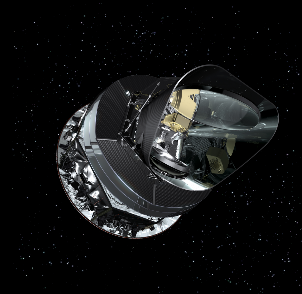


Cosmology

(3/3)

Laurence Perotto

Annecy-Le-Vieux, 2015, 16-22 July

Part II: Inhomogeneous Universe

The Standard Model of the Cosmology : Hot Big Bang + Structures growth

- Cosmic Inflation
- A pinch of phenomenology of the cosmological perturbations
- observables (LSS, CMB, BAO)

What the Big Bang Theory can do for us ?

Expanding Freidmann-Lemaître Universe → expansion confirmed by observations (e.g. SNIa)

Cosmological principle as a starting hyp. → validated by the observed CMB temperature map

Hot and dense primordial plasma in thermal equilibrium allowing nuclear reactions

confirmed by the CMB Black Body spectrum

the primordial light element abundances are correctly predicted

…and cannot…

[non exhaustive list]

1) What is the origin of the weak inhomogeities in the CMB temperature map ?

2) Why the CMB temperature so homogeneous on the whole sky ?

3) Why the Universe density so close to the critical density ?

⟶ something's missing : cosmic inflation

1) inhomogeneity origin problem

2) horizon problem

3) flatness problem

[4) historically (around 1980) lack of monopoles problem]

Flatness problem

$\Omega_k = 0$ is an unstable point if the Universe is dominated by a fluid of w>-1/3

Ensuring $\Omega_k \sim 0$ today and compensating the derive during the universe evolution require:

Initial conditions: $\Omega_k \sim 10^{-60}$

This is a so-called fine-tuning problem

Horizon problem

• Horizon : in any points, there is a maximum distance to which an observer can receive signal (past light cone)

• Distance travelled by 2 photons emitted in opposite direction (using ds=0)

$$d_{\rm h}(t_1,t_2) = 2\,a(t_2)\int_{r(t_1)}^{r(t_2)} \frac{dr}{\sqrt{1-kr^2}} = a(t_2)\int_{t_1}^{t_2}\frac{cdt}{a(t)}$$

For t_1 -> 0, it defines the causal horizon

• Angular size of the causal horizon at CMB decoupling

At CMB decoupling, MD : $a(t) \propto t^{2/3}$

$$d_{\rm h}(t_1,t_2) = 6\,ct_2^{2/3}\left(t_2^{1/3} - t_1^{1/3}\right)$$

$$d_{\rm h}(0,t_{\rm dec}) = 6\,ct_{\rm dec}$$

$$R_{\rm H} = cH^{-1} = \frac{3}{2}\,ct_{\rm dec}$$ constant Hubble radius

In RD or MD universe : the horizon size is about the Hubble radius

$$\theta = \frac{d_{\rm h}(0,t_{\rm dec})}{a_0\int_{t_{\rm dec}}^{t_0}\frac{cdt}{a(t)}} \sim 1^\circ$$

The homogeneous CMB temperature map: about $4\text{x}10^4$ non-causaly connected patches !

Early stage of accelerating expansion

These problems are solved if the Universe experiences an early stage of accelerating expansion before the Radiation Domination.

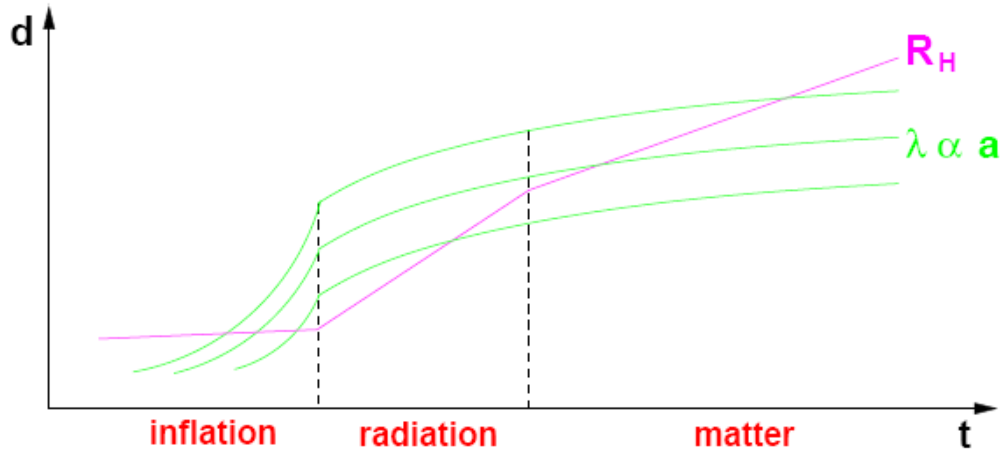
- if w<-1/3 : the scale factor expansion rate is accelerated and $\Omega_k = 0$ is an attractor

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

- if w=-1 : the energy density is constant;

  the horizon size exponentially increases $\propto \frac{c}{\mathrm{H}} e^{\mathrm{H}(\mathrm{t}_2 - \mathrm{t}_1)}$

  while the Hubble radius is constant.



At the end of inflation, 2 points much more distant than the Hubble radius can be in causal contact.

The physical horizon encompasses the whole observable Universe.

Inflation duration

The flatness problem is solved if $|\Omega_k(t_{\rm end})| \sim 10^{-60}$

$$\Omega_k \equiv \frac{-k}{\mathrm{H}^2\mathrm{a}^2} \longrightarrow \frac{\Omega_k(t_{\rm end})}{\Omega_k(t_{\rm beg})} = \left(\frac{a(t_{\rm beg})}{a(t_{\rm end})}\right)^2 = \left(\frac{e^{\mathrm{Ht_{beg}}}}{e^{\mathrm{Ht_{end}}}}\right)^2 = e^{-2\underbrace{\mathrm{H(t_{end}-t_{beg})}}_{\text{number of « e-fold »}}}$$

$$e^{-2\mathrm{N}} \lesssim 10^{-60} \longrightarrow \mathrm{N} \gtrsim 70$$

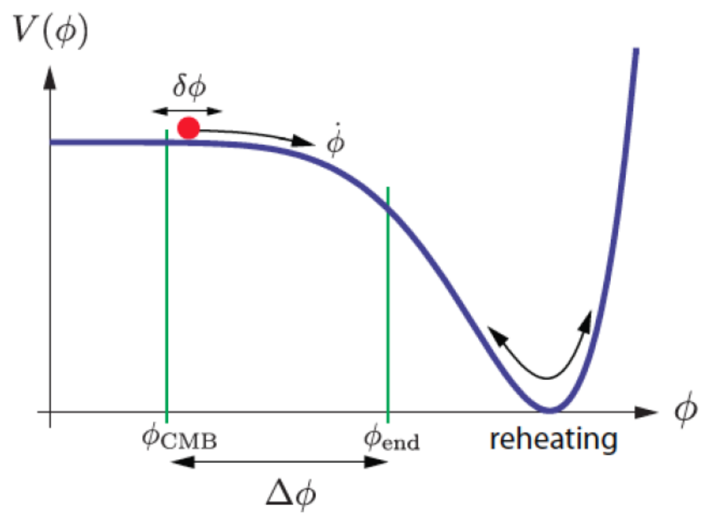
The scale factor at the end of inflation is multiplied by 10^{30}.

What is the inflation ?

An homogeneous scalar field has:

$$\rho = \frac{1}{2}\dot{\varphi}^2 + V(\varphi) \, ,$$
$$p = \frac{1}{2}\dot{\varphi}^2 - V(\varphi) \, .$$

if $\frac{1}{2}\dot{\phi}^2 \gg V(\phi) \longrightarrow \rho = -P$



Inflation model is based on scalar field(s) «slowly rolling» in a flat-ish potential

Origin of primordial inhomogeneities

- The inflation washes out matters
- In vacuum, quantum fluctuations arise (e.g. particle-antiparticle pairs creation)
- These quantum fluctuations are stretched by expansion and then freeze-out

Distance on which an event happening at $t=t_e$ can influence latter events

$$d_{\mathrm{eH}} = a(t_{\mathrm{e}}) \int_{t_{\mathrm{e}}}^{\infty} \frac{cdt}{a(t)} \qquad a \propto e^{\mathrm{Ht}} \qquad d_{\mathrm{eH}} = c\mathrm{H}^{-1} = \mathrm{R_H}$$

Expansion exponentially increases wavelengths of any fluctuctions, when they become > R_H freeze-out

- Inflation predictions:

same amount of primordial density fluctuations at all scale (Harison-Zel'dovitch flat spectrum)

a background of primordial gravitational waves with amplitude depending on the energy scale at the end of the inflation.

Part II: Inhomogeneous Universe

The Standard Model of the Cosmology : Hot Big Bang + Structures growth

- Cosmic Inflation
- A pinch of phenomenology of the cosmological perturbations
- observables (LSS, CMB, BAO)

Inhomogeneous Universe

- Large scales structures stem from quantum fluctuations made real by exponential expansion
- The primordial density inhomogeneities progressively grow by gravitational collapse (starting from the smallest)
- up to recent epoch ($z>1$) and at large enough scales (larger than galaxy clusters), the large scale structures of the Universe can be described as perturbations on an homogeneous background: a linear perturbation theory
- The late Universe and smaller scales are described using N-body numerical simulations

Linear perturbation theory (just general ideas)

- energy density with small inhomogeneities expands as

$$\rho(\vec{x},t) = \rho_0(t) + \delta\rho(\vec{x},t)$$

homogeneous background

perturbation

the density contrast is: $\delta(\vec{x},t) \equiv \dfrac{\delta\rho(\vec{x},t)}{\rho_0(t)}$

- Full treatment, linearized Einstein equations

$$\begin{aligned}\delta g_{\mu\nu}(\mathbf{x},t) &= g_{\mu\nu}(\mathbf{x},t) - \bar{g}_{\mu\nu}(t)\\ \delta T_{\mu\nu}(\mathbf{x},t) &= T_{\mu\nu}(\mathbf{x},t) - \bar{T}_{\mu\nu}(t)\end{aligned}$$

$$\delta G_{\mu\nu} = 8\pi G\, \delta T_{\mu\nu}$$

- Density and pressure evolution are described by the Boltzmann equation (CDM can be described as perfect fluid)

- need to follow pertubation evolutions for the radiation, baryon, CDM and spacetime curvature (almost equivalent to Newtonian potential)

- inflation predicts adiabatic initial conditions $\delta_b = \delta_d = \dfrac{4}{3}\delta_\gamma = \dfrac{4}{3}\delta_\nu = 4\dfrac{\delta T}{\bar{T}}$

Newtonian approach

The qualitative evolution emerges from the Newtonian approach

- Start from the equations governing a NR fluid motion :
  - Euler equation
  - Energy conservation
  - Poisson equation
- Linearity, comoving wavemodes k evolve independently: practical in Fourier space

$$\lambda(t) = a(t)\frac{2\pi}{k} \qquad \delta(\vec{k},t) = \int d^3\vec{x}\,\delta(\vec{x},t)\,e^{-i\vec{k}.\vec{x}}$$

- The gravitational amplification of the density perturbation is described by :

$$\ddot{\delta}_{\mathbf{k}} + 2\frac{\dot{\mathrm{a}}}{\mathrm{a}}\dot{\delta}_{\mathbf{k}} + \left(\frac{\mathrm{k}^2 c_{\mathrm{s}}^{\;2}}{\mathrm{a}^2} - 4\pi\,\mathrm{G}\rho_0\right)\delta = 0\ ,\quad c_{\mathrm{s}}^{\;2} = \frac{\delta\mathrm{P}}{\delta\rho}$$

depending on wavemodes size, acoustic oscillations can occur with sound speed c_s

The Jeans length

$$\mathrm{k}_{\mathrm{J}}^{\;2} c_{\mathrm{s}}^{\;2} = 4\pi\,\mathrm{G}\rho_0,\quad \lambda_{\mathrm{J}} = c_{\mathrm{s}}^{\;2}\sqrt{\frac{\pi}{G\rho_0}}$$

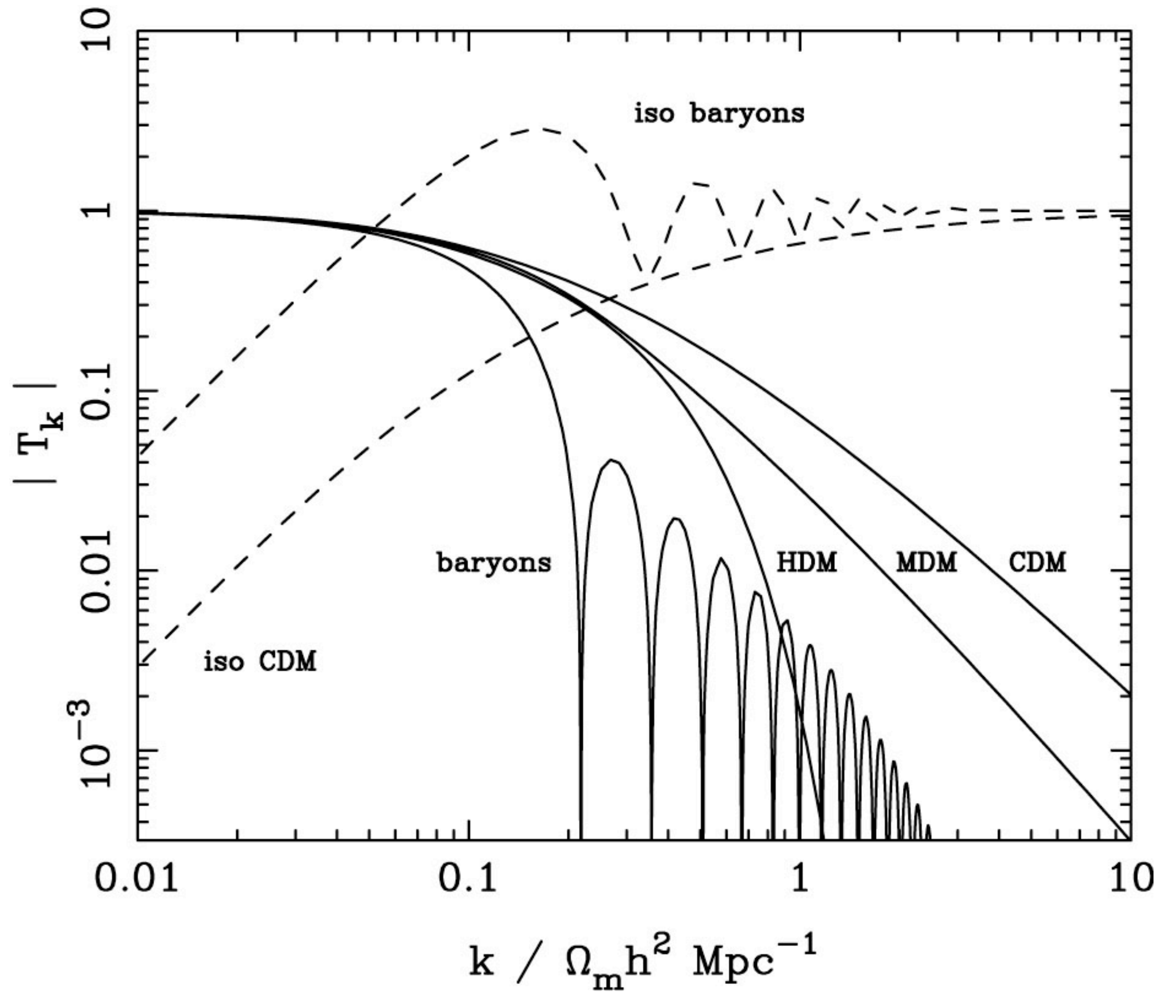
limit scale at which the radiation pressure becomes efficient to compensate gravitational collapse

