UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

Cosmology, the Cosmic Microwave Background, and Planck

Neckarzimmern, March 7, 2014

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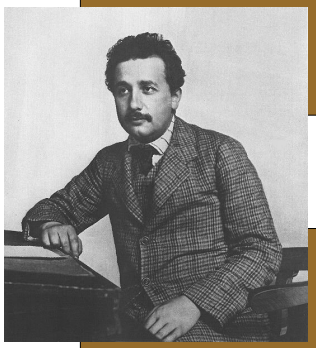
Uni Heidelberg, ZAH, ITA

Foundation

General Relativity

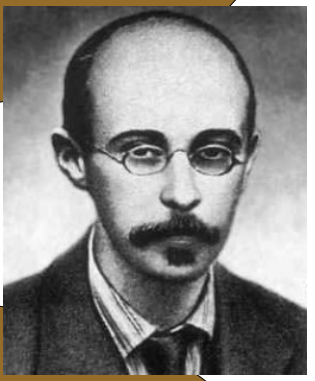
Symmetry Assumptions:
Homogeneity and isotropy
on average



Matter content:

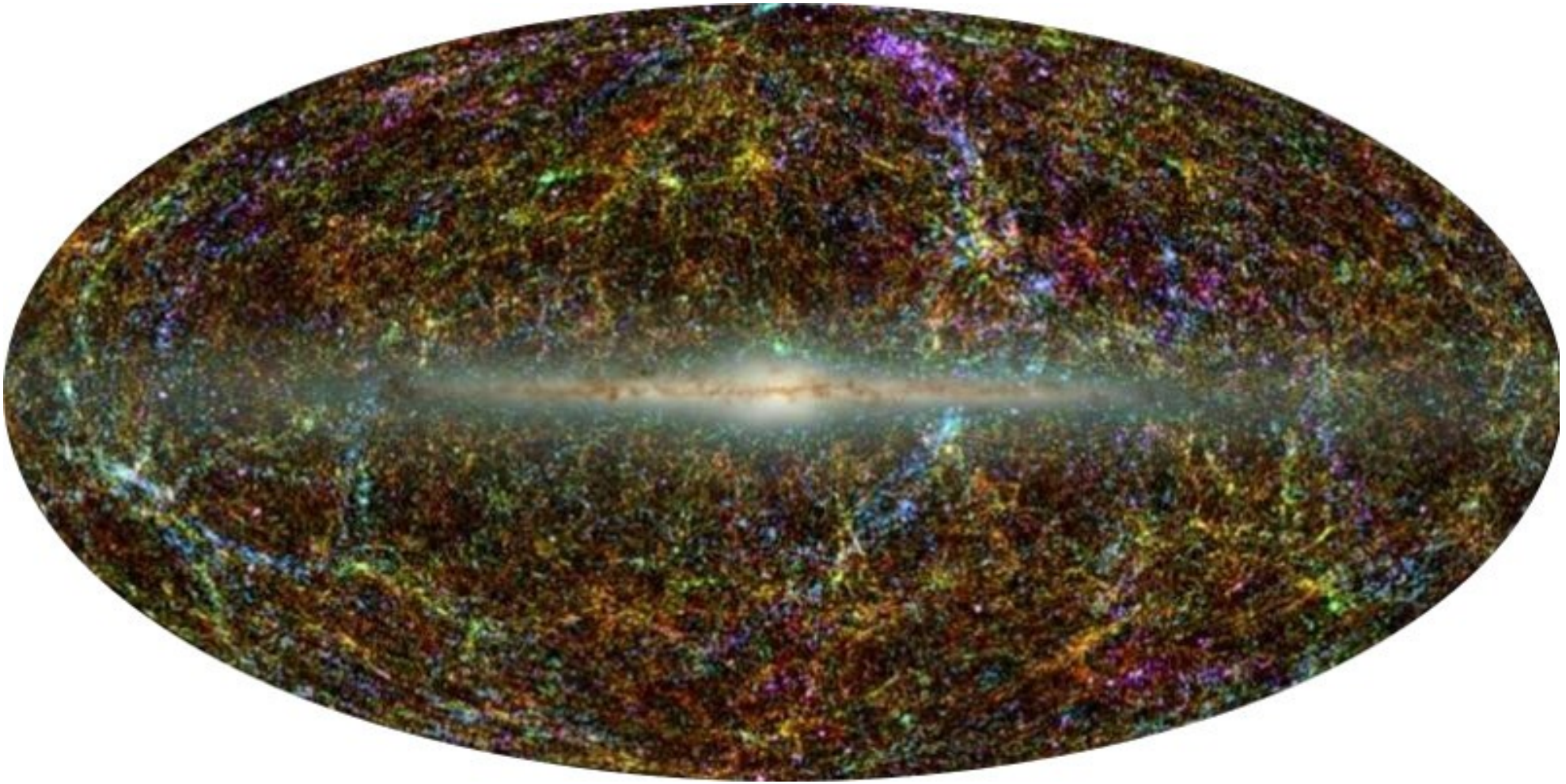
Energy-momentum tensor,
Containing radiation, matter,
anything else

Robertson-Walker
metric



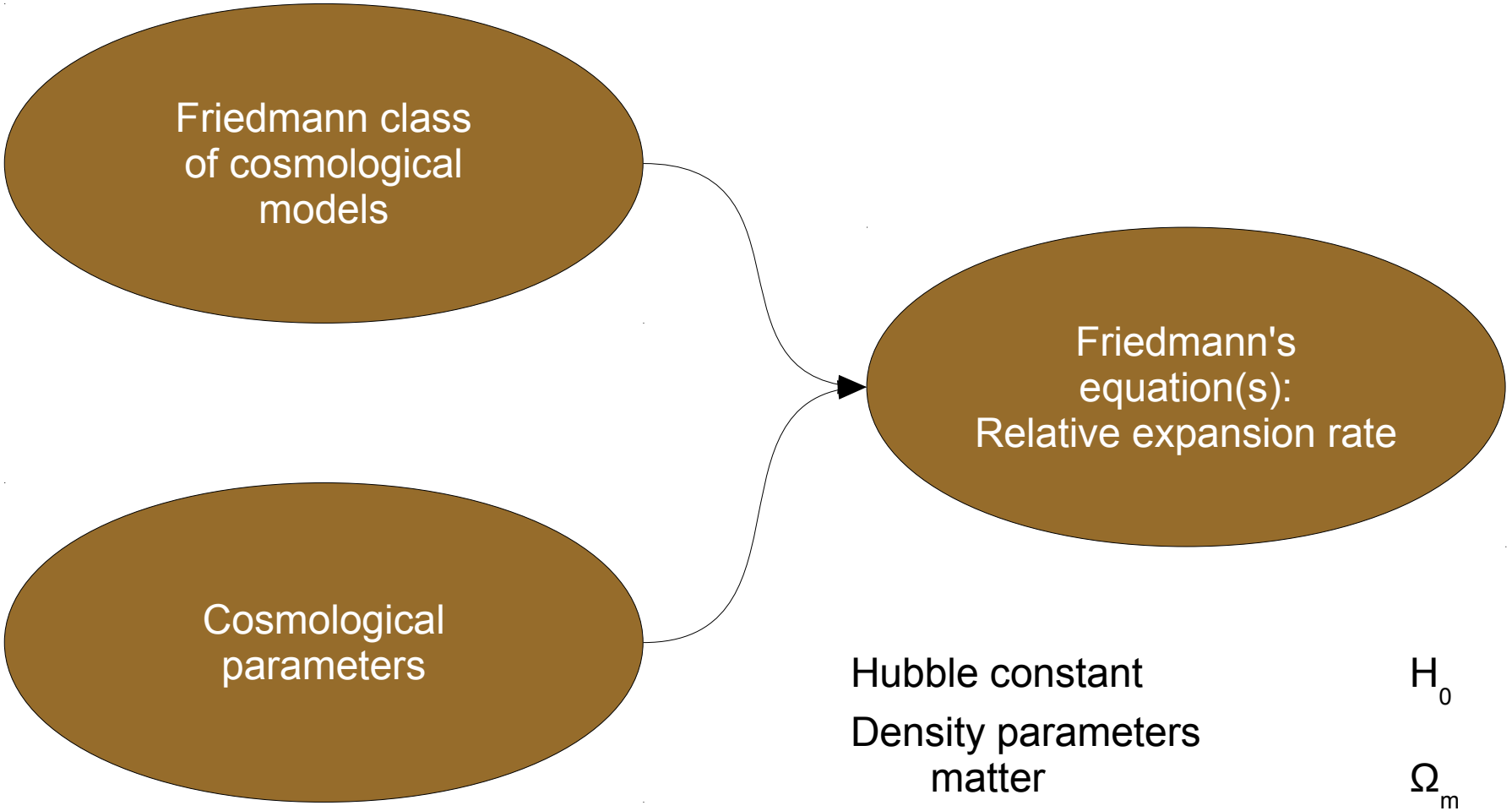
Friedmann class
of cosmological
models

Isotropy?



(2-micron All-Sky Survey, 2-MASS)

