

Neutrino HDM with PLANCK

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on behalf of the PLANCK Collaboration

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Outline

1. neutrino mass in cosmology
 - ▶ how cosmology constrains ν 's
 - ▶ current status
2. PLANCK
3. CMB lensing



Neutrino physics

1. **oscillations** late 90s : neutrinos do have mass !
2. β decay *direct* measurement : : $m_{\nu_e} \lesssim 2 \text{ eV}$
3. 2β decays : nature (Dirac/Majorana ?)
4. **cosmology** : *indirect* measurement of the absolute masss

$$M_\nu = \sum_i m_i$$

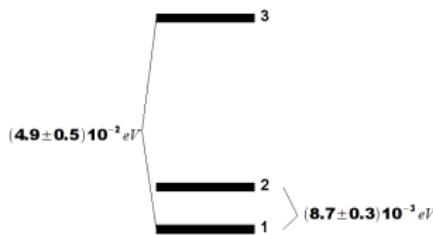
NB : I focuss on 3 "standard" massive ν 's with mixing (no chemical potential).

Neutrinos today

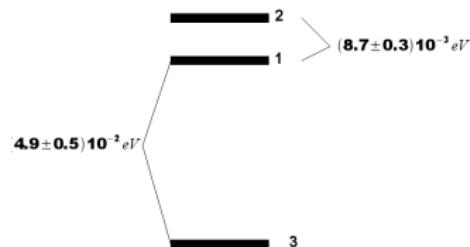
oscillations measure probabilities :

$$m_2^2 - m_1^2 = (7.67 \pm 0.22) 10^{-5} \text{ eV}^2$$
$$|m_3^2 - m_1^2| = (2.40 \pm 0.15) 10^{-3} \text{ eV}^2$$

Normal Hierarchy



Inverted Hierarchy



$$0.05 \lesssim M_\nu \lesssim 6 \text{ eV}$$

History of ν 's in cosmology

decoupling $\simeq 1$ MeV

then freezing with expansion $\langle E_\nu \rangle = 3.15 T_\nu(z)$

$T_\gamma^0 \simeq 2.7 \text{ K}$	$T_\nu^0 = \left(\frac{4}{11}\right)^{1/3} T_\gamma^0 = 1.9 \text{ K} = 1.1 \cdot 10^{-4} \text{ eV}$
$n_\gamma^0 = \frac{2\xi(3)}{\pi^2} T_\gamma^3 = 411 \text{ cm}^{-3}$	$n_\nu^0 = \frac{3}{11} n_\gamma = 112 \text{ cm}^{-3}/\text{species}$

Given oscillation results, at least 2 are non-relativistic today
i.e. contribute to **matter** budget

Can ν 's be DM ?

- ▶ **structure formation** : hot → top-down formation of galaxies
- ▶ **Tremaine-Gunn bound** : ν 's suffer *no inelastic collisions* → cannot squeeze ν -DM beyond a limit. Comparing to Galaxies core-radius+velocity dispersion → $M_\nu \gtrsim 100 - 300$ eV
- ▶ **cosmology** : $\Omega_\nu \simeq \frac{M_\nu(\text{eV})}{50\text{ eV}} \simeq 0.22 \rightarrow M_\nu \simeq 11$ eV

DM cannot be composed *solely* of ν 's. But a fraction is :

$$0.4 \lesssim f_\nu = \frac{\Omega_\nu}{\Omega_M} \lesssim 10\%$$

How does cosmology constrain M_ν ?

CMB direct effect

Information in the CMB if NRT was before decoupling :

$$M_\nu > 3.15 T_{\text{dec}} \simeq 1.8 \text{ eV}$$

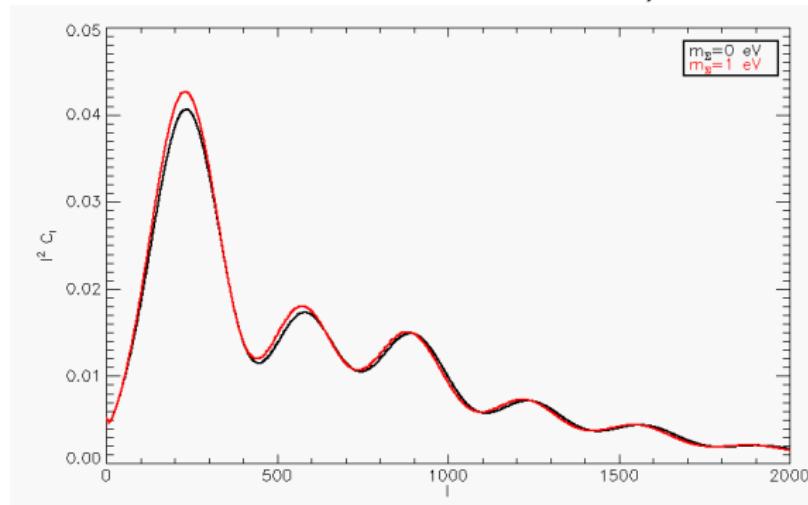
Actually transition not so sharp :

- ▶ WMAP-7 : $M_\nu < 1.3 \text{ eV}$
- ▶ CMB-alone data fit (C_ℓ) cannot do better (PLANCK)
- ▶ not true if we add CMB lensing...

