Probe Combination for Cosmic Microwave Background and Large Scale Structure Observations

Carlo Baccigalupi

SISSA

Conference on Exploring the Dark Side of the Universe, 2024

Outline

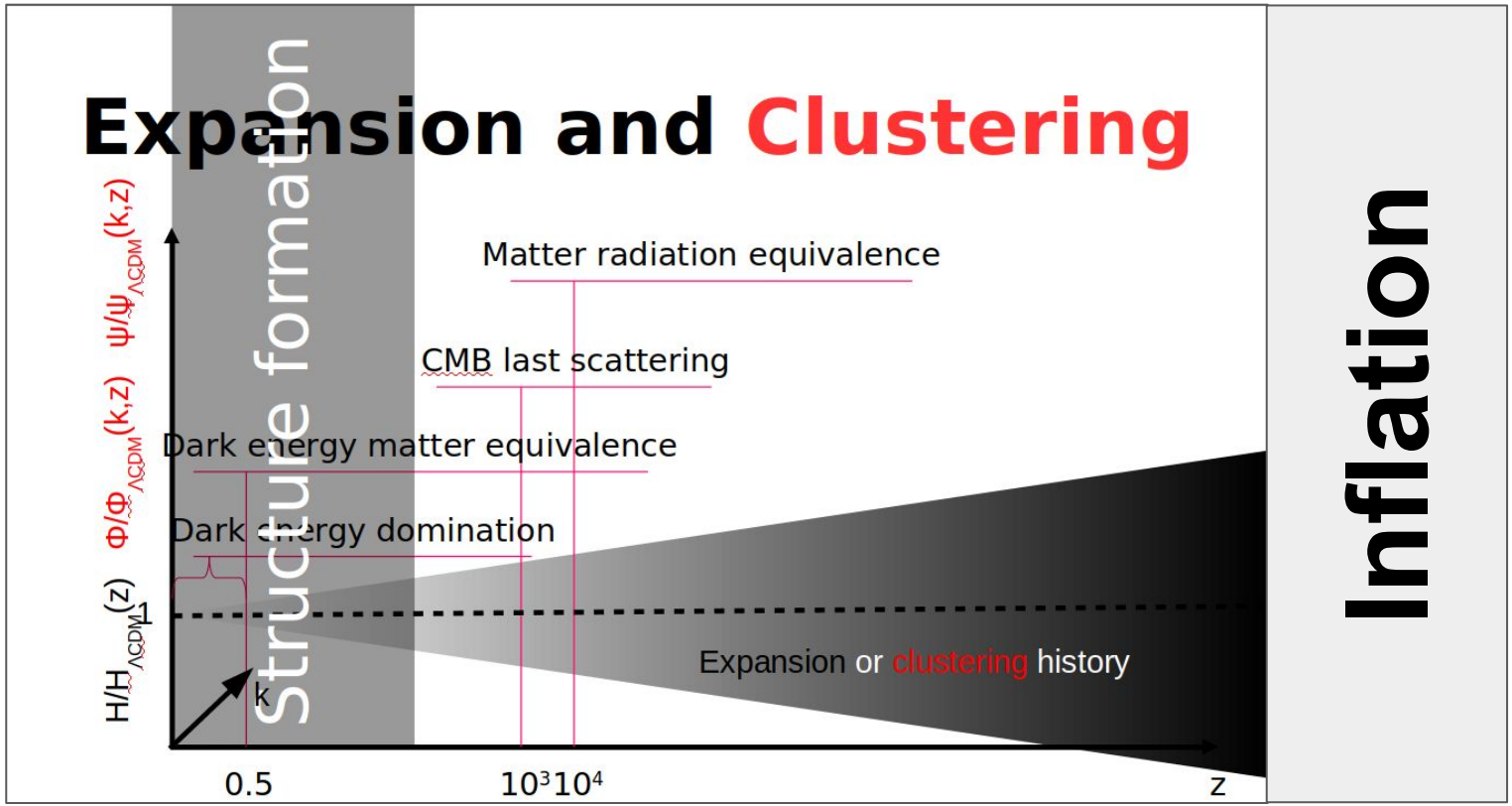
- (Some) Fundamental Physics in the Cosmological Light Cone
- Probe Combination
- Operating and Future Probes
- Remarks

Outline

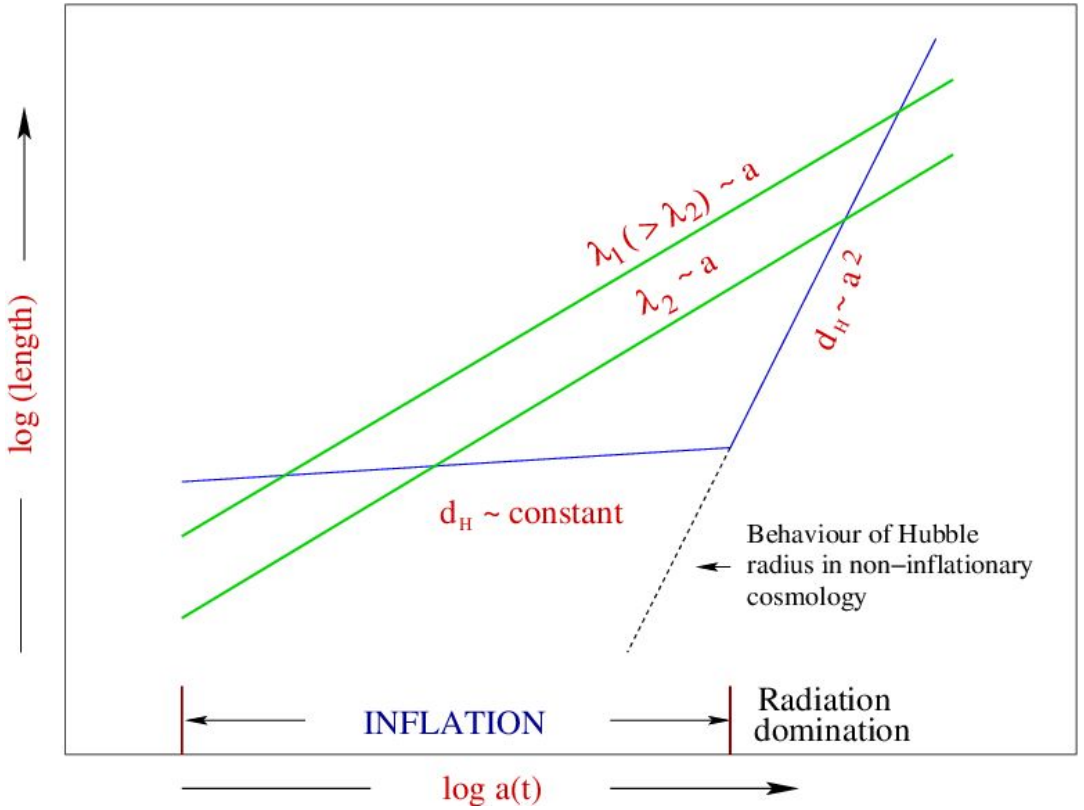
- (Some) Fundamental Physics in the Cosmological Light Cone
- Probe Combination
  - Early Cross-Correlations
  - Present Combinations
- Operating and Future Probes
  - Simons Observatory & Euclid
  - Euclid CMBXC WG Simulations & Analyses
  - CMB-S4 x LiteBIRD
- Remarks

