



OSSERVATORIO  
ASTRONOMICO DI PADOVA



UNIVERSITÀ  
DEGLI STUDI  
DI PADOVA

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

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th

September 14 , 2023



**SISSA**

# Outline

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

**CMB**

# Primeval Fireball

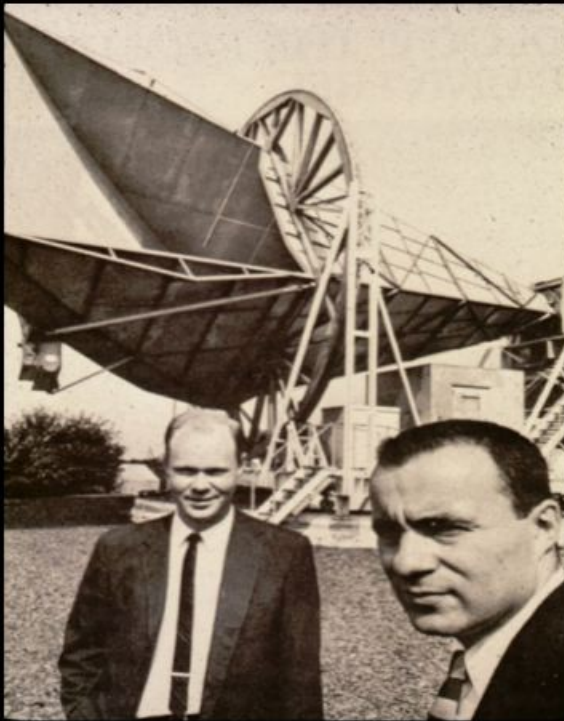
- compression in the early stages of an expanding universe causes lots of radiation arising from thermonuclear explosions
- Reactions are rapid enough to achieve thermalization and a black body spectrum
- It is possible to compute the rarefaction caused by the expansion since that epoch
- The relic radiation 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.

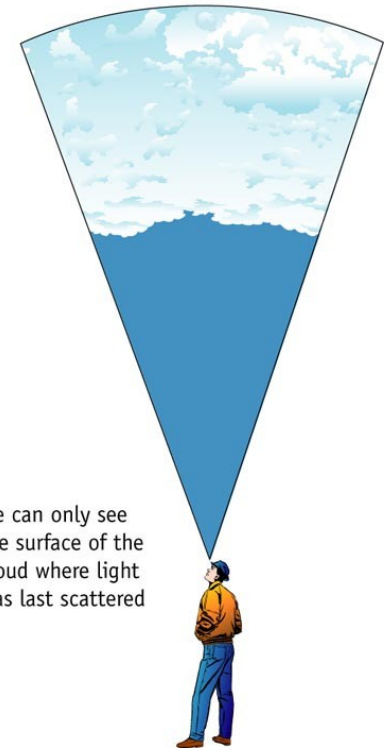
1964 - They become aware that the noise in their telescope is the cosmic background radiation predicted by the Big Bang theory.

# CMB: where and when?

- Opacity:  
 $\lambda = 1/n\sigma \ll \text{horizon}$   
where the horizon is the distance at which information get at each time, inverse of the Hubble expansion rate
- Decoupling:  $\lambda \approx \text{horizon}$
- Free streaming:  $\lambda \gg \text{horizon}$
- 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



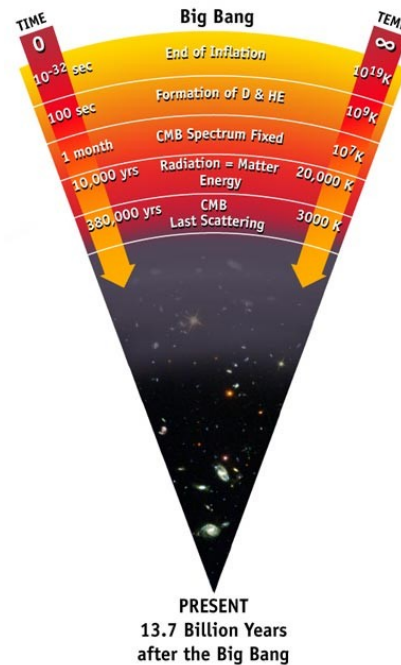
The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.



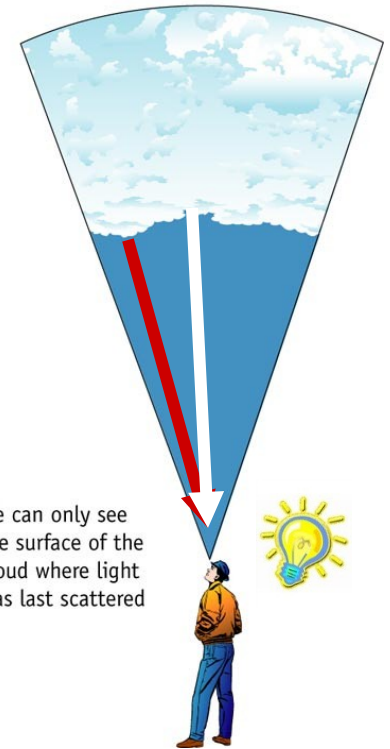
We can only see the surface of the cloud where light was last scattered

# A postcard from the Big Bang

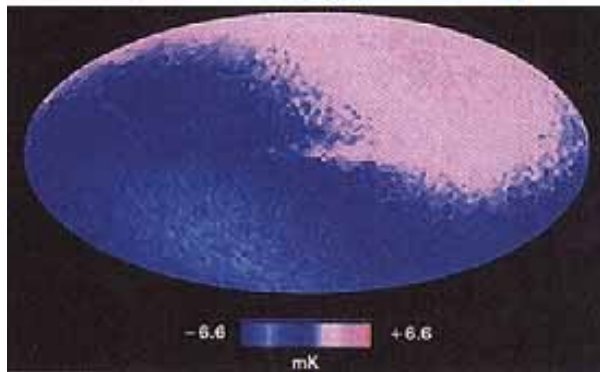
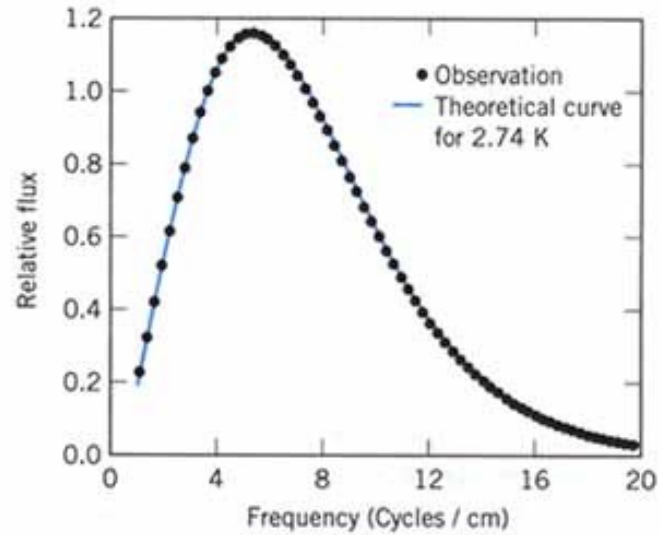
- From the Stephan Boltzmann law, regions at high temperature should carry high density
- The latter is activated by perturbations which are intrinsic of the fluid as well as of spacetime
- Thus, the maps of the CMB temperature is a kind of snapshot of primordial cosmological perturbations



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.



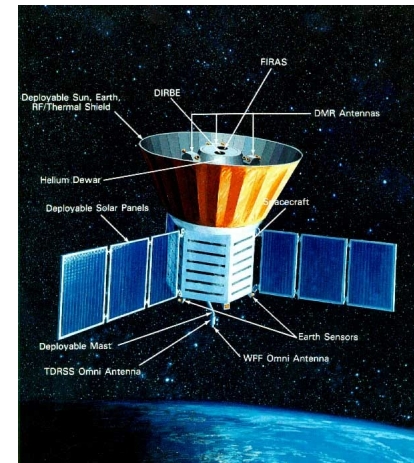
# COsmic Background Explorer



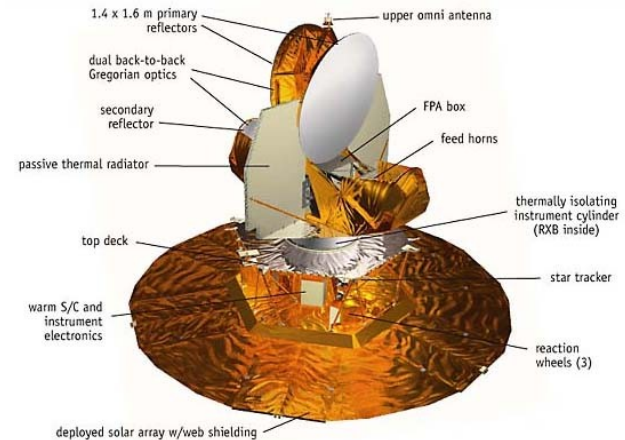
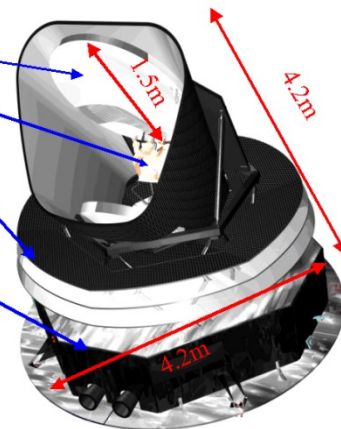


# From COBE to the Wilkinson Microwave Anisotropy Probe (WMAP) to Planck

- About 40 years of scientific and technological progresses
- Lots of experiments, people
- See [lambda.gsfc.nasa.gov](http://lambda.gsfc.nasa.gov)

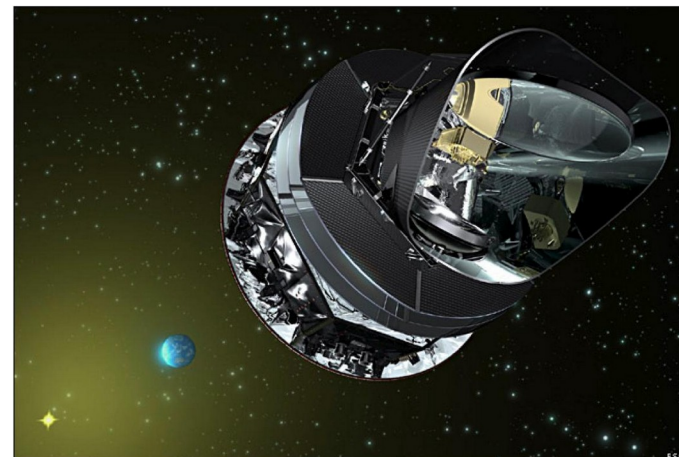
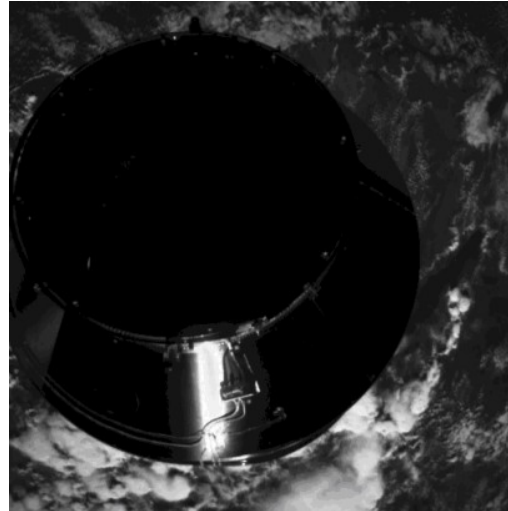


- PLM (charge Utile)
  - Télescope (1.5m)
  - Instruments plans focaux
  - Cryo-structure (radiateur, baffles, V-grooves)
- SVM
  - Avionique (Contrôle (data, attitude), gestion puissance, Télécom+ Electroniques Instruments)
- Satellite:
  - 2000kg, 1600W, 4.2mx 4.2m
  - Durée de vie 21 mois
  - Satellite en rotation 1tour/min

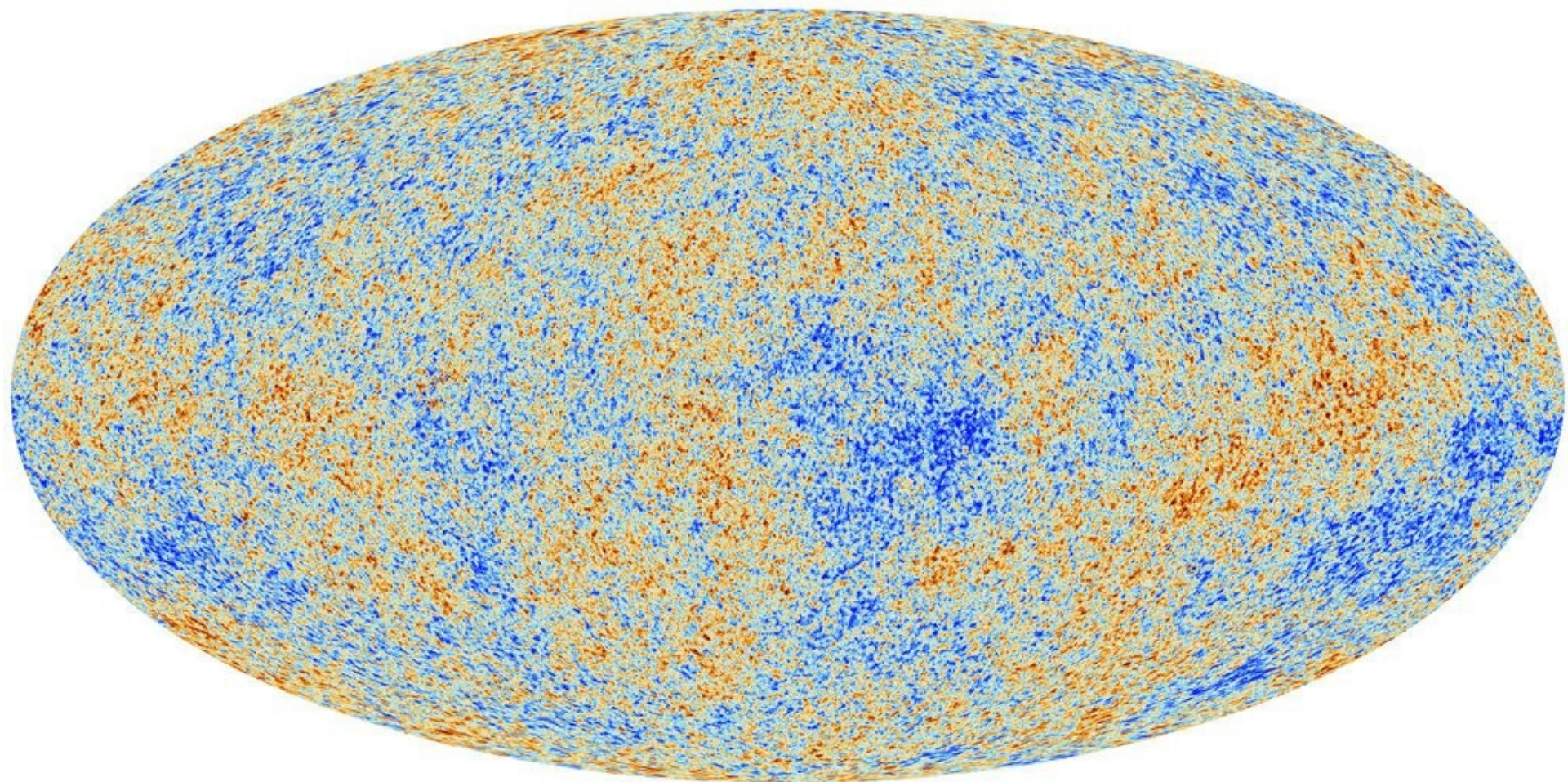


# The Planck Satellite

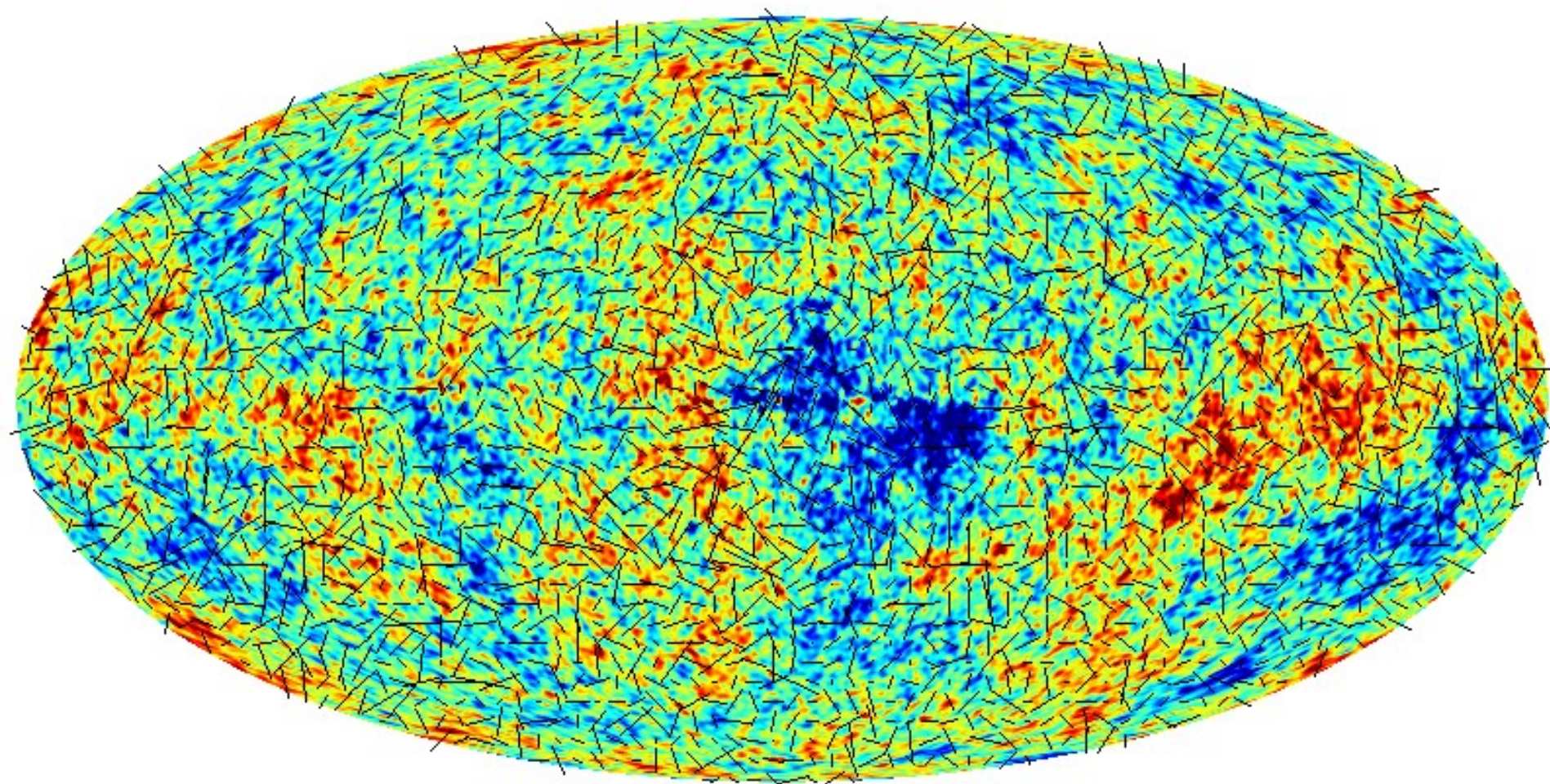
- ESA Medium Size Mission, NASA participation for the construction of part of the cooling systems
- About 400 scientists all over the world
- Two Data Analysis Centers, in Paris (IAP, High Frequency Instrument) and Trieste (INAF-Trieste & SISSA, Low Frequency Instrument)
- About 17 years from the initial 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



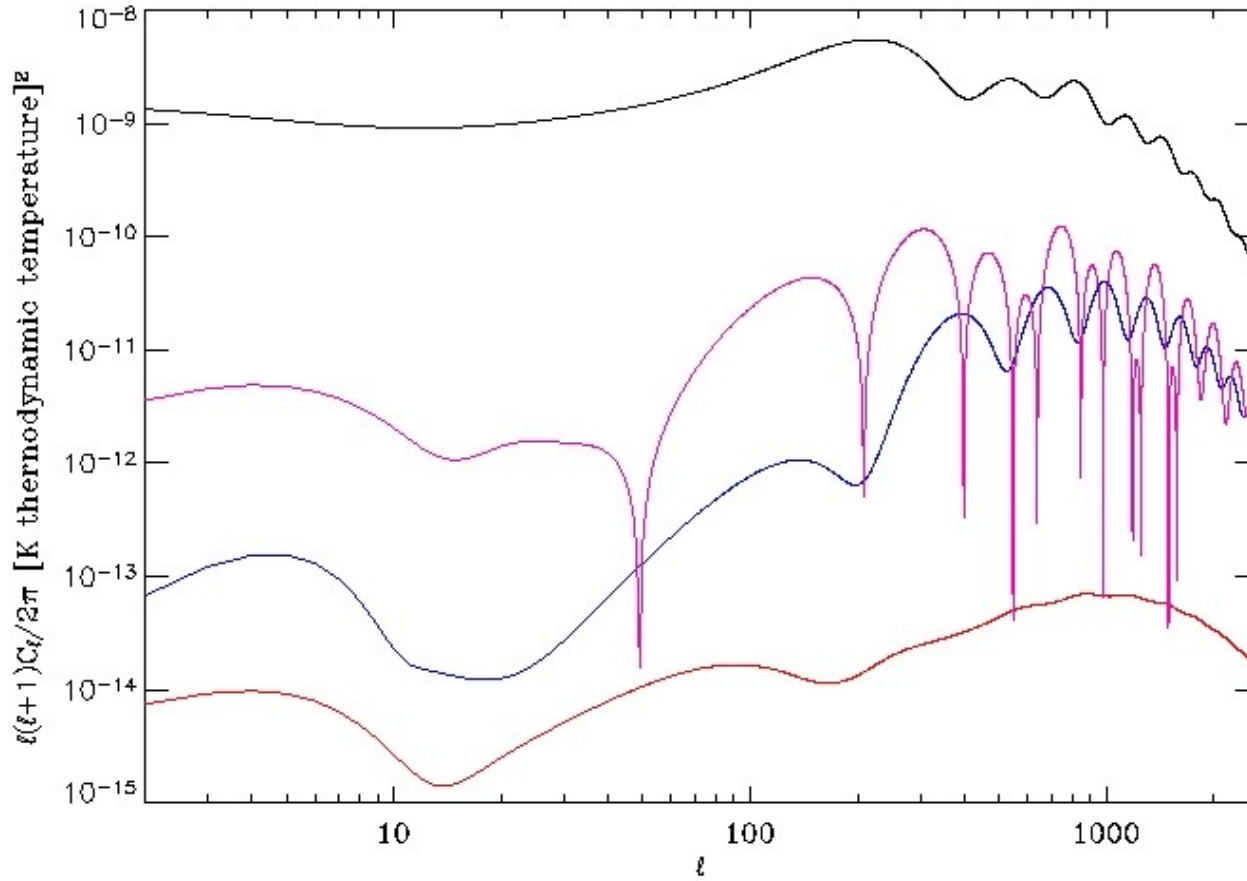
# CMB as seen by Planck



# CMB as seen by Planck



# CMB Angular Power Spectrum



Angle  $\approx 200/l$  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

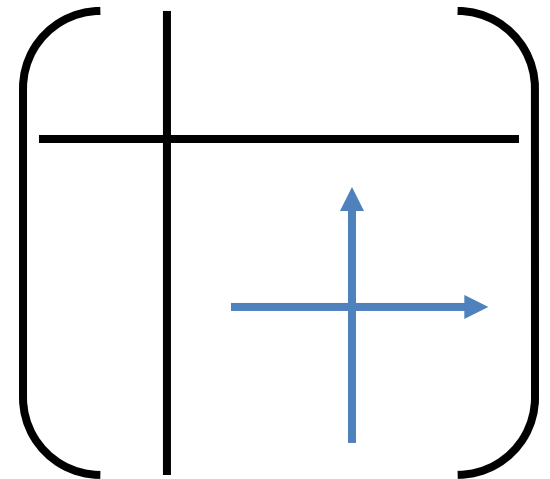
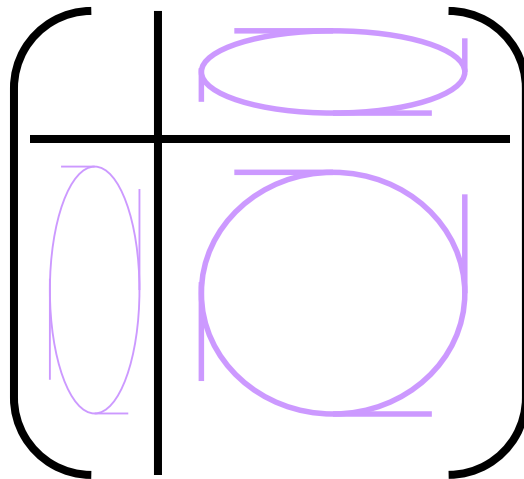
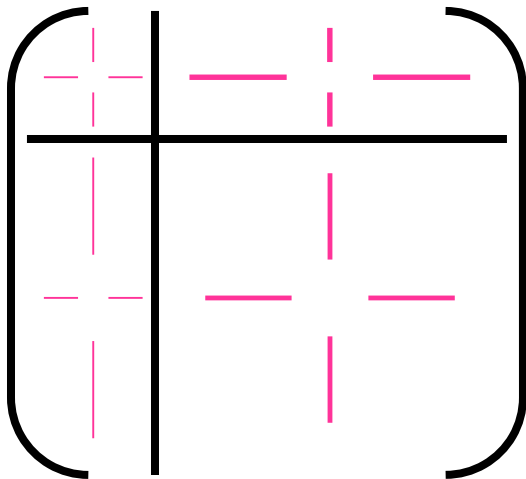
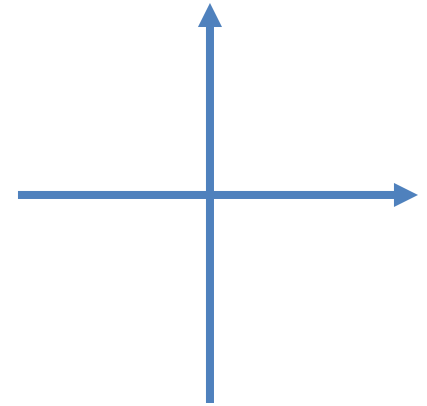
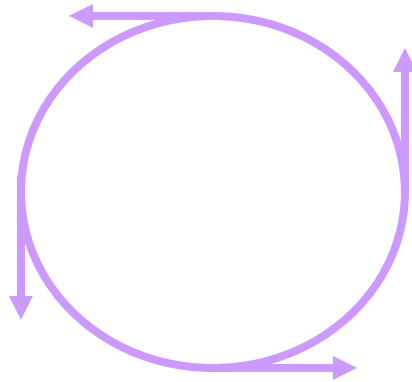
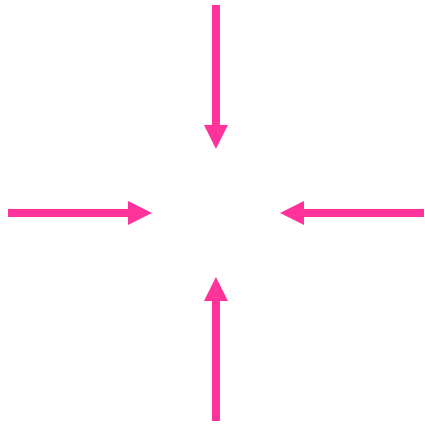
$$\frac{d \text{ neutrinos}}{dt} = \text{gravity} + \text{weak interaction}$$

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

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

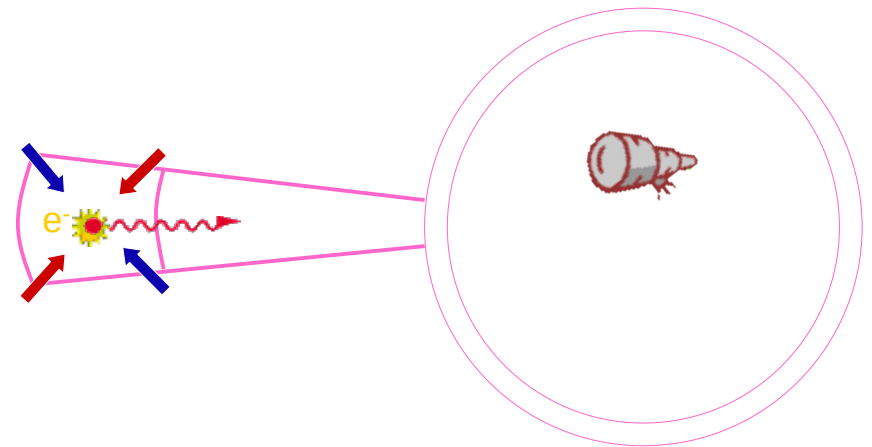
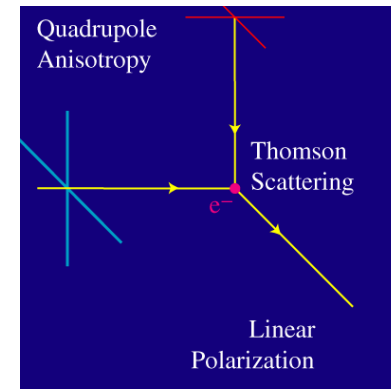


# CMB physics: gravity

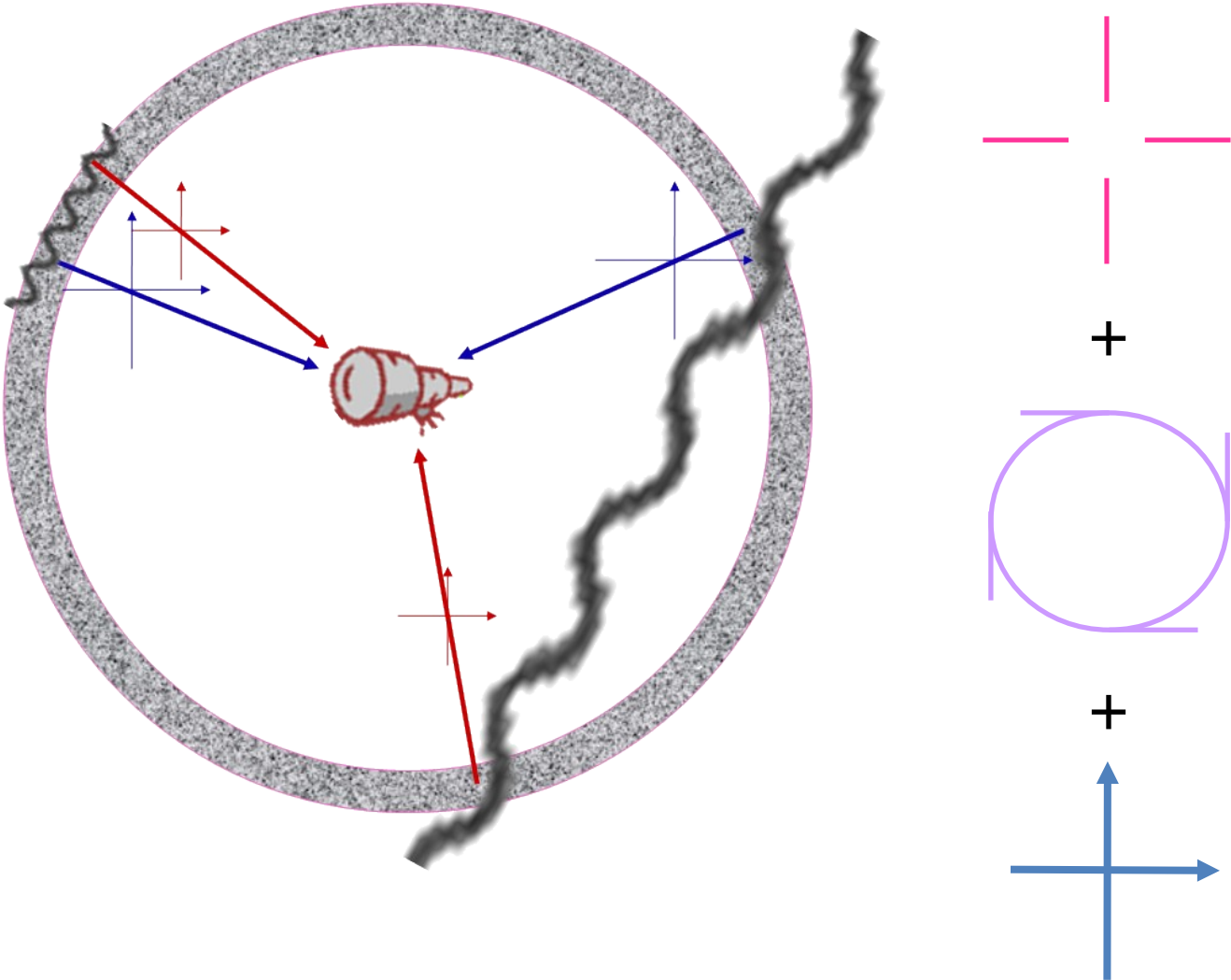


# CMB Physics: Compton scattering

- 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

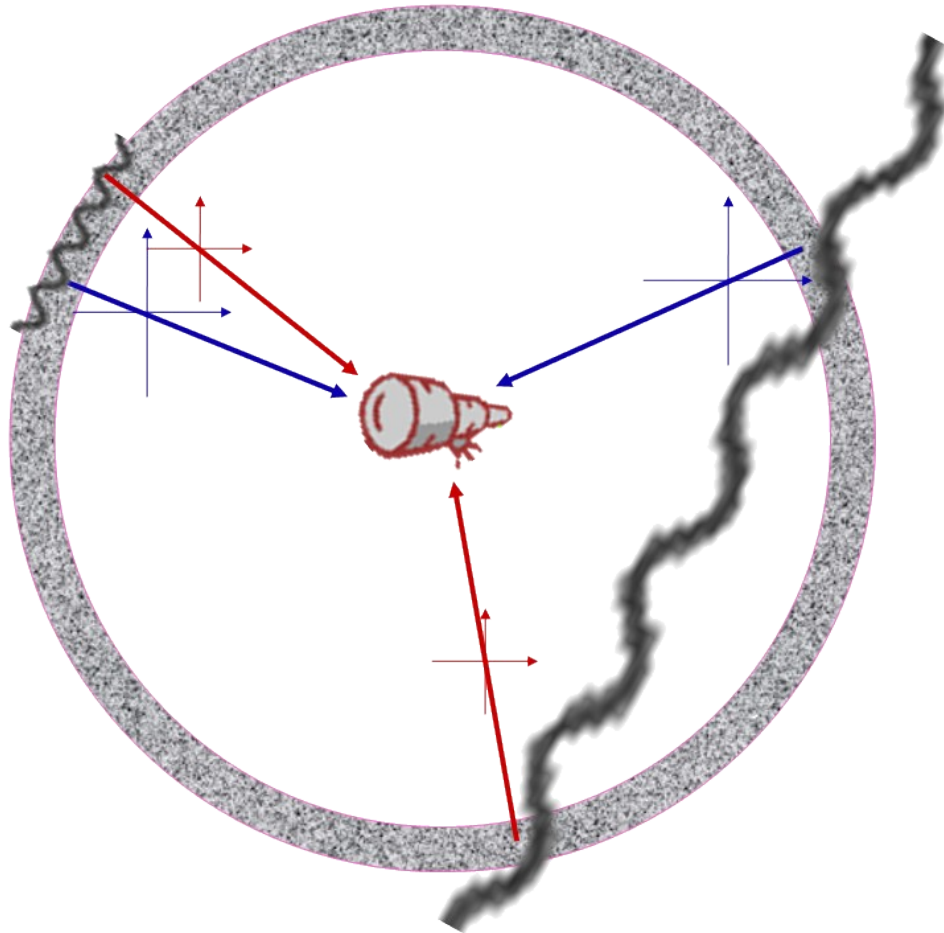
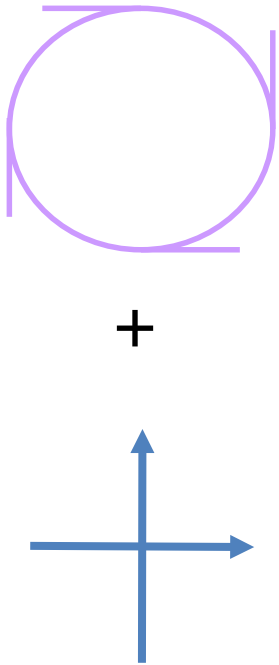


