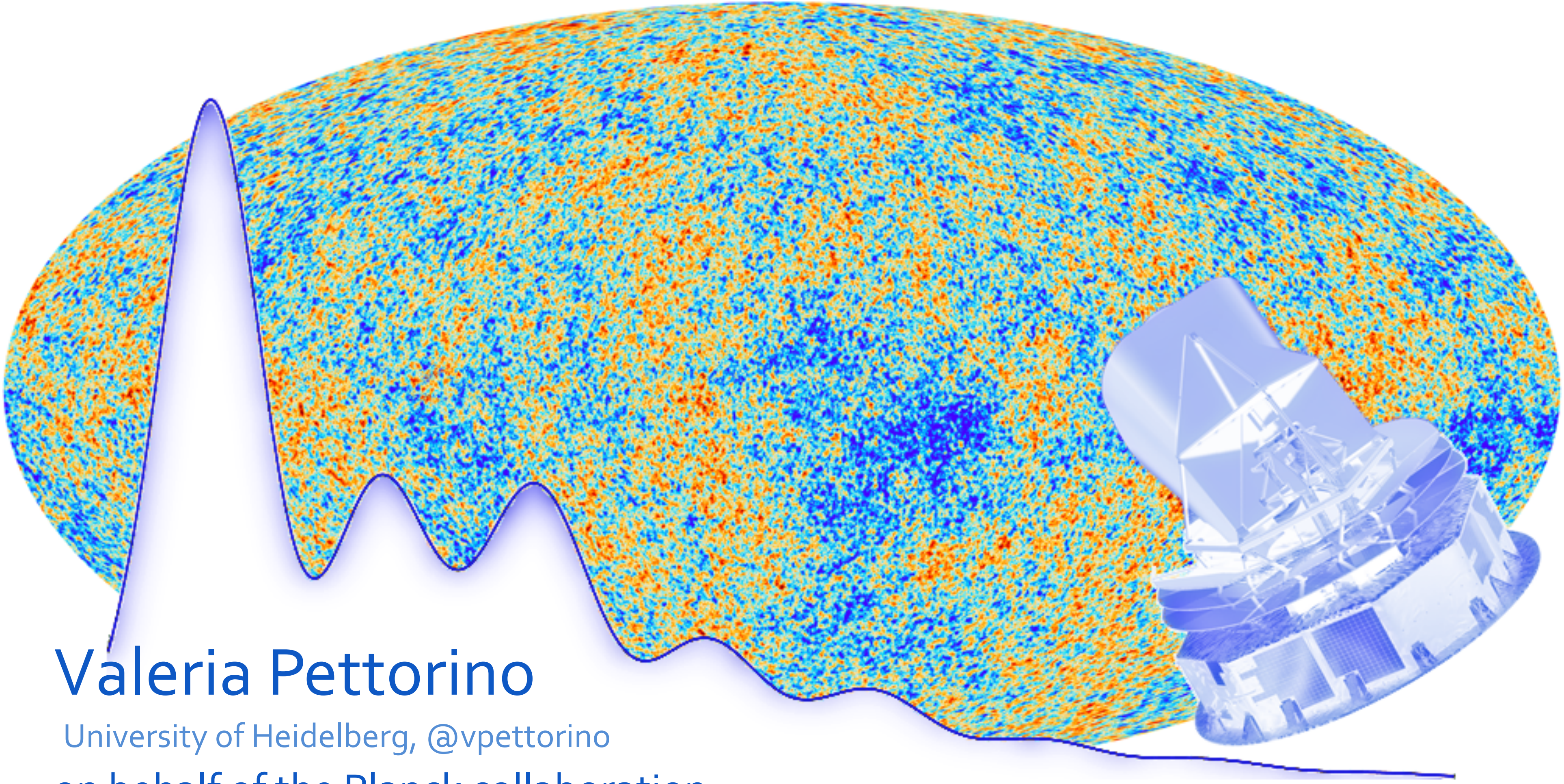
Cosmology after Planck 2015



Valeria Pettorino

University of Heidelberg, @vpettorino

on behalf of the Planck collaboration

Off-the-Beaten-Track Dark Matter and Astrophysical Probes of Fundamental Physics, ICTP

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

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HFI PLANCK
a look back to the birth of Universe

PLANCK LFI

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Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

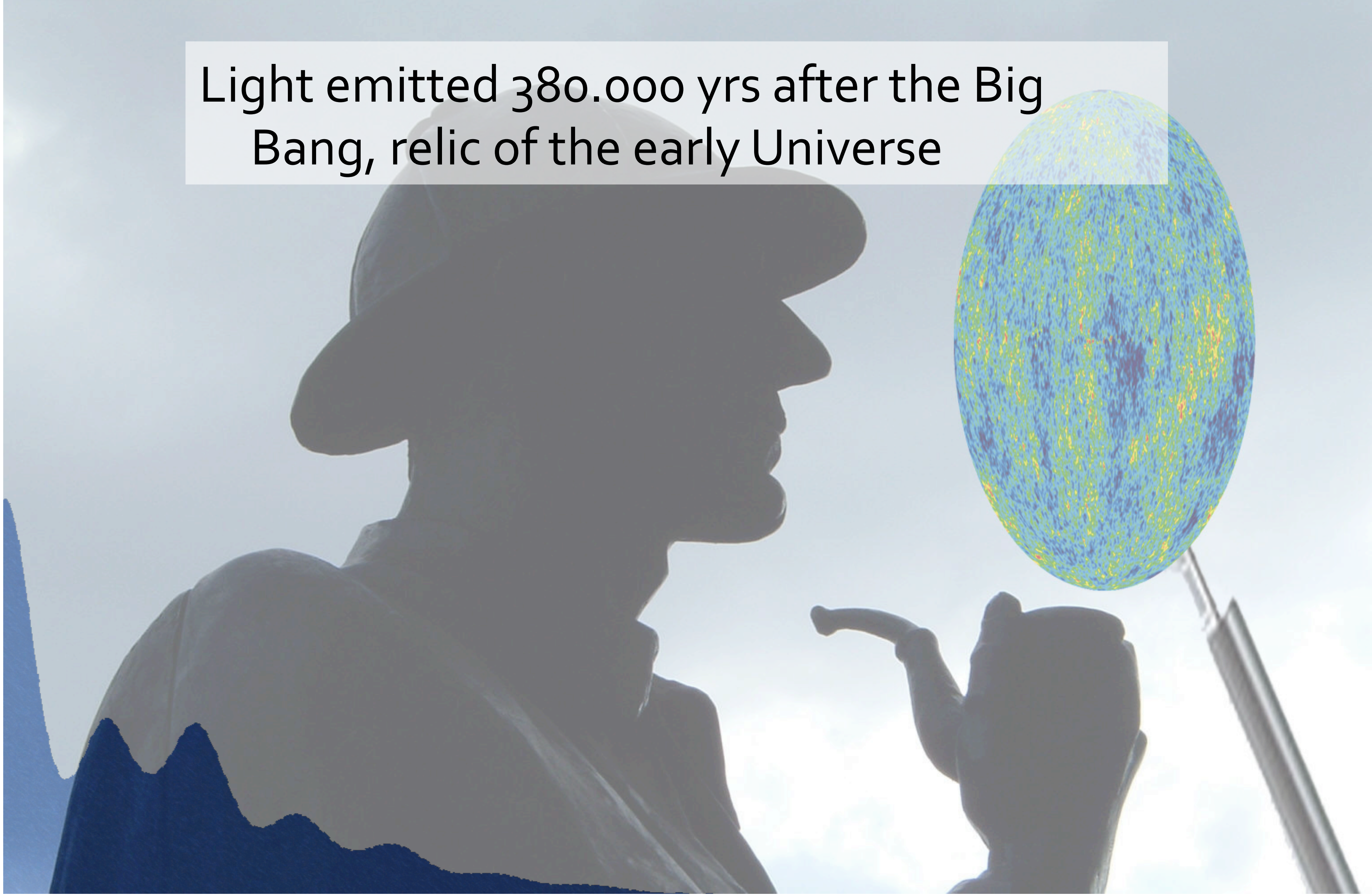
Plan of the talk

- Introduction
  - The Cosmic Microwave Background
  - Planck space mission

- Planck results on Cosmology
  - Cosmological parameters
  - Tests beyond the baseline model (neutrinos, relativistic degrees of freedom, BBN, ...)

Valeria Pettorino,
University of Heidelberg
16th April 2015, ICTP, Trieste

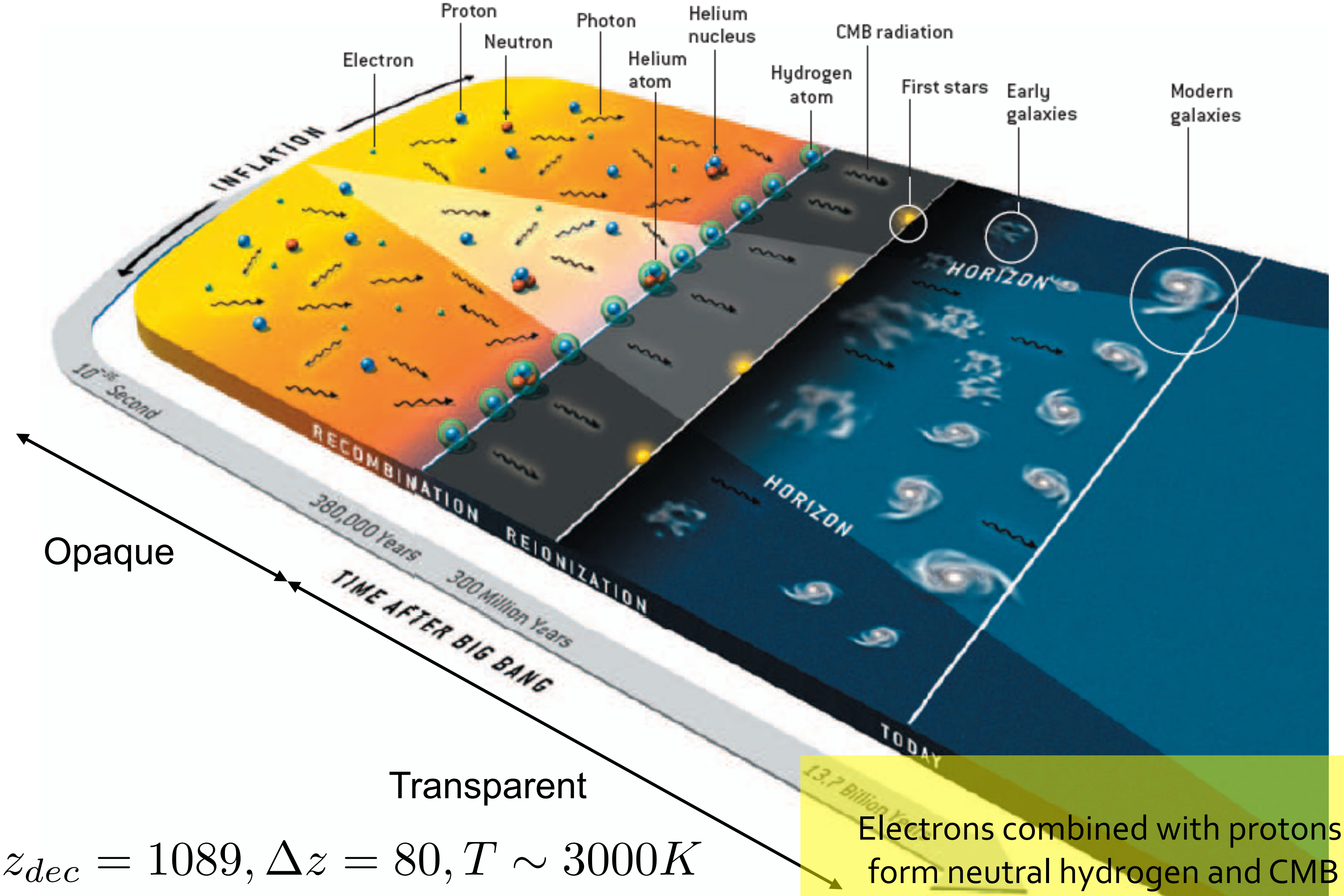
Cosmic Microwave Background



Light emitted 380.000 yrs after the Big Bang, relic of the early Universe

Hu & White, Sci. Am., 290 44 (20

Evolution of the universe



Opaque

Transparent

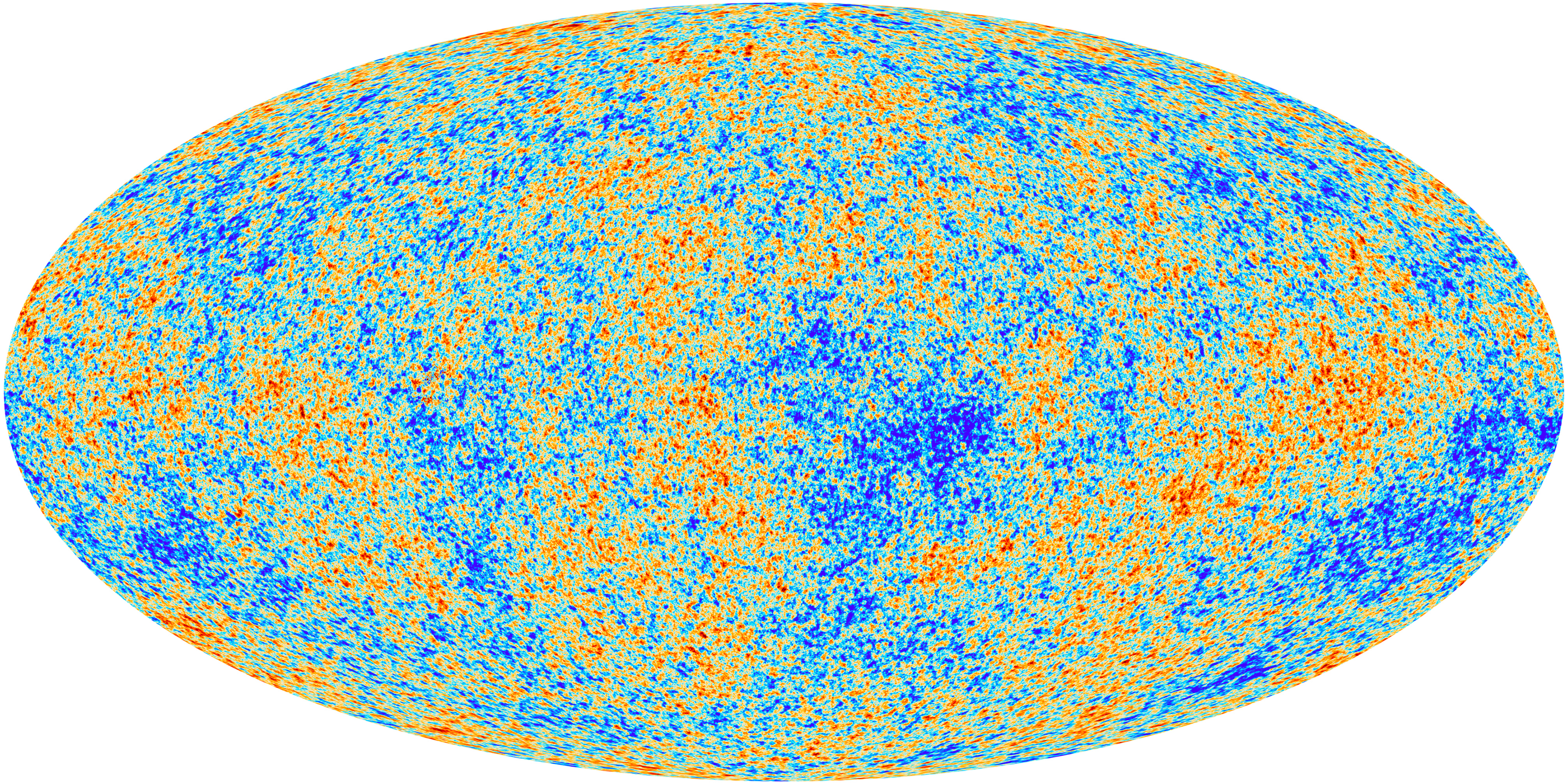
$$z_{dec} = 1089, \Delta z = 80, T \sim 3000K$$

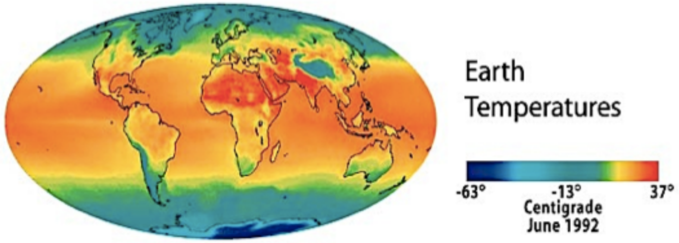
Hu & White, Sci. Am., 290 44 (2004)

Electrons combined with protons to form neutral hydrogen and CMB photons travelled freely until detecti (first in 1965, Penzias and Wilson)

CMB anisotropies

Now able to measure differences of 1 part over 100000 with a percent precision

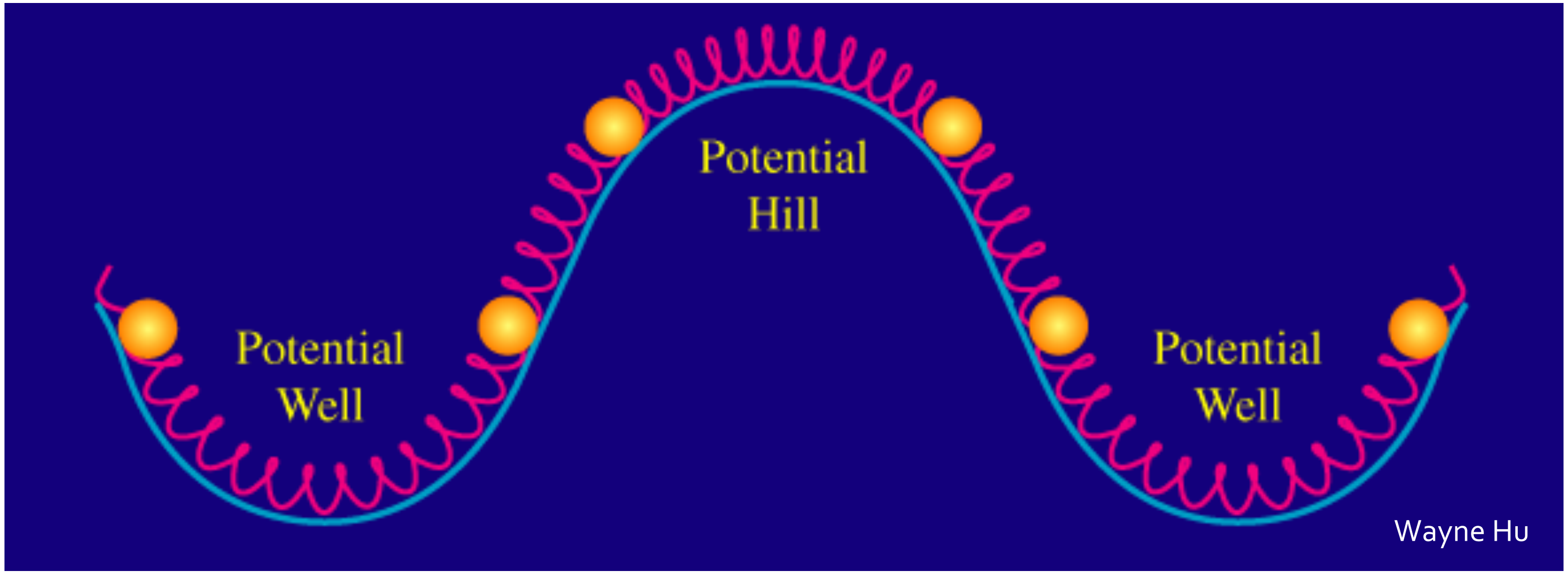




If you look at angles of about 1 degree or smaller you see anisotropies.

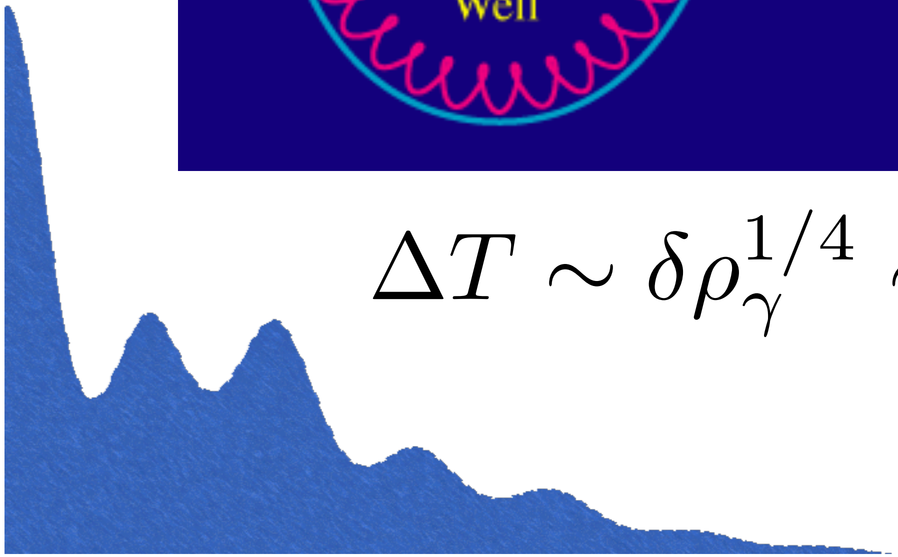
Acoustic oscillations

Temperature fluctuations are related to primordial density fluctuations.
Gravity and pressure of the baryon-photon fluid generate compressions and rarefactions.