(Some) Fundamental Physics in the Cosmological Light Cone

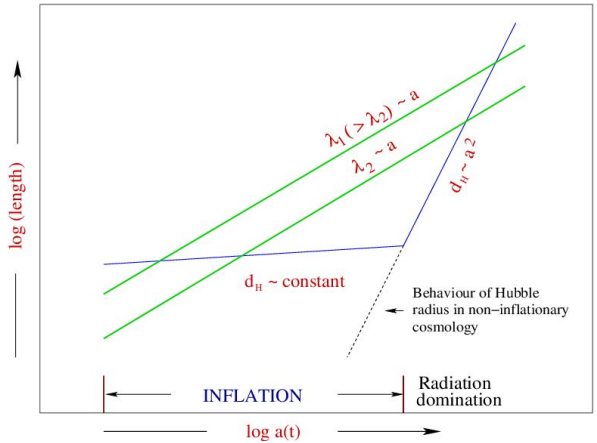
Expansion & Clustering

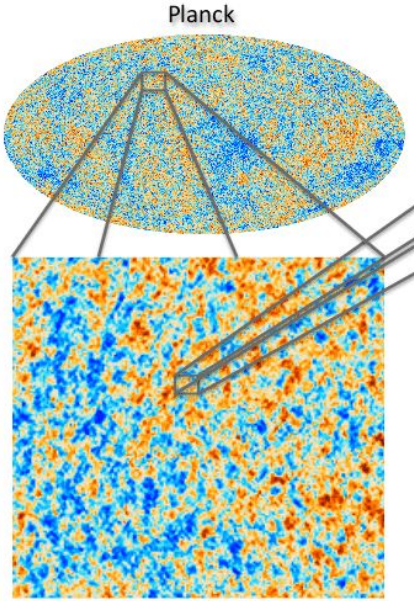


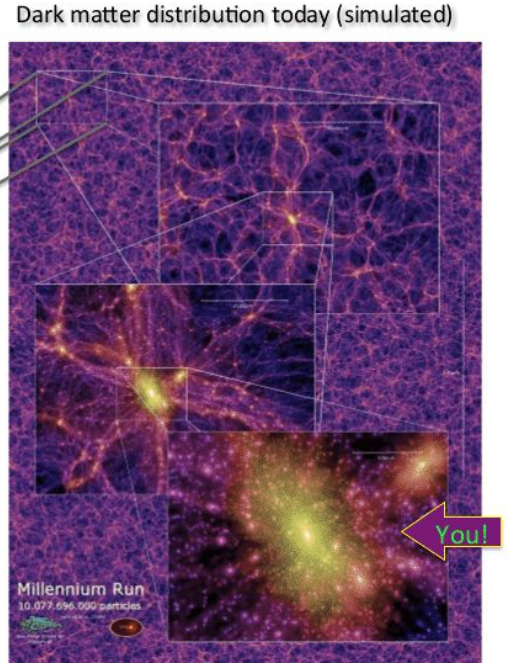
Inflationary Perturbations



Inflationary Perturbations

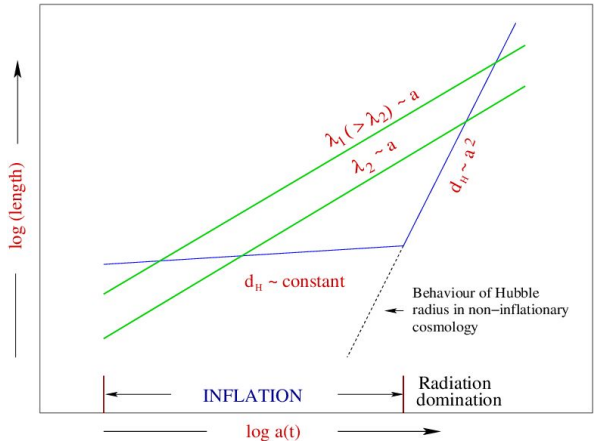


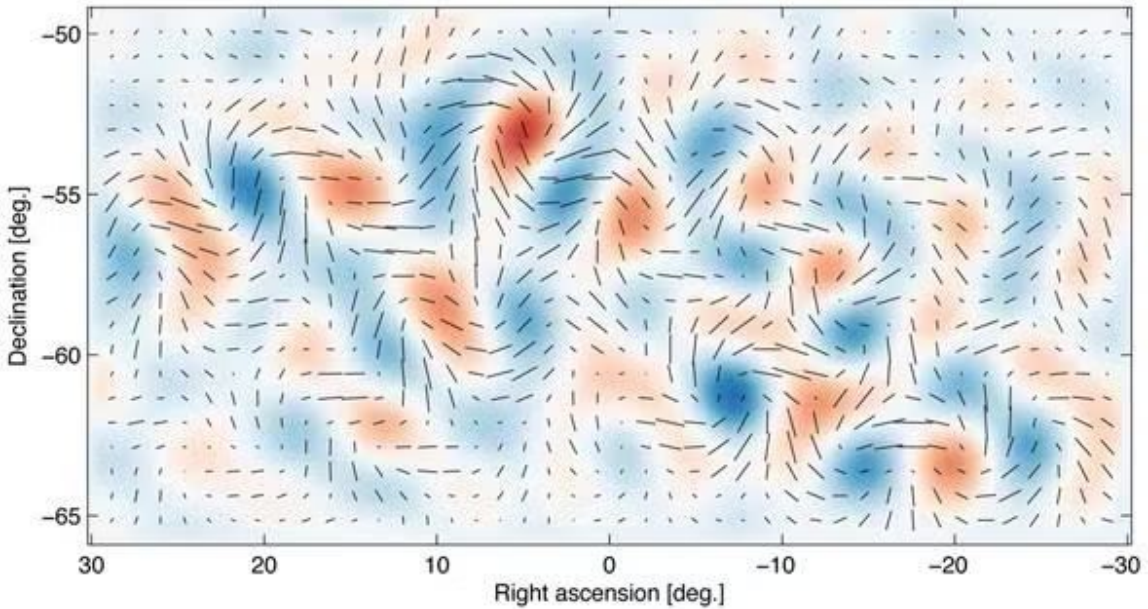




Planck 2020, PR4, Millennium Simulations

Inflationary Perturbations

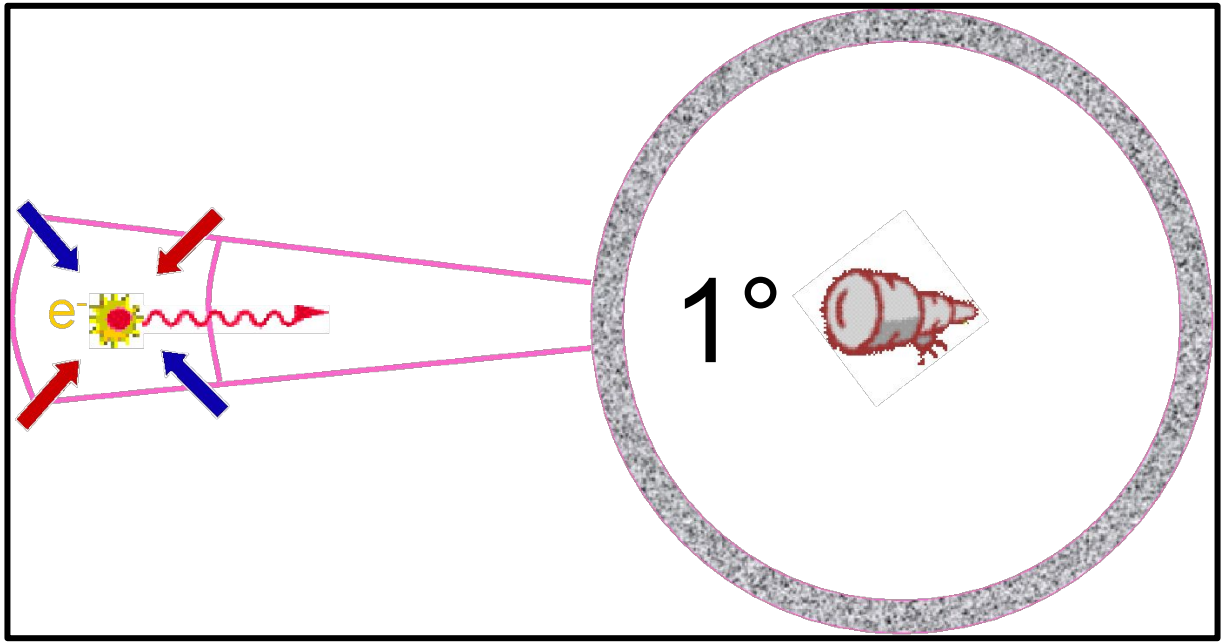




BICEP/Keck 2014

B-Modes from Cosmological Gravitational Waves

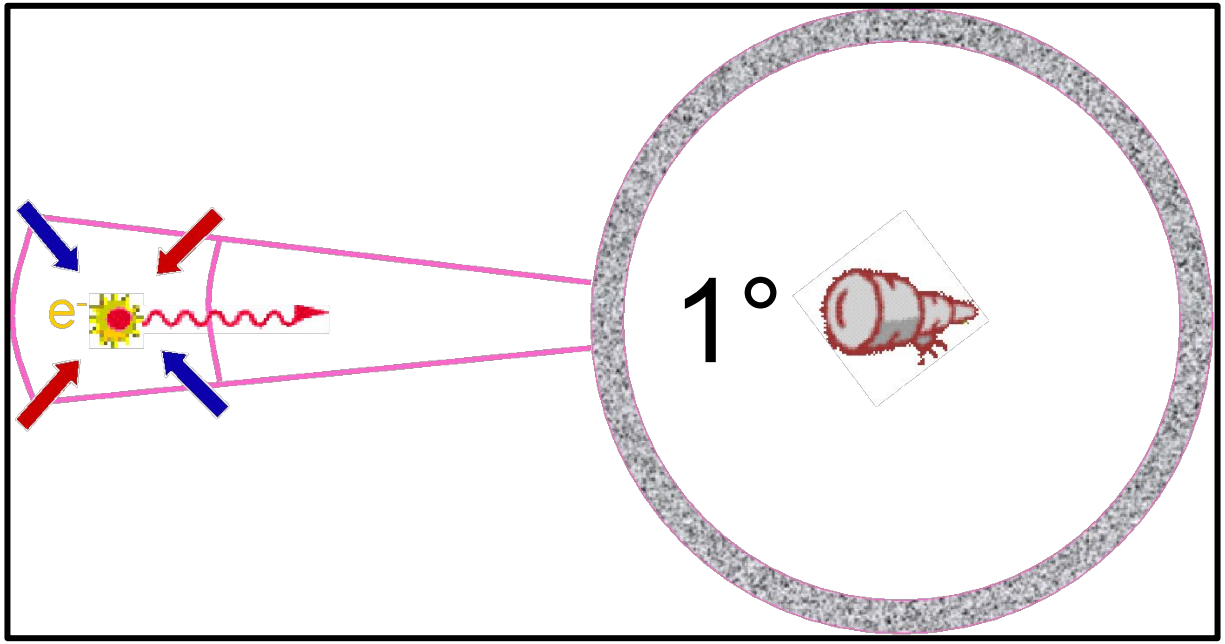
Gravitational waves not supported by sources, diffuse out rapidly below the Horizon scale, about 1 degree in the sky



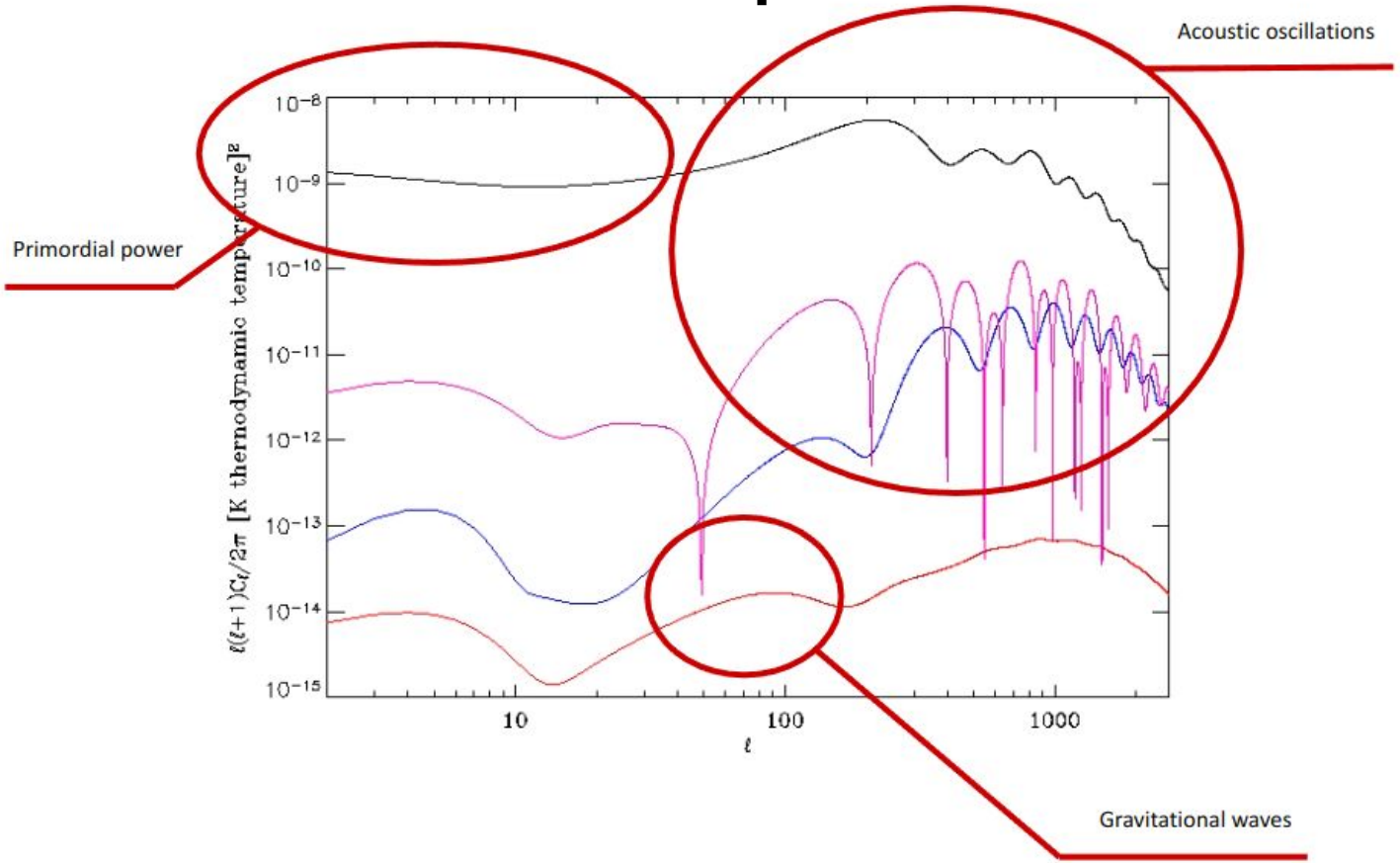
B-Modes from Cosmological Gravitational Waves

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

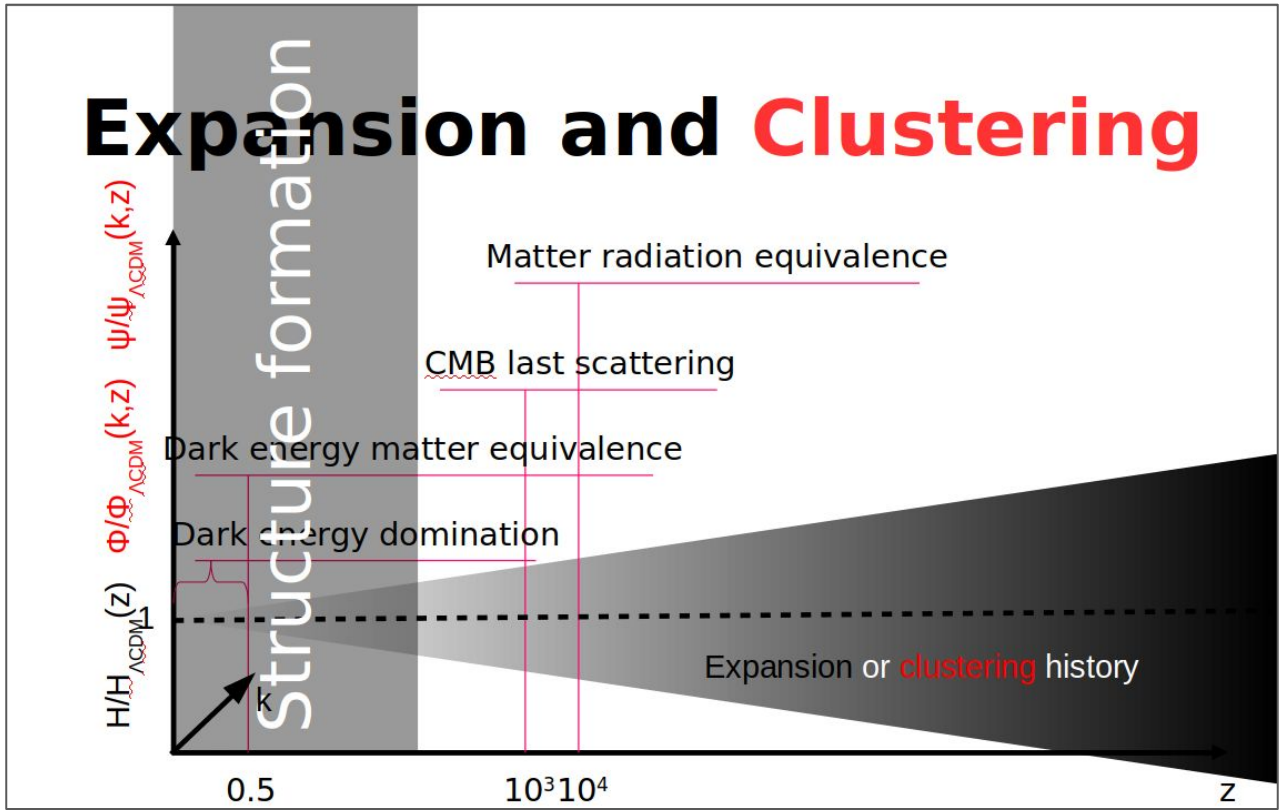
Decoupling time lasts for about 10 Mpc, no time for longer wavelenghts to contribute



