Cosmology

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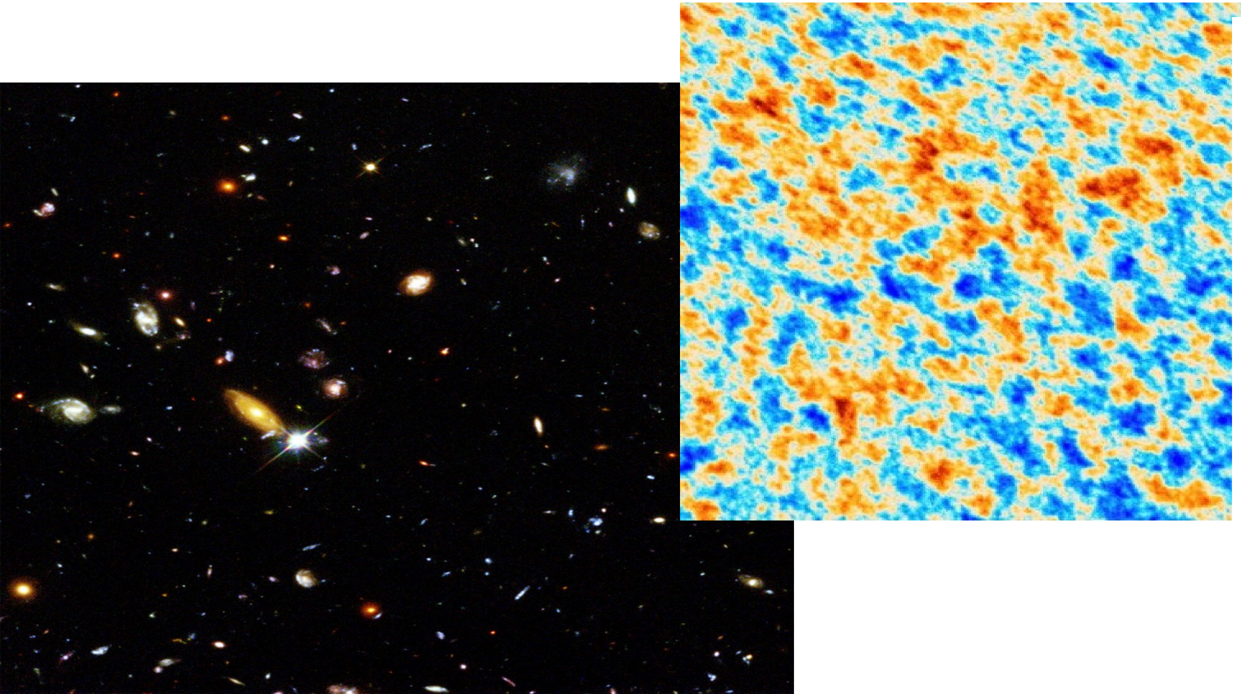

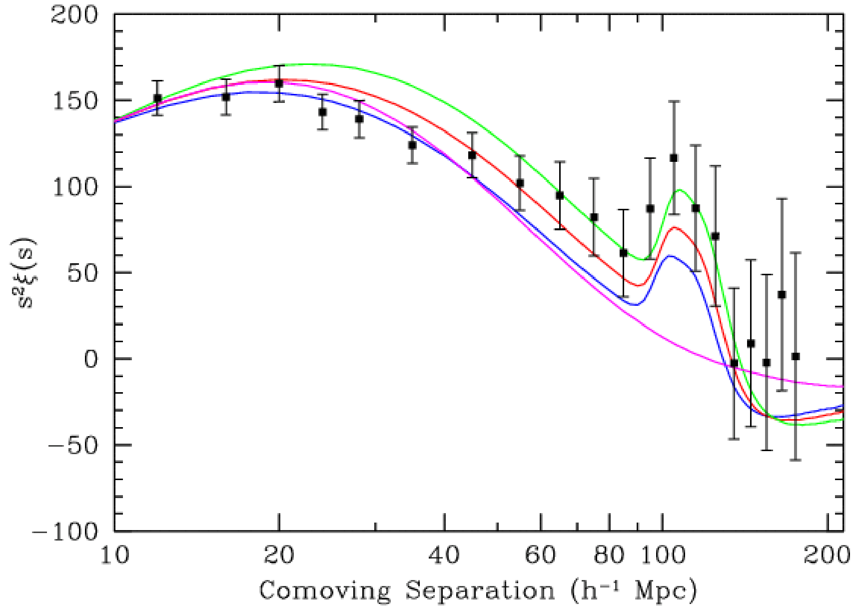

Three lectures

- “Basics” & highlights from the early universe.
- The accelerated expansion: observations and interpretation.
- Instruments: a few examples.

Textbooks :

- James Rich : “Fundamentals of Cosmology”
- John Peacock : “Cosmological physics”
- Scott Dodelson : “Modern Cosmology”
-

What is cosmology ?

- A branch of physics.
- That studies the universe as a whole:
  - History
  - Content, geometry (topology)
  - Formation of structures
  - Characteristic scales
  - ....

Only one universe:
one cannot replay
under varying
experimental conditions

↓

- ~~experimental~~ observational science

Messenger are (mostly) photons:
- X
- UV, visible, IR
- deep IR , millimetric
- radio, …

And gravitational wave astronomy is becoming real

Gravitation

On large scales, all other interactions vanish:

- Electro-magnetism : no forces, only waves
- Weak and strong forces have very short ranges
- However all interactions are at play in stars, galaxies, ….

Equivalence principle :

Gravitation couples to inertial mass

Gravitational and inertial forces are undistinguishable

Gravitation

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- Electro-magnetism : no forces, only waves
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Equivalence principle :

Gravitation couples to inertial mass

Gravitational and inertial forces are undistinguishable

By the way, we have absolutely no understanding
of the universality of free fall, which is probably
the best established physical law, up to solar system scales.

Metric theory of gravitation

Trajectories in space-time only depend on initial conditions, not mass.

→ one can encode gravitational forces into space-time geometry.
Trajectories follow “shortest paths” i.e. geodesics.

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu$$

Distance element

Metric tensor

→ there are no special coordinate systems. All are equivalent.

Einstein equations

Function of $g_{\mu\upsilon}$

Cosmological constant

Energy-momentum tensor

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R^{\sigma}_{\sigma} + \Lambda g_{\mu\nu} = 8\pi G \, T_{\mu\nu}$$

- This is General Relativity !
- Other metric theories are possible.
- Relates geometry (→ trajectories) to sources.
- 10 equations in general (4x4 symmetric)
- Covariant under general change of coordinates
- Non linear
- Radiation propagation is possible (and now observed)

Invariant
under a change of
coordinate mapping

$$S = \int \left[\frac{R^{\sigma}_{\sigma}}{8\pi G} + \mathcal{L}_{\mathrm{matter}} \right] \boxed{\sqrt{-det(g_{\mu\nu}) d^4x}}$$

Cosmological principle

The universe is homogeneous and isotropic

- no special position (Copernic) or direction
- … but no time invariance
- .. and spatial curvature is not defined

-> Friedman-Lemaitre-Robertson-Walker metric:

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

Scale factor

Comoving coordinate

k = -1,0,1 (curvature sign)

Friedman equation(s)

GR: Einstein Equations

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R^{\sigma}_{\sigma} + \Lambda g_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

FLRW metric

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

$$\boxed{H^2(t) \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3} - \frac{k}{a^2}}$$

This is sufficient, once specified how density (ρ) depends on a(t).

Alternatively :

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3}$$

A negative pressure can accelerate expansion.

Friedman equation(s)

$$\boxed{H^2(t) \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3} - \frac{k}{a^2}}$$

Curvature

Expansion rate called
Hubble parameter
H(now) = “Hubble constant”

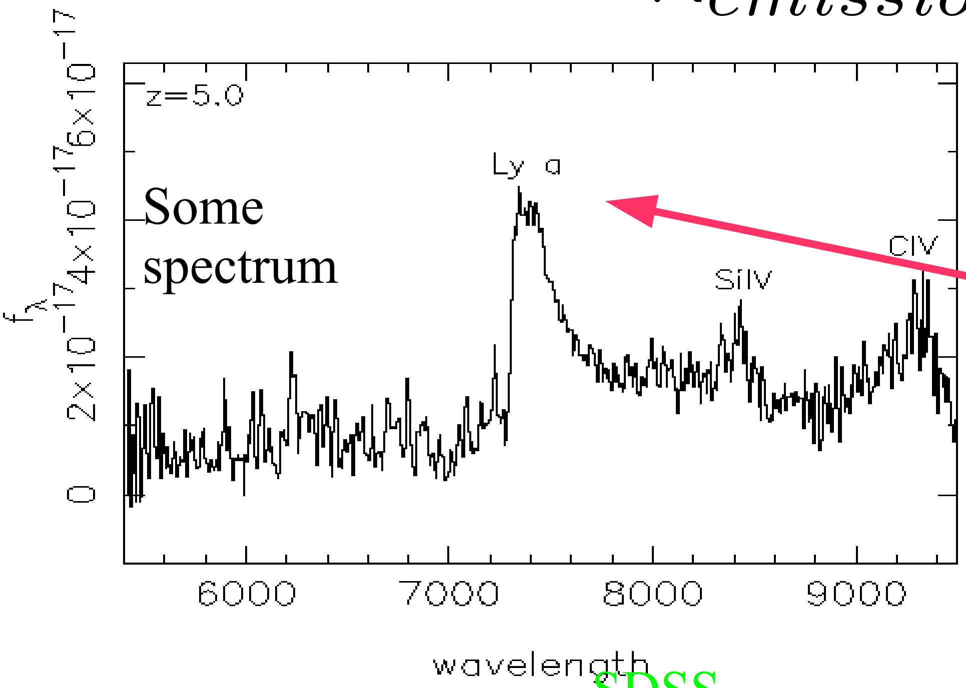
Density of
“stuff” matter,
radiation, ...

Cosmological
Constant:
density independent
of time/expansion

This is the relation between content and expansion history

Redshift z

$$1 + z \equiv \frac{\lambda_{reception}}{\lambda_{emission}} = \frac{a(now)}{a(emission)}$$



Some spectrum

SDSS

Assumes that emitter and receiver are both comoving (i.e. “attached” to matter)

Redshift allows us to measure scale factors !

Ly α : 1216 Ang. In the lab

z = 7400/1216 - 1 =~ 5.0

Shift to the red:

- a(t) increases with t
- expansion !

If the universe expands there should be an “initial singularity”

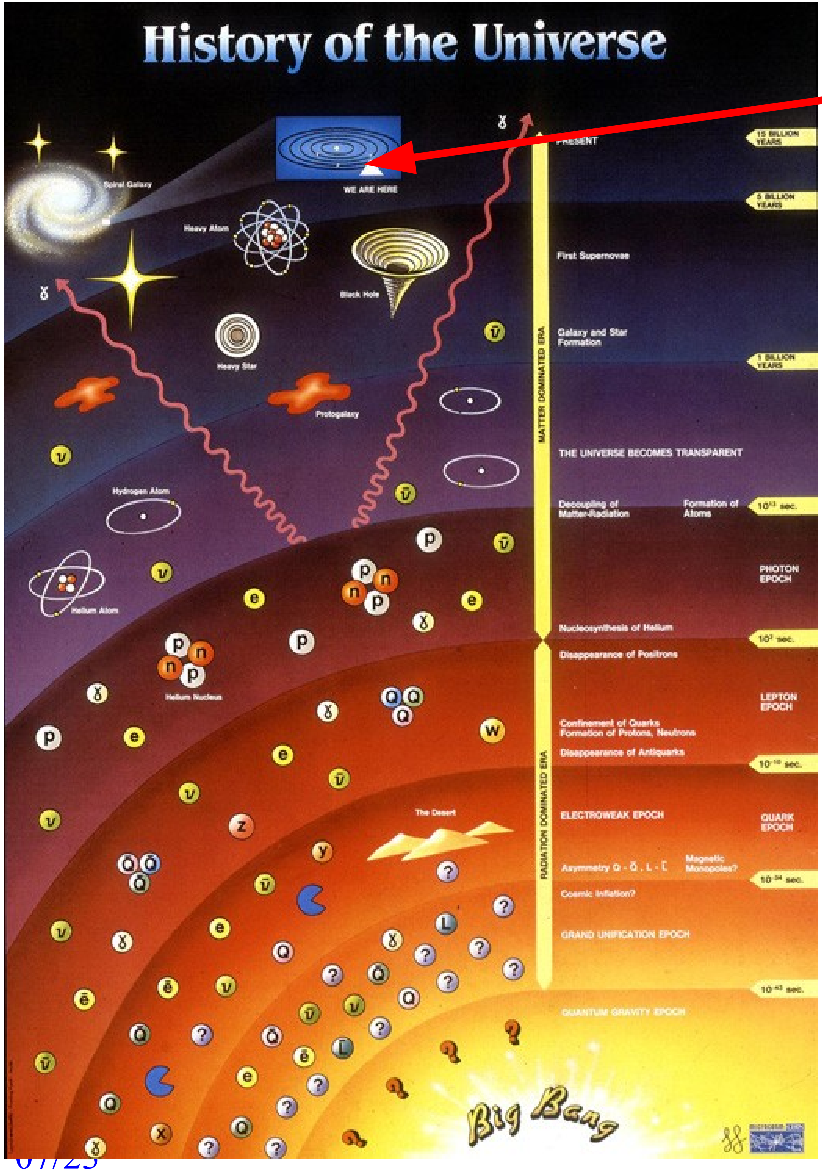
Pointed out by Lemaître (1927)

This is true for almost any “reasonable” content today.

This initial singularity is commonly called the Big Bang.

It violates time invariance: global energy conservation
is not realized.

The Big Bang sketch



You are here

Structures form
all the way

400 000 y Atoms form

3 mn

Light nuclei form

Few s Positrons disappear

….