Dynamics, Parameters

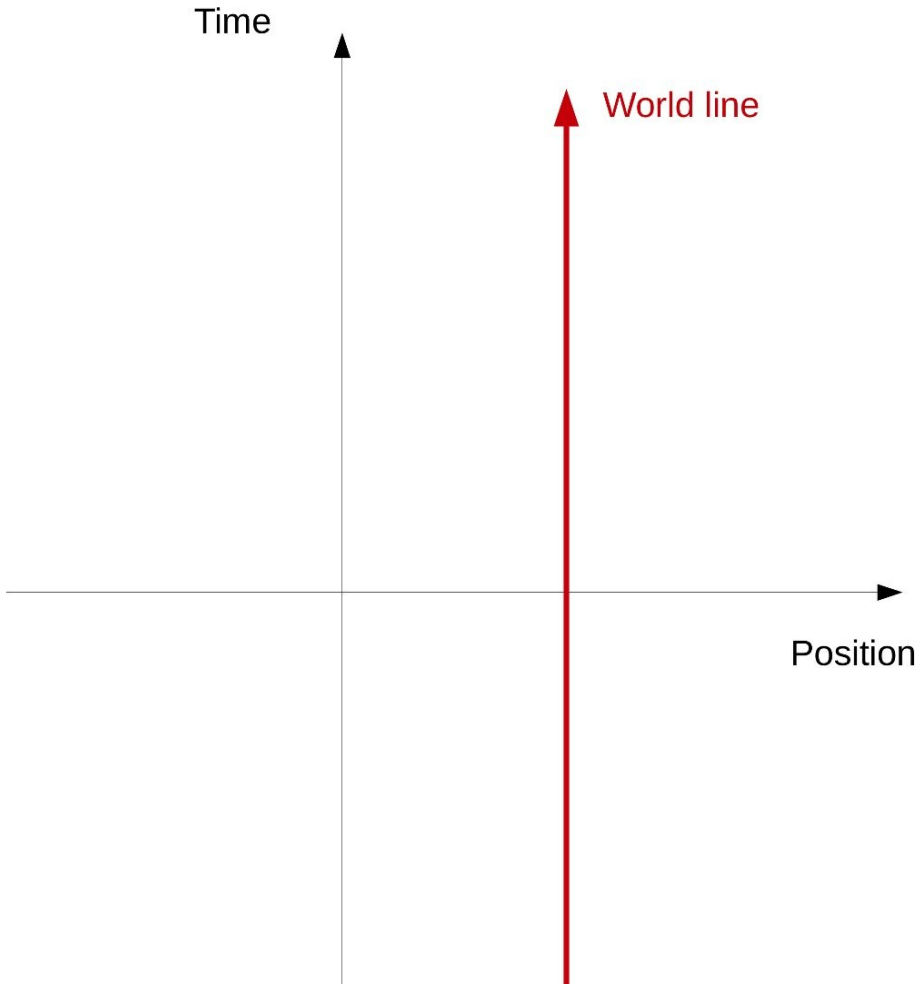


Hubble constant H_0

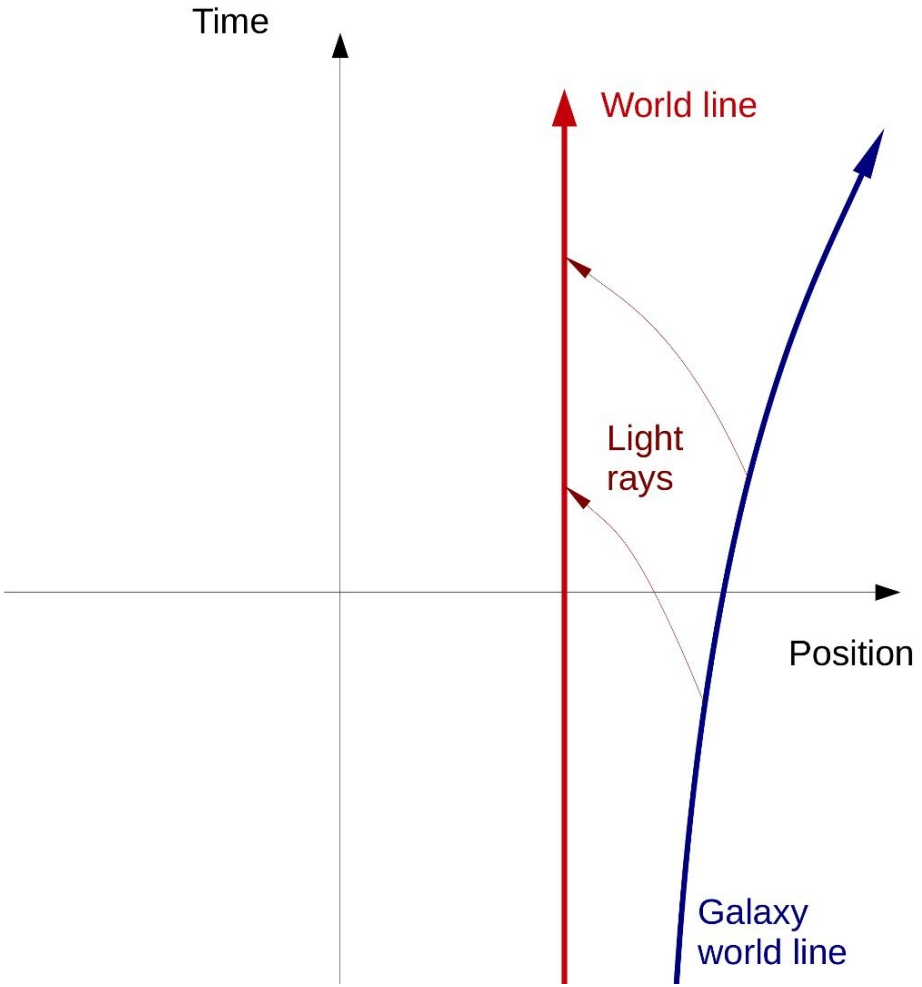
Density parameters

- matter Ω_m
- radiation Ω_r
- cosmological constant Ω_Λ
- several others

Space-Time Diagram, Redshift

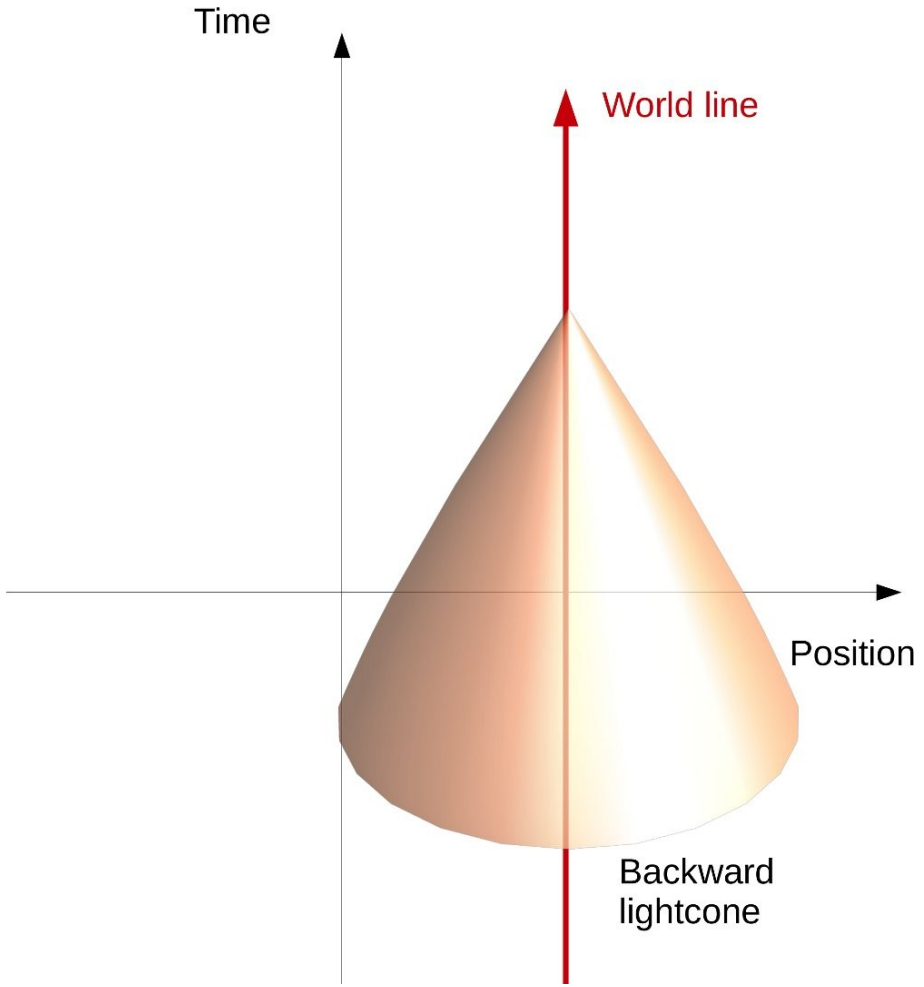


Minkowski diagram

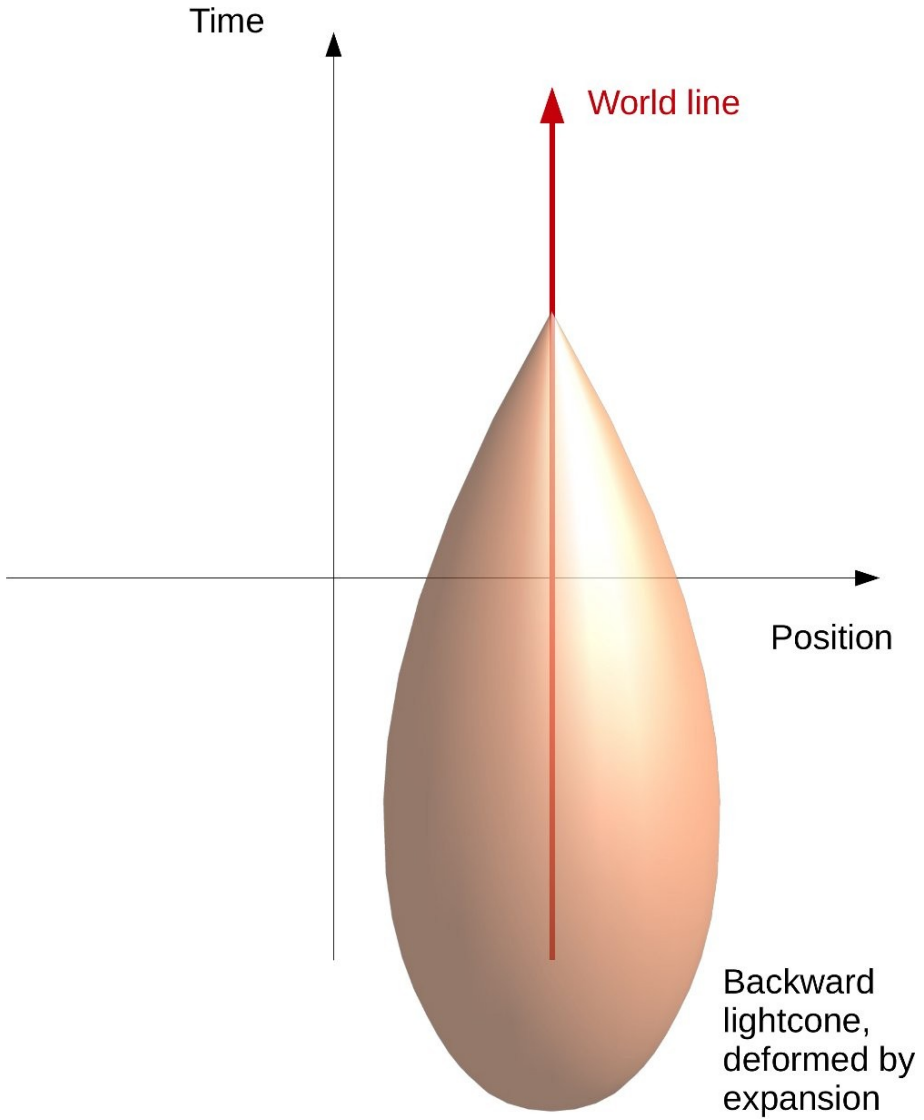


Redshift due to spatial expansion

The Observable Universe



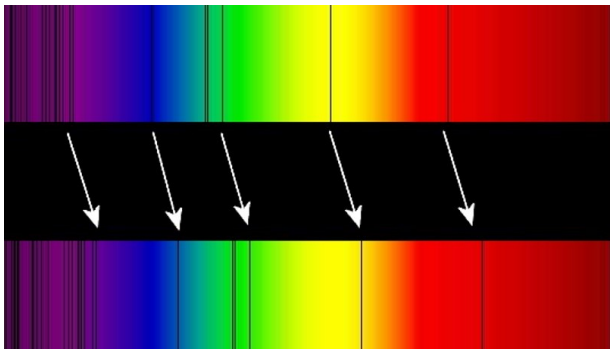
Causality and the observable Universe

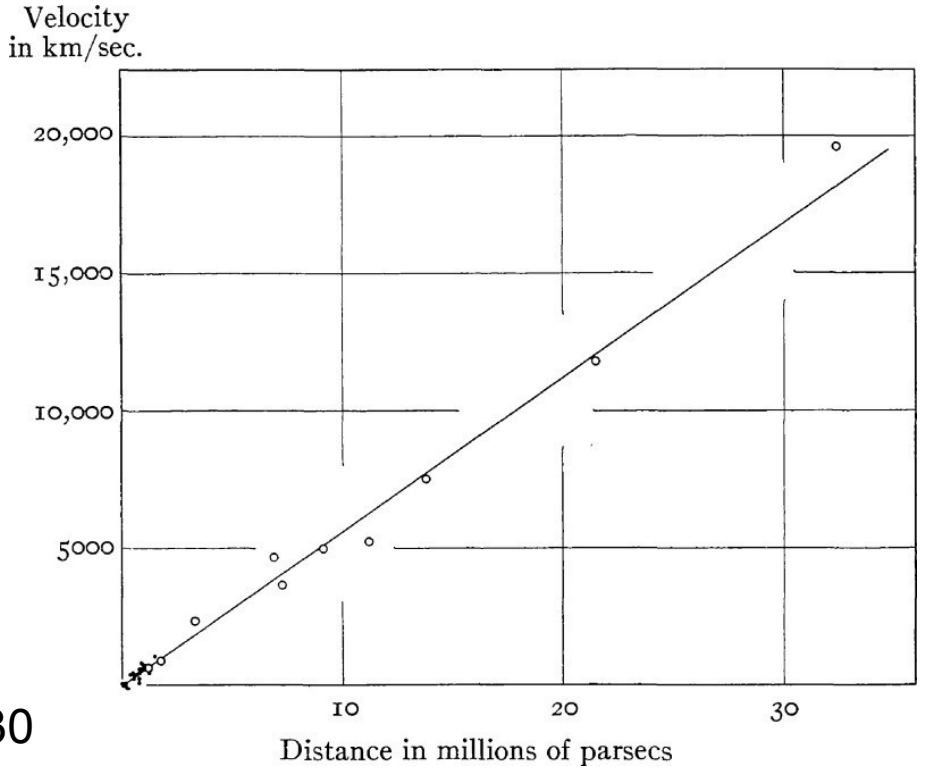


Galaxies recede

Carl Wirtz, Vesto Slipher, 1920s

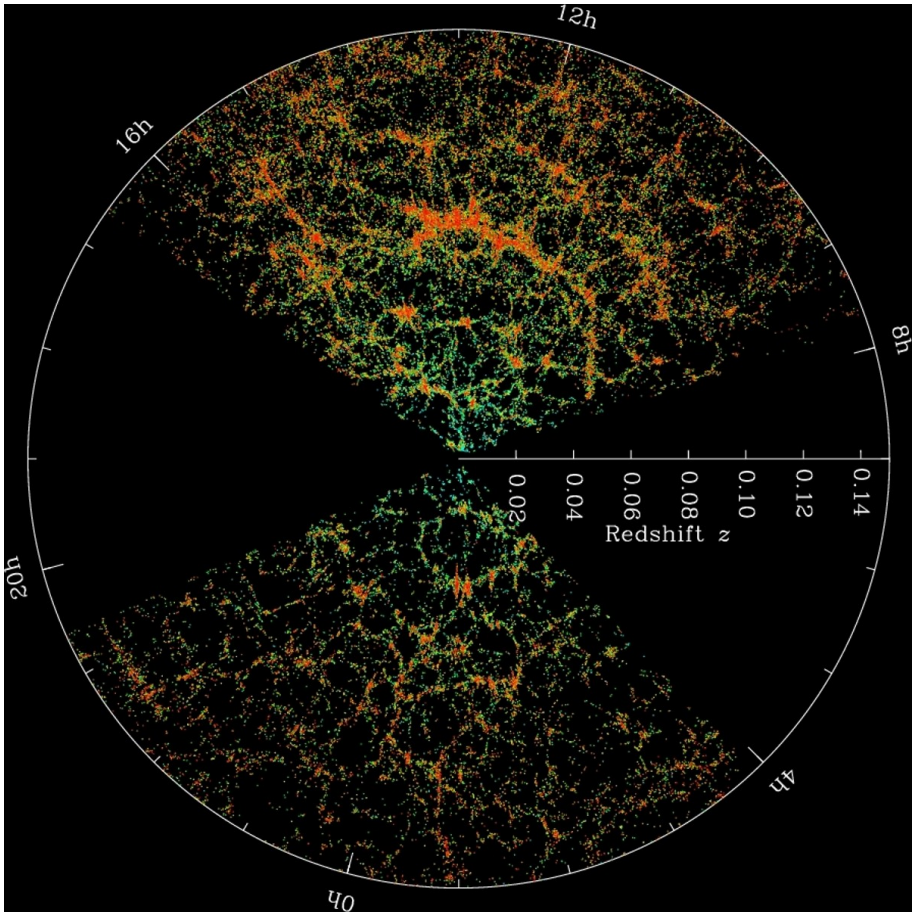
Edwin
Hubble

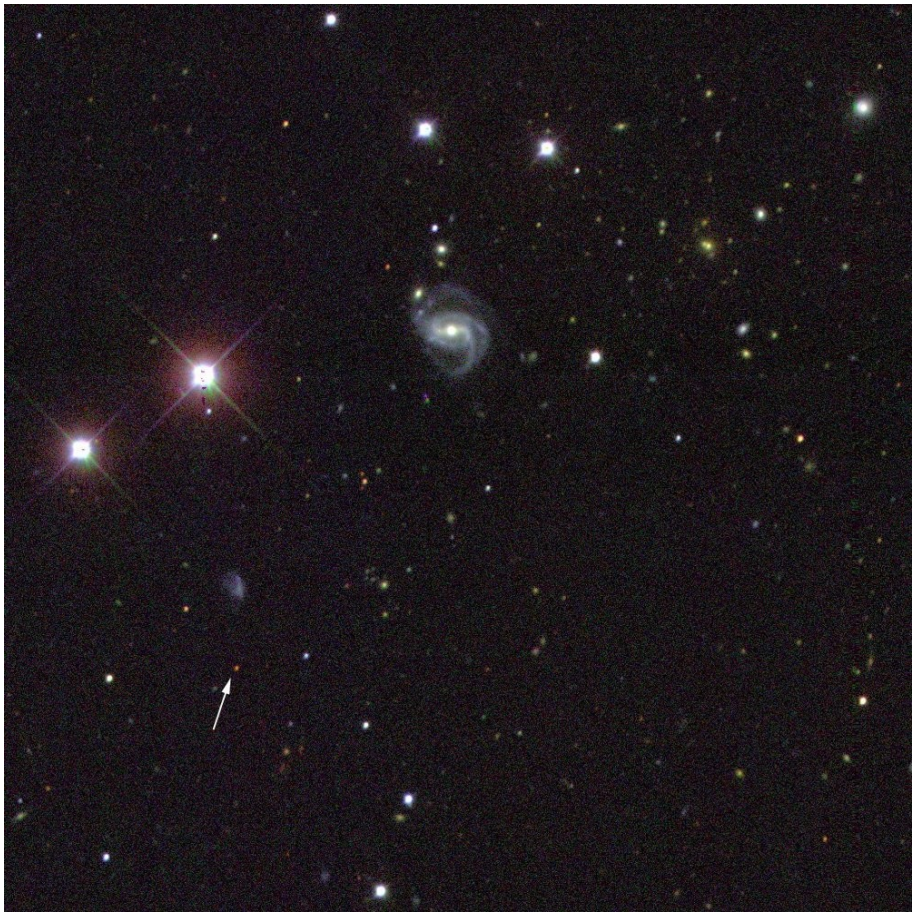




Hubble & Humason 1930

A Universe Without Big Bang?

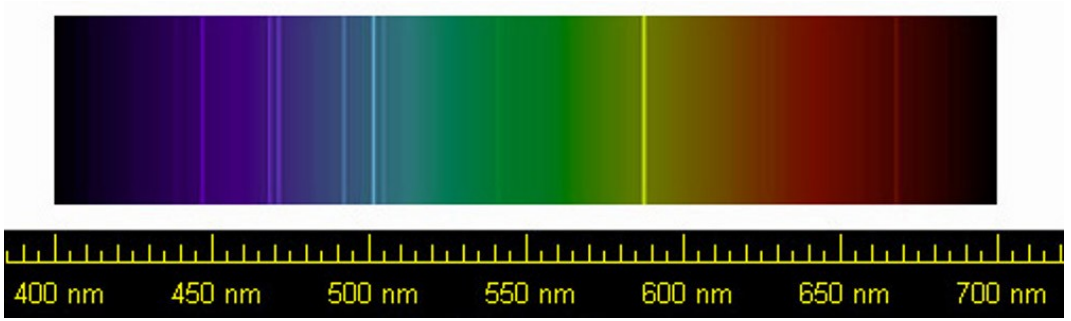


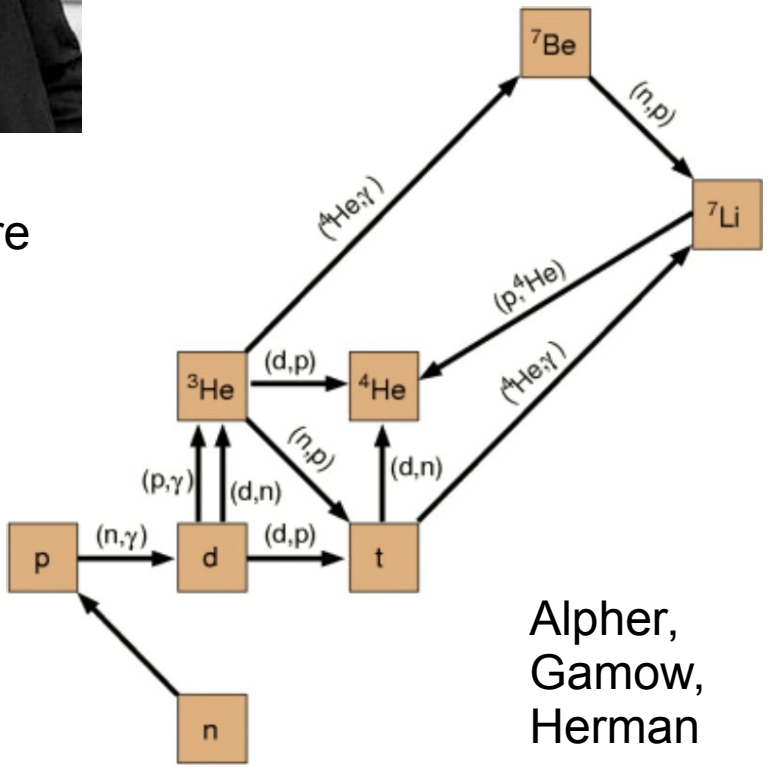


No: lower limits to matter density and cosmological redshift imply Big Bang!

Helium

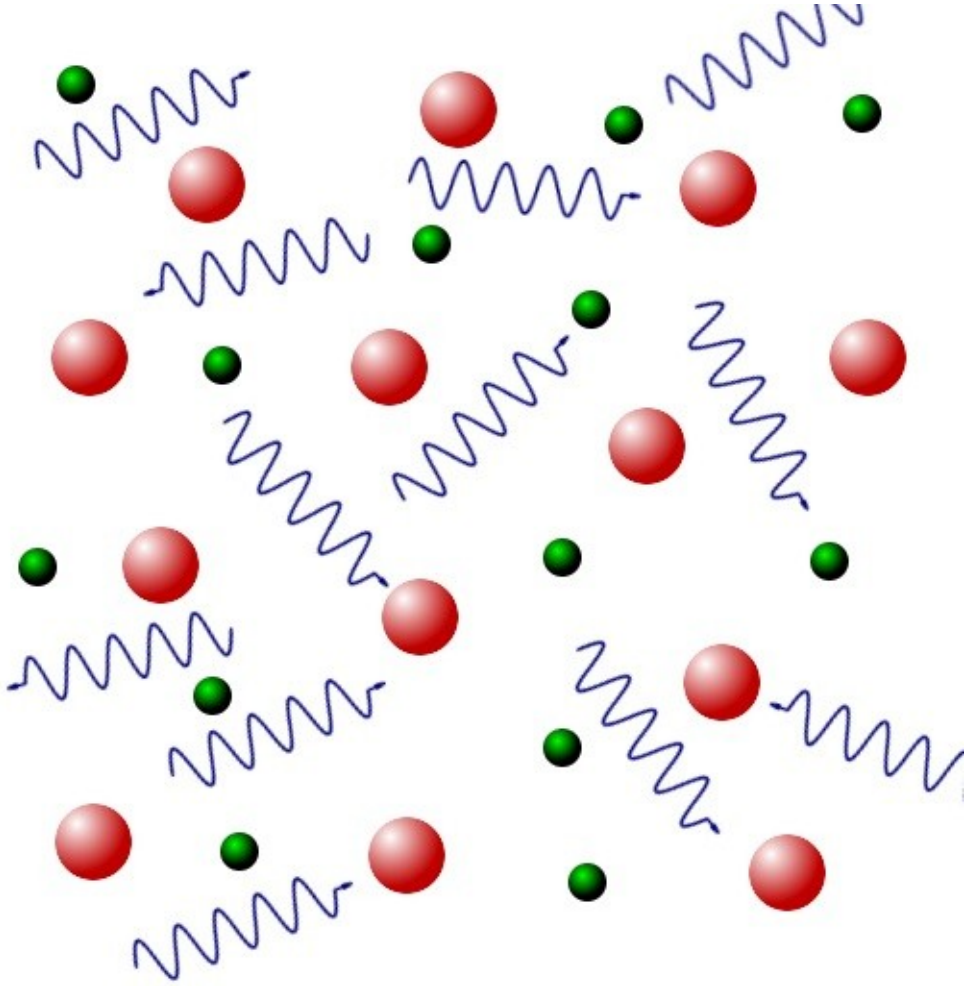
Georges Lemaitre



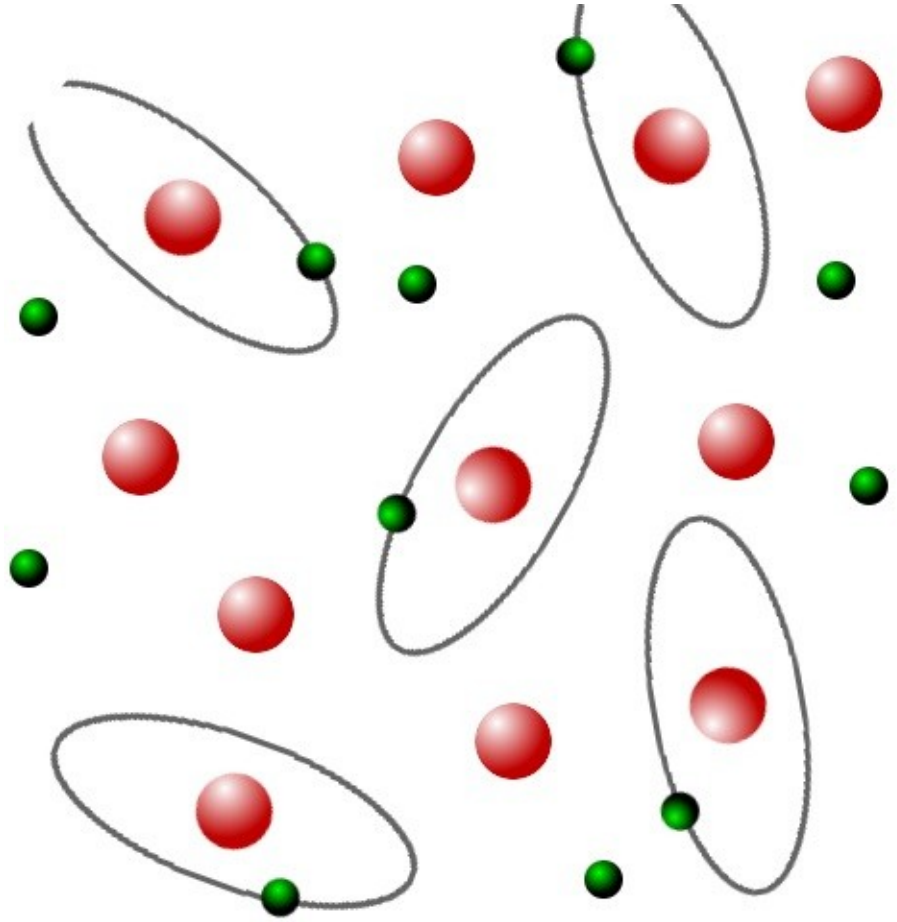


Alpher,
Gamow,
Herman

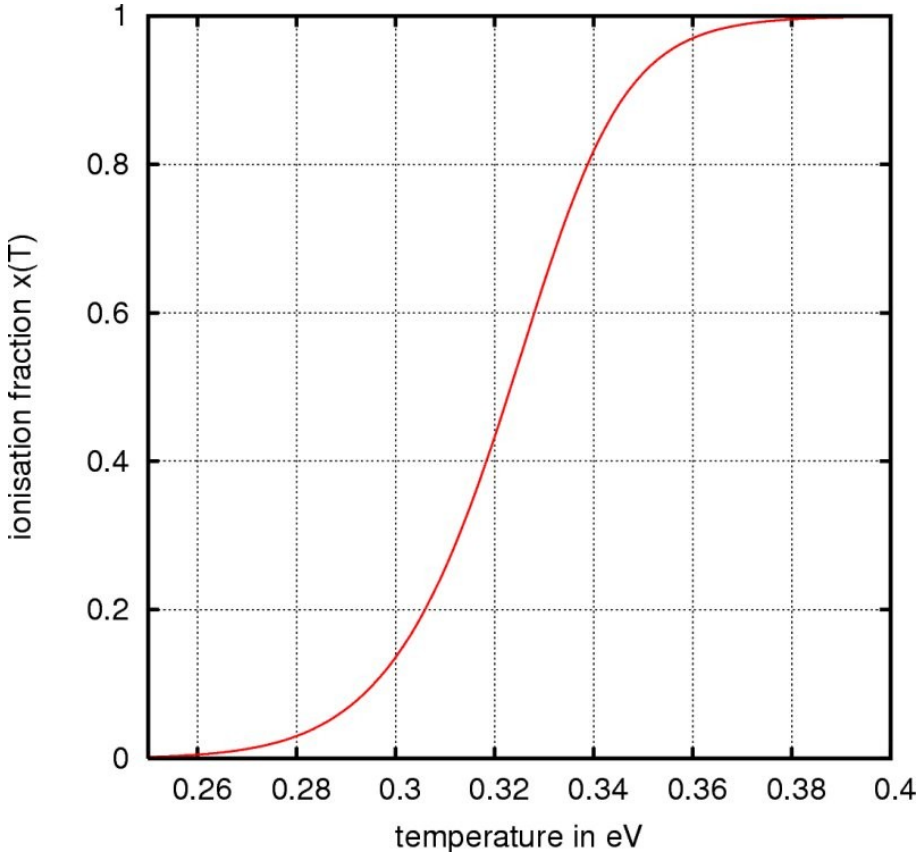
Cosmic Microwave Background



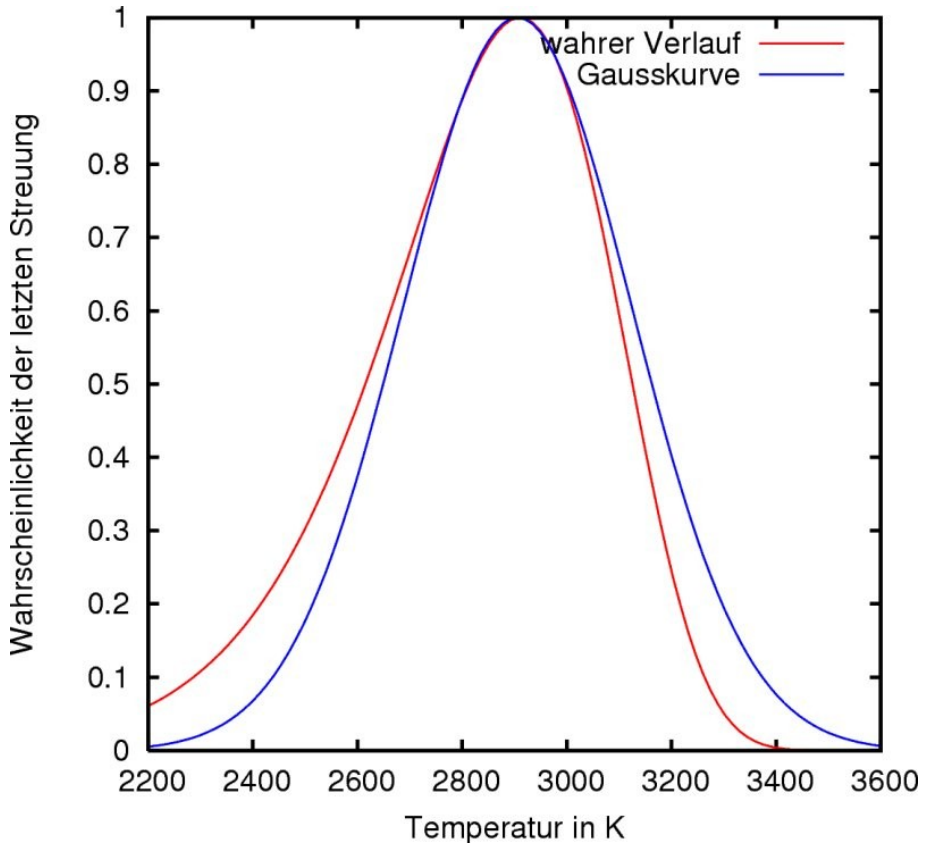
Cosmic Microwave Background decoupled when hydrogen recombined



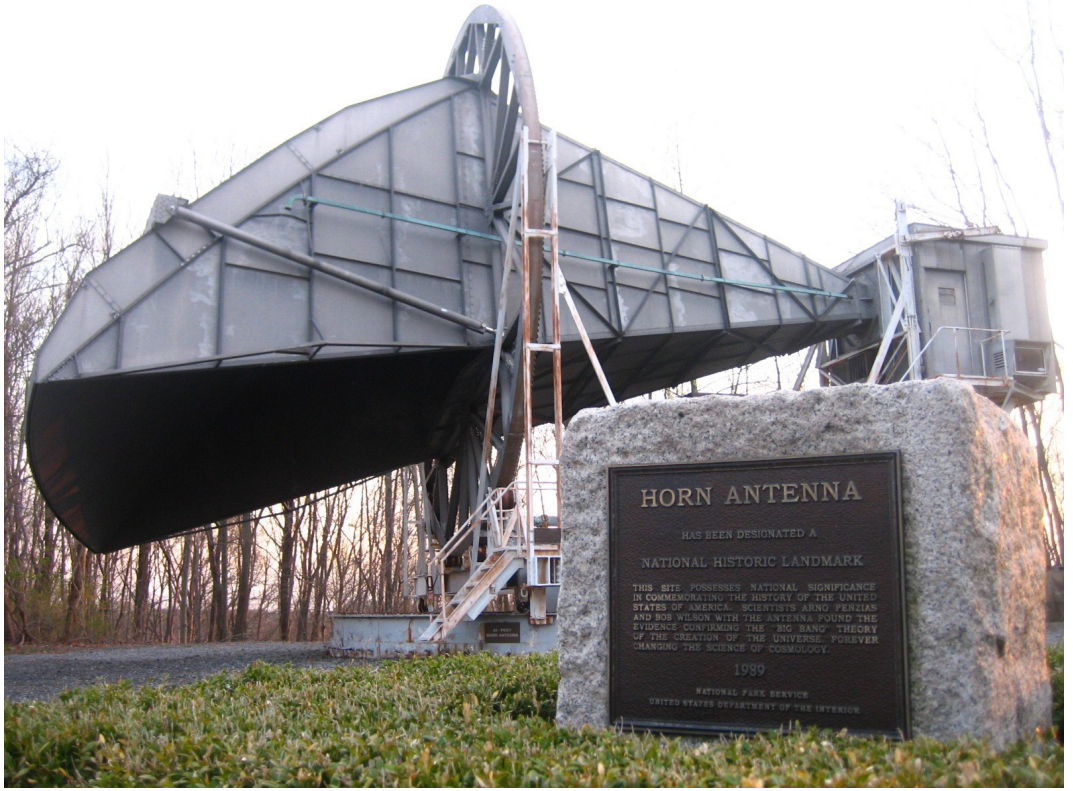
Energy Scale and Duration of Recombination



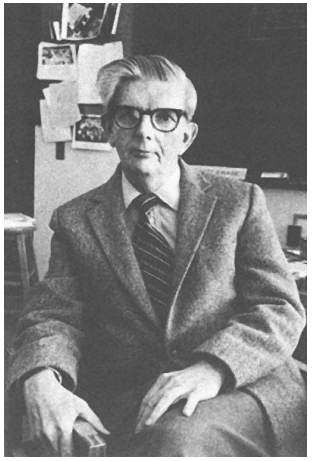
Recombination massively delayed to
0.32 eV instead of 13.6 eV
~ 400000 yr after Big Bang
~ 40000 yr duration



Discovery of the Cosmic Microwave Background

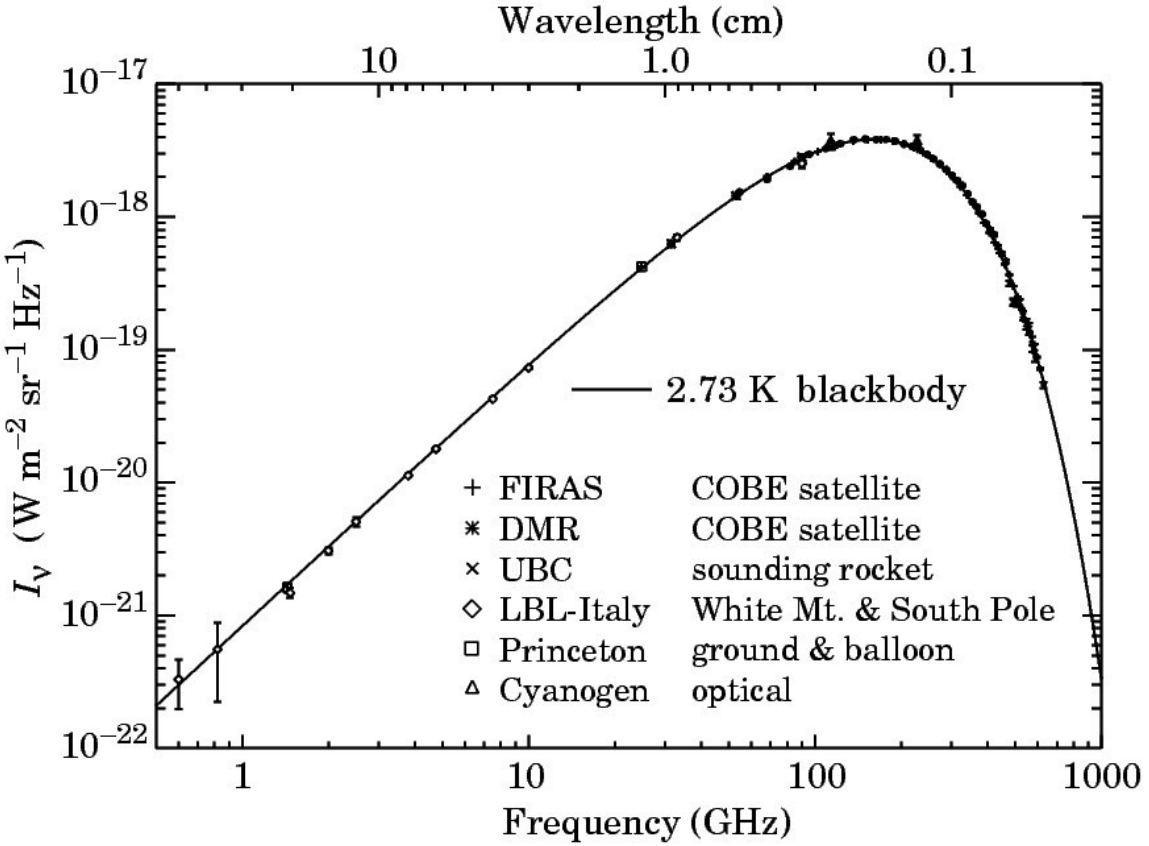


CMB had been predicted
Discovered by Penzias & Wilson 1965



Robert Dicke

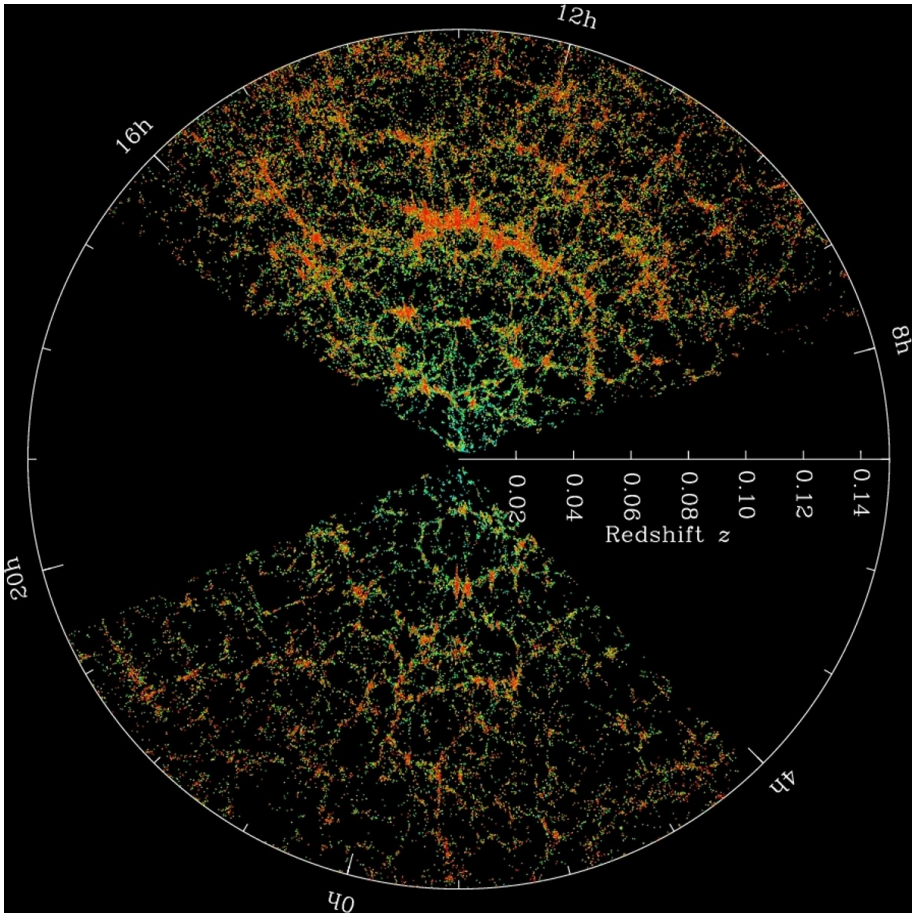
Thermal Radiation?