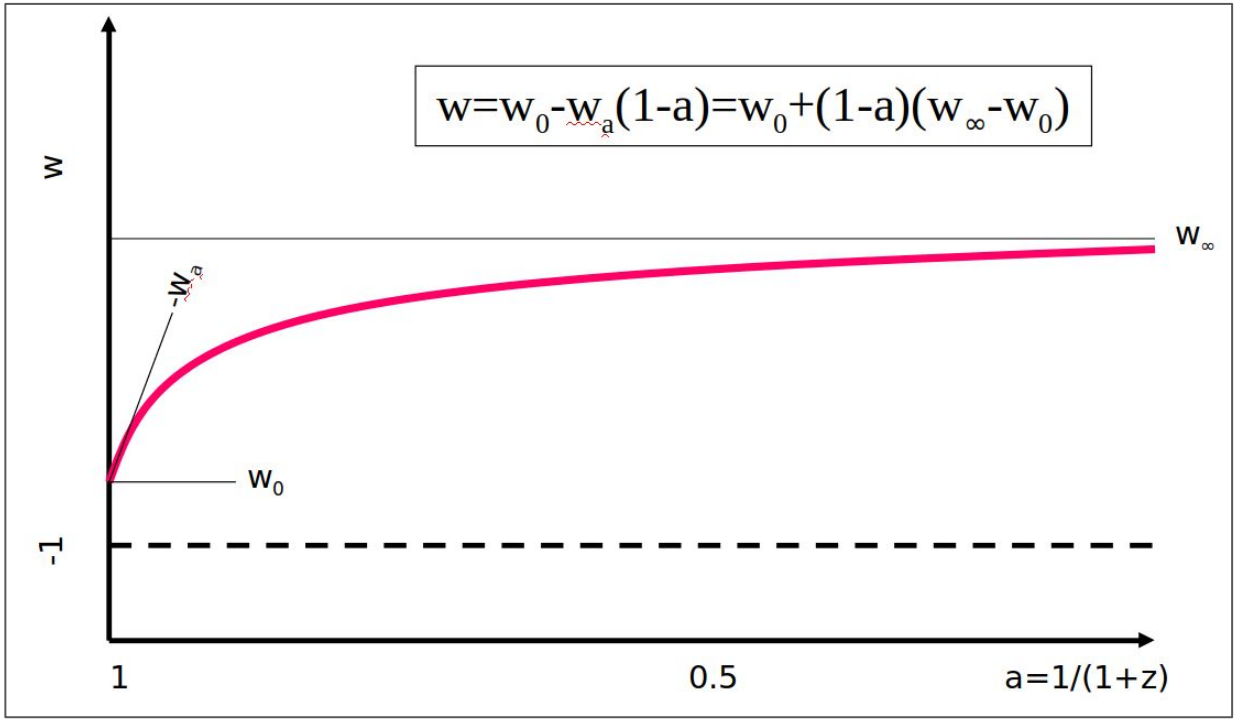
Gravitational Waves & CMB Spectra



Expansion & Clustering



Dark Energy & Modified Gravity



Modified Gravity

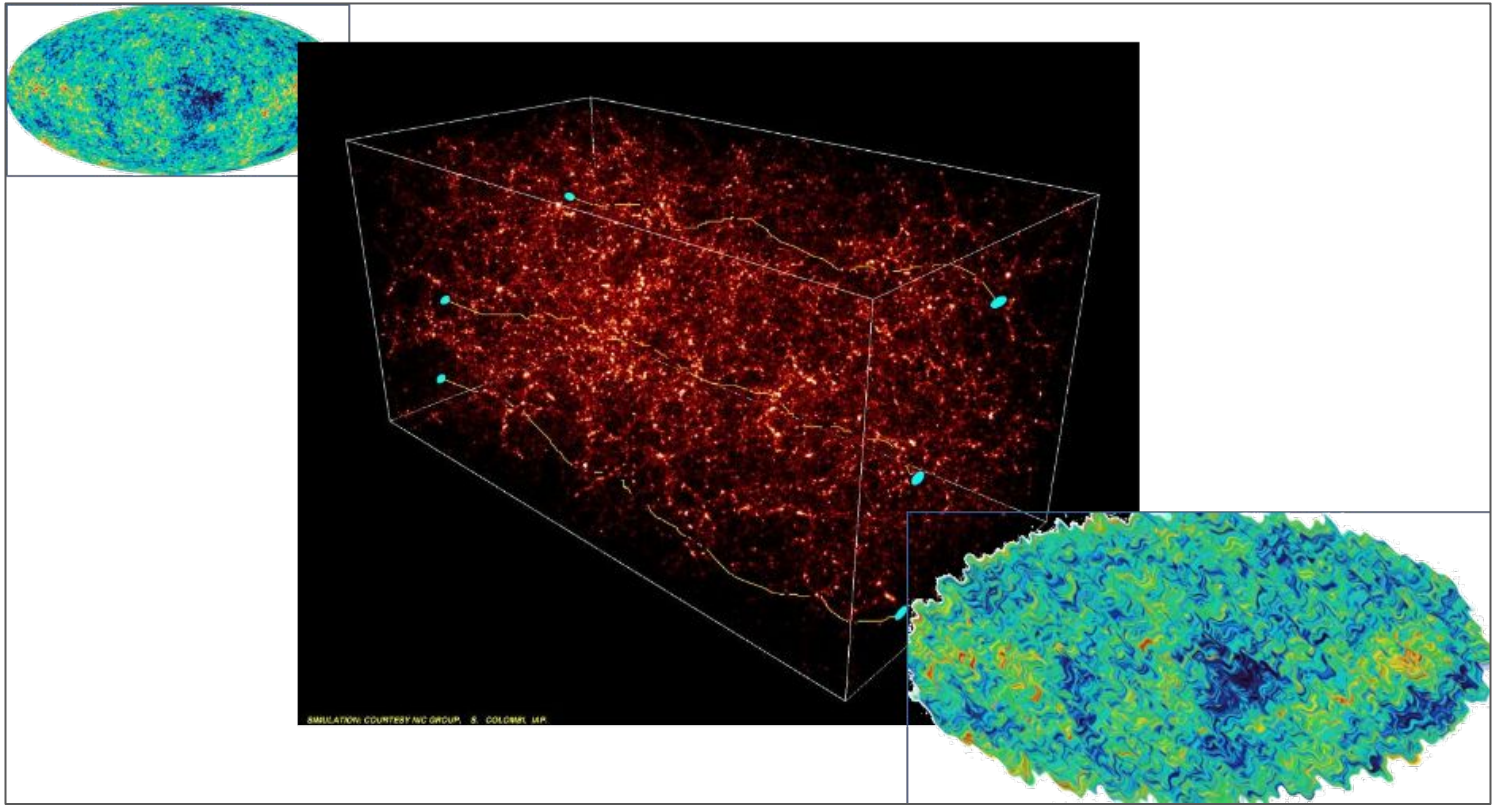
$\eta(a, k) \equiv \Phi/\Psi.$

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

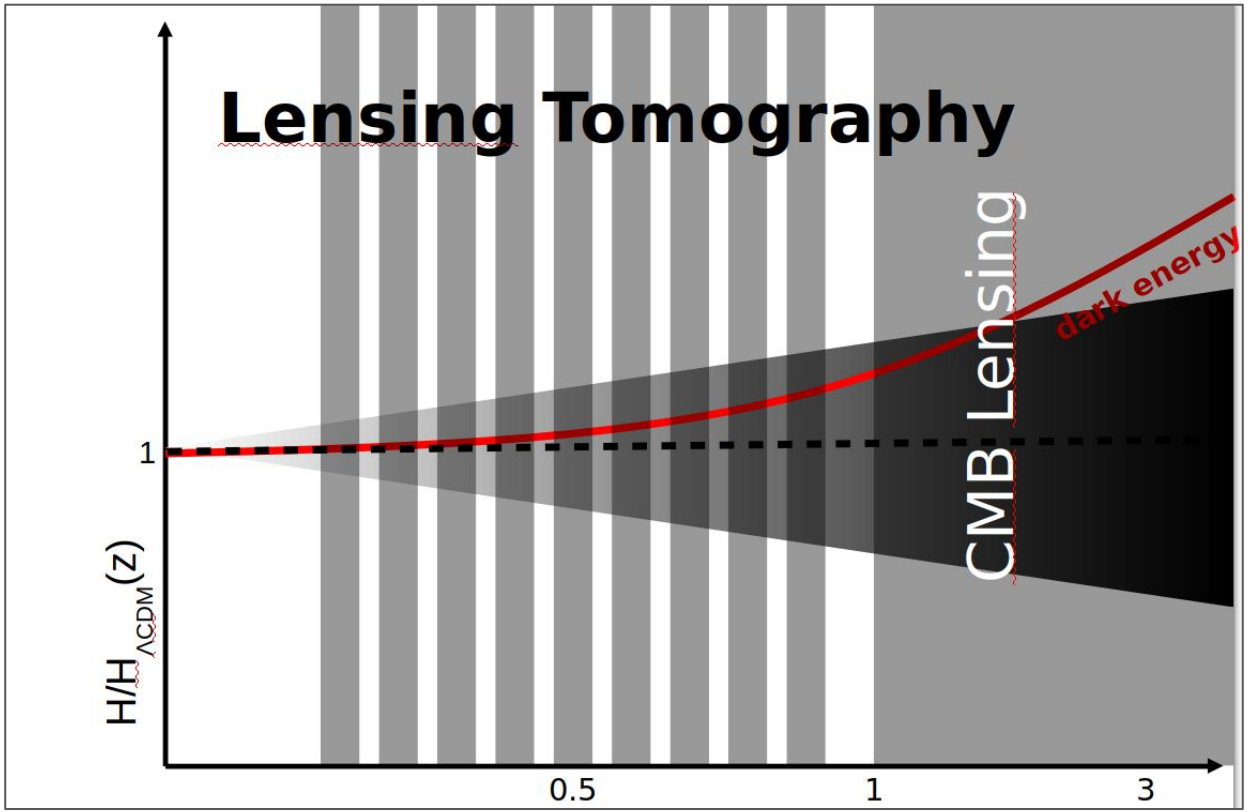
$-k^2\,\Psi \equiv 4\pi G a^2\,\eta(a, k)\rho\Delta$

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

Gravitational Lensing

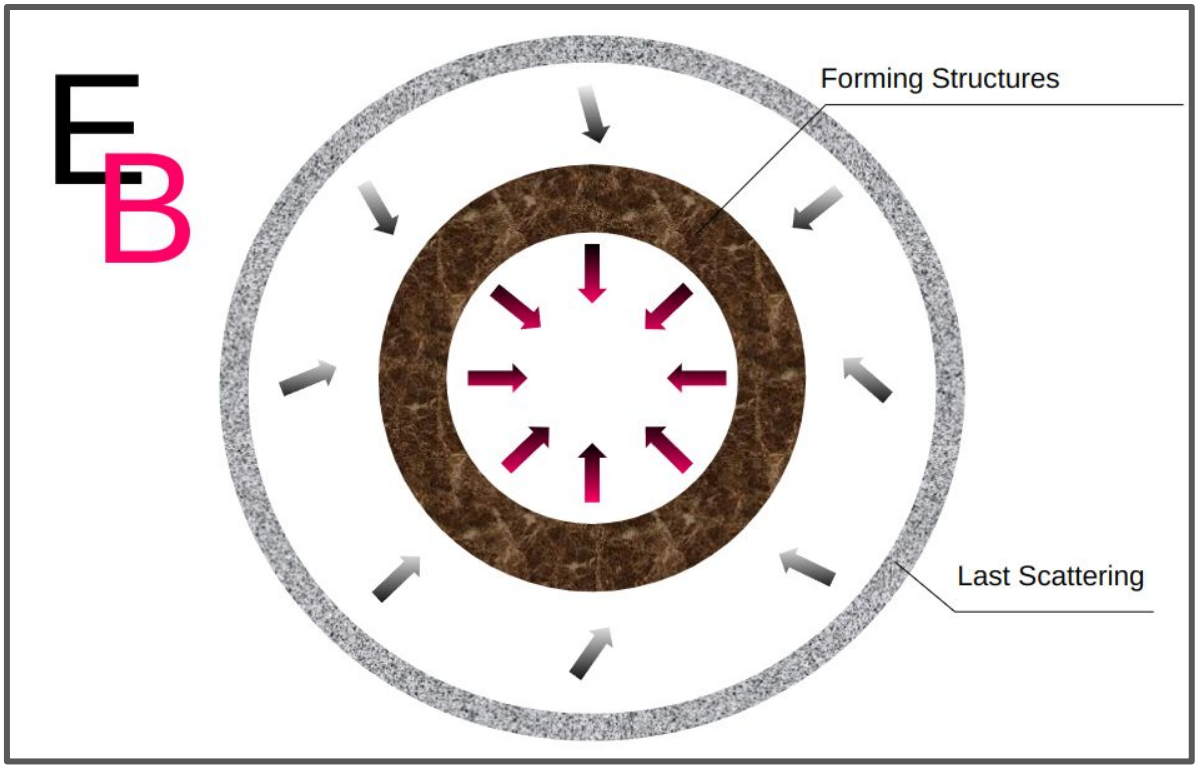


Combination, Correlation & Tomography



CMB Lensing

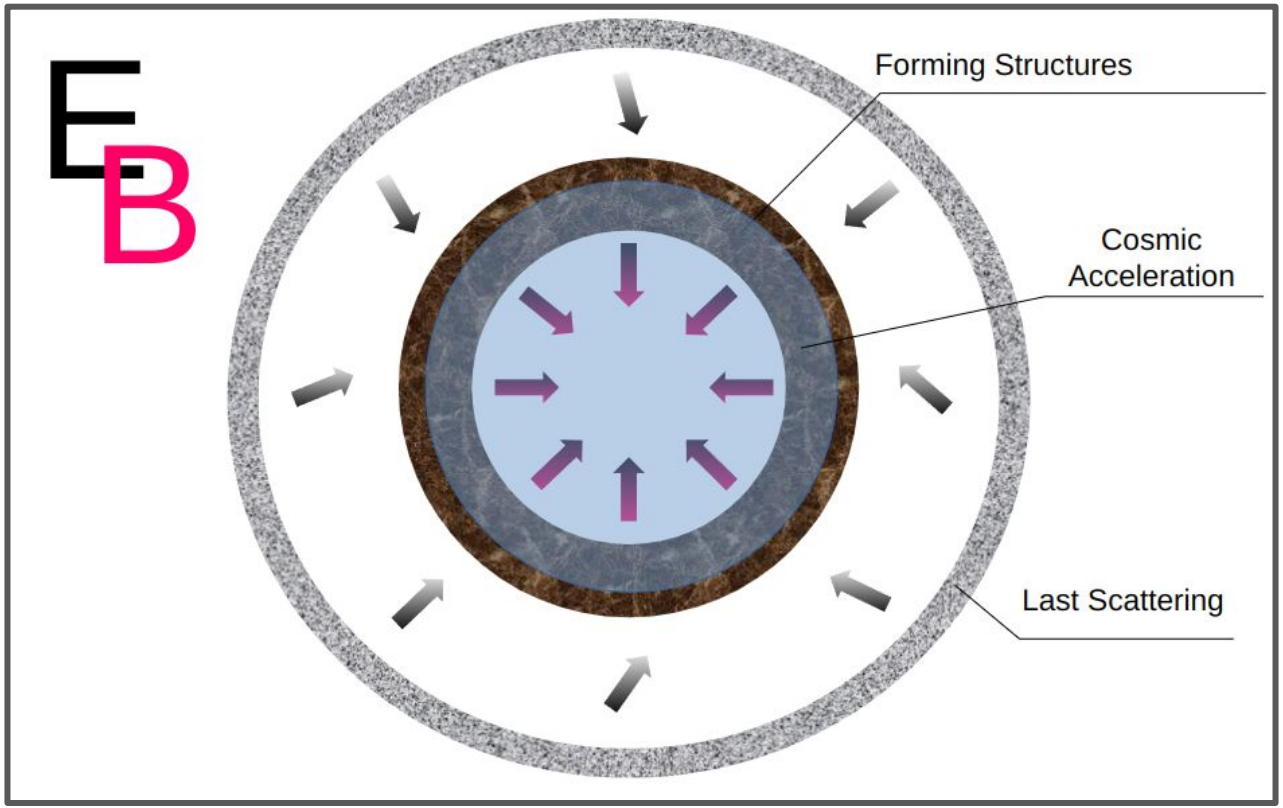
Forming Structures act as Lenses, over a large Redshift Interval, Peaking between 1 and 3



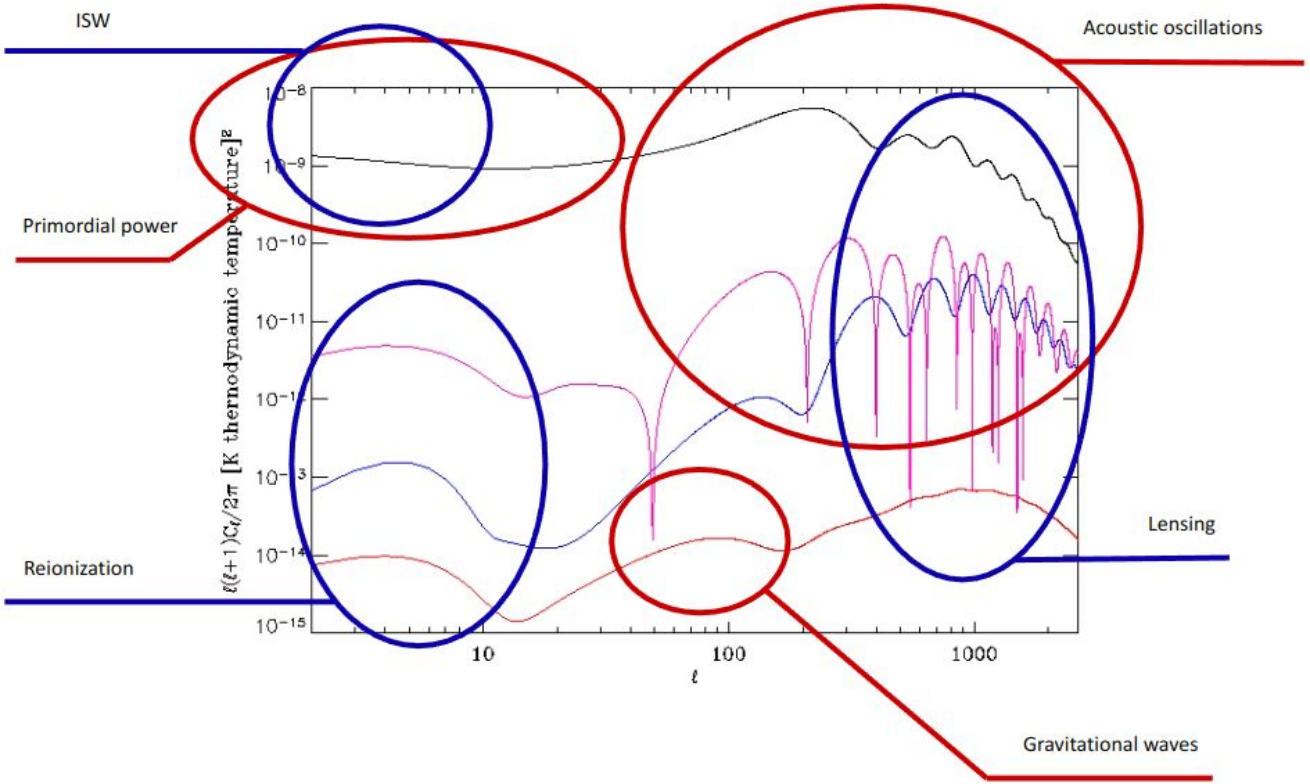
CMB Lensing

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

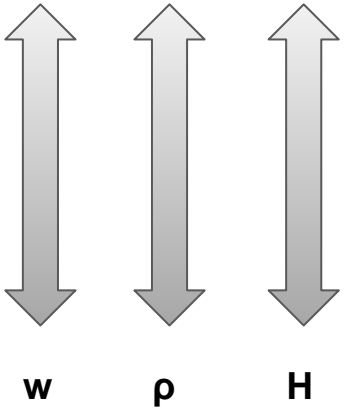
The CMB Lensing is a Probe for Dark Energy, by itself and in Cross-Correlation with LSS Probes

