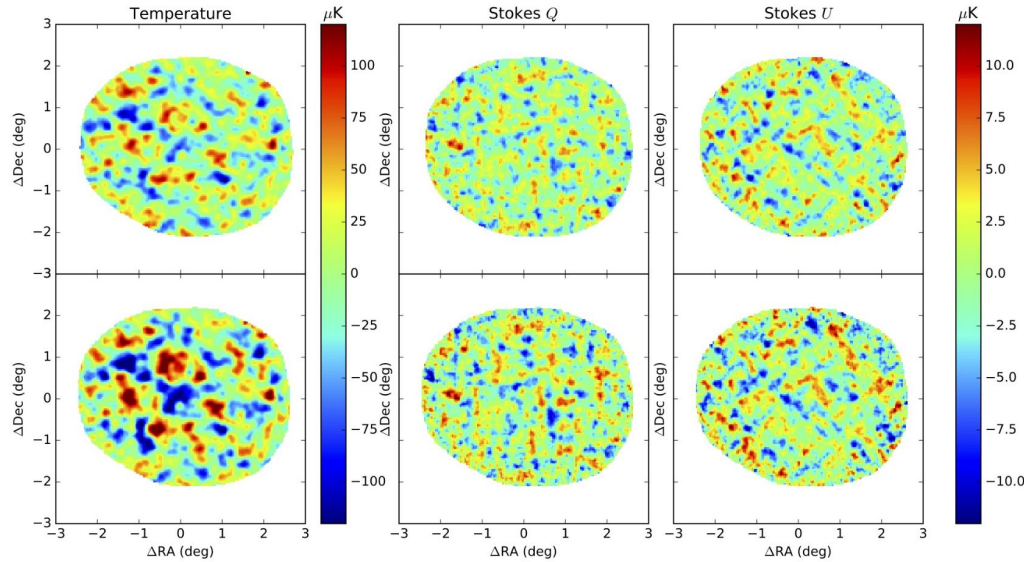
B-Mode Data: Challenges



B-Mode Data: Challenges



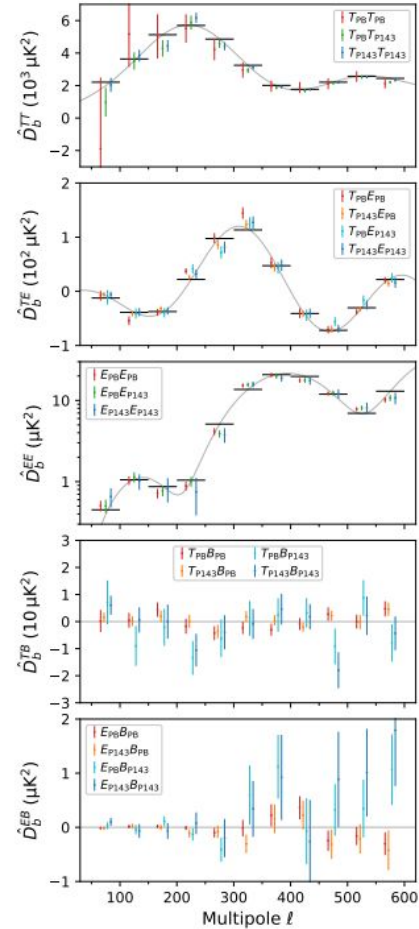
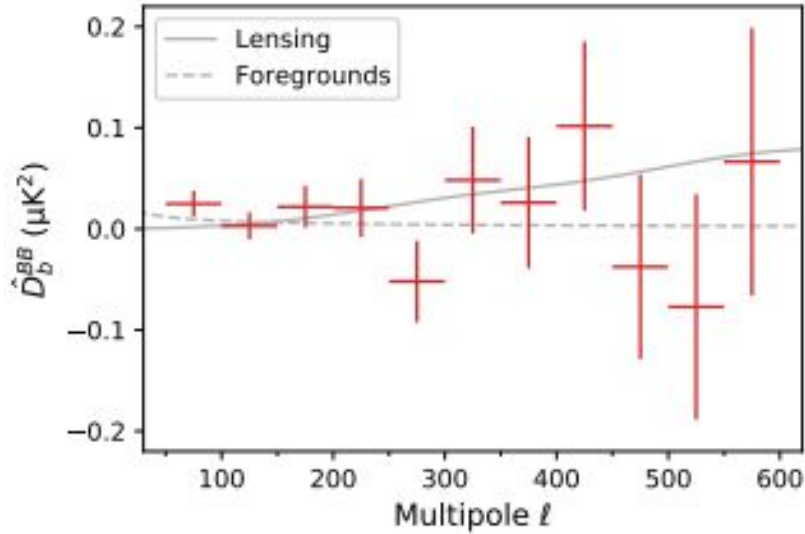
B-Mode Data: PolarBear



PolarBear Collaboration 2022

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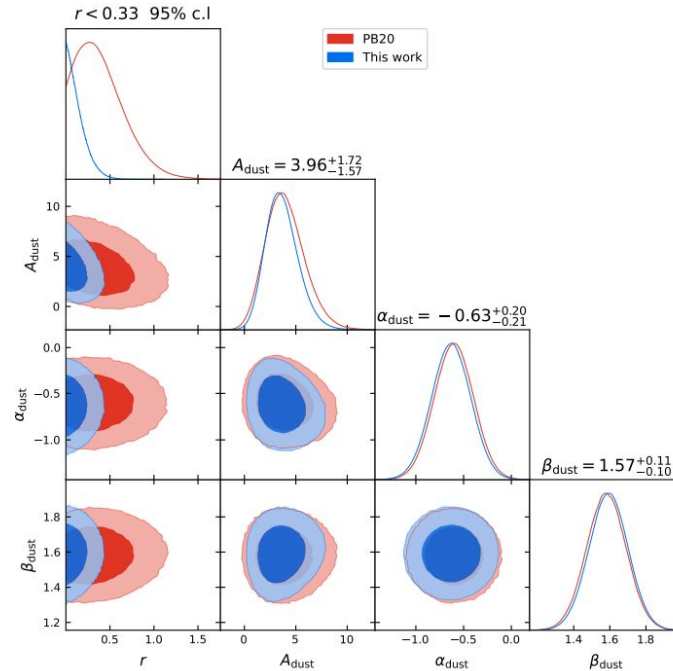
B-Mode Data: PolarBear



PolarBear Collaboration 2022

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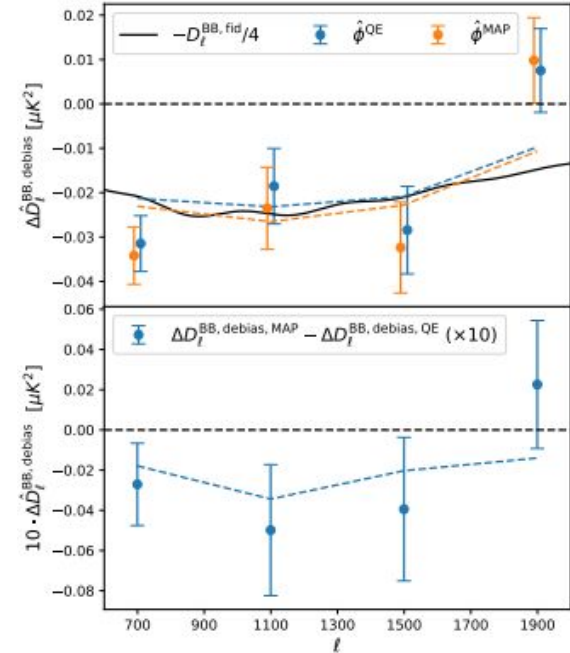
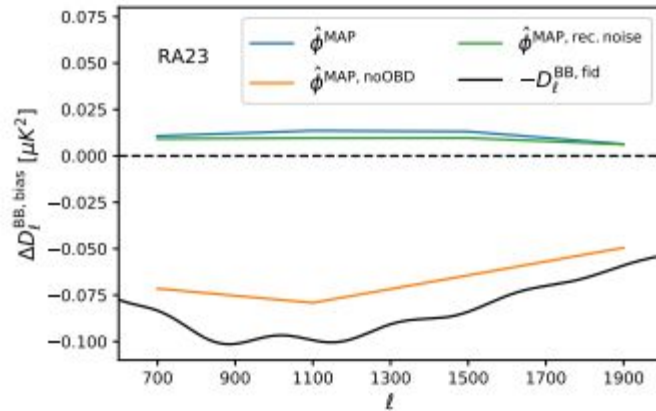
B-Mode Data: PolarBear



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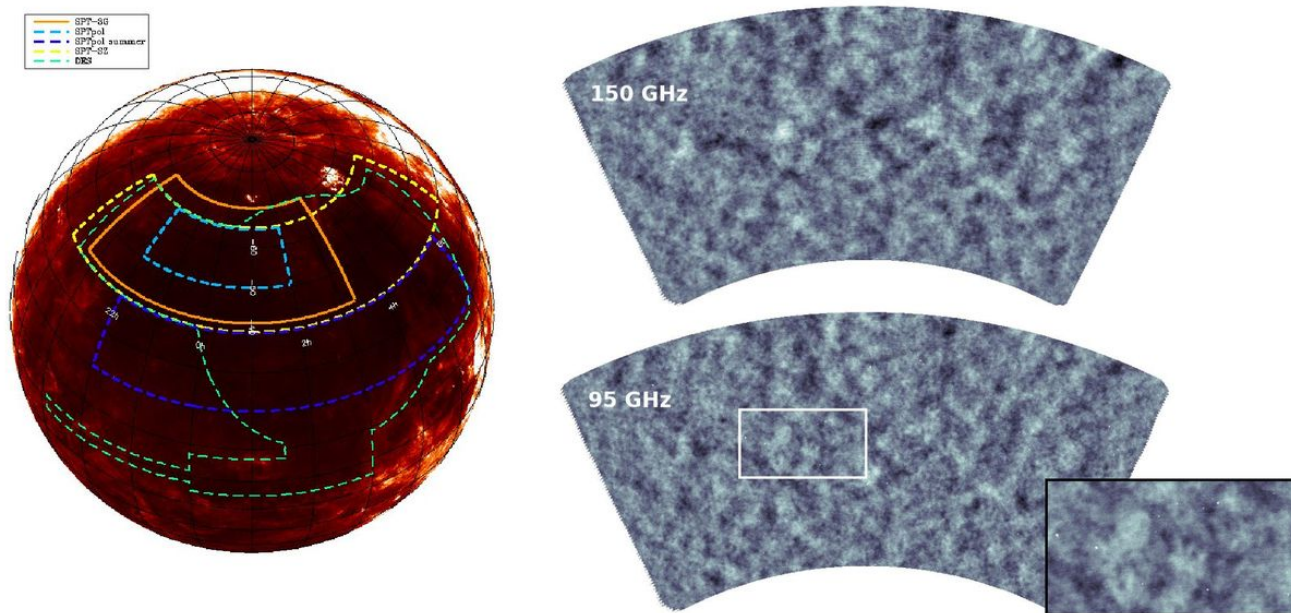
B-Mode Data: PolarBear



PolarBear Collaboration 2020

ui.adsabs.harvard.edu/link_gateway/2020PhRvL.124m1301A/axiv:1909.13832

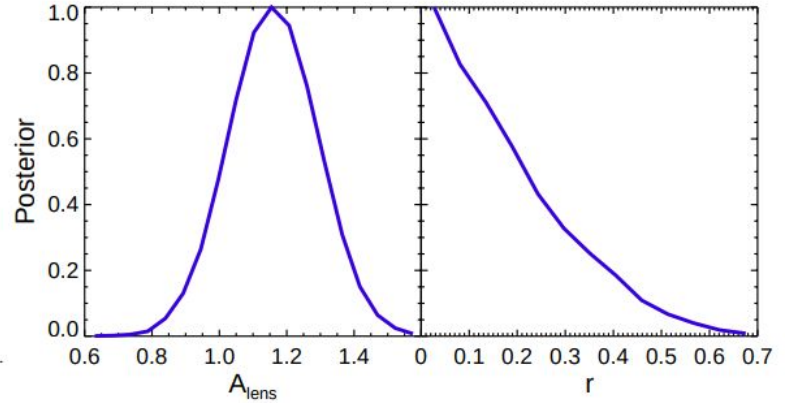
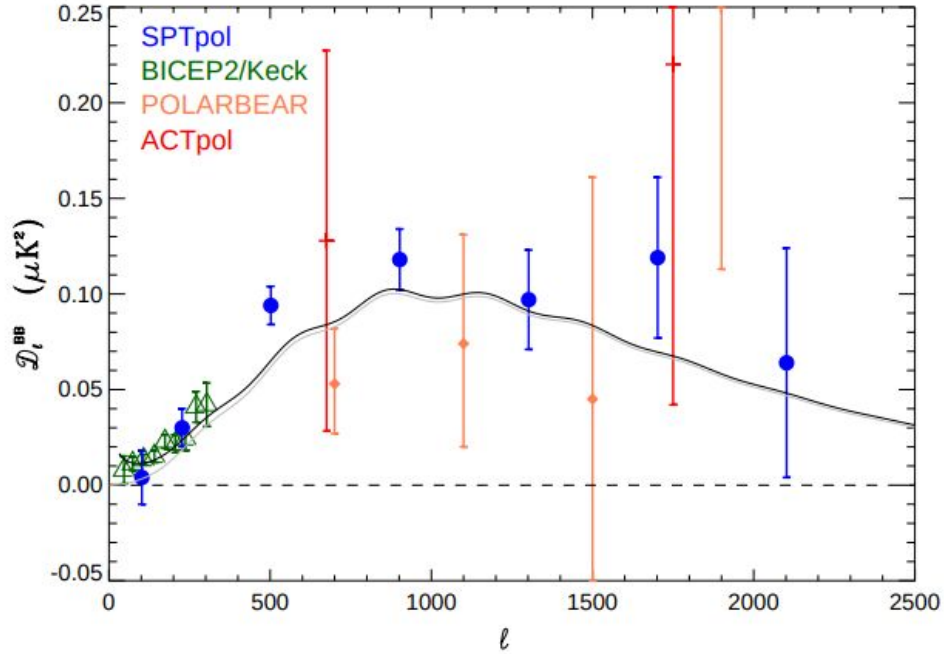
B-Mode Data: South Pole Telescope



