Statistical Analysis & Exploitation of Sky Maps for Cosmic Microwave Background Observations

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Outline

- Cosmic Microwave Background
- CMB Maps
- Cosmological Gravitational Waves
- Roadmap for Future Observations

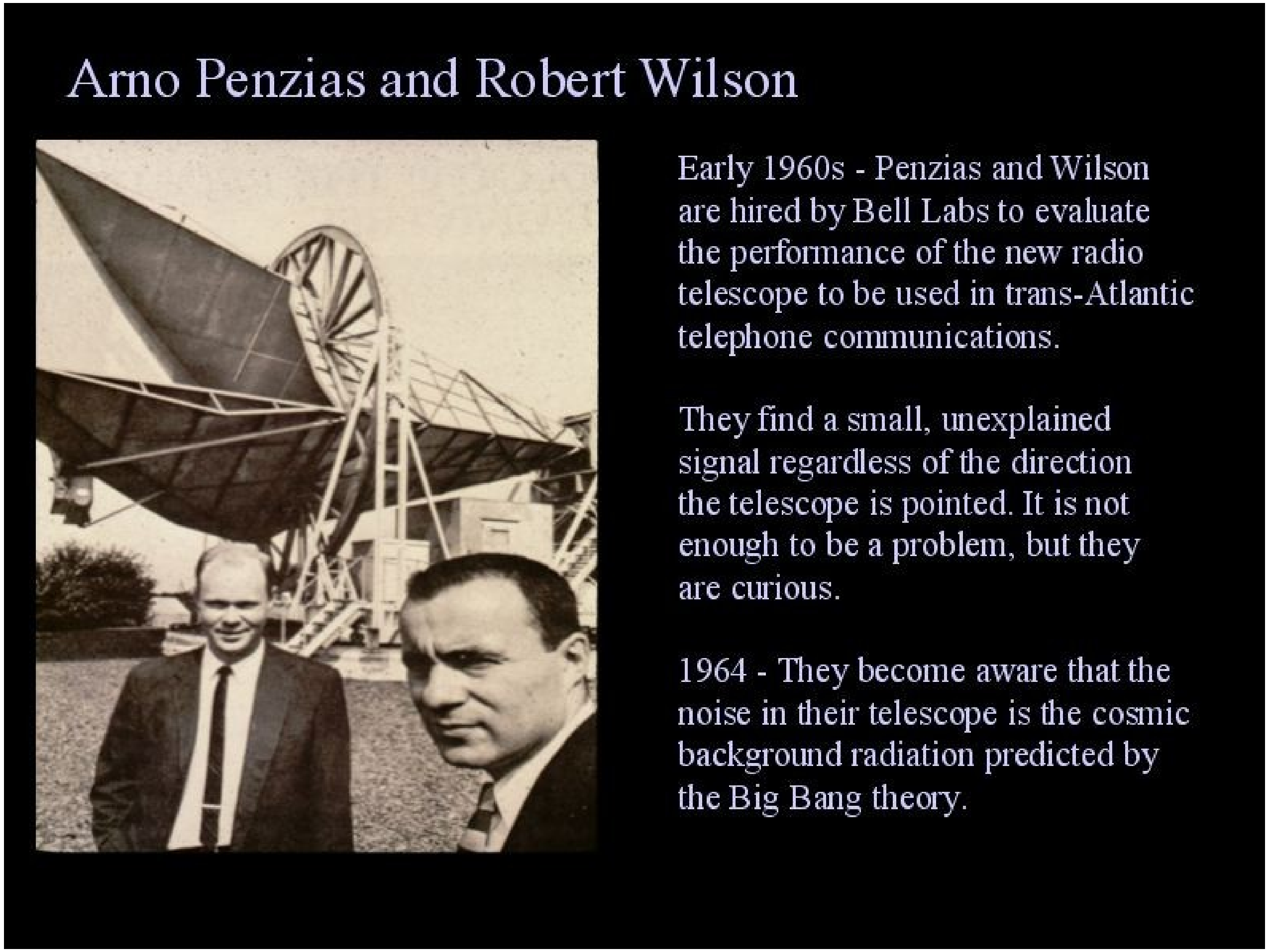
CMB

Primeval Fireball

- compression in the early stages of an expanding universe causes lots of radiation arising from thermonuclear explosions
- Reactions are rapid enough to achieve thermalization and a black body spectrum
- It is possible to compute the rarefaction caused by the expansion since that epoch
- The relic radiation is predicted to peak in microwaves, temperature of a few Kelvin, known today as the Cosmic Microwave Background (CMB, Gamow et al. 1948)

George Gamow, three years old in Odessa, Ukraine, 1907

Discovery



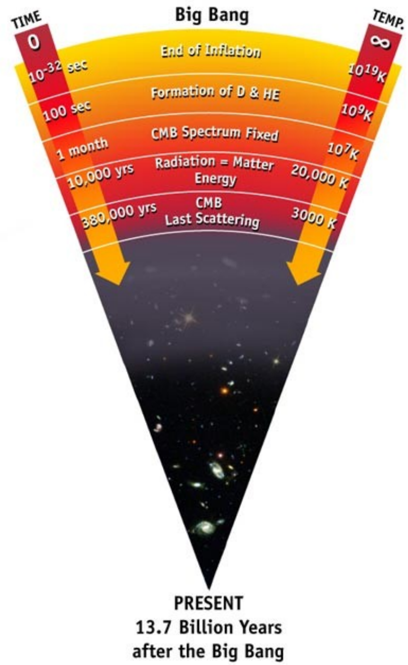
Arno Penzias and Robert Wilson
Early 1960s - Penzias and Wilson are hired by Bell Labs to evaluate the performance of the new radio telescope to be used in trans-Atlantic telephone communications.
They find a small, unexplained signal regardless of the direction the telescope is pointed. It is not enough to be a problem, but they are curious.
1964 - They become aware that the noise in their telescope is the cosmic background radiation predicted by the Big Bang theory.

CMB: where and when?

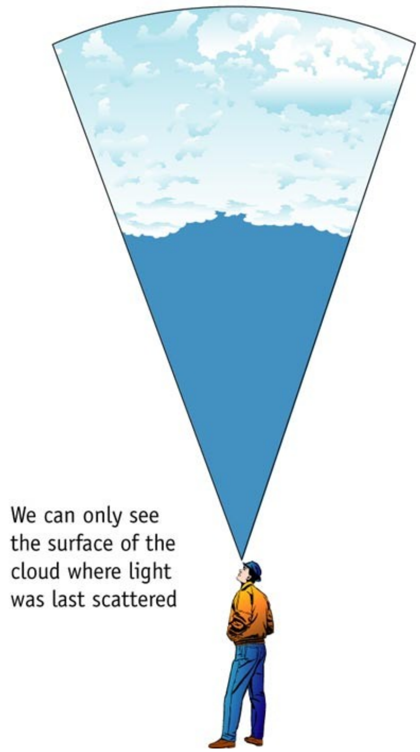
- Opacity:

  λ=1/nσ « horizon

  where the horizon is the distance at which information get at each time, inverse of the Hubble expansion rate
- Decoupling: λ ≈ horizon
- Free streaming: λ » horizon
- Cosmological expansion, Thomson cross section and electron abundance conspire to activate decoupling about 380000 years after the Big Bang, at about 3000 K CMB photon temperature

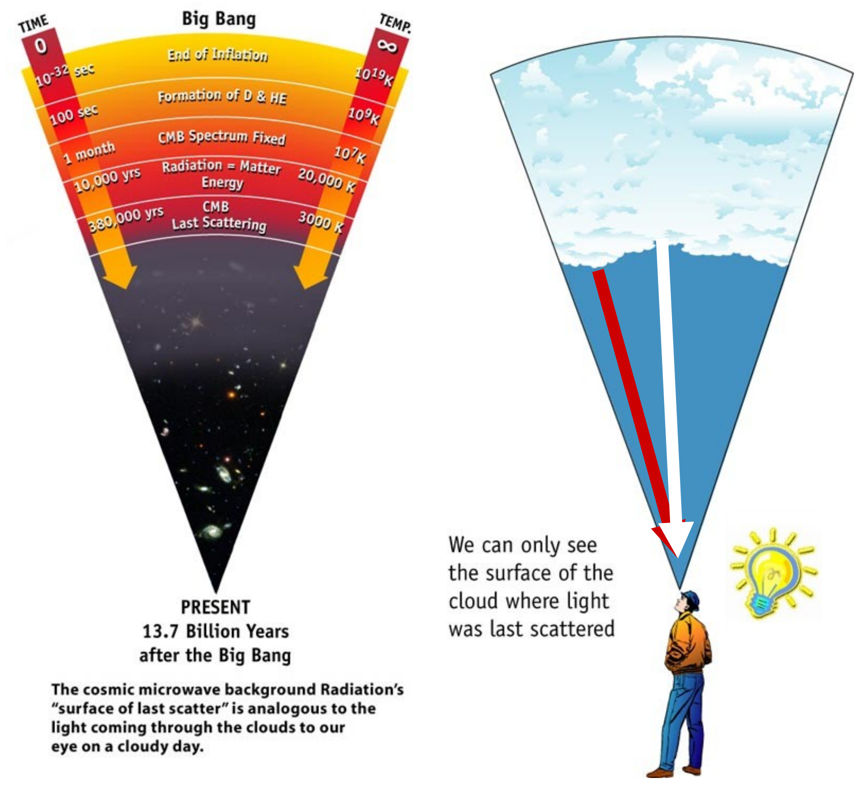


The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.

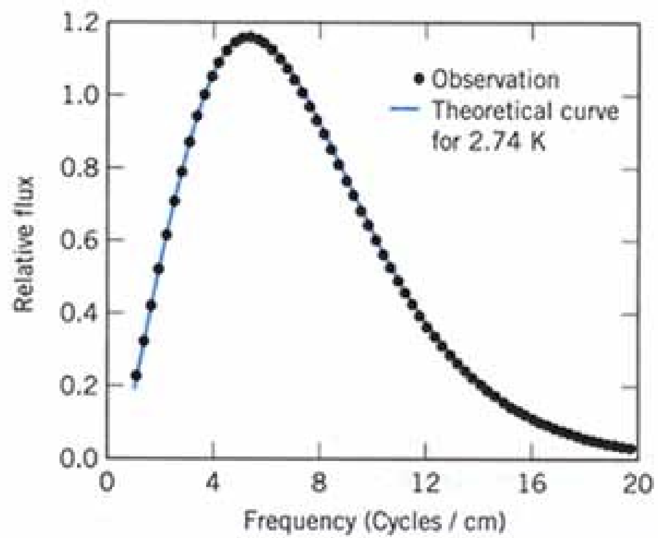


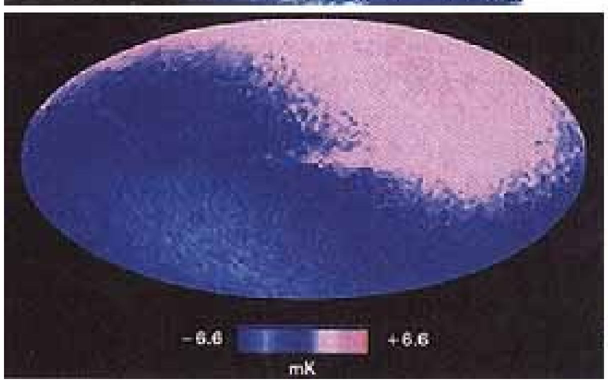
A postcard from the Big Bang

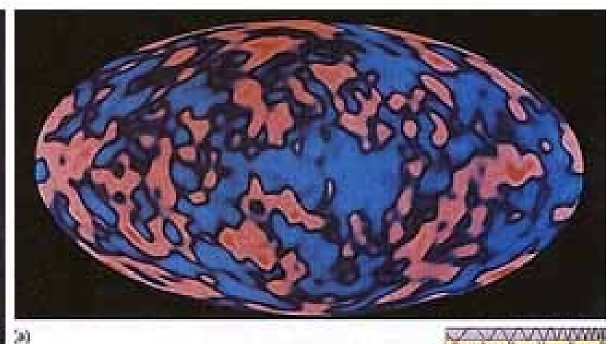
- From the Stephan Boltzmann law, regions at high temperature should carry high density
- The latter is activated by perturbations which are intrinsic of the fluid as well as of spacetime
- Thus, the maps of the CMB temperature is a kind of snapshot of primordial cosmological perturbations



COsmic Background Explorer

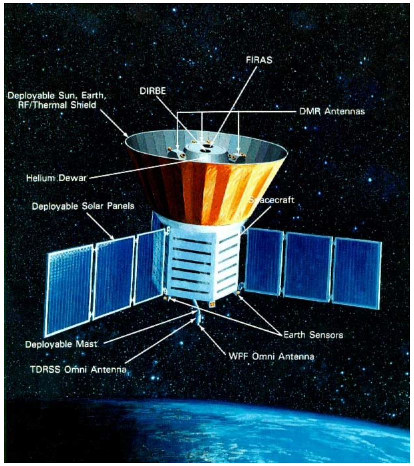


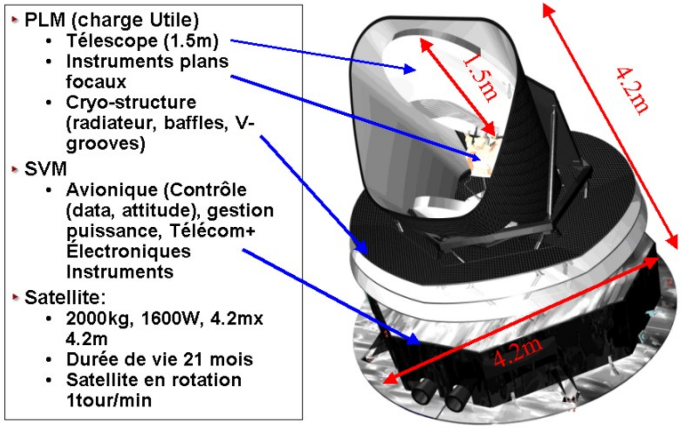


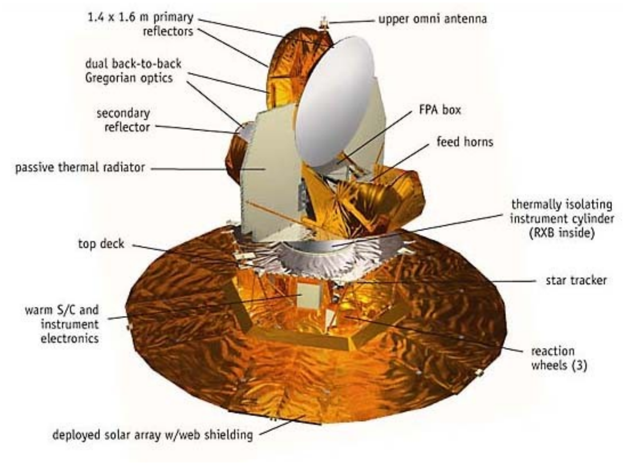


From COBE to the Wilkinson Microwave Anisotropy Probe (WMAP) to Planck

- About 40 years of scientific and technological progresses
- Lots of experiments, people
- See lambda.gfsc.nasa.gov

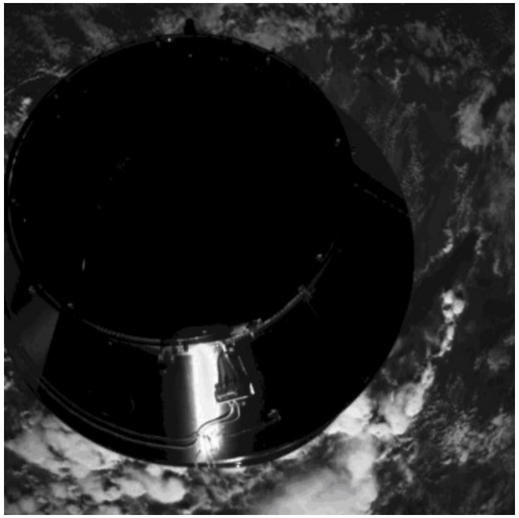


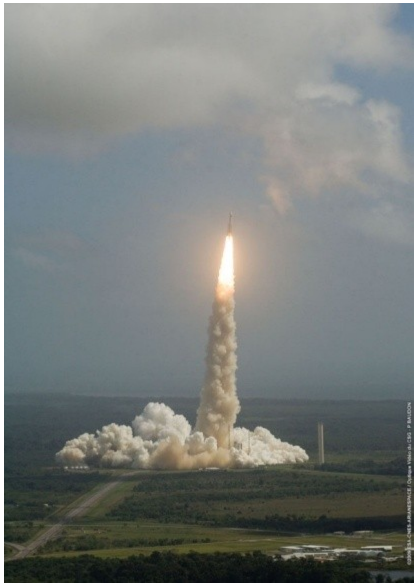


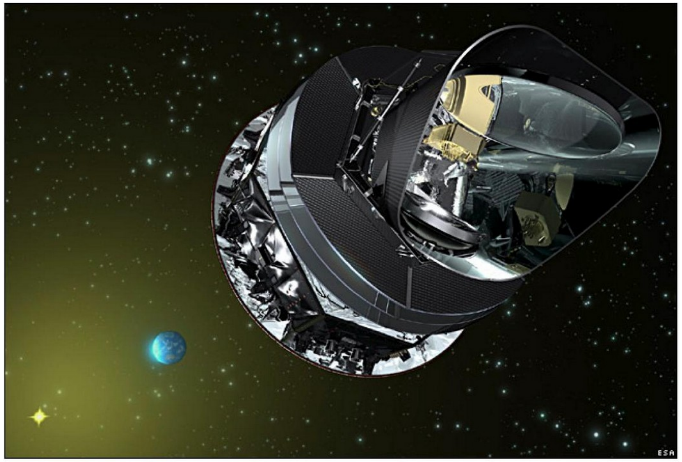


The Planck Satellite

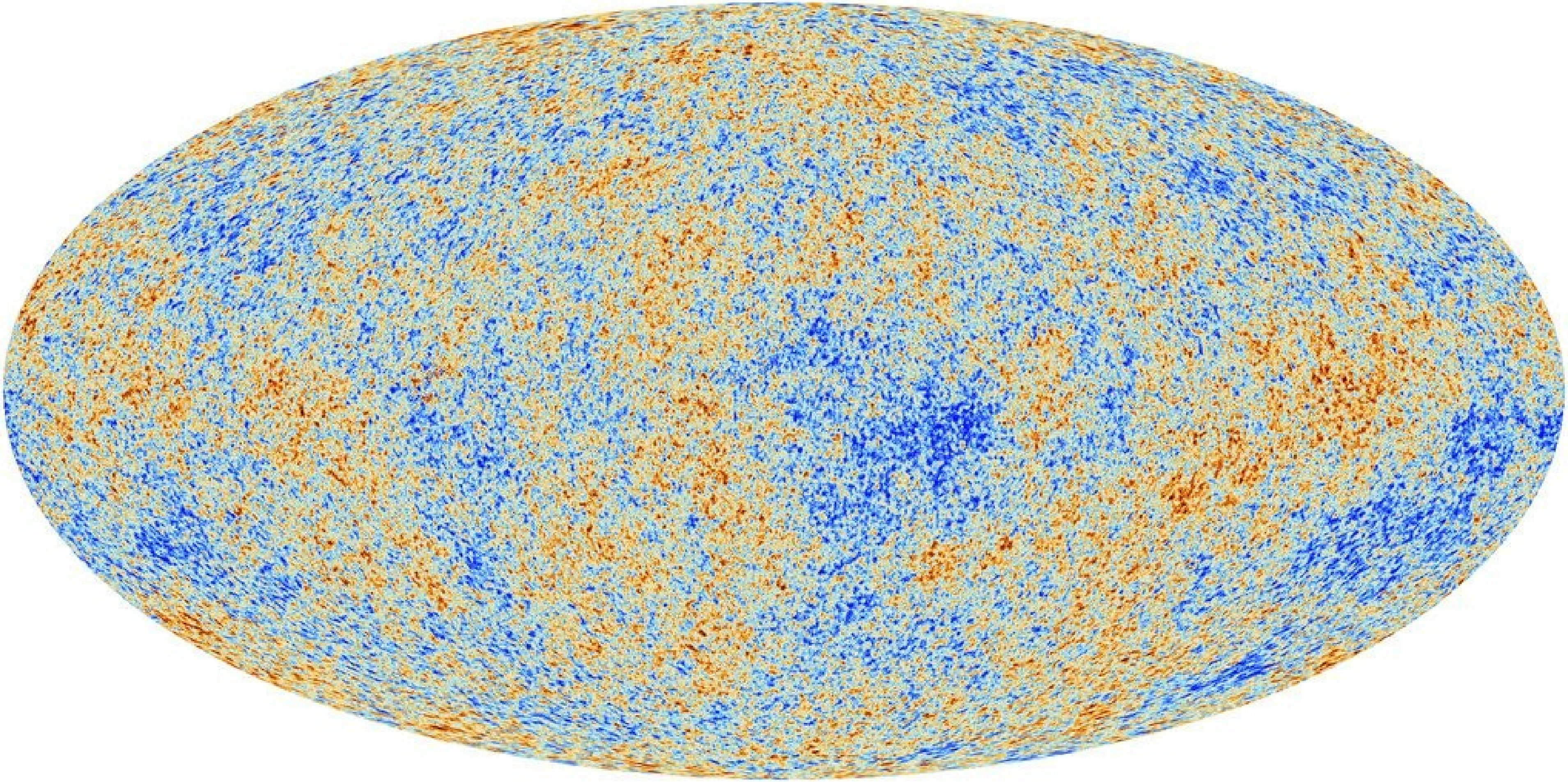
- ESA Medium Size Mission, NASA participation for the construction of part of the cooling systems
- About 400 scientists all over the world
- Two Data Analysis Centers, in Paris (IAP, High Frequency Insteument) and Trieste (INAF-Trieste & SISSA, Low Frequency Instrument)
- About 17 years from the initial ideas to the launch in 2009
- End of operations in 2009
- Data Analysis in progress, two main Data Releases happened in 2013, 2015, the last and definitive one is expected within 2017 or early 2018
- Tens of papers impacting all major aspects of Cosmology, Astrophysics







CMB as seen by Planck



Planck 2018

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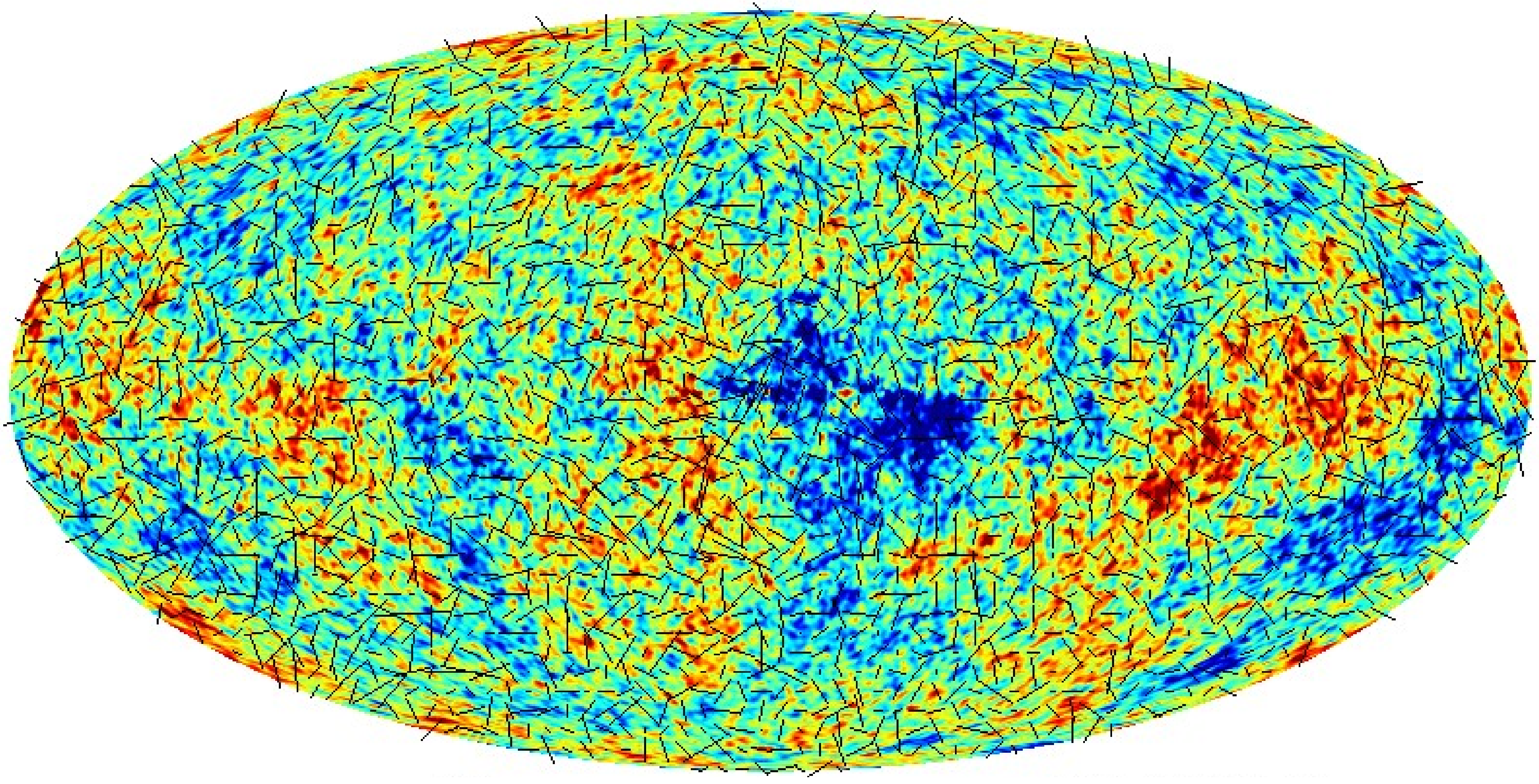
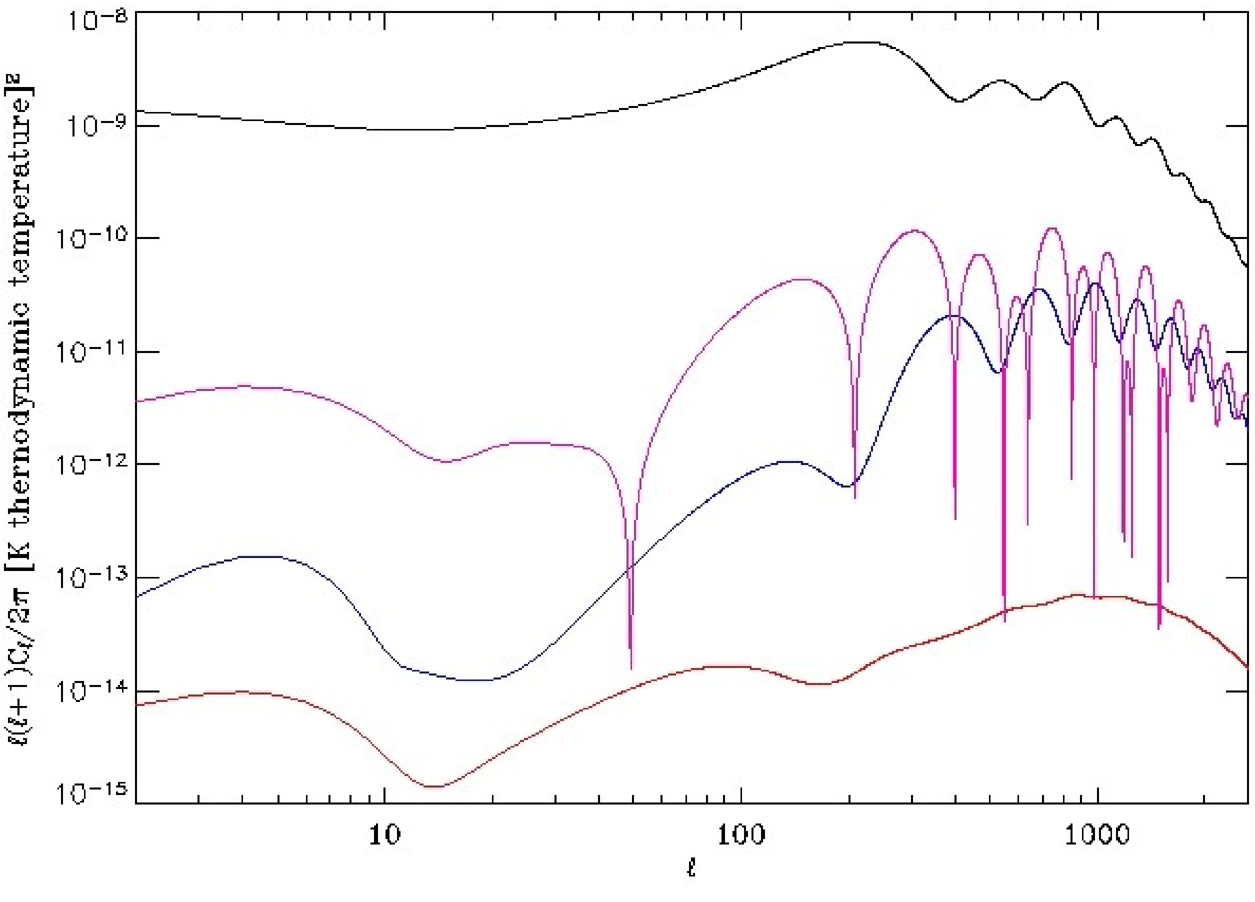


Planck 2018

CMB Angular Power Spectrum



Angle ≈ 200/l Degrees

CMB physics: Boltzmann equation

$$\frac{d\ \text{photons}}{dt} = \text{gravity} + \text{Compton scattering}$$

$$\frac{d\ \text{baryons+leptons}}{dt} = \text{gravity} + \text{Compton scattering}$$

CMB physics: Boltzmann equation

$$\frac{d\ \text{neutrinos}}{dt} = \text{gravity} + \text{weak interaction}$$

$$\frac{d\ \text{dark matter}}{dt} = \text{gravity} + \text{weak interaction (?)}$$

CMB physics: Boltzmann equation

$$\frac{d\ \text{neutrinos}}{dt} = \text{gravity} + \text{weak interaction}$$

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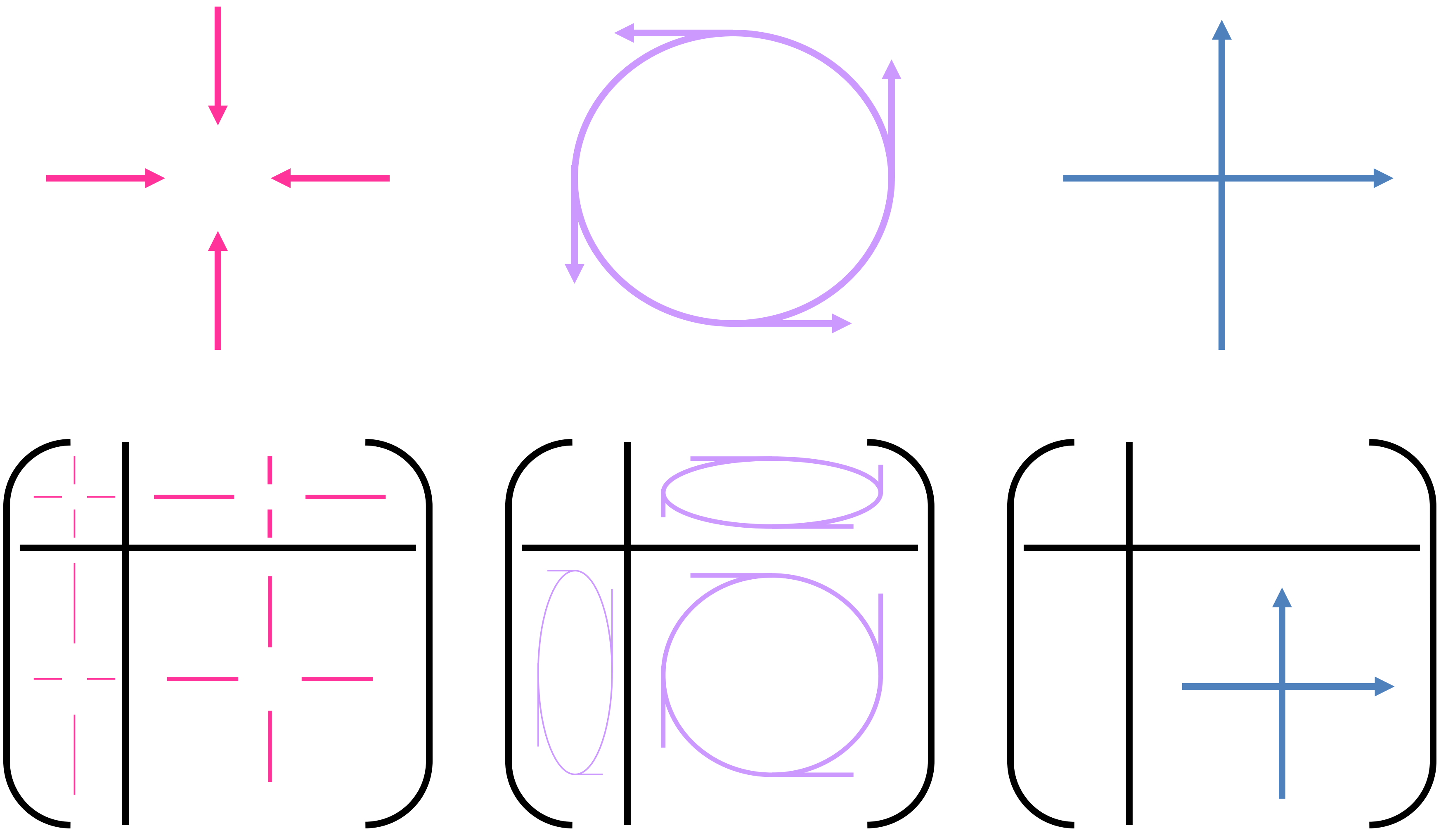
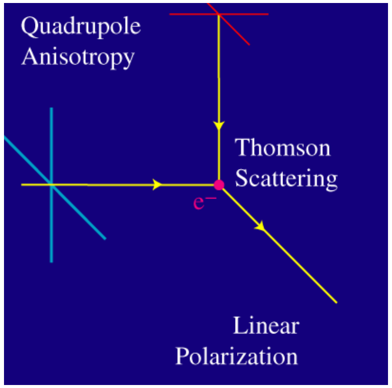
gravity = photons + neutrinos + baryons + leptons + dark matter

