Planck

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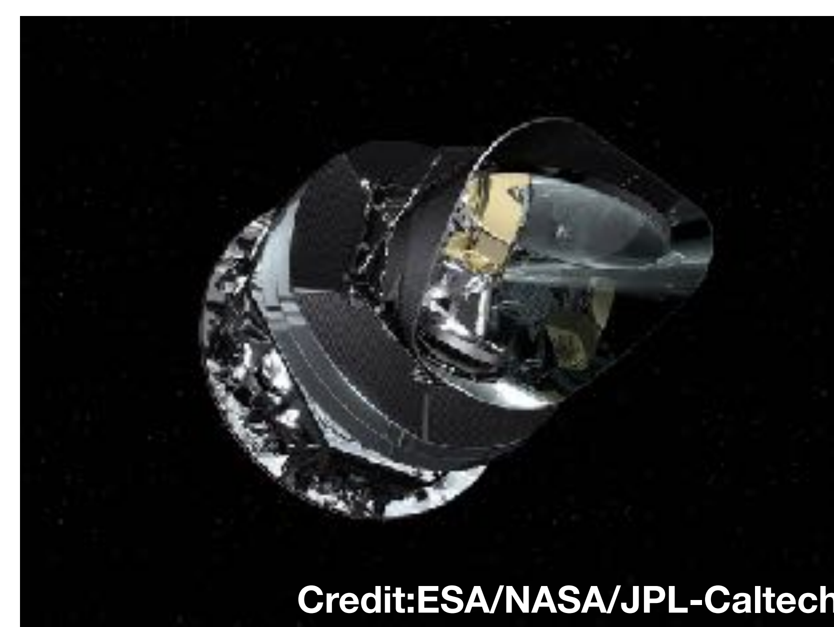
Advisor: Yi Mao, Jianfeng Zhou

European Space Agency
Agence spatiale européenne

planck



Outline

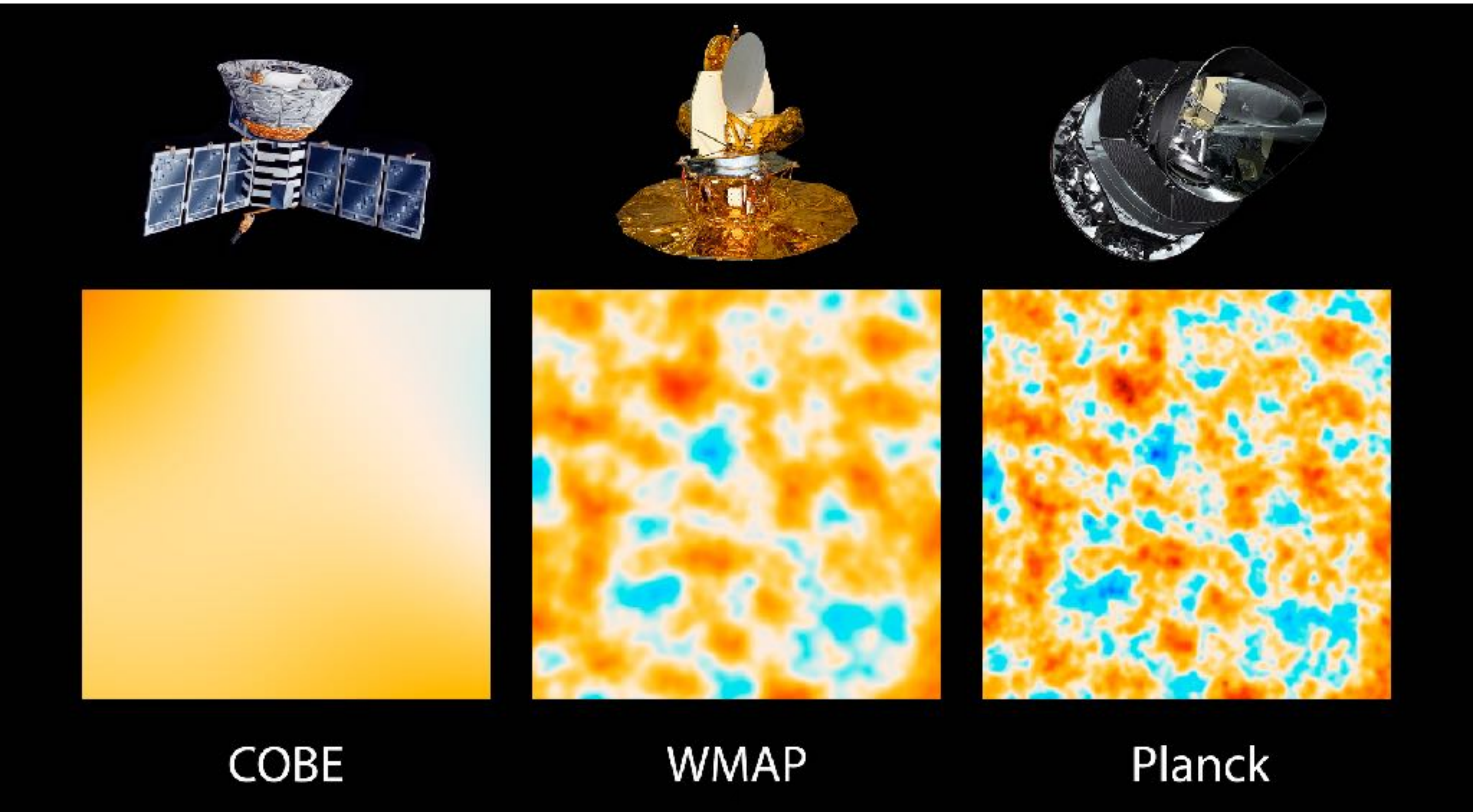
- What is Planck ?
- Planck's scientific highlights
  - Theory complement: CMB polarization
- Summary

Review of Microwave Astronomy History

- First discovered, Penzias and Wilson, 1964
- Ground-based observations, limited by atmospheric disturbance and artificial illumination.
- COBE: The first space-based measurements of the CMB, 1989-1992
- WMAP, 2001-2010
- Planck, 2009-2013
- (Post-Planck, S4)… …
- In modern cosmology, CMB measurements are one of the major pillars to test theories about the birth and evolution of the Universe — two Nobel prizes.

Comparison

360P **720P** **1080P**

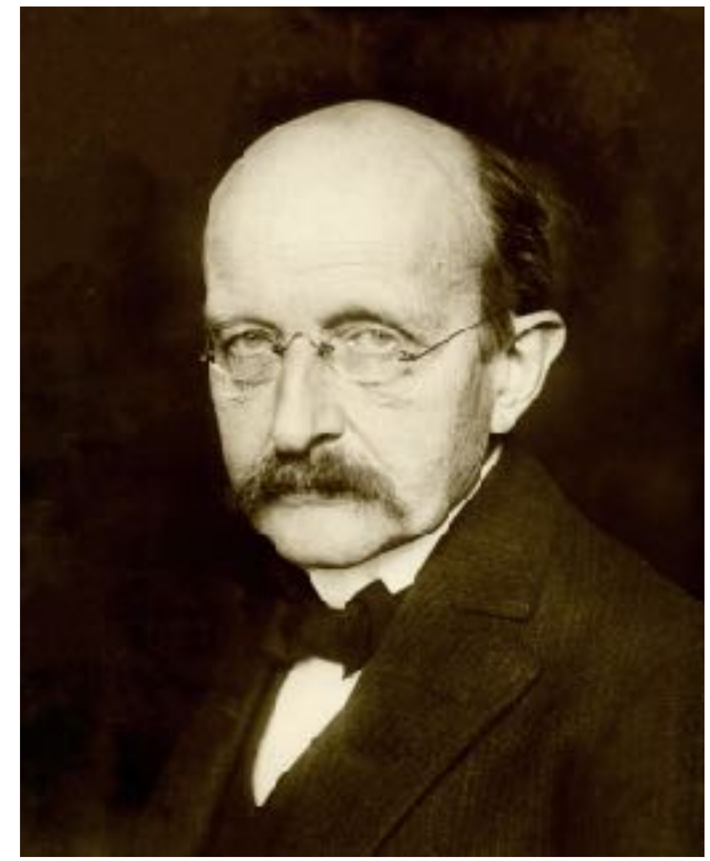


Planck Mission

- The mission substantially improved upon observations made by the NASA Wilkinson Microwave Anisotropy Probe (WMAP).

- The project was started around 1996 and was initially called **COBRAS/SAMBA**: the **CO**smic **B**ackground **R**adiation **A**nisotropy **S**atellite/**SA**tellite for **M**easurement of **B**ackground **A**nisotropies.

- Renamed in honor of the German physicist Max Planck (1858–1947)



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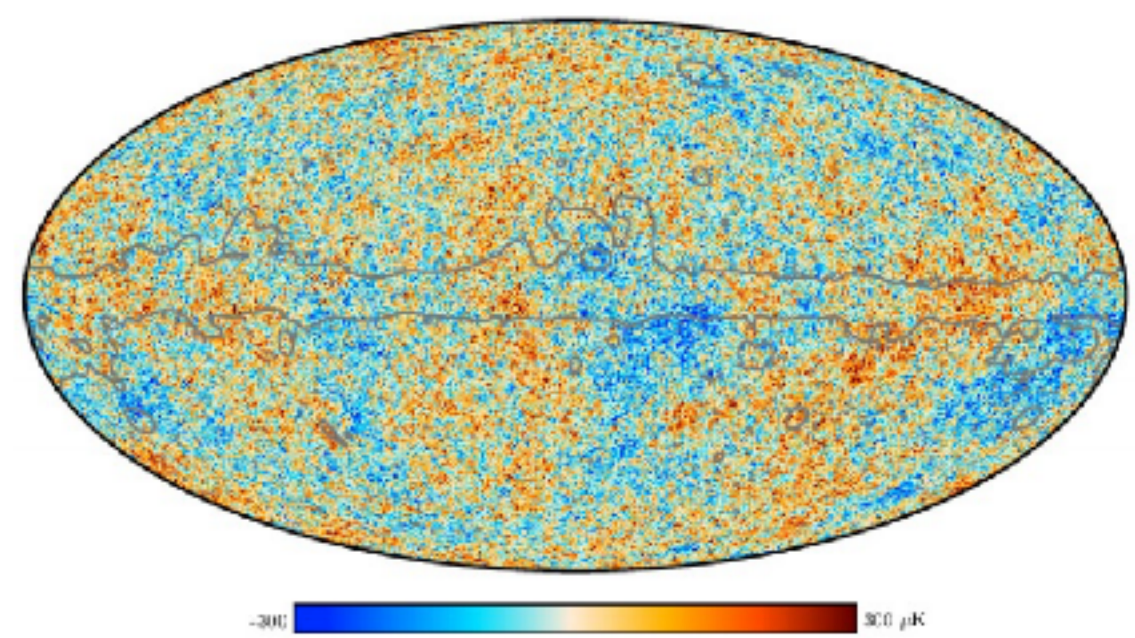
Planck Mission

- Launched on 14 May 2009
- Worked perfectly for 30 months, ~ twice the span originally required.
- Completed 5 full-sky surveys with High Frequency Instrument (HFI) and Low Frequency Instrument (LFI) instruments..
- LFI continued to survey the sky in 2013
- Turned off on 23 October 2013.

Data Release

- On 21 March 2013, the European-led research team behind the *Planck* cosmology probe released the mission's all-sky map of the cosmic microwave background.

- Results from an analysis of *Planck*'s full mission were made public on 1 December 2014 at a conference in Ferrara, Italy. A full set of papers detailing the mission results were released in February 2015.