Wayne Hu

$$\Delta T \sim \delta\rho_{\gamma}^{1/4} \sim A(k)cos(kc_s t)$$

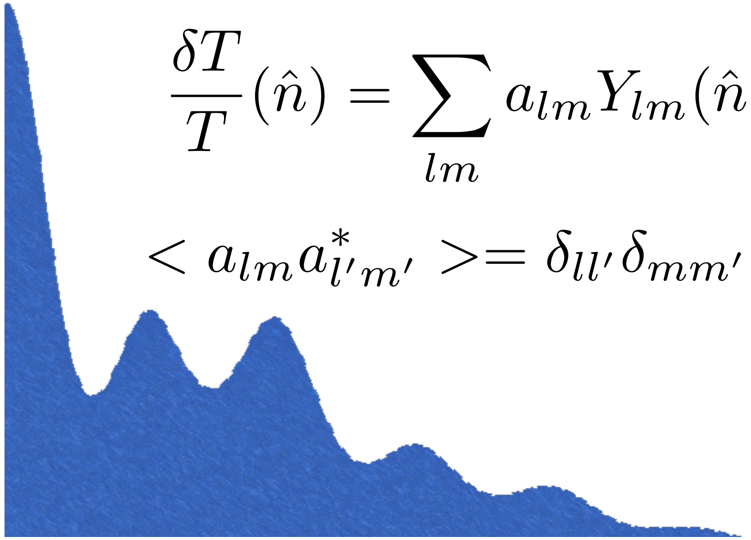


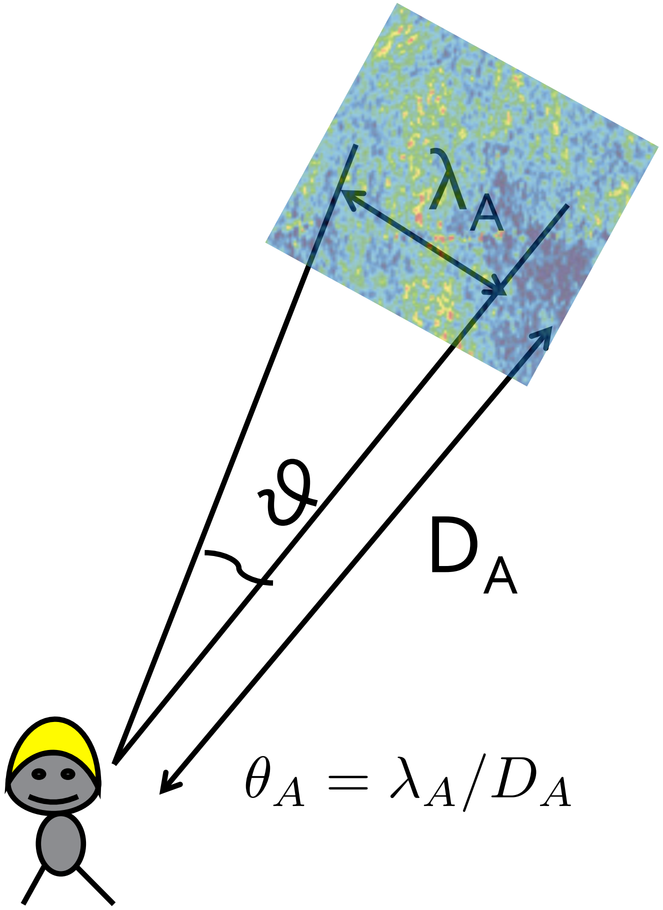
Evolution of perturbations

- Expand in Fourier space
- Project the fluctuations in the sky
- Spectra as 2 point correlation function of the coefficients of the expansion in spherical harmonics

$$\frac{\delta T}{T}(\hat{n}) = \sum_{lm} a_{lm} Y_{lm}(\hat{n})$$

$$< a_{lm} a^{*}_{l'm'} >= \delta_{ll'} \delta_{mm'} C_l$$

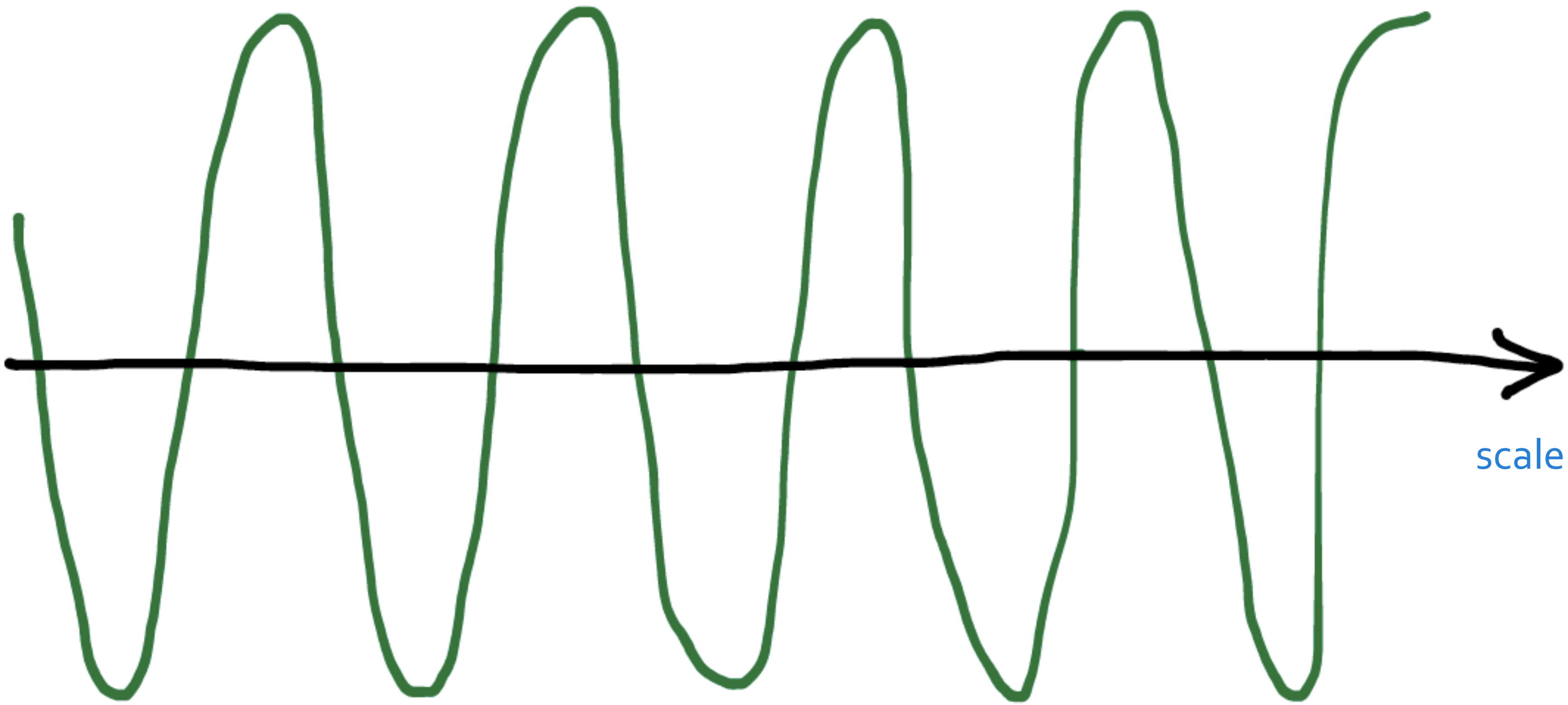




$$\theta_A = \lambda_A / D_A$$

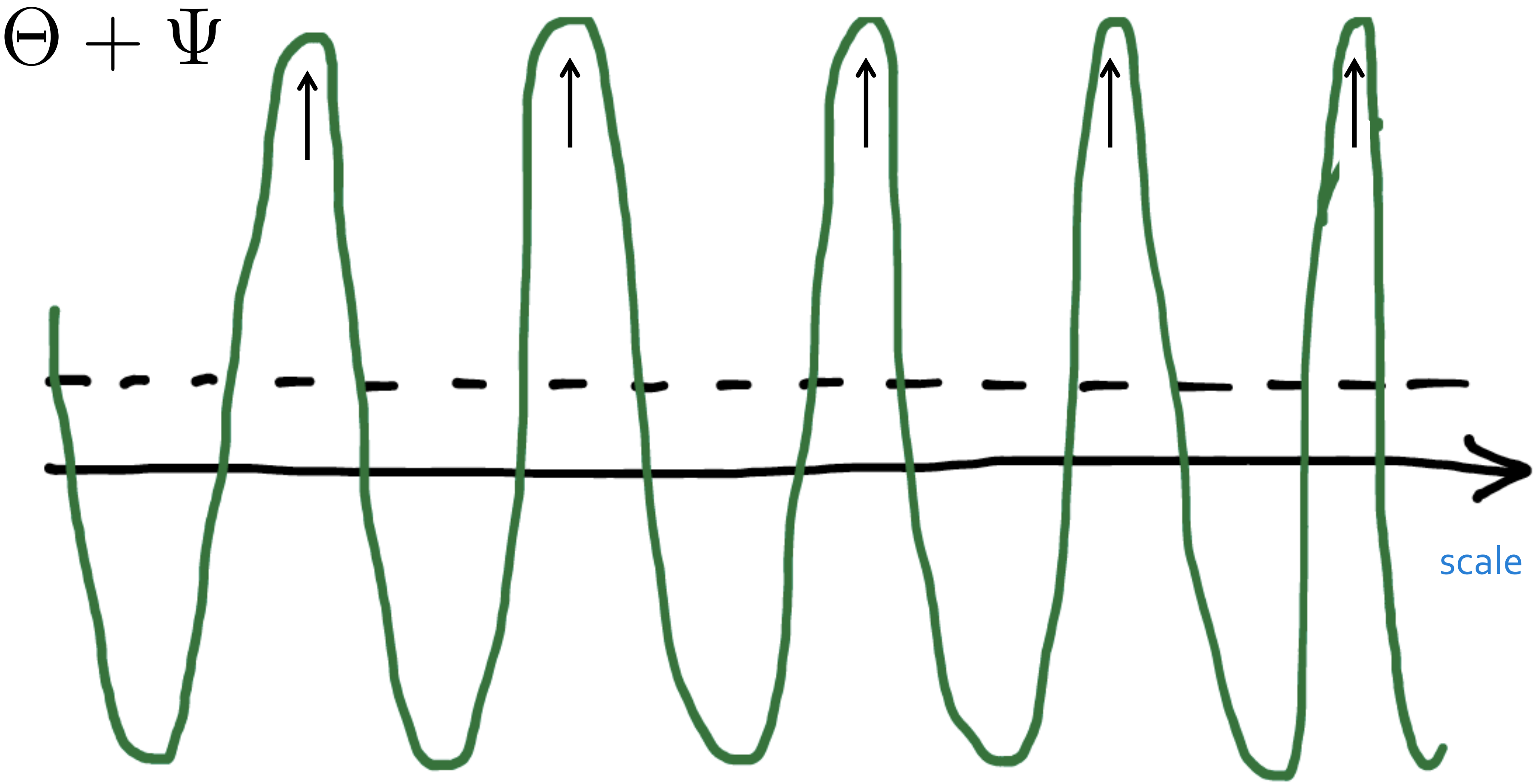
Oscillations of a tight fluid, equal amplitude

$\Theta + \Psi$



Baryon dragging

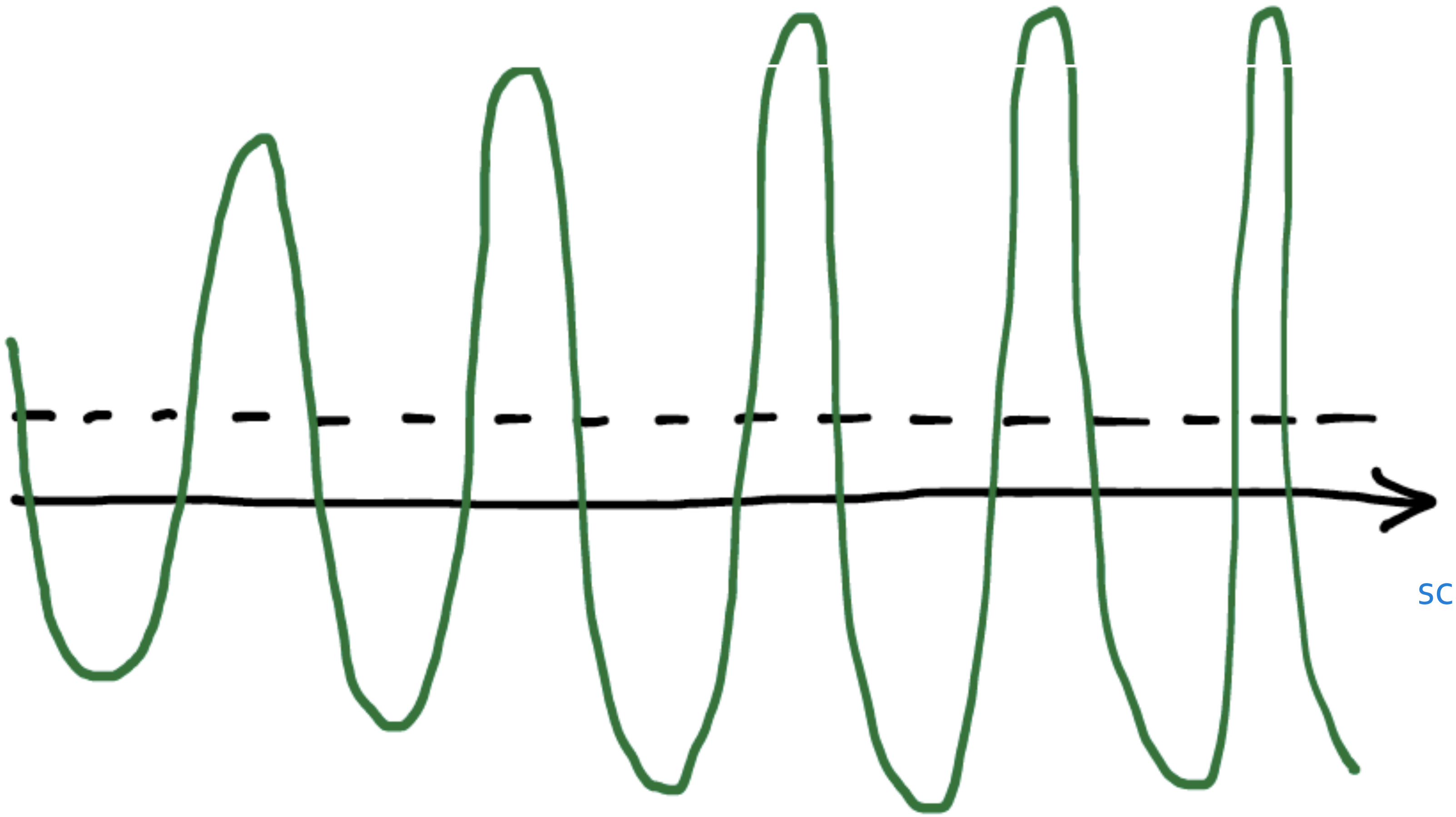
enhances compressions, shifts equilibrium point, change odd/even relative amplitude of the oscillations



Gravitational driving

Enhances small scales with respect to large ones: potentials are not constant, decay. Smaller scales enter horizon first, when there is more radiation. Decay more, loose less energy.