# CMB anisotropy: Total Intensity

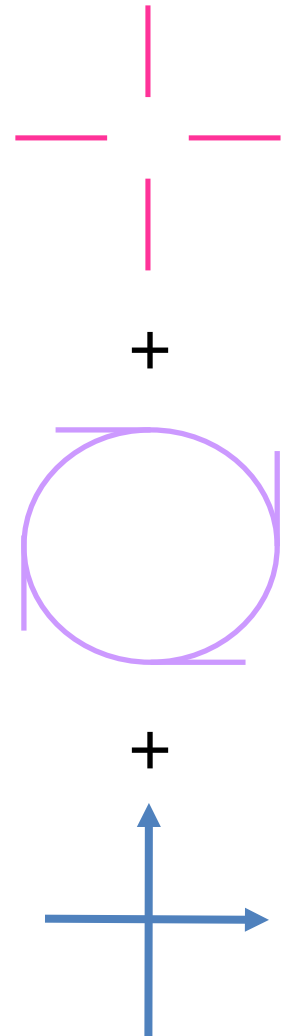


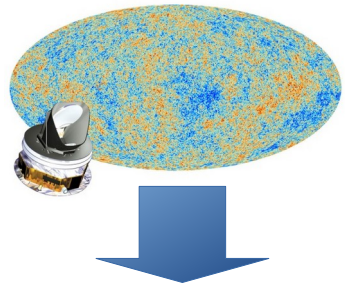
# CMB anisotropy: polarization

Curl (B):



Gradient (E):





# Anisotropies

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

spherical  
harmonics

$$X(\theta, \varphi) = \sum_{lm} a_{lm}^X Y_{lm}^s(\theta, \varphi)$$

$X = T, E, B$

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

$E$  and  $B$  modes have opposite parity

# Angular power spectrum

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

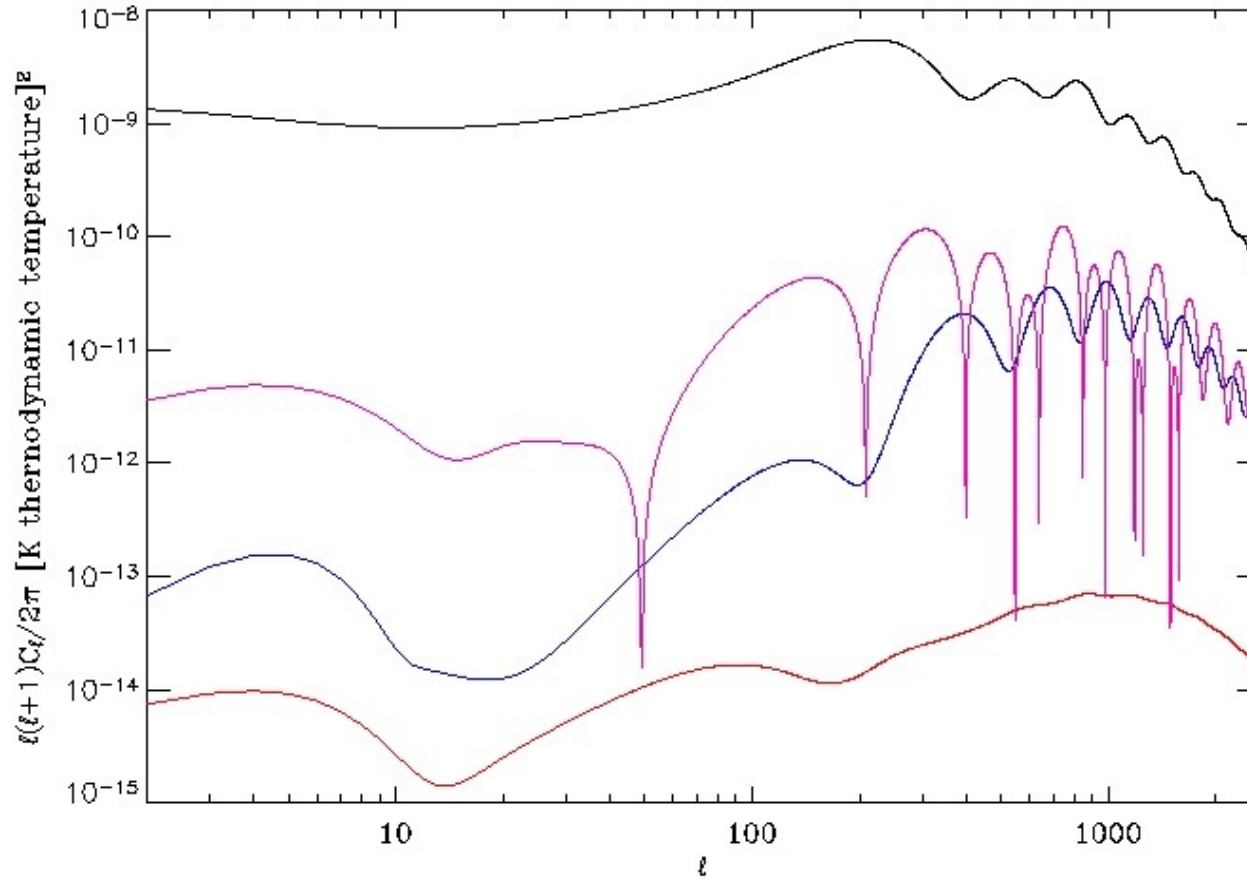
spherical  
harmonics

$$a_{lm}^X, X=T, E, B$$

Lossy  
compression

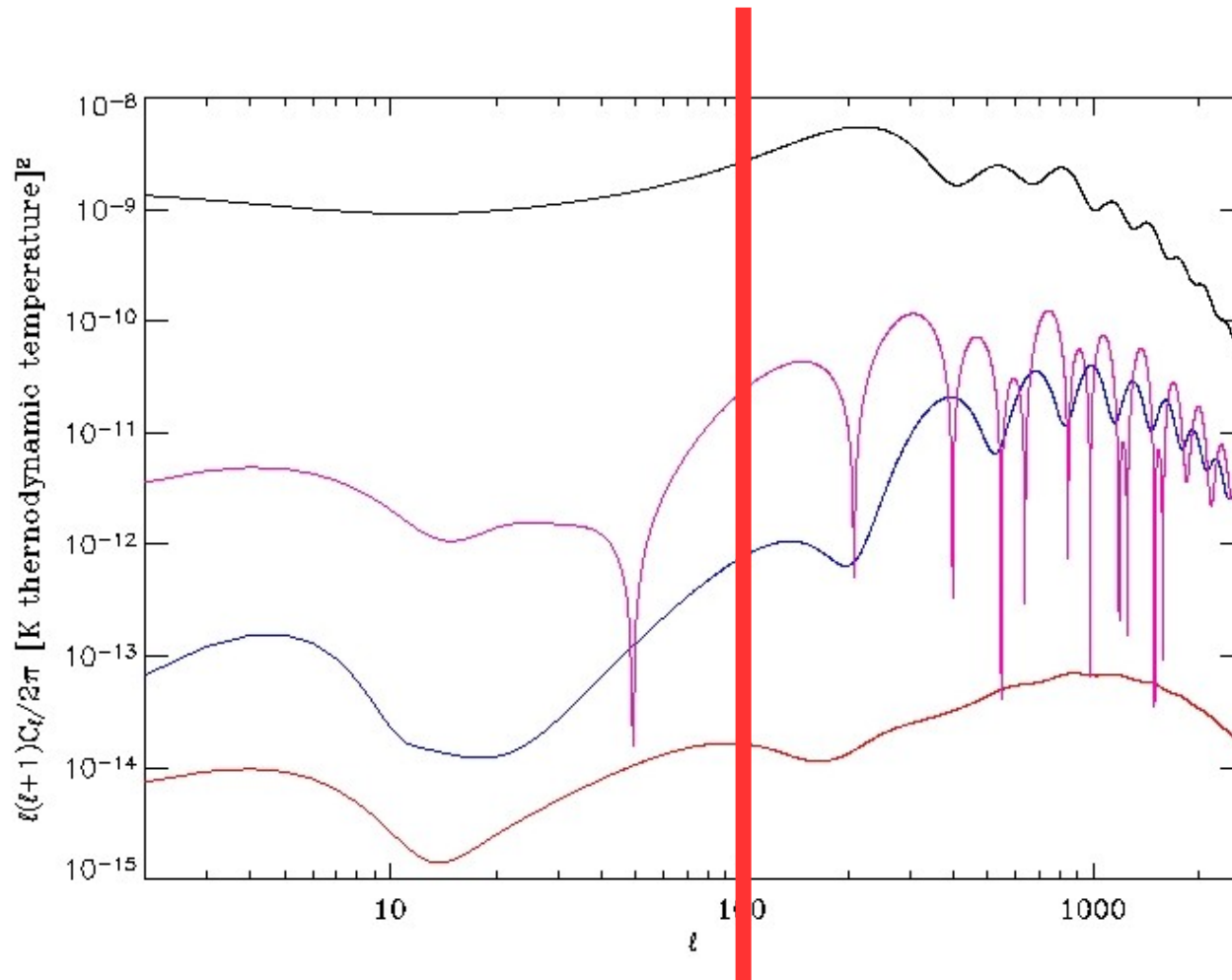
$$C_{l=\sum_m} [(a_{lm}^X)(a_{lm}^Y)^*]/(2l+1)$$

# CMB angular power spectrum



Angle  $\approx 200/\ell$  degrees

# CMB angular power spectrum

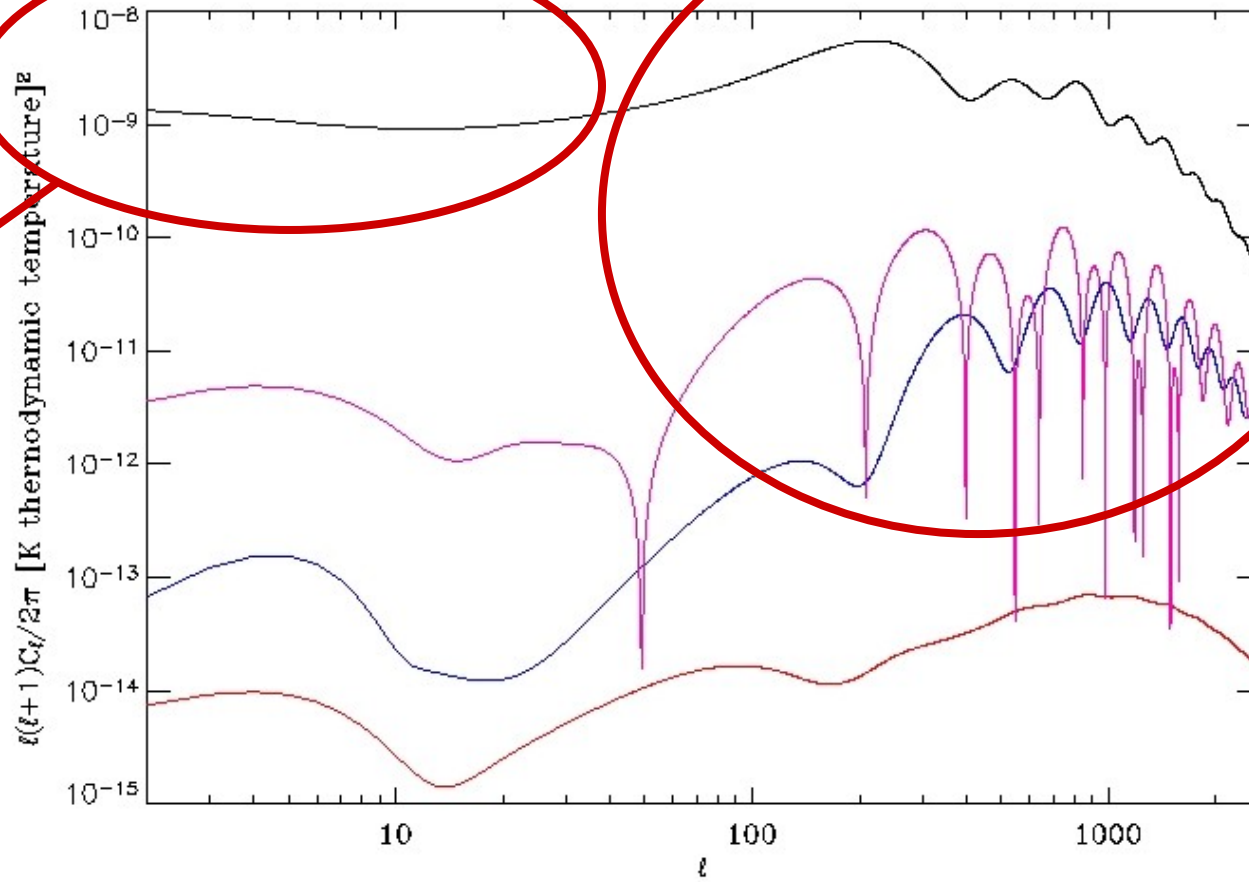


Angle  $\approx 200/l$  degrees



# CMB angular power spectrum

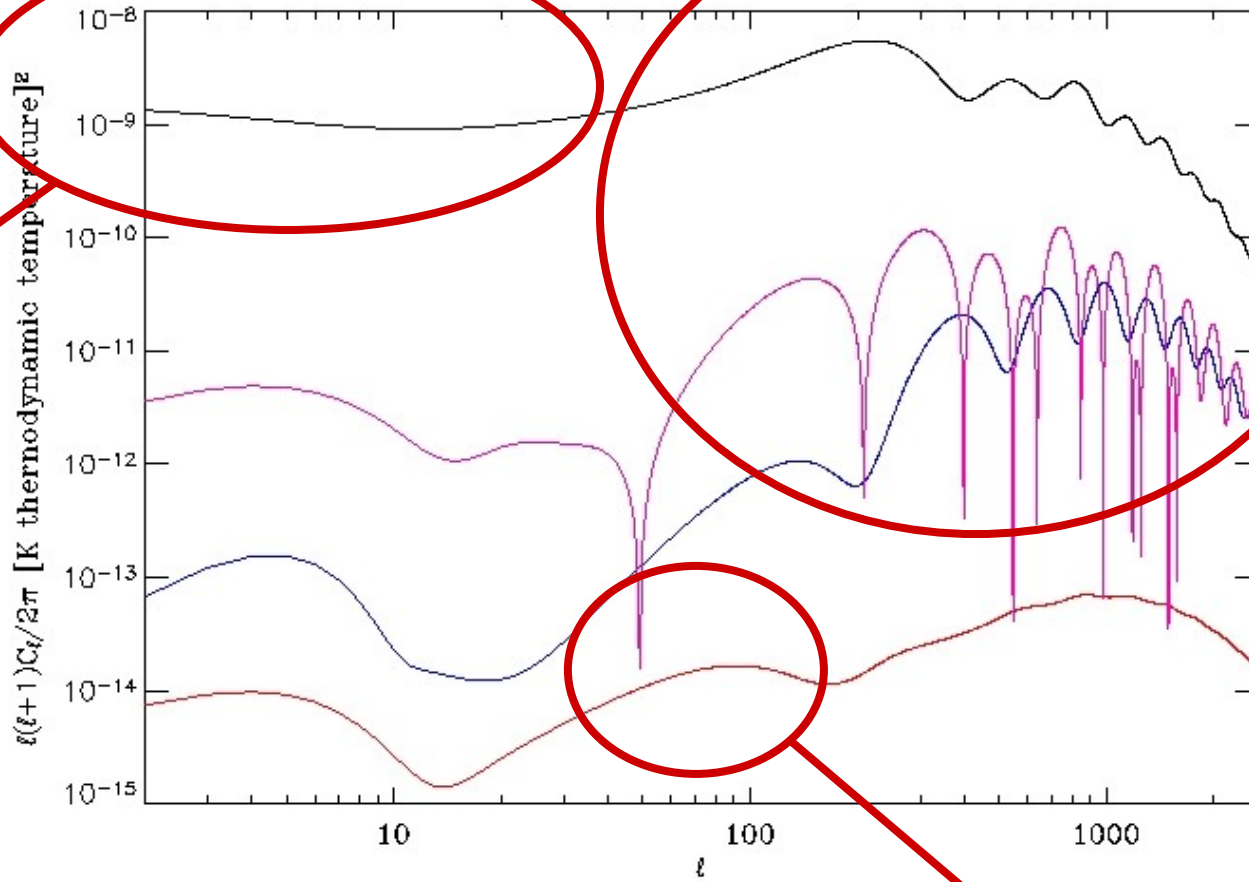
Acoustic oscillations



Angle  $\approx 200/\ell$  degrees

# CMB angular power spectrum

Acoustic oscillations

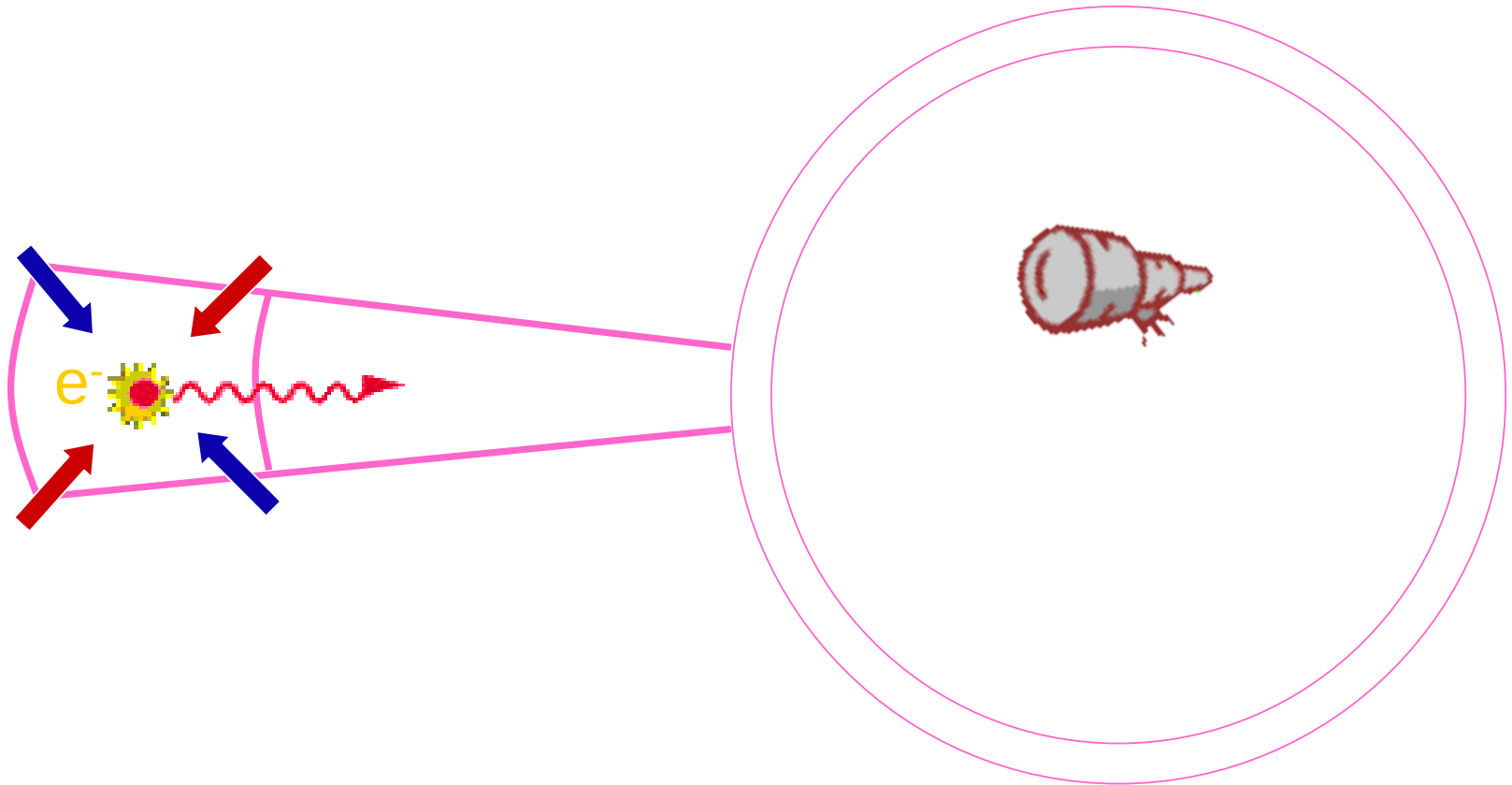


Primordial power

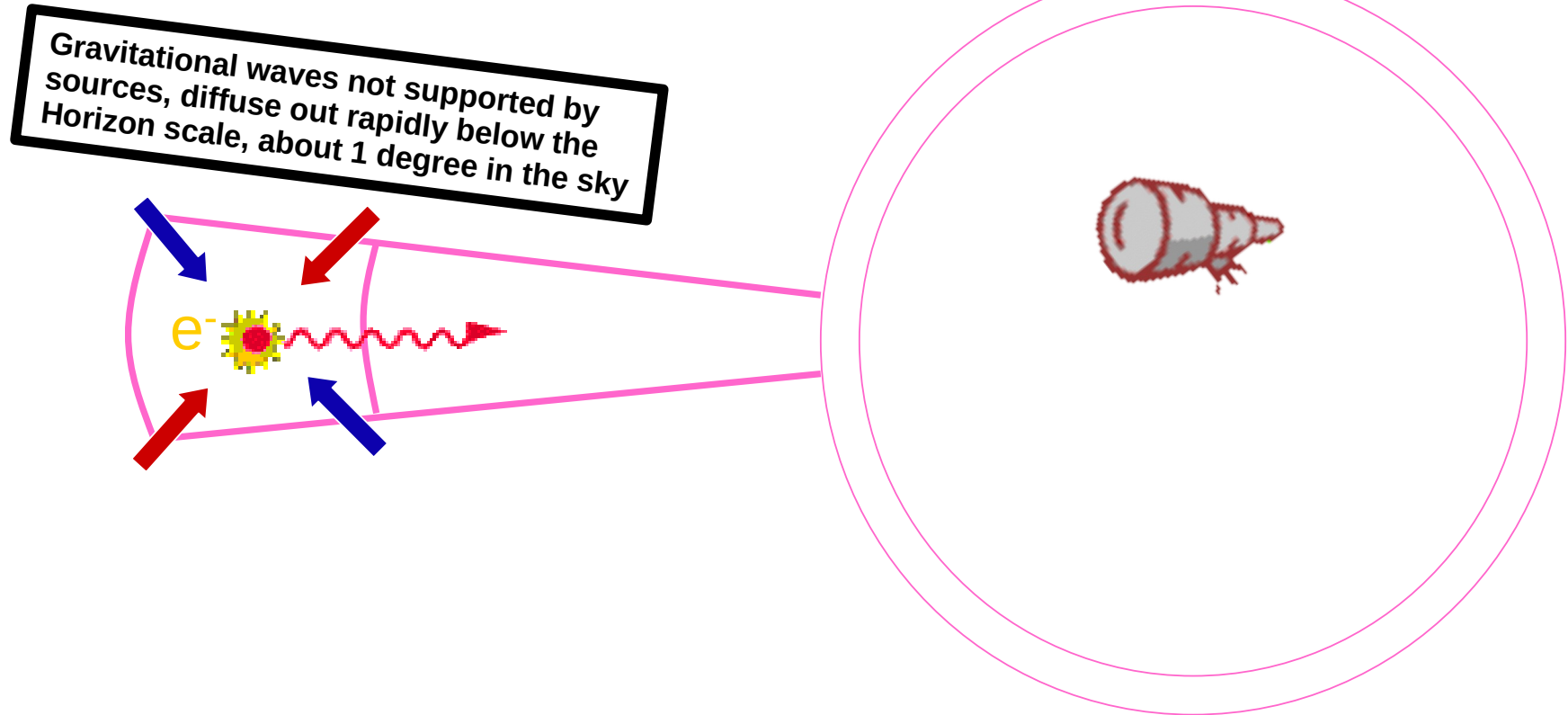
Angle  $\approx 200/l$  degrees

Gravitational waves

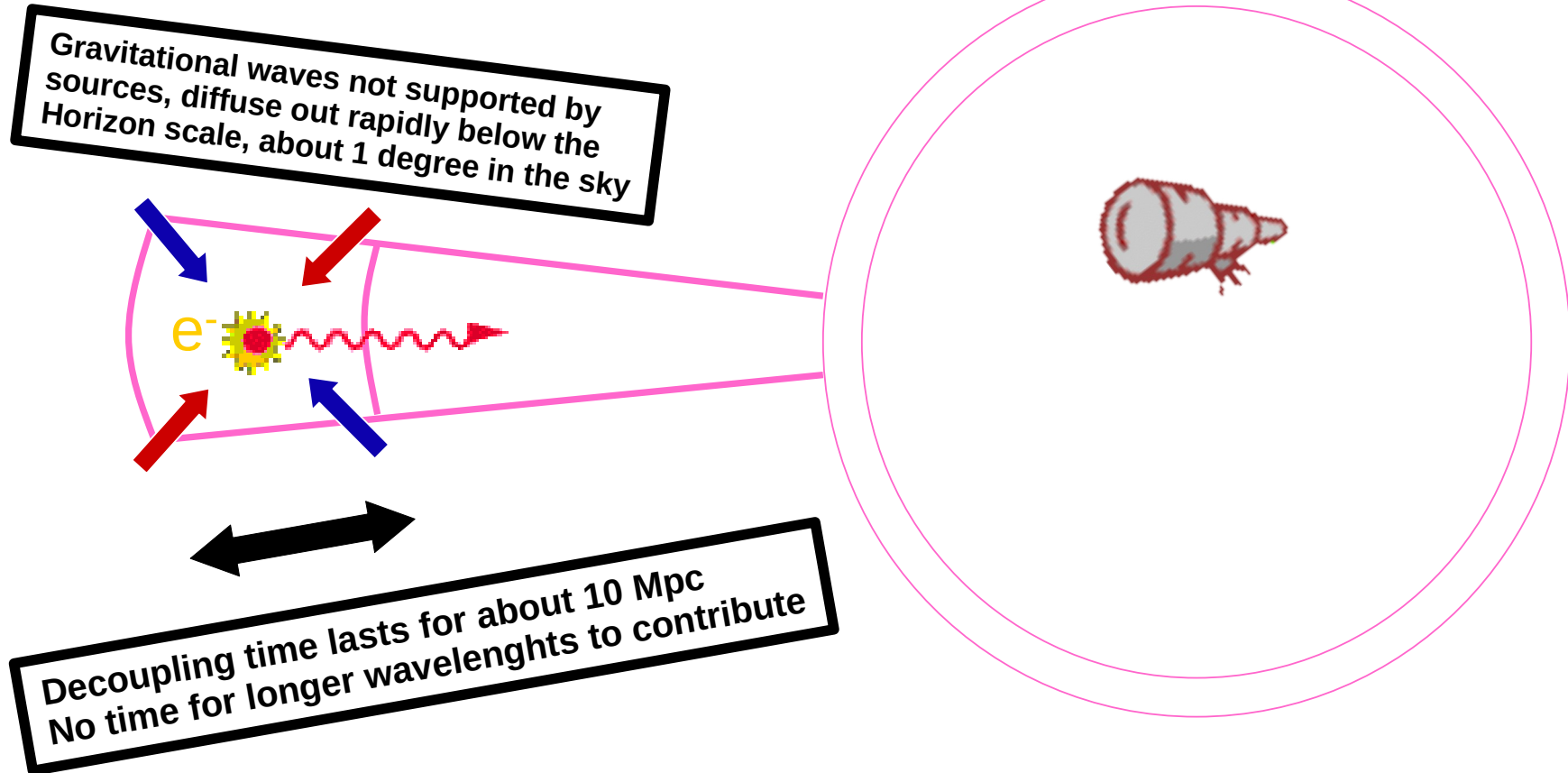
# The B-modes record GWs monochromatically in angle



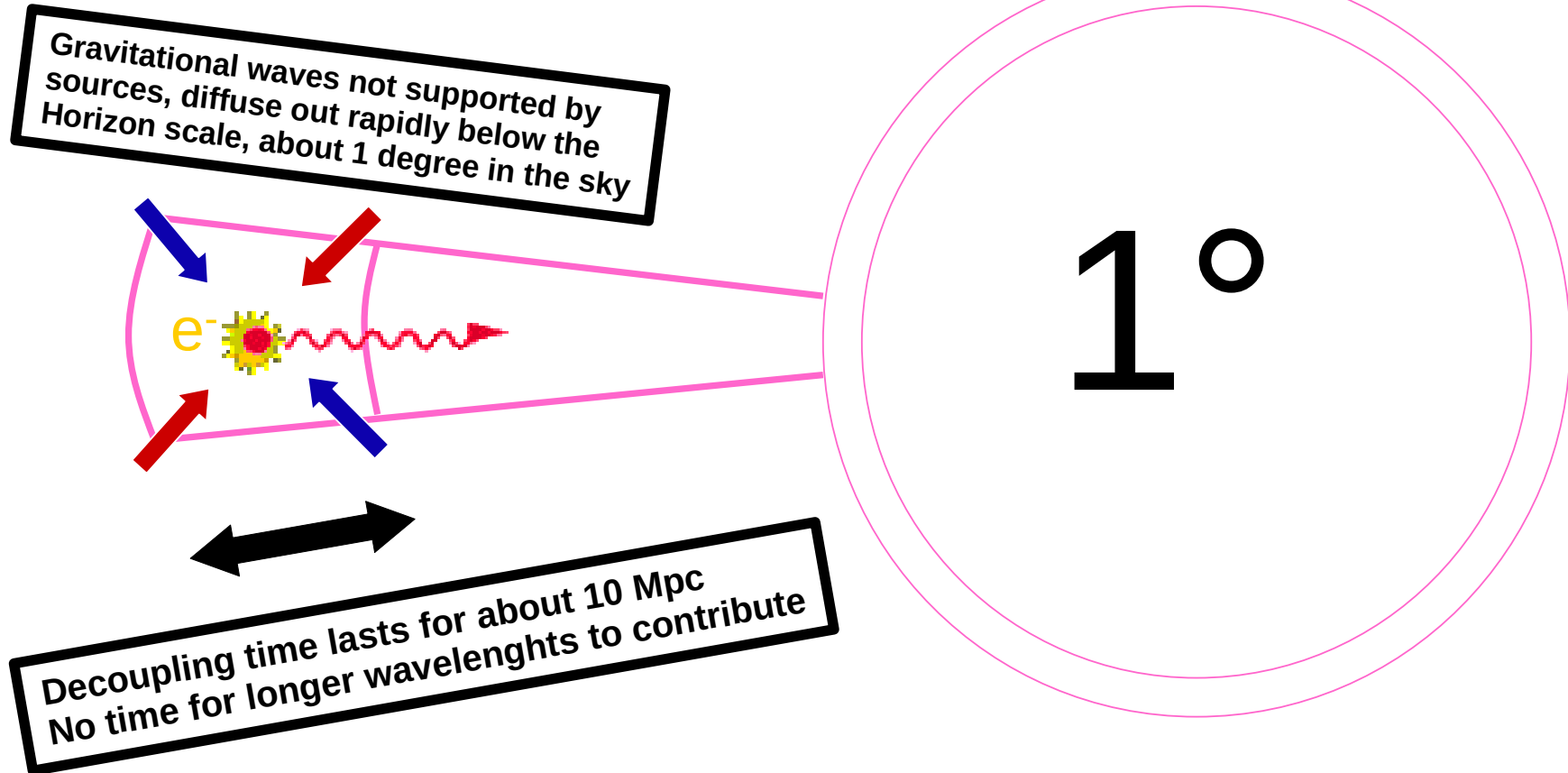
# The B-modes record GWs mono-chromatically in angle