CMB indirect (background) effect

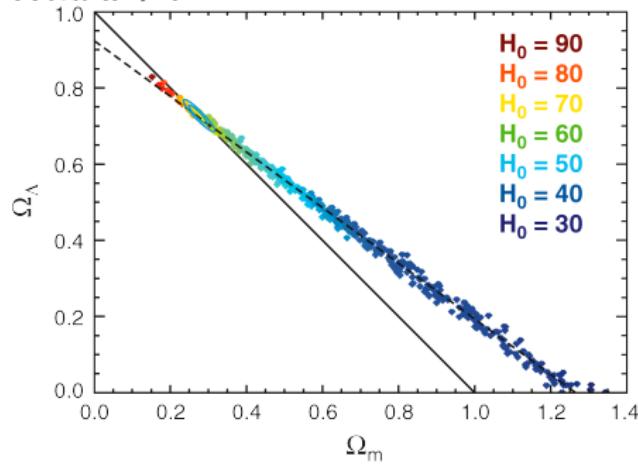
$$a_{eq} = \frac{\Omega_r^0}{\Omega_m^0} \rightarrow \frac{\Omega_r^0}{(1 - f_\nu)\Omega_m^0}$$

f_ν modifies the moment of matter-radiation equality (hence the developpment of acoustic oscillations)



f_ν degeneracies

CMB geometrical degeneracy
WMAP7 :

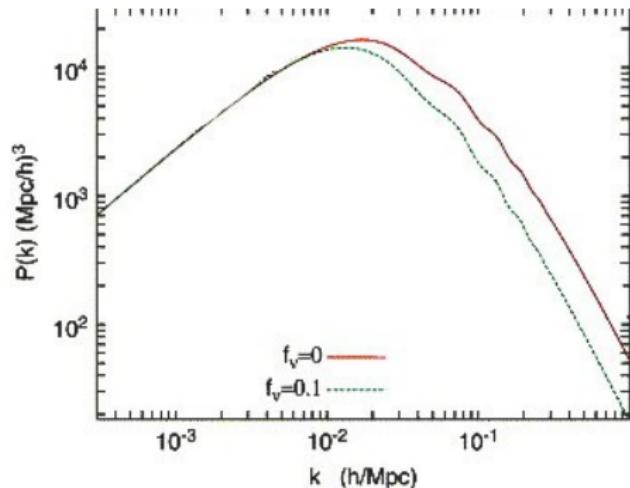


- ▶ $a_{\text{eq}} = \frac{\Omega_r}{(1 - f_\nu)\Omega_m}$
- ▶ need to **pinpoint** Ω_m (break this degeneracy) to get f_ν :
- ▶ needs a *combined fit* with : H_0 , BAO, SN, CMB – lensing...

Large scale structures

ν is HDM : cannot cluster below Jeans length **free streaming**

$$L_J = \frac{\langle p \rangle}{m} R_H$$



- ▶ powerfull probe
- ▶ \perp CMB
- ▶ but systematics
(biais, NLCor)

$$\frac{\Delta P}{P} \simeq -8f_\nu$$

WMAP7 results (95% CL)

Λ CDM (7 pars)

- ▶ WMAP : $M_\nu < 1.3 \text{ eV}$
- ▶ WMAP + BAO + H_0 : $M_\nu < 0.58 \text{ eV}$
- ▶ WMAP + LRG + H_0 : $M_\nu < 0.44 \text{ eV}$
- ▶ WMAP + BAO + SN : $M_\nu < 0.71 \text{ eV}$

$(H_0 = 74.2 \pm 3.6 \text{ km s}^{-1} \text{Mpc}^{-1})$

wCDM (8 pars)

- ▶ WMAP : $M_\nu < 1.4 \text{ eV}$
- ▶ WMAP + BAO + H_0 : $M_\nu < 1.3 \text{ eV}$ ($w = -1.44 \pm 0.27$)
- ▶ WMAP + LRG + H_0 : $M_\nu < 0.71 \text{ eV}$
- ▶ WMAP + BAO + SN : $M_\nu < 0.91 \text{ eV}$

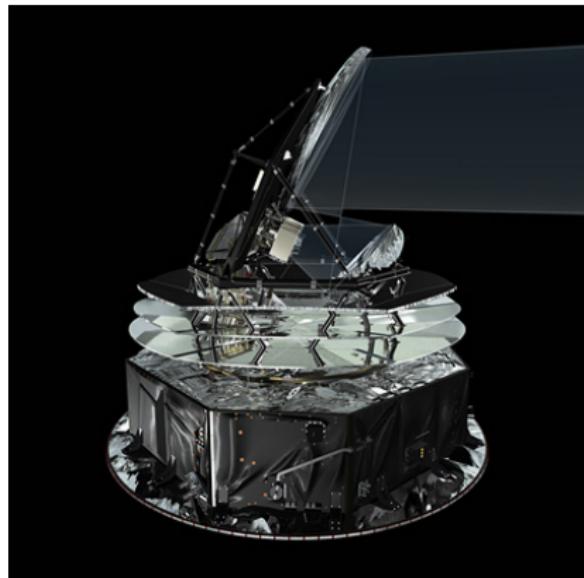
see also Reid et al., JCAP(2010)

Planck

ESA space mission to
(ultimately) measure the CMB
anisotropies (+astrophysics)