- large wavelengths : possible growth
- small wavelengths : gravitational collapse is conterbalanced by pressure

Jeans length is time dependent, larger and larger wavemodes can oscillate

Transfer functions

• All the physics is enclosed in a transfert functions: $$T(k,t) \equiv \frac{\delta(k,t)}{\delta(k,t_i)G(t)}$$



super-horizon plateau
(before they enter the horizon, pertubations are frozen)

acoustic oscillations
(when a perturbation enters the sound horizon)

damping
(small-scales perturbations are suppressed)

Outlines

- Part I: The Big Bang Theory
  - Homogeneous Universe
    - (Metric, Friedmann Eqs, Distances, Hubble law, SNIa)
  - Hot Big Bang Model
    - (thermal history, BBN)
- Part II: The Standard Model of the Cosmology
  - Cosmic Inflation
  - A pinch of phenomenology of the cosmological perturbations
  - observables (LSS, CMB, BAO)
- Part III: Recent results
  - Planck 2013
  - BICEP (2014-2015)
  - perspectives

The need of a stochastic description

- The primordial perturbations come from quantum fluctuations
- Each $\delta_{\mathbf{k}}$ is a Gaussian random variable

$$\mathcal{P}[\delta(\mathbf{k},\tau_0)] = \frac{1}{\sqrt{2\pi P(k)}} \exp\left(-\frac{|\delta(\mathbf{k},\tau_0)|^2}{2P(k)}\right)$$

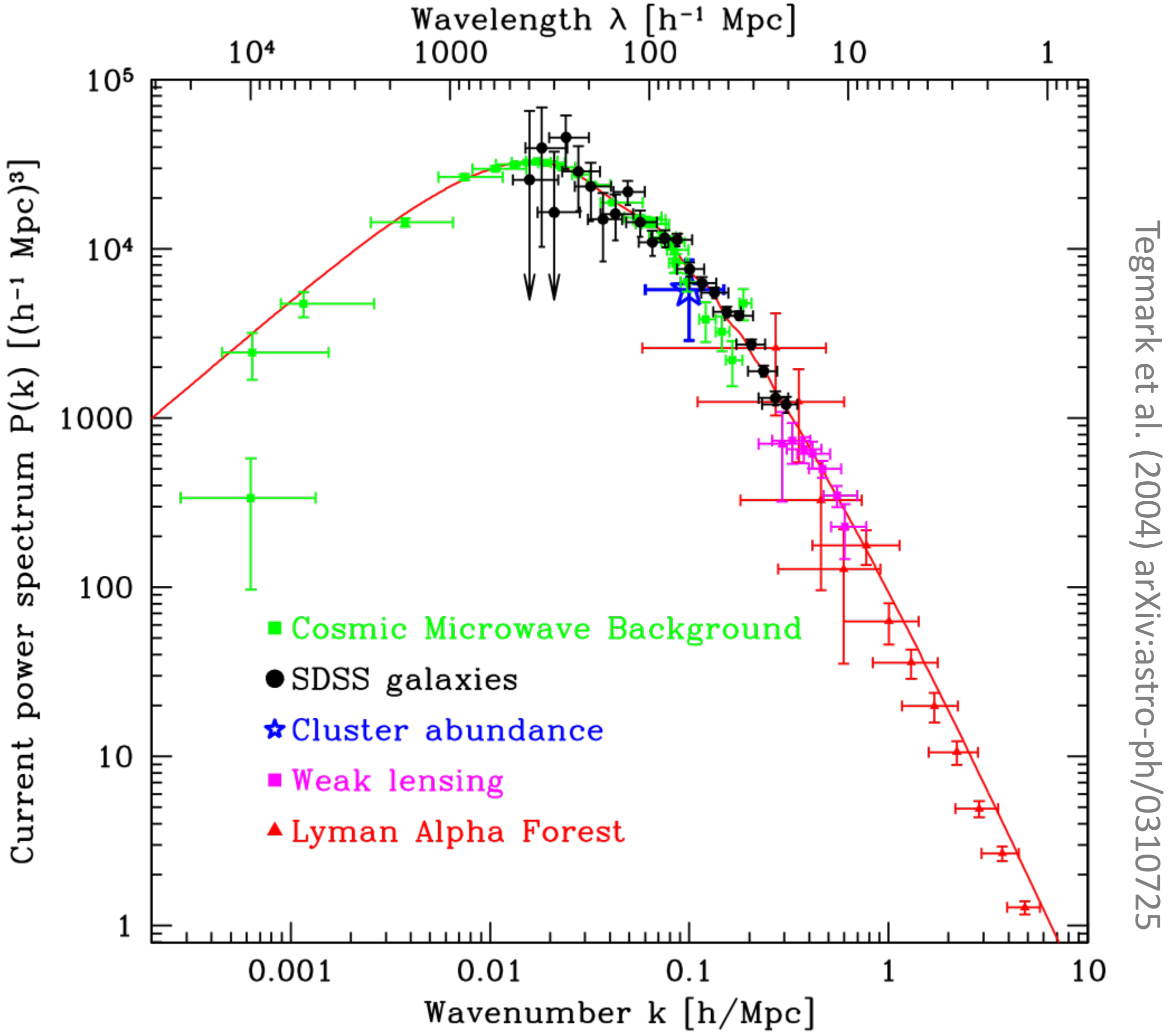
- All the information is encoded in the power spectrum :

$$P(k) = \langle|\delta(\mathbf{k},\tau_0)|^2\rangle$$

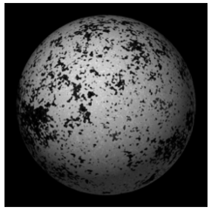
- function of the primordial power spectrum and the transfer function :

$$\langle|\delta(k,\tau_f)|^2\rangle = \langle|\delta(k,\tau_i)|^2\rangle\, T^2(k,\tau_f)$$

Matter power spectrum measurements



From the damping of small-scales wavemodes,
we infer that the dark matter is cold (NR at decoupling)



Description of the temperature anisotropies

- Within the perturbation theory, 4 contributions :

  – The intrinsic temperature

$$\left.\frac{\Delta \mathrm{T}}{\mathrm{T}_{\mathrm{CMB}}}\right|_{\mathrm{intrinsic}} = \frac{1}{3}\frac{\delta\rho}{\rho}$$

  – The Sachs-Wolfe effect (« Gravitational Doppler effect»)

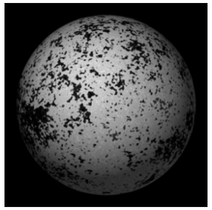
$$\left.\frac{\Delta \mathrm{T}}{\mathrm{T}_{\mathrm{CMB}}}\right|_{\mathrm{SW}} = \phi$$

  – The Doppler effect

$$\left.\frac{\Delta \mathrm{T}}{\mathrm{T}_{\mathrm{CMB}}}\right|_{\mathrm{Doppler}} = \mathrm{v}_{\mathrm{r}}$$

  – The Integrated SW effect

$$\left.\frac{\Delta \mathrm{T}}{\mathrm{T}_{\mathrm{CMB}}}\right|_{\mathrm{ISW}} = \int_{dec}^{0} d\tau\, \dot{\phi}$$



The angular power spectrum of the anisotropies

- A random Gaussian field :
  - All the information is encoded in the 2-points correlation function :

$$\left\langle \frac{\delta T}{\bar{T}}(\mathbf{n}) \frac{\delta T}{\bar{T}}(\mathbf{n}') \right\rangle$$

- Spherical harmonic decomposition

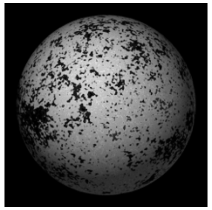
$$\frac{\Delta T}{T}(\hat{\vec{n}}) = \sum_{l,m} a_{lm}^{T}\, Y_l^m(\hat{\vec{n}})$$

- The angular power spectrum

$$\langle a^{\mathrm{T}}_{lm} a^{\mathrm{T}\,*}_{l'm'} \rangle = \delta_{ll'} \delta_{mm'} C_l^{\mathrm{TT}}$$

linear theory

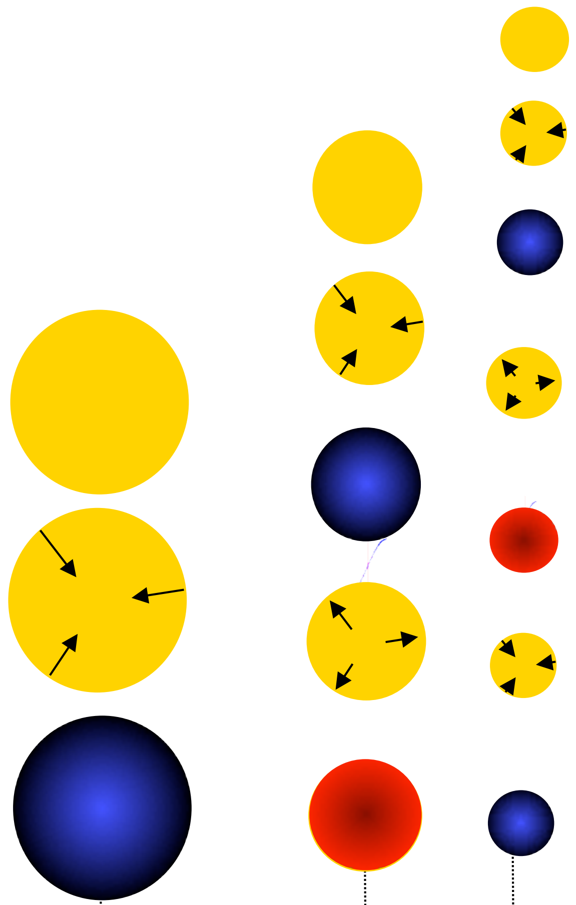
isotropy

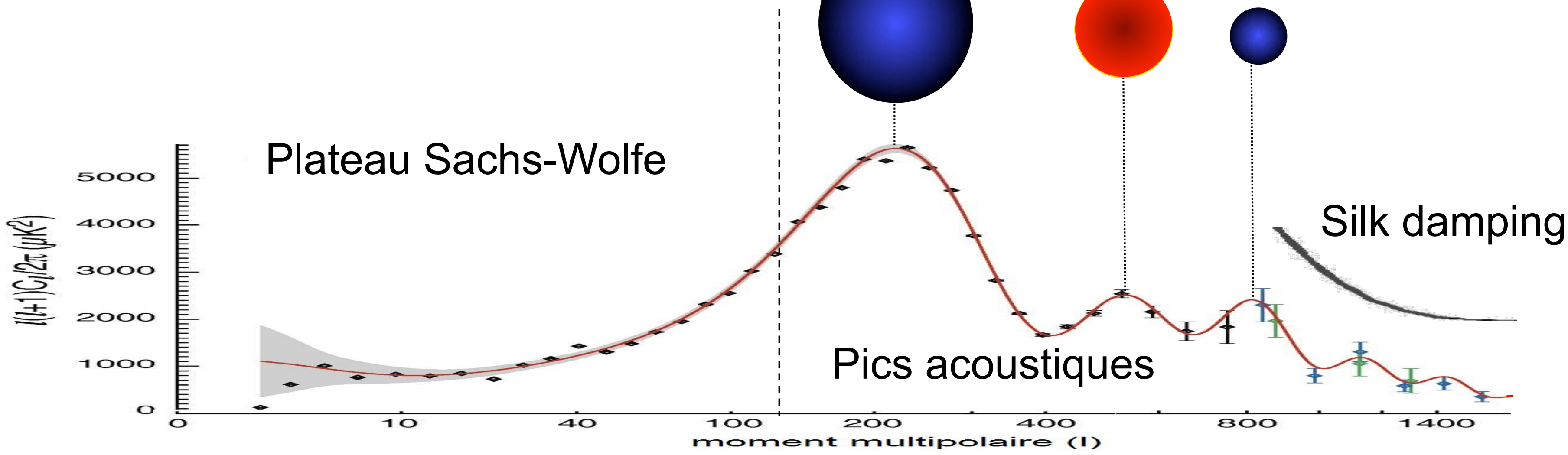


Cosmic Microwave Background

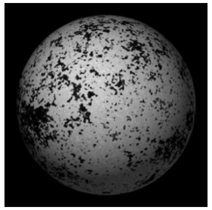
C_l phenomenology

- Evolution of the perturbations :
  - largest perturbations :
    growth factor only
  - perturbations in the Hubble radius :
    acoustic oscillations
  - smallest perturbation :
    photon diffusion erasing