South Pole Telescope 2020

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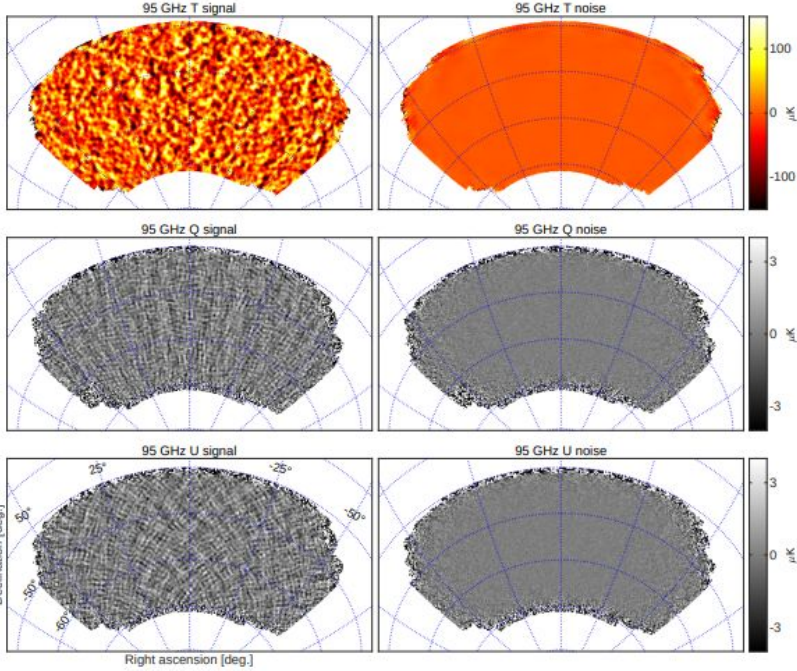
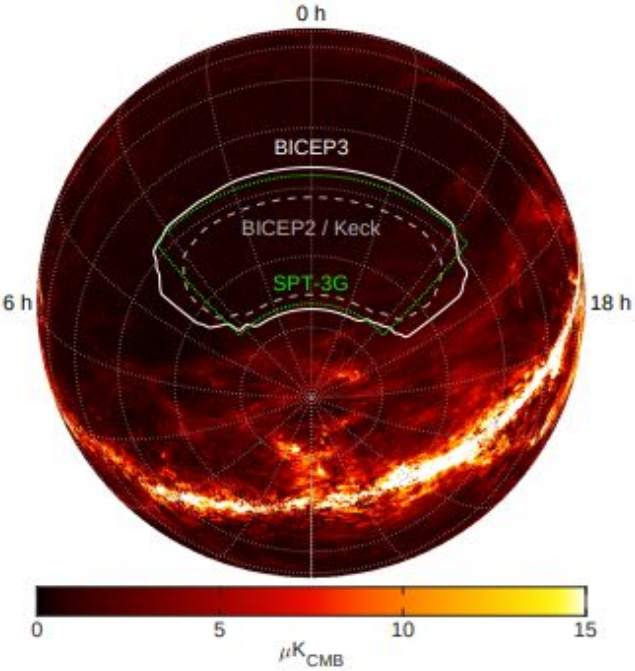
B-Mode Data: South Pole Telescope



South Pole Telescope 2020

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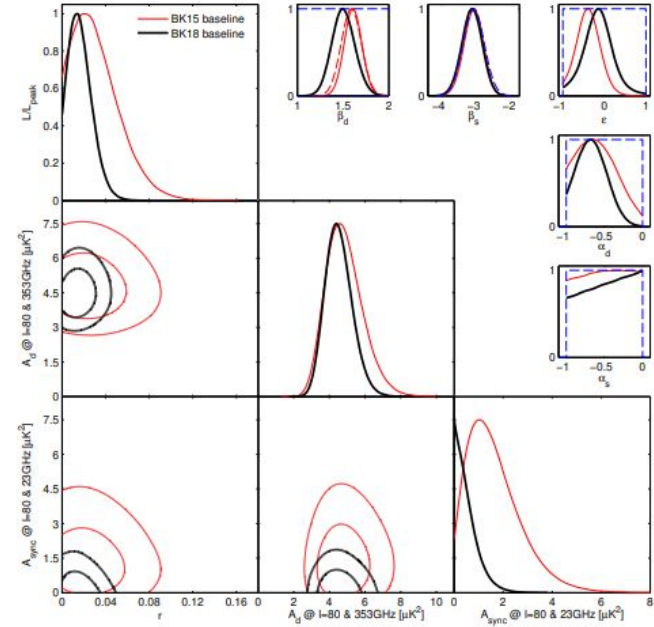
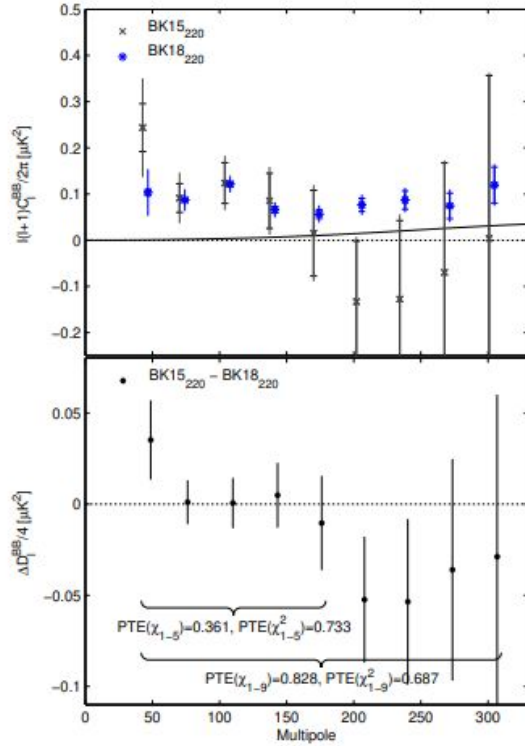
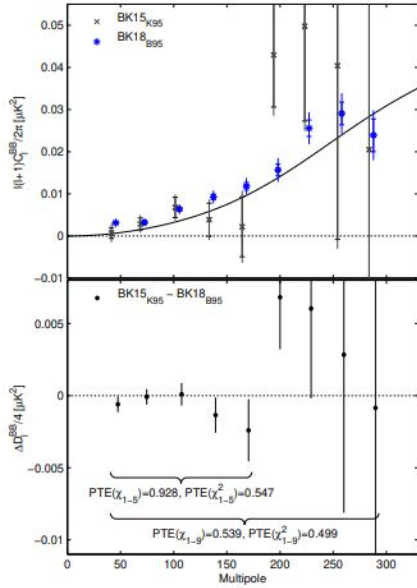
B-Mode Data: BICEP/Keck



BICEP/Keck Collaboration 2022

ui.adsabs.harvard.edu/link_gateway/2022ApJ...927...77A/2022arXiv:2110.00482

B-Mode Data: BICEP/Keck

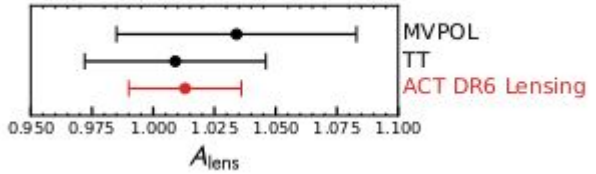
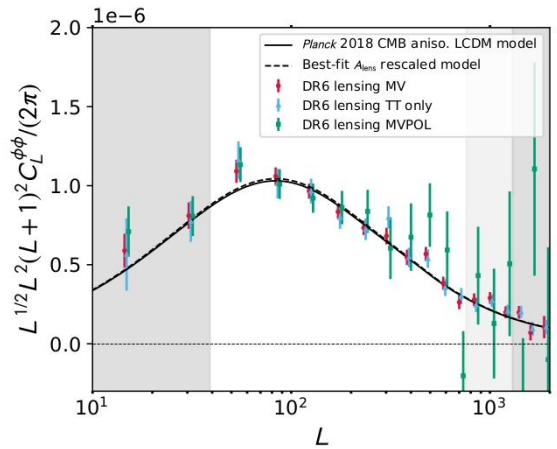
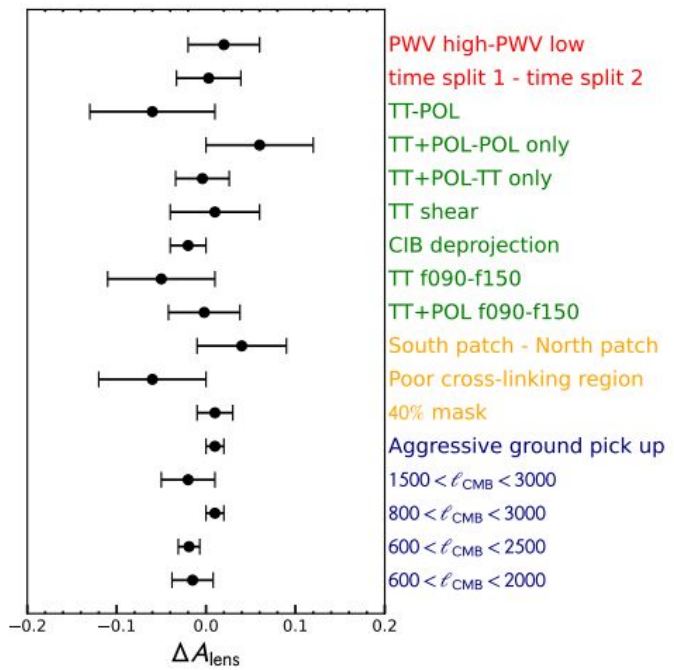


BICEP/Keck Collaboration 2021

ui.adsabs.harvard.edu/link_gateway/2021PhRvL.127o1301A/axiv:2110.00483

B-Mode Constraints

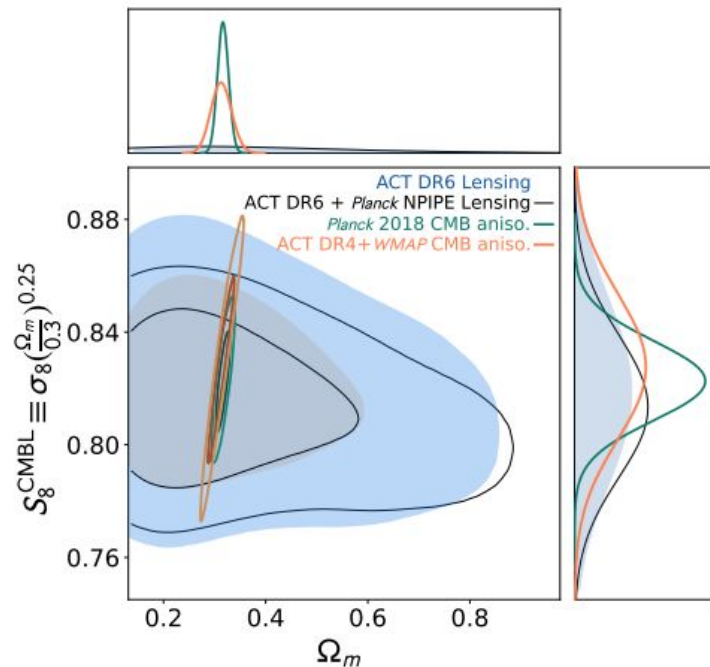
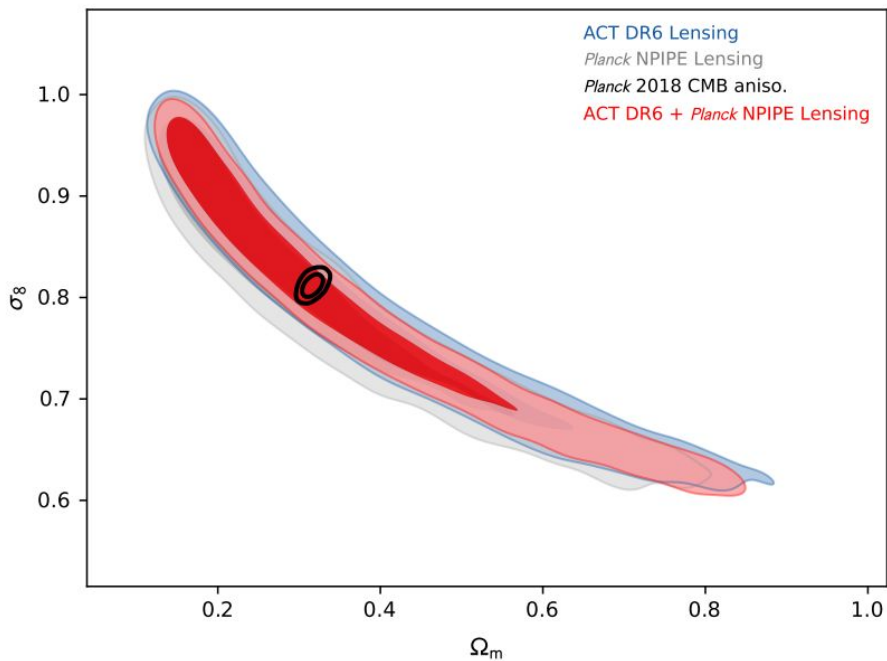
B-Mode Probe & Cosmological Tensions: Atacama Cosmology Telescope



ACT Collaboration 2023

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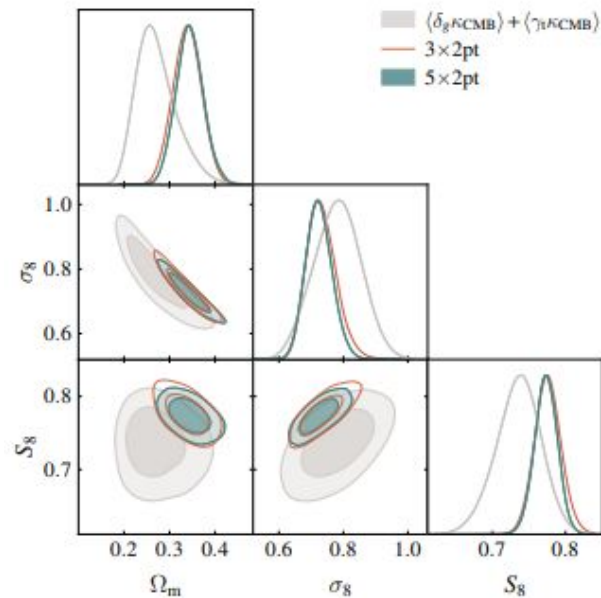
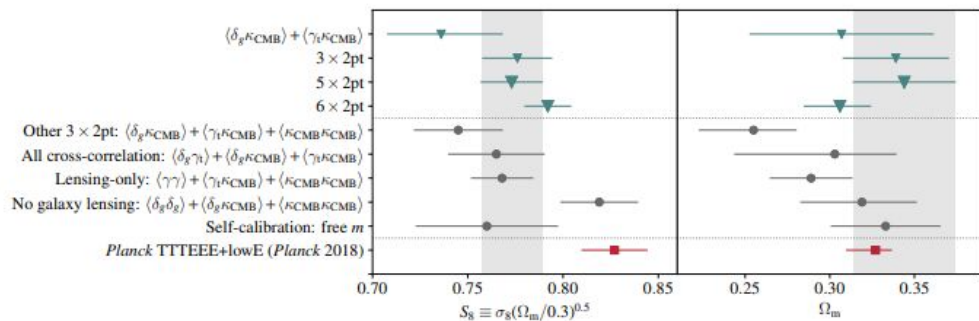
B-Mode Constraints: Atacama Cosmology Telescope