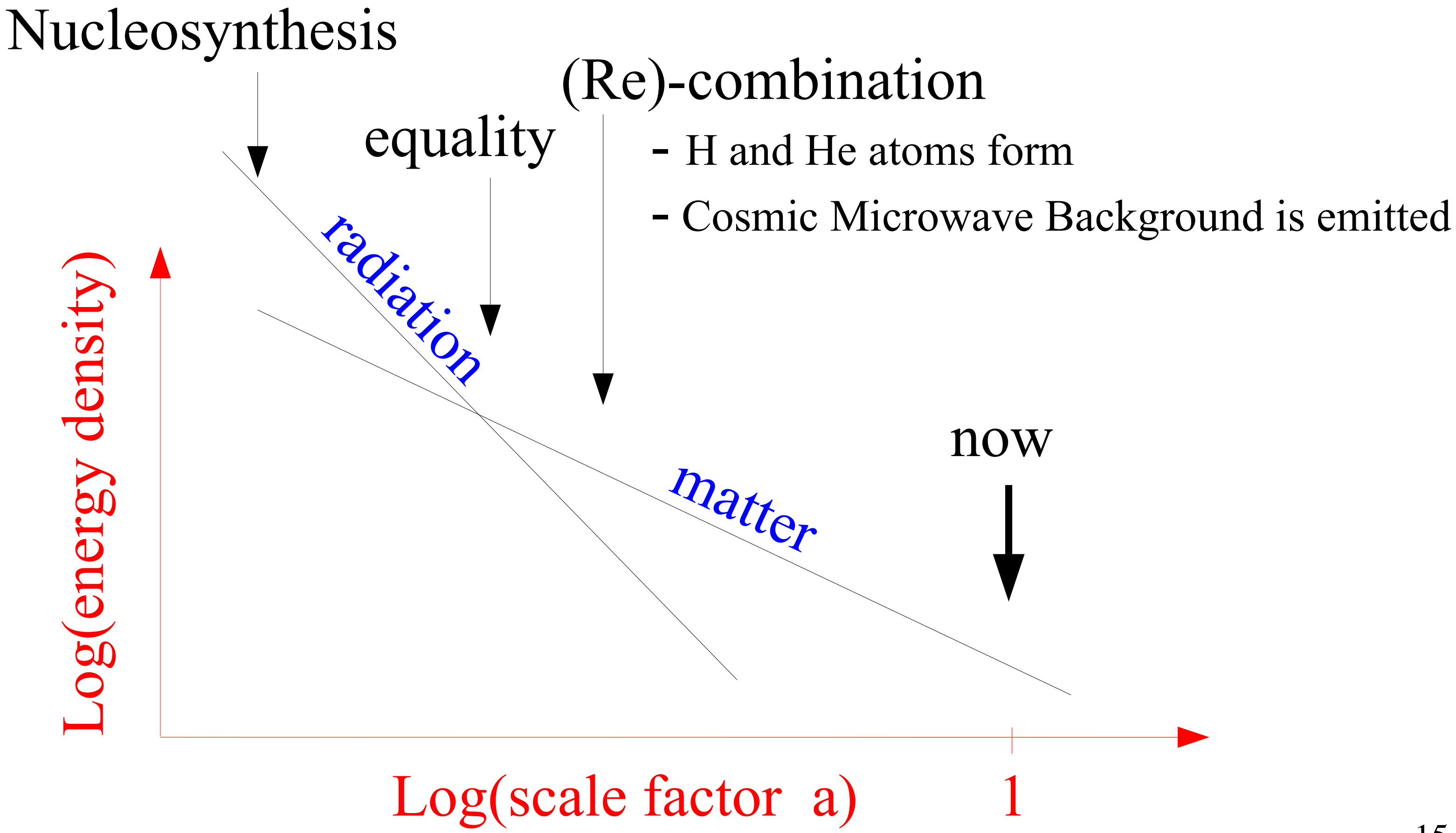
Qualitative cosmology

As time goes:

- Temperature decreases
- Densities decrease
- Lighter and lighter particles “freeze out” (cst comoving density)
- Bound states form (with smaller and smaller binding energies)
- Contrast to homogeneity increases

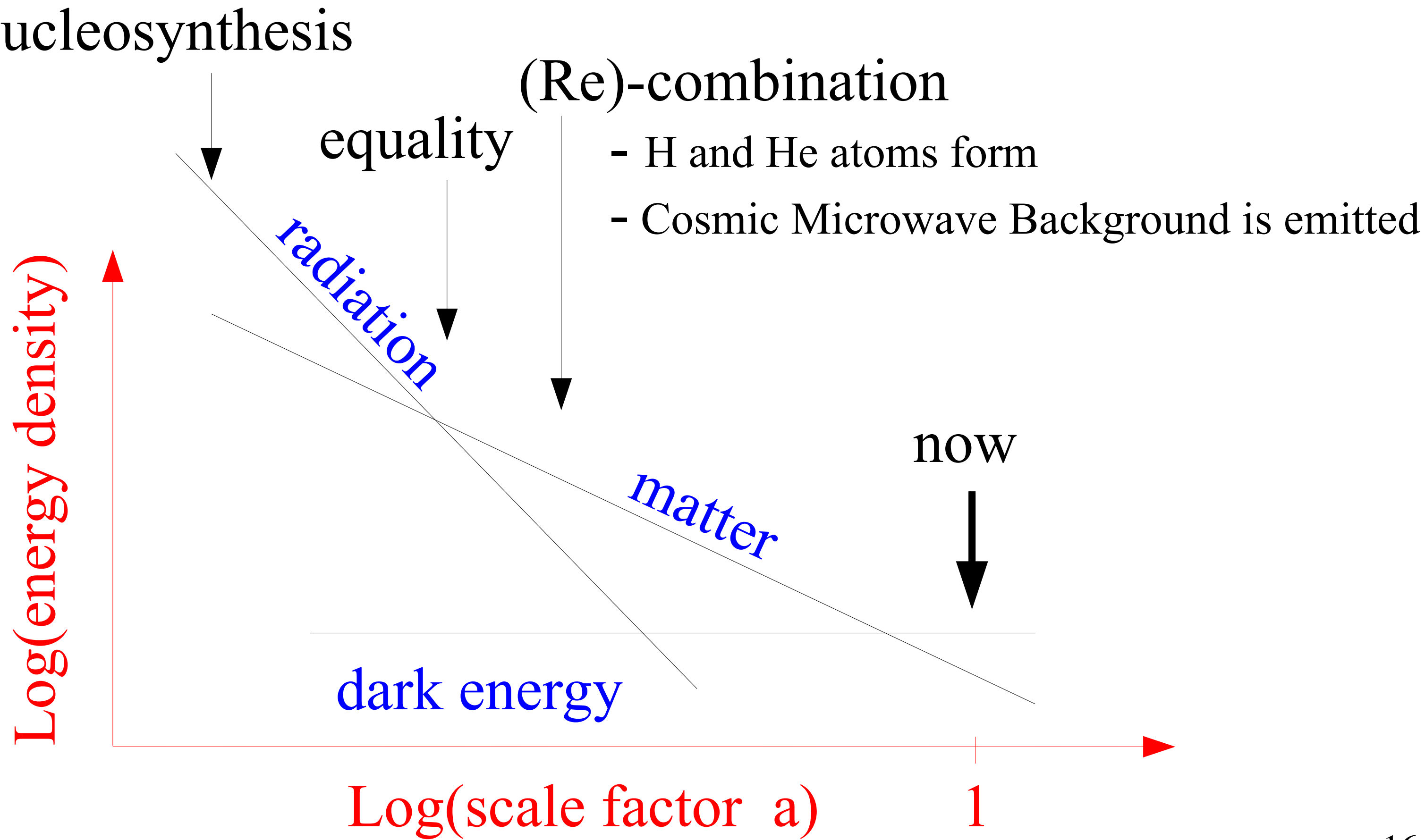
This is why high-energy accelerators are related to Big Bang

A brief history of the universe



- H and He atoms form
- Cosmic Microwave Background is emitted

A brief history of the universe



- H and He atoms form
- Cosmic Microwave Background is emitted

How long since Big Bang ?

$$H_0 \equiv \left.\frac{\dot{a}}{a}\right|_{\text{today}}$$

A factor of order 1 that depends on the details of expansion history

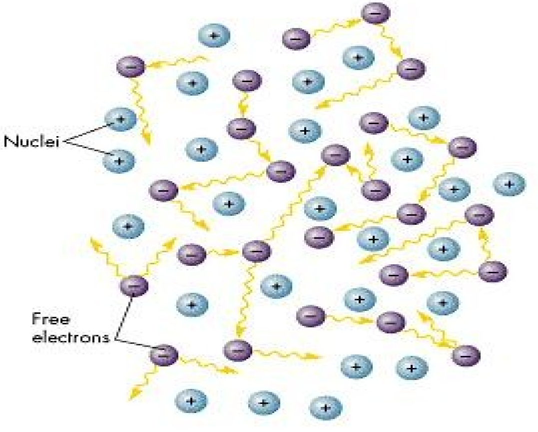
$$t_{\text{now}} - t_{\text{BB}} = O(1)/H_0$$

$$H_0^{-1} = 13.95\ 10^9 y\ \left(\frac{H_0}{70\ \text{km/s/Mpc}}\right)^{-1}$$

Observational evidence of the hot Big Bang scenario

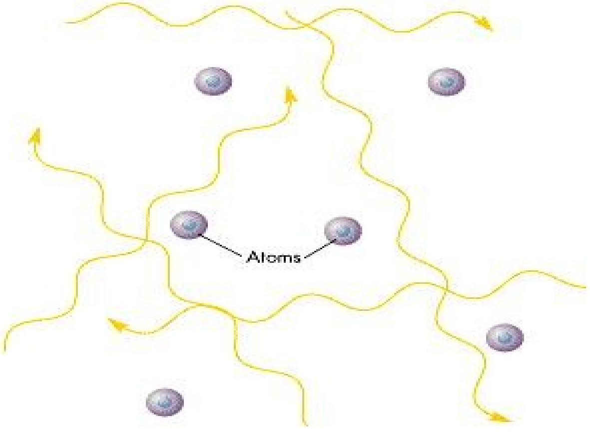
- The Cosmic Microwave Background (CMB)
- The cosmological abundance of light elements
- The evolution of large scale structures
- The age of oldest stars (~ 13 Gy)

The CMB emission
(cosmic microwave background)



A Before recombination: The universe was opaque

Before recombination



B After recombination: The universe was transparent

After recombination

“Recombination” should be called “combination”
… but is always called recombination.

CMB is a fossil remain of the hot big bang.
It still dominates the radiation energy budget

When did it happen?

Order 0: when energy of photons ~ 13.6 eV (H binding energy)

Order 1 : when there were as many photons >13.6 eV than electrons and protons

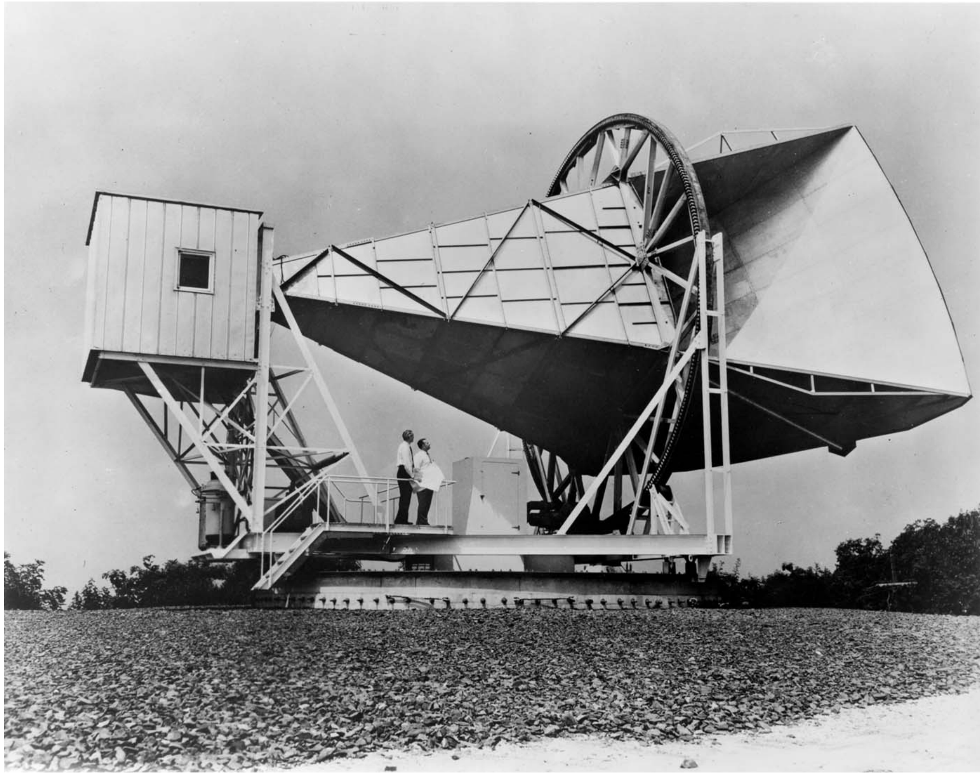
$$T_{rad} = 13.6\ eV\ \log\left(\frac{N_b}{N_\gamma}\right) \simeq 0.7\ eV \simeq 7000K$$

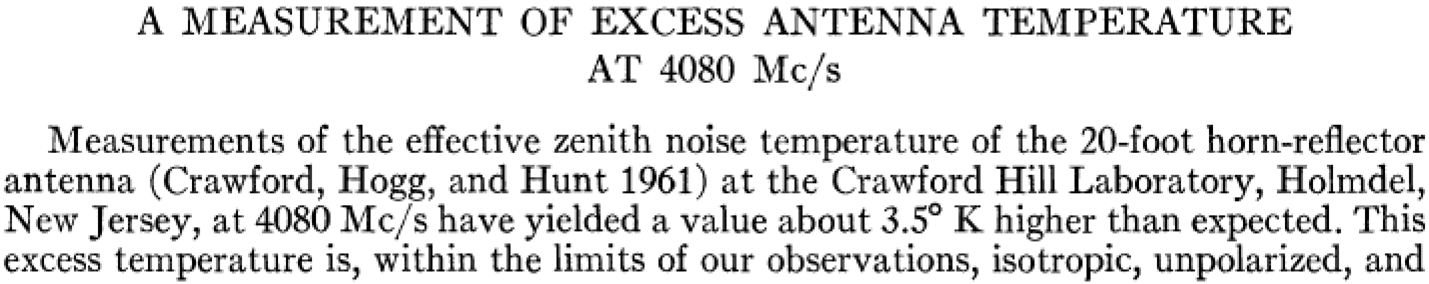
Order 1.5 : replace 13.6 by 3/4*13.6 (n=1 → n=2). Find 5000 K

Beyond : involved atomic physics and numerical codes. Find 3000 K
→ emitted ~ 380,000 years after BB

CMB detection (and identification) almost 60 years !