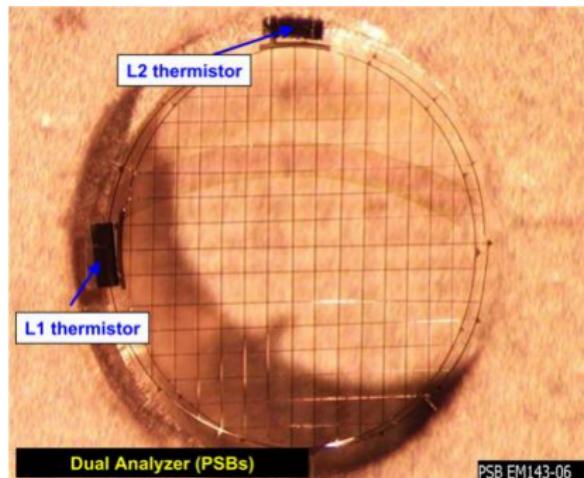
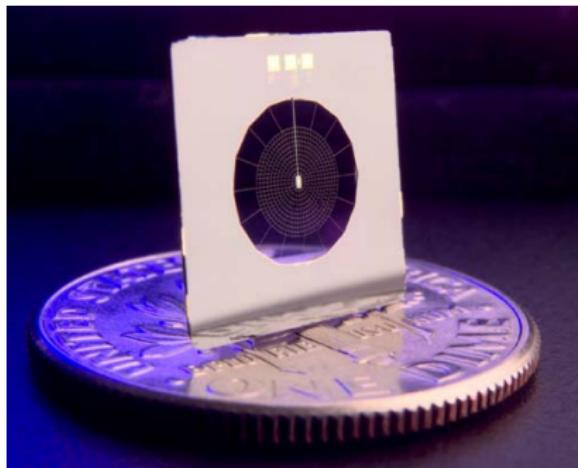
1. telescope (1.5m)
2. **LFI** : **22** radiometers 30-70 GHz, resolution 10-25 arcmin (\simeq WMAP)
3. **HFI** : **52** bolometers 100-857 GHz cooled down to 100 mK(!), resolution 5-9 arcmin.(**32** polarized)

\simeq 300 scientists



Planck-HFI technology

- ▶ 3 coolers (18K, 4 K, 1.6K) + $He^3 - He^4$ dilution → 100 mK : stability down to a few μK
- ▶ extremely low noise (limit on TT= photon noise)
- ▶ behaves as characterized on ground