ACT Collaboration 2023

ui.adsabs.harvard.edu/link_gateway/2020ApJ...893...85F/act.1911.10980

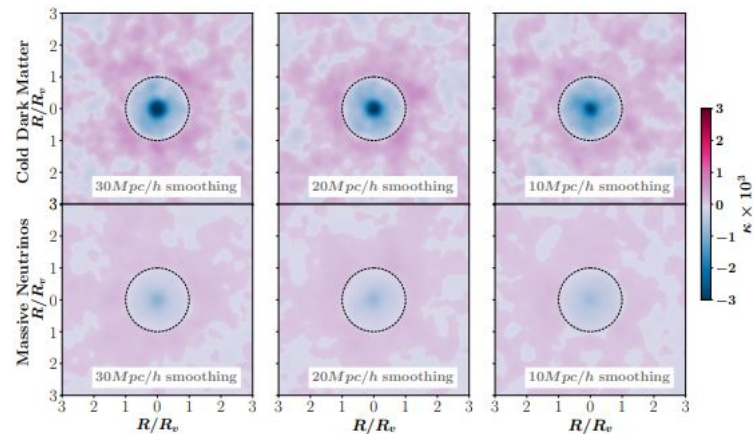
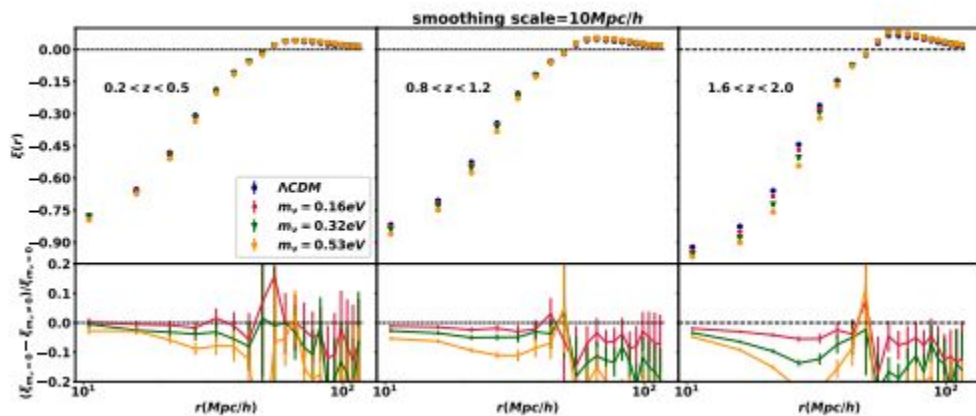
B-Mode Probe Constraints: South Pole Telescope



South Pole Telescope 2023

ui.adsabs.harvard.edu/link_gateway/2023PhRvD.107b3531A/https://arxiv.org/abs/2206.10824

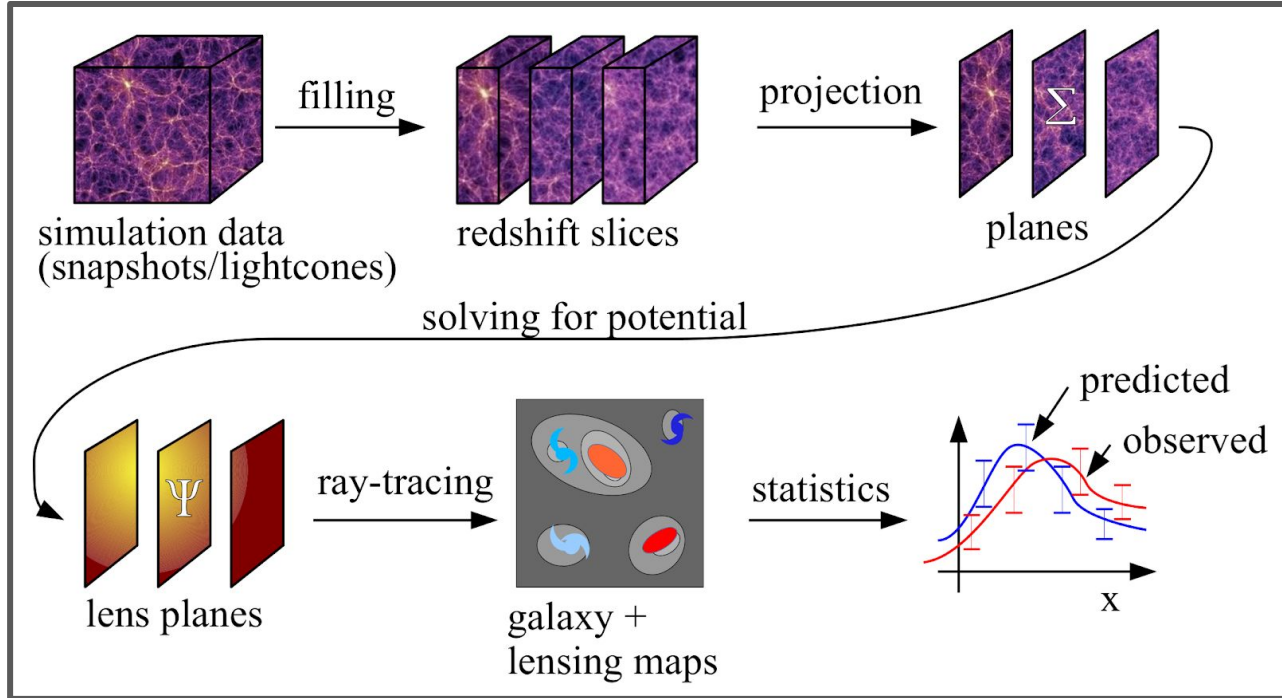
B-Mode Constraints: CMB-Lensing and Voids



Vielzeuf et al. 2023

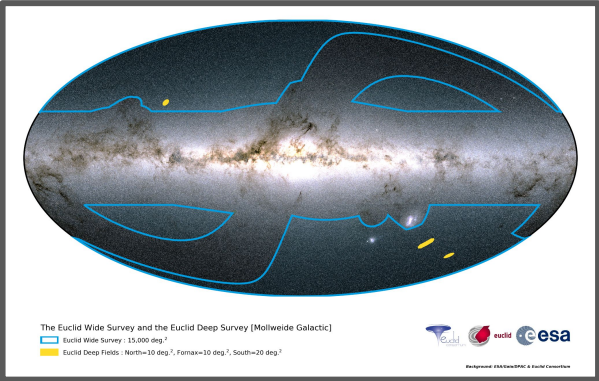
<https://ui.adsabs.harvard.edu/abs/2023JCAP...08..010V/abstract>

B-Mode Constraints: CMB-N-Body Pipeline



Future B-Mode Probes

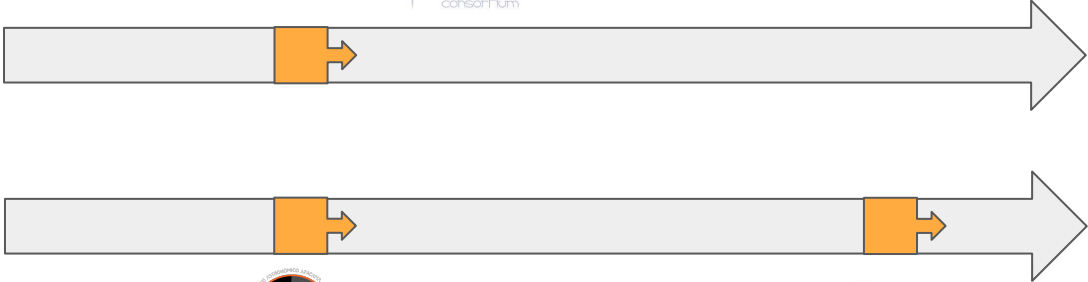
Future B-MoProbes: Timeline



2023



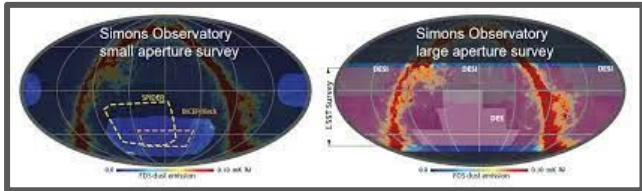
2028



Simons Observatory

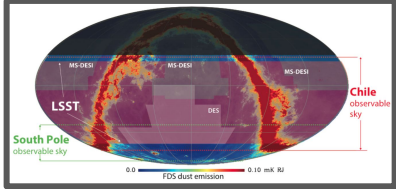
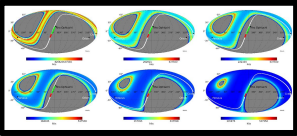


LiteBIRD



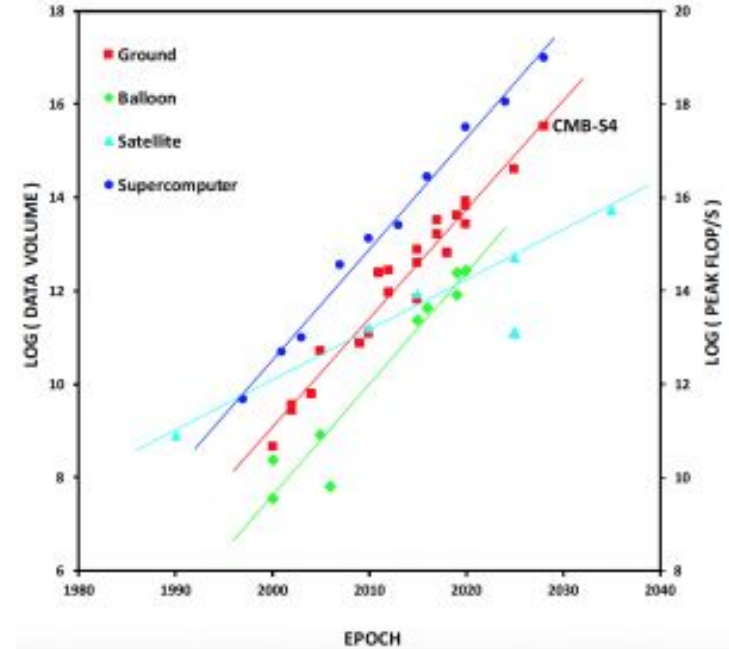
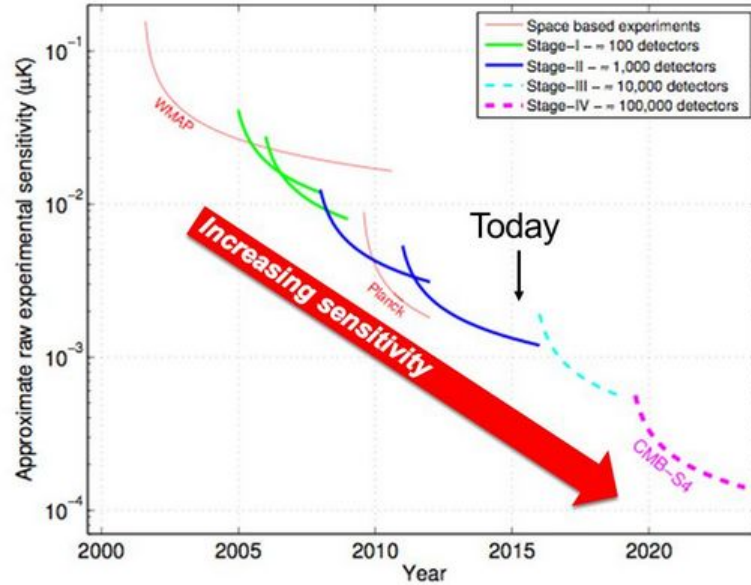
CMB-S4
Next Generation CMB Experiment

Low Frequency Surveys



Future B-Mode Probes: Data Challenges

A Moore's Law of CMB sensitivity



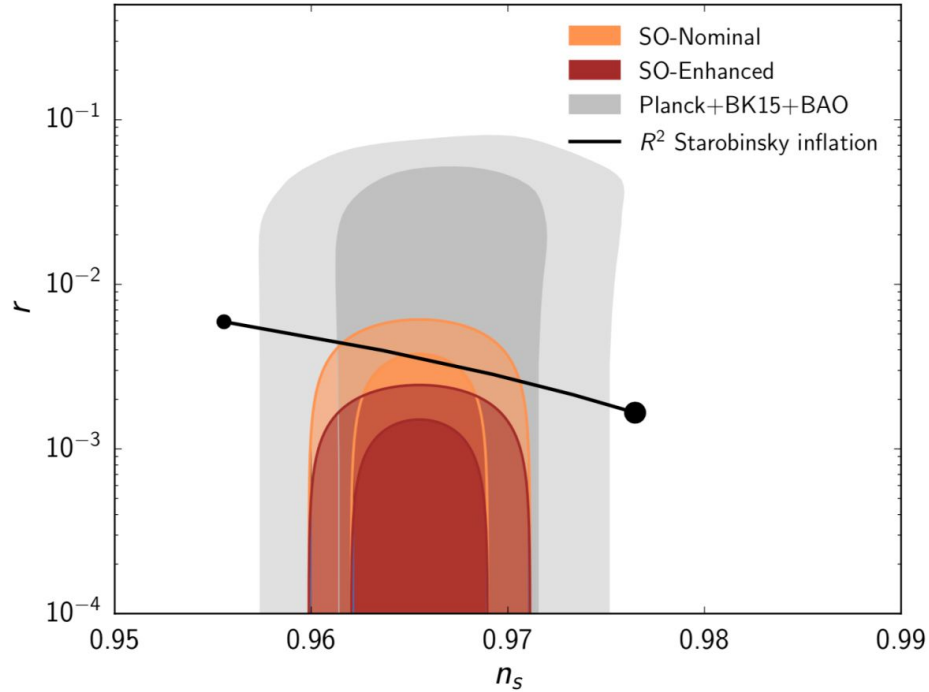
Future B-Mode Probes: Simons Observatory