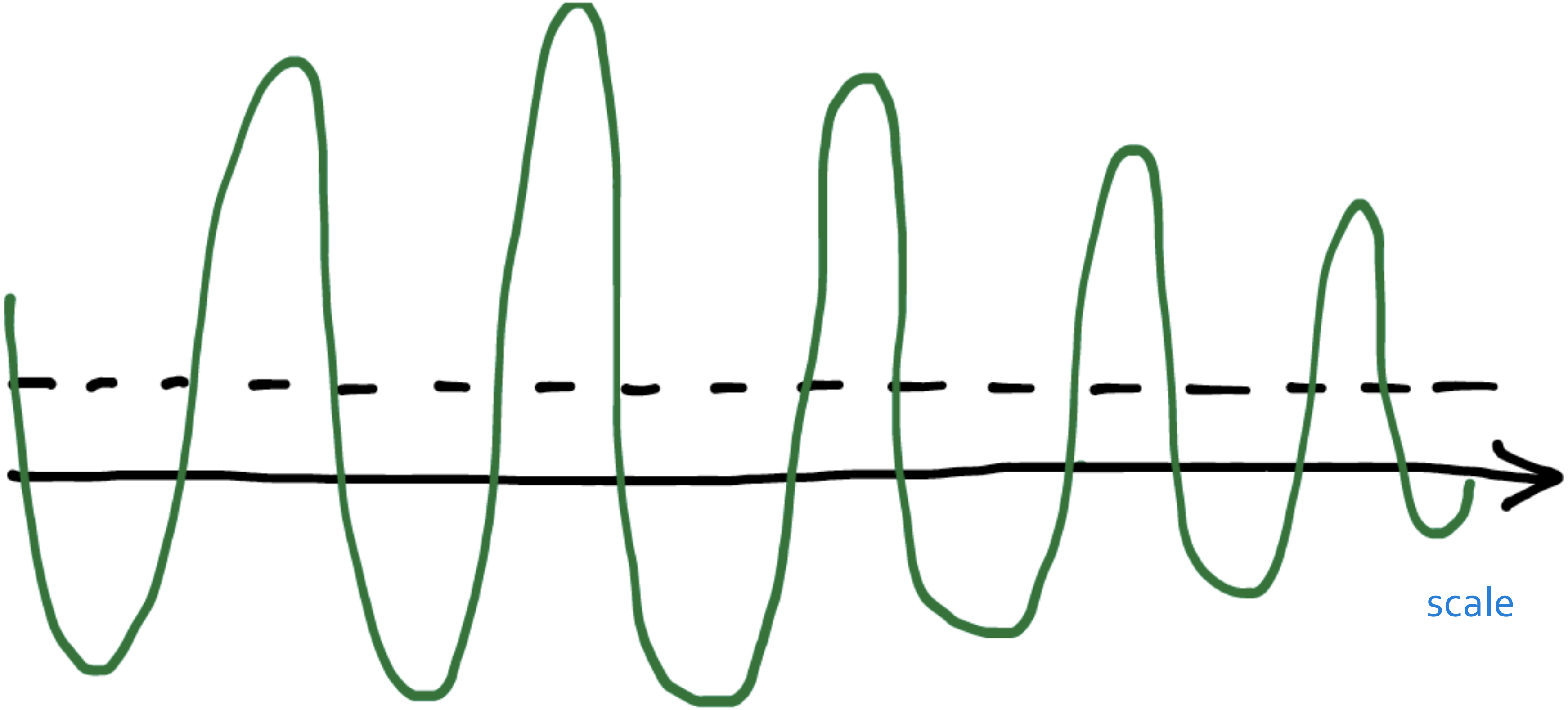
$\Theta + \Psi$



Diffusion damping

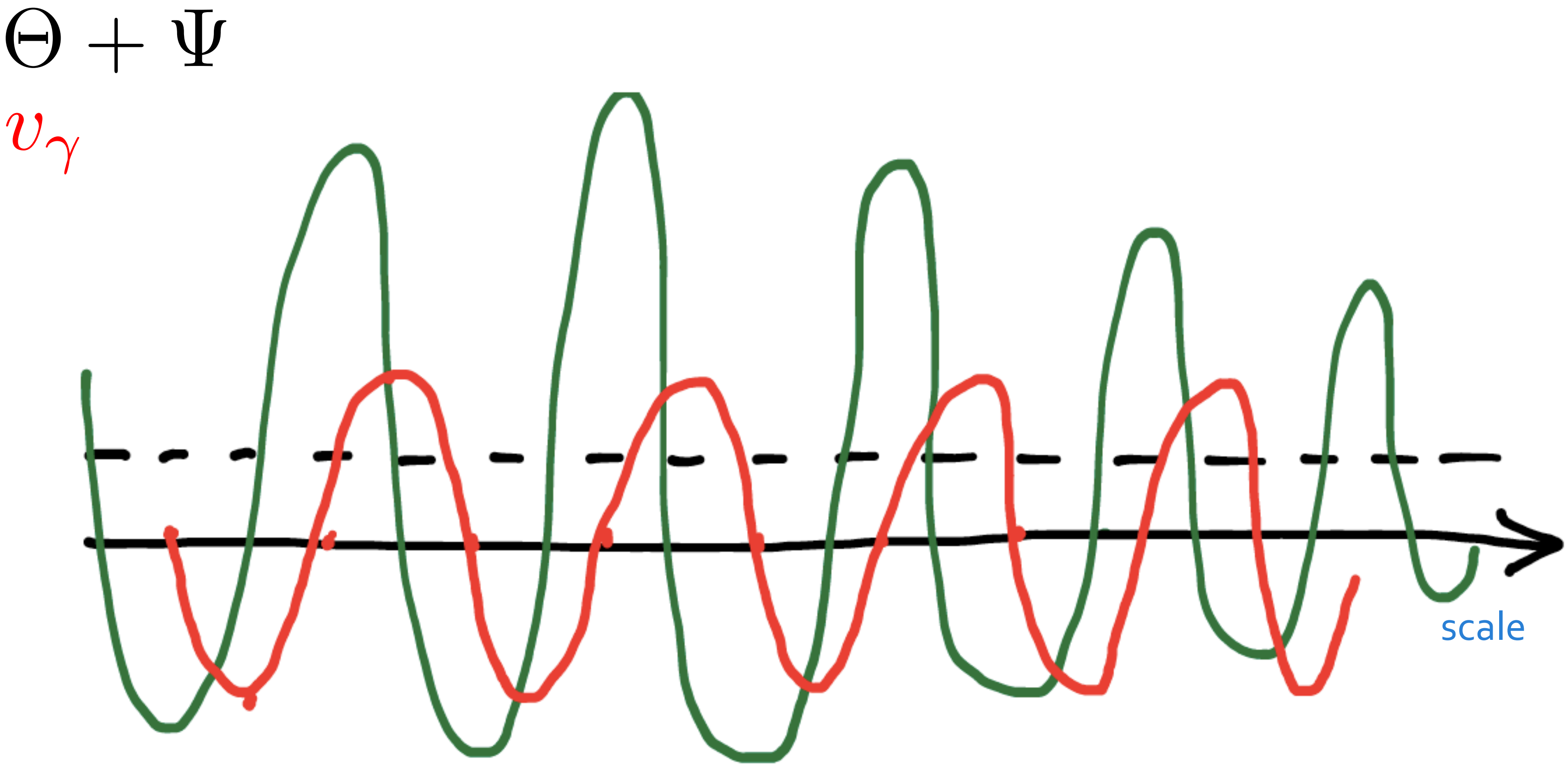
Suppresses small scales

$\Theta + \Psi$

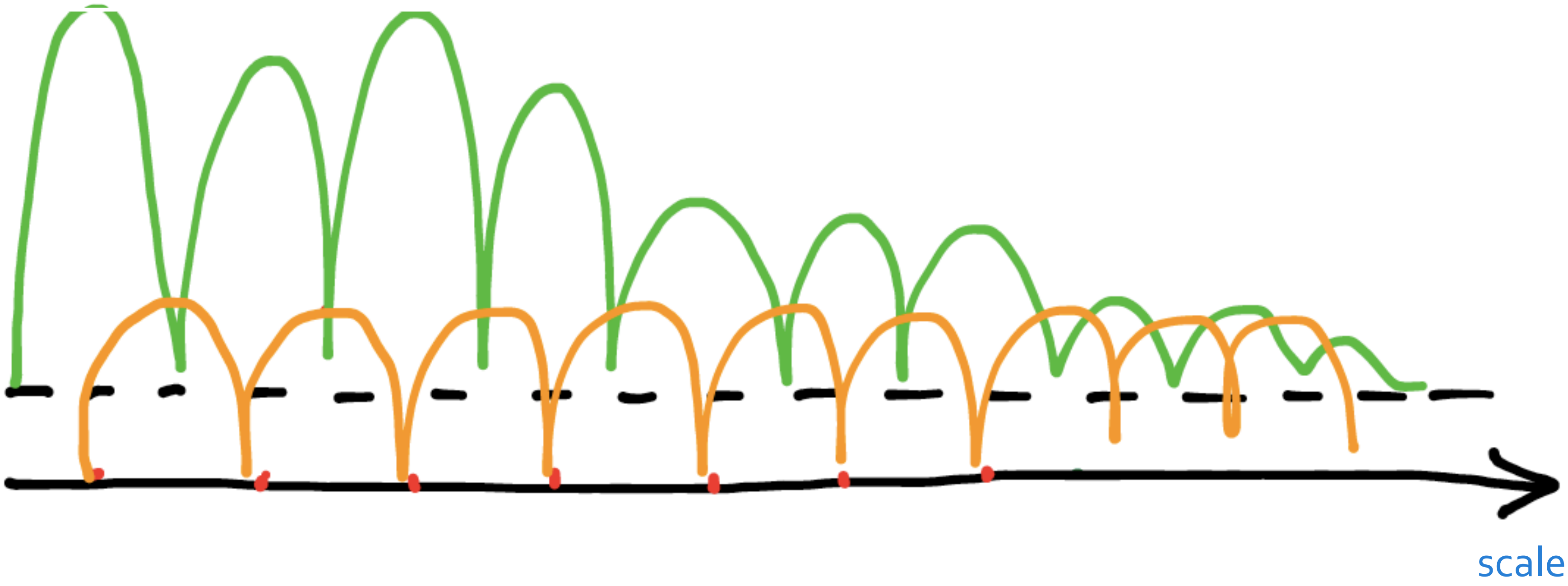


Doppler effect

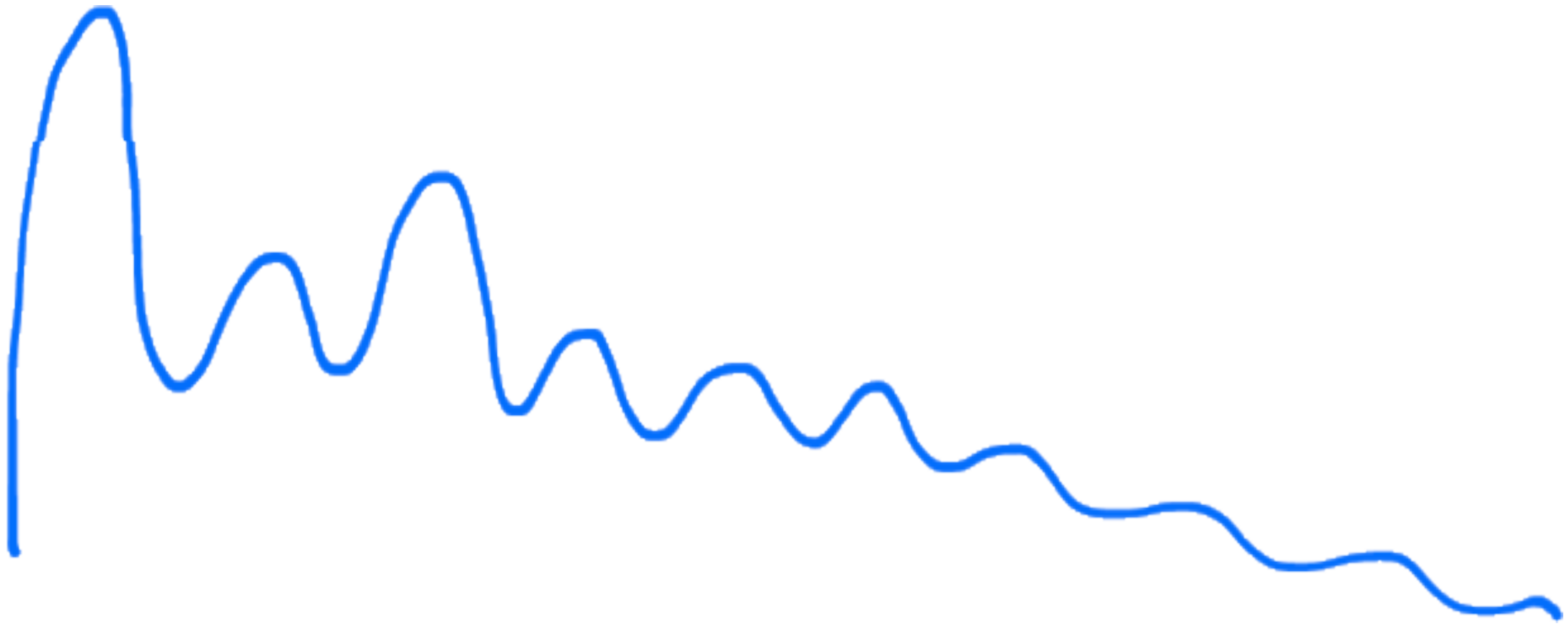
Due to the velocity of the fluid with respect to our reference system. At extrema, velocity is zero, has nodes where temperature oscillations have peaks and deeps. Out of phase.



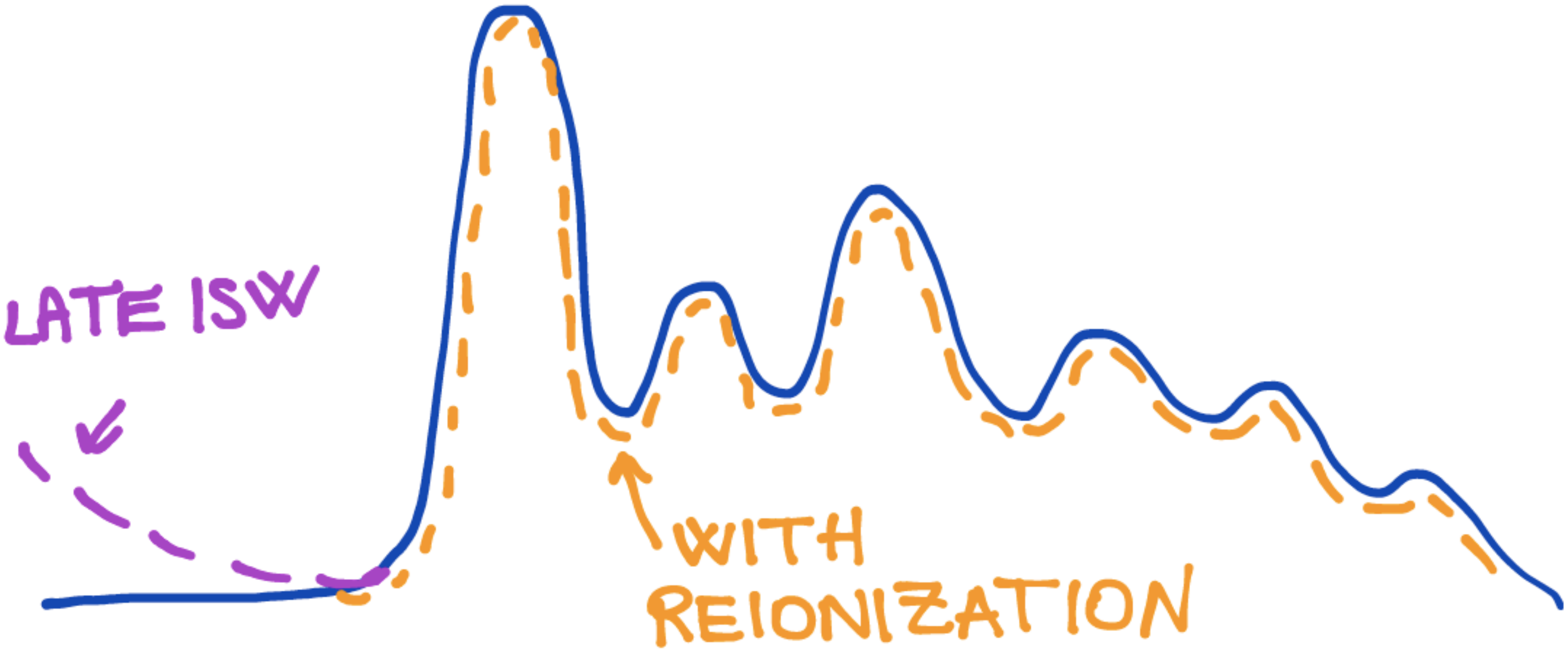
Square both



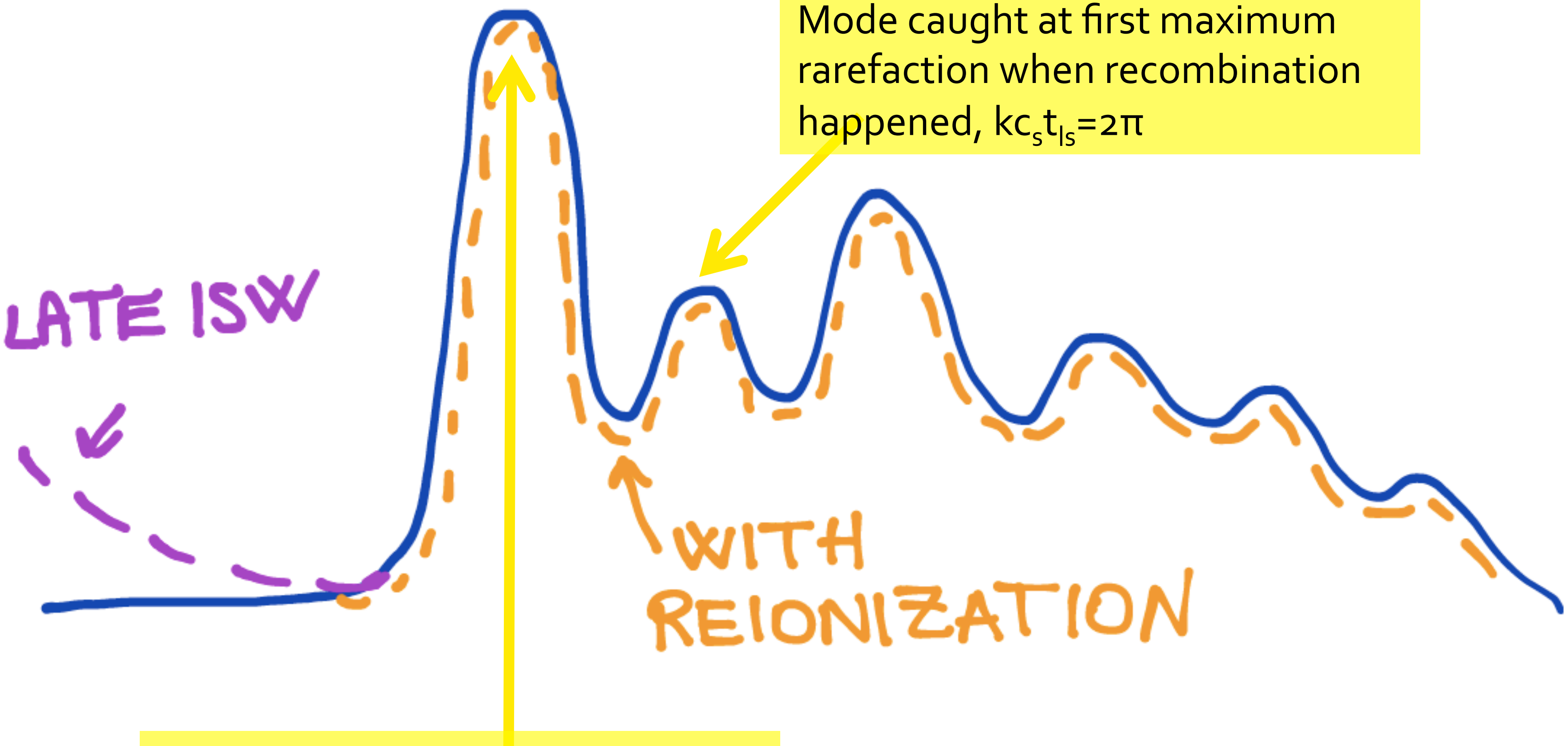
Sum



Modified along the line of sight



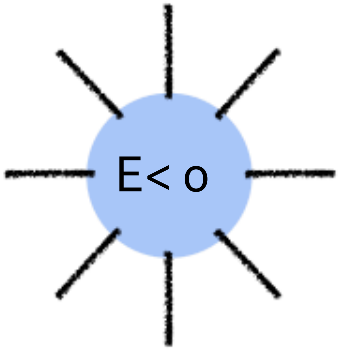
Modified along the line of sight

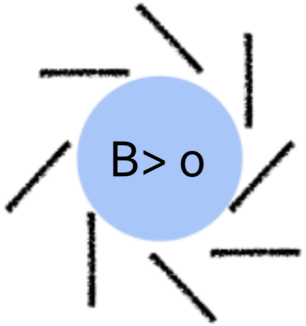


Mode caught at first maximum rarefaction when recombination happened, $kc_s t_{ls}=2\pi$

Mode caught at first maximum compression when recombination happened, $kc_s t_{ls}=\pi$

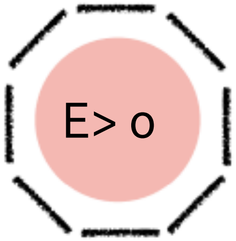
Summing over many waves, we get the following polarization patterns around **hot** and **cold** spots:

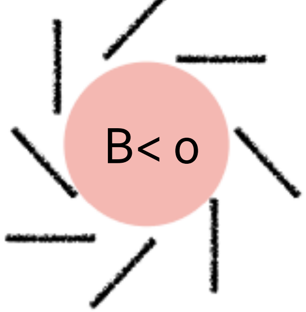




Density perturbations can
generate only E modes

Tensor perturbations (gravitational waves)
generate primordial E and B modes





E-mode

(grad)

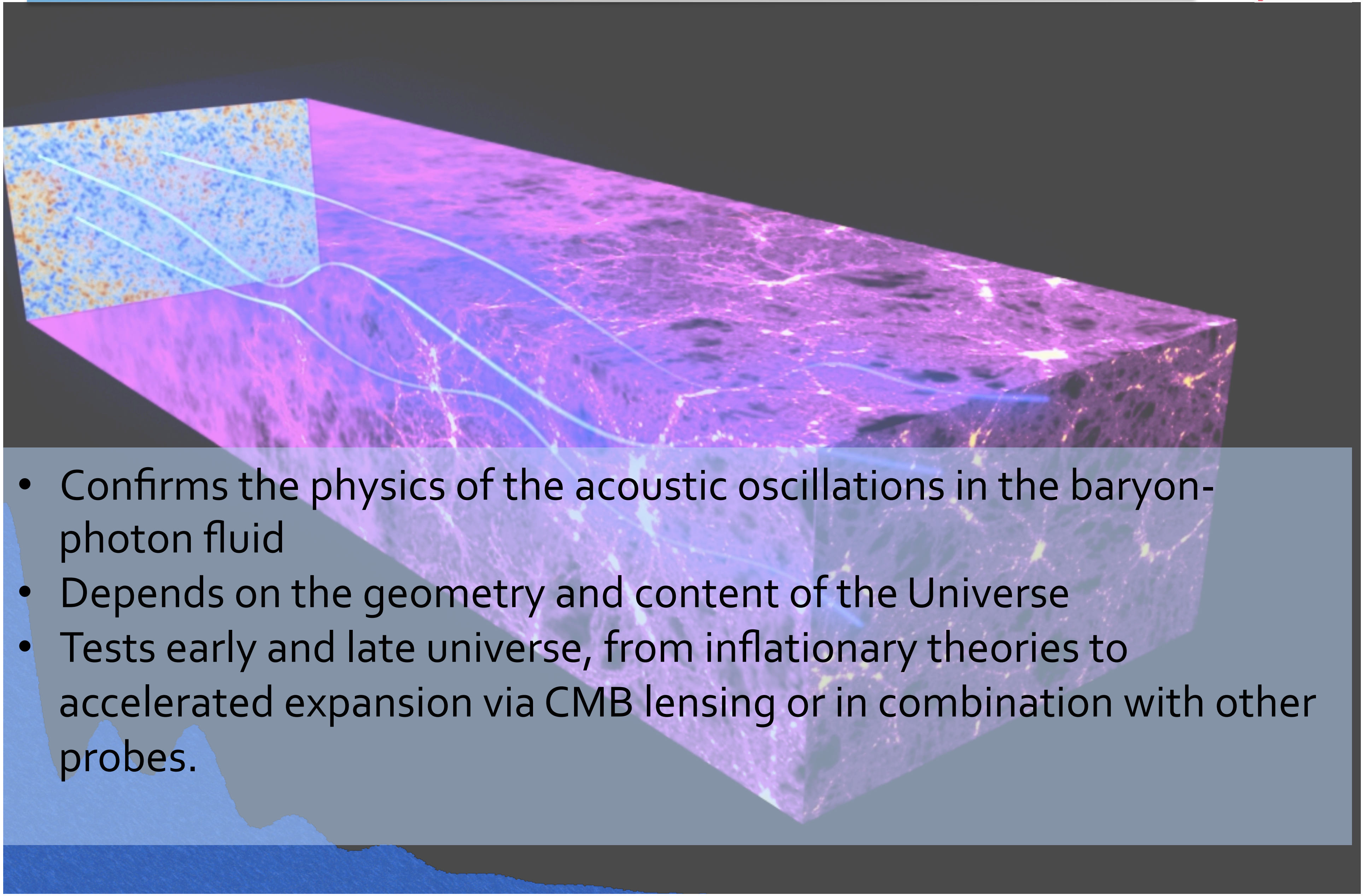
B-mode

(curl)

Courtesy of
D.Baumann

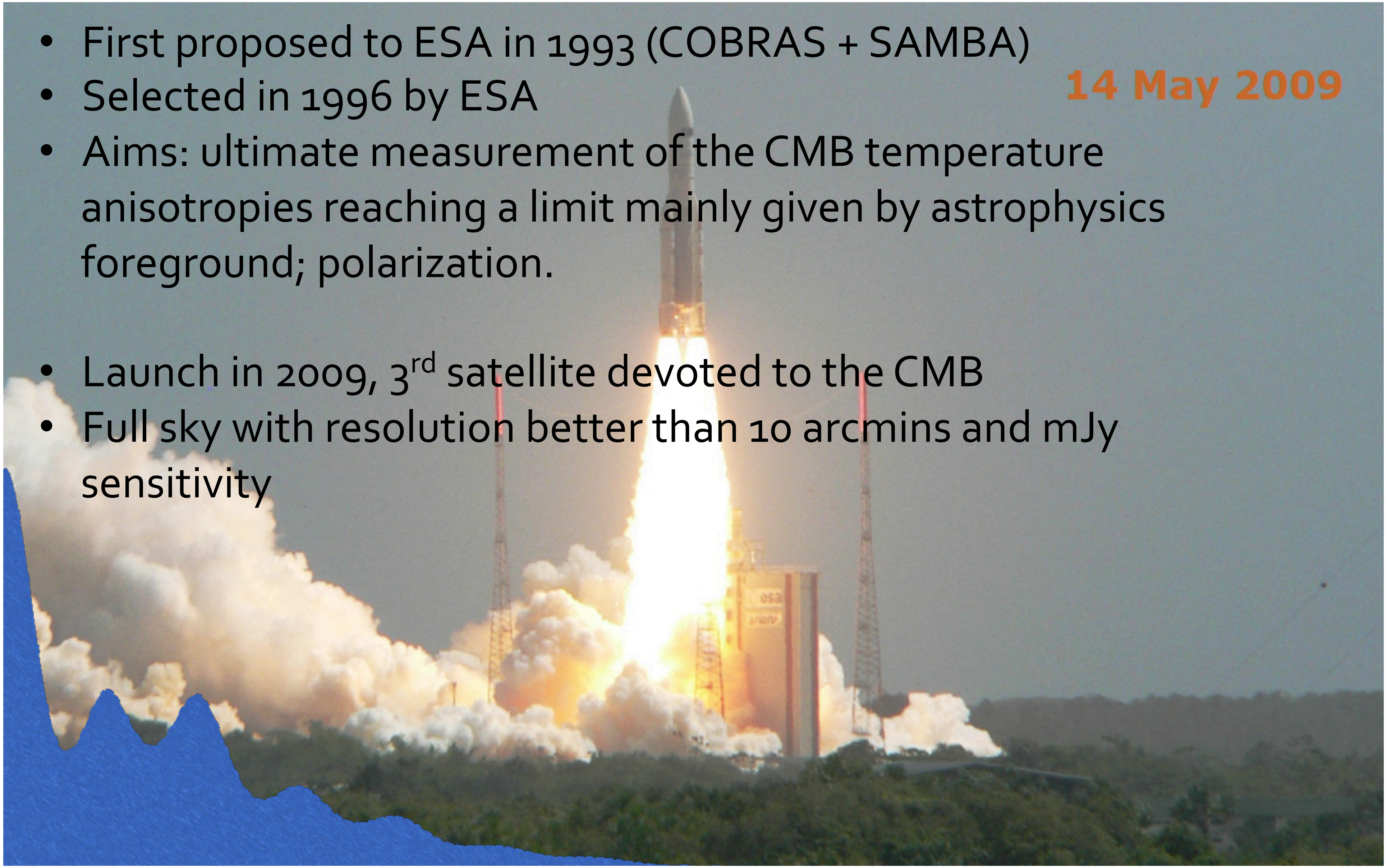
Polarization patterns defined in terms of their parity

Window to the early and late Universe



- Confirms the physics of the acoustic oscillations in the baryon-photon fluid
- Depends on the geometry and content of the Universe
- Tests early and late universe, from inflationary theories to accelerated expansion via CMB lensing or in combination with other probes.