(Penzias & Wilson, Bell Labs, 1965)

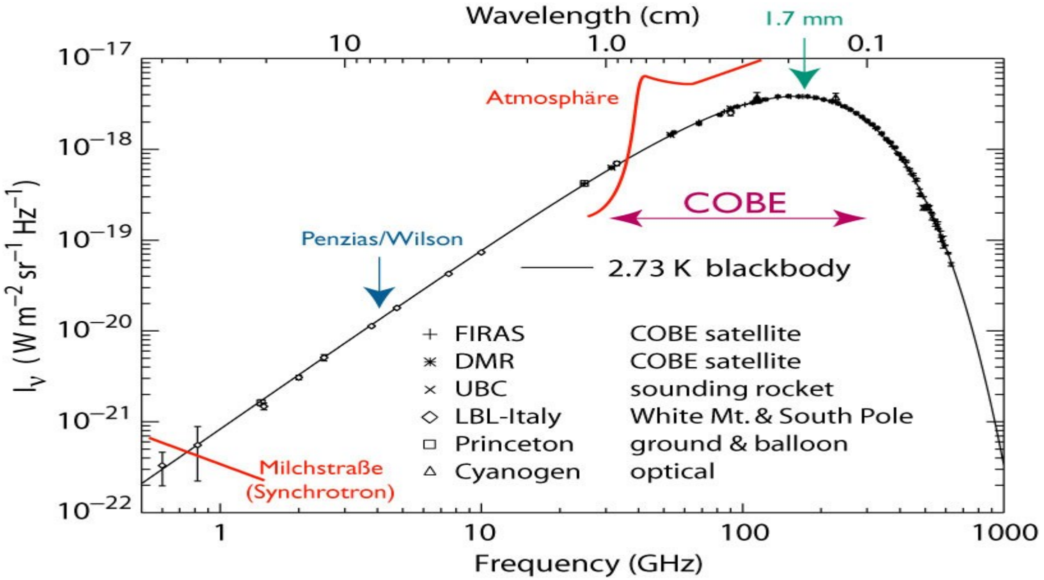




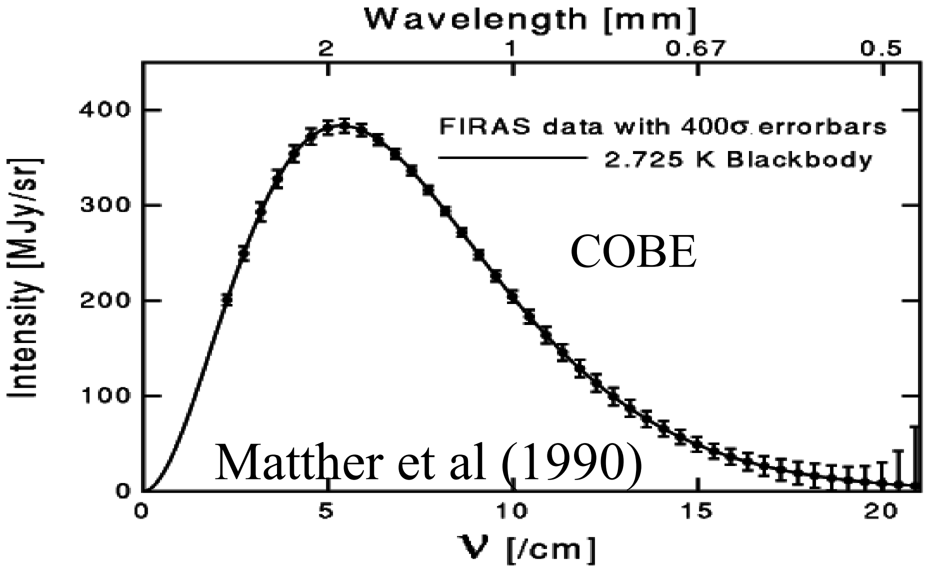
A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE
AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and

CMB spectrum: it has to be thermal...
...and it is thermal



(Prof. Dr. Karl - Heinz Kampert, Uni Wuppertal)



COBE

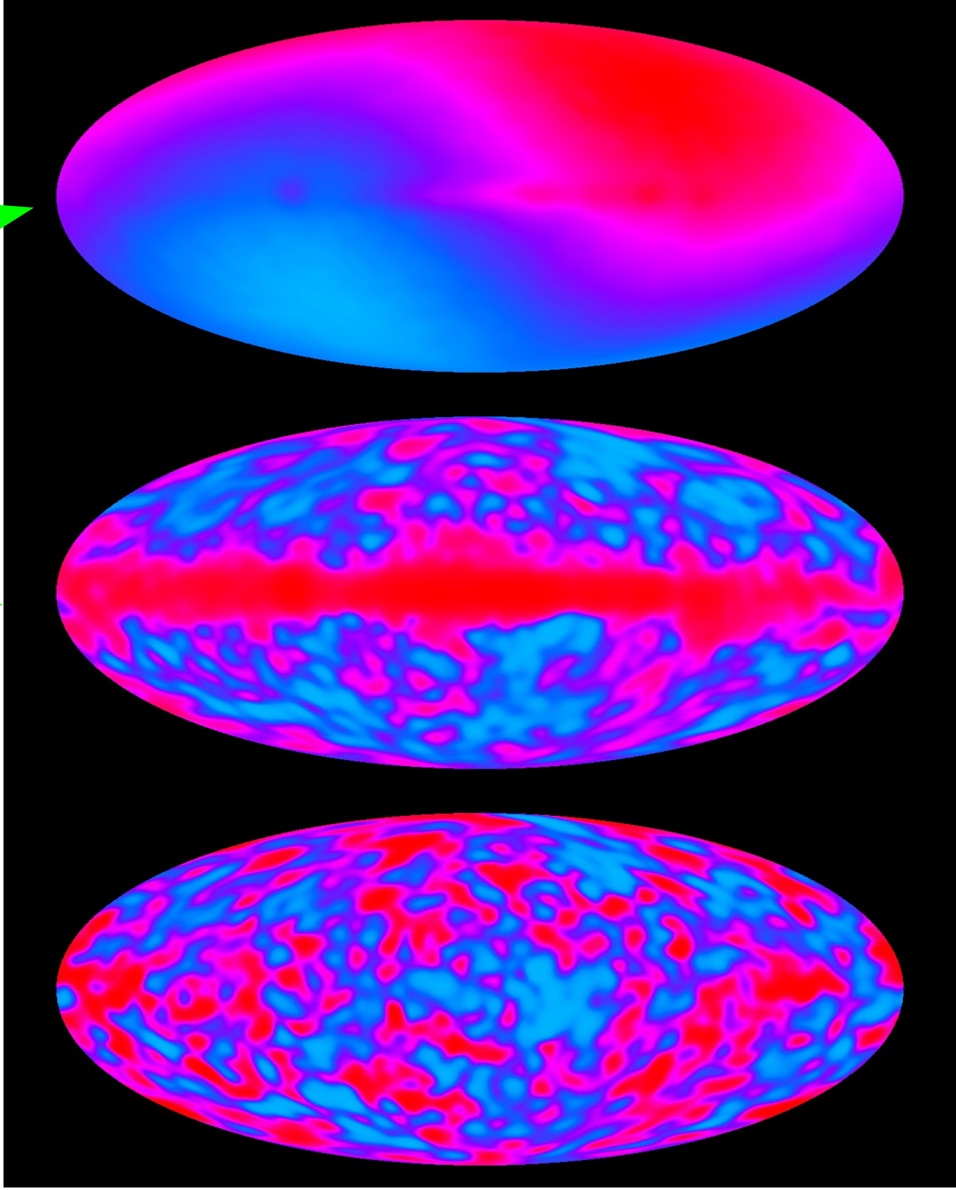
Matther et al (1990)

T = 2.7255 +/- 0.0006 (Fixsen, 2009 systematics- dominated)

the most precise cosmological measurement still

→ also delivers photon density : 413 cm^{-3} today

CMB anisotropies



Dipole due to
our peculiar velocity, O(10^{-3})

Milky Way emission

$$\frac{\delta T}{T} \sim 10^{-5}$$

(COBE DMR, Smoot et al, 1992)
First detection of CMB anisotropies

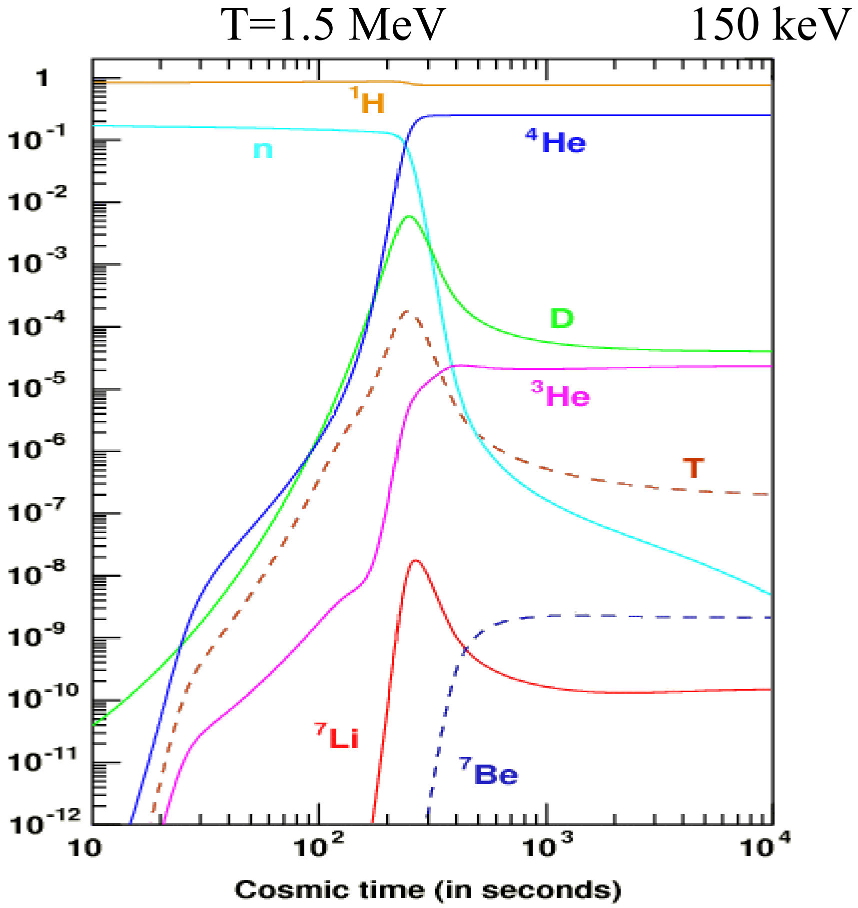
CMB anisotropies

- Anisotropies refers to temperature changes as a function of position on the sky.
- The variations are small : 10^{-5} rms.
- The physics that give rise to the evolution of these fluctuations is precisely calculable (by perturbation theory), and is hence very safe.
- This allows to constrain many parameters of the cosmological model, in particular the densities (matter, baryons, …), curvature, and the Hubble constant.
- The latest full-sky measurement of these anisotropies is due to *Planck* (launched in 2009). Latest analysis : 2018.

Observational evidence of the hot Big Bang scenario

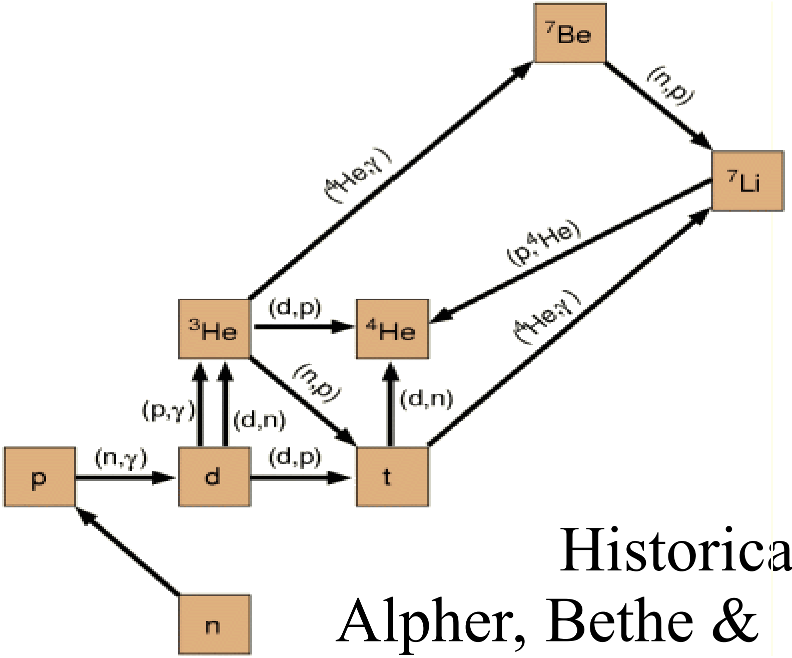
- The Cosmic Microwave Background (CMB)
- The cosmological abundance of light elements
- The evolution of large scale structures
- The age of oldest stars (~ 13 Gy)

Big Bang Nucleosynthesis



E. Vangioni (IAP)

Nucleosynthesis (i.e. forming light nuclei)
-starts at T ~ MeV (t~100 s)
- stops when density gets too low
(or run out of neutrons)



Historical paper:
Alpher, Bethe & Gamow (1948)

Nucleosynthesis (2)

Main drivers :

$\eta = N_{\text{baryons}}/N_{\text{photons}}$

Expansion rate (depends on the number of neutrino flavours)

Measurements of abundances :

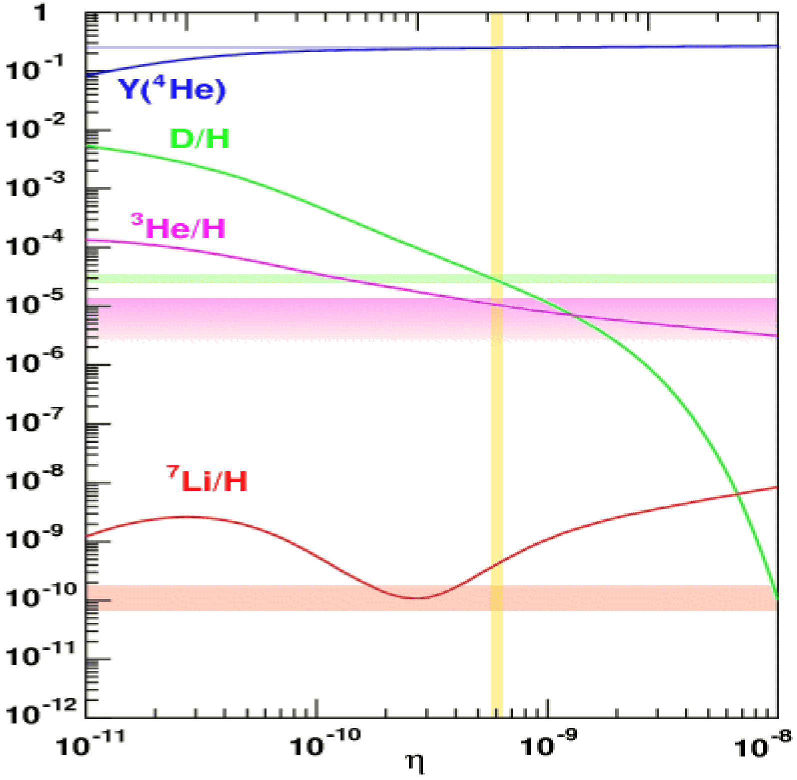
Helium fraction is 0.24 (safe)

D/H is hard to measure (settled now).