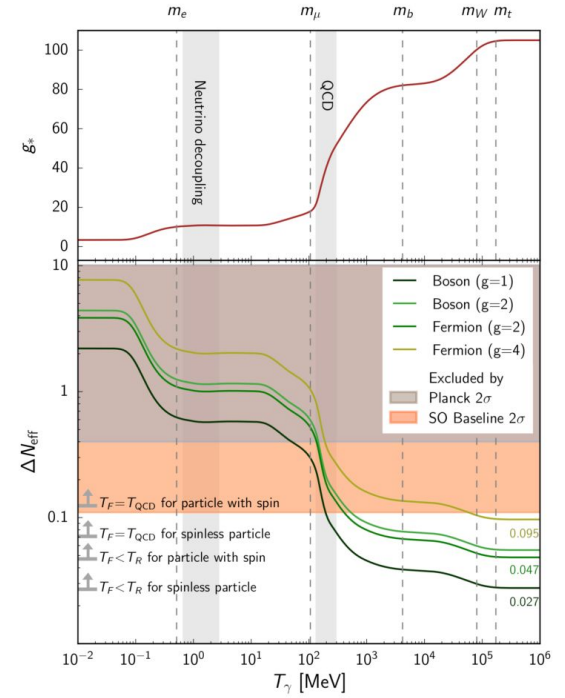
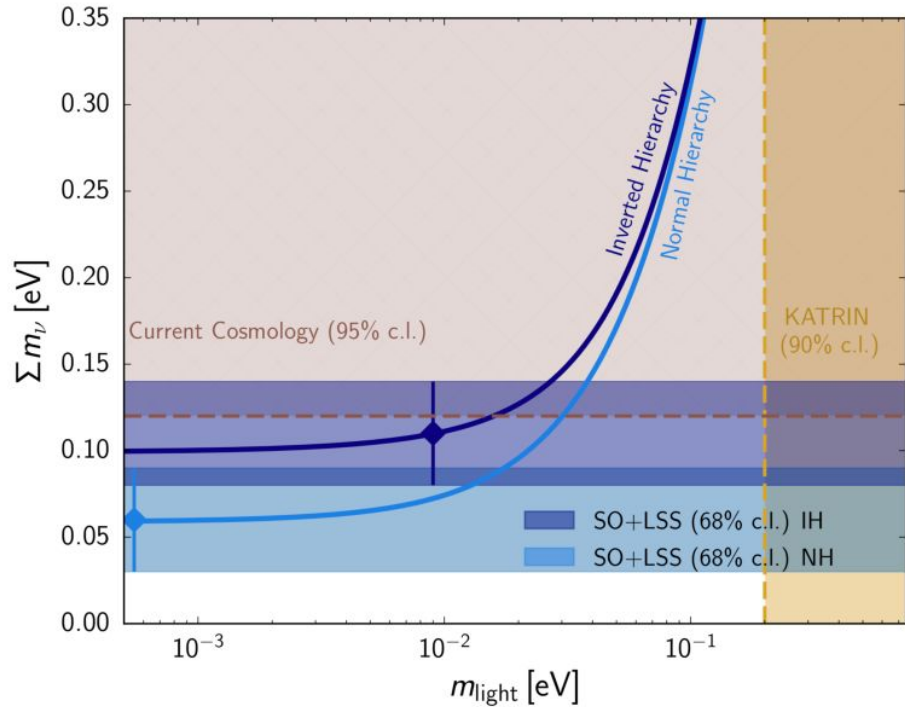
The Simons Observatory
Searching For Our Cosmic Origins



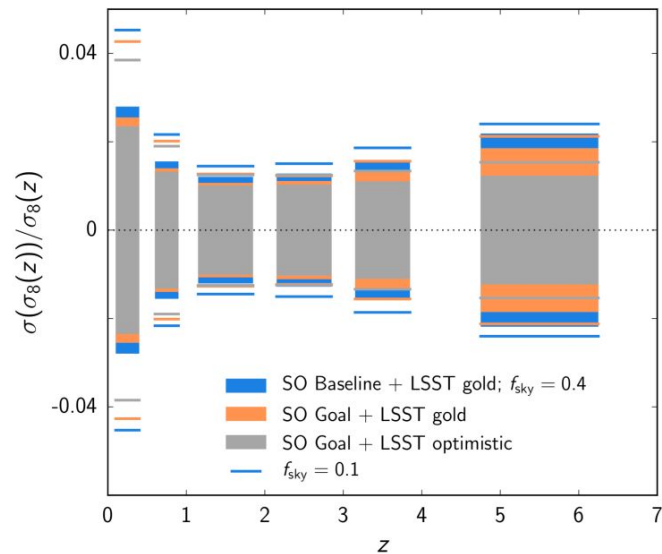
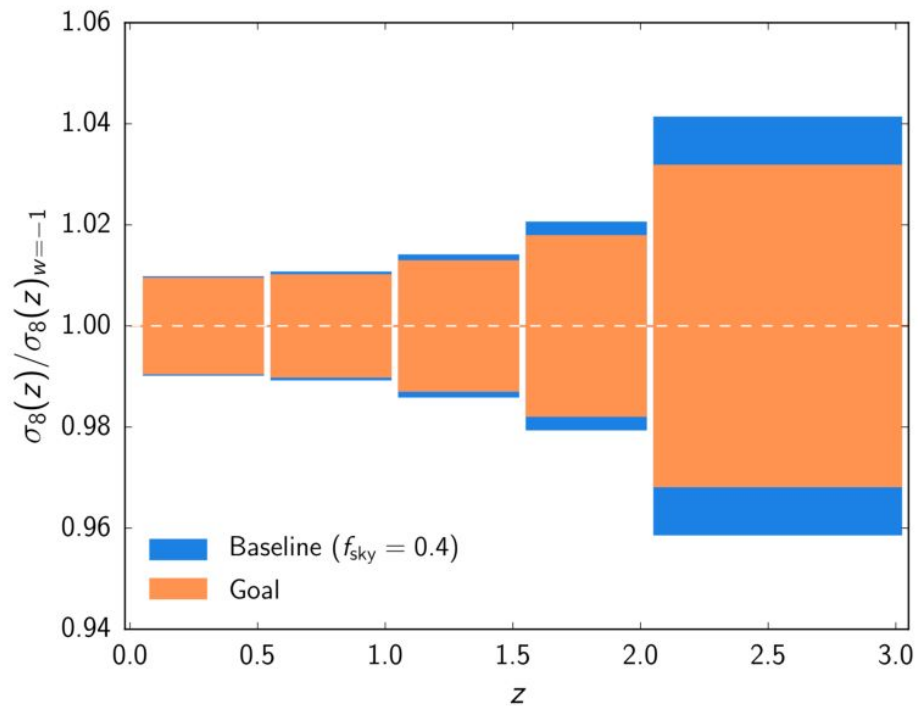
Future B-Mode Probes: Simons Observatory



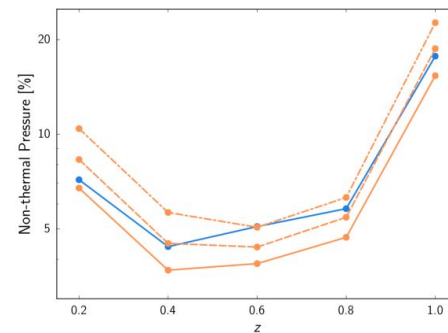
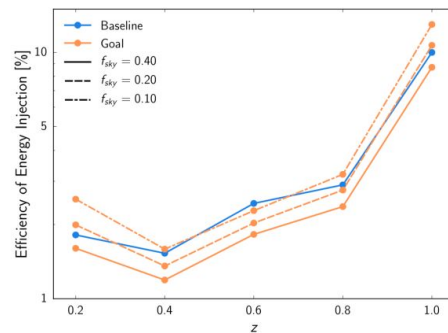
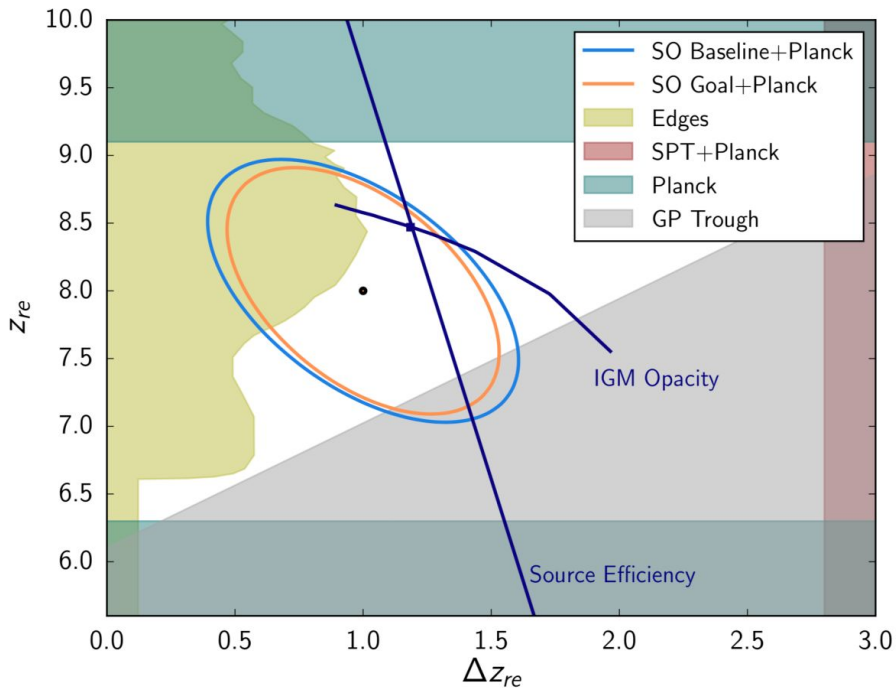
Future B-Mode Probes: Simons Observatory



Future B-Mode Probes: Simons Observatory



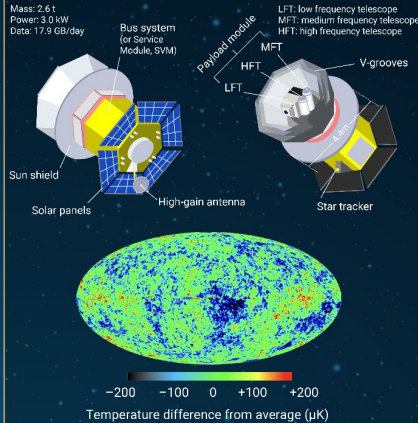
Future B-Mode Probes: Simons Observatory



Future B-Mode Probes: LiteBIRD

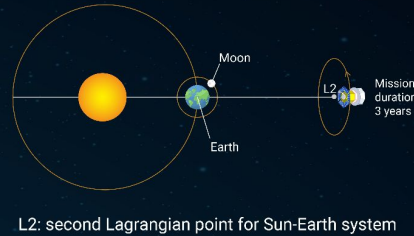
LiteBIRD: A New Frontier in the Search of Cosmic Inflation Imprint

LiteBIRD, Japan Aerospace Exploration Agency's new satellite will map the Cosmic Microwave Background (CMB) polarization over the entire sky



Primary objectives of LiteBIRD:

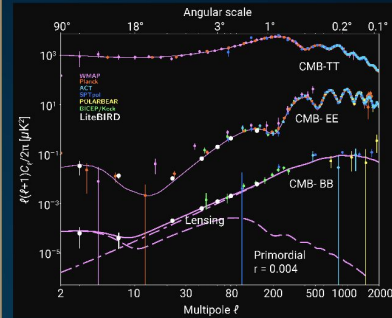
- ✓ Detect signal from cosmic inflation
- ✓ Rule out competing inflationary models



- ✓ Three telescopes
- ✓ Cryogenic cooling to 4.8 K
- ✓ 15 frequency bands (34–448 GHz)

Aims to measure CMB B-mode power spectrum at large angular scales

- Multipole range: **2 to 200**
- Angular scale: **1° to 90°**

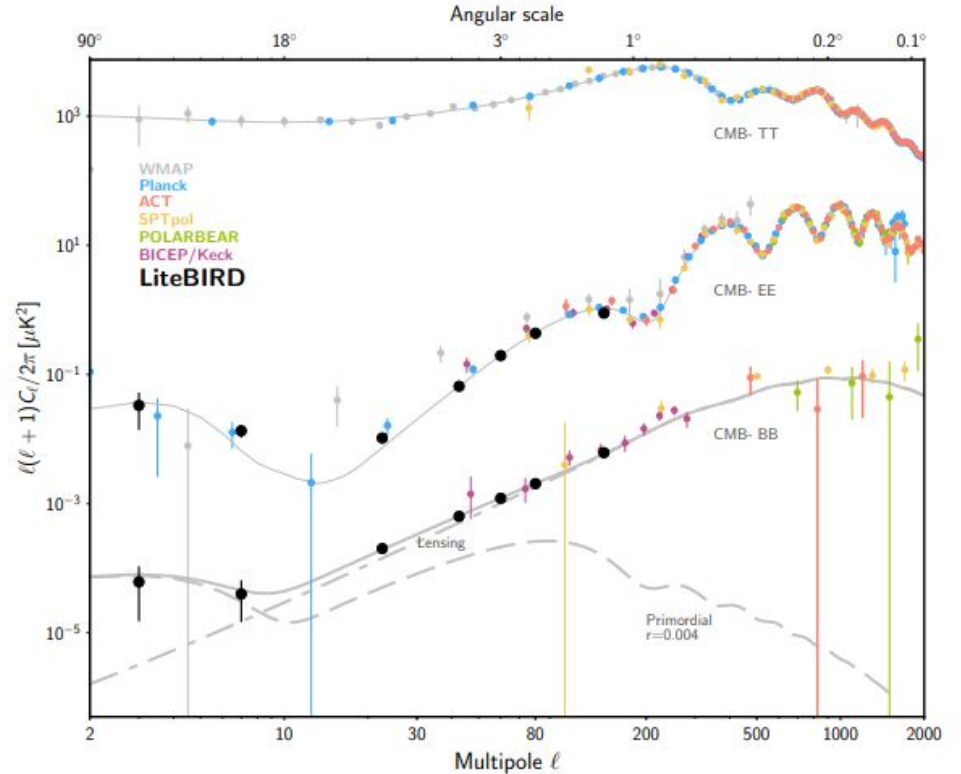
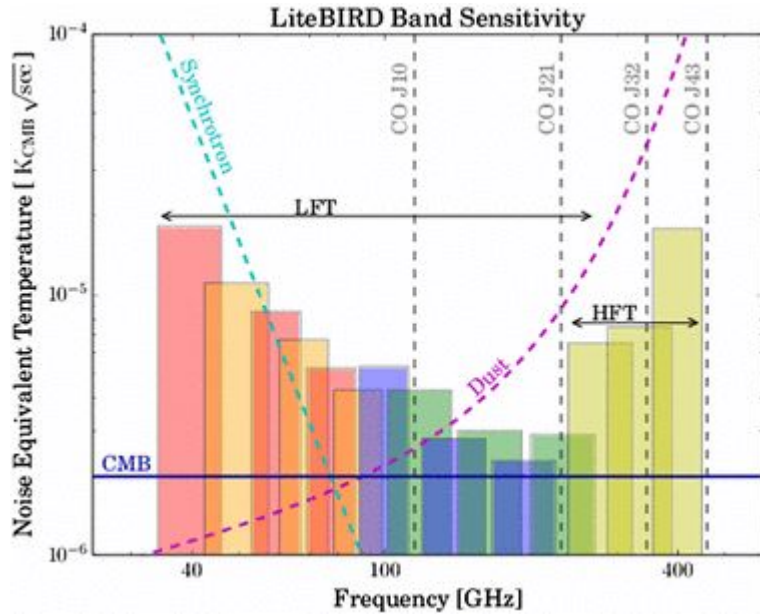


Scientific outcome: Detection of primordial gravitational waves

- ✓ **10³x** more sensitive than LISA (Laser Interferometer Space Antenna)
- ✓ Unprecedented sensitivity of 2.2 $\mu\text{K-arcmin}$
- ✓ Typical angular resolution of 0.5° at 100 GHz

The state-of-the-art facilities of LiteBIRD can lead us to a better understanding of the early universe and the physics laws governing it