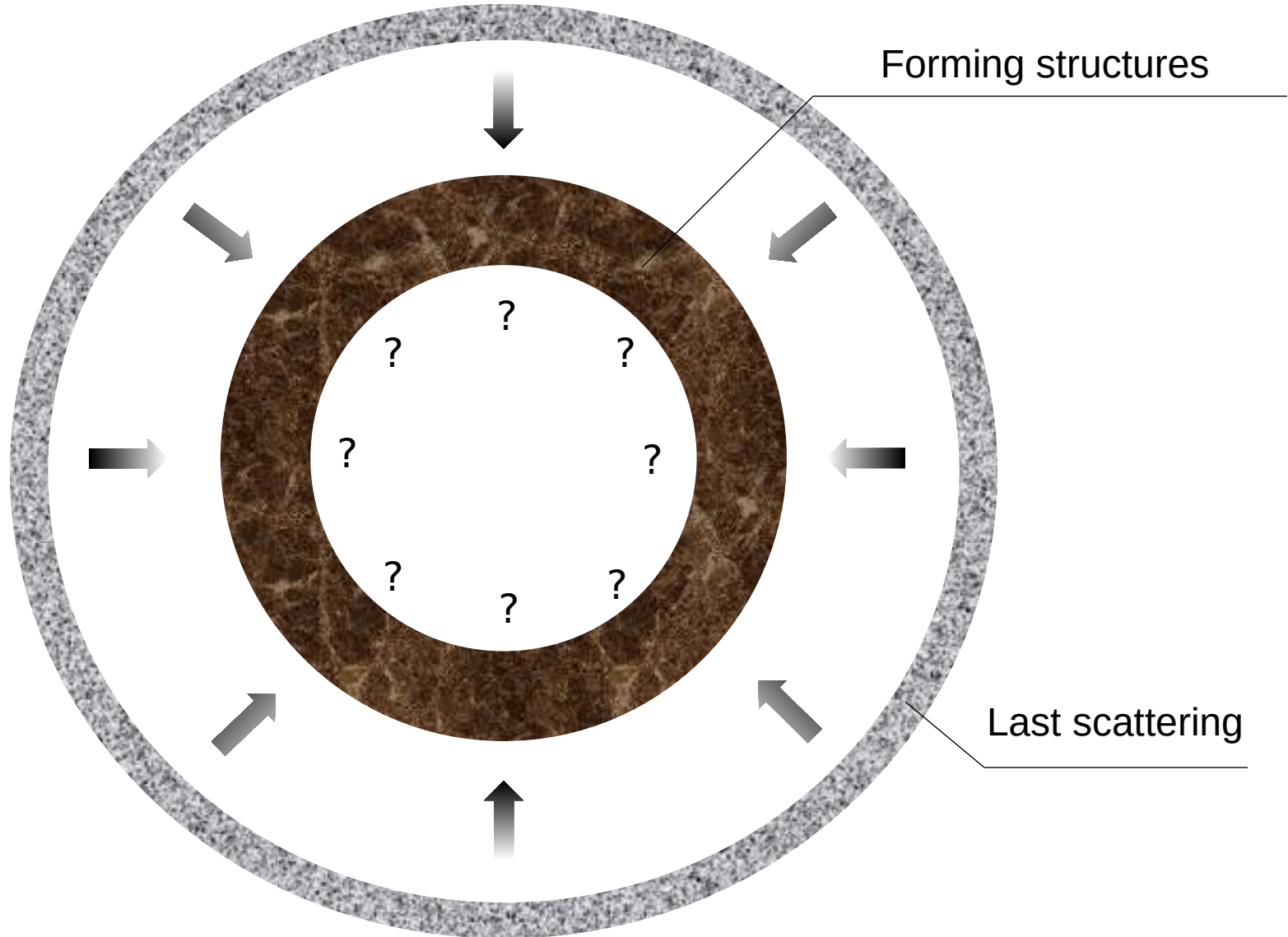
# The B-modes record GWs mono-chromatically in angle



# The B-modes record GWs mono-chromatically in angle



# CMB and Large Scale Structure



# Categories for LSS effects on CMB

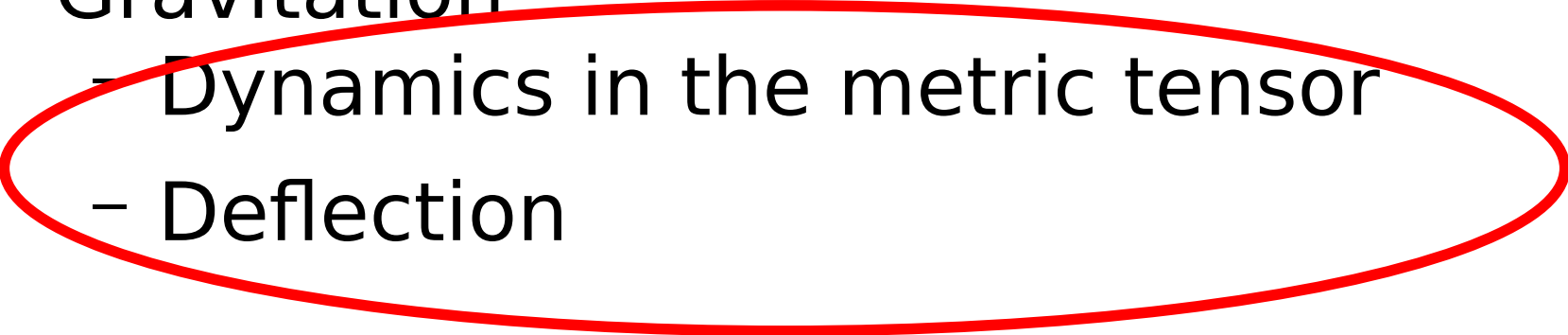
- Re-scattering
- Gravitation



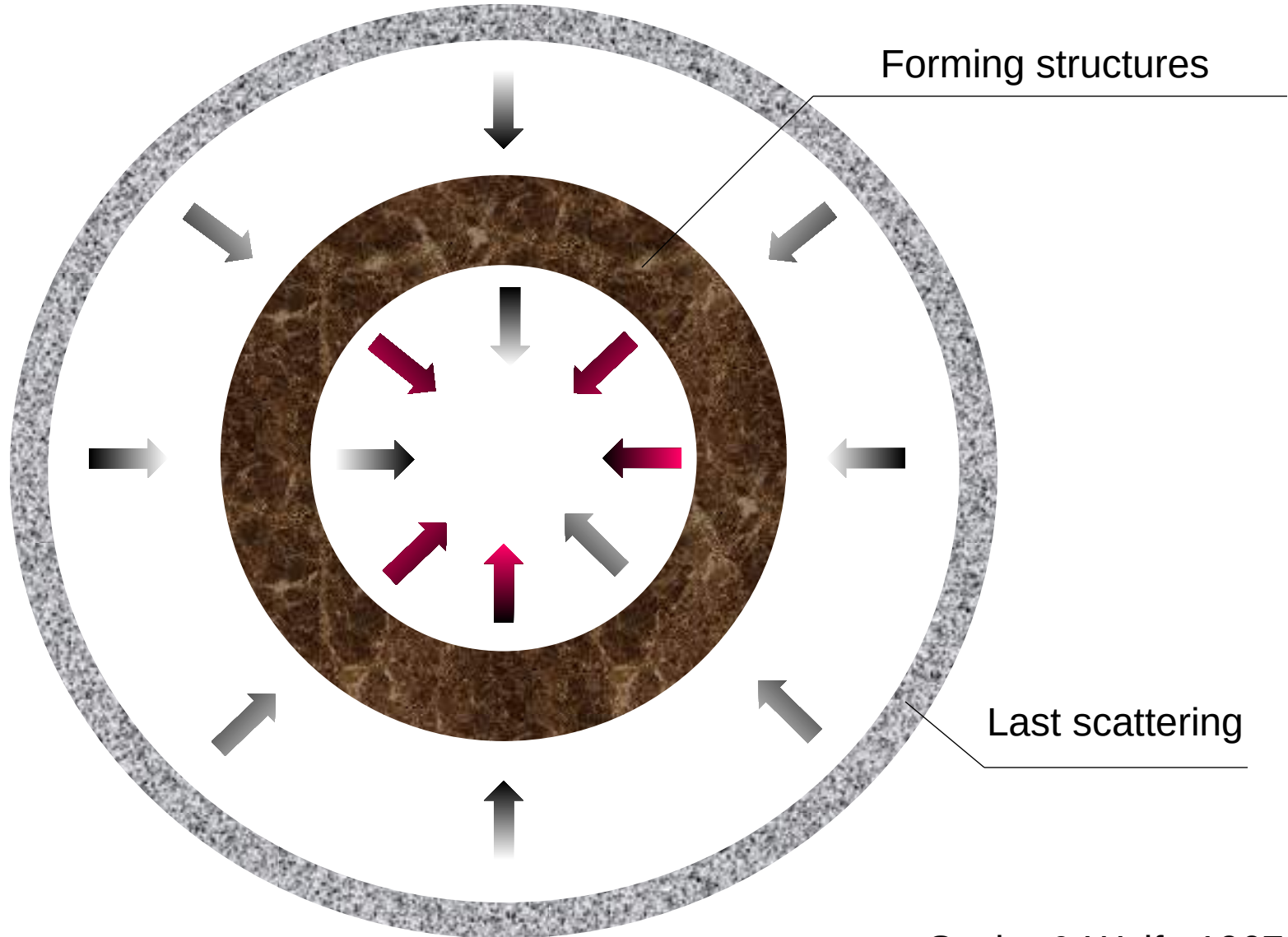
# Categories for LSS effects on CMB

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

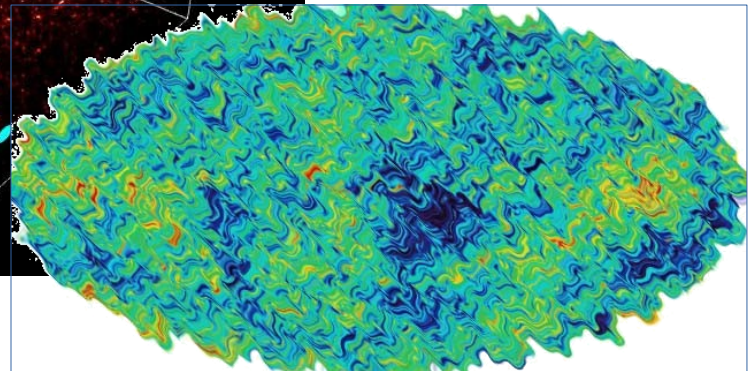
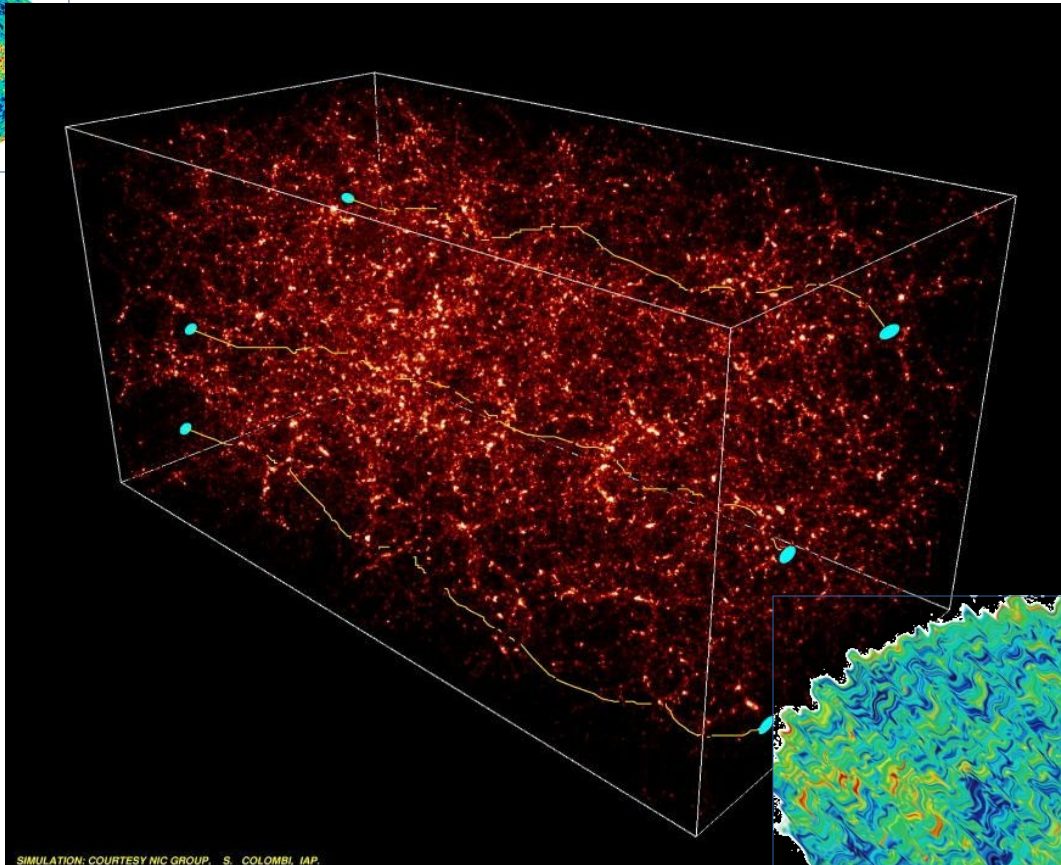
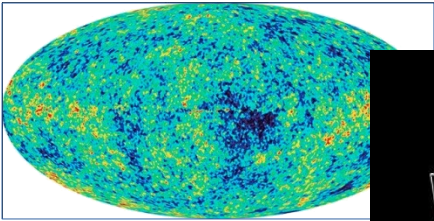
# Categories for LSS effects on CMB

- Re-scattering
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    - Deflection
- 

# Integrated Sachs-Wolfe



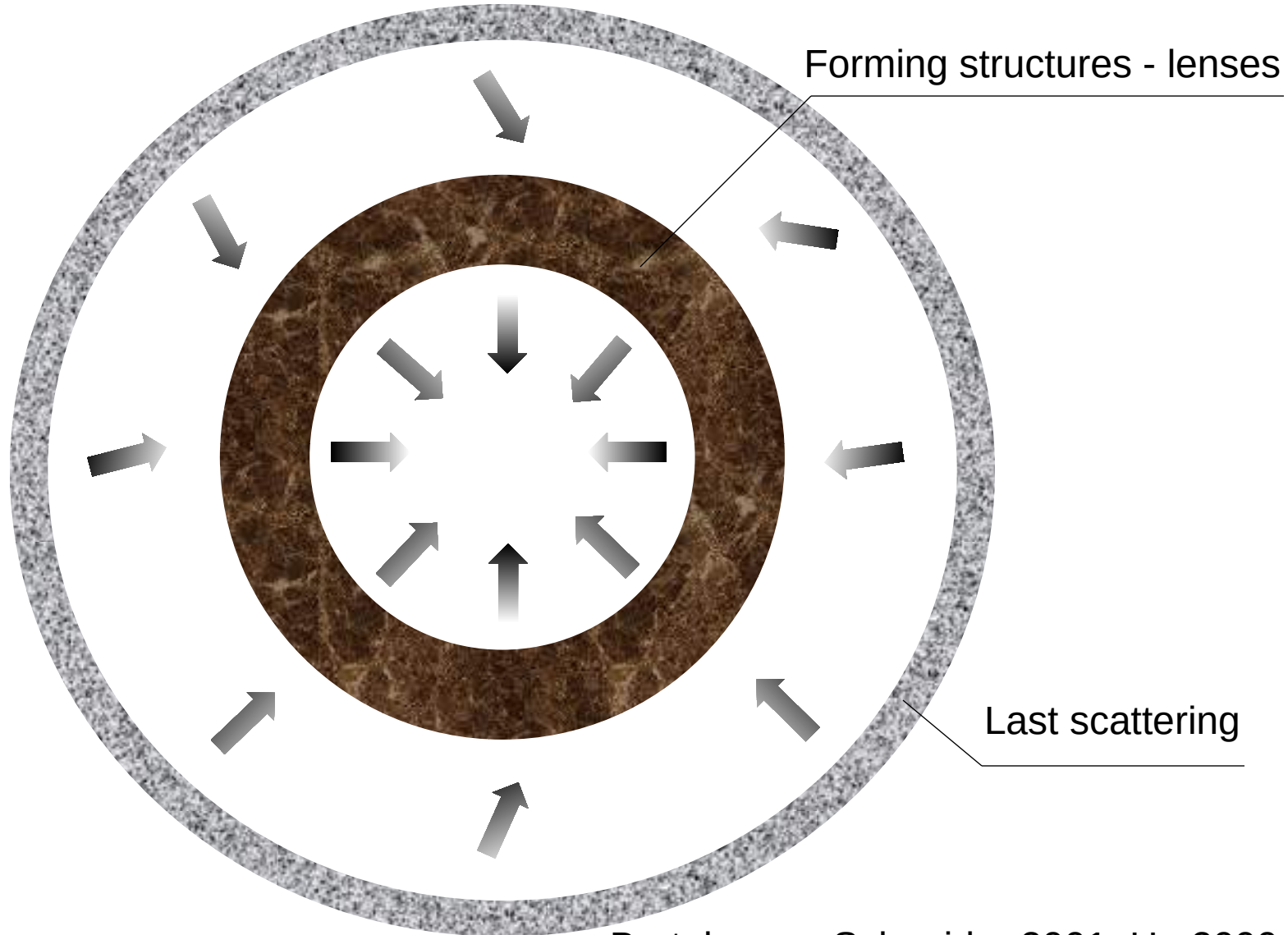
# CMB lensing



SIMULATION: COURTESY NIC GROUP, S. COLOMBI, IAP.

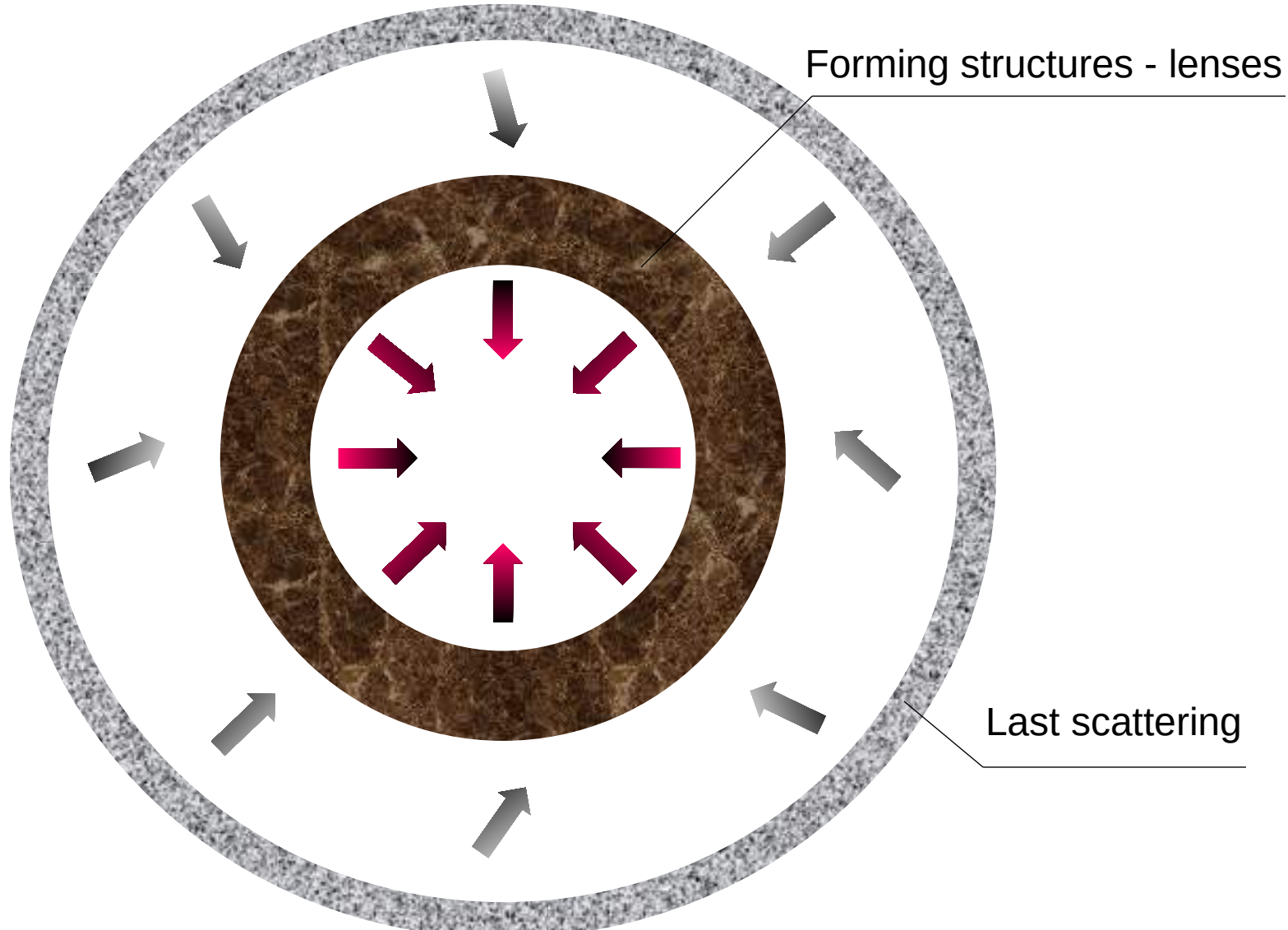
# CMB lensing

T



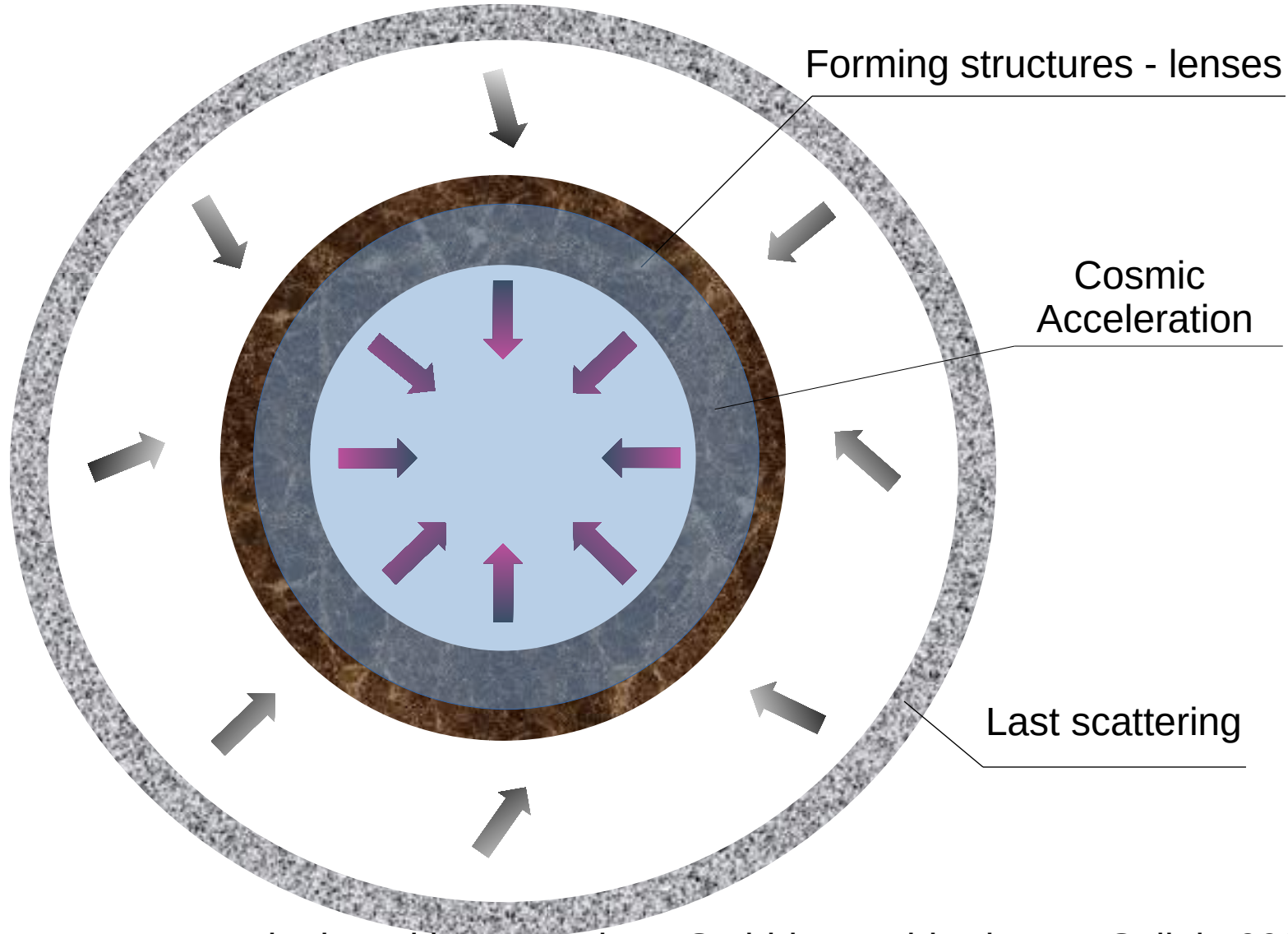
# CMB lensing

E  
B



# CMB lensing

E  
B

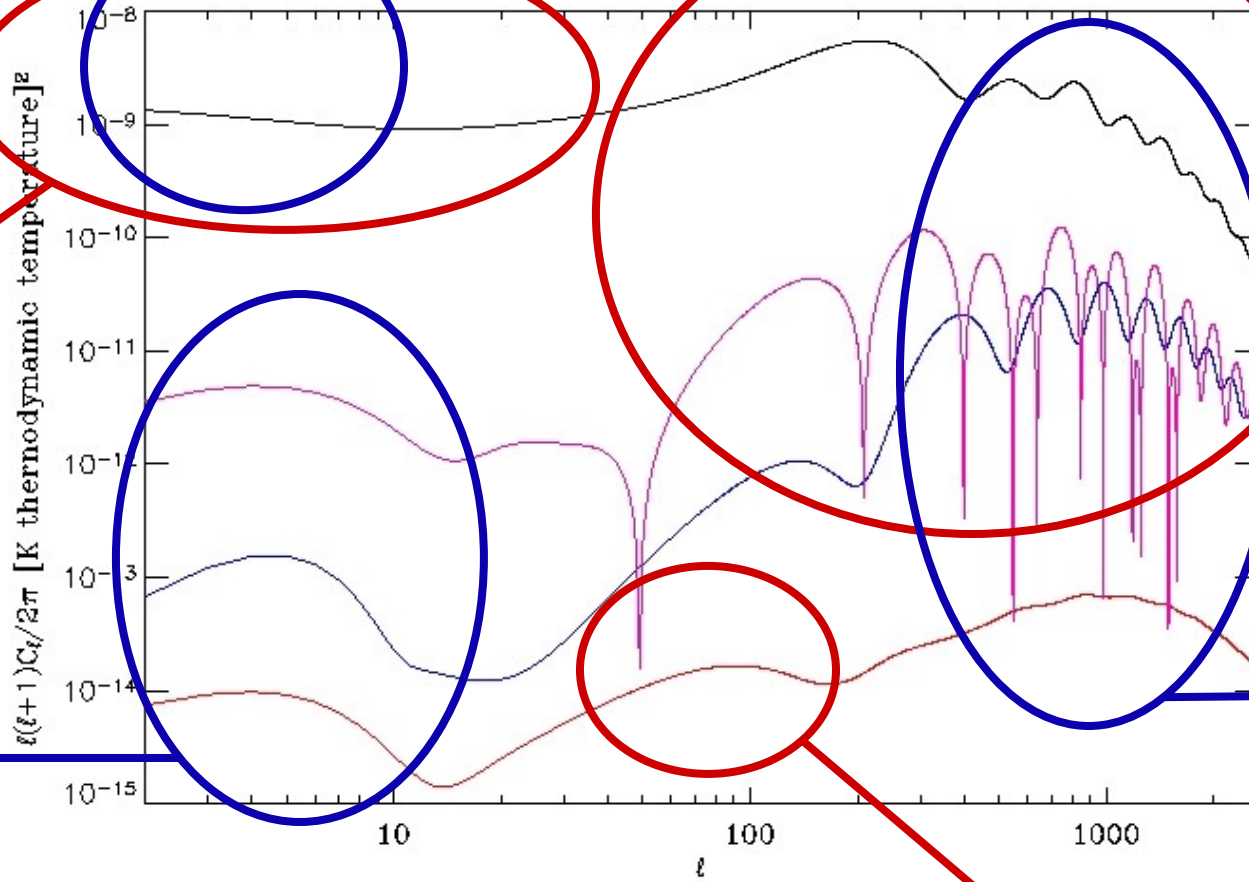


# CMB angular power spectrum

ISW

Acoustic oscillations

Primordial power



Lensing

Reionization

Angle  $\approx 200/l$  degrees

Gravitational waves



# Higher Order Statistics

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

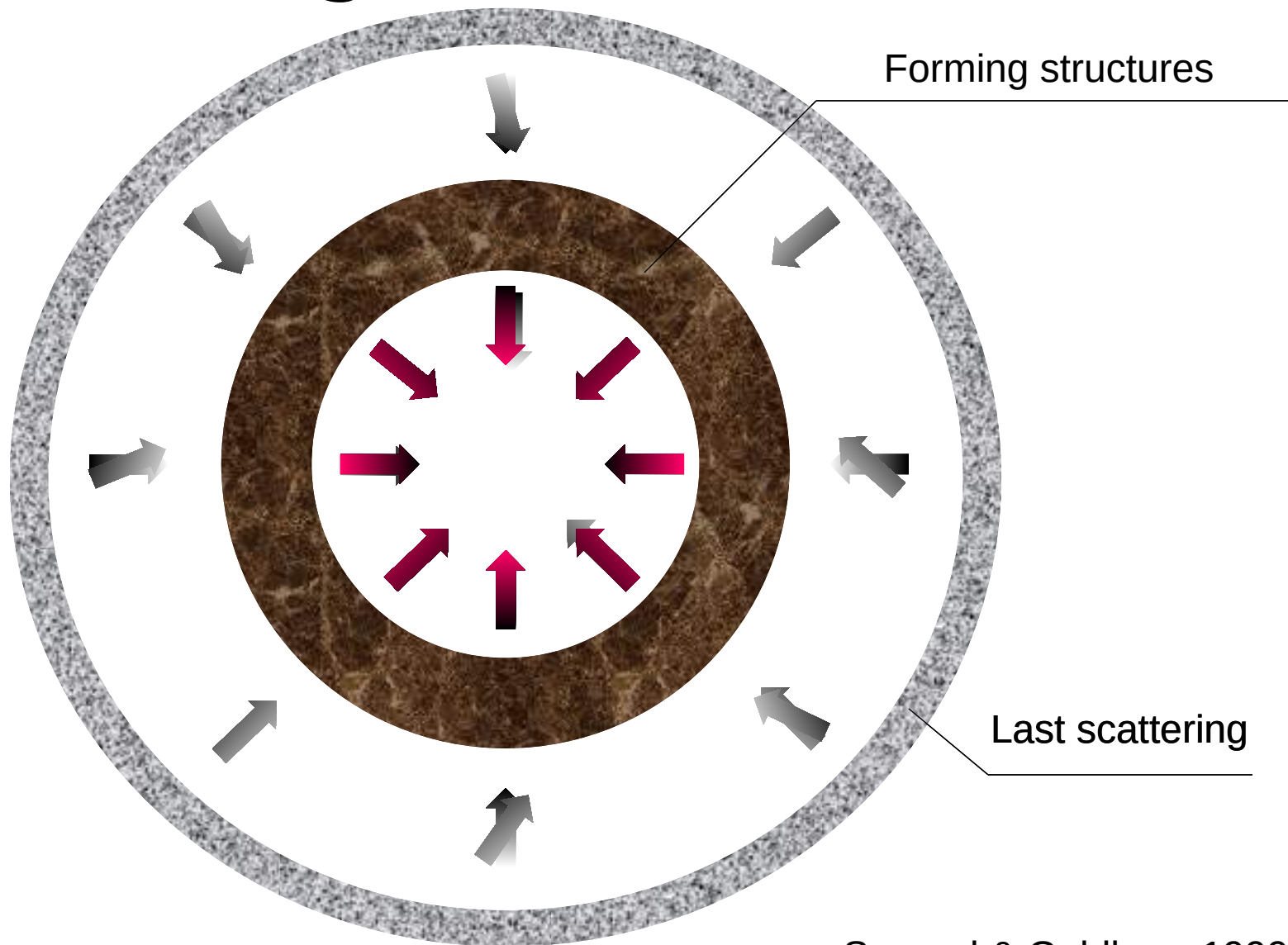
spherical  
harmonics

$$a_{lm}^X, X=T, E, B$$

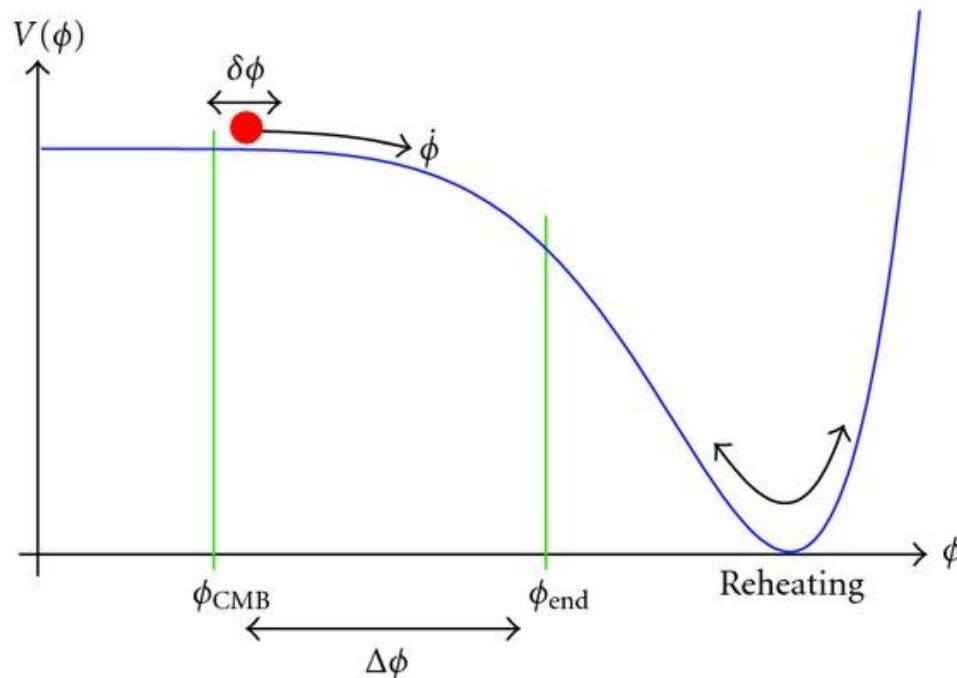
$$B_{|1|2|3} =$$

$$= \sum_{m_1, m_2, m_3} [ \binom{l_1}{m_1} \binom{l_2}{m_2} \binom{l_3}{m_3} (a_{l_1 m_1}^X) (a_{l_2 m_2}^Y) (a_{l_3 m_3}^Z) ]$$