Awards

- **2018 Marcel Grossman Institutional Award**
- **2018 Shaw Prize in Astronomy**
- **2018 Gruber Cosmology Prize.**
- **Royal Astronomical Society 2018 Group Award**.
- **François Bouchet**
- **2016 Lancelot M. Berkeley - New York Community Trust Prize for Meritorious Work in Astronomy**
- **2015 AIAA Space Systems Award**
- **Edison-Volta Prize**
- **COSPAR Space Science Award for 2014**.
- **Grand Prix scientifique 2014 of the Fondation Louis D.**
- **Le Prix La Recherche 2014**
- **2014 IPMA Awards**
- **2014 Amaldi medal by SIGRAV**
- **2013 Physics World Top 10 Breakthrough of the Year award**.

Instruments

LFI Radiometers 30-70 GHz, T = 20 K
HFI Bolometers 100-857 GHz, T = 0.1 K

Frequency (GHz)	Bandwidth ($\Delta\nu/\nu$)	Resolution (arcmin)	Sensitivity (total intensity) $\Delta T/T$, 14 month observation (10^{-6})	Sensitivity (polarization) $\Delta T/T$, 14 month observation (10^{-6})
30	0.2	33	2.0	2.8
44	0.2	24	2.7	3.9
70	0.2	14	4.7	6.7
100	0.33	10	2.5	4.0
143	0.33	7.1	2.2	4.2
217	0.33	5.5	4.8	9.8
353	0.33	5.0	14.7	29.8
545	0.33	5.0	147	N/A
857	0.33	5.0	6700	N/A

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Science Objectives

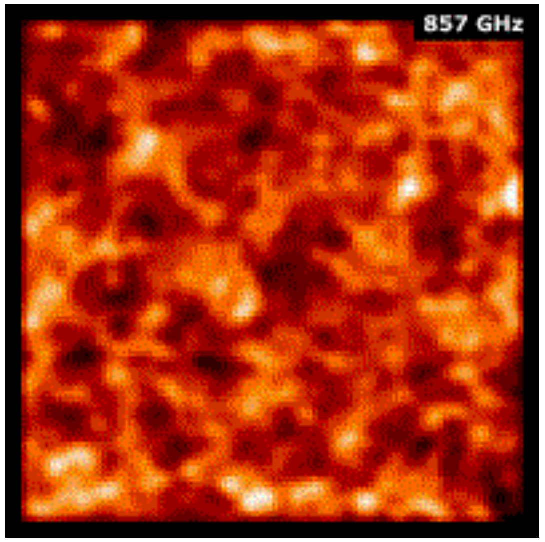
Planck's primary science objectives are to:

- Map CMB anisotropies
- Test inflationary models of the early universe
- Search for primordial gravitational waves
- Measure the amplitude of structures in CMB
- Perform measurements of the Sunyaev-Zeldovich effect

Planck has the ability to:

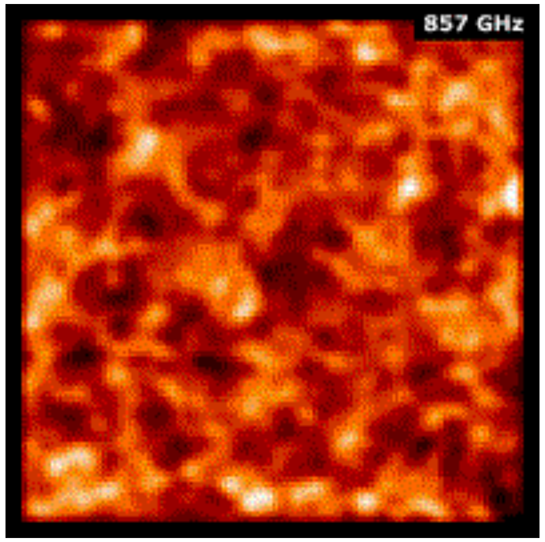
- Detect much **smaller temperature variations** in the CMB than previous missions
- Perform CMB measurements with a **higher angular resolution** than ever before
- Measure over a **wider band of frequencies** to enhance the separation of the CMB from interfering foreground signals

CIB



- the **C**osmic **I**nfrared **B**ackground
- In contrast to the CMB, which is the diffuse light from the early Universe, the CIB is a cumulative background with contributions from all of the star-forming galaxies across cosmic history.
- Observations of fluctuations in the CIB performed with Planck at different wavelengths have been used to trace the large-scale distribution of star-forming galaxies at different epochs in cosmic history.

CIB



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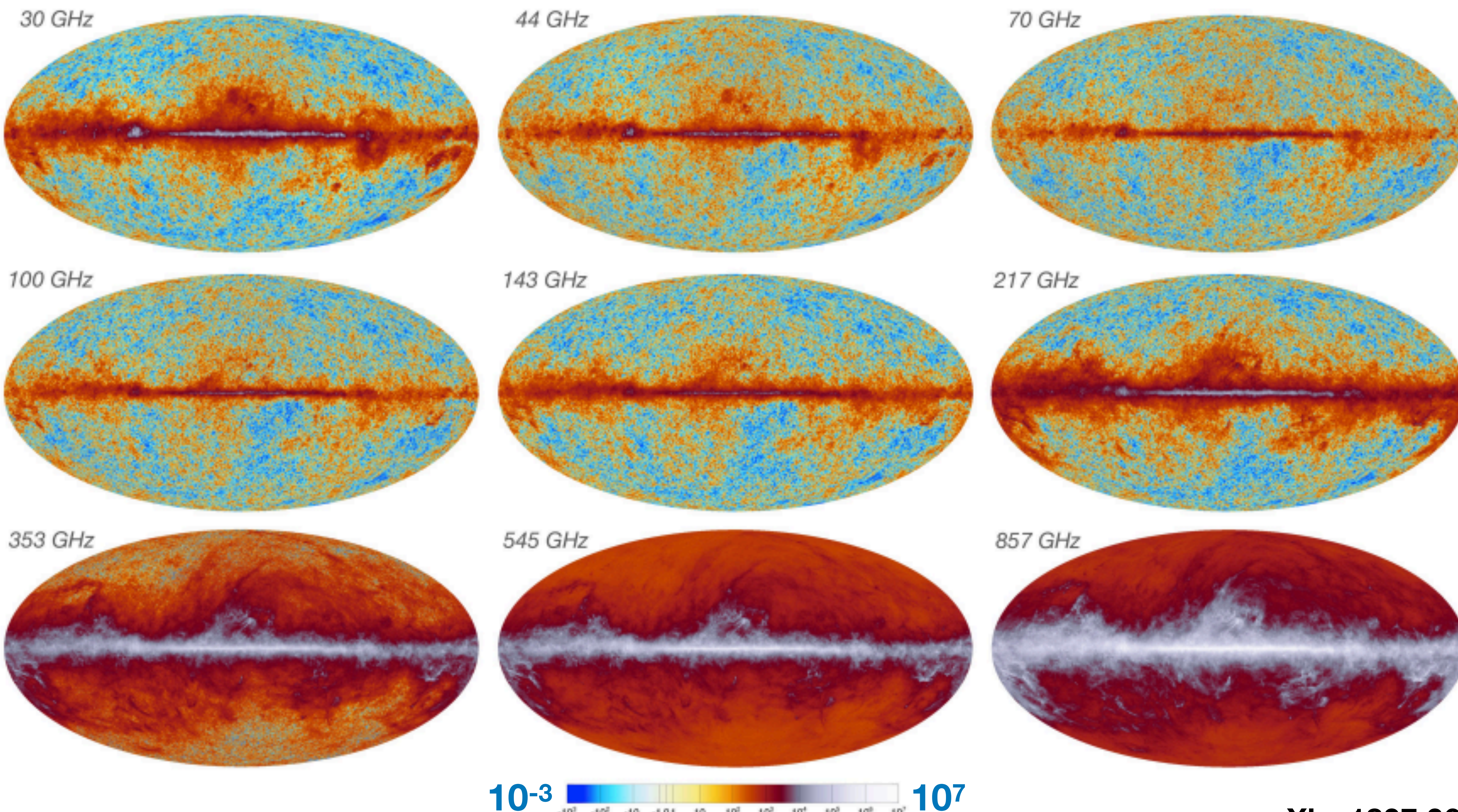
Scientific Highlights

- All Sky Map
- Angular Power Spectrum
- CMB Polarization
- Dark Matter Distribution
- New Discovery with SZ effect
- Cosmic Inflation
- Constraints on ΛCDM Model
- …

All Sky Map



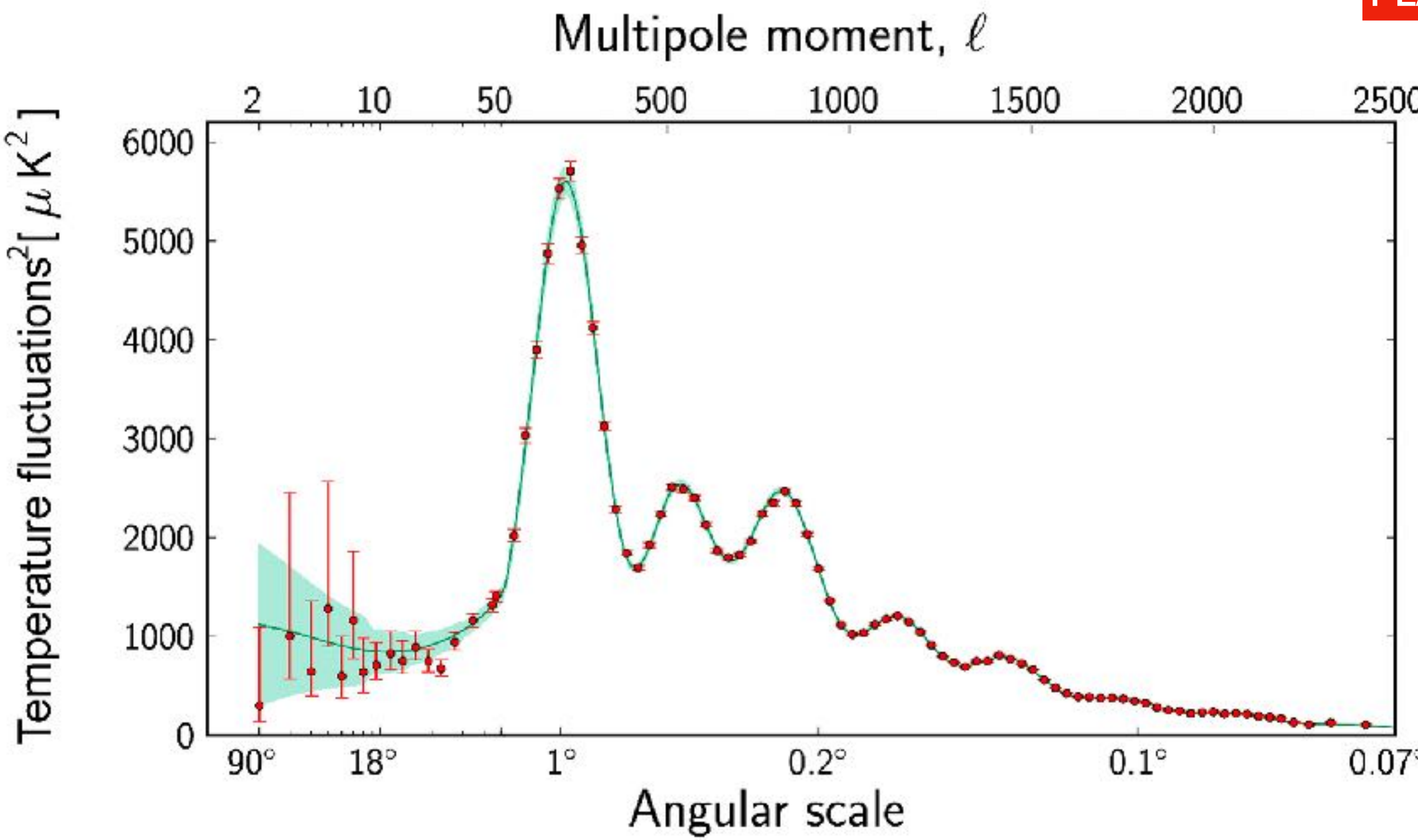
arXiv: 1807.06205

30-353 GHz: $\delta T[\mu K_{cmb}]$;