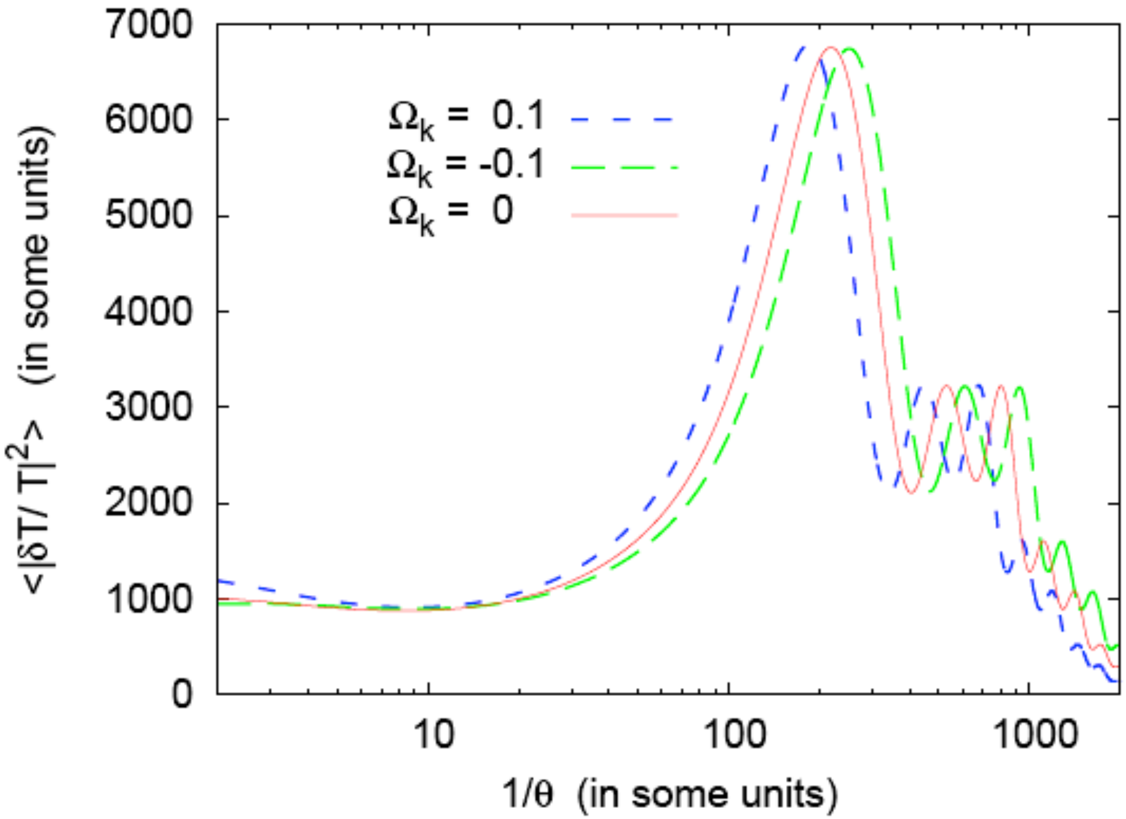
$$l \propto 1/\theta.$$



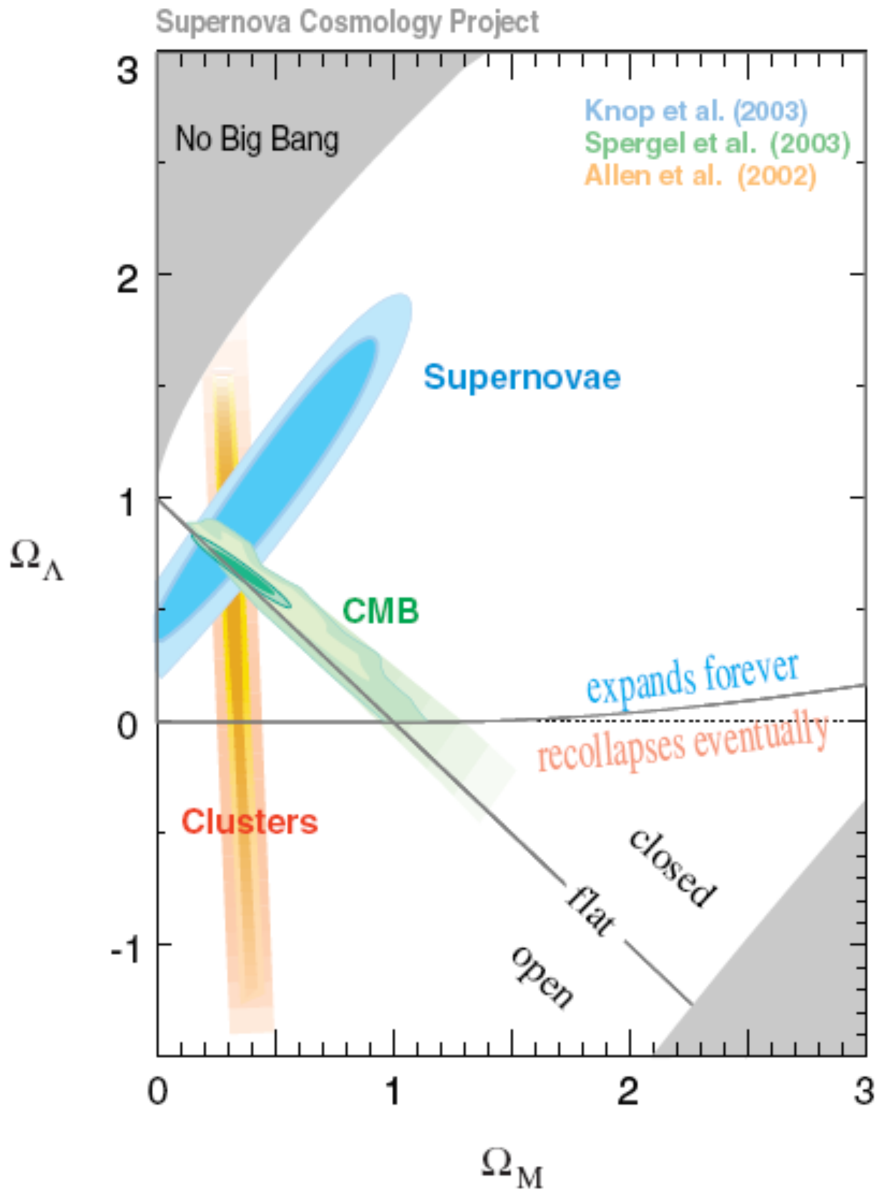
Constraints on the Universe geometry

- The first acoustic pic : a standard ruler
  - the last perturbation entered in the sound horizon
  - The size of the sound horizon at decoupling is both :
    - calculable
    - observed

$$d_s^{\text{flat}} = a(t) \int_0^t \frac{c_s\, dt'}{a(t')}$$



Parameter degeneracy breaking



Recent results (in Planck Collab. 2015)

Planck TT, TE, EE C_ell:

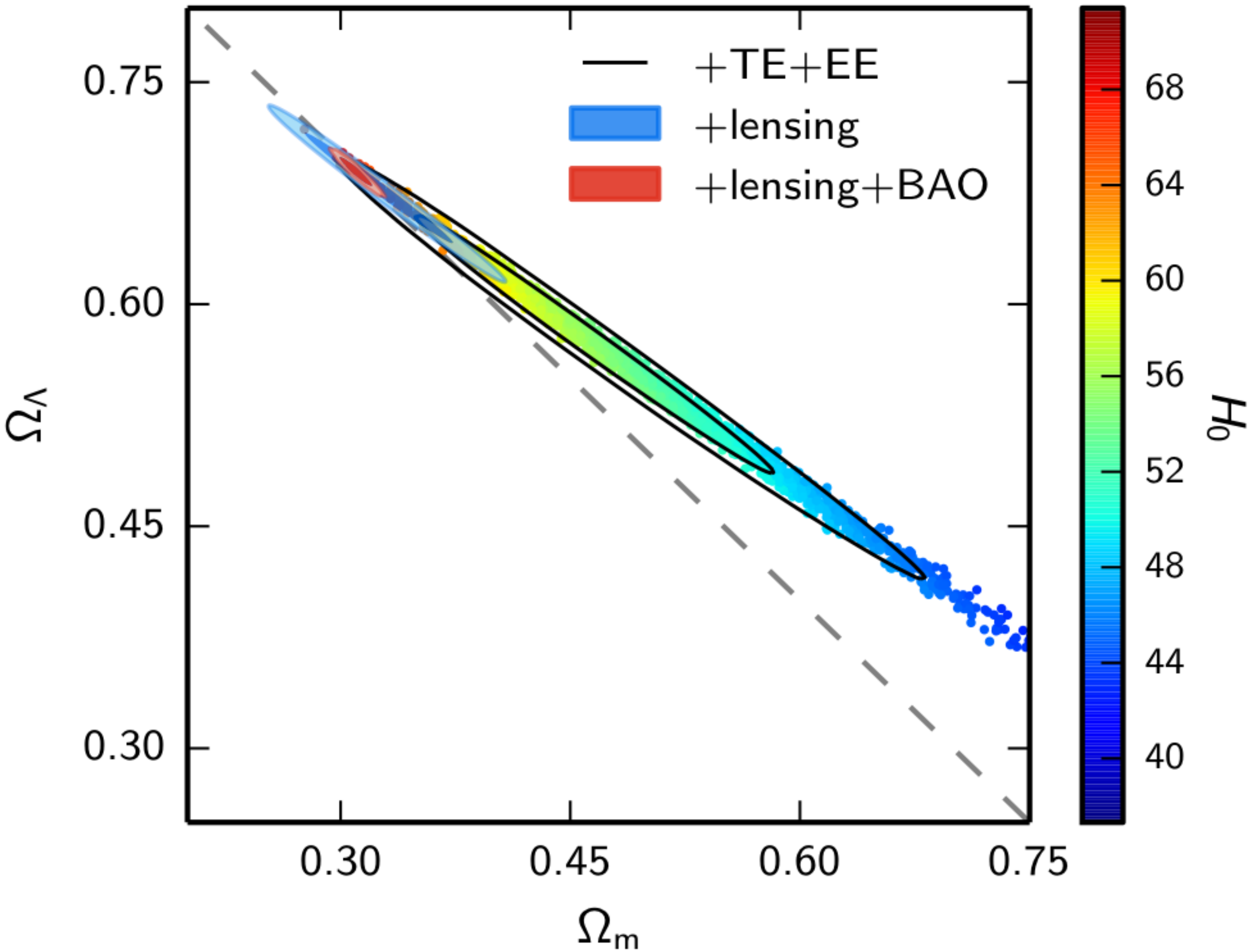
$$\Omega_K = -0.040^{+0.038}_{-0.041}$$

Planck TT, TE, EE C_ell
+ CMB lensing

$$\Omega_K = -0.005^{+0.016}_{-0.017}$$

Planck TT, TE, EE C_ell
+ CMB lensing (~P(k))
+ BAO (standard ruler)