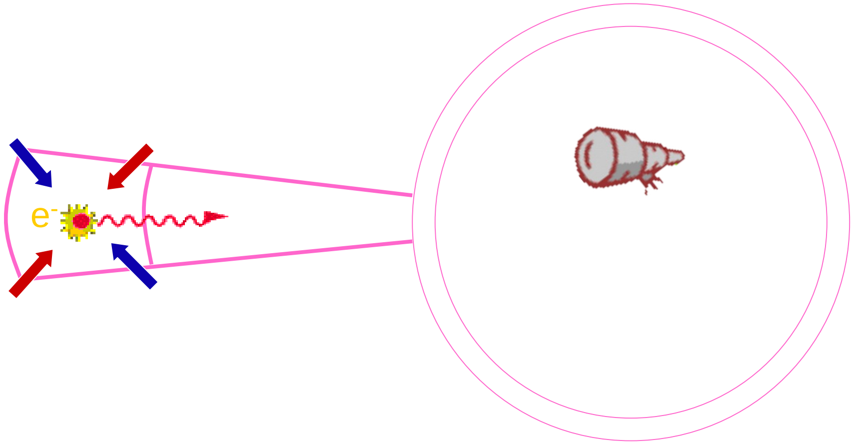
CMB physics: gravity



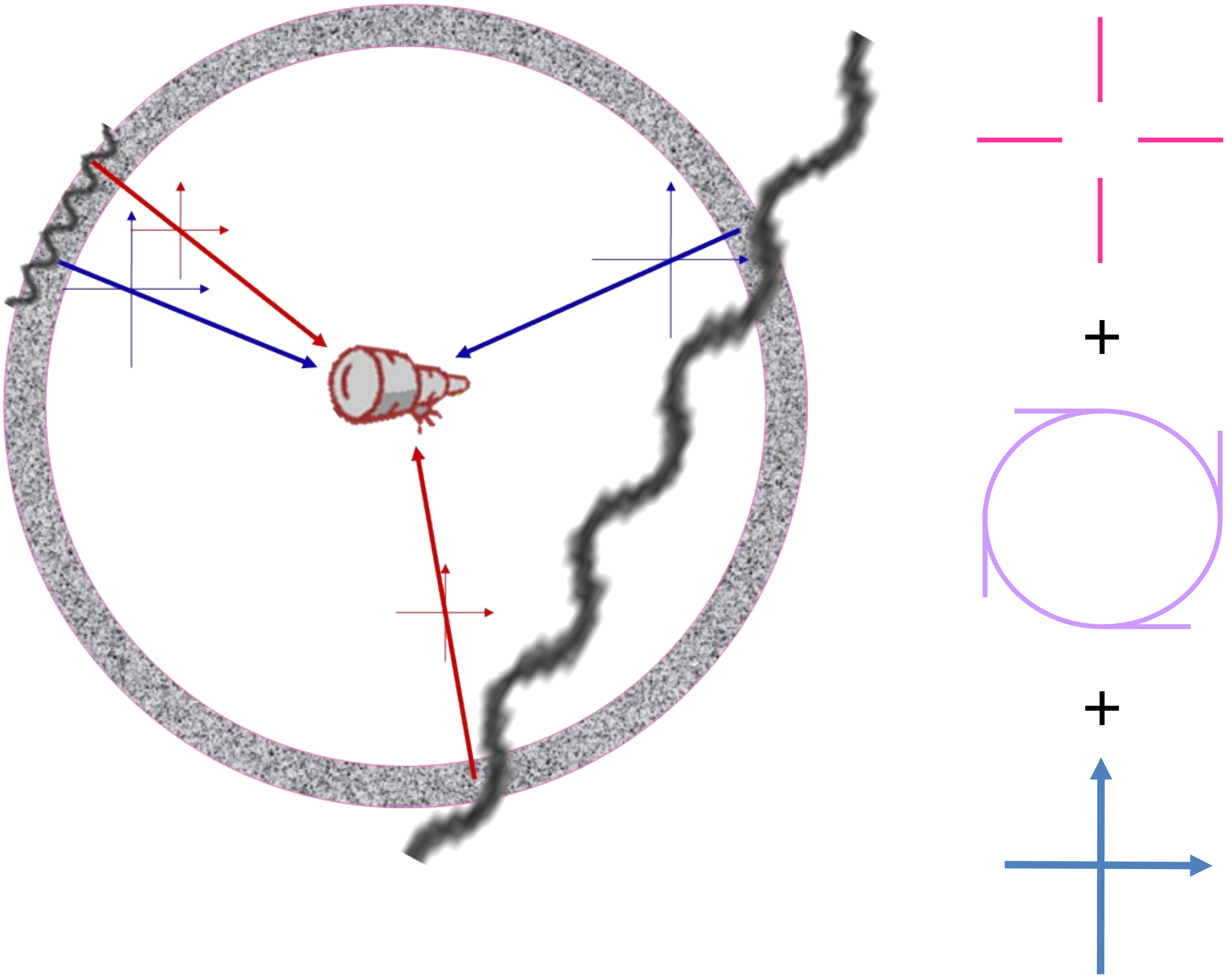
CMB Physics: Compton scattering

- Compton scattering is anisotropic
- An anisotropic incident intensity determines a linear polarization in the outgoing radiation
- At decoupling that happens due to the finite width of last scattering and the cosmological local quadrupole

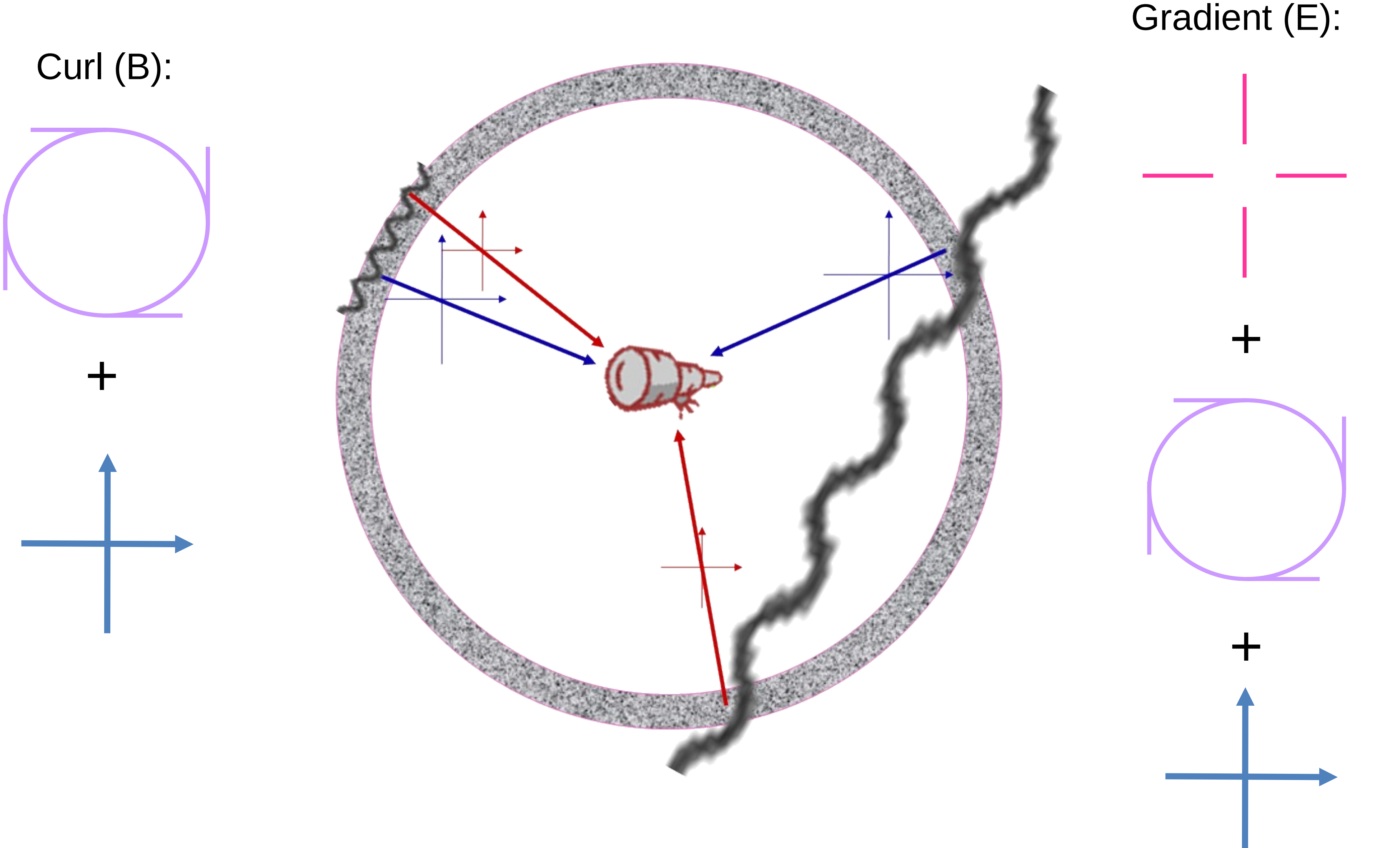


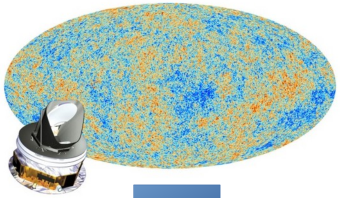


CMB anisotropy: Total Intensity



CMB anisotropy: polarization





Anisotropies

$T(\theta,\varphi)$, $Q(\theta,\varphi)$, $U(\theta,\varphi)$, $V(\theta,\varphi)$

spherical
harmonics

$$X(\theta,\varphi)=\Sigma_{lm}\, a_{lm}^{X}\, Y^{s}_{lm}(\theta,\varphi)$$

$X=T,E,B$

$s=0$ for T, 2 for Q and U

E and B modes have opposite parity

Angular power spectrum

$T(\theta,\varphi)$, $Q(\theta,\varphi)$, $U(\theta,\varphi)$, $V(\theta,\varphi)$

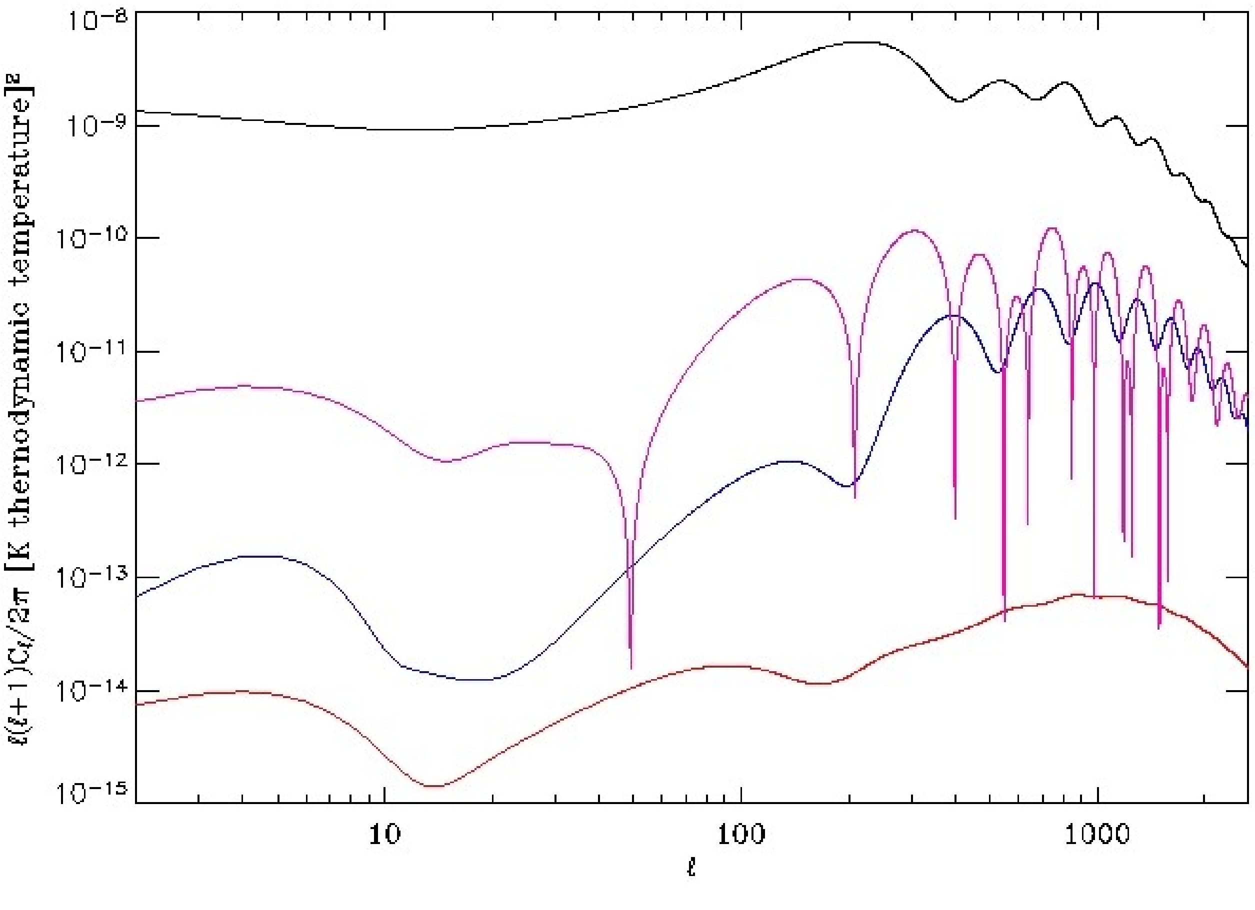
spherical harmonics

a^X_{lm}, $X=T,E,B$

Lossy compression

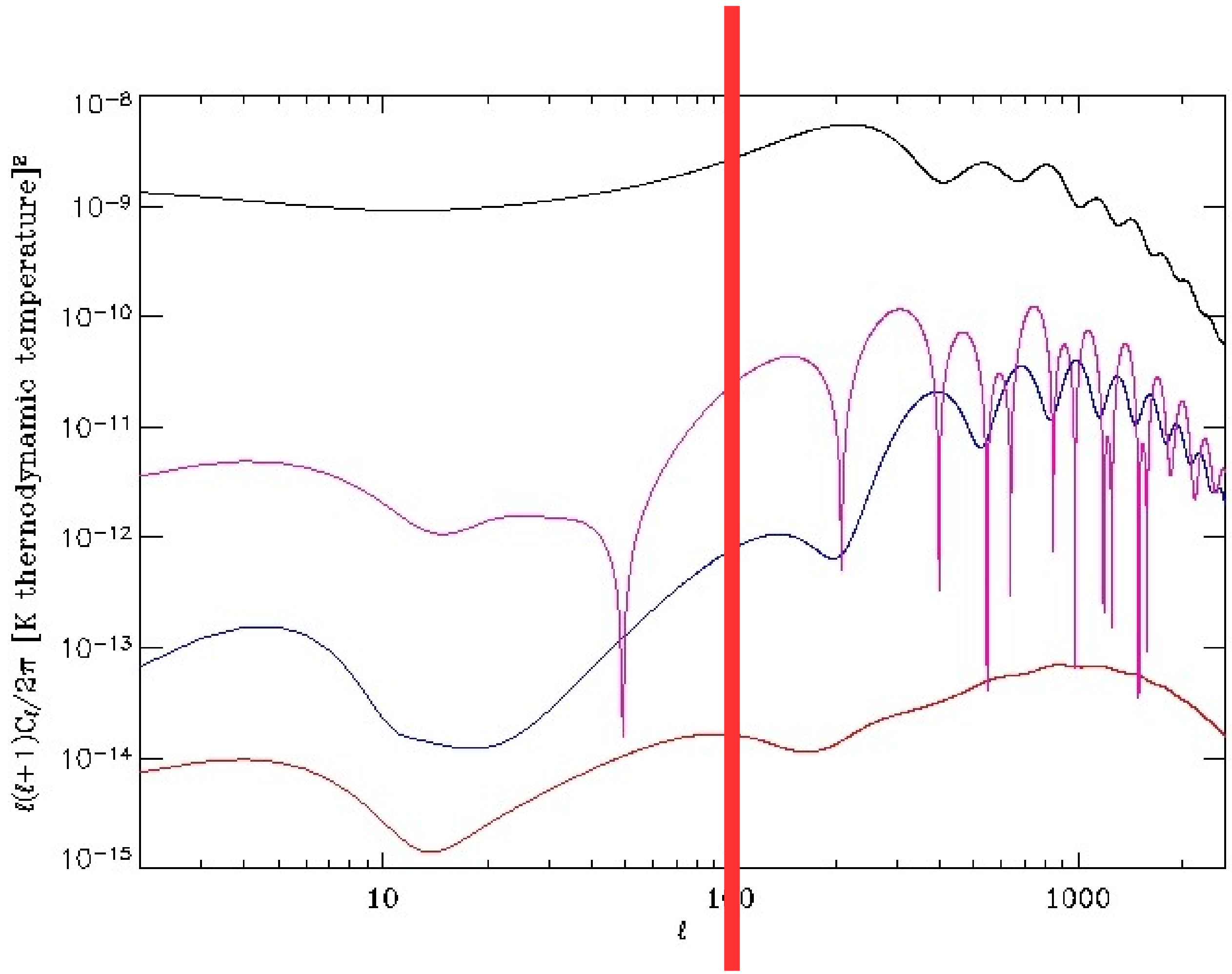
$C_{l=}\Sigma_m [(a_{lm}{}^X)(a_{lm}{}^Y)^*]/(2l+1)$

CMB angular power spectrum



Angle ≈ 200/l degrees

CMB angular power spectrum

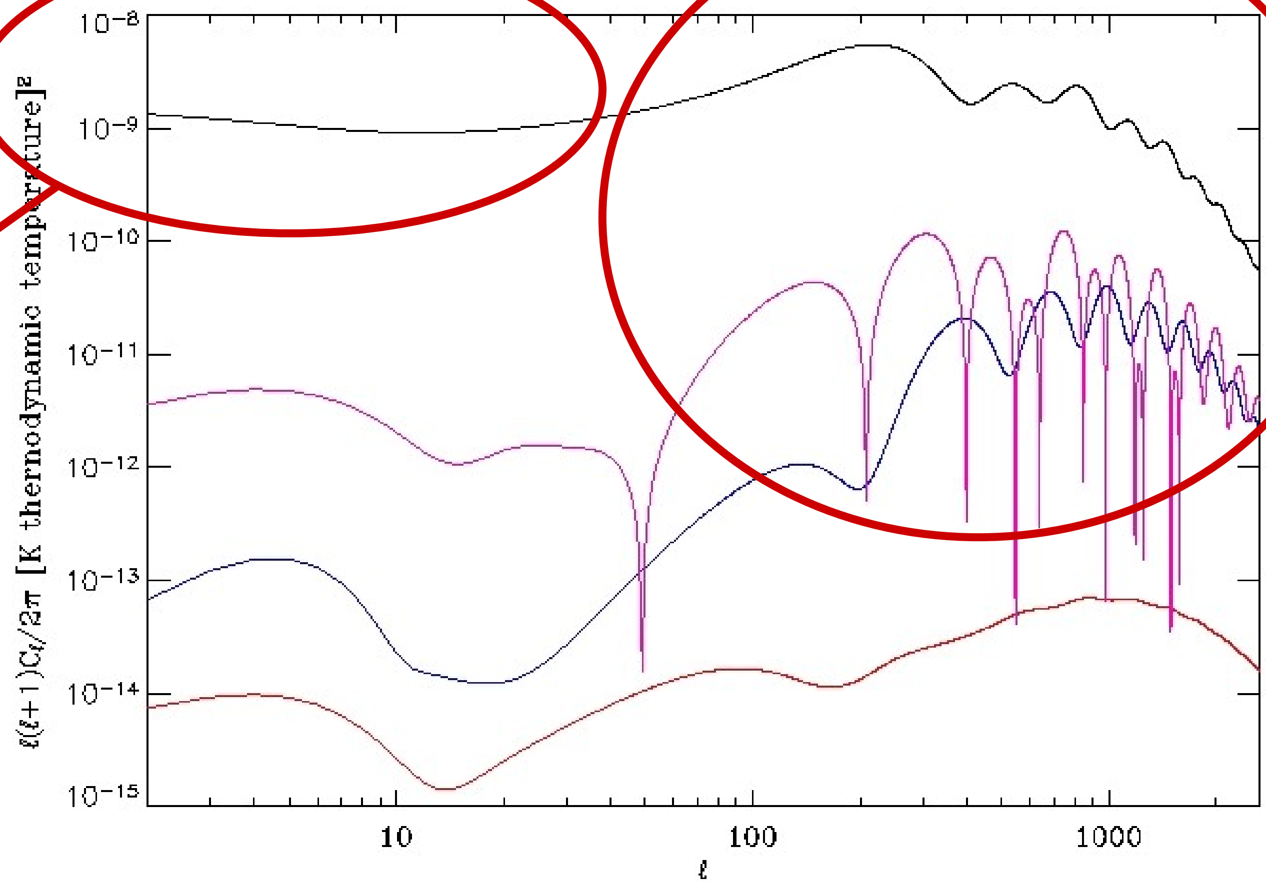


Angle ≈ 200/l degrees

CMB angular power spectrum

Acoustic oscillations

Primordial power



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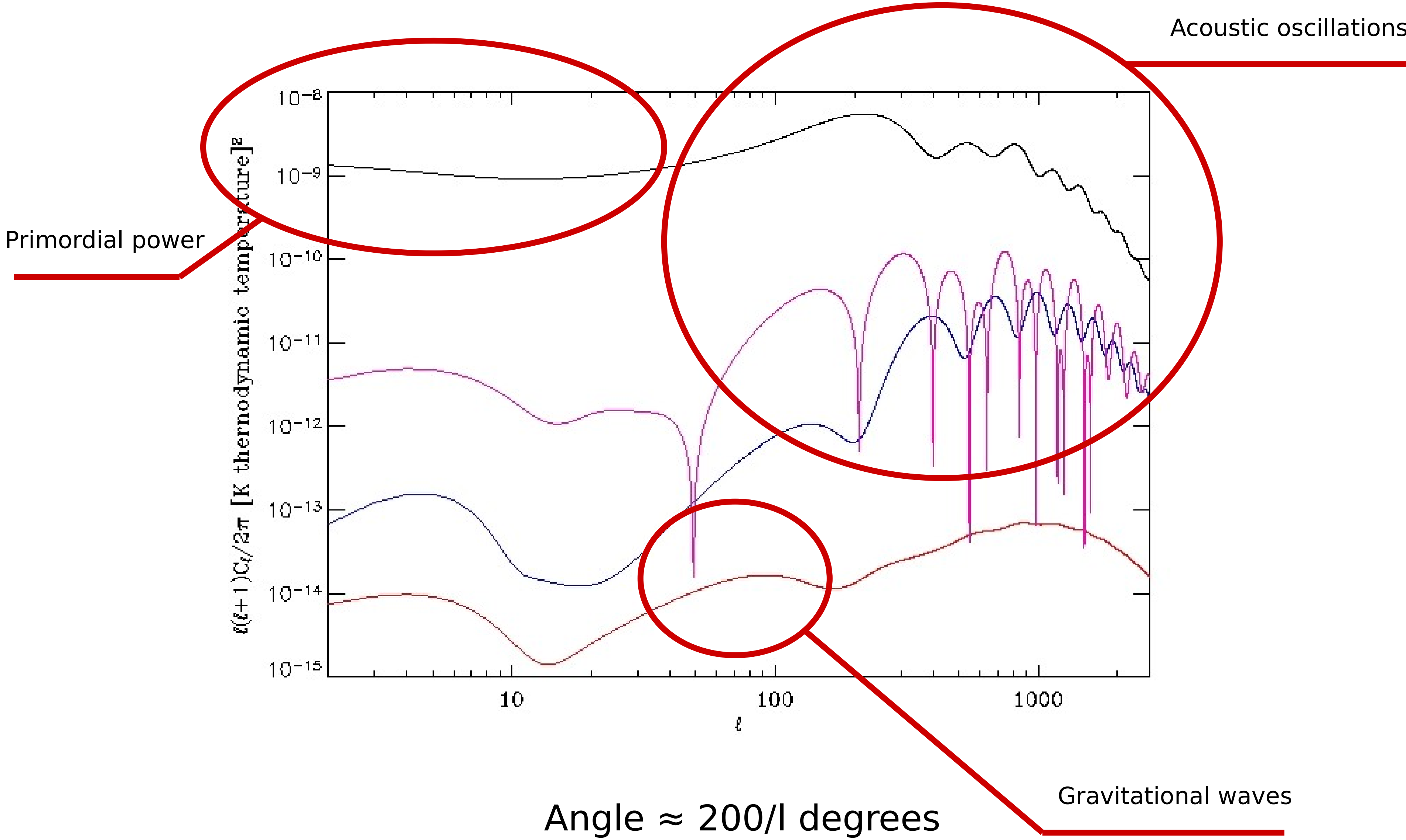
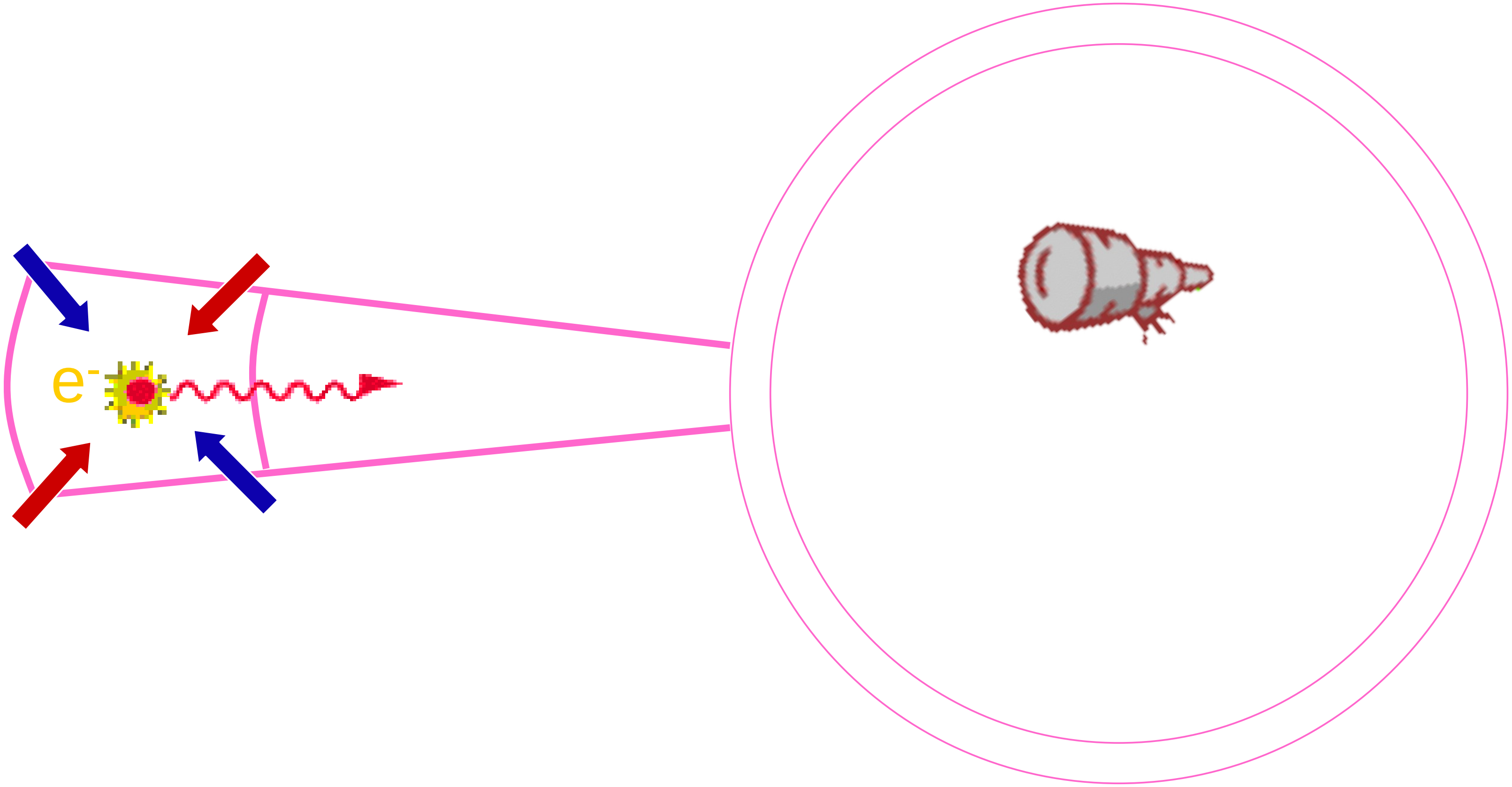
CMB angular power spectrum



Angle ≈ 200/l degrees

The B-modes record GWs mono-chromatically in angle



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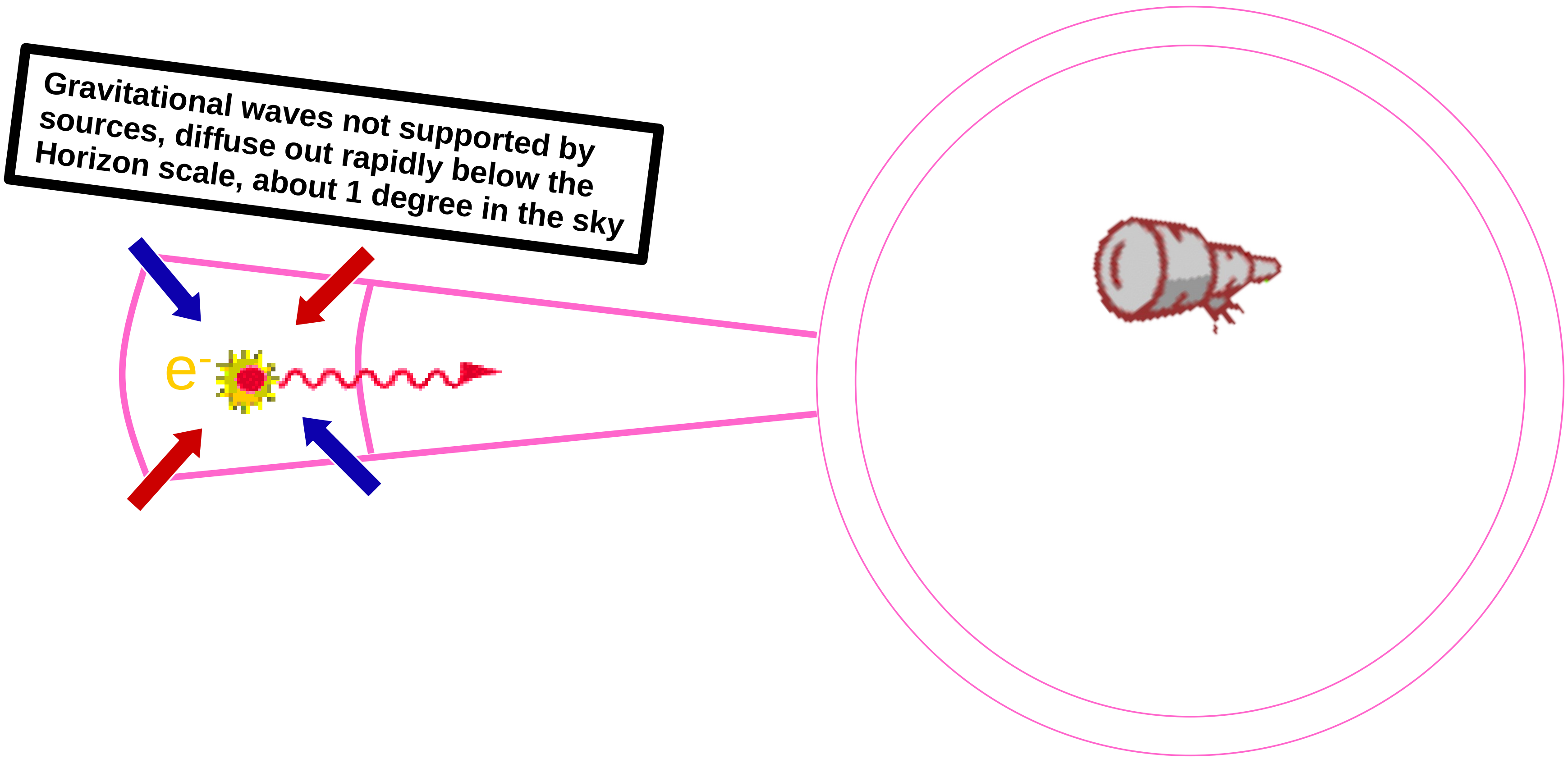

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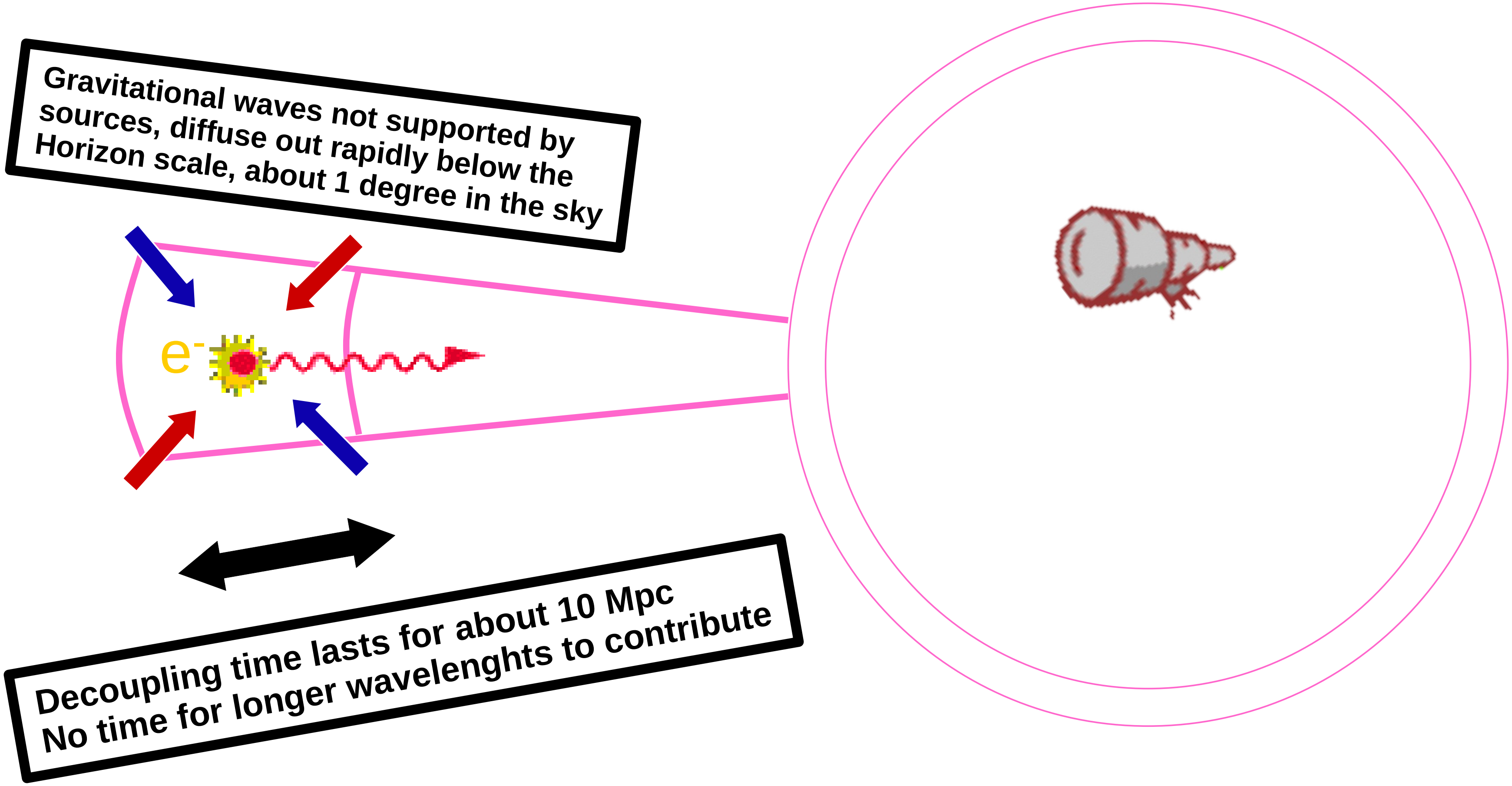