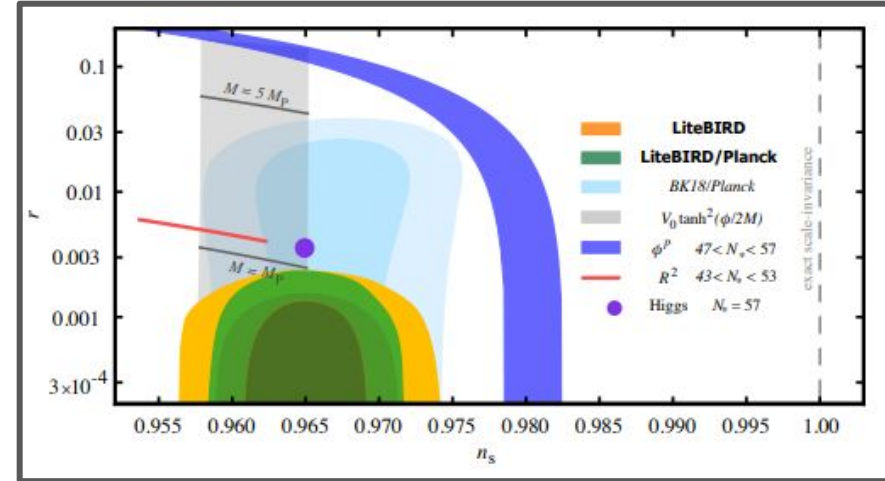
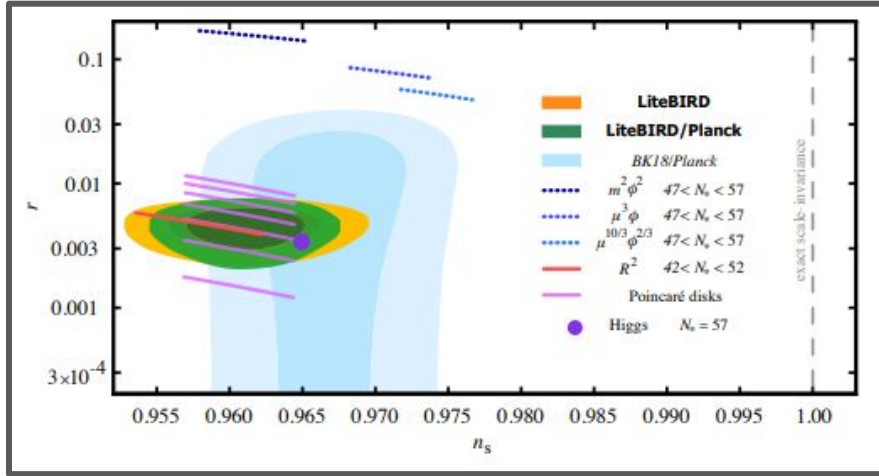
Future B-Mode Probes: LiteBIRD



LiteBIRD Collaboration, PTEP 2022

ui.adsabs.harvard.edu/abs/arXiv:2202.02773

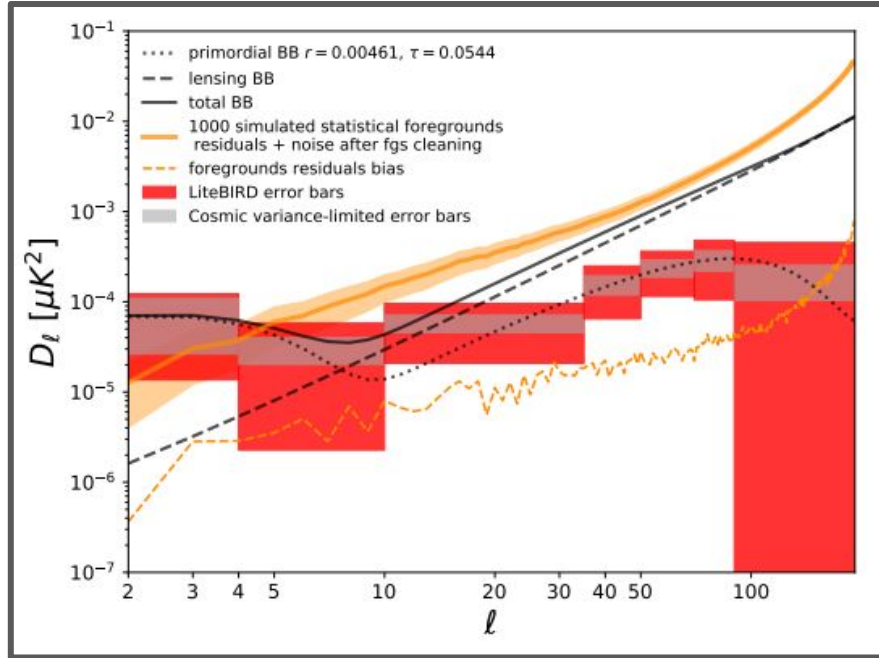
Future B-Mode Probes: LiteBIRD



LiteBIRD Collaboration, PTEP 2022

ui.adsabs.harvard.edu/abs/arXiv:2202.02773

Future B-Mode Probes: LiteBIRD

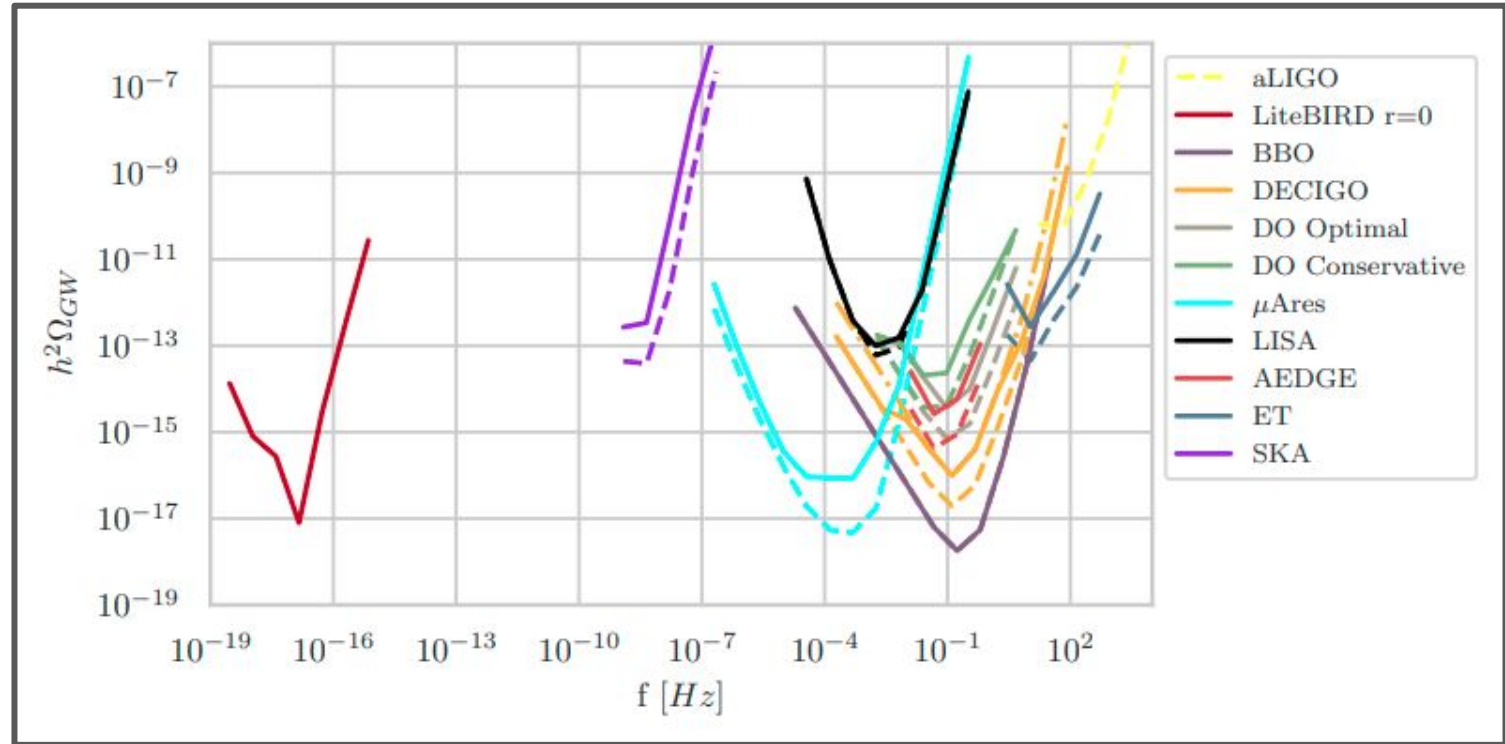


	ID	ν [GHz]	$\delta\nu$ [GHz] ($\delta\nu/\nu$)	Beam size [arcmin]	No. of detectors	NET _{arr} [$\mu\text{K}\sqrt{\text{s}}$]	Sensitivity [$\mu\text{K}\sqrt{\text{arcmin}}$]
LFT	1	40	12 (0.30)	70.5	48	18.50	37.42
LFT	2	50	15 (0.30)	58.5	24	16.54	33.46
LFT	3	60	14 (0.23)	51.1	48	10.54	21.31
LFT comb.	4	68	16 (0.23)	(41.6, 47.1)	(144, 24)	(9.84, 15.70)	(19.91, 31.77)
LFT comb.	5	78	18 (0.23)	(36.9, 43.8)	(144, 48)	(7.69, 9.46)	(15.55, 19.13)
LFT comb.	6	89	20 (0.23)	(33.0, 41.5)	(144, 24)	(6.07, 14.22)	(12.28, 28.77)
LFT/ MFT comb.	7	100	23 (0.23)	30.2/ 37.8	144/ 366	5.11/ 4.19	10.34 8.48
LFT/ MFT comb.	8	119	36 (0.30)	26.3/ 33.6	144/ 488	3.8/ 2.82	7.69 5.70
LFT/ MFT comb.	9	140	42 (0.30)	23.7/ 30.8	144/ 366	3.58/ 3.16	7.25 6.38
MFT	10	166	50 (0.30)	28.9	488	2.75	5.57
MFT/ HFT comb.	11	195	59 (0.30)	28.0/ 28.6	366/ 254	3.48/ 5.19	7.05 10.50
HFT	12	235	71 (0.30)	24.7	254	5.34	10.79
HFT	13	280	84 (0.30)	22.5	254	6.82	13.80
HFT	14	337	101 (0.30)	20.9	254	10.85	21.95
HFT	15	402	92 (0.23)	17.9	338	23.45	47.45
Total					4508		2.16

LiteBIRD Collaboration, PTEP 2022

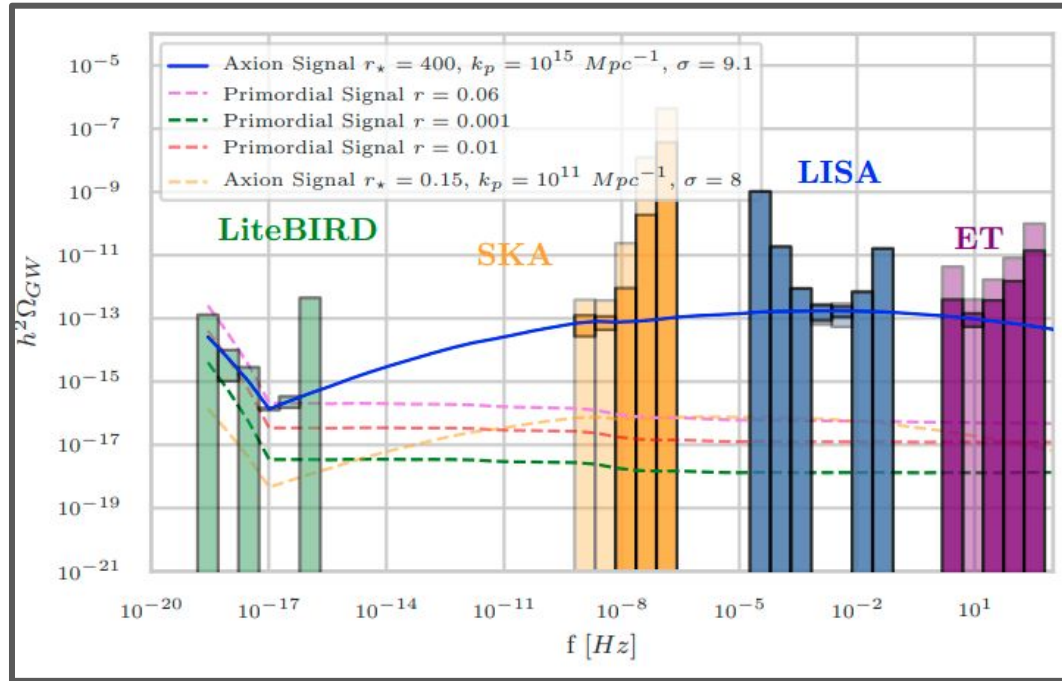
ui.adsabs.harvard.edu/abs/arXiv:2202.02773

Future B-Mode Probes: LiteBIRD

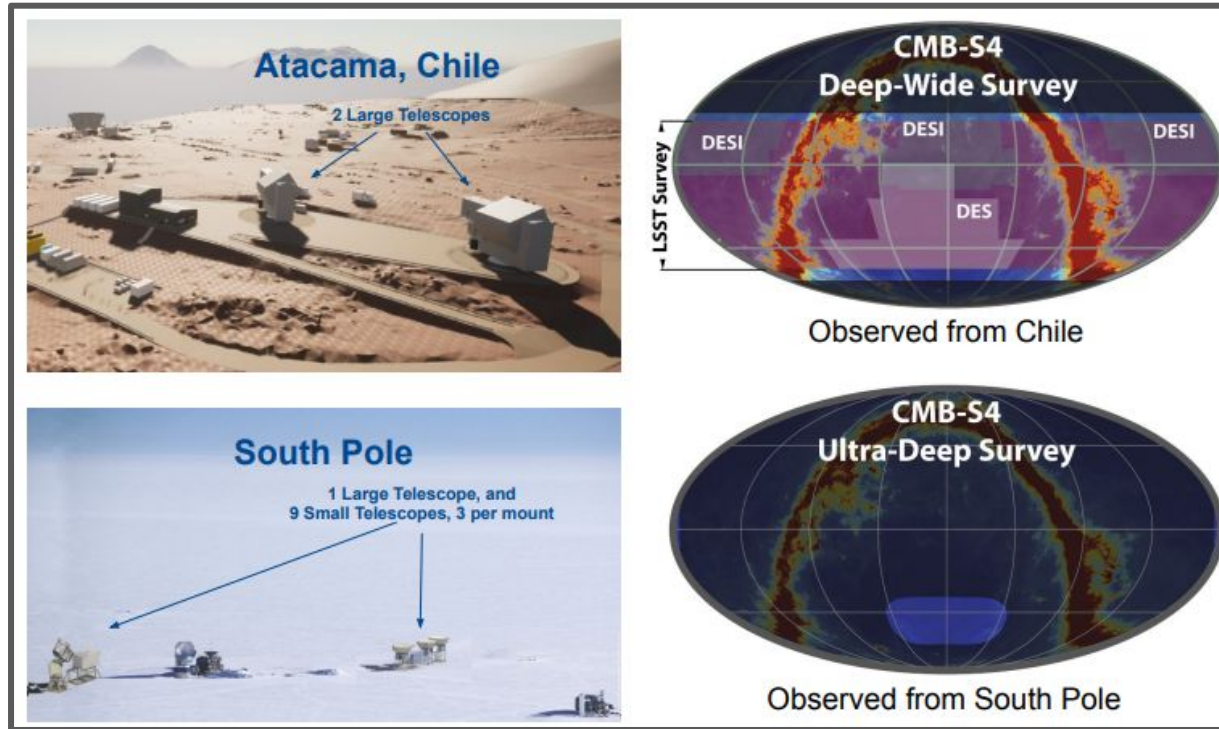


Campeti, Komatsu, Poletti, Baccigalupi, 2021, JCAP 01, 012, [arXiv:2007.04241](https://arxiv.org/abs/2007.04241)