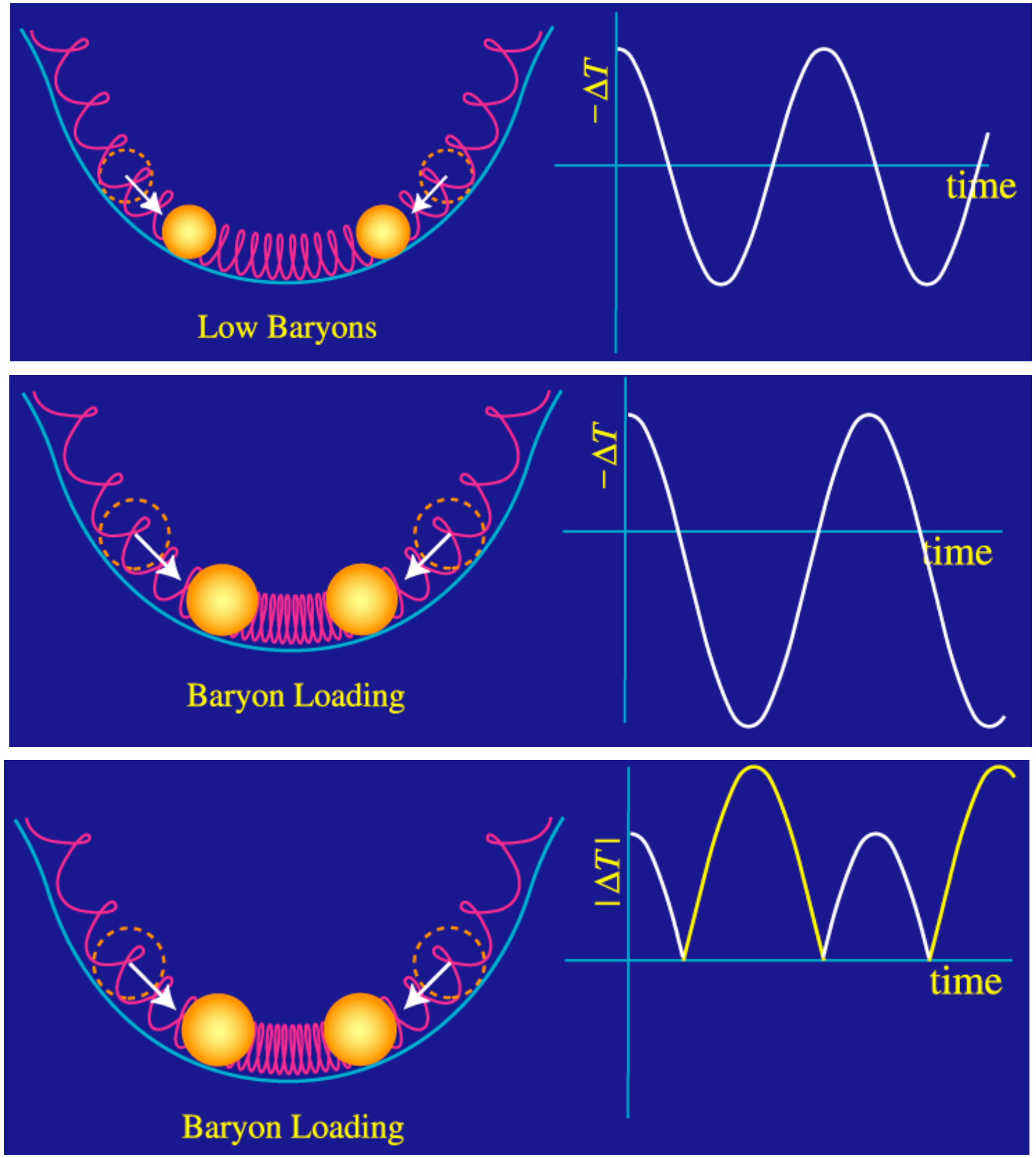
$$\Omega_K = 0.000 \pm 0.005$$



Our Universe is spatially flat to a 0.5% accuracy

Baryonometer

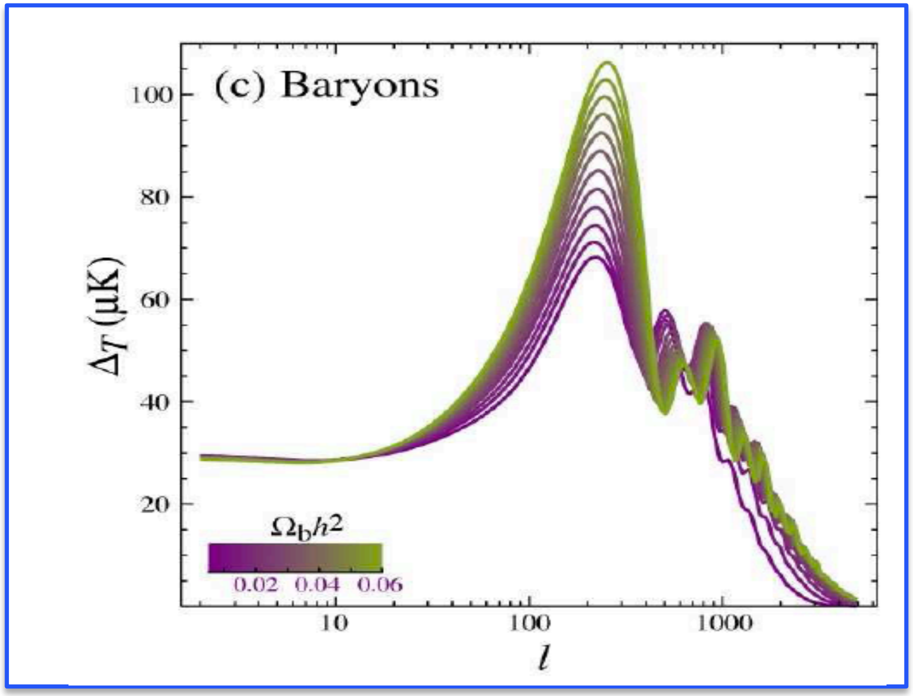
From Wayne Hu website:



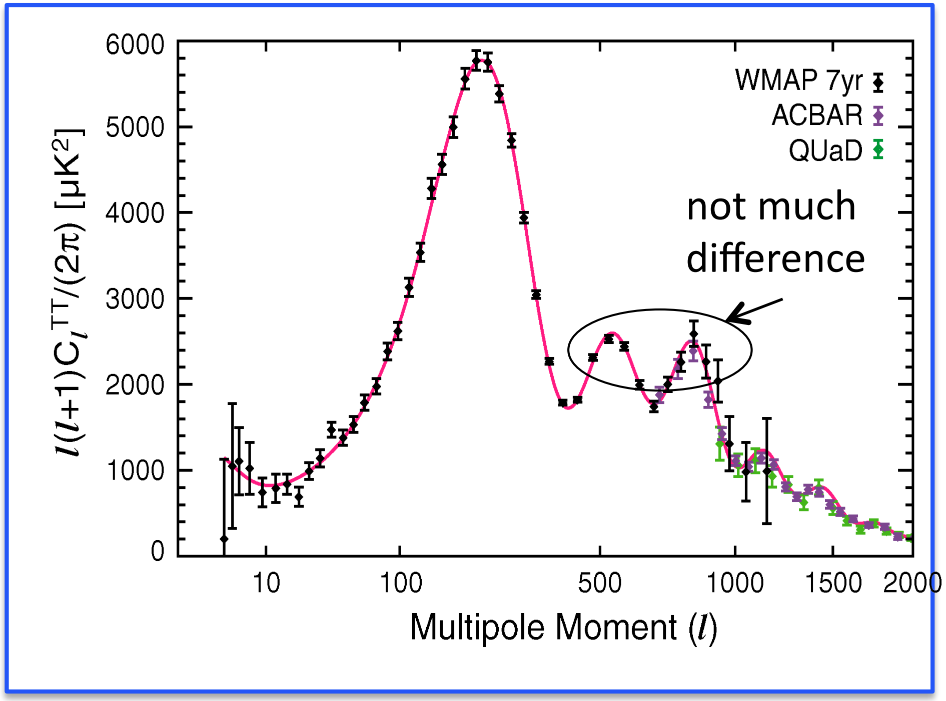
Odd peaks (compression maxima) enhancement over even peaks (dillution maxima)

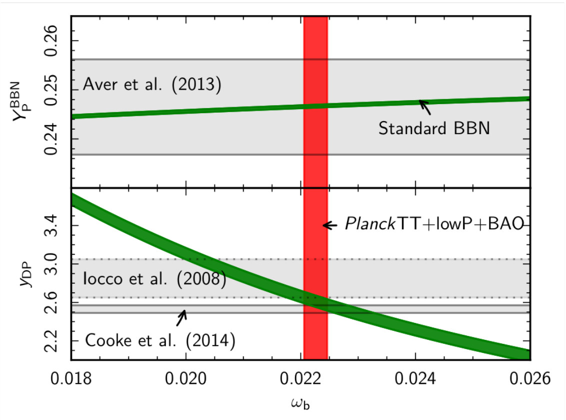
Baryonometer

models



data





The baryon density is measured at 1% accuracy level using Planck data alone

Bibliography

References for Part II:

- Introduction to Cosmology, by Julien Lesgourgues
  http://lesgourg.web.cern.ch/lesgourg/courses
- Primordial Cosmology, Patrick Peter, Jean-Philippe Uzan, Oxford Univ. Press (2009)
  Cosmologie Primordial, Collection Échelles (2005)
- Cosmological Physics, John, A., Peacock, Cambridge edition (1999)
- TASI Lectures: Introduction to Cosmology, Mark Trodden & Sean M. Carroll
  http://arxiv.org/abs/astro-ph/0401547
- Wayne Hu website: http://background.uchicago.edu/~whu/

Other references :

- Gravitation and Cosmology : Steven Weinberg, Wiley edition (1972)
- The early Universe, Edward W. Kolb & Michael S. Turner, Frontiers in Physics (1990)
- Structure formation in the Universe, T. Padmanabhan, Cambridge Univ. Press (1993)

Outlines

- Part I: The Big Bang Theory
  - Homogeneous Universe
    - (Metric, Friedmann Eqs, Distances, Hubble law, SNIa)
  - Hot Big Bang Model
    - (thermal history, BBN)

- Part II: The Standard Model of the Cosmology
  - Cosmic Inflation
  - A pinch of phenomenology of the cosmological perturbations
  - observables (LSS, CMB, BAO)

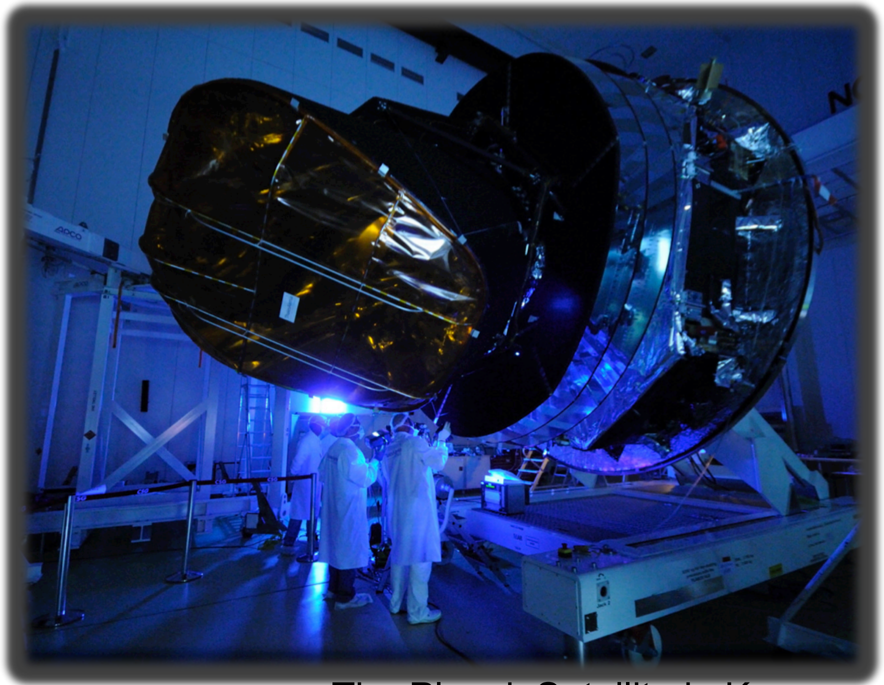
- Part III: Recent results
  - Planck 2013
  - BICEP (2014-2015)
  - perspectives

The Planck Satellite

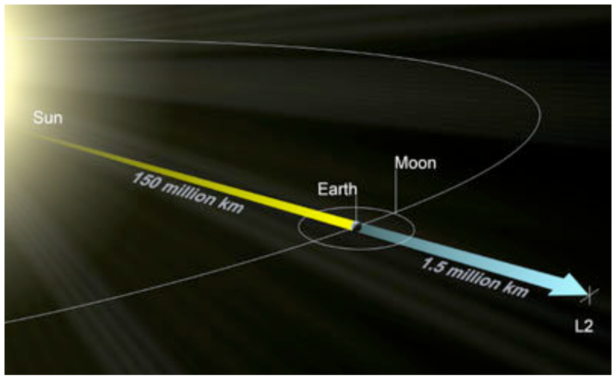
Designed in the 90's to provide the definitive measure of the CMB temperature anisotropies

full-sky (large angular scales)
resolution of 5 arcmin (small angular scales)
9 frequency observation channel (foregrounds control)
cooling at 0.1K (cosmic variance limited)

also sensitive to the CMB polarisation



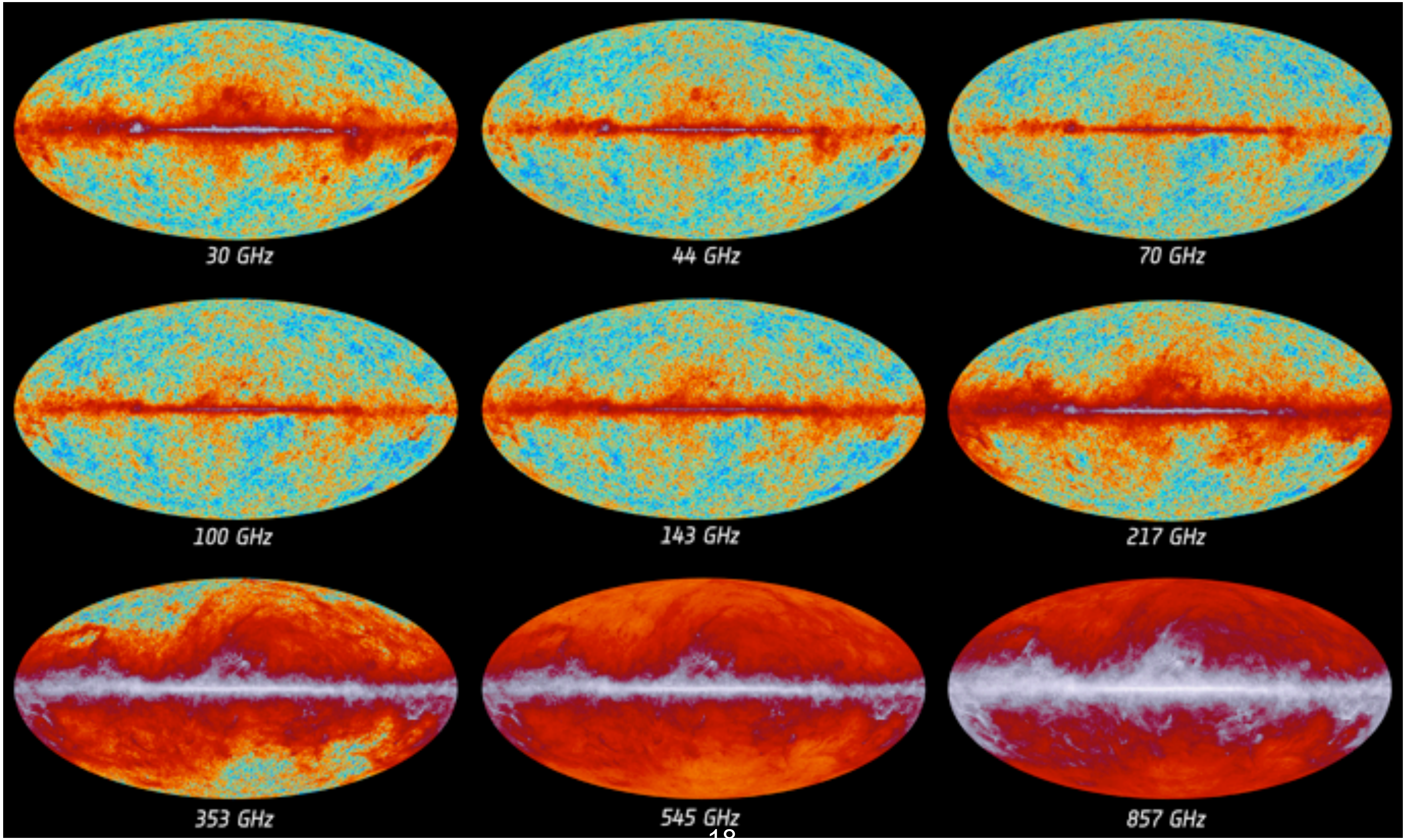
The Planck Satellite in Kourou
a month before the launch
Crédit : ESA