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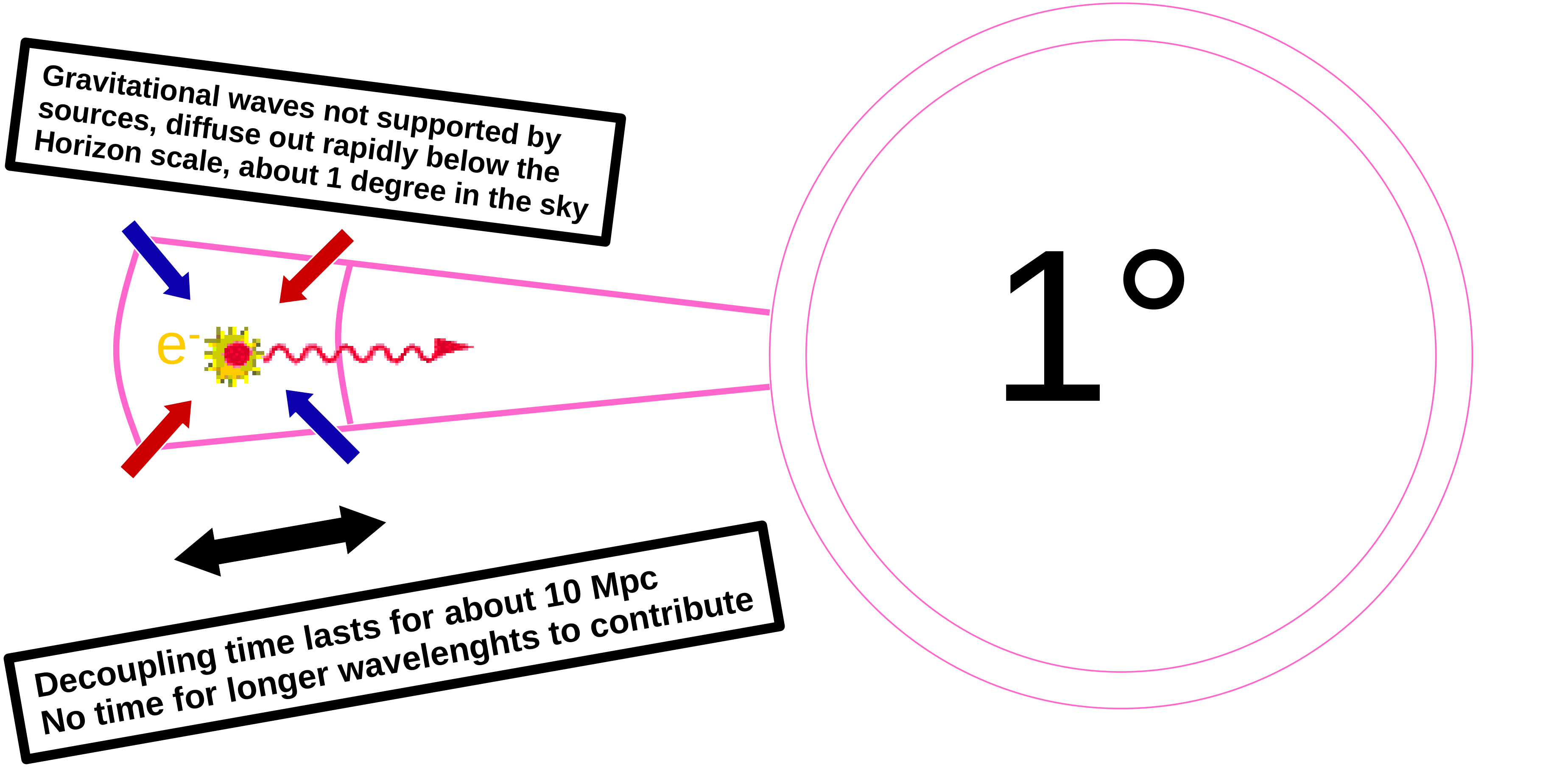
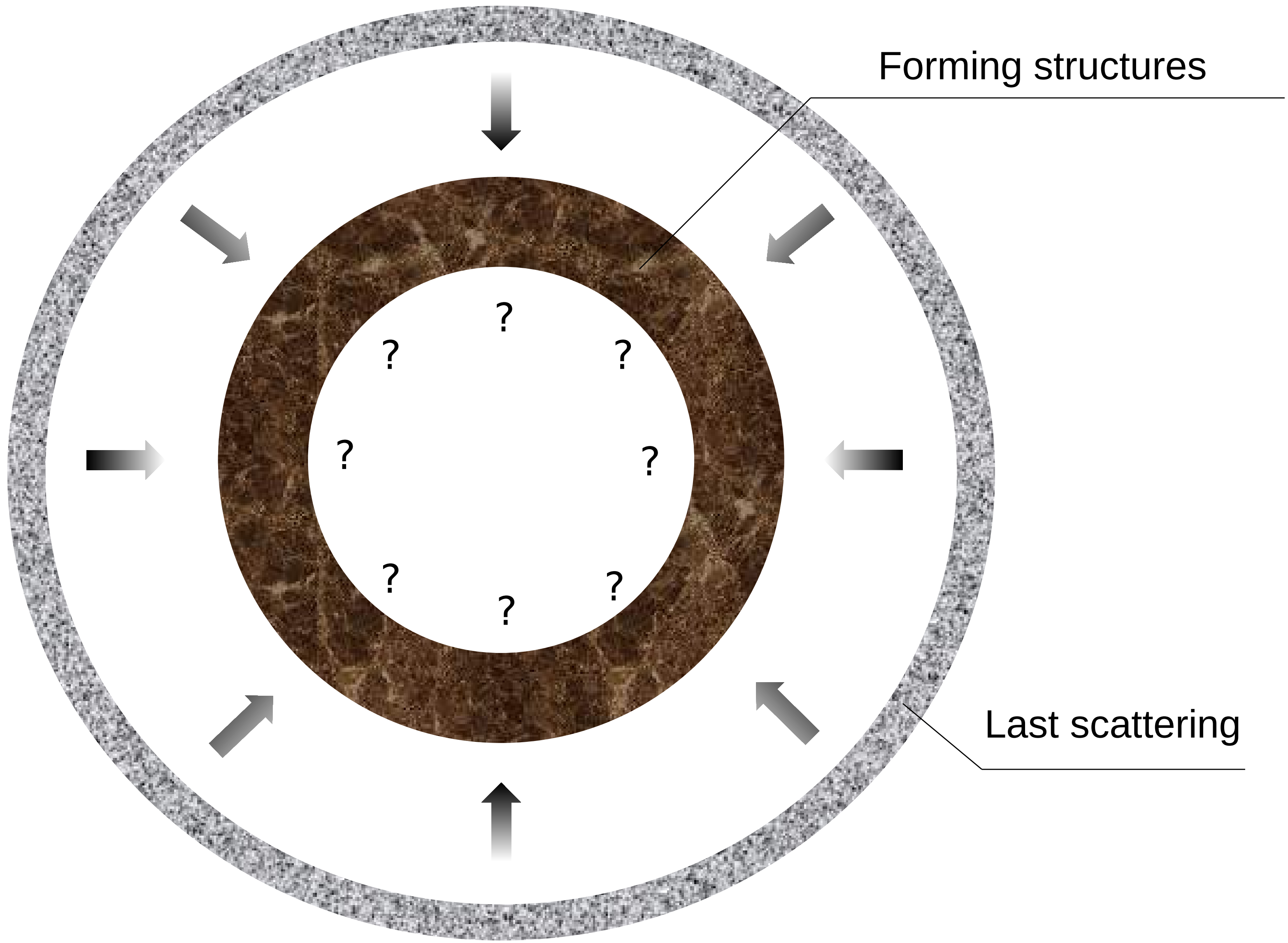


CMB and Large Scale Structure



Categories for LSS effects on CMB

- Re-scattering
- Gravitation

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- Re-scattering
  - Re-ionization
- Gravitation
  - Dynamics in the metric tensor
  - Deflection

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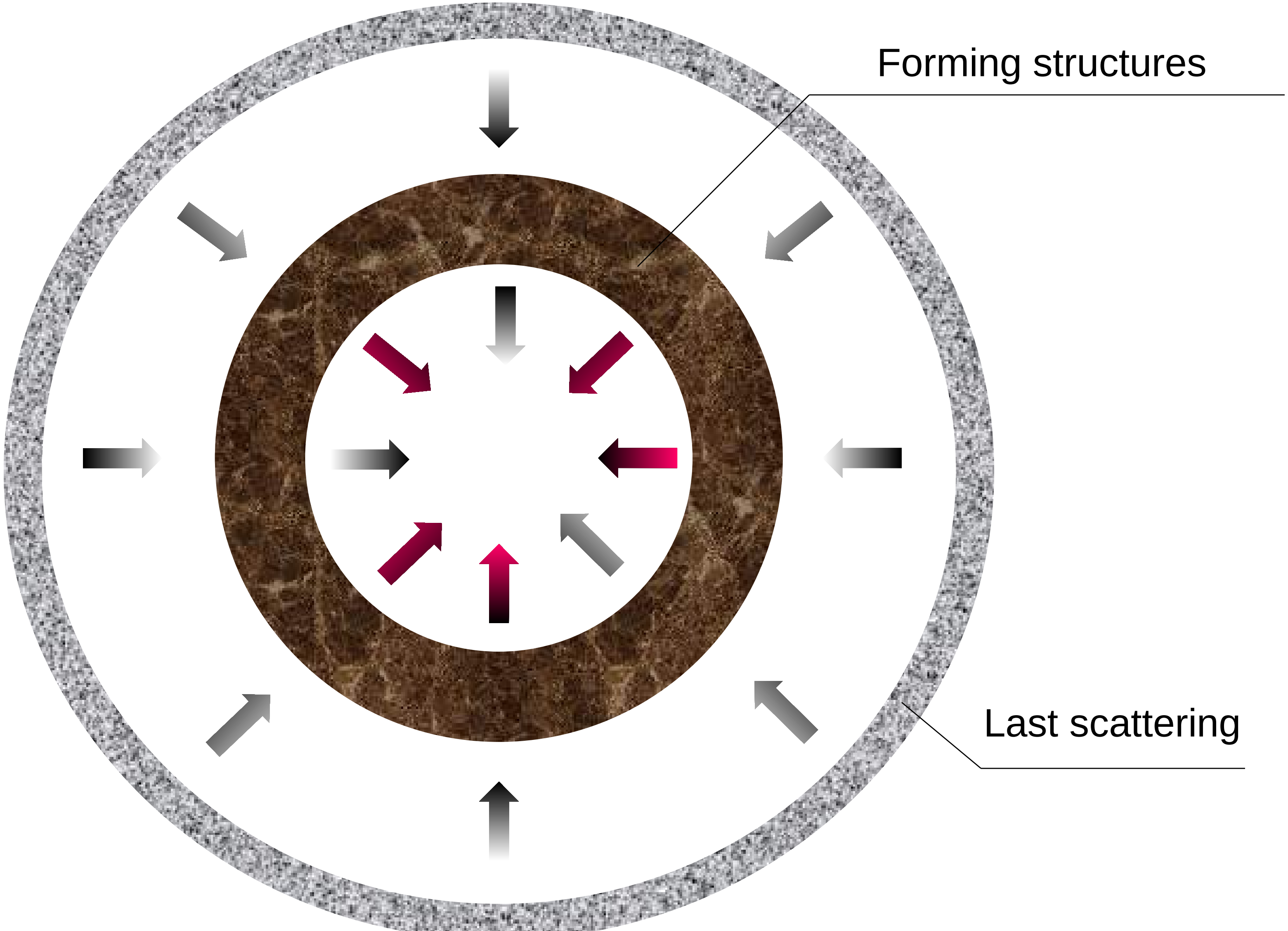
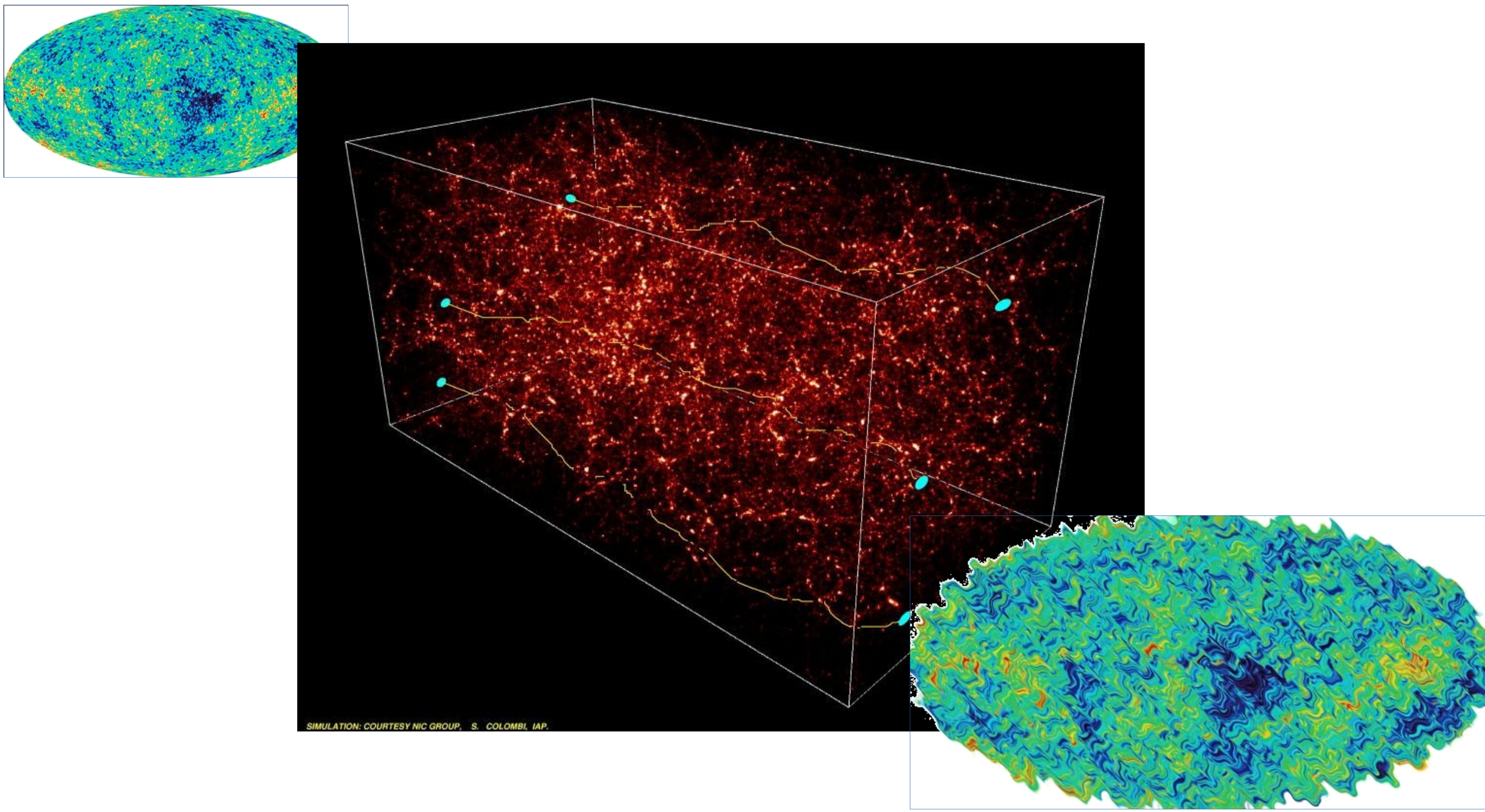
Integrated Sachs-Wolfe



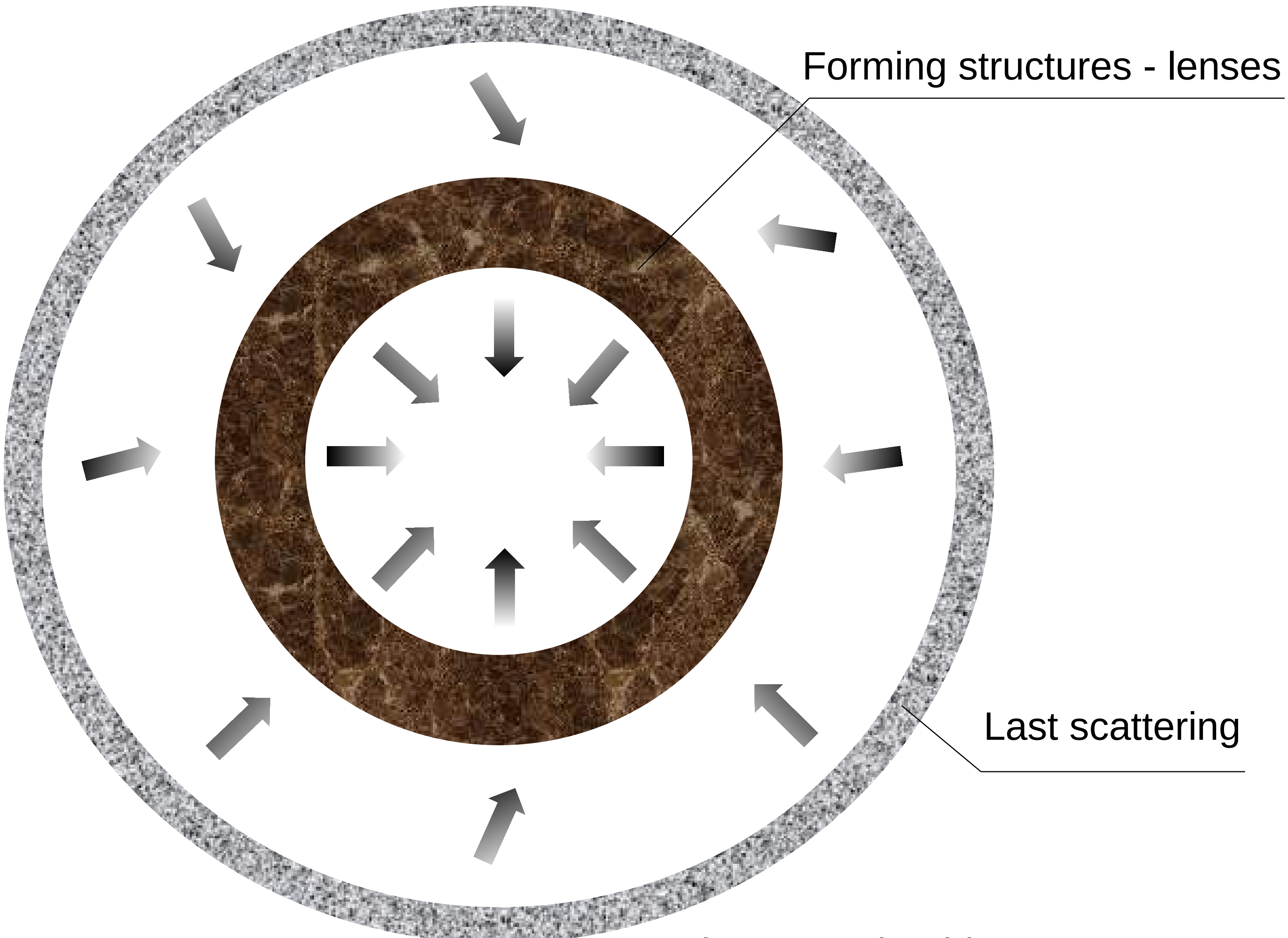
Sachs & Wolfe 1967

CMB lensing



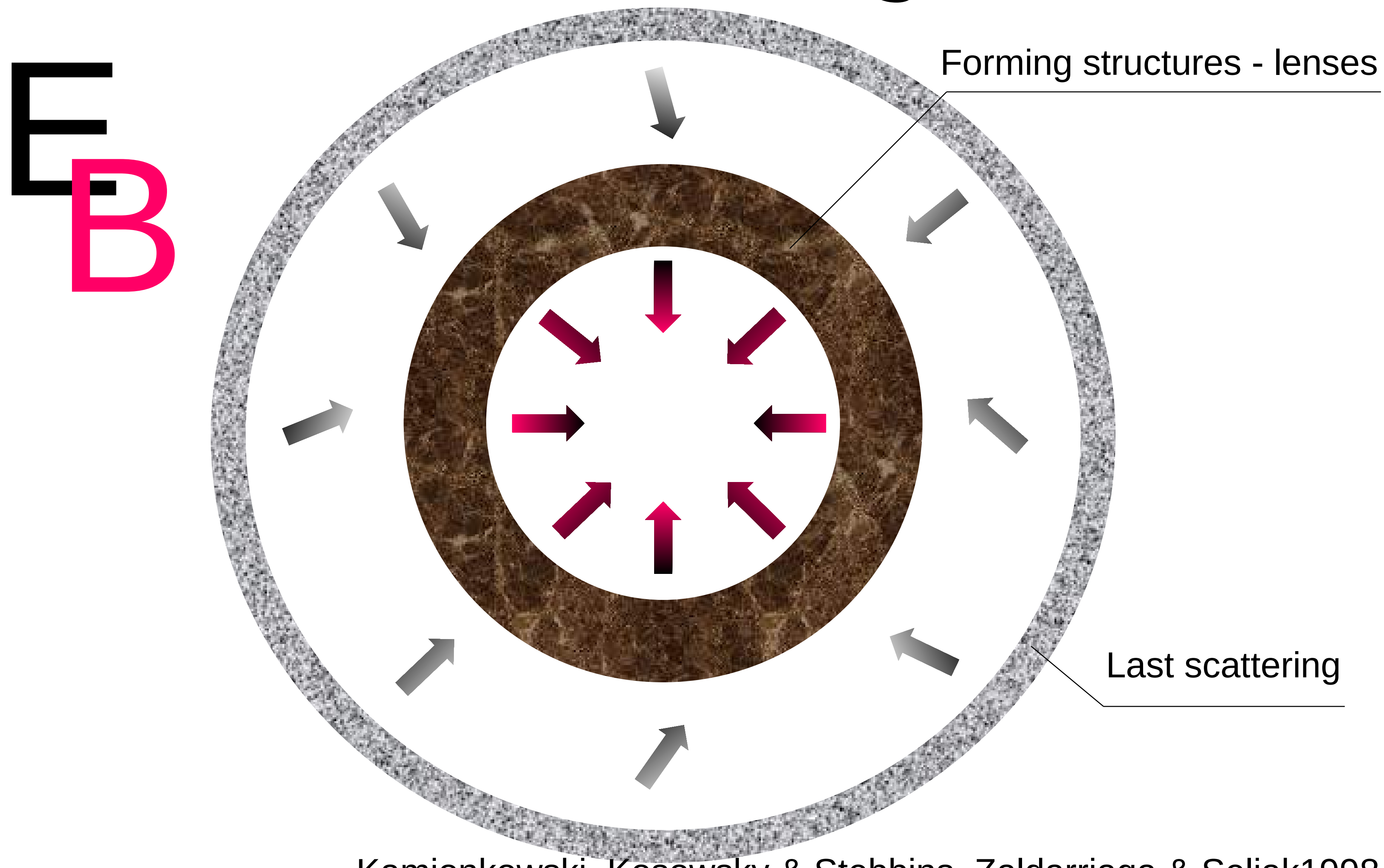
CMB lensing

T



Bartelmann, Schneider 2001, Hu 2000

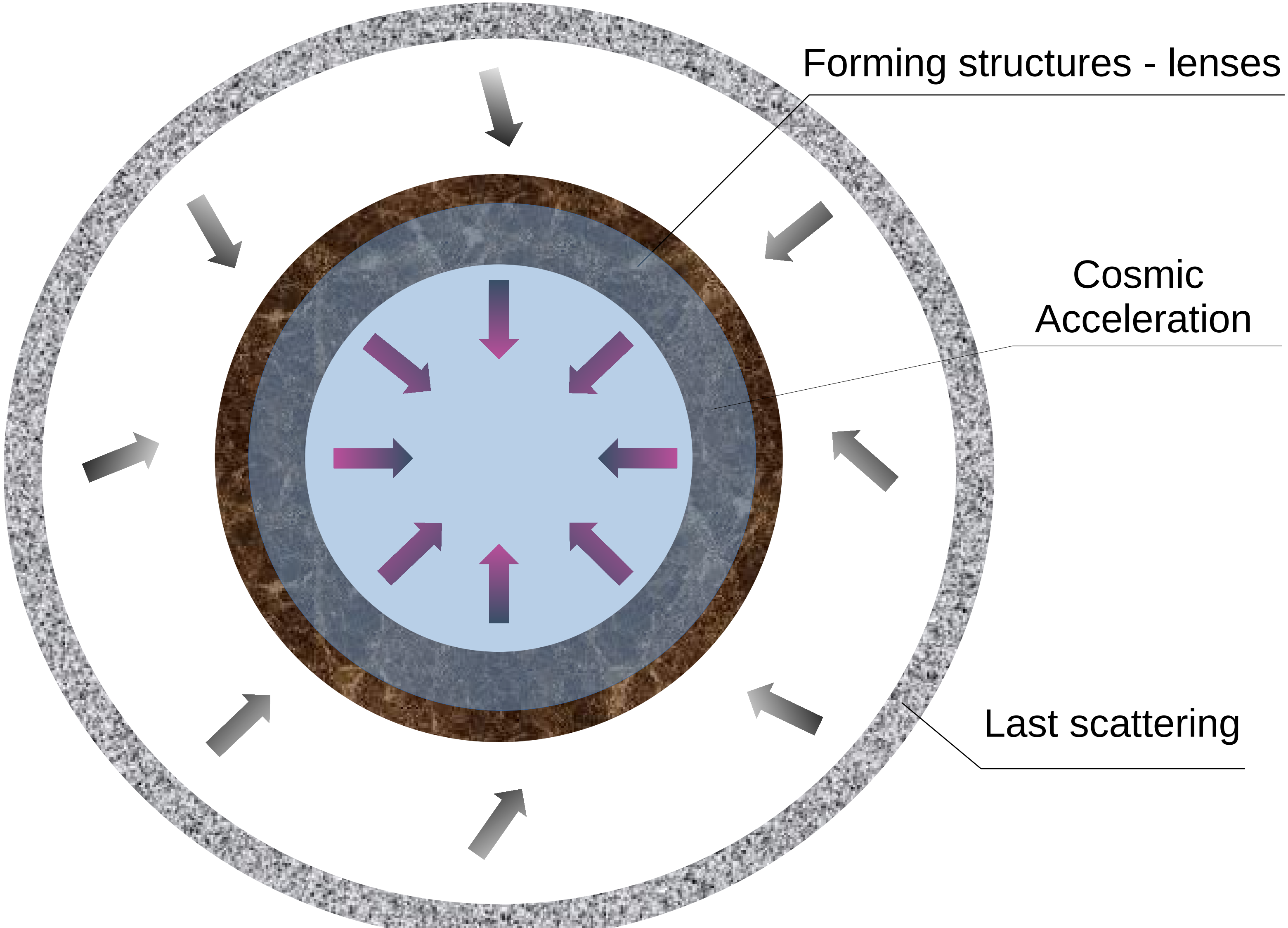
CMB lensing



Kamionkowski, Kosowsky & Stebbins, Zaldarriaga & Seljak1998

CMB lensing

E
B



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CMB angular power spectrum

ISW

Acoustic oscillations

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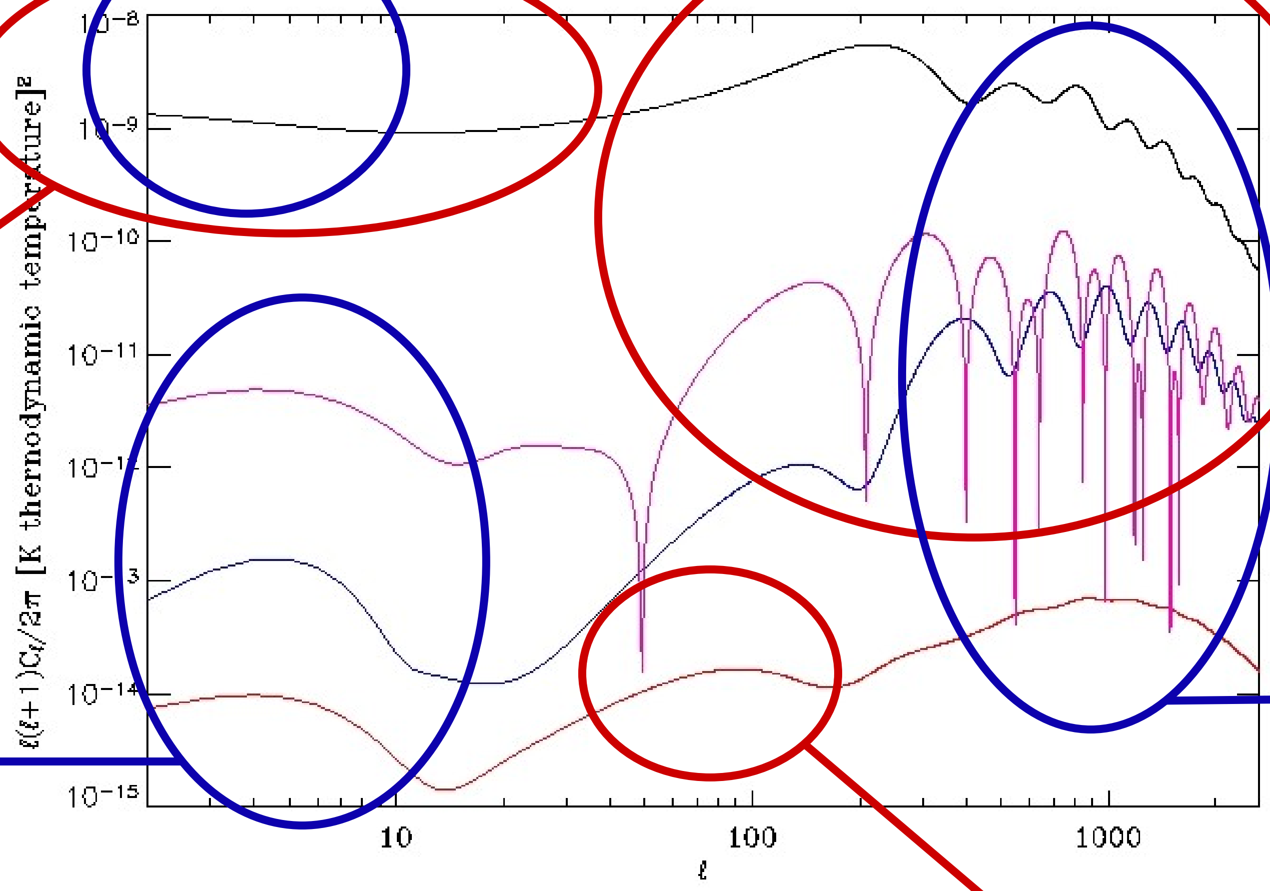


Lensing

Reionization

Gravitational waves

Angle ≈ 200/l degrees

Higher Order Statistics

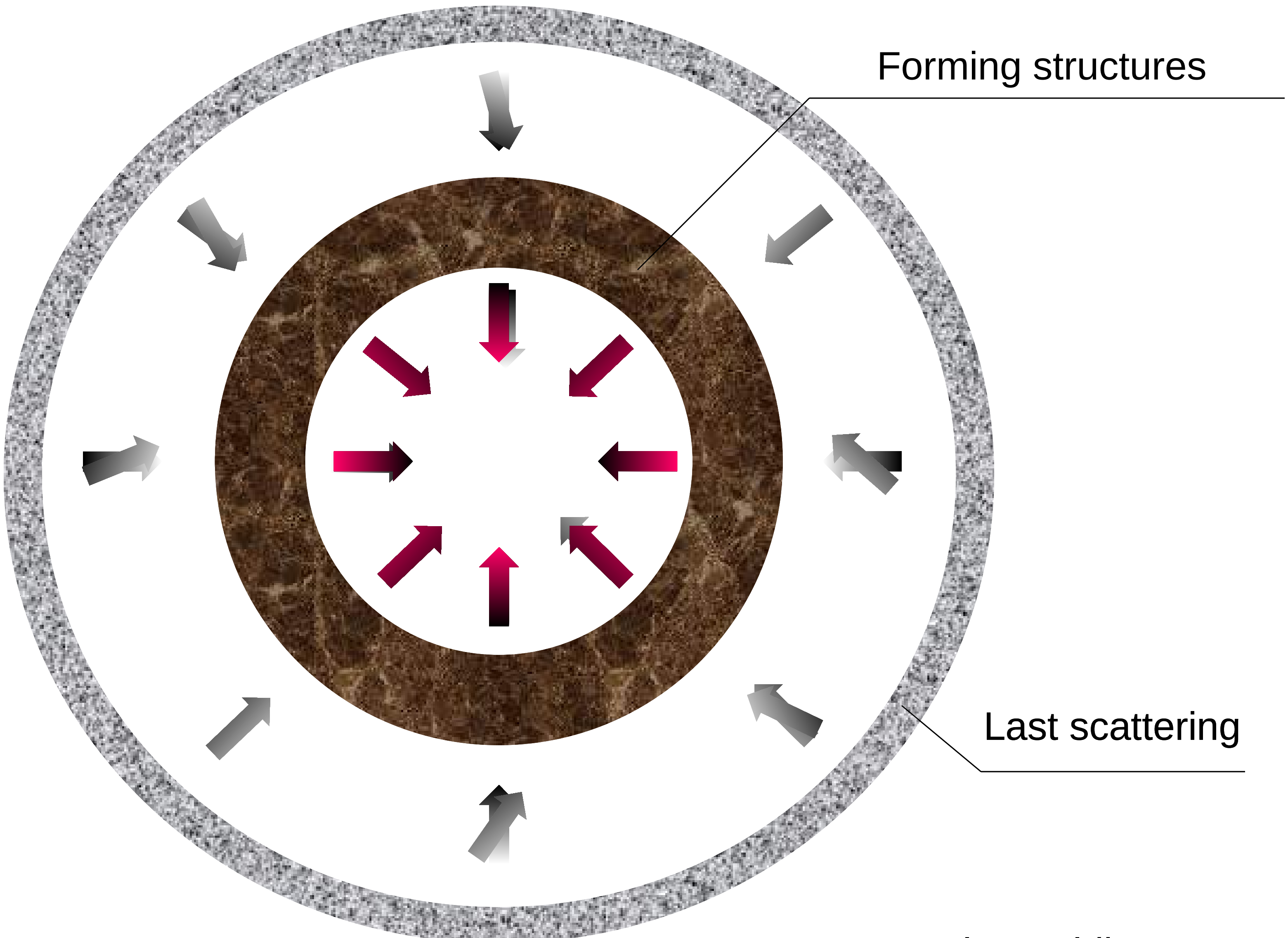
$T(\theta,\varphi)$, $Q(\theta,\varphi)$, $U(\theta,\varphi)$, $V(\theta,\varphi)$

spherical harmonics

$a^X{}_{lm}$, $X=T,E,B$

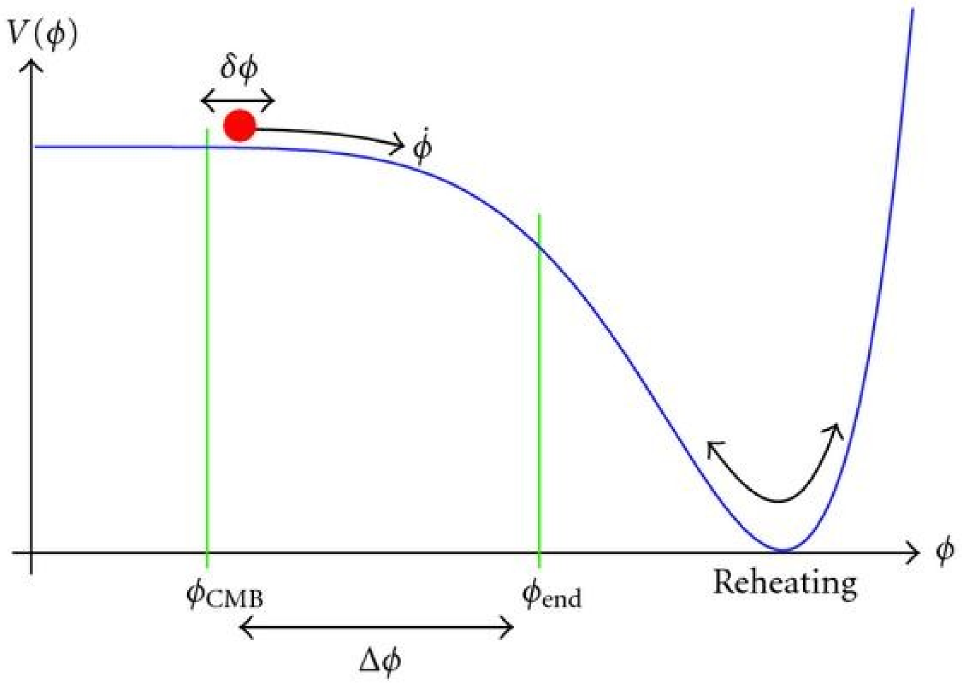
$$B_{l1l2l3}=$$
$$=\Sigma_{m1,m2,m3}\,[({}^{l1}{}_{m1}{}^{l2}{}_{m2}{}^{l3}{}_{m3})(a_{l1m1}{}^{X})(a_{l2m2}{}^{Y})(a_{l3m3}{}^{Z})]$$

