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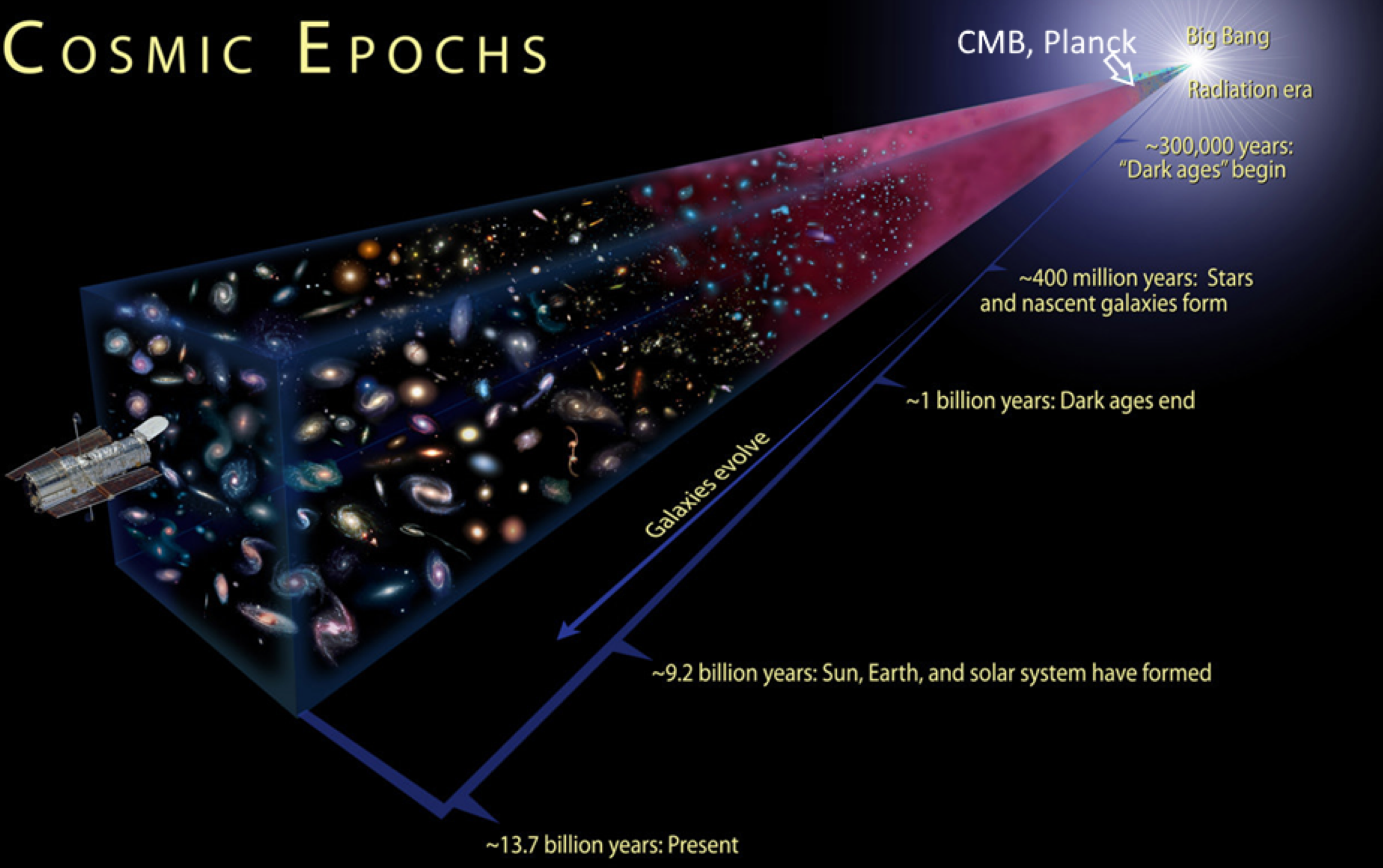
PLANCK MISSION:
A CORNERSTONE OF MODERN COSMOLOGY

Planck Memorial Scientific Symposium – MTA 2018.10.10-11

COSMIC EPOCHS



CMB, Planck

Big Bang

Radiation era

~300,000 years:
"Dark ages" begin

~400 million years: Stars
and nascent galaxies form

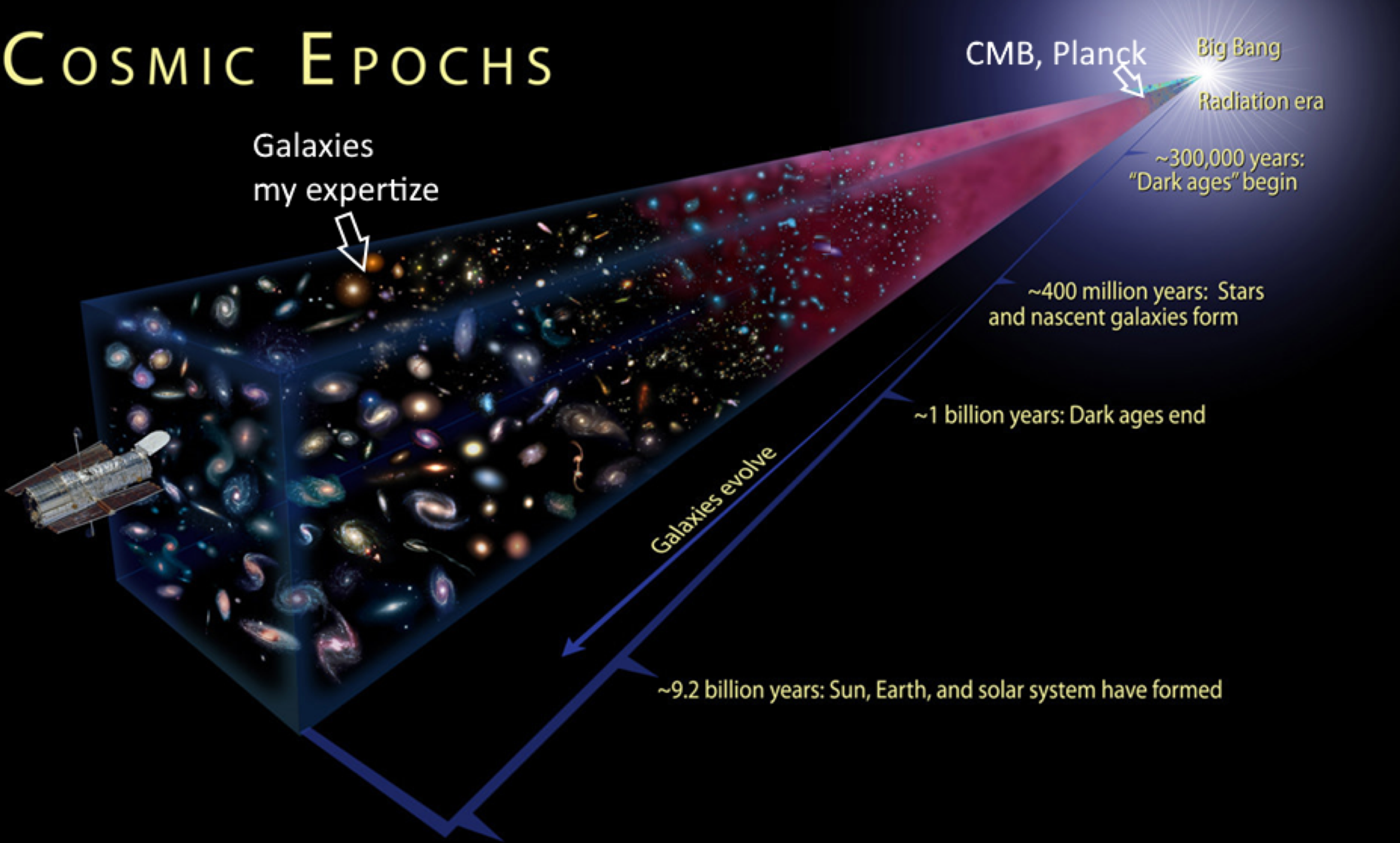
~1 billion years: Dark ages end

Galaxies evolve

~9.2 billion years: Sun, Earth, and solar system have formed

~13.7 billion years: Present

COSMIC EPOCHS



Galaxies
my expertize

CMB, Planck

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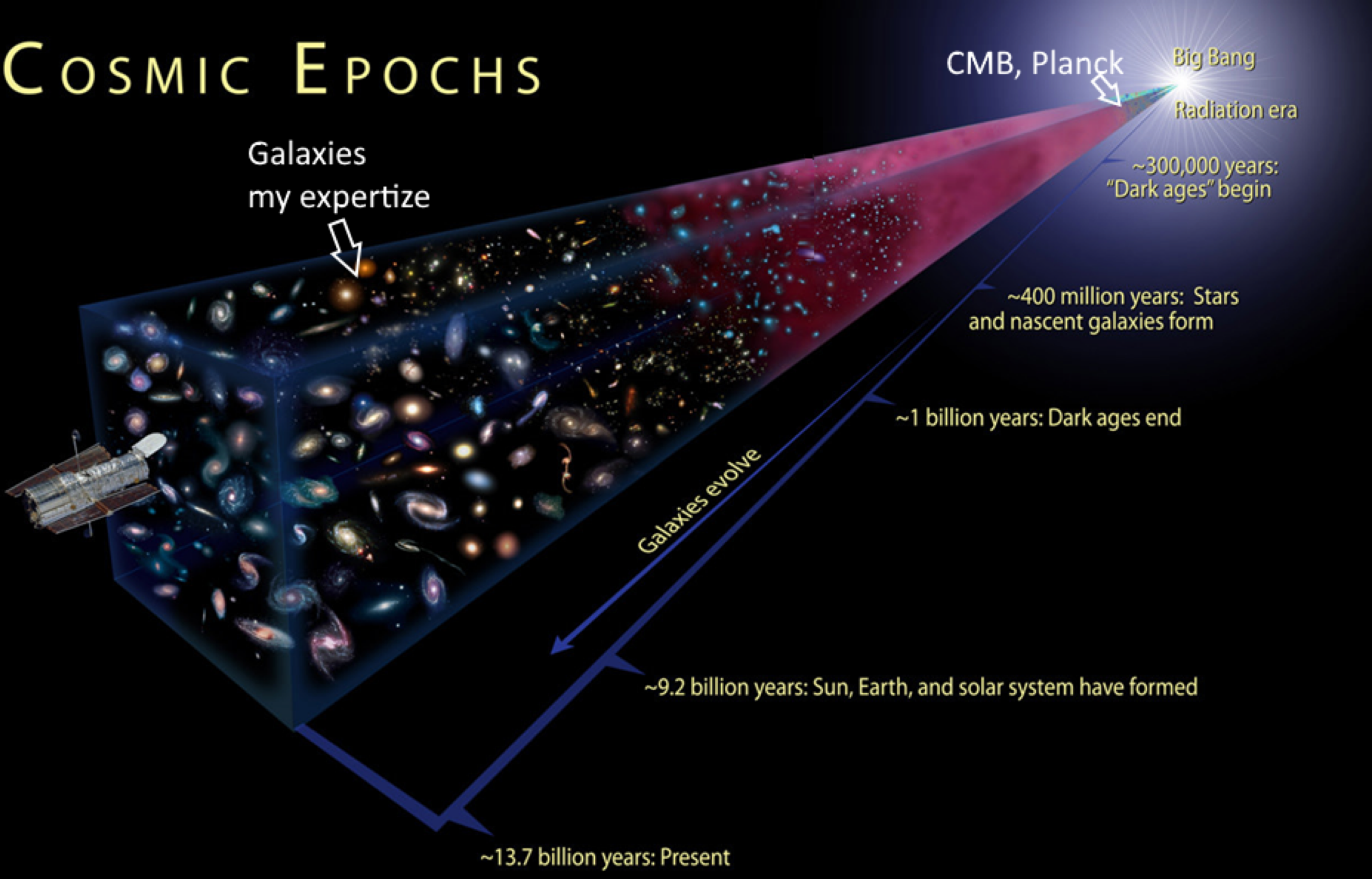


CMB, Planck

Galaxies
my expertize

Borrowing slides, images from: Risa Wechsler, Ken Ganga, David L. Clements arxiv1707.09220, Wayne Hu, Martin White, Hervé Dole , COBE-, WMAP-, Planck collaborations

THE ΛCDM MODEL OF THE UNIVERSE

The ΛCDM model

- Einstein (1915) + Cosmological constant (1917), unstable „Einstein's biggest blunder"

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} - \Lambda g_{\mu\nu}$$

- Hubble (1929): Expanding universe, „**Hubble diagram**" (inverted)

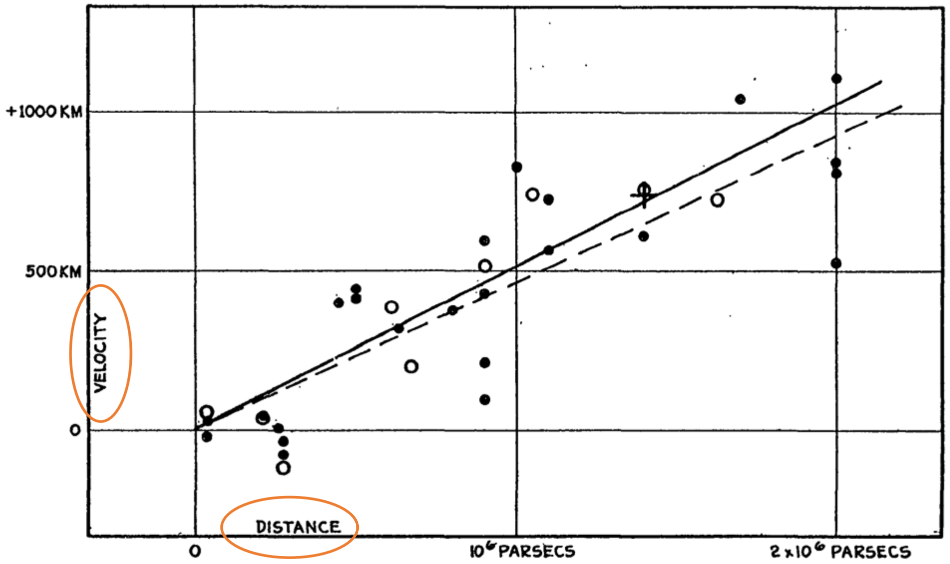


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

Cosmological constant was **dropped until the 90's** when it appeared again as Dark Energy.

Friedmann–Lemaître–Robertson–Walker (FLRW, ΛCDM) model

- Assuming that the universe is
  - Homogeneous
  - Isotropic

$$ds^2 = -c^2\,dt^2 + a(t)^2\left(\frac{\mathrm{d}r^2}{1-kr^2} + r^2\left(\mathrm{d}\theta^2 + \sin^2\theta\,\mathrm{d}\phi^2\right)\right)$$

scale factor

curvature

- Friedmann equations (1922)

Hubble parameter →

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3}$$

- Dimensionless version

$$\rho_c = \frac{3H^2}{8\pi G} \qquad \Omega \equiv \frac{\rho}{\rho_c} = \frac{8\pi G\rho}{3H^2}$$

critical density

radiation

matter

curvature

dark energy

$$\frac{H^2}{H_0^2} = \Omega_{0,R}a^{-4} + \Omega_{0,M}a^{-3} + \Omega_{0,k}a^{-2} + \Omega_{0,\Lambda}$$

Observables of the ΛCDM model – before CMB

- Redshift

$$a = \frac{1}{1+z}$$

$$1 + z = \frac{\lambda_{\text{obsv}}}{\lambda_{\text{emit}}}$$

Can be calculated from observed size of large scale structures (BAO) : “standard rulers”

Can be calculated from observed magnitudes (luminosities) of “standard candles”

- Cosmological distances

$$H(z) = H_0 E(z) \qquad d_H = c/H_0$$

$$E(z) = \sqrt{\Omega_r (1+z)^4 + \Omega_m (1+z)^3 + \Omega_k (1+z)^2 + \Omega_\Lambda}$$

Comoving distance:

$$d_C(z) = d_H \int_0^z \frac{dz'}{E(z')}$$

Transverse comoving distance:

$$d_M(z) = \begin{cases} \frac{d_H}{\sqrt{\Omega_k}} \sinh\left(\sqrt{\Omega_k}\, d_C(z)/d_H\right) & \text{for } \Omega_k > 0 \\ d_C(z) & \text{for } \Omega_k = 0 \\ \frac{d_H}{\sqrt{|\Omega_k|}} \sin\left(\sqrt{|\Omega_k|}\, d_C(z)/d_H\right) & \text{for } \Omega_k < 0 \end{cases}$$

Angular diameter distance:

$$d_A(z) = \frac{d_M(z)}{1+z}$$

Luminosity distance:

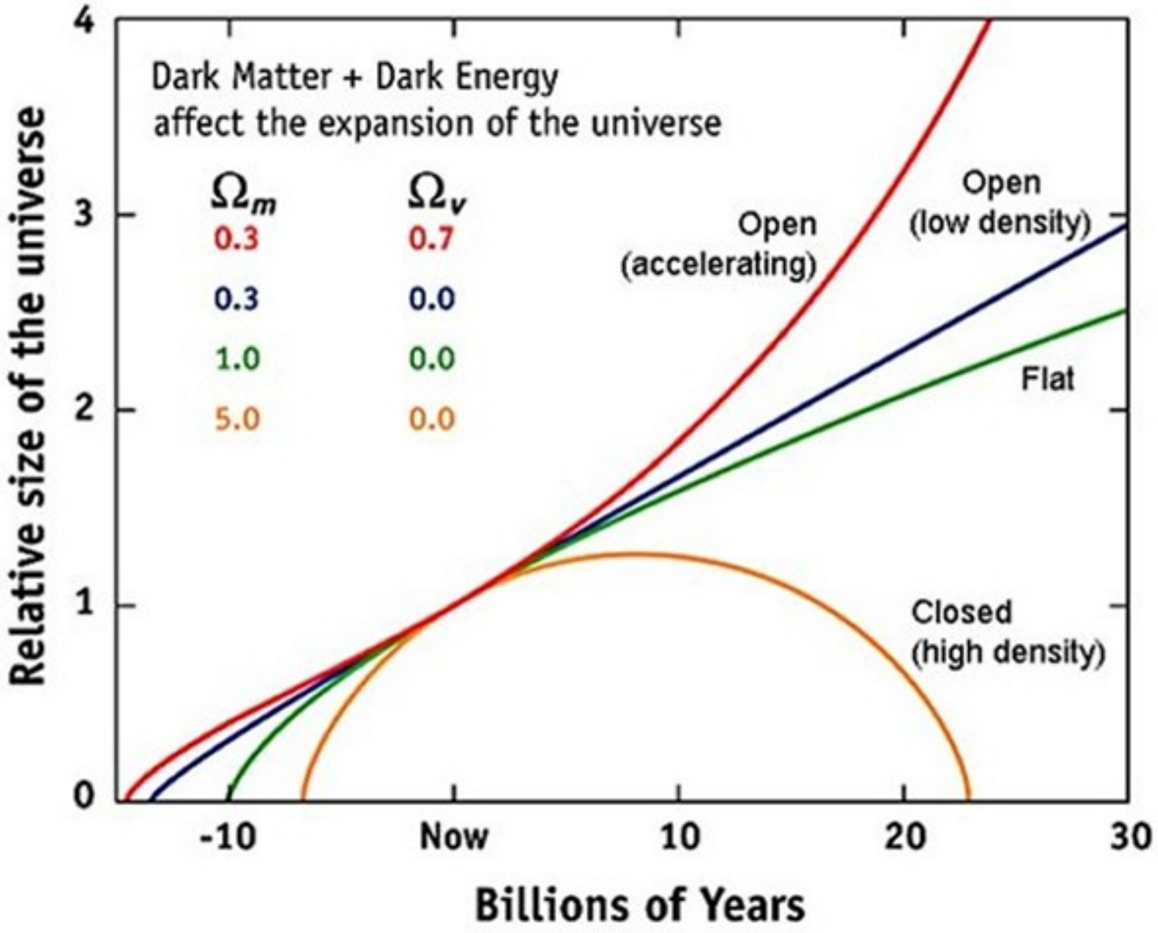
$$d_L(z) = (1+z) d_M(z)$$

Light-travel distance:

$$d_T(z) = d_H \int_0^z \frac{dz'}{(1+z')E(z')}$$

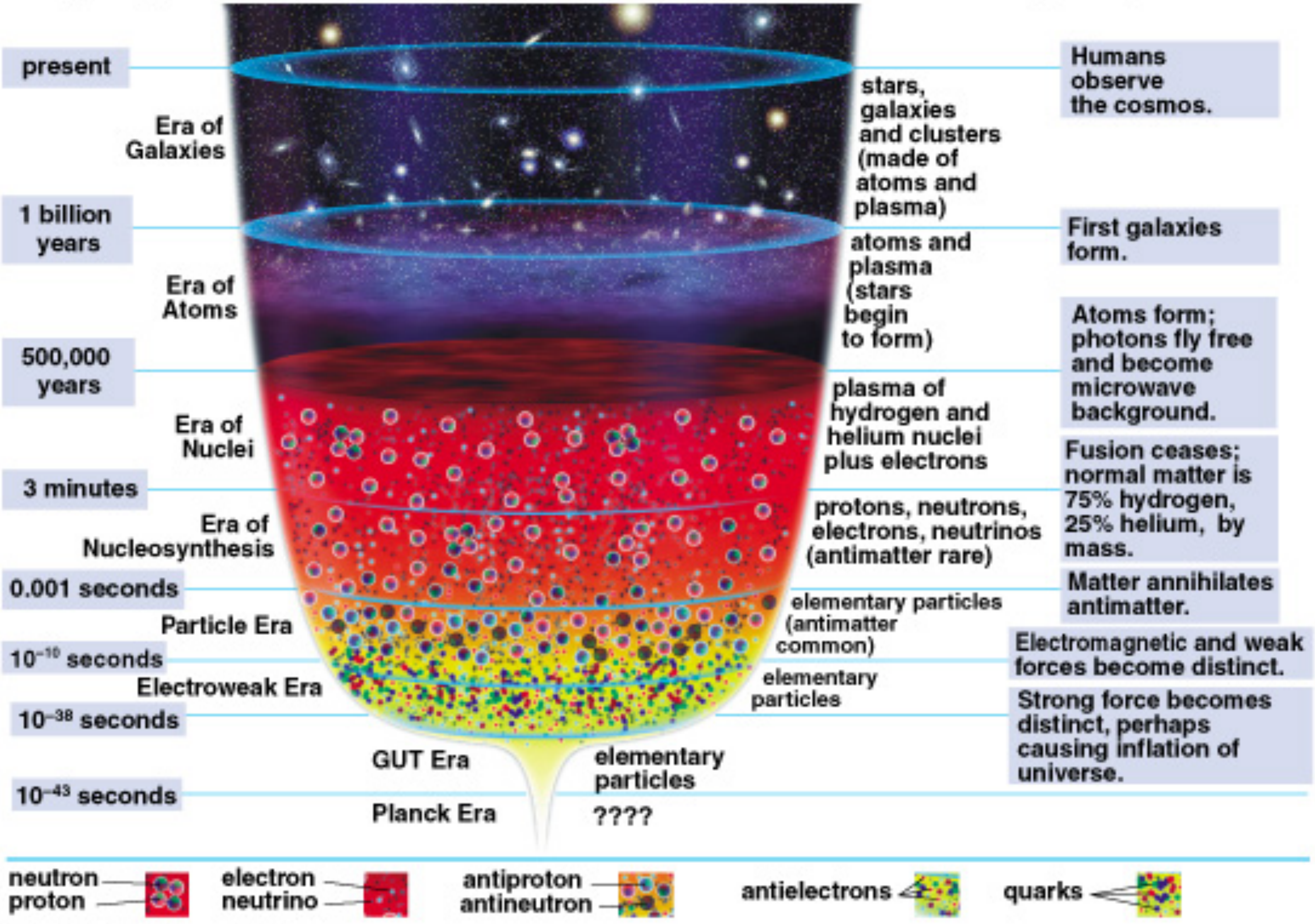
Fate of the universe

- Density is Destiny!
- Parameters can be estimated with various sensitivities from various observations :
  - Matter content: supernovae
  - Flatness: cosmic microwave background