# ISW-Lensing Cross-Correlation



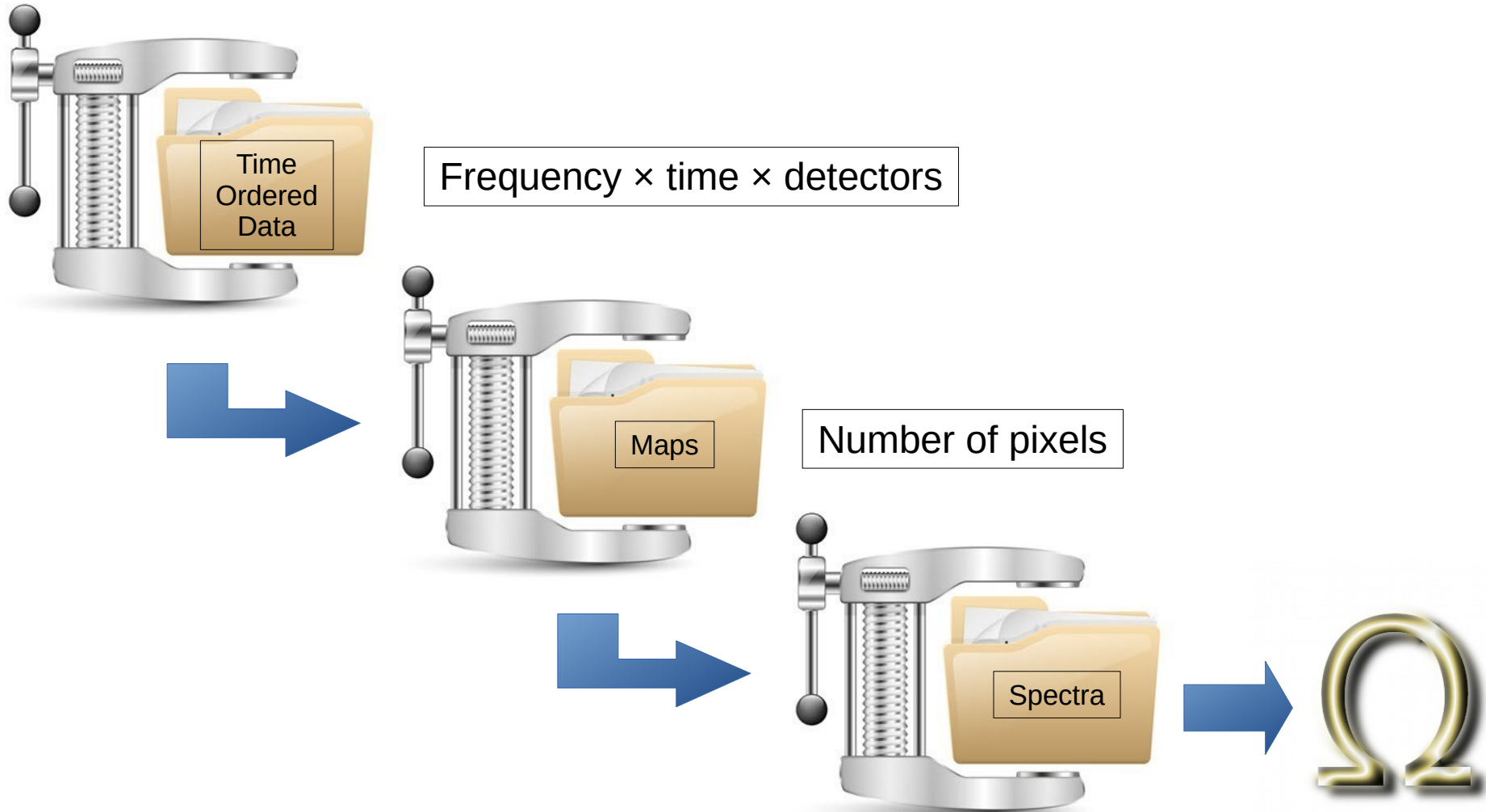
# Primordial non-Gaussianities



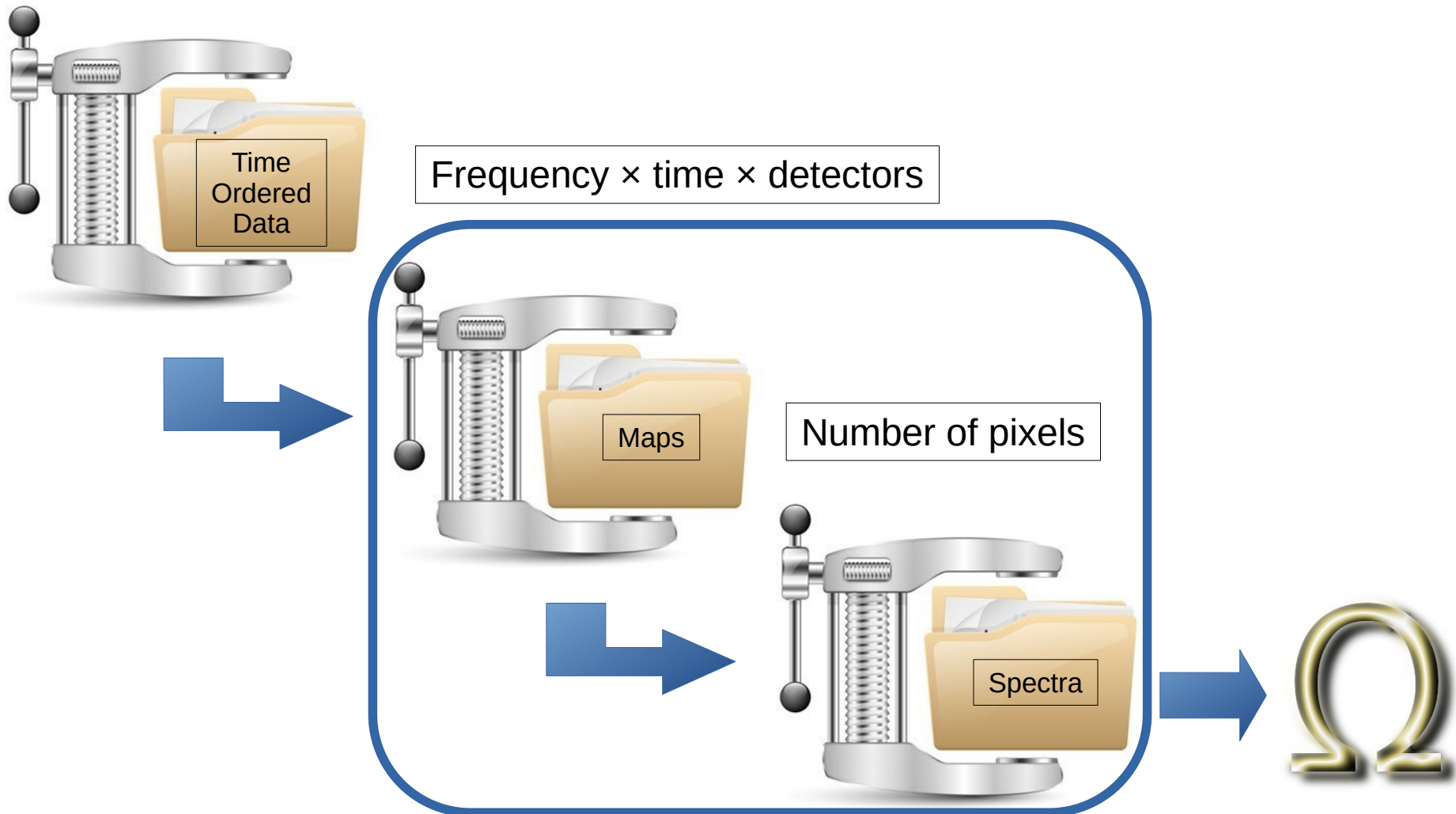
$$\Phi = \varphi_G + f_{\text{NL}}(\varphi_G^2 - \langle \varphi_G^2 \rangle)$$

# Analysis

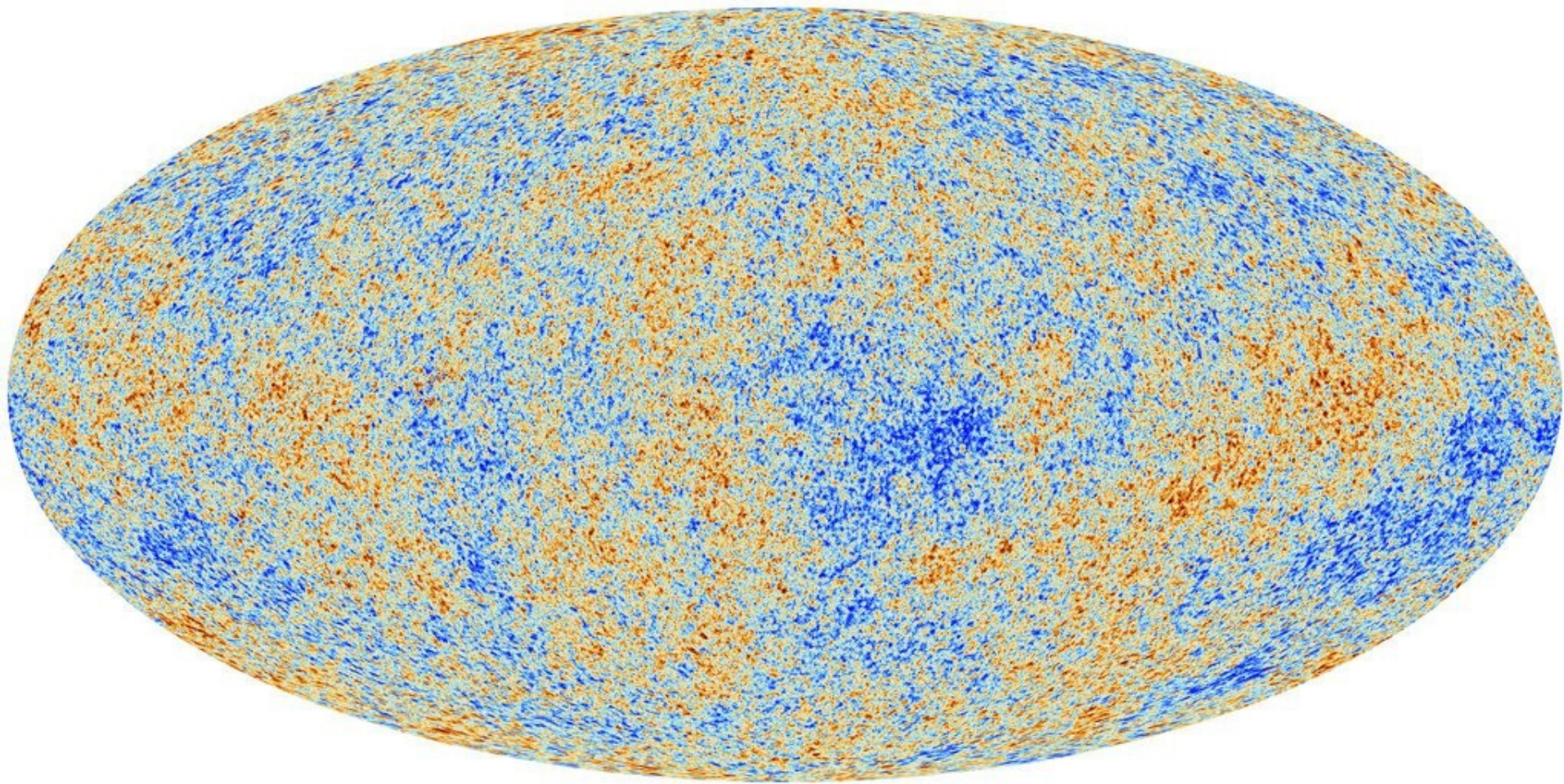
# CMB Data Analysis: Titanic Compression



# CMB Data Analysis: Titanic Compression



# CMB as seen by Planck

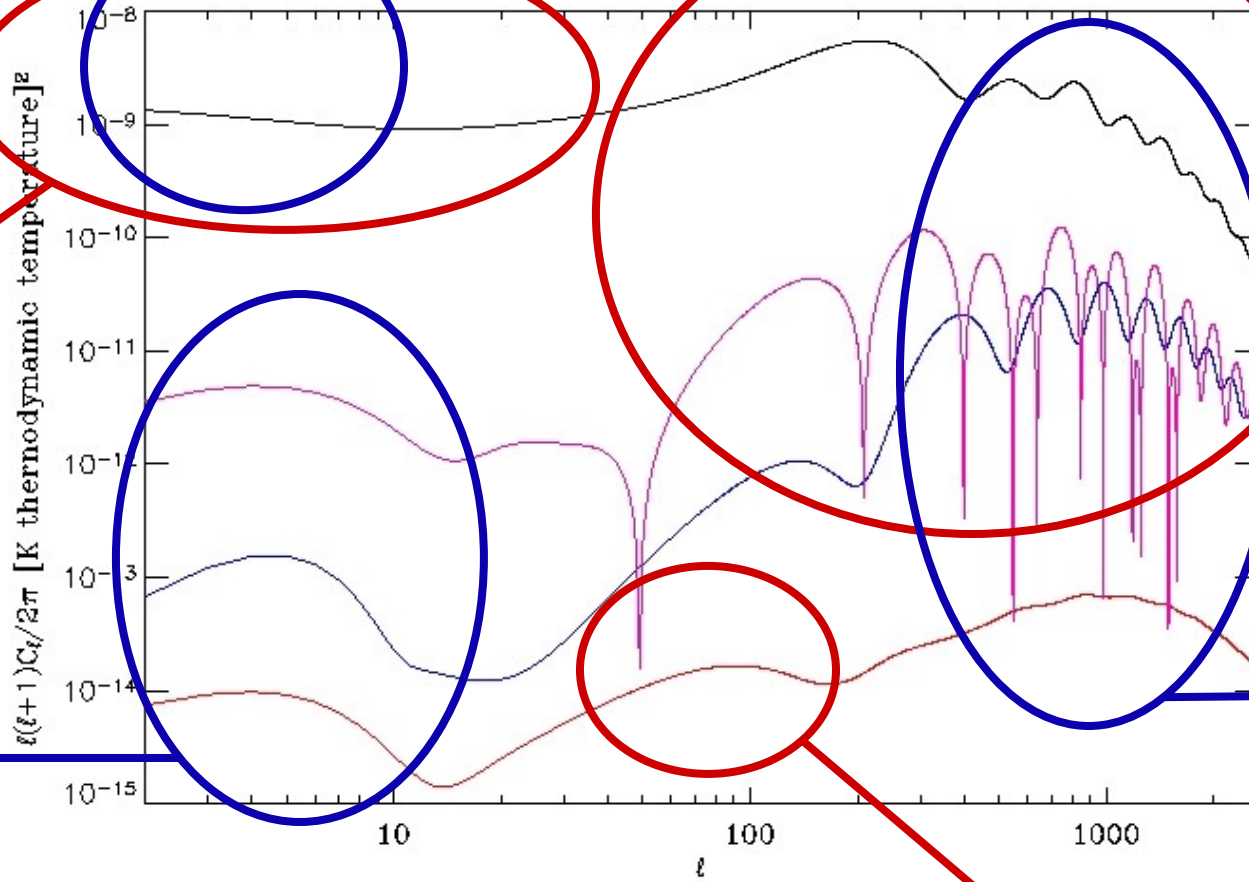


# CMB angular power spectrum

ISW

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Lensing

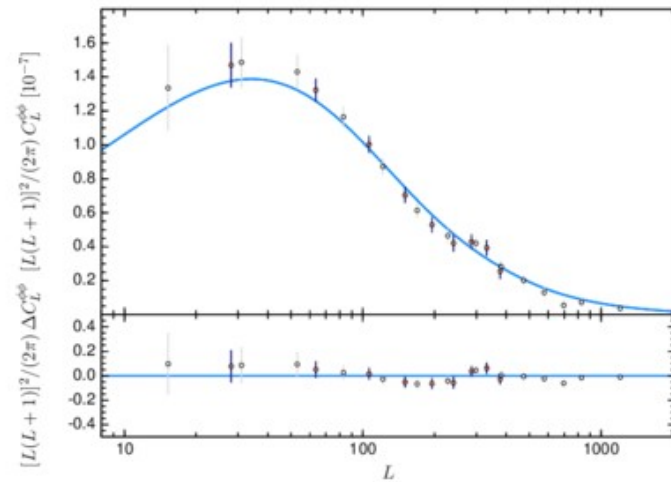
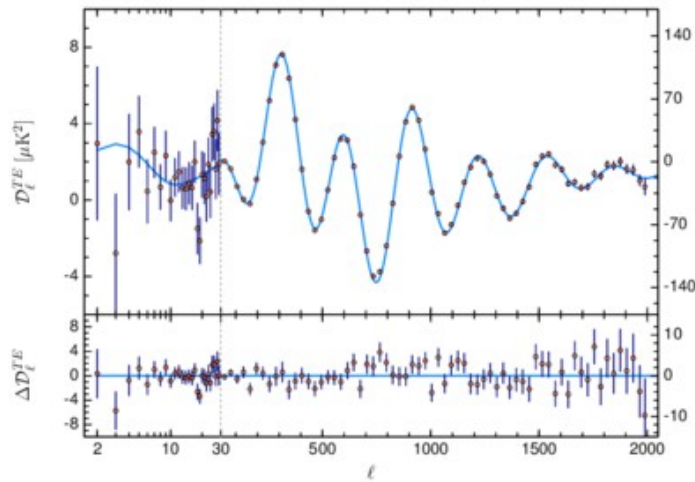
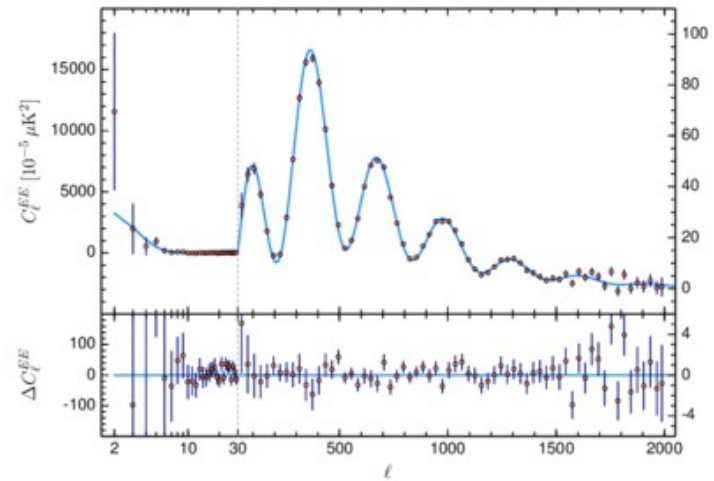
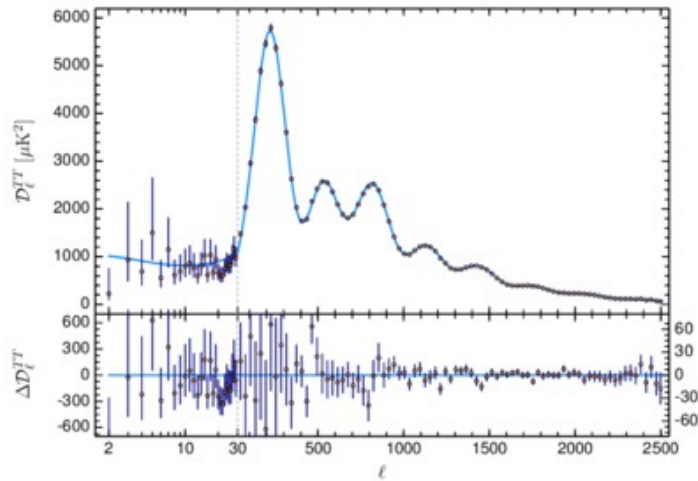
Reionization

Angle  $\approx 200/l$  degrees

Gravitational waves



# CMB as seen by Planck



# Higher Order Statistics

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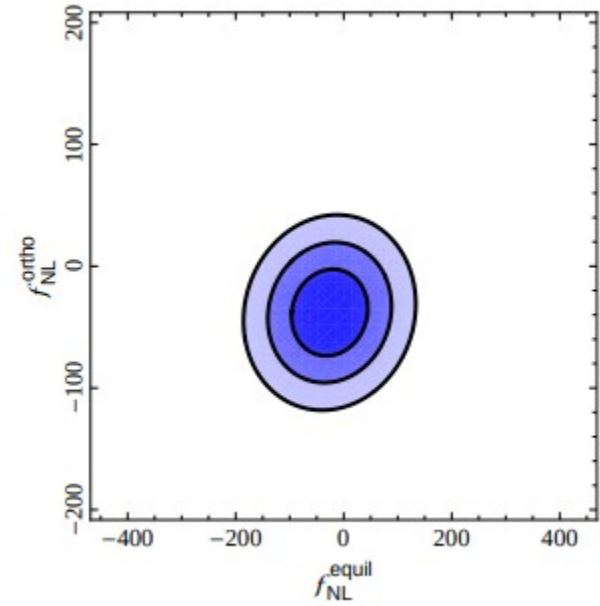
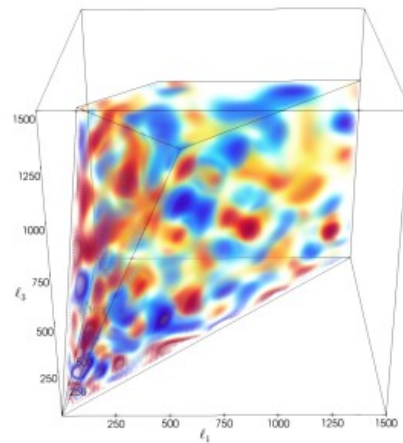
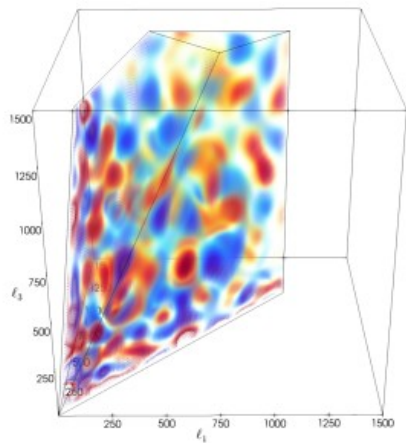
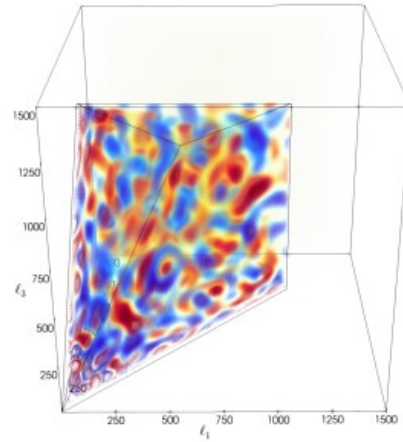
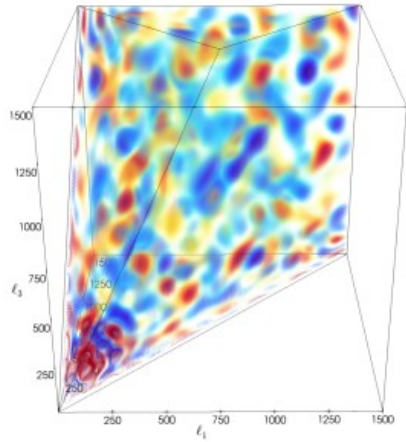
spherical  
harmonics

$$a_{lm}^X, X=T, E, B$$

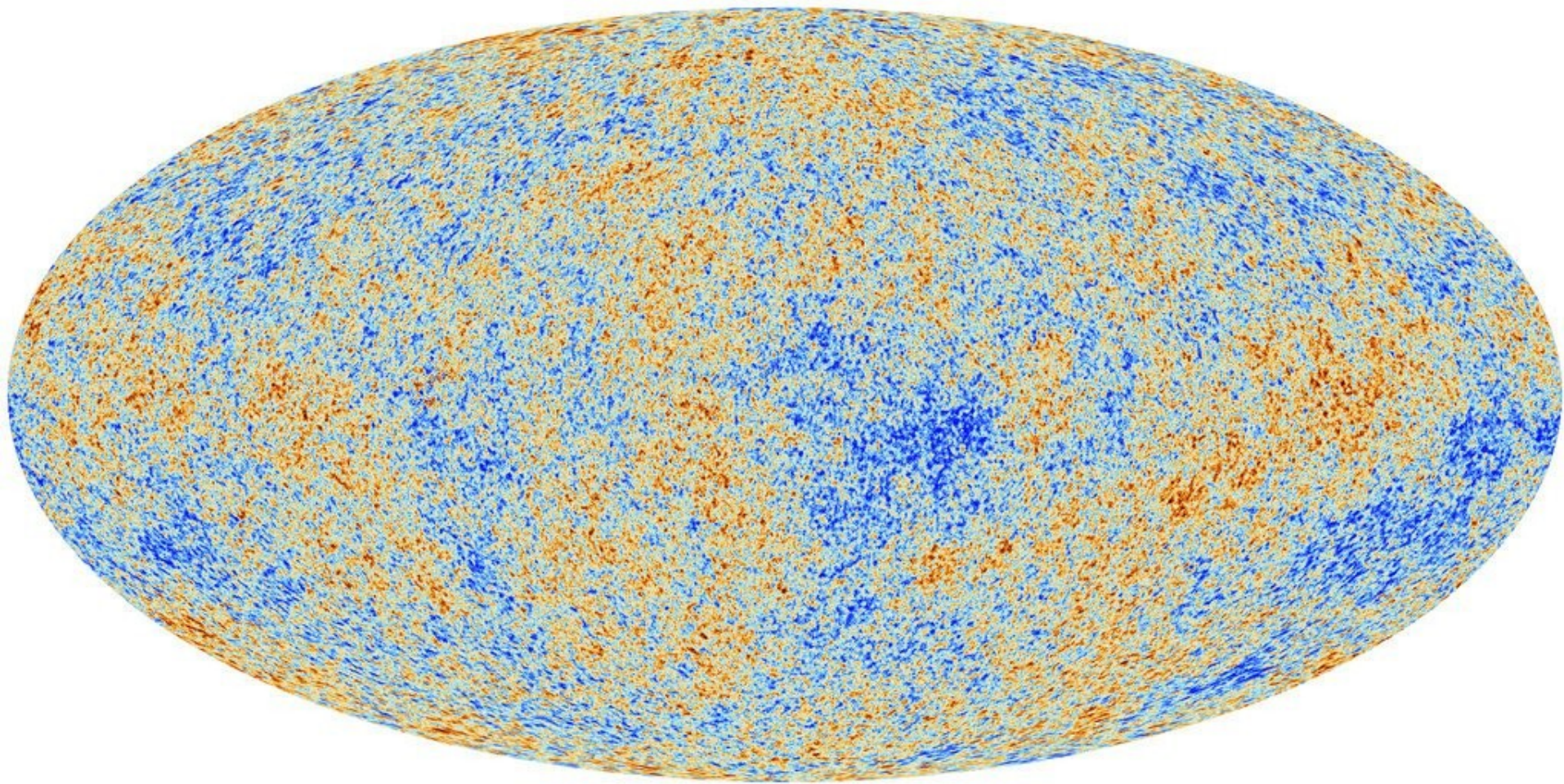
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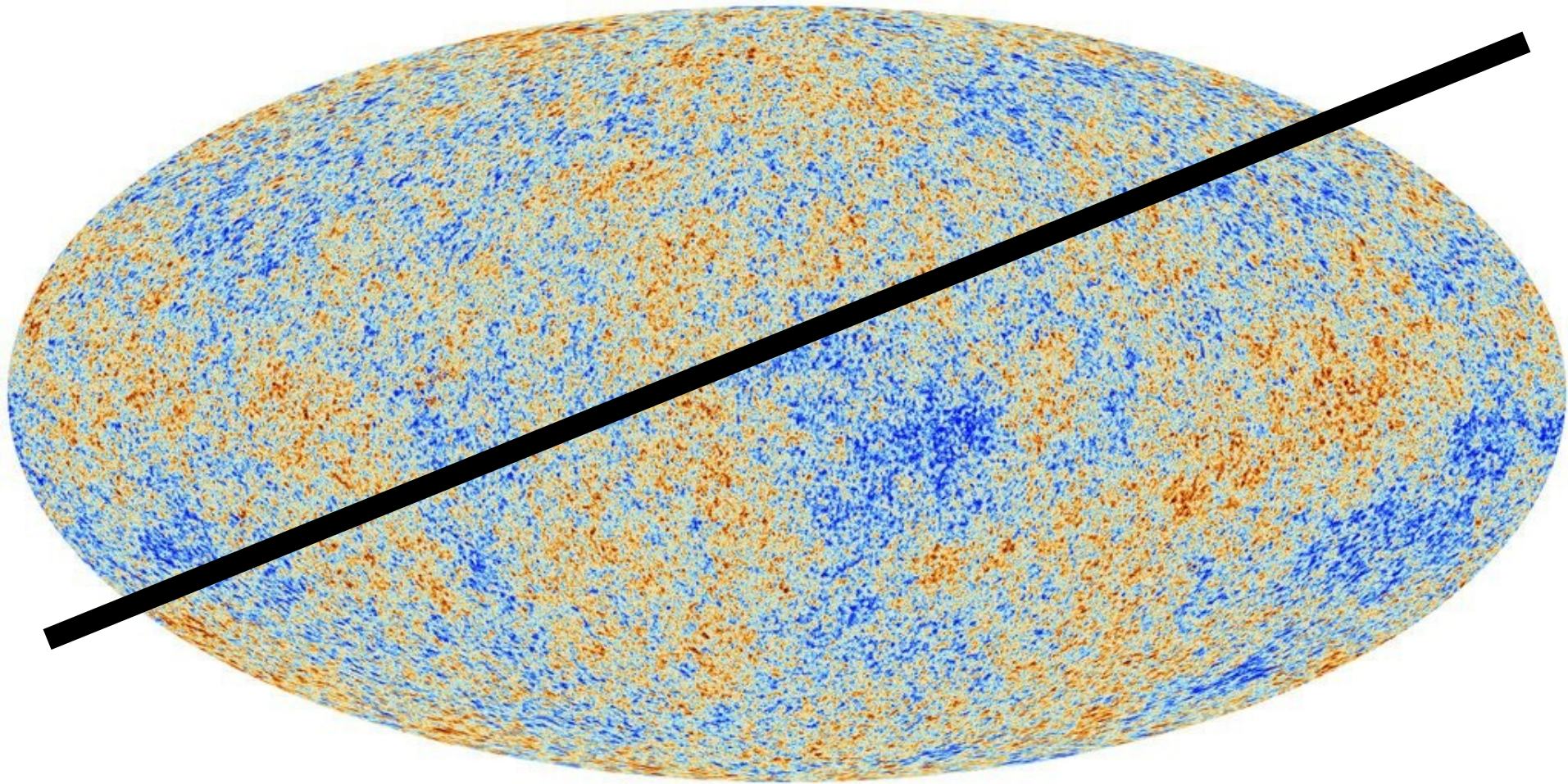
# CMB as seen by Planck



# CMB as seen by Planck



# CMB as seen by Planck



# Isotropy & Statistics

Astronomy & Astrophysics manuscript no. Planck\_2018\_Isotropy\_and\_Statistics  
September 15, 2020

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

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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  $\Lambda$ CDM 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  $\Lambda$ CDM 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

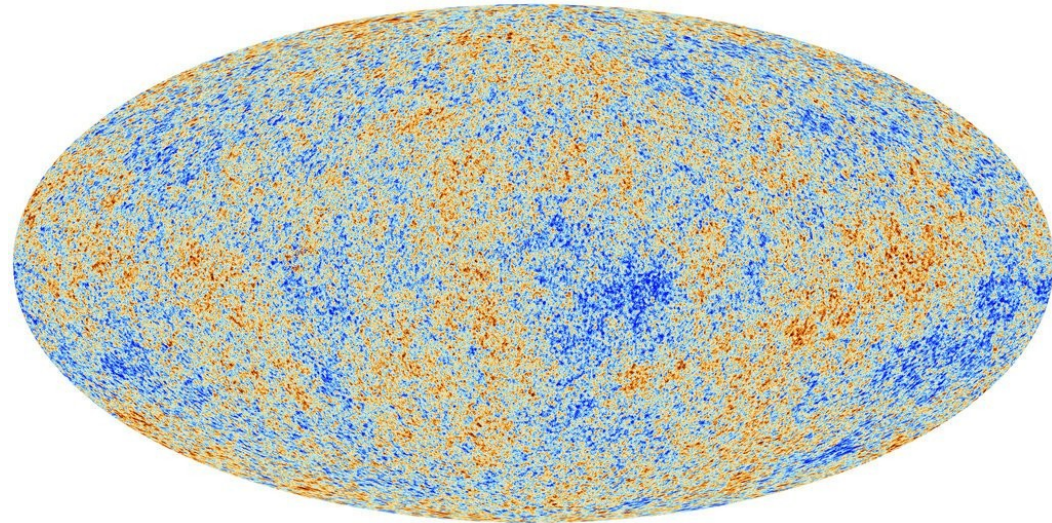
### 1. Introduction

This paper, one of a set associated with the 2018 release of data from the *Planck*<sup>1</sup> 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  $\Lambda$ CDM 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-

ctors provided through a collaboration between ESA and a scientific consortium led and funded by Denmark, and additional contributions from NASA (USA).