ISW-Lensing Cross-Correlation



Spergel & Goldberg 1999

Primordial non-Gaussianities

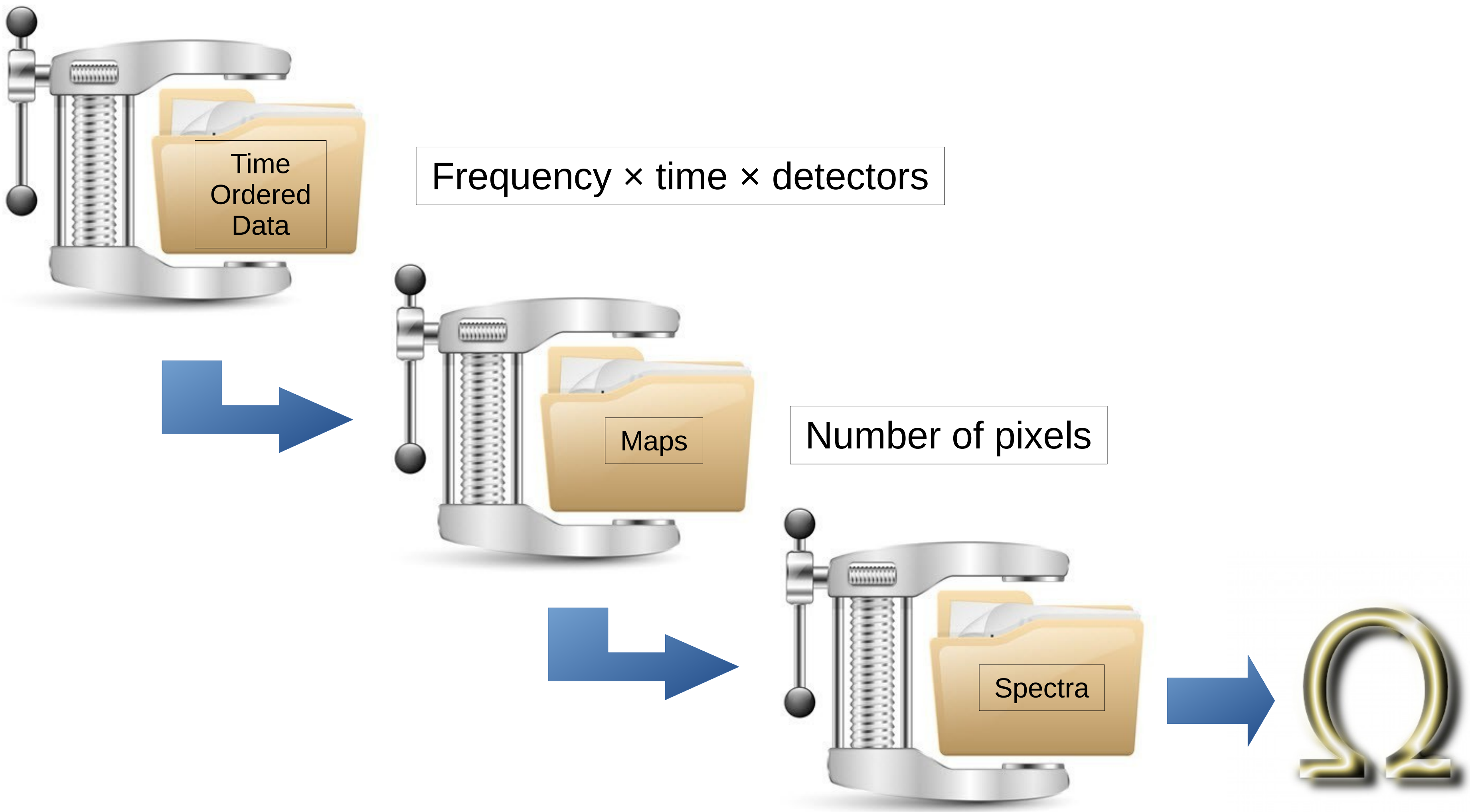


$$\Phi = \varphi_G + f_{NL}(\varphi_G^2 - \langle\varphi_G^2\rangle)$$

Gangui et al. 1994

Analysis

CMB Data Analysis: Titanic Compression



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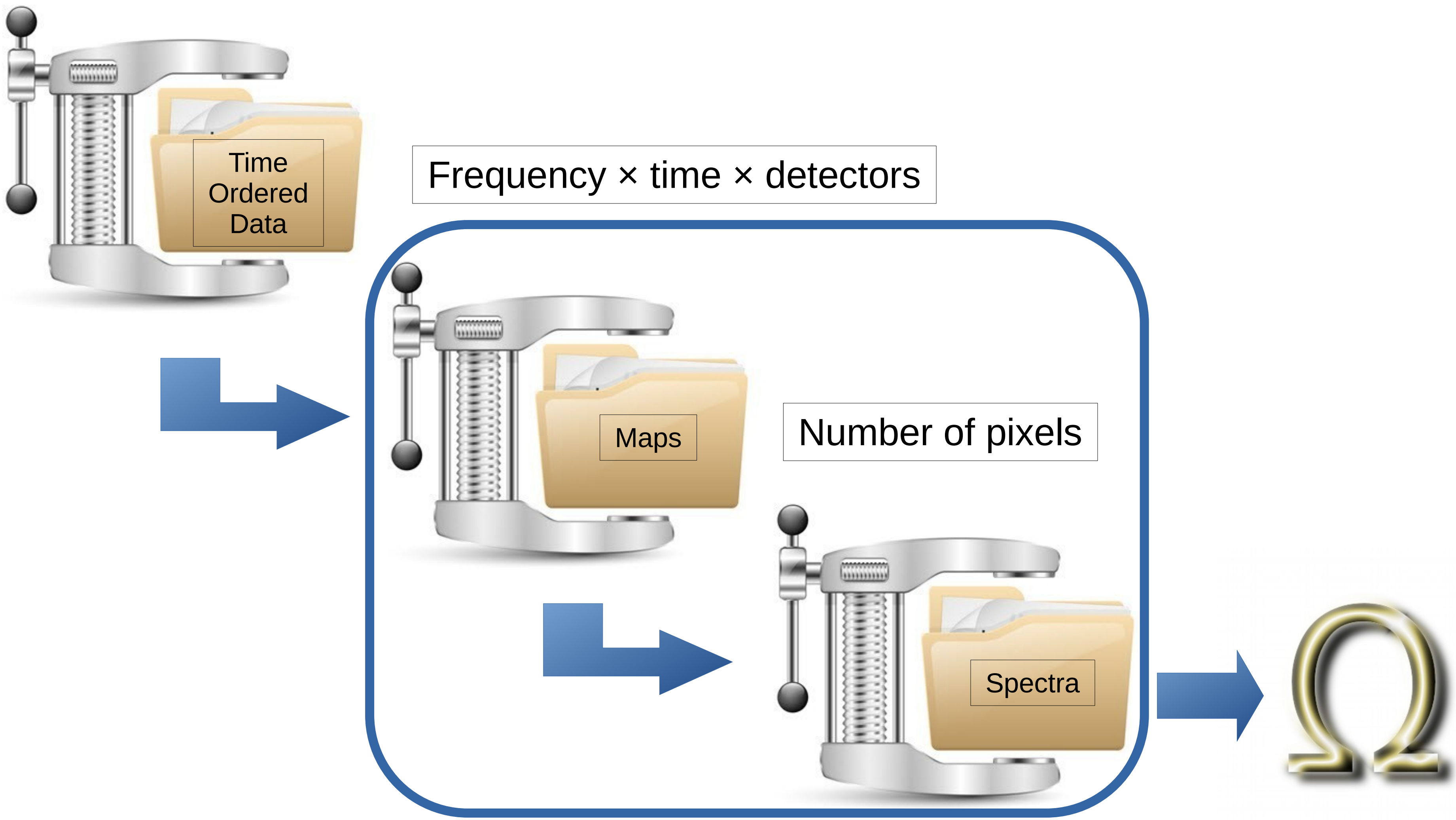

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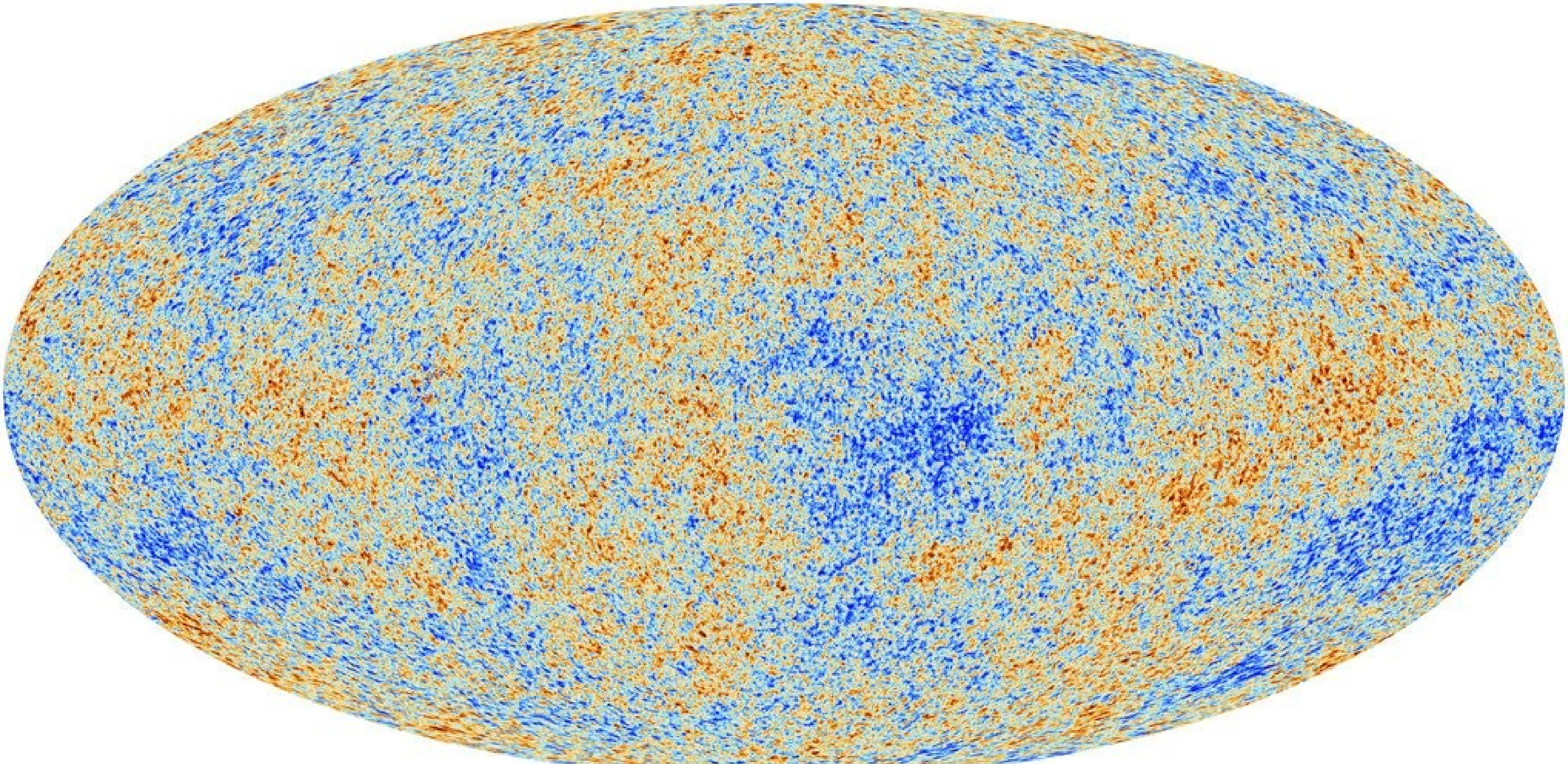
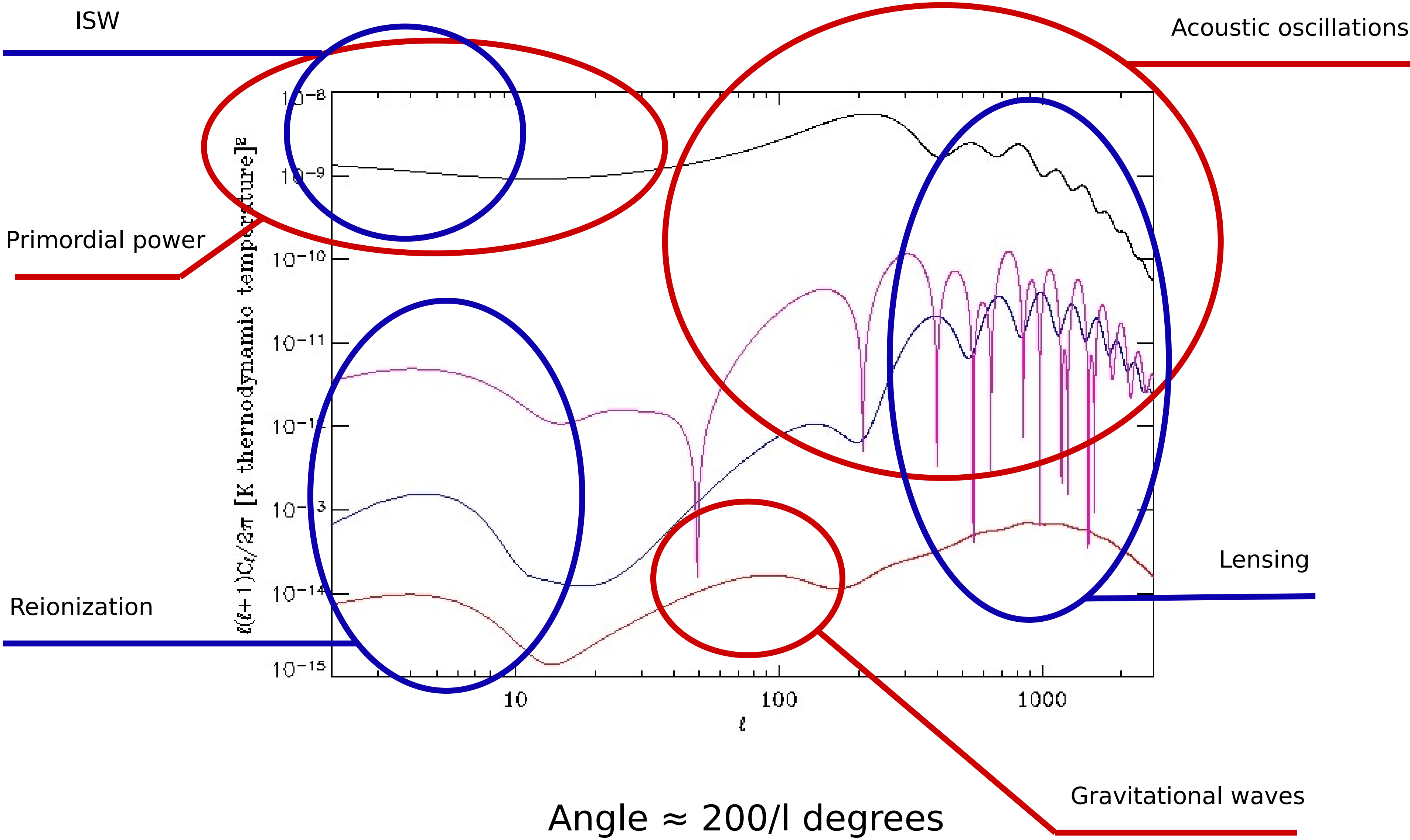


Planck 2018

CMB angular power spectrum



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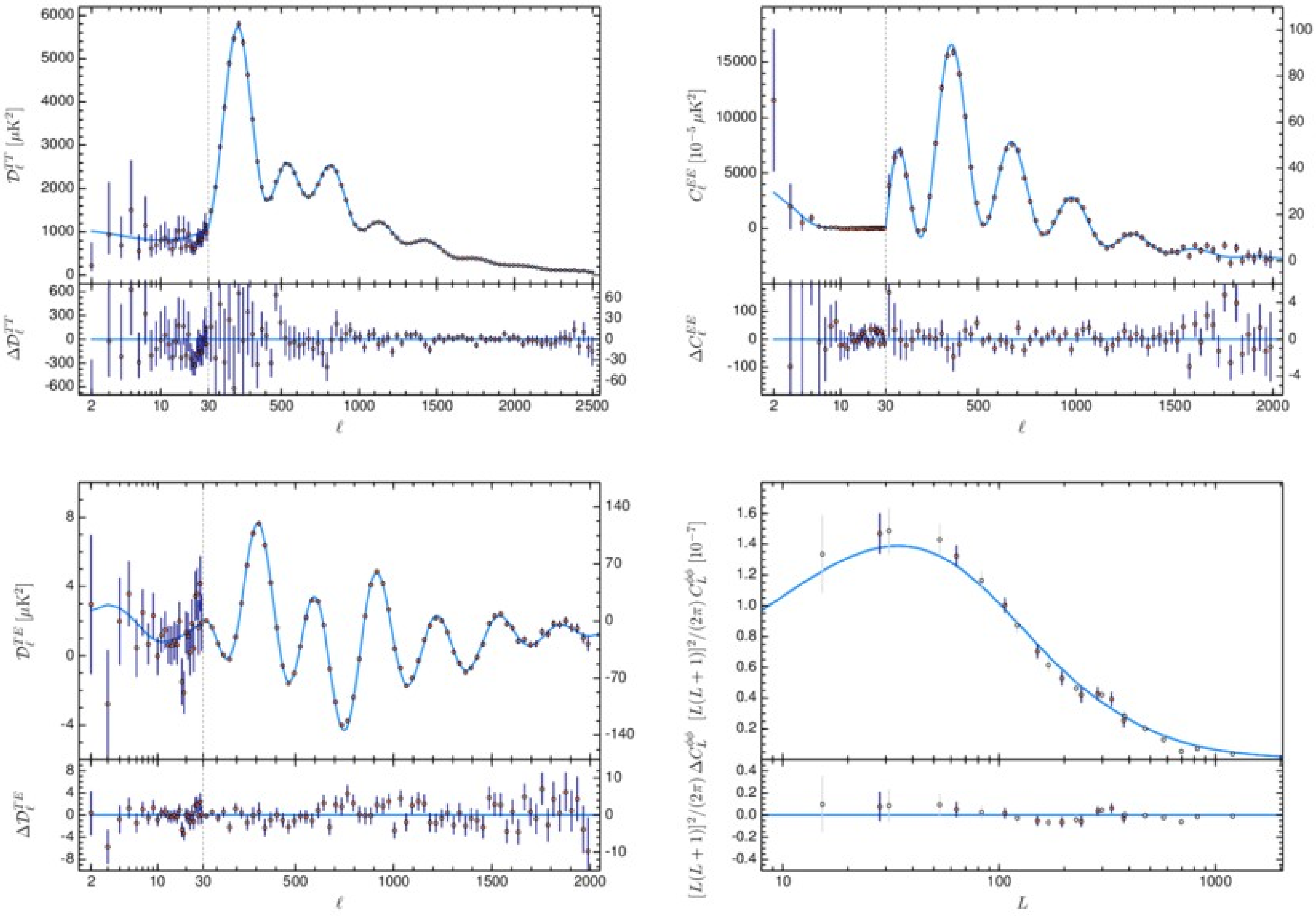

Planck 2018

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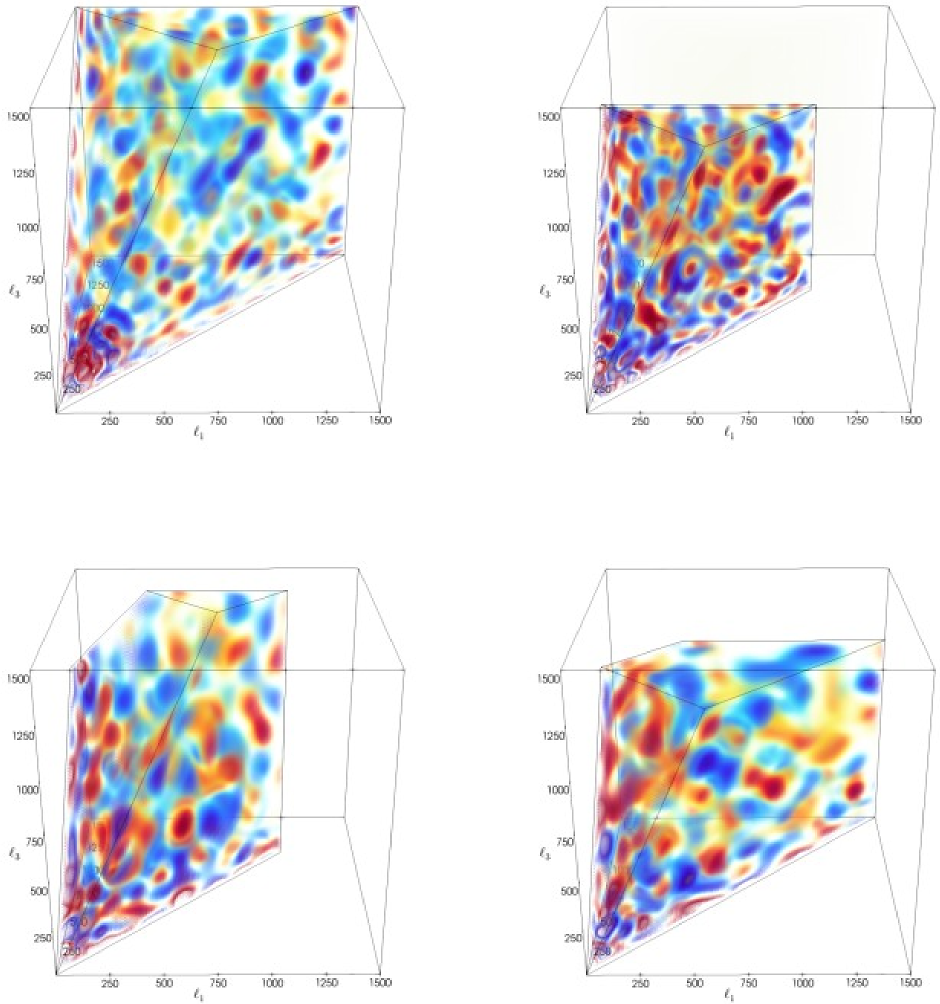

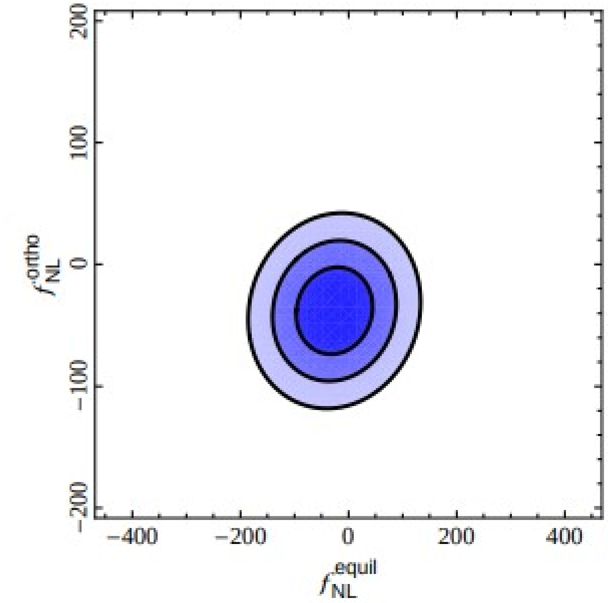

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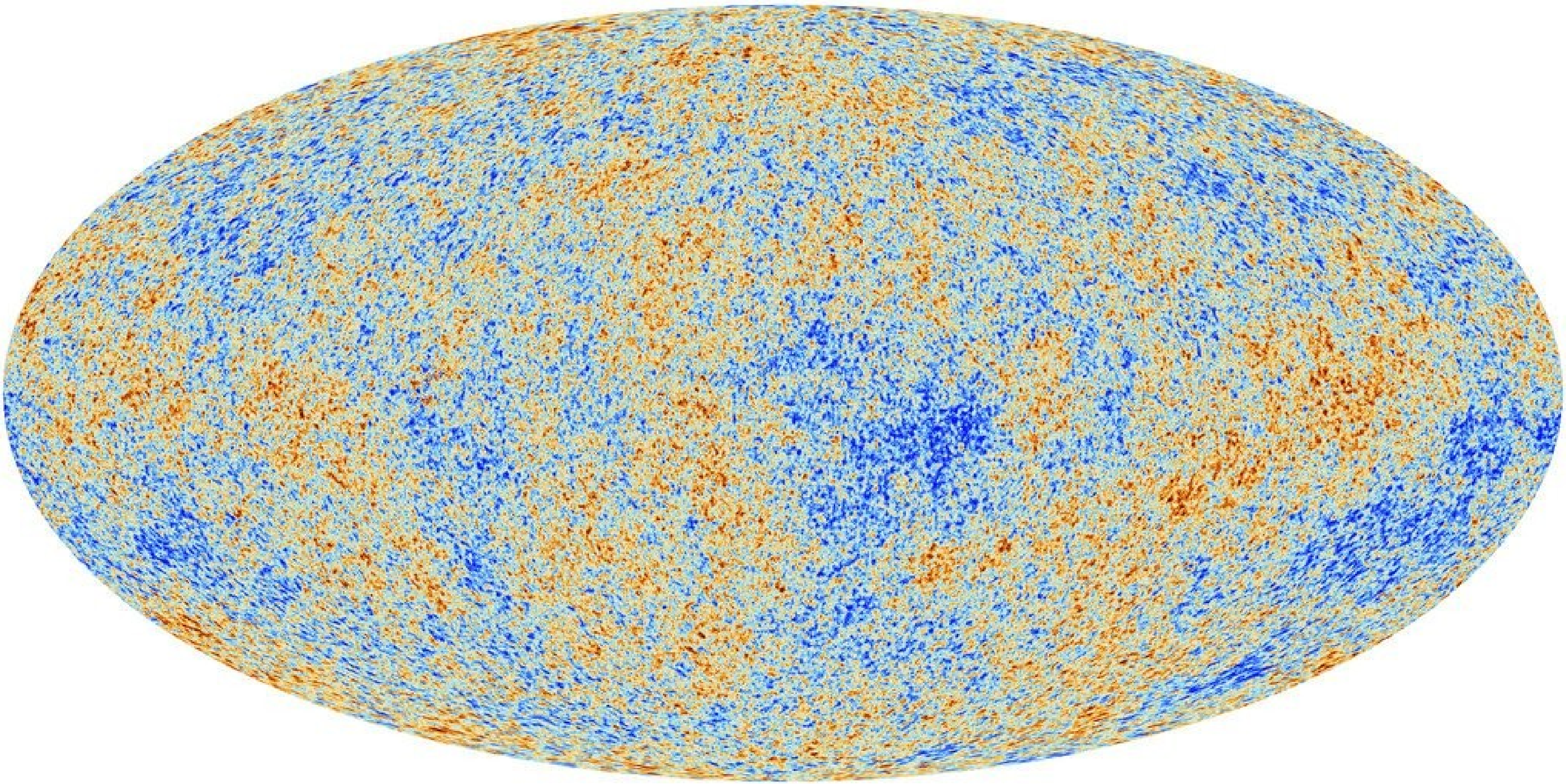

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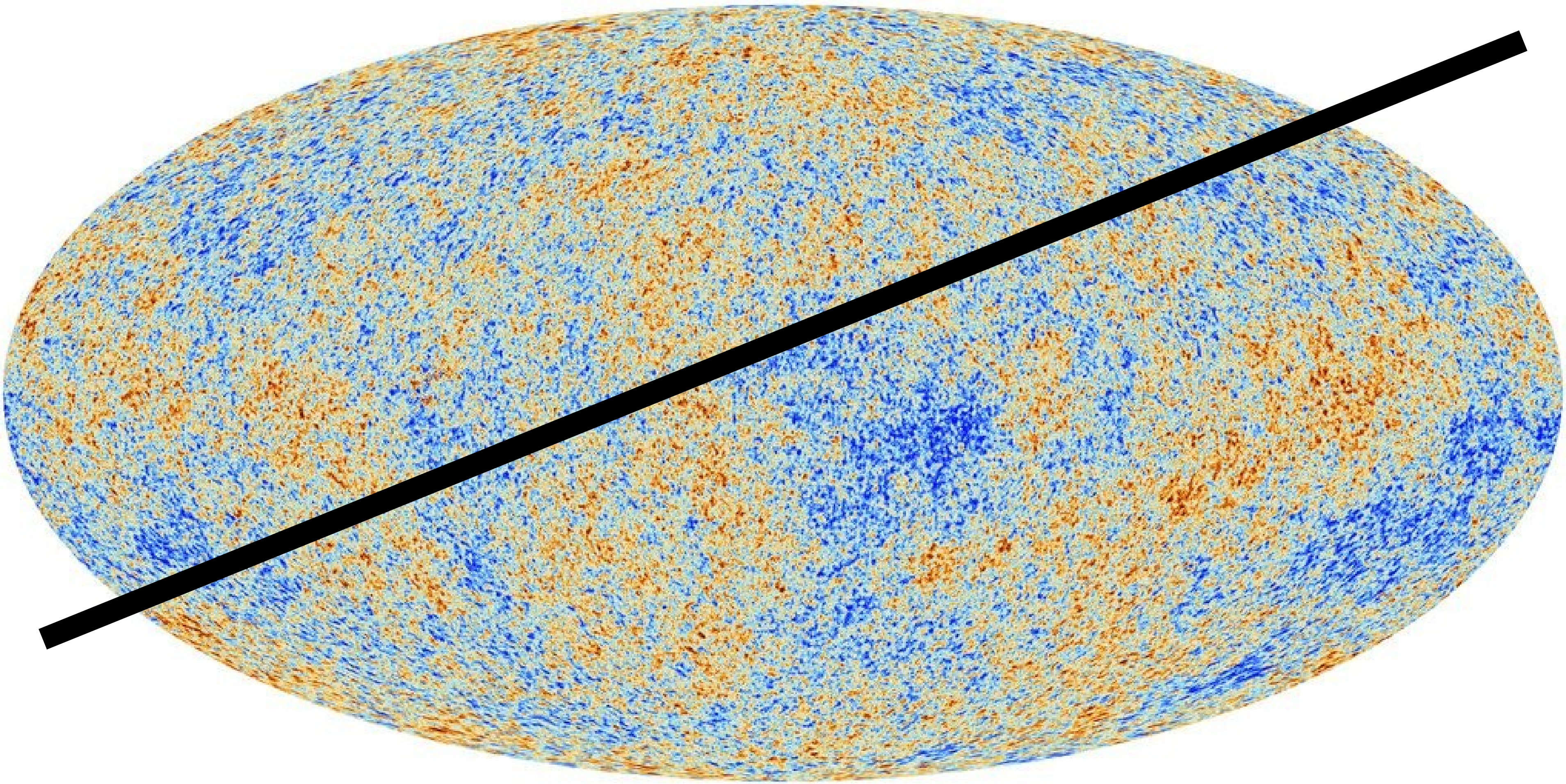

Planck 2018

Isotropy & Statistics

Astronomy & Astrophysics manuscript no. Planck_2018_Isotropy_and_Statistics
September 15, 2020

Planck 2018 results. VII. Isotropy and Statistics of the CMB

Planck Collaboration: Y. Akrami[14,49,51], M. Ashdown[58,5], J. Aumont[85], C. Baccigalupi[68], M. Ballardini[20,36], A. J. Banday[85,8 *], R. B. Barreiro[53], N. Bartolo[25,54], S. Basak[75], K. Benabed[48,84], M. Bersanelli[28,40], P. Bielewicz[67,66,68], J. J. Bock[55,10], J. R. Bond[7], J. Borrill[12,82], F. R. Bouchet[48,79], F. Boulanger[78,47,48], M. Bucher[2,6], C. Burigana[39,26,42], R. C. Butler[36], E. Calabrese[72], J.-F. Cardoso[48], B. Casaponsa[53], H. C. Chiang[22,6], L. P. L. Colombo[28], C. Combet[60], D. Contreras[19], B. P. Crill[55,10], P. de Bernardis[27], G. de Zotti[37], J. Delabrouille[2], J.-M. Delouis[48,84], E. Di Valentino[56], J. M. Diego[53], O. Doré[55,10], M. Douspis[47], A. Ducout[59], X. Dupac[31], G. Efstathiou[58,50], F. Elsner[63], T. A. Enßlin[63], H. K. Eriksen[51], Y. Fantaye[3,18], R. Fernandez-Cobos[53], F. Finelli[36,42], M. Frailis[38], A. A. Fraisse[22], E. Franceschi[36], A. Frolov[77], S. Galeotta[38], S. Galli[57], K. Ganga[2], R. T. Génova-Santos[52,15], M. Gerbino[83], T. Ghosh[71,9], J. González-Nuevo[16], K. M. Górski[55,86 **], A. Gruppuso[36,42], J. E. Gudmundsson[83,22], J. Hamann[76], W. Handley[58,5], F. K. Hansen[51], D. Herranz[53], E. Hivon[48,84], Z. Huang[73], A. H. Jaffe[46], W. C. Jones[22], E. Keihänen[21], R. Keskitalo[12], K. Kiiveri[21,35], J. Kim[63], N. Krachmalnicoff[68], M. Kunz[13,47,3], H. Kurki-Suonio[21,35], G. Lagache[4], J.-M. Lamarre[78], A. Lasenby[5,58], M. Lattanzi[26,43], C. R. Lawrence[55], M. Le Jeune[2], F. Levrier[78], M. Liguori[25,54], P. B. Lilje[51], V. Lindholm[21,35], M. López-Caniego[31], Y.-Z. Ma[56,70,65], J. F. Macías-Pérez[60], G. Maggio[38], D. Maino[28,40,44], N. Mandolesi[36,26], A. Mangilli[8], A. Marcos-Caballero[53], M. Maris[38], P. G. Martin[7], E. Martínez-González[53 ***], S. Matarrese[25,54,33], N. Mauri[42], J. D. McEwen[64], P. R. Meinhold[23], A. Mennella[28,40], M. Migliaccio[30,45], M.-A. Miville-Deschênes[1,47], D. Molinari[26,36,43], A. Moneti[48], L. Montier[85,8], G. Morgante[36], A. Moss[74], P. Natoli[26,81,43], L. Pagano[47,78], D. Paoletti[36,42], B. Partridge[34], F. Perrotta[68], V. Pettorino[1], F. Piacentini[27], G. Polenta[81], J.-L. Puget[47,48], J. P. Rachen[17], M. Reinecke[63], M. Remazeilles[56], A. Renzi[54], G. Rocha[55,10], C. Rosset[2], G. Roudier[2,78,55], J. A. Rubiño-Martín[52,15], B. Ruiz-Granados[52,15], L. Salvati[47], M. Savelainen[21,35,62], D. Scott[19], E. P. S. Shellard[11], C. Sirignano[25,54], R. Sunyaev[63,80], A.-S. Suur-Uski[21,35], J. A. Tauber[32], D. Tavagnacco[38,29], M. Tenti[41], L. Toffolatti[16,36], M. Tomasi[28,40], T. Trombetti[39,43], L. Valenziano[36], J. Valiviita[21,35], B. Van Tent[61], P. Vielva[53 †], F. Villa[36], N. Vittorio[30], B. D. Wandelt[48,84,24], I. K. Wehus[51], A. Zacchei[38], J. P. Zibin[19], and A. Zonca[69]

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ABSTRACT

Analysis of the *Planck* 2018 data set indicates that the statistical properties of the cosmic microwave background (CMB) temperature anisotropies are in excellent agreement with previous studies using the 2013 and 2015 data releases. In particular, they are consistent with the Gaussian predictions of the ΛCDM cosmological model, yet also confirm the presence of several so-called "anomalies" on large angular scales. The novelty of the current study, however, lies in being a first attempt at a comprehensive analysis of the statistics of the polarization signal over all angular scales, using either maps of the Stokes parameters, Q and U, or the E-mode signal derived from these using a new methodology (which we describe in an appendix). Although remarkable progress has been made in reducing the systematic effects that contaminated the 2015 polarization maps on large angular scales, it is still the case that residual systematics (and our ability to simulate them) can limit some tests of non-Gaussianity and isotropy. However, a detailed set of null tests applied to the maps indicates that these issues do not dominate the analysis on intermediate and large angular scales (i.e., $\ell \lesssim 400$). In this regime, no unambiguous detections of cosmological non-Gaussianity, or of anomalies corresponding to those seen in temperature, are claimed. Notably, the stacking of CMB polarization signals centred on the positions of temperature hot and cold spots exhibits excellent agreement with the ΛCDM cosmological model, and also gives a clear indication of how *Planck* provides state-of-the-art measurements of CMB temperature and polarization on degree scales.

Key words. Cosmology: observations – cosmic background radiation – polarization – methods: data analysis – methods: statistical

1. Introduction

This paper, one of a set associated with the 2018 release of data from the *Planck*[1] mission (Planck Collaboration I 2020), describes a compendium of studies undertaken to determine the statistical properties of both the temperature and polarization anisotropies of the cosmic microwave background (CMB).