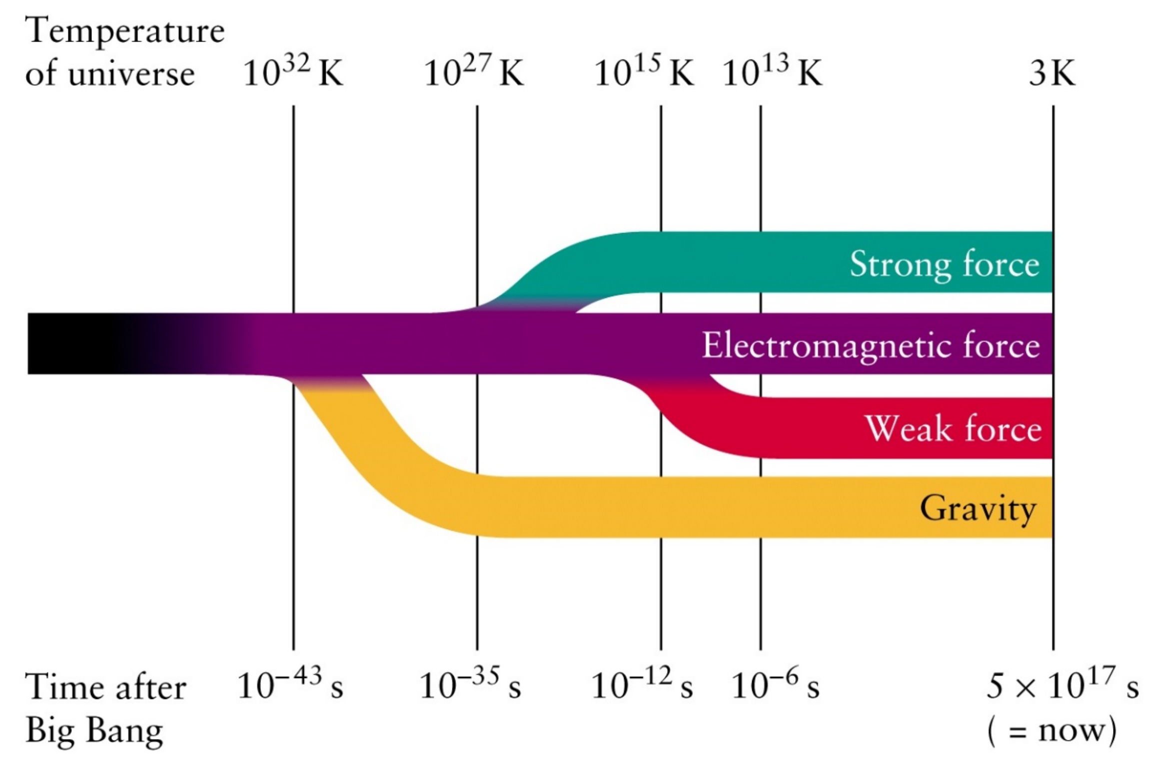
SHORT HISTORY OF THE UNIVERSE

From Planck era to Planck

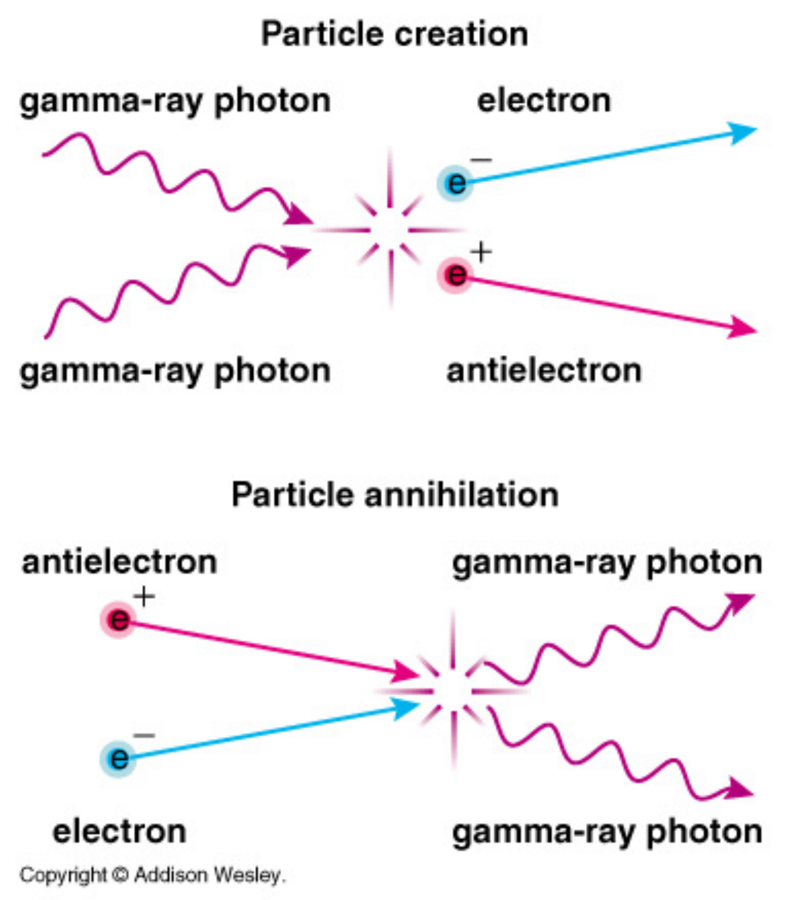


Time Since Big Bang	Era	Contents	Major Events Since Big Bang
present			Humans observe the cosmos.
	Era of Galaxies	stars, galaxies and clusters (made of atoms and plasma)	
1 billion years			First galaxies form.
	Era of Atoms	atoms and plasma (stars begin to form)	
500,000 years			Atoms form; photons fly free and become microwave background.
	Era of Nuclei	plasma of hydrogen and helium nuclei plus electrons	
3 minutes			Fusion ceases; normal matter is 75% hydrogen, 25% helium, by mass.
	Era of Nucleosynthesis	protons, neutrons, electrons, neutrinos (antimatter rare)	
0.001 seconds			Matter annihilates antimatter.
	Particle Era	elementary particles (antimatter common)	
10^{-10} seconds			Electromagnetic and weak forces become distinct.
	Electroweak Era	elementary particles	
10^{-38} seconds			Strong force becomes distinct, perhaps causing inflation of universe.
	GUT Era	elementary particles	
10^{-43} seconds			
	Planck Era	????	

- $<10^{-43}$ seconds: Planck era
  - before the Planck time (all known laws of physics break down)
- 10^{-43} - 10^{-38} seconds: GUT era
  - all four forces are "unified" (have the same strength)
- 10^{-38} -10^{-10} seconds: electroweak era
  - the electromagnetic and weak force become distinct.



- 10^{-10} - 0.001 seconds: particle era
  - plasma of fundamental particles (matter and anti-matter)
  - for some unknown reason, there must have been slightly more matter than anti-matter, at least in our corner of the Universe
  - at the end of the particle era, matter and anti-matter annihilate, leaving mostly matter. Photons outnumber protons by a billion to 1.



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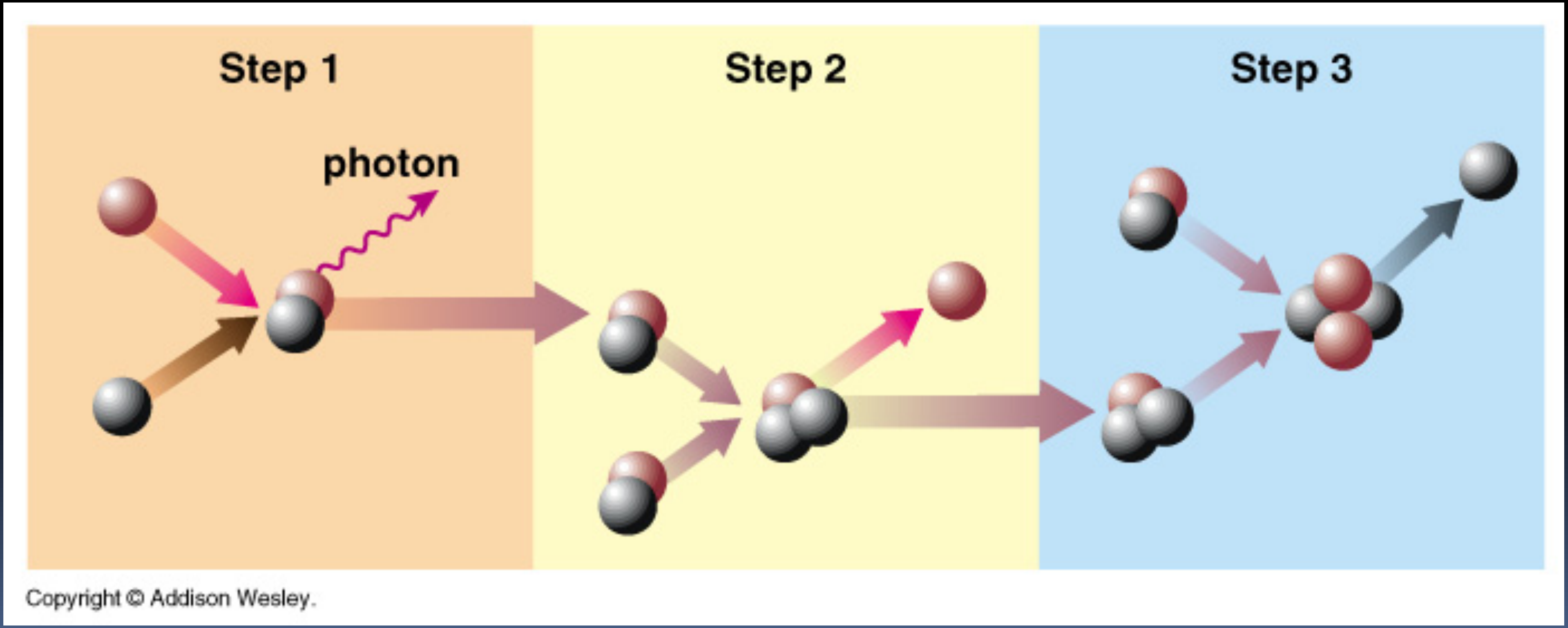
Big Bang Nucleosynthesis

- 0.001 seconds– 3 minutes: nucleosynthesis

  temperatures of 10^9 K allow hydrogen nuclei to fuse into helium nuclei.

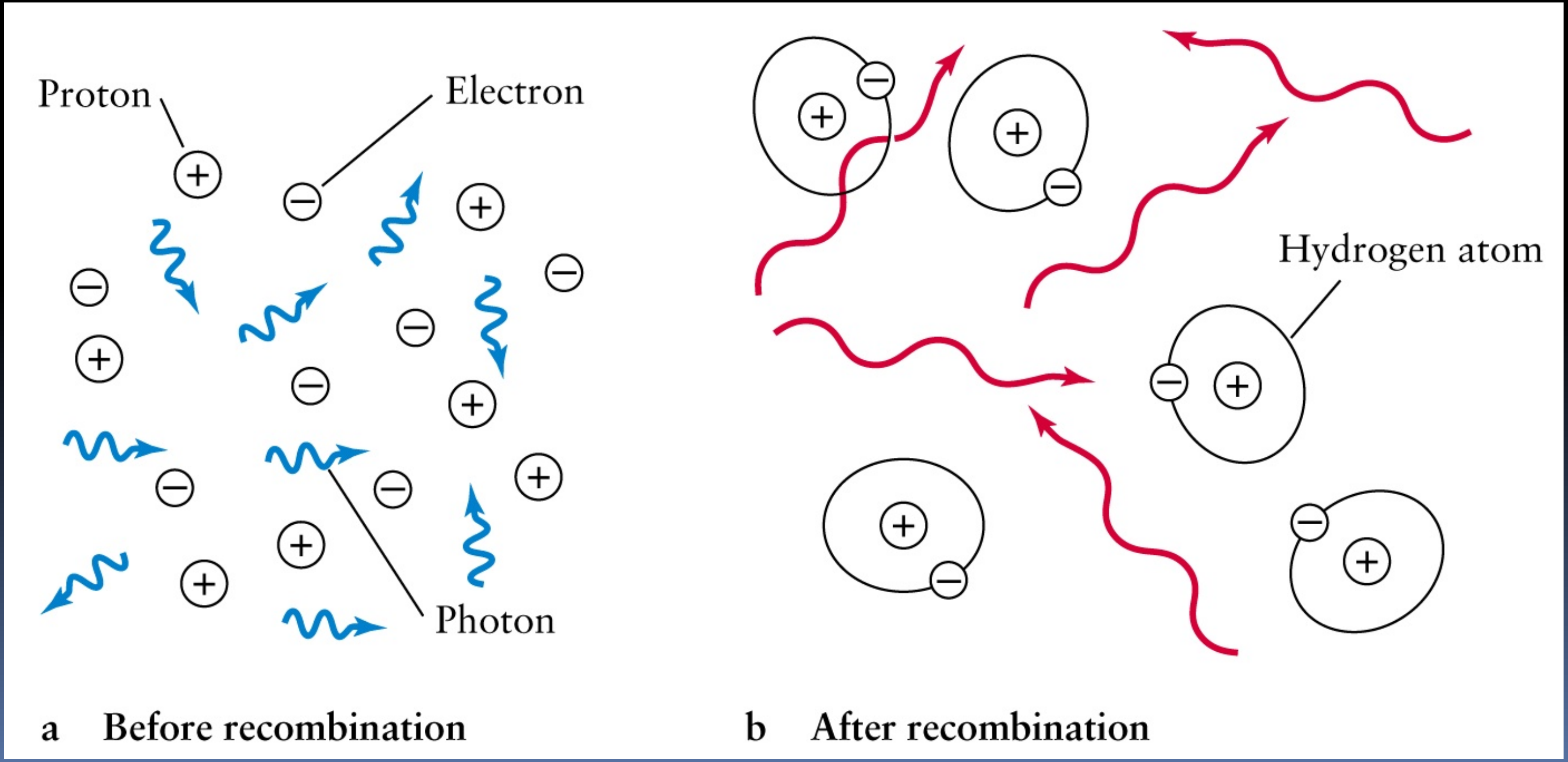


the density of baryons

- at very high temperatures (>10^{11} K) protons and neutrons can change into one another
- as the Universe cools, protons (which are slightly less massive) become favored
- ratio of protons to neutrons at the time when nucleosynthesis begins is predicted to be 7 to 1
- deuterium is formed in the course of fusing hydrogen to helium, and some is still left over
- the observed ratio of deuterium to hydrogen and helium tells us the density of baryons (protons and neutrons) during the era of nucleosynthesis
- observations of deuterium abundance show that the density of baryons is about 5 % of the critical density
- hydrogen 75 % , helium 25% (plus small amount of lithium)

Recombination

- 3 minutes – 500,000 years : recombination
  - hydrogen and helium nuclei capture electrons and become neutral atoms. The Universe becomes transparent to photons.
  - 10^9 photons for each baryon



Decoupling

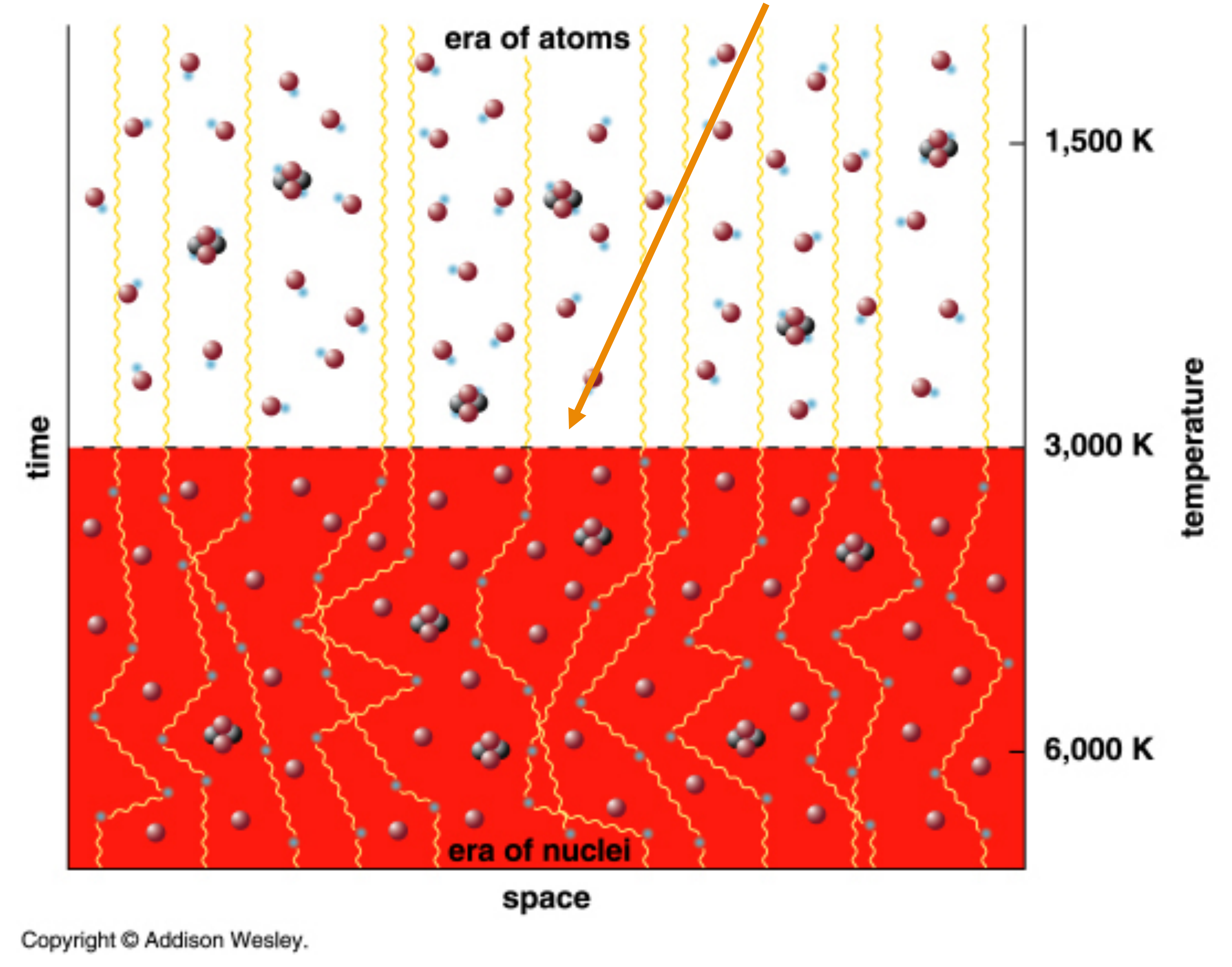
mean free path of the photons ~= horizon size of the universe

electrons attached to atoms, photons stream through

380 000 yrs

electron plasma "soup" traps photons

Relic radiation from the last scattering surface: CMB



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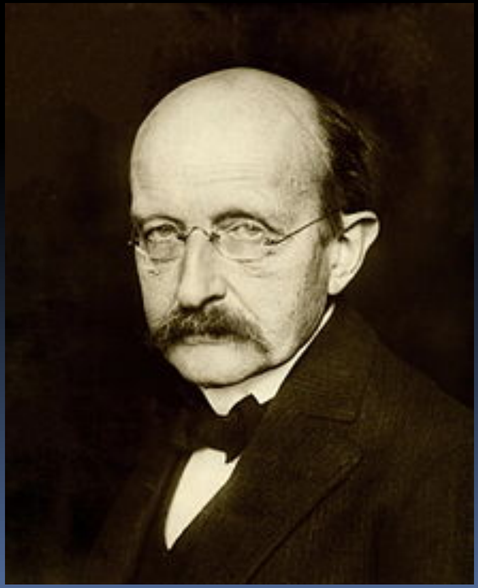
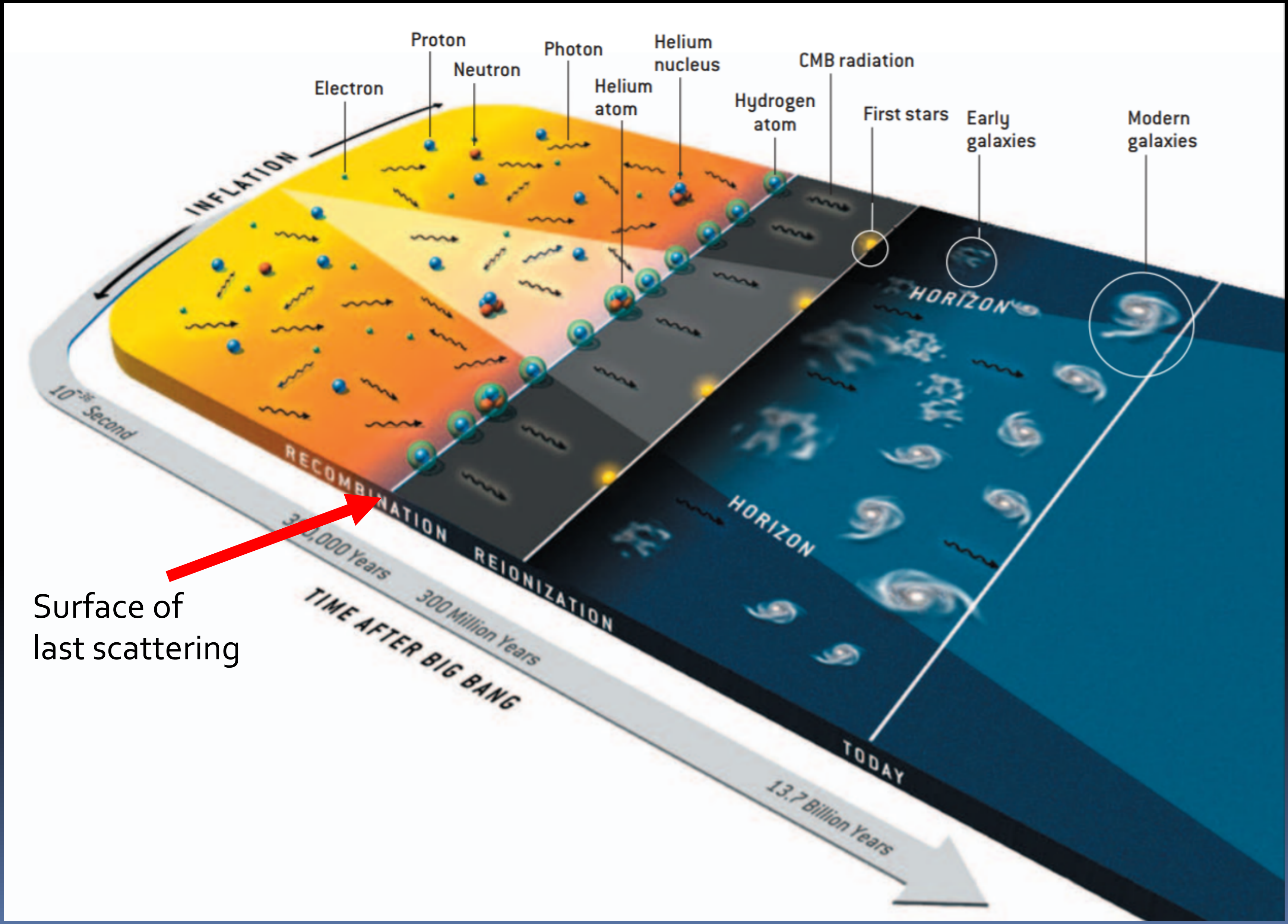
Stars and Galaxies

- The plasma of neutral atoms gradually cools and protogalactic clouds form.
- The first stars form out of the hydrogen and helium, make heavy elements, etc.
- Supernovae create even heavier elements
- Planets
- Life
- Physicists, Planck …