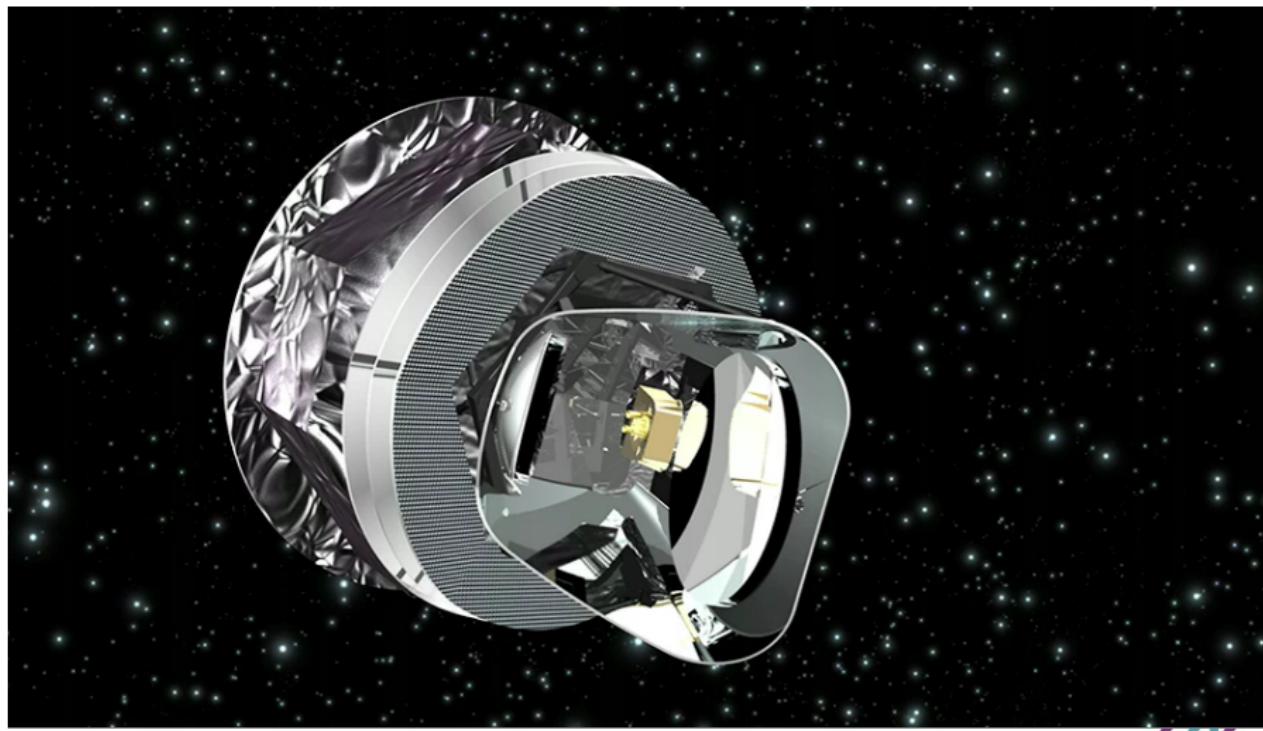


PSB EM143-06

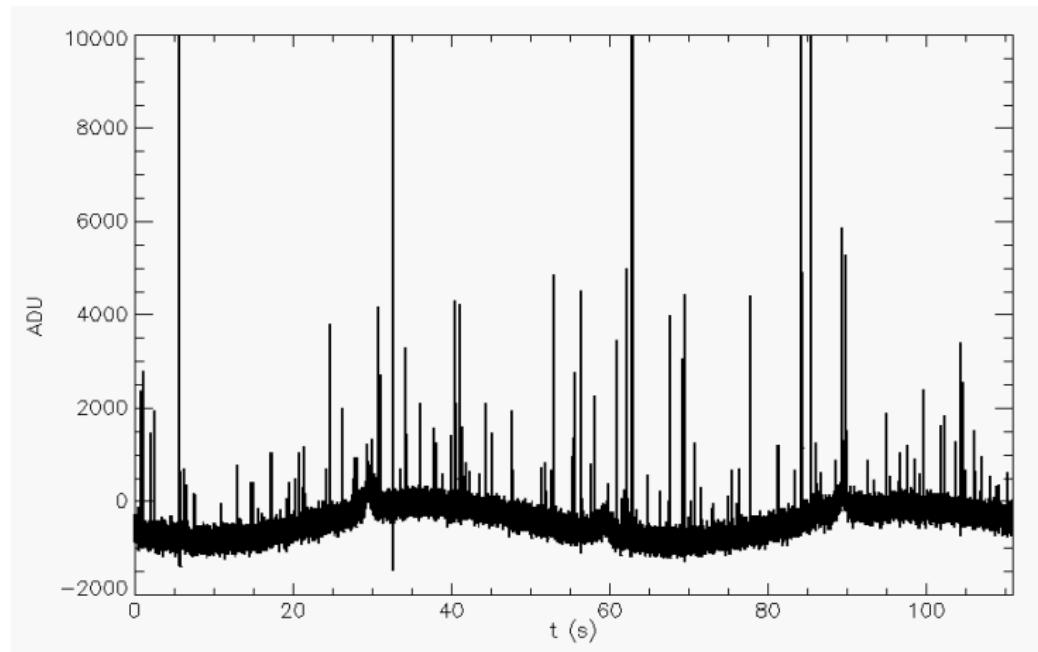
Planck/Herschel launch



Taking data at Lagrange point L2



Real data !



Components separation

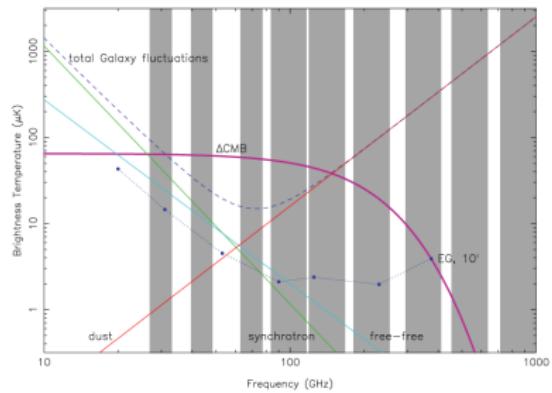
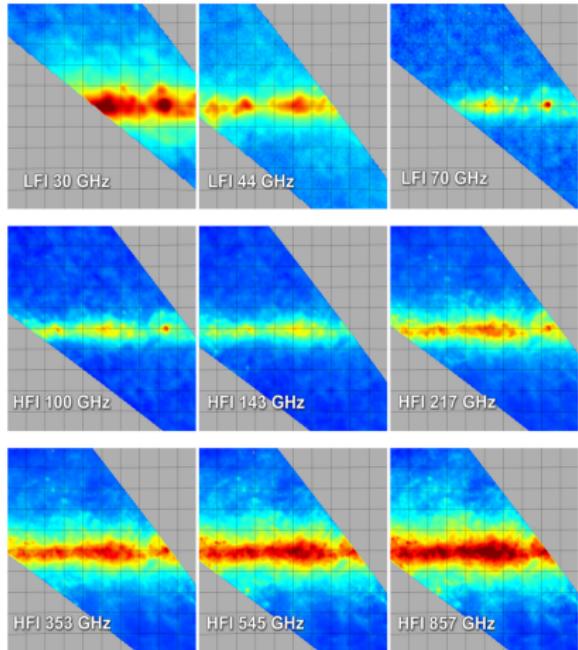
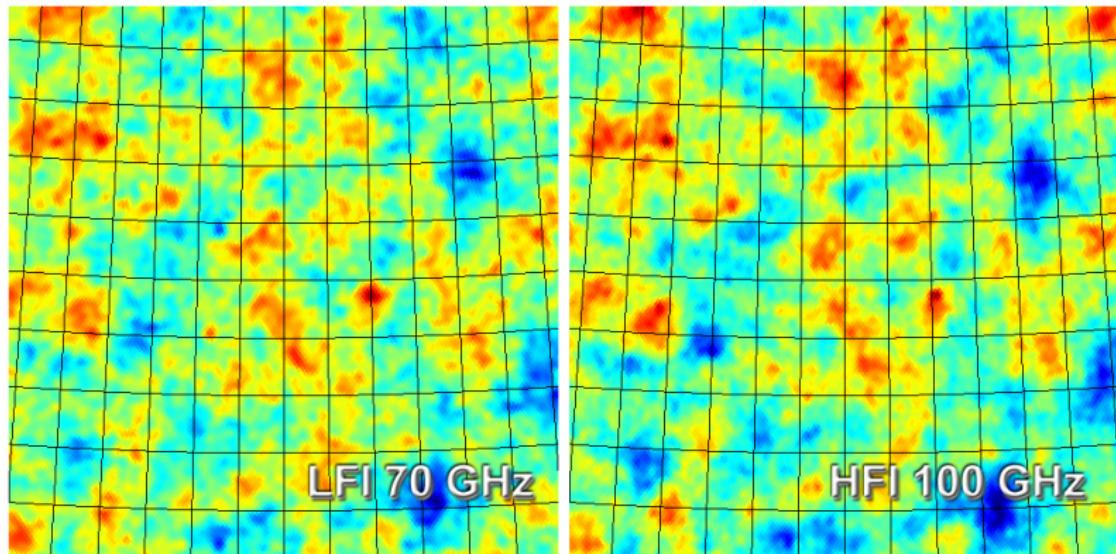


FIG. 1.3.— Spectrum of the CMB, and the frequency coverage of the Planck channels. Also indicated are the spectra of other sources of fluctuations in the microwave sky. Dust, synchrotron, and free-free temperature fluctuation (i.e., unpolarized) levels correspond to the WMAP Kp2 levels (85% of the sky; Bennett et al. 2003). The CMB and Galactic fluctuation levels depend on angular scales, and are shown for $\sim 1^\circ$. On small angular scales, extragalactic sources dominate. The minimum in diffuse foregrounds and the closest window on CMB fluctuations occurs near 70 GHz. The highest HFI frequencies are primarily sensitive to dust.