545 and 857 GHz: surface brightness [kJy/sr]

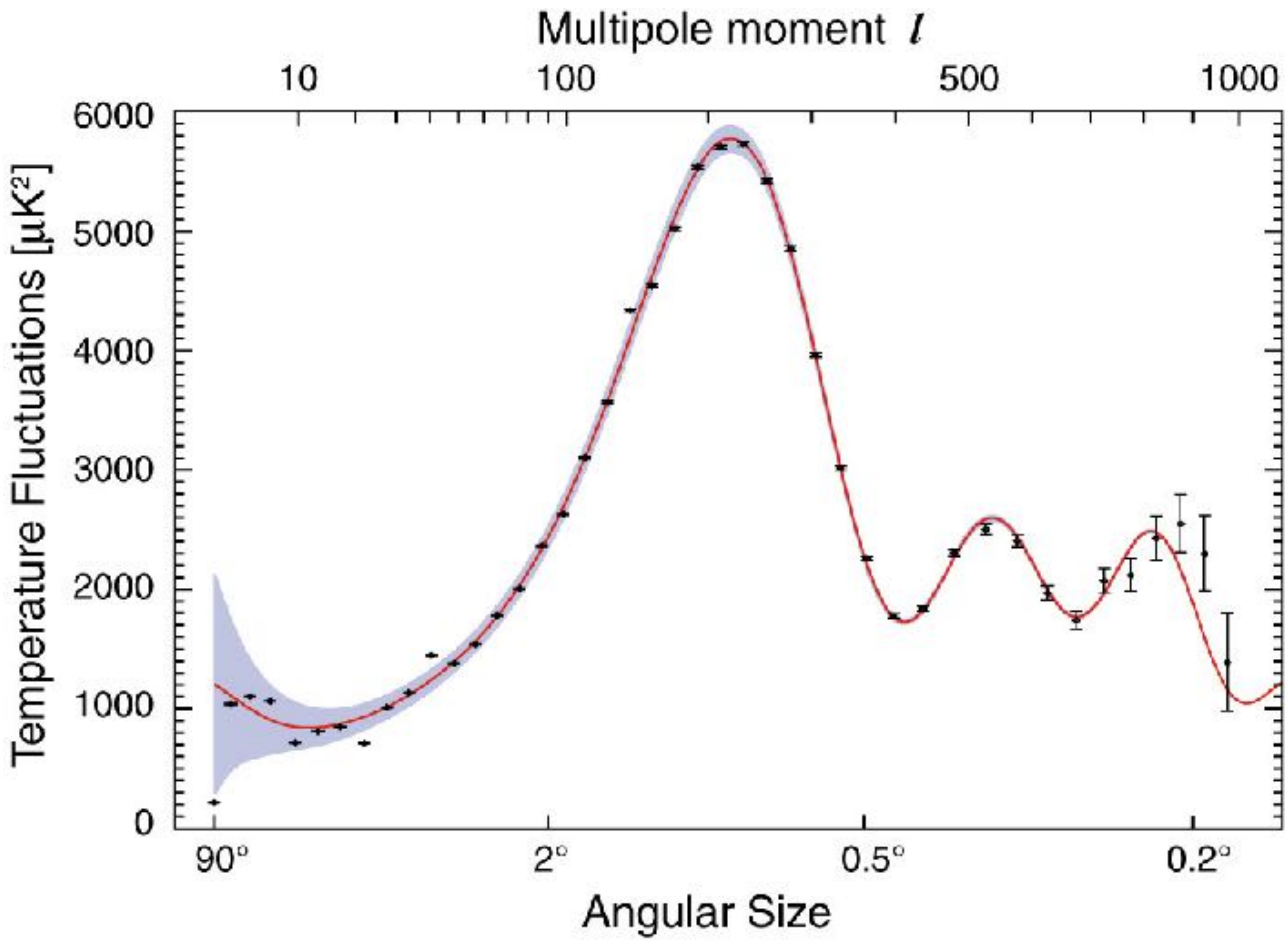
Scientific Results

PLANCK



Scientific Results

WMAP

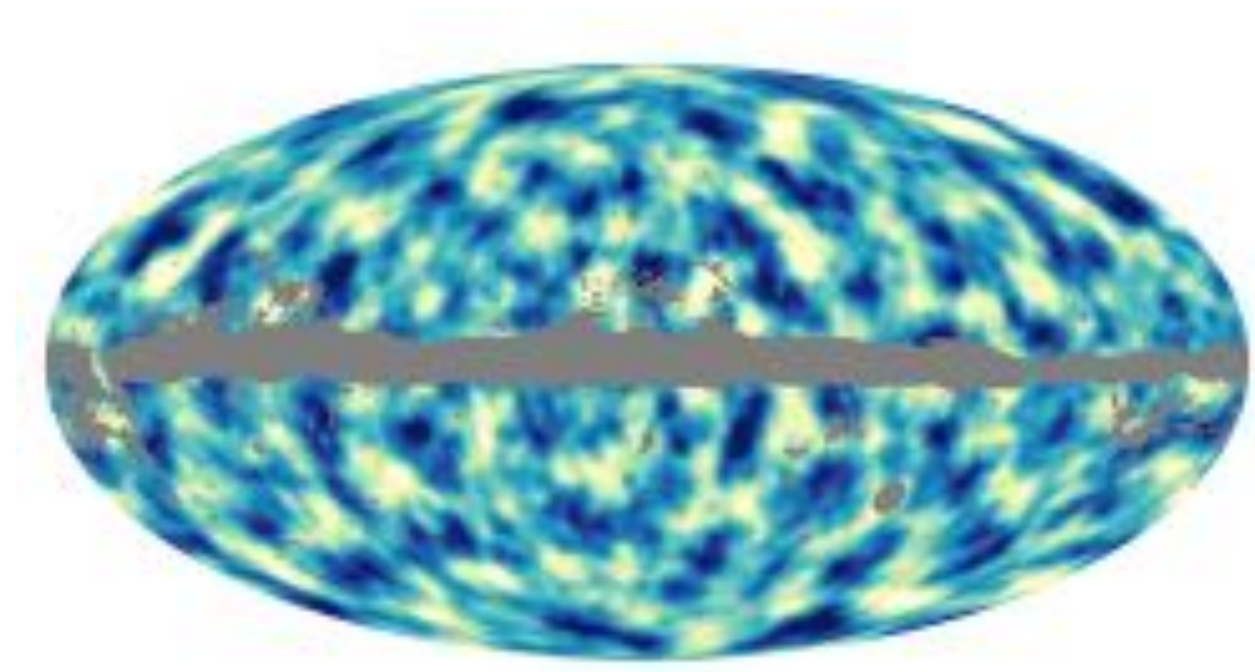


Dark Matter Distribution

- Gravitational lensing effect: deflection -> distortion

- Map over the entire sky for the first time

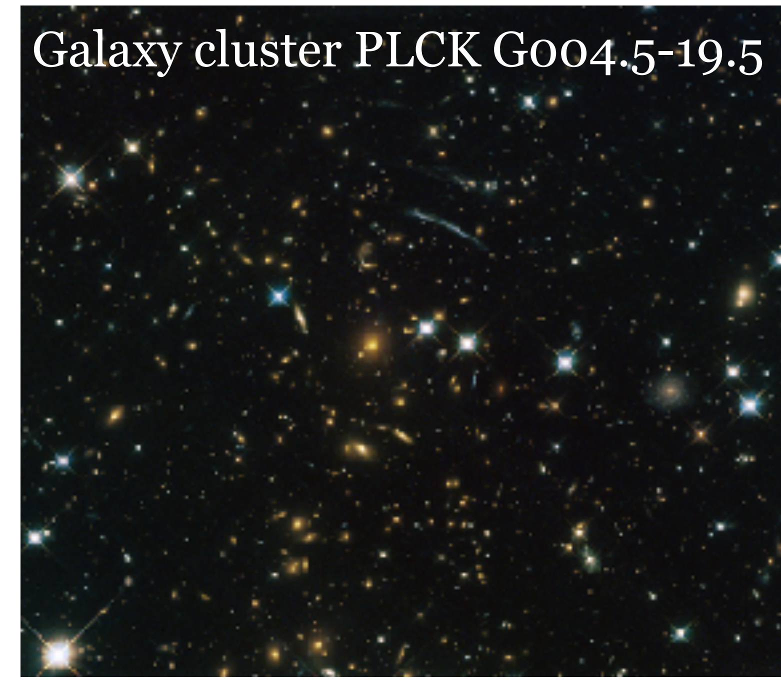
- Evolution of structure formation in the Universe



SZ effect: Galaxy Cluster Discovering and Gas Bridging

- Sunyaev-Zel'dovich effect (SZ effect): photons from the CMB scatter off free electrons in the gas that permeates galaxy clusters, their energy is changed in a distinctive way.

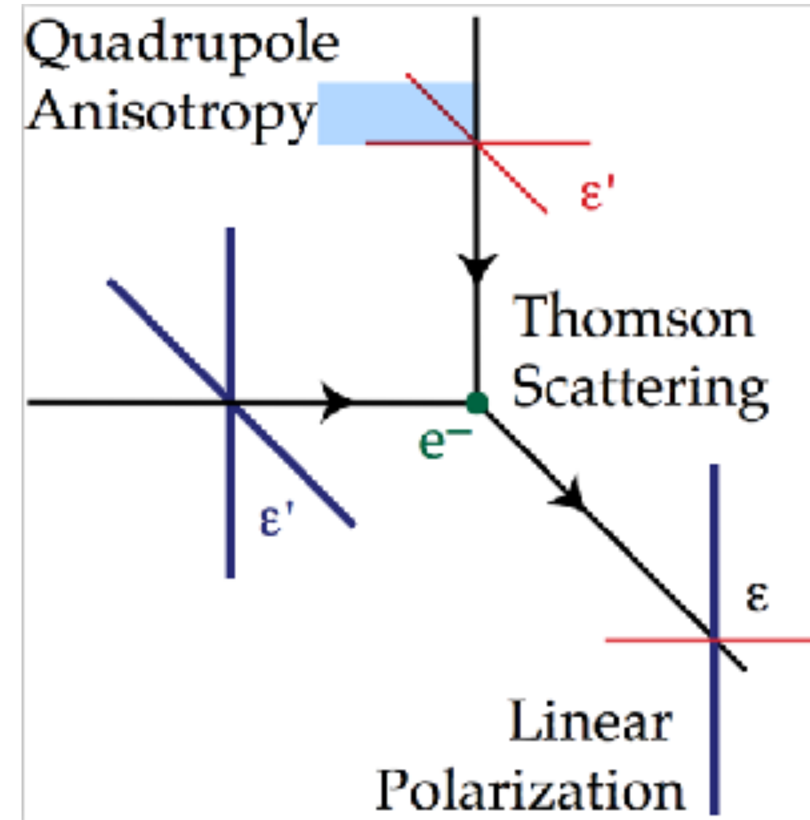
- Identify galaxy clusters from observations of the CMB:
  - ✤ > 1000 galaxy clusters across the entire sky, including almost 400 brand new detections.
  - ✤ Several superclusters and the first observation of inter-cluster gas bridging two clusters.