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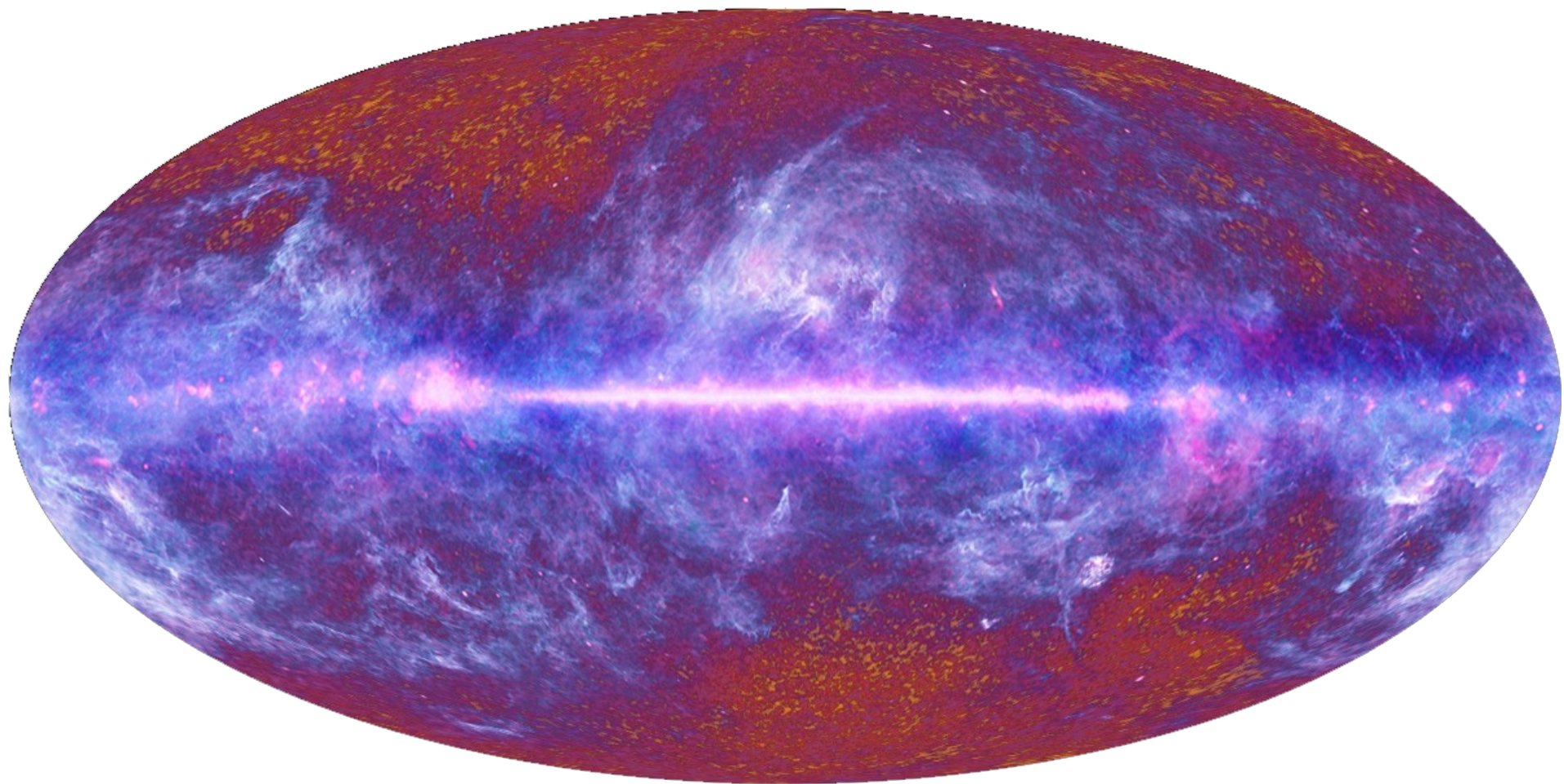
\*\* Corresponding author: K. M. Górski [krzysztof.m.gorski@jpl.nasa.gov](mailto:krzysztof.m.gorski@jpl.nasa.gov)

\*\*\* Corresponding author: E. Martínez-González [martinez@ifca.uvic.es](mailto:martinez@ifca.uvic.es)

<sup>1</sup> Corresponding author: P. Vielva [vielva@ifca.unican.es](mailto:vielva@ifca.unican.es)

<sup>1</sup> *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 re-

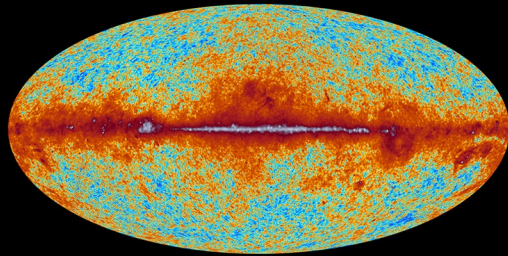
# Sky as seen by Planck



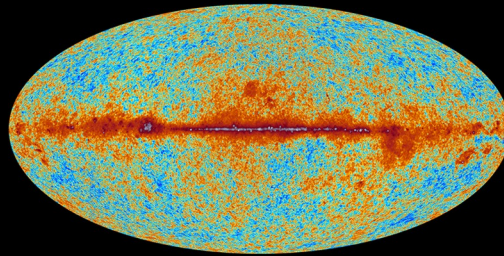


planck

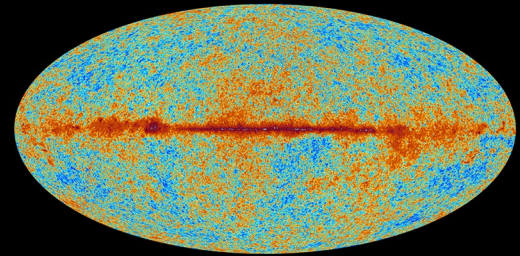
# The sky as seen by Planck



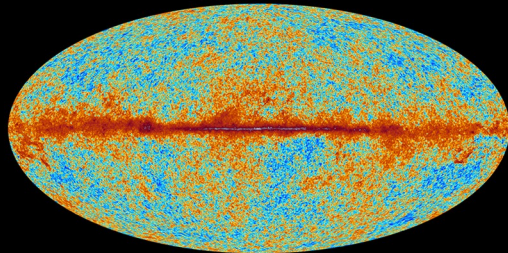
30 GHz



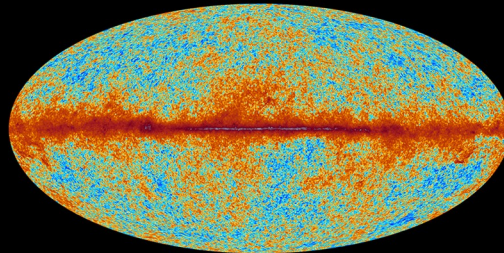
44 GHz



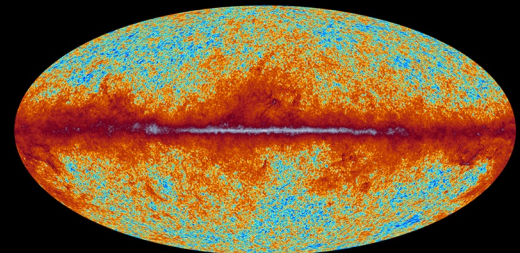
70 GHz



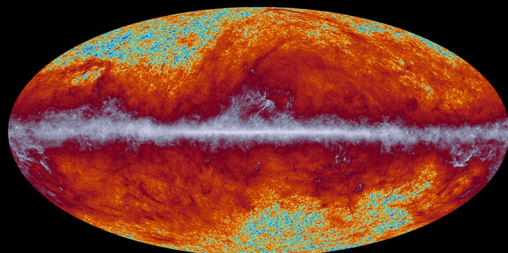
100 GHz



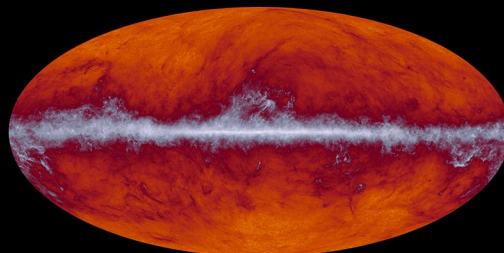
143 GHz



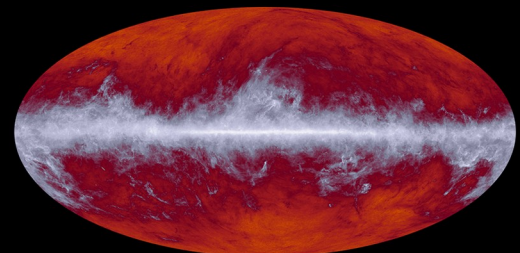
217 GHz



353 GHz



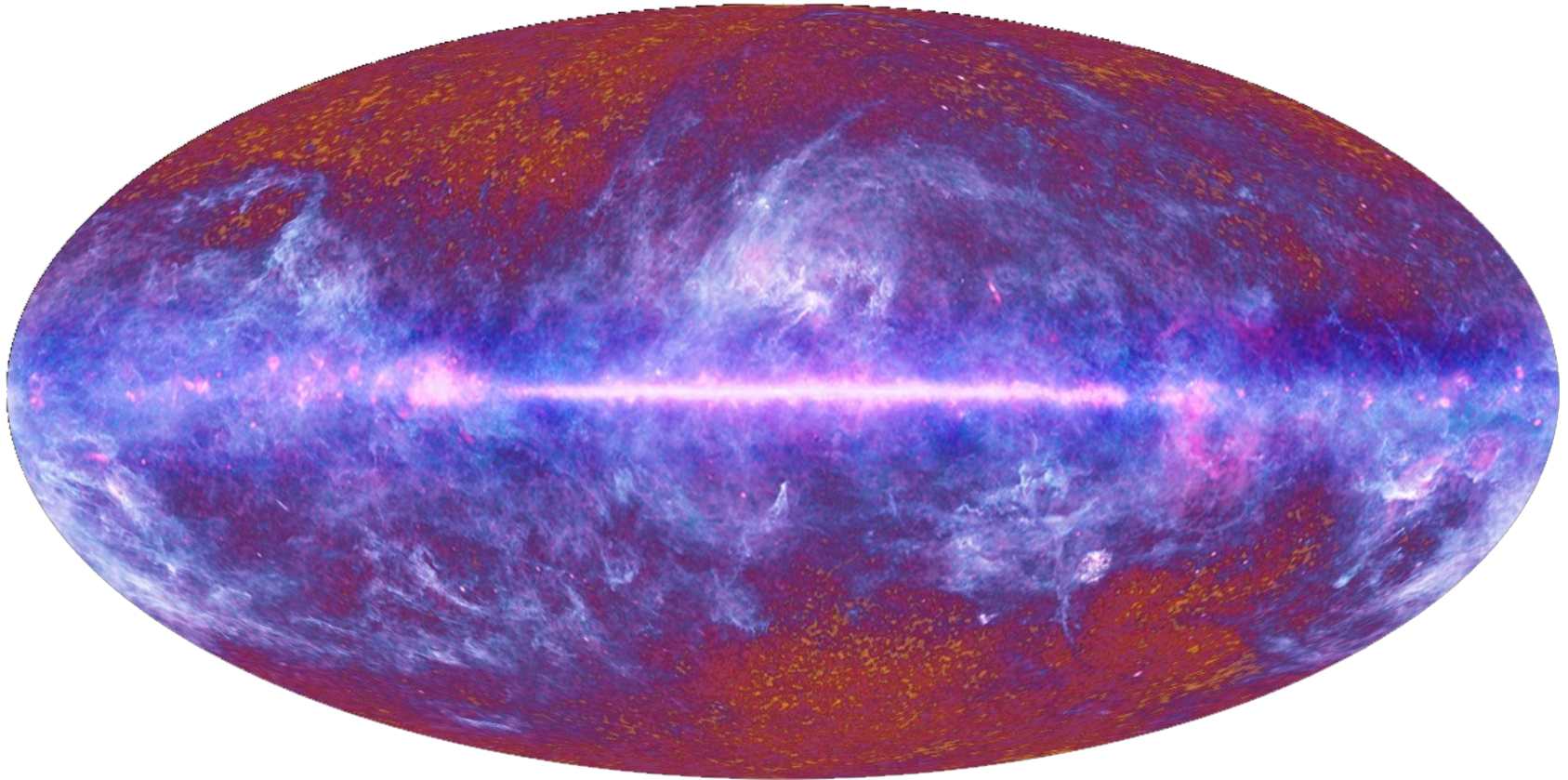
545 GHz



857 GHz



$F = A(\text{sky direction}) \times F(\text{frequency})$

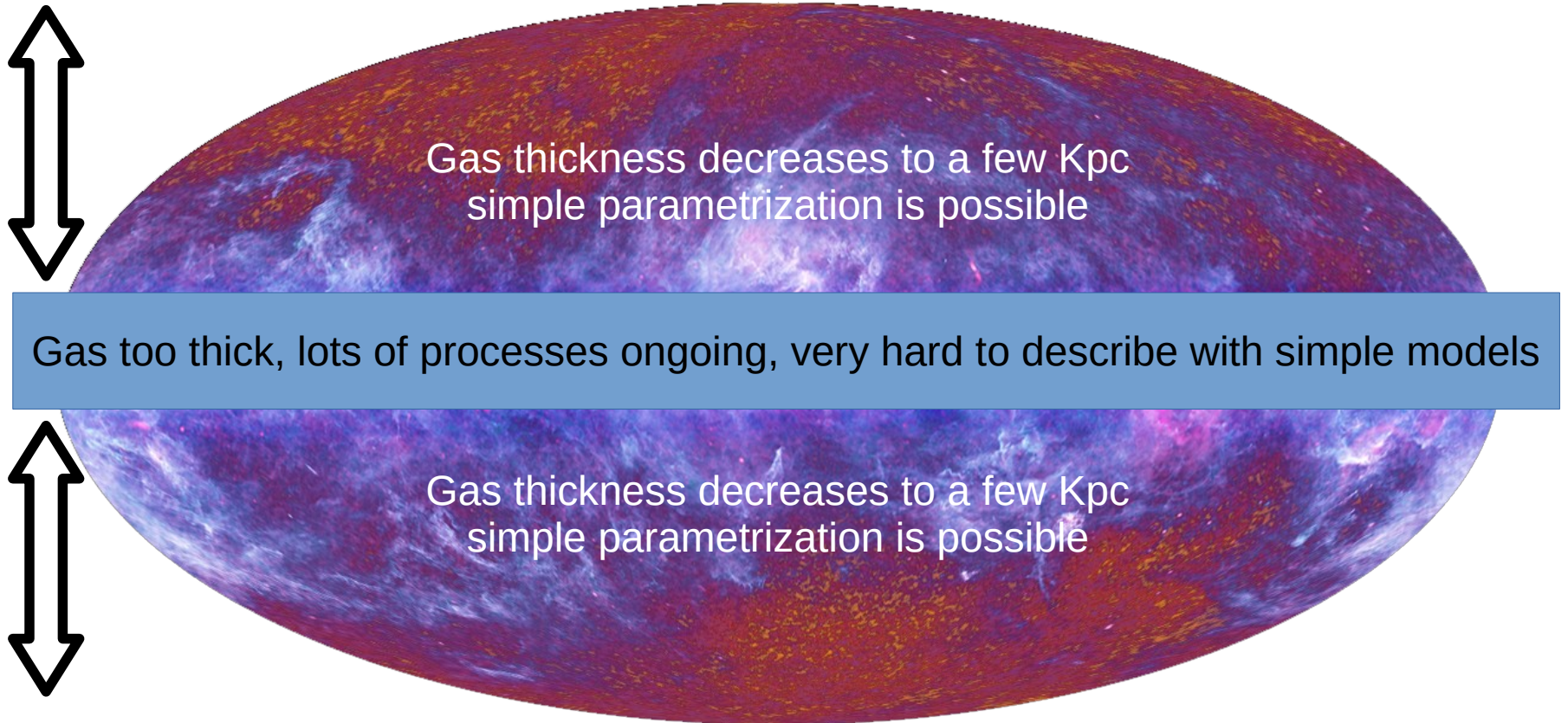


$$F=A \text{ (sky direction)} \times F(\text{frequency})$$

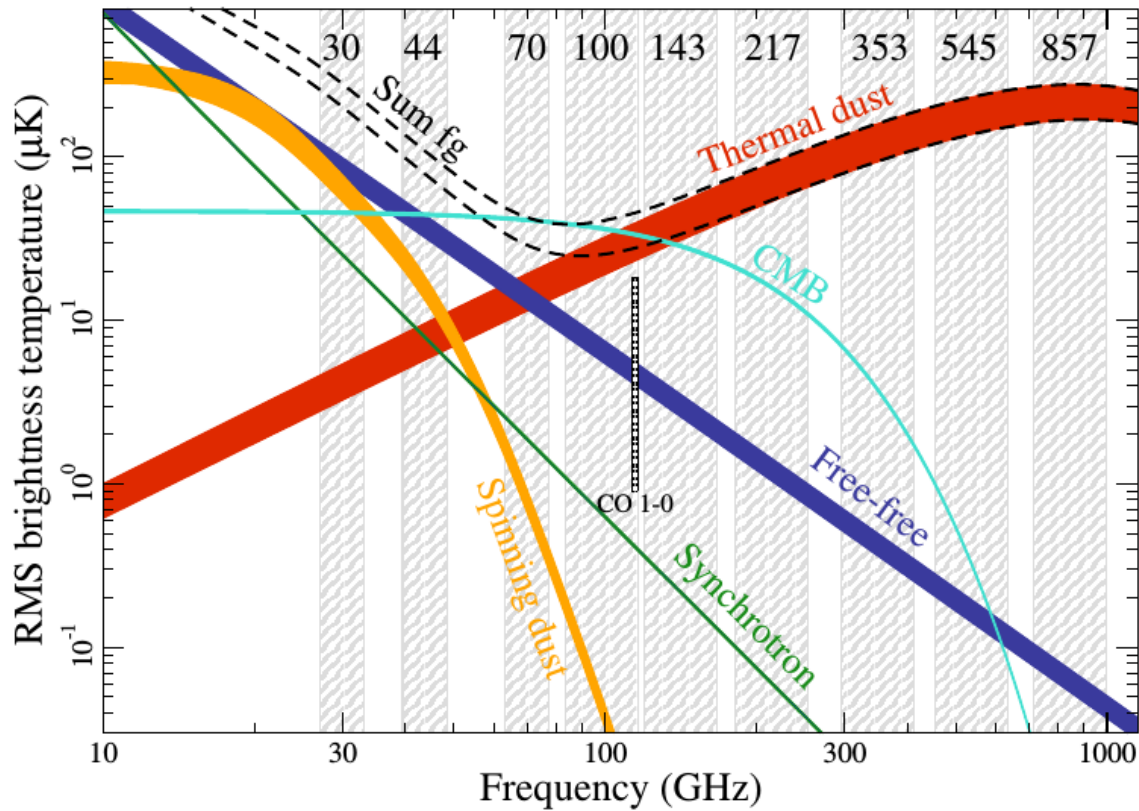


Gas too thick, lots of processes ongoing, very hard to describe with simple models

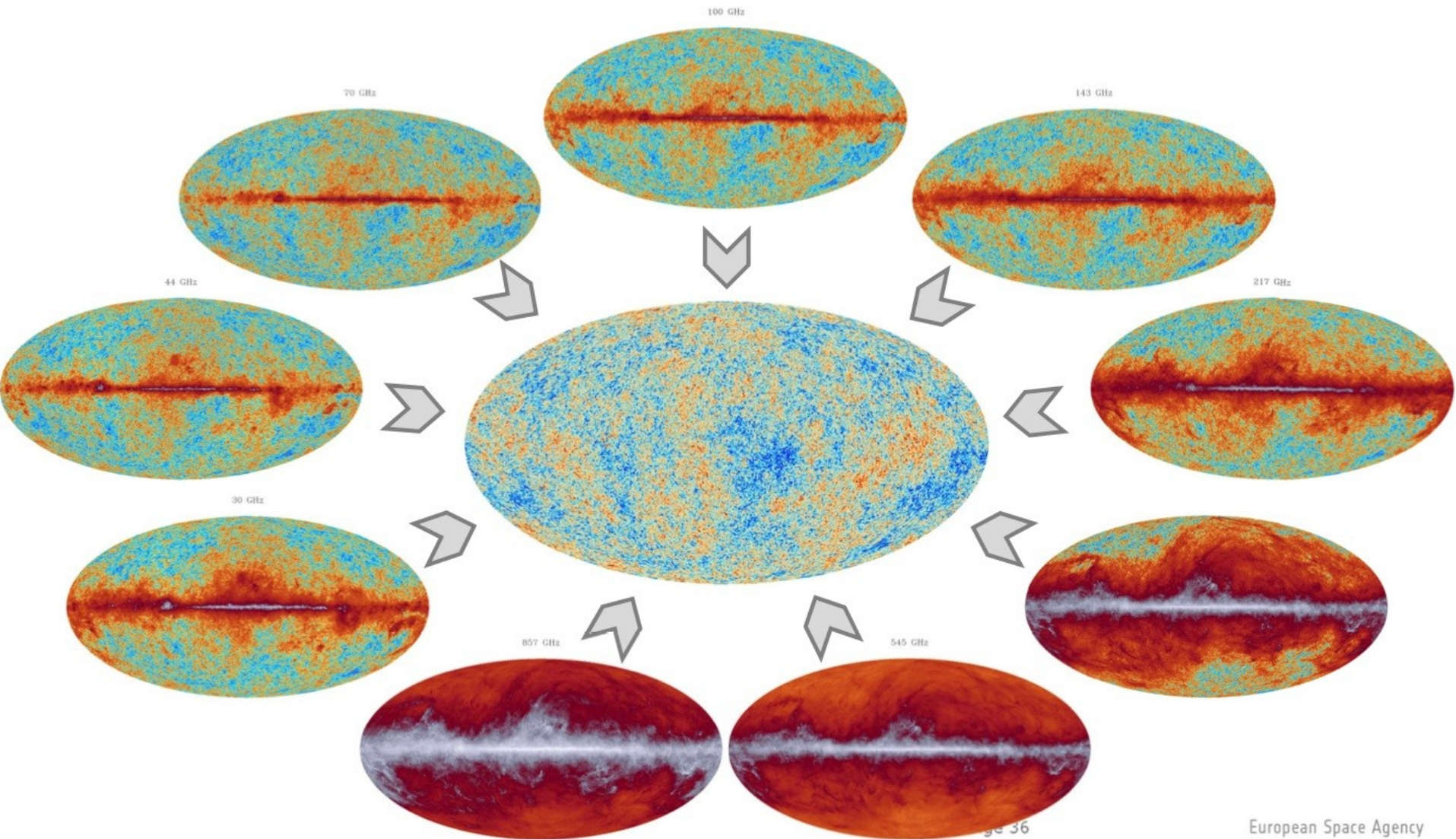
$$F = A \text{ (sky direction)} \times F \text{ (frequency)}$$



# Foregrounds and frequency



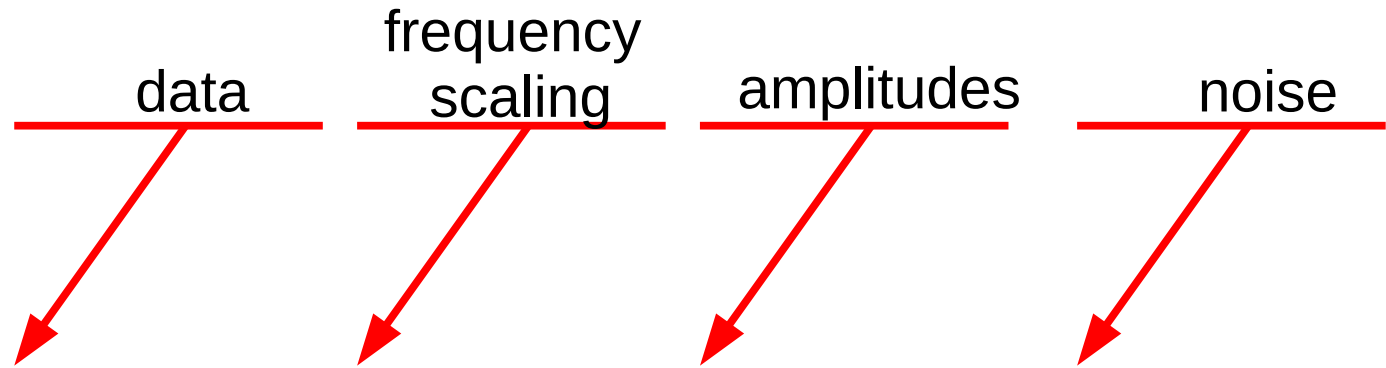
# Component separation



# Component separation

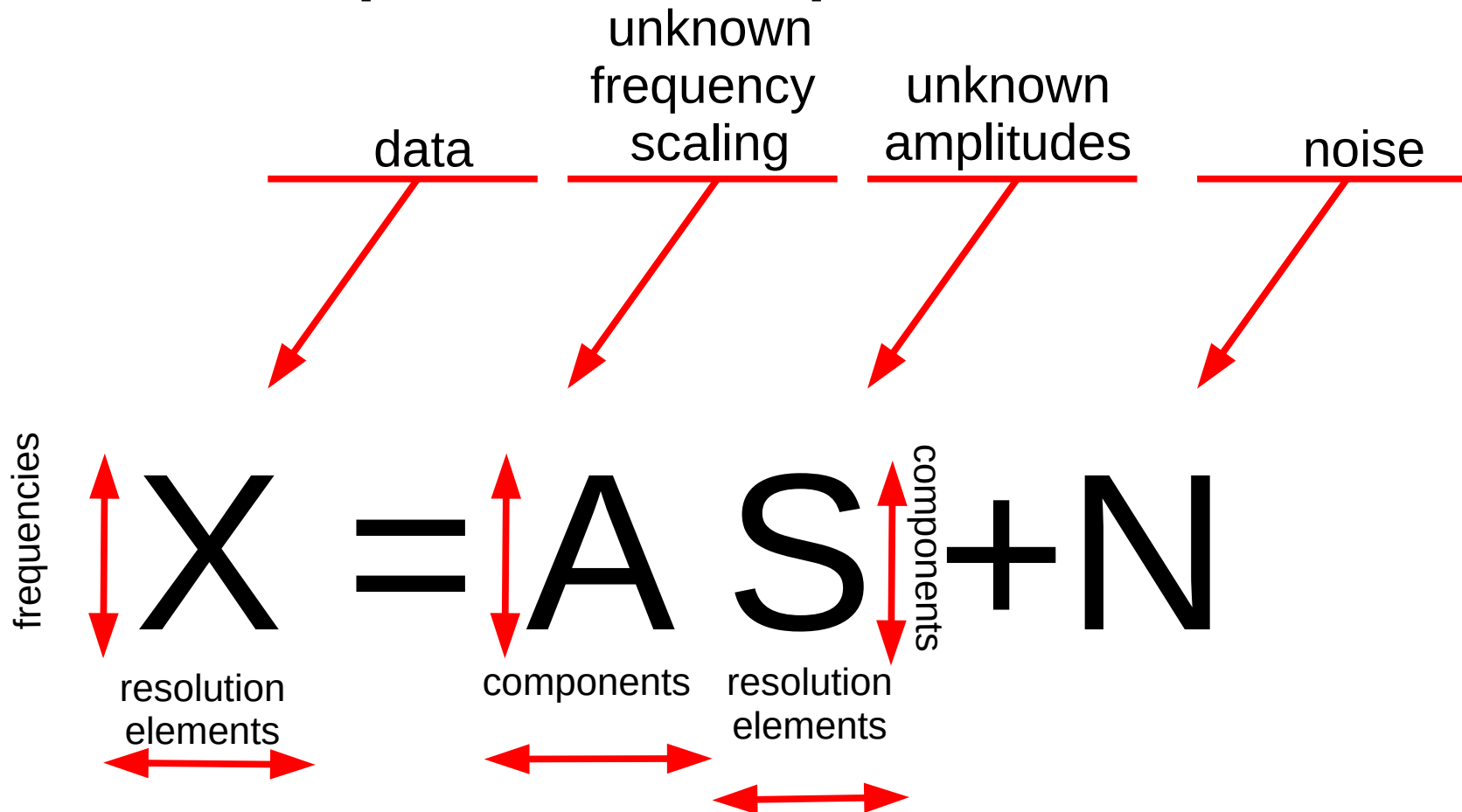
$$X = AS + N$$

# Component separation



$$X = AS + N$$

# 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:

$$\sum_i w_i X_i \quad \sum_i w_i = 1$$

# Component separation

- Operating 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

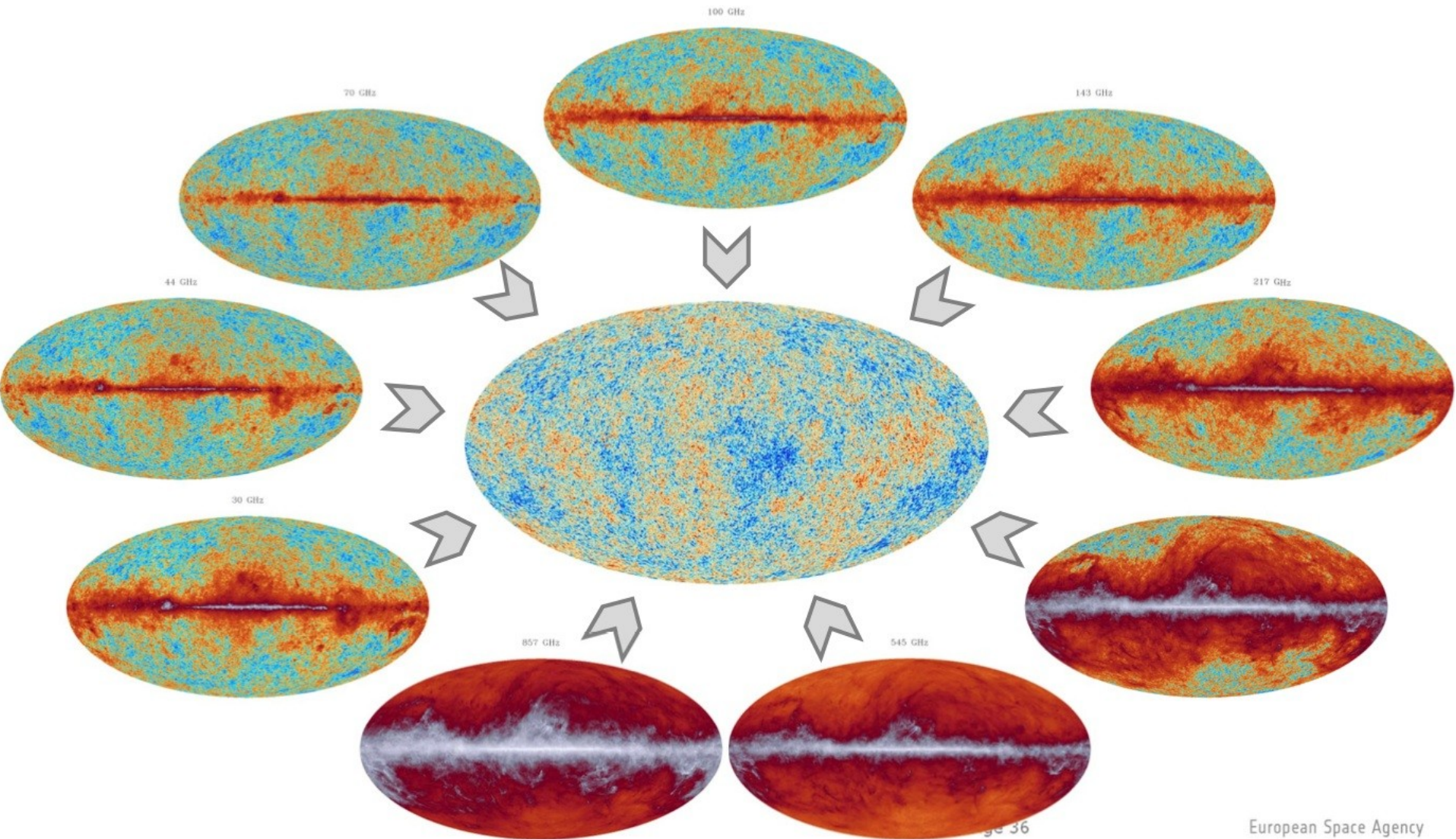
# Component separation

- 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)