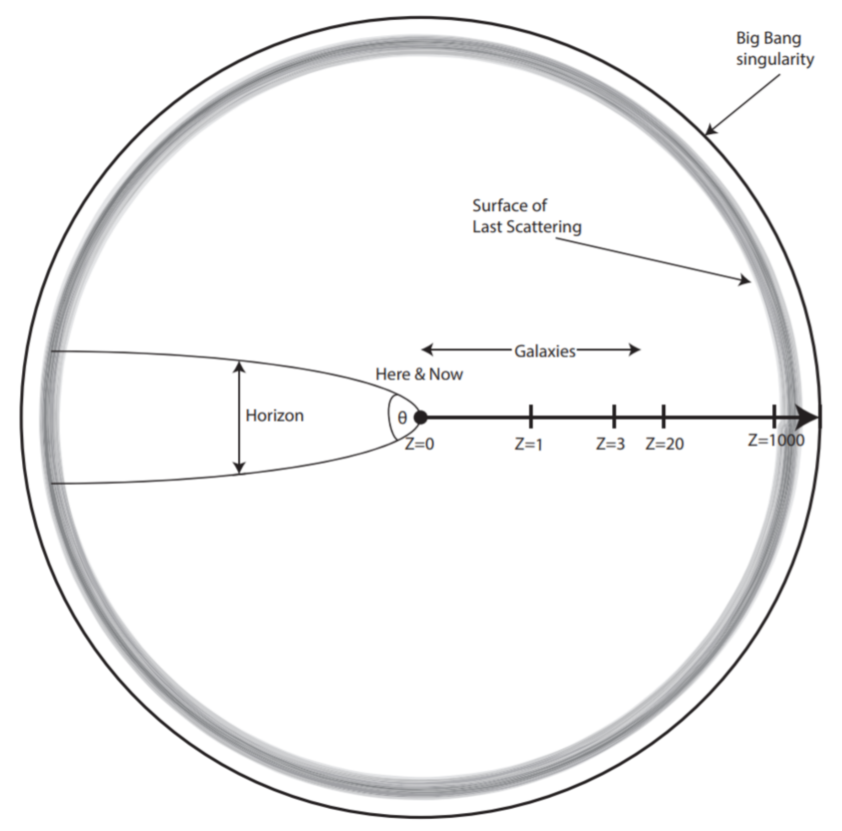


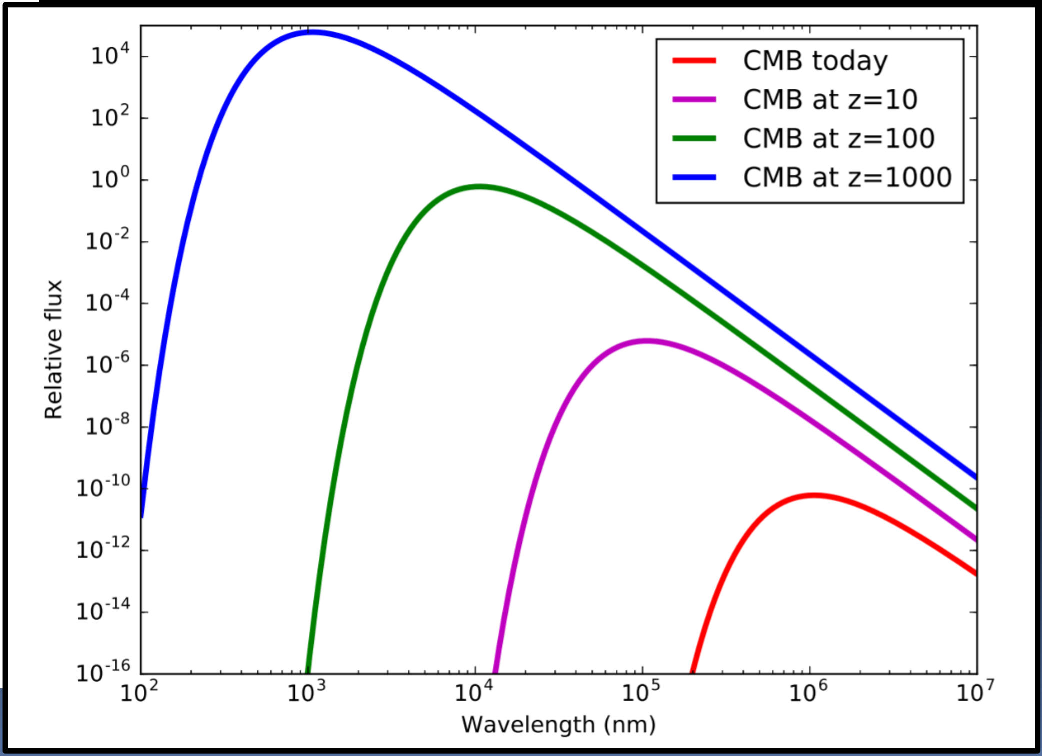
Cosmic microwave background



Surface of
last scattering

- Before recombination: thermal equilibrium ~1100K
- After recombination: free black body “Planck” radiation
- Expansion – redshift: redshifted black body radiation is a black body radiation at lower temperature

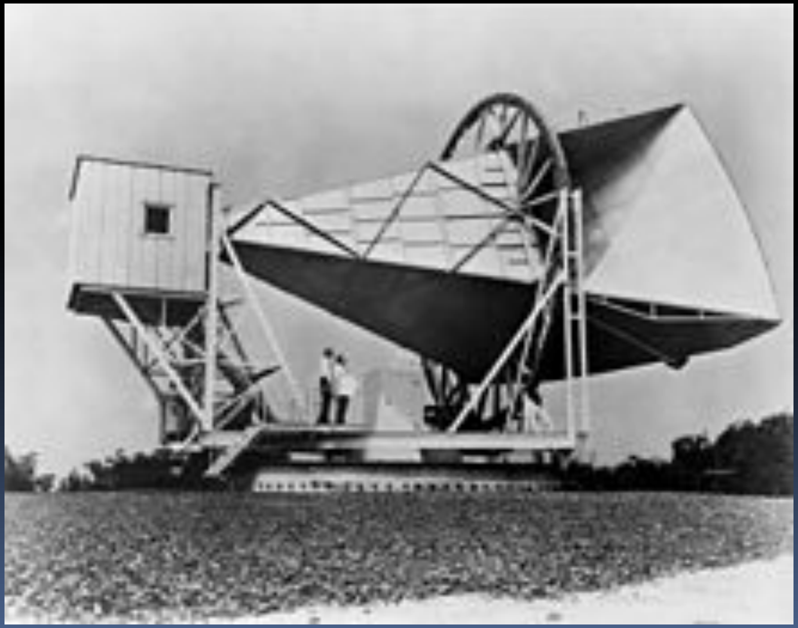


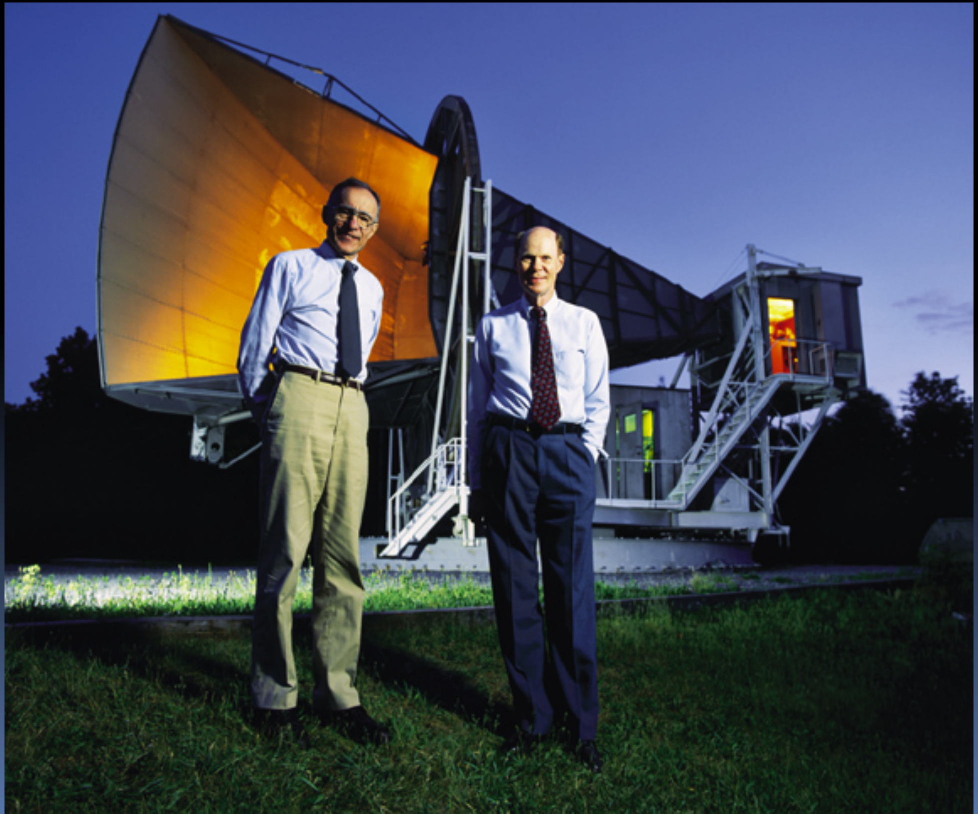


CMB OBSERVATION

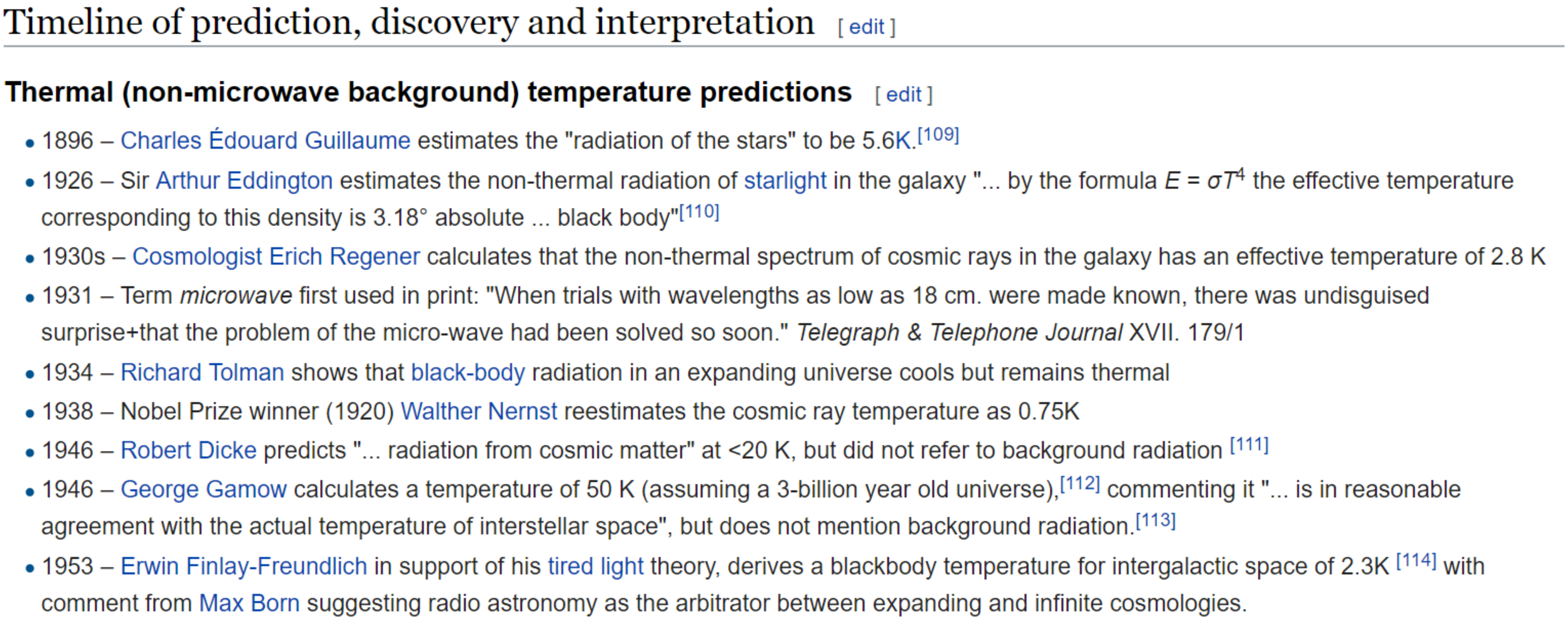
Penzias & Wilson, 1964, Nobel prize 1978

- Predicted earlier, Alpher&Herman ’48, Gamow, Zeldovich, Dicke ’60s
- ’64: Princeton group planned measurement: Dicke, Wilkinson, Roll. “we have been scooped”





More history …



Timeline of prediction, discovery and interpretation [edit]

Thermal (non-microwave background) temperature predictions [edit]

- 1896 – Charles Édouard Guillaume estimates the "radiation of the stars" to be 5.6K.[109]
- 1926 – Sir Arthur Eddington estimates the non-thermal radiation of starlight in the galaxy "... by the formula $E = \sigma T^4$ the effective temperature corresponding to this density is 3.18° absolute ... black body"[110]
- 1930s – Cosmologist Erich Regener calculates that the non-thermal spectrum of cosmic rays in the galaxy has an effective temperature of 2.8 K
- 1931 – Term *microwave* first used in print: "When trials with wavelengths as low as 18 cm. were made known, there was undisguised surprise+that the problem of the micro-wave had been solved so soon." *Telegraph & Telephone Journal* XVII. 179/1
- 1934 – Richard Tolman shows that black-body radiation in an expanding universe cools but remains thermal
- 1938 – Nobel Prize winner (1920) Walther Nernst reestimates the cosmic ray temperature as 0.75K
- 1946 – Robert Dicke predicts "... radiation from cosmic matter" at <20 K, but did not refer to background radiation [111]
- 1946 – George Gamow calculates a temperature of 50 K (assuming a 3-billion year old universe),[112] commenting it "... is in reasonable agreement with the actual temperature of interstellar space", but does not mention background radiation.[113]
- 1953 – Erwin Finlay-Freundlich in support of his tired light theory, derives a blackbody temperature for intergalactic space of 2.3K [114] with comment from Max Born suggesting radio astronomy as the arbitrator between expanding and infinite cosmologies.

Microwave background radiation predictions and measurements [edit]

- 1941 – Andrew McKellar detected the cosmic microwave background as the coldest component of the interstellar medium by using the excitation of CN doublet lines measured by W. S. Adams in a B star, finding an "effective temperature of space" (the average bolometric temperature) of 2.3 K[31][115]
- 1946 – George Gamow calculates a temperature of 50 K (assuming a 3-billion year old universe),[112] commenting it "... is in reasonable agreement with the actual temperature of interstellar space", but does not mention background radiation.
- 1948 – Ralph Alpher and Robert Herman estimate "the temperature in the universe" at 5 K. Although they do not specifically mention microwave background radiation, it may be inferred.[116]
- 1949 – Ralph Alpher and Robert Herman re-re-estimate the temperature at 28 K.
- 1953 – George Gamow estimates 7 K.[111]
- 1956 – George Gamow estimates 6 K.[111]
- 1955 – Émile Le Roux of the Nançay Radio Observatory, in a sky survey at $\lambda = 33$ cm, reported a near-isotropic background radiation of 3 kelvins, plus or minus 2.[111]
- 1957 – Tigran Shmaonov reports that "the absolute effective temperature of the radioemission background ... is 4±3 K".[117] It is noted that the "measurements showed that radiation intensity was independent of either time or direction of observation ... it is now clear that Shmaonov did observe the cosmic microwave background at a wavelength of 3.2 cm"[118][119]
- 1960s – Robert Dicke re-estimates a microwave background radiation temperature of 40 K[111][120]
- 1964 – A. G. Doroshkevich and Igor Dmitrievich Novikov publish a brief paper suggesting microwave searches for the black-body radiation predicted by Gamow, Alpher, and Herman, where they name the CMB radiation phenomenon as detectable.[121]
- 1964–65 – Arno Penzias and Robert Woodrow Wilson measure the temperature to be approximately 3 K. Robert Dicke, James Peebles, P. G. Roll, and D. T. Wilkinson interpret this radiation as a signature of the big bang.
- 1966 – Rainer K. Sachs and Arthur M. Wolfe theoretically predict microwave background fluctuation amplitudes created by gravitational potential variations between observers and the last scattering surface (see Sachs-Wolfe effect)
- 1968 – Martin Rees and Dennis Sciama theoretically predict microwave background fluctuation amplitudes created by photons traversing time-dependent potential wells
- 1969 – R. A. Sunyaev and Yakov Zel'dovich study the inverse Compton scattering of microwave background photons by hot electrons (see Sunyaev-Zel'dovich effect)
- 1983 – Researchers from the Cambridge Radio Astronomy Group and the Owens Valley Radio Observatory first detect the Sunyaev-Zel'dovich effect from clusters of galaxies
- 1983 – RELIKT-1 Soviet CMB anisotropy experiment was launched.
- 1990 – FIRAS on the Cosmic Background Explorer (COBE) satellite measures the black body form of the CMB spectrum with exquisite precision, and shows that the microwave background has a nearly perfect black-body spectrum and thereby strongly constrains the density of the intergalactic medium.
- January 1992 – Scientists that analysed data from the RELIKT-1 report the discovery of anisotropy in the cosmic microwave background at the Moscow astrophysical seminar.[122]
- 1992 – Scientists that analysed data from COBE DMR report the discovery of anisotropy in the cosmic microwave background.[123]
- 1995 – The Cosmic Anisotropy Telescope performs the first high resolution observations of the cosmic microwave background.
- 1999 – First measurements of acoustic oscillations in the CMB anisotropy angular power spectrum from the TOCO, BOOMERANG, and Maxima Experiments. The BOOMERanG experiment makes higher quality maps at intermediate resolution, and confirms that the universe is "flat".
- 2002 – Polarization discovered by DASI.[124]
- 2003 – E-mode polarization spectrum obtained by the CBI.[125] The CBI and the Very Small Array produces yet higher quality maps at high resolution (covering small areas of the sky).
- 2003 – The Wilkinson Microwave Anisotropy Probe spacecraft produces an even higher quality map at low and intermediate resolution of the whole sky (WMAP provides *no* high-resolution data, but improves on the intermediate resolution maps from BOOMERanG).

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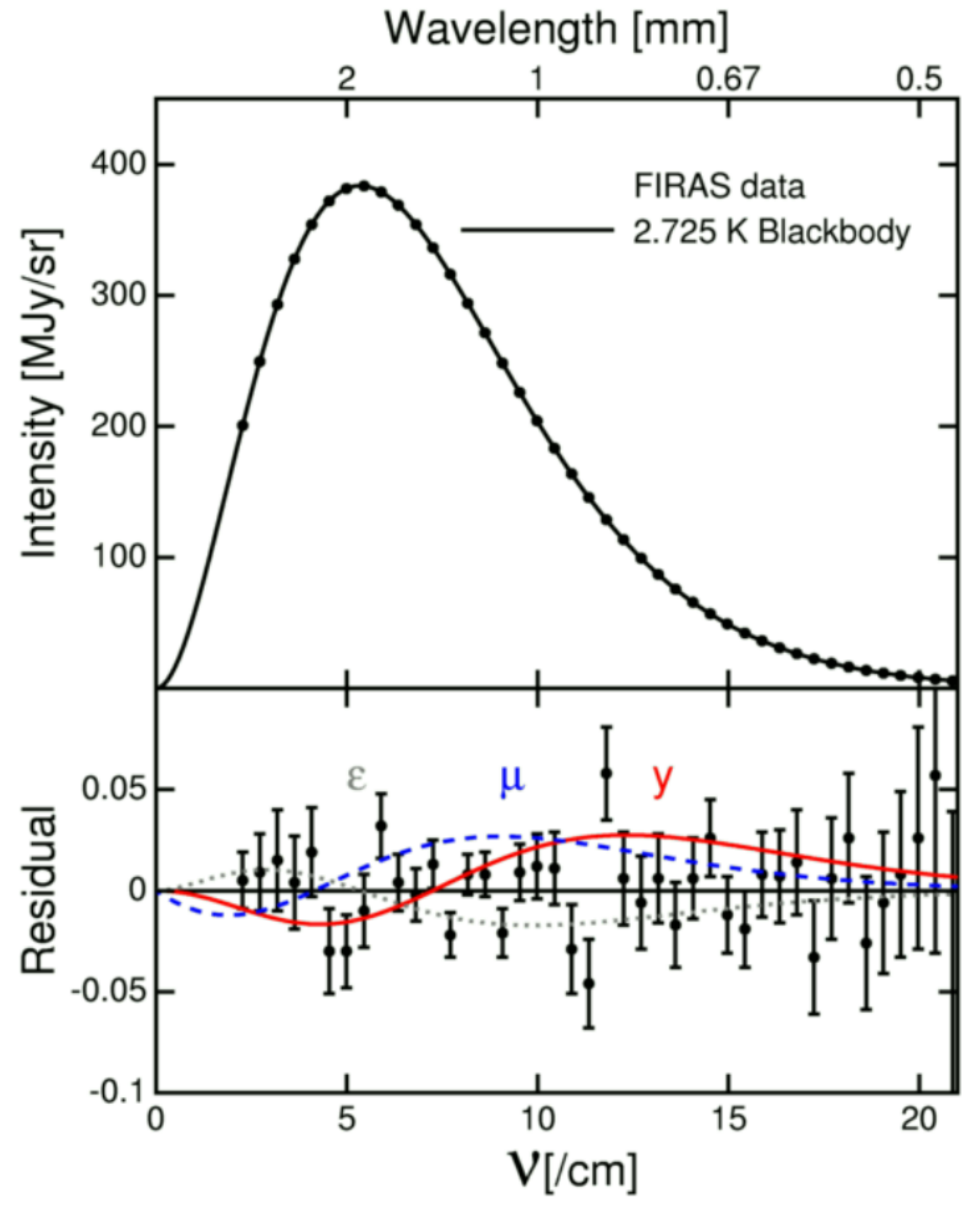
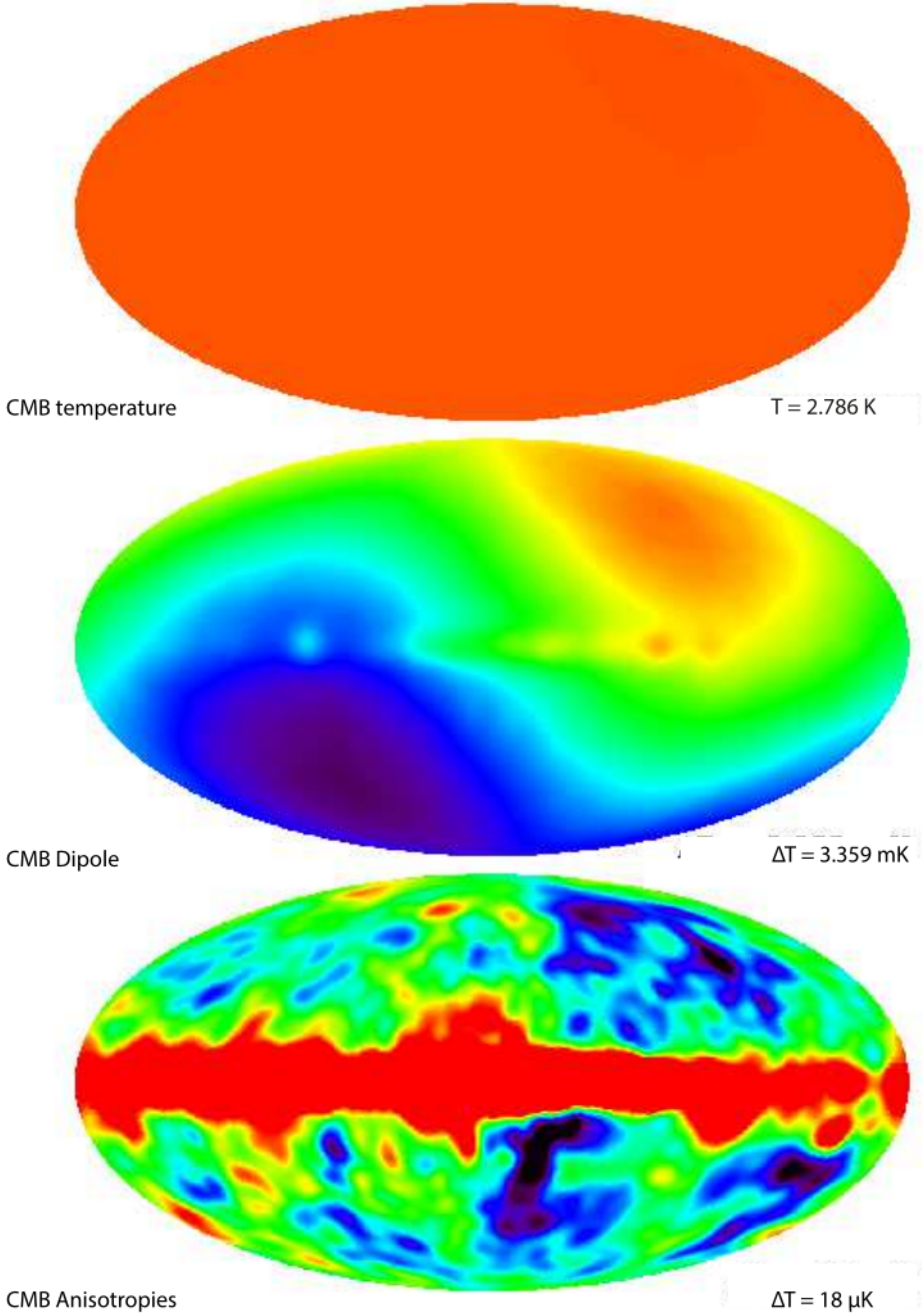
- 2004 – E-mode polarization spectrum obtained by the CBI.[126]
- 2004 – The Arcminute Cosmology Bolometer Array Receiver produces a higher quality map of the high resolution structure not mapped by WMAP.
- 2005 – The Arcminute Microkelvin Imager and the Sunyaev-Zel'dovich Array begin the first surveys for very high redshift clusters of galaxies using the Sunyaev-Zel'dovich effect.
- 2005 – Ralph A. Alpher is awarded the National Medal of Science for his groundbreaking work in nucleosynthesis and prediction that the universe expansion leaves behind background radiation, thus providing a model for the Big Bang theory.
- 2006 – The long-awaited three-year WMAP results are released, confirming previous analysis, correcting several points, and including polarization data.
- 2006 – Two of COBE's principal investigators, George Smoot and John Mather, received the Nobel Prize in Physics in 2006 for their work on precision measurement of the CMBR.
- 2006–2011 – Improved measurements from WMAP, new supernova surveys ESSENCE and SNLS, and baryon acoustic oscillations from SDSS and WiggleZ, continue to be consistent with the standard Lambda-CDM model.
- 2010 – The first all-sky map from the Planck telescope is released.
- 2013 – An improved all-sky map from the Planck telescope is released, improving the measurements of WMAP and extending them to much smaller scales.
- 2014 – On March 17, 2014, astrophysicists of the BICEP2 collaboration announced the detection of inflationary gravitational waves in the B-mode power spectrum, which if confirmed, would provide clear experimental evidence for the theory of inflation.[64][65][66][67][69][127] However, on 19 June 2014, lowered confidence in confirming the cosmic inflation findings was reported.[69][71][72]
- 2015 – On January 30, 2015, the same team of astronomers from BICEP2 withdrew the claim made on the previous year. Based on the combined data of BICEP2 and Planck, the European Space Agency announced that the signal can be entirely attributed to dust in the Milky Way.[128]