Li is destroyed in stars.

Bottom line:

- $\eta = 6\ 10^{-10}$ explains measured abundances
- Photon density is known → yields baryon density



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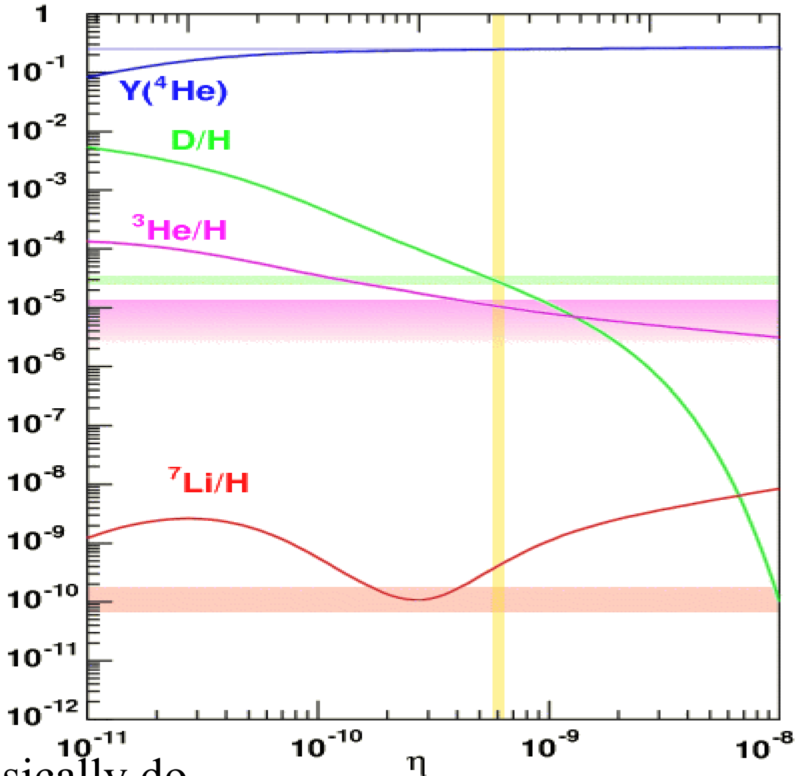
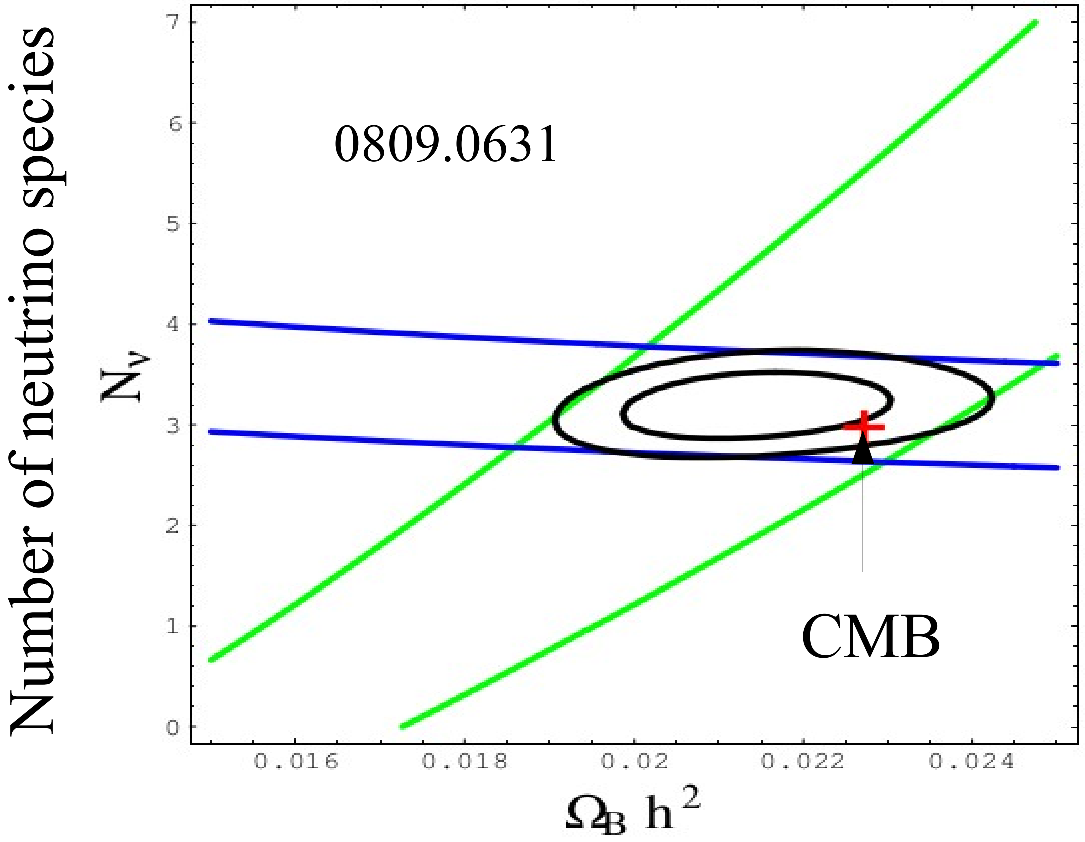


We basically do not understand this number

E. Vangioni (IAP)

Nucleosynthesis (3)



Deuterium

Helium

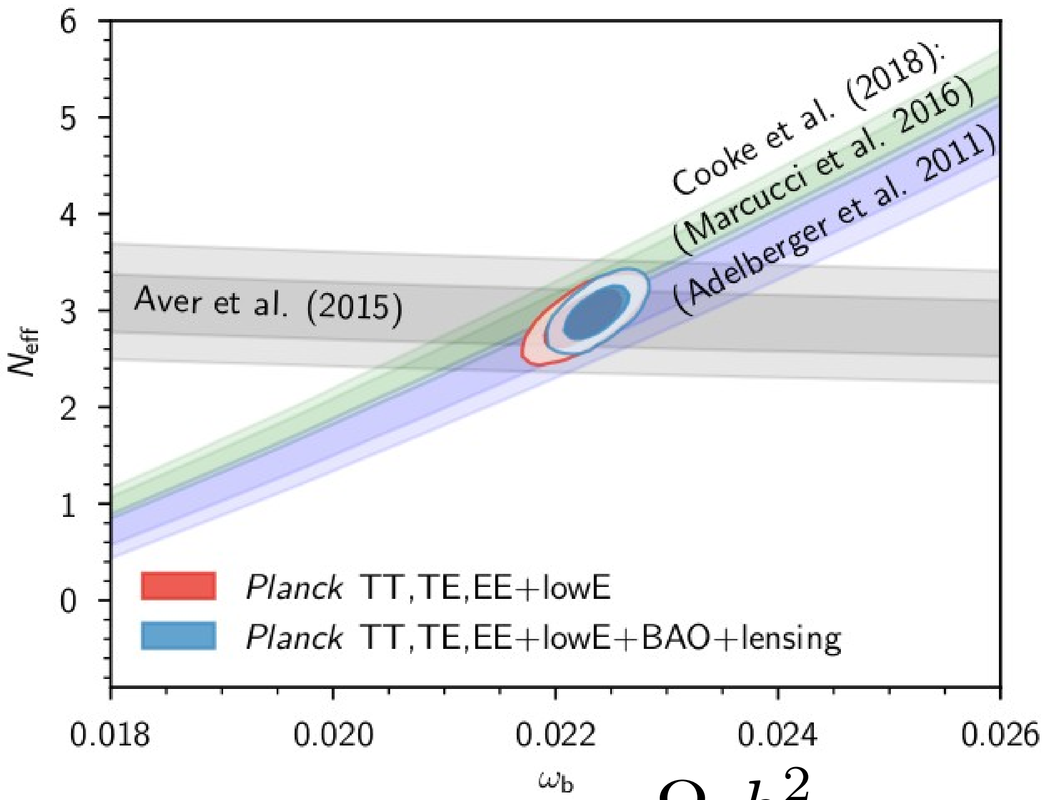
$\Omega_b \sim= 0.045$

Much lower than Ω_m

Baryon density (and h~0.7)

Baryon density and Nν, from CMB and BBN in 2018

1807.06209



$\Omega_b h^2$

Constraints have improved in 10 years, and the compatibility is still remarkable

A great success of physical cosmology.

Observational evidence of the Big Bang scenario

- The Cosmological Microwave Background.
- The cosmological abundance of light elements.
- The evolution of large scale structures.
- The age of oldest stars:

  The age of stars can be evaluated using stellar evolution models

  The oldest observed stars are ~13 Gyr old.

So, there was a hot Big Bang about 13 Gyr ago

Or, …. everything looks like there was one ….

Two relics are well explained by a hot Big Bang:

- Light nuclei (~3 mn)
- CMB (~ 400 000 yr), thermal and isotropic.
- They agree about the baryon density and N_ν

~~Experimental~~ Observational Program :

- figure out the (average) content
- (understand the formation of structures.)

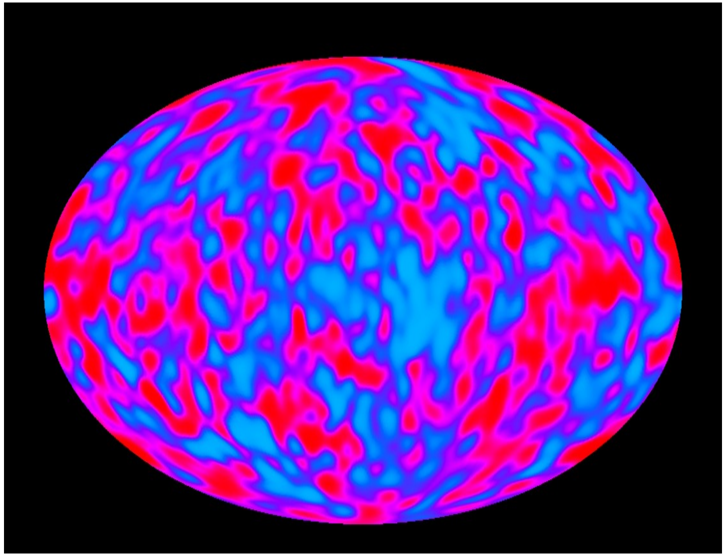
Summary

- The universe expands (the redder the fainter)

  → Density goes down with time
- There was an initial very high density phase : the “Big Bang”
- Big Bang Nucleosynthesis implies specific abundances of light nuclei
- A high density initial phase imposes that there is relic thermal radiation : CMB
- Constraints from BBN and CMB agree about the number of neutrinos species and baryon density
- The baryon density represents ~5% of the critical density

Cloud #1: the horizon problem (the smoothness problem)

$$\frac{\delta T}{T} \sim 10^{-5} \longrightarrow$$



- The CMB is extremely uniform
- It was emitted ~400,000 y after BB
- In a matter+radiation dominated universe, this corresponds to an horizon of ~250 Mpc, i.e. ~ 2 degrees on the sky at z~1100.

→ CMB patches more than ~ 2 degrees apart were never causally connected in the past

- How comes that they have the same temperature ?

→ invent a fast expansion phase in the early universe

→ need some extra component to achieve that

Cloud #2 : the flatness problem

Friedman equation : $$H^2(a) = \frac{8\pi G}{3}\rho - \frac{k}{a^2}$$

$$1 - \frac{8\pi G\rho}{3H^2} \equiv 1 - \Omega(a) = -\frac{k}{(Ha)^2}$$

Ha decreases with time, so $|1-\Omega(a)|$ increases with time

We have today $|1-\Omega| < 0.1$, so it had to be much smaller in the past.

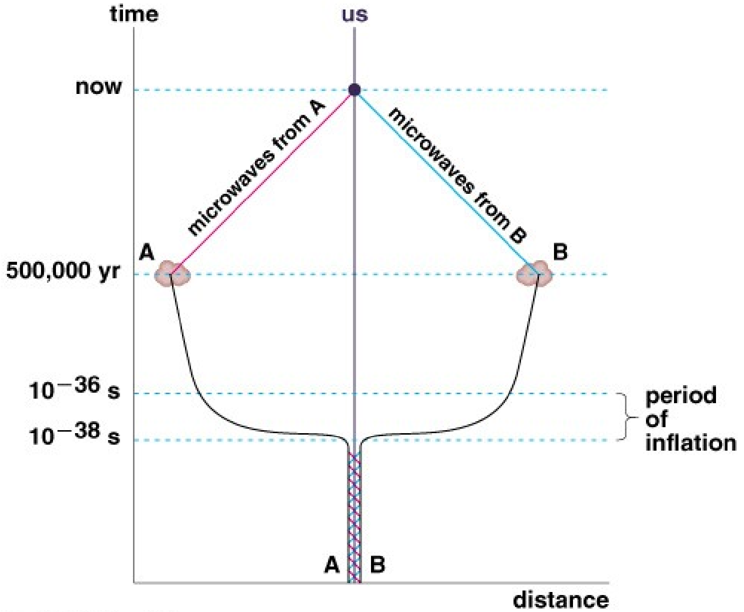
→ fine tuning required

→ a dynamical process setting curvature to 0 would be nice.

Inflation: an accelerated expansion phase

- Pulls things apart.

Apparently unconnected places were indeed connected before (much before actually)



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- Dilutes any curvature.
  - In an exponential expansion phase, H~Cst
  - Curvature contributes to H as $1/a^2$, it just decays.

Inflation : one more scalar

$$H(t) \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2}$$

With ρ=Constant, we eventually have an exponential expansion

For an homogeneous scalar field, $\rho = \frac{\dot{\phi}^2}{2} + V(\phi)$

So, a quasi-static scalar field $\dot{\phi} \simeq 0$

- slowly rolling down its potential,
- has an almost constant energy density
- … and provides a quasi-exponential expansion.

A purely static scalar field delivers a never ending inflation, which is not what we want. So the potential should ensure that inflation ends.