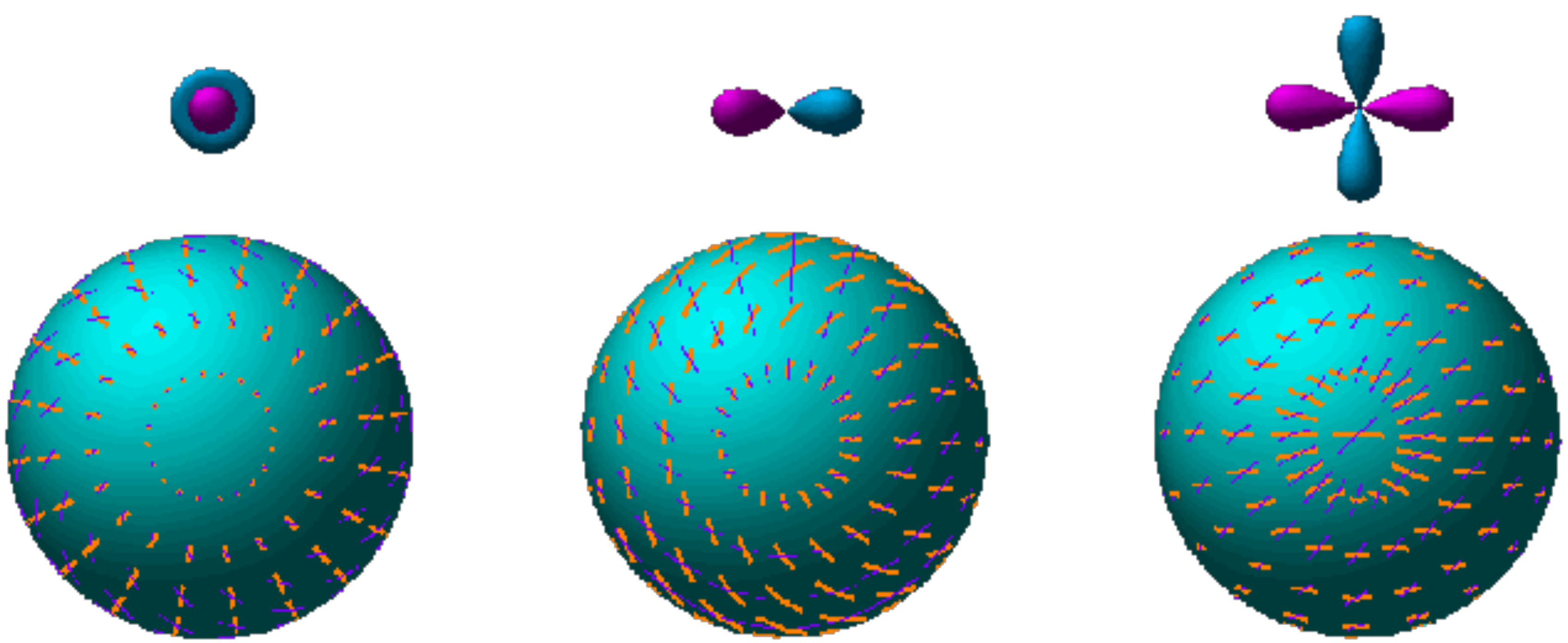
Credit: ESA/Hubble & NASA, RELICS

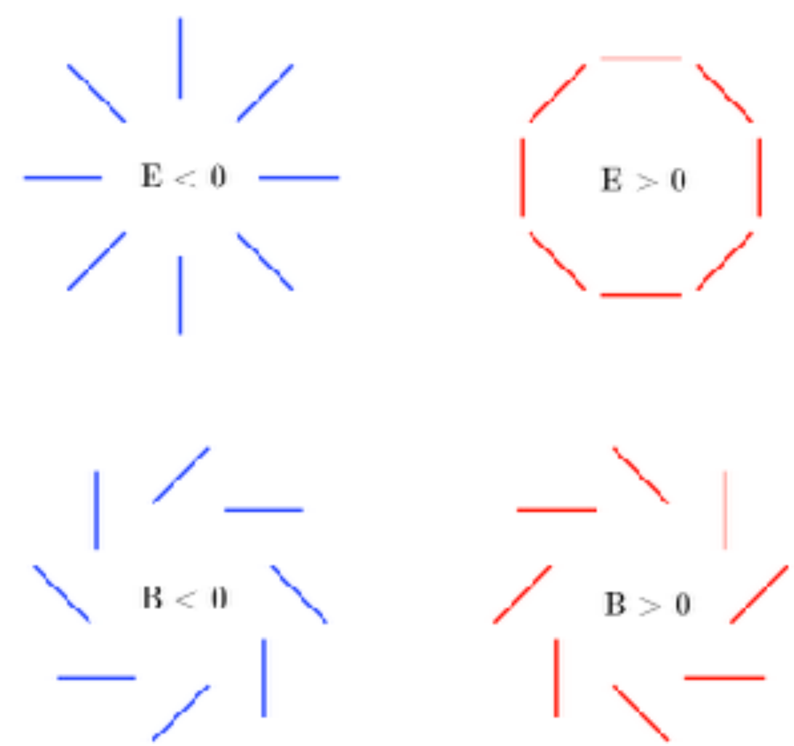
CMB Polarization

- Polarization is a tensor
- E mode & B mode
- Source: Baryon perturbation; Primordial tensor perturbation



Scalar Perturbation | **Vector Perturbation** | **Tensor Perturbation**





credit: Wayne Hu

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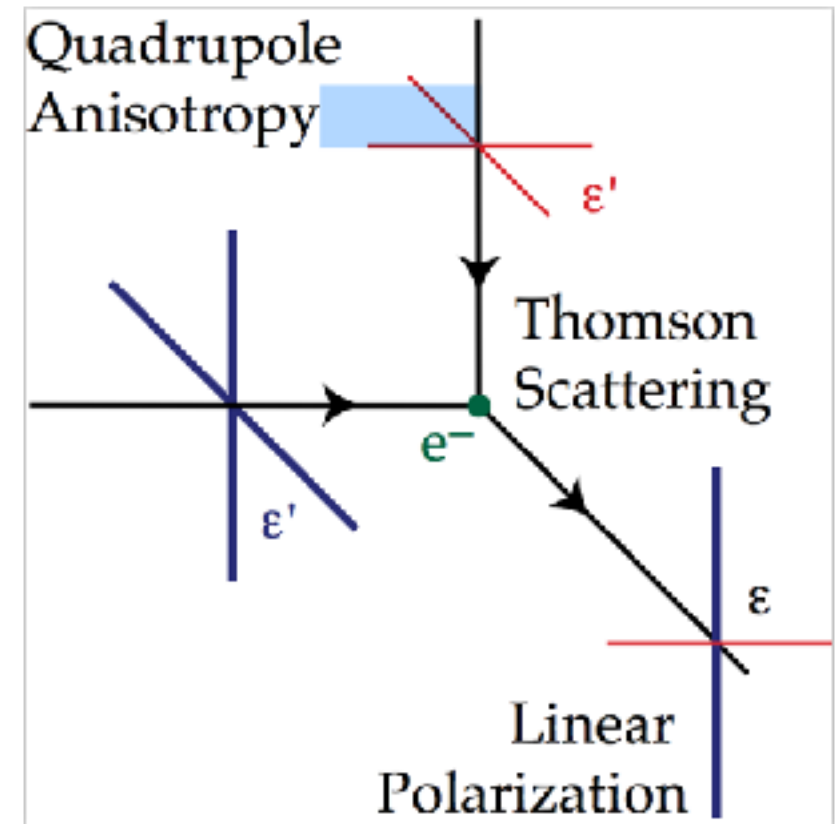

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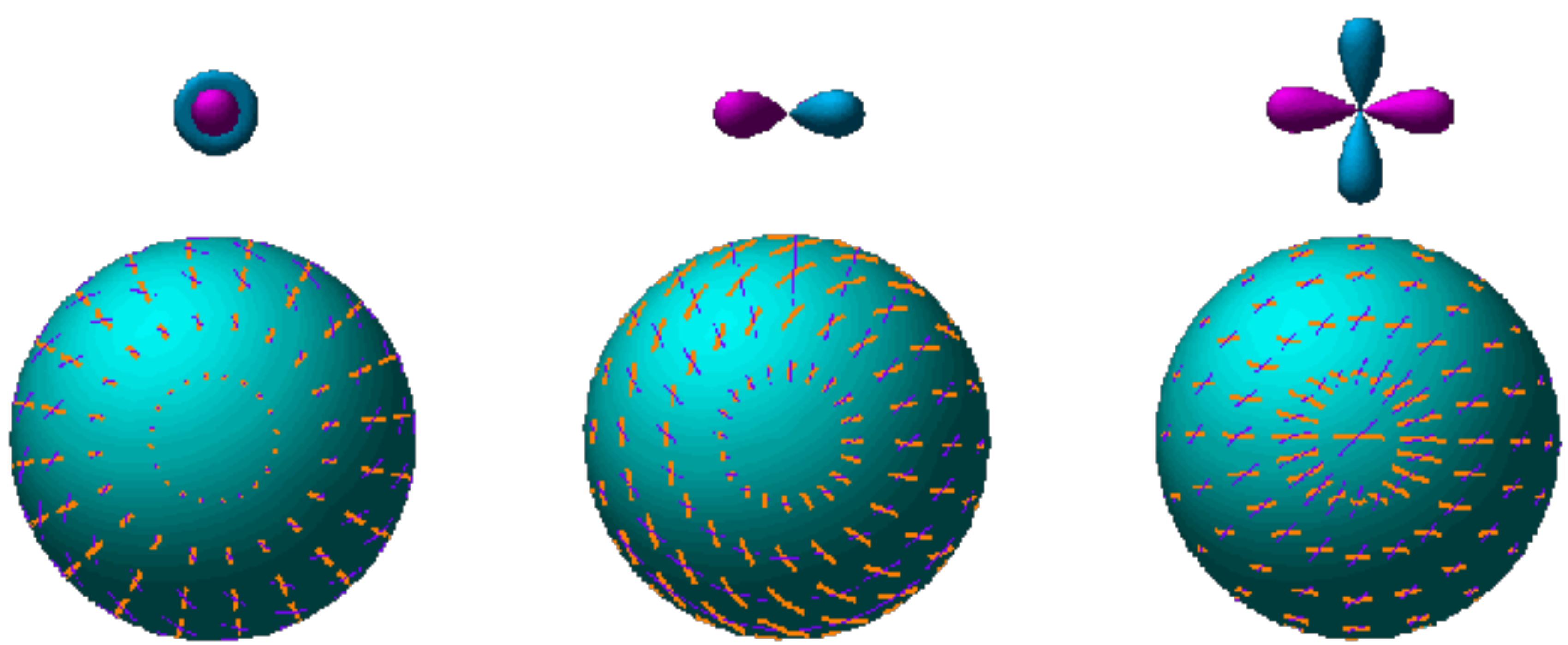