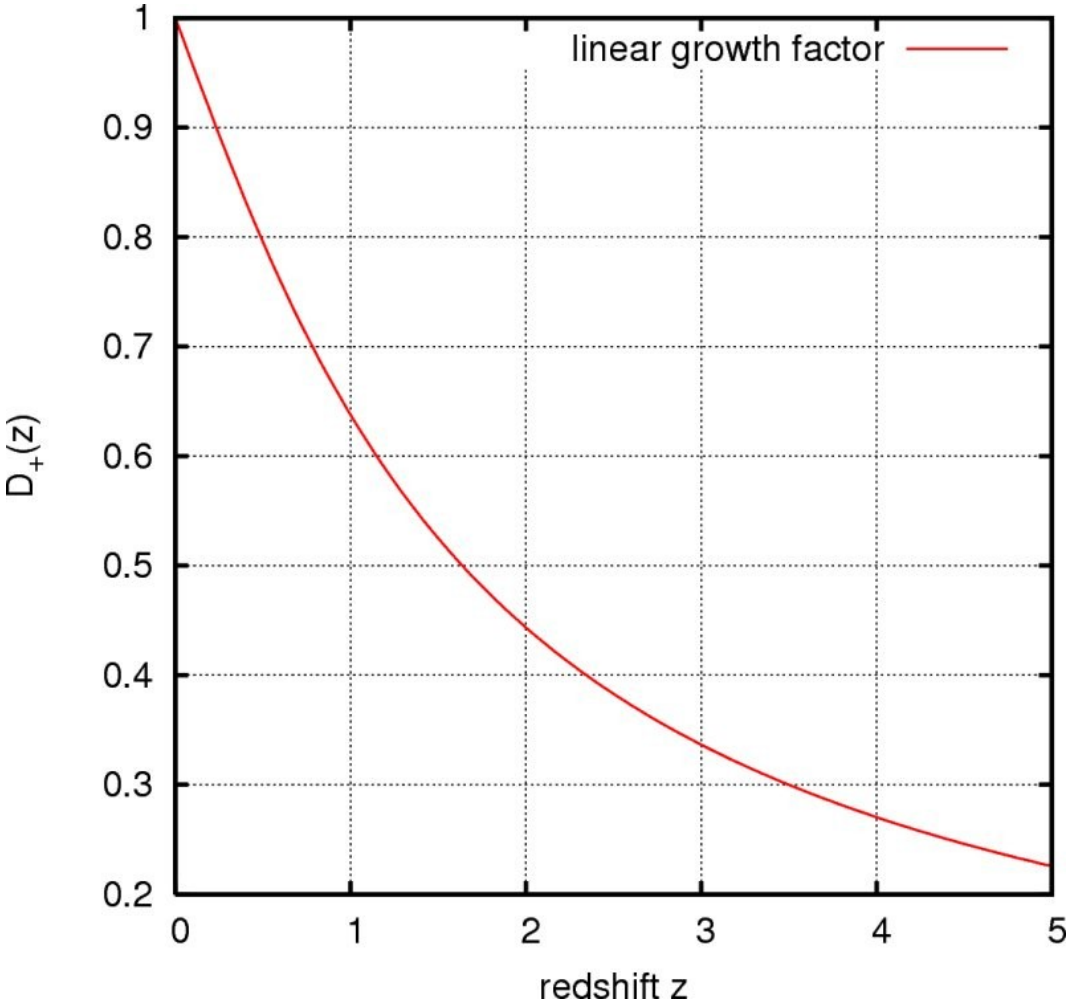
Best measured black-body
Spectrum, COBE 1992

John Mather

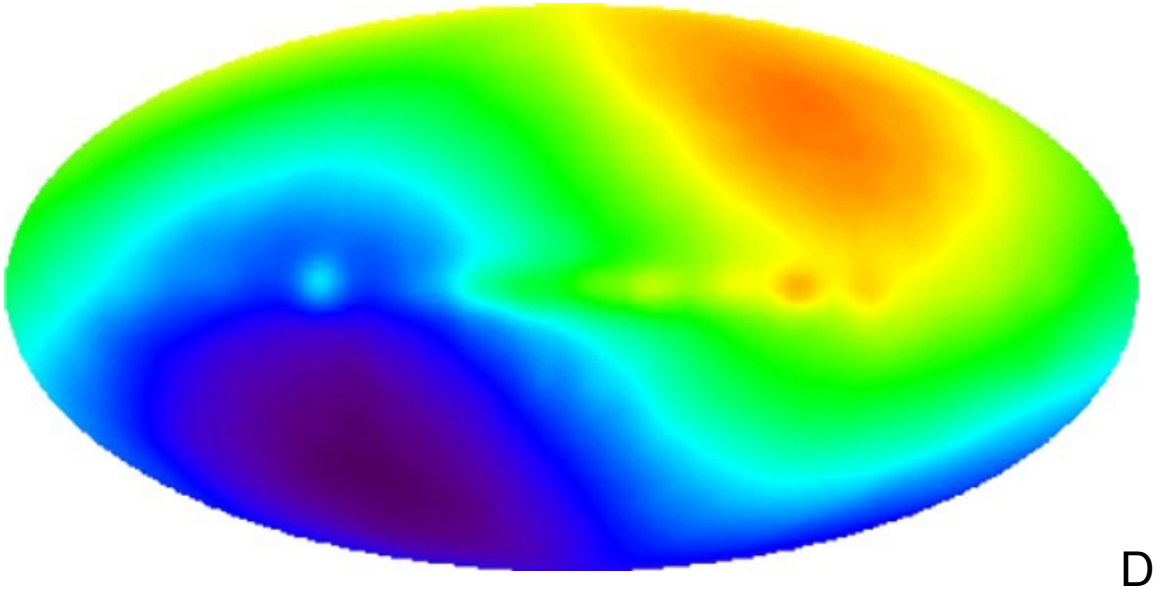
Structures in the CMB?



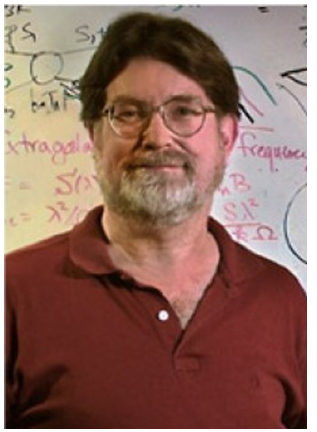
Temperature fluctuations
at mK level expected