Inflation predictions

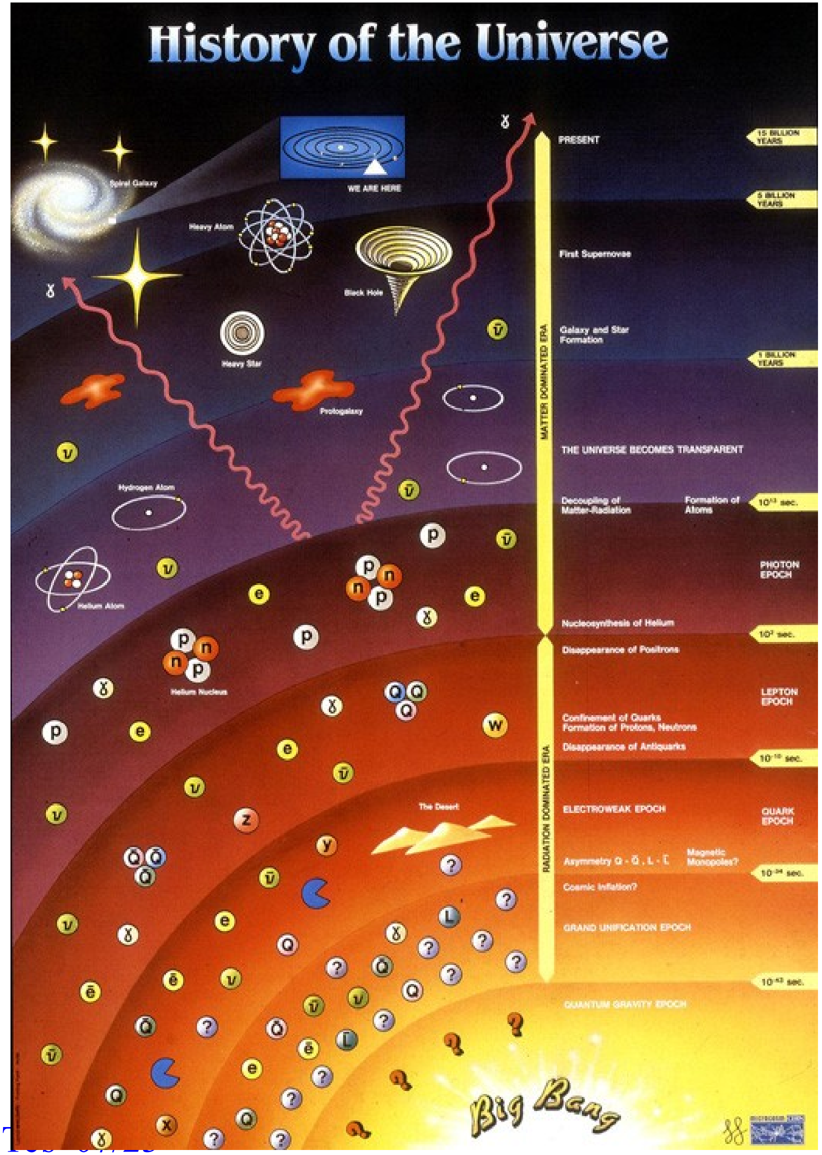
- The universe is flat (at the 10^{-5} level)
- The universe is initially very homogeneous (to the same level).
- Quantum fluctuations of the inflation field are the initial conditions of the perturbations we see.

  → sets the energy scale to ~ 10^{16} GeV
- These perturbations are scalar (potential) or tensor (metric)
- The initial power spectrum of scalar perturbations is $P(k) = A\, k^n$

  with $n<1$ and close to 1.
- A specific model of inflation predicts both the spectral index and the ratio of tensor to scalar perturbations.

  But there are a lot of models...

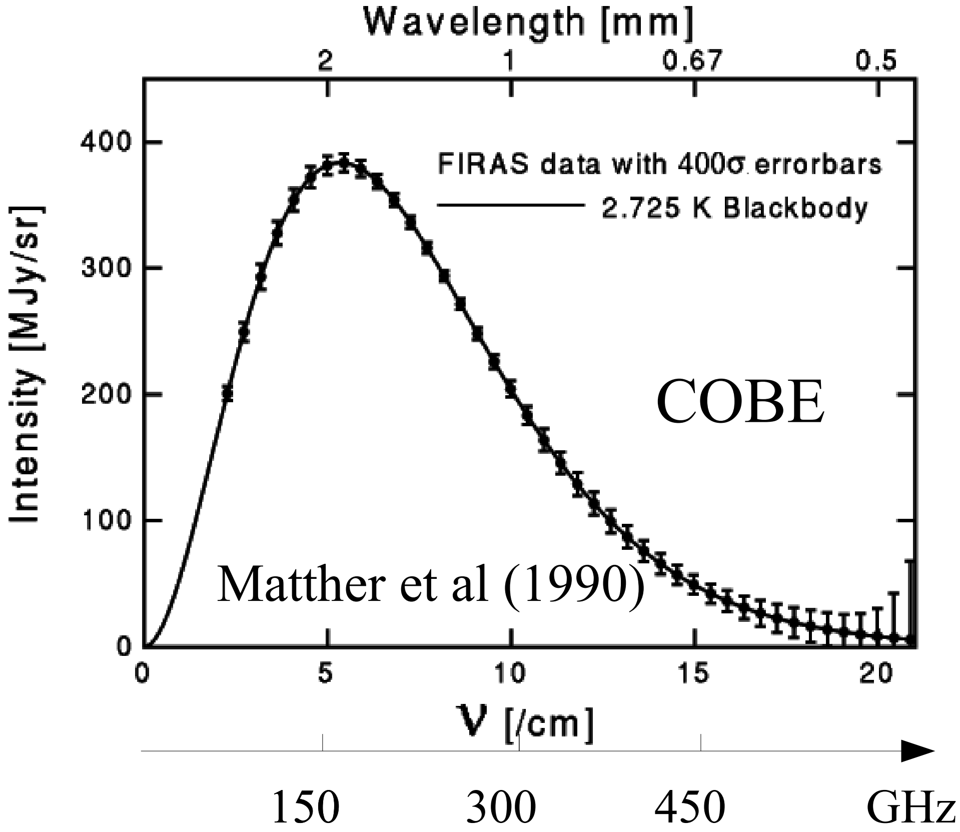
The Cosmic Microwave Background



CMB is emitted here (recombination)

Physics before recombination is very well described by first order perturbations

Spectrum ?



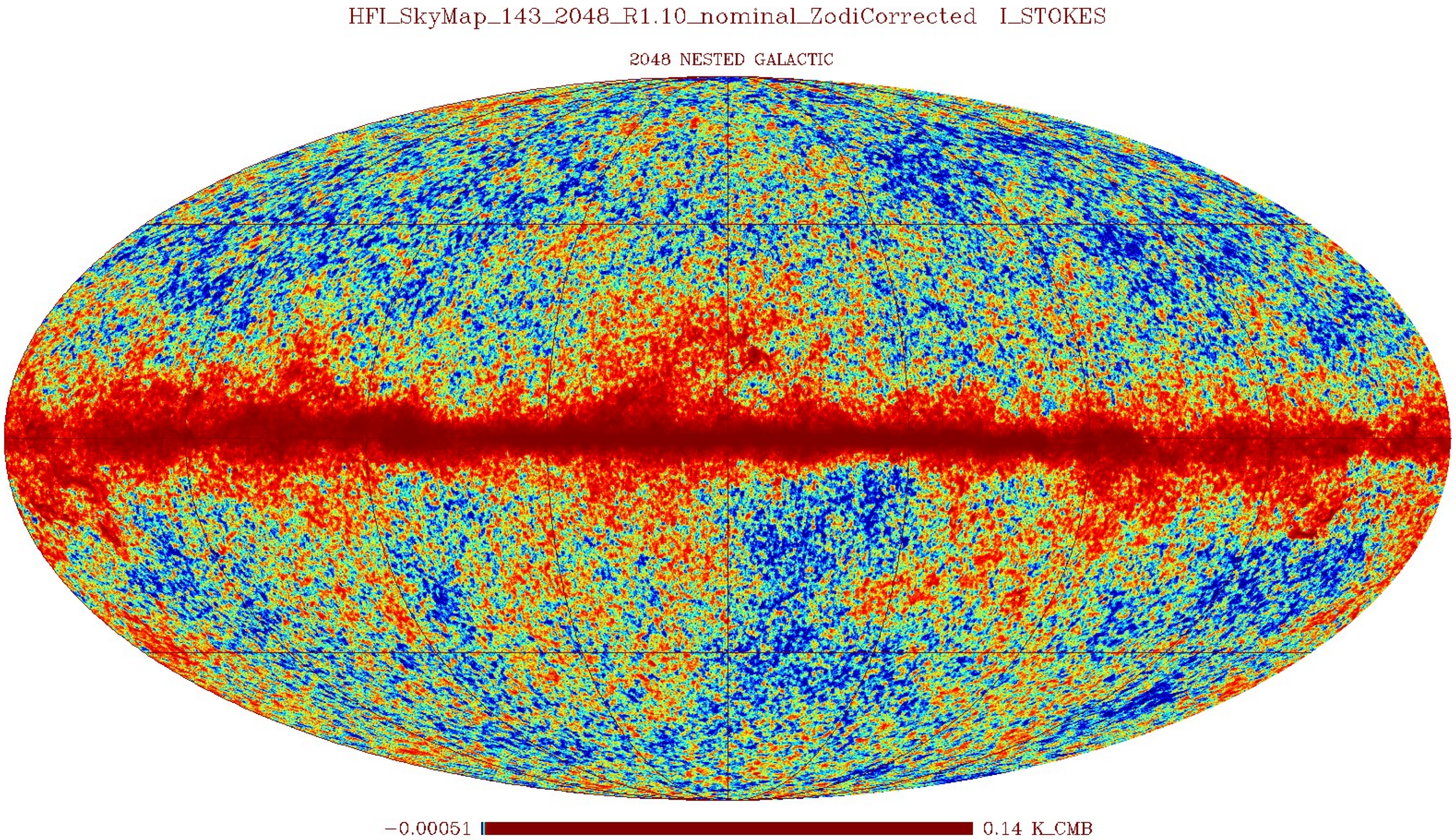
COBE

Matther et al (1990)

T=2.72 K

Peak at ~:
- 5 cm^{-1}
- 2 mm
- 150 GHz

The anisotropies at ~143 GHz

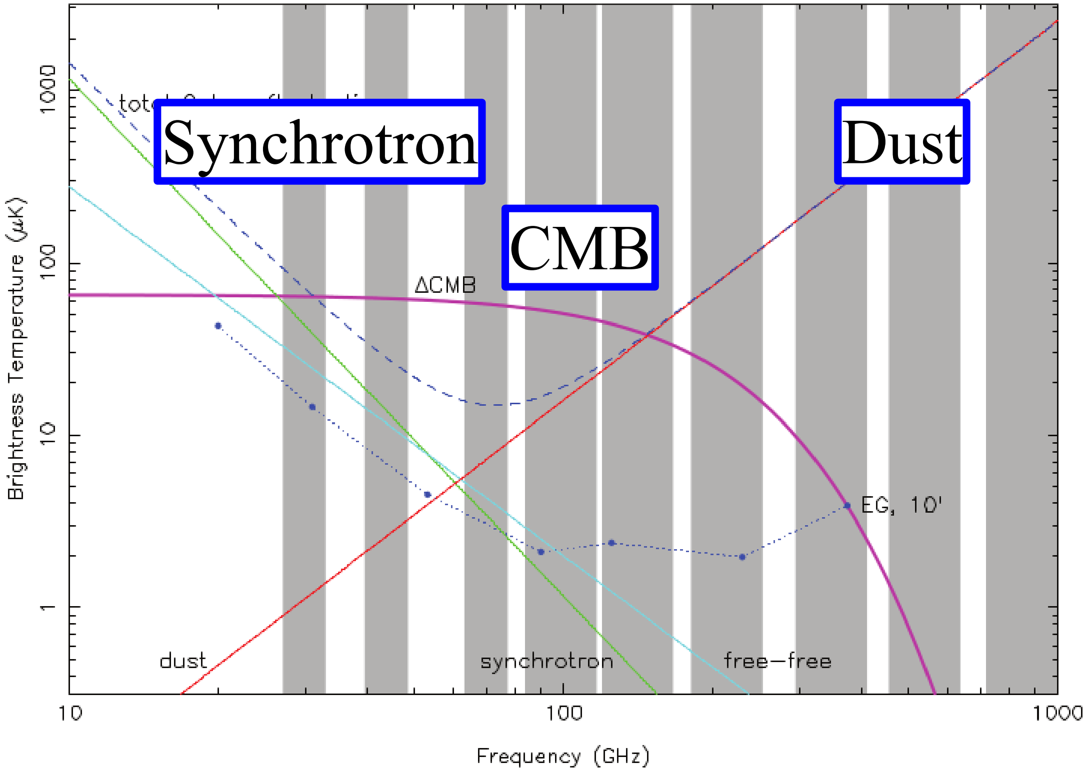


Galactic
coordinates

← Galactic
plane

Planck

Emissions at 30 → 900 GHz

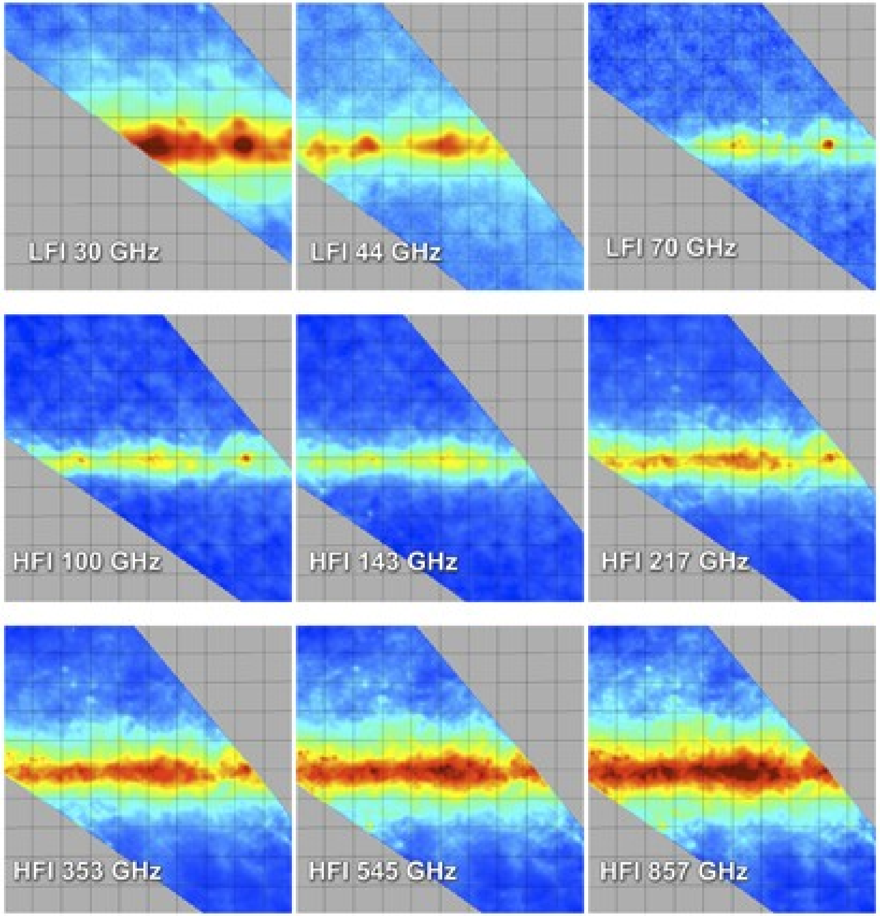


Synchrotron and dust
are both concentrated
In the galactic plane

Intensity of fluctuations at the degree angular scale.