The ΛCDM model explains the structure of the CMB in detail (Planck Collaboration VI 2020), yet it remains entirely appropriate to look for hints of departures from, or tensions with, the standard cosmological model, by examining the statistical properties of the observed radiation. Indeed, in recent years, tantalizing evidence has emerged from the WMAP and *Planck* full-sky measurements of the CMB temperature fluctuations of the presence of such "anomalies," and indicating that a modest degree of devia-

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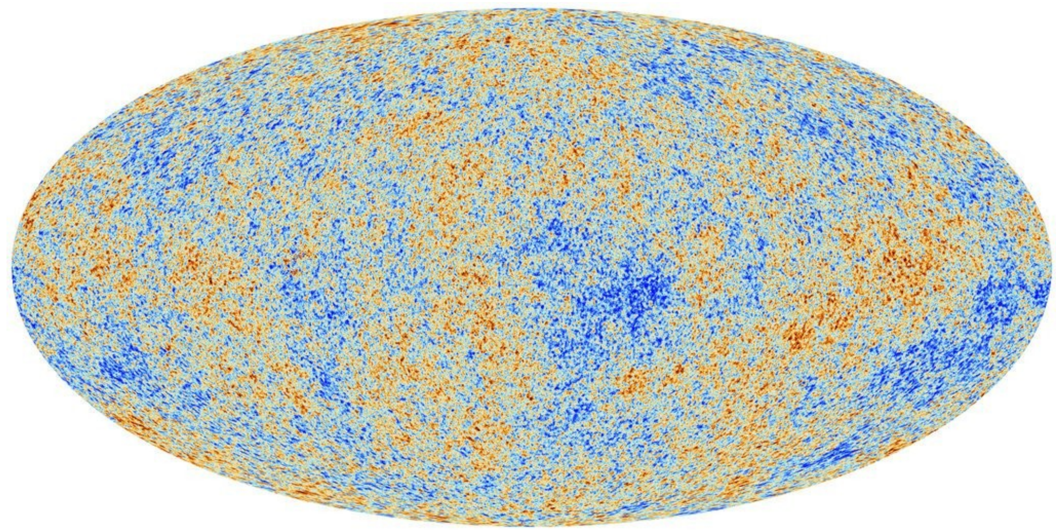
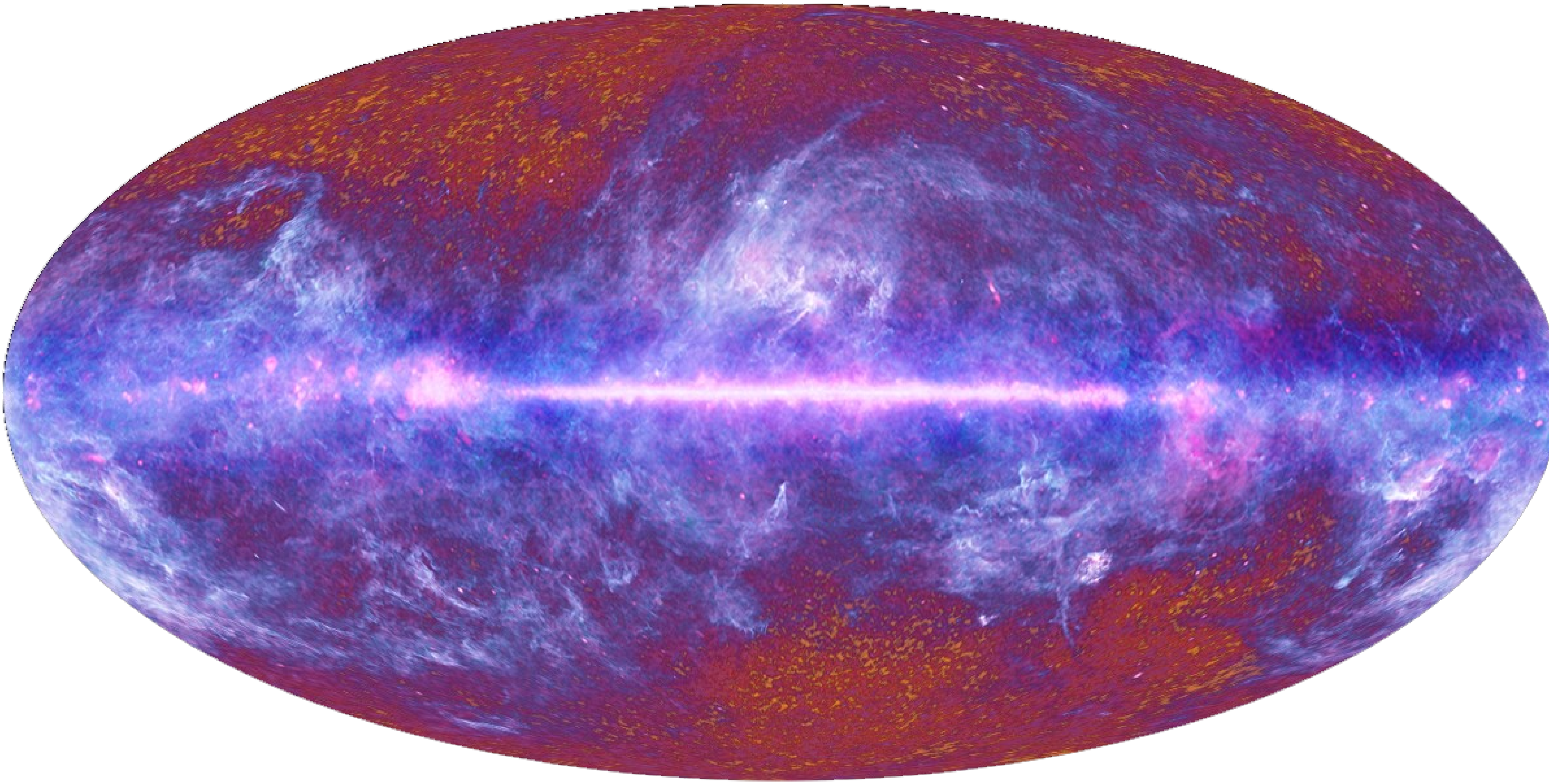
[1] *Planck* (http://www.esa.int/Planck) is a project of the European Space Agency (ESA) with instruments provided by two scientific consortia funded by ESA member states and led by Principal Investigators from France and Italy, telescope reflectors provided through a collaboration between ESA and a scientific consortium led and funded by Denmark, and additional contributions from NASA (USA).

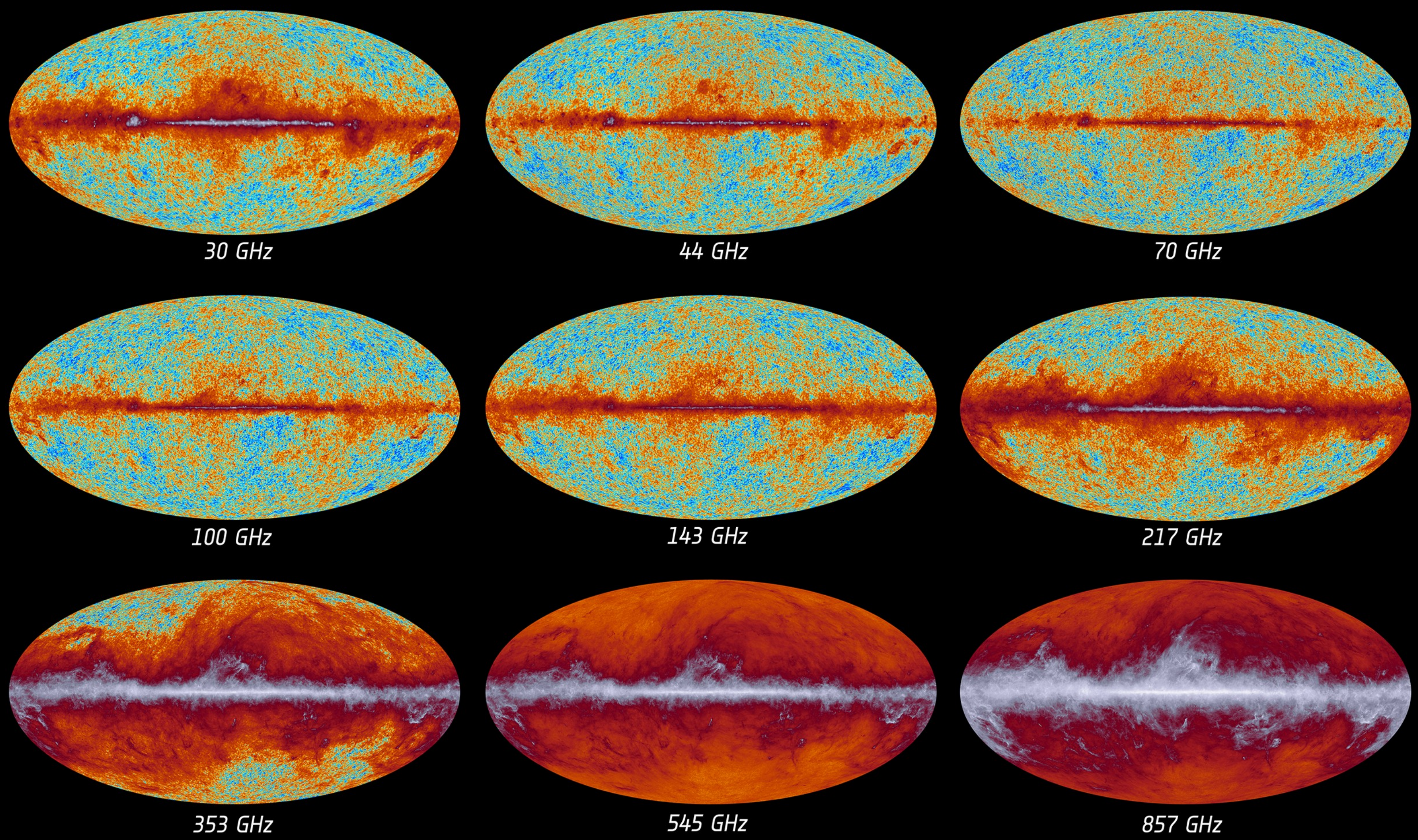


Planck 2018

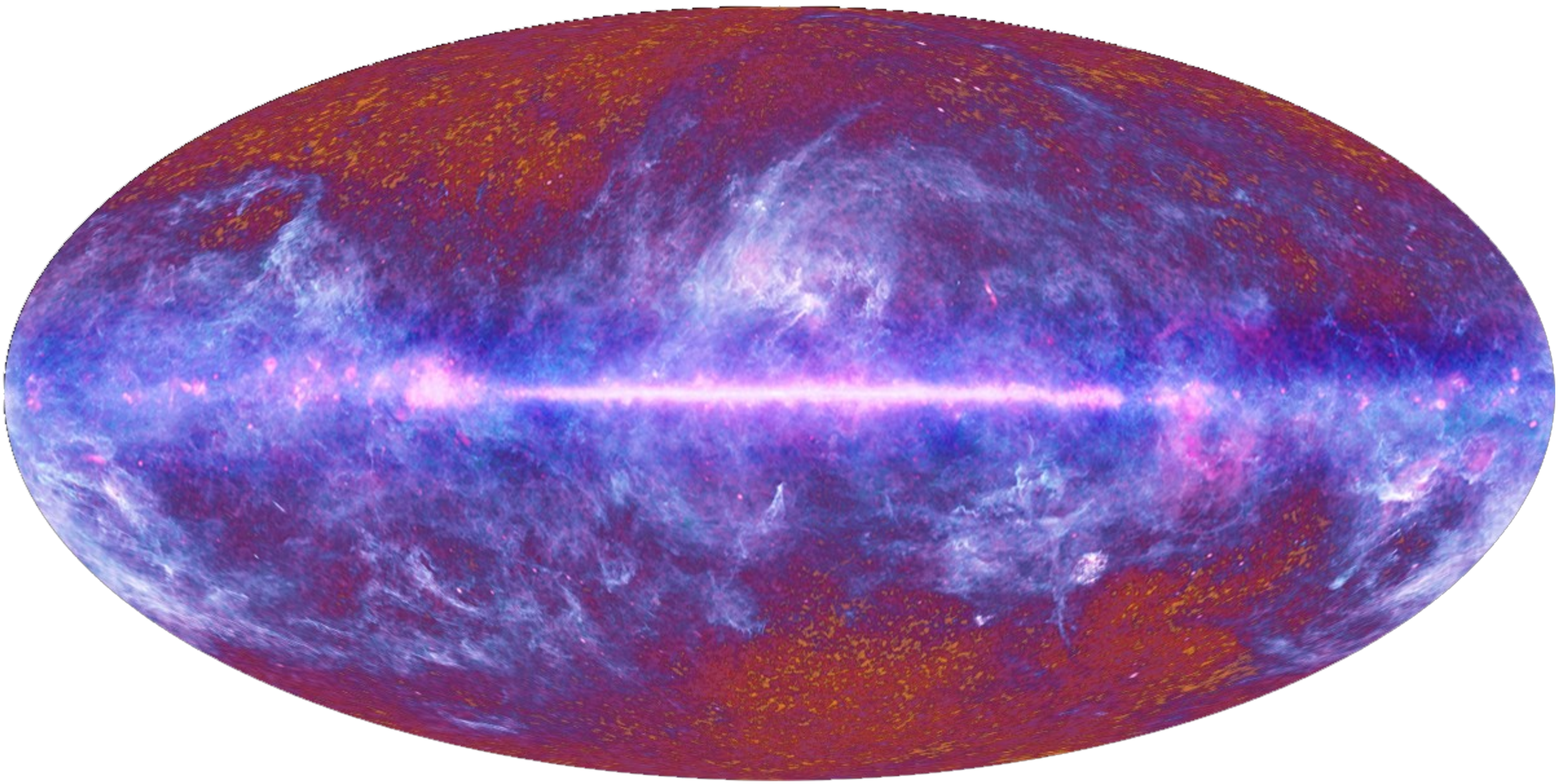
Sky as seen by Planck



The sky as seen by Planck



F=A (sky direction) × F(frequency)

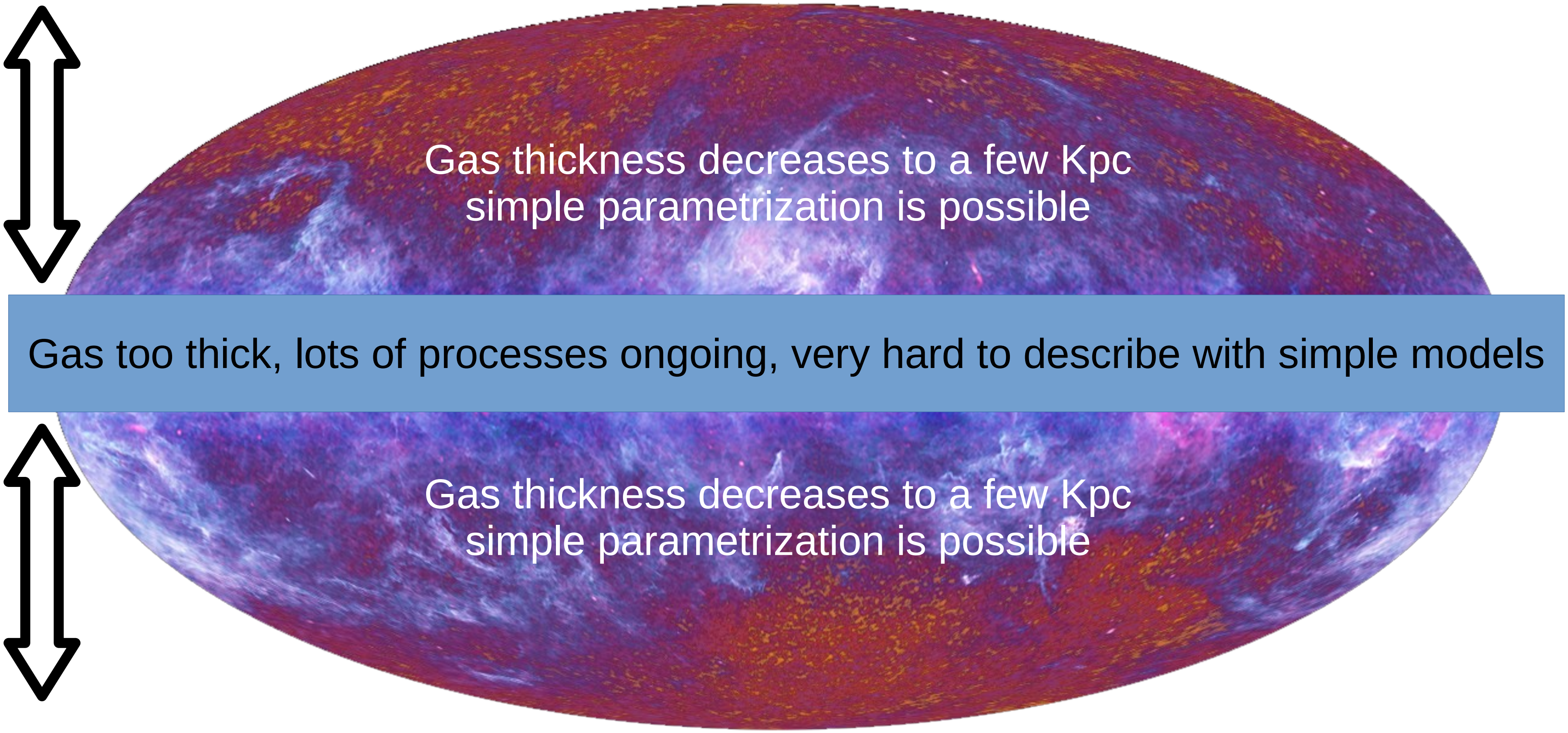


F=A (sky direction) × F(frequency)

Gas too thick, lots of processes ongoing, very hard to describe with simple models

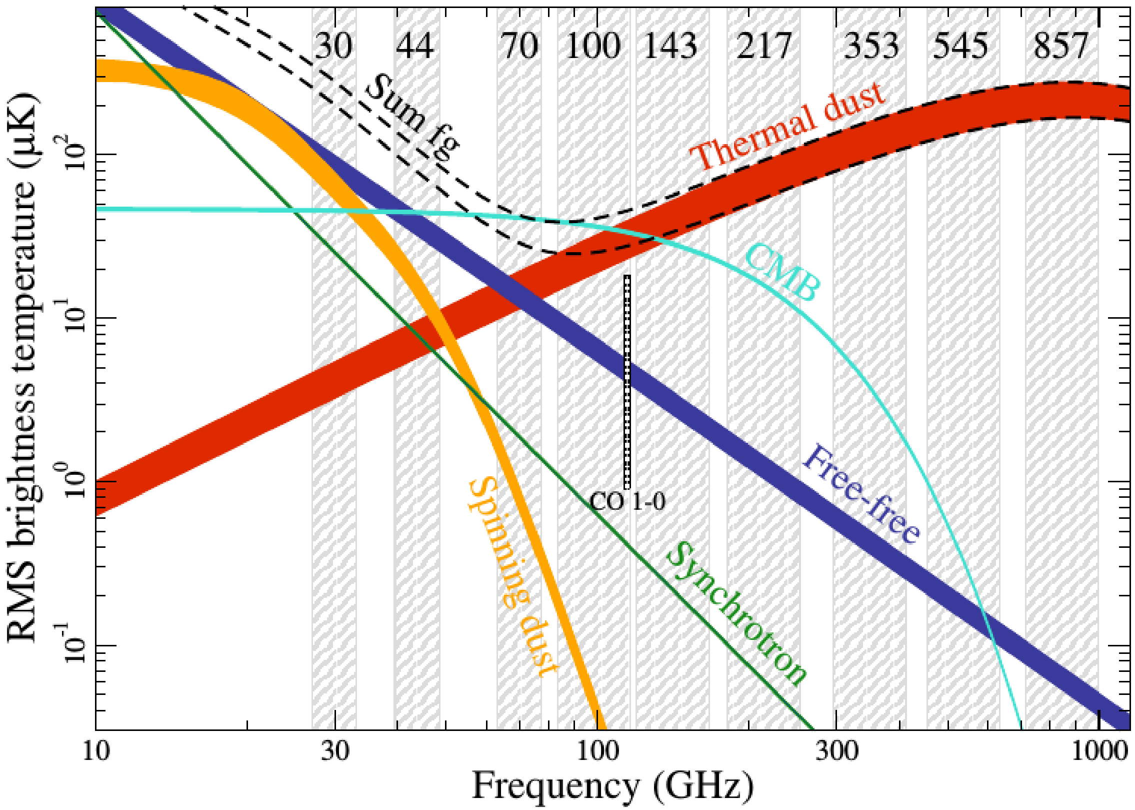
Planck 2013

F=A (sky direction) × F(frequency)



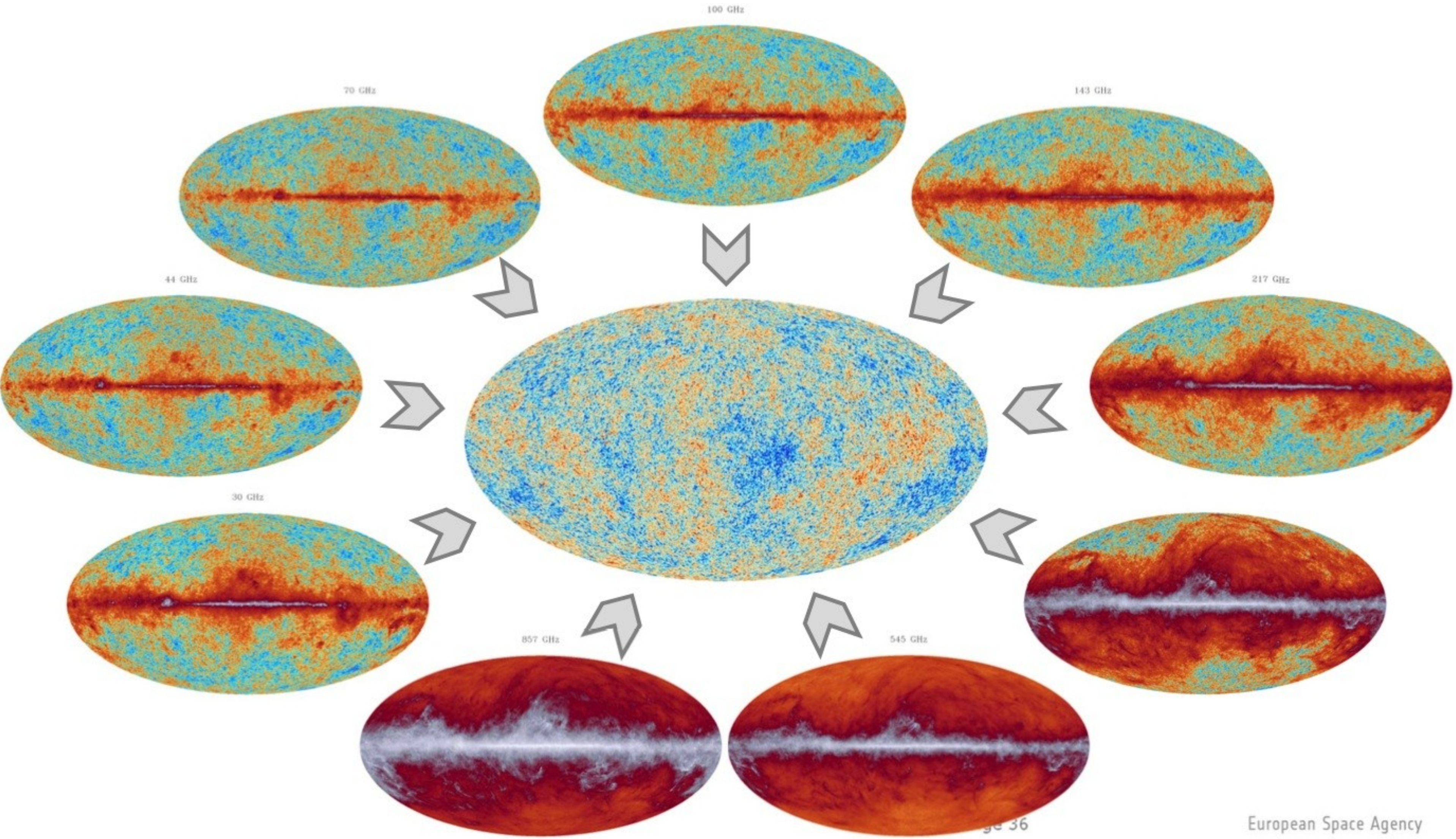
Planck 2013

Foregrounds and frequency



Planck 2015

Component separation



Component separation

$$X = A S + N$$

Component separation

data

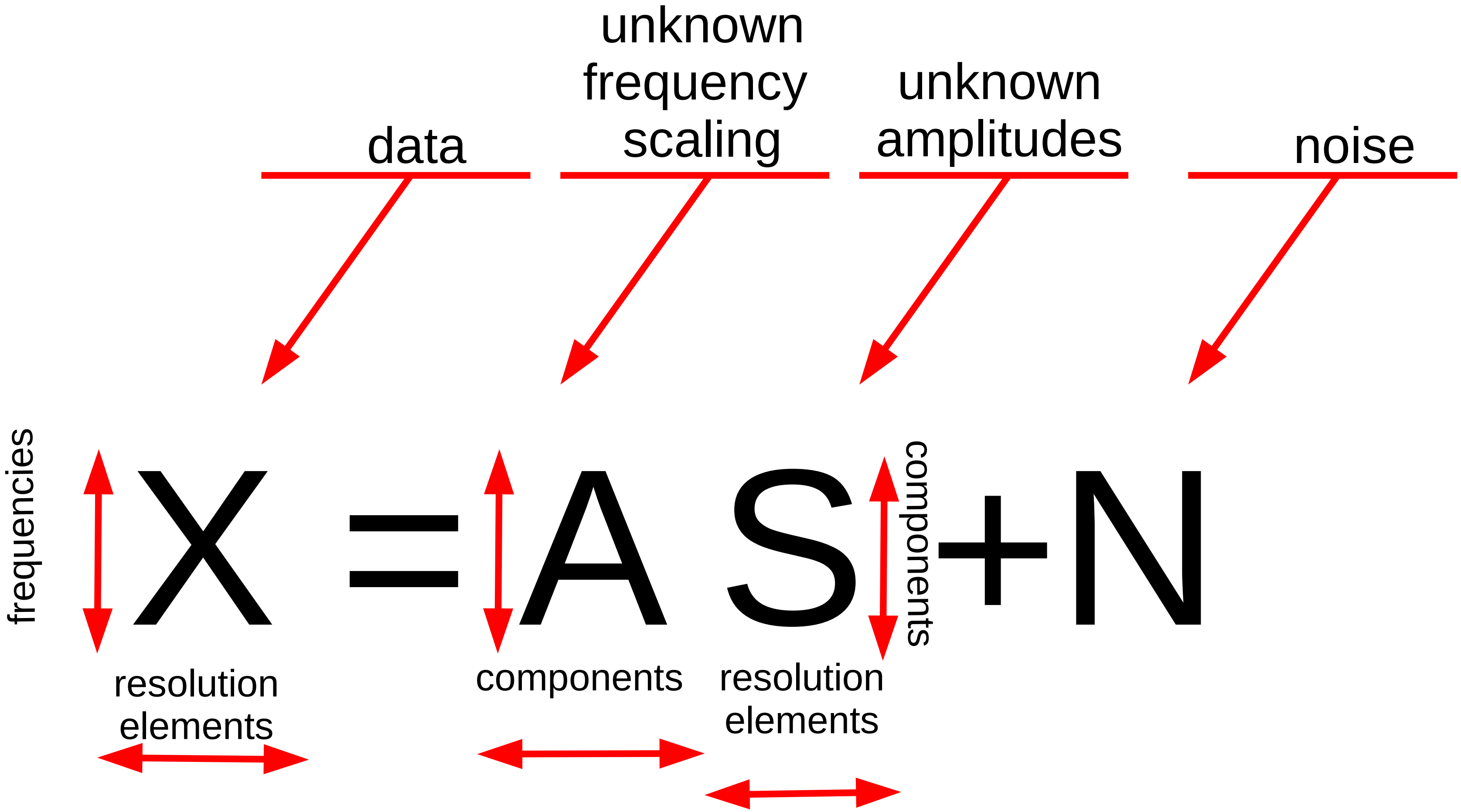
frequency scaling

amplitudes

noise

$$X = A\,S + N$$

Component separation



Component separation

- On foregrounds you...
  - Know nothing
  - Know something

Component separation

- Thus if you...
  - Know nothing, you
    - Look for minimum variance internal linear combination
  - Know something, you
    - Model foreground unknowns and fit

Component separation

- If you know nothing, you
  - Look for minimum variance internal linear combination, constrained to scale as a black body:

$$\sum_i w_i X_i \qquad \sum_i w_i = 1$$

Component separation

- Opearting domains: you can choose to cast your minimum variance search, or your fit, in
  - Pixel domain
  - Harmonic domain
  - Intermediate (needlets, wavelets) domain

Component separation

- Thus if you...
  - Know nothing, you
    - Look for minimum variance internal linear combination
      - In the pixel domain
      - In the needlet domain
  - Know something, you
    - Model foreground unknowns and fit
      - In the pixel domain
      - In the needlet domain

Component separation

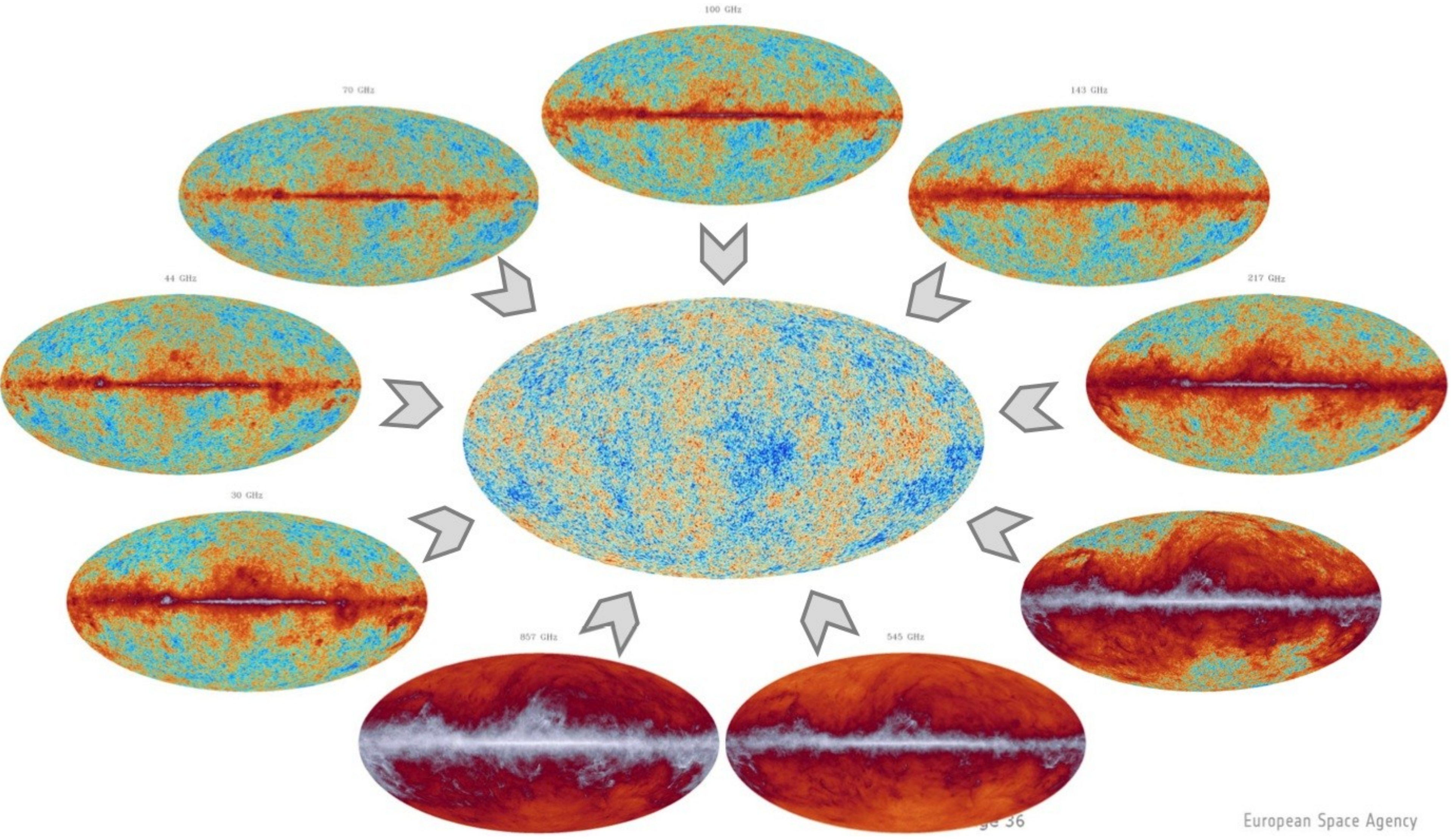
- Thus if you...
  - Know nothing, you
    - Look for minimum variance internal linear combination
      - In the pixel domain – SEVEM
      - In the needlet domain – NILC
  - Know something, you
    - Model foreground unknowns and fit
      - In the pixel domain – COMMANDER
      - In the needlet domain – SMICA

Component separation

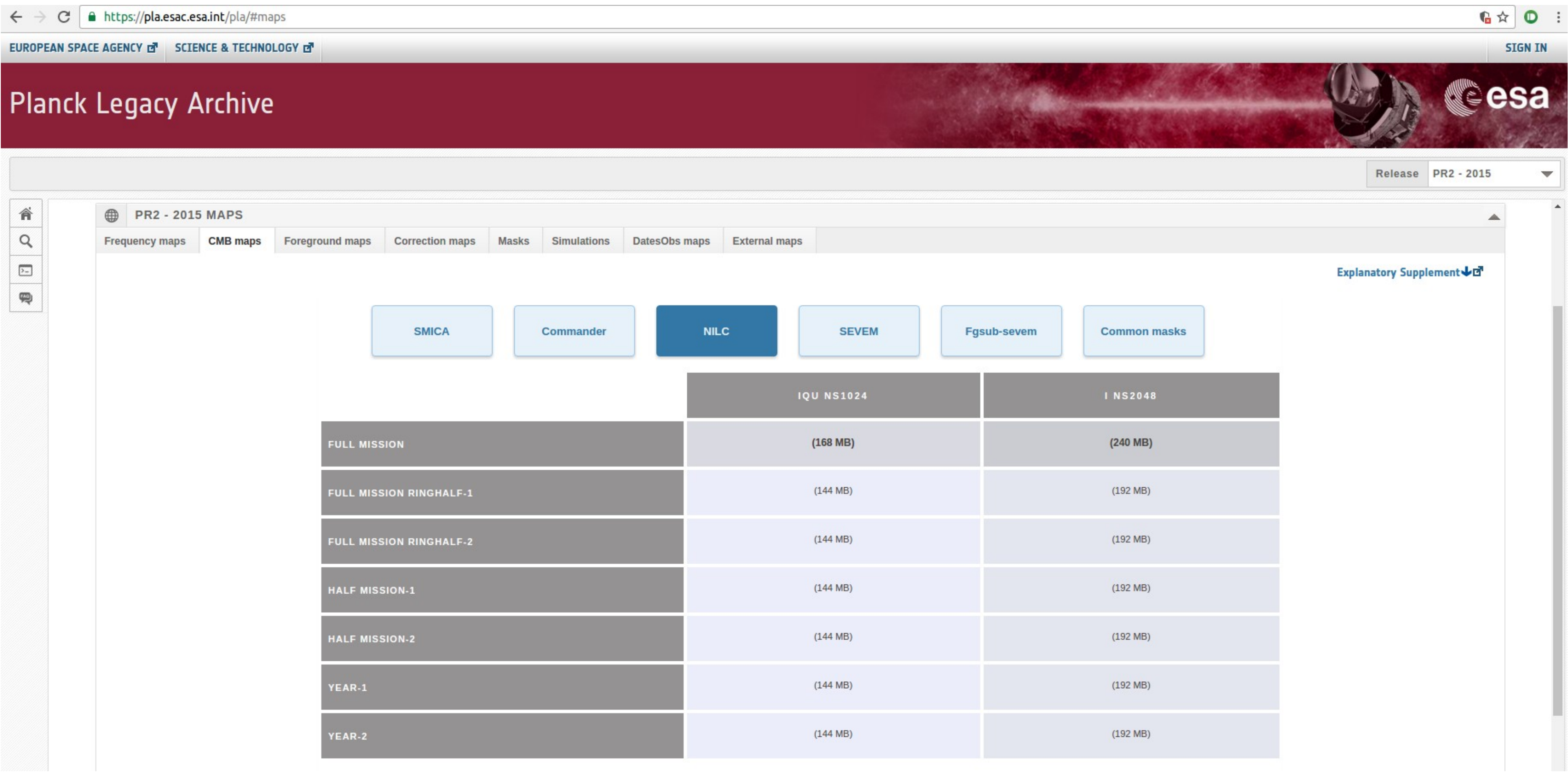
- Thus if you...
  - Know nothing, you
    - Look for minimum variance internal linear combination
      - In the pixel domain – SEVEM (CMB only)
      - In the needlet domain – NILC (CMB only)
  - Know something, you
    - Model foreground unknowns and fit
      - In the pixel domain – COMMANDER (CMB and foregrounds)
      - In the needlet domain – SMICA (CMB and foregrounds)