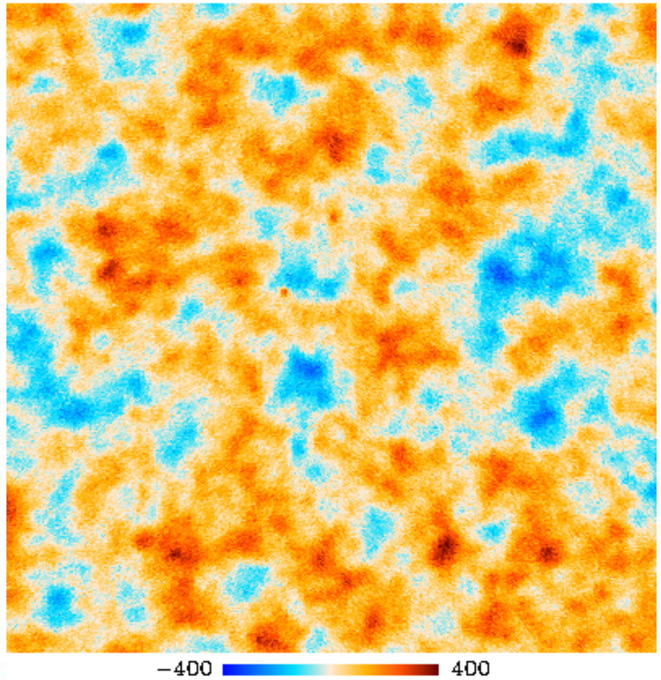
Launch in May 2009, and End of data integration in autumn 2012

Planck Collab. 2013
Planck Collab. 2015
final release is imminent

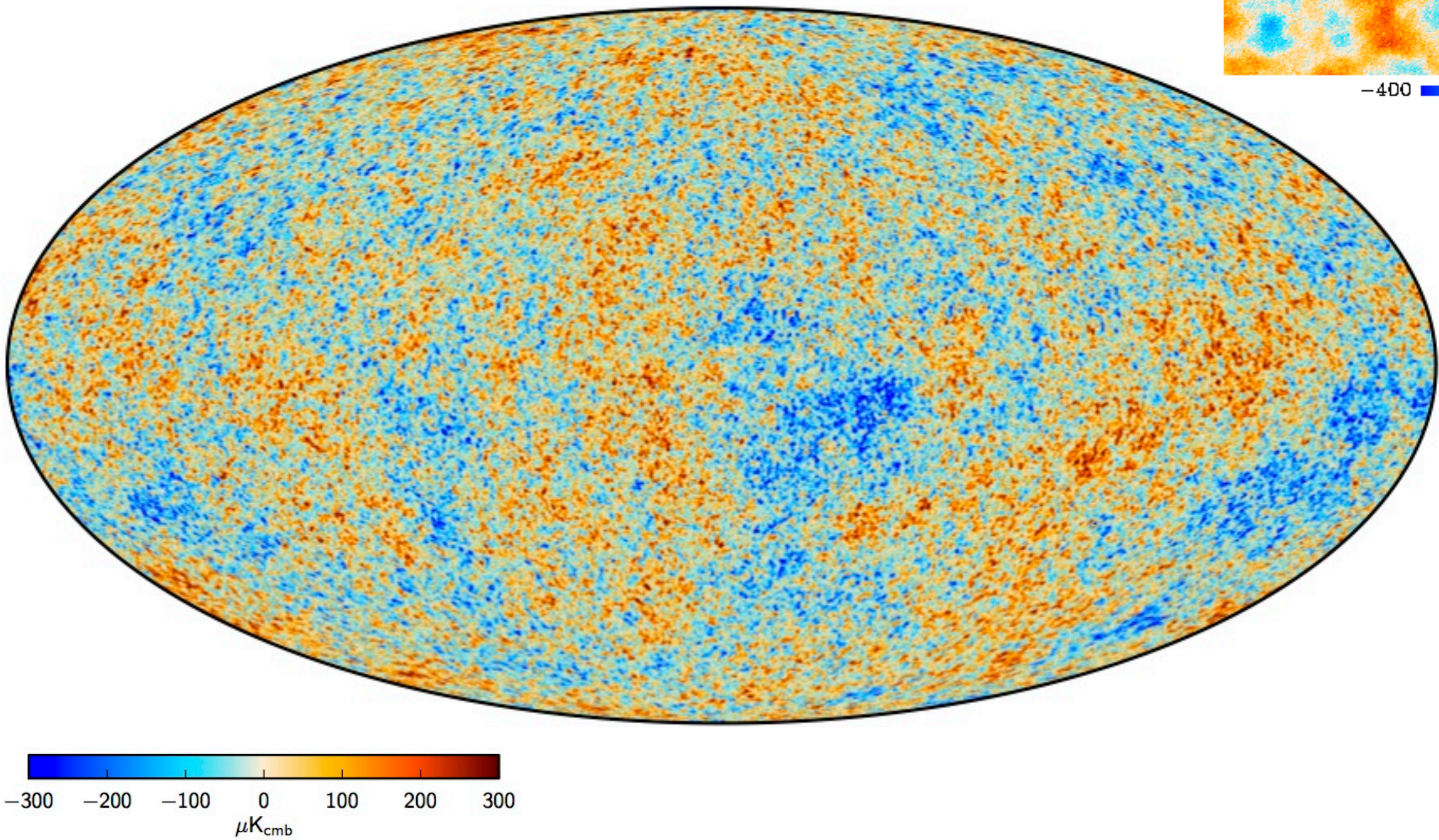
PLANCK temperature individual frequency band maps



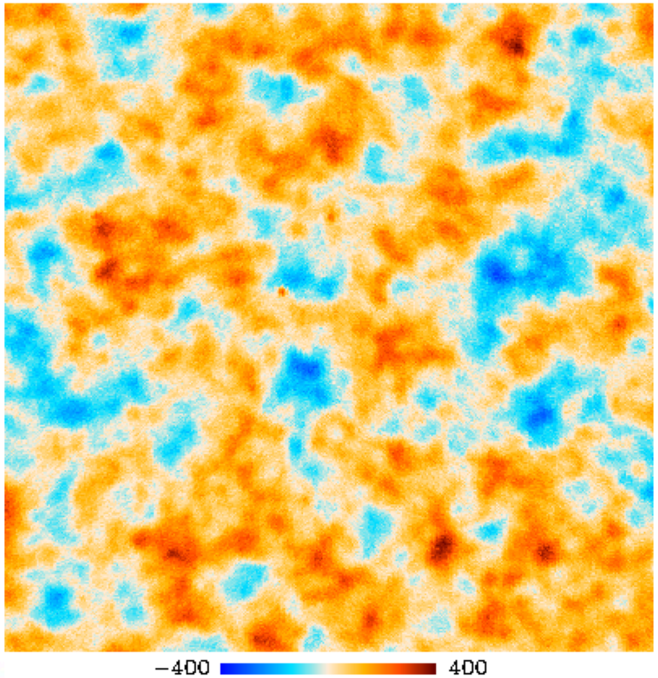
Foreground cleaned temperature map



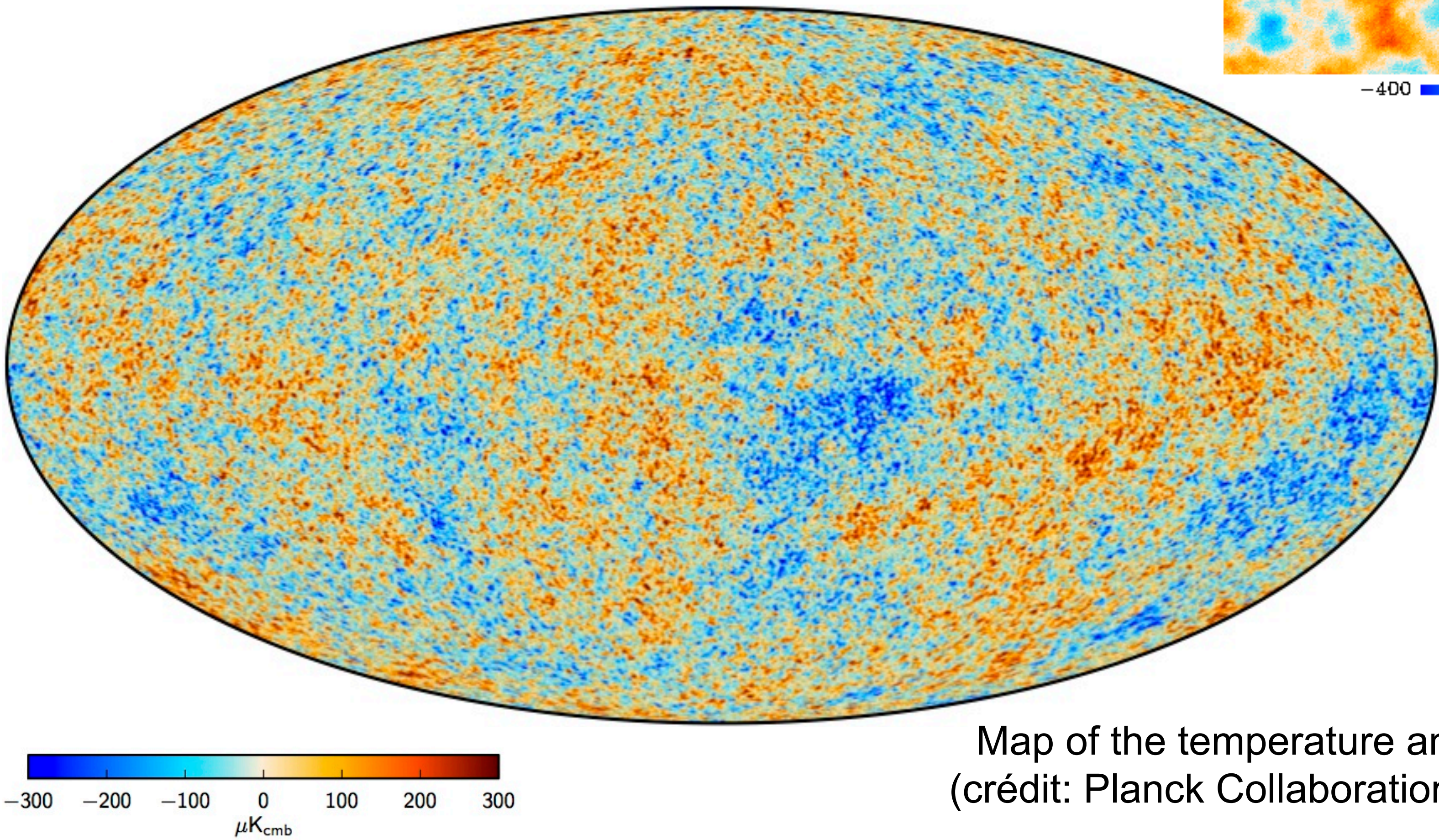
nominal mission (2013)



Foreground cleaned temperature map



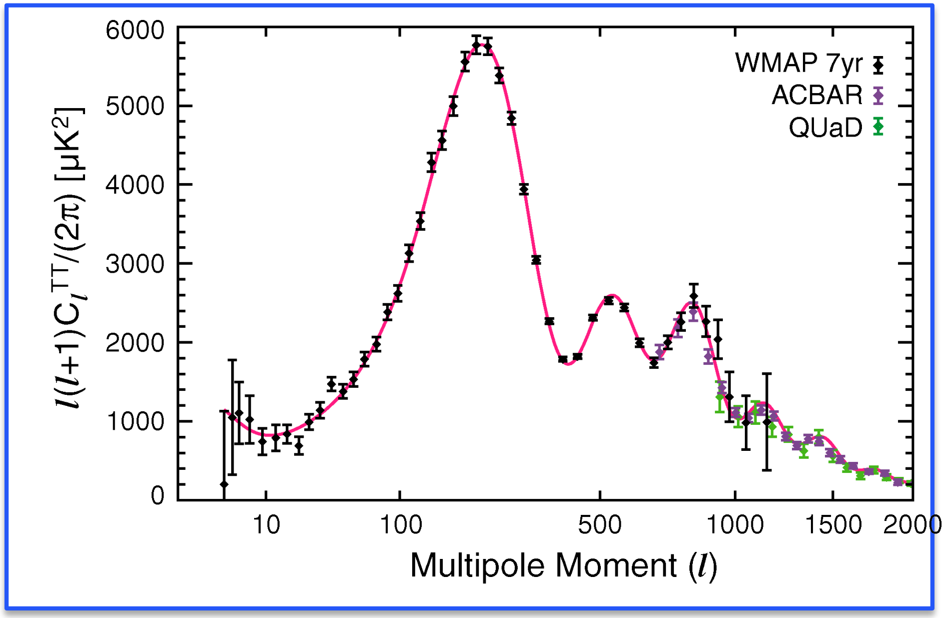
full mission
(2015)



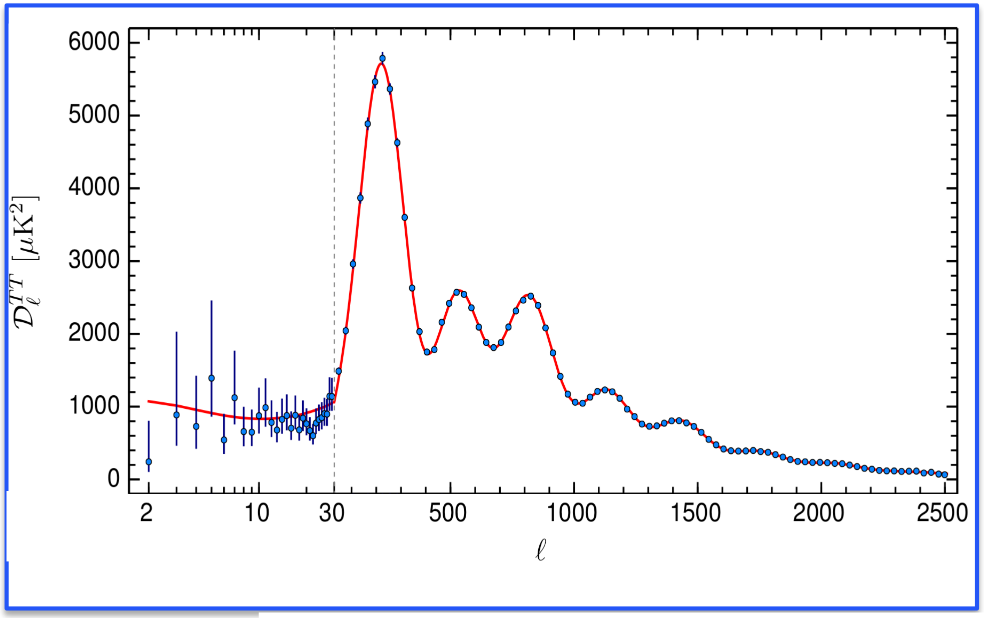
Map of the temperature anisotropies
(crédit: Planck Collaboration XIII, 2015)