The way out: multi-band observations

Galactic plane



Synchrotron

Dust

The Planck concept (1996)

Perform the "ultimate" measurement of the Cosmic Microwave Background (CMB) temperature anisotropies:

- full sky coverage
- angular resolution to 5' (below, foregrounds dominate)
- sensitivity limited by foregrounds

→ spectral coverage : 30 → 850 GHz.

Instruments: radiometers (30→60), bolometers (90→ 850)

- Mission selected by ESA in 1996 (studies started in 93...) for a launch in 2003.

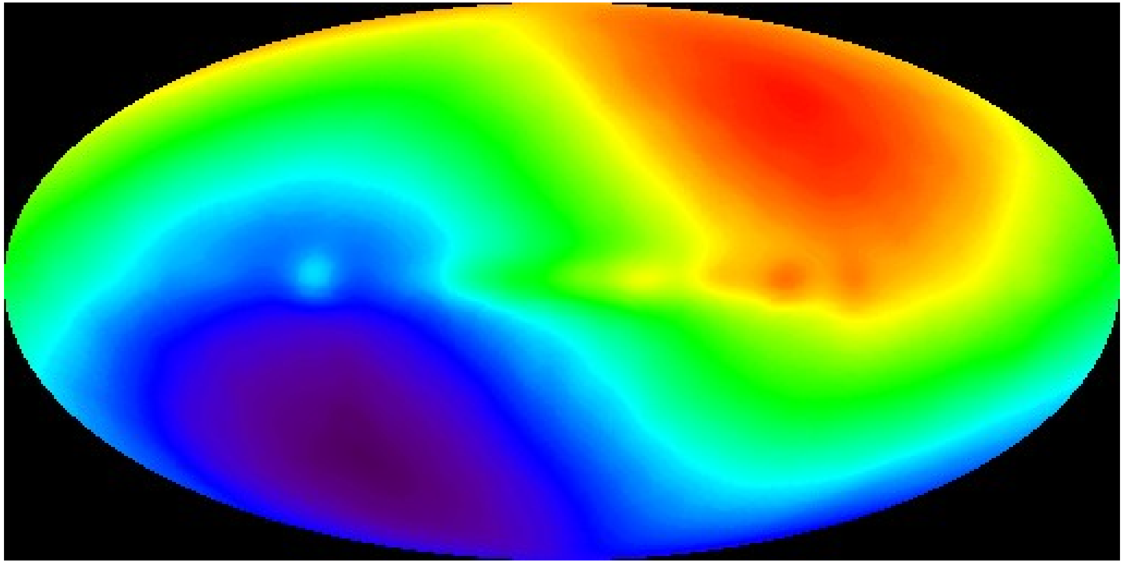
→ launch delayed (2003 → 2007, crash of Ariane 501)

→ polarisation capabilities became a "must-do"

→ more delays

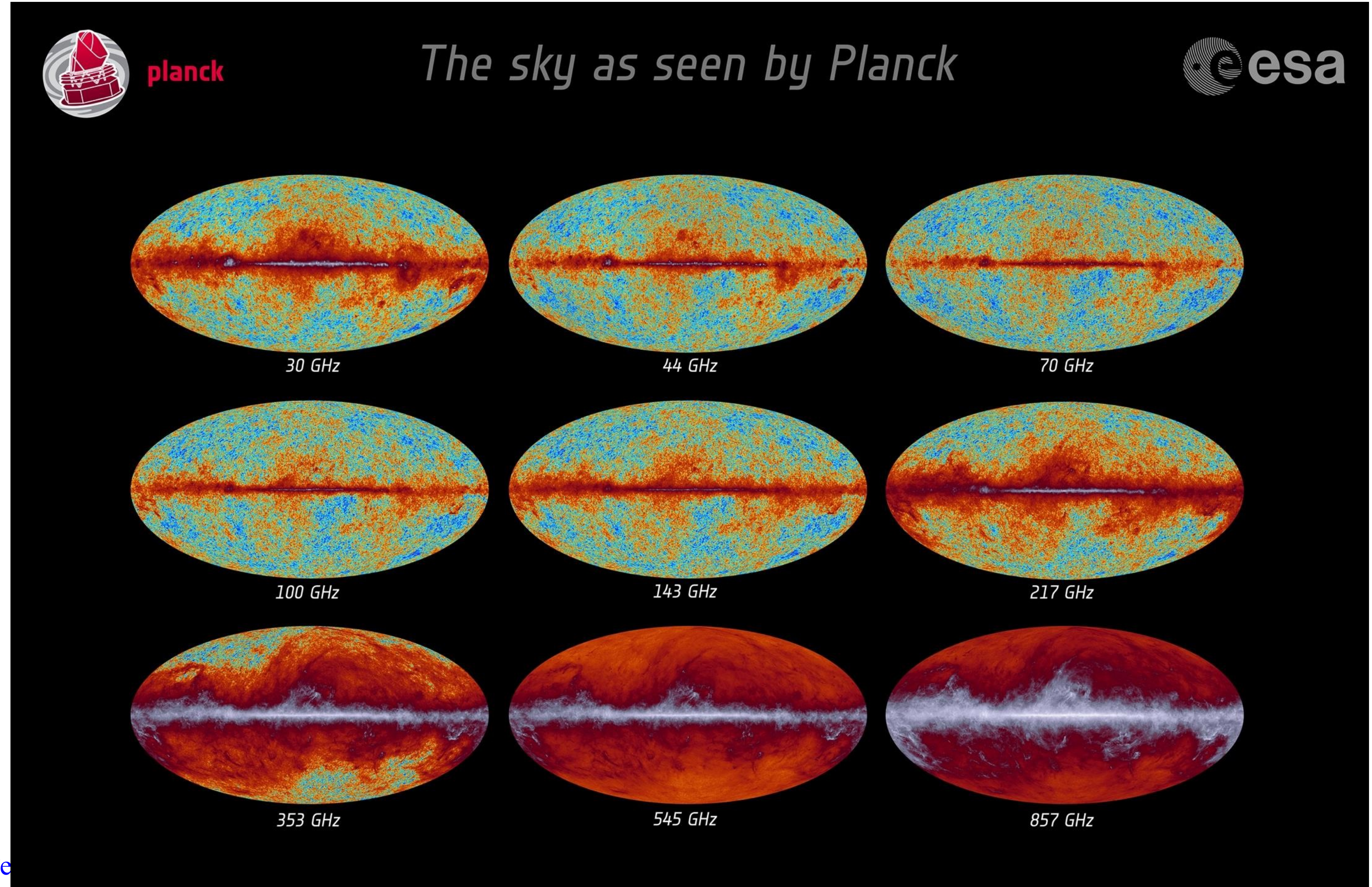
- Launch in May 2009.

The dipole: the ether's revenge

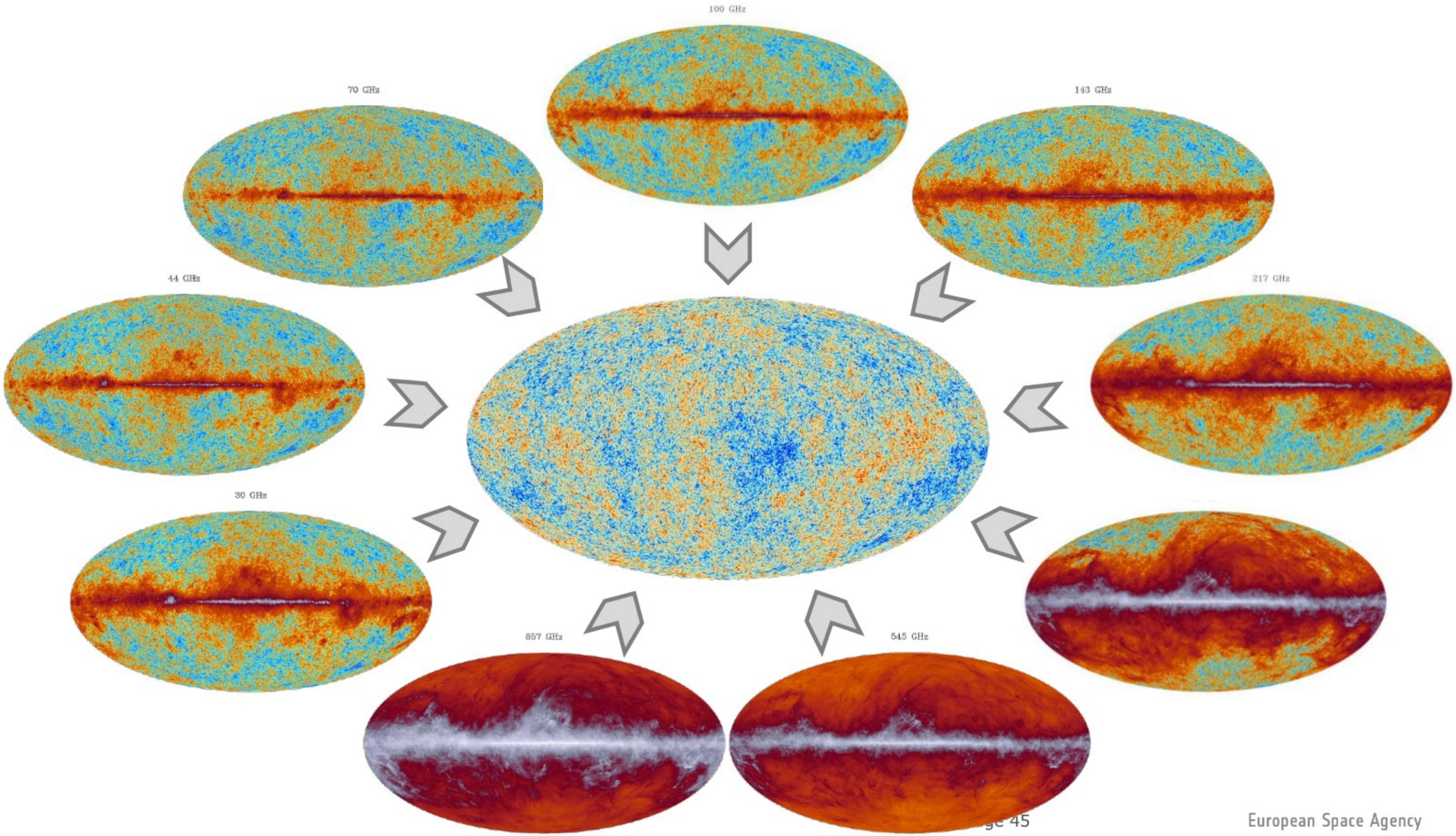


We are not at rest w.r.t CMB

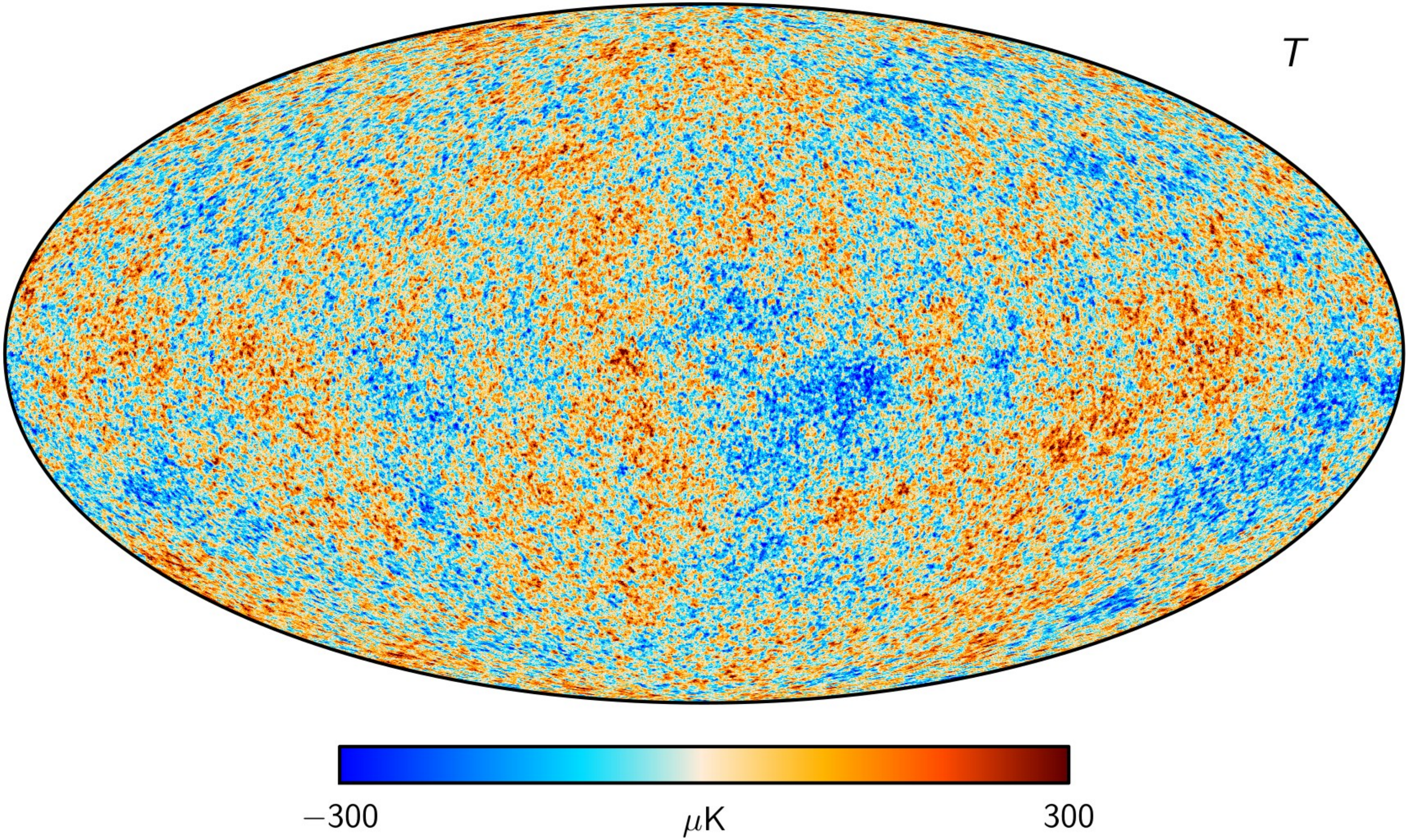
Average CMB temperature : 2.7 K
Amplitude of the dipole : 3.35 mK
→ velocity w.r.t CMB = 369 km/s
Amplitude of the CMB anisotropies : ~ 30 μK