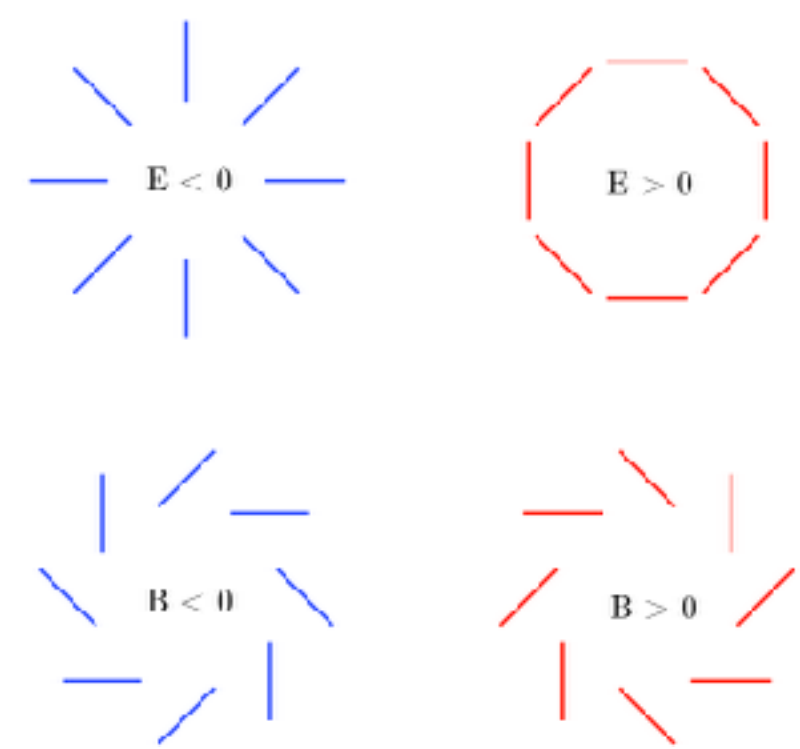

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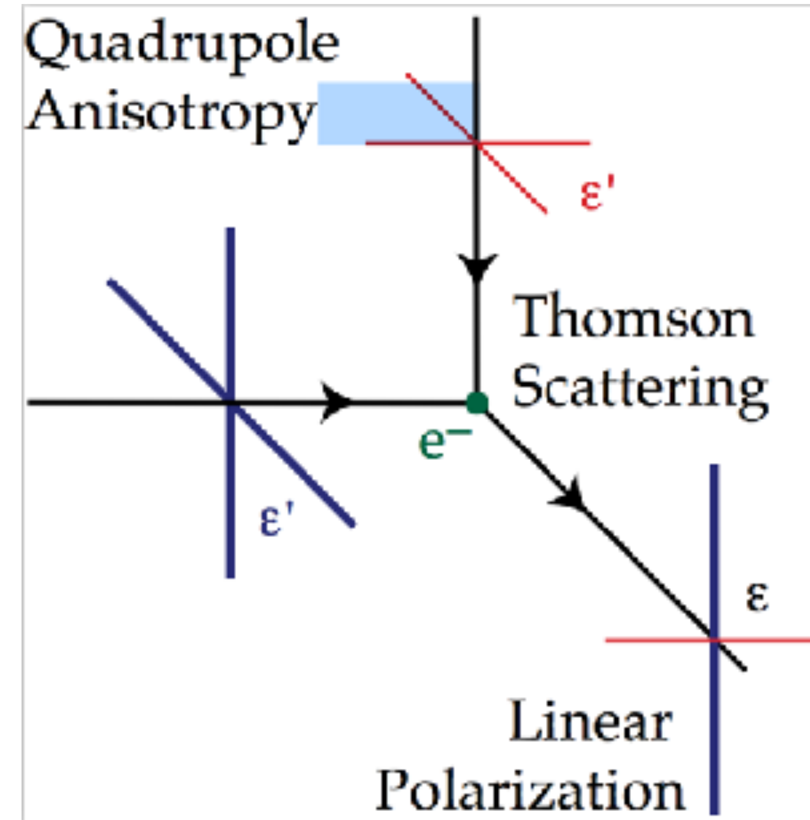

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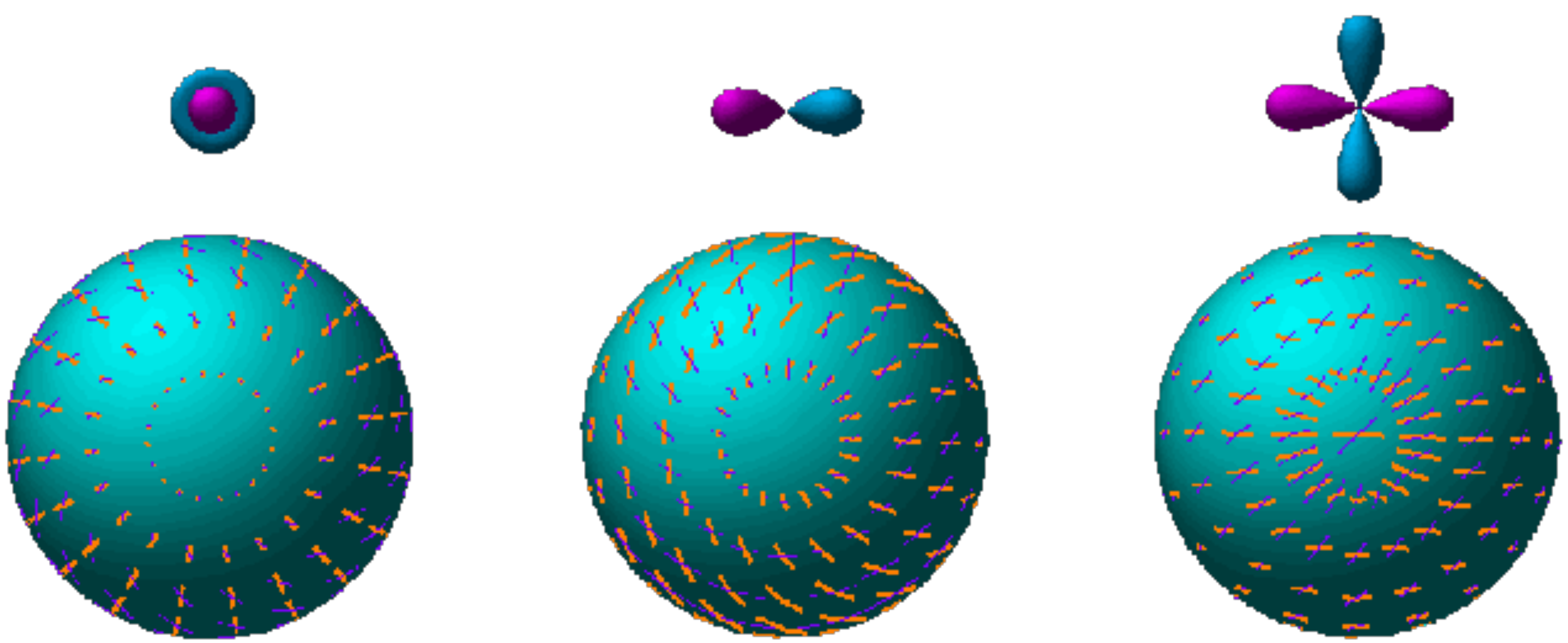

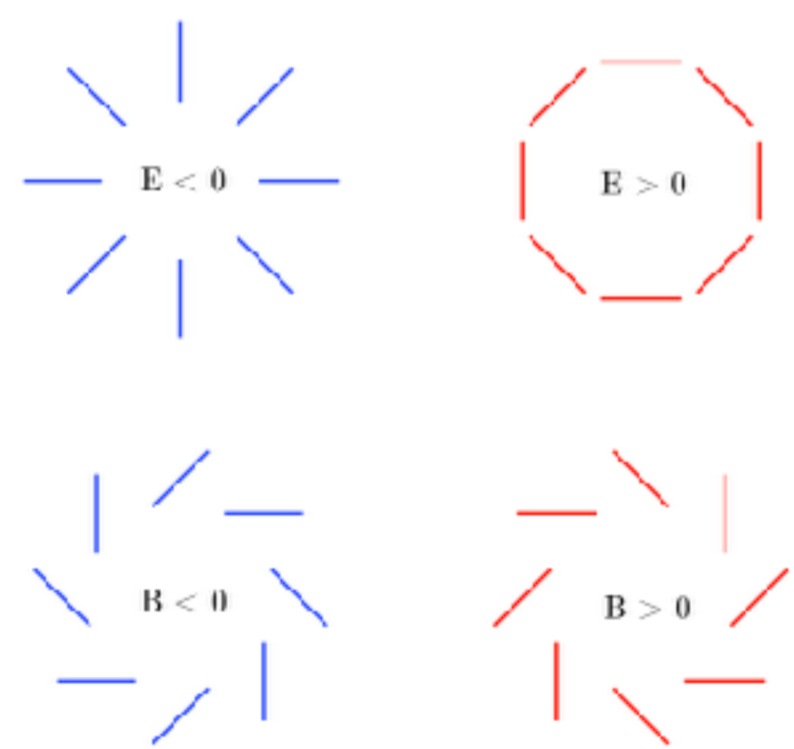

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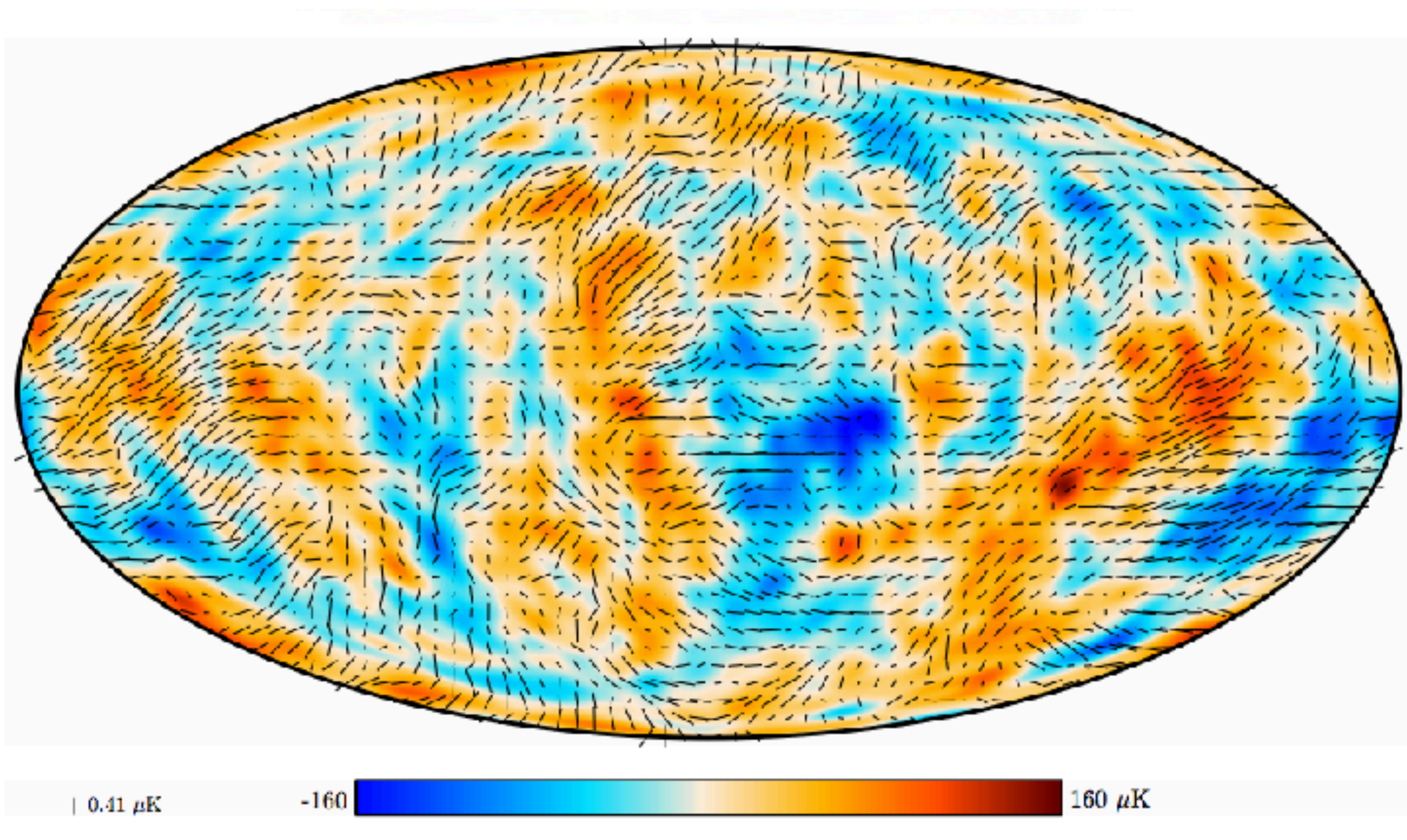