Most perfect black body radiation

- Smaller errorbars than line width!
- 2.72548±0.00057 K

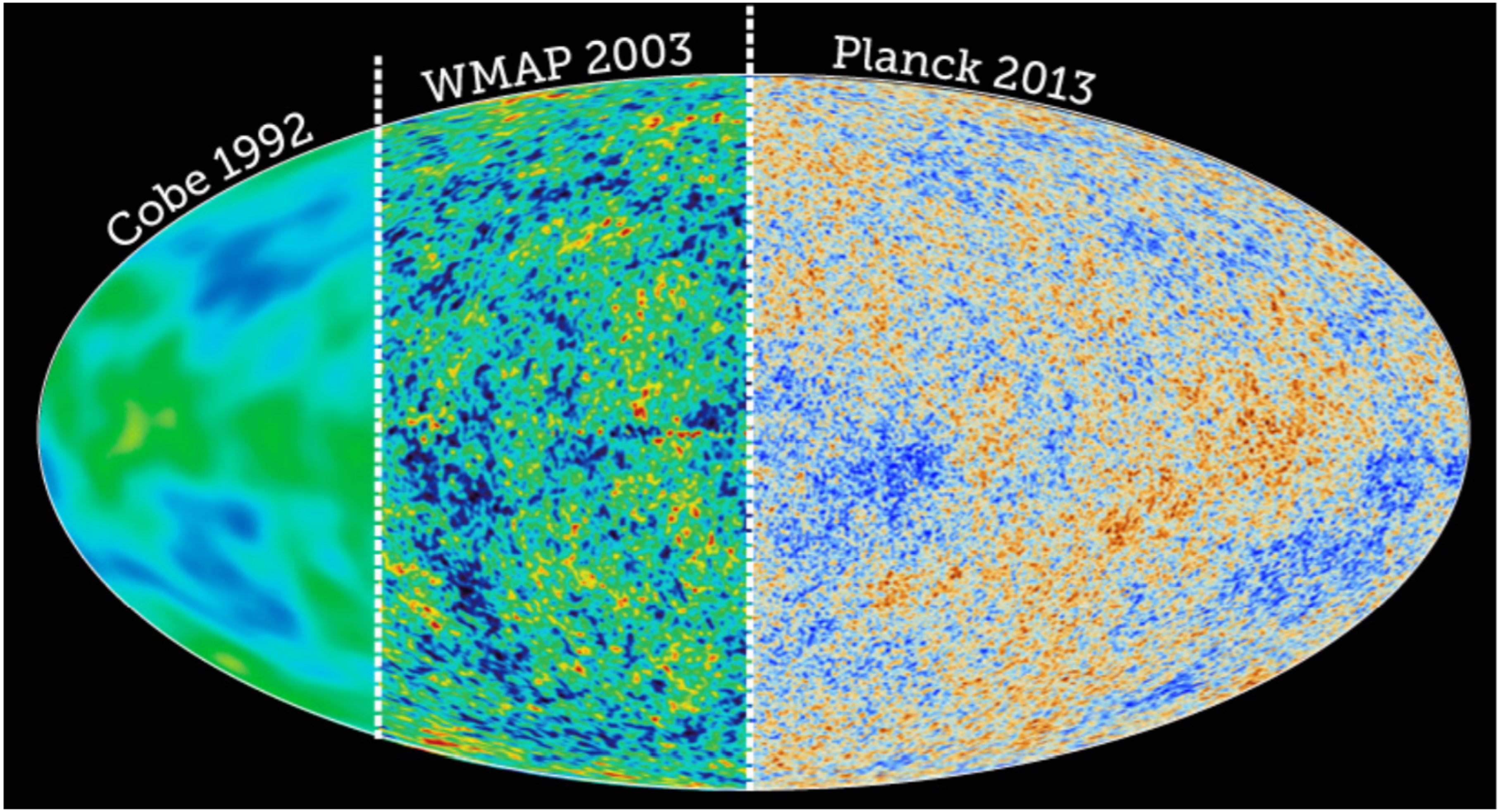




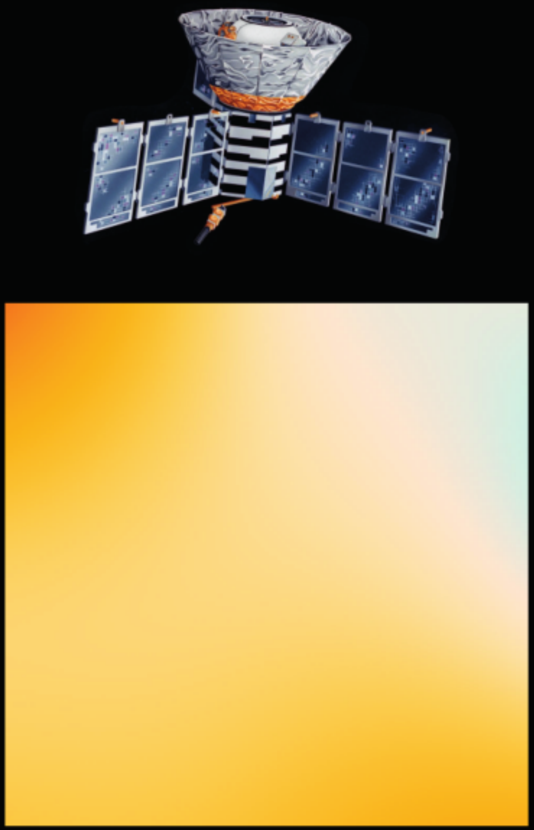
Doppler dipole:
Solar system:368 ± 2 km s^{-1}
Local Group: 627 ± 22 km s^{-1}

PLANCK SPACE OBSERVATORY

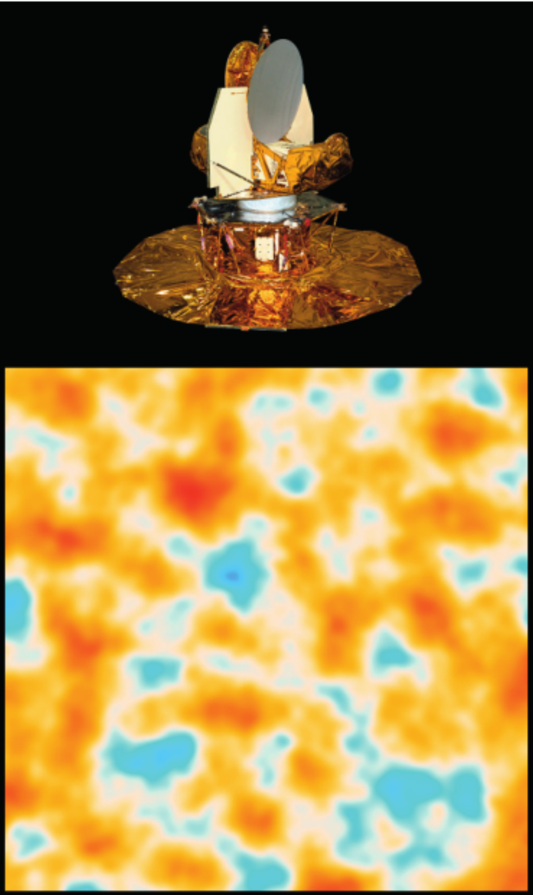
Predecessors: COBE 1992, WMAP 2003 (NASA) + Earth based observations



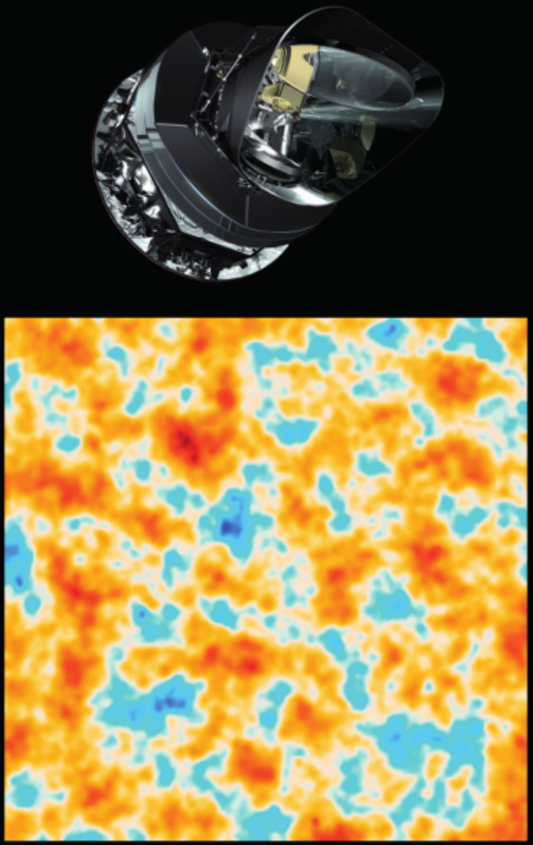
Planck sensitivity in 1yr ~ 1000 years of WMAP



COBE



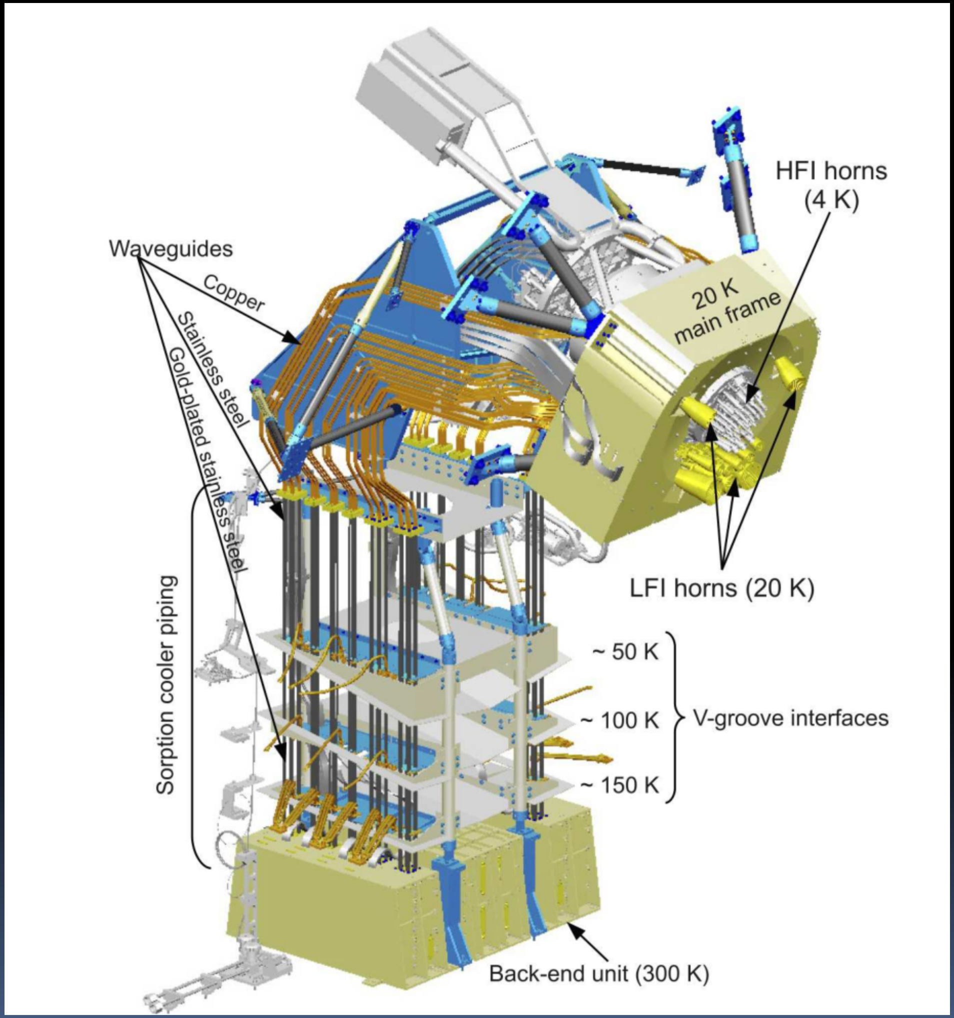
WMAP



Planck

Planck space observatory facts

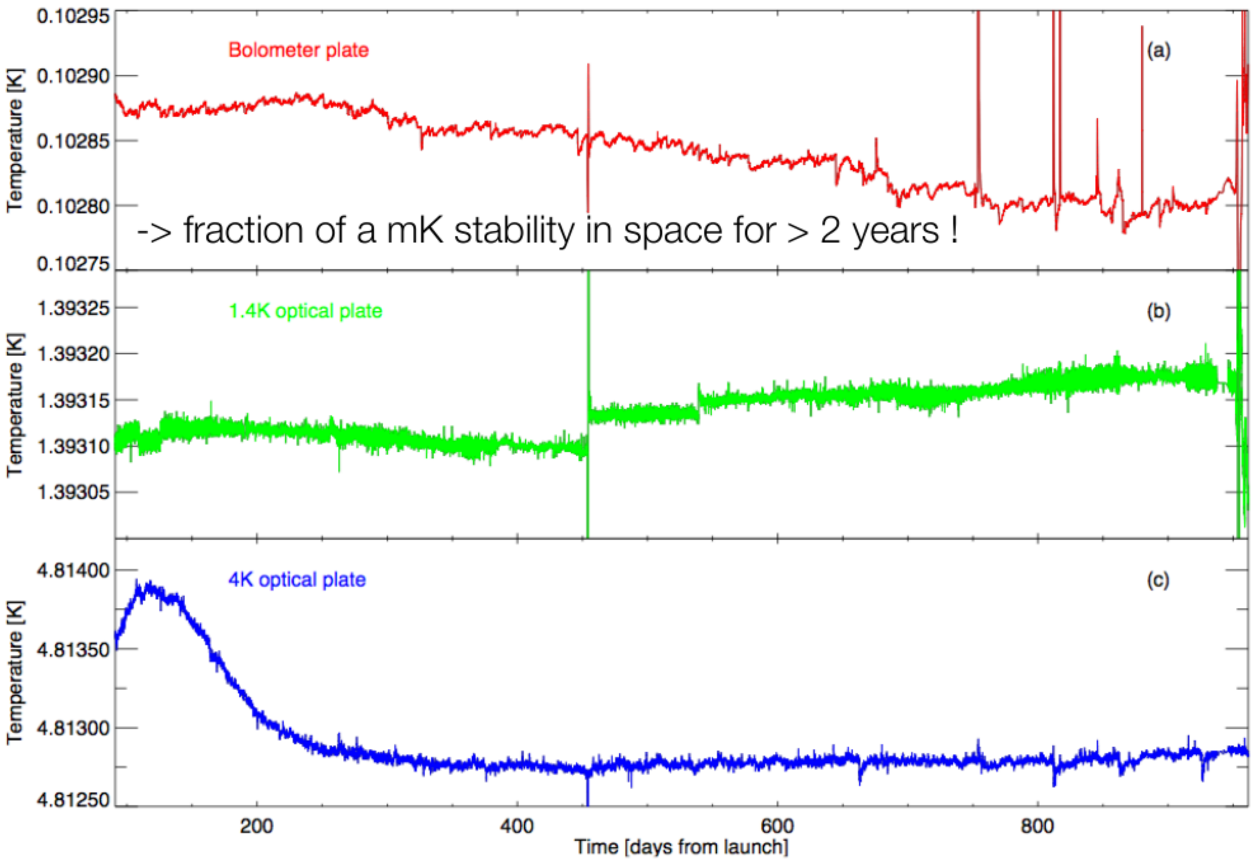
- selected in 1996 by ESA
- launched in 2009
- High- and Low Frequency Instruments (HFI,LFI)
- HFI cooled at 100 mK -> bolometer technology
- 29 months of operation (goal was 12: nominal mission)



Cooling!

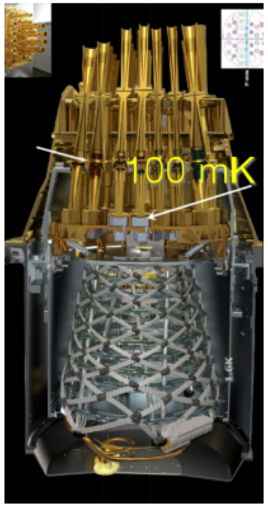
a technological success

stability: 0.1mK !



-> fraction of a mK stability in space for > 2 years !

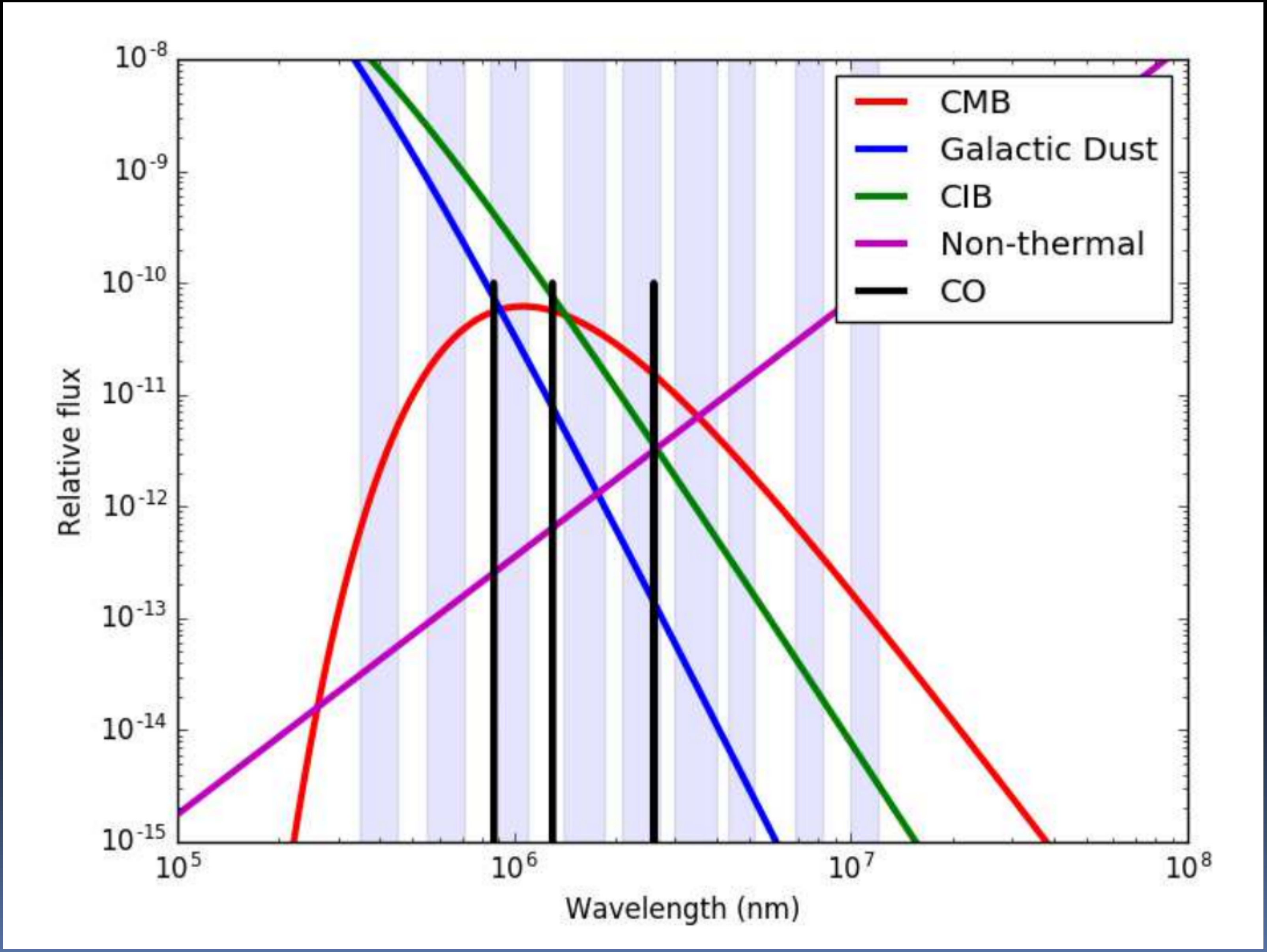
Fig. 7. The impressive stability of the HFI thermal stages during operations. Shown is the temperature evolution of the bolometer stage (*top*), the 1.6 K optical filter stage (*middle*) and the 4-K cooler reference load stage (*bottom*). The horizontal axis displays days since the beginning of the nominal mission.