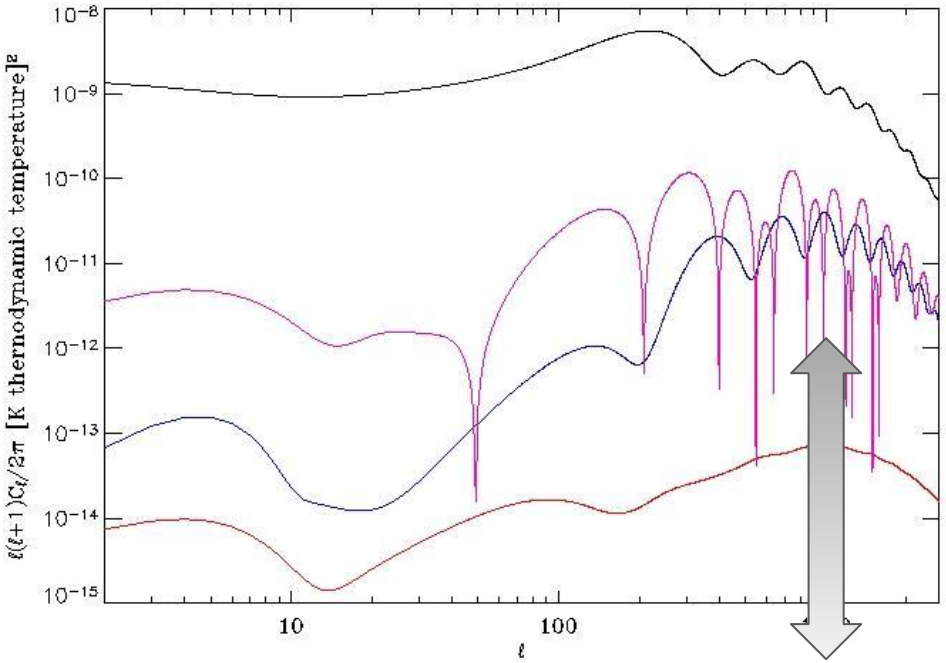


Powering CMB Angular Power Spectra



Dark Energy and CMB Lensing



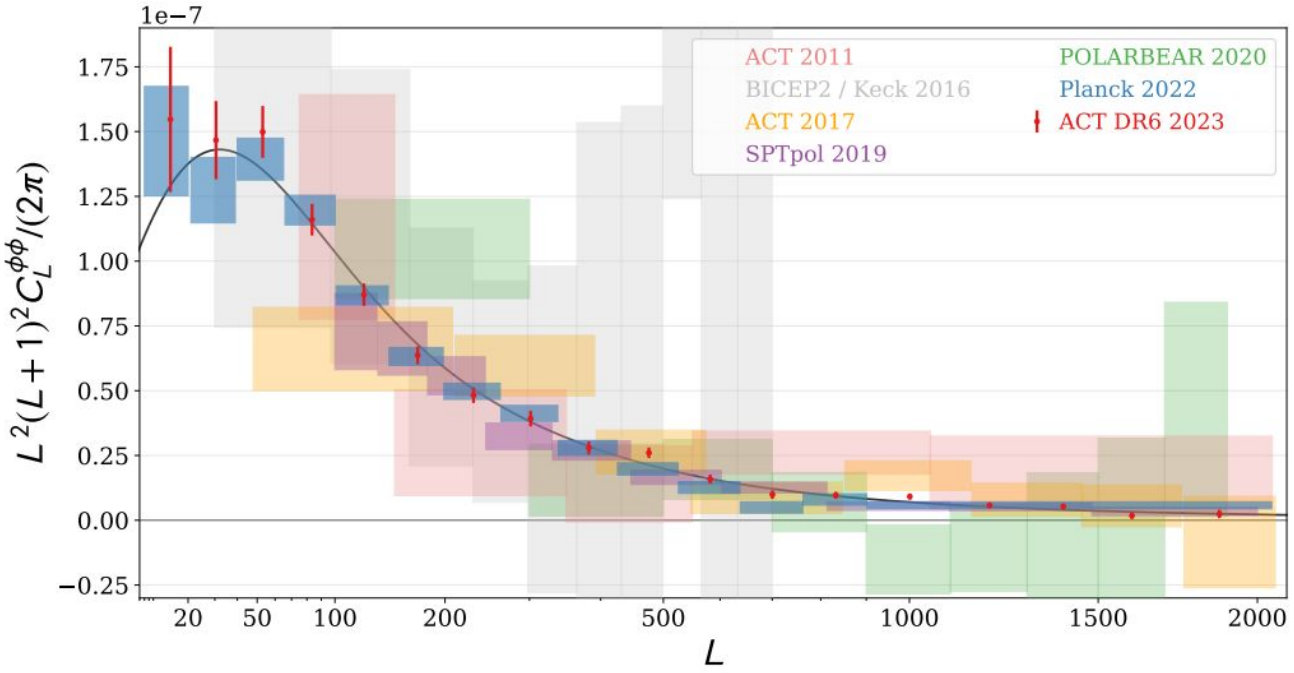


Angle ≈ 200/ℓ degrees

Viviana Acquaviva & CB 2006

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

CMB Lensing Data

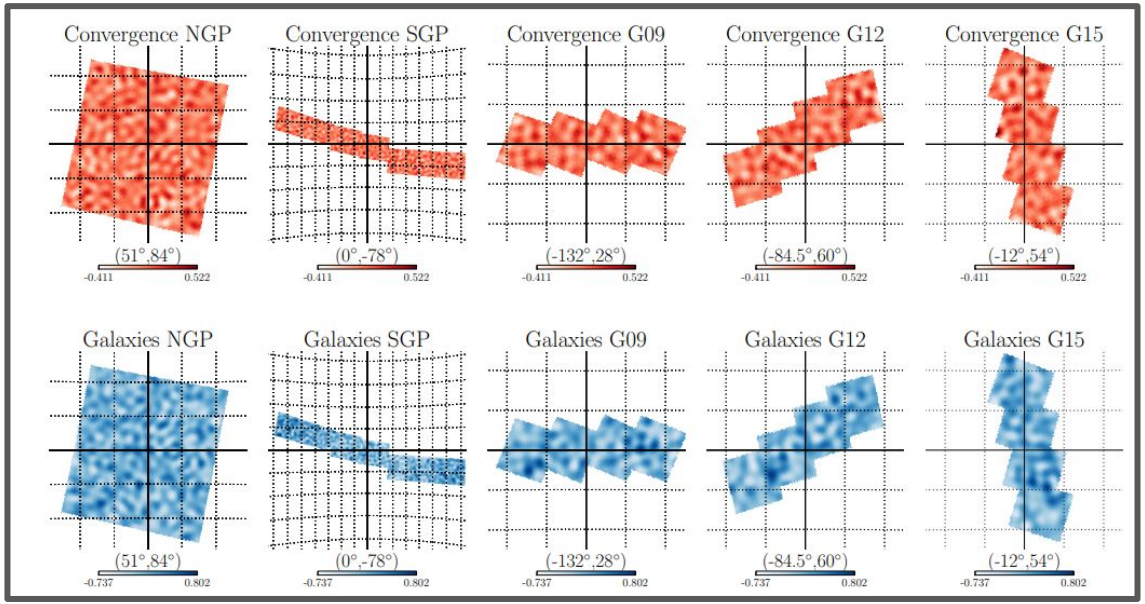


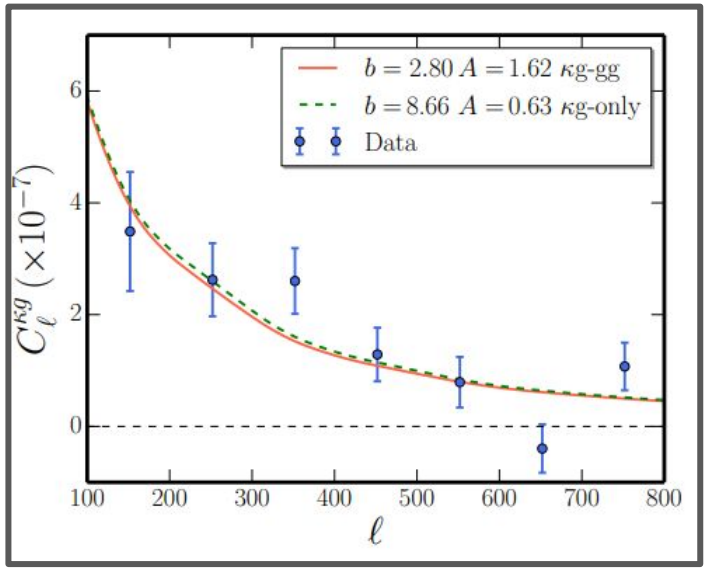
ACT Collaboration 2023

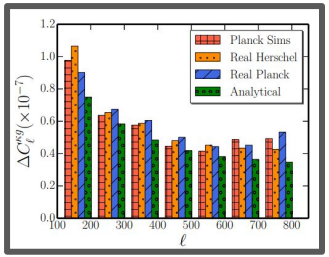
ui.adsabs.harvard.edu/link_gateway/2023arXiv230405202Q/arxiv:2304.05202