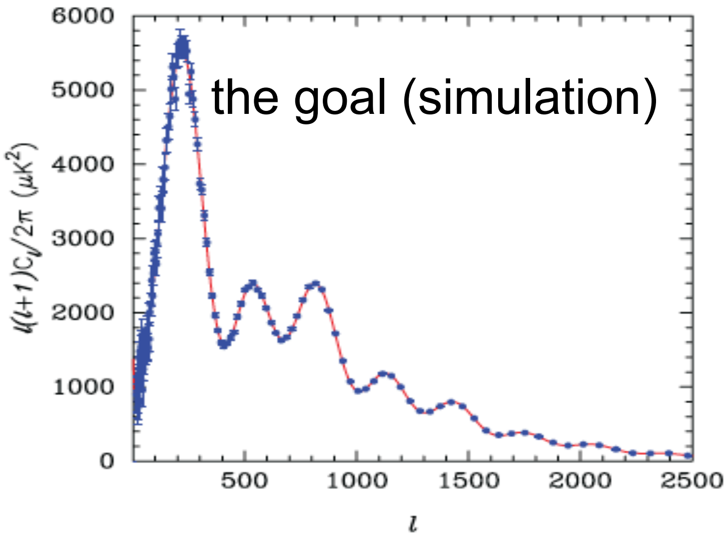
Improvement of TT power spectrum measurements

BEFORE PLANCK (2010)



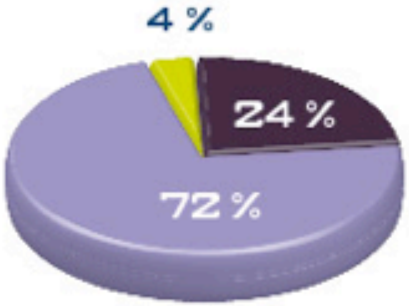
PLANCK RESULTS (2015)



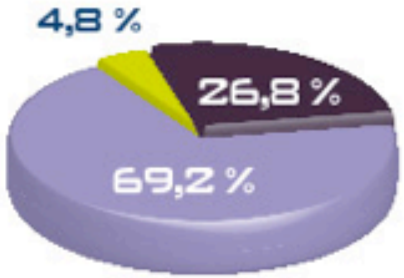


Implications for Cosmology

BEFORE (2010)



AFTER (2013)

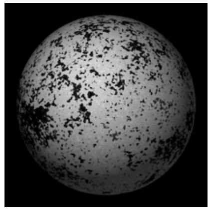


The simpliest 6-parameters LCDM model suffices to describe the data

$$\Omega_\Lambda,\, \Omega_{\rm CDM},\, \Omega_b,\, A_s,\, n_s,\, \tau$$

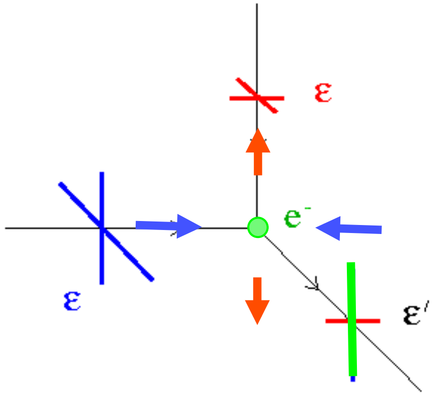
These parameters are measured at the 1% accuracy level

It imposes constraints on any exotic extensions to the model



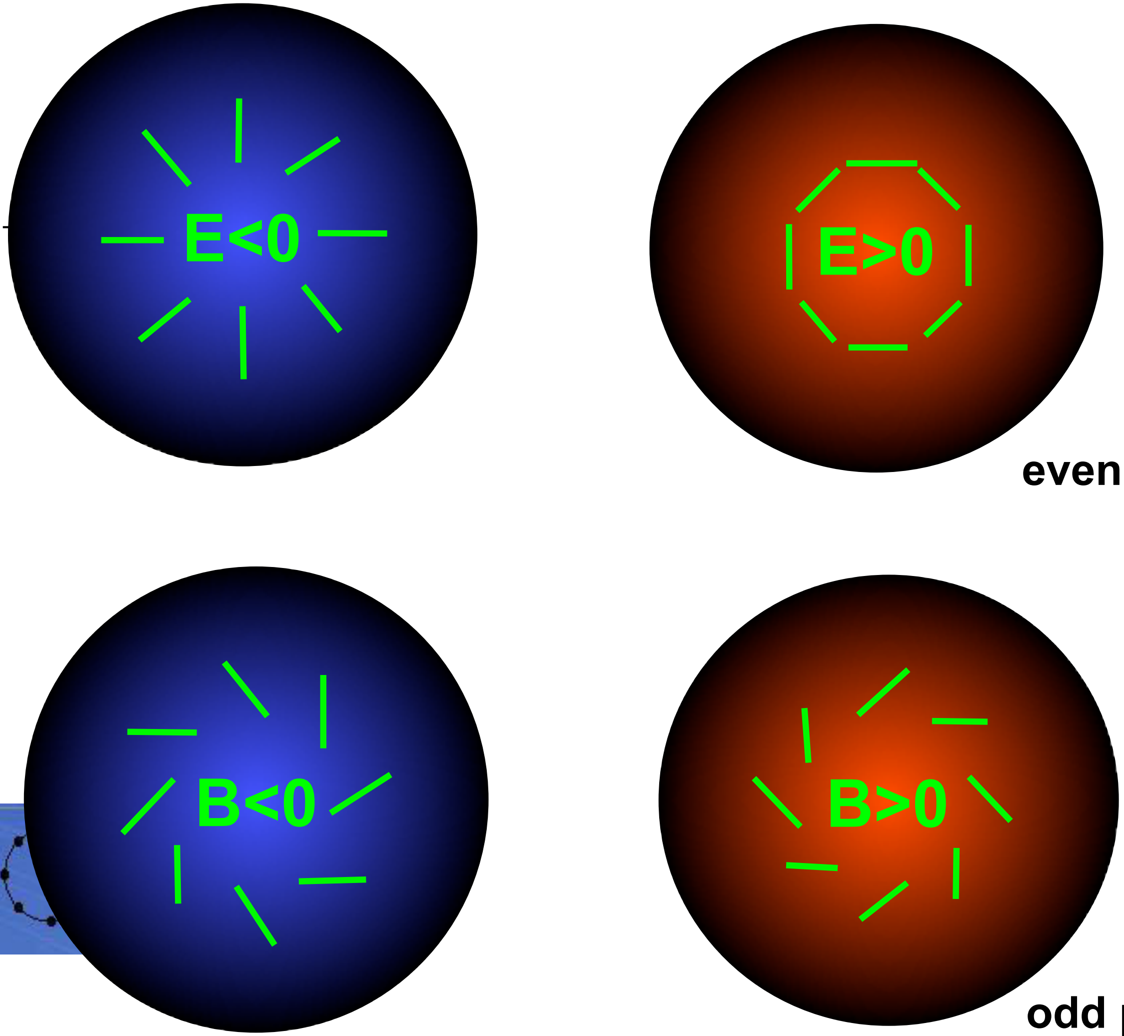
Cosmic Microwave Background

CMB polarisation (intuitive introduction)



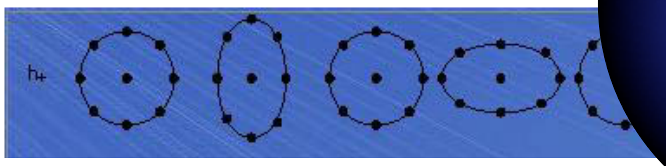
Thomson scattering:

$$\frac{d\sigma_T}{d\Omega} \propto |\vec{\epsilon}_i.\vec{\epsilon}_d|^2$$

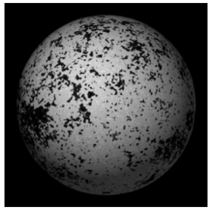


even parity

odd parity



Gravitational waves



CMB polarisation (mathematical introduction)

- Coherence matrix

$$(\vec{e}_1, \vec{e}_2, \vec{k}) \qquad \mathcal{C} = \begin{pmatrix} \langle |E_1|^2 \rangle & \langle E_1 E_2^* \rangle \\ \langle E_2 E_1^* \rangle & \langle |E_2|^2 \rangle \end{pmatrix} = \frac{1}{2} \begin{pmatrix} I + Q & U - iV \\ U + iV & I - Q \end{pmatrix}$$

- Stockes parameters
  - depend on the local basis
  - spin 2 quantities

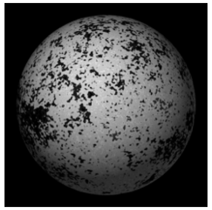
$$Q' = Q \cos 2\theta + U \sin 2\theta$$
$$U' = -Q \sin 2\theta + U \cos 2\theta$$

$$Q \pm i U \to Q' \pm i U' = e^{\mp 2 i \theta} (Q \pm i U).$$

- E and B modes
  - Scalar fields
  - Independant of
    the choice of the basis

$$(Q + iU)(\hat{\vec{n}}) = \sum_{lm} a_{2,lm}\; {}_2Y_l^m(\hat{\vec{n}})$$
$$(Q - iU)(\hat{\vec{n}}) = \sum_{lm} a_{-2,lm}\; {}_{-2}Y_l^m(\hat{\vec{n}})$$

$$a_{lm}^E = -(a_{2,lm} + a_{-2,lm})/2$$
$$a_{lm}^B = i(a_{2,lm} - a_{-2,lm})/2.$$



Polarized angular power spectra

- E- and B-modes are Gaussian scalar random fields

$$E(\hat{\vec{n}}) = \Sigma_{lm} a^E_{lm} Y^m_l(\hat{\vec{n}})$$

$$B(\hat{\vec{n}}) = \Sigma_{lm} a^B_{lm} Y^m_l(\hat{\vec{n}})$$

- The observables of the CMB

$$\langle a^X_{lm} a^{X'*}_{l'm'} \rangle = \delta_{ll'} \delta_{mm'} C^{XX'}_l \qquad \{T, E, B\}$$

- Power spectrum estimates

$$C^{TE}_l = \frac{1}{2l+1} \sum_m a^{T*}_{lm} a^E_{lm}$$

- Errorbars

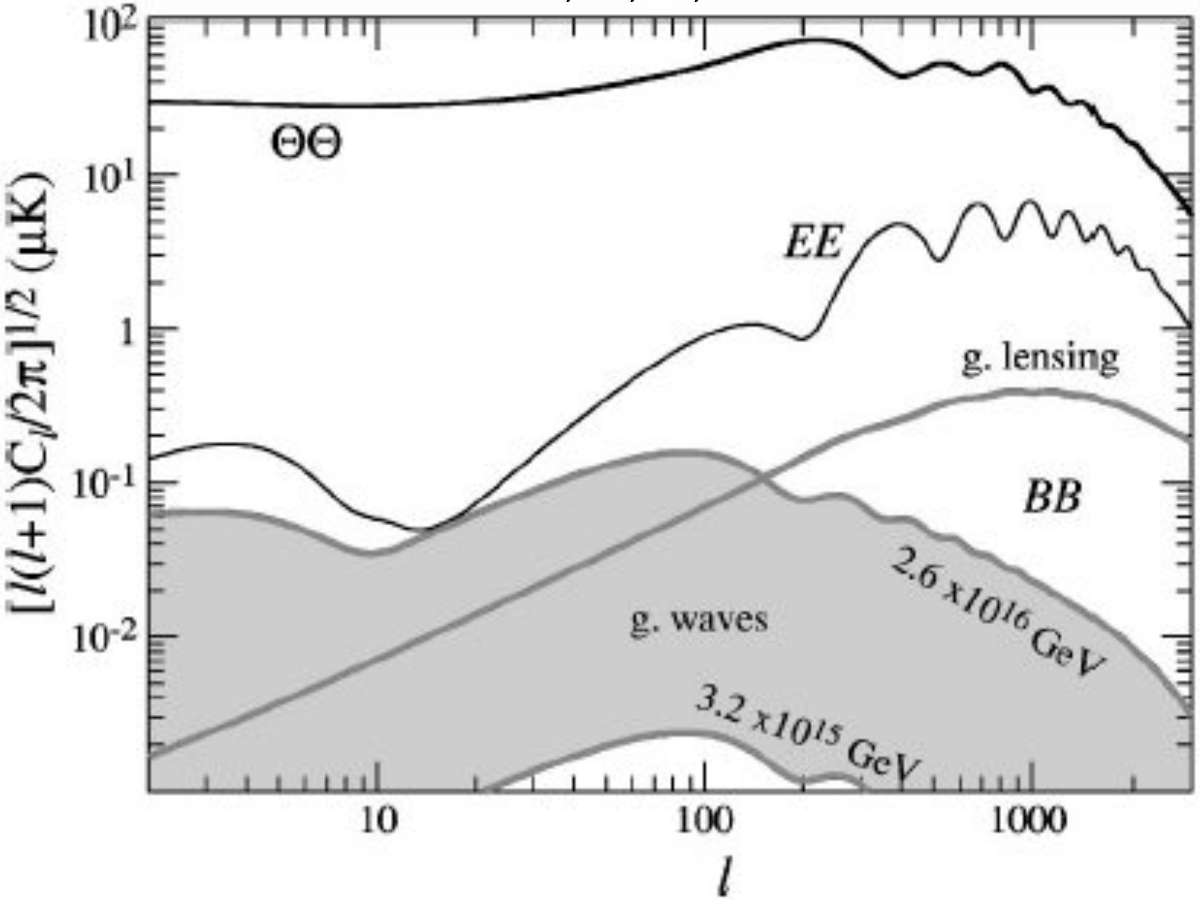
$$\Delta C^P_l = \sqrt{\frac{2}{(2l+1) f_{sky} \Delta l}} (C^P_l + N^P_l)$$

cosmic variance

$$N^P_l = (\theta_{fwhm} \sigma_P)^2 exp\left[l(l+1)\theta^2_{fwhm}/8 \ln 2\right]$$