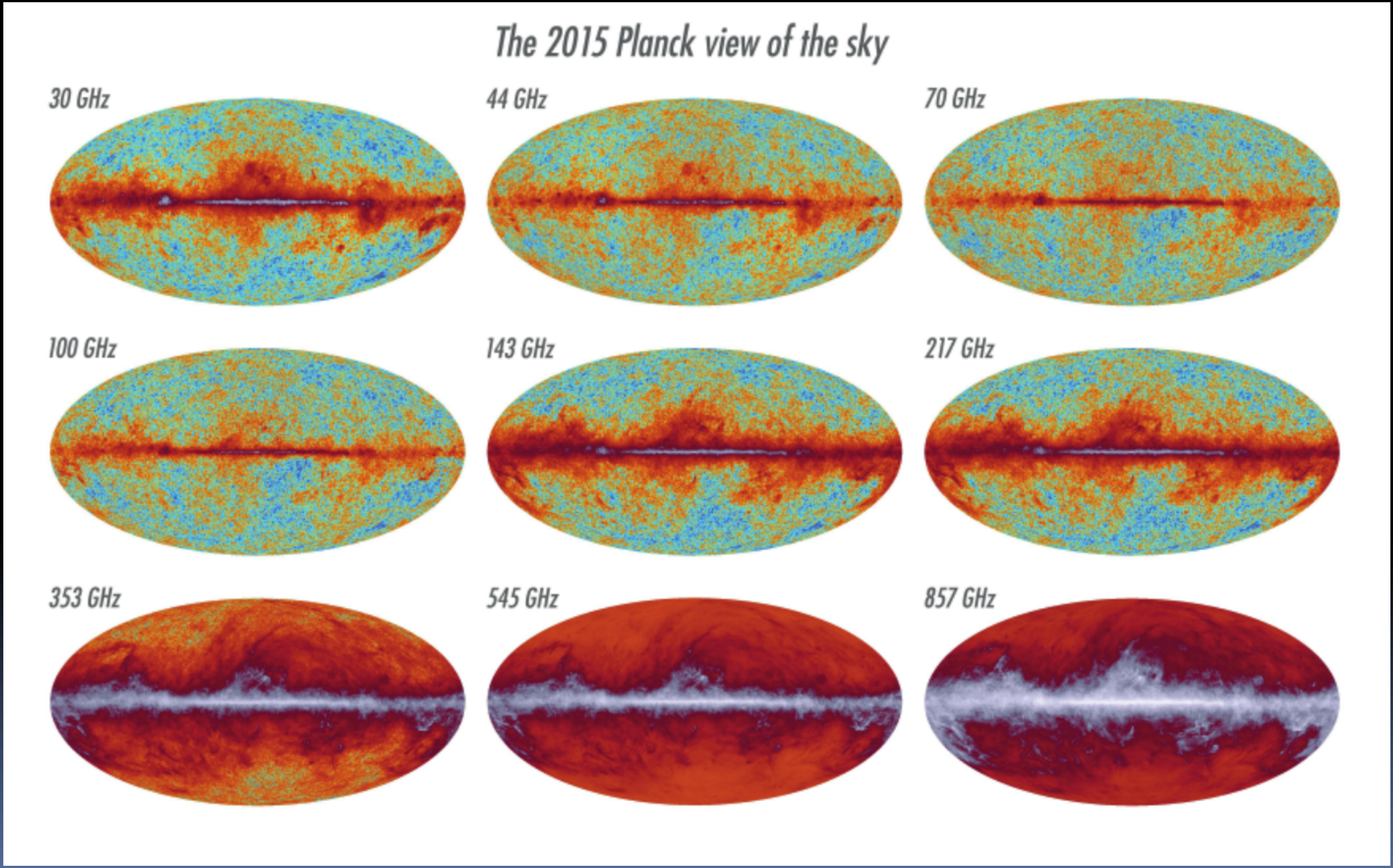
Cryostat:
dilution He3/He4

Planck Collab, 2013, 1

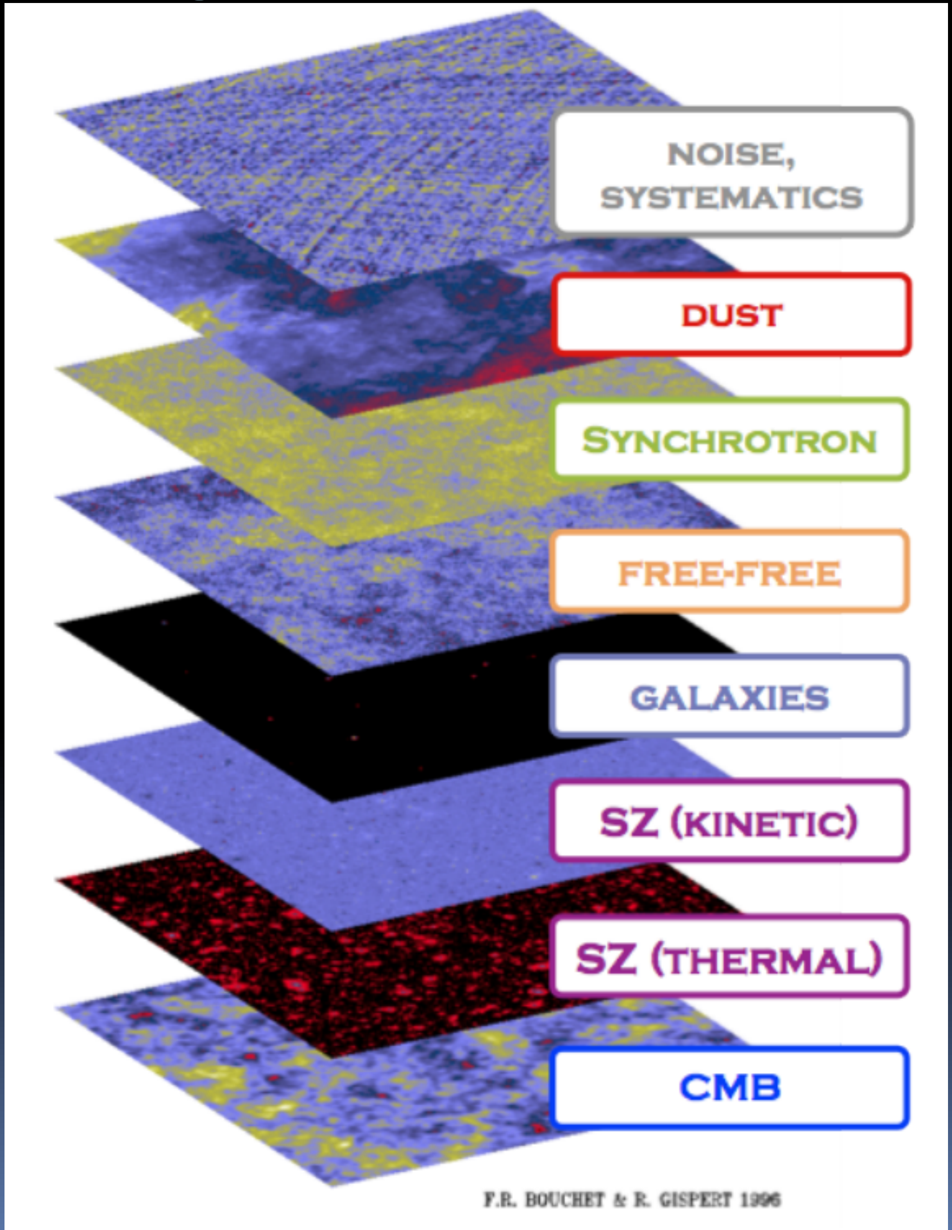
9 bands:
30,44,70,100,143,217,353,545,857 Ghz



Planck maps

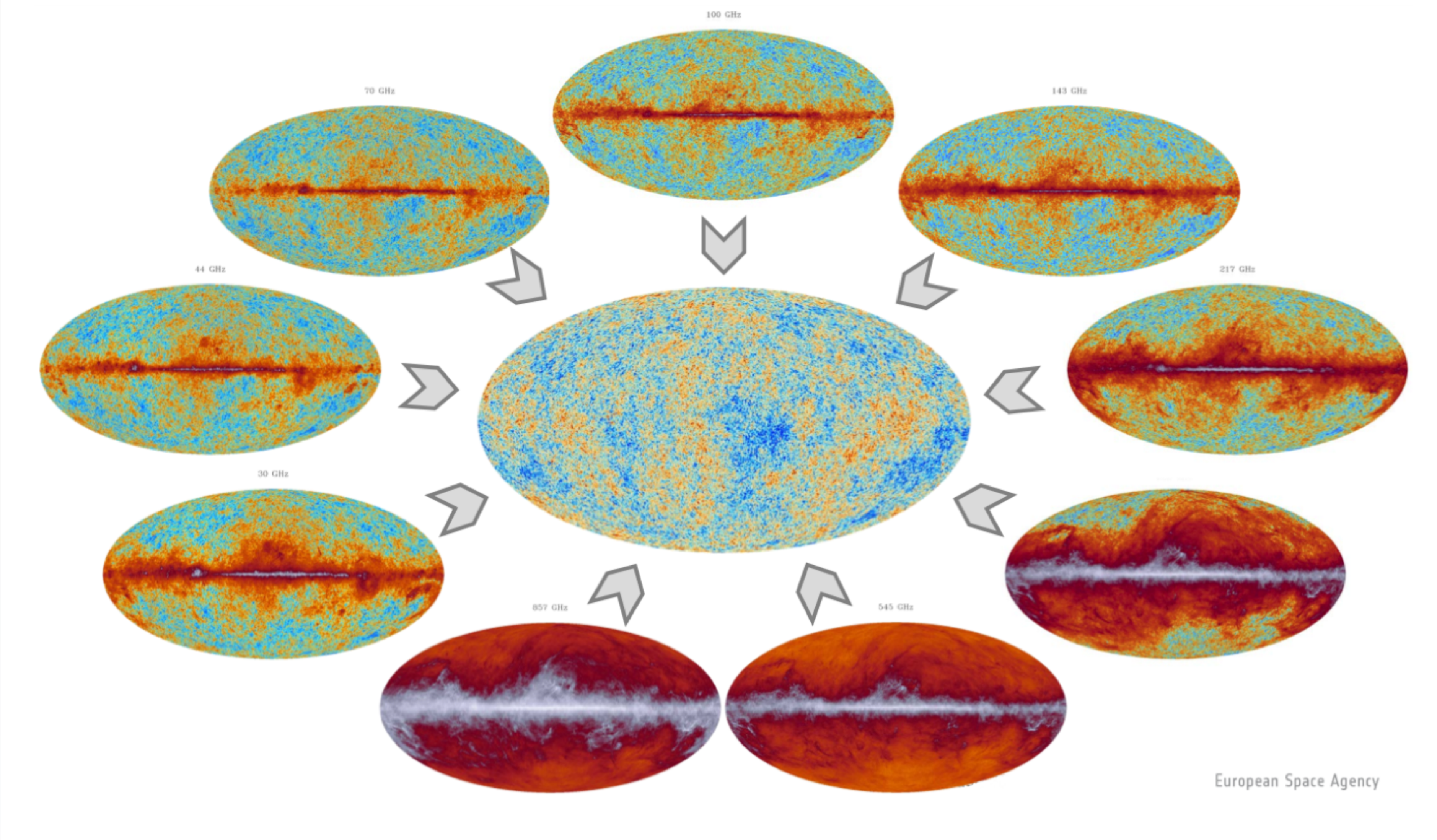

The 2015 Planck view of the sky
30 GHz
44 GHz
70 GHz
100 GHz
143 GHz
217 GHz
353 GHz
545 GHz
857 GHz

Signal is hidden below several layers of noise and foregrounds



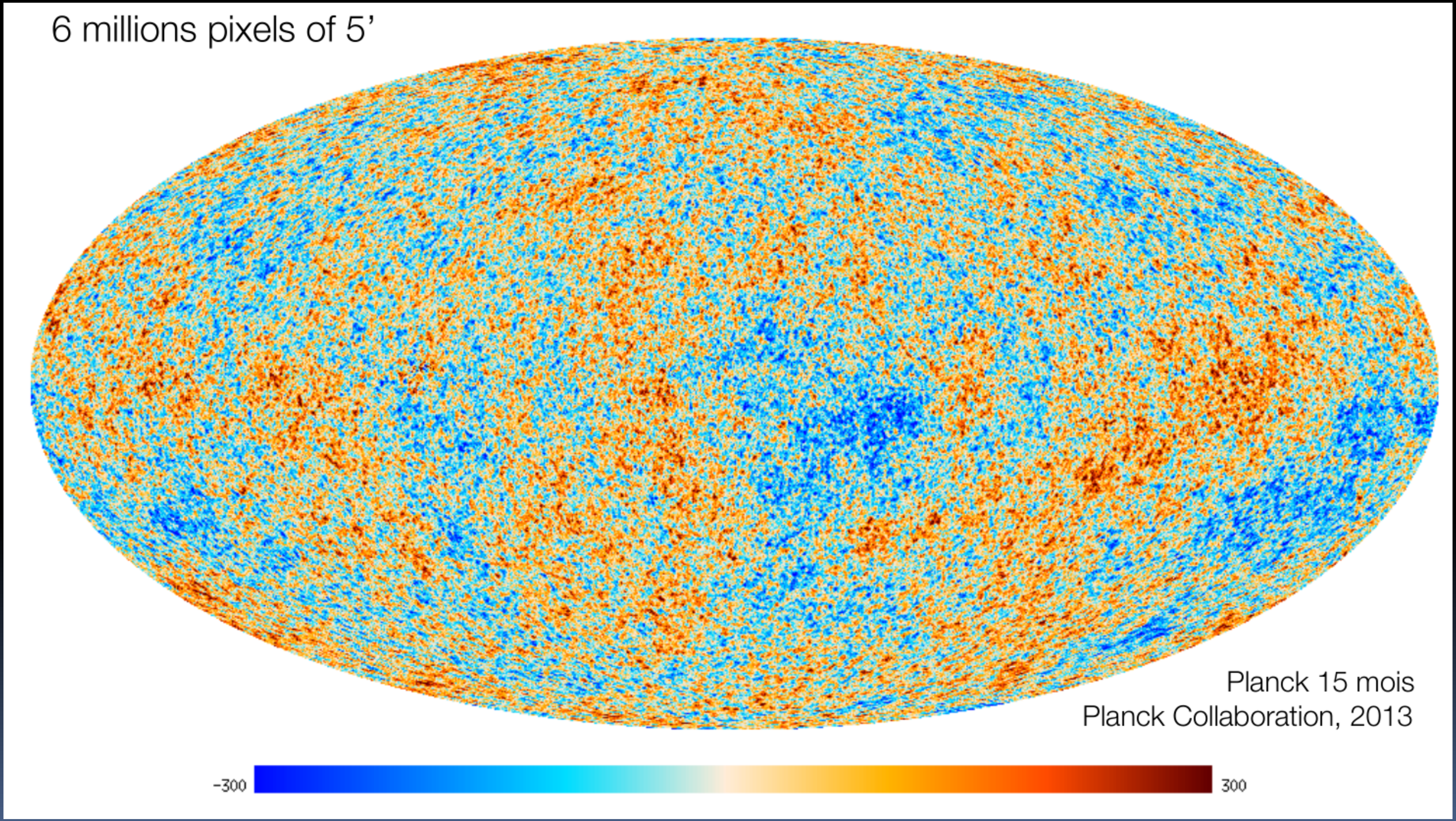
F.R. BOUCHET & R. GISPERT 1996

Component separation: various foregrounds affect each band in different way

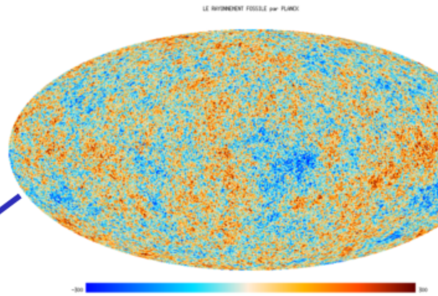


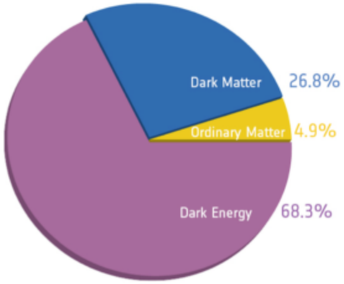
European Space Agency

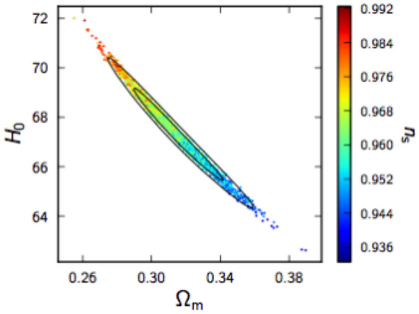
The “map”

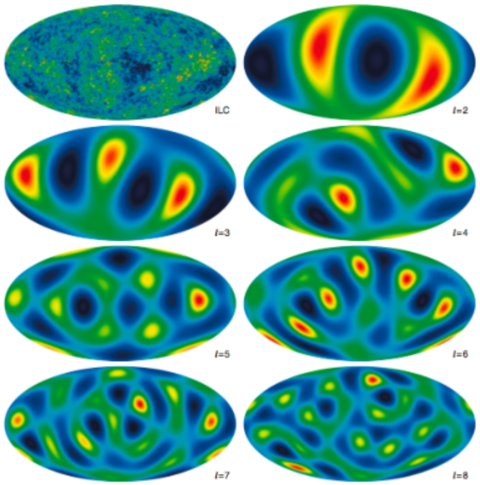

6 millions pixels of 5’
Planck 15 mois
Planck Collaboration, 2013
-300
300

From maps to cosmological parameters



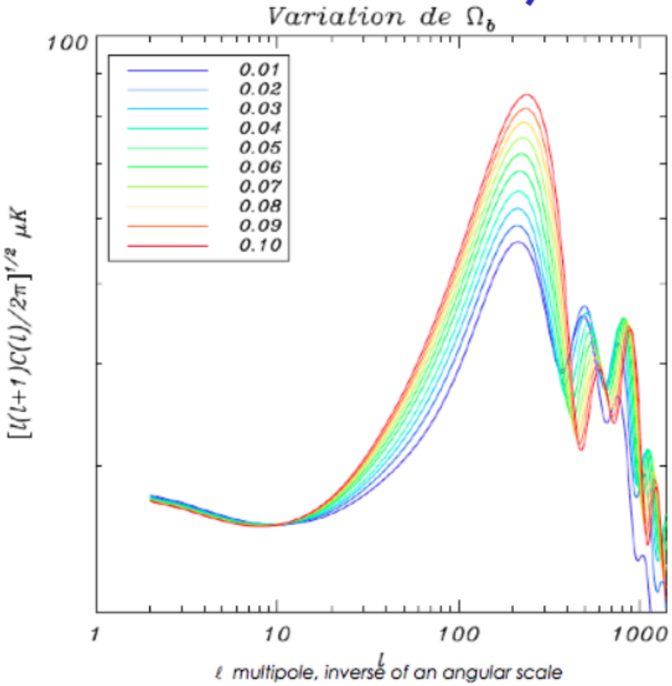




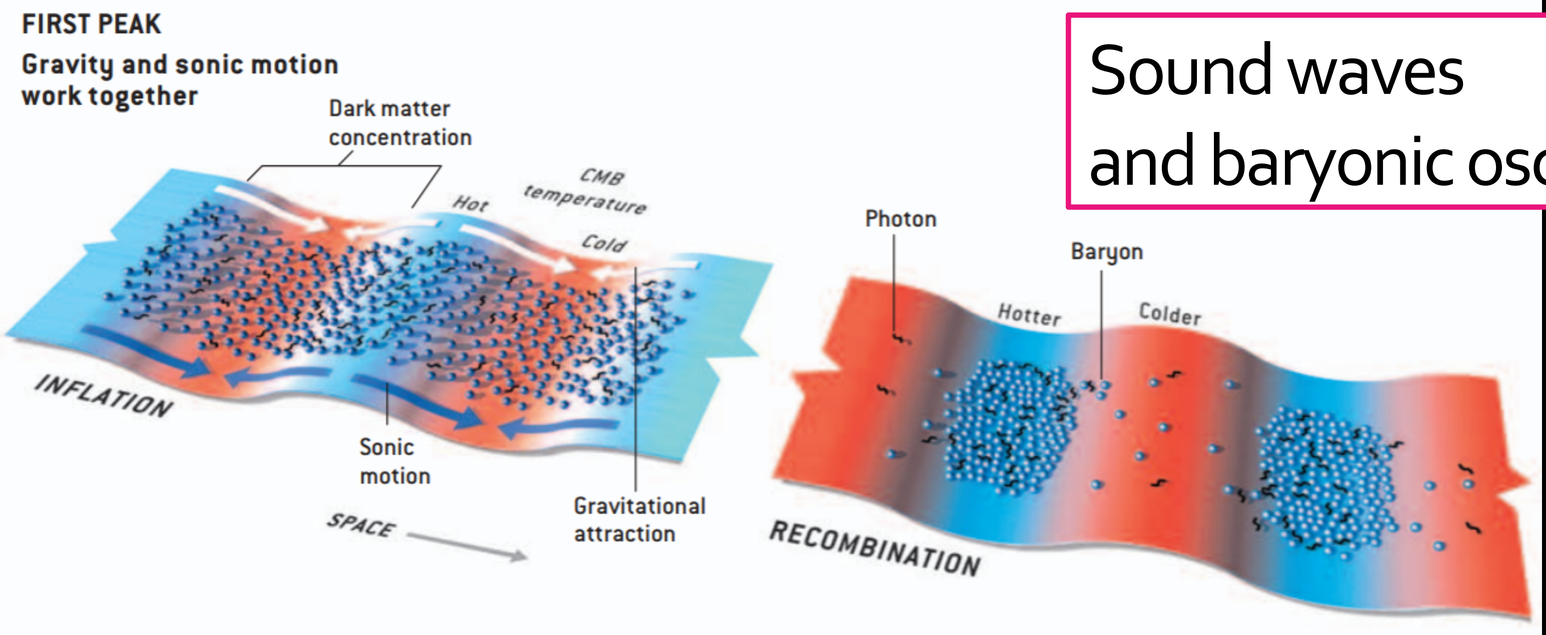


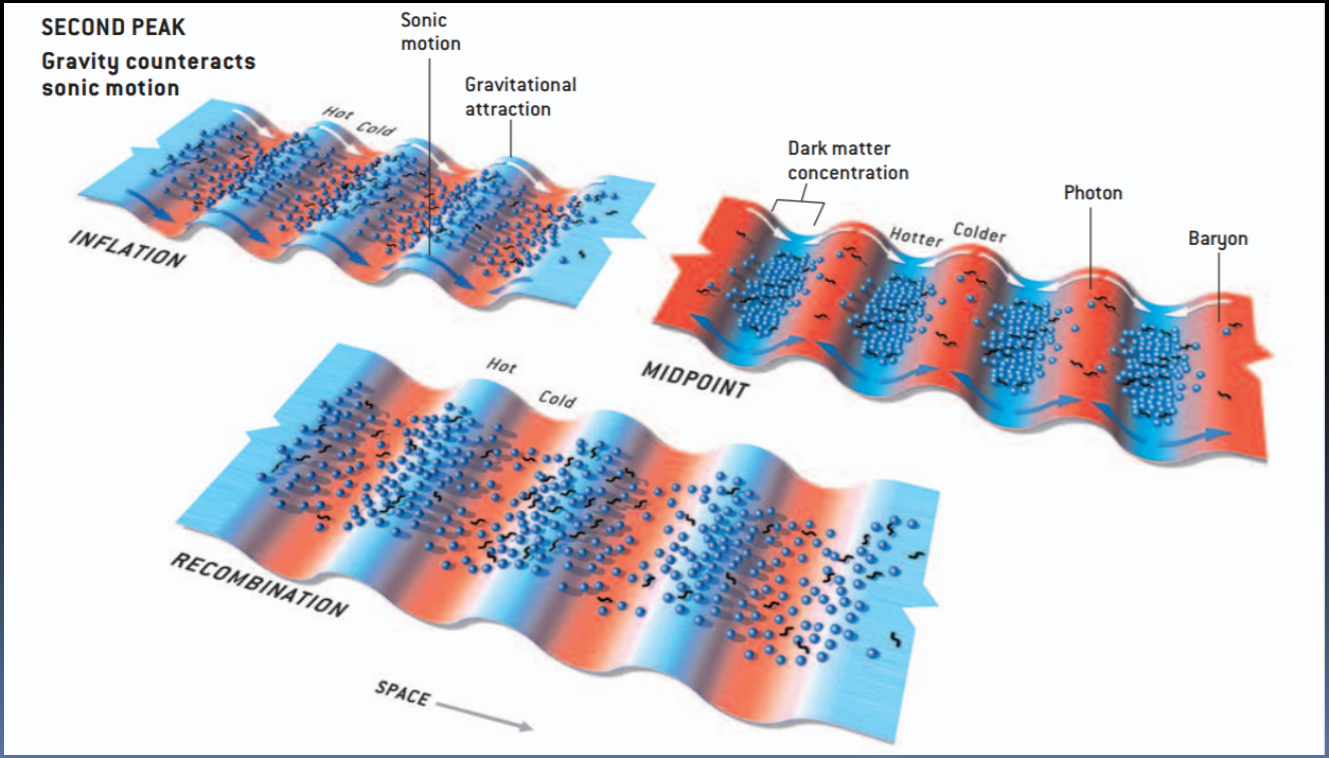
$$\frac{\Delta T(\mathbf{n})}{T_0} = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m}^{T} Y_{\ell m}(\mathbf{n})$$