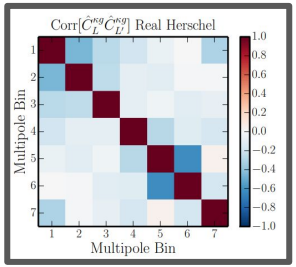
Probe Combination

Galaxy Clustering & CMB Lensing





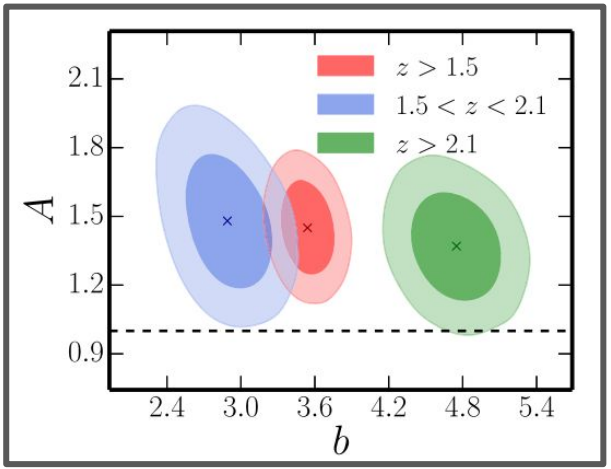


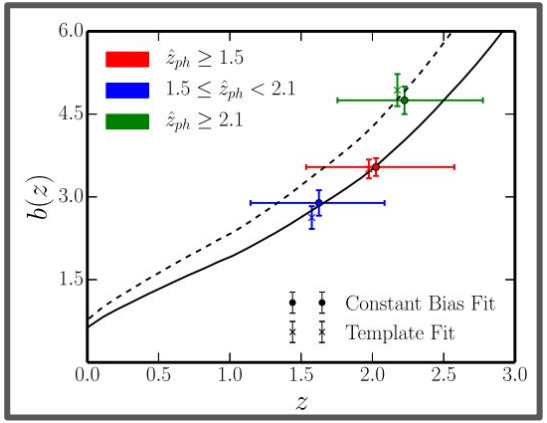


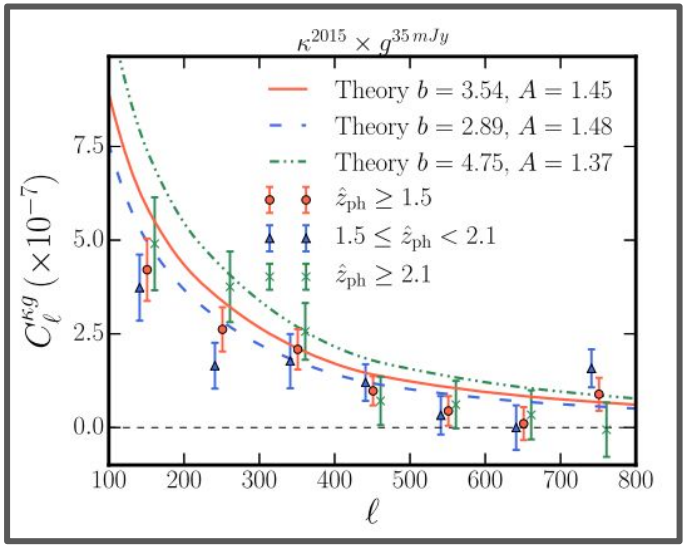
Herschel x Planck

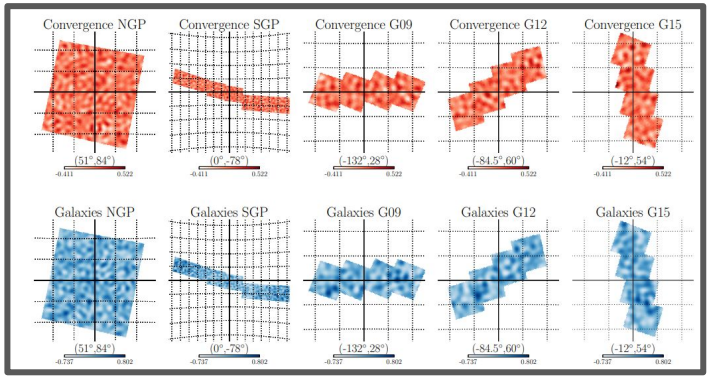
Federico Bianchini et al. 2015

Galaxy Clustering & CMB Lensing



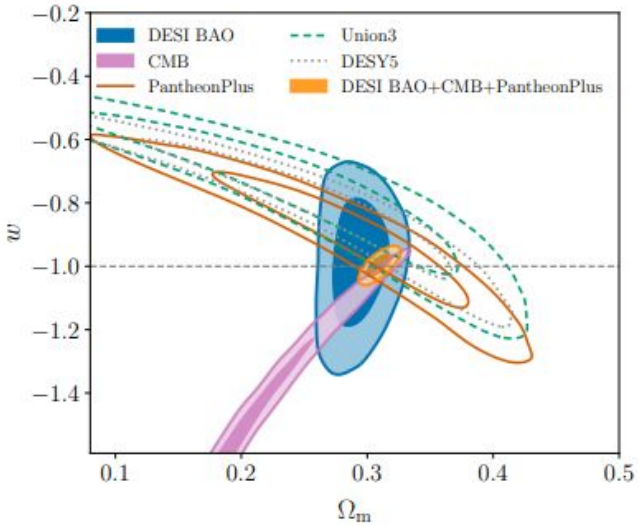






Federico Bianchini et al. 2016

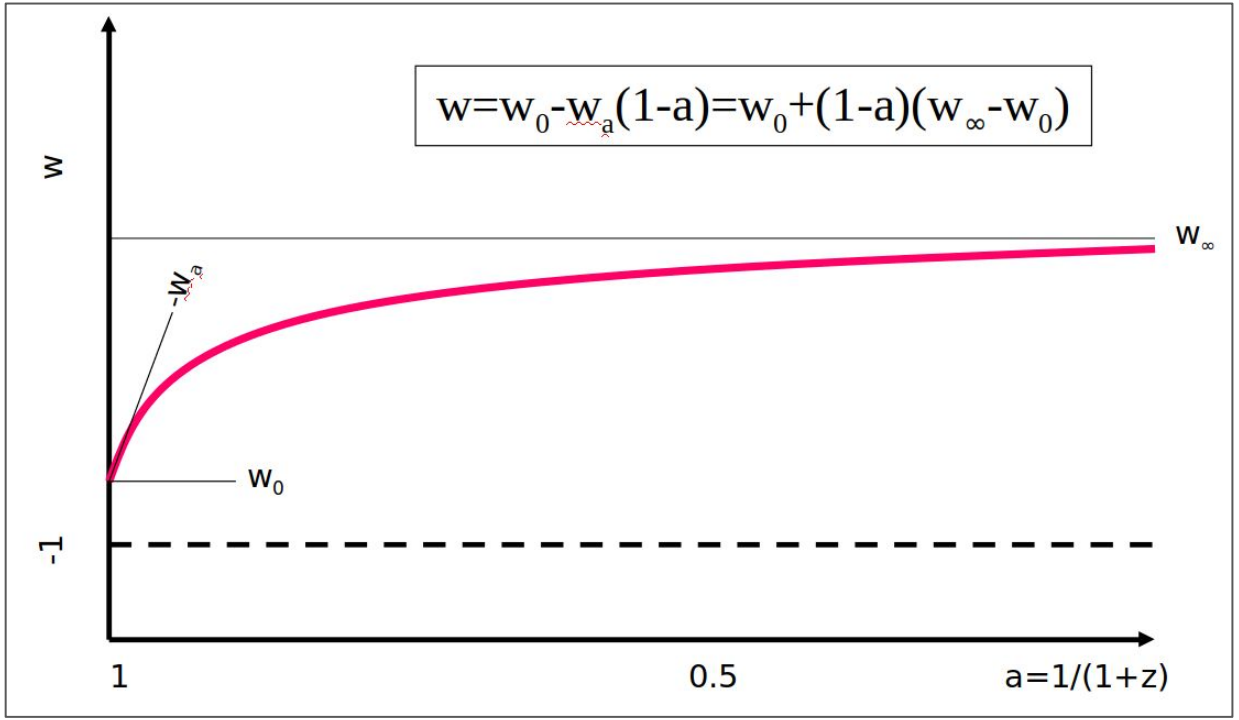
Dark Energy Spectroscopic Instrument



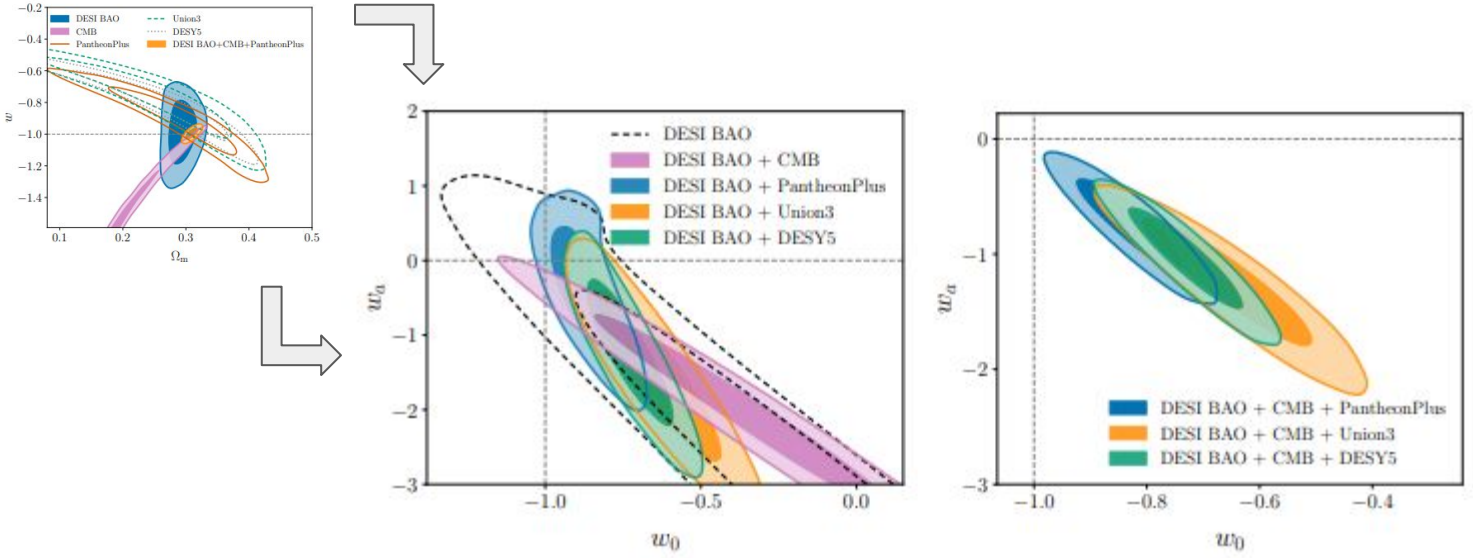
Dark Energy Spectroscopic Instrument 2024

https://ui.adsabs.harvard.edu/abs/2024arXiv240403002D/abstract

Dark Energy Dynamics



Dark Energy Spectroscopic Instrument

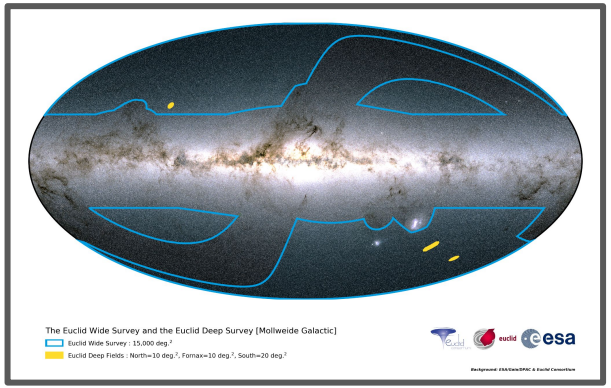


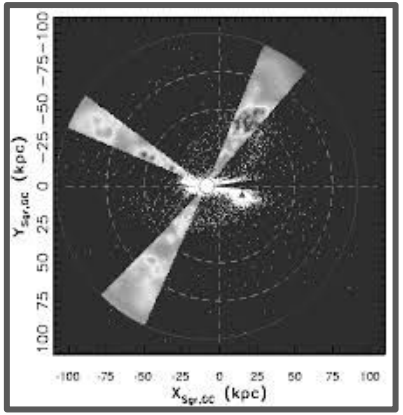
Dark Energy Spectroscopic Instrument 2024