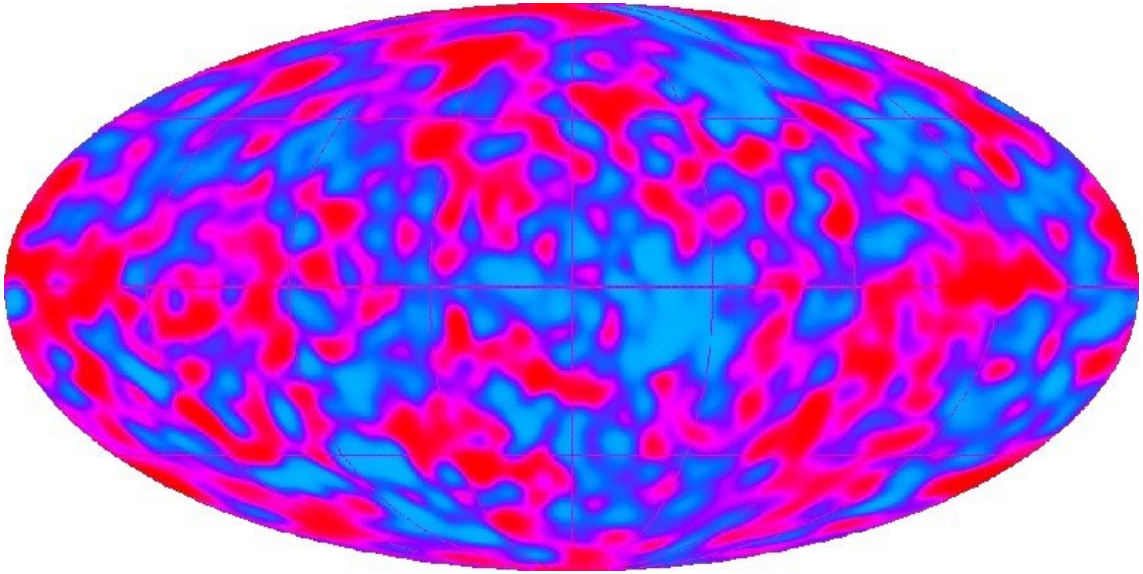
Temperature Fluctuations



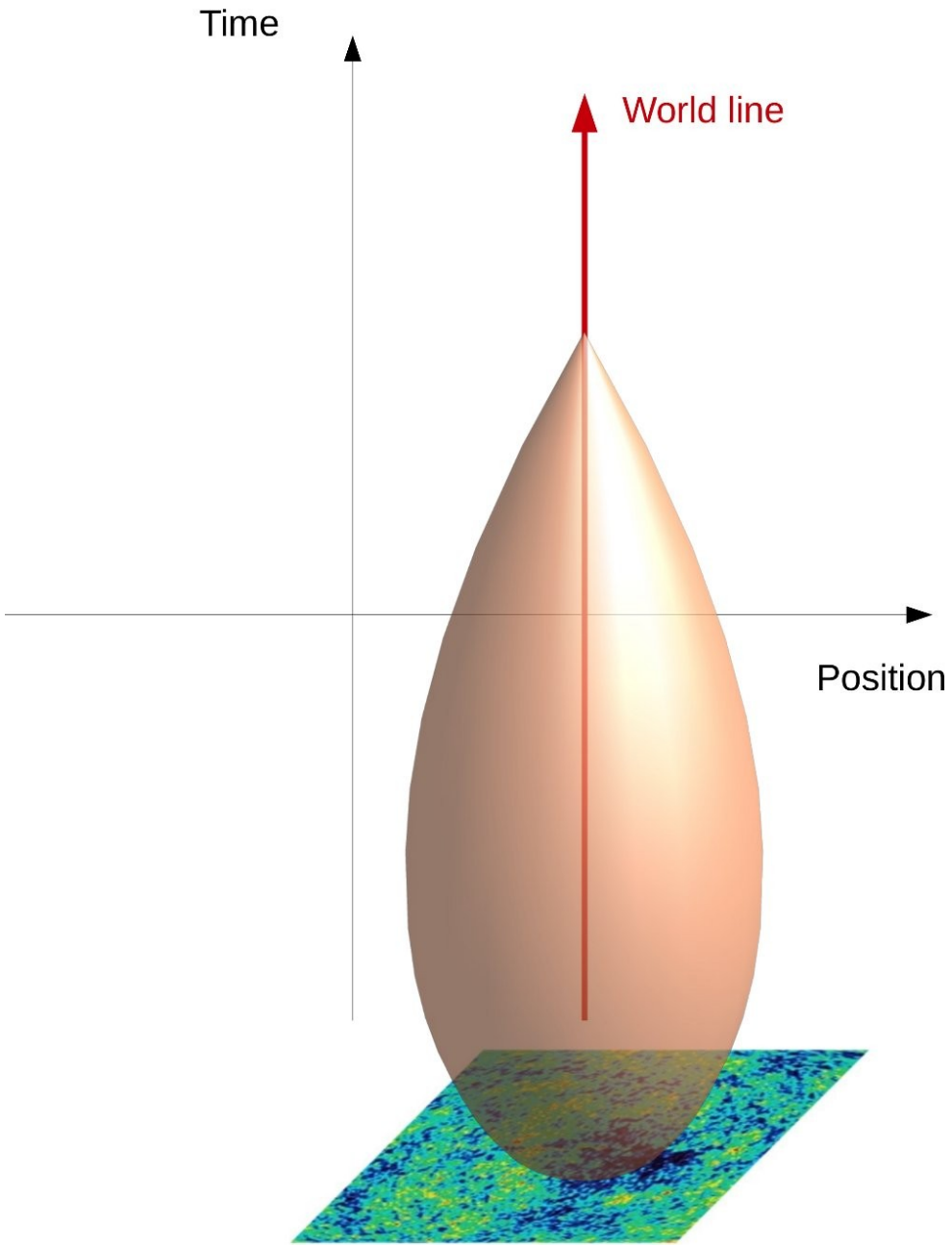
George Smoot



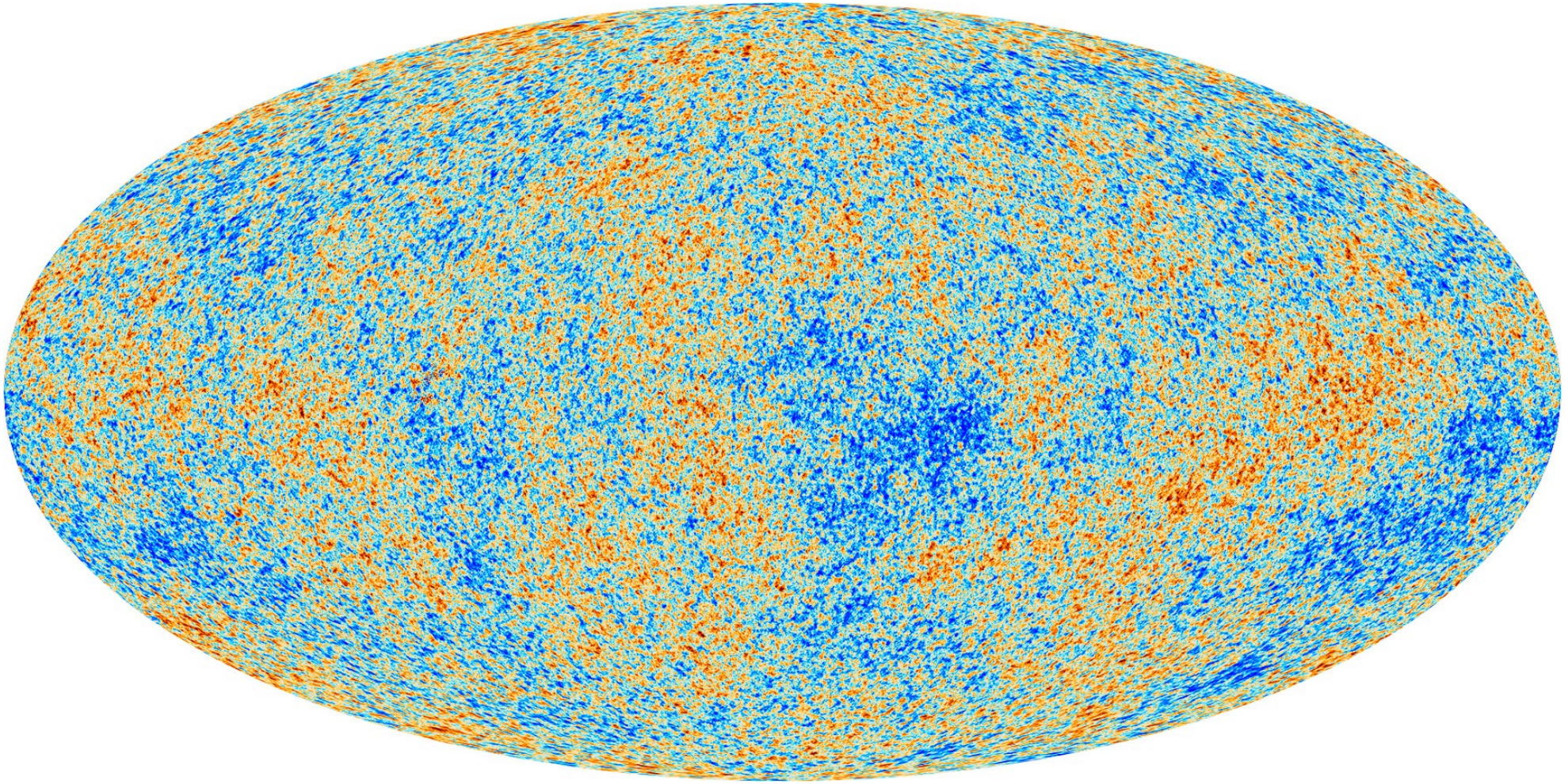
Discovered by COBE at μK level



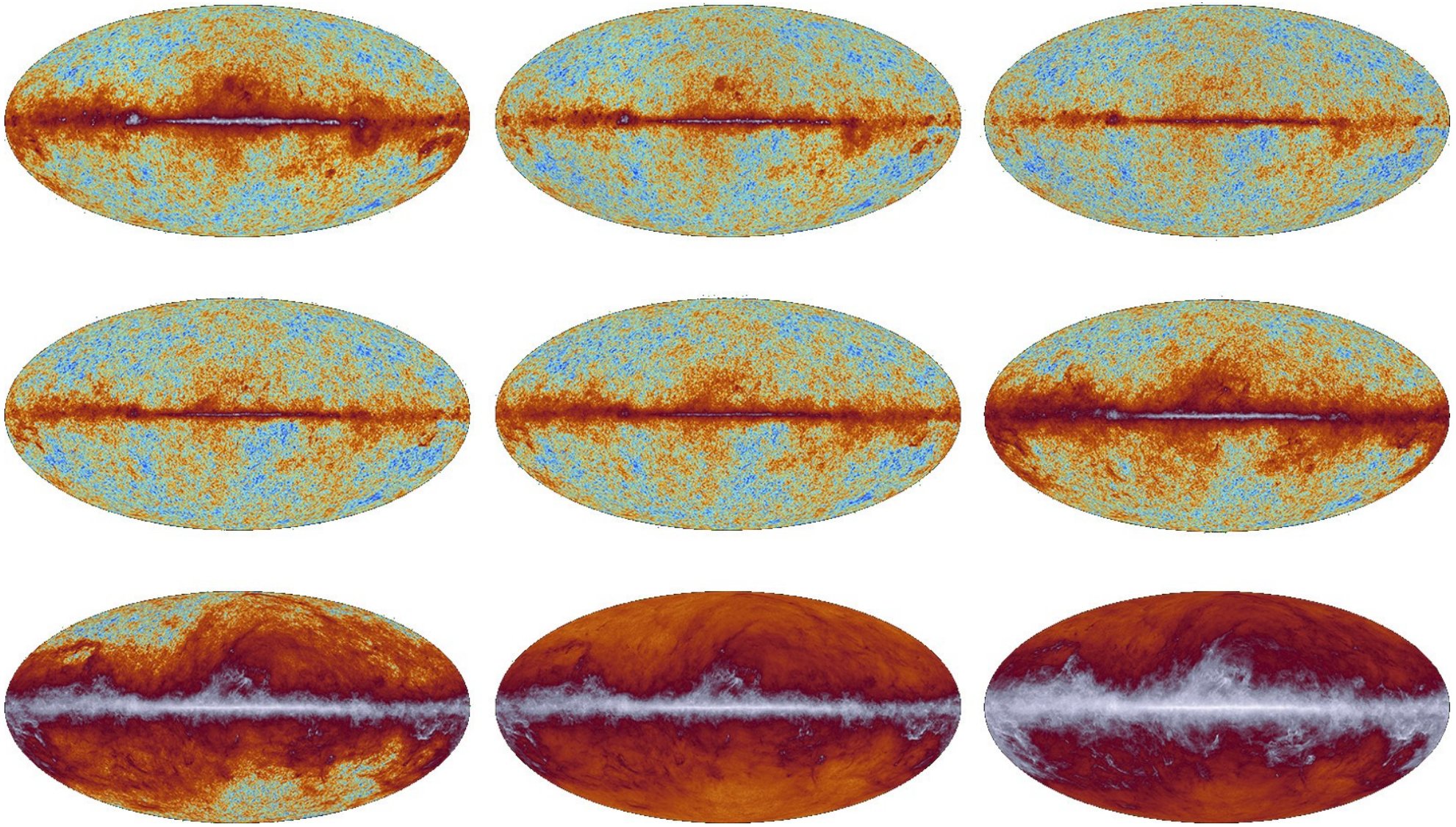
The CMB in the Backward Light Cone



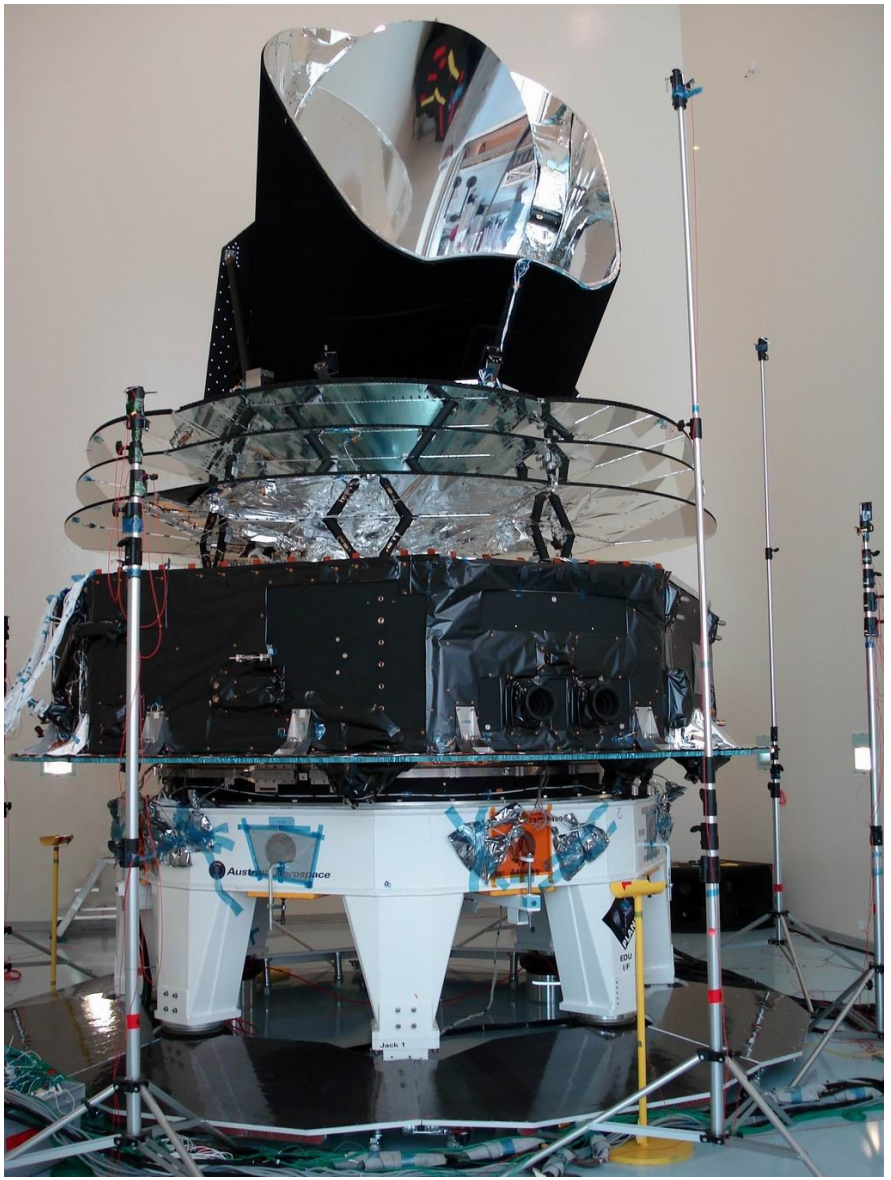
Structures in the microwave sky

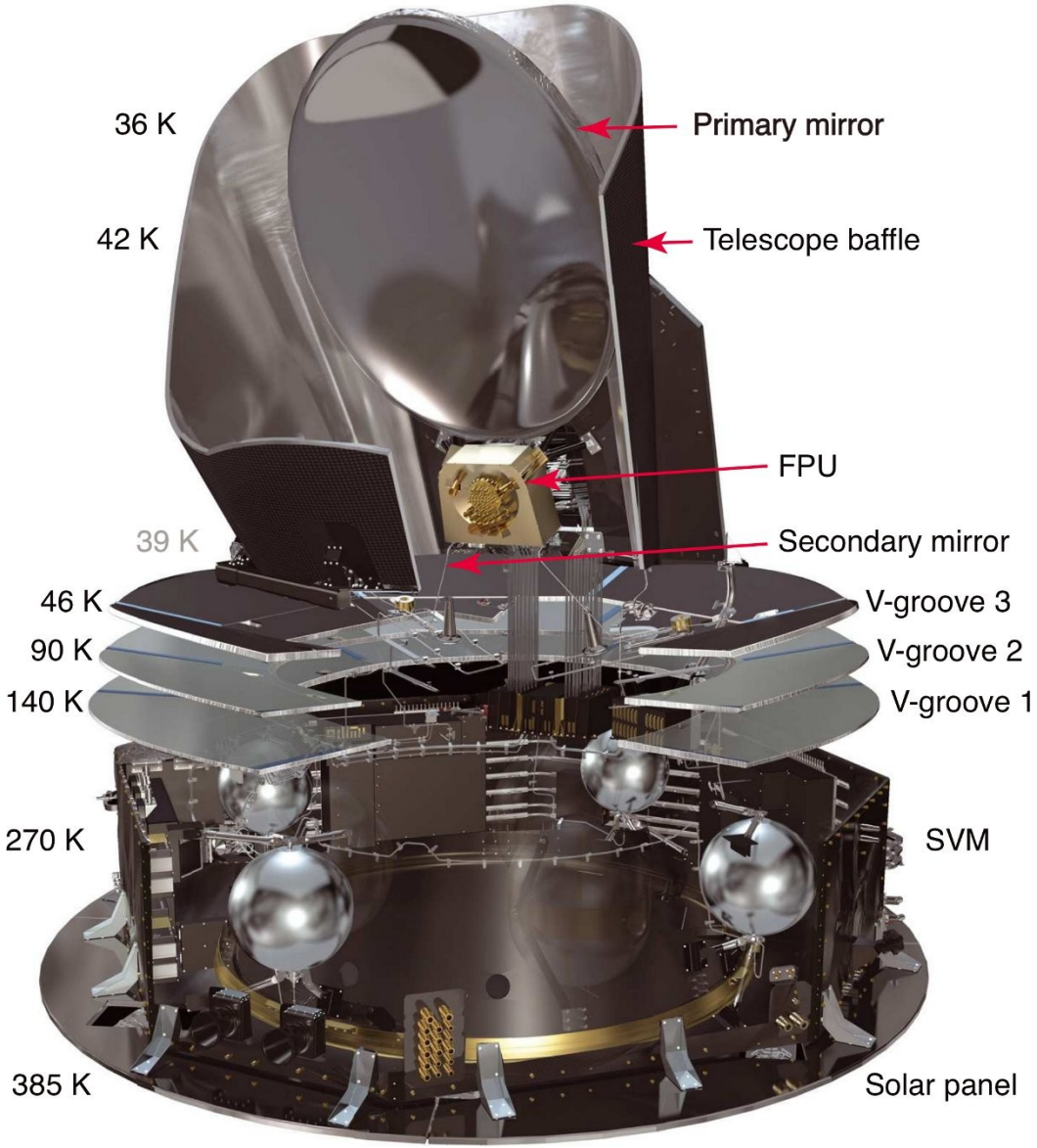


Microwave foregrounds

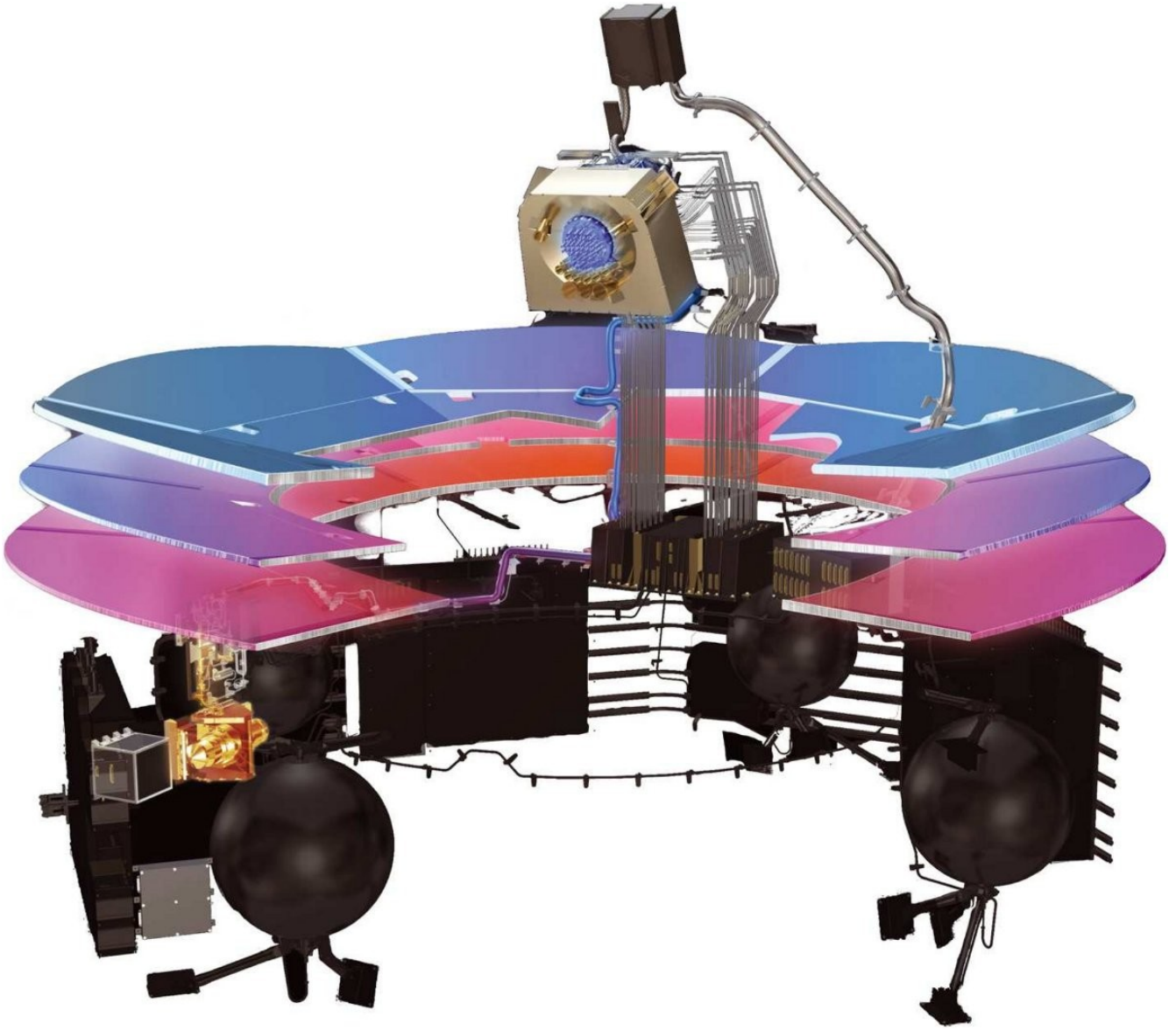


The Planck satellite





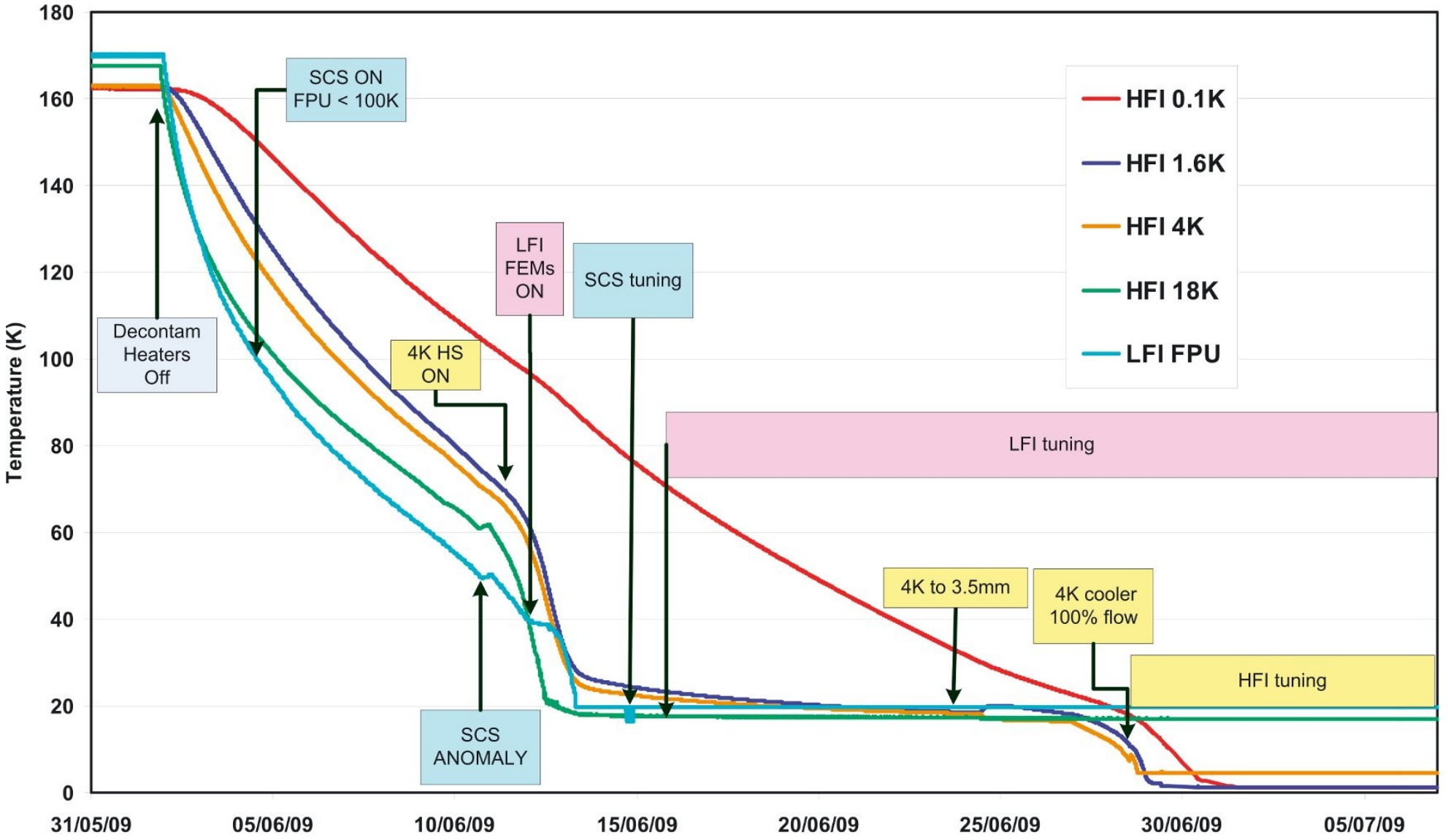
The Planck satellite



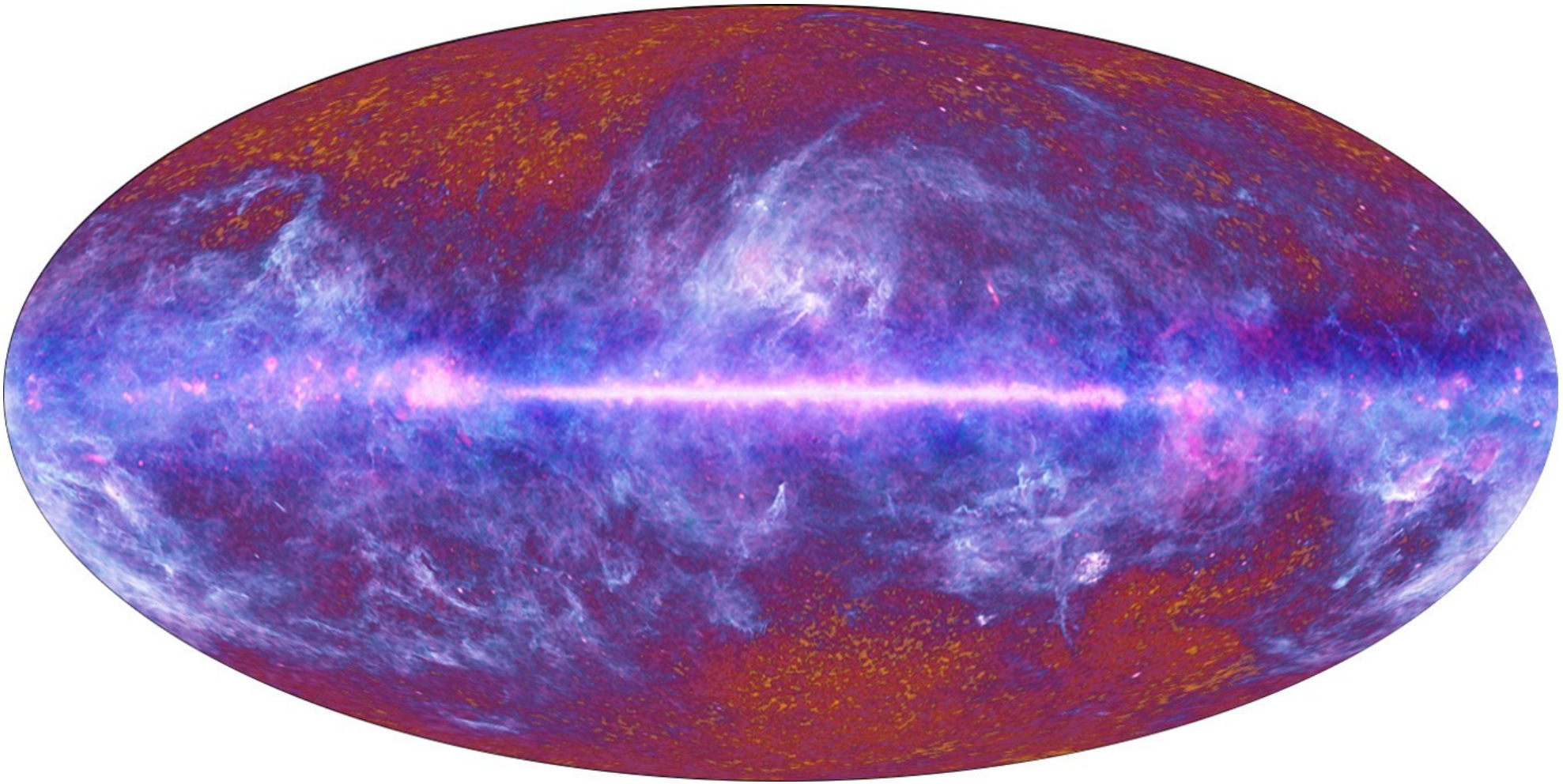
May 14, 2009, 3:12 CEST

Where is Planck, and why?

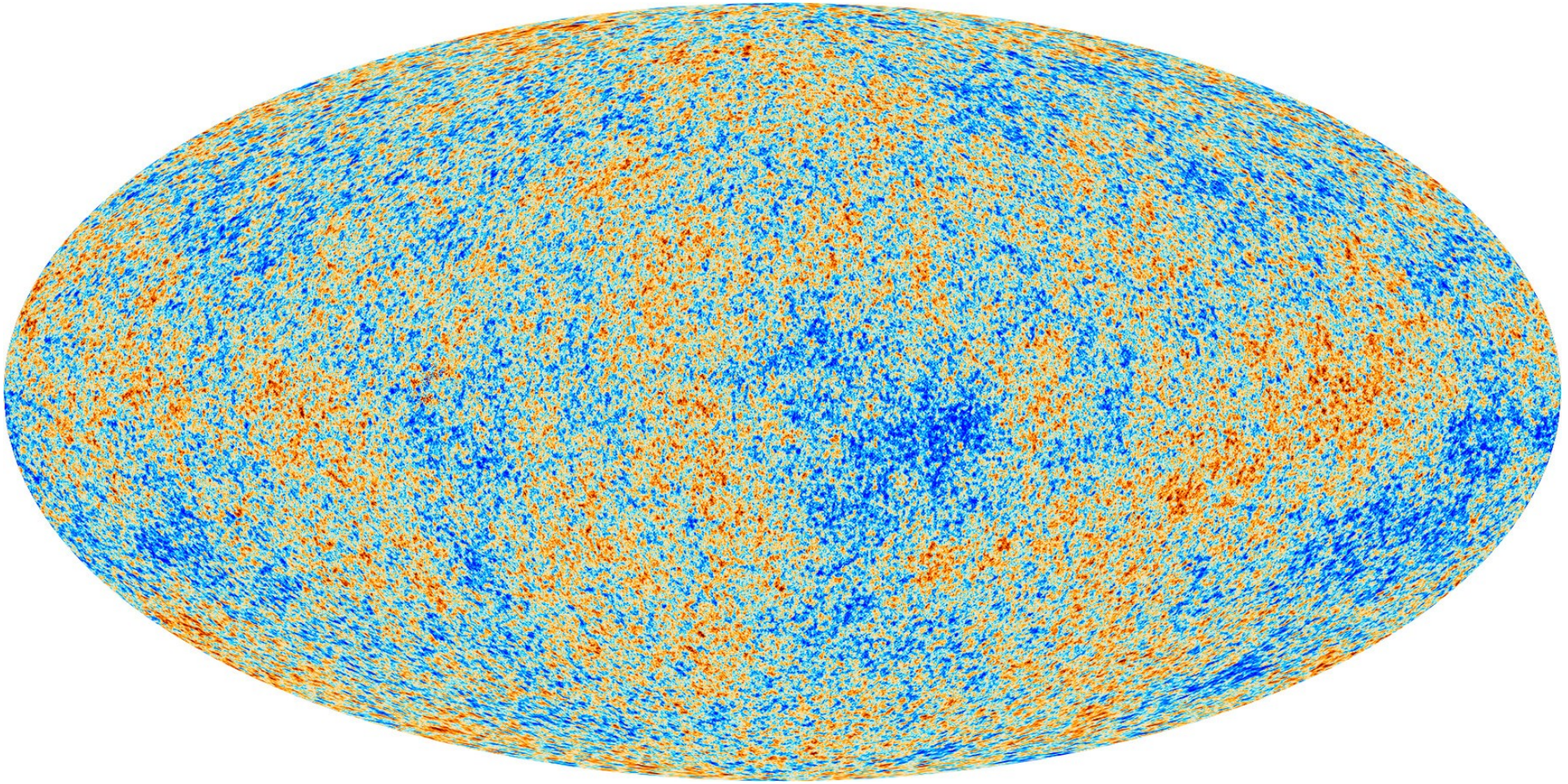
Where is Planck, and why?