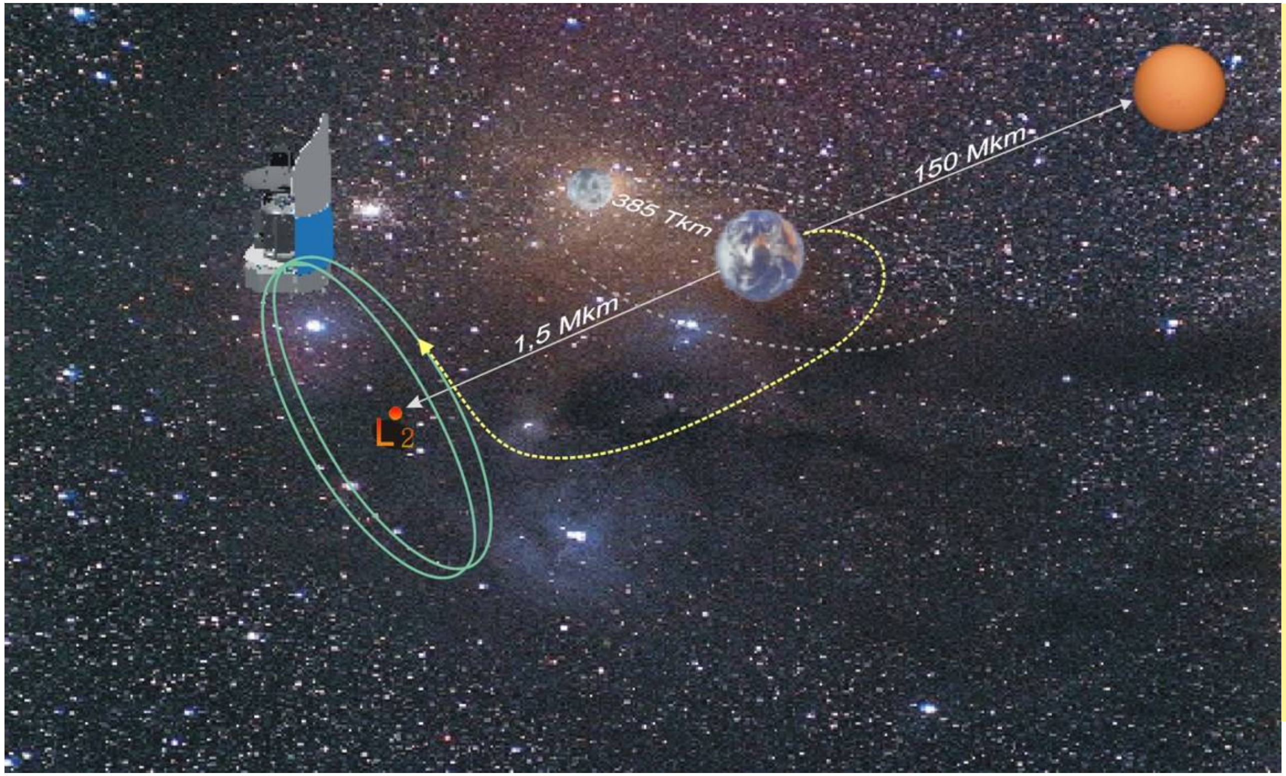
The Planck project



- First proposed to ESA in 1993 (COBRAS + SAMBA)
- Selected in 1996 by ESA
- Aims: ultimate measurement of the CMB temperature anisotropies reaching a limit mainly given by astrophysics foreground; polarization.

- Launch in 2009, 3rd satellite devoted to the CMB
- Full sky with resolution better than 10 arcmins and mJy sensitivity

14 May 2009

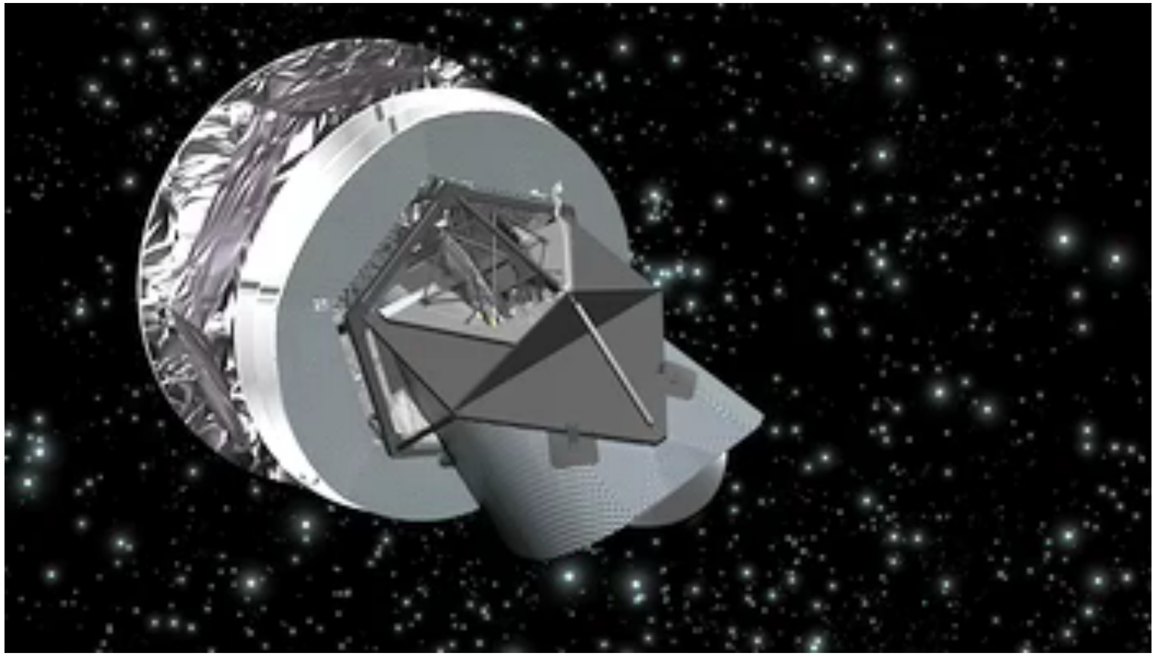


- Nominal mission completed in November 2010 (15.5 months). In practice, twice the nominal mission (full surveys: 5 HFI; 8 LFI) 12 Aug 2009 – 23 Oct 2013

2013 data release was based on the nominal mission
2015 based on full mission

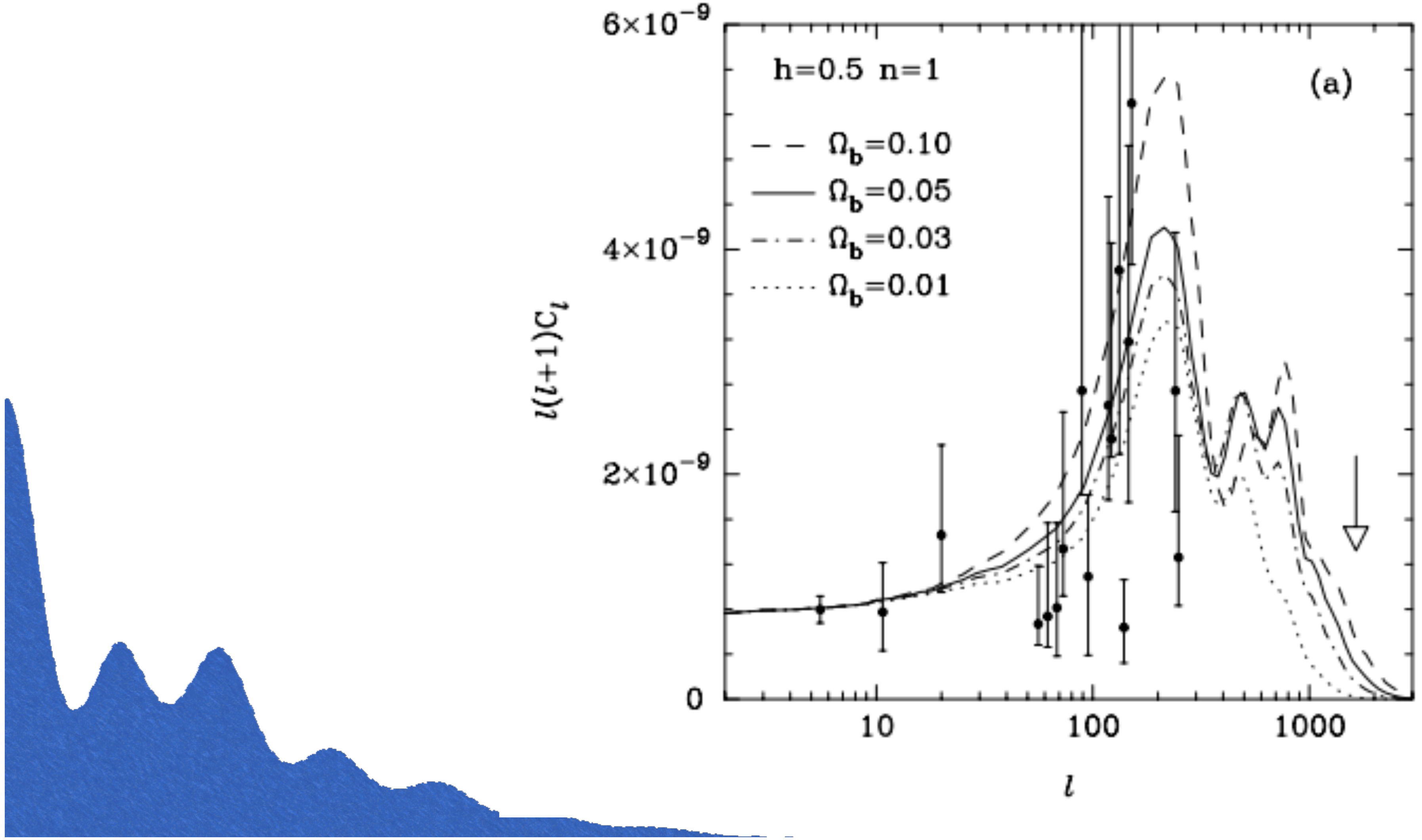
Placed in orbit around L2.
Scans the entire sky twice per year.
The spacecraft spins with 1 rotation per minute, tracing circles on the celestial sphere.

Multiple passes over same sky by each detector at each position of the axis.

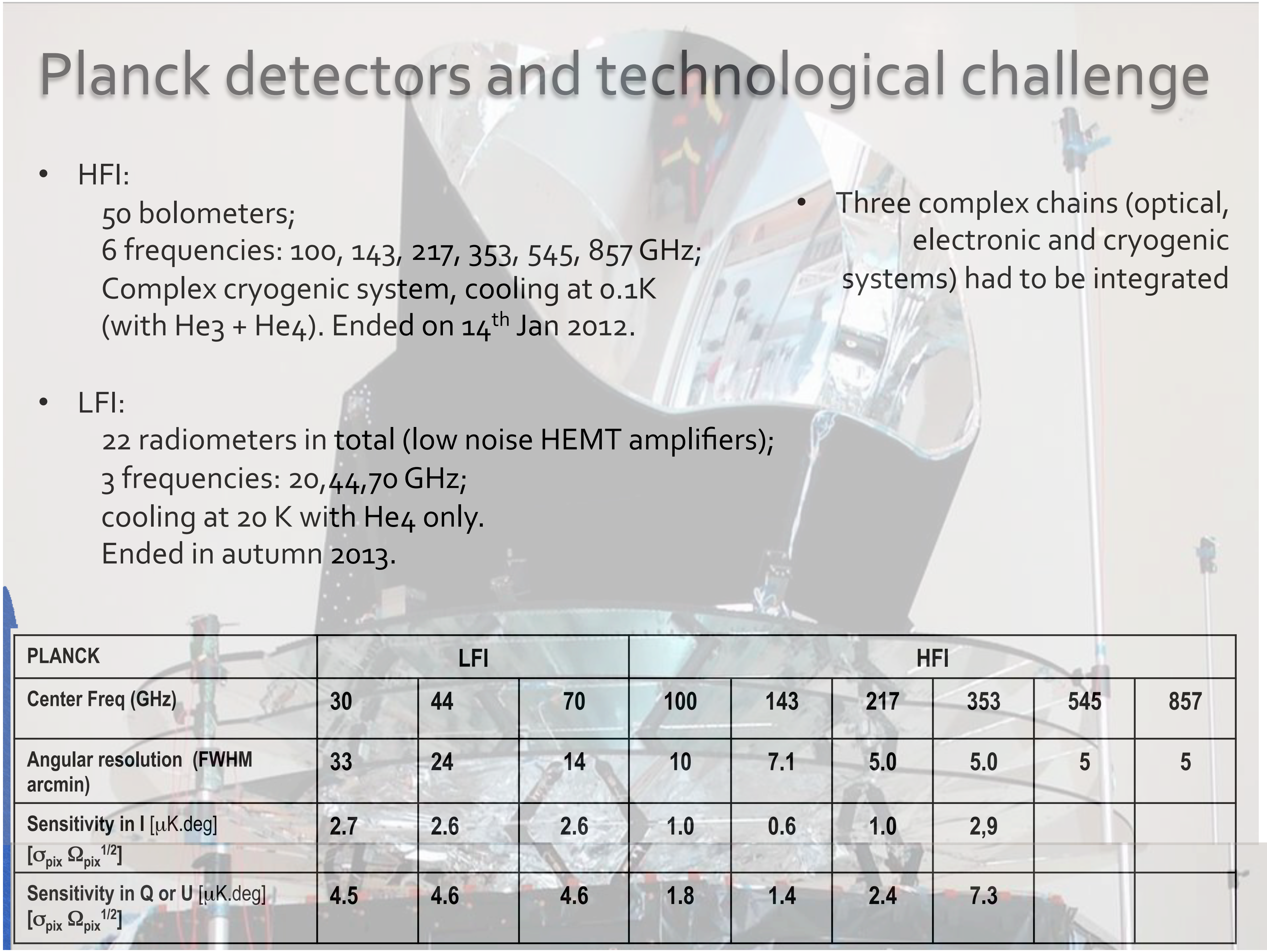


A long way to this achievement

From Planck (COBRAS/SAMBA) Redbook, 1996
http://www.rssd.esa.int/SA/PLANCK/include/report/complete.pdf



Planck detectors and technological challenge



- HFI:
  50 bolometers;
  6 frequencies: 100, 143, 217, 353, 545, 857 GHz;
  Complex cryogenic system, cooling at 0.1K
  (with He3 + He4). Ended on 14th Jan 2012.

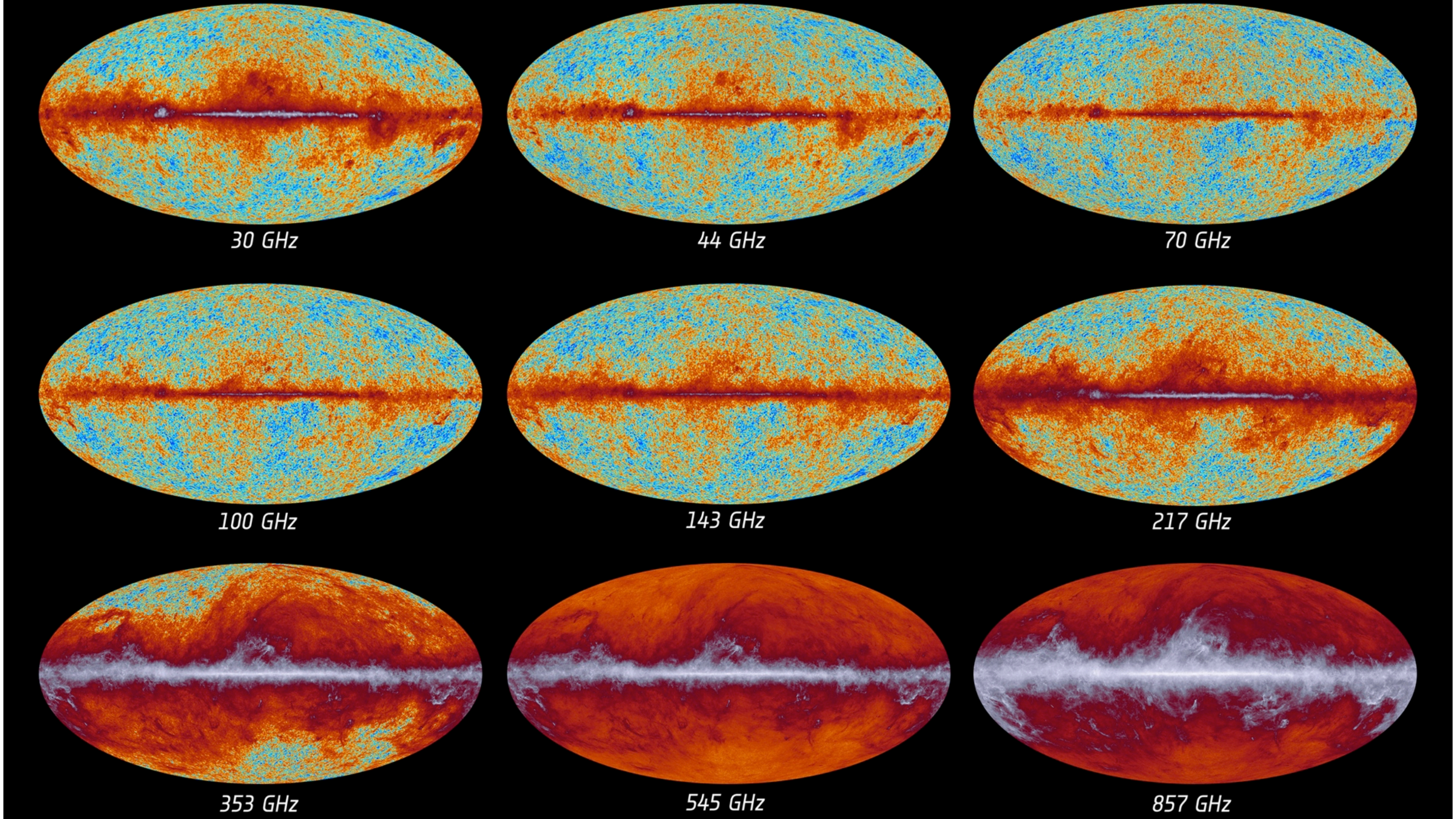
- LFI:
  22 radiometers in total (low noise HEMT amplifiers);
  3 frequencies: 20,44,70 GHz;
  cooling at 20 K with He4 only.
  Ended in autumn 2013.

- Three complex chains (optical, electronic and cryogenic systems) had to be integrated

PLANCK	LFI			HFI					
Center Freq (GHz)	30	44	70	100	143	217	353	545	857
Angular resolution (FWHM arcmin)	33	24	14	10	7.1	5.0	5.0	5	5
Sensitivity in I [μK.deg] [$\sigma_{pix} \Omega_{pix}^{1/2}$]	2.7	2.6	2.6	1.0	0.6	1.0	2,9		
Sensitivity in Q or U [μK.deg] [$\sigma_{pix} \Omega_{pix}^{1/2}$]	4.5	4.6	4.6	1.8	1.4	2.4	7.3		

The sky seen at different frequencies

Maps and data available in the Planck Legacy Archive



30 GHz

44 GHz

70 GHz

100 GHz

143 GHz

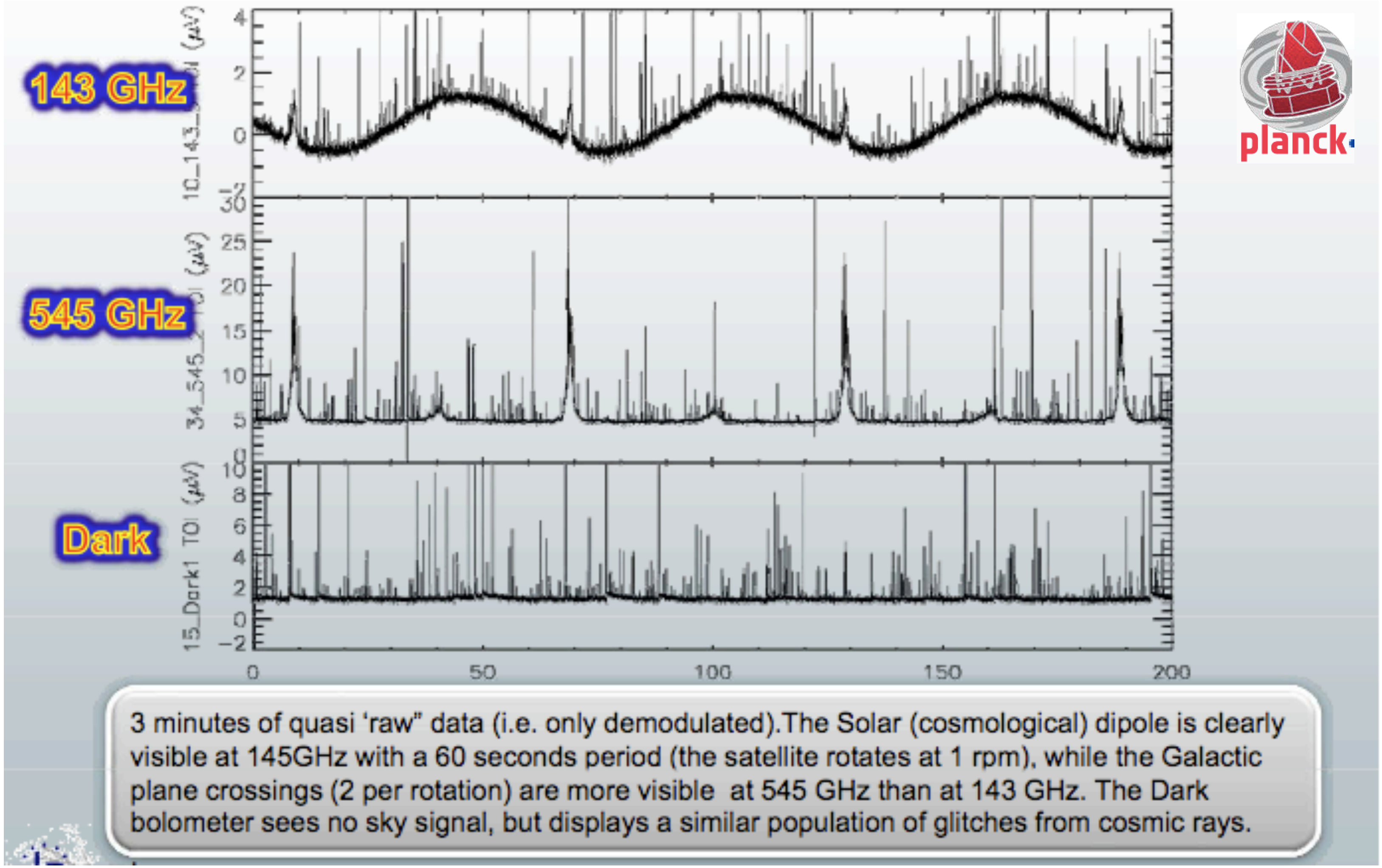
217 GHz

353 GHz

545 GHz

857 GHz

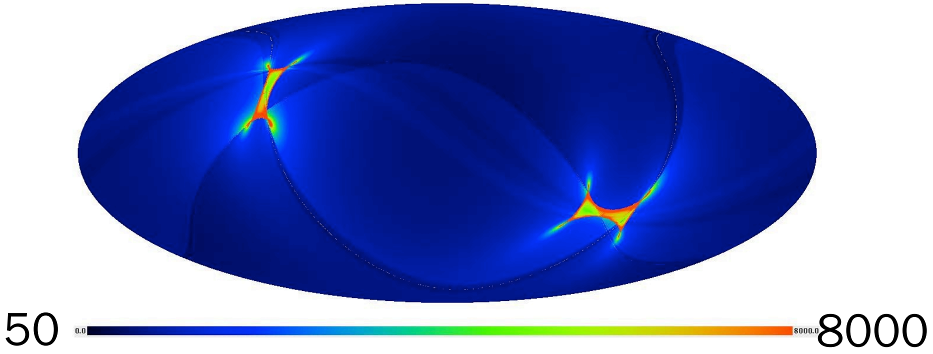
Time ordered data



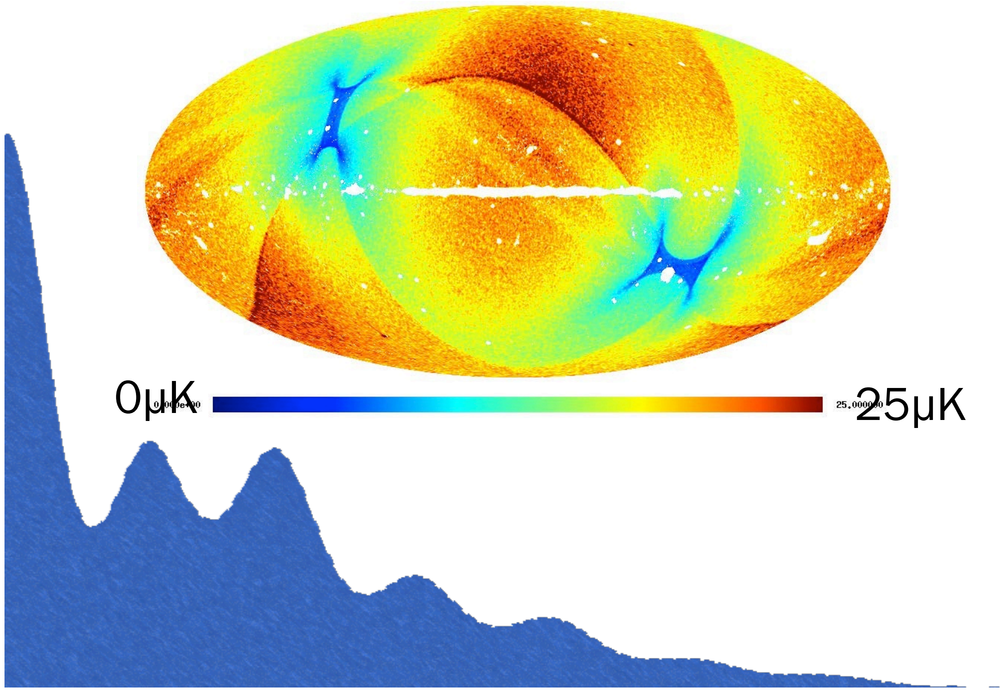
3 minutes of quasi 'raw" data (i.e. only demodulated).The Solar (cosmological) dipole is clearly visible at 145GHz with a 60 seconds period (the satellite rotates at 1 rpm), while the Galactic plane crossings (2 per rotation) are more visible at 545 GHz than at 143 GHz. The Dark bolometer sees no sky signal, but displays a similar population of glitches from cosmic rays.