Planck 2013, XII, 2015, IX

Component separation



The Planck Legacy Archive



https://pla.esac.esa.int/pla/#maps

EUROPEAN SPACE AGENCY | SCIENCE & TECHNOLOGY | SIGN IN

Planck Legacy Archive

esa

Release PR2 - 2015

PR2 - 2015 MAPS

Frequency maps | CMB maps | Foreground maps | Correction maps | Masks | Simulations | DatesObs maps | External maps

Explanatory Supplement

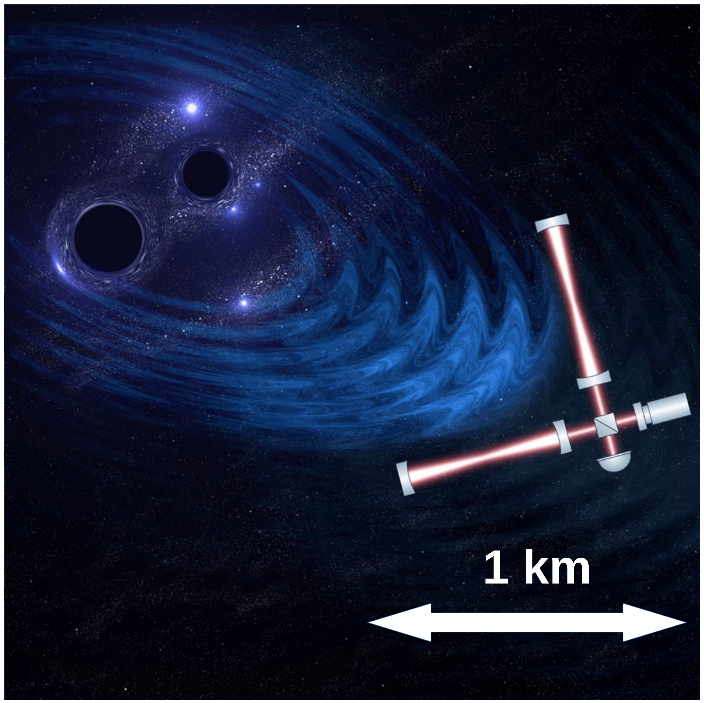
SMICA | Commander | NILC | SEVEM | Fgsub-sevem | Common masks

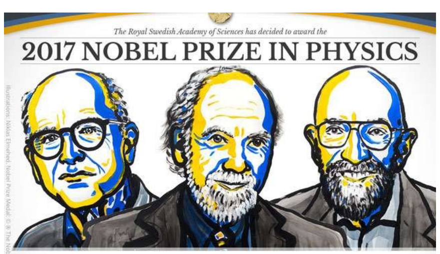
	IQU NS1024	I NS2048
FULL MISSION	(168 MB)	(240 MB)
FULL MISSION RINGHALF-1	(144 MB)	(192 MB)
FULL MISSION RINGHALF-2	(144 MB)	(192 MB)
HALF MISSION-1	(144 MB)	(192 MB)
HALF MISSION-2	(144 MB)	(192 MB)
YEAR-1	(144 MB)	(192 MB)
YEAR-2	(144 MB)	(192 MB)

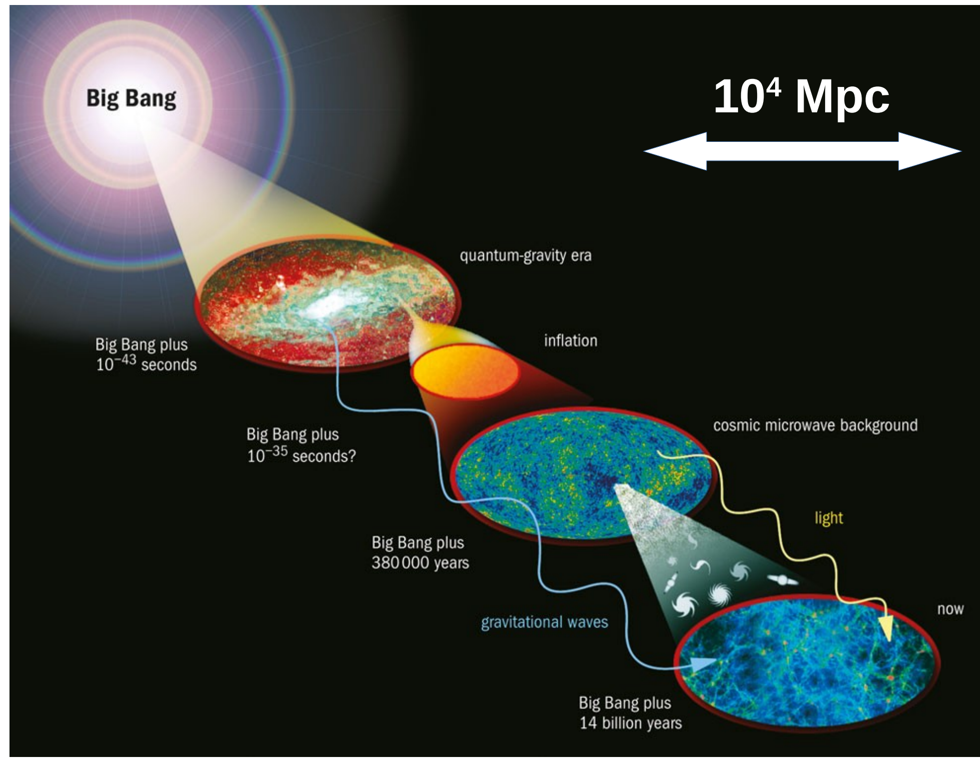
Cosmological Gravitational Waves

Astrophysical vs Cosmological GWs

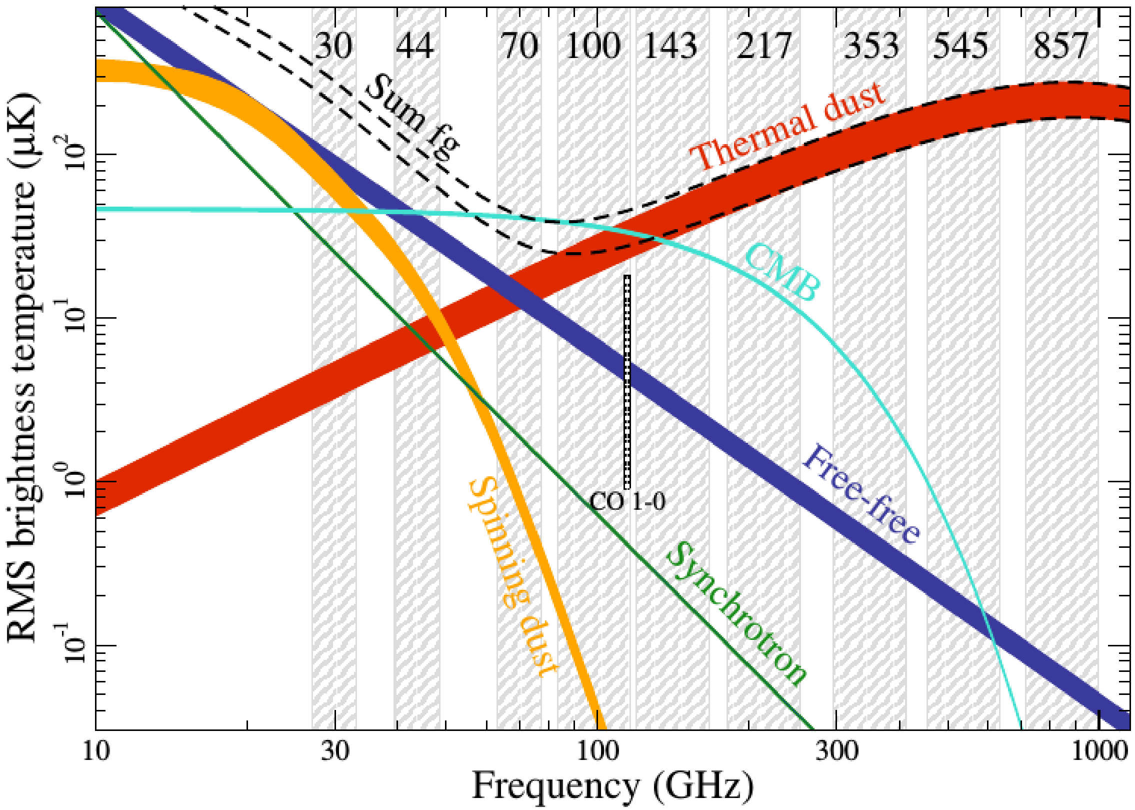
1 km





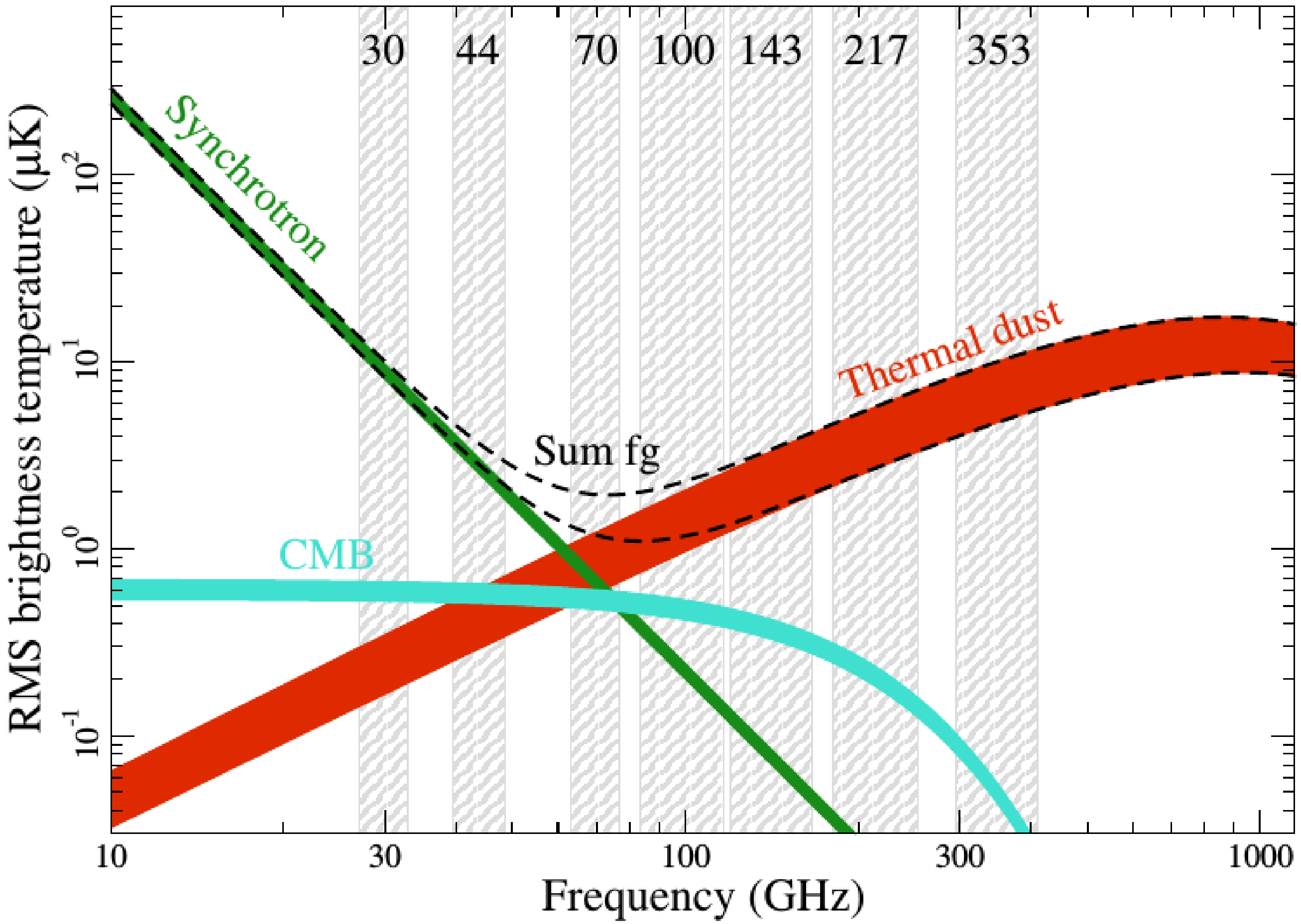


Polarized Foregrounds are worse



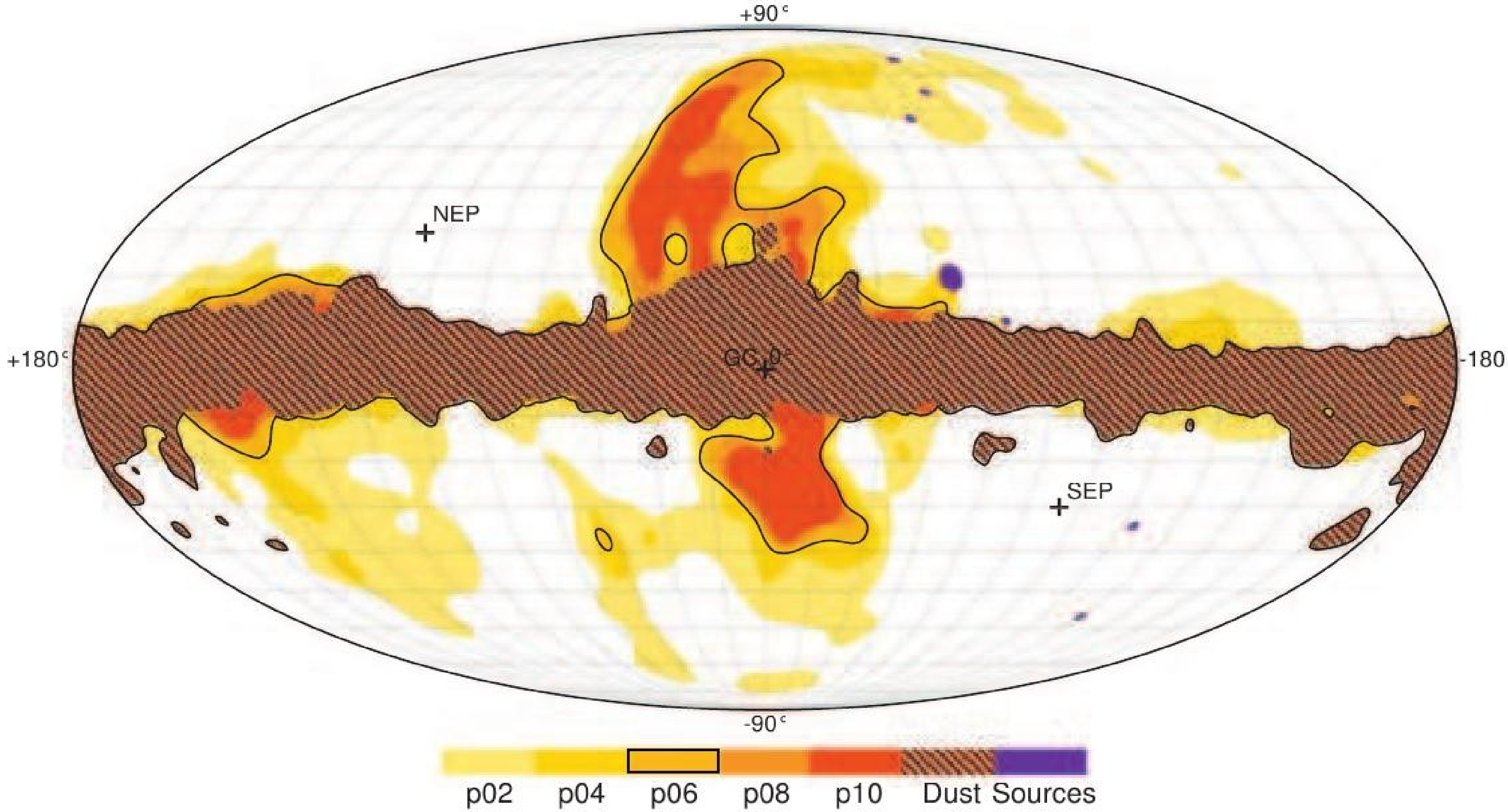
Planck 2018

Polarized Foregrounds are worse



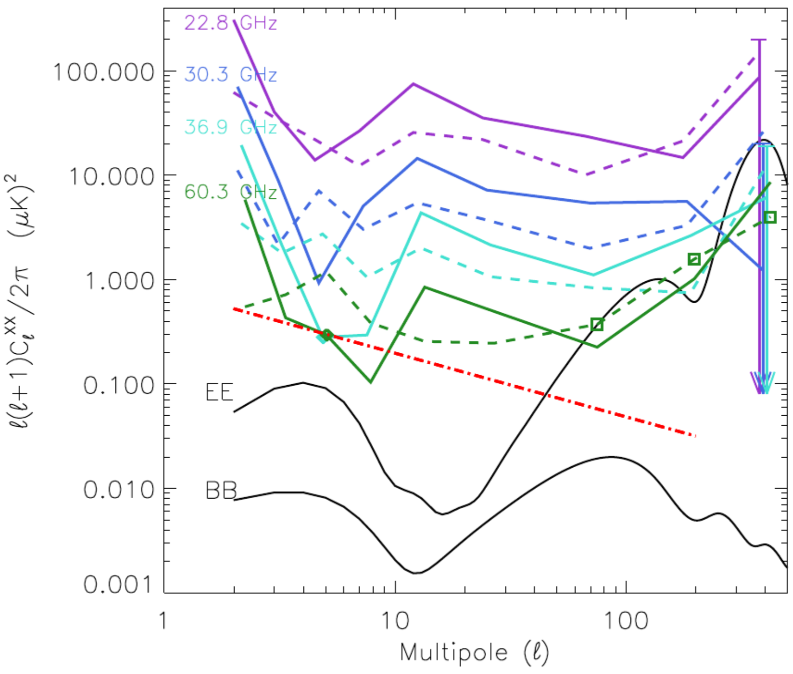
Planck 2018

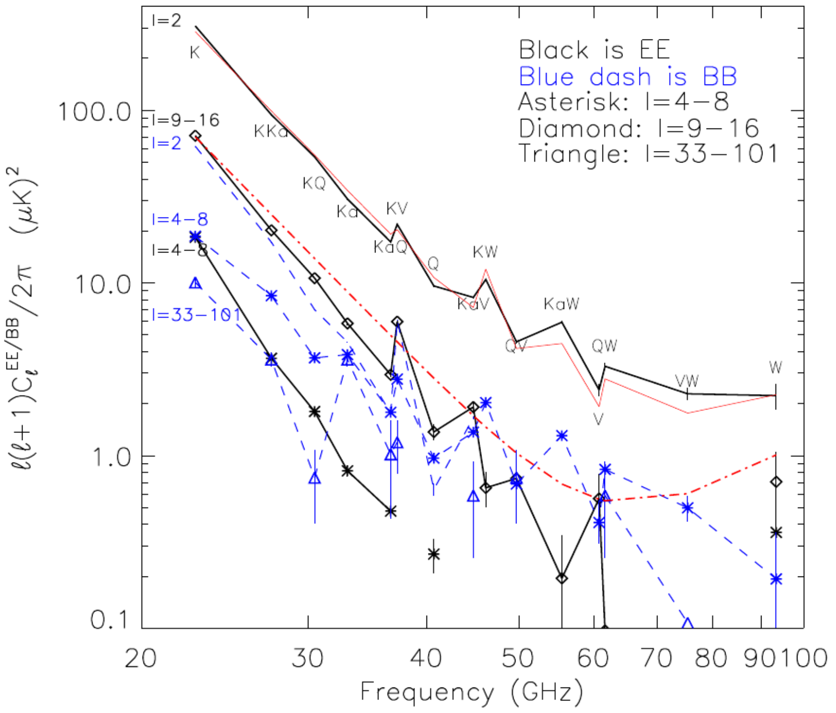
Sky masking in polarization



WMAP 2007

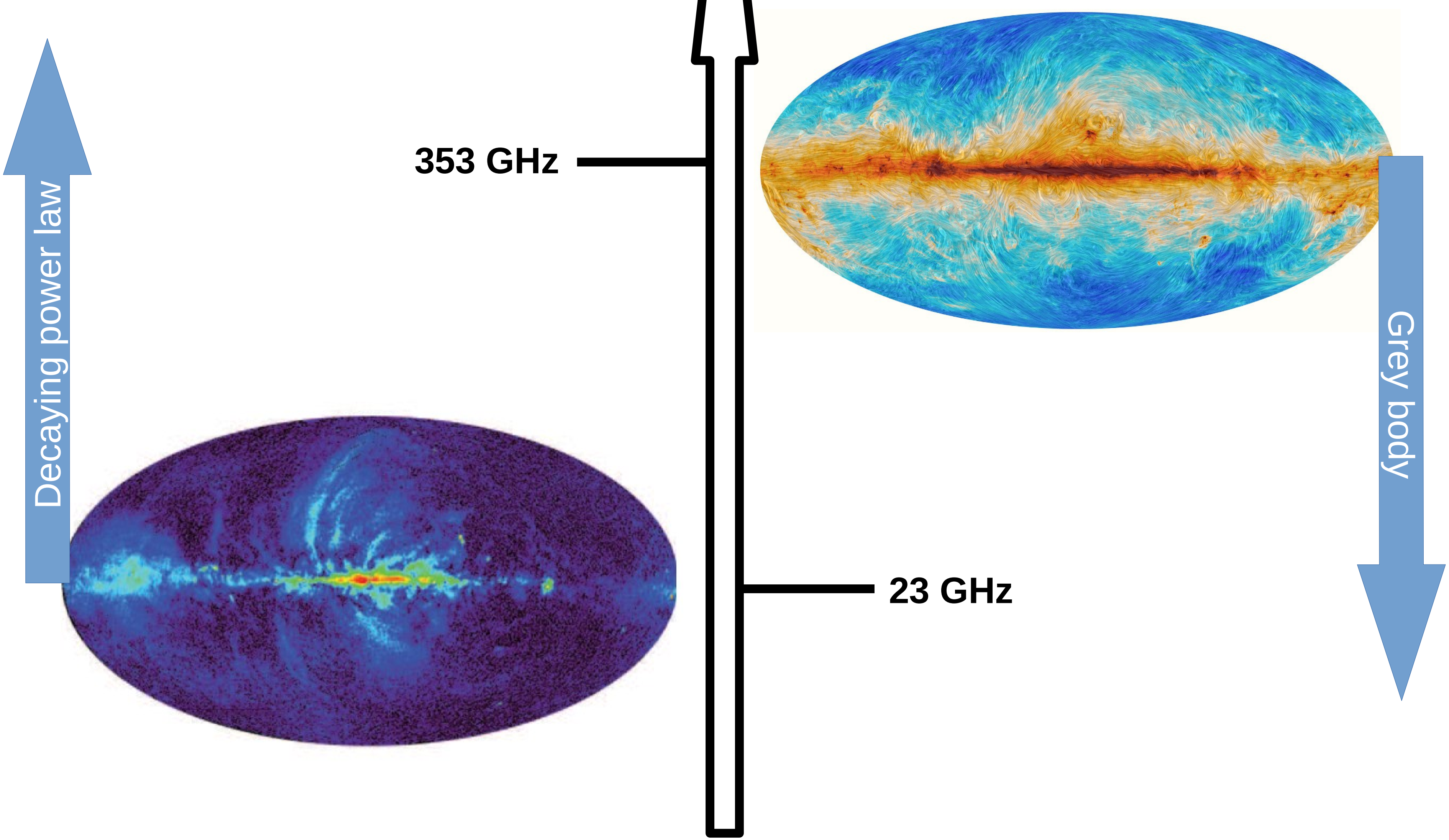
WMAP polarised foregrounds



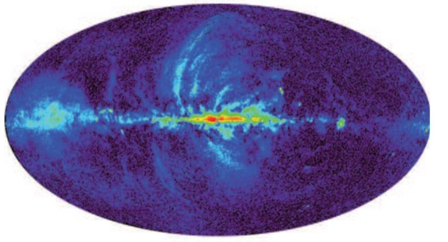


WMAP 2007

Galactic polarized foregrounds

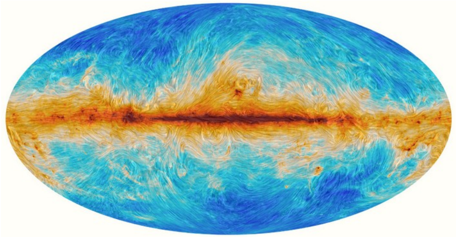


Polarized synchrotron



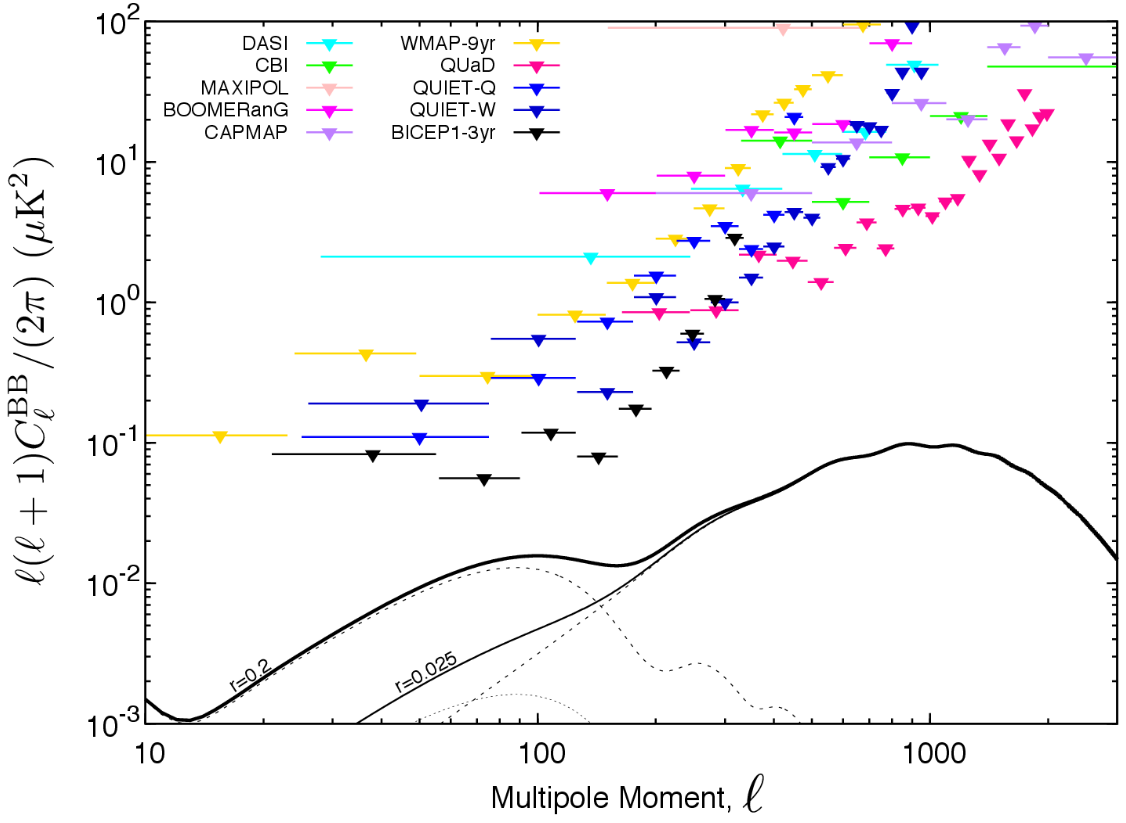
- Amplitude: cosmic ray electrons spilarizing around the Galactic magnetic field
- Frequency scaling: approximate decaying power law frequency scaling ($F_{RJ} \sim f^{-3}$), determined by the electron distribution in energy
- Data: total intensity and polarization, several surveys at radio frequencies, WMAP and Planck at microwave frequencies
- Data at the required quality for B-mode cleaning: none

Polarized dust



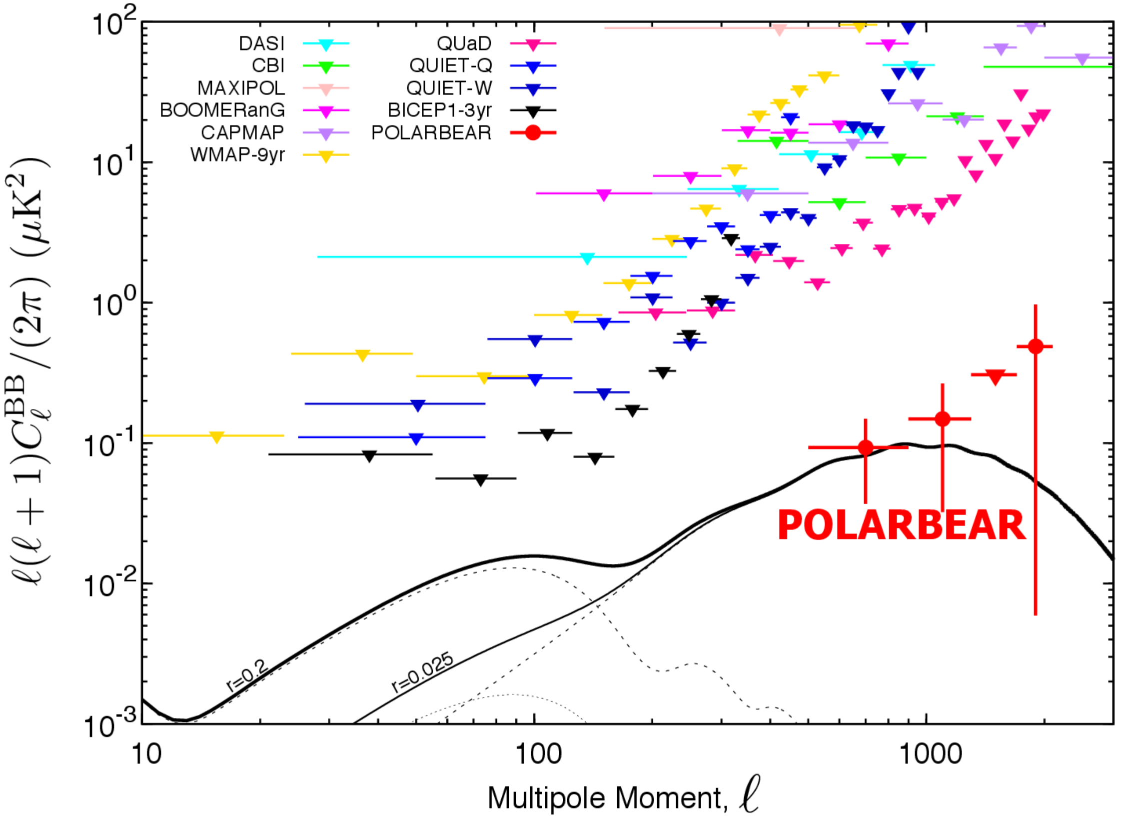
- Amplitude: magnetized dust grains emitting almost thermally, linearly polarized via local alignment with the Galactic magnetic field
- Frequency scaling: grey body $F_{RJ} \sim BB(f) \times f^{1.5}$
- Total intensity data: high resolution (few arcminutes) and sensitivity (IRAS and Planck) at 3000, 857, 545, 353 GHz for total intensity, degree scale mapping of temperature and emissivity
- Polarization data: Planck 2015 at 353 GHz
- Data at the required quality for B-mode cleaning: none

Early 2014



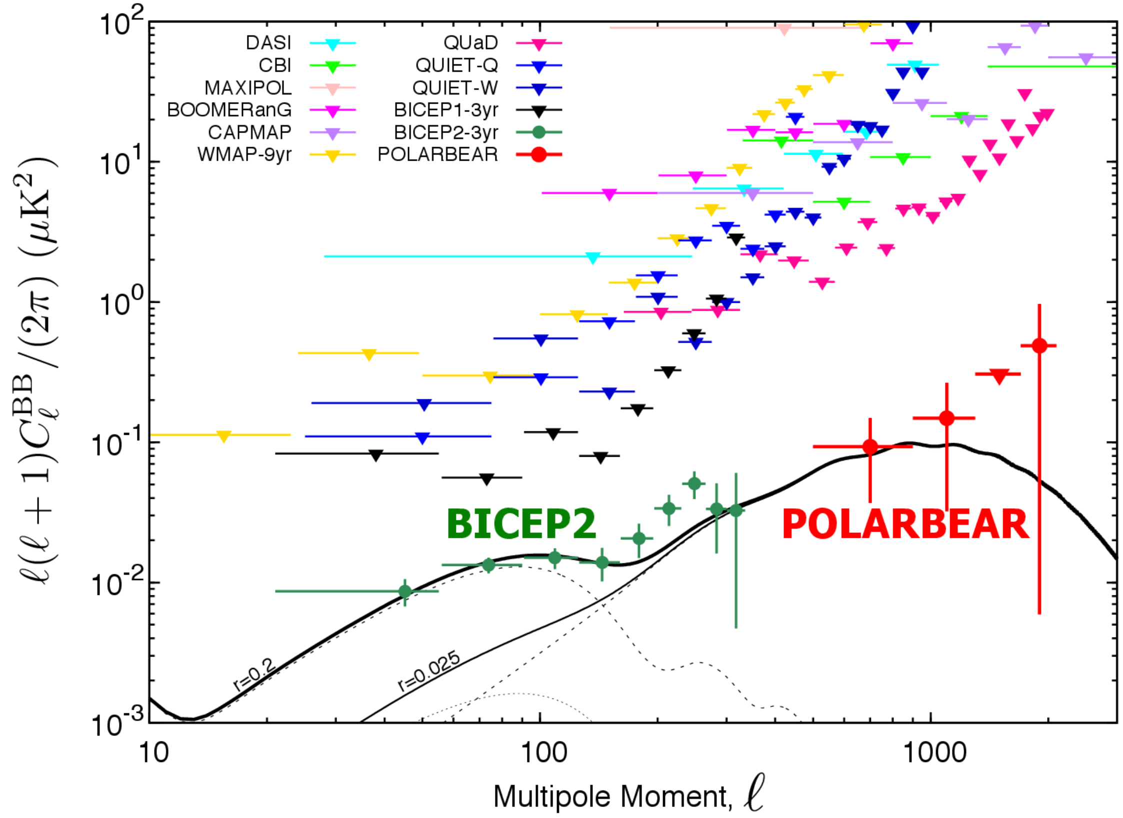
DASI
CBI
MAXIPOL
BOOMERanG
CAPMAP
WMAP-9yr
QUaD
QUIET-Q
QUIET-W
BICEP1-3yr
r=0.2
r=0.025
Multipole Moment, ℓ
$\ell(\ell+1)C_\ell^{BB}/(2\pi)\ (\mu K^2)$