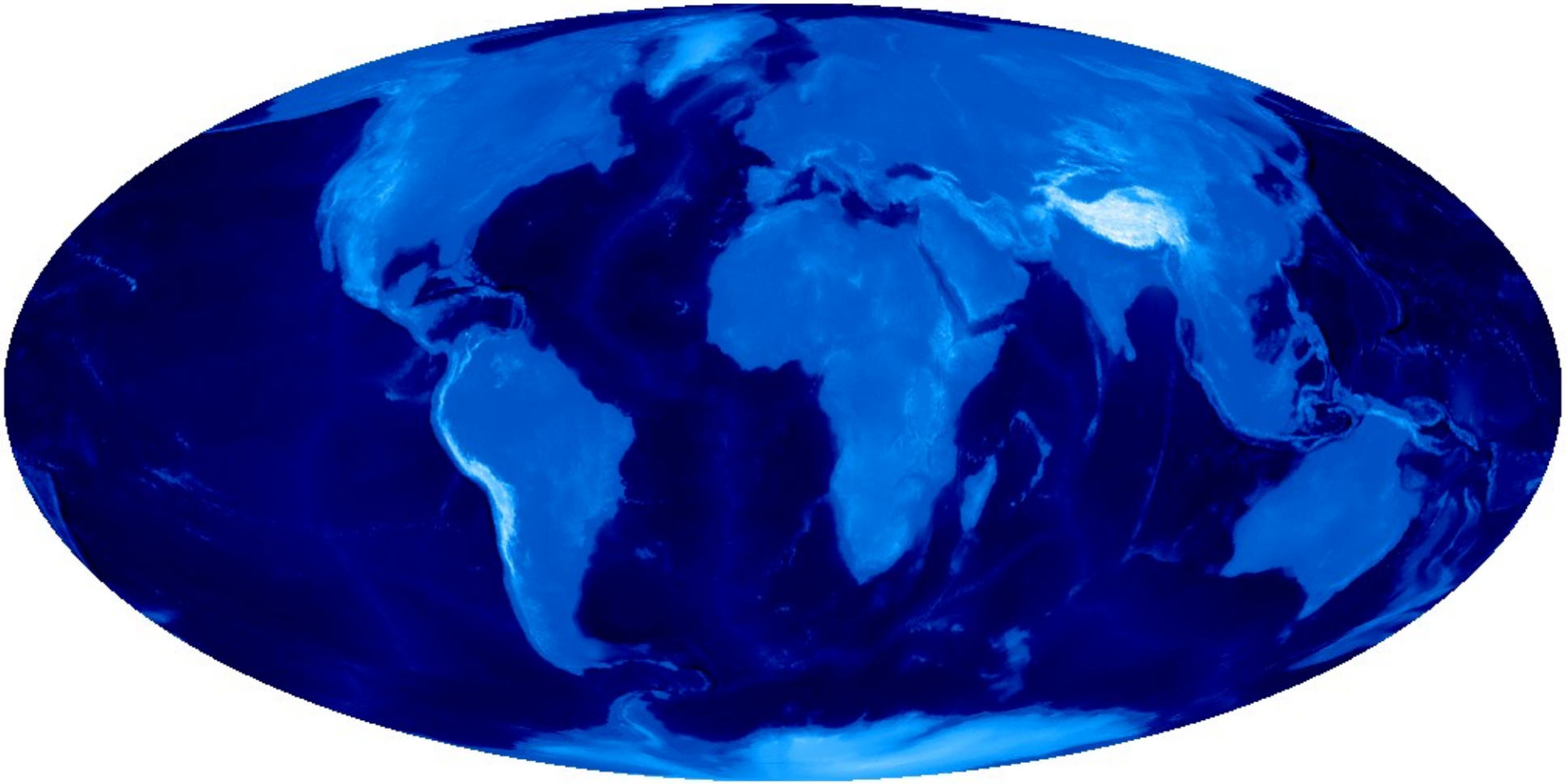
Planck's view of the Sky



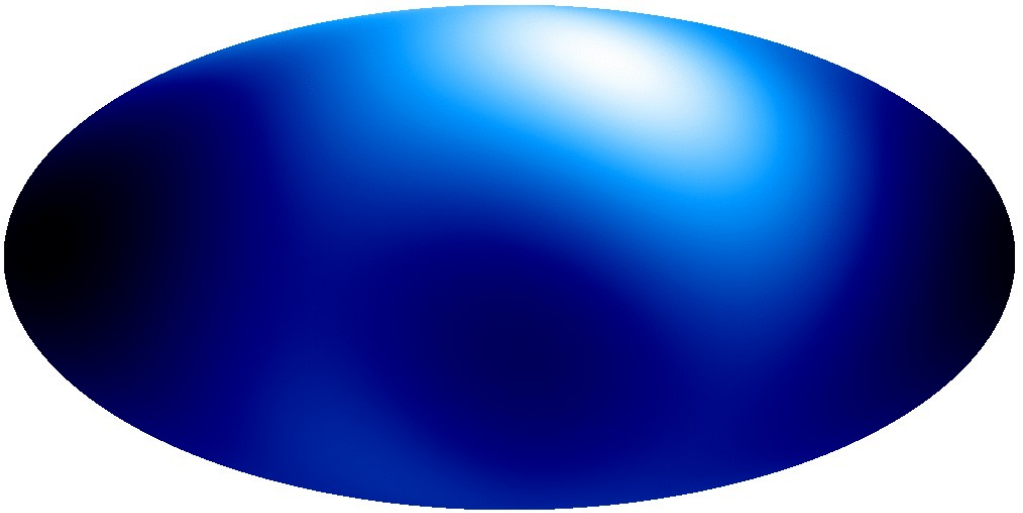
Planck's view of the Sky

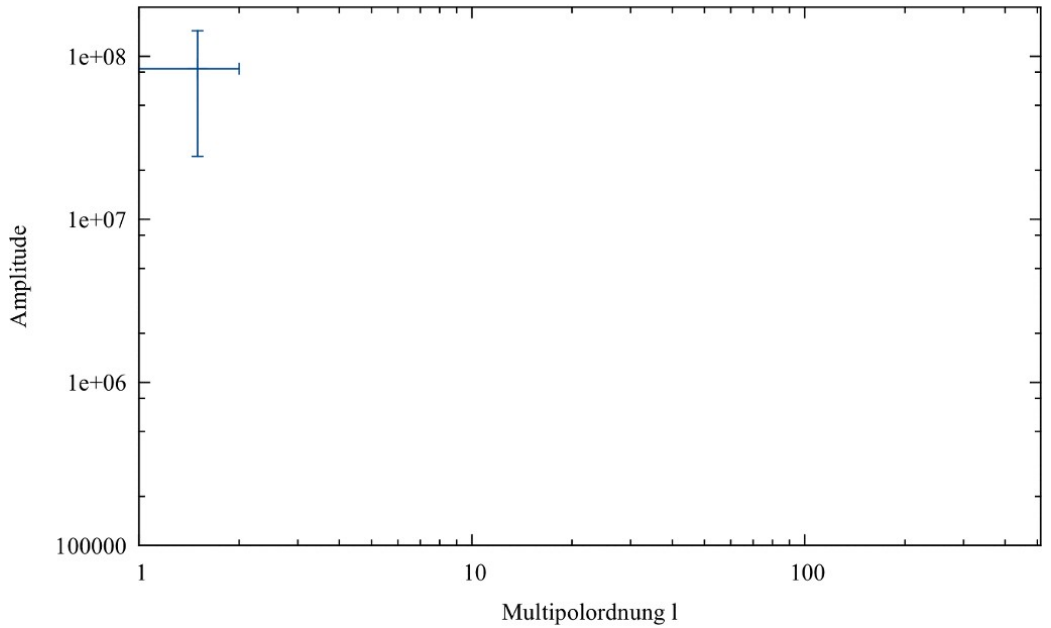


Analysis of sky maps

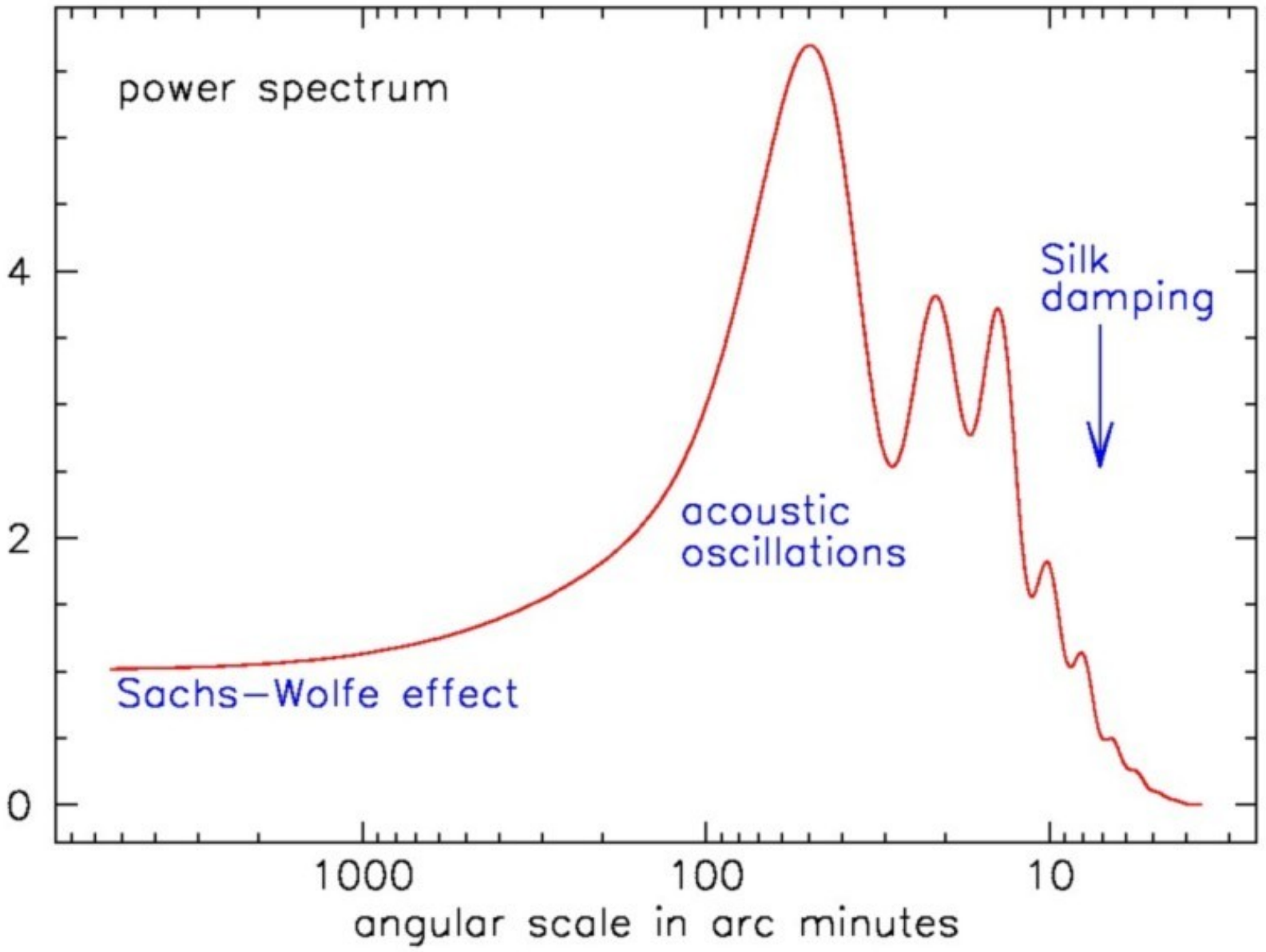


Analysis of sky maps

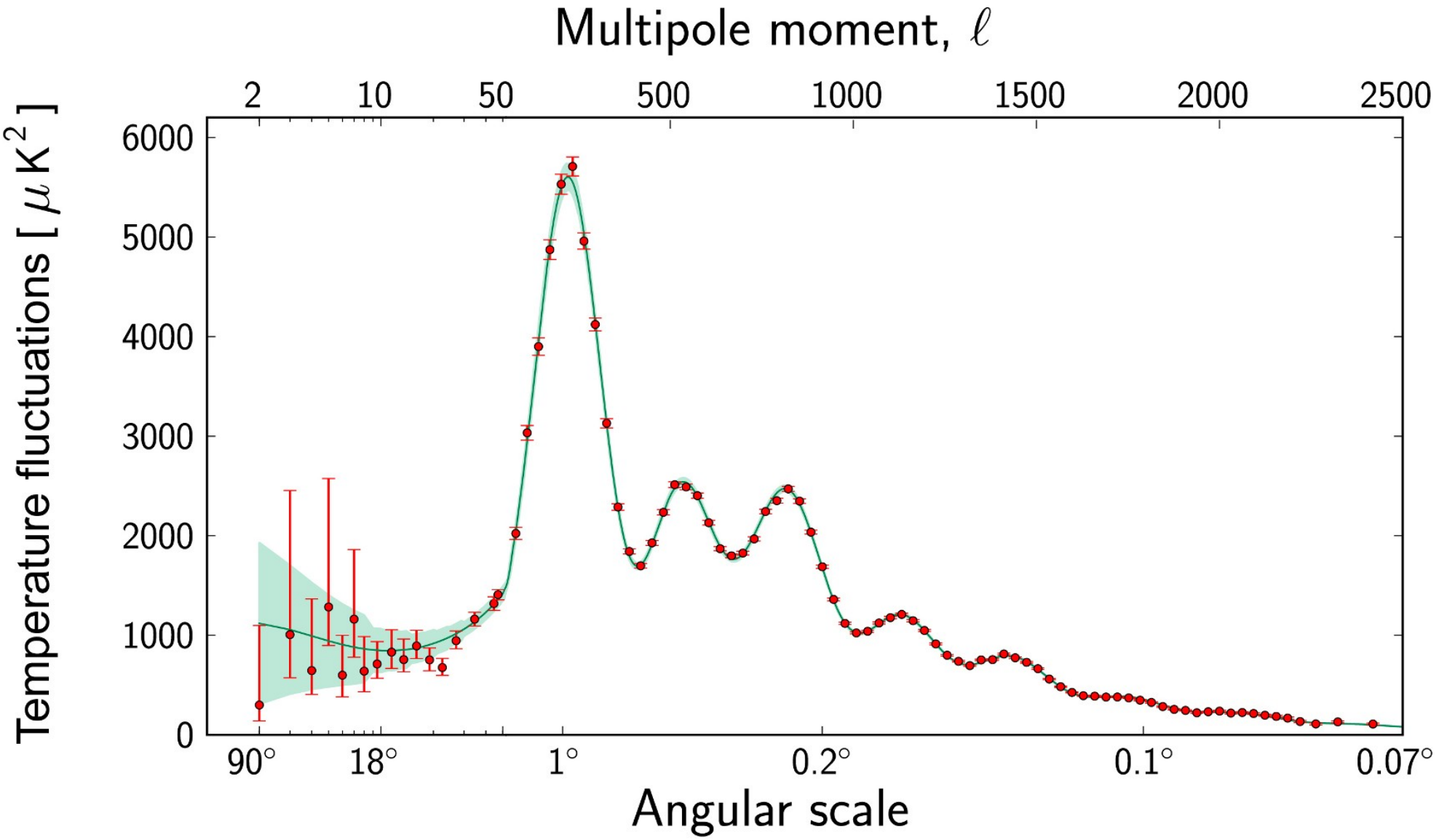




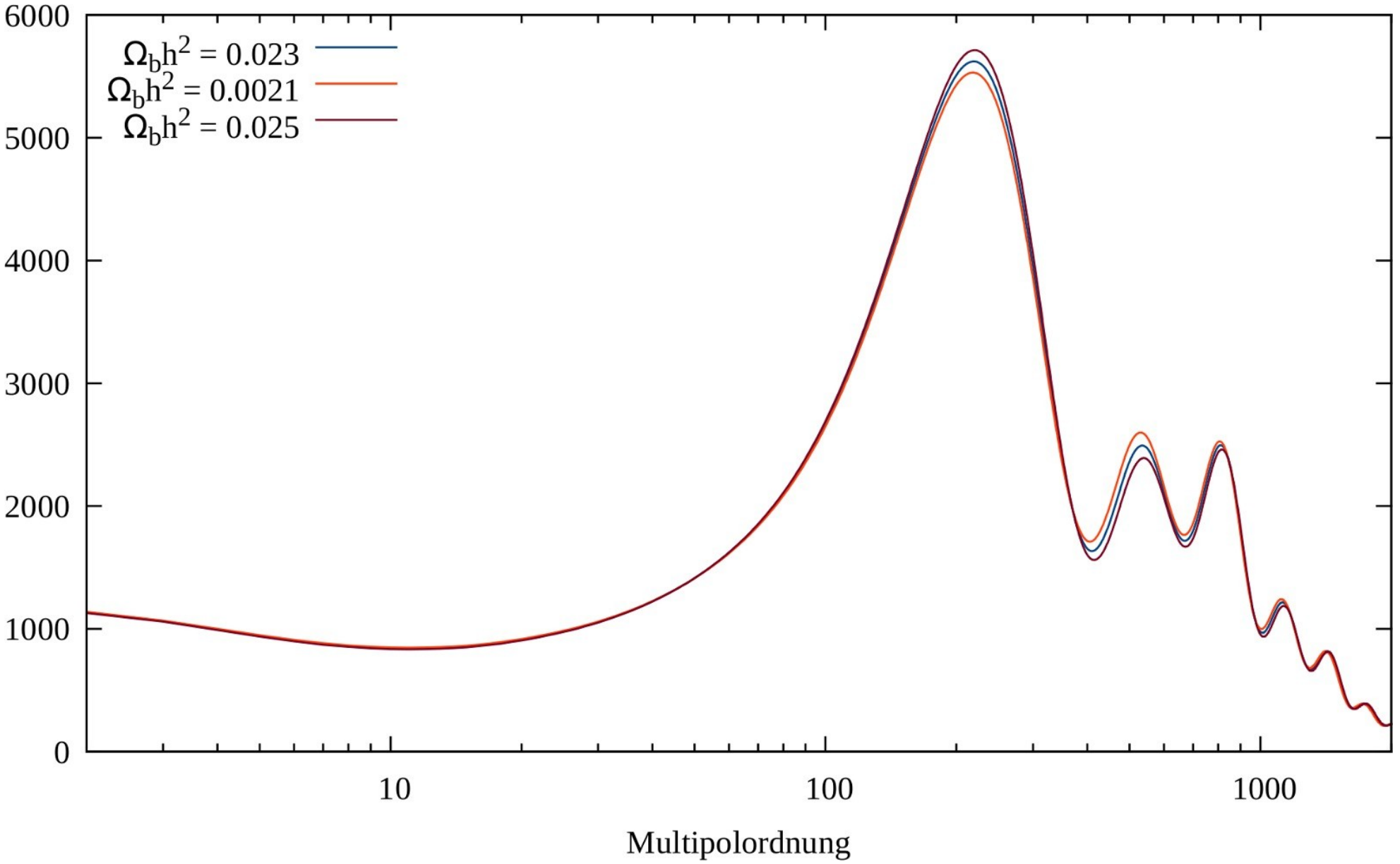
The CMB power spectrum



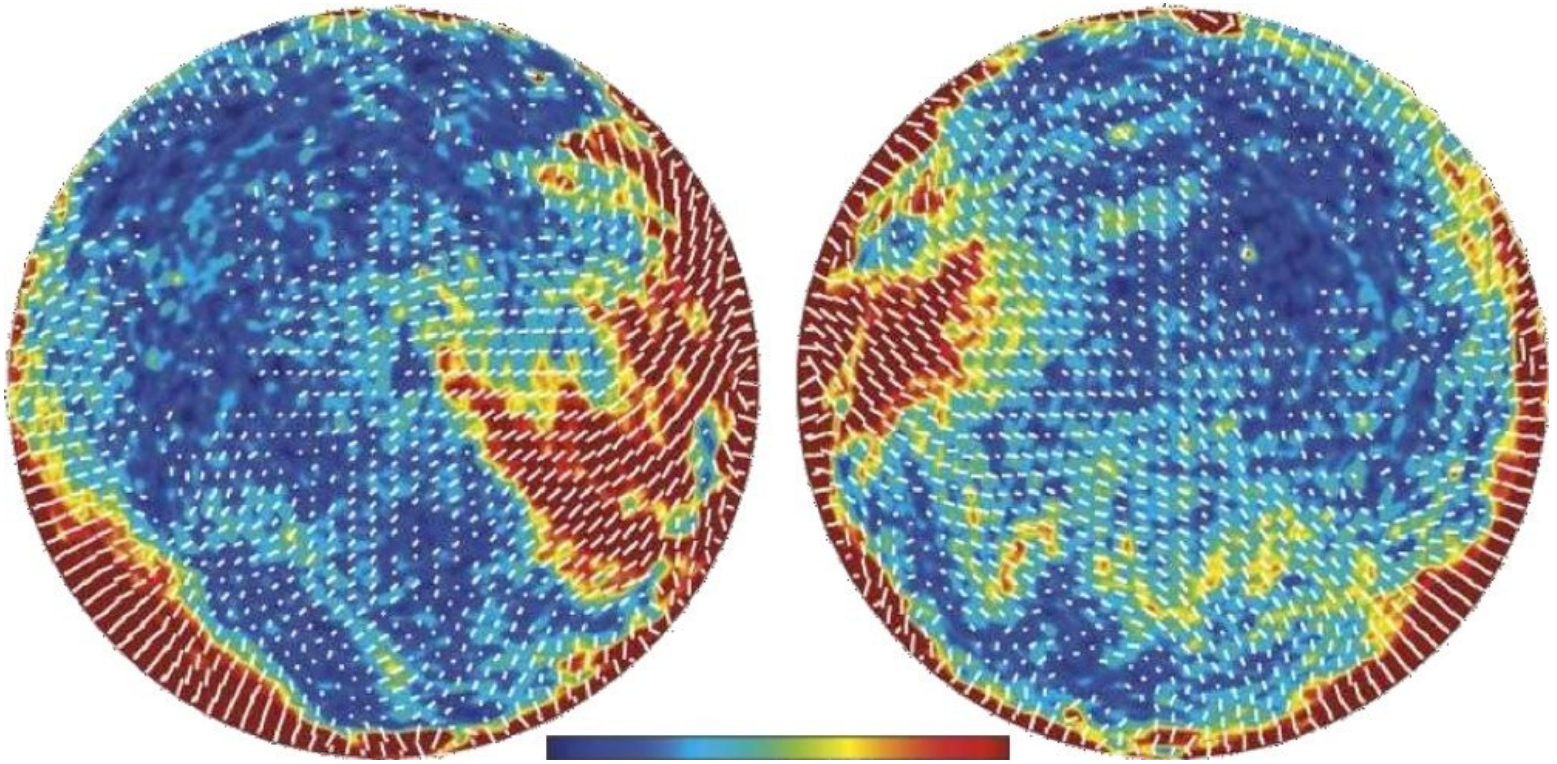
Structure in Planck's sky

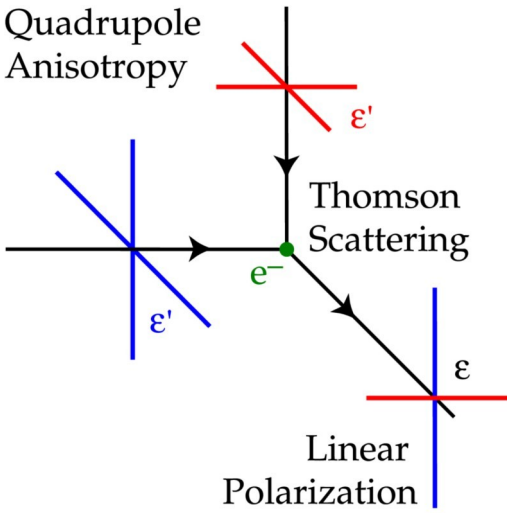


Structure in Planck's sky

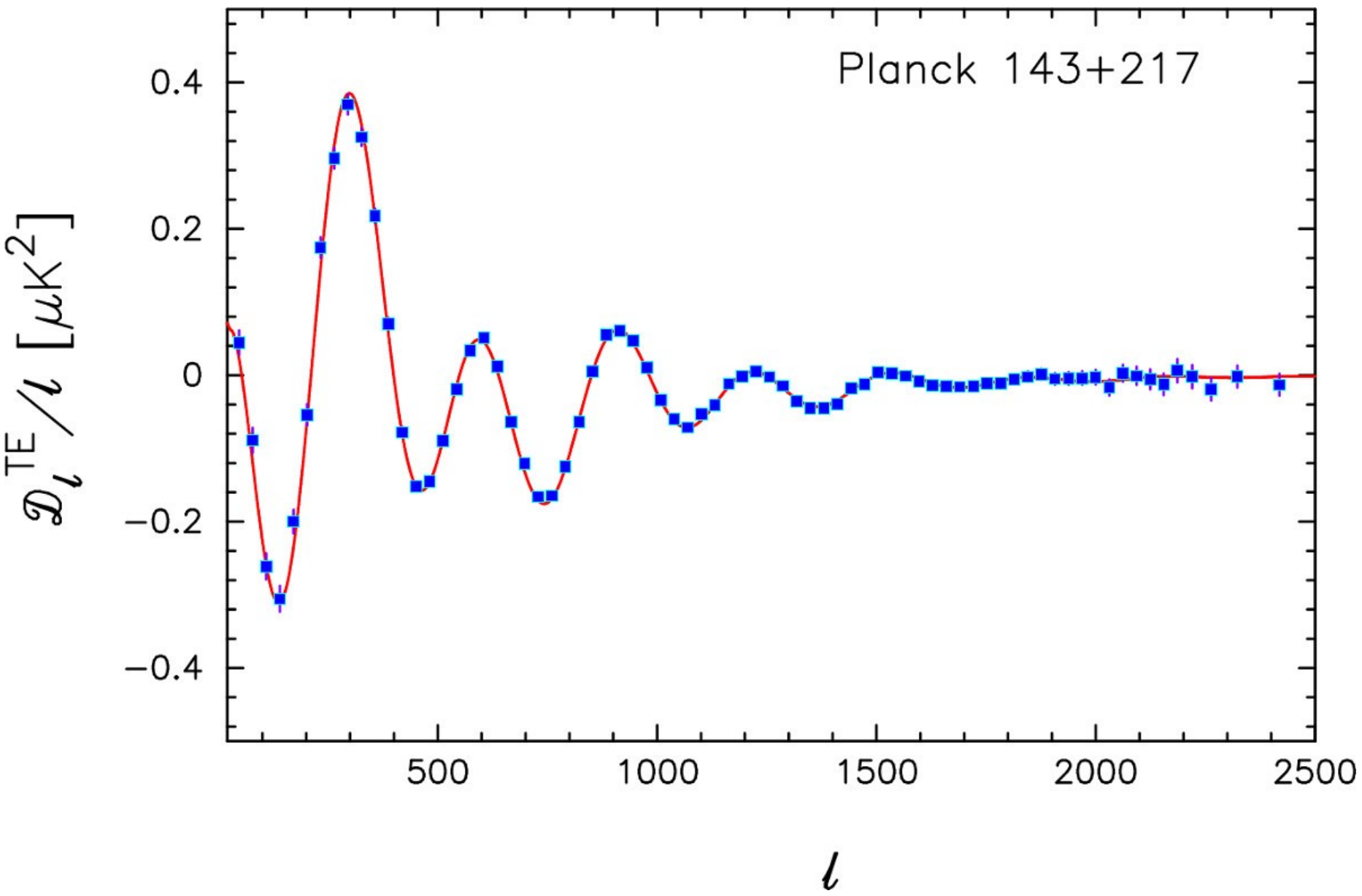


CMB polarisation

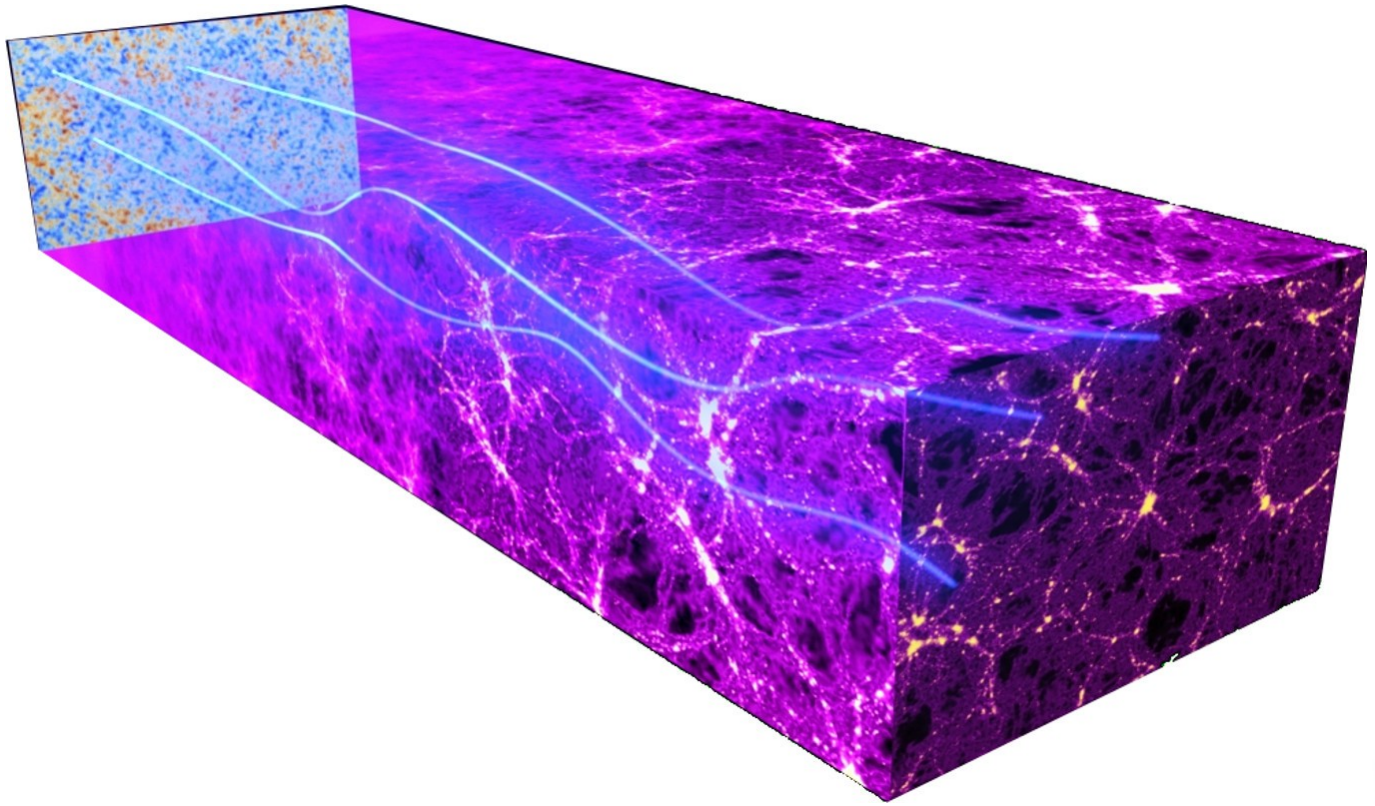


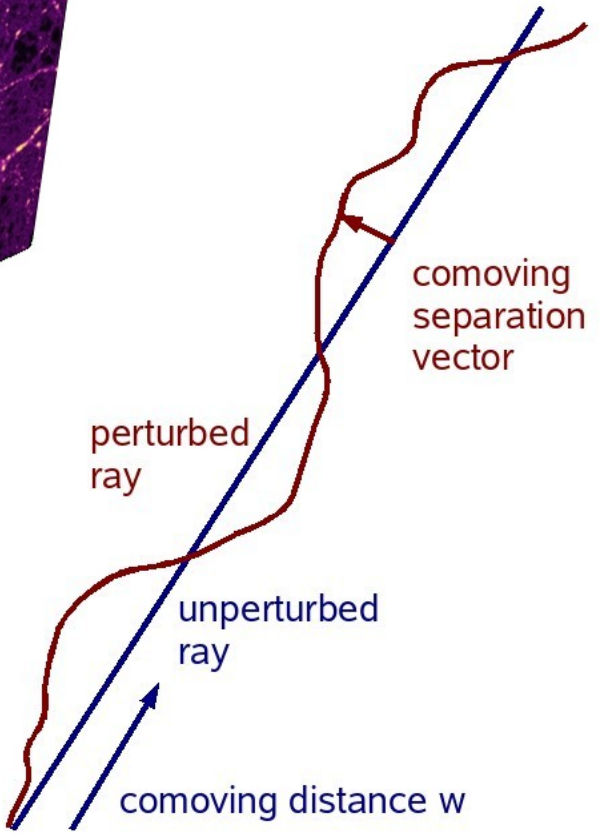