$$C_\ell^{TT} = \langle a_{\ell m}^{T} \cdot a_{\ell m}^{T\star} \rangle$$

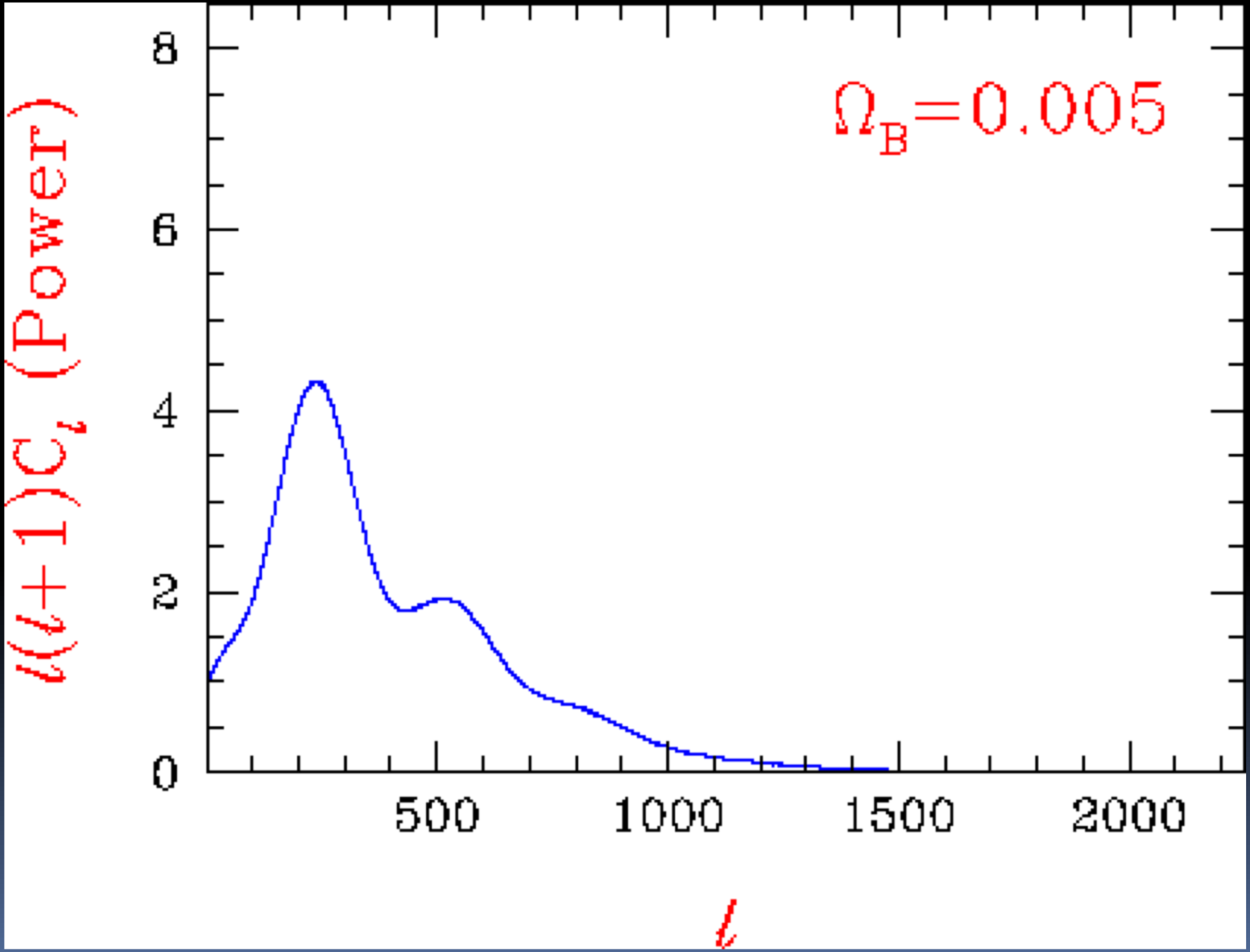


Sound waves and baryonic oscillations

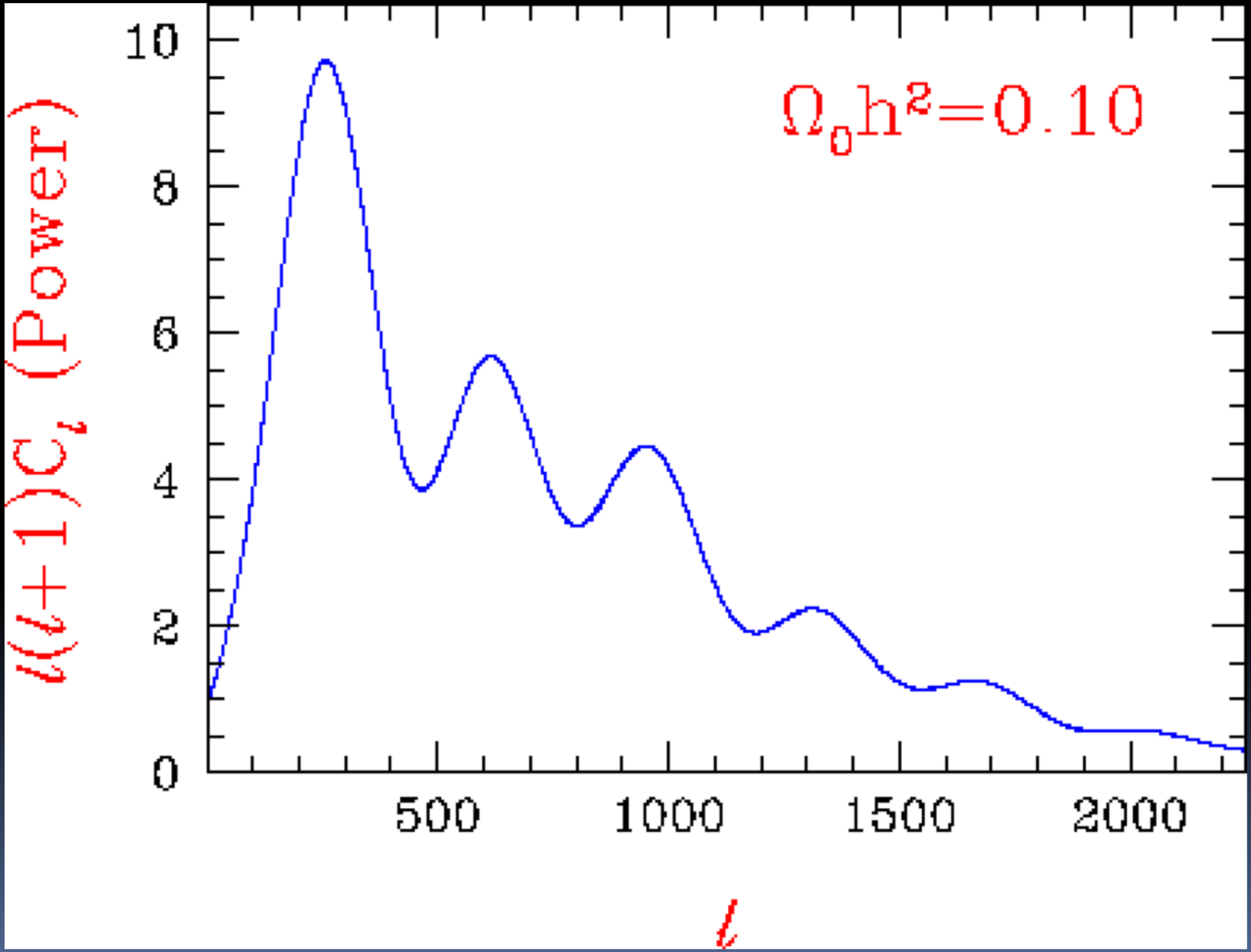




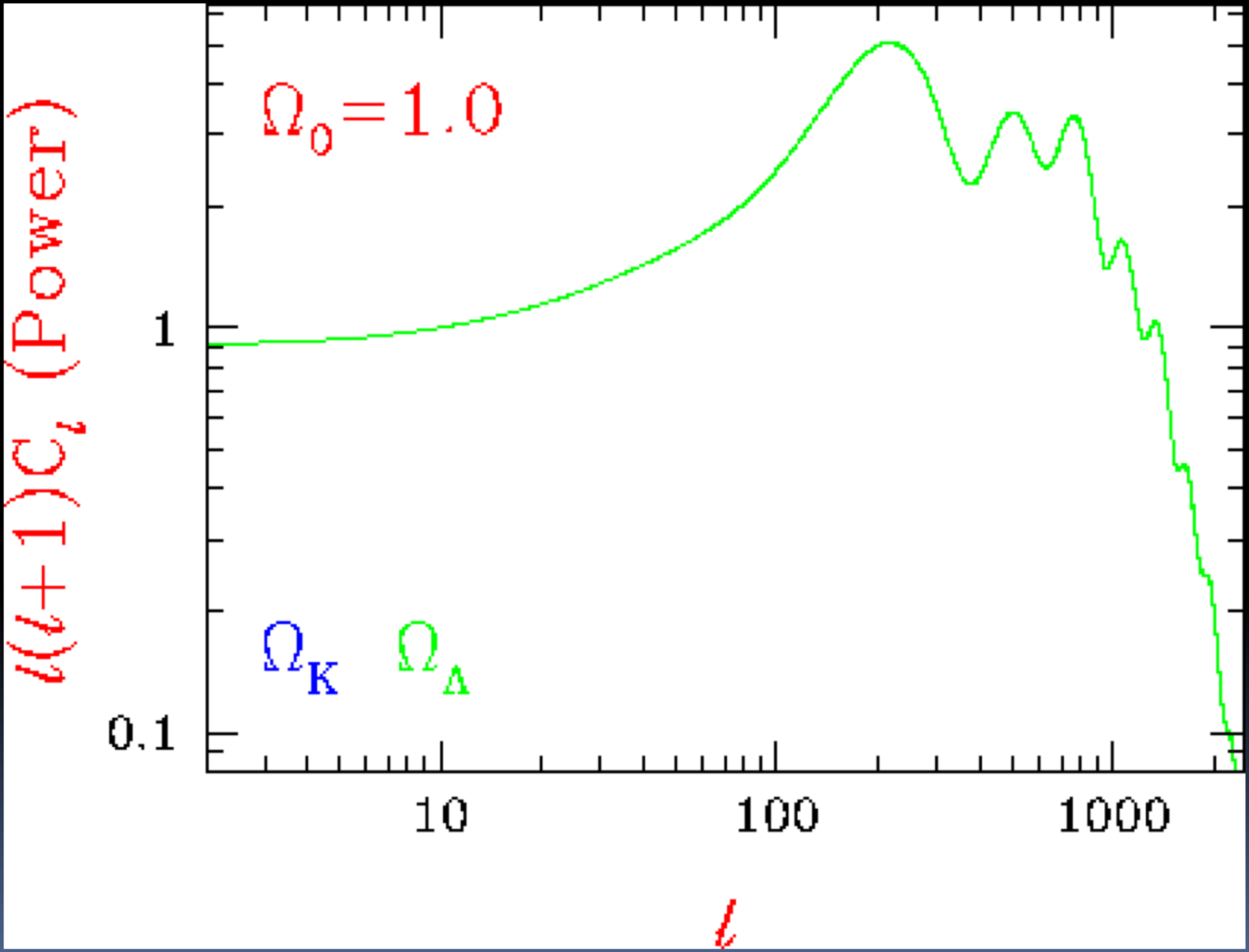
Effect of cosmological parameters (theory)



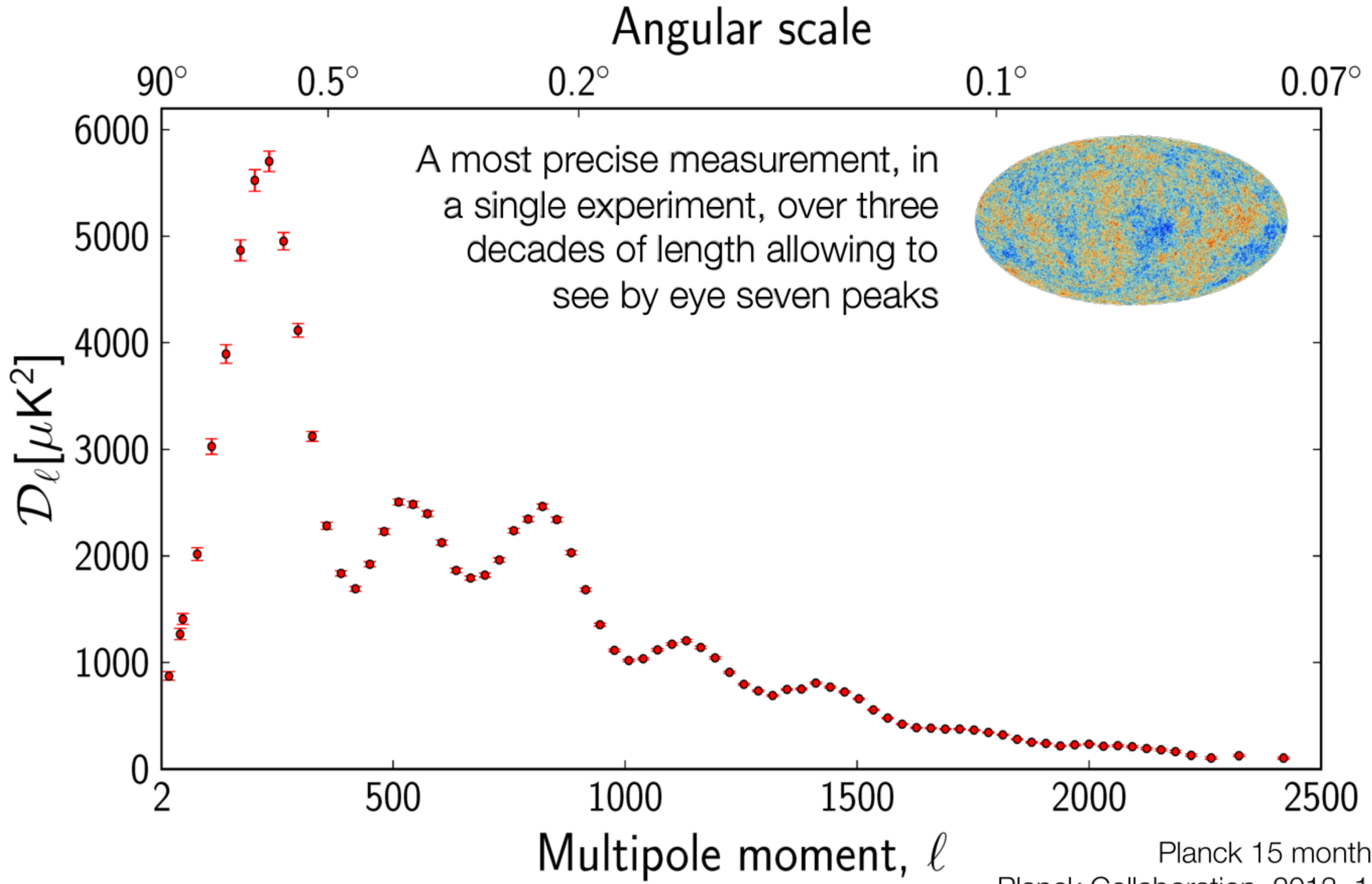
Effect of cosmological parameters (theory)



Effect of cosmological parameters (theory)



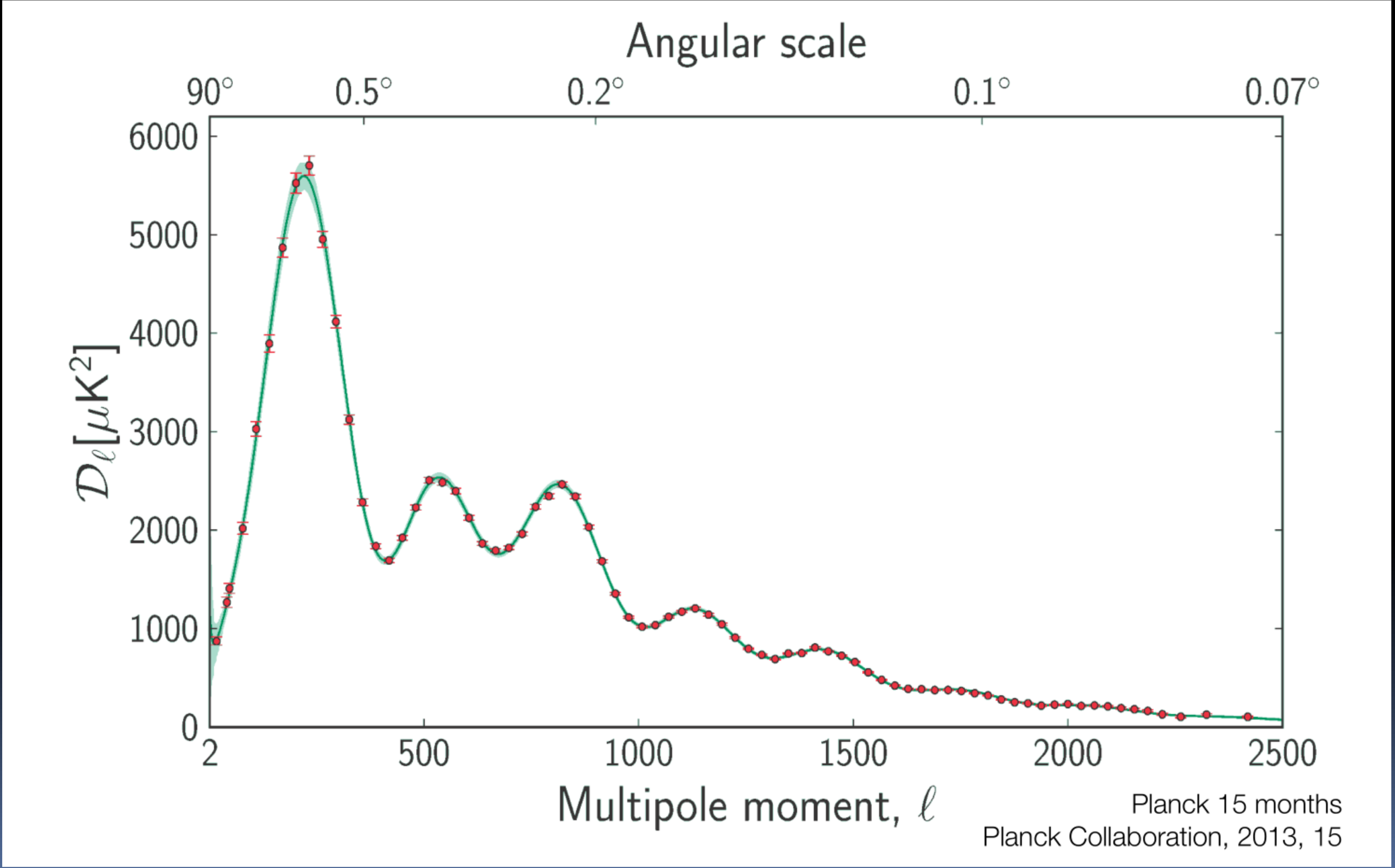
Spectrum of temperature anisotropies



A most precise measurement, in a single experiment, over three decades of length allowing to see by eye seven peaks

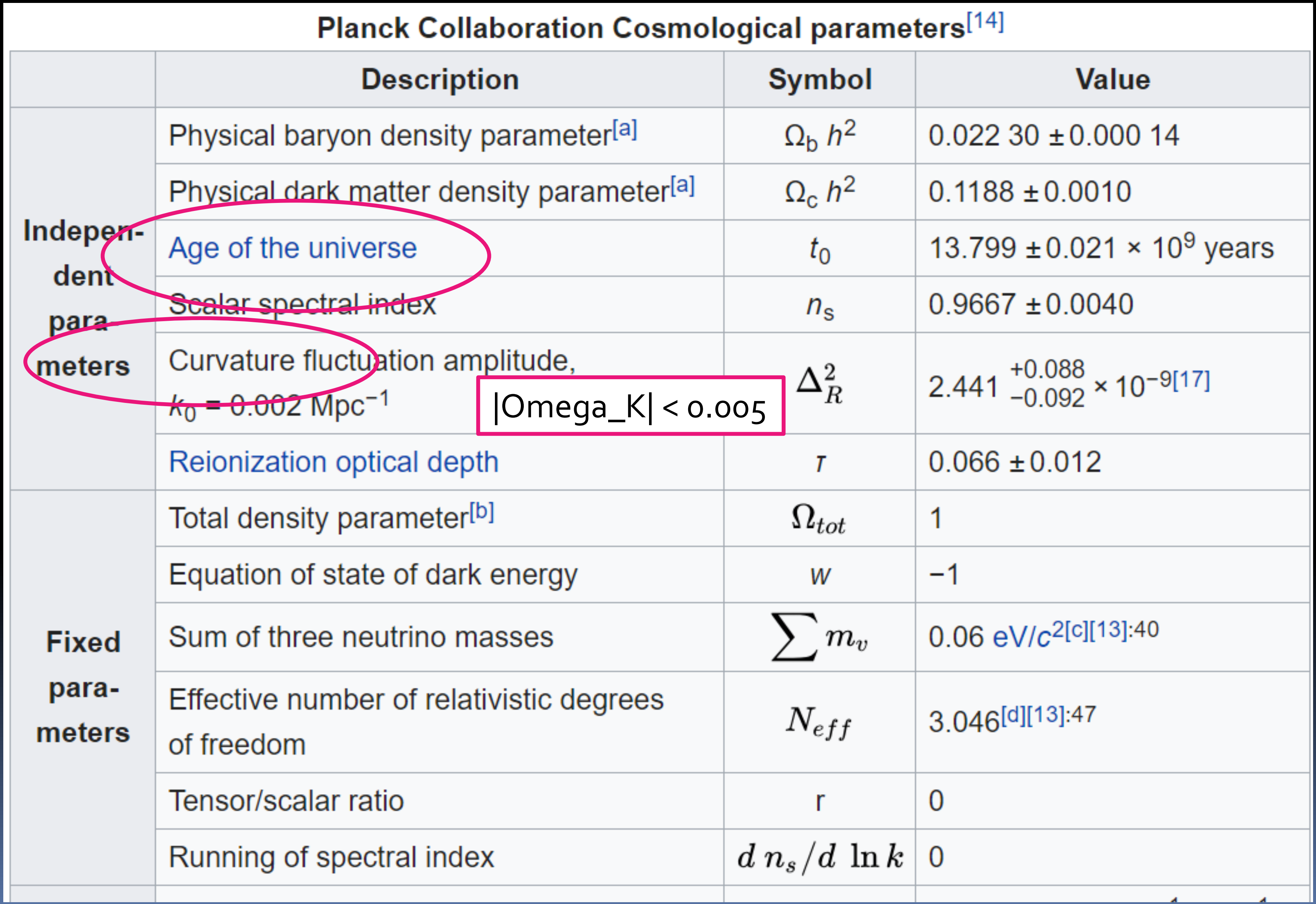
Planck 15 months
Planck Collaboration, 2013, 15

6 parameter model fit



Planck 15 months
Planck Collaboration, 2013, 15

Cosmological parameters



Planck Collaboration Cosmological parameters[14]