The sky as seen by Planck
30 GHz
44 GHz
70 GHz
100 GHz
143 GHz
217 GHz
353 GHz
545 GHz
857 GHz

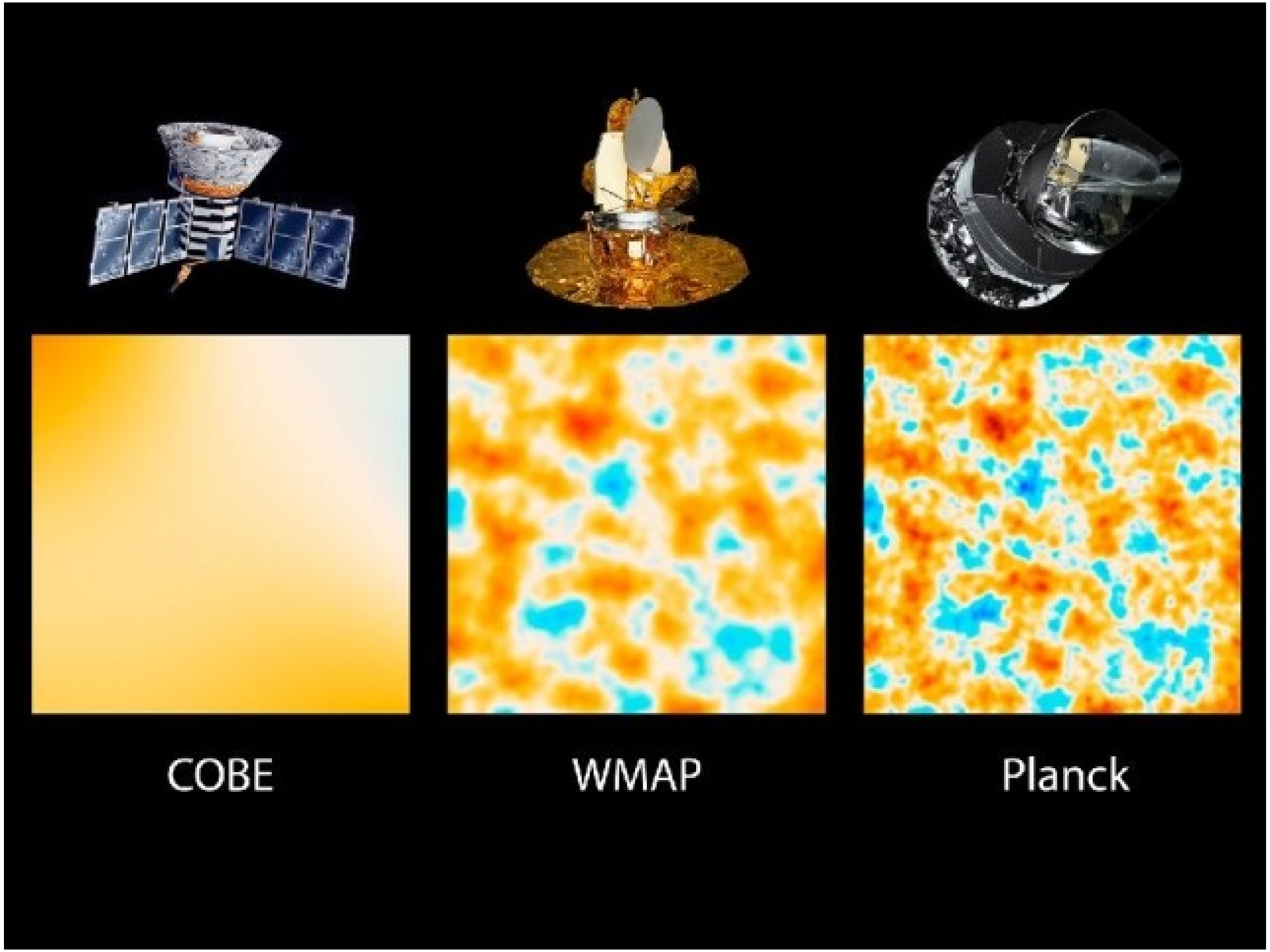
Combine the data to get the CMB



Temperature anisotropies (Planck 2018)



Two decades of CMB anisotropies

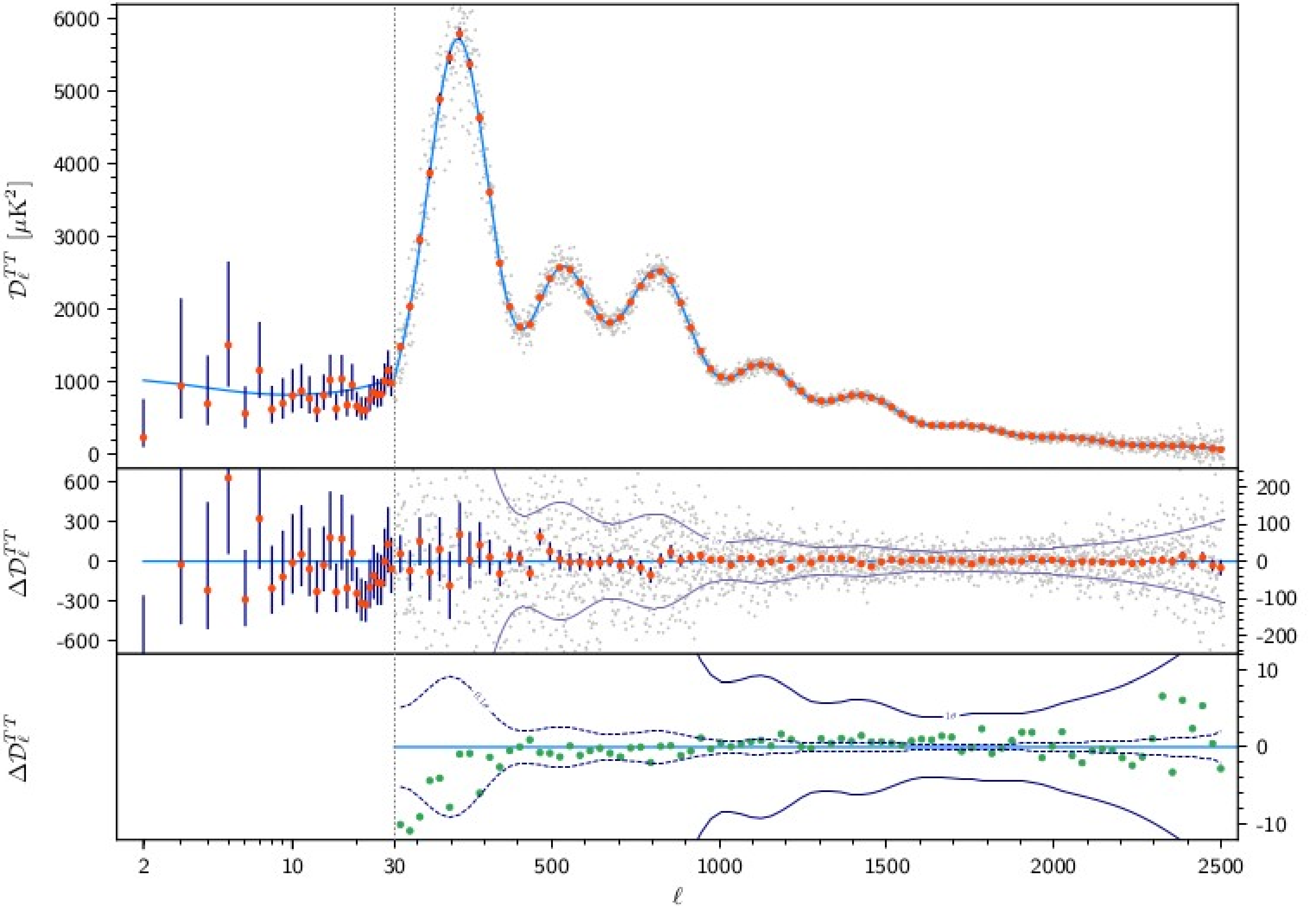


Power spectrum

- Because of statistical isotropy, we can condense the map information into one dimension
- “Fourier Transform” the map : $$\frac{\delta T(\theta,\phi)}{T} = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta,\phi)$$
- Statistical isotropy : $$C_\ell = \frac{1}{2\ell+1}\sum_m |a_{\ell m}|^2$$
- The C_l coefficients are invariant by rotation. They are predicted by theory.

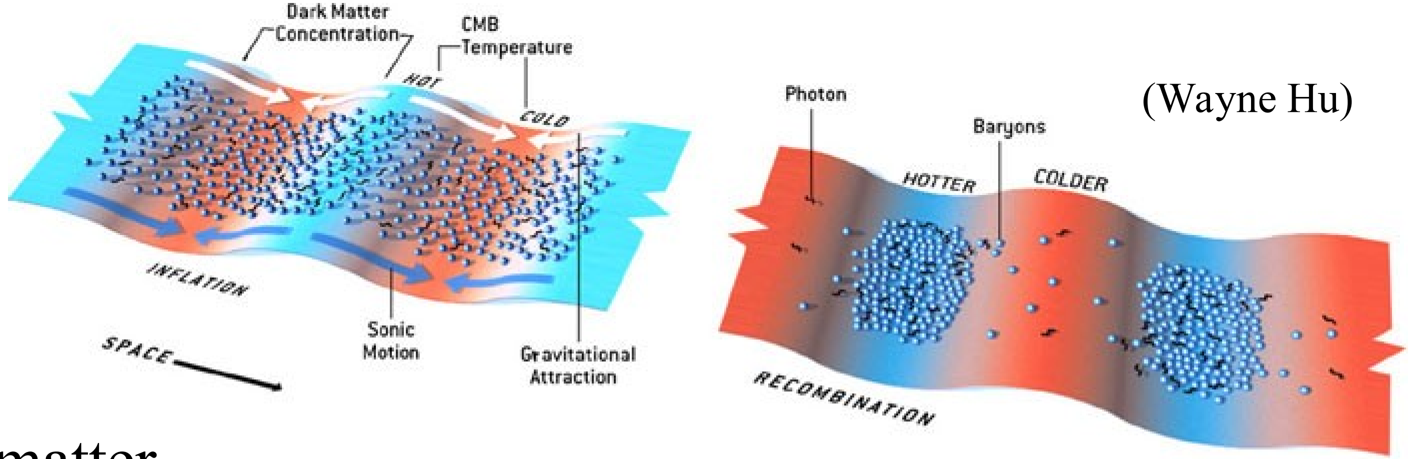
Angular power spectrum

Dominated by a
series
of peaks



(Planck 2018)

Why peaks ? Sound waves



(Wayne Hu)

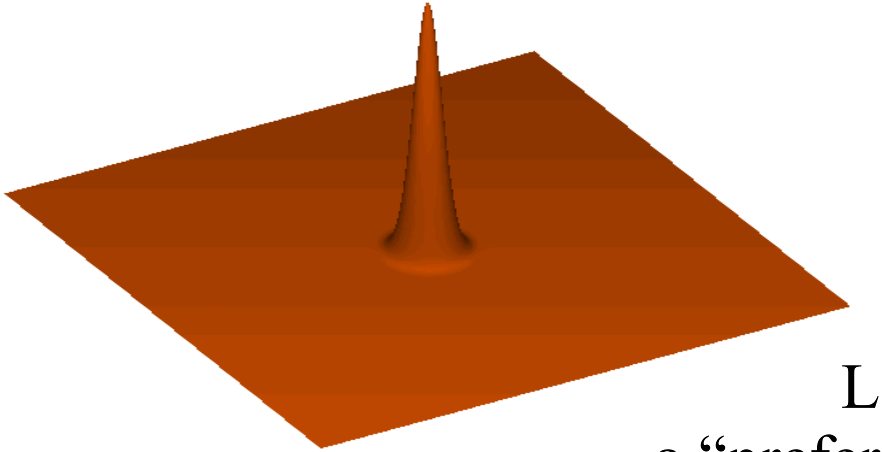
Two forces at play:

- Denser regions attract matter
- Radiation in denser regions gets hotter and repels charged particles

→ Sound waves in the plasma

Relics of early perturbations: sound horizon

- Sound waves in the early plasma (before recombination)
  - The dominant contribution to the CMB anisotropies on small scales (< ~2 degrees).



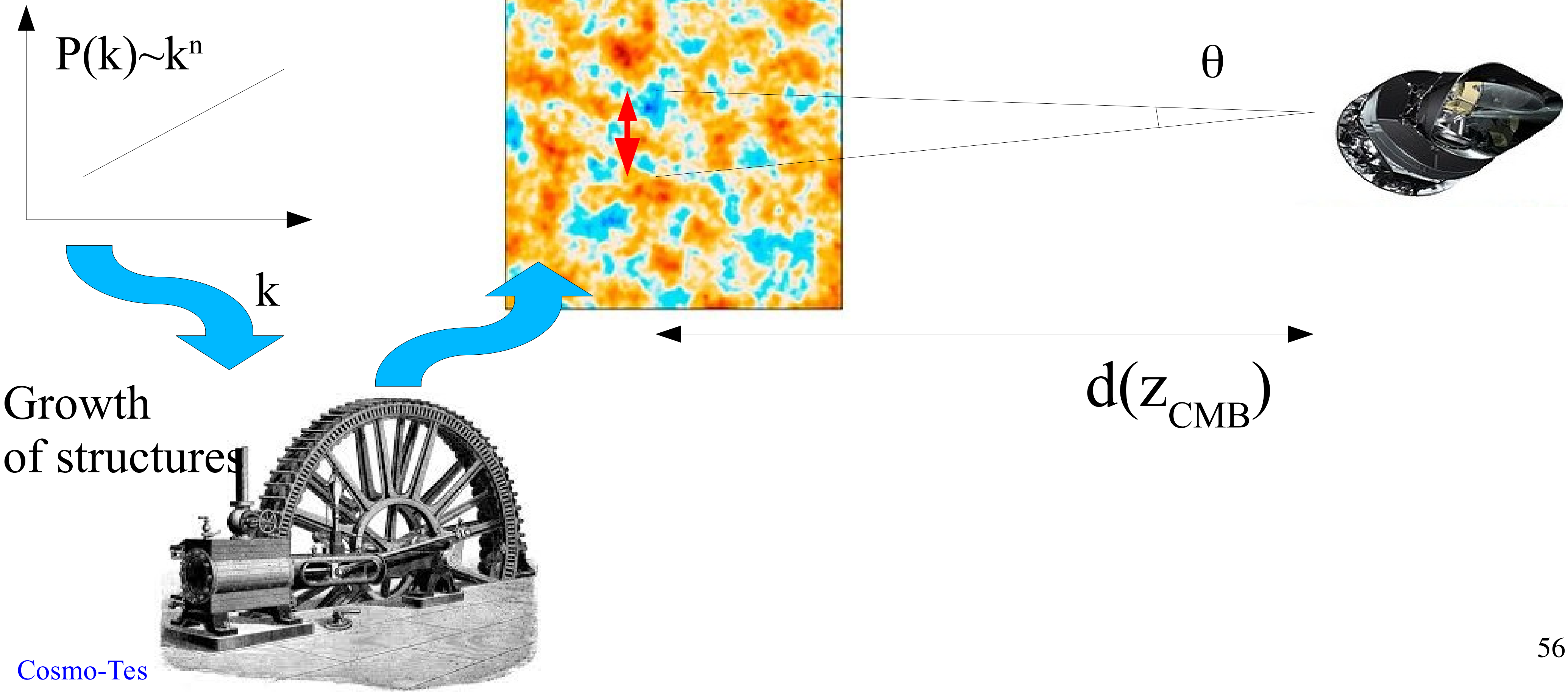
Sound waves propagate in the primordial plasma until recombination where the pattern just freezes.