Structure in Planck's sky



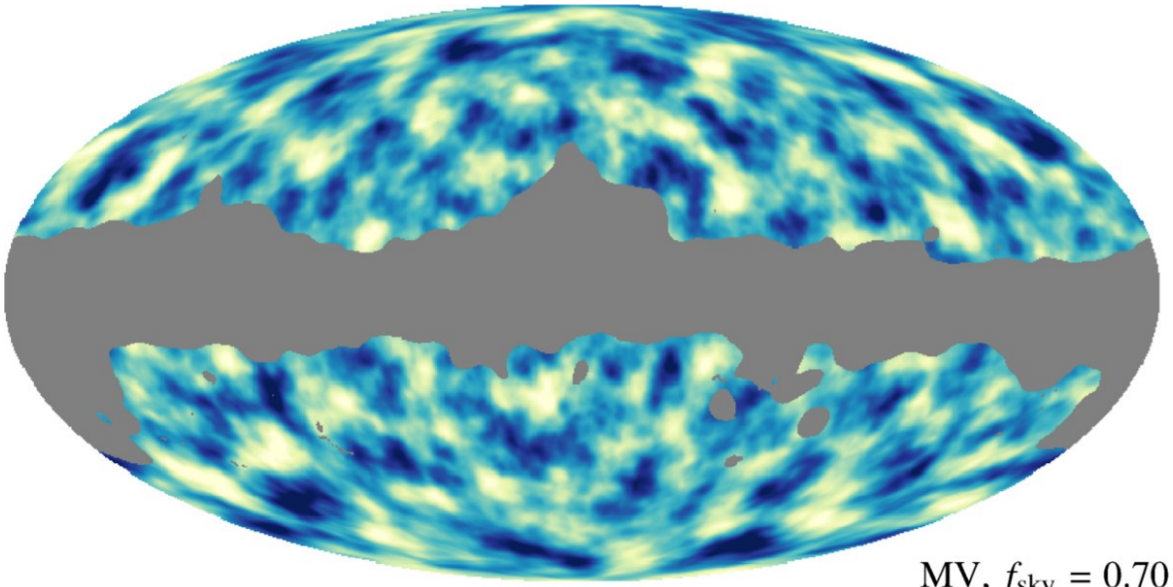
Photon travel



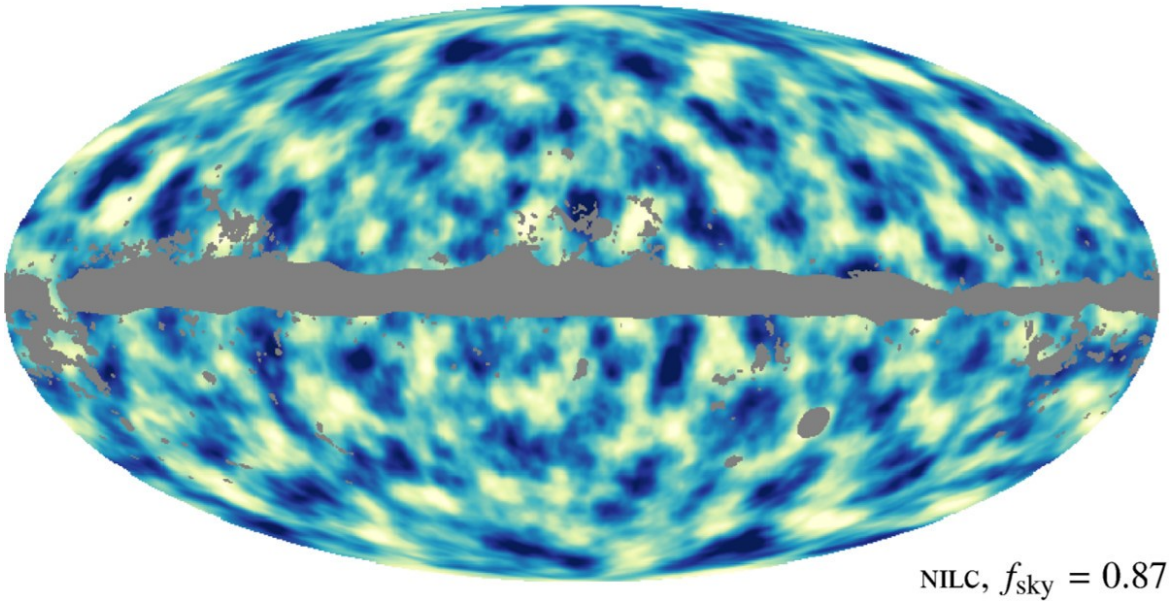


Photon travel

Photon travels

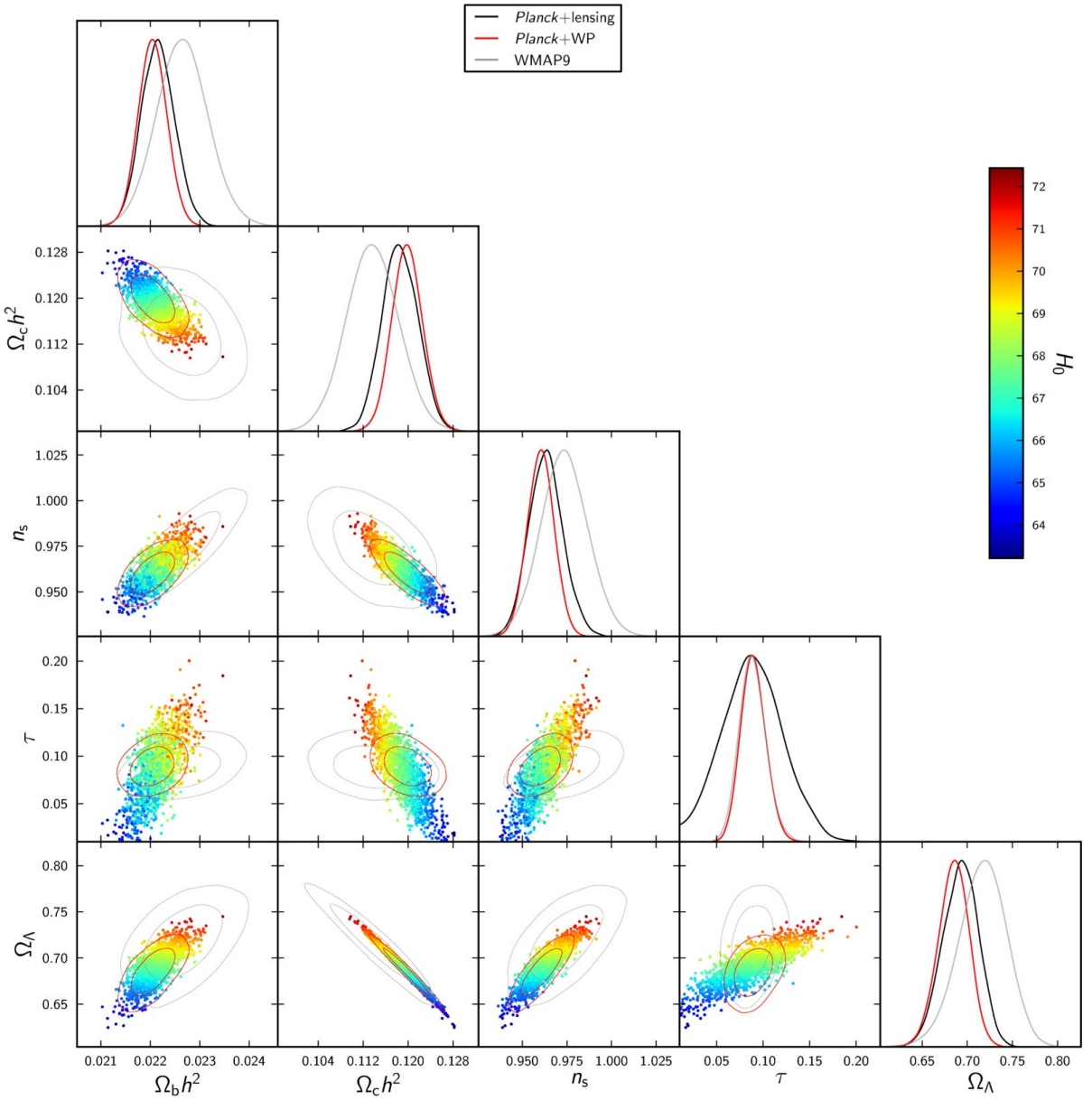


MV, $f_{\rm sky} = 0.70$

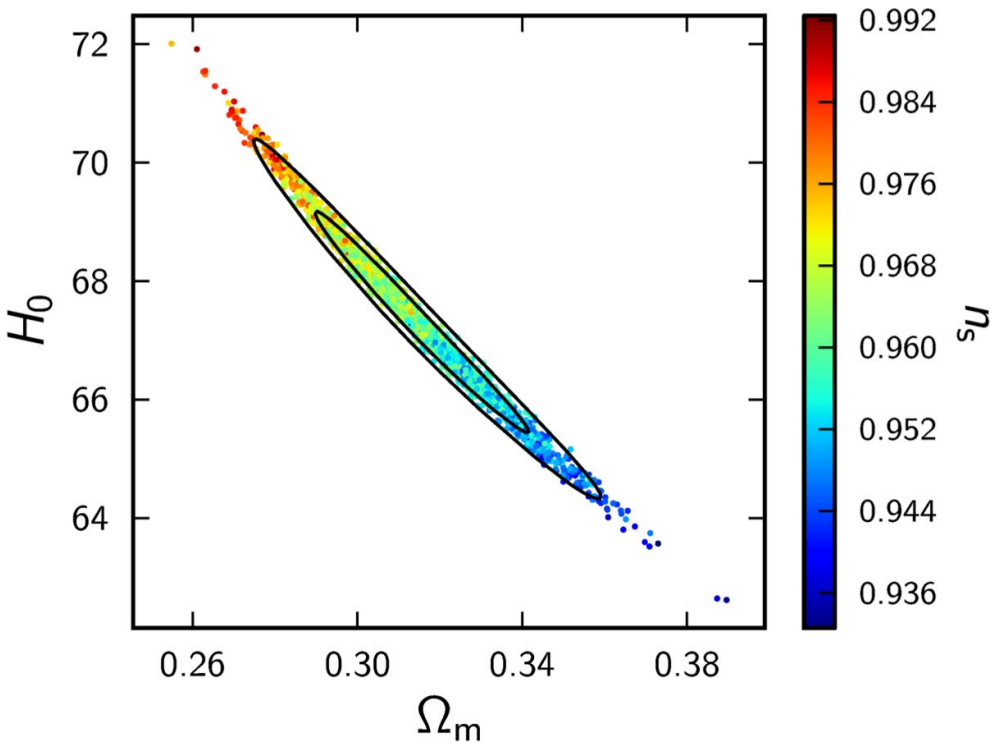


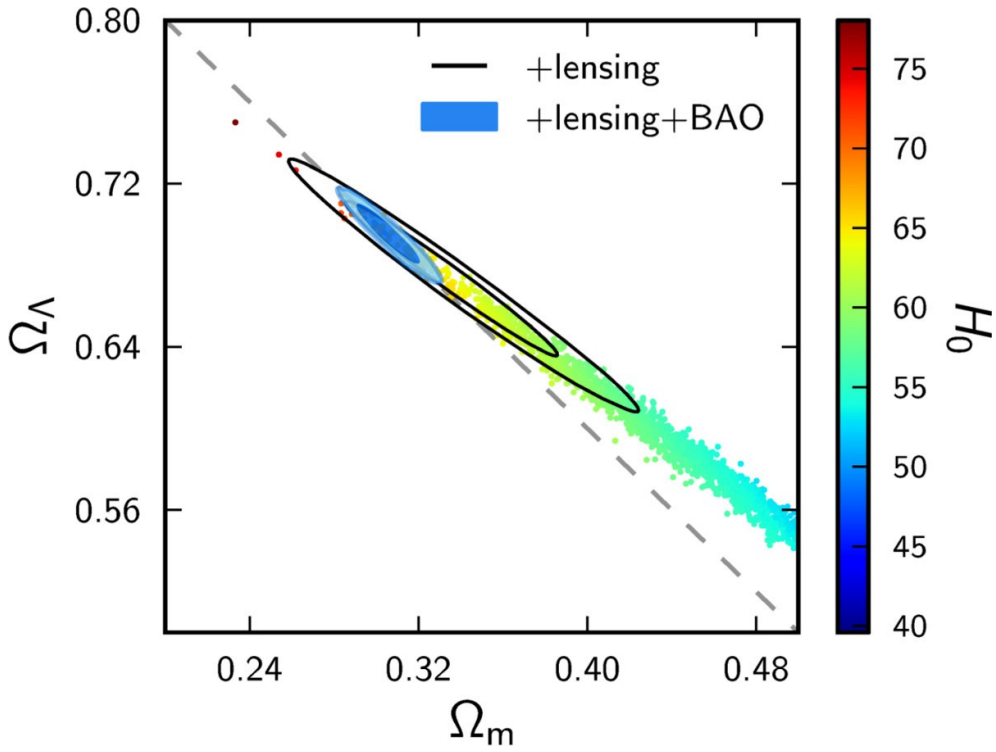
NILC, $f_{\rm sky} = 0.87$

The world according to Planck

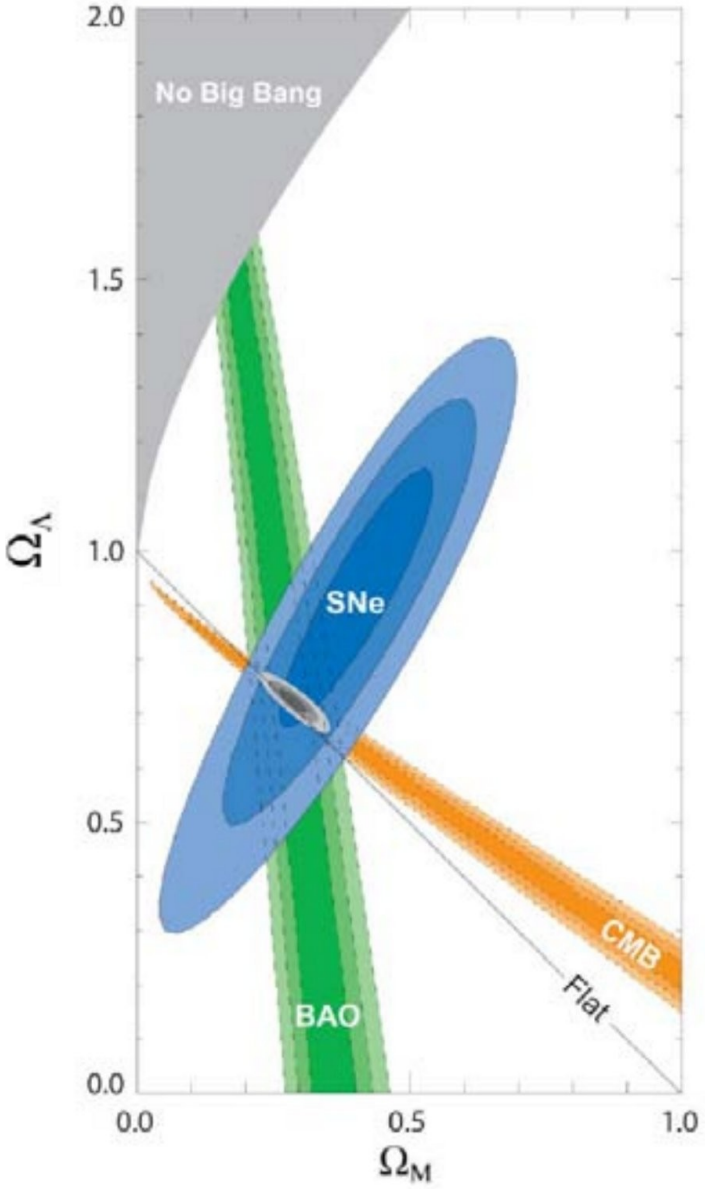


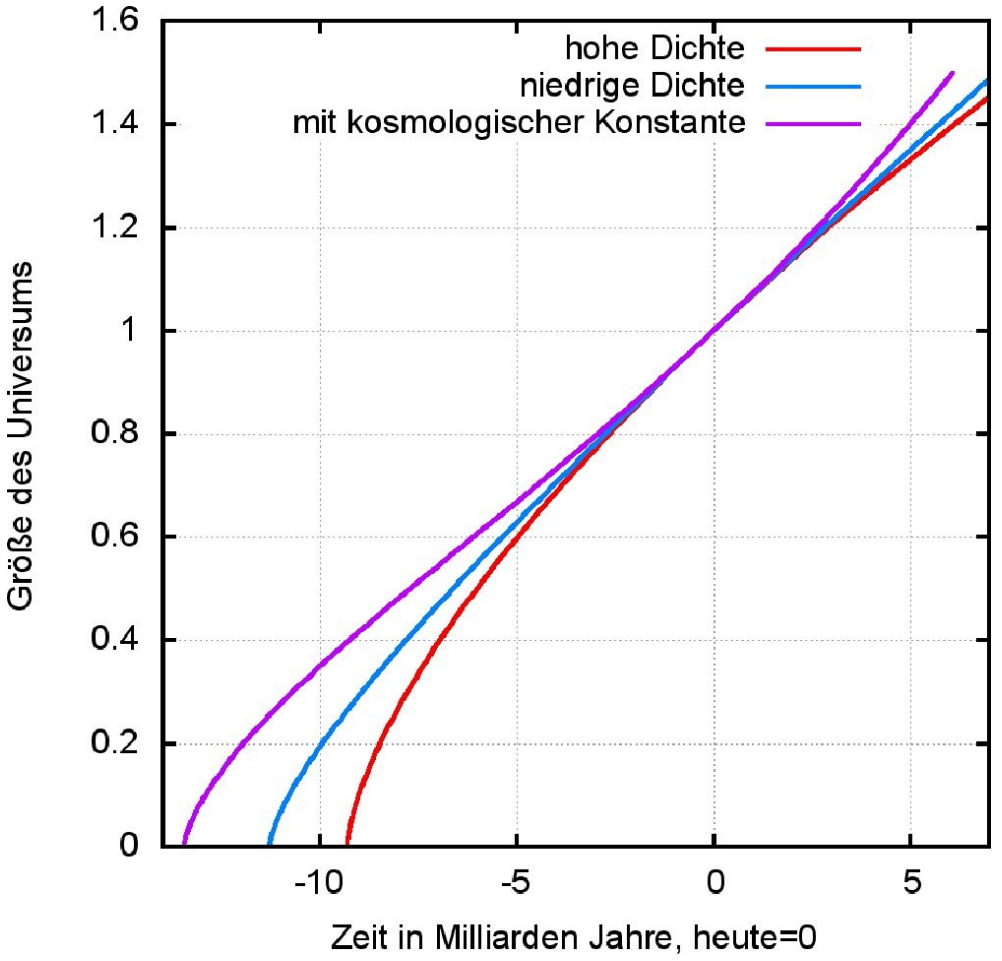
The world acording to Planck



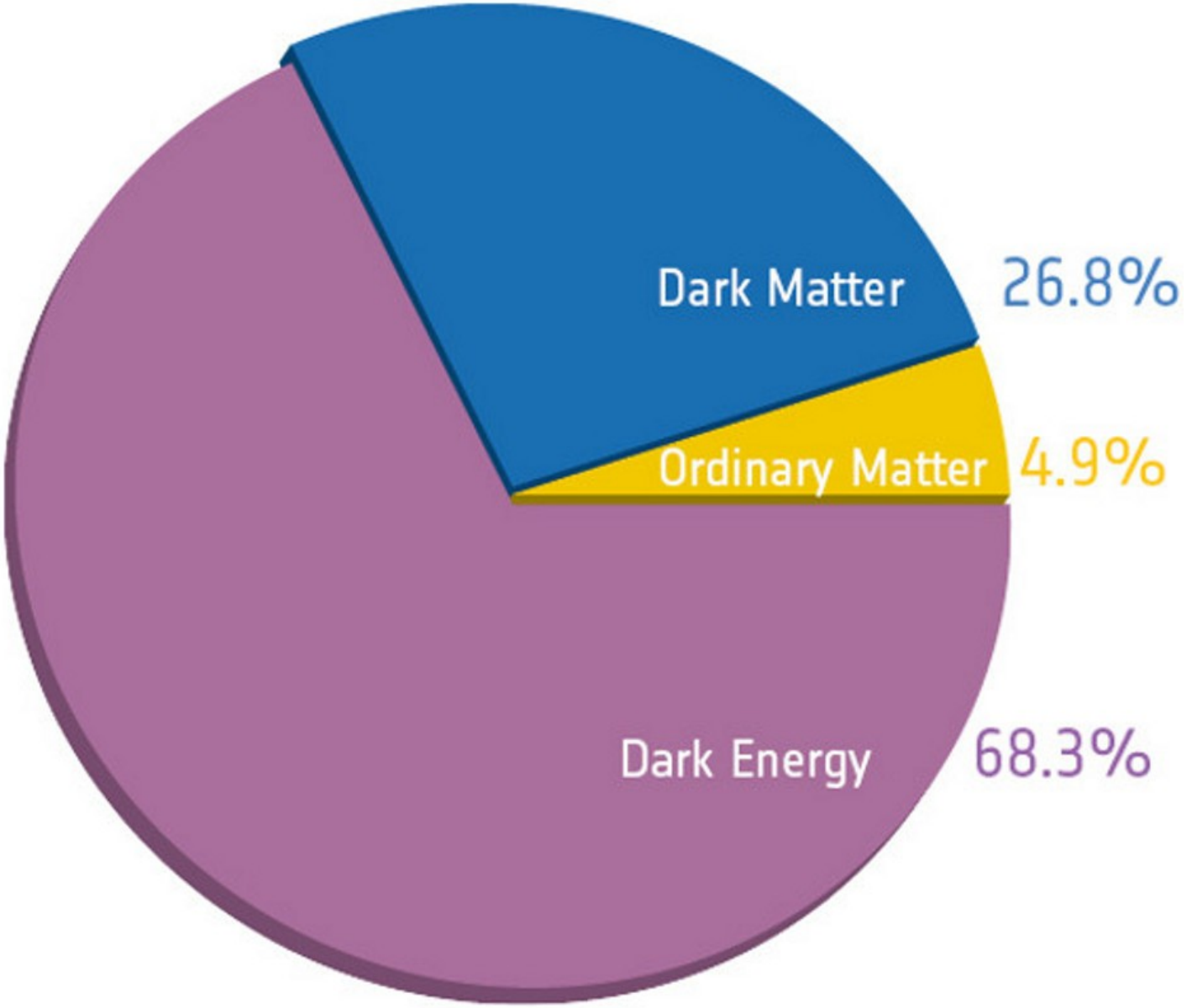


The world according to Planck

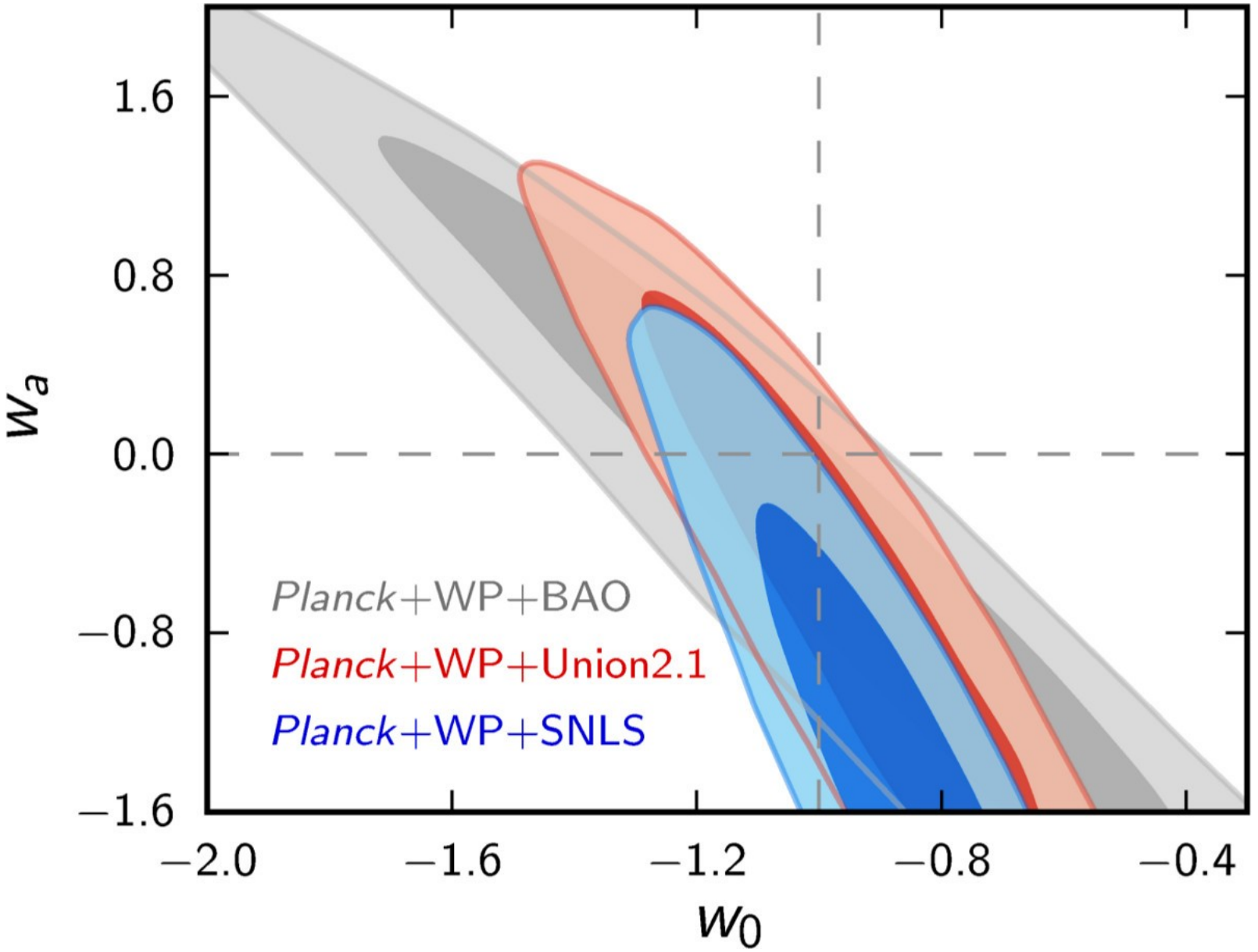




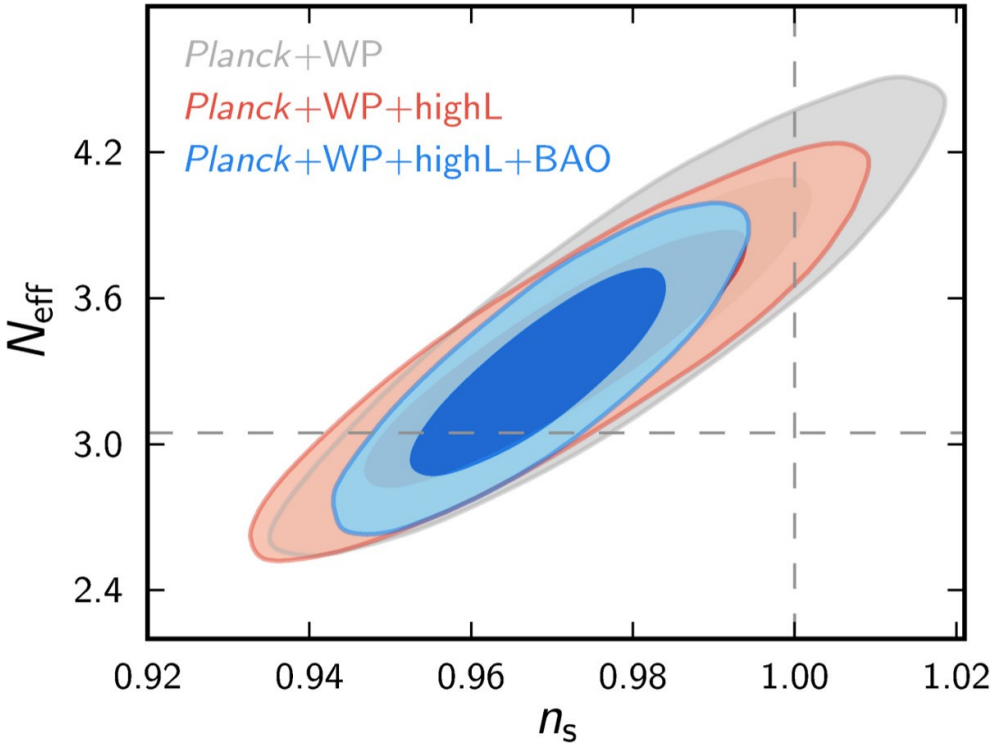