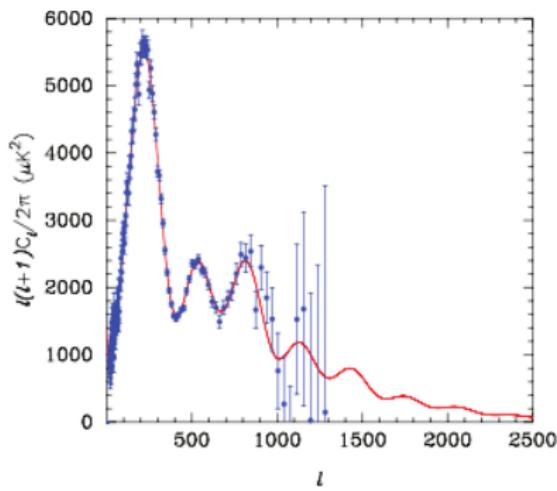
CMB



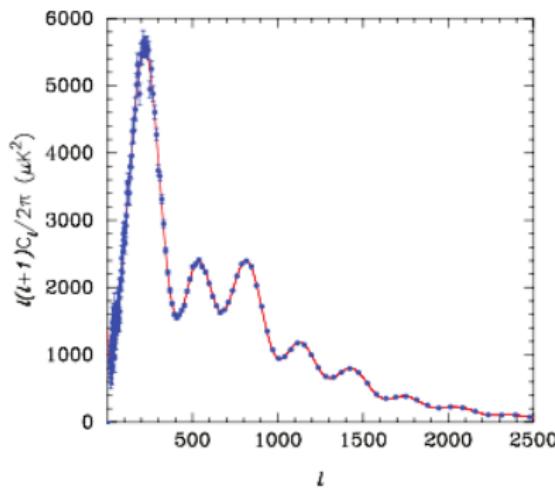
Power spectrum (expected) results

from PLANCK Blue Book. (sorry...)

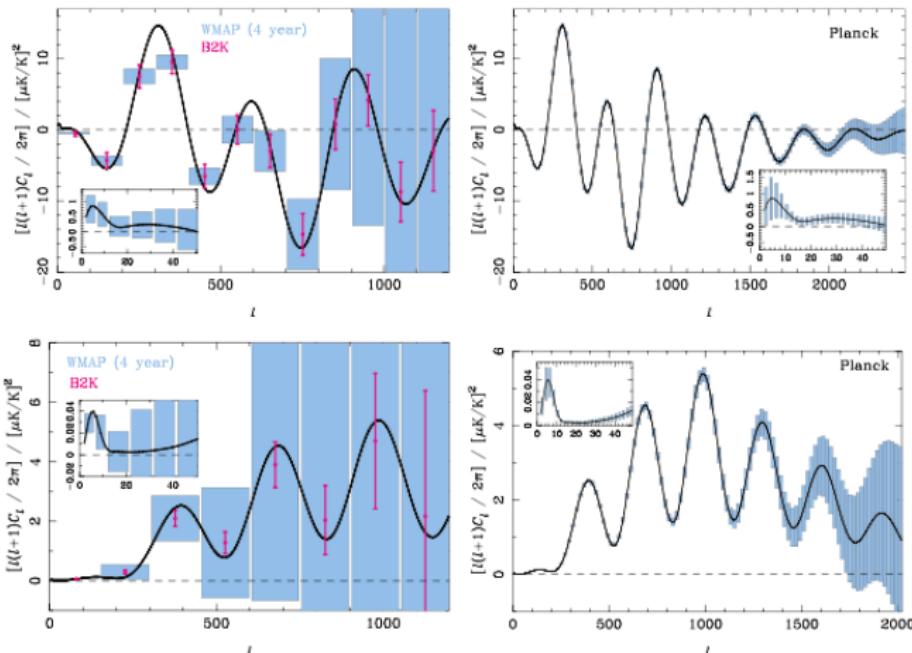
WMAP



PLANCK



Power spectrum (expected) results : polarization



sensitivity on tensor modes up to $r = \frac{A_T}{A_s} \simeq 0.05$

Cosmology

PLANCK will allow **huge** improvements on cosmological fits
On ν side, under the same hypotheses (Λ CDM) limit should go down to $\simeq 0.3$ eV (or a measurement !)

but there is more...