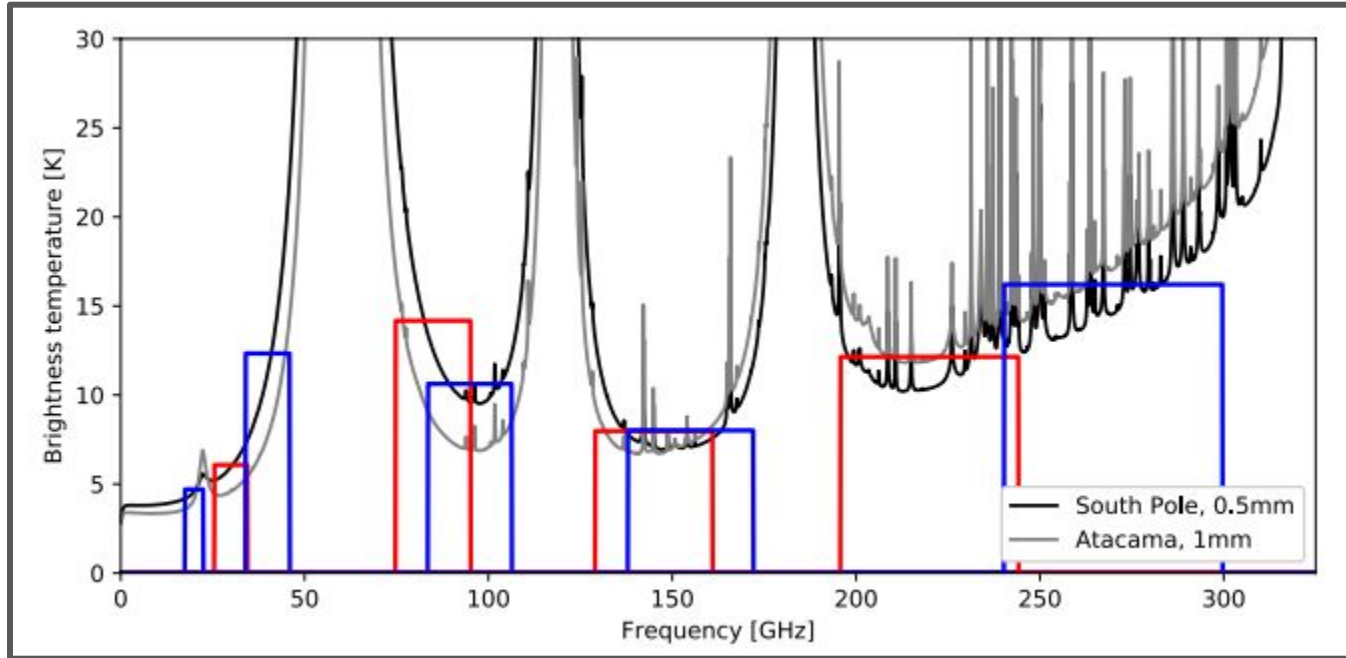
Future B-Mode Probes: LiteBIRD



Future B-Mode Probes: CMB-Stage IV



Future B-Mode Probes: CMB-Stage IV



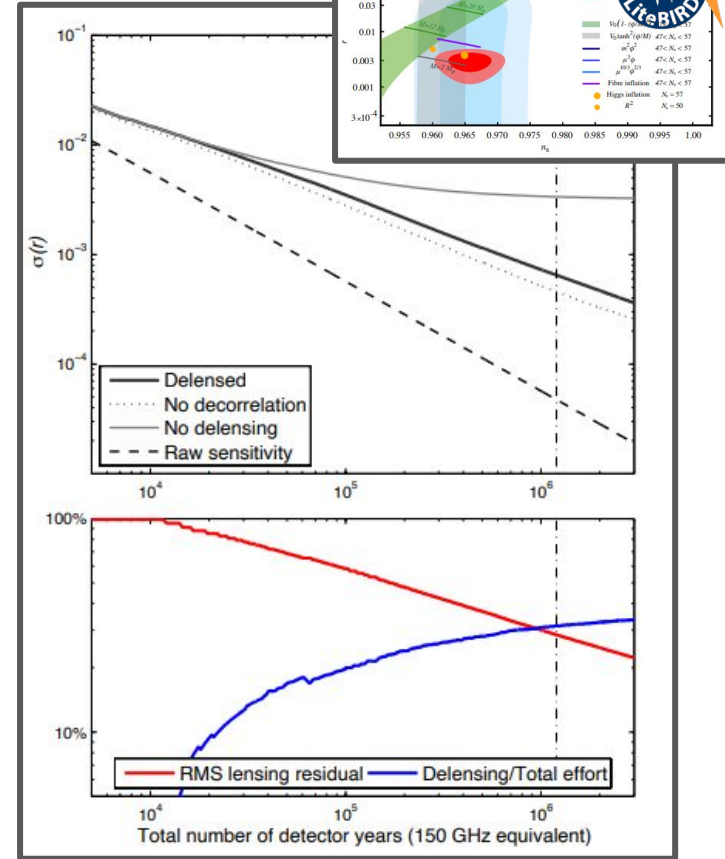
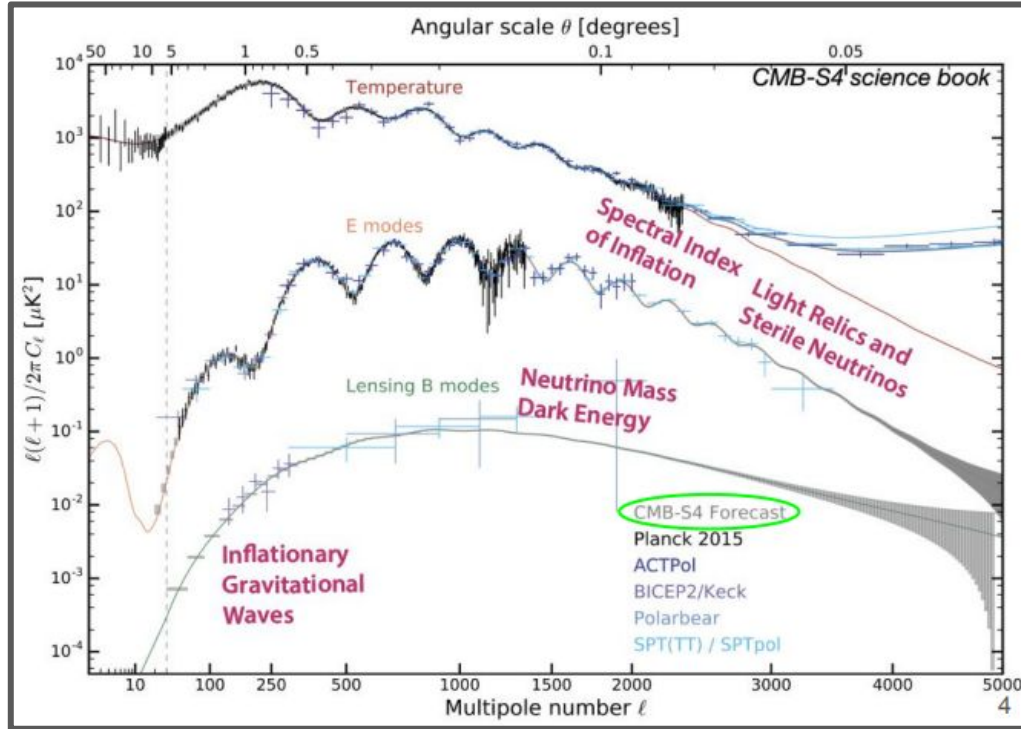
Future B-Mode Probes: CMB-Stage IV LAT Receivers

Property	ULF	LF		MF		HF	
Center frequency (GHz)	20	27	39	93	145	225	278
FWHM (arcmin)	10.0	7.4	5.1	2.2	1.4	1.0	0.9
Fractional bandwidth	0.25	0.22	0.46	0.38	0.28	0.27	0.16
NET ($\mu\text{K}\sqrt{\text{s}}$) per detector	438	383	250	302	356	737	1840
$N_{\text{detectors}}$ per tube	160	320	320	3460	3460	3744	3744
N_{wafers} per tube	4	4		4		4	
Chile (Wide Field Survey – 2 LATs)							
N_{tubes} per LAT	0	2	12		5		
Data rate (2 LATs)	10.8 TB/day						
South Pole (Delensing Survey – 1 LAT)							
N_{tubes}	1	2	12		4		
Data rate (1 LAT)	5.0 TB/day						
Total (3 LATs)							
$N_{\text{detectors}}$	160	1920	1920	124560	124560	52416	52416
$N_{\text{detectors}}$ total	357952						
N_{wafers}	4	24	144		56		
N_{wafers} total	228						

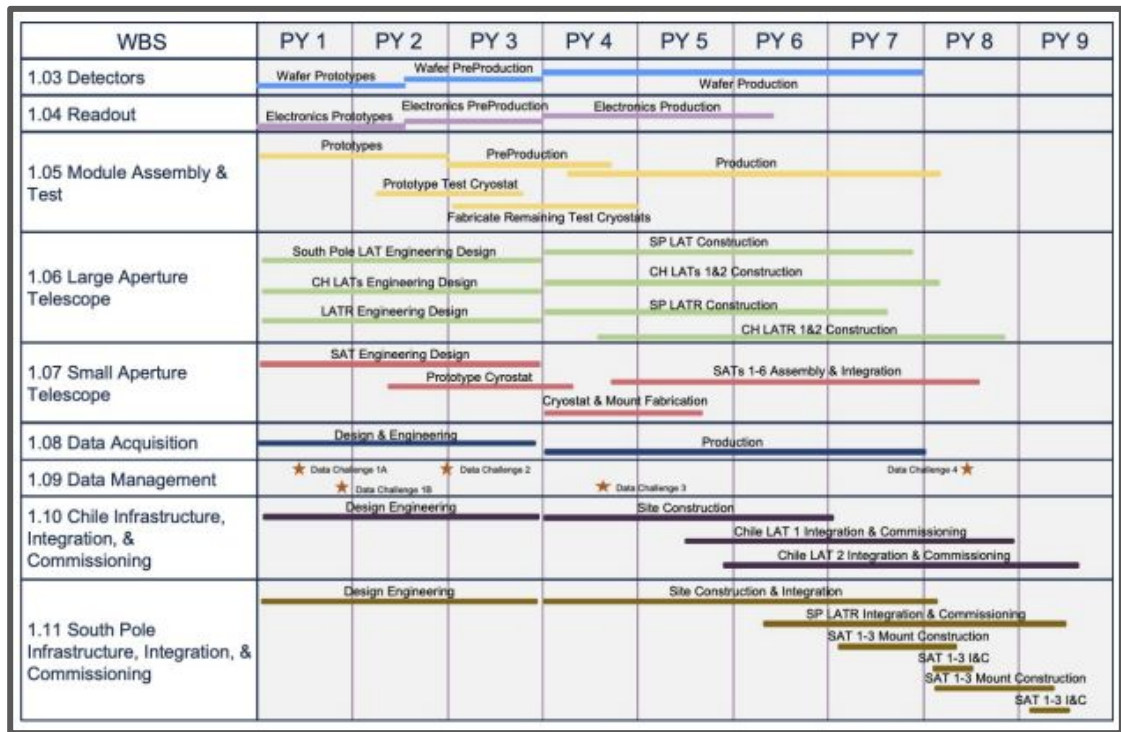
Future B-Mode Probes: CMB-Stage IV SAT Receivers

Property	LF		CF High		CF Low		HF	
Center frequency (GHz)	30	40	85	145	95	155	220	270
Primary lens diameter (cm)	55	55	55	55	55	55	44	44
FWHM (arcmin)	72.8	72.8	25.5	25.5	22.7	22.7	13	13
Fractional bandwidth	0.3	0.3	0.24	0.22	0.24	0.22	0.22	0.22
NET ($\mu\text{K}\sqrt{\text{s}}$) per detector	177	224	270	238	309	331	747	1281
N_{det} per optics tube	288	288	3524	3524	3524	3524	8438	8438
N_{tubes}	2		6		6		4	
N_{wafers}	24		72		72		36	
N_{wafers} total	204							
$N_{\text{detectors}}$	576	576	21144	21144	21144	21144	33752	33752
$N_{\text{detectors}}$ total	153232							
Data rate (18 optics tubes)	1.7 TB/day							

Future B-Mode Probes: CMB-Stage IV



CMB-Stage IV



Concluding Remarks

- **B-Mode Probes Primary Targets are Cosmological Gravitational Waves and Gravitational Lensing**
- **Gravitational Lensing is Sensitive to the Dynamics of Dark Energy and Matter**
- **Gravitational Lensing is Measured Internally, Cross-Correlated with Large Scale Structure Probe, and Subtracted for Optimizing Measurements of Cosmological Gravitational Waves**
- **Substantial Impact Already on Constraints on Dark Energy, Matter, Cosmological Tensions**
- **No Evidence for Deviations from Cosmic Concordance, Stable Low H_0 Measure**
- **Huge Program Ahead, Tomographic Analysis Towards a Network of Ground and Space Based Probes**