https://ui.adsabs.harvard.edu/abs/2024arXiv240403002D/abstract

Operating and Future Probes

Roadmap





2024

2030+

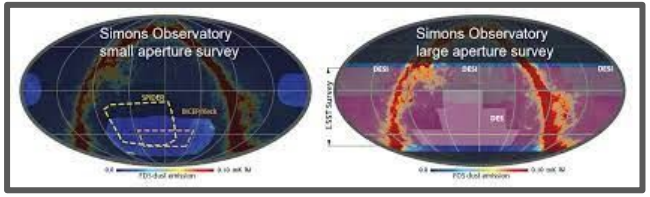
Atacama Cosmology Telescope

SPT

SIMONS ARRAY

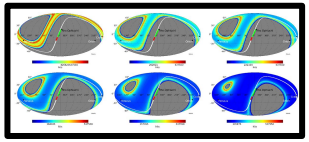
Simons Observatory

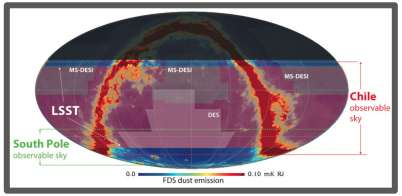
LiteBIRD



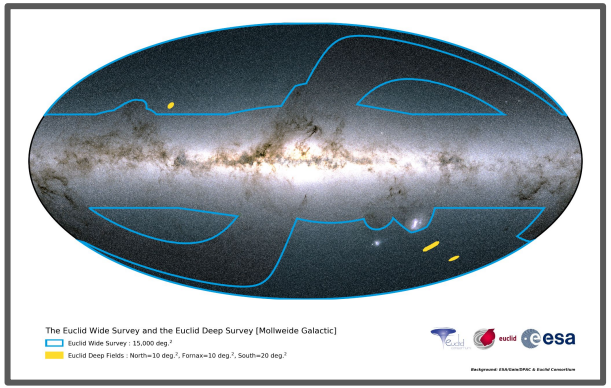
CMB-S4
Next Generation CMB Experiment

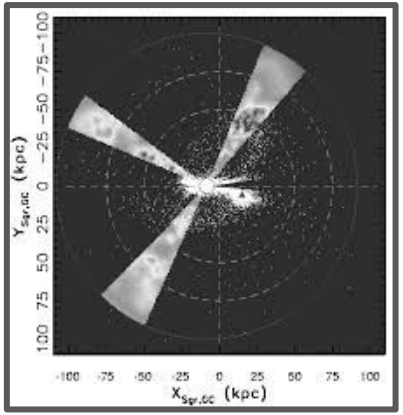
Low Frequency Surveys





Roadmap





2024

2030+

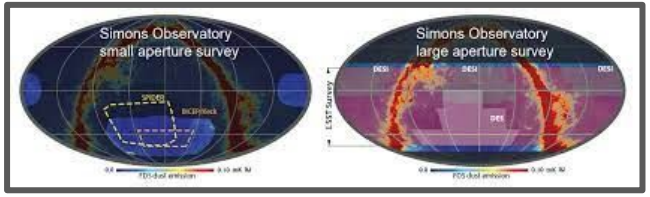
Atacama Cosmology Telescope

SPT

SIMONS ARRAY

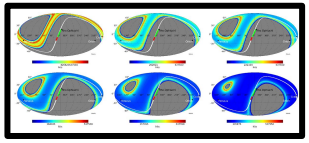
Simons Observatory

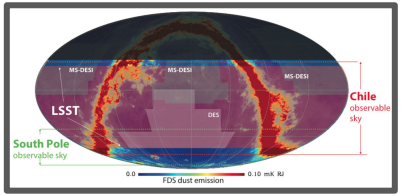
LiteBIRD



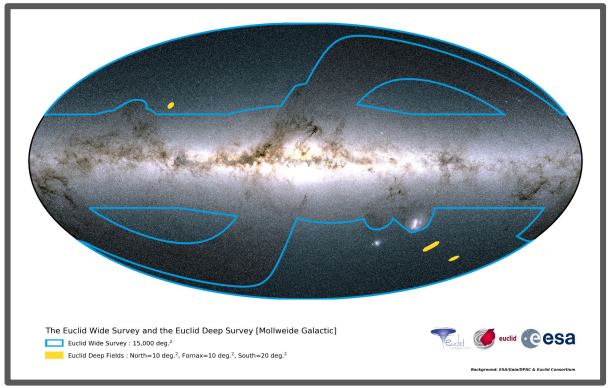
CMB-S4
Next Generation CMB Experiment

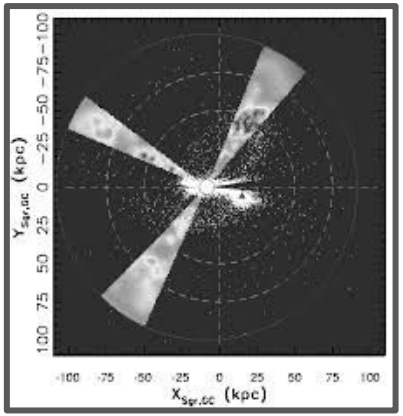
Low Frequency Surveys





Roadmap





2024

2030+

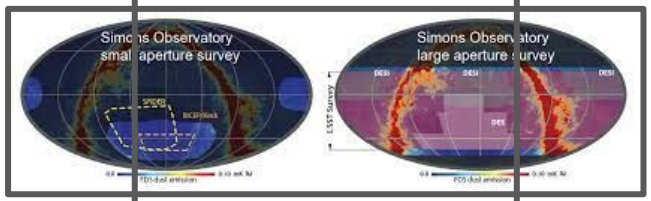
Atacama Cosmology Telescope

SPT

SIMONS ARRAY

Simons Observatory

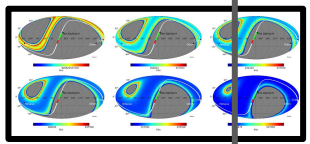
LiteBIRD

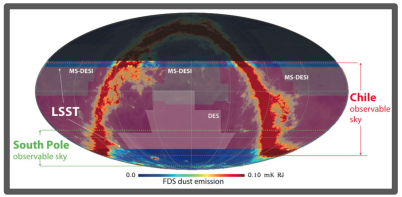


CMB-S4

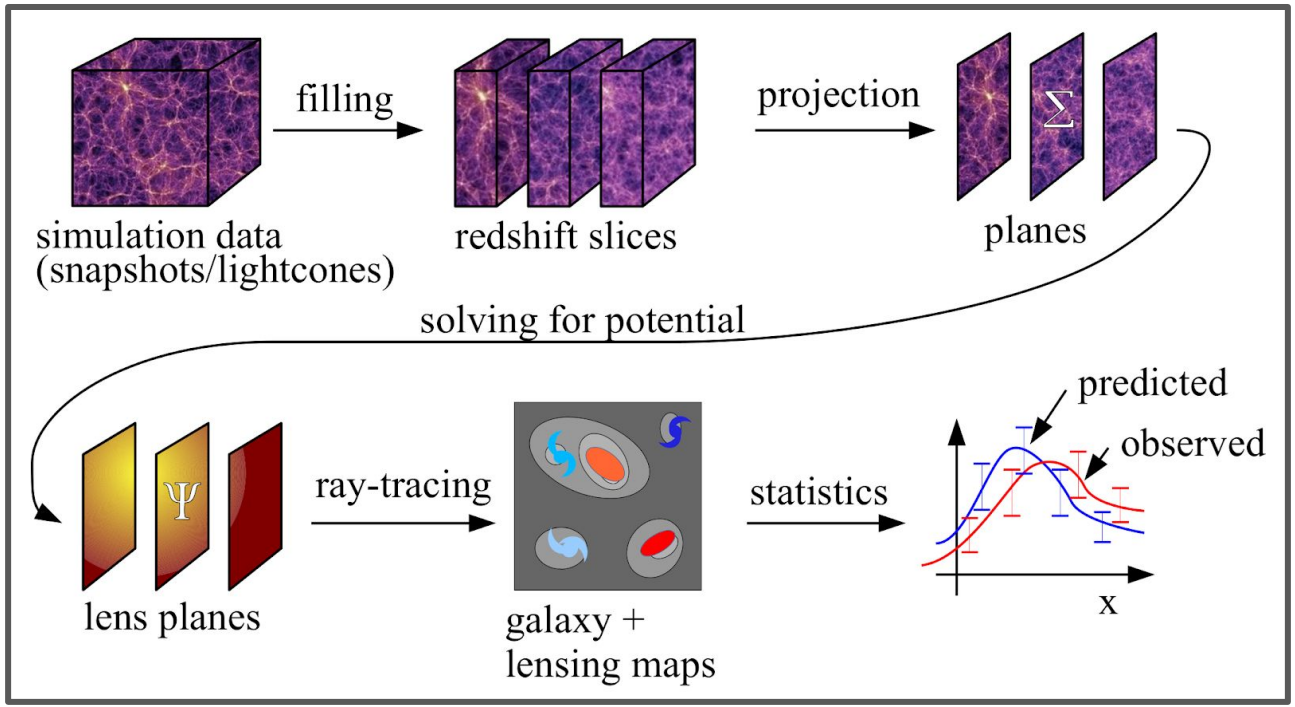
Next Generation CMB Experiment

Low Frequency Surveys



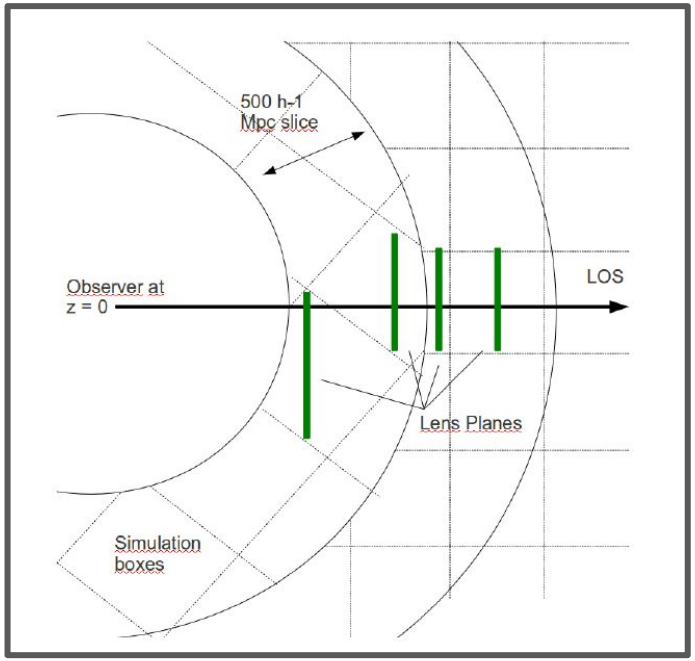


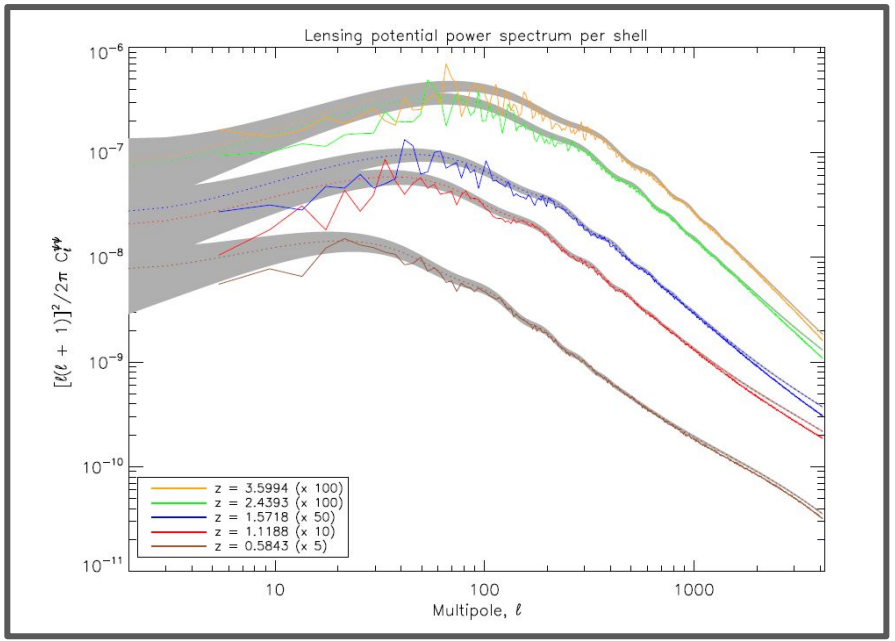
Euclid CMBXC: CMB-N-Body Pipeline



Euclid CMBXC Working Group, Simulations & Covariance Key Project

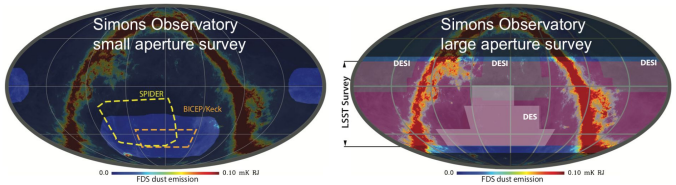
Euclid CMBXC: CMB-N-Body Pipeline

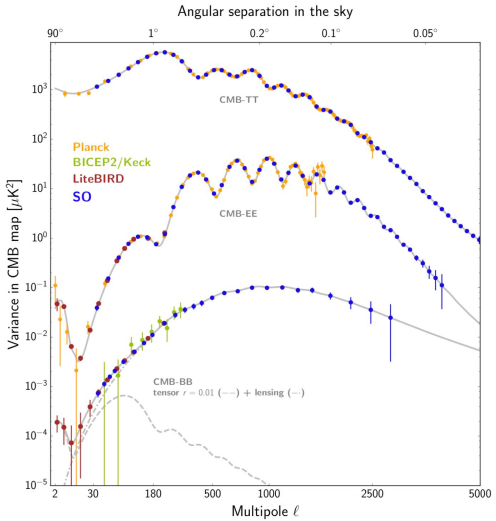


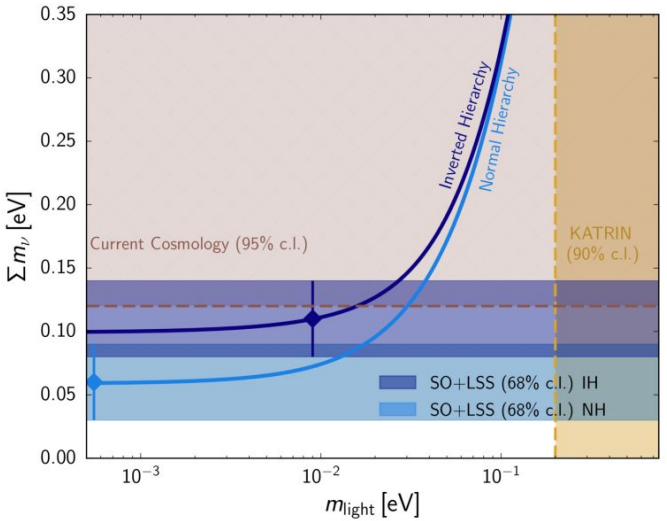


Euclid CMBXC Working Group, Simulations & Covariance Key Project

Operating B-Mode Probes: Simons Observatory

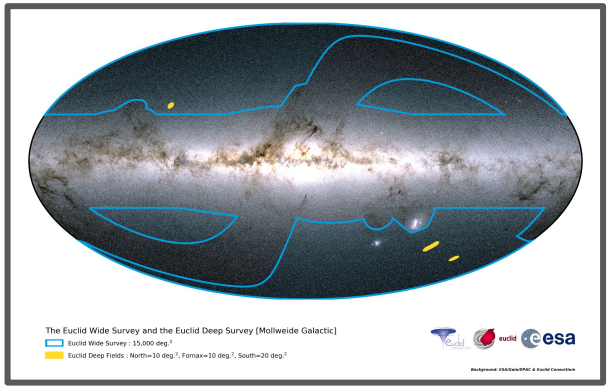


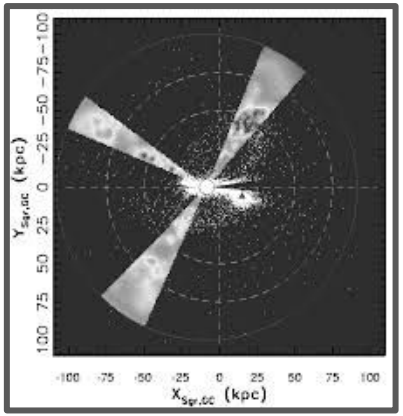




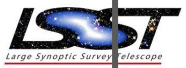
simonsobservatory.org

Roadmap





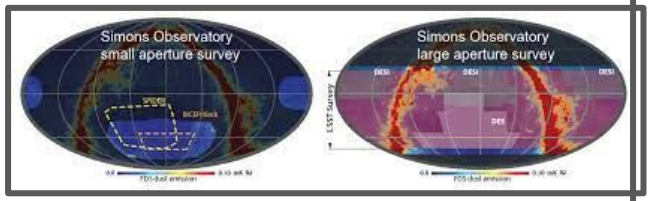
2024



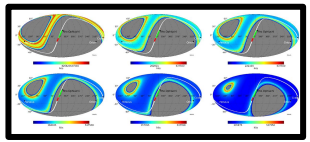
2030+