From time ordered data to maps

- Correct for systematics: detector noise and response, cooling instabilities and seasonal effects, cosmic rays, pointing errors, shape of the beam, …



Map of time exposition:
for how long pixels were
observed by Planck
(in s/deg^2)



Noise map:
noise per pixel for combined map
at 5’ resolution in μK
(average: 17μK)

Not only CMB!
CMB + noise + foregrounds

Foregrounds

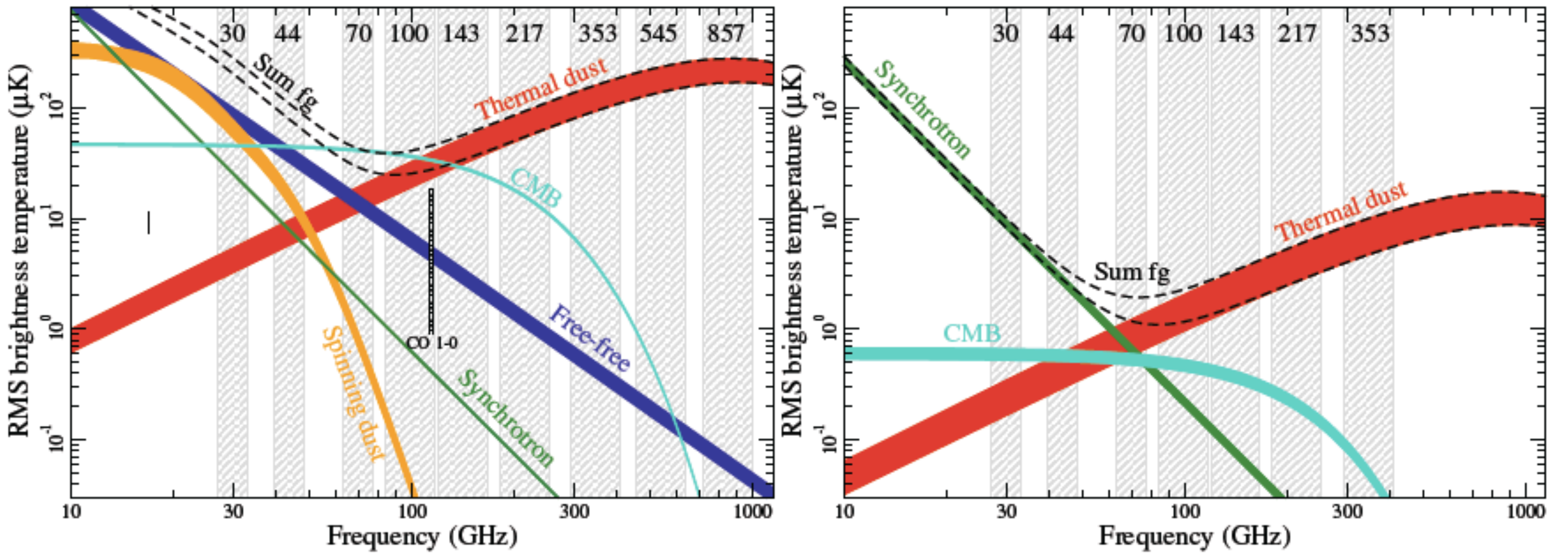


Fig. 16. Brightness temperature rms as a function of frequency and astrophysical component for temperature (*left*) and polarization (*right*). For temperature, each component is smoothed to an angular resolution of 1° FWHM, and the lower and upper edges of each line are defined by masks covering 81 and 93 % of the sky, respectively. For polarization, the corresponding smoothing scale is 40′, and the sky fractions are 73 and 93 %.

Low frequencies:

synchrotron

free-free (free electrons scattering off ions without being captured)

radio point sources;

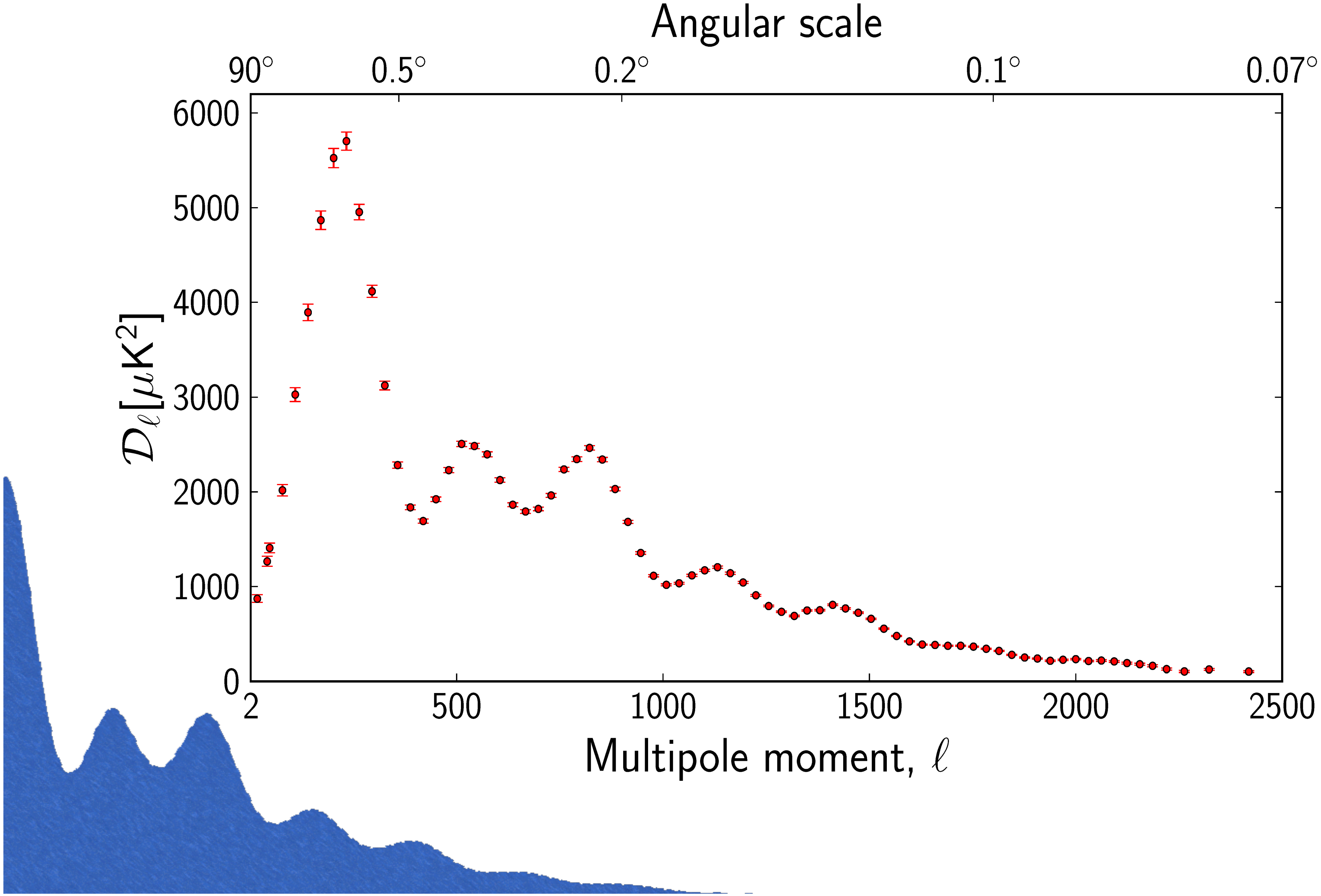
High frequencies:

Dust

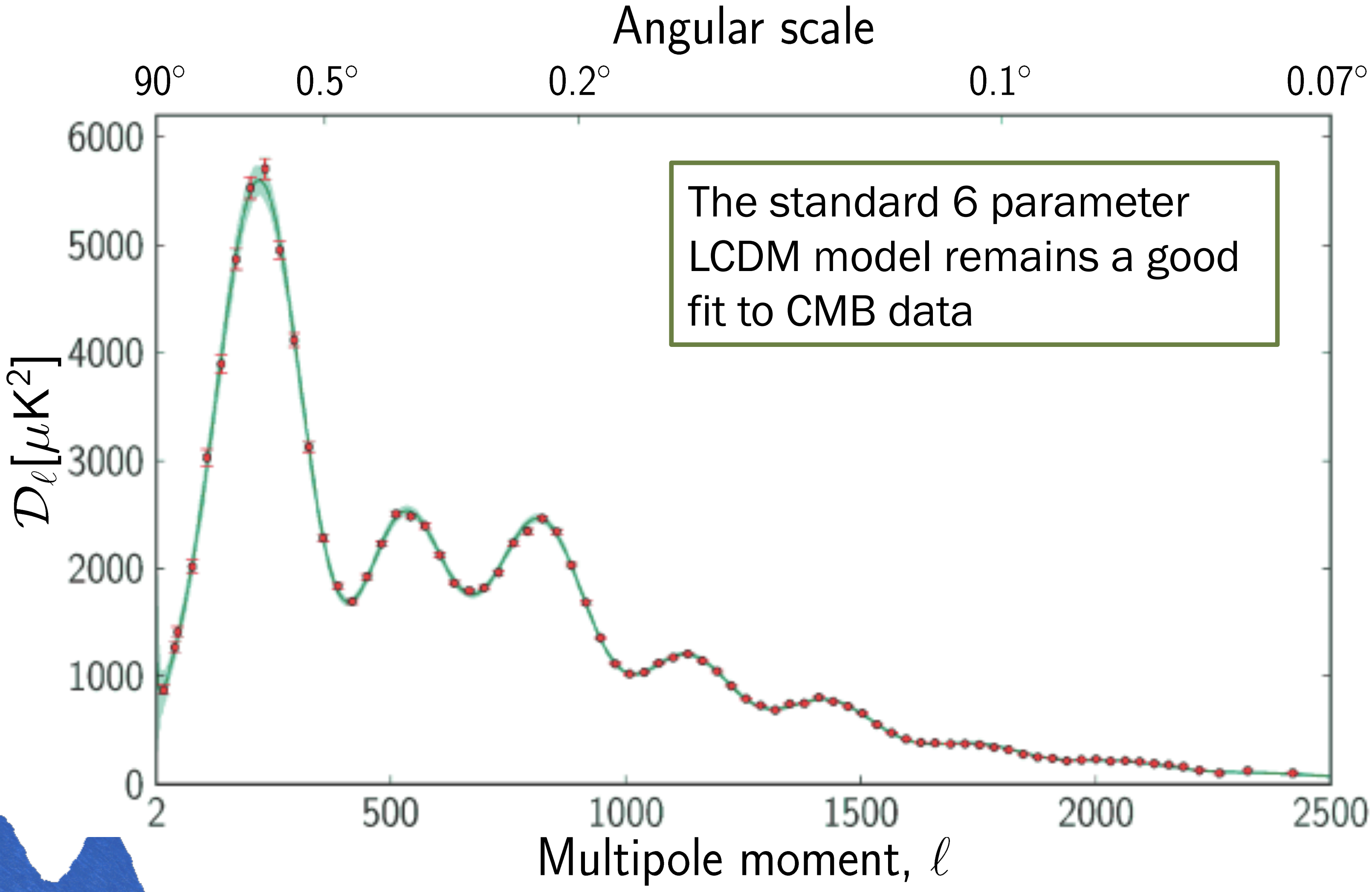
Foregrounds can be:

1. Removed (using different channels)
2. Masked
3. Fitted together with CMB spectrum

Power spectrum (2013)

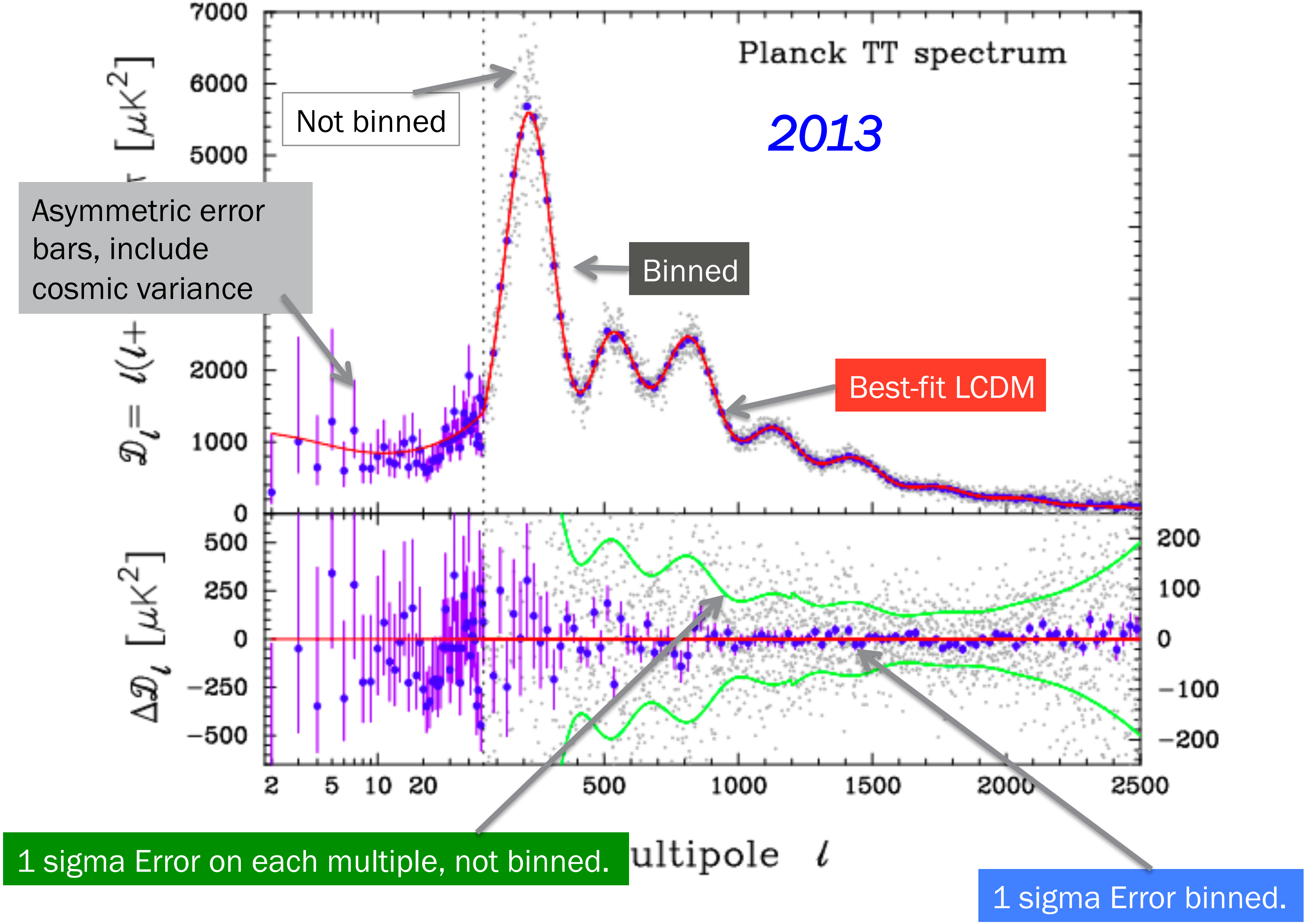


ΛCDM is a very good fit



The standard 6 parameter LCDM model remains a good fit to CMB data

Quite impressive. From terabytes of data to 6 parameters



2013

Not binned

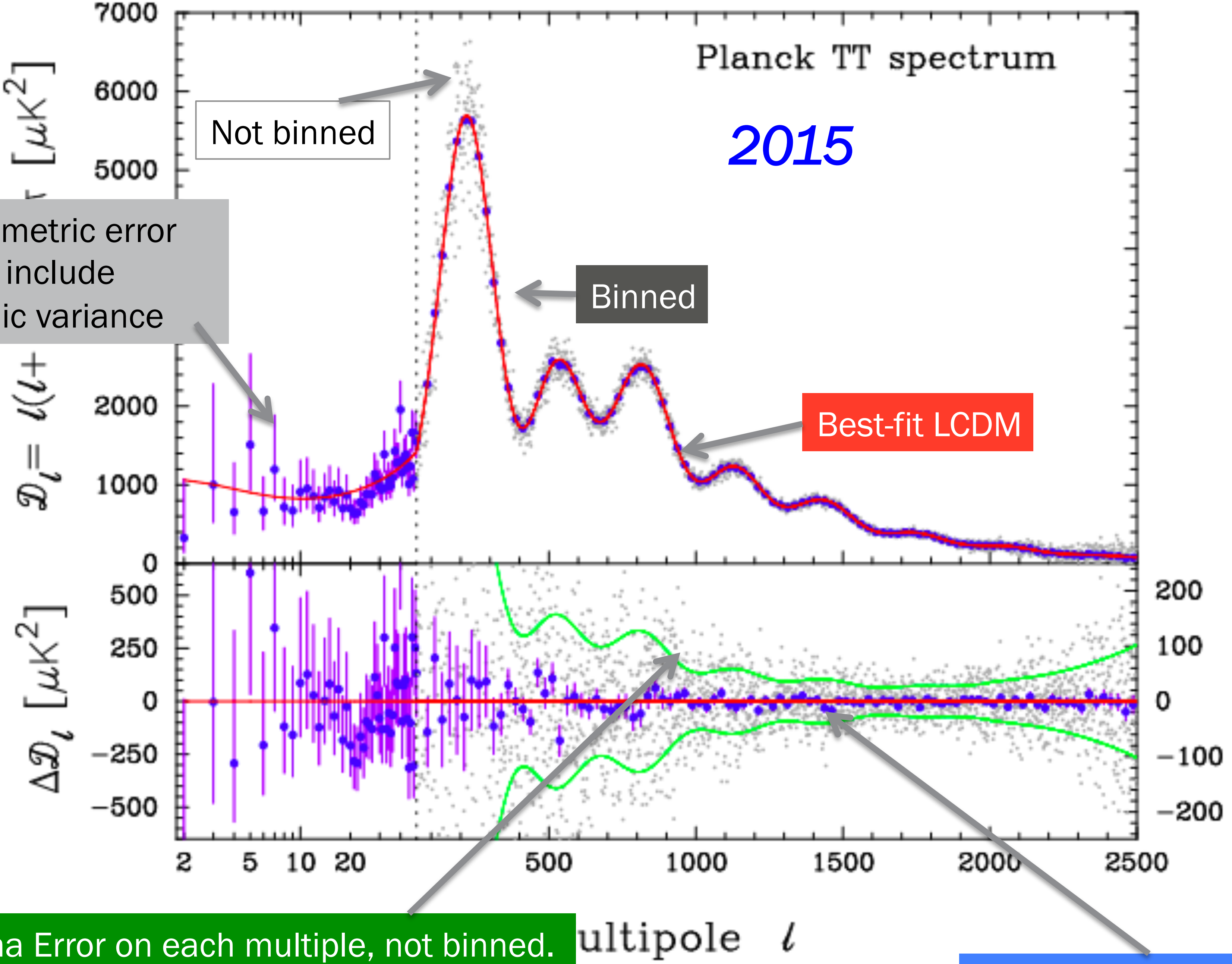
Asymmetric error bars, include cosmic variance

Binned

Best-fit LCDM

1 sigma Error on each multiple, not binned.

1 sigma Error binned.



2015

Not binned

Binned

Asymmetric error bars, include cosmic variance

Best-fit LCDM

1 sigma Error on each multiple, not binned.

1 sigma Error binned.