The world according to Planck

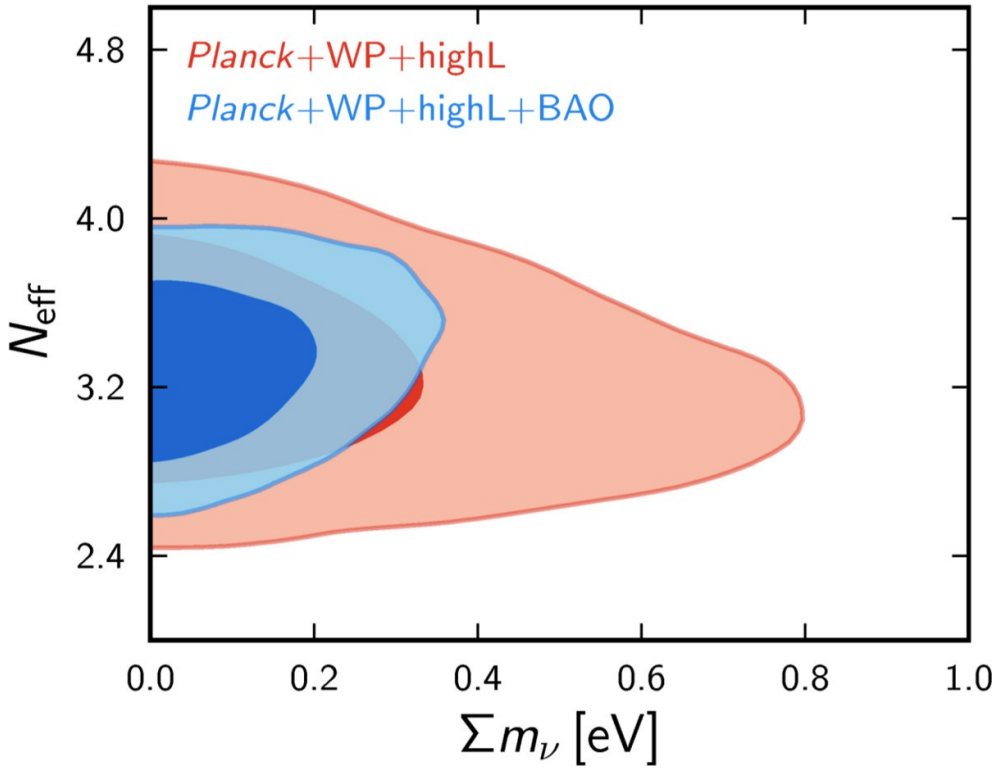


Dark energy

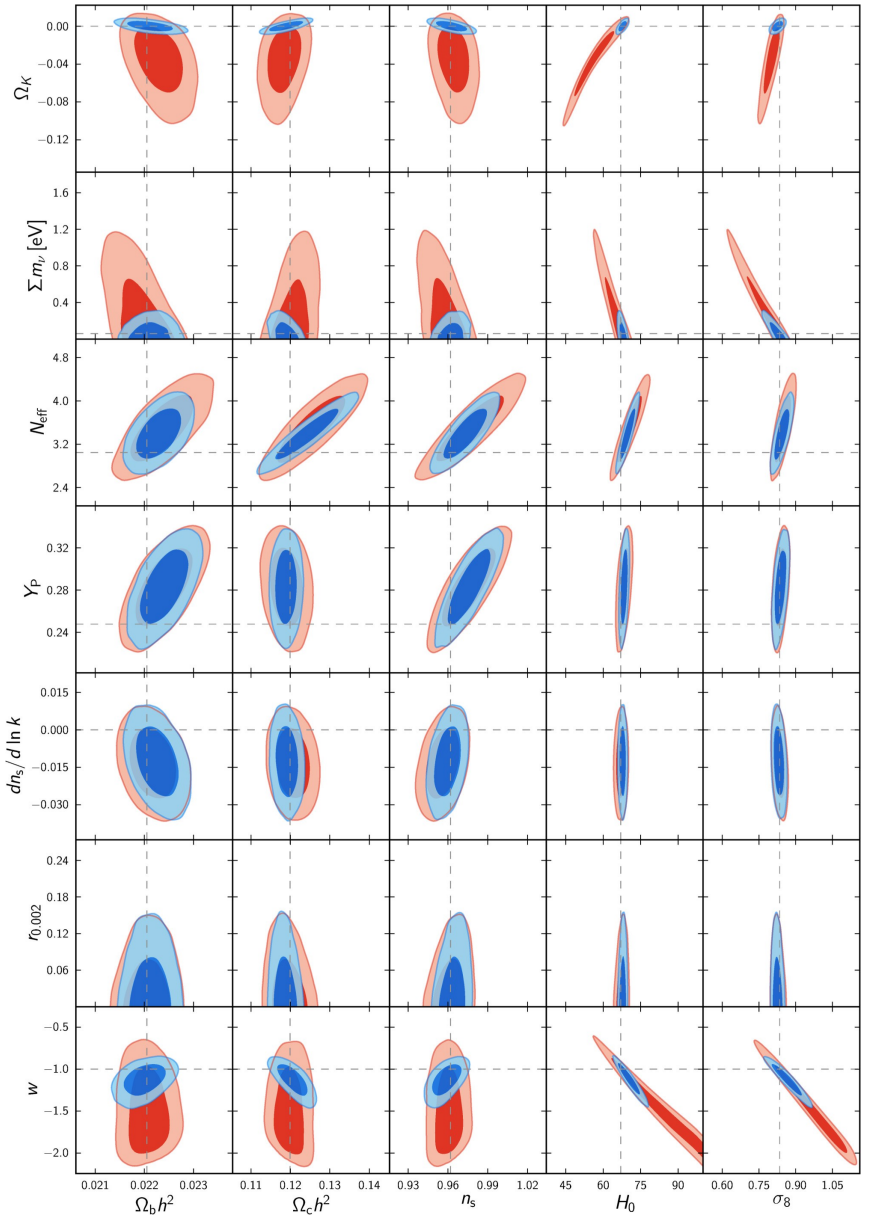

1.6
0.8
0.0
−0.8
−1.6
w_a
−2.0
−1.6
−1.2
−0.8
−0.4
w_0
Planck+WP+BAO
Planck+WP+Union2.1
Planck+WP+SNLS

Secondary parameters

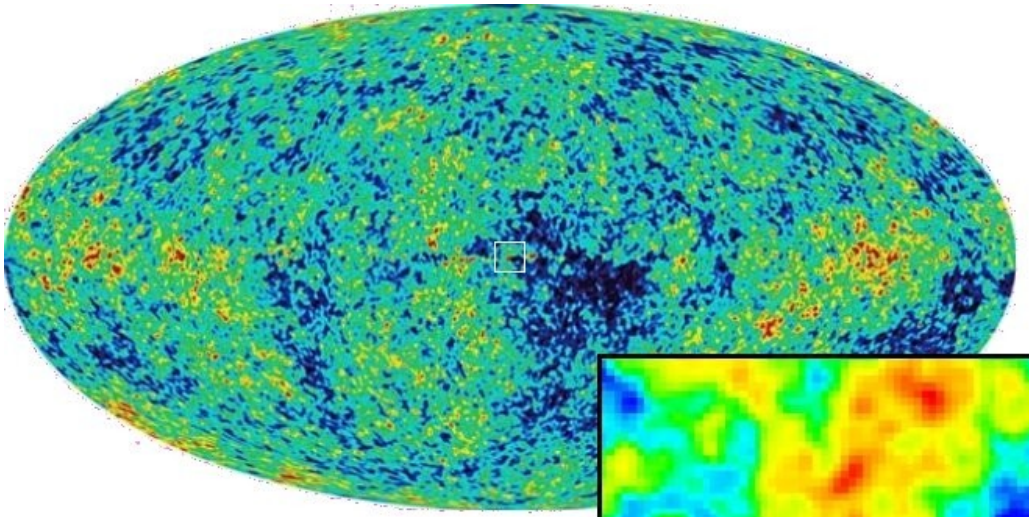


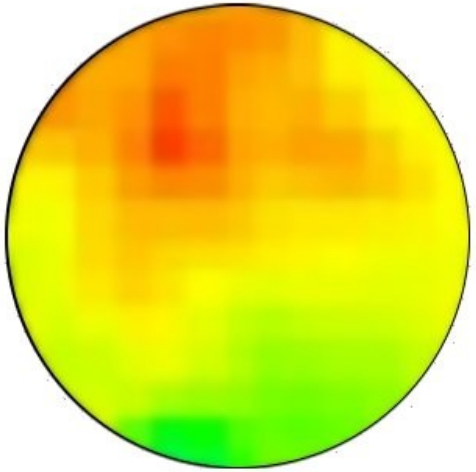


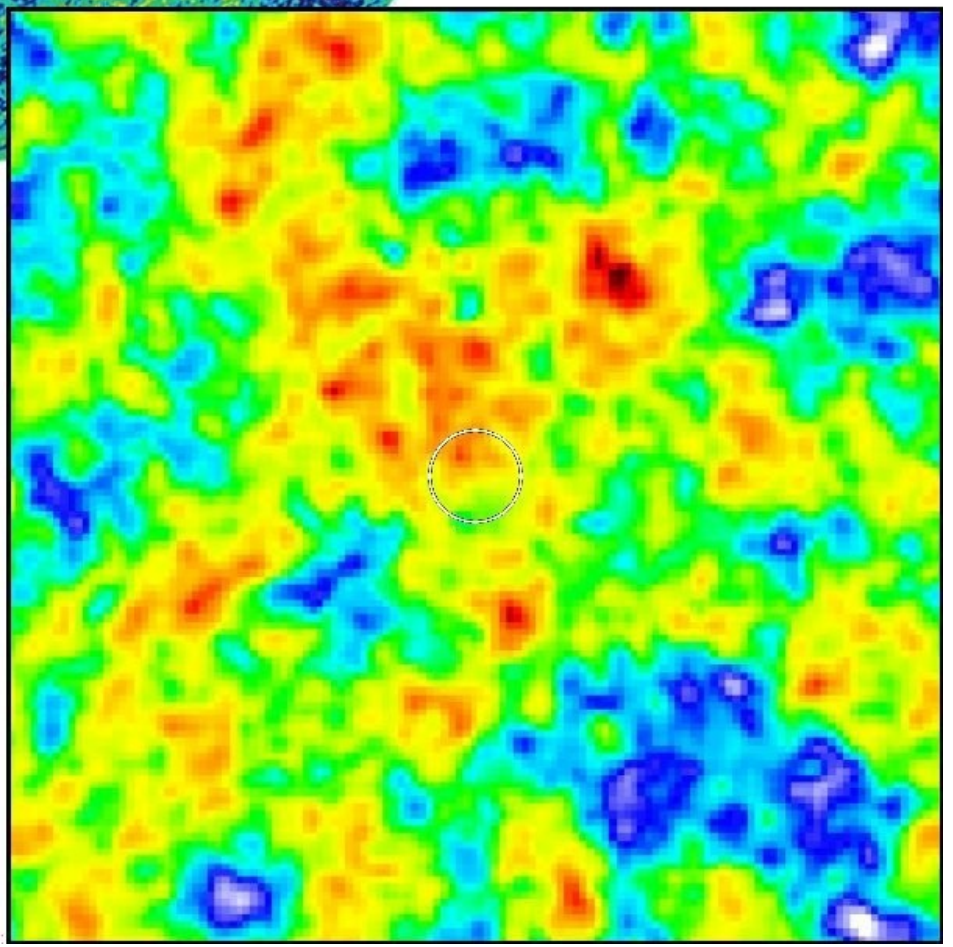
Secondary parameters



Causality?







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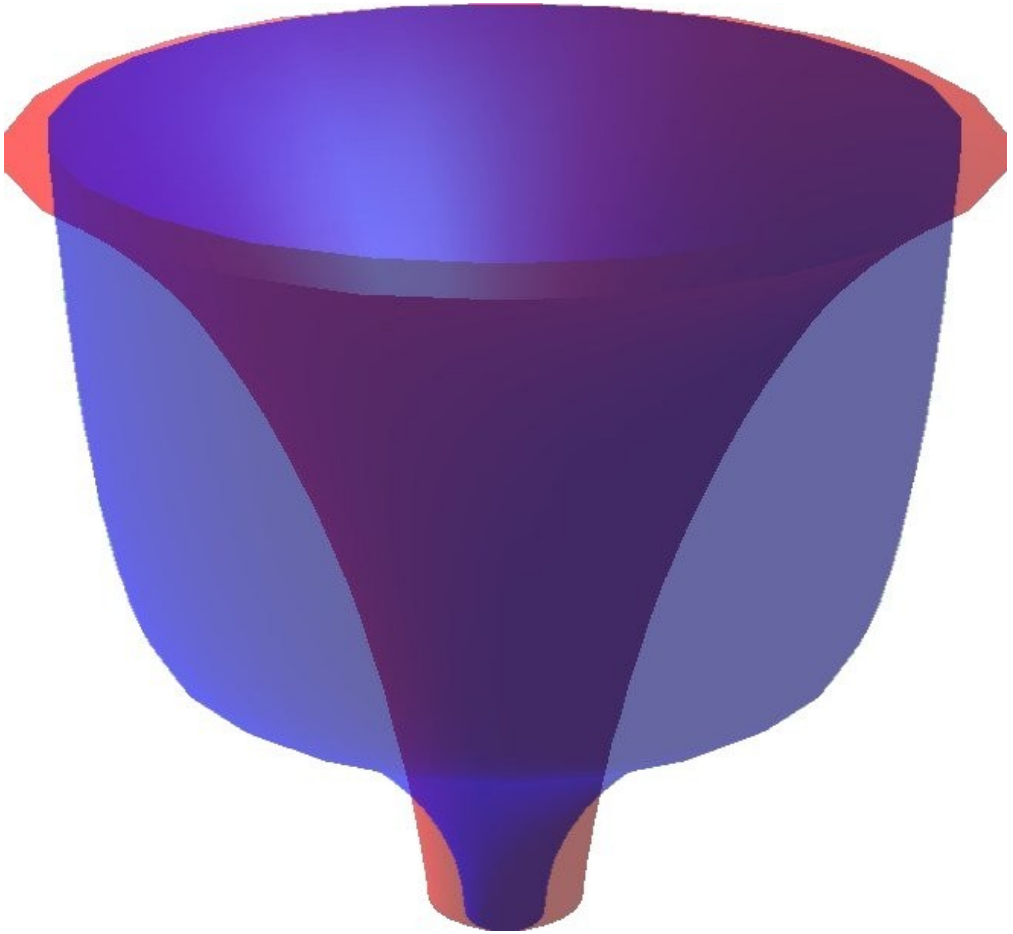
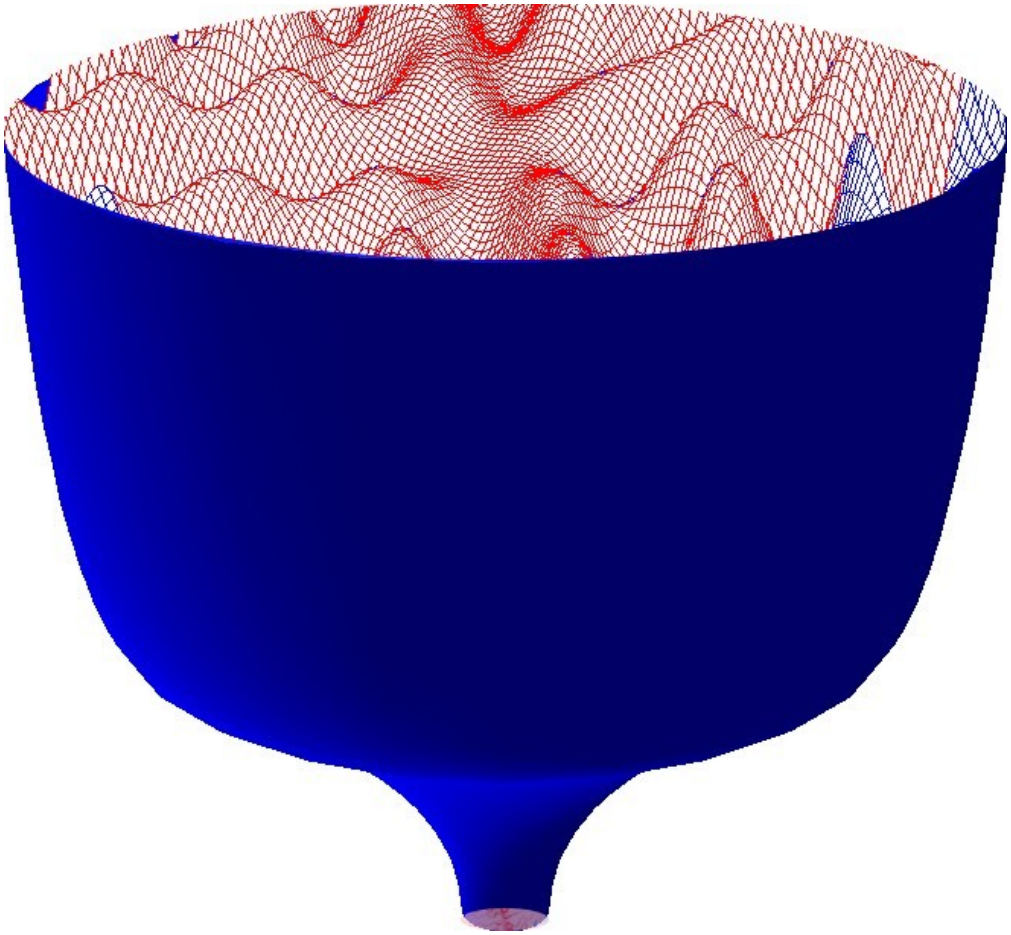
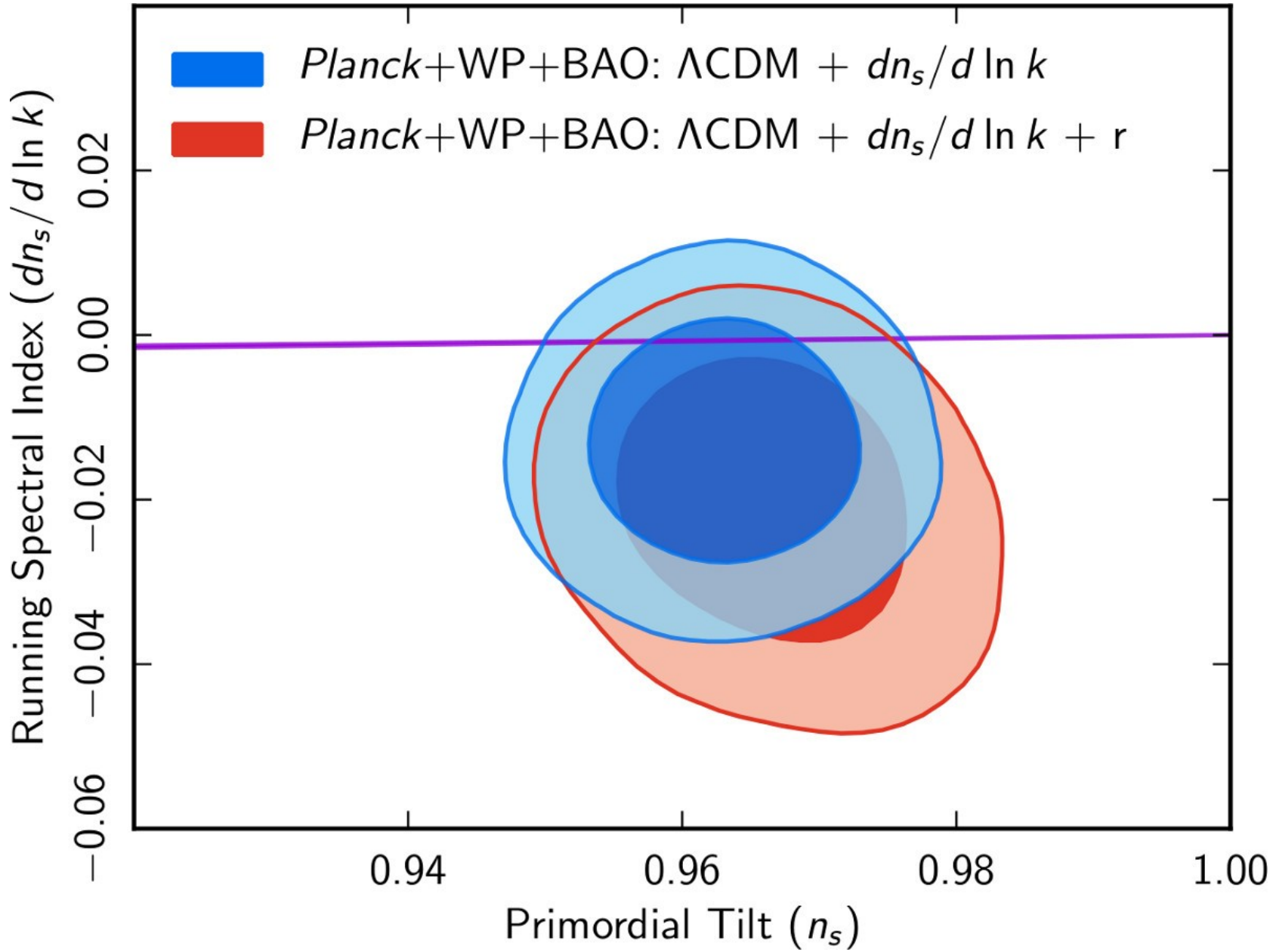
Inflation and its Consequences