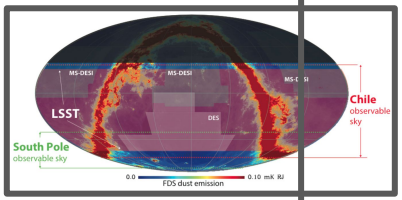
Simons Observatory

LiteBIRD

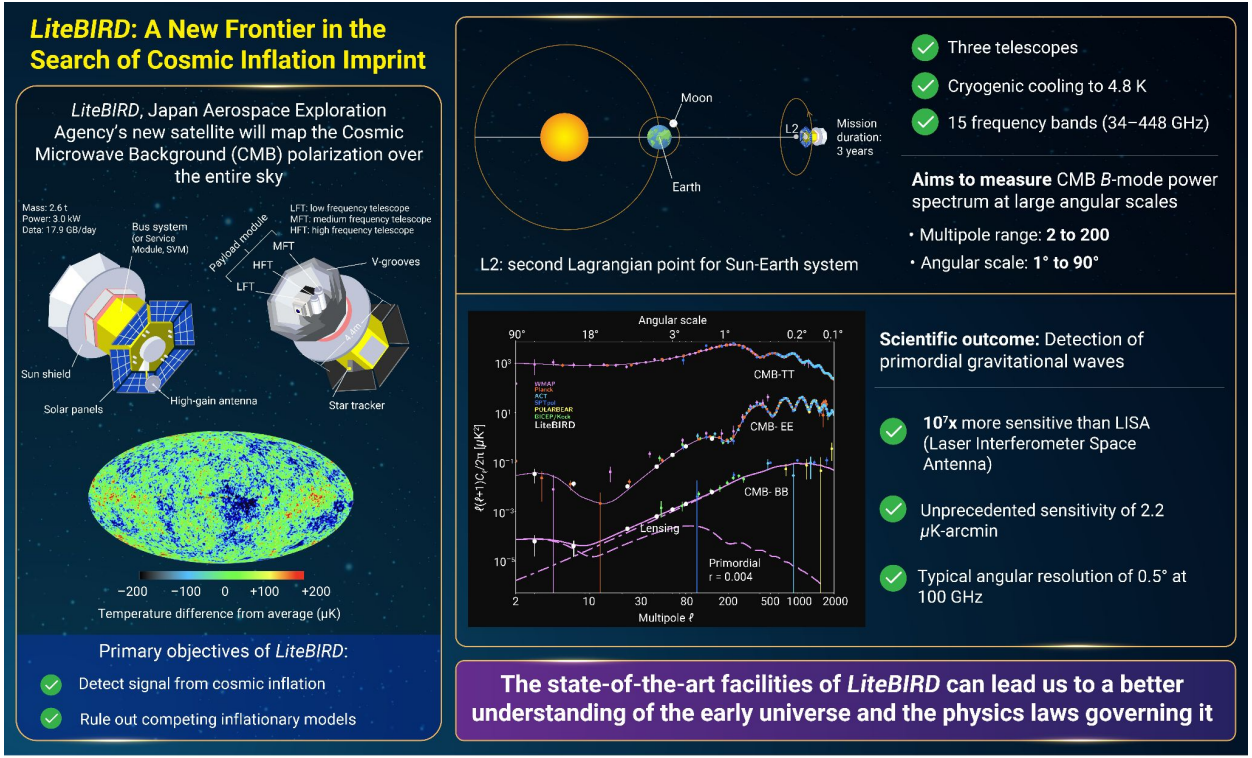


Low Frequency Surveys





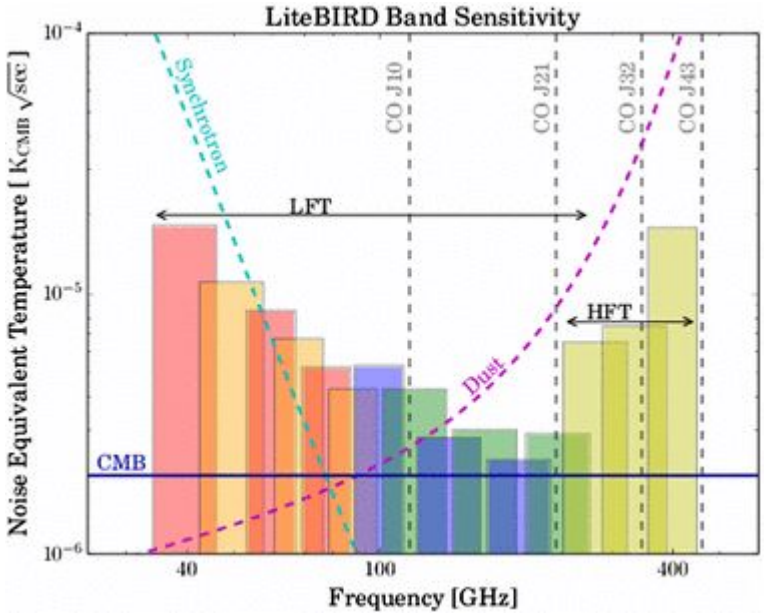
Future B-Mode Probes: LiteBIRD

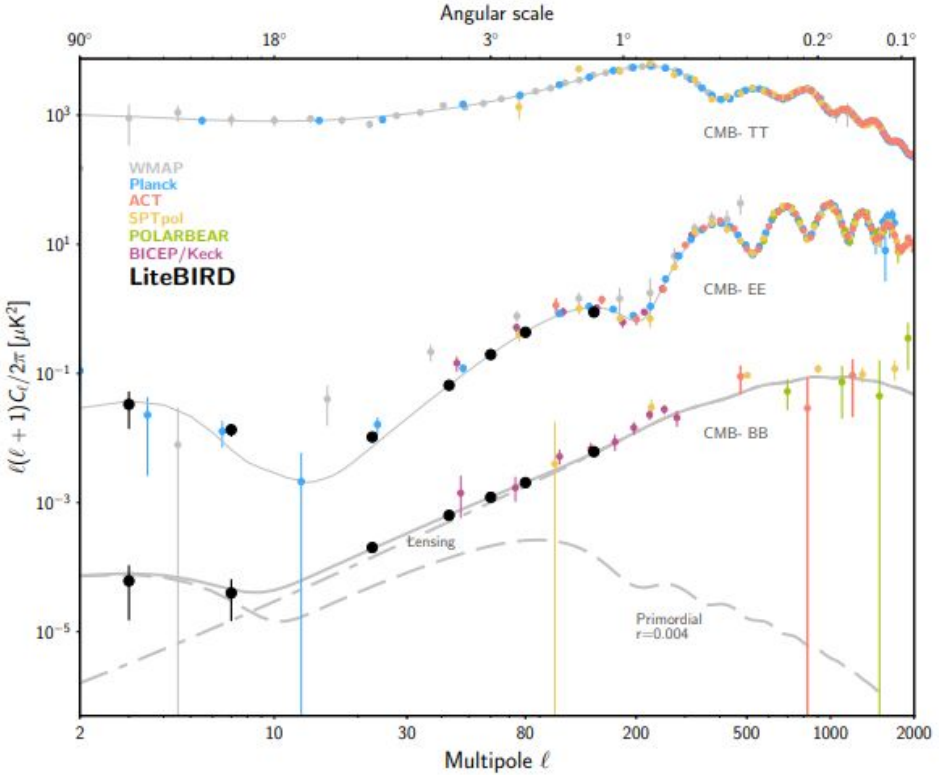


Probing Cosmic Inflation with the *LiteBIRD* Cosmic Microwave Background Polarization Survey
LiteBIRD Collaboration (2022) | *Progress of Theoretical and Experimental Physics* | DOI: 10.1093/ptep/ptac150

PTEP Progress of Theoretical and Experimental Physics

Future B-Mode Probes: LiteBIRD

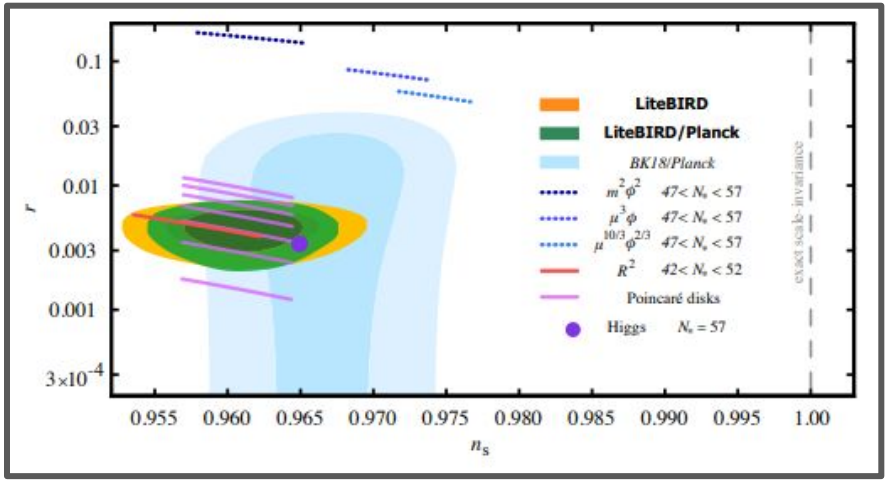


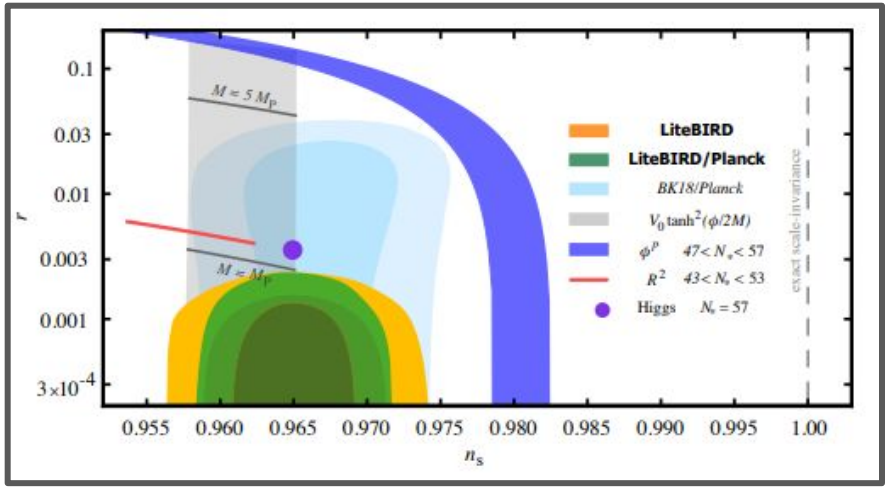


LiteBIRD Collaboration, PTEP 2022

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

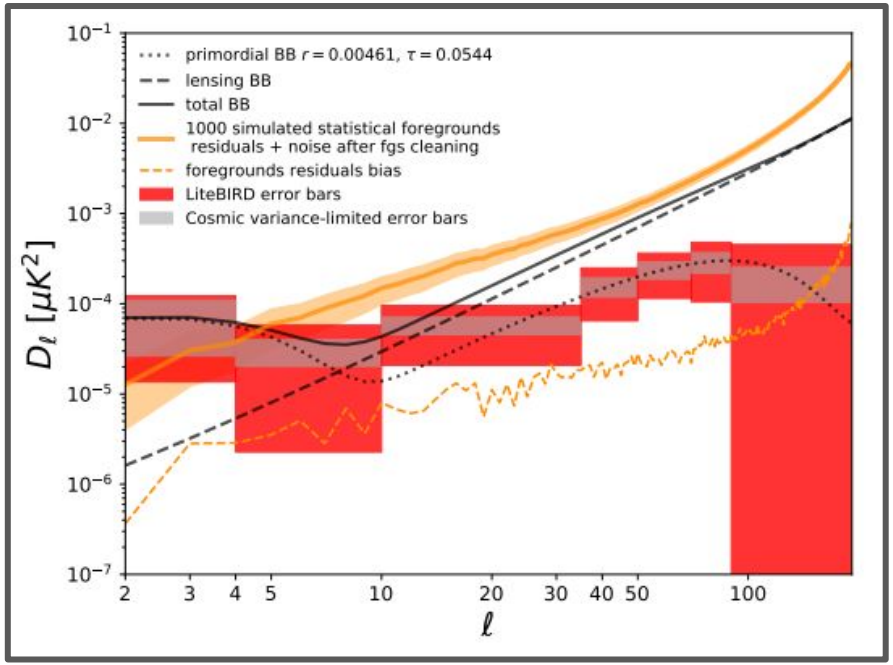
Future B-Mode Probes: LiteBIRD





LiteBIRD Collaboration, PTEP 2022
ui.adsabs.harvard.edu/abs/arXiv:2202.02773

Future B-Mode Probes: LiteBIRD

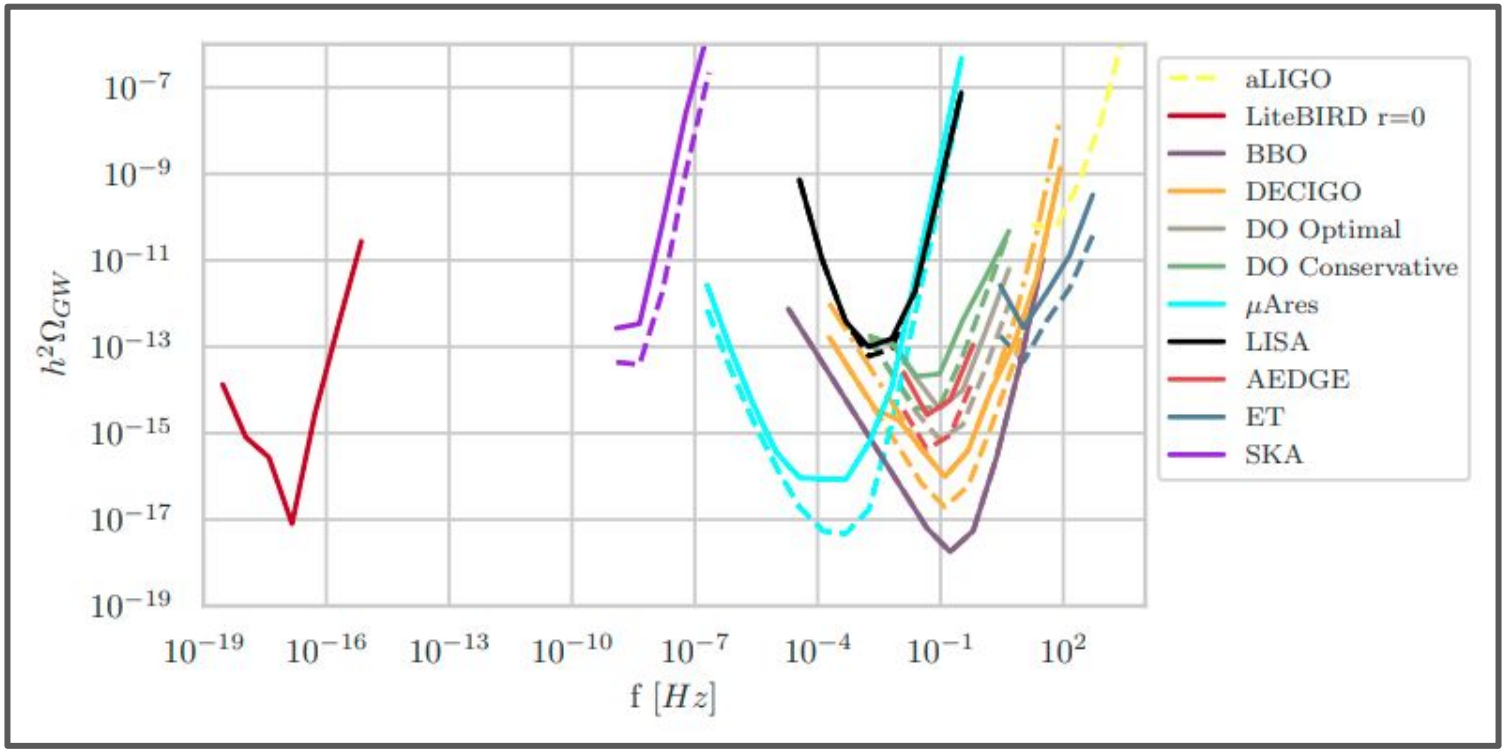


	ID	ν [GHz]	$\delta\nu$ [GHz] ($\delta\nu/\nu$)	Beam size [arcmin]	No. of detectors	NET$_{arr}$ [$\mu K\sqrt{s}$]	Sensitivity [μK-arcmin]
LFT	1	40	12 (0.30)	70.5	48	18.50	37.42
LFT	2	50	15 (0.30)	58.5	24	16.54	33.46
LFT	3	60	14 (0.23)	51.1	48	10.54	21.31
LFT	4	68	16 (0.23)	(41.6, 47.1)	(144, 24)	(9.84, 15.70)	(19.91, 31.77)
comb.						8.34	16.87
LFT	5	78	18 (0.23)	(36.9, 43.8)	(144, 48)	(7.69, 9.46)	(15.55, 19.13)
comb.						5.97	12.07
LFT	6	89	20 (0.23)	(33.0, 41.5)	(144, 24)	(6.07, 14.22)	(12.28, 28.77)
comb.						5.58	11.30
LFT/	7	100	23 (0.23)	30.2/	144/	5.11/	10.34
MFT				37.8	366	4.19	8.48
comb.						3.24	6.56
LFT/	8	119	36 (0.30)	26.3/	144/	3.8/	7.69
MFT				33.6	488	2.82	5.70
comb.						2.26	4.58
LFT/	9	140	42 (0.30)	23.7/	144/	3.58/	7.25
MFT				30.8	366	3.16	6.38
comb.						2.37	4.79
MFT	10	166	50 (0.30)	28.9	488	2.75	5.57
MFT/	11	195	59 (0.30)	28.0/	366/	3.48/	7.05
HFT				28.6	254	5.19	10.50
comb.						2.89	5.85
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