(1) Contents and expansion

Baryon density	$\Omega_b h^2$
CDM density	$\Omega_c h^2$
Peak position	θ ($\sim r_s/D_A$)

(2) Initial fluctuations

Amplitude at k=0.05/Mpc	A_s
Spectral index	n_s

(3) Impact of reionization

Reionization optical depth	τ

(1) Contents and expansion rate

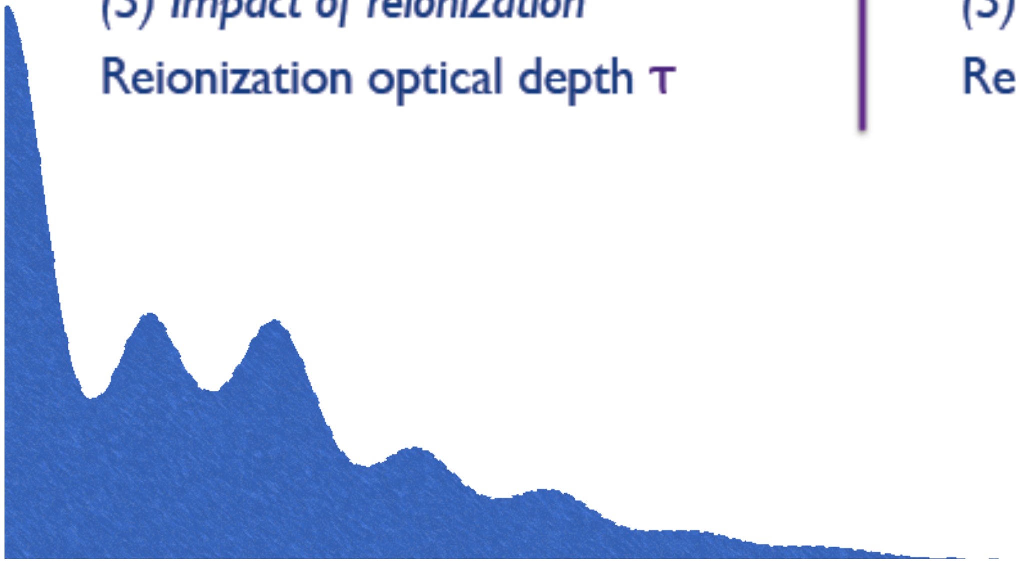
Baryon fraction	Ω_b
CDM fraction	Ω_c
Cosmol constant fraction	$\Omega_\Lambda = 1 - \Omega_b - \Omega_c$
Expansion rate	H_0

(2) Late-time size of fluctuations

Amplitude on 8 Mpc/h scales	σ_8

(3) Reionization

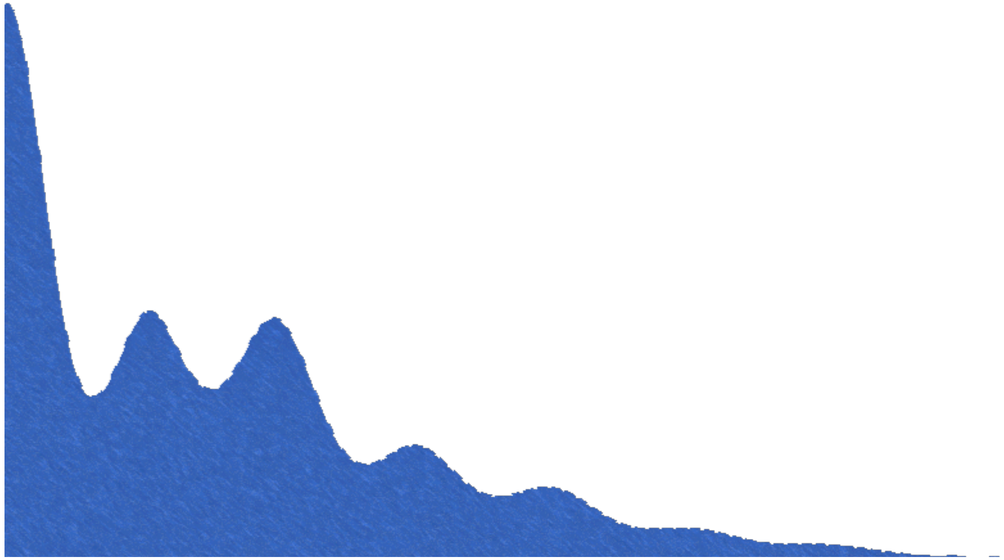
Redshift of reonization	z_{re}



J. Dunkley

New in 2015

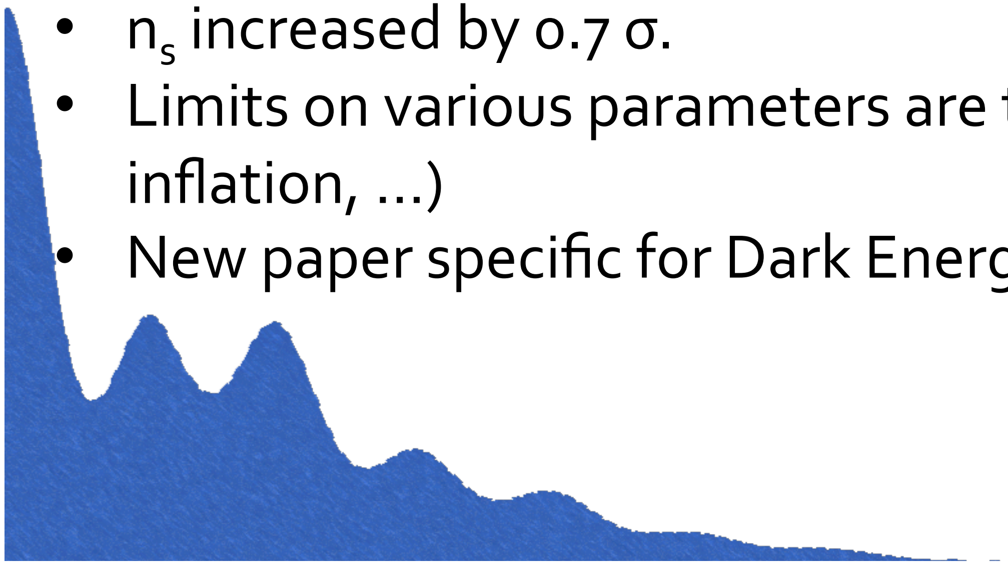
- More data (29 (HFI) and 49 (LFI) months instead of 15.5)
- Improved analysis on systematics, calibration, beams
- 10x more simulations to assess uncertainties
- Larger fraction of sky used and better foreground models (ex. dust at all frequencies)
- Detection of lensing at 40 σ
- Polarization (to be improved in 2016)



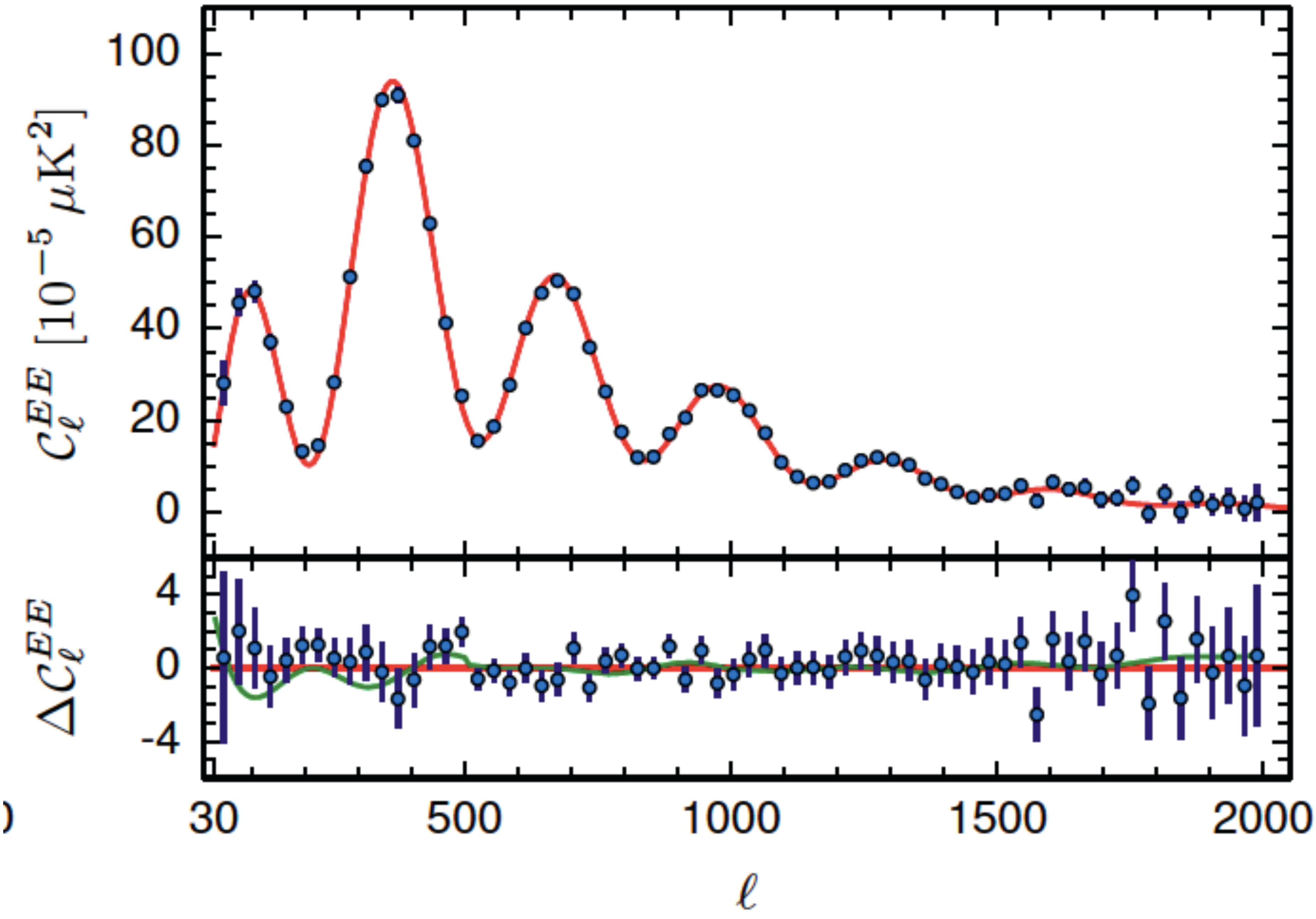
New in 2015

Overall, cosmological parameters are very similar to 2013 (changes mainly in A_s and τ). ΛCDM is still a very good fit.

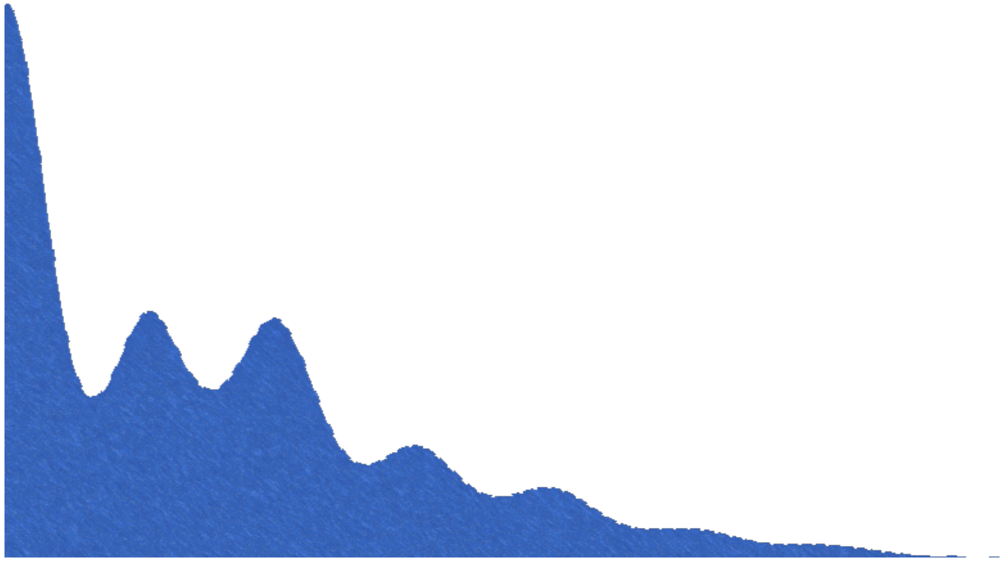
- Uncertainty reduced by a factor 2-3
- Calibration changed (increased by 0.8%). Excellent agreement among LFI, HFI, WMAP
- Optical depth (and reionization redshift) decreased of 1σ
- σ_8 is almost unchanged.
- n_s increased by $0.7\ \sigma$.
- Limits on various parameters are tighter (curvature, neutrinos, inflation, ...)
- New paper specific for Dark Energy and Modified Gravity



Red line: prediction of the model based on the temperature spectrum. Not the fit to TE data.

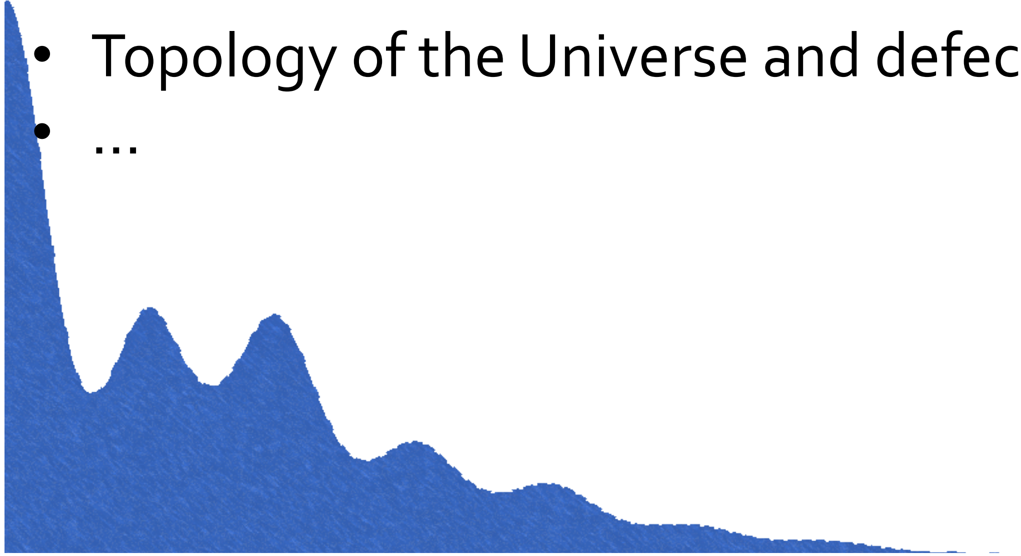


Main results



Summary list of topics

- Gravitational Lensing
- Curvature
- Dark Energy and Modified Gravity
- Neutrino masses
- Extra relativistic particles
- BBN
- Non-Gaussianity
- Spectral index
- Inflation
- Topology of the Universe and defects
- …



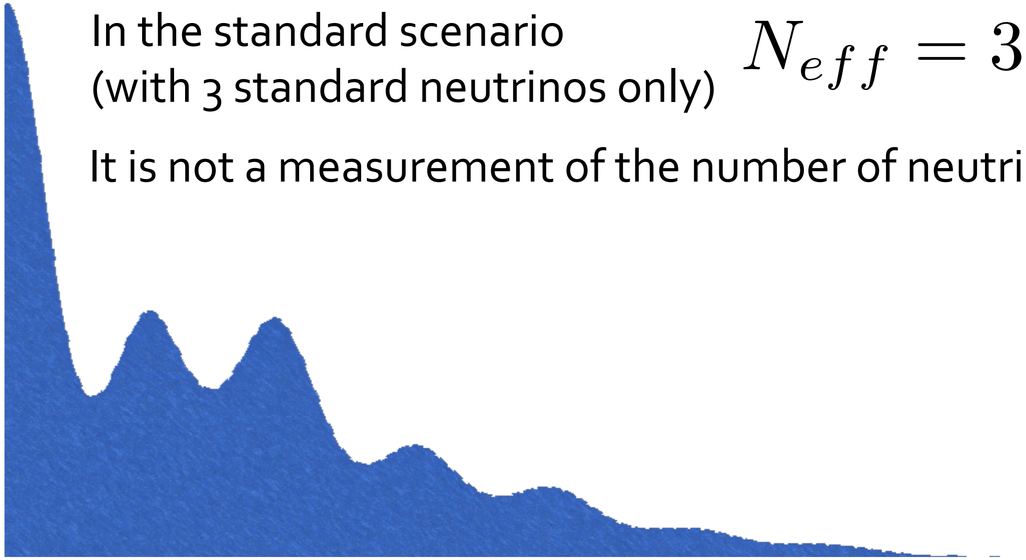
Effective number of relativistic species

N_{eff} is the density of degrees of freedom beyond photons that are relativistic during RDE. Expressed in terms of photon density:

$$\rho_r = \rho_r + \rho_\nu + \rho_x = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\right]\rho_\gamma$$

A way to measure: $\dfrac{\rho_\nu + \rho_x}{\rho_\gamma}$

Mangano etal 2002, 2005
Pastor



In the standard scenario
(with 3 standard neutrinos only) $N_{eff} = 3.046$

It is not a measurement of the number of neutrinos.

Results on N_{eff}

Compatible with 3.046

$$\begin{aligned} N_{\rm eff} &= 3.13 \pm 0.32 \quad \textit{Planck}\ \rm TT{+}lowP\,; \\ N_{\rm eff} &= 3.15 \pm 0.23 \quad \textit{Planck}\ \rm TT{+}lowP{+}BAO\,; \\ N_{\rm eff} &= 2.99 \pm 0.20 \quad \textit{Planck}\ \rm TT,TE,EE{+}lowP\,; \\ N_{\rm eff} &= 3.04 \pm 0.18 \quad \textit{Planck}\ \rm TT,TE,EE{+}lowP{+}BAO\,. \end{aligned}$$

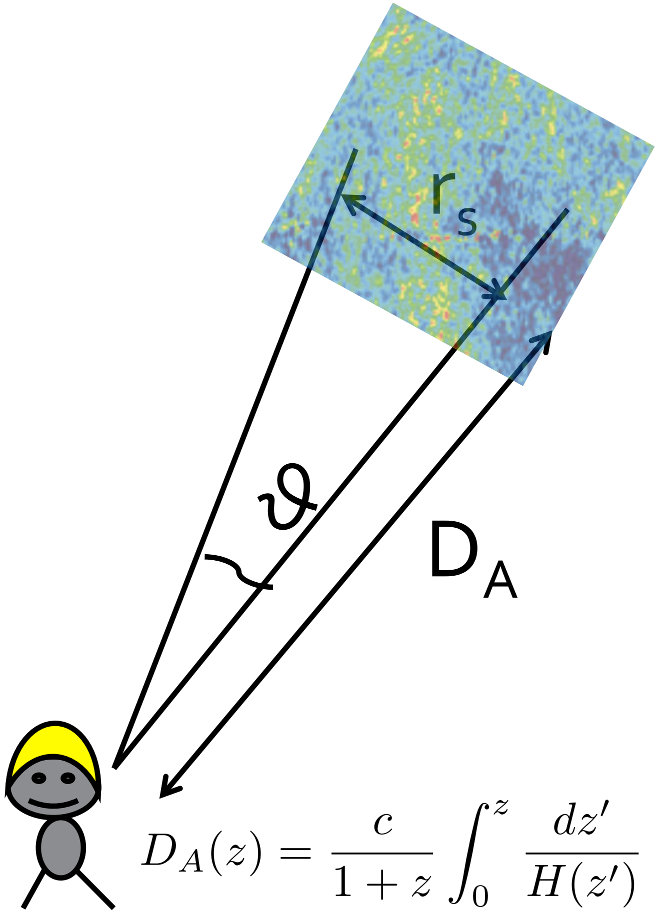
Higher N_{eff} would lead to:

-> early Universe expands faster;

-> the sound horizon at recombination is smaller (less time to travel);

-> Planck measure accurately the scale r_s/D_A
If r_s is smaller, D_A has to be smaller too to fit data;

-> Recombination is closer to us, **H_0 larger**



$$D_A(z) = \frac{c}{1+z}\int_0^z \frac{dz'}{H(z')}$$

Consistency with other data

- BBN
- Baryonic Acoustic Oscillations (BAO) ←
- Supernovae

(in very good agreement)

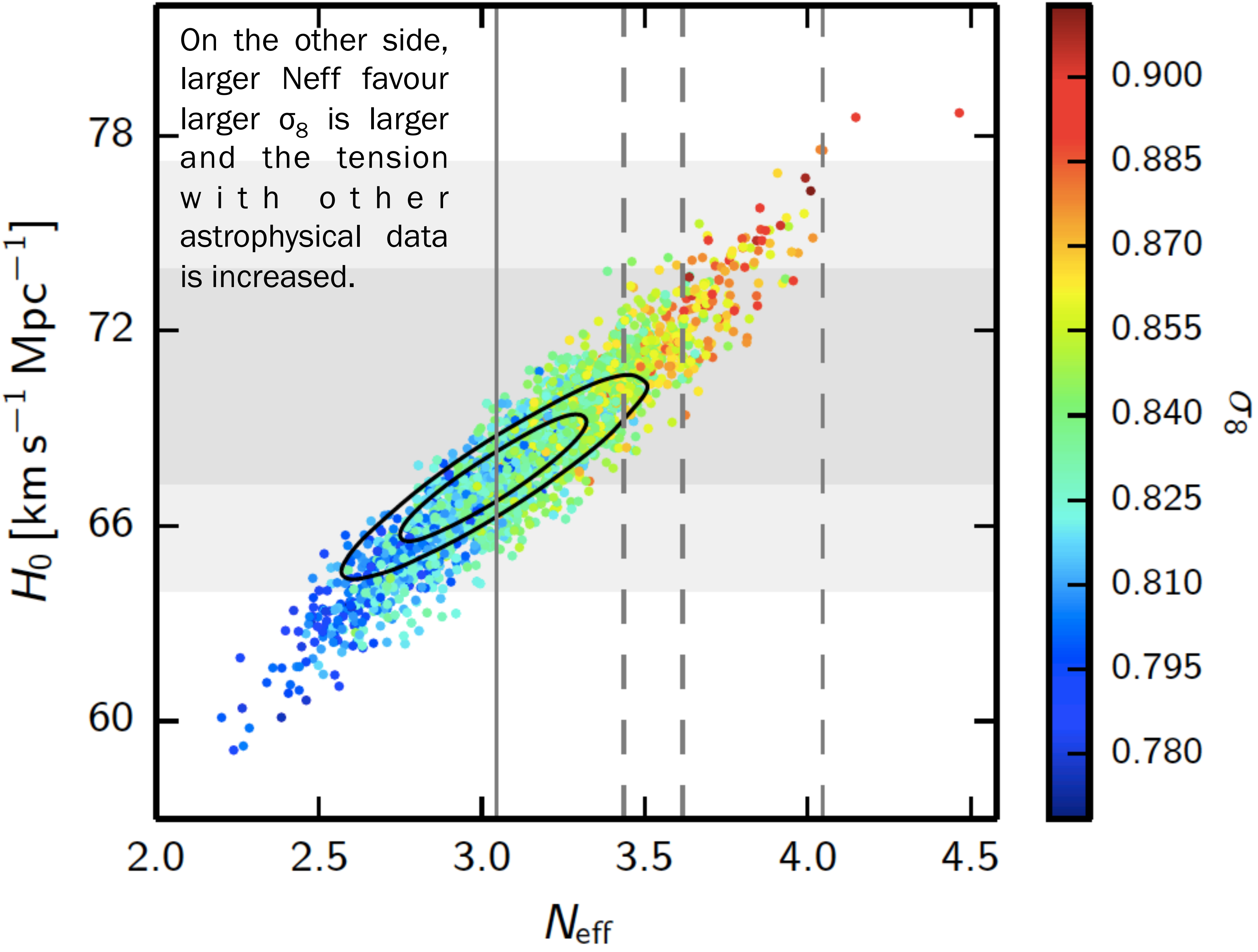
- Direct measurements of H_o (?)

Planck prefers lower H_0?

- Redshift Space distortions
- Galaxy Weak Lensing ←
- Clusters

(some possible tensions)

Planck prefers higher σ_8?



On the other side, larger Neff favour larger σ_8 is larger and the tension with other astrophysical data is increased.