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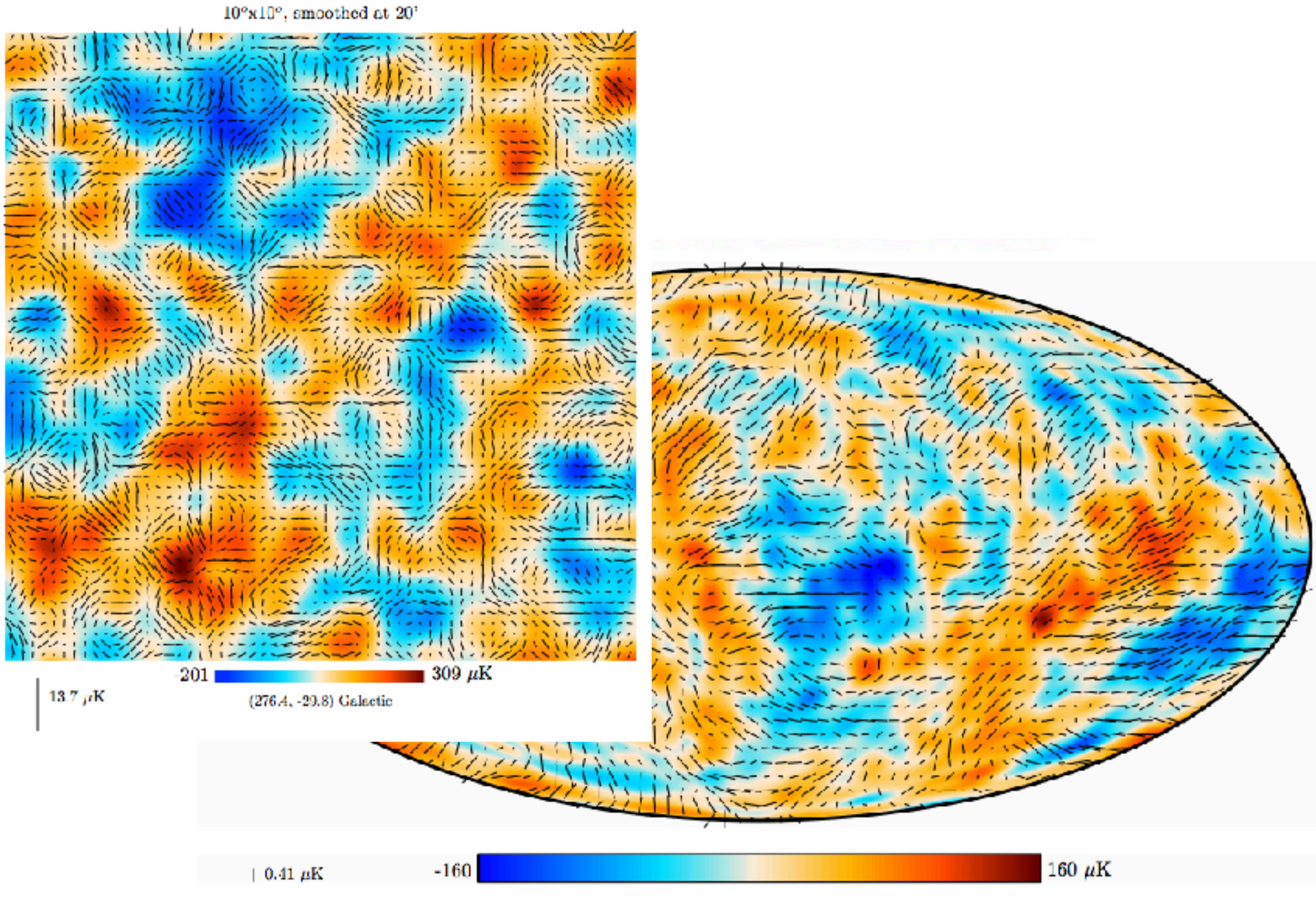

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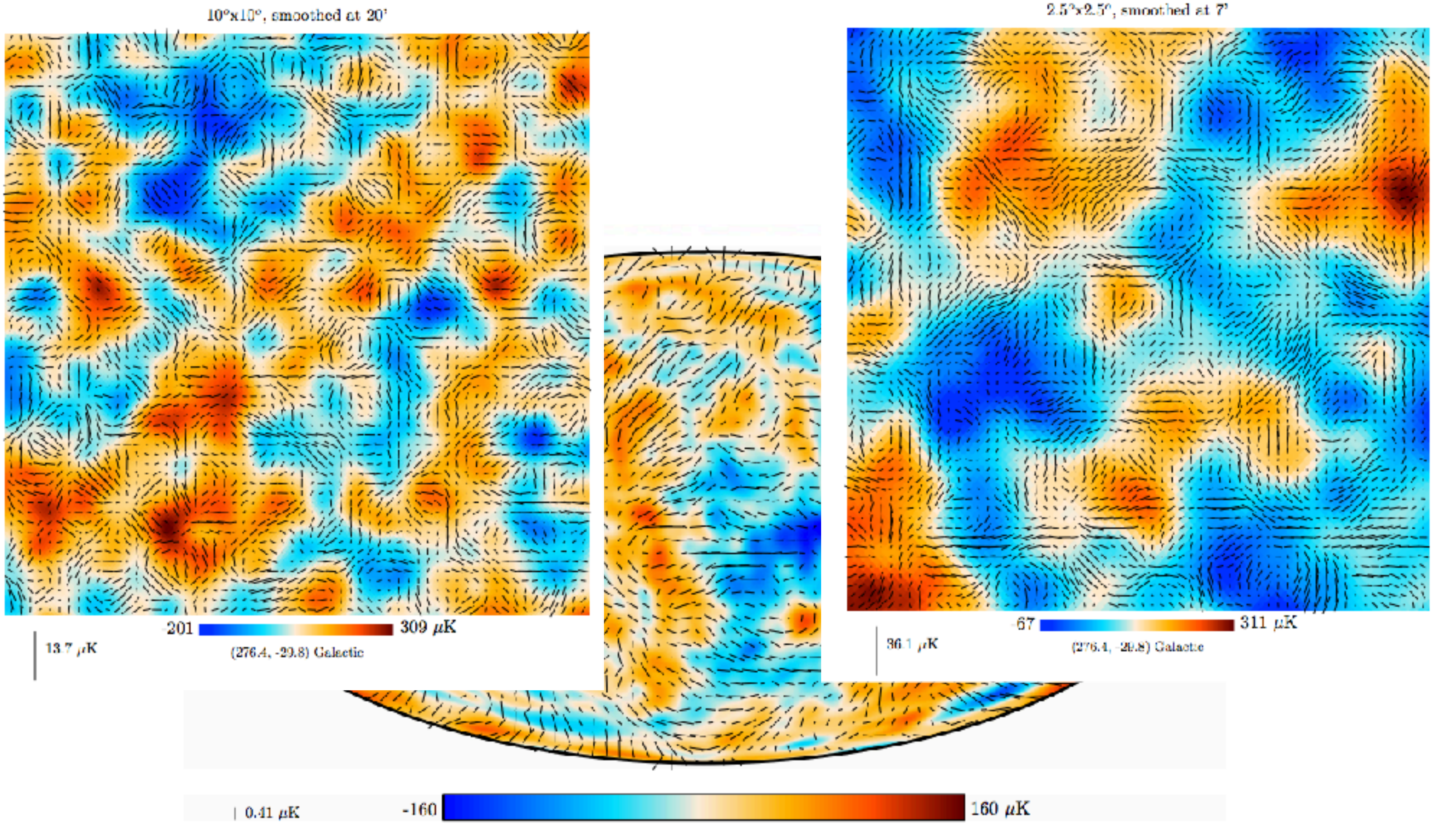
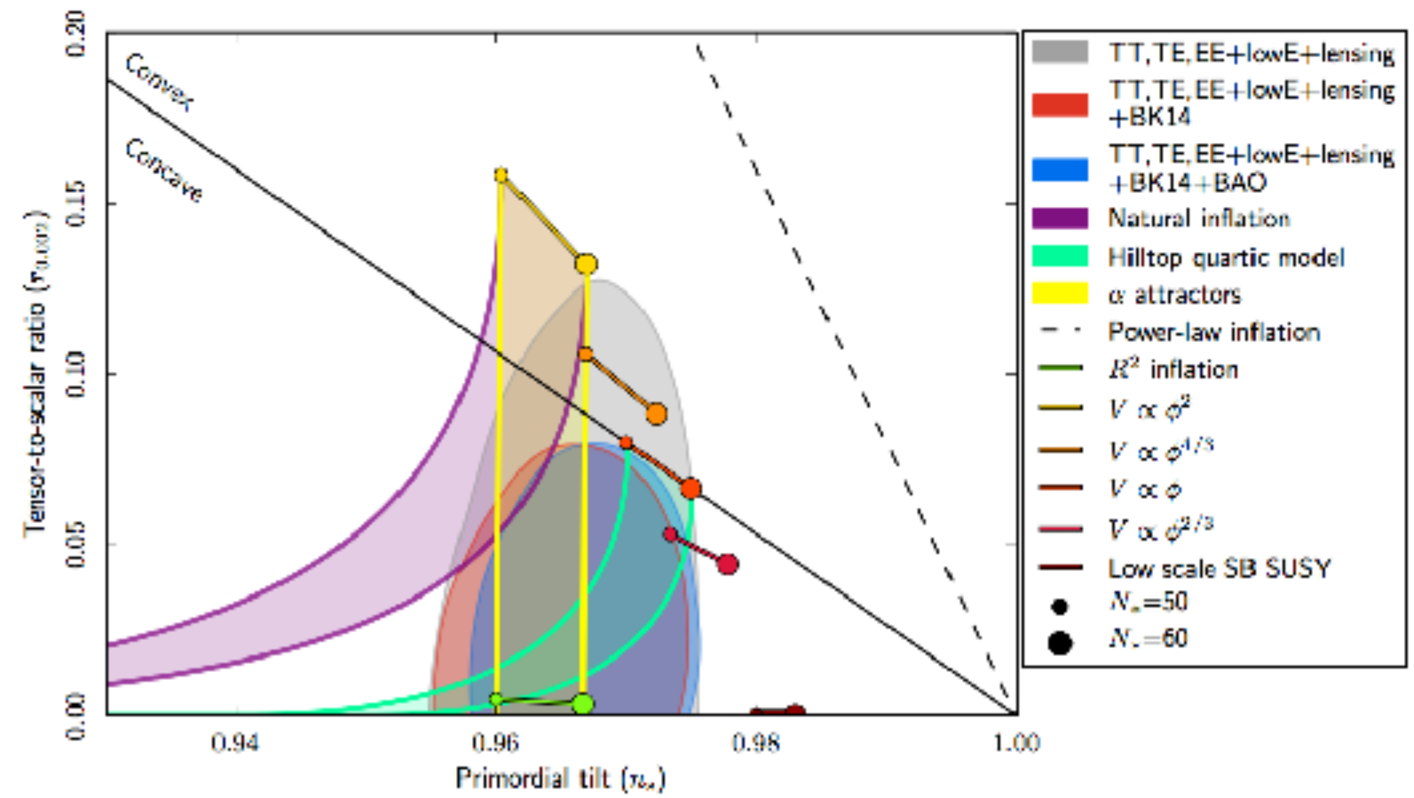


Cosmic Inflation

- The **spectral index, n_s** is one for a scale-invariant Harrison–Zel'dovich spectrum. The simplest inflation models predict that n_s is between 0.92 and 0.98

- $n_s = 0.968 \pm 0.006$, and a tensor-to-scalar ratio that is less than 0.07. These are considered an important confirmation of the theory of inflation.