# Component separation





# The Planck Legacy Archive

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## Planck Legacy Archive

Release PR2 - 2015

PR2 - 2015 MAPS

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

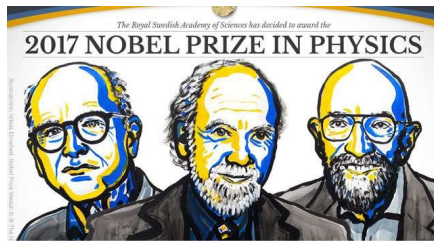
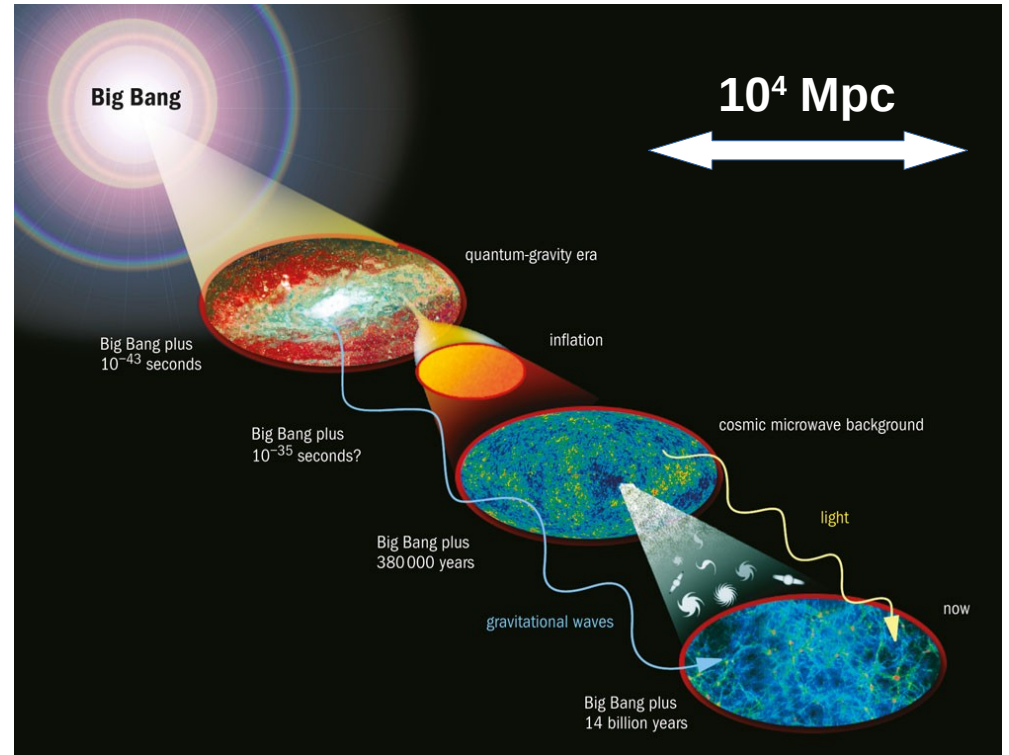
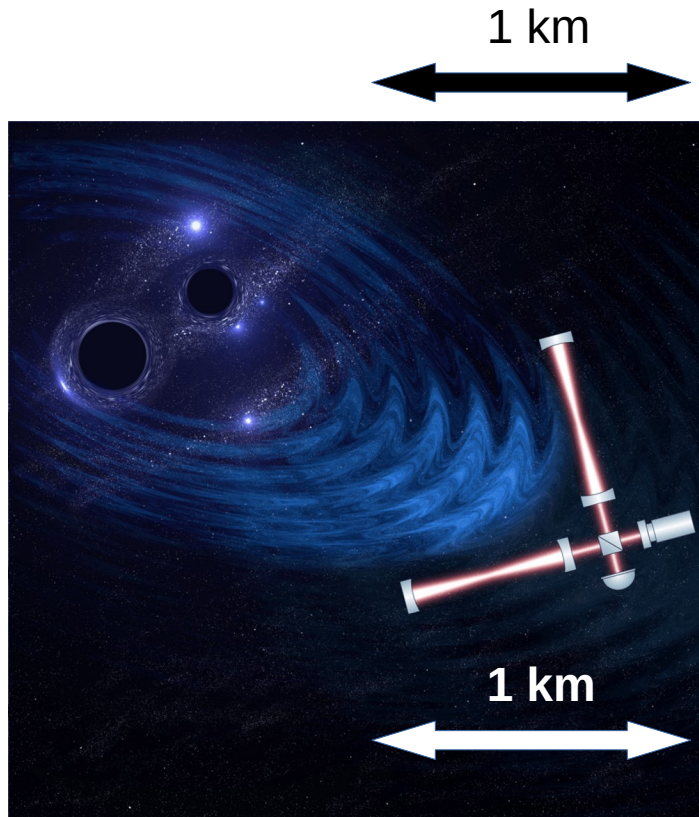
[Explanatory Supplement](#)

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

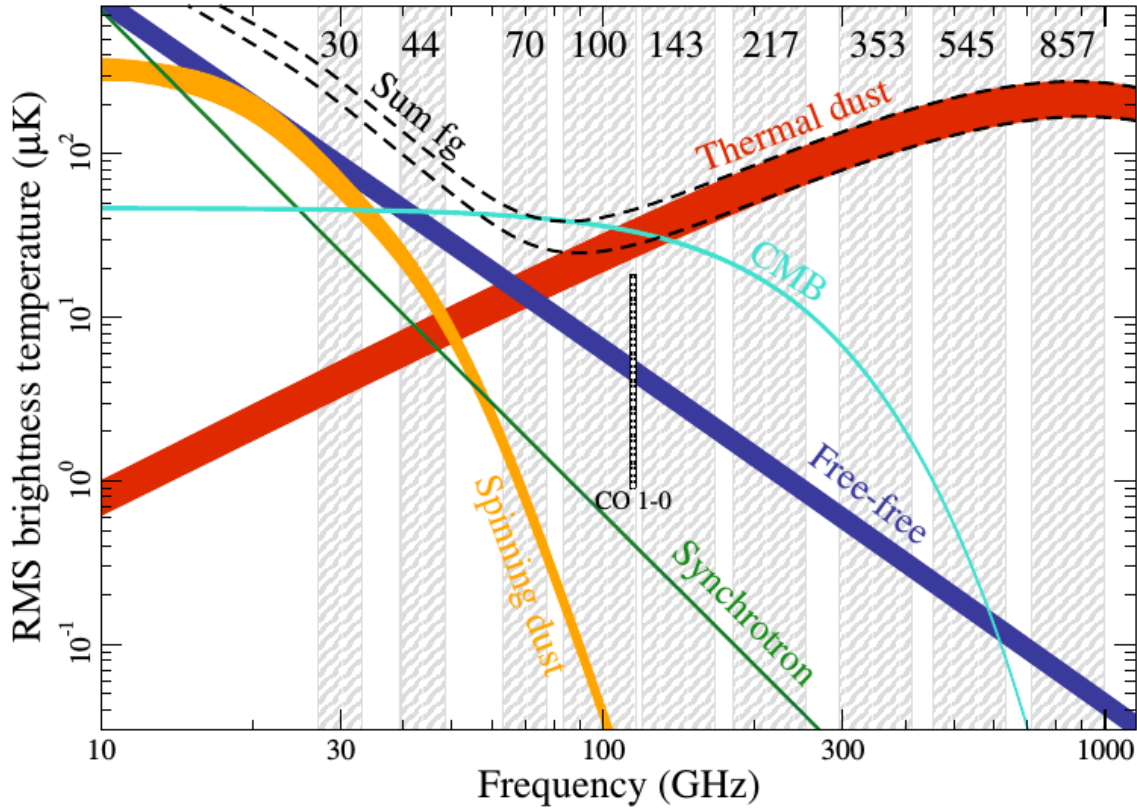
	IQU NS1024	I NS2048
FULL MISSION	(168 MB)	(240 MB)
FULL MISSION RINGHALF-1	(144 MB)	(192 MB)
FULL MISSION RINGHALF-2	(144 MB)	(192 MB)
HALF MISSION-1	(144 MB)	(192 MB)
HALF MISSION-2	(144 MB)	(192 MB)
YEAR-1	(144 MB)	(192 MB)
YEAR-2	(144 MB)	(192 MB)

# Cosmological Gravitational Waves

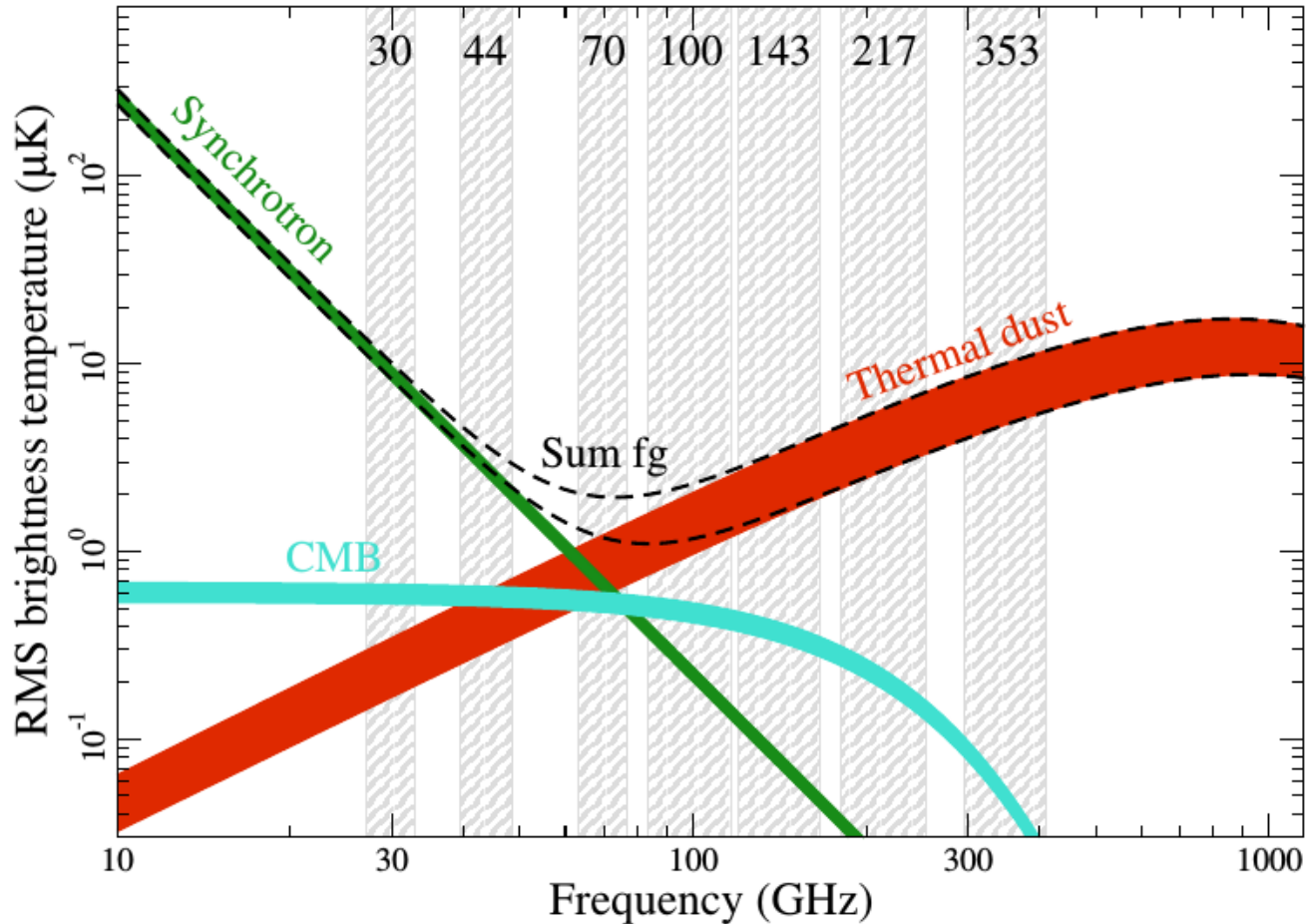
# Astrophysical vs Cosmological GWs



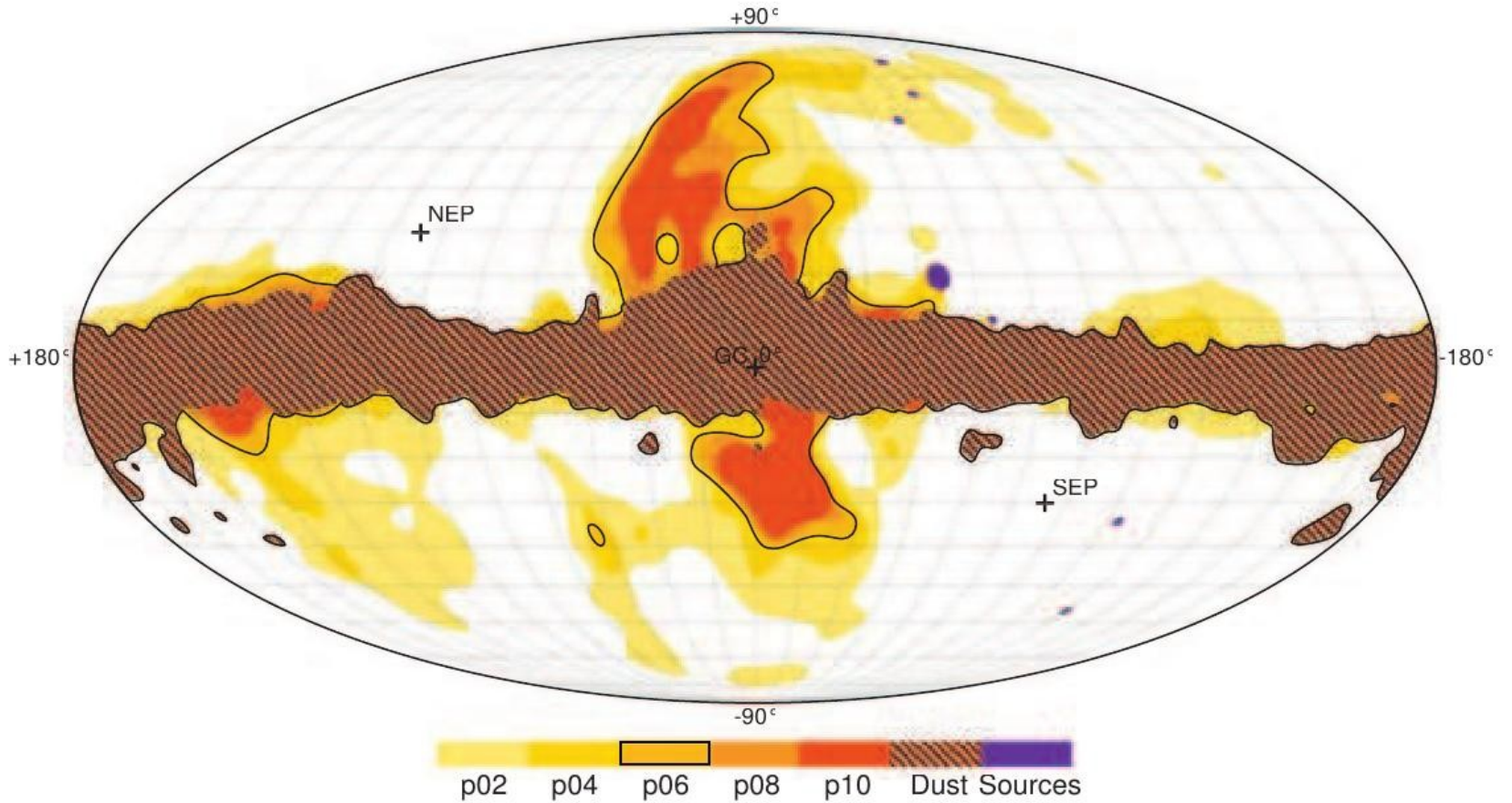
# Polarized Foregrounds are worse



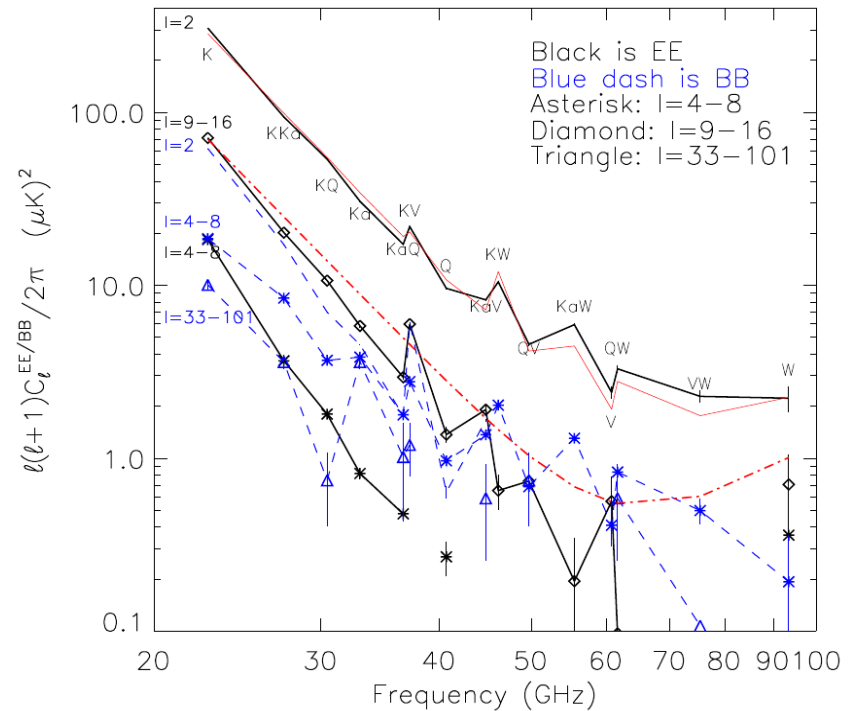
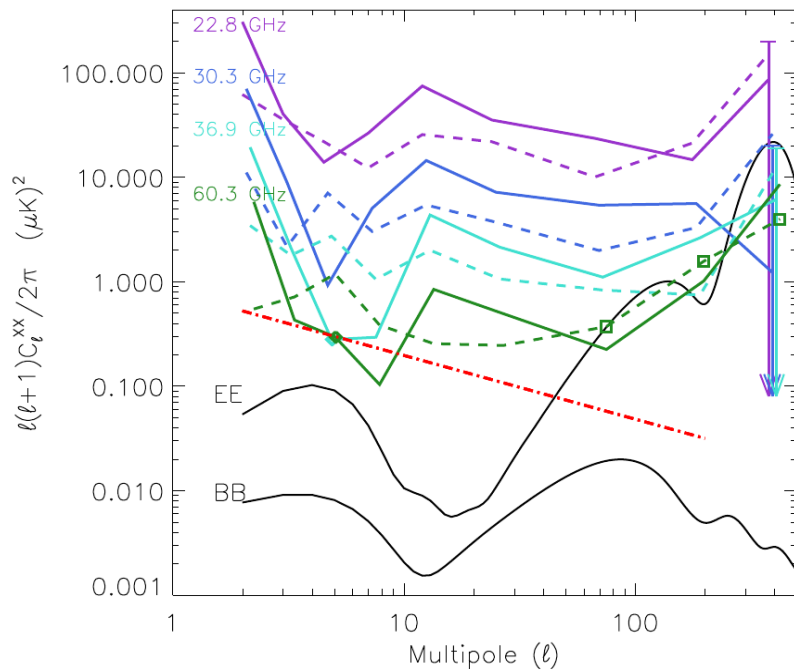
# Polarized Foregrounds are worse



# Sky masking in polarization

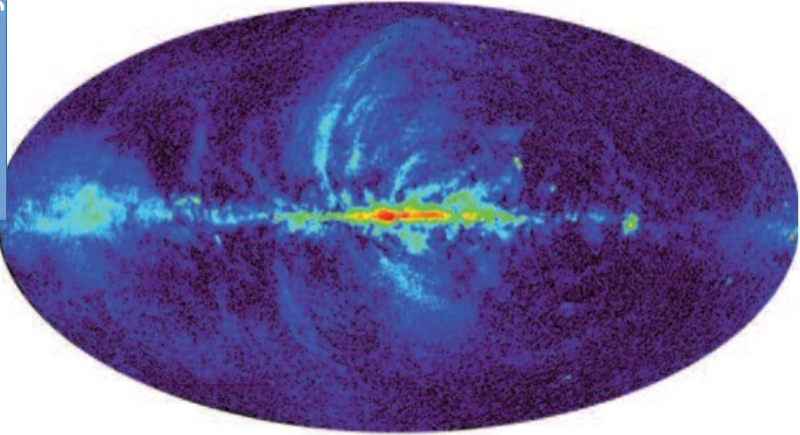


# WMAP polarised foregrounds

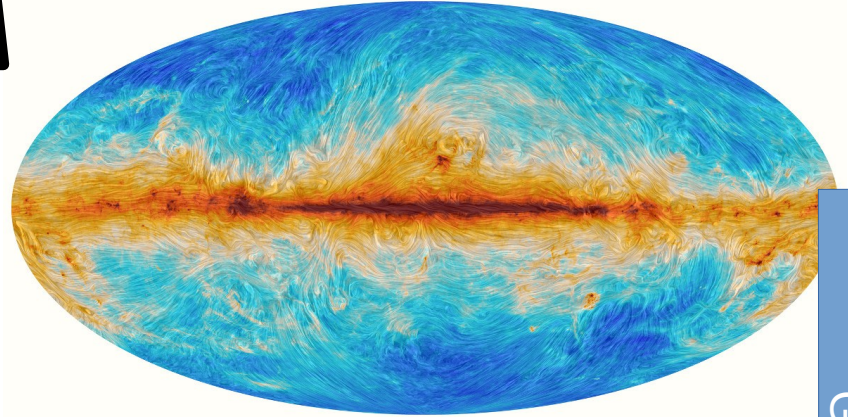


# Galactic polarized foregrounds

Decaying power law



353 GHz



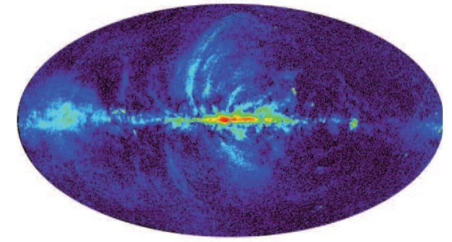
Grey body

23 GHz



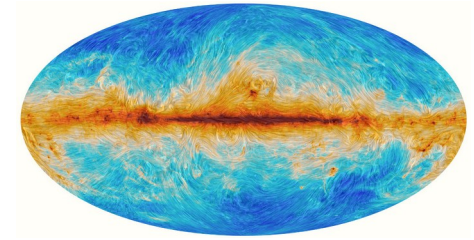


# Polarized synchrotron



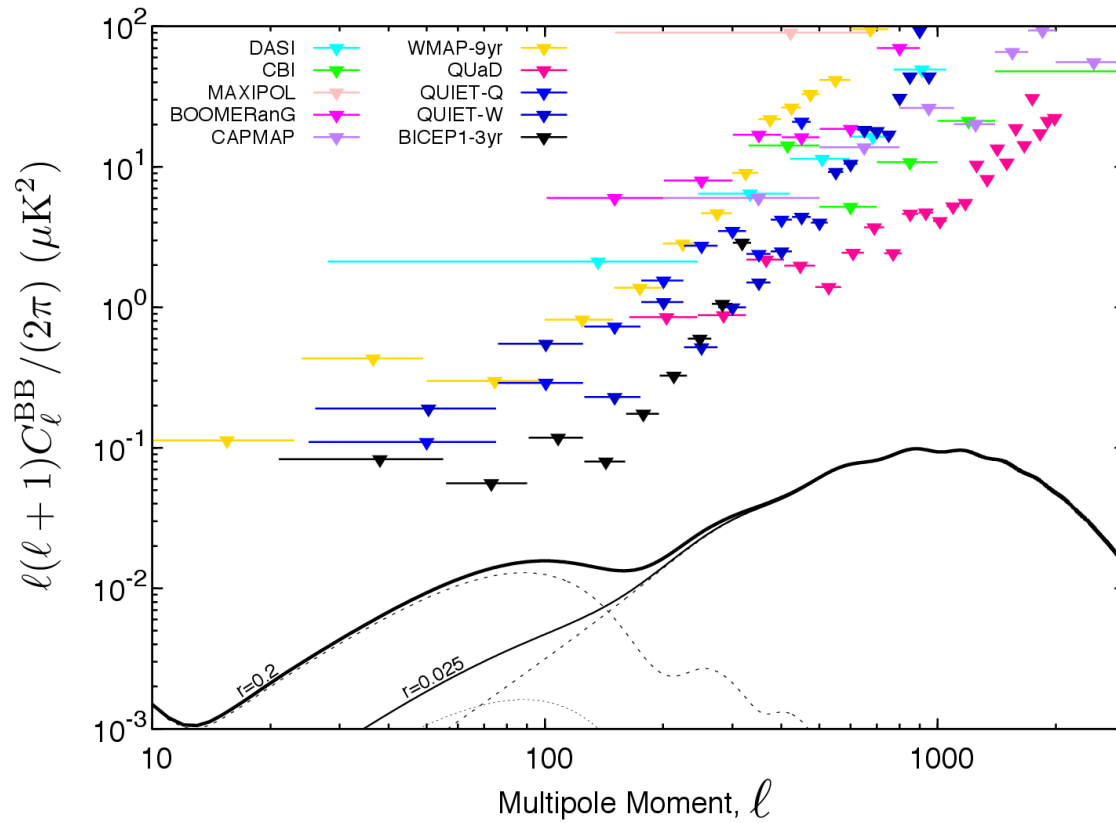
- Amplitude: cosmic ray electrons spiraling around the Galactic magnetic field
- Frequency scaling: approximate decaying power law frequency scaling ( $F_{RJ} \sim f^{-3}$ ), determined by the electron distribution in energy
- Data: total intensity and polarization, several surveys at radio frequencies,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

# Polarized dust

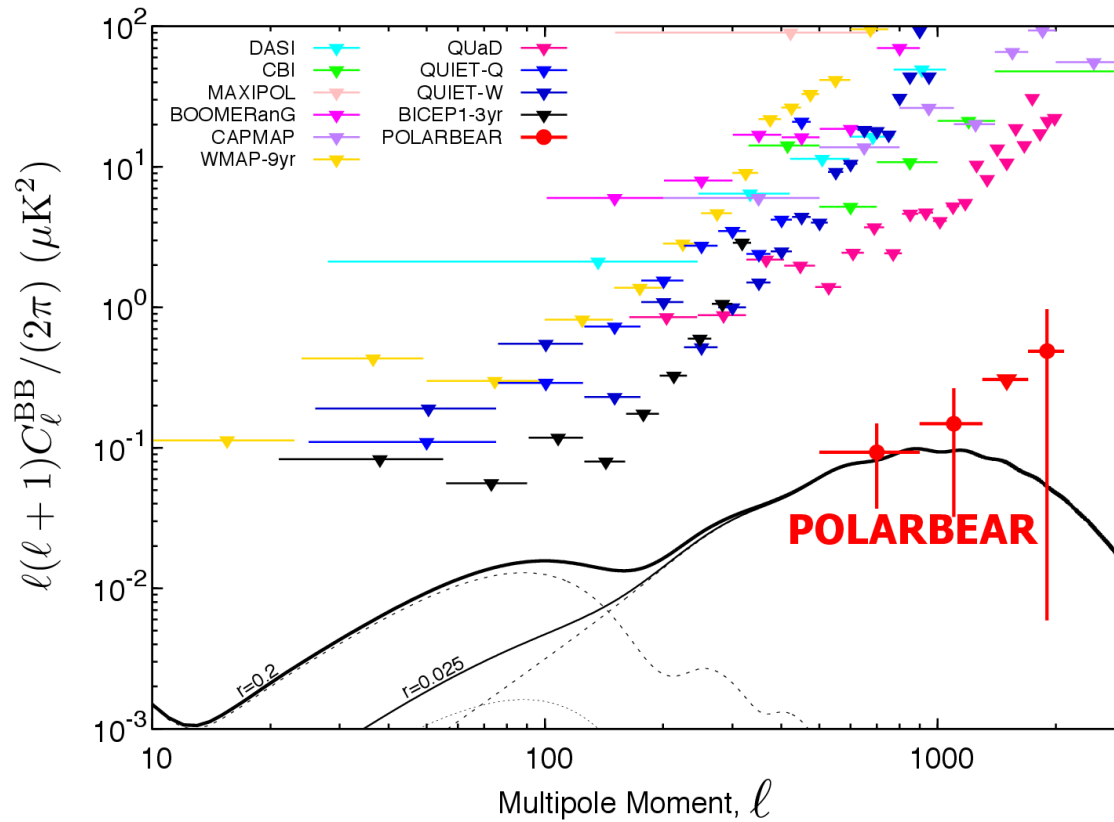


- Amplitude: magnetized dust grains emitting almost thermally, linearly polarized via local alignment with the Galactic magnetic field
- Frequency scaling: grey body  $F_{RJ} \sim BB(f) \times f^{1.5}$
- Total intensity data: high resolution (few arcminutes) and sensitivity (IRAS and Planck) at 3000, 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