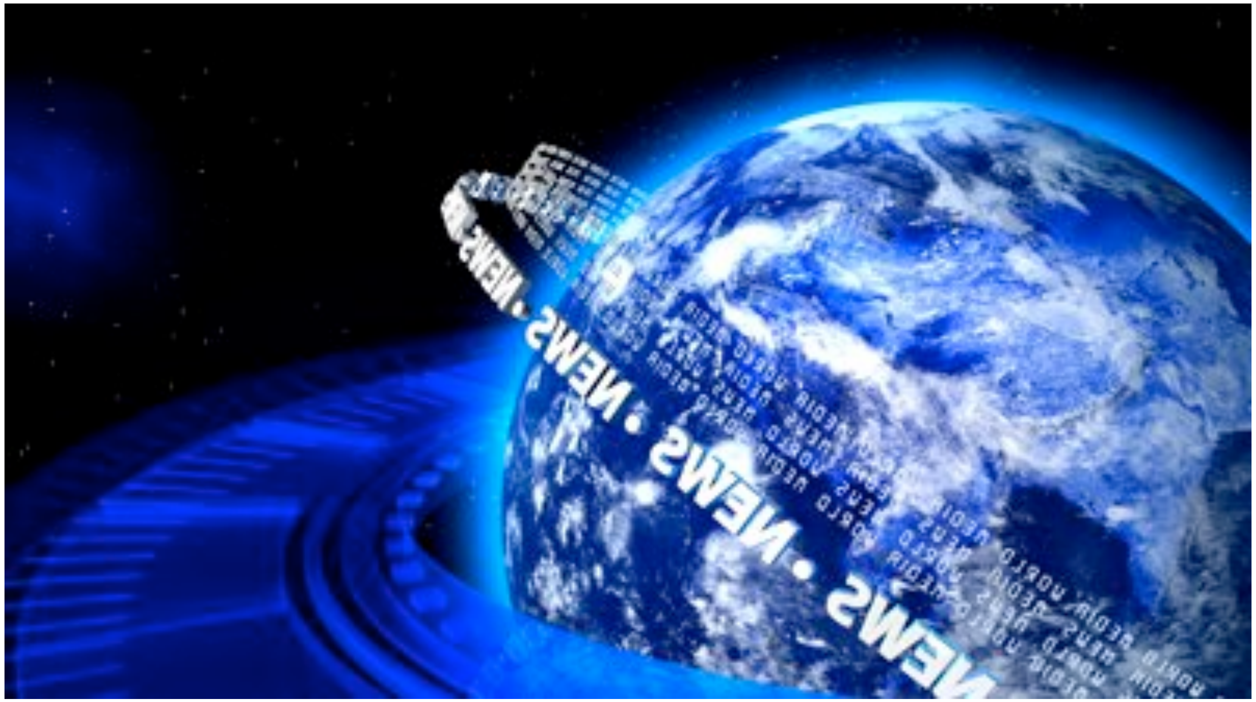
4 angular power spectra

TT, TE, EE, BB

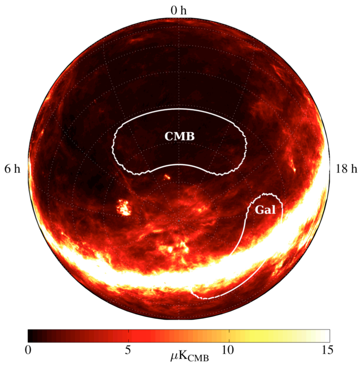


the primordial B-mode power spectrum depends on the amplitude of the gravitational waves that were emitted during the cosmic inflation.
their amplitude is parametrized by the tensor-to-scalar ratio *r*.

The BICEP2 saga



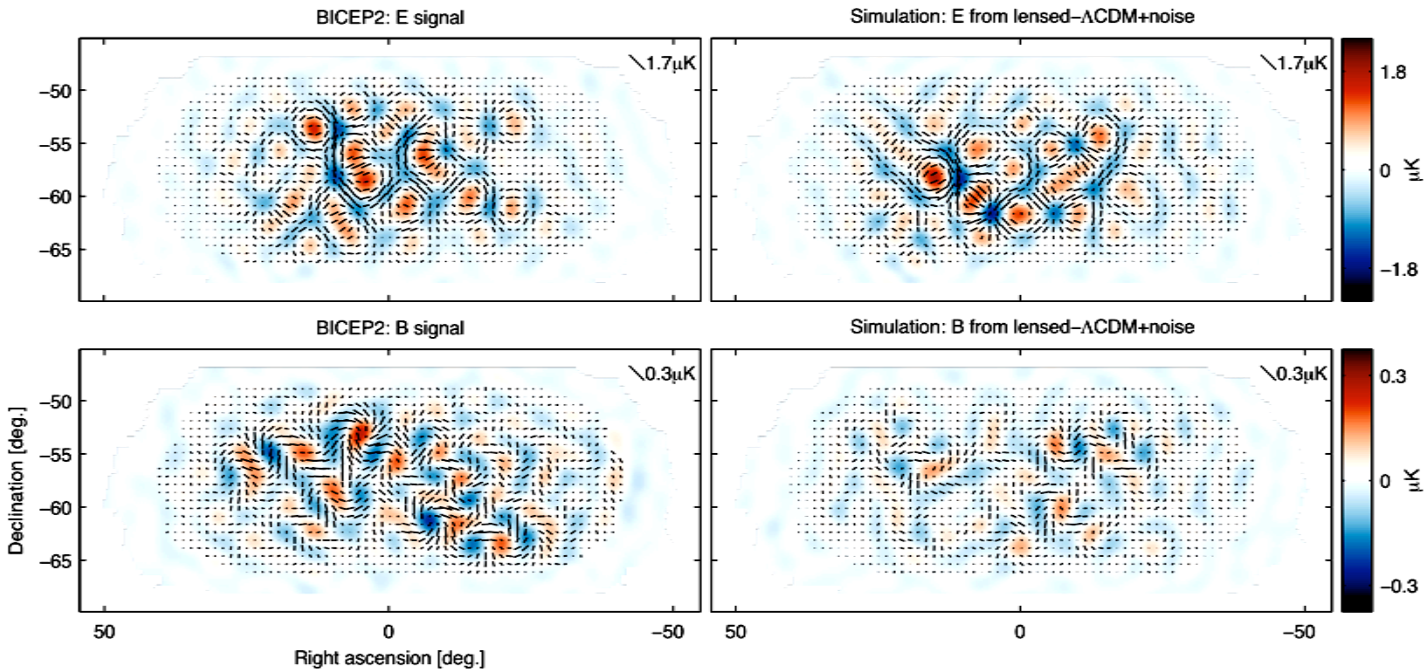
Detection of the primordial B-mode !



observation of about 1% sky area at 150GHz
(with the same sensitivity than PLANCK on the full-sky)

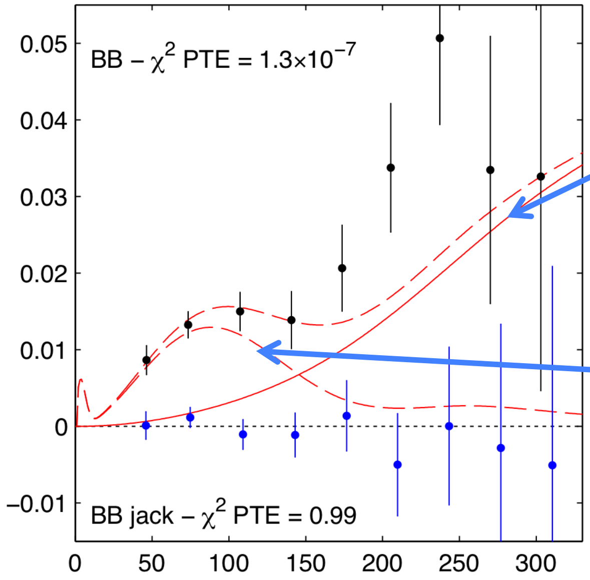
data

simulation assuming r=0



A B-mode excess is observed !

Detection of the primordial B-mode !



model without gravitational waves (r=0)

Best fitting primordial B-mode model

17 March 2014

BICEP2 Collab. arXiv:1403.3985v1

disfavoring synchrotron or dust at 2.3σ and 2.2σ, respectively. The observed B-mode power spectrum is well-fit by a lensed-ΛCDM + tensor theoretical model with tensor/scalar ratio $r = 0.20^{+0.07}_{-0.05}$, with $r = 0$ disfavored at 7.0σ. Subtracting the best available estimate for foreground dust modifies the likelihood slightly so that $r = 0$ is disfavored at 5.9σ.

Between the end of March and the beginning of May:

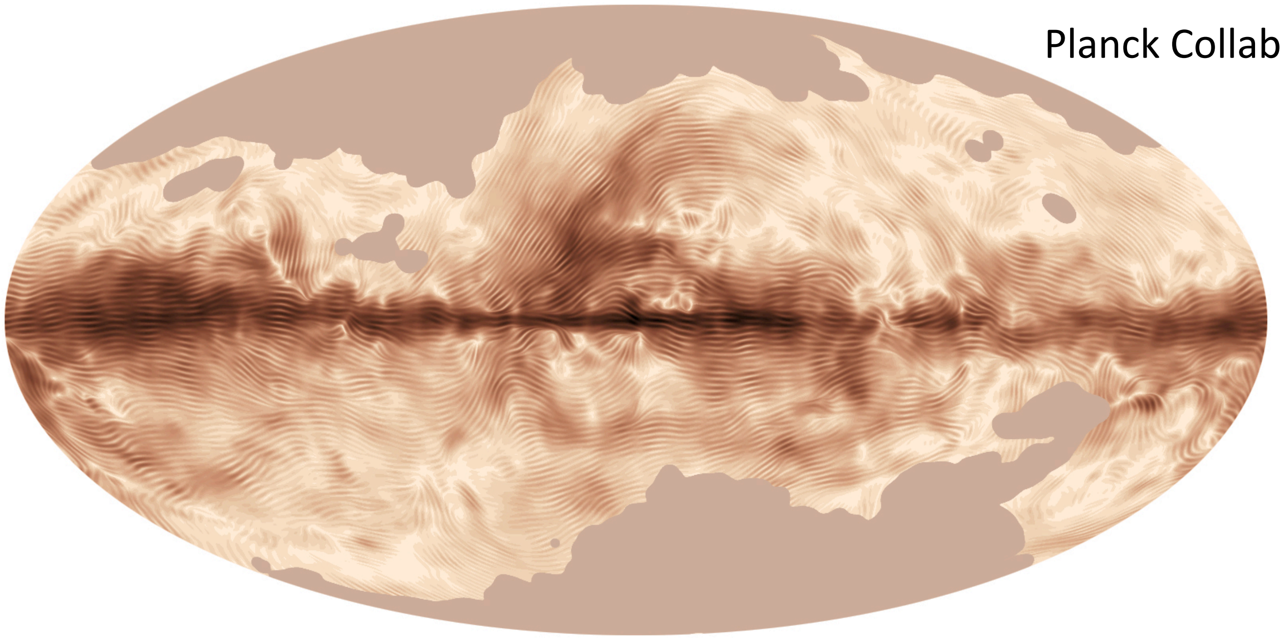
- 2 papers argued that the polarized dust contamination can be of importance…
- about 75 papers discussed inflationary models that can describe the measured excess

The polarized galactic dust (=killjoy)

In May, Planck releases information on the polarized galactic dust at intermediate latitudes

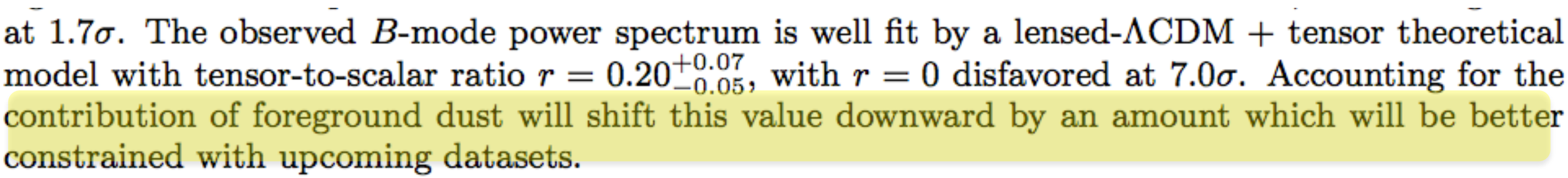
Planck Collab. arXiv:1405.0871

Planck Collab. arXiv:1405.0874



June, 23rd: slightly updated version of the BICEP2

BICEP2 Collab. arXiv:1403.3985v3

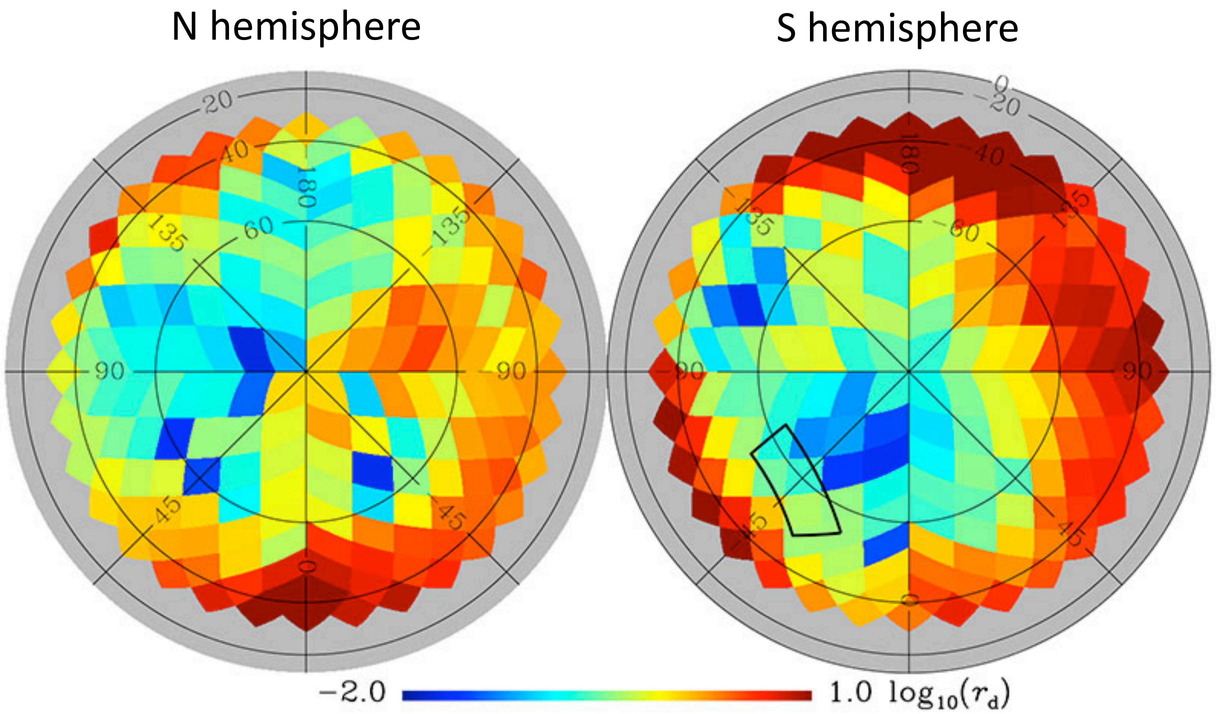


at 1.7σ. The observed B-mode power spectrum is well fit by a lensed-ΛCDM + tensor theoretical model with tensor-to-scalar ratio $r = 0.20^{+0.07}_{-0.05}$, with $r = 0$ disfavored at 7.0σ. Accounting for the contribution of foreground dust will shift this value downward by an amount which will be better constrained with upcoming datasets.