- non-Gaussianity, f_{NL}



Prediction	Measurement
A spatially flat universe	$\Omega_K = 0.0007 \pm 0.0019$
with a *nearly* scale-invariant (red)	
spectrum of density perturbations,	$n_s = 0.967 \pm 0.004$
which is almost a power law,	$dn/d\ln k = -0.0042 \pm 0.0067$
dominated by scalar perturbations,	$r_{0.002} < 0.07$
which are Gaussian	$f_{NL} = 2.5 \pm 5.7$
and adiabatic,	$\alpha_{-1} = 0.00013 \pm 0.00037$
with negligible topological defects	$f < 0.01$

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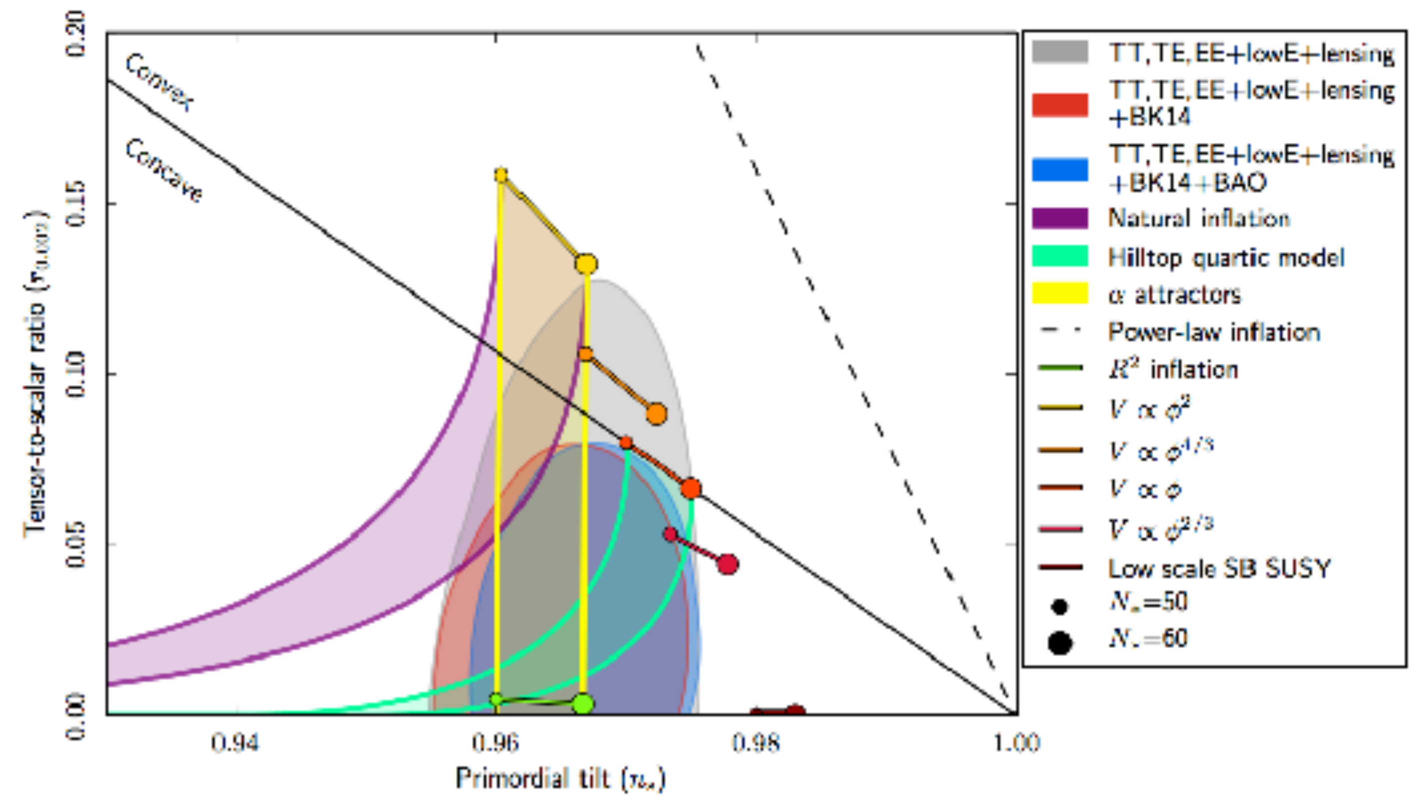

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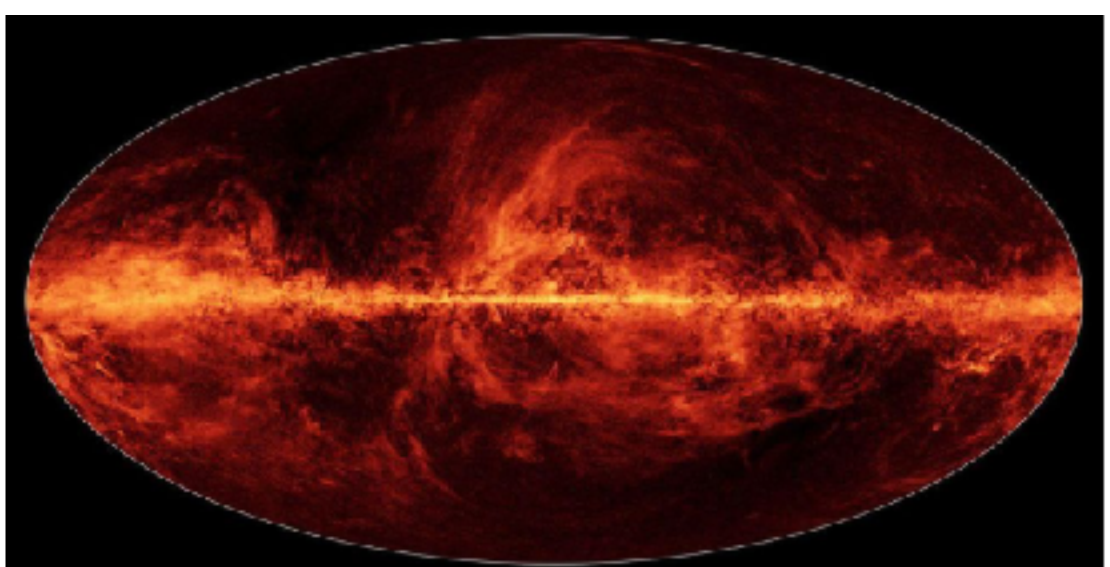
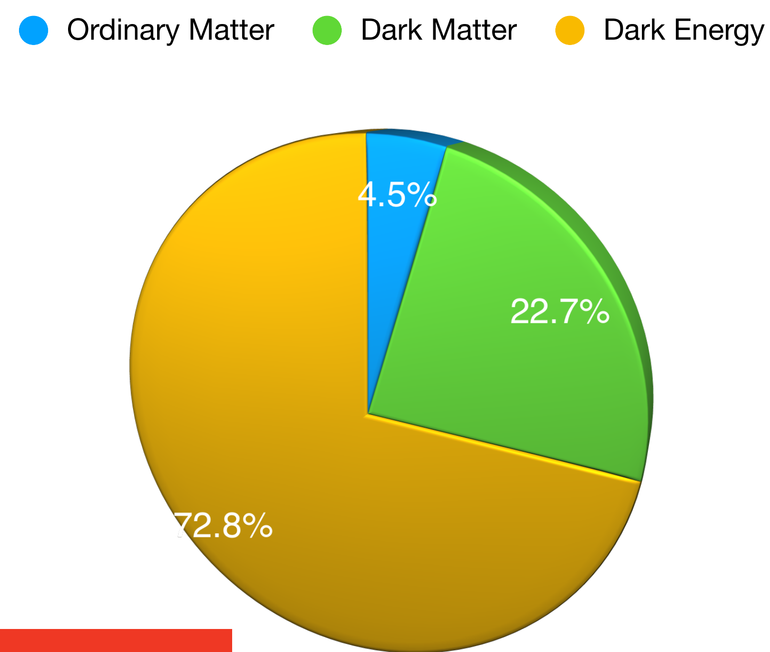
Dust Measurement

- In 2014, BICEP-II (Background Imaging of Cosmic Extragalactic Polarization) report that they had detected *B*-modes from primordial gravitational waves in the early universe.

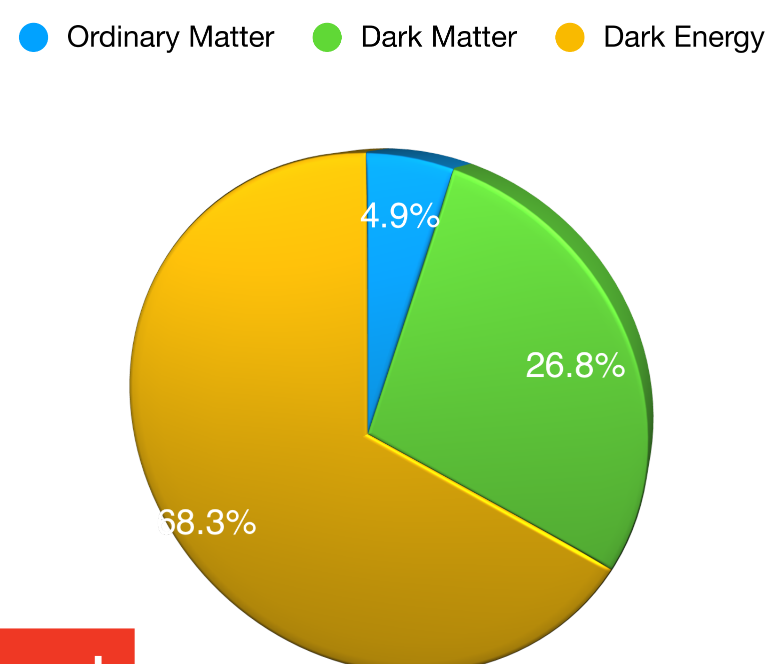
- A joint analysis of BICEP2 and Planck data was published and the European Space Agency announced that the signal can be entirely attributed to dust in the Milky Way.