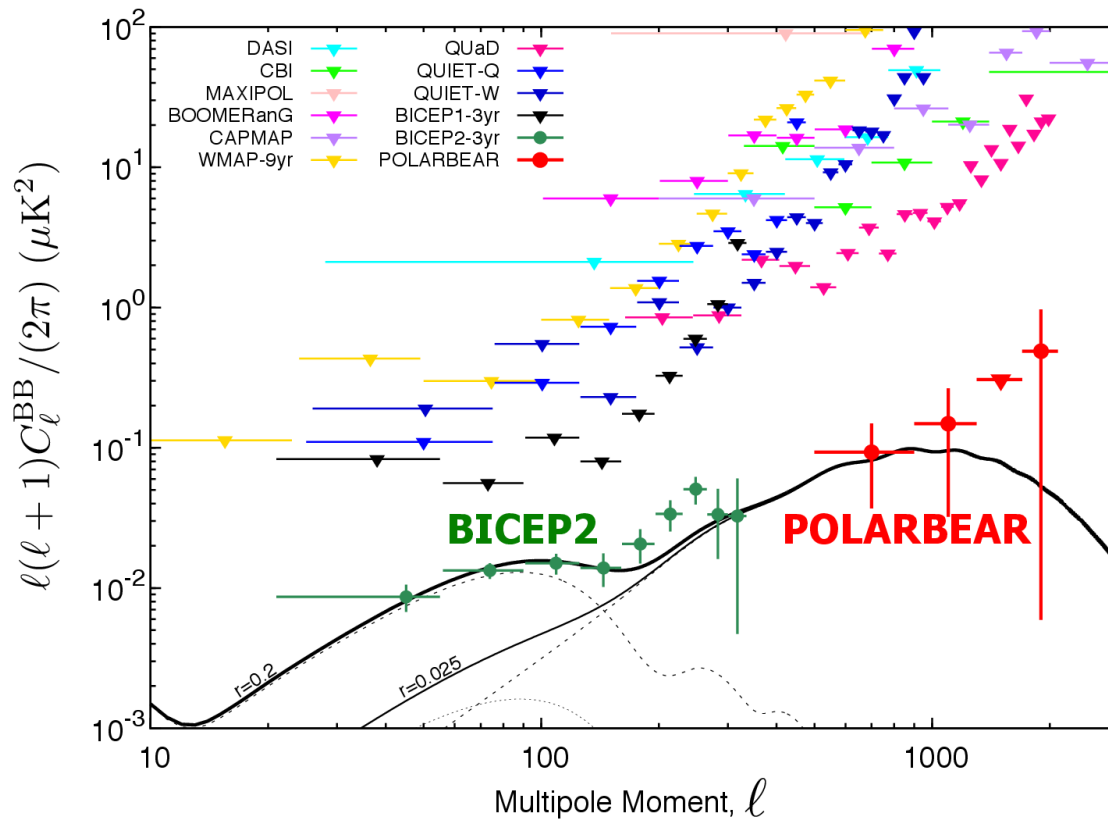
# Early 2014



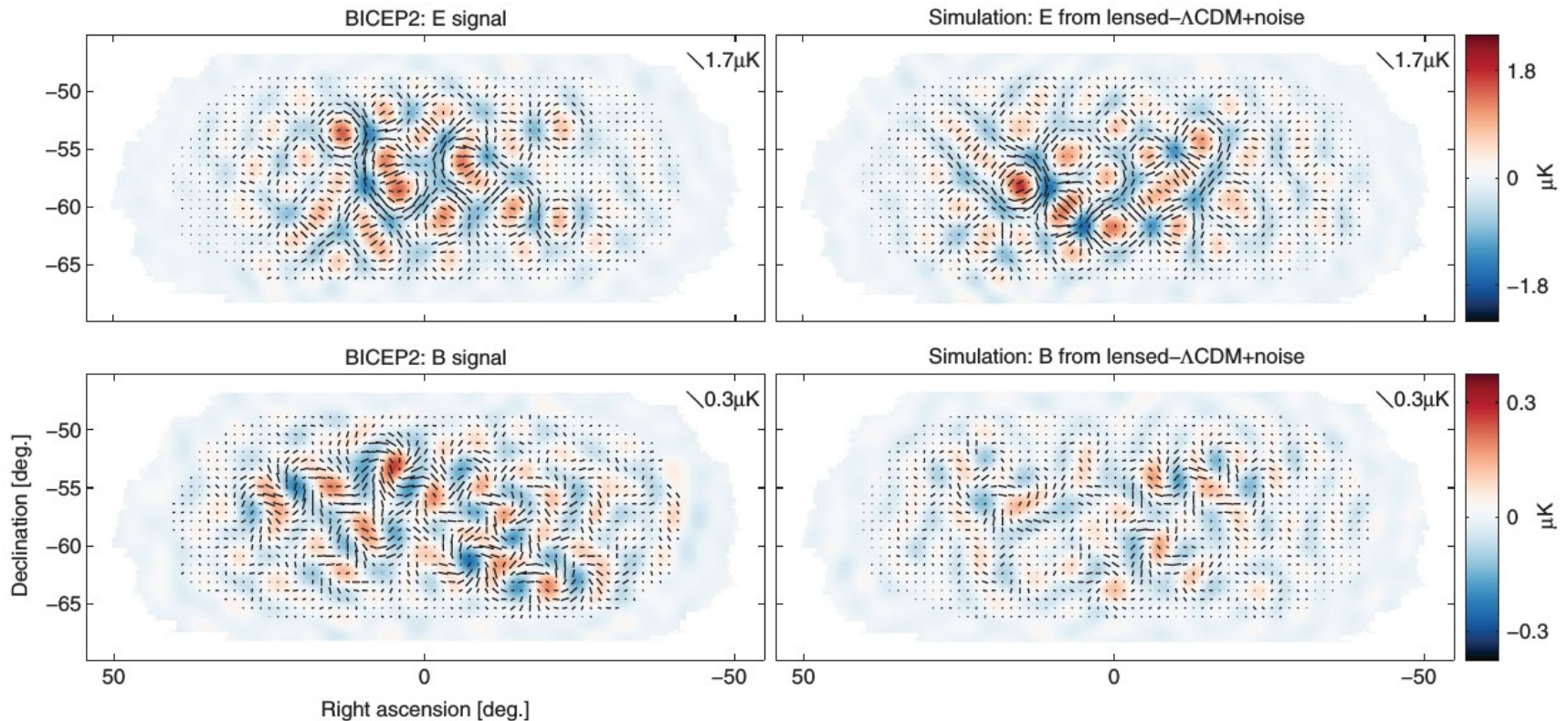
# March 2014



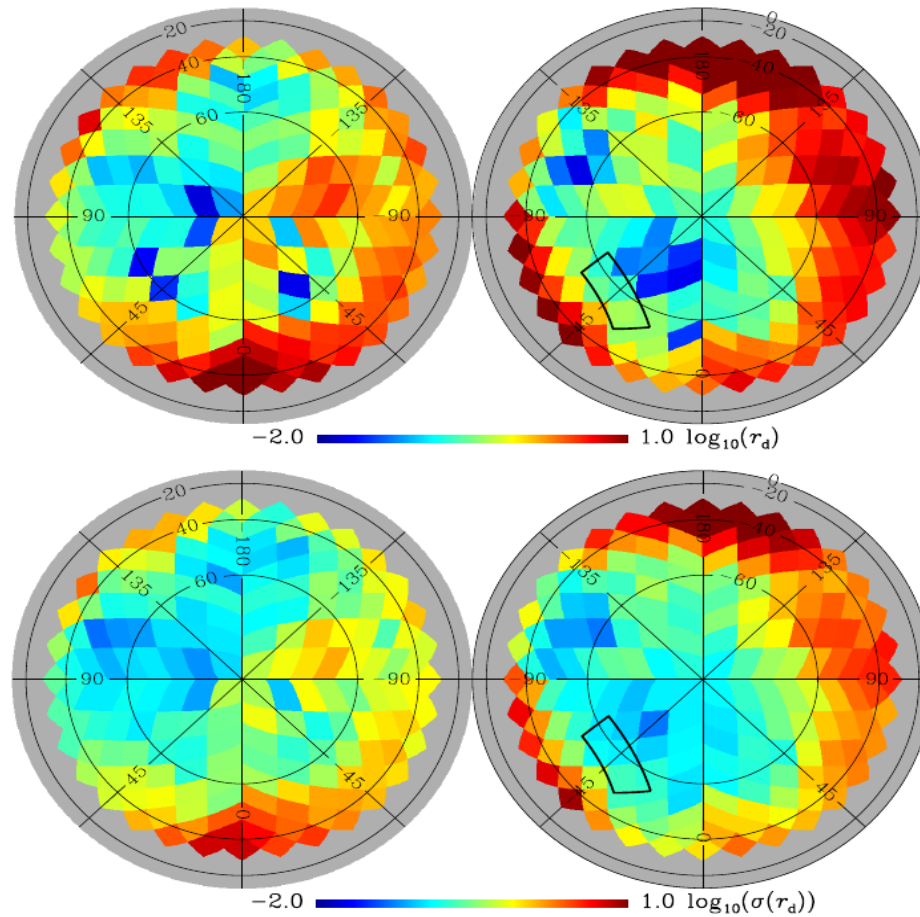
# March 2014



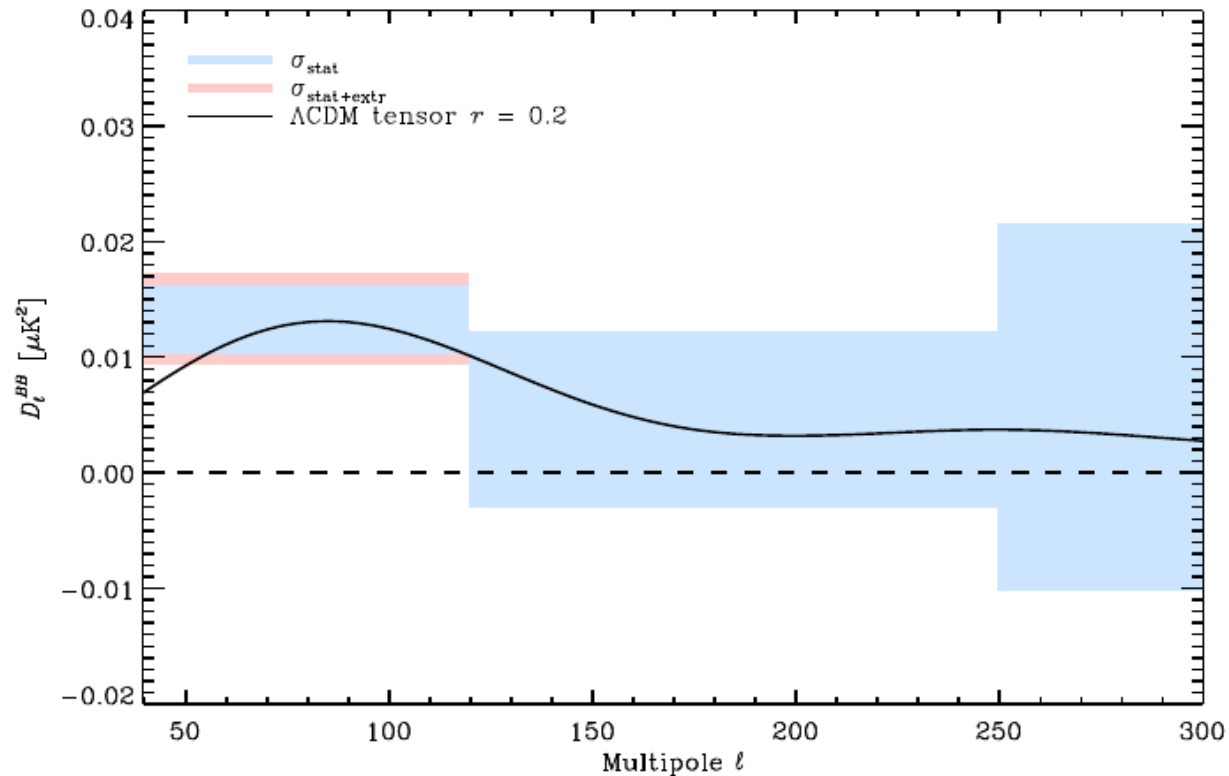
# The B-modes at degree scale



# Planck observed dust polarization at high latitudes

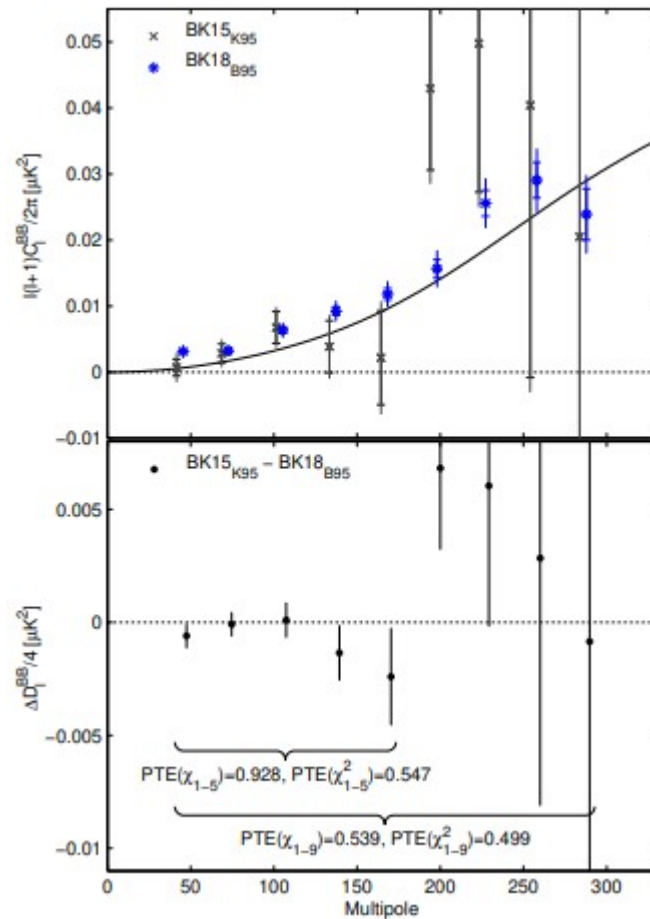


# Planck observed dust polarization in the BICEP2 area





# Planck × Bicep2 × KECK



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

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

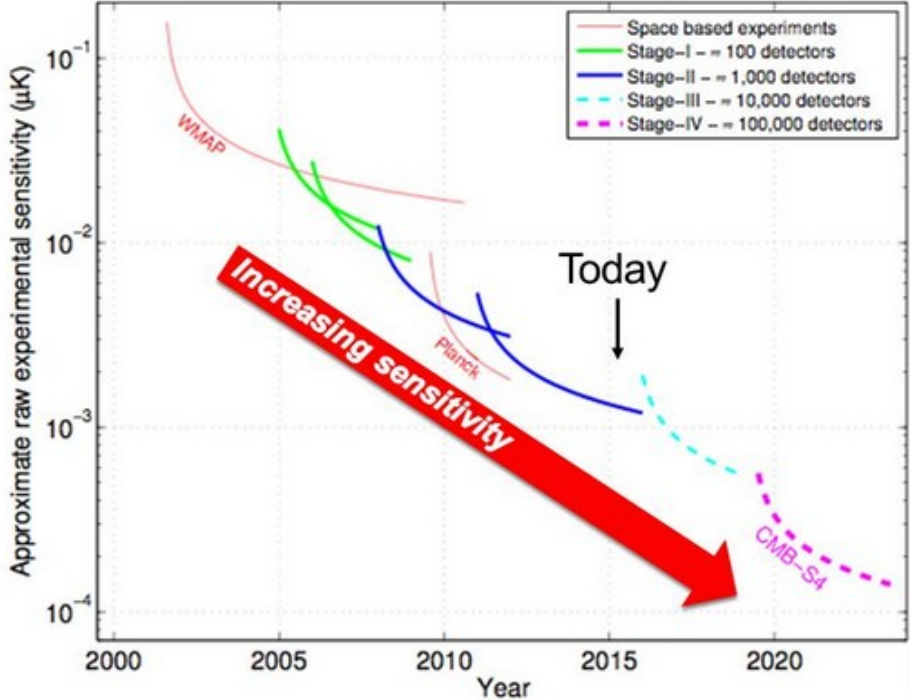
Planck × Bicep2 × KECK

$r < 0.036$  at 95% C.L.

# Roadmap till 2030

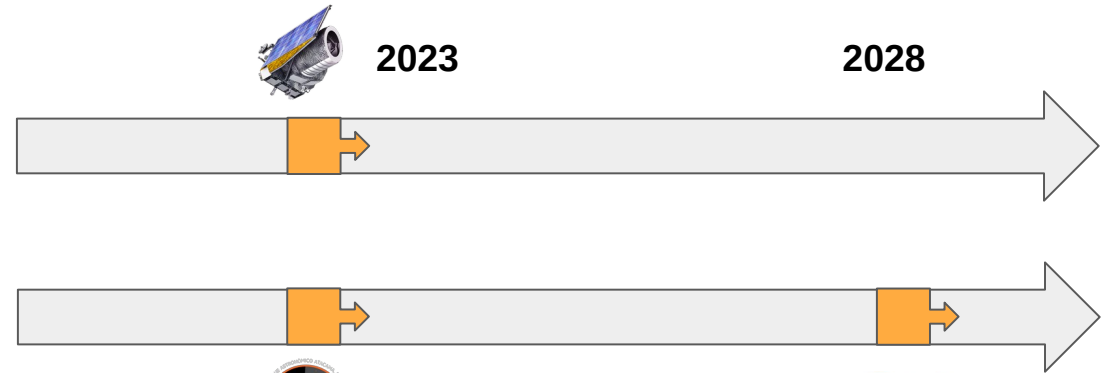
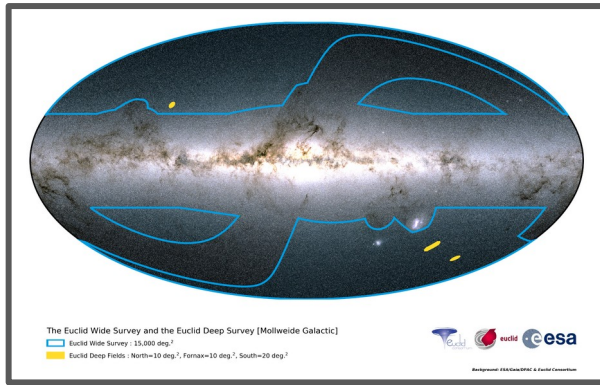
# Future B-Mode Probes: Datasets

A Moore's Law of CMB sensitivity



Plot by Julian Borrill

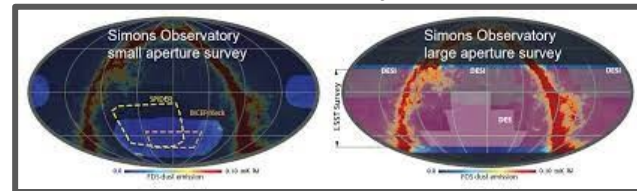
# Future B-Mode Probes: Timeline



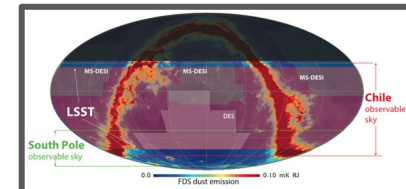
Simons Observatory



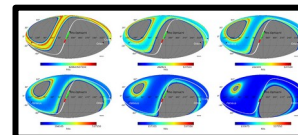
LiteBIRD



**CMB-S4**  
Next Generation CMB Experiment



Low Frequency Surveys



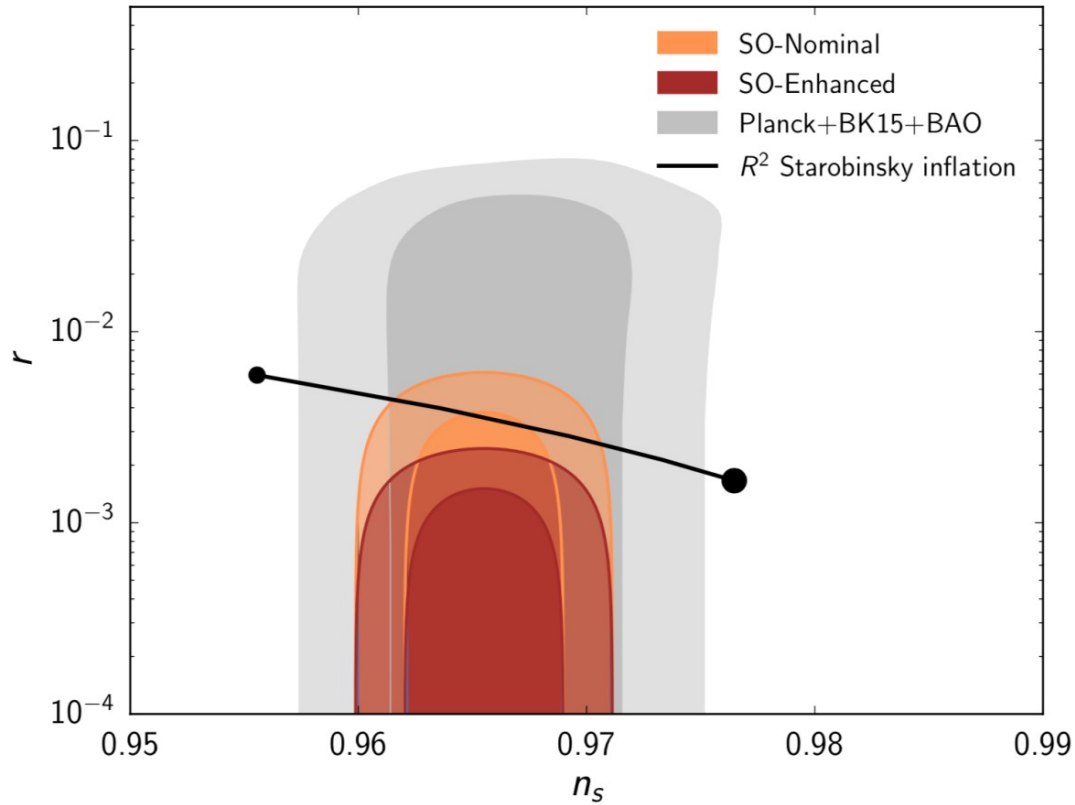
# Future B-Mode Probes: Simons Observatory



[simonsobservatory.org](http://simonsobservatory.org)

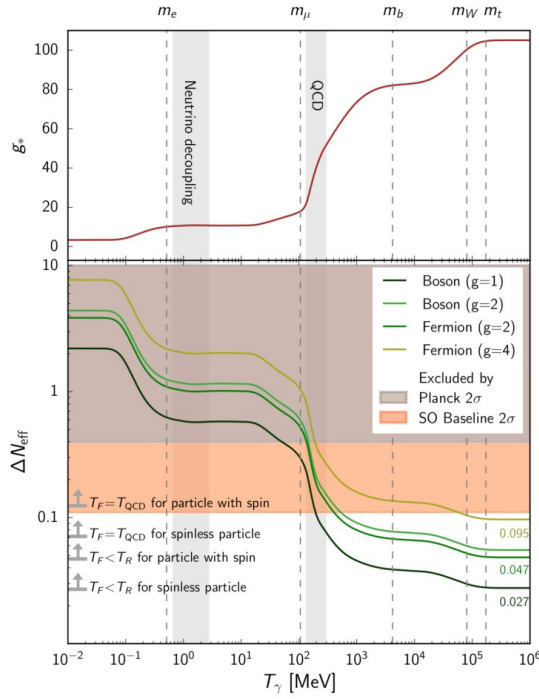
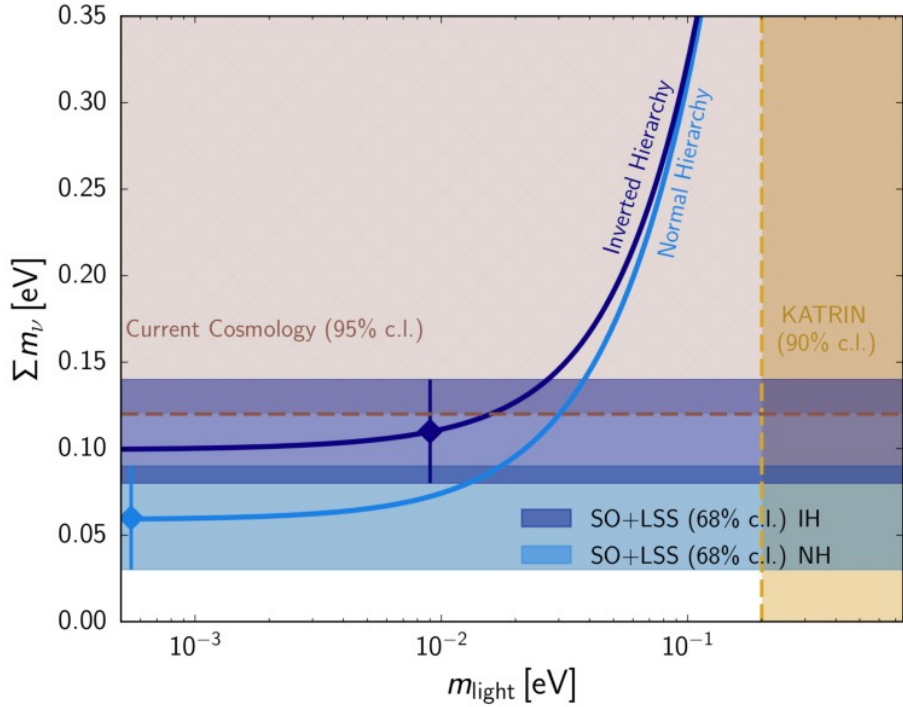


# Future B-Mode Probes: Simons Observatory



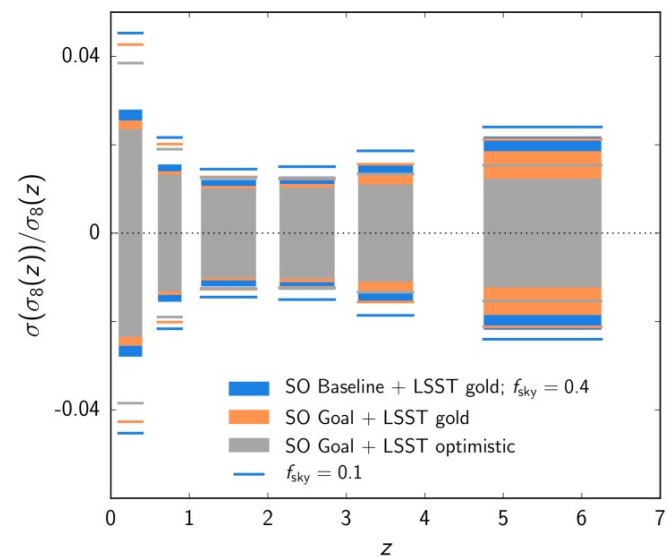
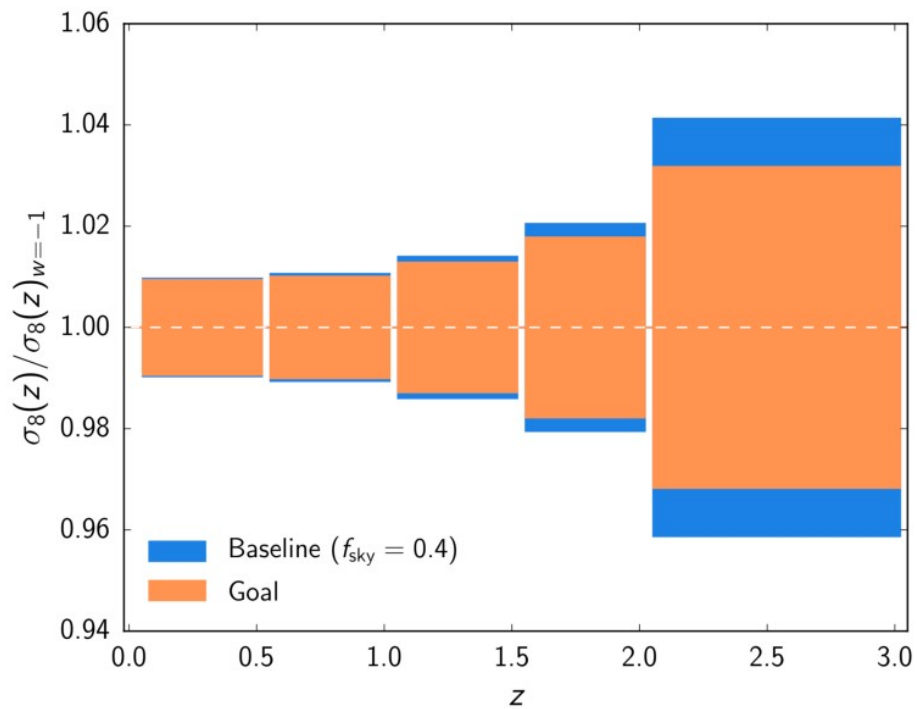
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# Future B-Mode Probes: Simons Observatory



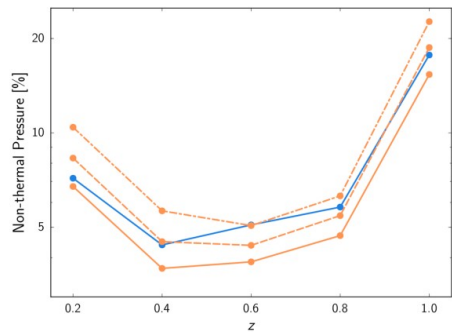
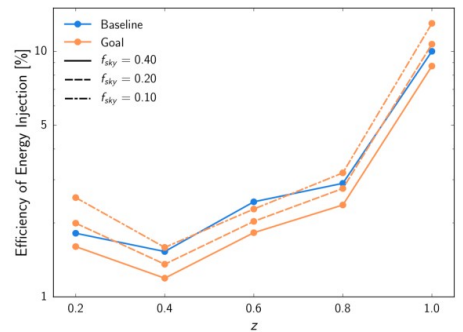
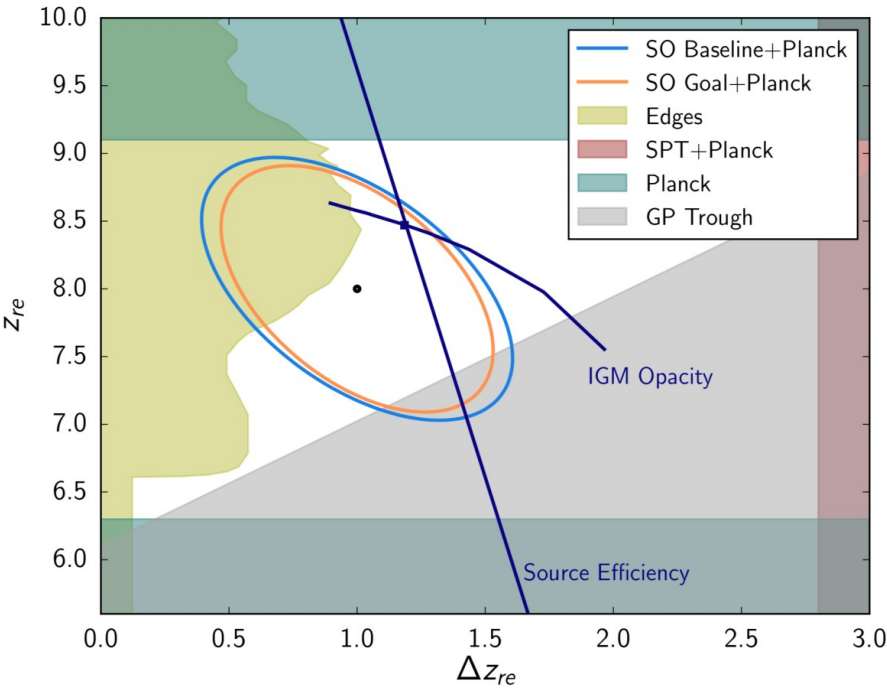
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# Future B-Mode Probes: Simons Observatory



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# Future B-Mode Probes: Simons Observatory



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# Future B-Mode Probes: LiteBIRD

CMB foregrounds for B-mode studies  
Tenerife, Spain, October 15-18, 2018



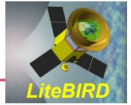
## LiteBIRD

Masashi Hazumi

- 1) Institute of Particle and Nuclear Studies (IPNS), High Energy Accelerator Research Organization (KEK)
- 2) Kavli Institute for Mathematics and Physics of the Universe (Kavli IPMU), The University of Tokyo
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- 4) Graduate School for Advanced Studies (SOKENDAI)

for LiteBIRD Joint Study Group

## LiteBIRD Joint Study Group



About 180 researchers from Japan, North America & Europe

Experience: CMB exp., X-ray satellites, other large proj. (HEP, ALMA etc.)



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

2018/10/16

LiteBIRD @ Tenerife foregrounds conference

2

### Cosmic Orbital and Suborbital Microwave Observations



# 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)

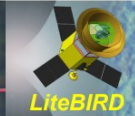
## Schedule after Phase-A1



- 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

# Future B-Mode Probes: LiteBIRD

## LiteBIRD full success



1. The mission shall measure the tensor-to-scalar ratio  $r$  with a total uncertainty of  $\delta r < 1 \times 10^{-3}$ . This value shall include contributions from instrument statistical noise fluctuations, instrumental systematics, residual foregrounds, lensing B-modes, and observer bias, and shall not rely on future external datasets.
2. The mission shall obtain full-sky CMB linear polarization maps for achieving  $>5\sigma$  significance using data between  $\ell=2$  and  $\ell=10$ , data between  $\ell=11$  and  $\ell=200$  separately, assuming  $r=0.01$ . We assume a fiducial optical depth of  $\tau = 0.05$  for this calculation.