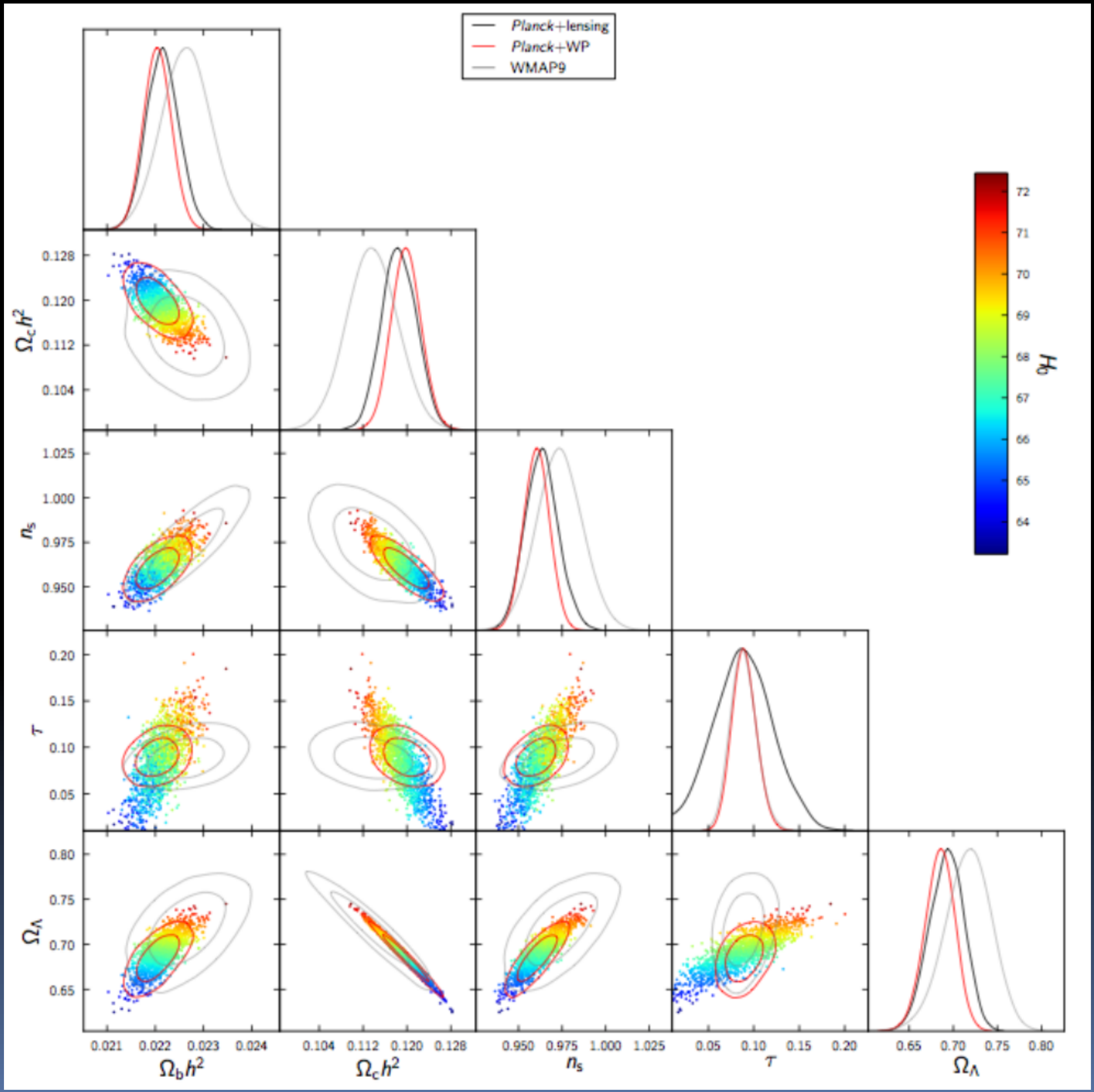
	Description	Symbol	Value
Independent parameters	Physical baryon density parameter[a]	$\Omega_b h^2$	0.022 30 ± 0.000 14
	Physical dark matter density parameter[a]	$\Omega_c h^2$	0.1188 ± 0.0010
	Age of the universe	t_0	$13.799 \pm 0.021 \times 10^9$ years
	Scalar spectral index	n_s	0.9667 ± 0.0040
	Curvature fluctuation amplitude, $k_0 = 0.002\ \mathrm{Mpc}^{-1}$	Δ_R^2	$2.441^{+0.088}_{-0.092} \times 10^{-9}$[17]
	Reionization optical depth	τ	0.066 ± 0.012
Fixed parameters	Total density parameter[b]	Ω_{tot}	1
	Equation of state of dark energy	w	−1
	Sum of three neutrino masses	$\sum m_\nu$	0.06 eV/c^2[c][13]:40
	Effective number of relativistic degrees of freedom	N_{eff}	3.046[d][13]:47
	Tensor/scalar ratio	r	0
	Running of spectral index	$d\, n_s / d \ln k$	0

|Omega_K| < 0.005

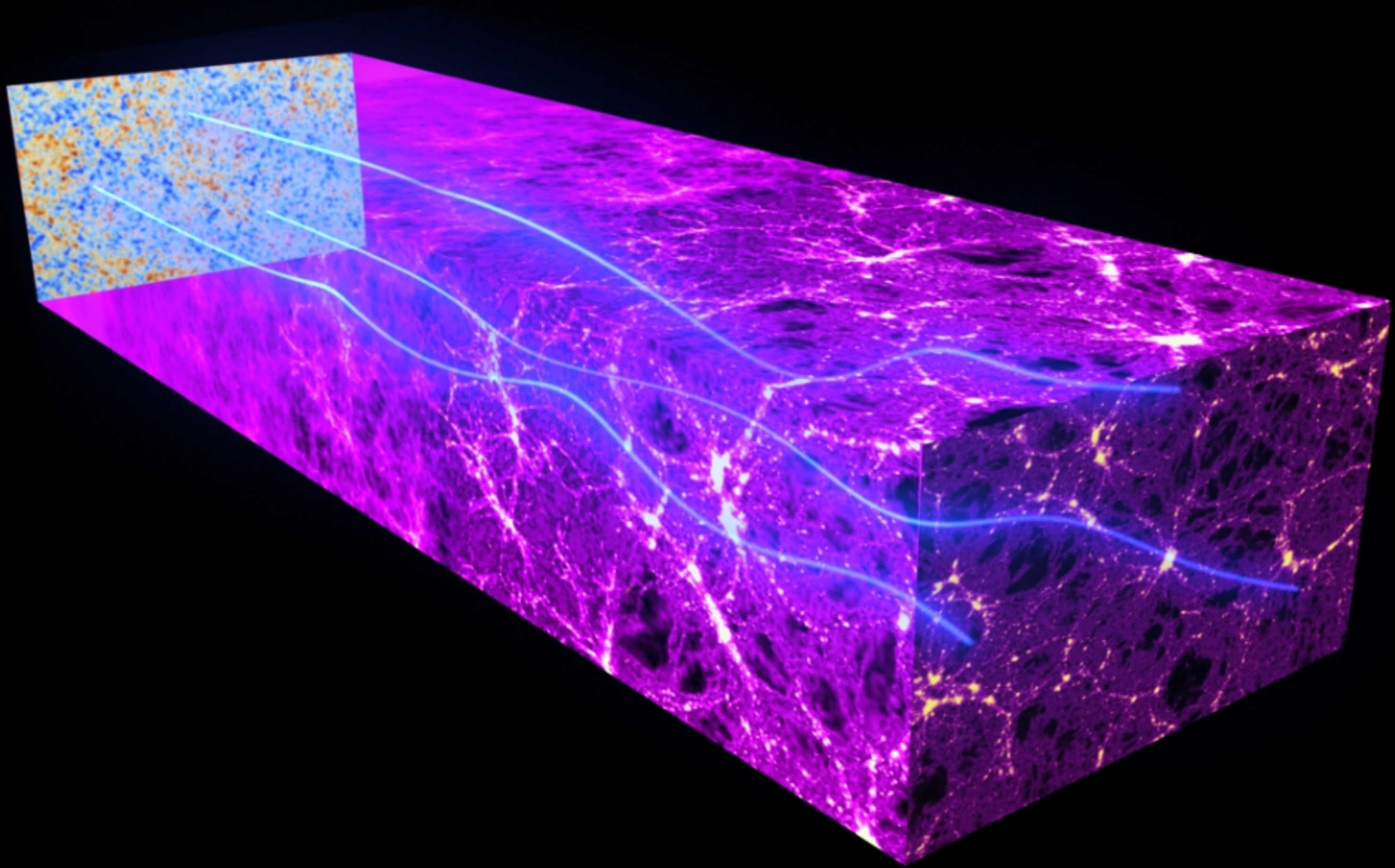
Cosmological parameters

Calcu-lated values	Hubble constant	H_0	67.74 ± 0.46 km s^{-1} Mpc^{-1}
	Baryon density parameter[b]	Ω_b	0.0486 ± 0.0010[e]
	Dark matter density parameter[b]	Ω_c	0.2589 ± 0.0057[f]
	Matter density parameter[b]	Ω_m	0.3089 ± 0.0062
	Dark energy density parameter[b]	Ω_Λ	0.6911 ± 0.0062
	Critical density	ρ_{crit}	$(8.62 \pm 0.12) \times 10^{-27}$ kg/m^3[g]
	Fluctuation amplitude at $8h^{-1}$ Mpc	σ_8	0.8159 ± 0.0086
	Redshift at decoupling	z_*	1 089.90 ± 0.23
	Age at decoupling	t_*	377 700 ± 3200 years[17]
	Redshift of reionization (with uniform prior)	z_{re}	$8.5^{+1.0}_{-1.1}$[18]

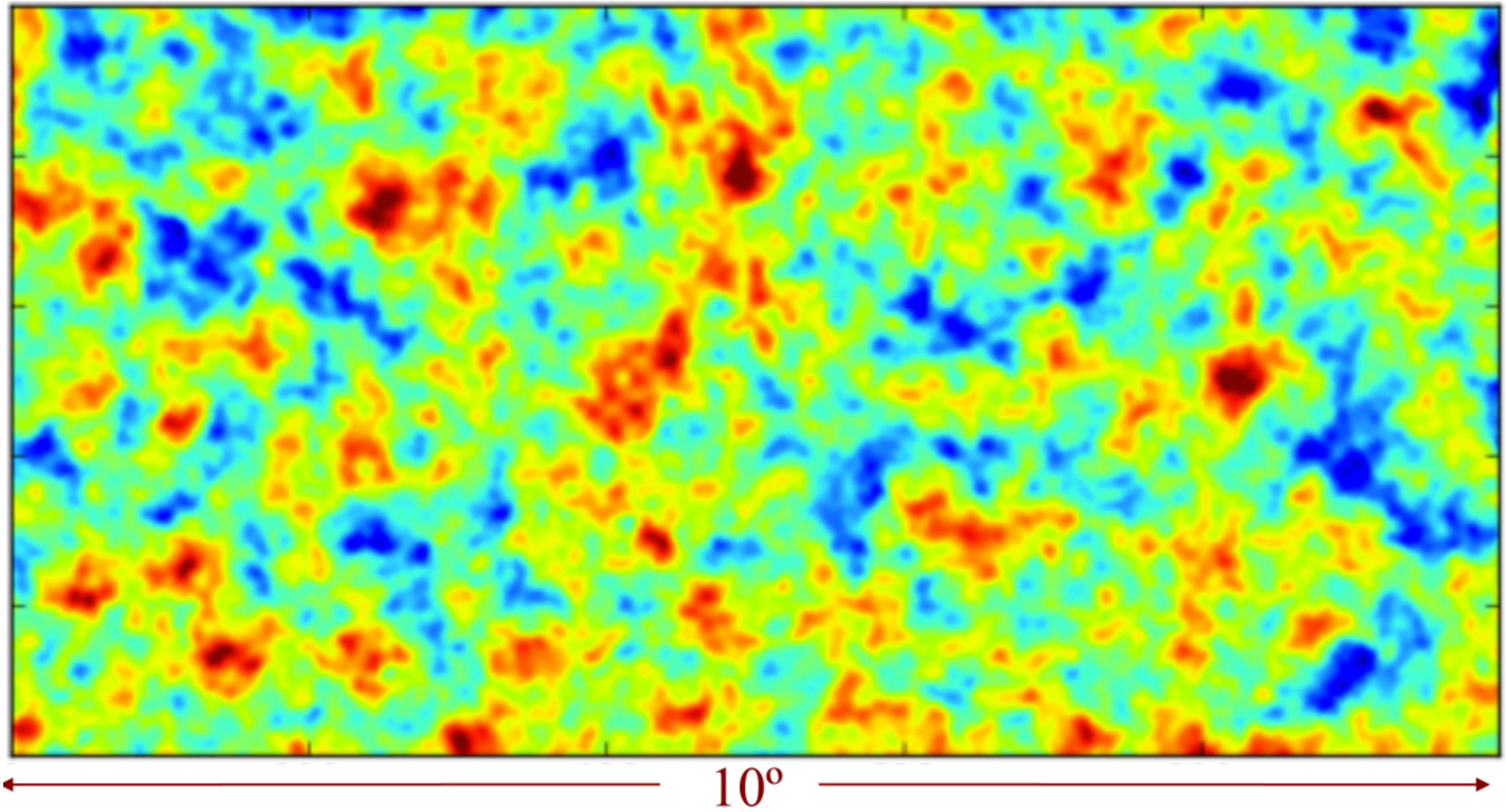
Cosmological parameters



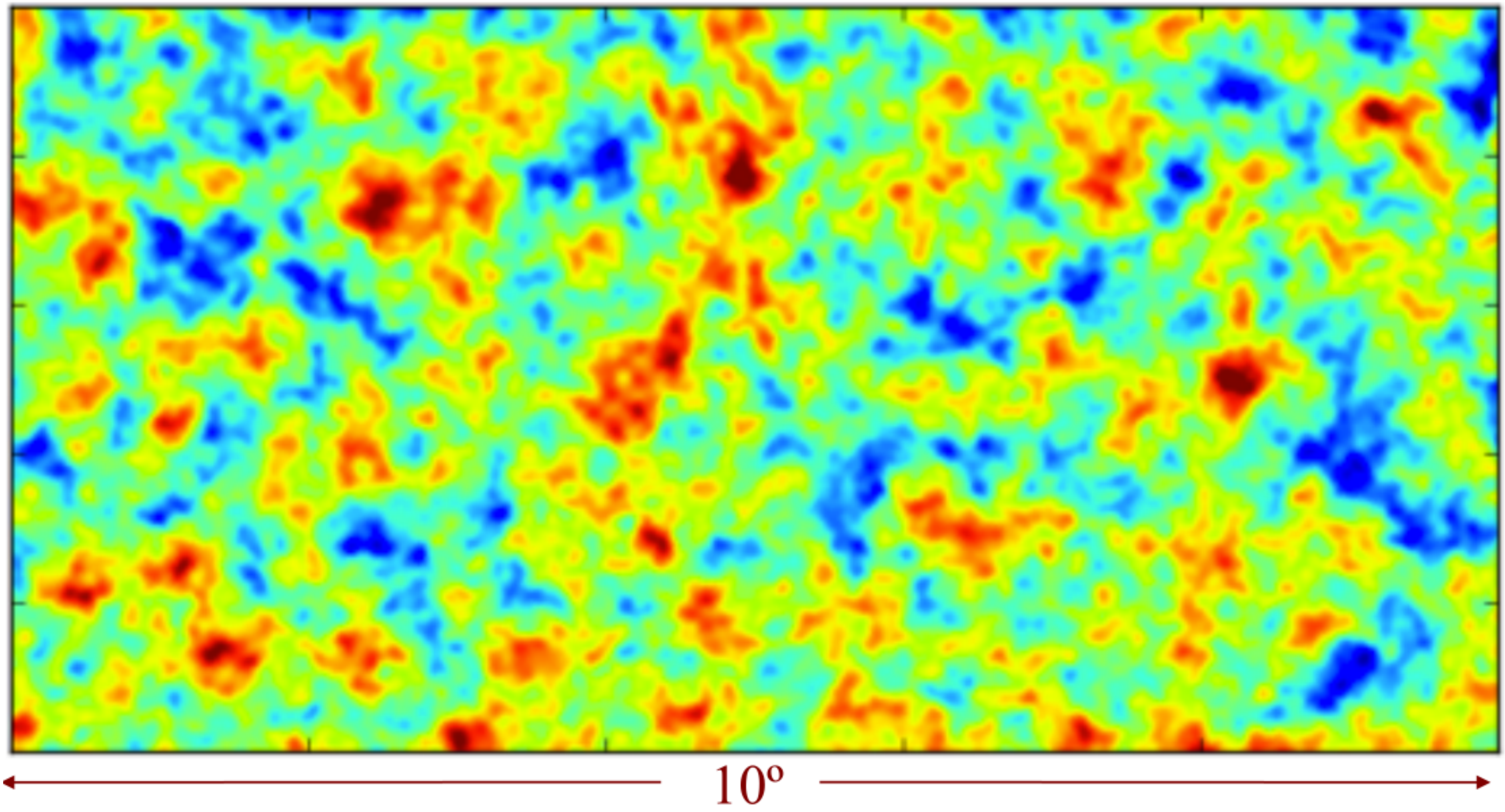
Several other effects can be detected: lensing



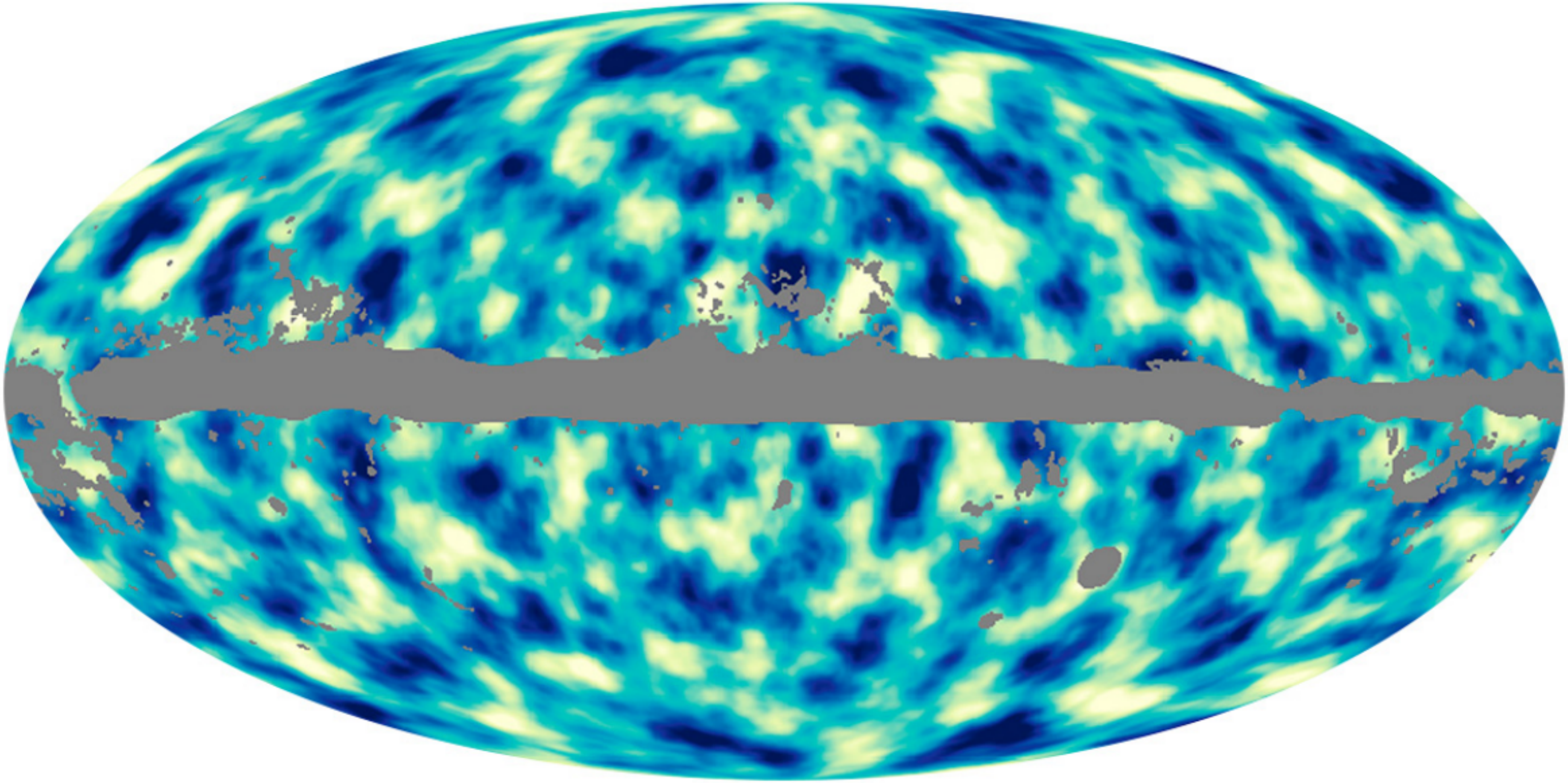
Without lensing



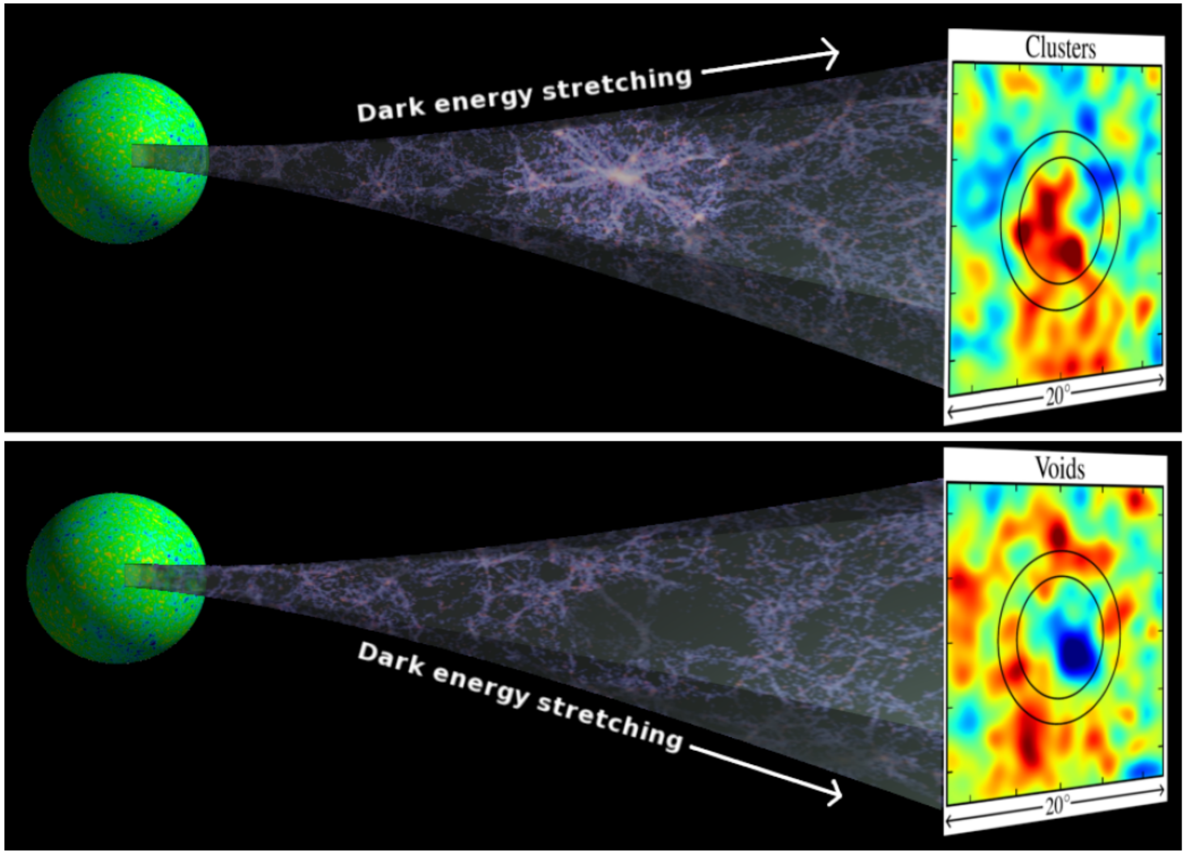
With lensing



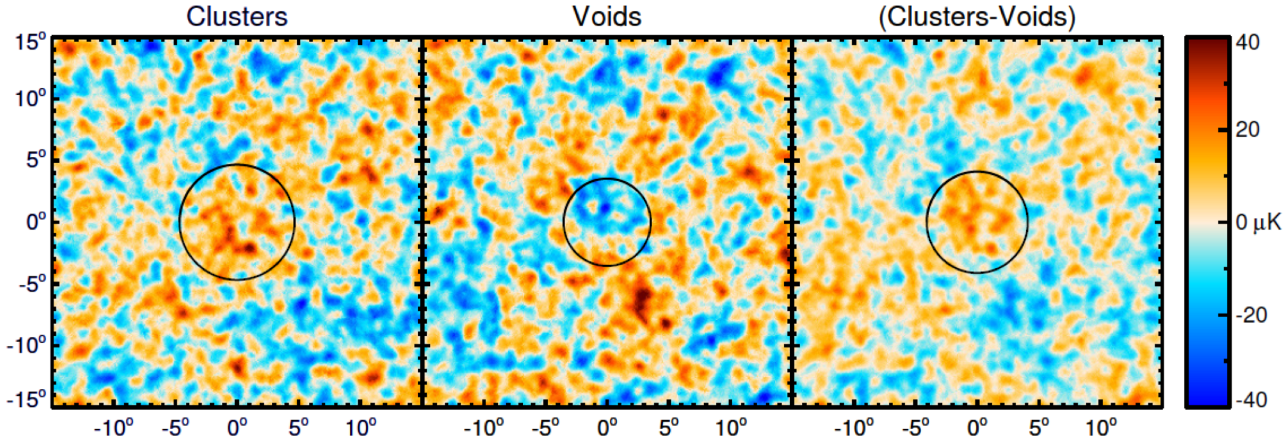
Dark matter distribution



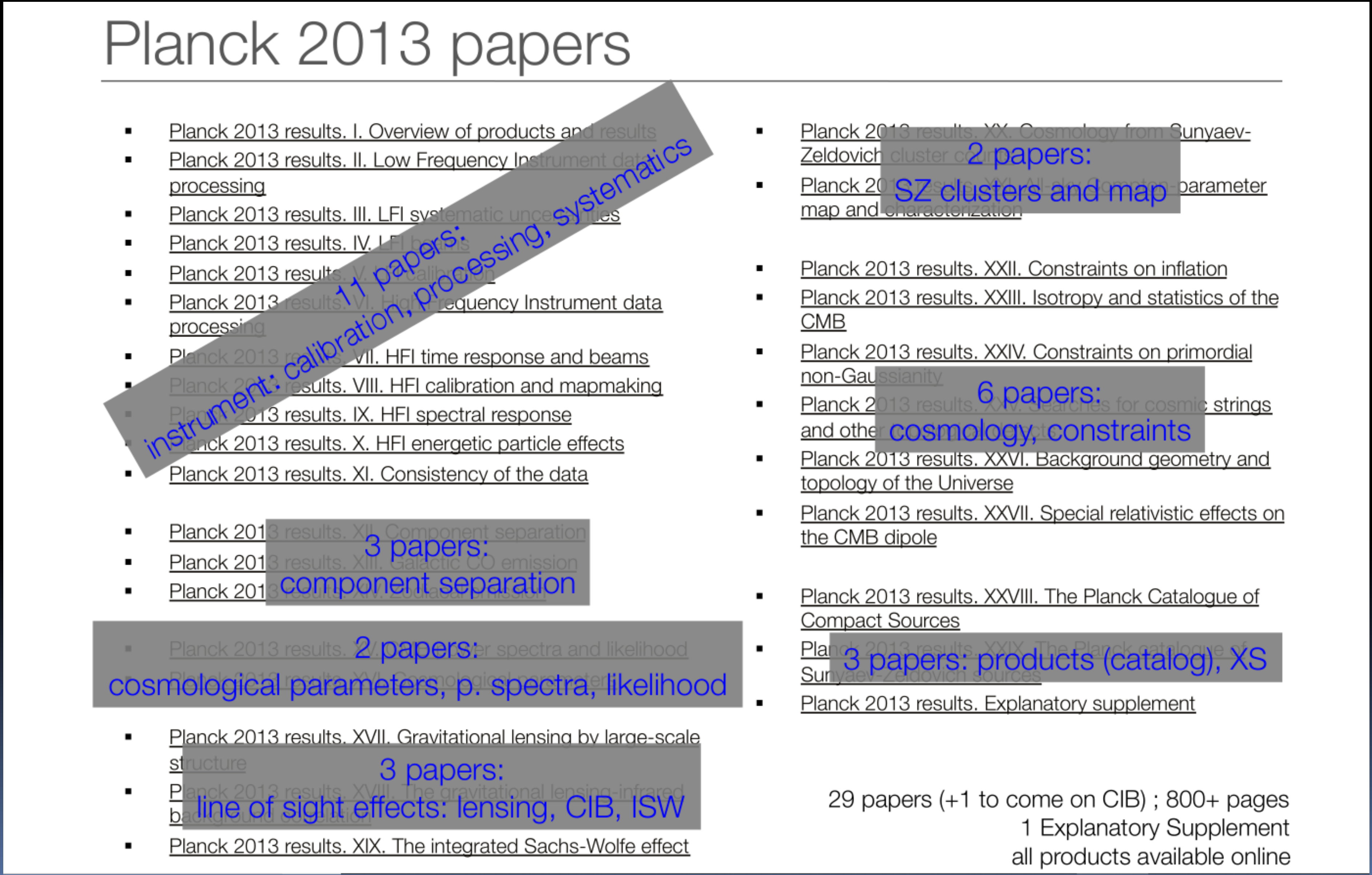
Integrated Sachs-Wolfe (**ISW**) effect



- Only if expansion is accelerated
- Few μK on top of the ~300μK CMB signal



Results



Planck 2013 papers

- Planck 2013 results. I. Overview of products and results
- Planck 2013 results. II. Low Frequency Instrument data processing
- Planck 2013 results. III. LFI systematic uncertainties
- Planck 2013 results. IV. LFI beams
- Planck 2013 results. V. LFI calibration
- Planck 2013 results. VI. High Frequency Instrument data processing
- Planck 2013 results. VII. HFI time response and beams
- Planck 2013 results. VIII. HFI calibration and mapmaking
- Planck 2013 results. IX. HFI spectral response
- Planck 2013 results. X. HFI energetic particle effects
- Planck 2013 results. XI. Consistency of the data