CMB lensing

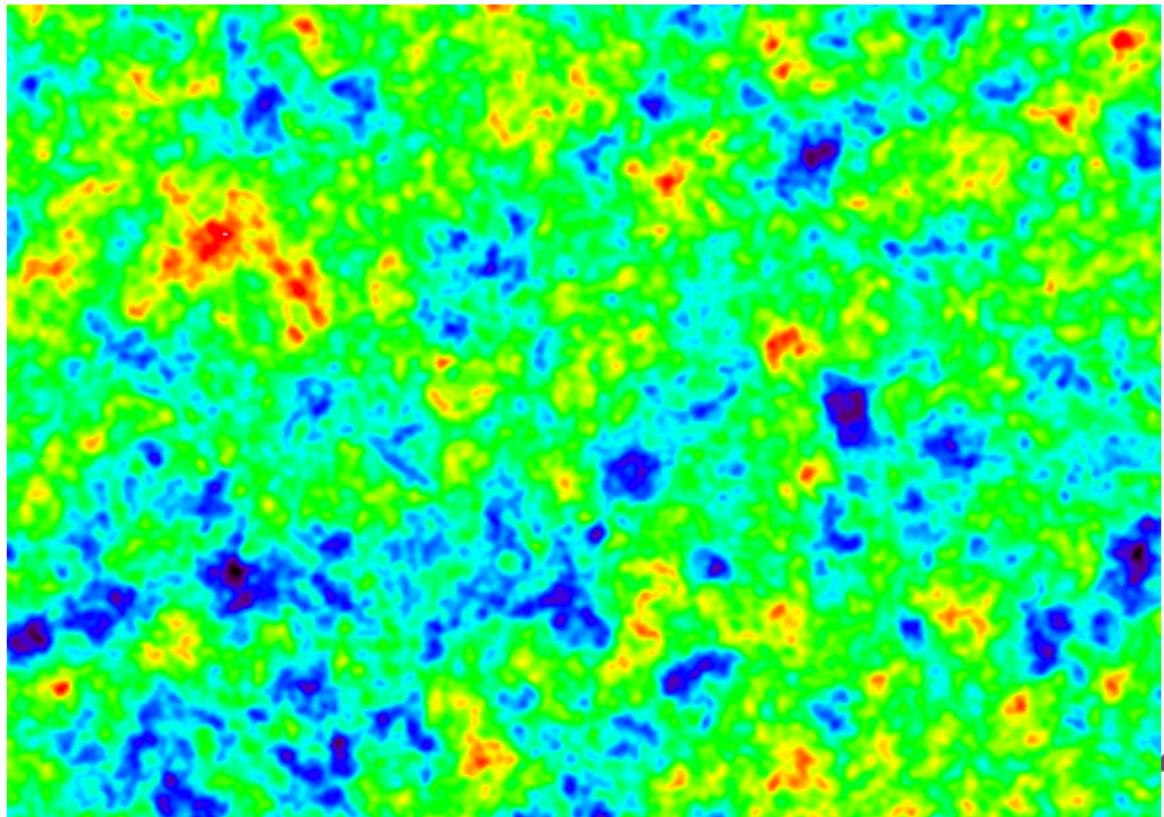
CMB photons are scattered by matter to us → remapping

$$T_{\text{obs}}(\vec{n}) = T_{\text{CMB}}(\vec{n} + \vec{\nabla}\Phi(\vec{n}))$$

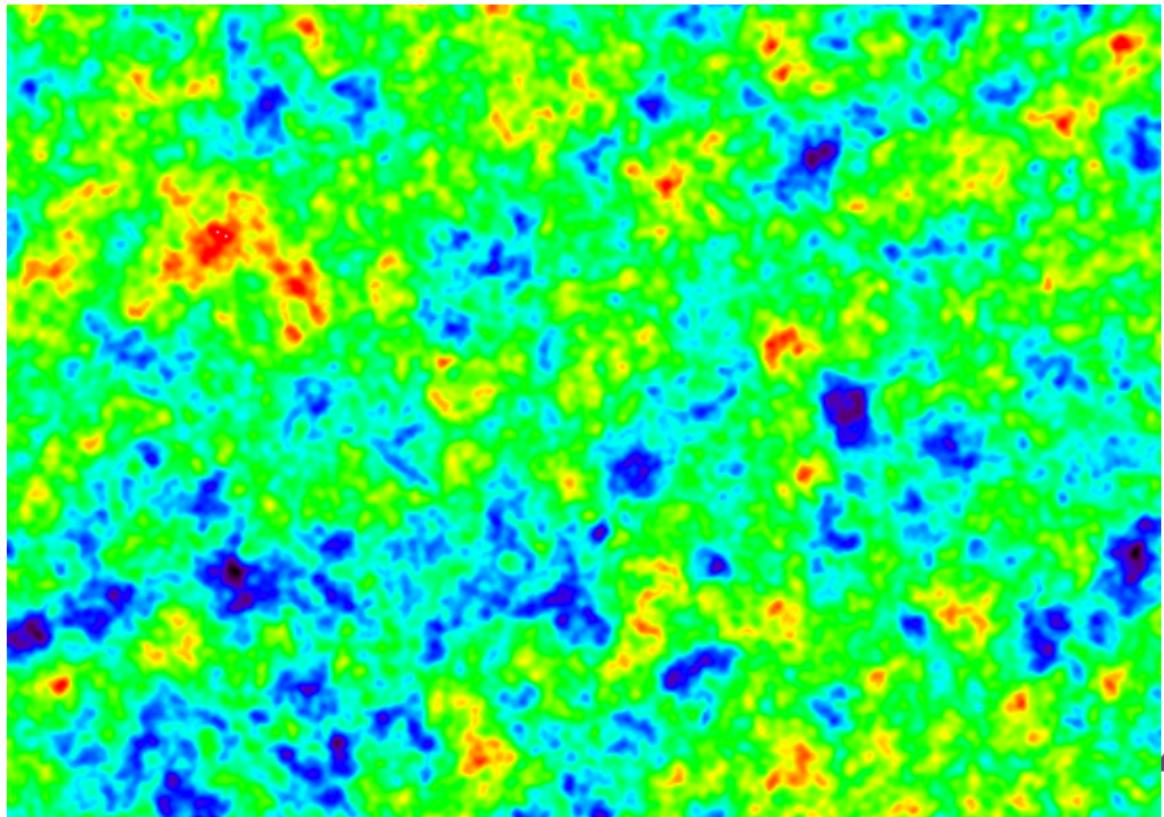
- ▶ never directly measured
- ▶ deflection $\simeq 2.5\text{arcmin}$
- ▶ Φ gaussian field : statistical reconstruction of PS : C_l^Φ

Very challenging (exciting !)