Sound horizon: distance travelled by sound waves Until recombination

Leaves :

- a “preferred angle” (~2 °) in the CMB anisotropies,
- a preferred length (140 Mpc) in the matter density fluctuations

A 6-parameter model



$P(k) \sim k^n$

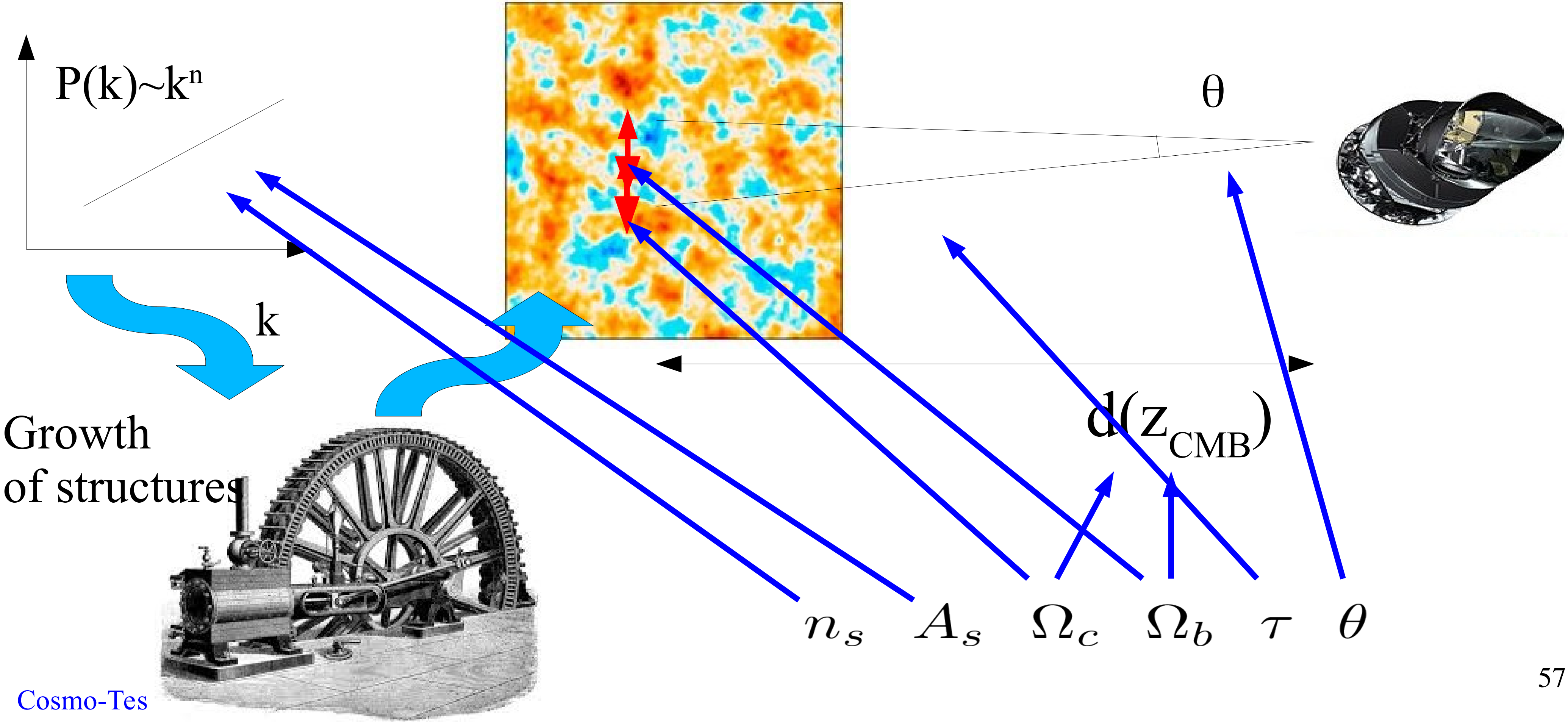
k

θ

$d(z_{CMB})$

Growth
of structures

A 6-parameter model



$P(k) \sim k^n$

k

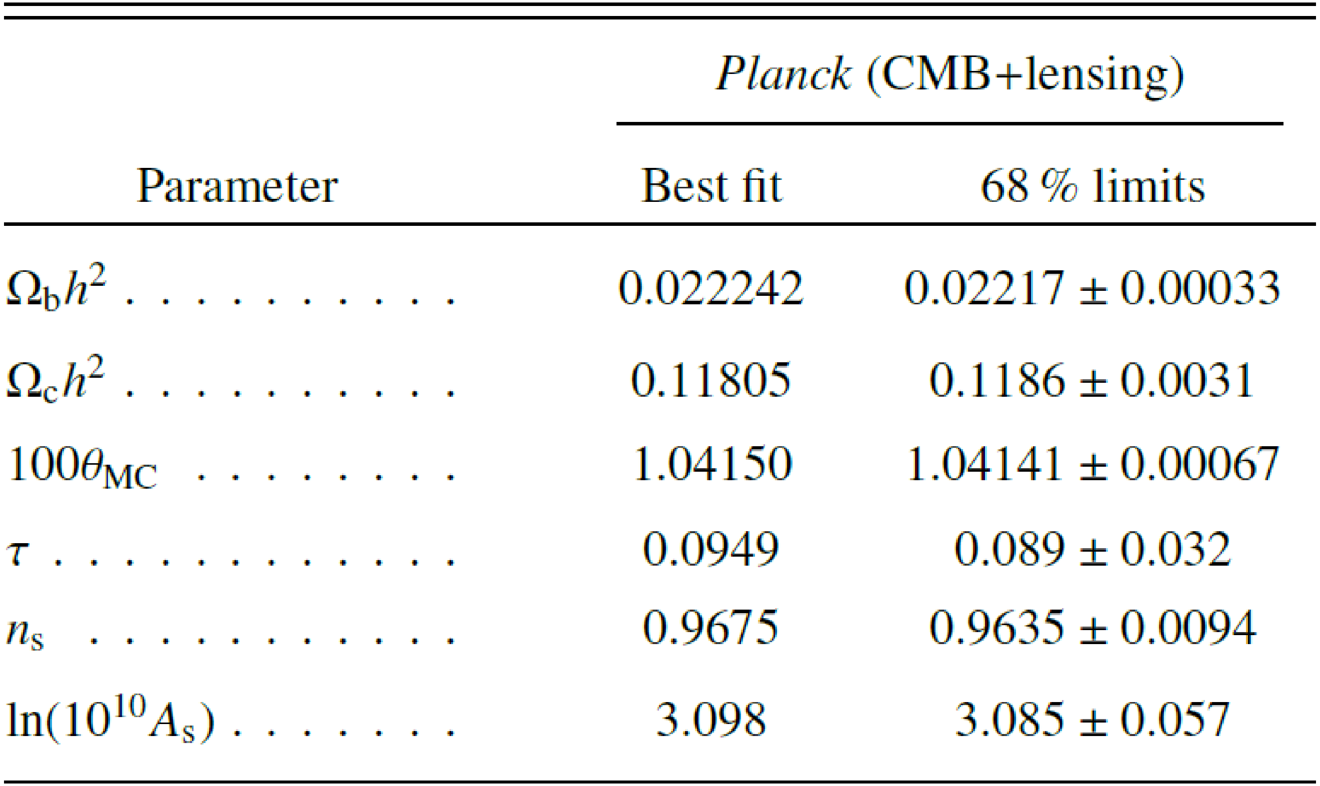
Growth
of structures

θ

$d(z_{CMB})$

n_s A_s Ω_c Ω_b τ θ

Great results for a flat ΛCDM universe



	Planck (CMB+lensing)	
Parameter	Best fit	68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067
τ	0.0949	0.089 ± 0.032
n_s	0.9675	0.9635 ± 0.0094
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057

← Same as BBN

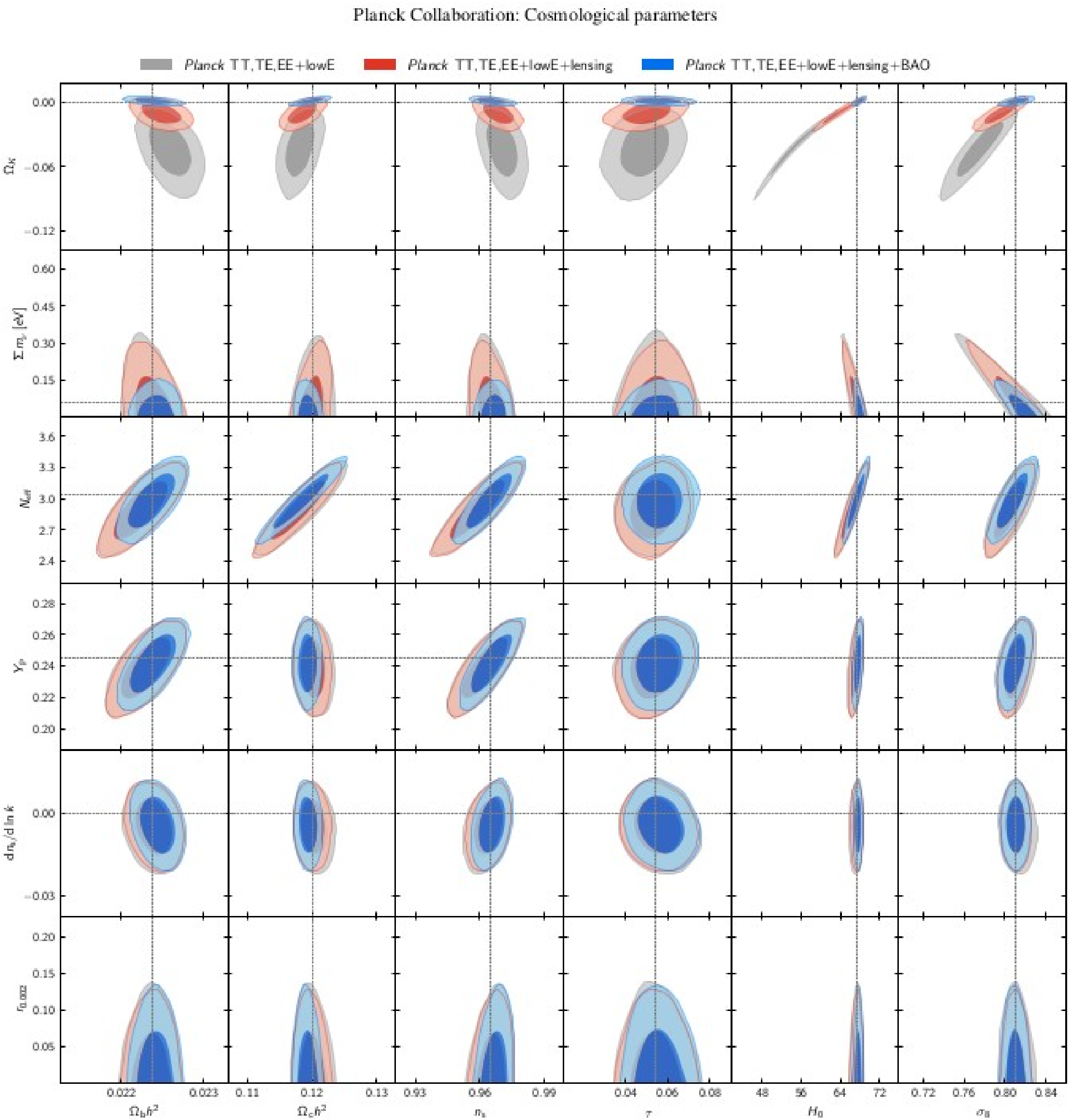
← Different from 1, as predicted by inflation

(Planck, 2013)

Current Planck CMB results

- Those are called Planck “2018” (1807.06209)
- They also use polarisation data, not just temperature.
- They even use lensing by the matter inhomogeneities on the light path.
  - $\Omega_b h^2 = 0.02237 \pm 0.00015$, $\Omega_M h^2 = 0.1424 \pm 0.0012$
  - Universe is flat to 1% to 0.3% (depending on the data combination)
  - Neutrino masses add up to less than ~0.25 eV
  - There are 3 +/- 0.3 neutrinos (relativistic neutrino-like degrees of freedom at recombination).

(1807.06209)


Planck Collaboration: Cosmological parameters
Planck TT,TE,EE+lowE
Planck TT,TE,EE+lowE+lensing
Planck TT,TE,EE+lowE+lensing+BAO
Ω_K
0.00
−0.06
−0.12
Σm_ν [eV]
0.60
0.45
0.30
0.15
$N_{\rm eff}$
3.6
3.3
3.0
2.7
2.4
Y_P
0.28
0.26
0.24
0.22
0.20
$dn_s/d\ln k$
0.00
−0.03
$r_{0.002}$
0.20
0.15
0.10
0.05
0.022
0.023
$\Omega_b h^2$
0.11
0.12
0.13
$\Omega_c h^2$
0.93
0.96
0.99
n_s
0.04
0.06
0.08
τ
48
56
64
72
H_0
0.72
0.76
0.80
0.84
σ_8

Summary

- CMB temperature anisotropies have been accurately measured.
- This data constrains the cosmological parameters tightly, especially if one combines with late-time probes.
- The minimal model id called ΛCDM :
  - Baryons, dark matter, radiation (photons and neutrinos)
  - The right amount of Λ to make it flat.
  - Baryons amount to ~5% of the total. We have no idea about the remainder.
- Extensions to the model are constrained (one at a time) to be small.