March 2014

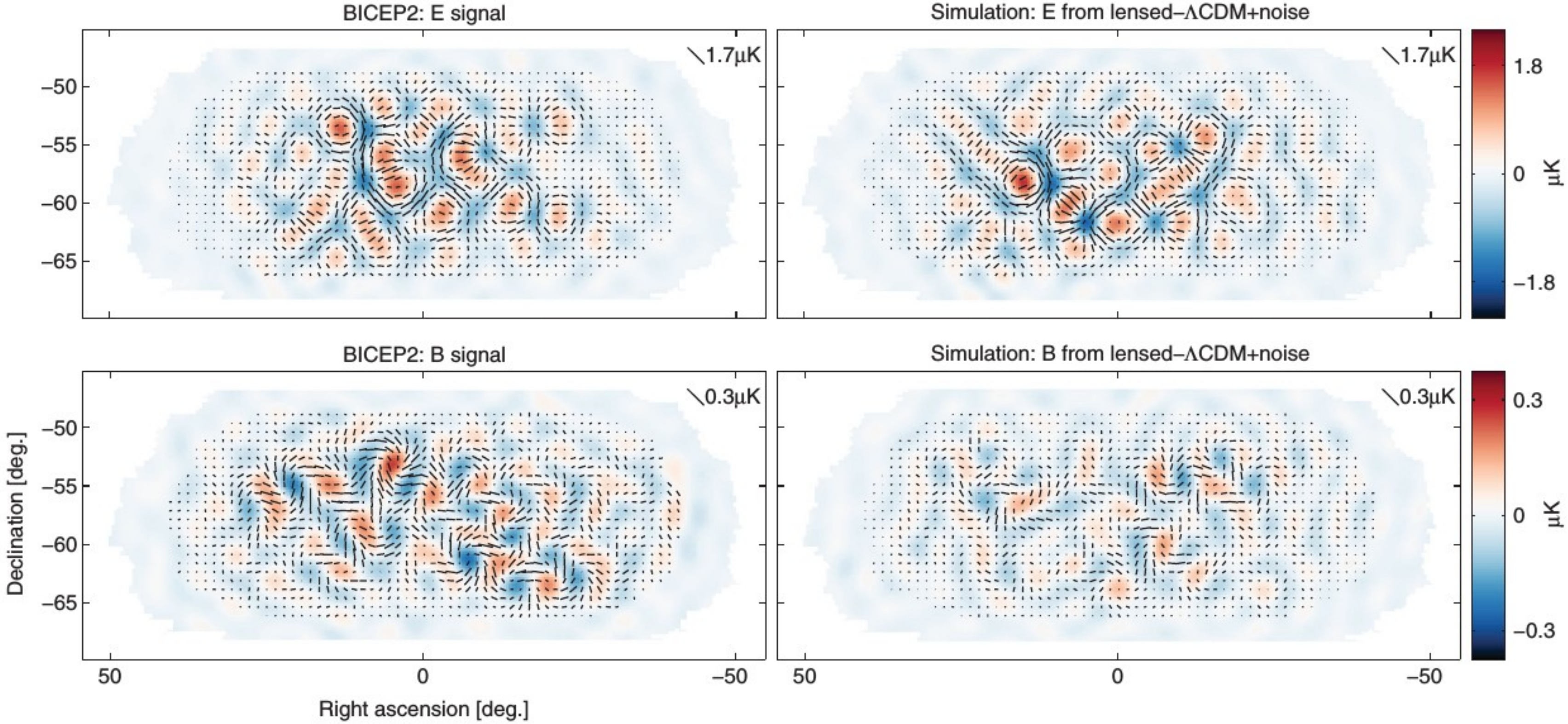


DASI
CBI
MAXIPOL
BOOMERanG
CAPMAP
WMAP-9yr
QUaD
QUIET-Q
QUIET-W
BICEP1-3yr
POLARBEAR
POLARBEAR
r=0.2
r=0.025
$\ell(\ell+1)C_\ell^{BB}/(2\pi)\ (\mu K^2)$
Multipole Moment, ℓ
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10
100
1000

March 2014

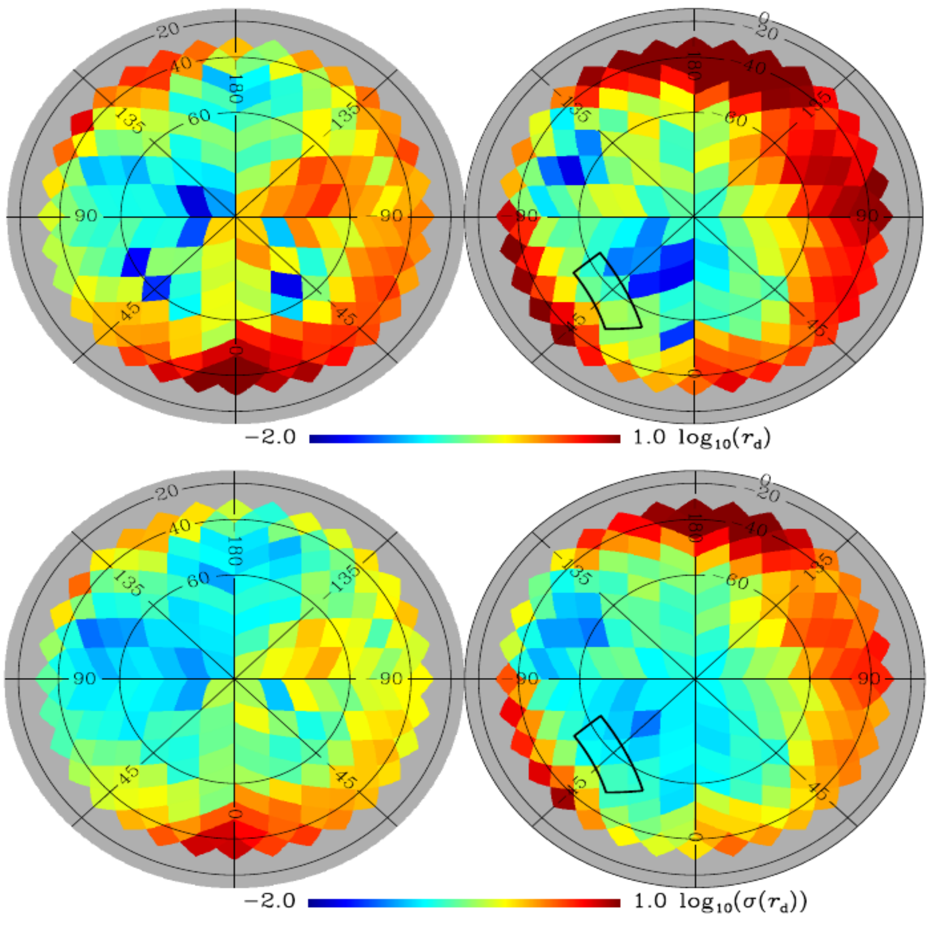

DASI
CBI
MAXIPOL
BOOMERanG
CAPMAP
WMAP-9yr
QUaD
QUIET-Q
QUIET-W
BICEP1-3yr
BICEP2-3yr
POLARBEAR
BICEP2
POLARBEAR
r=0.2
r=0.025
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10
100
1000
Multipole Moment, ℓ
$\ell(\ell+1)C_\ell^{BB}/(2\pi)\ (\mu K^2)$

The B-modes at degree scale



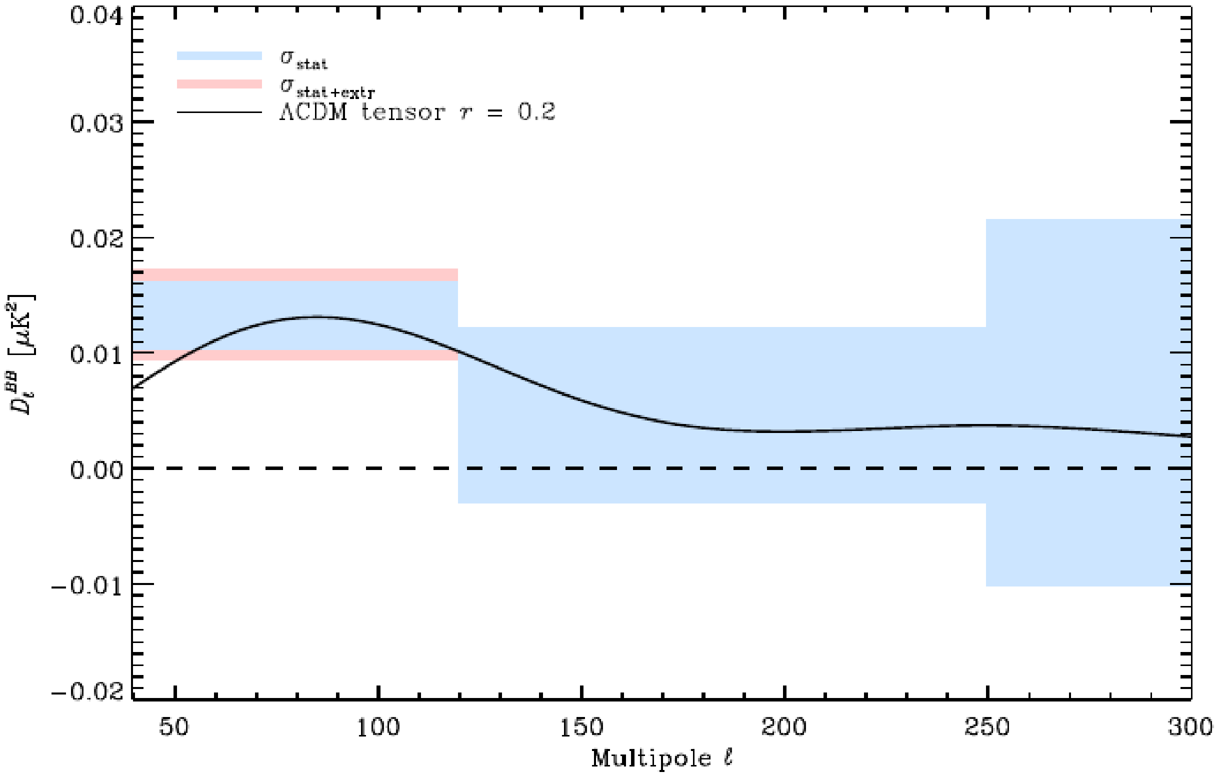
BICEP 2014

Planck observed dust polarization at high latitudes



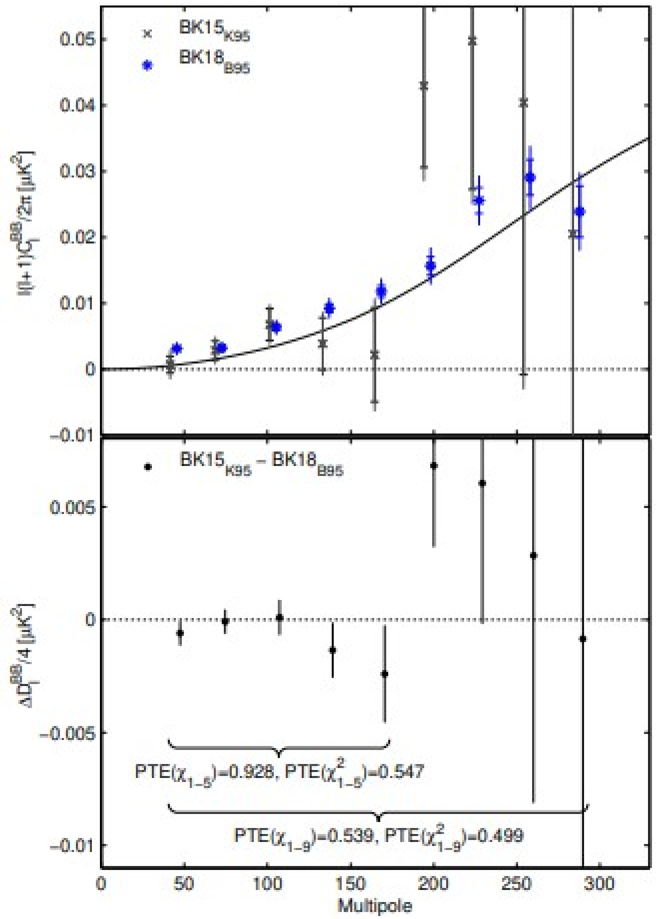
Planck 2014

Planck observed dust polarization in the BICEP2 area



Planck 2014

Planck × Bicep2 × KEcK



BKP 2018

Measuring the Abundance of Cosmological Gravitational Waves through the Tensor to Scalar Ratio

$$r = \frac{\text{Power in GWs}}{\text{Power in Density}}$$

Measuring the Abundance of Cosmological Gravitational Waves through the Tensor to Scalar Ratio

$$r = \frac{\text{Tensors}}{\text{Scalars}}$$

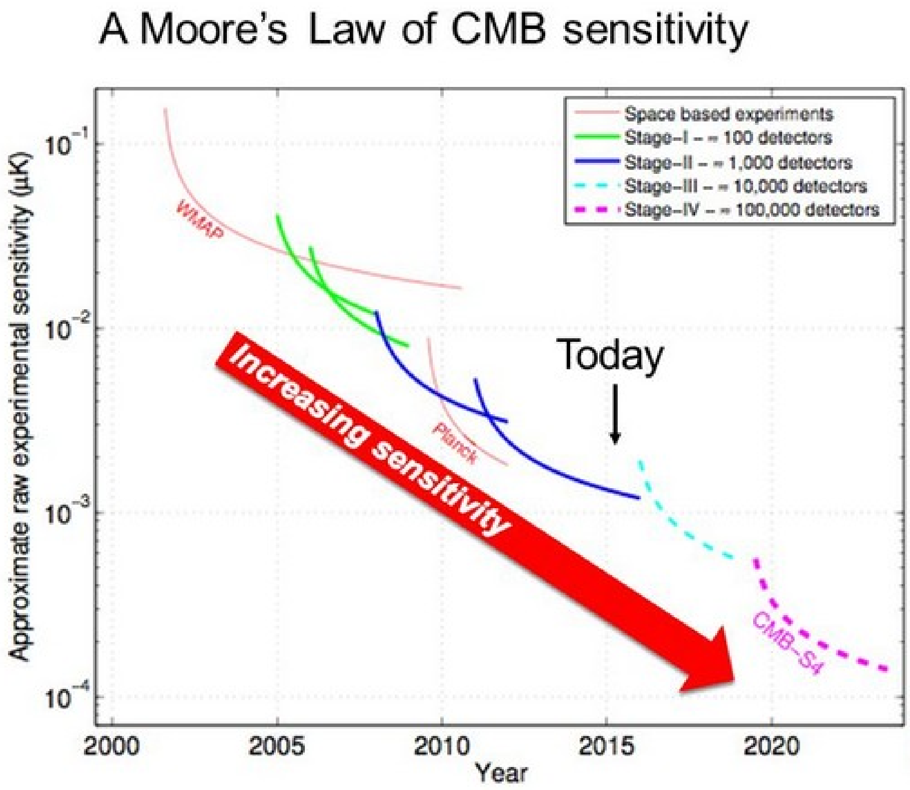
Planck × Bicep2 × KEcK

$$r < 0.036 \text{ at } 95\% \text{ C.L.}$$

BKP 2021

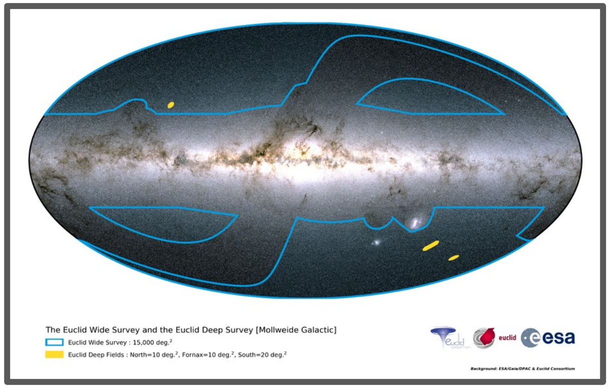
Roadmap till 2030

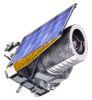
Future B-Mode Probes: Datasets



Plot by Julian Borrill

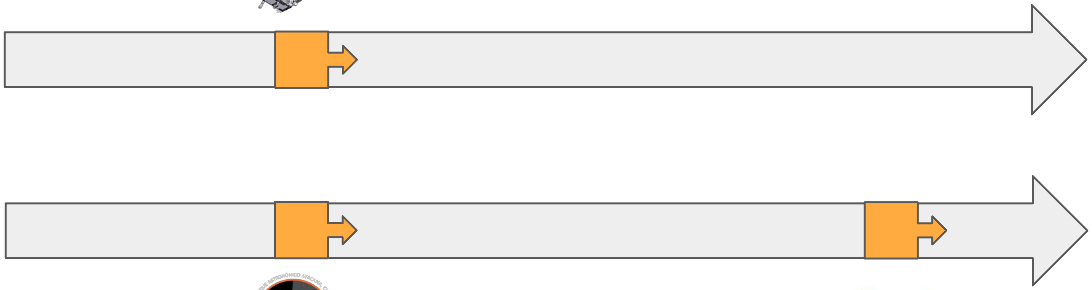
Future B-Mode Probes: Timeline





2023

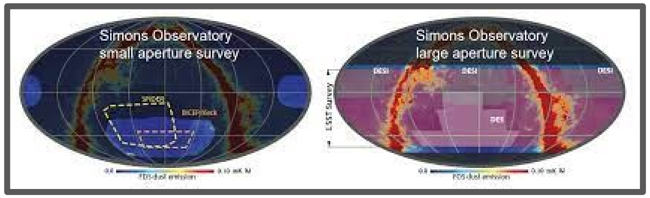
2028

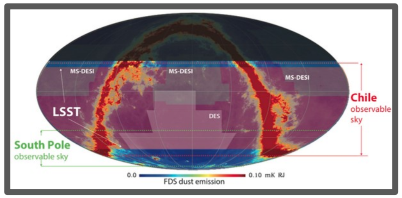


Simons Observatory

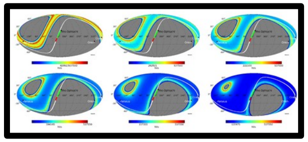
LiteBIRD

CMB-S4 Next Generation CMB Experiment





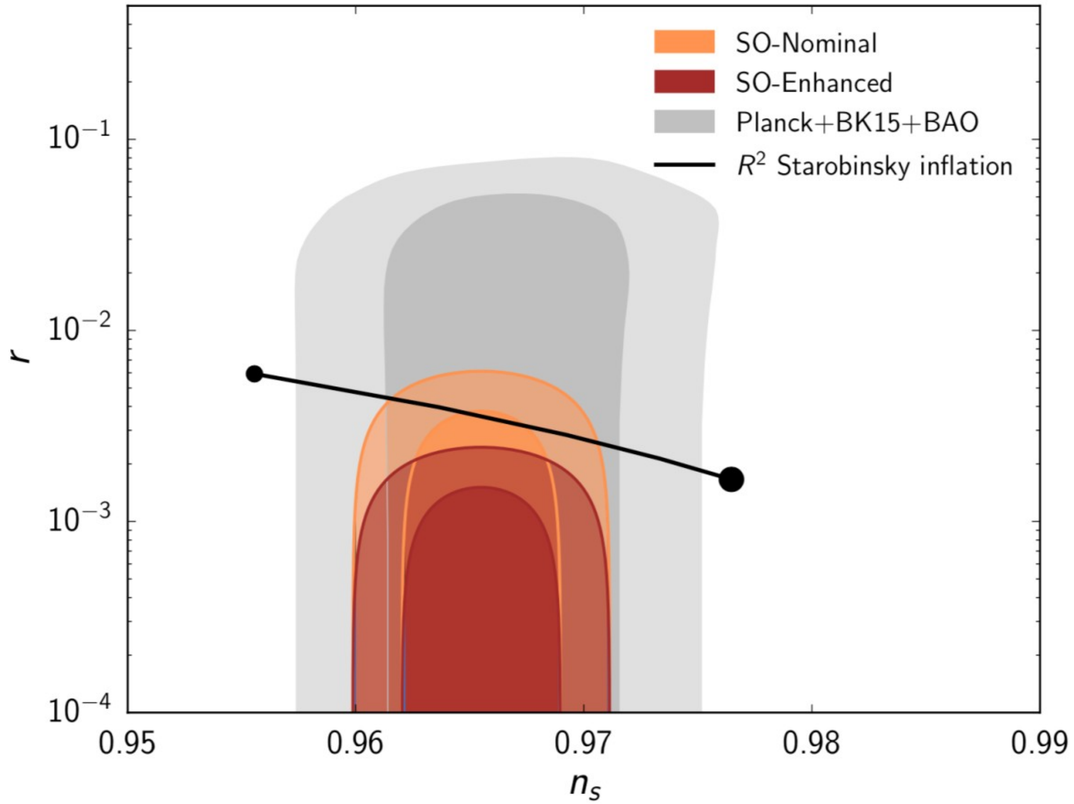
Low Frequency Surveys



Future B-Mode Probes: Simons Observatory

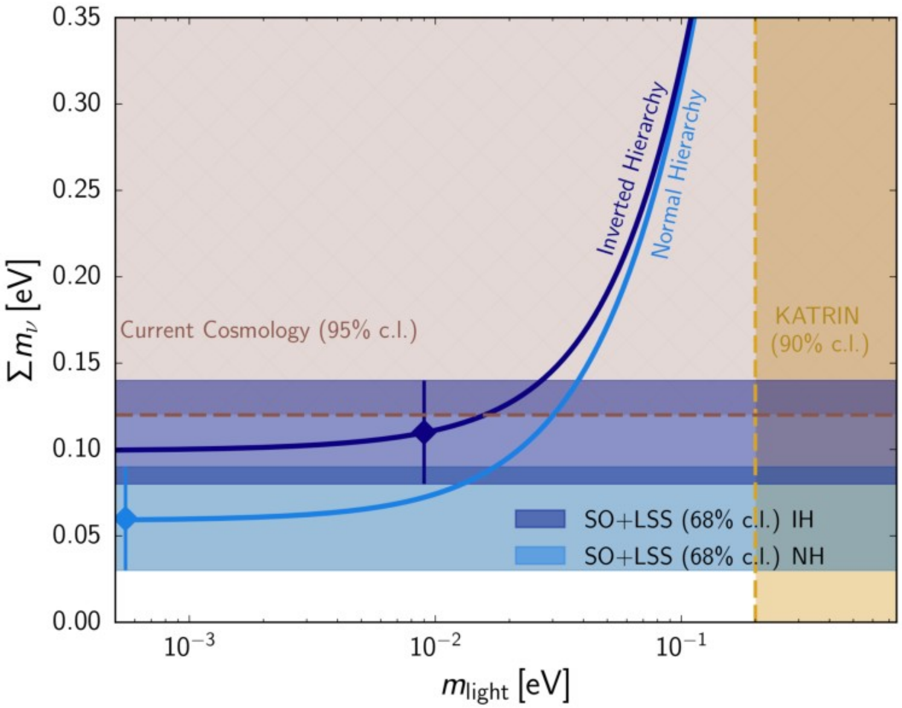
simonsobservatory.org

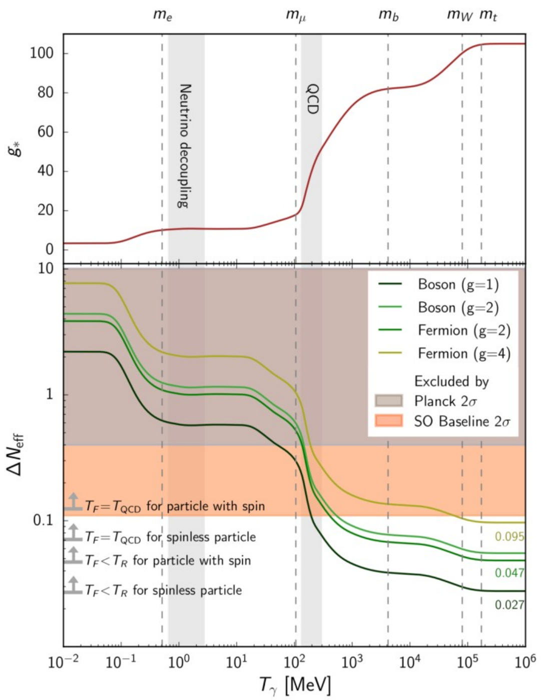
Future B-Mode Probes: Simons Observatory



simonsobservatory.org

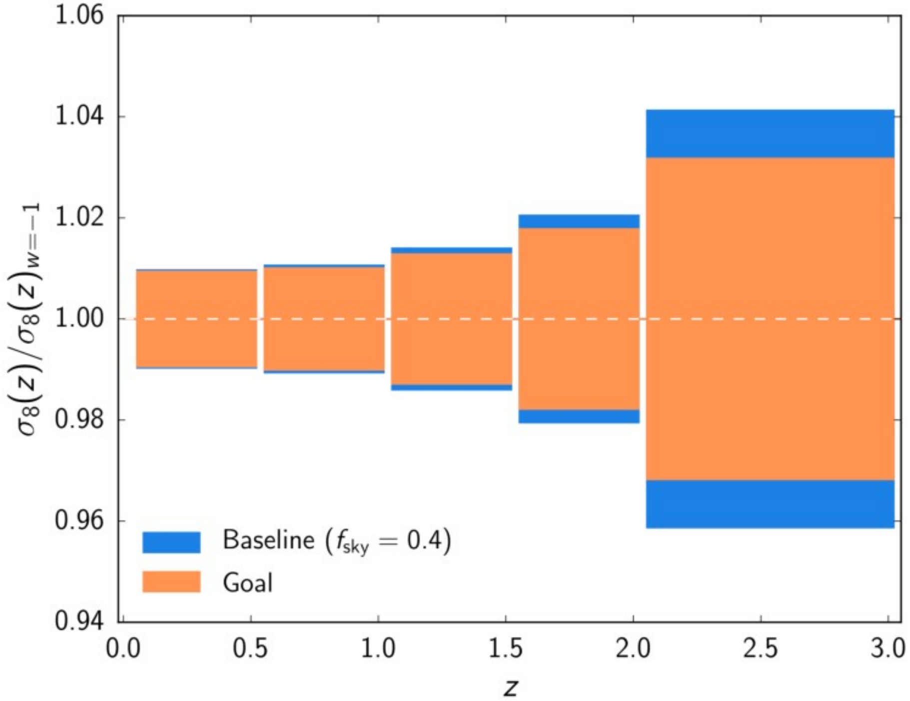
Future B-Mode Probes: Simons Observatory

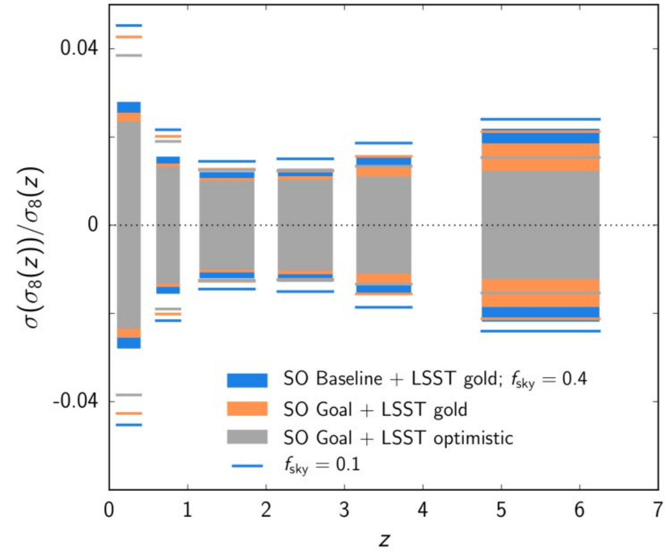




simonsobservatory.org

Future B-Mode Probes: Simons Observatory





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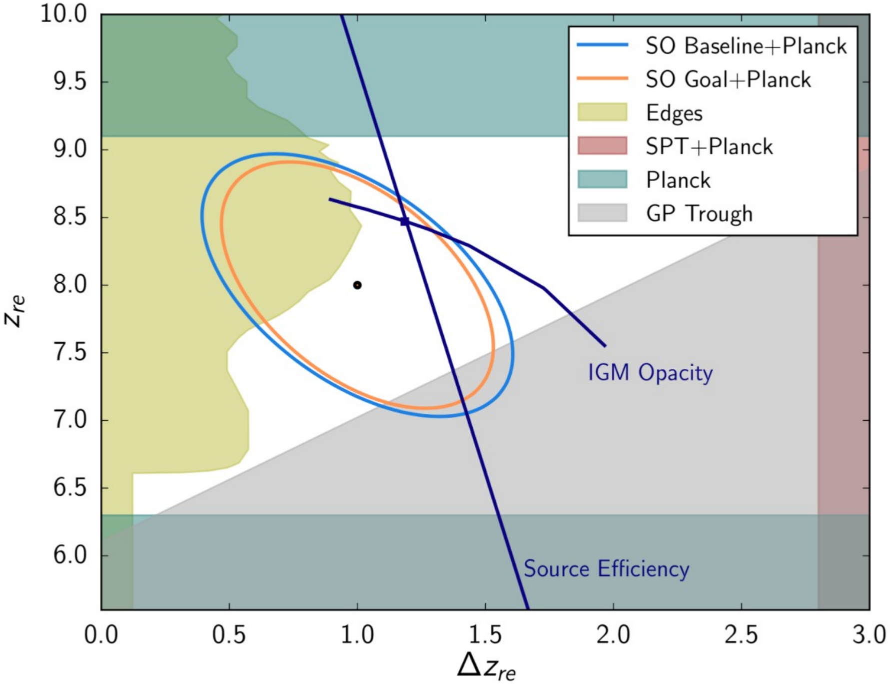
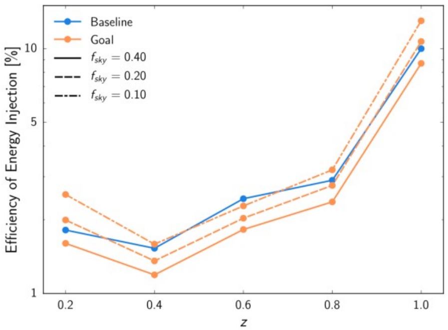
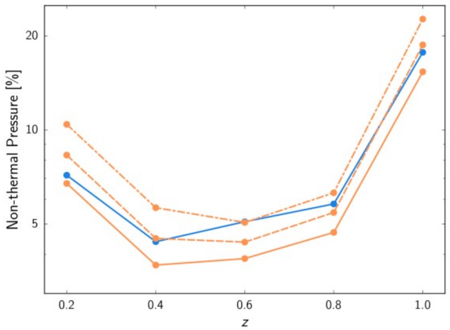
Future B-Mode Probes: Simons Observatory







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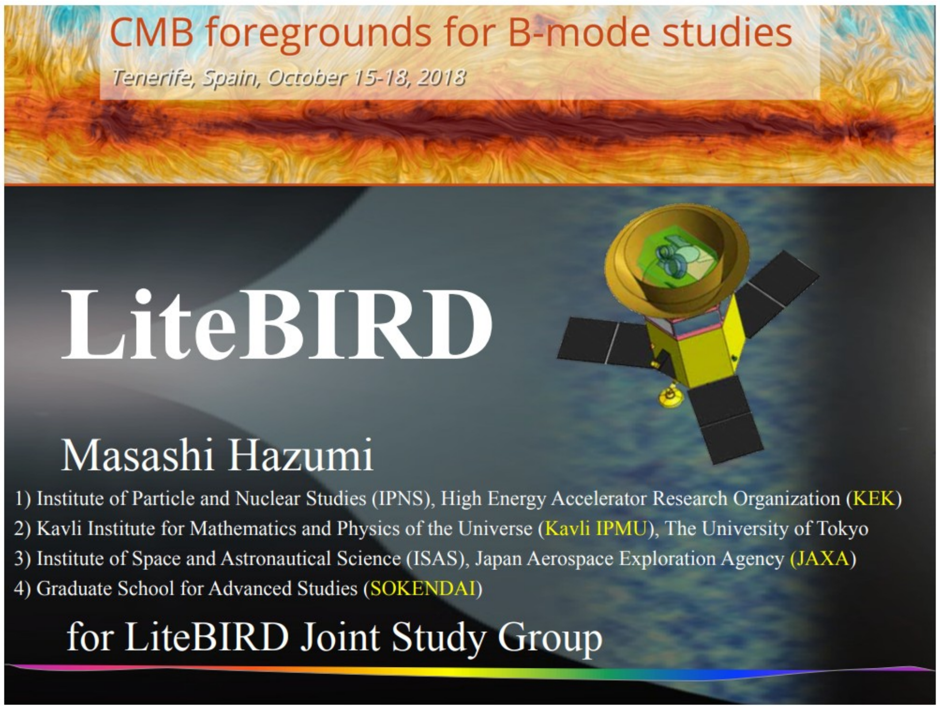
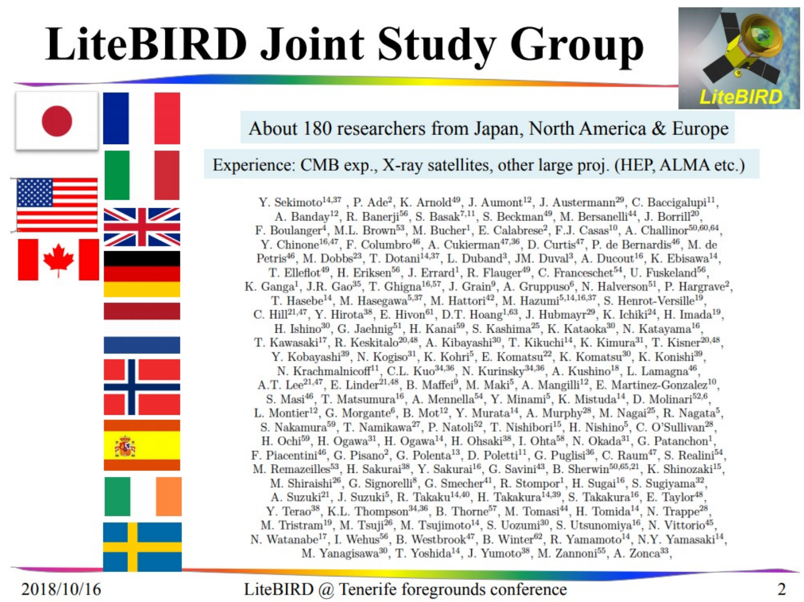
Future B-Mode Probes: LiteBIRD





Future B-Mode Probes: LiteBIRD

LiteBIRD project overview

- JAXA L-class mission candidate with a solid basis in Japan
  - JAXA prefers a focused mission even for L-class
  - Test of inflation is one of the most important objectives in JAXA roadmap
  - MEXT (funding agency) chose LiteBIRD as one of 10 flag-ship future large projects among all areas of research
- Phase-A1 concept development at ISAS/JAXA (Sep.2016 – Aug. 2018) completed
  - The most advanced status among all CMB space mission proposals in the world
- Strong international contributions
  - US: Focal plane/cold readout technology development (NASA)
  - Canada: Science contribution studies and science maturity studies (CSA)
  - Europe:
    - Studies at Concurrent Design Facility (ESA) with the European consortium
    - Italy: Phase A commitment (ASI)
    - France: Phase A commitment (CNES)

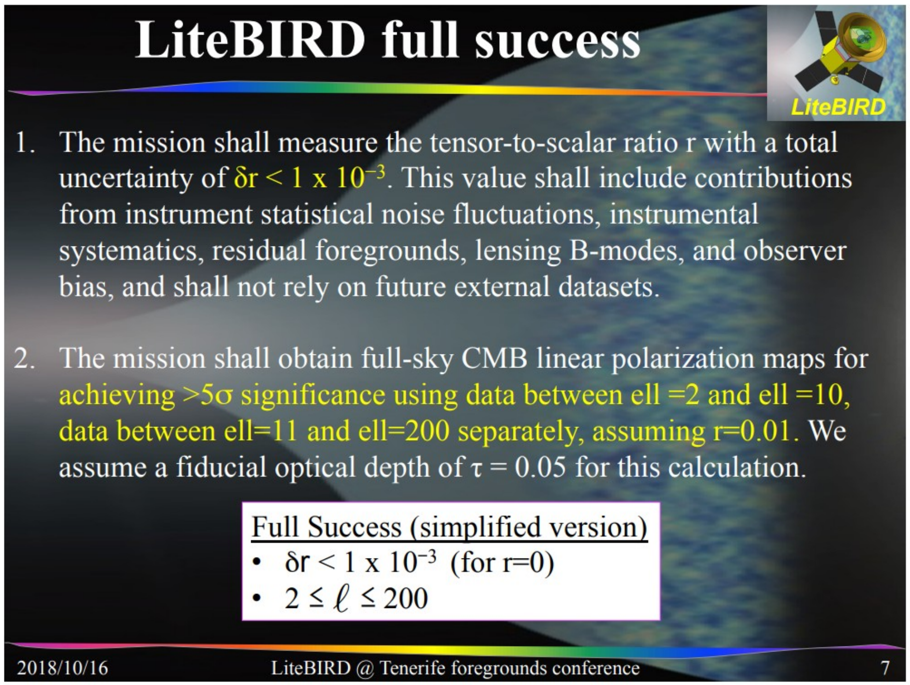
2018/10/16 LiteBIRD @ Tenerife foregrounds conference 4

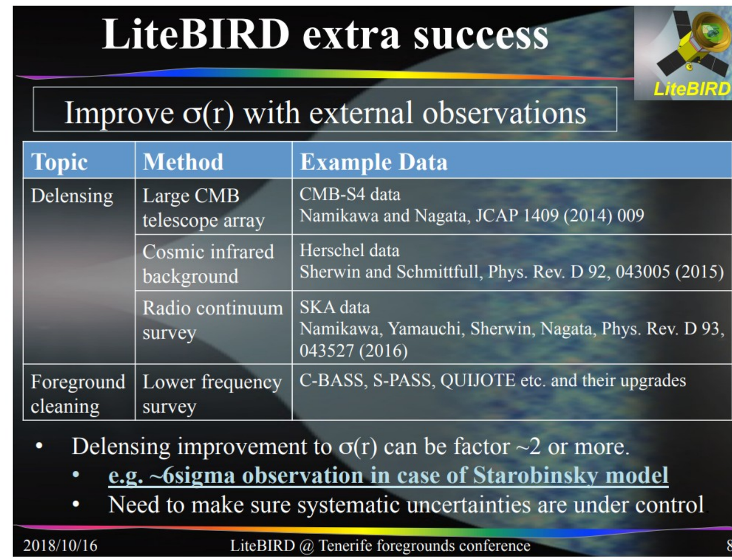
Schedule after Phase-A1

- Final down selection in early 2019
  - LiteBIRD or OKEANOS (solar-power sail), i.e. only two candidates remain
- Launch in 2027
- Observation in L2 for 3 years

2018/10/16 LiteBIRD @ Tenerife foregrounds conference 5

Future B-Mode Probes: LiteBIRD



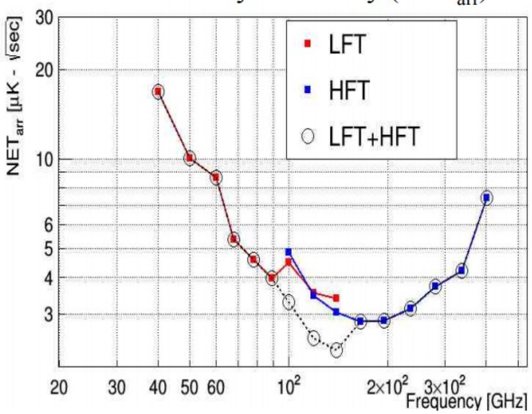


Future B-Mode Probes: LiteBIRD

Sensitivity

- Good sensitivities under available focal planes
- Further optimization possible w/ minor design impact

Detector array sensitivity (NET_{arr})



NET_{arr} → Sky sensitivity

Frequency [GHz]	$NET_{CMB,Arr}$ [$\mu K \cdot \sqrt{s}$]	Sensitivity [μK – arcmin]
40	16.76	34.99
50	10.04	20.96
60	8.67	18.09
68	5.37	11.21
78	4.57	9.54
89	3.97	8.29
100	3.39	6.88
119	2.49	5.19
140	2.27	4.75
166	2.85	5.96
195	2.86	5.97
235	3.13	6.52
280	3.73	7.79
337	4.22	8.82
402	7.40	15.44

(3yr obs.)