BICEP2 B-mode excess explained by the dust

September 2014: PLANCK releases the full-sky map of the polarized galactic dust and estimates the B-mode amplitude due to the dust

Planck Collab. arXiv:1409.5738



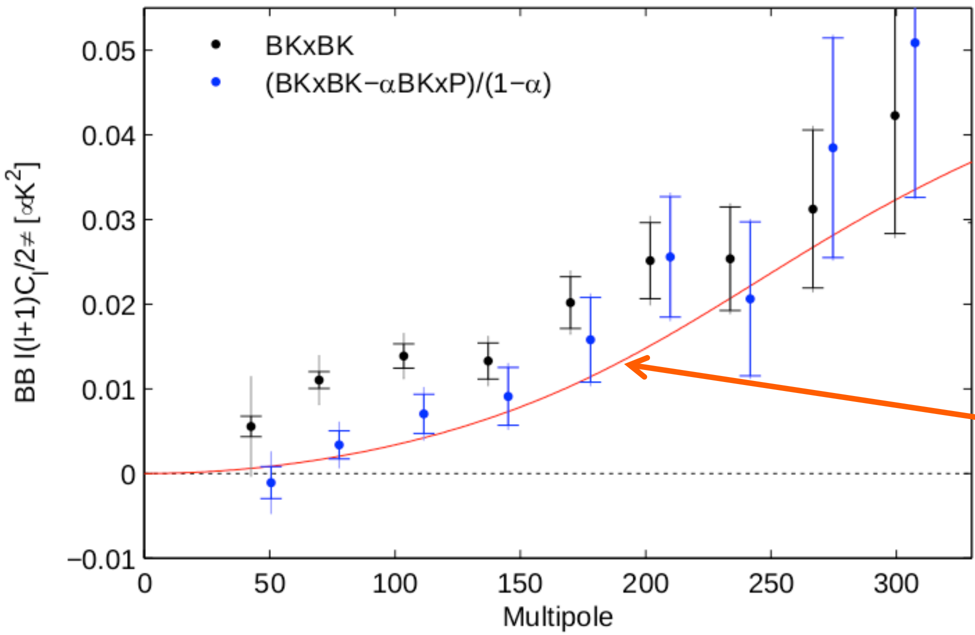
Significant contribution from the dust even at high galactic latitudes that suffices to explain the B-mode excess seen by BICEP2

The joint BICEP2-Keck Array-PLANCK analysis

Autumn 2014: The Keck Array (same field, same frequency band) completes a data analysis based on the 2012-2013 observation campaign.

BICEP2-Keck Array Collab. arXiv:1502.00643

Feb. 2015: The BICEP2-Keck Array and PLANCK teams re-analyse all the data together



B for BICEP2
K for *Keck Array*
P for PLANCK at 353GHz

r=0 ΛCDM model

If the polarized dust is corrected for, no need of primordial B-modes anymore…

The joint BICEP2-Keck Array-PLANCK analysis

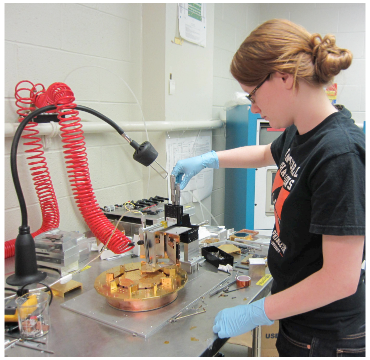
BICEP2-Keck Array Collab. arXiv:1502.00643

We report the results of a joint analysis of data from BICEP2/*Keck Array* and *Planck*. BICEP2 and *Keck Array* have observed the same approximately 400 deg^2 patch of sky centered on RA 0h, Dec. -57.5°. The combined maps reach a depth of 57 nK deg in Stokes Q and U in a band centered at 150 GHz. *Planck* has observed the full sky in polarization at seven frequencies from 30 to 353 GHz, but much less deeply in any given region (1.2 μK deg in Q and U at 143 GHz). We detect 150×353 cross-correlation in B-modes at high significance. We fit the single- and cross-frequency power spectra at frequencies $\geq$ 150 GHz to a lensed-ΛCDM model that includes dust and a possible contribution from inflationary gravitational waves (as parameterized by the tensor-to-scalar ratio r), using a prior on the frequency spectral behavior of polarized dust emission from previous *Planck* analysis of other regions of the sky. We find strong evidence for dust and no statistically significant evidence for tensor modes. We probe various model variations and extensions, including adding a synchrotron component in combination with lower frequency data, and find that these make little difference to the r constraint. Finally we present an alternative analysis which is similar to a map-based cleaning of the dust contribution, and show that this gives similar constraints. The final result is expressed as a likelihood curve for r, and yields an upper limit $r_{0.05} < 0.12$ at 95% confidence. Marginalizing over dust and r, lensing B-modes are detected at 7.0 σ significance.

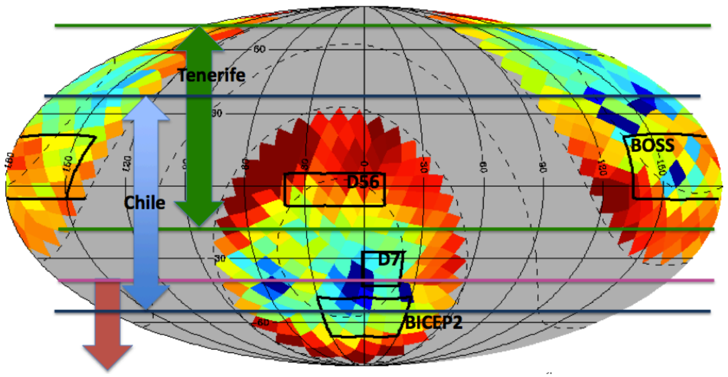
This is not the end of the story

QUIJOTE

POLARBEAR 2 / Simons Array



Advanced ACTpol



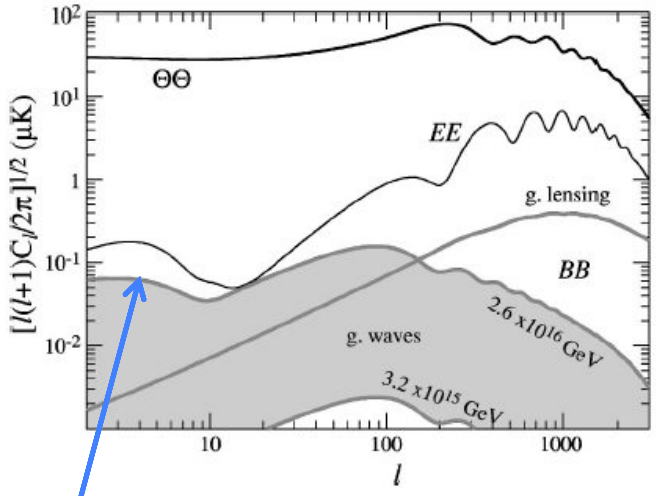
South Pole

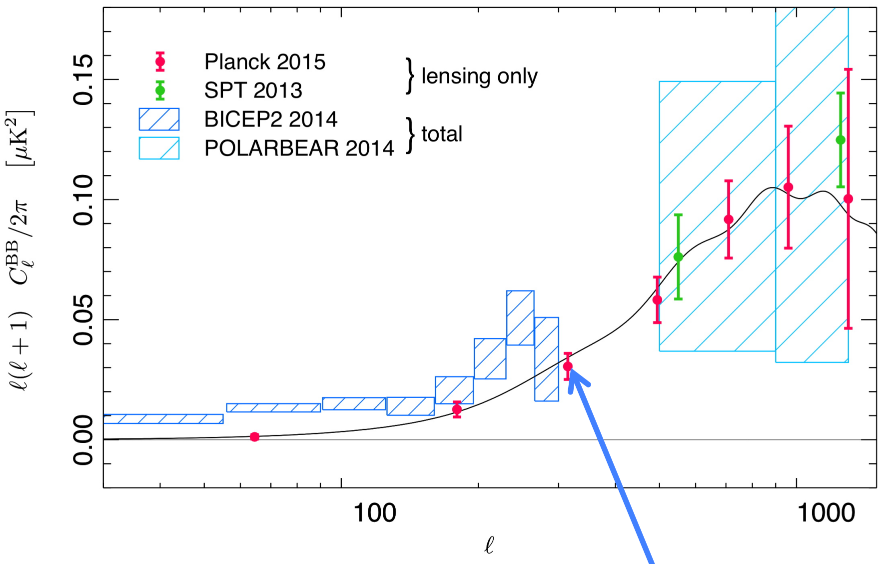
crédit: Page, Ferrara, 2014

BICEP3

Advanced SPTpol

Soon: PLANCK CMB-dominated polarization maps release





Only Planck can acess the reionisation bump

PLANCK provides a precise measure of the lensing induced B-mode

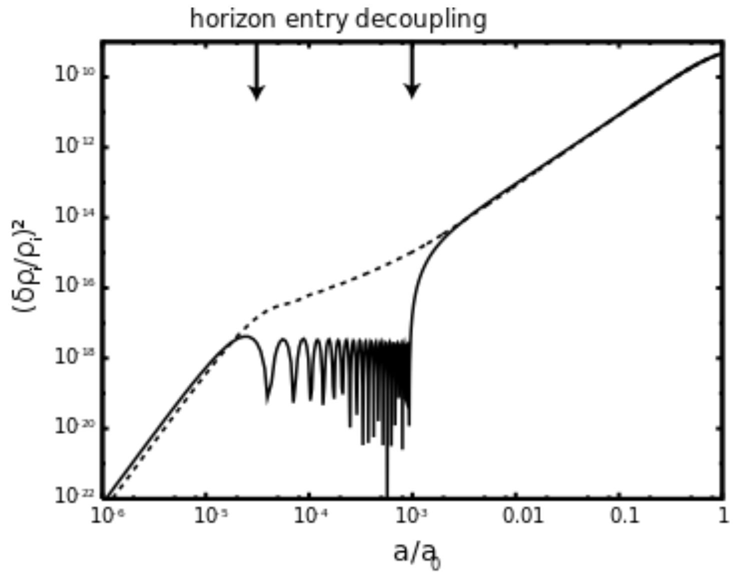
Bibliography

References for Part III:

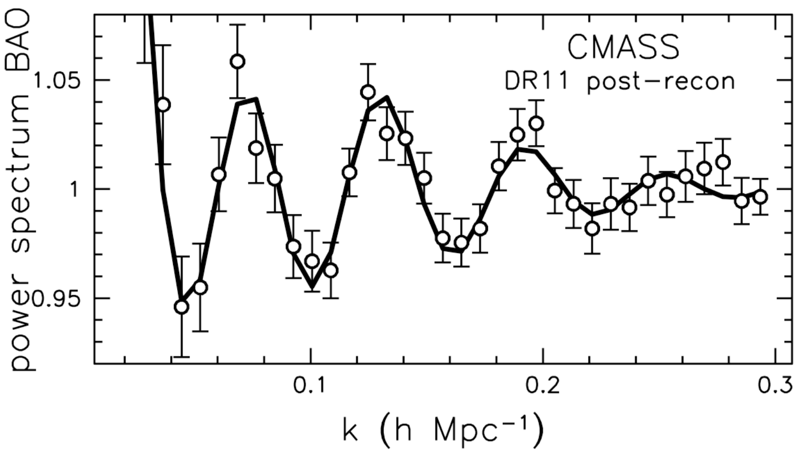
- ESA web page on the Planck Mission:
  http://sci.esa.int/science-e/www/area/index.cfm?fareaid=17
- CNES (Centre National d'Etudes Spaciales) web page on the Planck mission:
  http://missions-scientifiques.cnes.fr/PLANCK/index.htm
- site grand public de HFI-France : http://public.planck.fr/
- BICEP and Keck Array Experiments Public Web Pages:
  http://bicepkeck.org/web_page_links.html

BACKUP

Impact of the baryons



In the early universe, baryons are tighly coupled to radiation and experience acoustic oscillations.
After decoupling, they fall into the dark matter potential well.
In return, it lets an imprint in the matter distribution



Baryon Oscillation Spectroscopic Survey (BOSS) of the SDSS
Anderson et al. (2014)