CMB



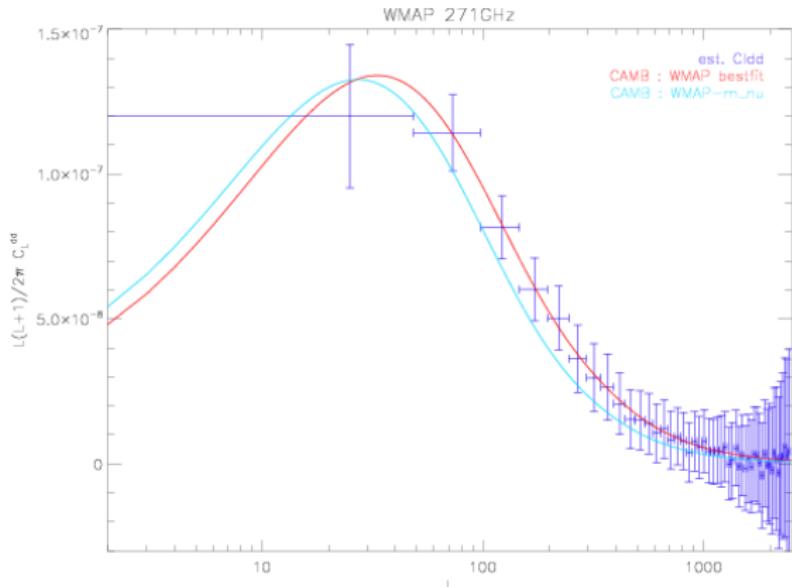
\tilde{CMB}



Why is it interesting for neutrinos ?

$$C_\ell^\phi \simeq 8\pi^2/\ell^3 \int_0^{r_{LS}} r dr P_\Psi(\ell/r, \eta_0 - r) \left(\frac{r - r_{LS}}{r_{LS}} \right)^2$$

$P(k)$ on the same dataset (no bias, NLcor!) : ν free-streaming

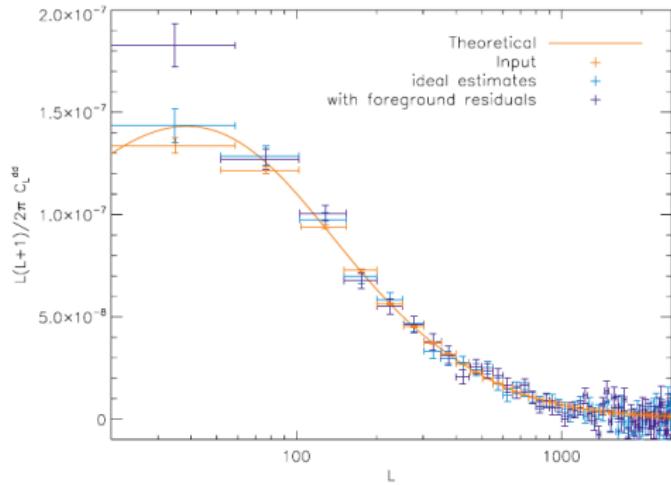


Systematics

many systematics under study...

some addressed in Perotto et al., AA(2010)

- ▶ does CMB lensing survives component separation ?

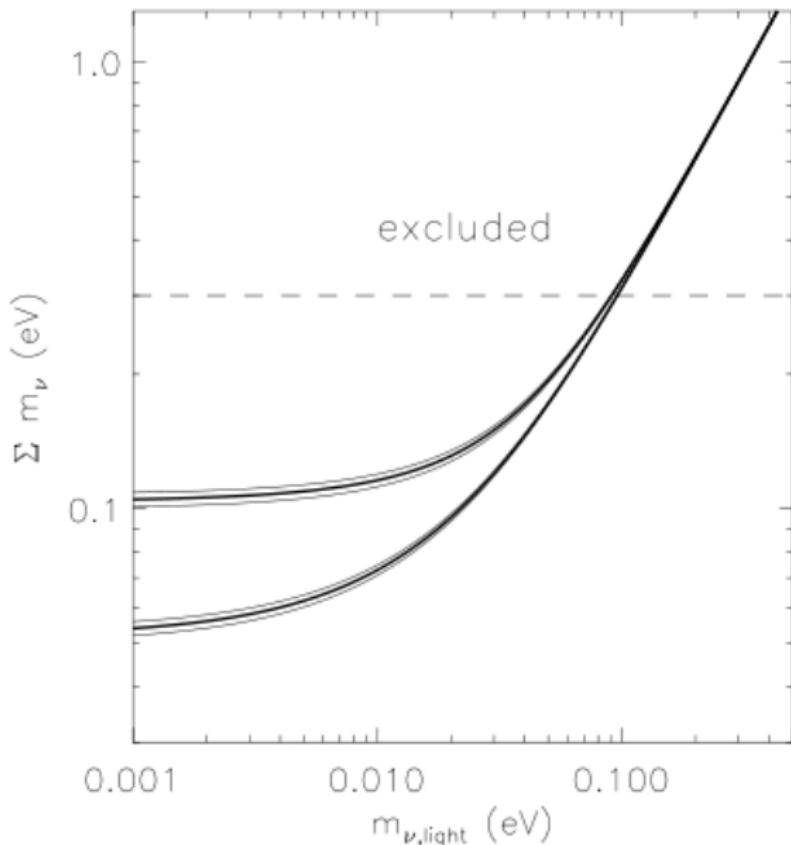


- ▶ how to deal with large masks (Galaxy) ? : inpainting

Conclusions

- ▶ PLANCK completed 1st survey : **4 expected till 2012**
- ▶ data releases : beg-2011 **source catalog** (point sources, cold cores, SZ clusters...)
- ▶ beg. 2012 : **cosmological data**
- ▶ PLANCK does not test directly the **nature** of DM (nor Dirac/Majorana ν 's)
- ▶ but high quality data allows **testing models** : Λ CDM, inflation, axions ...
- ▶ **CMB lensing** new information → systematic free measurement of $P(k)$
- ▶ if $M_\nu \gtrsim 0.2 - 0.3$ eV will be measured by PLANCK (but not hierarchy)
- ▶ otherwise wait till next generation of WL surveys (LSTT, Euclid)