### Full Success (simplified version)

- $\delta r < 1 \times 10^{-3}$  (for  $r=0$ )
- $2 \leq \ell \leq 200$

## LiteBIRD extra success



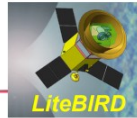
### Improve $\sigma(r)$ with external observations

Topic	Method	Example Data
Delensing	Large CMB telescope array	CMB-S4 data Namikawa and Nagata, JCAP 1409 (2014) 009
	Cosmic infrared background	Herschel data Sherwin and Schmittfull, Phys. Rev. D 92, 043005 (2015)
	Radio continuum survey	SKA data Namikawa, Yamauchi, Sherwin, Nagata, Phys. Rev. D 93, 043527 (2016)
Foreground cleaning	Lower frequency survey	C-BASS, S-PASS, QUIJOTE etc. and their upgrades

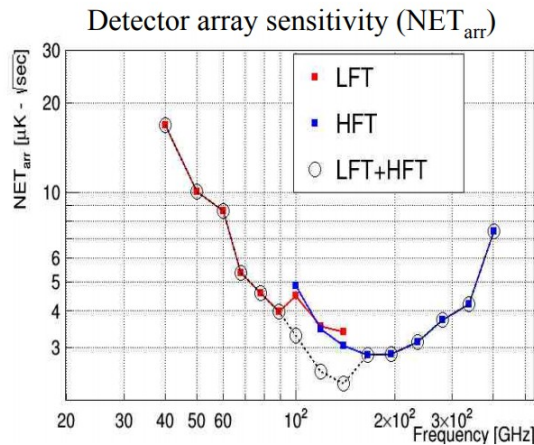
- Delensing improvement to  $\sigma(r)$  can be factor  $\sim 2$  or more.
  - e.g.  $\sim 6\sigma$  observation in case of Starobinsky model
  - Need to make sure systematic uncertainties are under control

# Future B-Mode Probes: LiteBIRD

## Sensitivity



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



$NET_{arr} \rightarrow$  Sky sensitivity

Frequency [GHz]	$NET_{CMB,Arr}$ [ $\mu K \cdot \sqrt{s}$ ]	Sensitivity [ $\mu K - \text{arcmin}$ ]
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



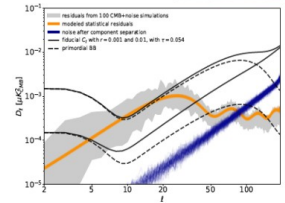
### Methodology

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

- AME is effectively absorbed by synchrotron curvature

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

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

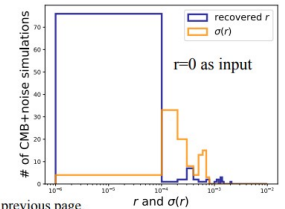


### Results\*

"Multipatch technique" (extension of xForecast)

- $\sigma(r=0) = 0.0005$  😊
- Negligibly small bias 😊

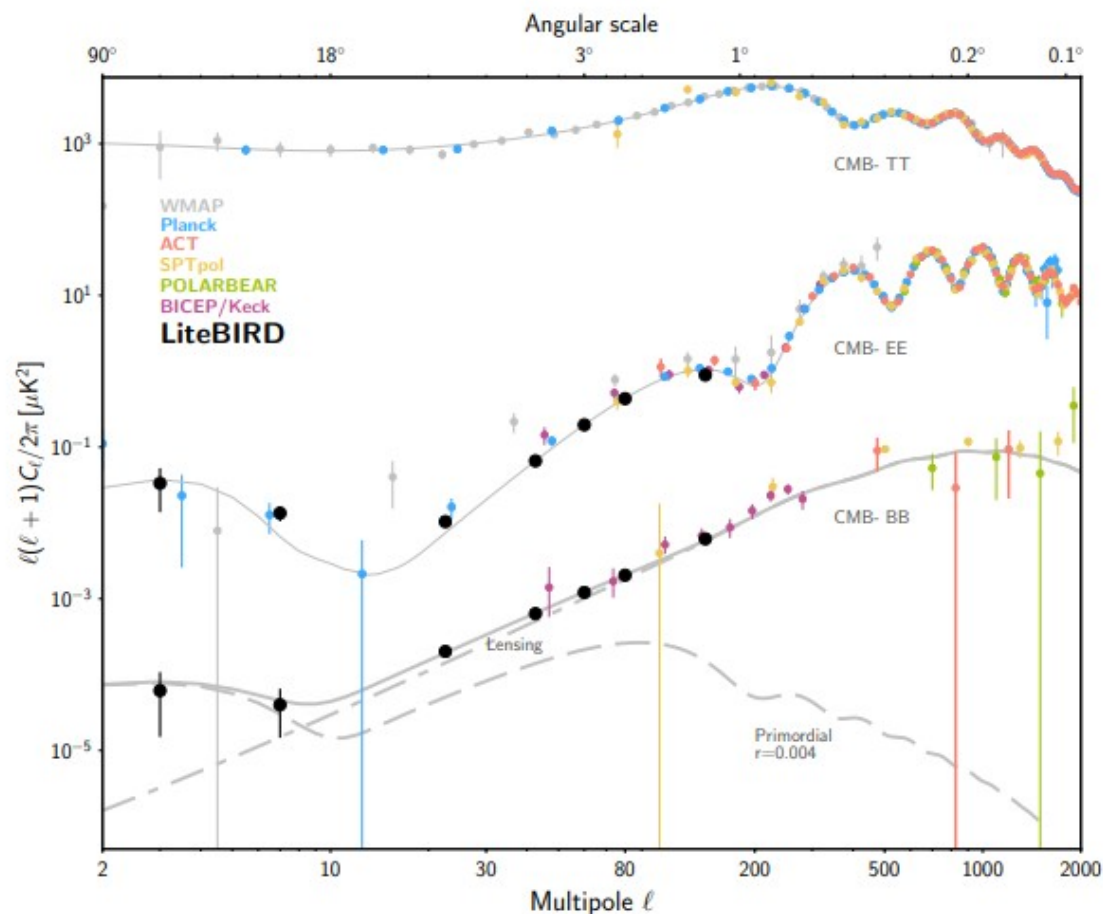
Consistent results from COMMANDER! 😊



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



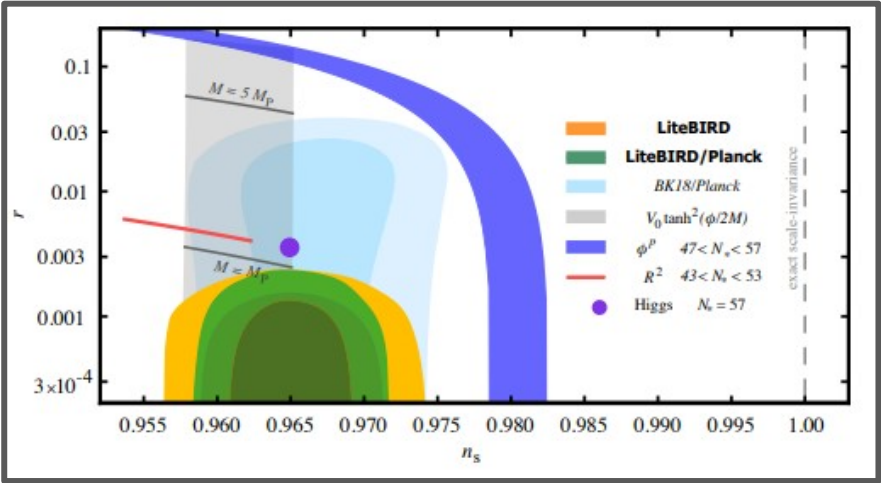
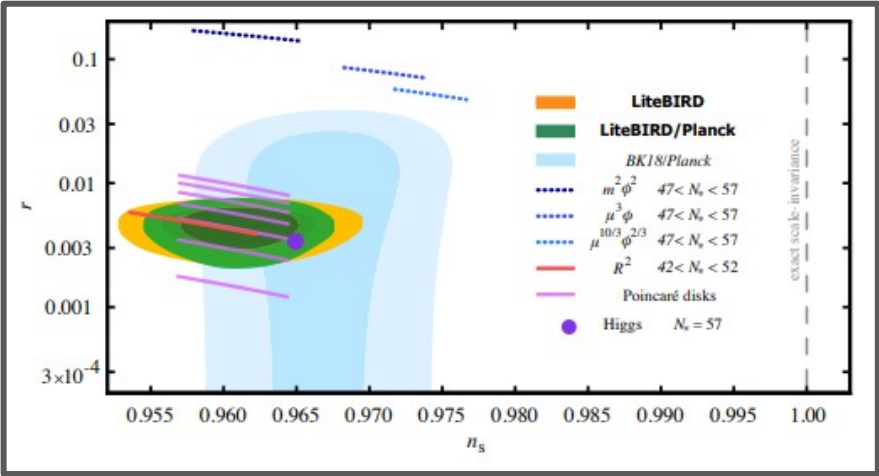
# Future B-Mode Probes: LiteBIRD



LiteBIRD Collaboration, PTEP 2022

[ui.adsabs.harvard.edu/abs/arXiv:2202.02773](https://ui.adsabs.harvard.edu/abs/arXiv:2202.02773)

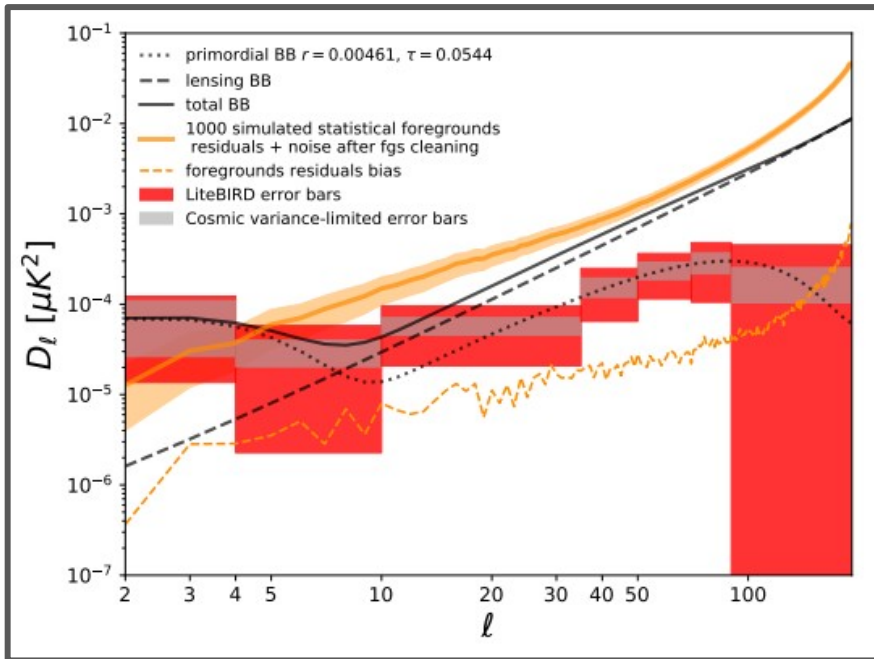
# Future B-Mode Probes: LiteBIRD



LiteBIRD Collaboration, PTEP 2022

[ui.adsabs.harvard.edu/abs/arXiv:2202.02773](https://ui.adsabs.harvard.edu/abs/arXiv:2202.02773)

# Future B-Mode Probes: LiteBIRD

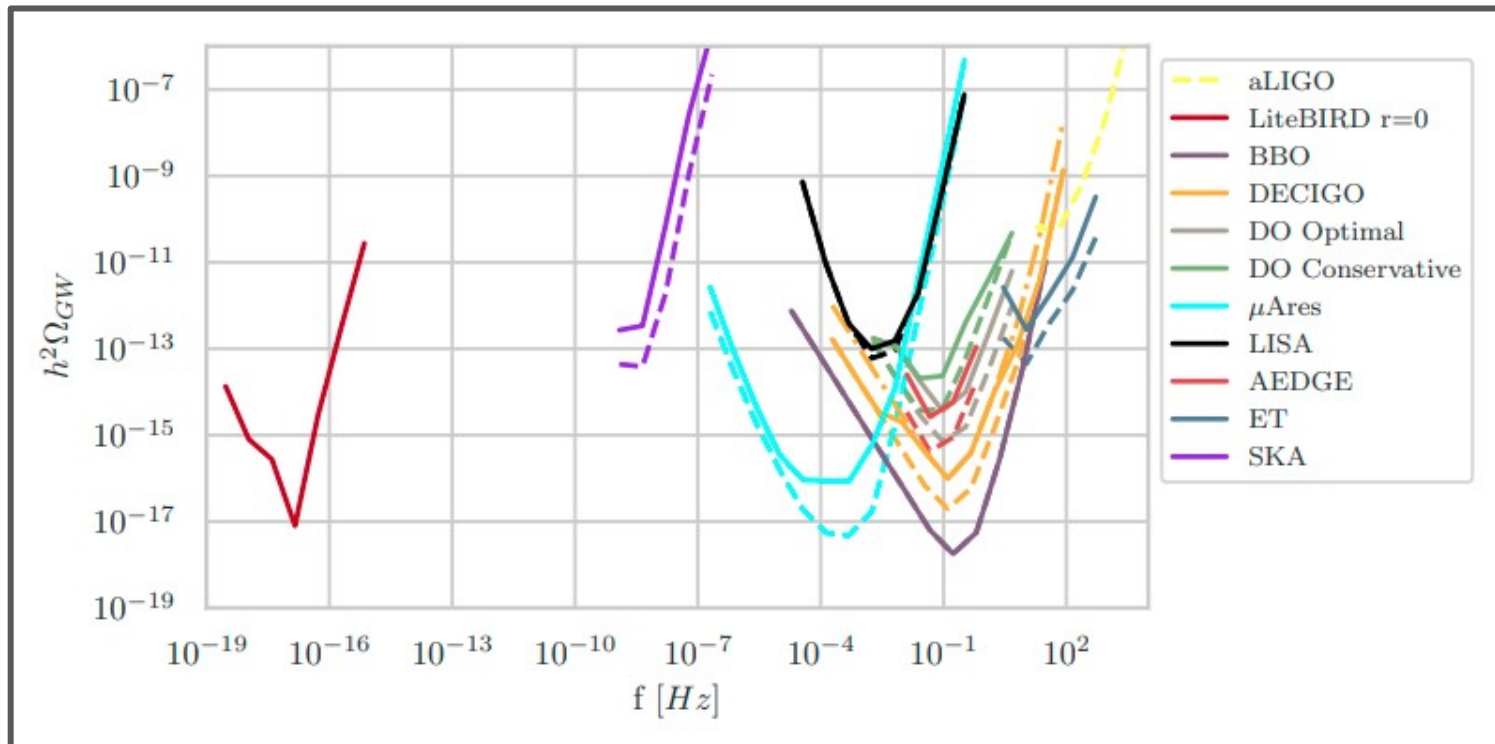


	ID	$\nu$ [GHz]	$\delta\nu$ [GHz] ( $\delta\nu/\nu$ )	Beam size [arcmin]	No. of detectors	NET <sub>arr</sub> [ $\mu\text{K}\sqrt{\text{s}}$ ]	Sensitivity [ $\mu\text{K-arcmin}$ ]
LFT	1	40	12 (0.30)	70.5	48	18.50	37.42
LFT	2	50	15 (0.30)	58.5	24	16.54	33.46
LFT	3	60	14 (0.23)	51.1	48	10.54	21.31
LFT	4	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/ MFT	7	100	23 (0.23)	30.2/ 37.8	144/ 366	5.11/ 4.19	10.34 8.48
comb.						3.24	6.56
LFT/ MFT	8	119	36 (0.30)	26.3/ 33.6	144/ 488	3.8/ 2.82	7.69 5.70
comb.						2.26	4.58
LFT/ MFT	9	140	42 (0.30)	23.7/ 30.8	144/ 366	3.58/ 3.16	7.25 6.38
comb.						2.37	4.79
MFT	10	166	50 (0.30)	28.9	488	2.75	5.57
MFT/ HFT	11	195	59 (0.30)	28.0/ 28.6	366/ 254	3.48/ 5.19	7.05 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

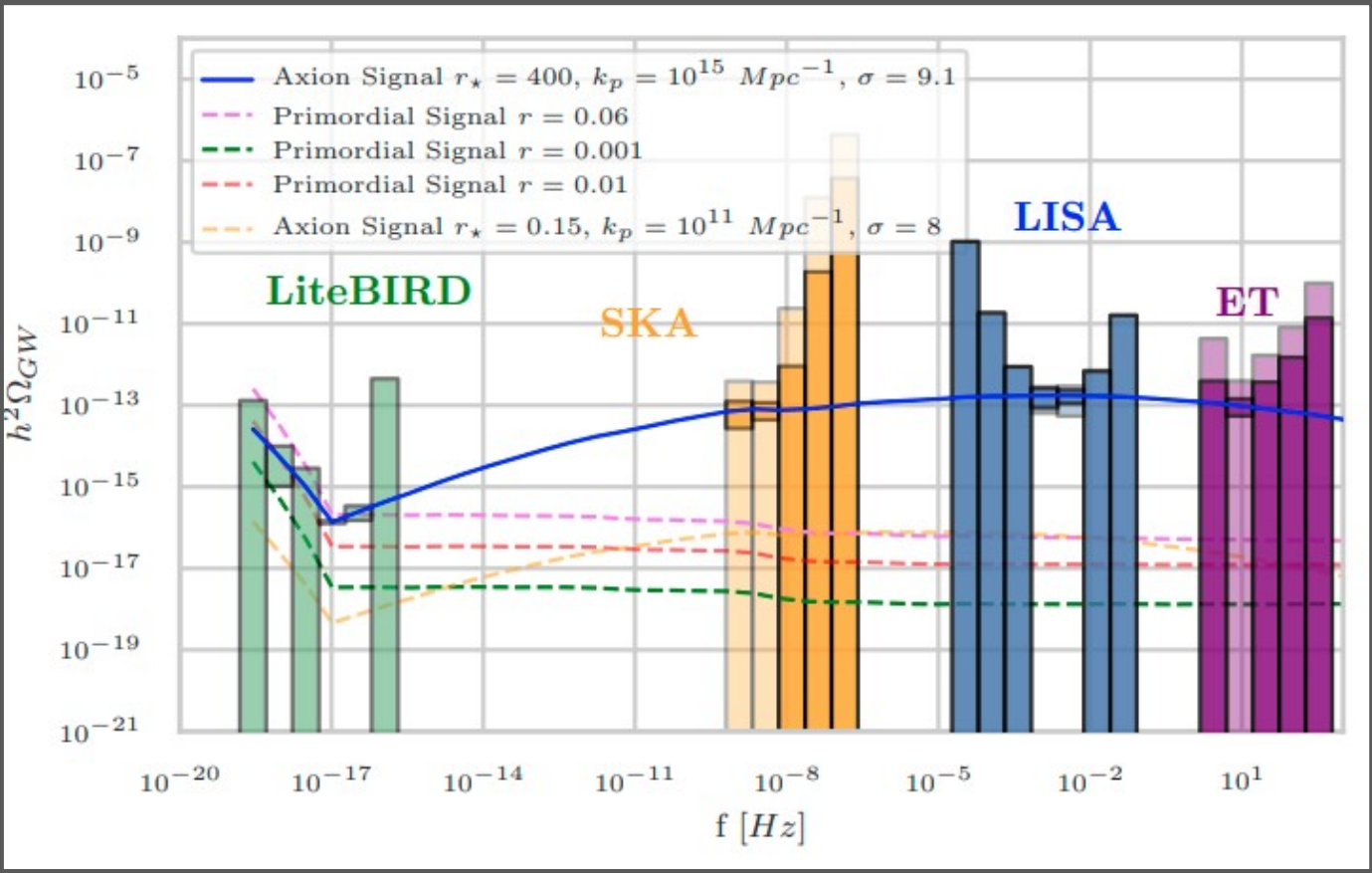
[ui.adsabs.harvard.edu/abs/arXiv:2202.02773](https://ui.adsabs.harvard.edu/abs/arXiv:2202.02773)

# Future B-Mode Probes: LiteBIRD



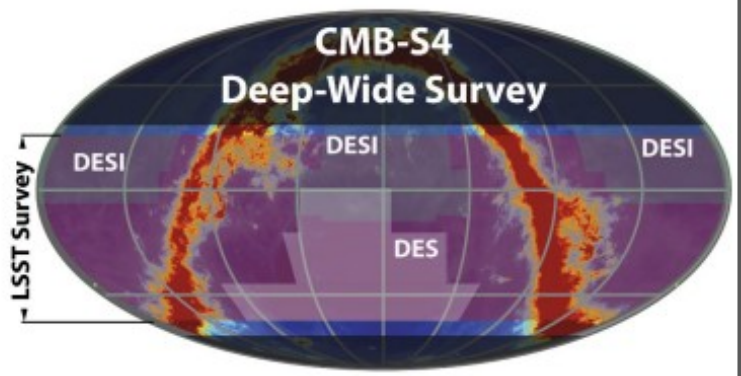
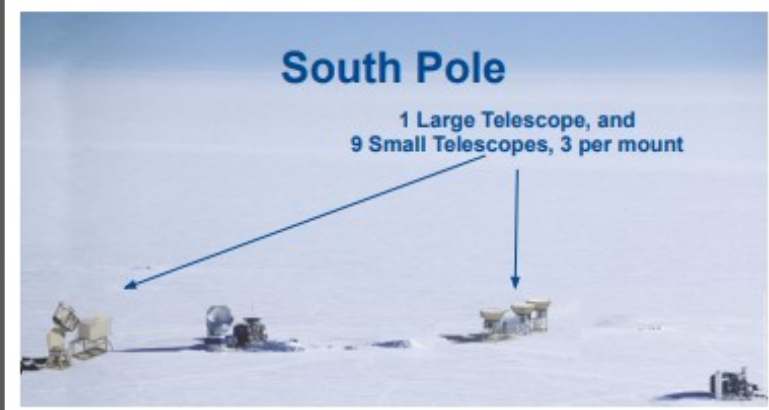
Campeti et al., 2021

# Future B-Mode Probes: LiteBIRD

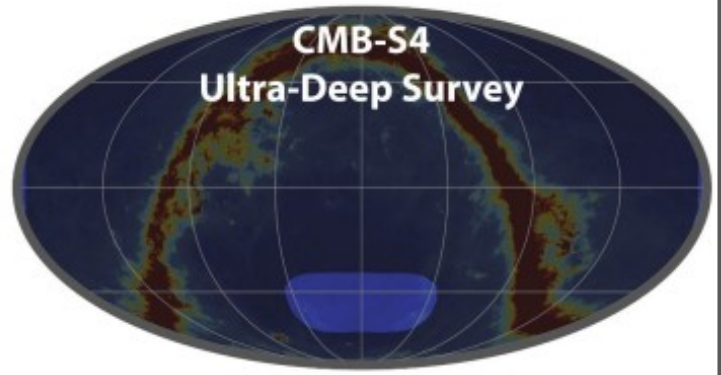


Campeti et al. 2021

# Future B-Mode Probes: CMB-Stage IV

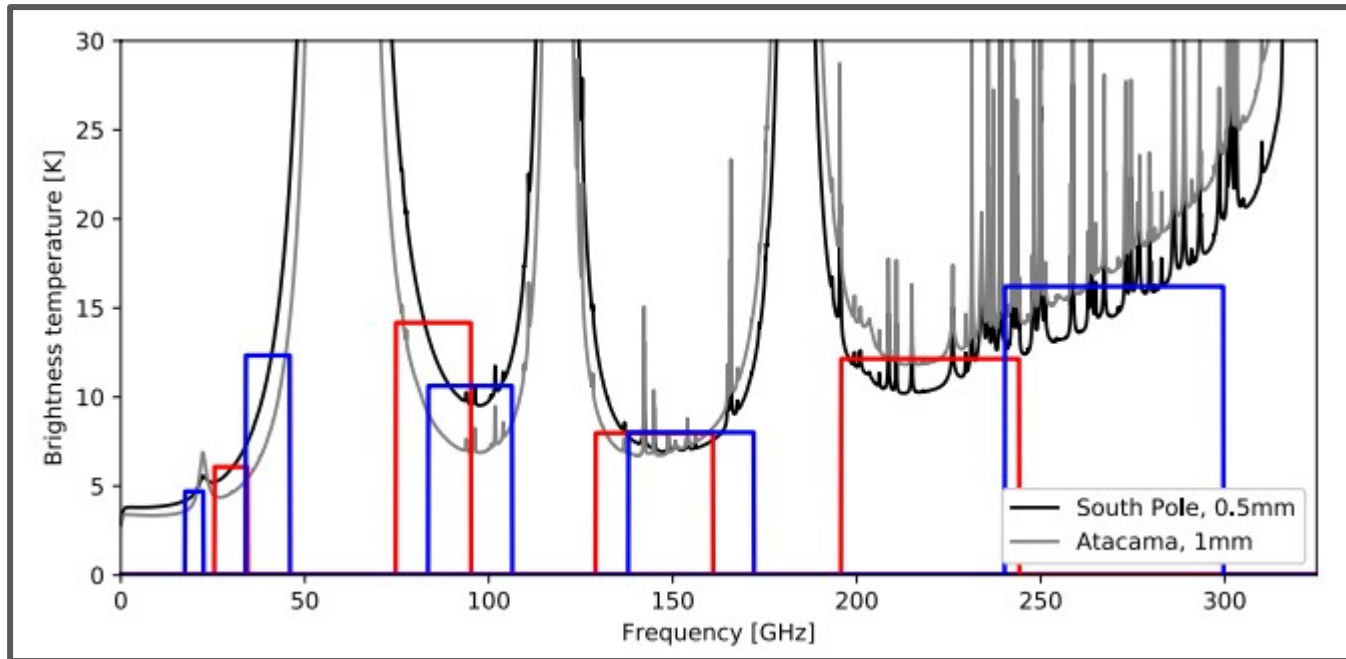


Observed from Chile



Observed from South Pole

# Future B-Mode Probes: CMB-Stage IV



# 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	1.7	1.0	0.8
Fractional bandwidth	0.25	0.22	0.46	0.38	0.3	0.2	0.2
NET ( $\mu\text{K}\sqrt{\text{s}}$ ) per detector	438	383	250	302	302	225	225
$N_{\text{detectors}}$ per tube	160	320	320	3460	3460	3460	3460
$N_{\text{wafers}}$ per tube	4	4		4			
Chile (Wide Field Survey – 2 LATs)							
$N_{\text{tubes}}$ per LAT	0	2		12			
Data rate (2 LATs)	10.8 TB/day						
South Pole (Delensing Survey – 1 LAT)							
$N_{\text{tubes}}$	1	2		12			
Data rate (1 LAT)	5.0 TB/day						
Total (3 LATs)							
$N_{\text{detectors}}$	160	1920	1920	124560	124560	124560	124560
$N_{\text{detectors}}$ total	357952						
$N_{\text{wafers}}$	4	24		144			
$N_{\text{wafers}}$ total	228						

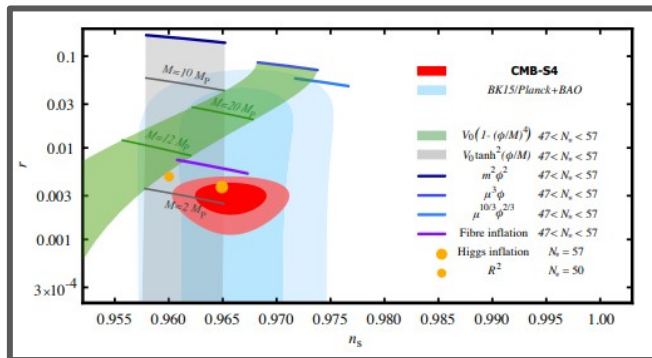
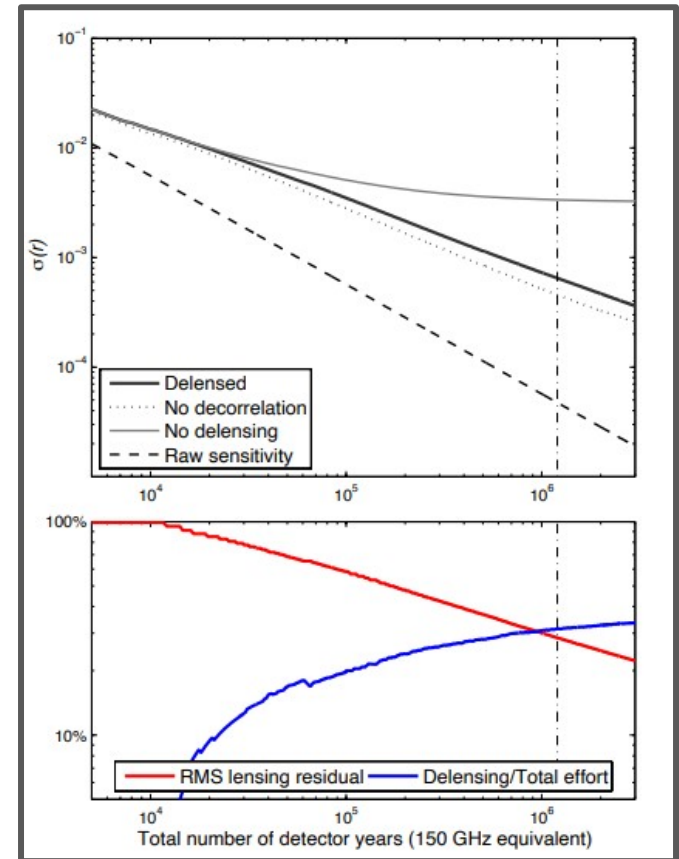
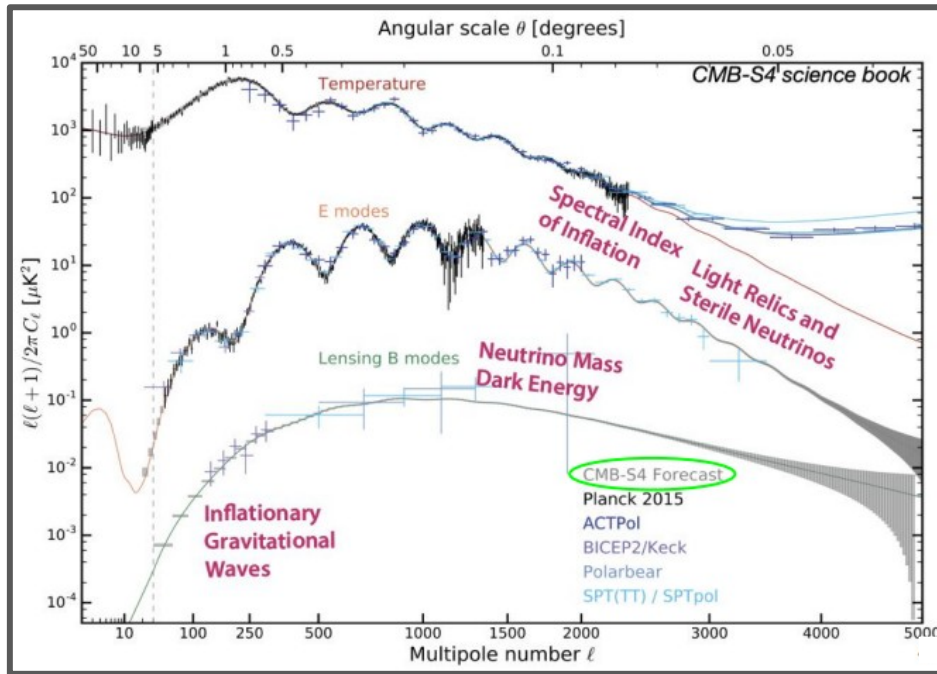
  

Property	LF		CF High		CF Low		HF	
Center frequency (GHz)	30	40	85	145	95	155	220	270
Primary lens diameter (cm)	55	55	55	55	55	55	44	44
FWHM (arcmin)	72.8	72.8	25.5	25.5	22.7	22.7	13	13
Fractional bandwidth	0.3	0.3	0.24	0.22	0.24	0.22	0.22	0.22
NET ( $\mu\text{K}\sqrt{\text{s}}$ ) per detector	177	224	270	238	309	331	747	1281
$N_{\text{det}}$ per optics tube	288	288	3524	3524	3524	3524	8438	8438
$N_{\text{tubes}}$	2		6		6		4	
$N_{\text{wafers}}$	24		72		72		36	
$N_{\text{wafers}}$ 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-S4

# CMB-Stage IV

WBS	PY 1	PY 2	PY 3	PY 4	PY 5	PY 6	PY 7	PY 8	PY 9
1.03 Detectors	Wafer Prototypes	Wafer PreProduction				Wafer Production			
1.04 Readout	Electronics Prototypes	Electronics PreProduction		Electronics Production					
1.05 Module Assembly & Test	Prototypes	PreProduction			Production				
		Prototype Test Cryostat							
			Fabricate Remaining Test Cryostats						
1.06 Large Aperture Telescope	South Pole LAT Engineering Design			SP LAT Construction					
	CH LATs Engineering Design			CH LATs 1&2 Construction					
	LATR Engineering Design			SP LATR Construction					
					CH LATR 1&2 Construction				
1.07 Small Aperture Telescope	SAT Engineering Design				SATs 1-6 Assembly & Integration				
		Prototype Cyrostat							
			Cryostat & Mount Fabrication						
1.08 Data Acquisition	Design & Engineering				Production				
1.09 Data Management	★ Data Challenge 1A	★ Data Challenge 2						Data Challenge 4 ★	
	★ Data Challenge 1B			★ Data Challenge 3					
1.10 Chile Infrastructure, Integration, & Commissioning	Design Engineering			Site Construction					
					Chile LAT 1 Integration & Commissioning				
					Chile LAT 2 Integration & Commissioning				
1.11 South Pole Infrastructure, Integration, & Commissioning	Design Engineering			Site Construction & Integration					
					SP LATR Integration & Commissioning				
					SAT 1-3 Mount Construction				
					SAT 1-3 I&C				
					SAT 1-3 Mount Construction				
							SAT 1-3 I&C		
								SAT 1-3 I&C	



# 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!