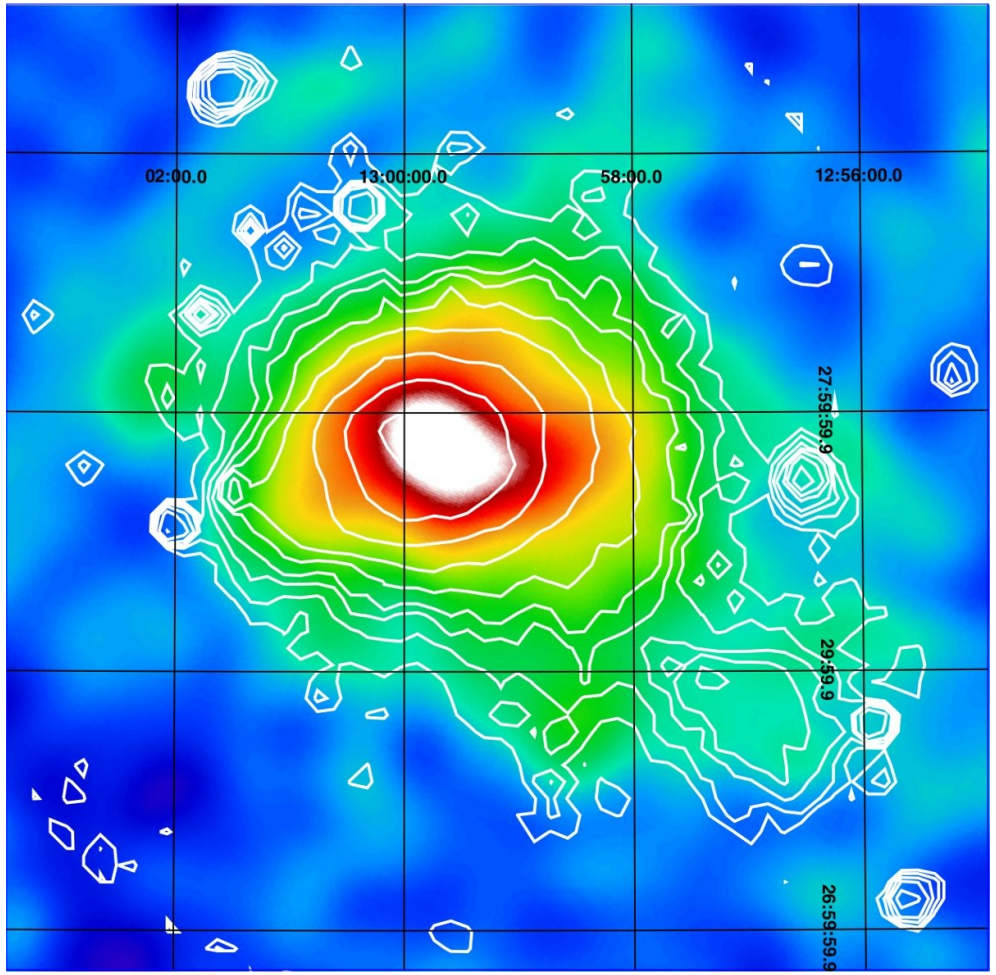


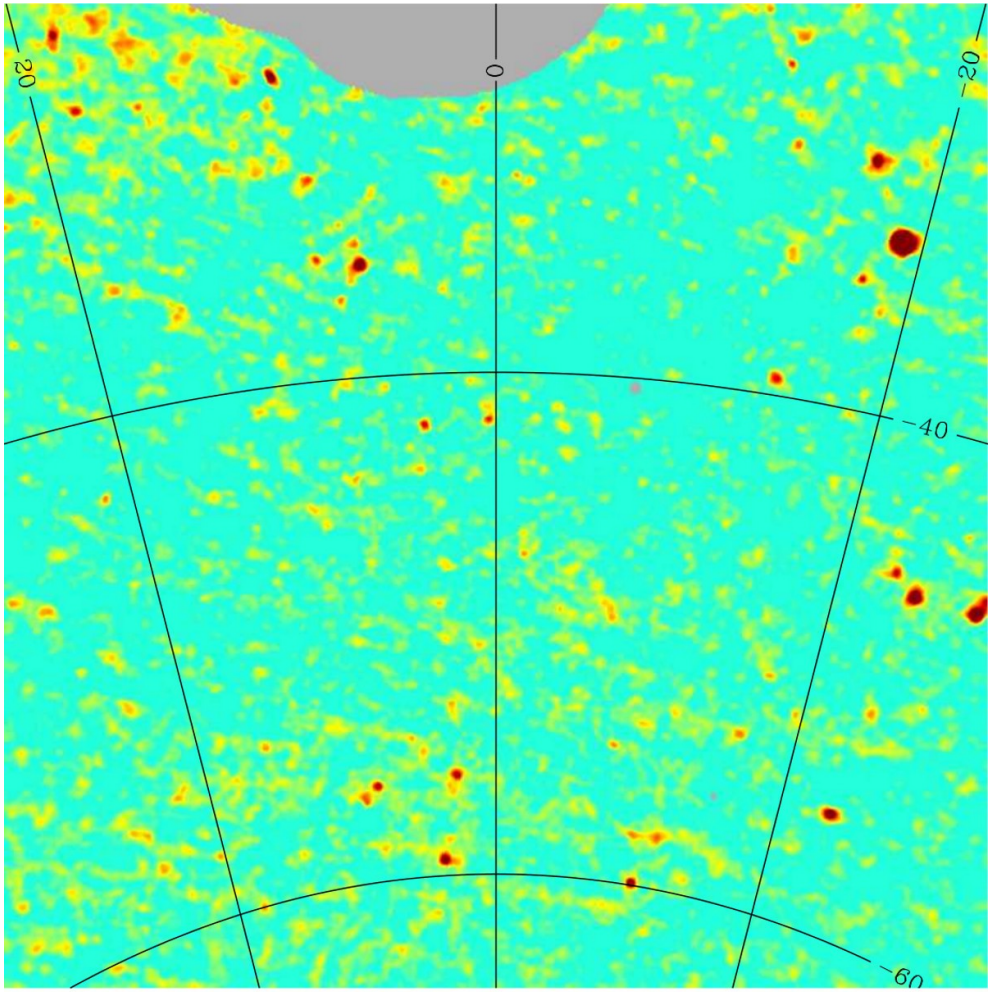


Inflation

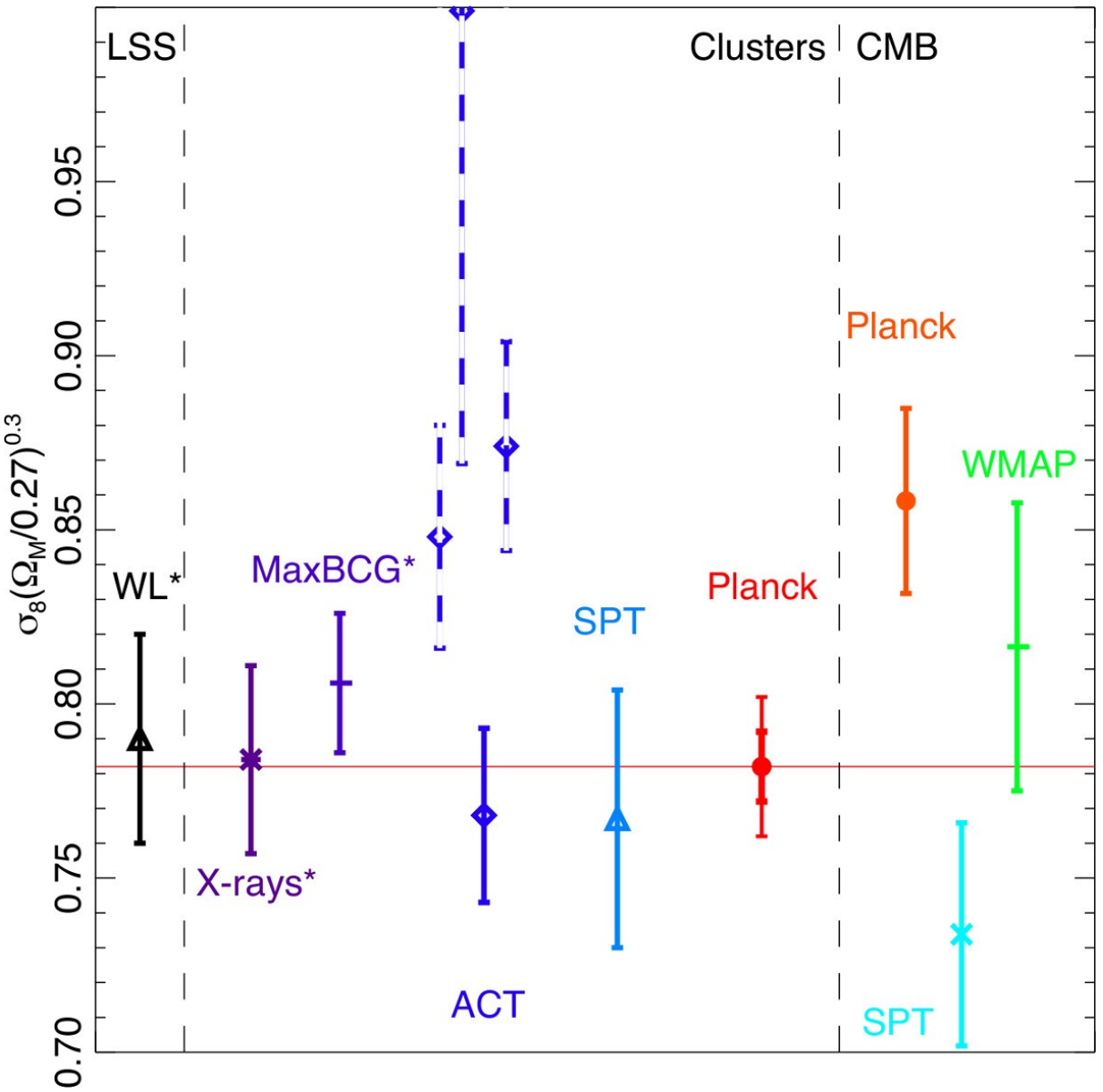

Planck+WP+BAO: ΛCDM + $dn_s/d\ln k$
Planck+WP+BAO: ΛCDM + $dn_s/d\ln k$ + r
Running Spectral Index ($dn_s/d\ln k$)
0.02
0.00
−0.02
−0.04
−0.06
0.94
0.96
0.98
1.00
Primordial Tilt (n_s)

Galaxy clusters

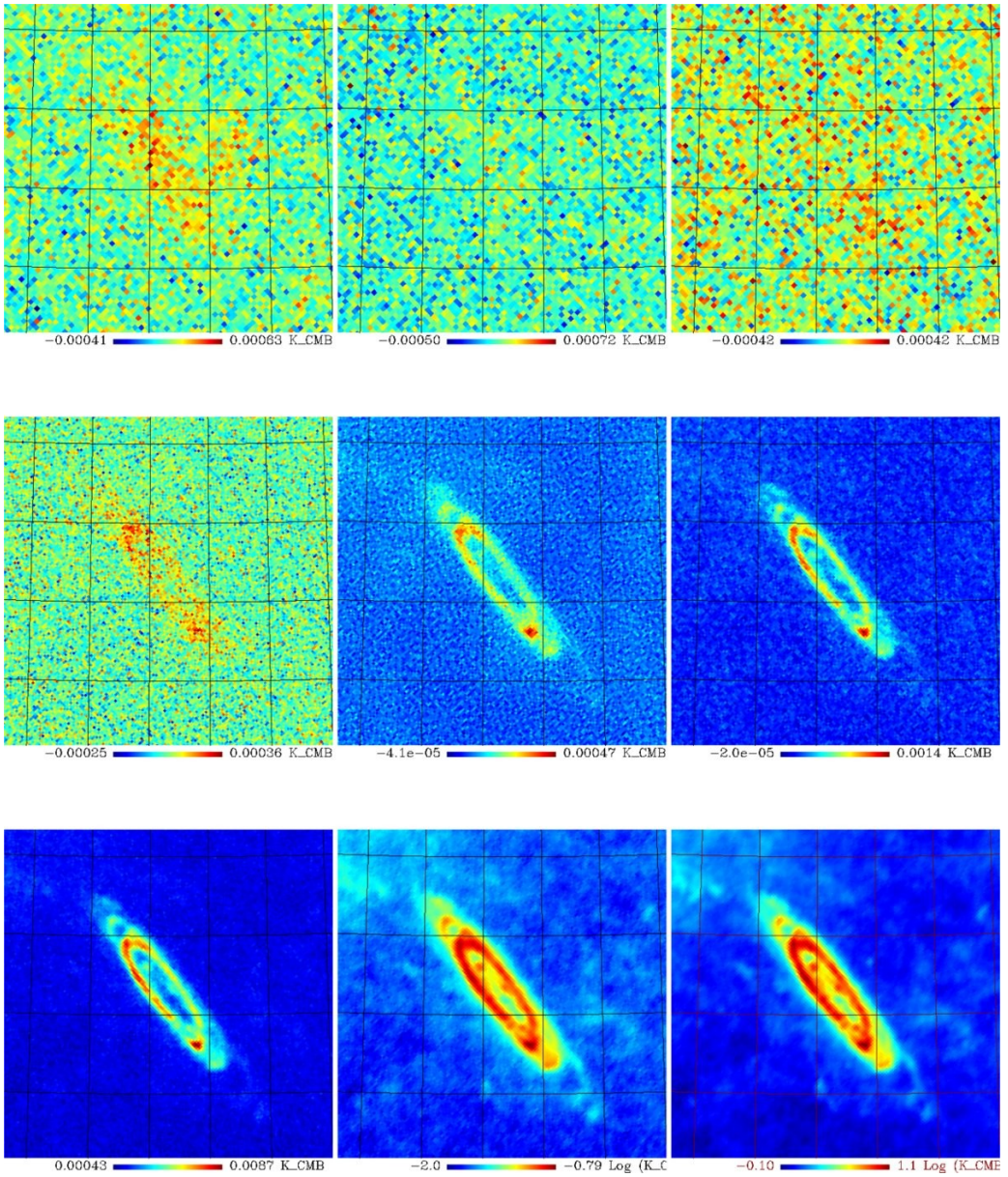




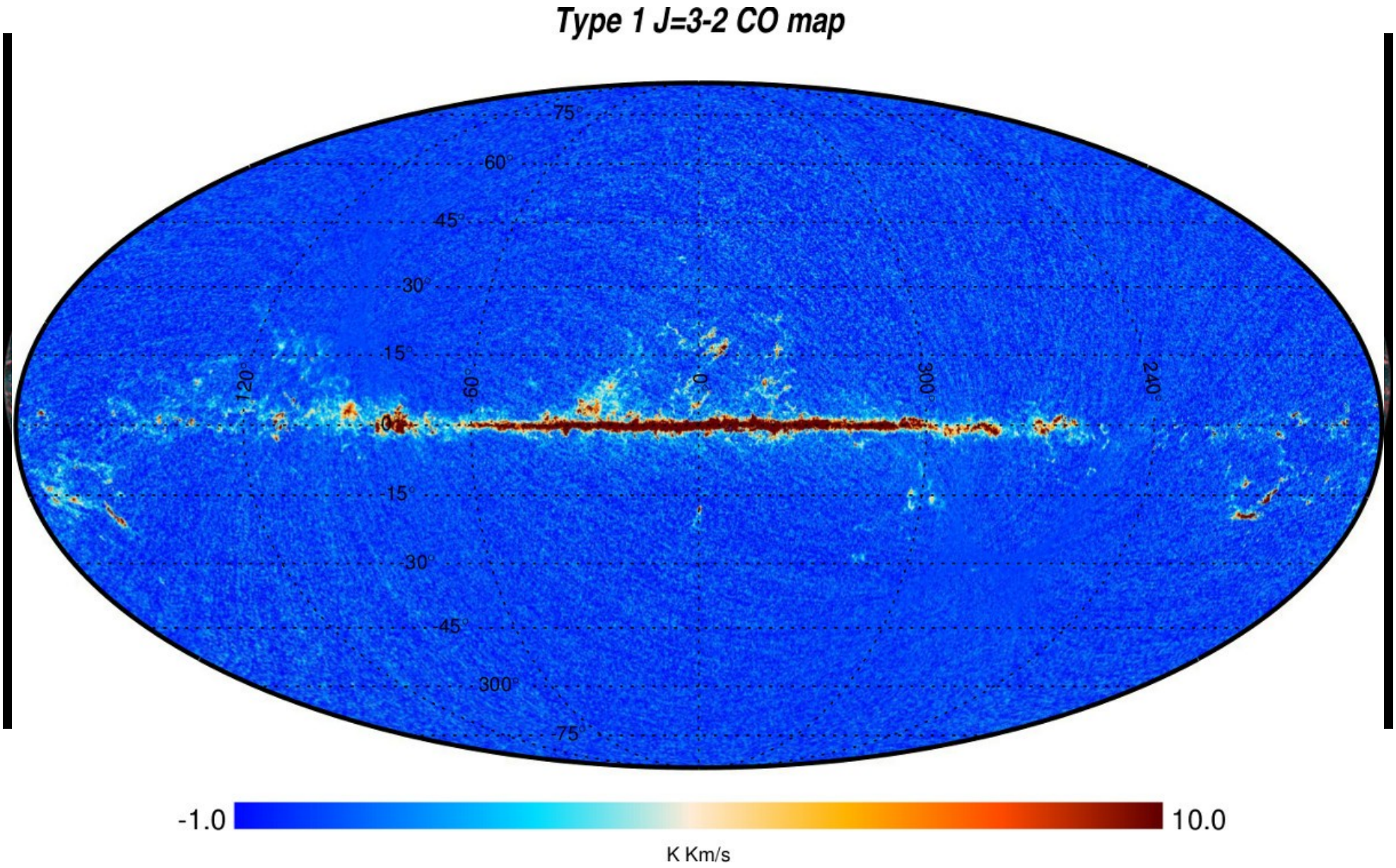
The world according to Planck



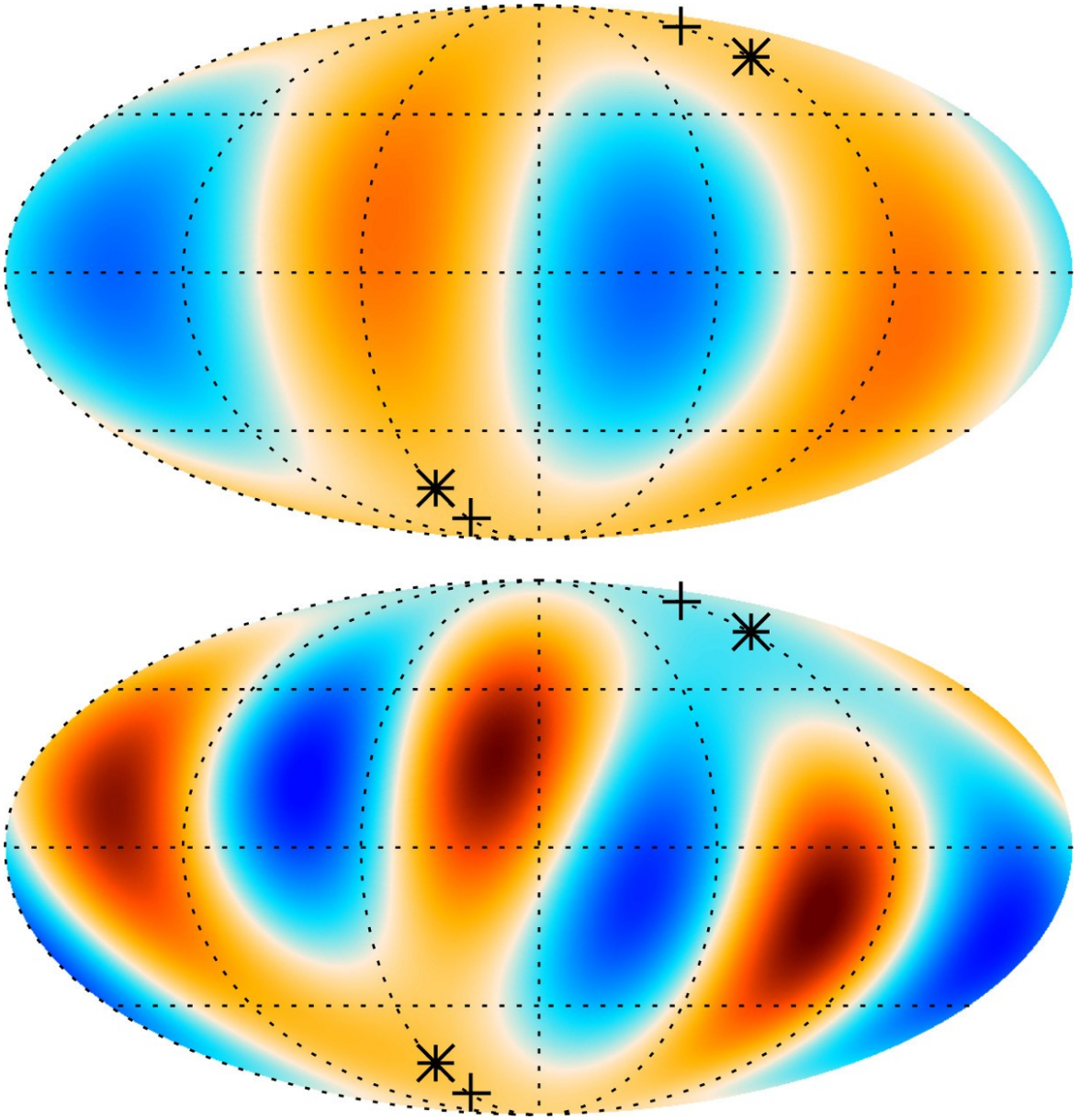
Astronomy with Planck



Astronomy with Planck



Planck's problems



Planck's numbers

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	Planck		*Planck*+lensing		*Planck*+WP	
Parameter	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6964	0.693 ± 0.019	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3036	0.307 ± 0.019	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8344	0.834 ± 0.027	0.8285	0.823 ± 0.018	0.8347	0.829 ± 0.012
z_{re}	11.35	$11.4^{+4.0}_{-2.8}$	11.45	$10.8^{+3.1}_{-2.5}$	11.37	11.1 ± 1.1
H_0	67.11	67.4 ± 1.4	68.14	67.9 ± 1.5	67.04	67.3 ± 1.2
$10^9 A_s$	2.215	2.23 ± 0.16	2.215	$2.19^{+0.12}_{-0.14}$	2.215	$2.196^{+0.051}_{-0.060}$
$\Omega_m h^2$	0.14300	0.1423 ± 0.0029	0.14094	0.1414 ± 0.0029	0.14305	0.1426 ± 0.0025
$\Omega_m h^3$	0.09597	0.09590 ± 0.00059	0.09603	0.09593 ± 0.00058	0.09591	0.09589 ± 0.00057
Y_P	0.247710	0.24771 ± 0.00014	0.247785	0.24775 ± 0.00014	0.247695	0.24770 ± 0.00012
Age/Gyr	13.819	13.813 ± 0.058	13.784	13.796 ± 0.058	13.8242	13.817 ± 0.048
z_*	1090.43	1090.37 ± 0.65	1090.01	1090.16 ± 0.65	1090.48	1090.43 ± 0.54
r_*	144.58	144.75 ± 0.66	145.02	144.96 ± 0.66	144.58	144.71 ± 0.60
$100\theta_*$	1.04139	1.04148 ± 0.00066	1.04164	1.04156 ± 0.00066	1.04136	1.04147 ± 0.00062
z_{drag}	1059.32	1059.29 ± 0.65	1059.59	1059.43 ± 0.64	1059.25	1059.25 ± 0.58
r_{drag}	147.34	147.53 ± 0.64	147.74	147.70 ± 0.63	147.36	147.49 ± 0.59
k_D	0.14026	0.14007 ± 0.00064	0.13998	0.13996 ± 0.00062	0.14022	0.14009 ± 0.00063
$100\theta_D$	0.161332	0.16137 ± 0.00037	0.161196	0.16129 ± 0.00036	0.161375	0.16140 ± 0.00034
z_{eq}	3402	3386 ± 69	3352	3362 ± 69	3403	3391 ± 60
$100\theta_{eq}$	0.8128	0.816 ± 0.013	0.8224	0.821 ± 0.013	0.8125	0.815 ± 0.011
$r_{drag}/D_V(0.57)$	0.07130	0.0716 ± 0.0011	0.07207	0.0719 ± 0.0011	0.07126	0.07147 ± 0.00091

The world according to Planck

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