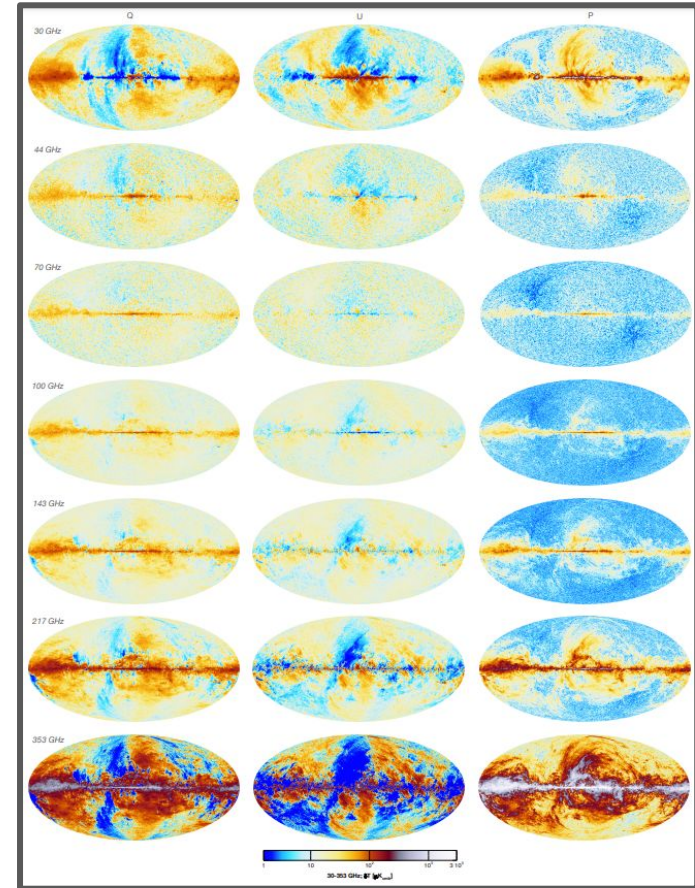
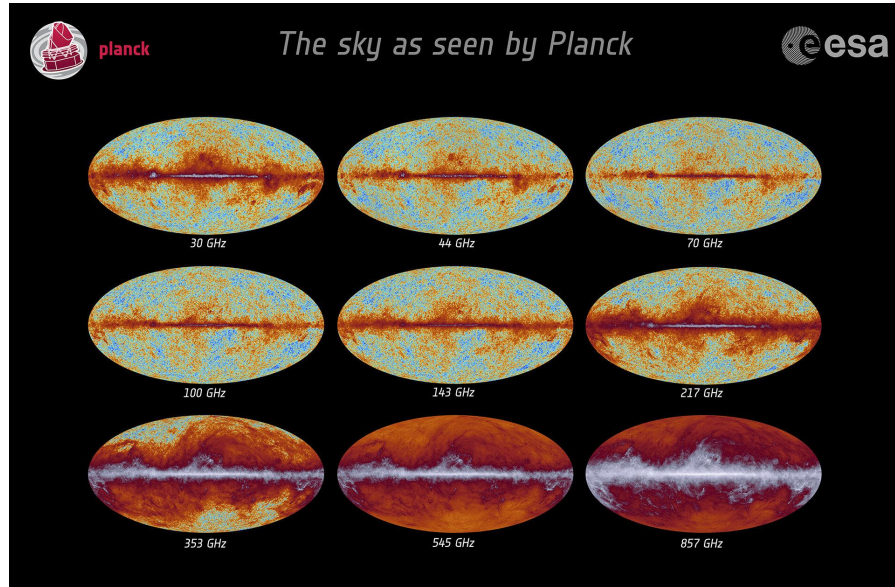
Back-Ups

B-Mode Data: The Planck Satellite

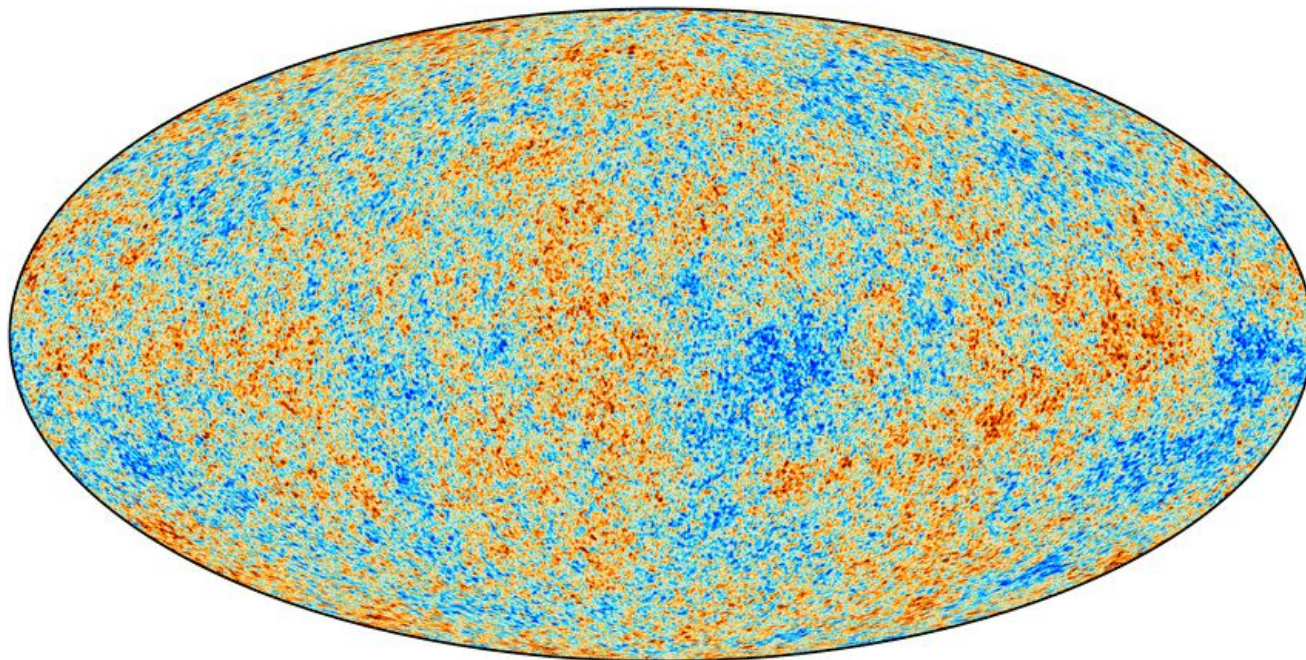
ROLE	Space observatory
LAUNCH DATE	14 May 2009
LAUNCHER/LOCATION	Ariane 5 EC (dual-launch w/Herschel) Kourou, French Guiana
LAUNCH MASS	1900 kg
ORBIT	Lissajous orbit at the second Lagrange point (L2)
PERIOD	Annual
NOMINAL MISSION	2.5 years - extended to mid-August 2013. Mission ended 23 October 2013.



B-Mode Data: Planck

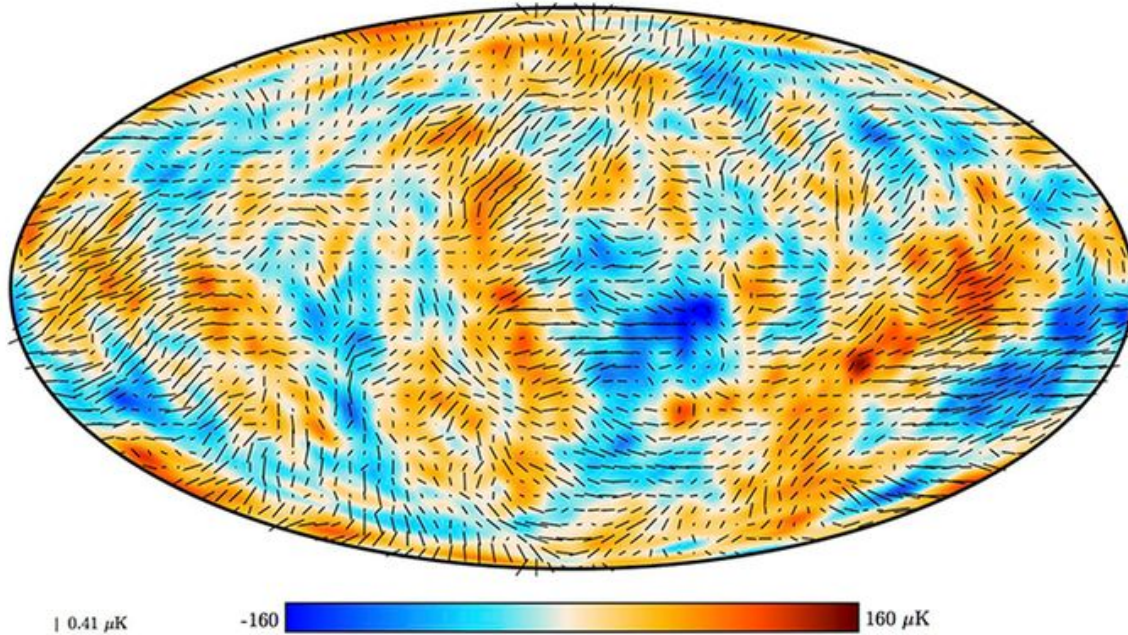


B-Mode Data: Planck Total Intensity

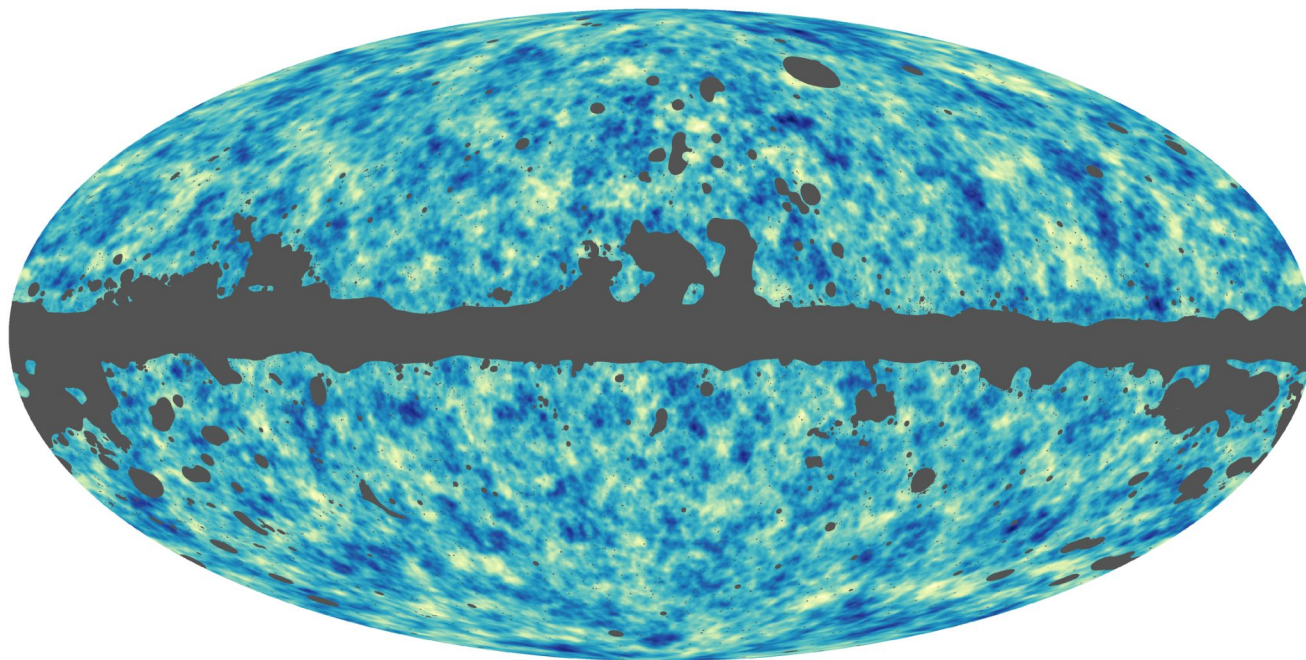


Planck 2018, IV, www.cosmos.esa.int/web/planck

B-Mode Data: Planck Polarization

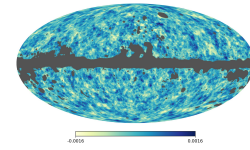
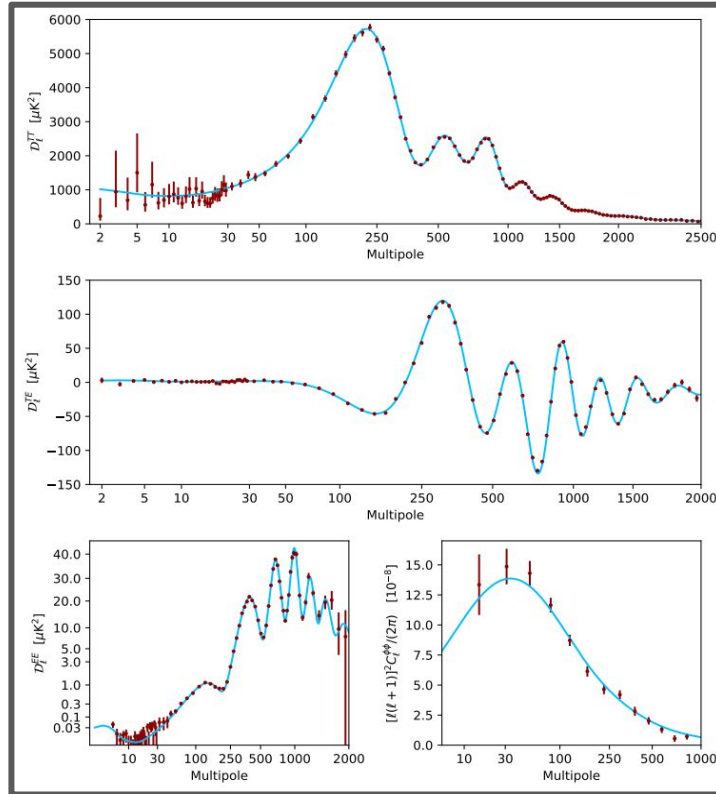
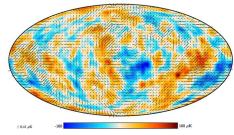
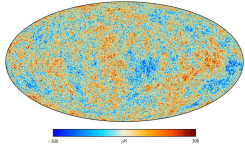


B-Mode Data: Planck Lensing

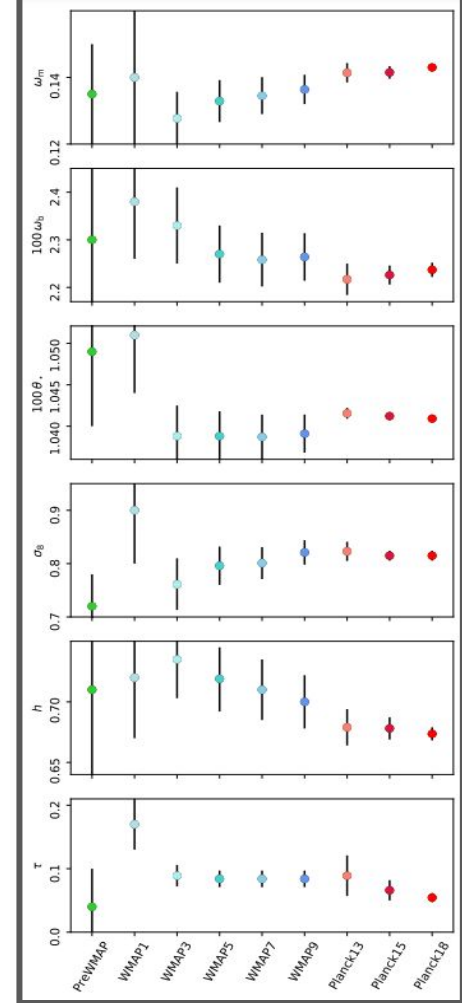
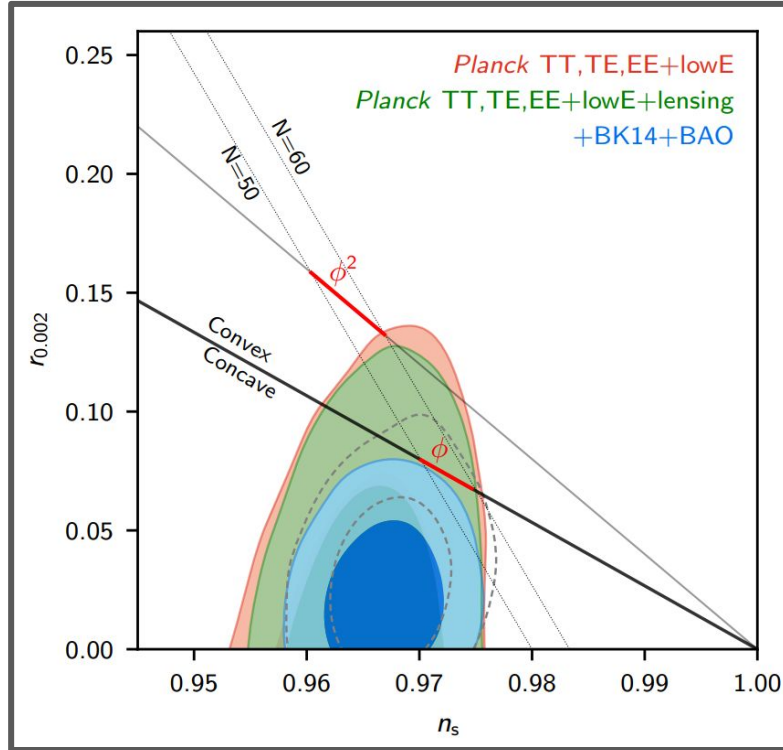
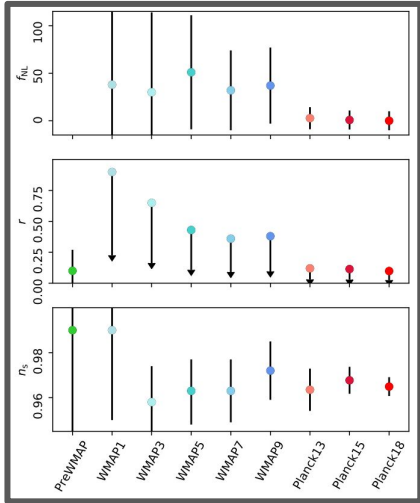