11 papers: instrument: calibration, processing, systematics

- Planck 2013 results. XII. Component separation
- Planck 2013 results. XIII. Galactic CO emission
- Planck 2013 results. XIV. Zodiacal emission

3 papers: component separation

- Planck 2013 results. XV. CMB power spectra and likelihood
- Planck 2013 results. XVI. Cosmological parameters

2 papers: cosmological parameters, p. spectra, likelihood

- Planck 2013 results. XVII. Gravitational lensing by large-scale structure
- Planck 2013 results. XVIII. The gravitational lensing-infrared background correlation
- Planck 2013 results. XIX. The integrated Sachs-Wolfe effect

3 papers: line of sight effects: lensing, CIB, ISW

- Planck 2013 results. XX. Cosmology from Sunyaev-Zeldovich cluster counts
- Planck 2013 results. XXI. All-sky Compton-parameter map and characterization

2 papers: SZ clusters and map

- Planck 2013 results. XXII. Constraints on inflation
- Planck 2013 results. XXIII. Isotropy and statistics of the CMB
- Planck 2013 results. XXIV. Constraints on primordial non-Gaussianity
- Planck 2013 results. XXV. Searches for cosmic strings and other topological defects
- Planck 2013 results. XXVI. Background geometry and topology of the Universe
- Planck 2013 results. XXVII. Special relativistic effects on the CMB dipole

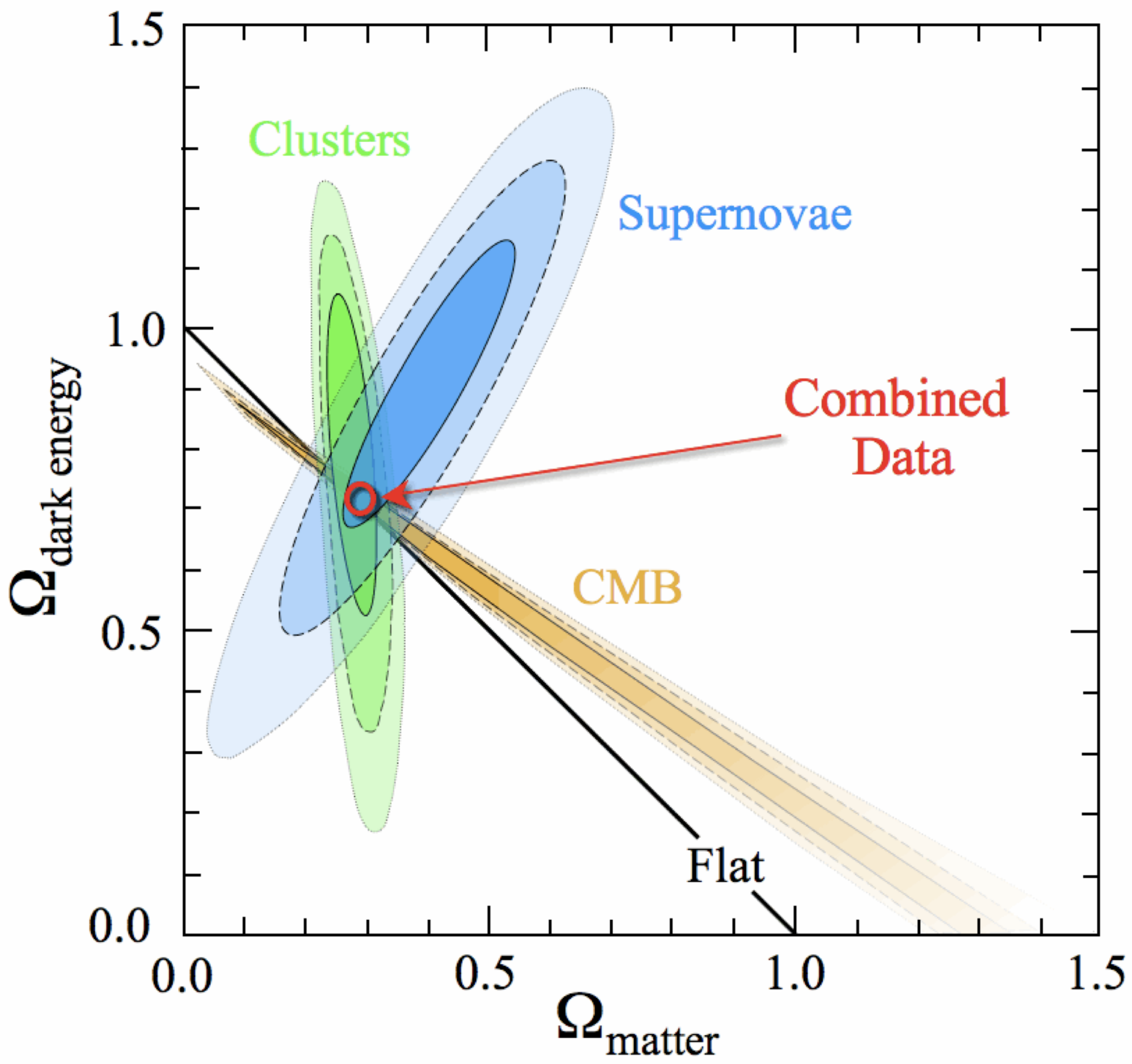
6 papers: cosmology, constraints

- Planck 2013 results. XXVIII. The Planck Catalogue of Compact Sources
- Planck 2013 results. XXIX. The Planck catalogue of Sunyaev-Zeldovich sources
- Planck 2013 results. Explanatory supplement

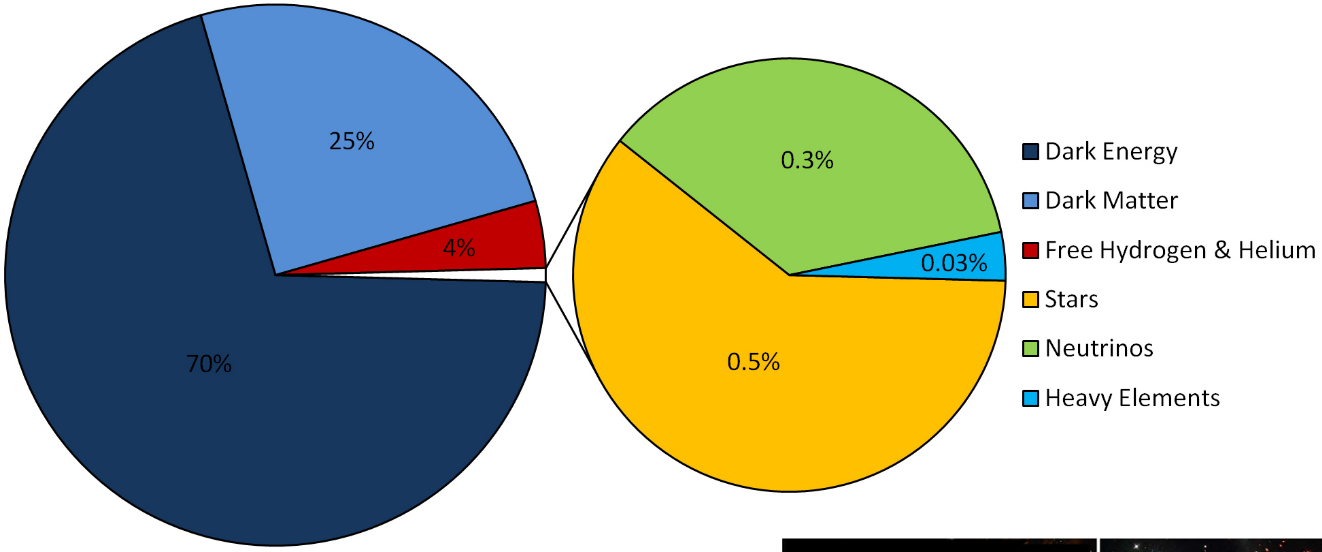
3 papers: products (catalog), XS

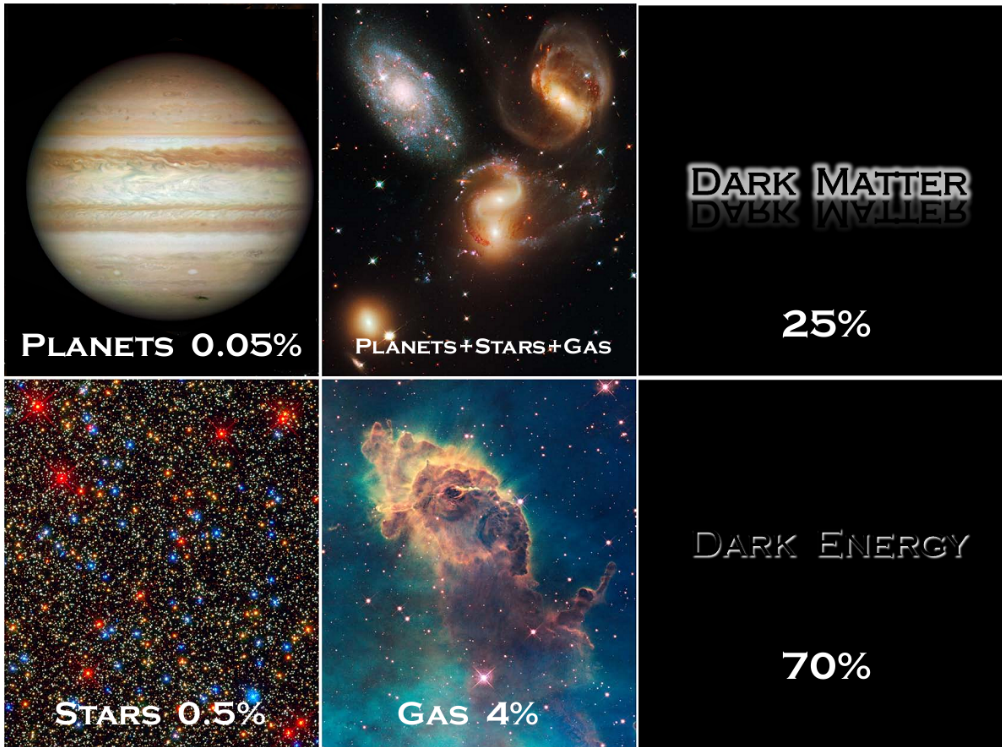
29 papers (+1 to come on CIB) ; 800+ pages
1 Explanatory Supplement
all products available online

Concordance model: the other “cornerstones”

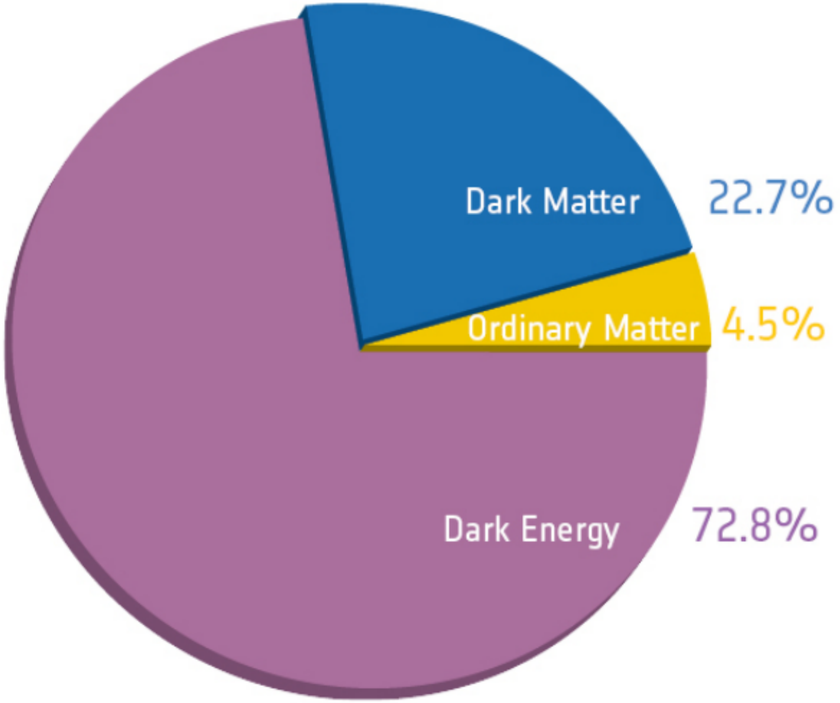


Components of the Universe: Lambda CDM model

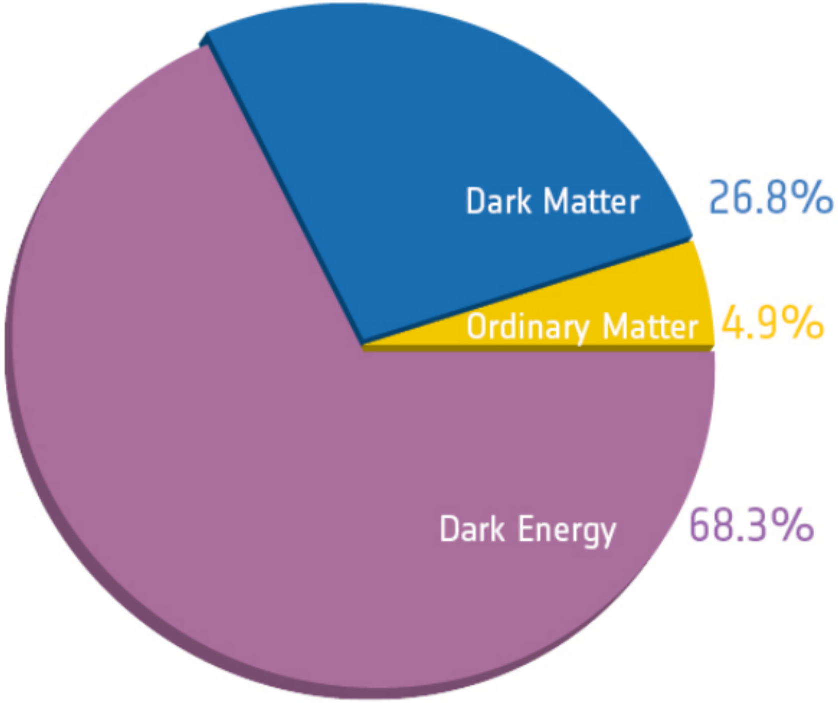




Precision cosmology: universe got heavier and older (WMAP 13.77±0.059 -> 13.799±0.021 Gyr)



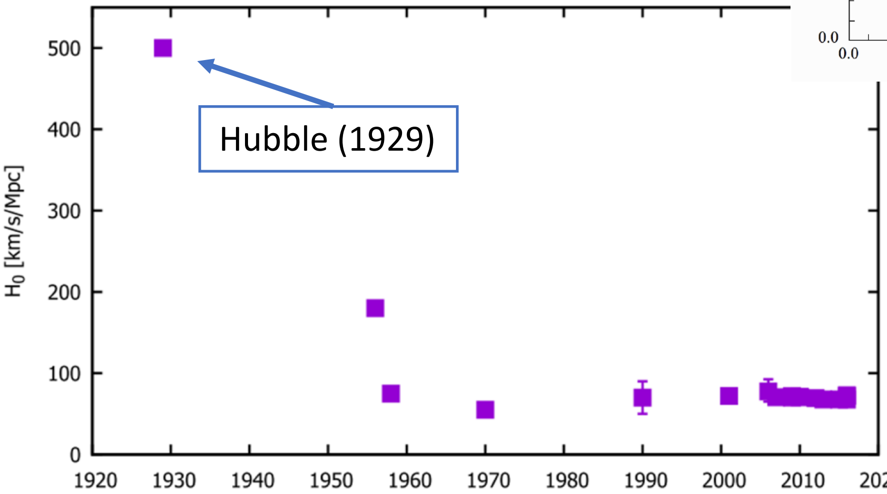
Before Planck



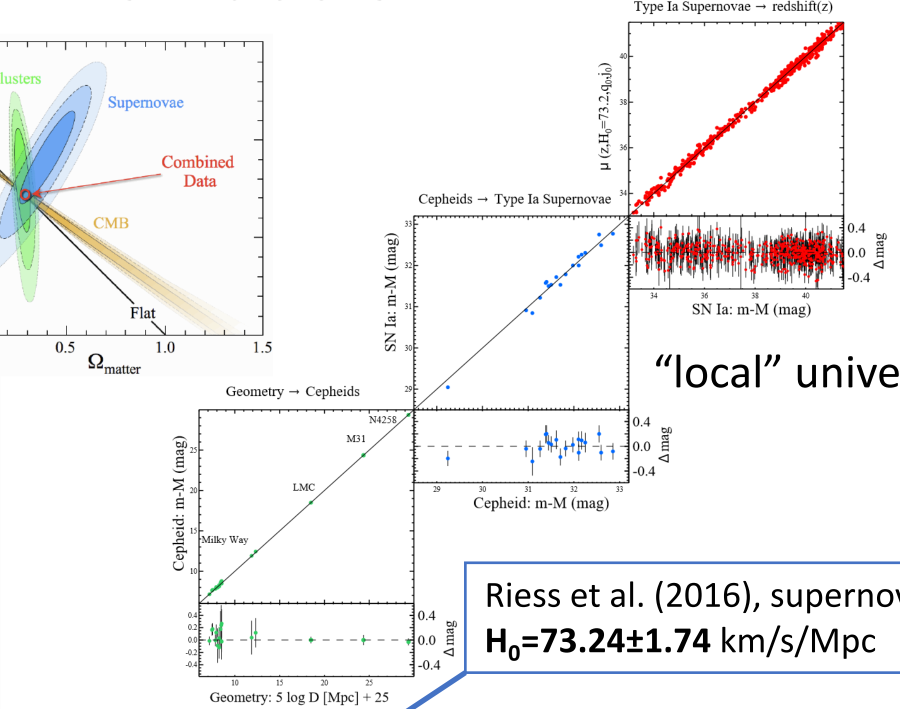
After Planck

Cracks on the ΛCDM theory: the **Hubble** constant **tension** (3.4σ)

Better observations: errorbars shrink



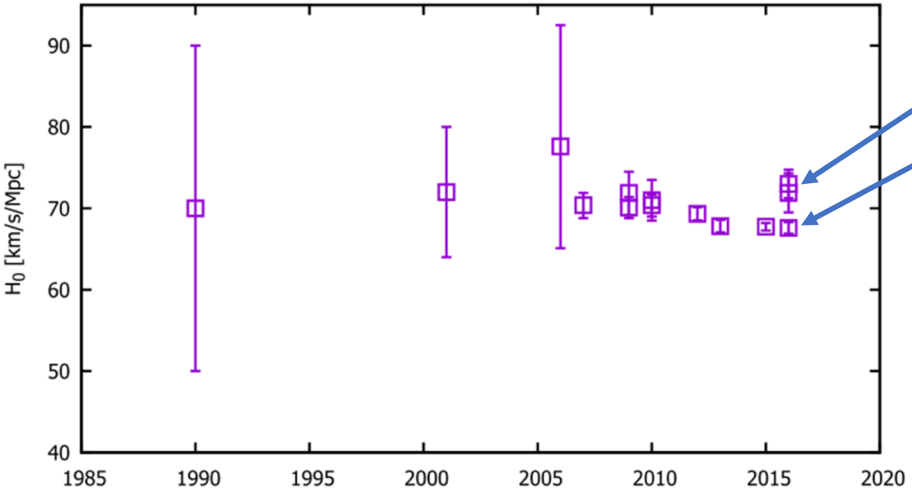
Hubble (1929)

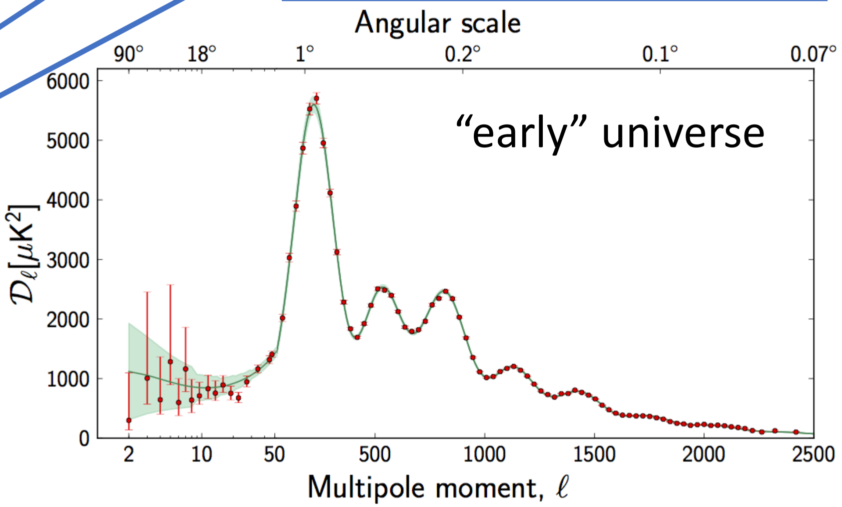


“local” universe

Riess et al. (2016), supernovae
H_0=73.24±1.74 km/s/Mpc

Planck collaboration (2015), CMB
H_0=67.74±0.46 km/s/Mpc





“early” universe

Era of precision cosmology:
Planck result together with other new “cornerstone” observations may lead to new cosmological model!

THANK YOU FOR YOUR ATTENTION!

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Planck results together with other new "cornerstone" observations may lead to new cosmological model!

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