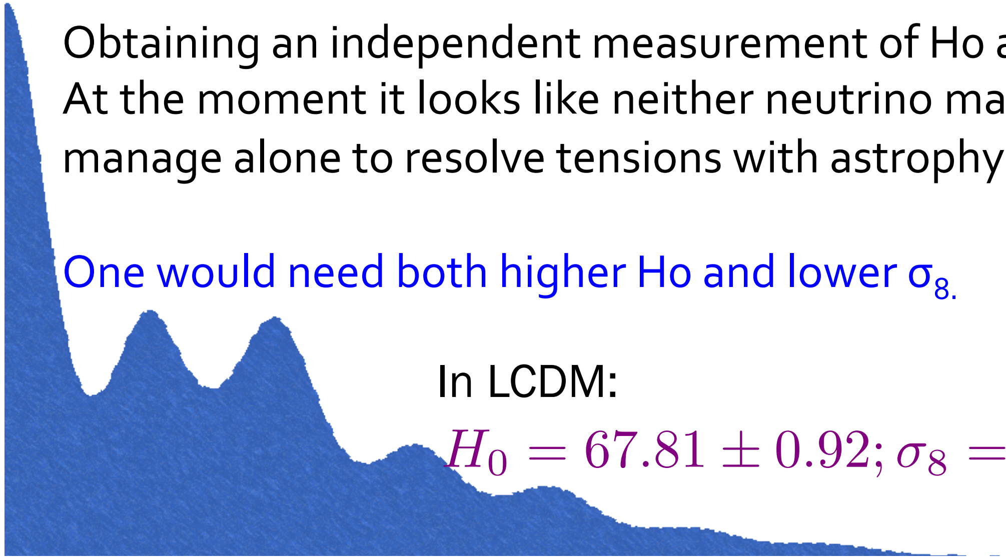
Example: $N_{\rm eff} = 3.046 + \Delta N_{\rm eff}$

$$H_0 = 70.6 \pm 1.0 \quad (68\%, \textit{Planck}\ \mathrm{TT+lowP};\ \Delta N_{\rm eff} = 0.39)$$

Higher value of the expansion than in LCDM.

$$\left.\begin{aligned} \sigma_8 &= 0.850 \pm 0.015 \\ n_s &= 0.983 \pm 0.006 \end{aligned}\right\} \textit{Planck}\ \mathrm{TT+lowP};\ \Delta N_{\rm eff} = 0.39$$

Higher σ_8 and bluer spectrum.

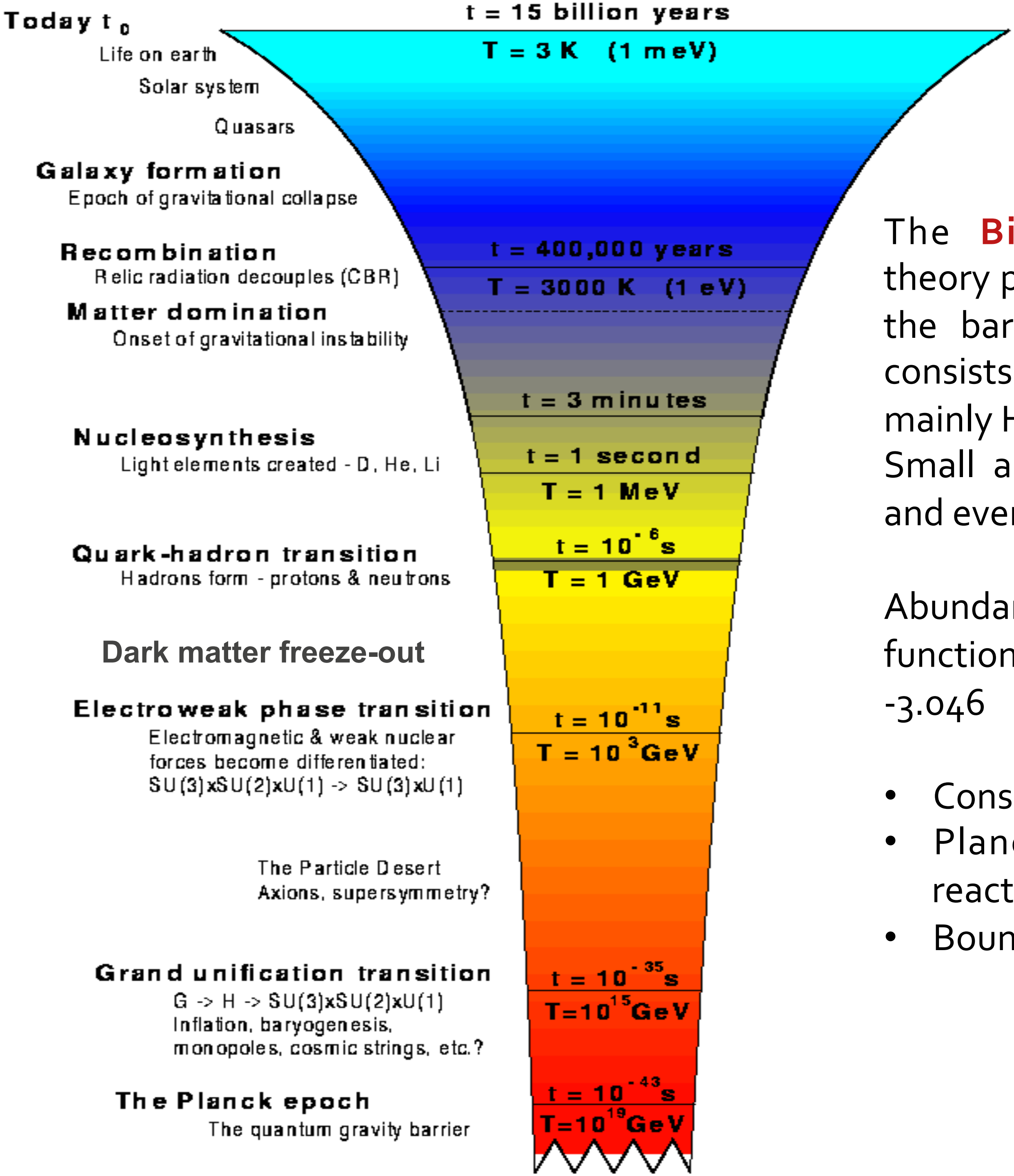


Obtaining an independent measurement of Ho and σ_8 would help to test also $N_{\rm eff}$
At the moment it looks like neither neutrino masses nor extra relativistic degrees of freedom manage alone to resolve tensions with astrophysical data sets.

One would need both higher Ho and lower σ_8.

In LCDM:

$$H_0 = 67.81 \pm 0.92; \sigma_8 = 0.8149 \pm 0.0093; n_s = 0.9677 \pm 0.0060$$



The **Big Bang Nucleosynthesis** theory predicts that roughly 24±1% of the baryonic mass of the Universe consists of He^4, with the rest made of mainly Hydrogen.
Small amounts: 0.01% of deuterium and even smaller quantities of lithium.

Abundance of light elements is a function of $\omega_b = \Omega_b h^2$ and $\Delta N_{eff} = N_{eff} - 3.046$

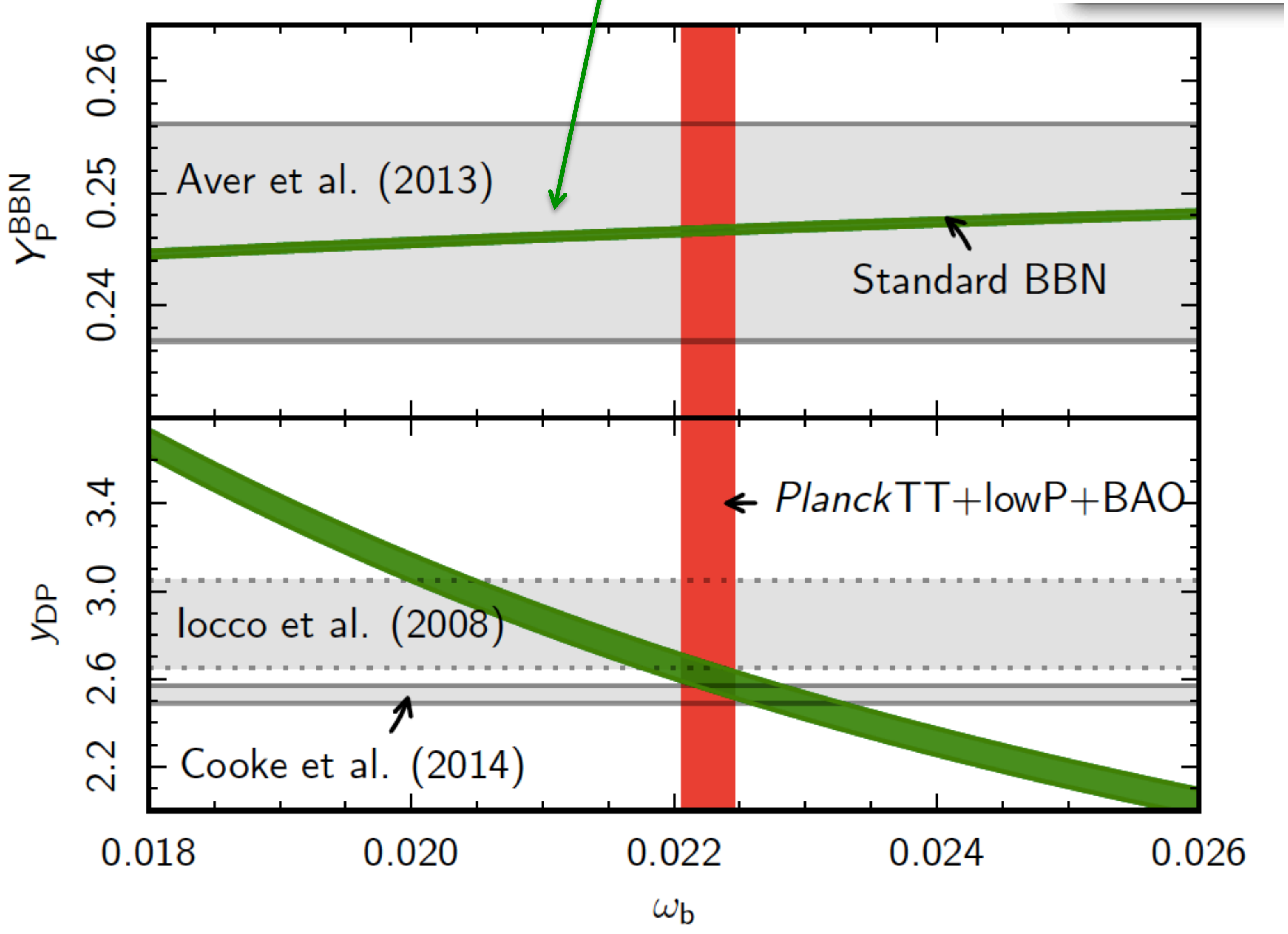
- Consistency with CMB
- Planck constraints on nuclear reaction rates
- Bounds on primordial abundances

BBN predictions for He4 and D derived using the PArthENoPE code (Pisanti etal 2008)

$Y_P^{BBN} \equiv 4n_{He}/n_b$

$Y_{DP} \equiv 10^5 n_D/n_H$

For D, theoretical errors become comparable with the ones of the CMB. Planck results can be used to investigate nuclear reaction rates.



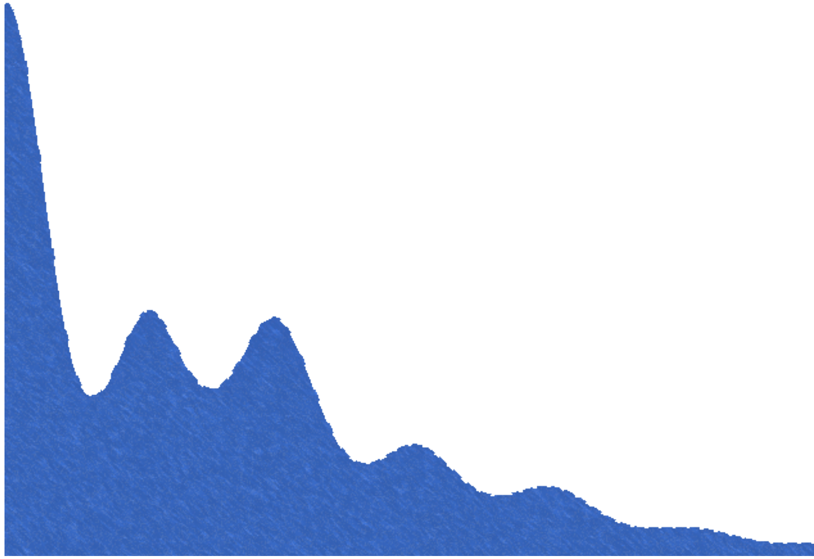
Big Bang Nucleosynthesis

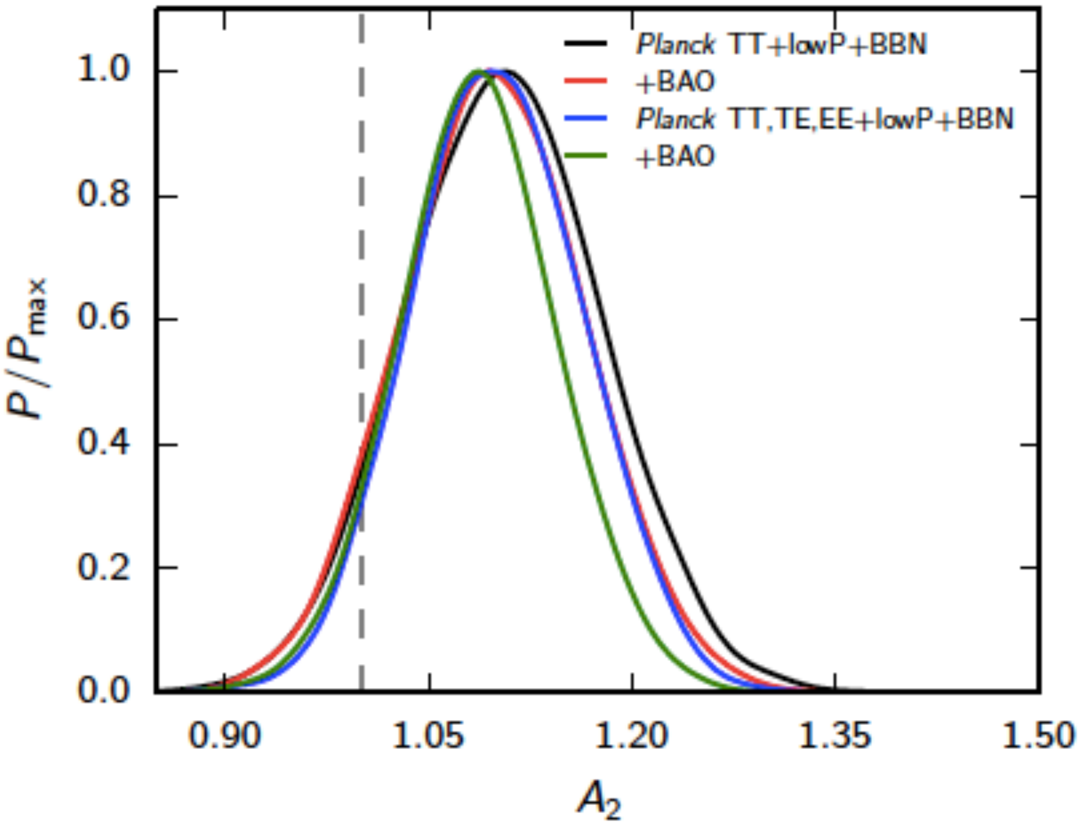
For deuterium, main uncertainty comes from process converting D into He.

Rescale the reaction thermal rate by a factor A_2 (that you would expect to be 1 if the standard value assumed in BBN was true).

Instead the peak is about 10% higher than 1.

Uncertainties in nuclear reaction rates dominate (underestimated?).

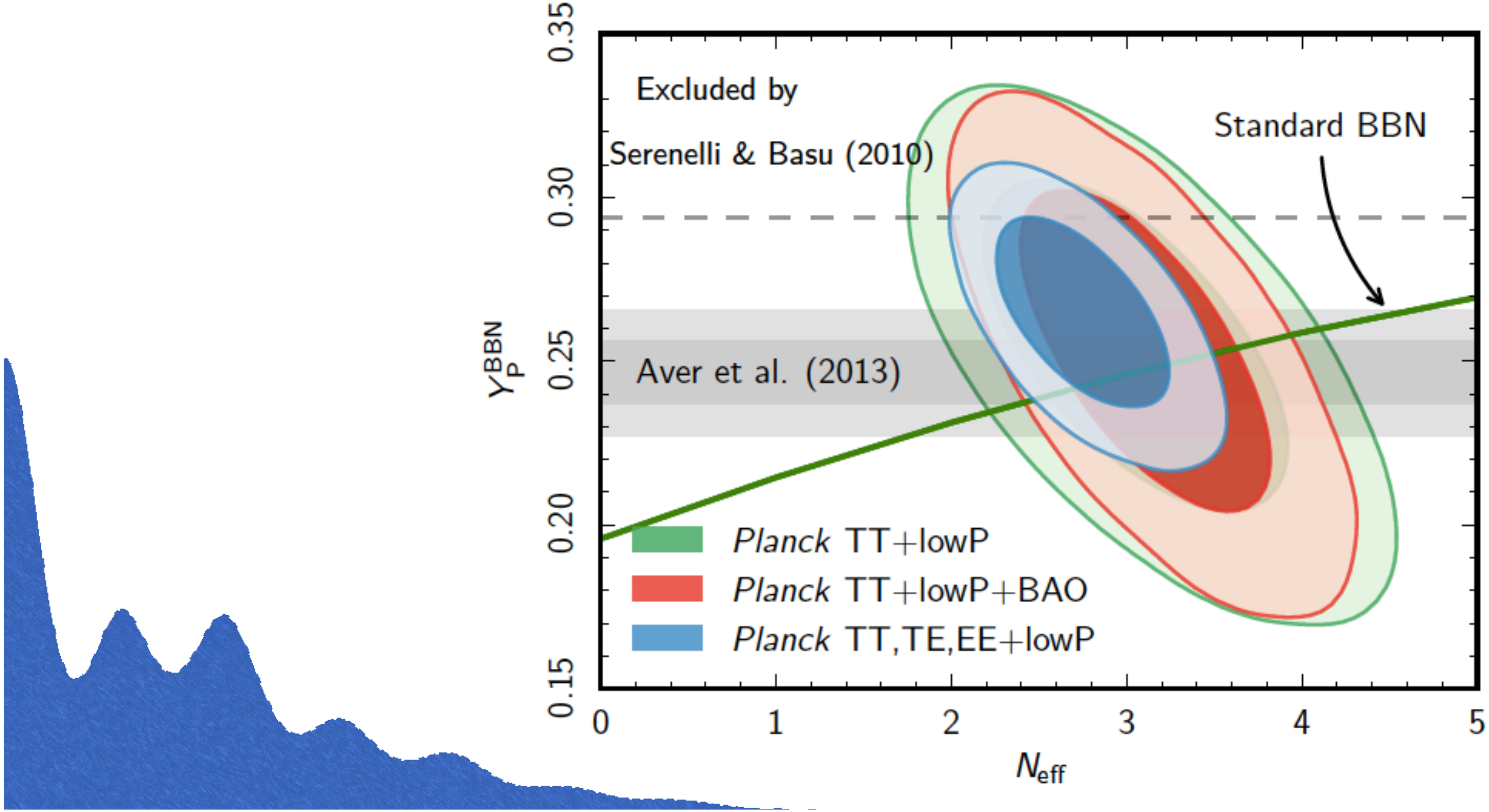




Measuring primordial abundances

Planck can also measure primordial abundances directly (rather than via ω_b and N_{eff}): they modify the density of free electrons on which photons scatter.

We allow Y_P^{BBN} to vary (fixing or not N_{eff}). Polarization reduces uncertainties.



Neutrinos and the CMB

Assume constant neutrino mass, with a Fermi Dirac distribution.