Planck 2017, VIII, www.cosmos.esa.int/web/planck

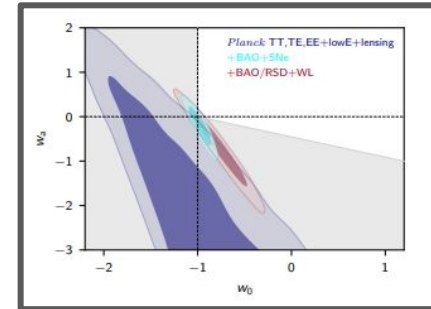
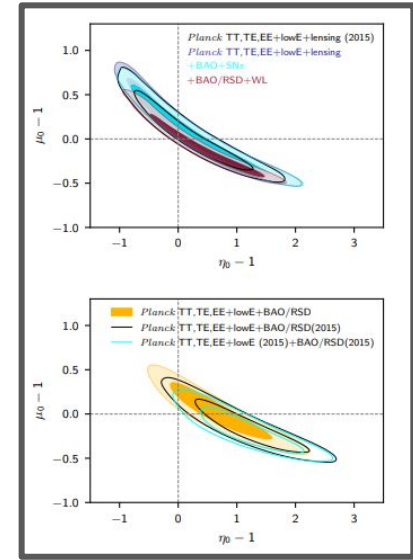
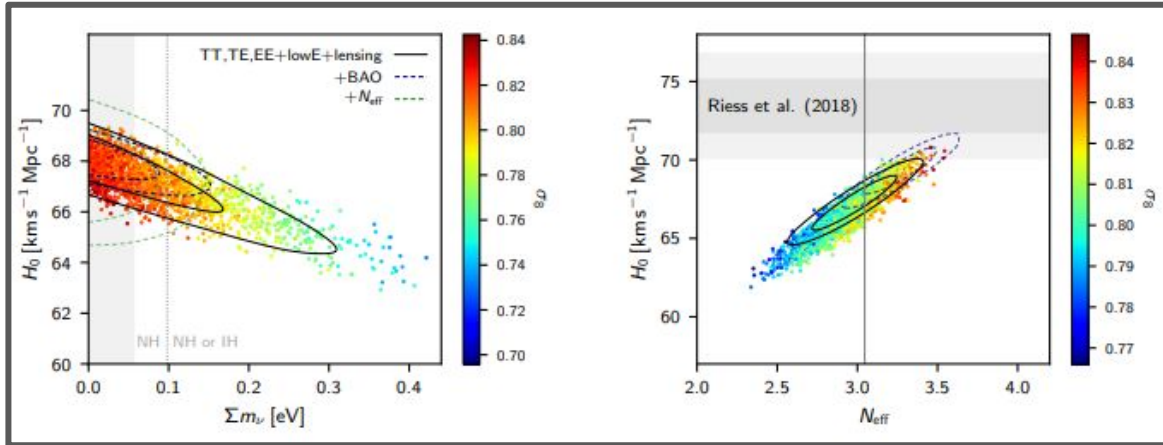
B-Mode Data: Planck Spectra



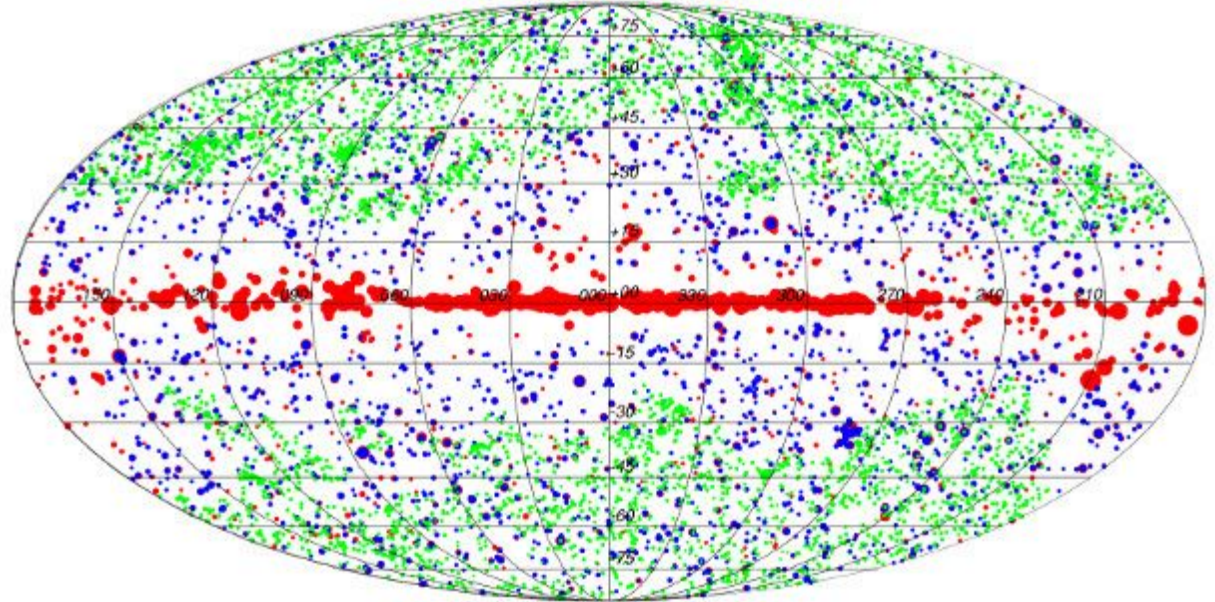
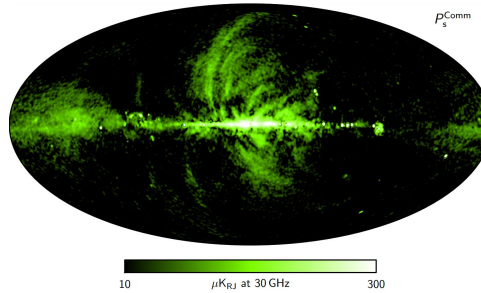
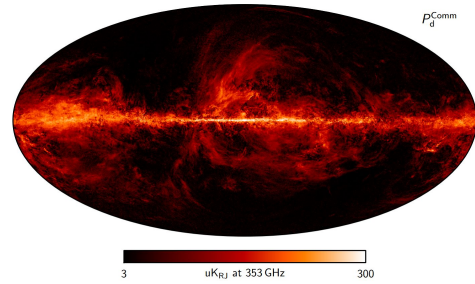
B-Mode Data: Planck Cosmology



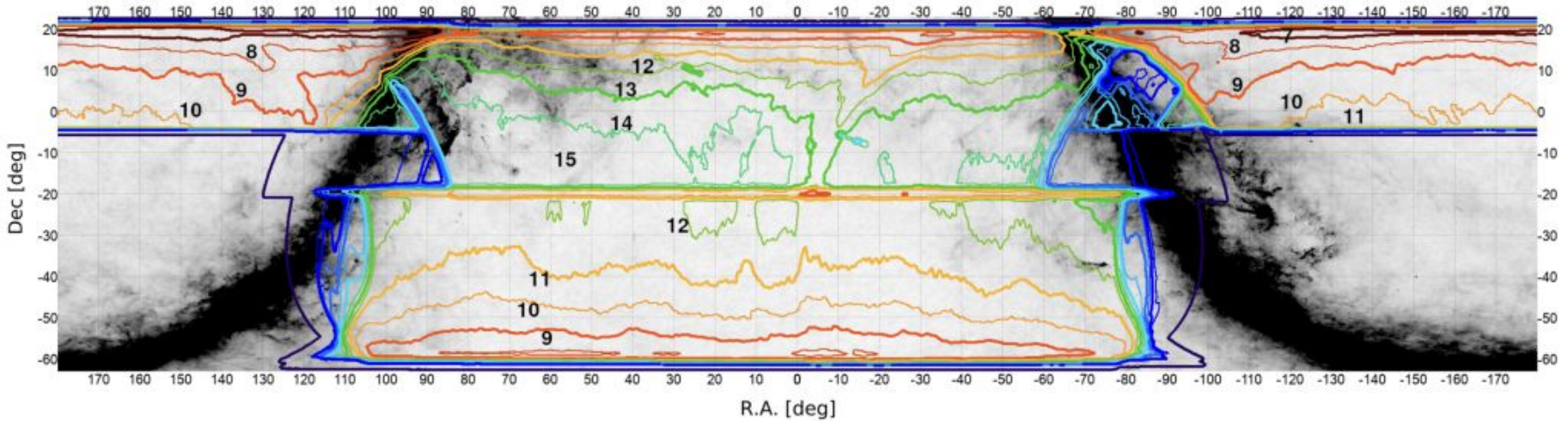
B-Mode Data: Planck Particle Physics



B-Mode Data: Planck Astrophysics



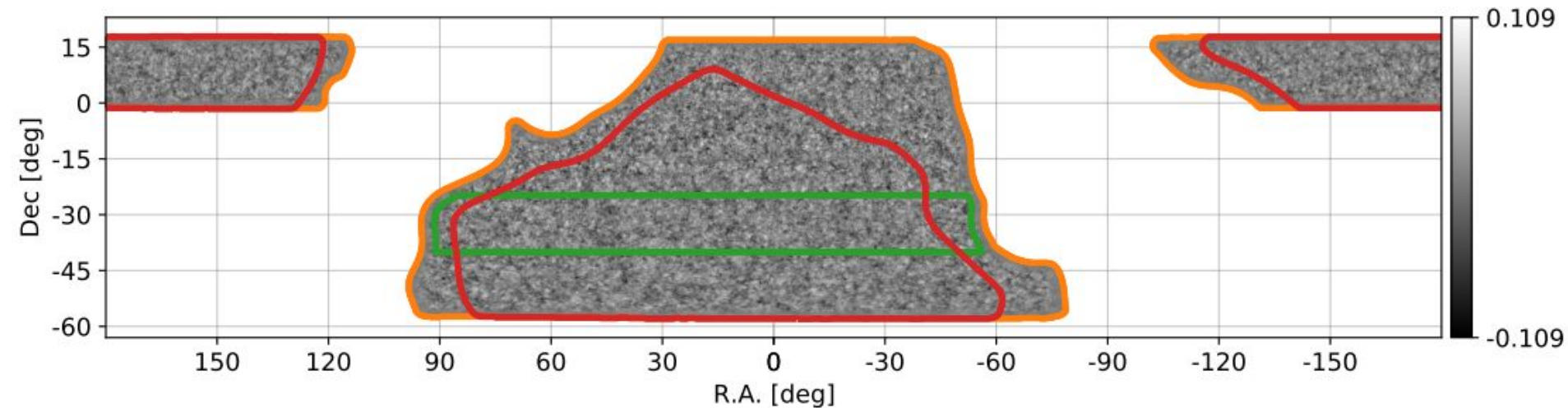
B-Mode Data: Atacama Cosmology Telescope



ACT Collaboration 2023

ui.adsabs.harvard.edu/link_gateway/2023arXiv230405202Q/arxiv:2304.05202

B-Mode Data: Atacama Cosmology Telescope



ACT Collaboration 2023

ui.adsabs.harvard.edu/link_gateway/2023arXiv230405202Q/arxiv:2304.05202

Community & Support: PNRR Space

PE15

Attività Spaziali Space It Up

Tavolo Tecnico

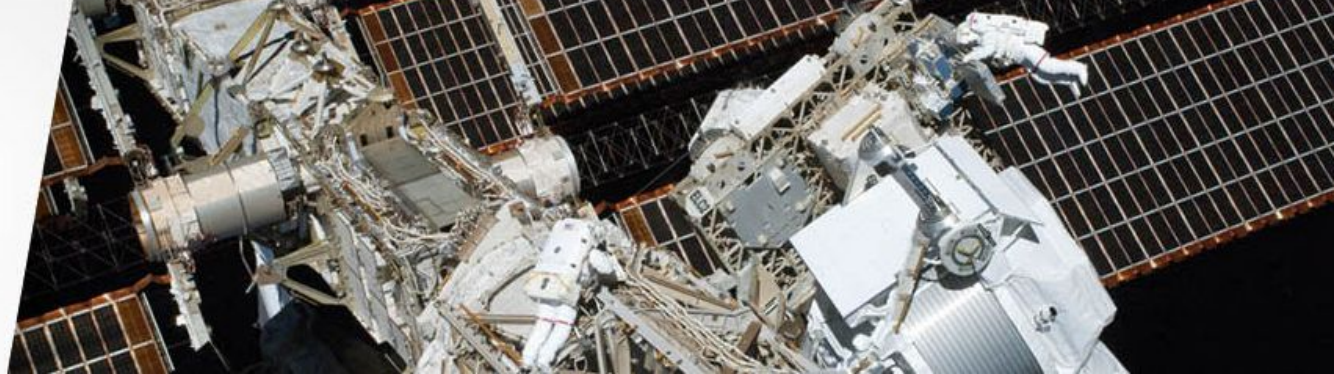
Meeting 06/09/2022





PhD SST

Space Science
and Technology



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36 Fellowships, Selection Ongoing, Active Curricula on

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- 5. Space Sensing and Instrumentation**
- 6. Engineering and Satellite Platform Technology**
- 7. Economics, Law and Space Diplomacy**

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