Word of caution on cosmological fits

- ▶ Bayesian analysis : what are the **priors** ? How is the geometrical degeneracy resolved ?
 - ▶ **how many parameters** are fitted [$6 \rightarrow 20$] ? i.e. what is the "Standard cosmological model" ? Λ CDM ? wCDM ? inflation ?
 - ▶ which **probes/datasets** ? CMB, LSS, SN, BAO, $Ly(\alpha)$, WL, $H(z)$
 - ▶ Are **systematics** taken into account ? SN1a, LSS, $Ly\alpha$...
- many results (and everyone convinced to be right !)

More results !

Reid et al., (2010)

model	base dataset	-	+maxBCG	$+H_0$	+maxBCG+ H_0
Λ CDM	WMAP5	1.3	1.1	0.59	0.40
Λ CDM	WMAP5+BAO+SN	0.67	0.35	0.59	0.31
Λ CDM + α	WMAP5	1.34	1.25	0.54	0.39
Λ CDM + r	WMAP5	1.36	1.18	0.83	0.40
w CDM	WMAP5+BAO+SN	0.80	0.52	0.72	0.47
dark coupling	WMAP5+ $P_{halo}(k)$ +SN	-	-	0.51	-

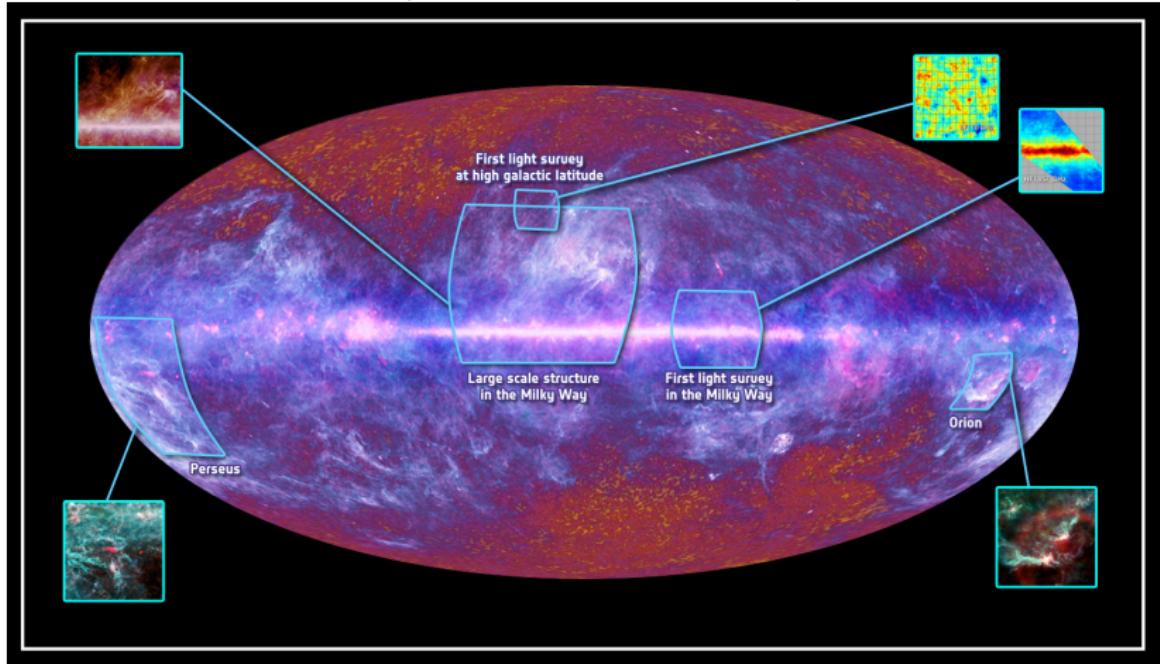
model	base dataset	U.L. (eV)
Λ CDM	WMAP5	1.3
w CDM	WMAP5	1.5
Λ CDM	WMAP5+BAO+SN	0.67
w CDM	WMAP5+BAO+SN	0.80
Λ CDM	WMAP5+ $P_{halo}(k)$	0.62
w CDM	WMAP5+BAO+SN+ <i>Chandra Clusters</i>	0.33
Λ CDM	WMAP3+WL mass function	1.43
Λ CDM	WMAP3+Ly- α +CMB small +BAO+SN+SDSS & 2dF $P(k)$	0.17
Λ CDM	WMAP5+Ly- α +CMB small + α + H_0 2001 [45]	0.28
Λ CDM	WMAP3+ H_0 + $H(z)$	0.50
Λ CDM	WMAP5+SN+BAO+WL	0.54
Λ CDM	WMAP5+ $b(L)$ + $P_{LRG}(k)$ 2006	0.28
w CDM	WMAP5+ $b(L)$ + $P_{LRG}(k)$ 2006	0.59

$M_\nu \lesssim 1$ eV is safe for a "minimal" SM

NB : ongoing theoretical efforts for LSS NLcor.

Survey

1.5 full sky completed (expecting $\simeq 4$ in total)



The Planck one-year all-sky survey



(c) ESA, HFI and LFI consortia, July 2010