Foreground cleaning

Methodology

Synchrotron: $[Q_s, U_s](\hat{n}, \nu) = [Q_s, U_s](\hat{n}, \nu_*) \left(\frac{\nu}{\nu_*}\right)^{\beta_s(\hat{n}) + C_s(\hat{n}) \ln(\nu/\nu_*^C)}$

- AME is effectively absorbed by synchrotron curvature

Dust: $[Q_d, U_d](\hat{n}, \nu) = [Q_d, U_d](\hat{n}, \nu_*) \left(\frac{\nu}{\nu_*}\right)^{\beta_d(\hat{n}) - 2} \frac{B[\nu, T_d(\hat{n})]}{B[\nu_*, T_d(\hat{n})]}$

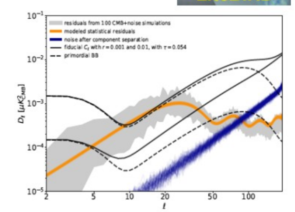
(8 parameters in each sky region) x (12 x N_{side}^2)
= 6144 parameters w/ $N_{side} = 8$
to take spatial variations into account

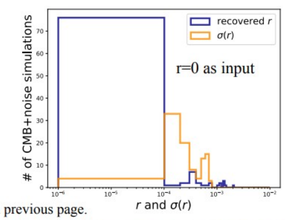
Results*

"Multipatch technique" (extension of xForecast)

- σ(r=0) = 0.0005 ☺
- Negligibly small bias ☺

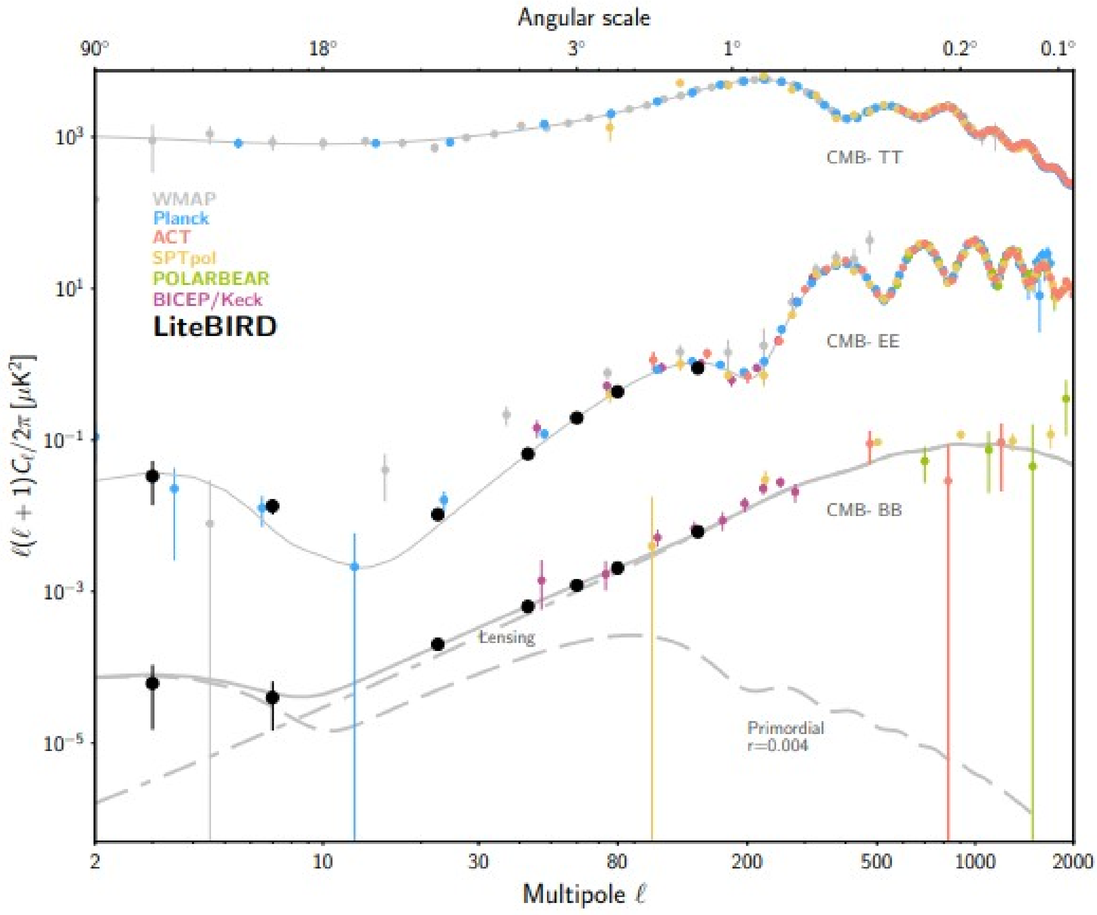
Consistent results from COMMANDER! ☺





* Assumed time loss of ADR cycles. Detector config. slightly different from previous page.

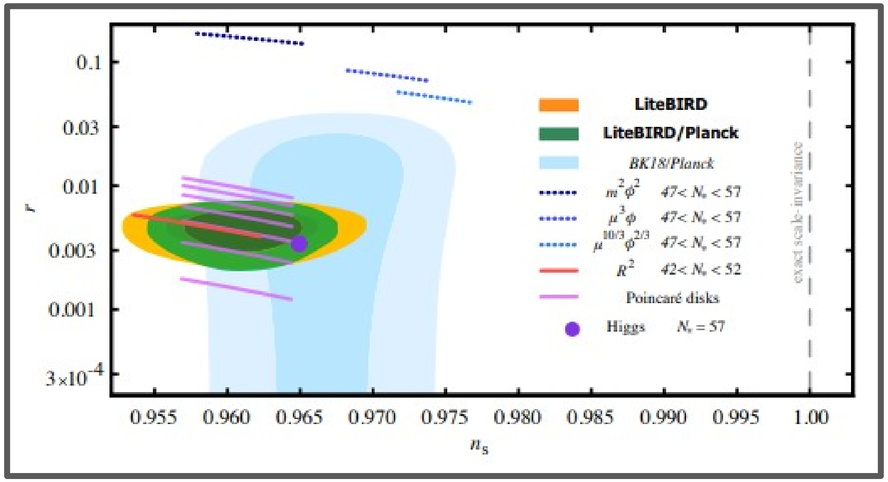
Future B-Mode Probes: LiteBIRD

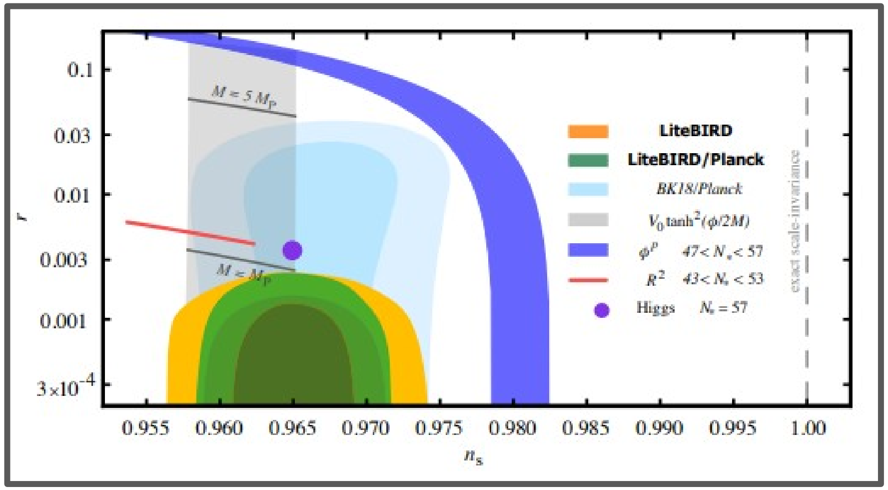


LiteBIRD Collaboration, PTEP 2022

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

Future B-Mode Probes: LiteBIRD





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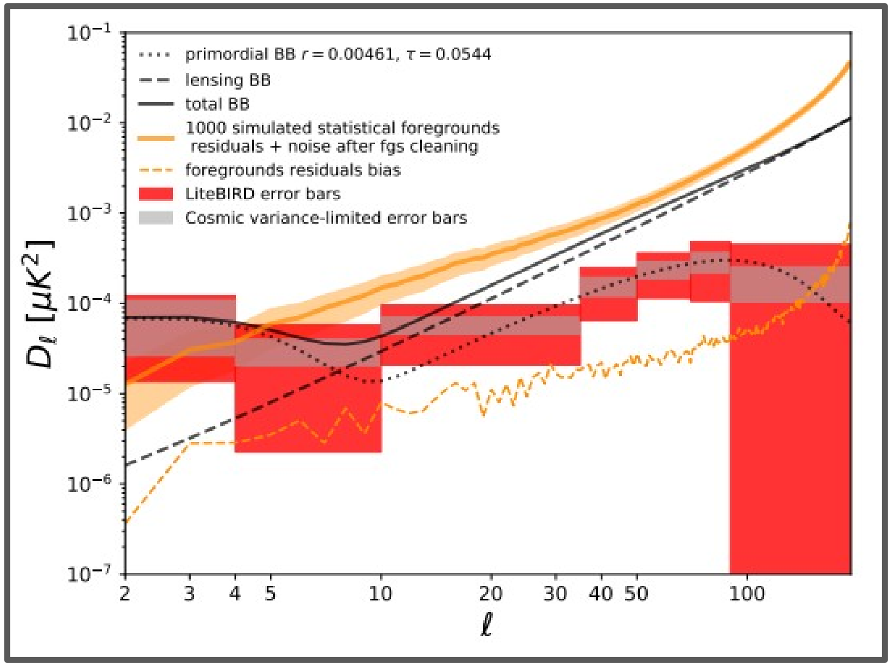
Future B-Mode Probes: LiteBIRD

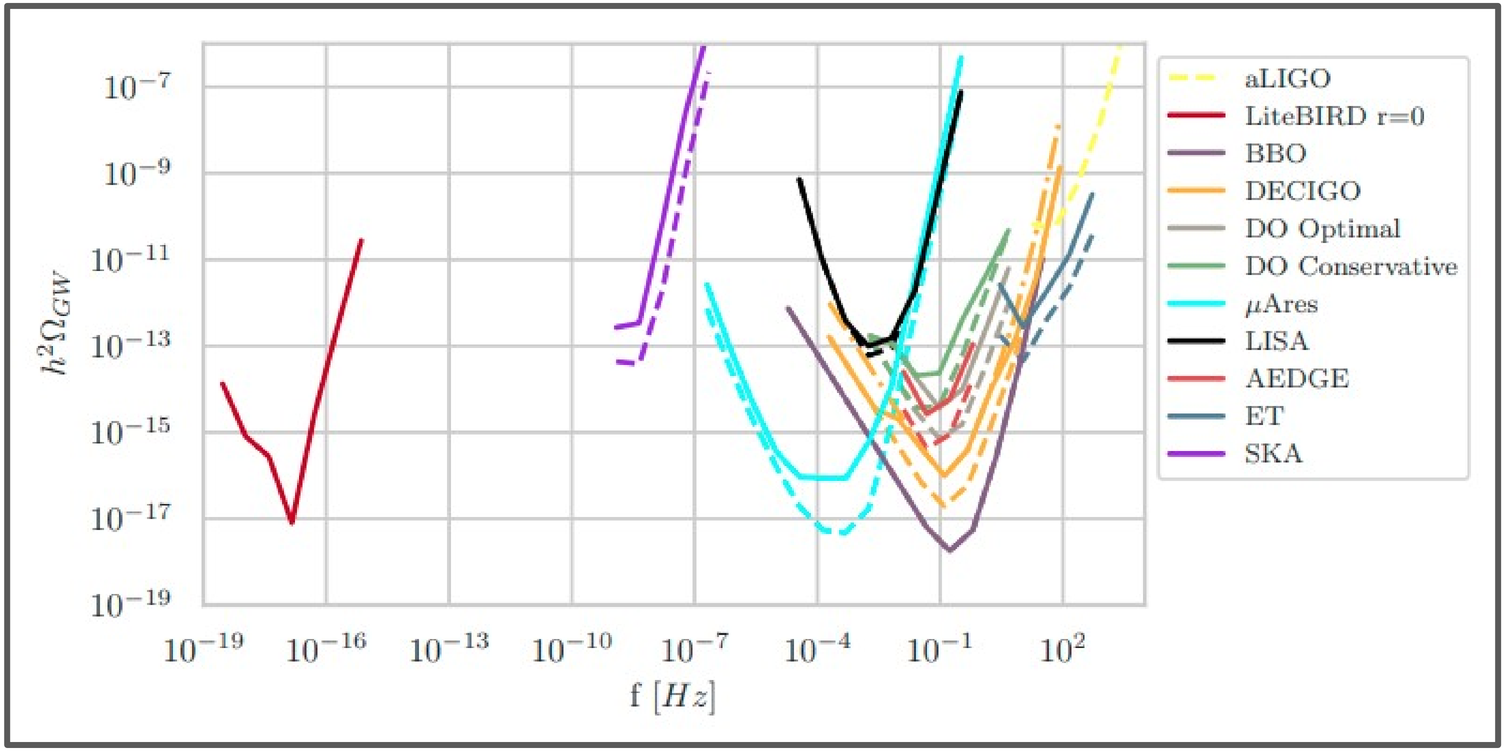


	ID	ν [GHz]	$\delta\nu$ [GHz] ($\delta\nu/\nu$)	Beam size [arcmin]	No. of detectors	NET_{arr} [$\mu K\sqrt{s}$]	Sensitivity [μK-arcmin]
LFT	1	40	12 (0.30)	70.5	48	18.50	37.42
LFT	2	50	15 (0.30)	58.5	24	16.54	33.46
LFT	3	60	14 (0.23)	51.1	48	10.54	21.31
LFT comb.	4	68	16 (0.23)	(41.6, 47.1)	(144, 24)	(9.84,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

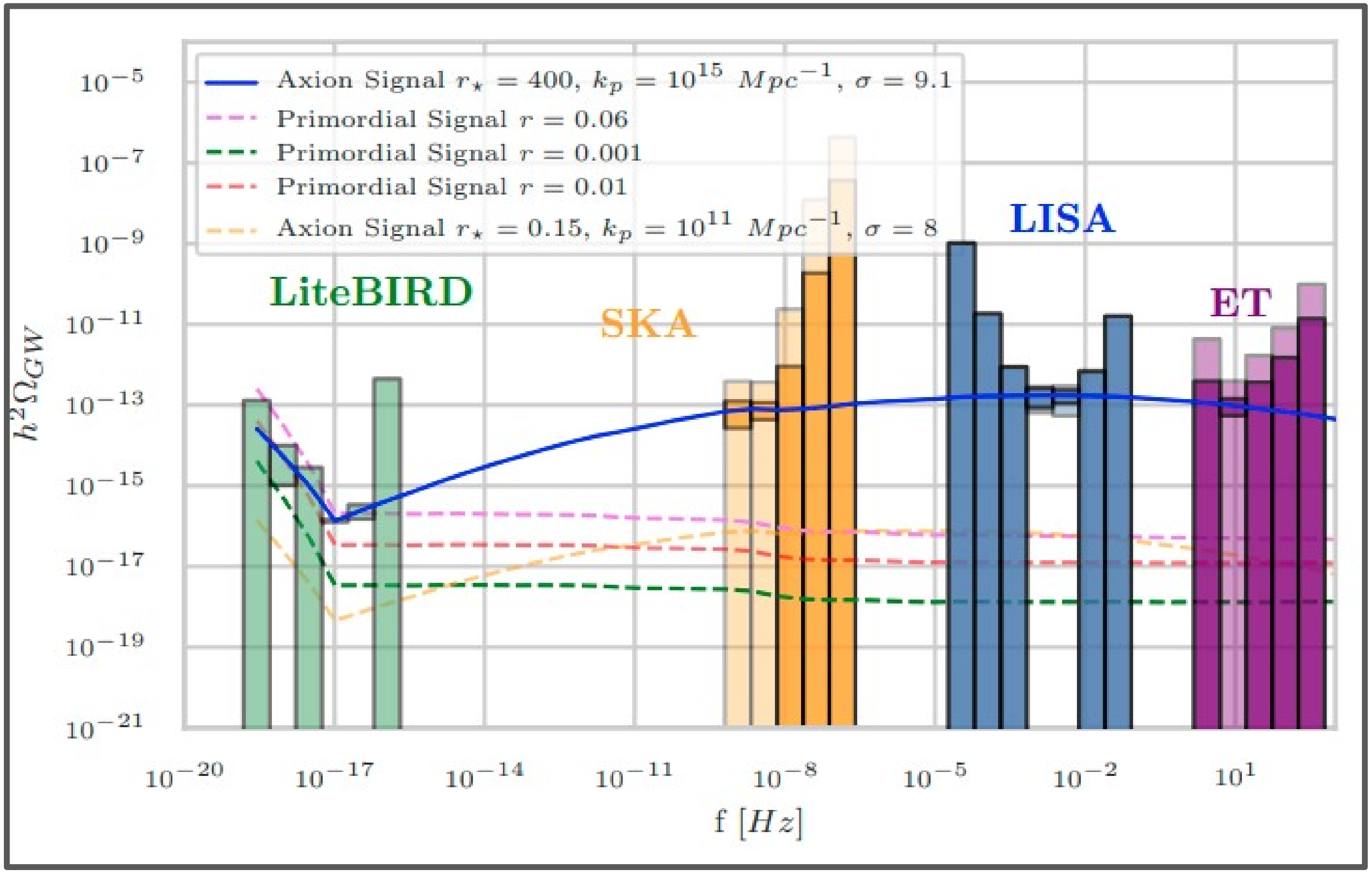
ui.adsabs.harvard.edu/abs/arXiv:2202.02773

Future B-Mode Probes: LiteBIRD



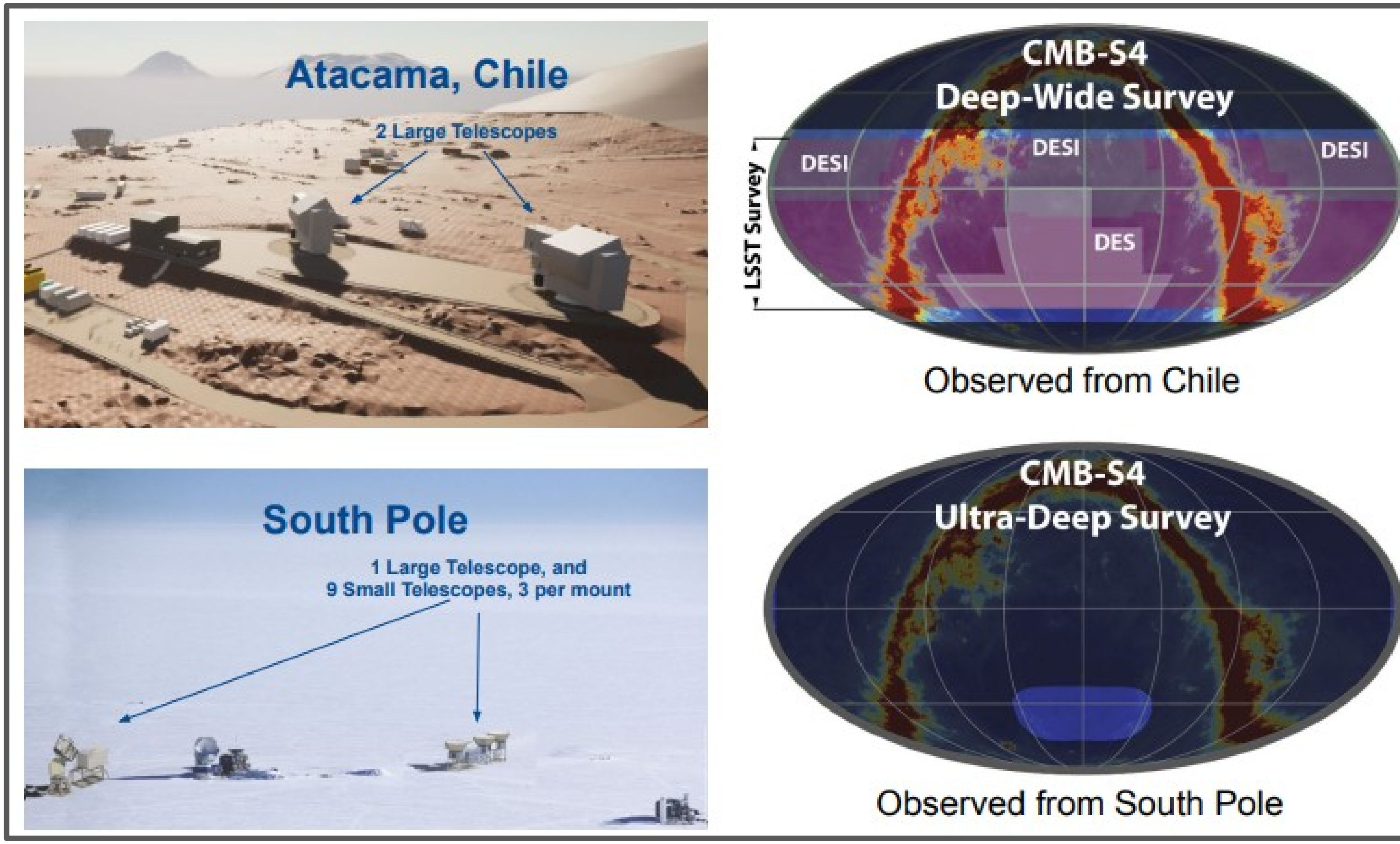
Campeti et al., 2021

Future B-Mode Probes: LiteBIRD



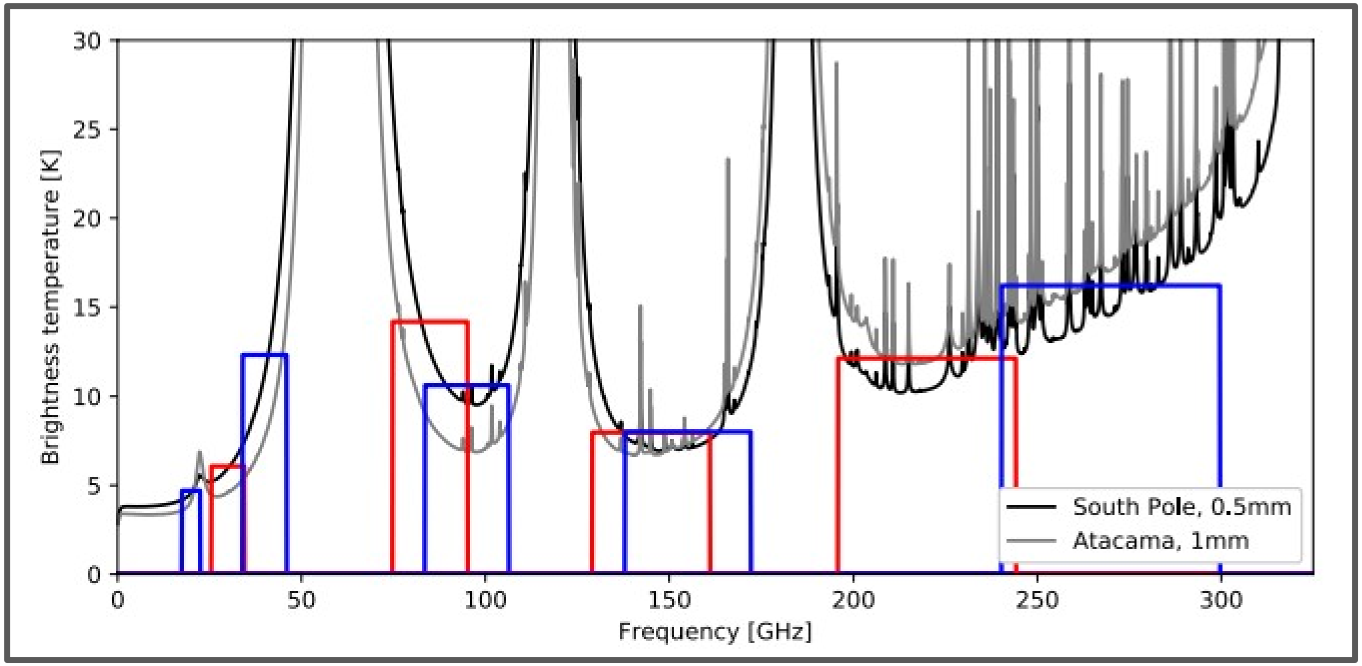
Campeti et al. 2021

Future B-Mode Probes: CMB-Stage IV



CMB-S4

Future B-Mode Probes: CMB-Stage IV



CMB-S4

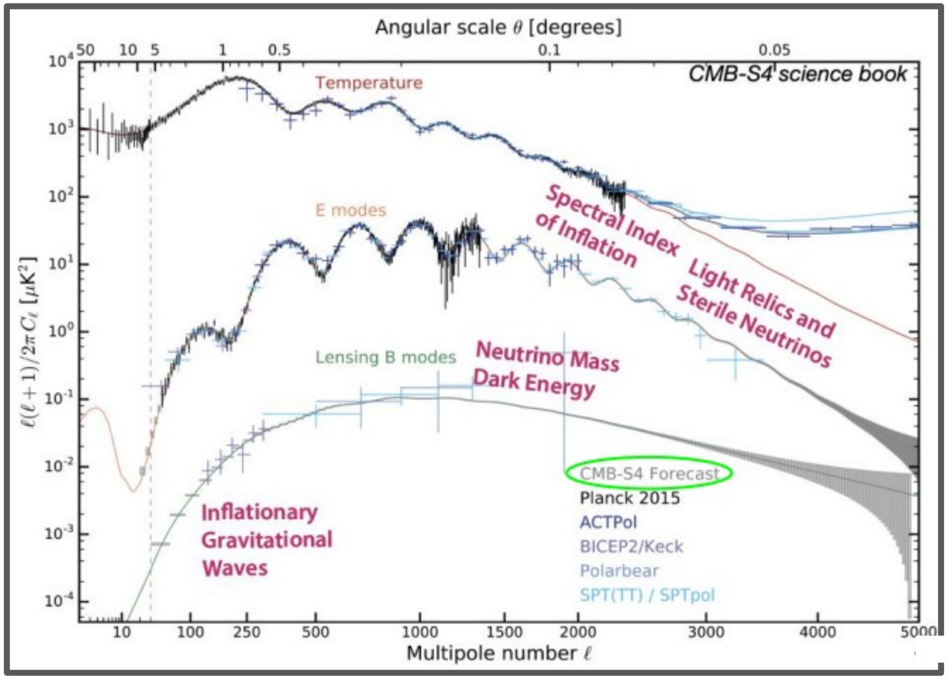
Future B-Mode Probes: CMB-Stage IV LAT and SAT Receivers

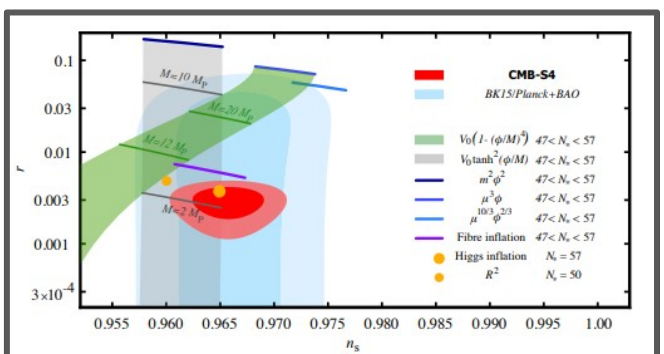
Property	ULF	LF		MF		HF	
Center frequency (GHz)	20	27	39	93	145	225	278
FWHM (arcmin)	10.0	7.4	5.1	2.2	[illegible]	[illegible]	[illegible]
Fractional bandwidth	0.25	0.22	0.46	0.38	[illegible]	[illegible]	[illegible]
NET ($\mu K\sqrt{s}$) per detector	438	383	250	302	[illegible]	[illegible]	[illegible]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

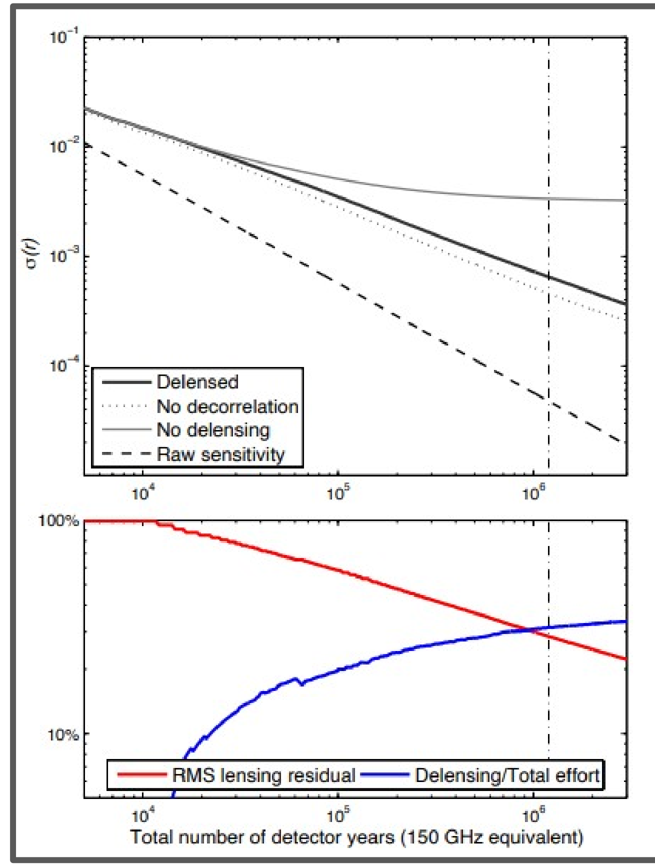
Property	LF		CF High		CF Low		HF	
Center frequency (GHz)	30	40	85	145	95	155	220	270
Primary lens diameter (cm)	55	55	55	55	55	55	44	44
FWHM (arcmin)	72.8	72.8	25.5	25.5	22.7	22.7	13	13
Fractional bandwidth	0.3	0.3	0.24	0.22	0.24	0.22	0.22	0.22
NET ($\mu K\sqrt{s}$) per detector	177	224	270	238	309	331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

CMB-S4

Future B-Mode Probes: CMB-Stage IV



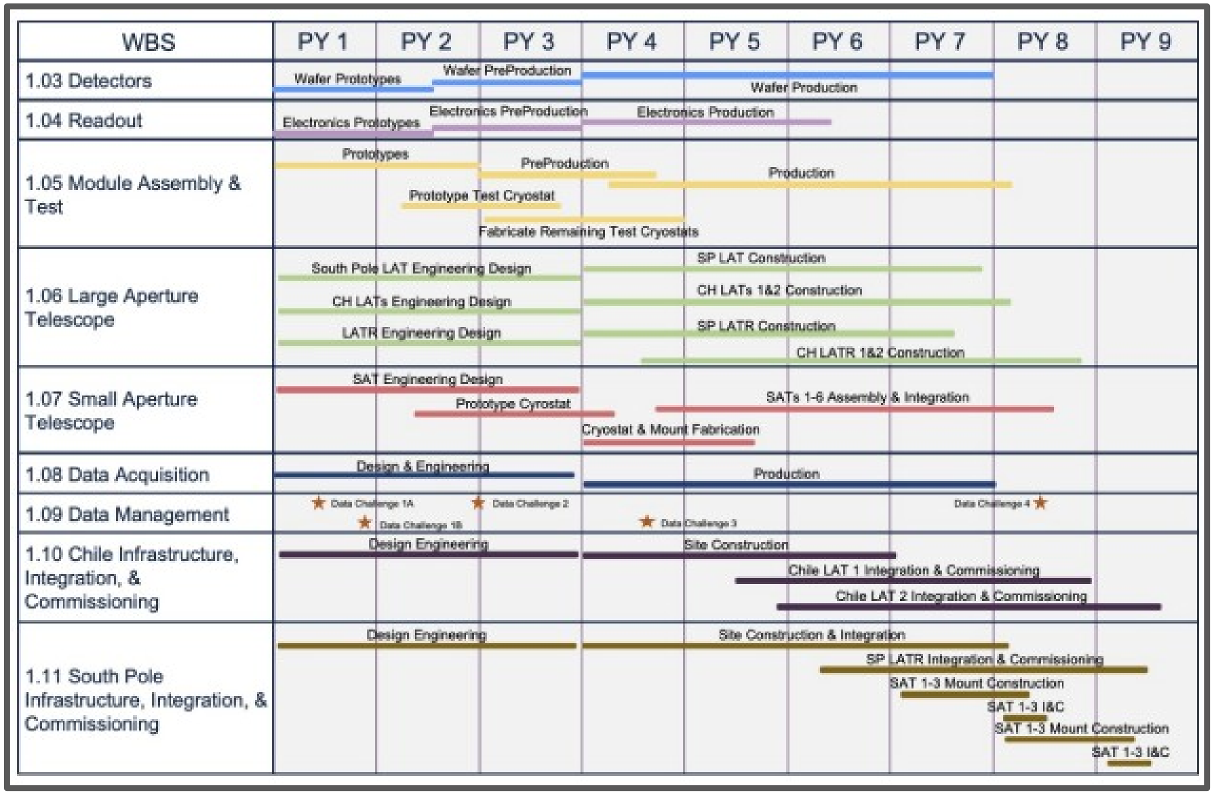




CMB-S4

arxiv.org/abs/2208.12619

CMB-Stage IV



CMB-S4

Concluding Remarks

- **Maps of the CMB contain most important effects from the Early Universe and Large Scale Structure**
- **Effects extend from the whole sky down to the Arcminute Scale**
- **Probes are Signal Dominated till the Arcminute Scale**
- **Huge Analysis Infrastructure in Place, mostly focused on the Two Point Correlation Function, with most important constraints from the 3 point correlation function and overall distribution of perturbations across the Sky**
- **B-Mode Probes Primary Targets are Cosmological Gravitational Waves and Gravitational Lensing**
- **Huge Program Ahead, Towards a Network of Ground and Space Based Probes**
- **Discussion!**