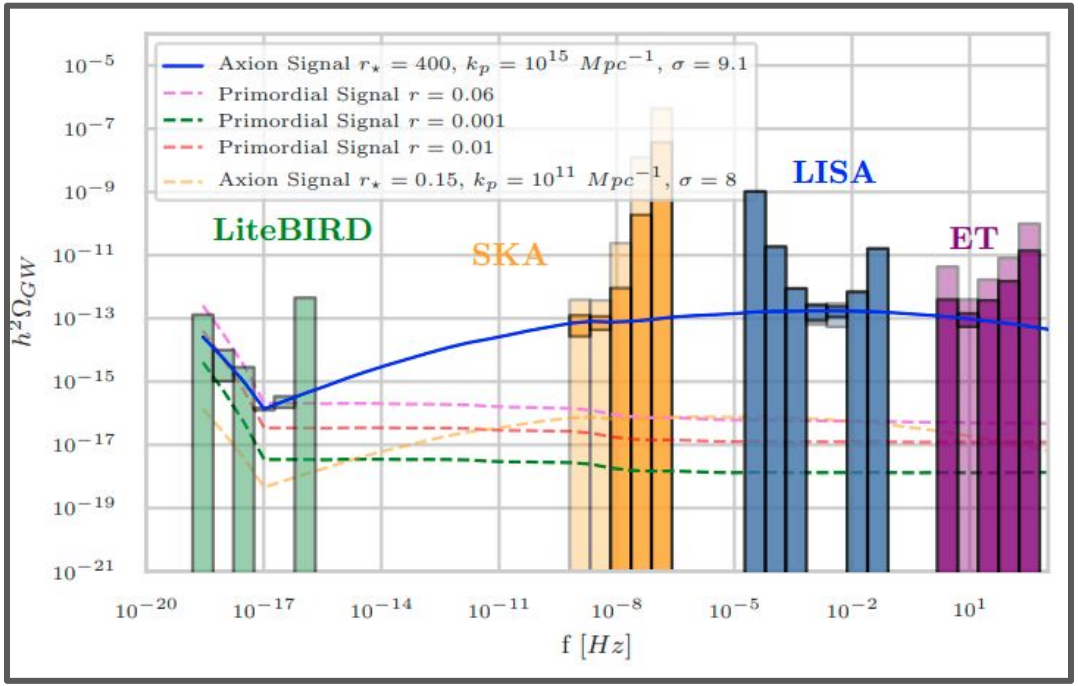
ui.adsabs.harvard.edu/abs/arXiv:2202.02773

Future B-Mode Probes: LiteBIRD



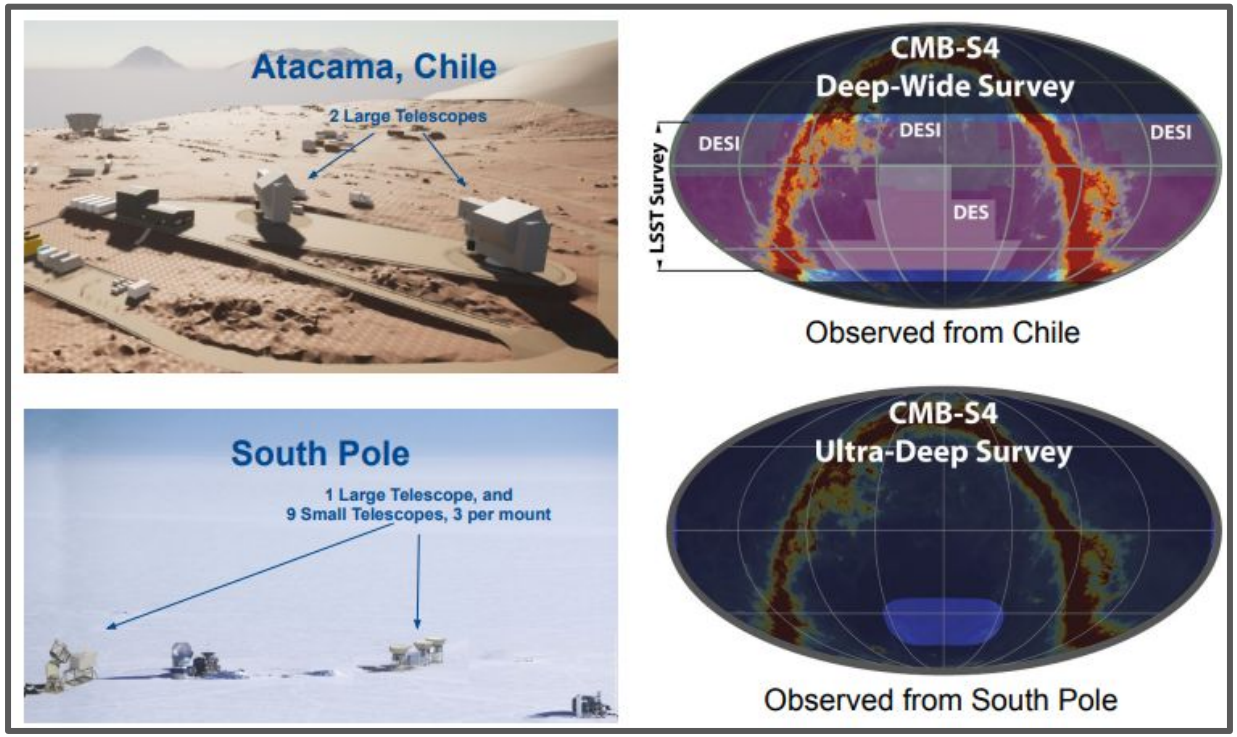
Campeti, Komatsu, Poletti, Baccigalupi, 2021, JCAP 01, 012, arXiv:2007.04241

Future B-Mode Probes: LiteBIRD



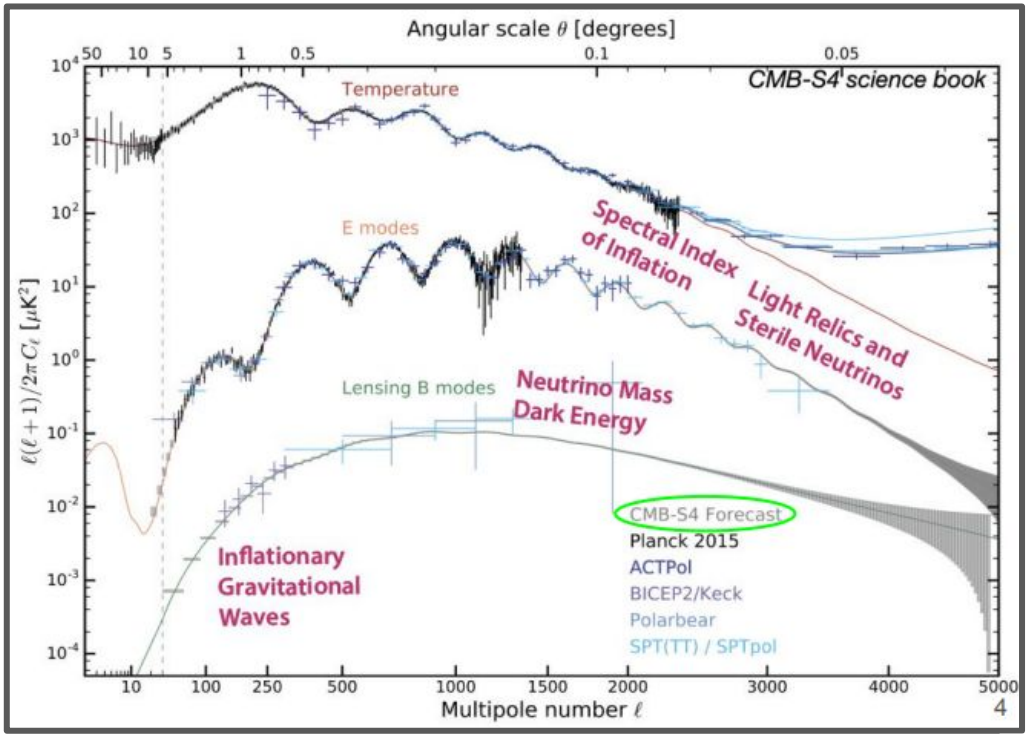
Campeti, Komatsu, Poletti, Baccigalupi et al., 2021, JCAP 01, 012, [arXiv:2007.04241]

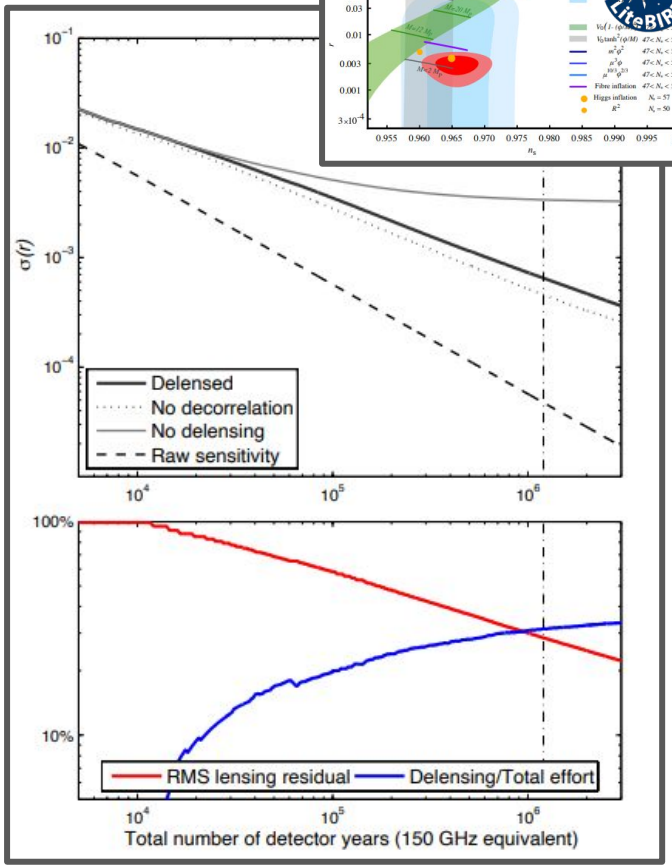
Future B-Mode Probes: CMB-Stage IV



CMB-S4

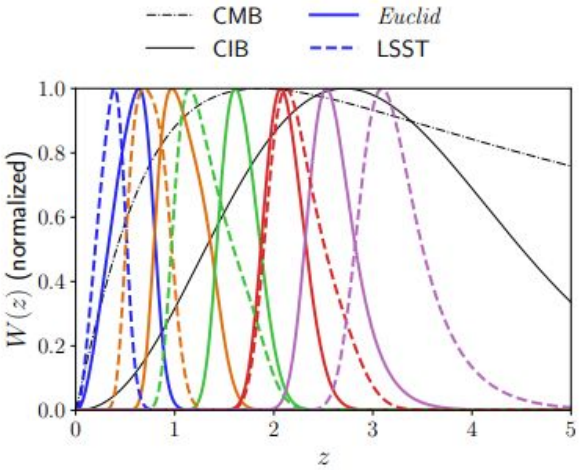
Future B-Mode Probes: CMB-Stage IV

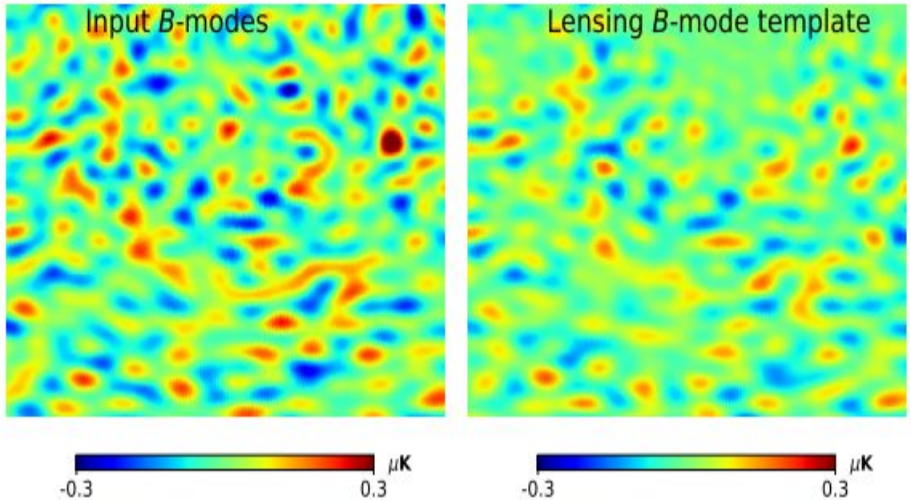




arxiv.org/abs/2208.12619

CMB-Stage IV x LiteBIRD

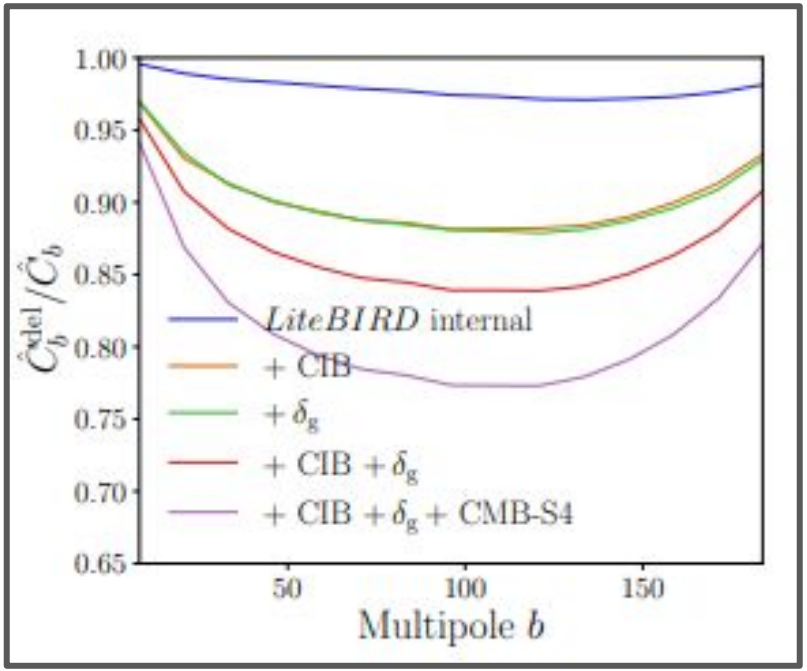




Namiwaka et al. for the LiteBIRD Collaboration
https://ui.adsabs.harvard.edu/abs/2023arXiv231205194N/abstract

CMB-Stage IV x LiteBIRD

	$\sigma(r) \times 10^3$
No-delensing	1.44
LiteBIRD internal	1.41
+ CIB	1.30
+ δ_g	1.31
+ CIB + δ_g	1.25
+ CIB + δ_g + CMB-S4	1.21



Namiwaka et al. for the LiteBIRD Collaboration
https://ui.adsabs.harvard.edu/abs/2023arXiv231205194N/abstract

Remarks

- **Combining Probes Rapidly Becoming Main Stream in Cosmology, Leading All Constraints**
- **Incomplete Review in This Talk, Limited to Lensing and Early Universe, All Systems Involved Across the Light Cone, from Galaxies, Clusters, to CMB Polarization from the Early Universe**
- **Challenges**
  - **Computational Resources**
  - **Management of Combined Probes**
  - **Model Dependence on Astrophysics, Dark Energy and Modified Gravity**
  - **Accurate Predictivity and Covariance**
  - **…**
- **Probe Combination is now Infrastructure in Large Collaborations, Organized Efforts involving High Performance Computing are Vital to Collaborations,**
- **Memorandum of Understanding in place and in progress for this and the next Decade**