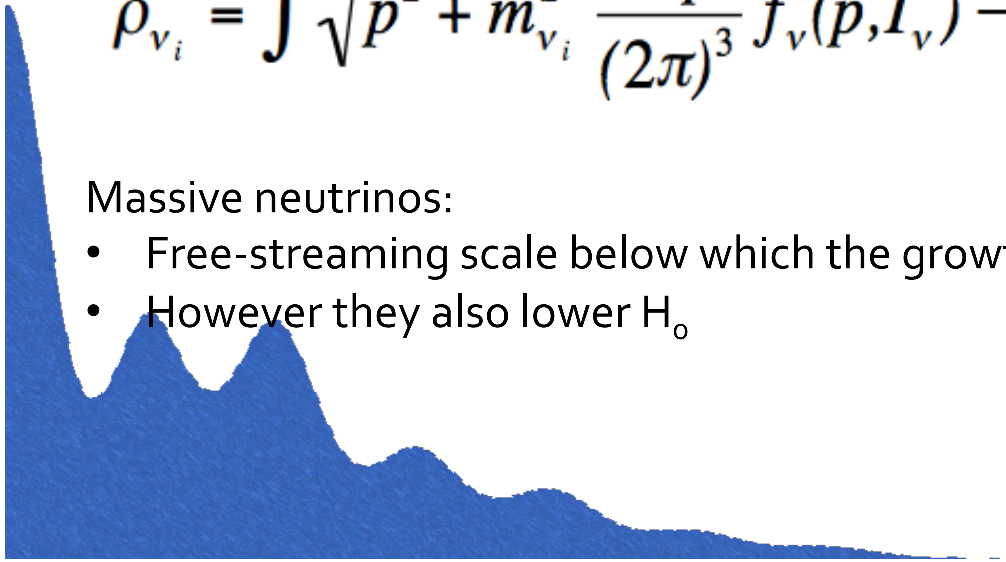
Neutrinos affect CMB:

- Enhance radiation (potentials decay more, early ISW)

Lesgourges, Mangano, Pastor ‘Neutrino Cosmology’

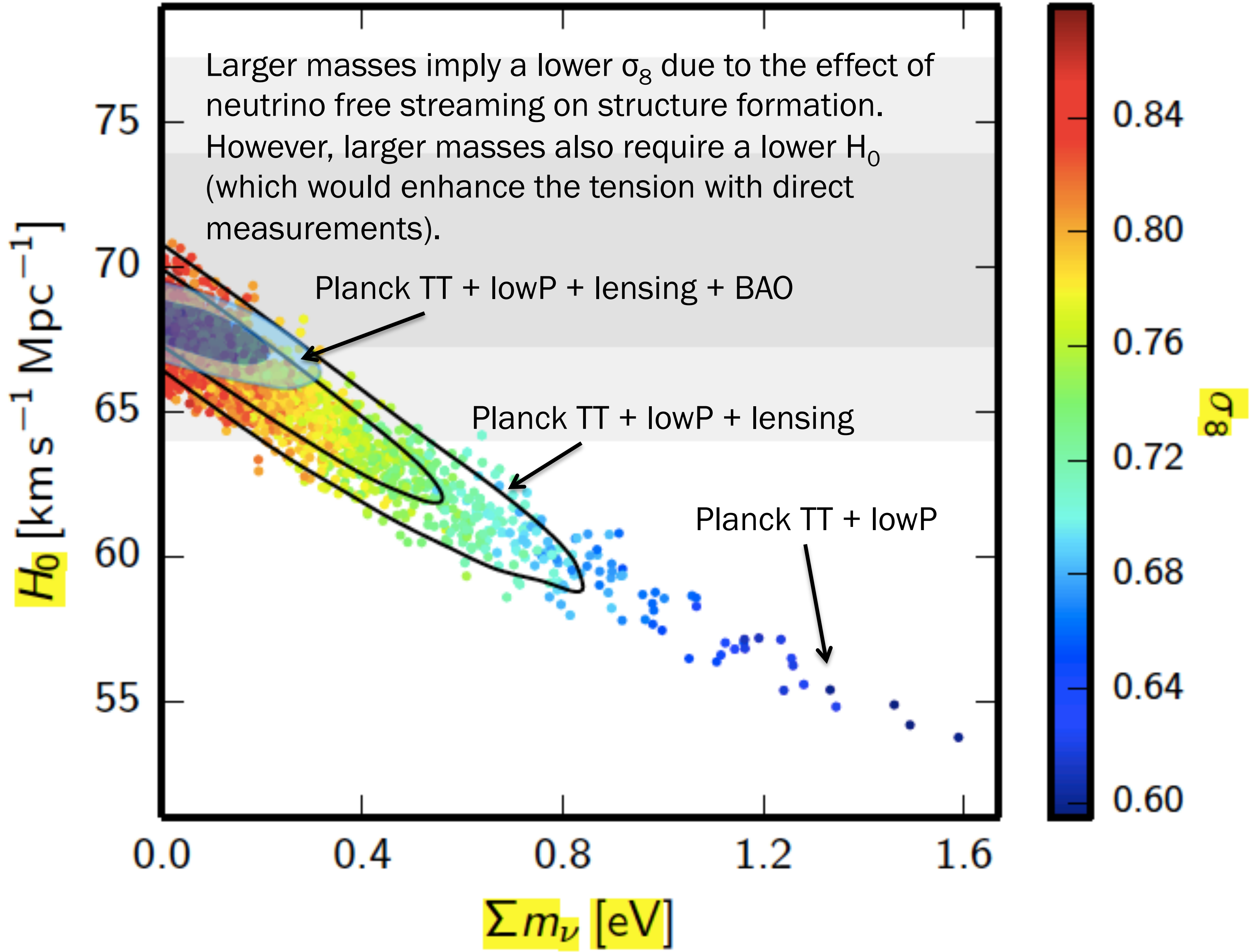
$$n_\nu = \int \frac{d^3 p}{(2\pi)^3} f_\nu(p, T_\nu) = \frac{3}{11} n_\gamma = \frac{6\zeta(3)}{11\pi^2} T^3_{CMB}$$

$$\rho_{\nu_i} = \int \sqrt{p^2 + m^2_{\nu_i}} \frac{d^3 p}{(2\pi)^3} f_\nu(p, T_\nu) \rightarrow \frac{7\pi^2}{120} \left(\frac{4}{11}\right)^{4/3} T^4_{CMB}$$



Massive neutrinos:

- Free-streaming scale below which the growth is suppressed.
- However they also lower H_o



Larger masses imply a lower σ_8 due to the effect of neutrino free streaming on structure formation. However, larger masses also require a lower H_0 (which would enhance the tension with direct measurements).

Planck TT + lowP + lensing + BAO

Planck TT + lowP + lensing

Planck TT + lowP

Neutrino perturbations

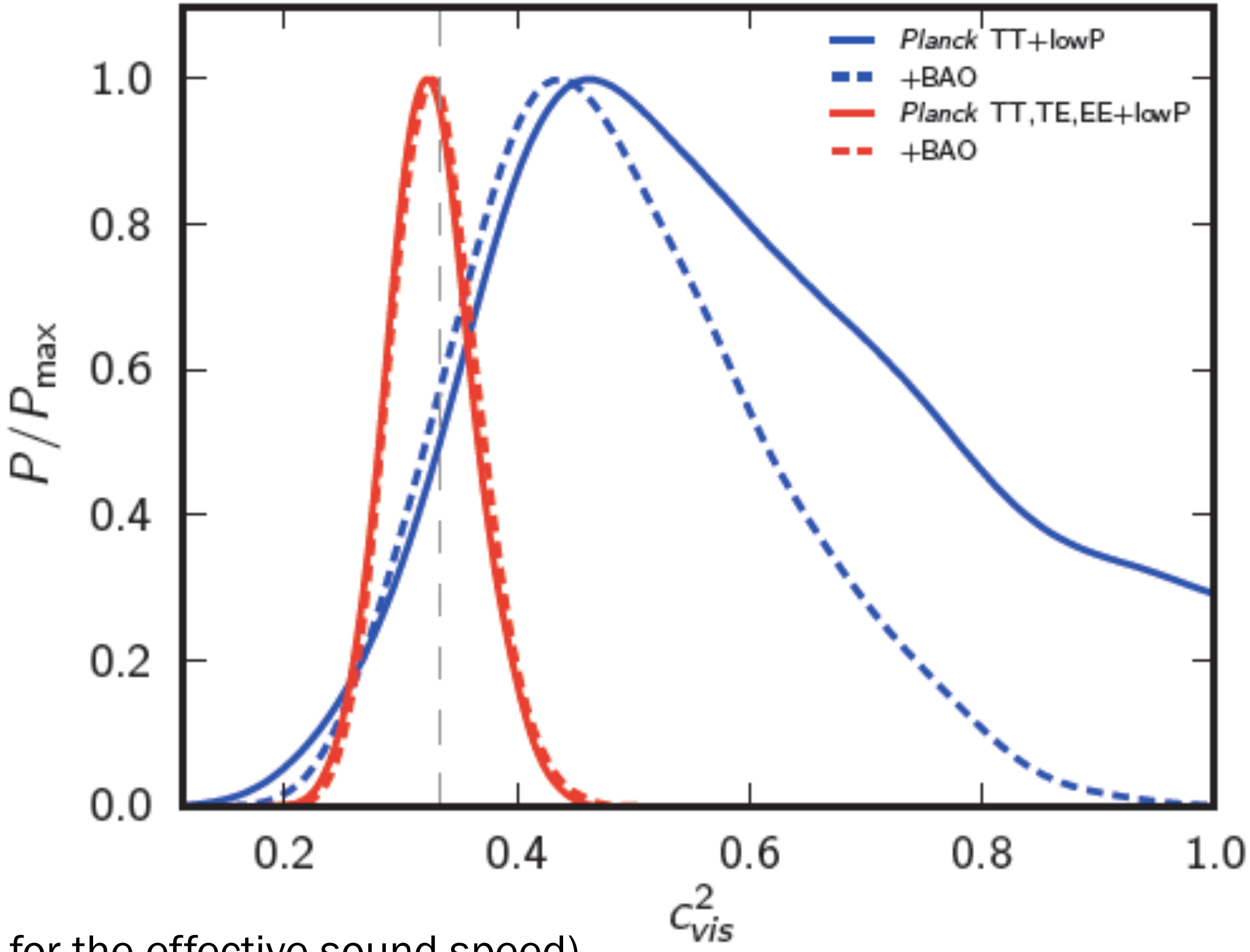
Neutrinos affect the background (changing the expansion rate, sound horizon and damping scale) and the perturbations. For massless neutrinos:

$$
\begin{aligned}
\dot{\delta}_\nu &= \frac{\dot{a}}{a}\left(1-3c_{\rm eff}^2\right)\left(\delta_\nu + 3\frac{\dot{a}}{a}\frac{q_\nu}{k}\right) - k\left(q_\nu + \frac{2}{3k}\dot{h}\right);\\
\dot{q}_\nu &= k\,c_{\rm eff}^2\left(\delta_\nu + 3\frac{\dot{a}}{a}\frac{q_\nu}{k}\right) - \frac{\dot{a}}{a}q_\nu - \frac{2}{3}k\pi_\nu;\\
\dot{\pi}_\nu &= 3k\,c_{\rm vis}^2\left(\frac{2}{5}q_\nu + \frac{4}{15k}(\dot{h}+6\dot{\eta})\right) - \frac{3}{5}kF_{\nu,3};\\
\dot{F}_{\nu,\ell} &= \frac{k}{2\ell+1}\left(\ell F_{\nu,\ell-1} - (\ell+1)F_{\nu,\ell+1}\right), \quad (\ell \geq 3).
\end{aligned}
$$

Both $c_{\rm eff}$ (neutrino sound speed) and $c_{\rm vis}$ (parameterizing the anisotropic stress and changing neutrino viscosity) expected to be 1/3

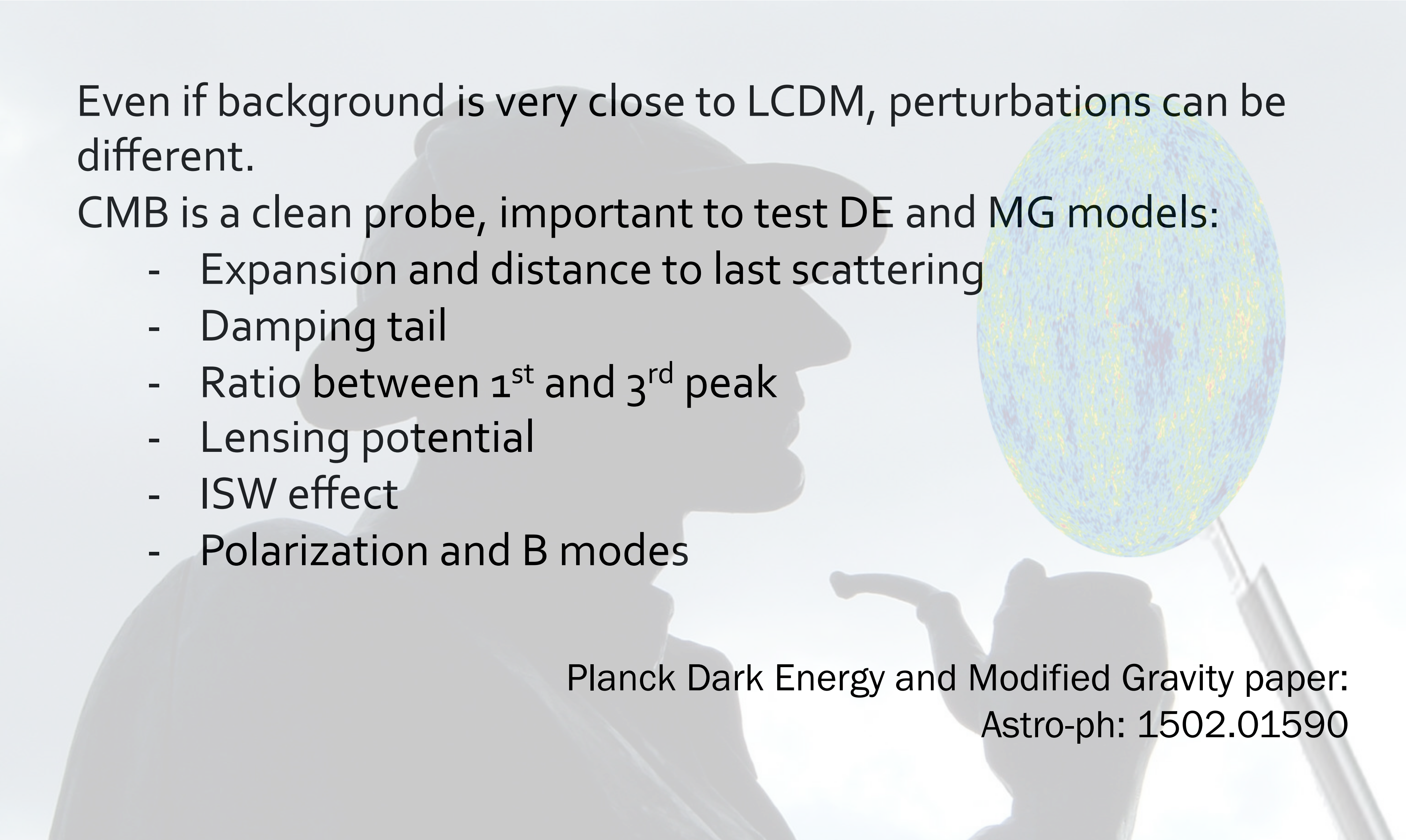
Neutrino viscosity

Polarization confirms the standard picture for neutrino perturbations.



(Analogous plot for the effective sound speed)

CMB as a probe for DE and MG



Even if background is very close to LCDM, perturbations can be different.

CMB is a clean probe, important to test DE and MG models:

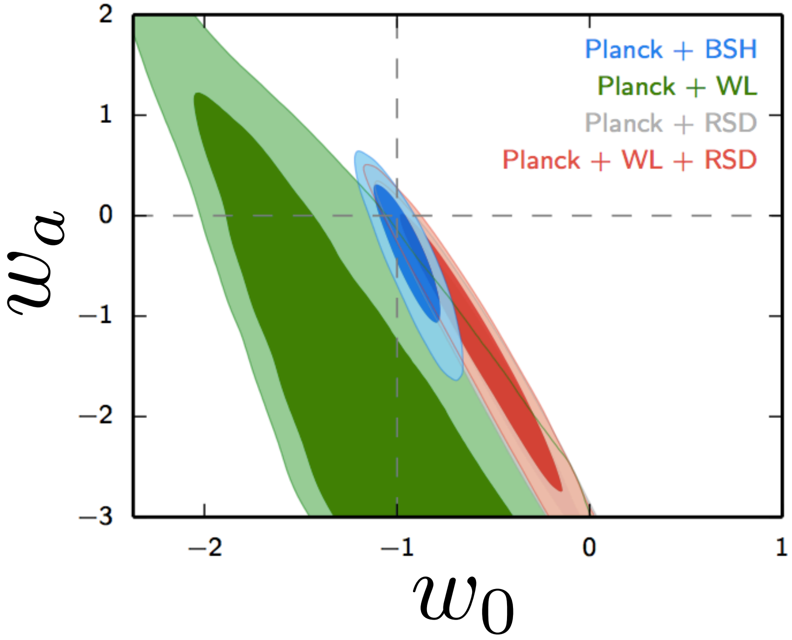
- Expansion and distance to last scattering
- Damping tail
- Ratio between 1st and 3rd peak
- Lensing potential
- ISW effect
- Polarization and B modes

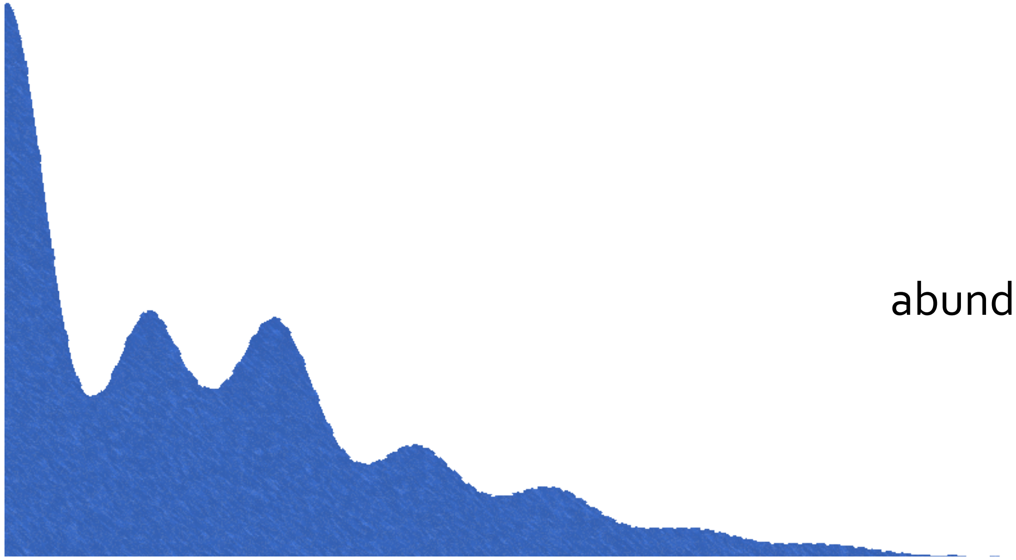
Planck Dark Energy and Modified Gravity paper:
Astro-ph: 1502.01590

Results: equation of state

$$w(a) = w_0 + (1 - a)w_a$$

Planck in agreement with LCDM.
Marginal tension when adding WL data





WL data would prefer lower matter abundance and higher expansion parameter.

Dark energy and modified gravity

2 functions of the gravitational potentials:

μ modifies the Poisson equation

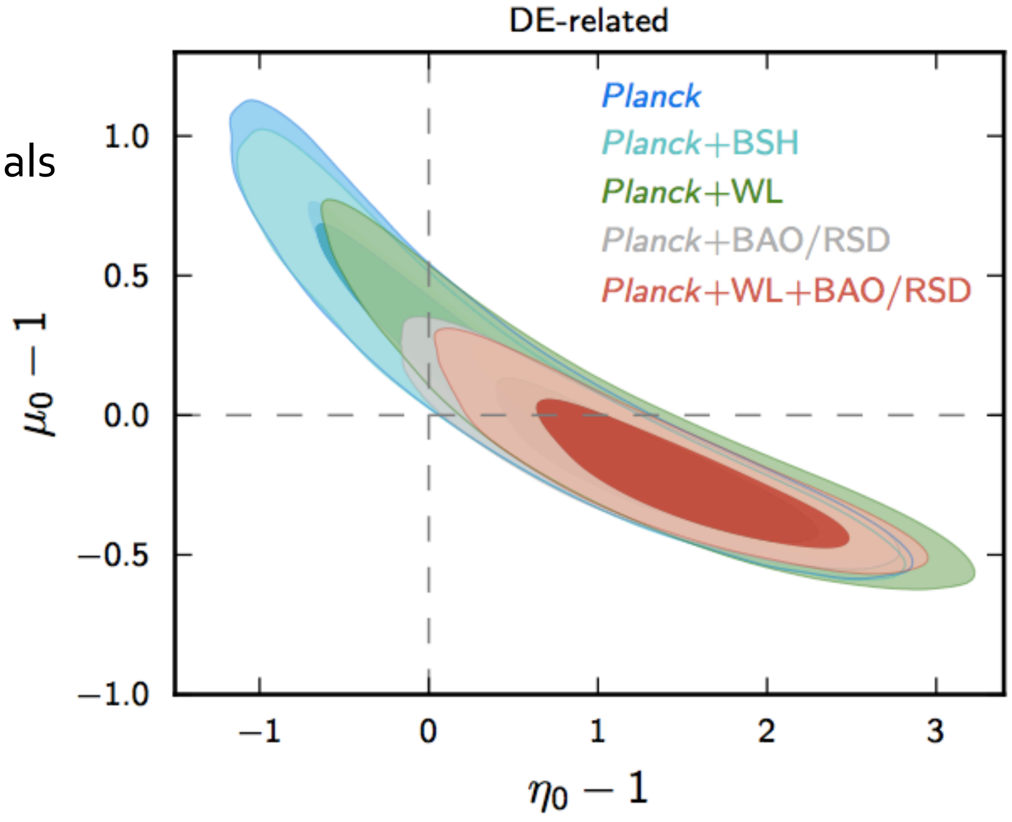
η is the ratio of the gravitational potentials

Marginal tension with LCDM when including external data sets

Closer to LCDM if we include CMB lensing

$$-k^2\Psi \equiv 4\pi G a^2 \mu(a, \boldsymbol{k})\rho\Delta$$

$$\eta(a, \boldsymbol{k}) \equiv \Phi/\Psi$$

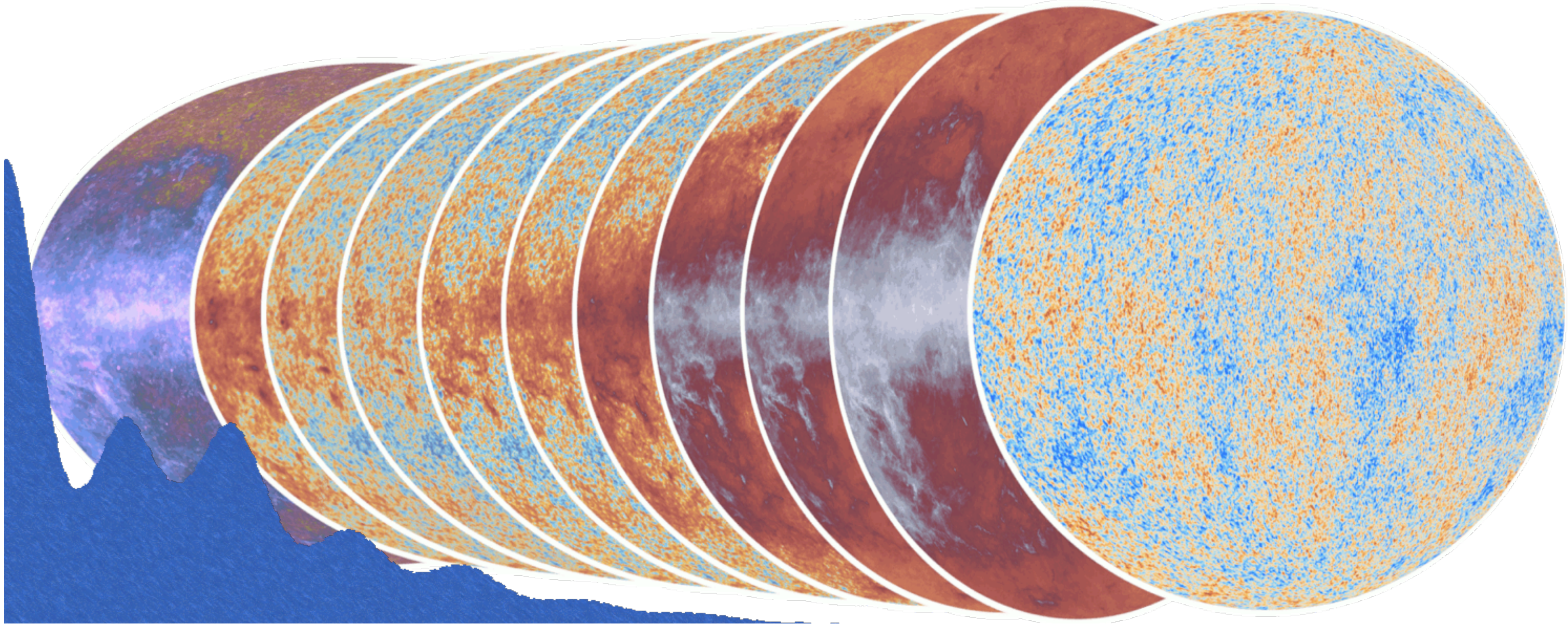


Astro-ph: 1502.01590

Conclusions

- Huge success already from a technical point of view: Planck worked without interruption for over twice the intended period and met all performance requirements

- 2015 release is in very good agreement with a LCDM model
- Things to be clarified (H_0, σ_8)



Observed and not observed.