New Cosmic Recipe and constraints on ΛCDM Model



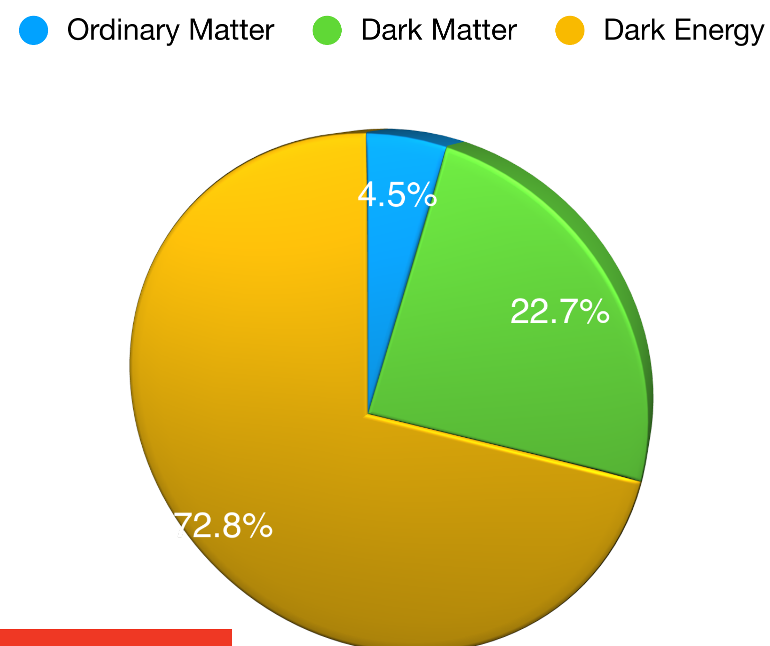
Before Planck



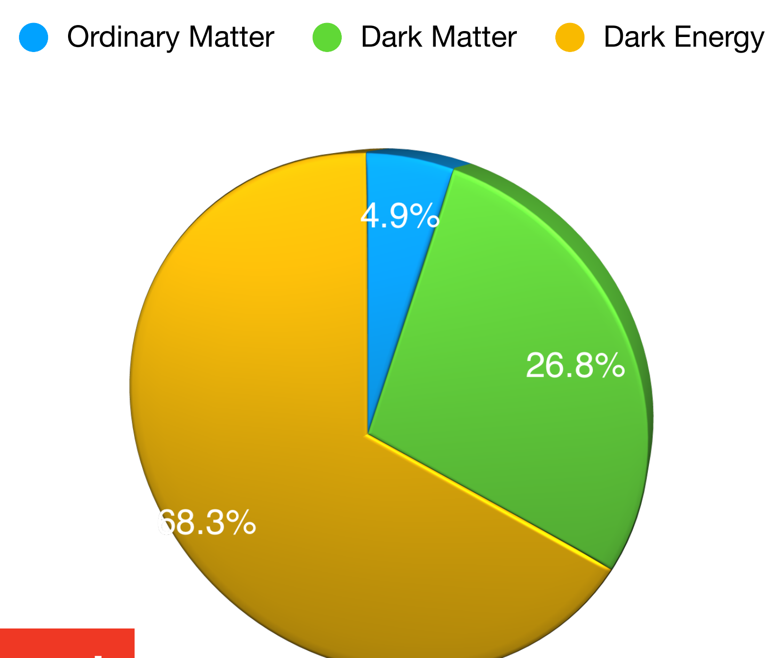
Planck

Parameter	*Planck* alone	*Planck* + BAO
$\Omega_b h^2$	0.022383	0.022447
$\Omega_c h^2$	0.12011	0.11923
$100\theta_{MC}$	1.040909	1.041010
τ	0.0543	0.0568
$\ln(10^{10}A_s)$	3.0448	3.0480
n_s	0.96605	0.96824
H_0 [km s^{-1}Mpc^{-1}] . . .	67.32	67.70
Ω_Λ	0.6842	0.6894
Ω_m	0.3158	0.3106
$\Omega_m h^2$	0.1431	0.1424
$\Omega_m h^3$	0.0964	0.0964
σ_8	0.8120	0.8110
$\sigma_8(\Omega_m/0.3)^{0.5}$	0.8331	0.8253
z_{re}	7.68	7.90
Age [Gyr]	13.7971	13.7839

New Cosn constraints



Before Planck

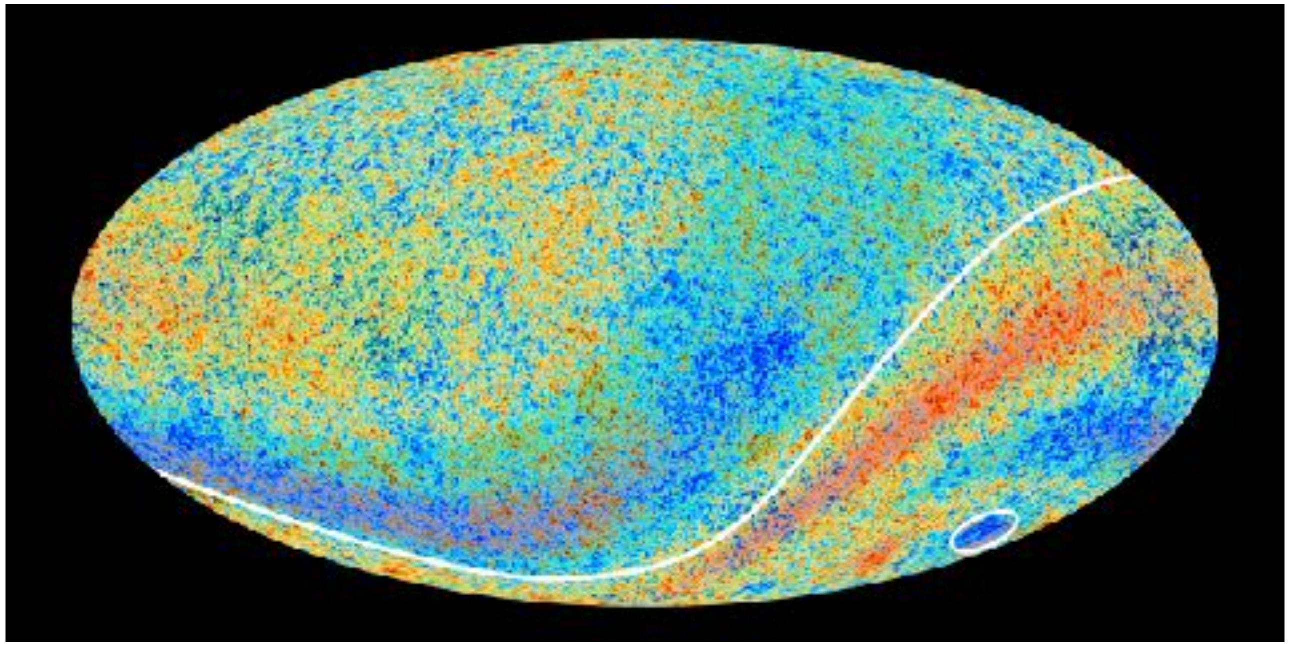


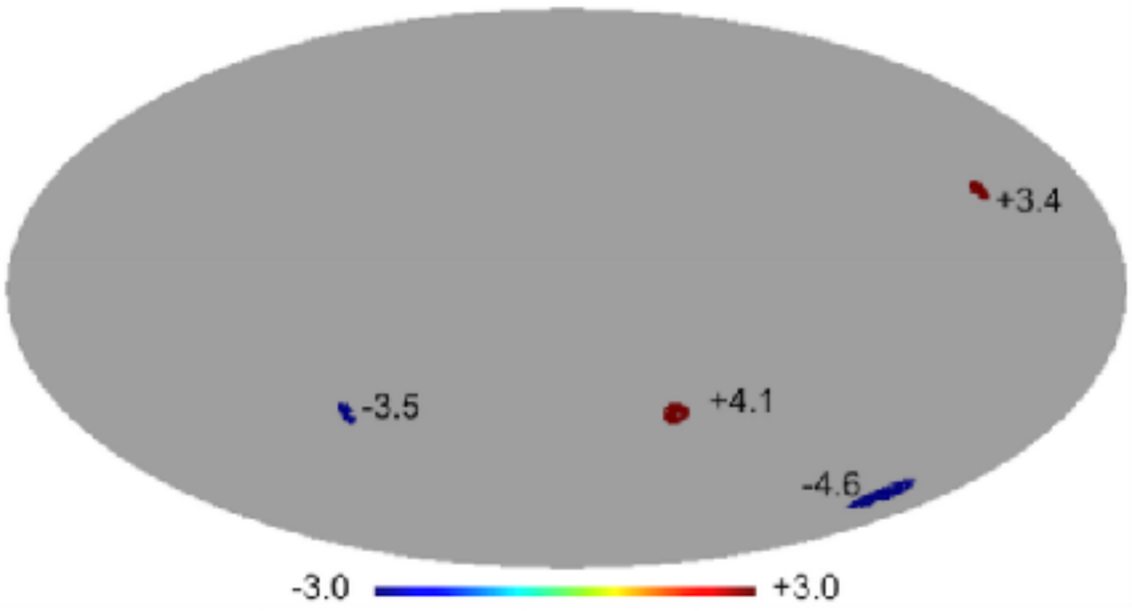
Planck

Parameter	*Planck* alone	*Planck* + BAO
$\Omega_b h^2$	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9649 ± 0.0042	0.9665 ± 0.0038
H_0	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.6847 ± 0.0073	0.6889 ± 0.0056
Ω_m	0.3153 ± 0.0073	0.3111 ± 0.0056
$\Omega_m h^2$	0.1430 ± 0.0011	0.14240 ± 0.00087
$\Omega_m h^3$	0.09633 ± 0.00030	0.09635 ± 0.00030
σ_8	0.8111 ± 0.0060	0.8102 ± 0.0060
$\sigma_8(\Omega_m/0.3)^{0.5}$ . . .	0.832 ± 0.013	0.825 ± 0.011
z_{re}	7.67 ± 0.73	7.82 ± 0.71
Age[Gyr]	13.797 ± 0.023	13.787 ± 0.020
r_*[Mpc]	144.43 ± 0.26	144.57 ± 0.22
$100\theta_*$	1.04110 ± 0.00031	1.04119 ± 0.00029
r_{drag}[Mpc]	147.09 ± 0.26	147.57 ± 0.22
z_{eq}	3402 ± 26	3387 ± 21
$k_{eq}[\mathrm{Mpc}^{-1}]$	0.010384 ± 0.000081	0.010339 ± 0.000063
Ω_K	-0.0096 ± 0.0061	0.0007 ± 0.0019
Σm_ν [eV]	< 0.241	< 0.120
N_{eff}	$2.89^{+0.36}_{-0.38}$	$2.99^{+0.34}_{-0.33}$
$r_{0.002}$	< 0.101	< 0.106

Unexplained Features -> New Physics

- The fluctuations in the CMB temperatures at large angular scales do not match those predicted by the standard model – their signals are not as strong as expected from the smaller scale structure revealed by Planck.
- An asymmetry in the average temperatures on opposite hemispheres of the sky. This runs counter to the prediction made by the standard model that the Universe should be broadly similar in any direction we look.
- A cold spot extends over a patch of sky that is much larger than expected.





Post-Planck: Questions Remain in Cosmology

– What is the mechanism for the generation of fluctuations in the early Universe?
– If it is inflation, as we suspect, what is the inflaton, what determines the initial state, and how does inflation end?
– How did baryogenesis occur?
– What is the dark matter?
– Are there additional, light, relic particles?
– What is causing the accelerated expansion of the Universe today? – How did the Universe reionize?
– How do astrophysical objects form and evolve in the cosmic web?

Summary

- Planck was the third-generation space mission dedicated to measurement of CMB anisotropies.
- Planck imaged the anisotropies of the CMB over the whole sky, with unprecedented sensitivity and angular resolution.
- Test and constrain the inflationary ΛCDM model in high precision.

Reference

- arXiv: 1807.06205
- http://sci.esa.int/planck/
- http://www.esa.int/Our_Activities/Space_Science/Planck/
- https://www.nasa.gov/mission_pages/planck/
- http://background.uchicago.edu/~whu/polar/webversion/

Thanks for your attention!