Limits on Dark Radiation, Early Dark Energy and Relativistic Degrees of Freedom

Phys. Rev. D 83 (2011) 123504, arXiv:1103.4132

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Azores School on Observational Cosmology
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RELATIVISTIC EXCESS

Total radiation density : $\rho_r = \rho_\gamma + \rho_\nu$

$$\rho_\nu = \rho_\gamma \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}$$

N_{eff} is the effective number of neutrinos .

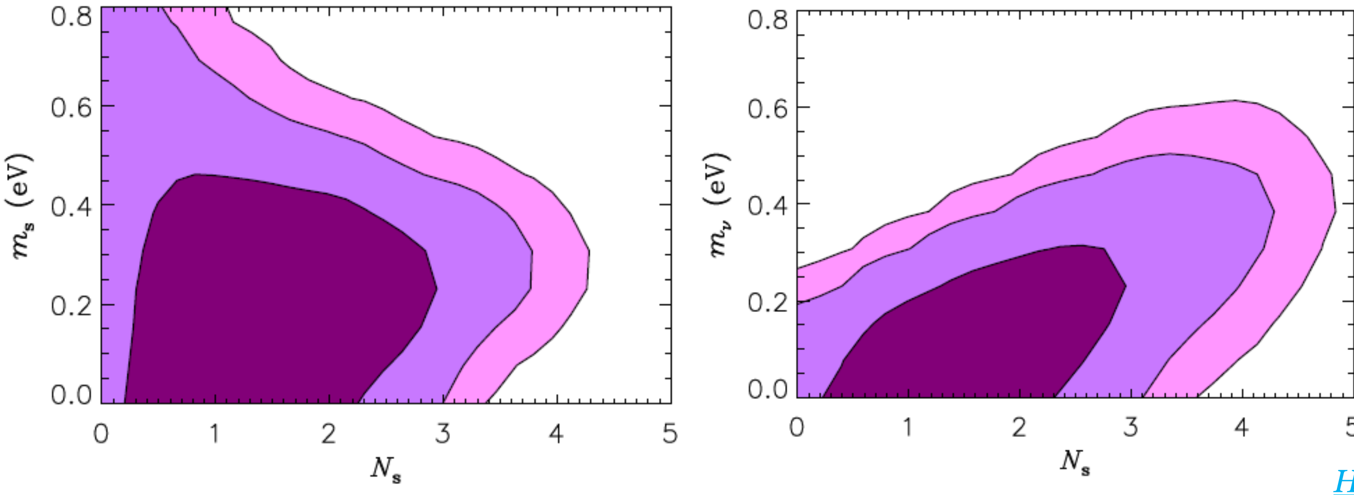
In the standard model N_{eff} describes **3 massless neutrinos**. Considering then the entropy transfer with the thermal bath it reduces to :

$$N_{\rm eff} = 3.046$$

- **wmap7+BAO+Ho** $N_{\rm eff} = 4.34^{+0.86}_{-0.88}$ (68% CL)
- **wmap7+DR7** $N_{\rm eff} = 4.78^{+1.86}_{-1.79}$ at 95%
- **wmap7+ACT** $N_{\rm eff} = 5.3 \pm 1.3$ (68% CL)
- **wmap7+SPT** $N_{\rm eff} = 3.85 \pm 0.62$ (68% CL)

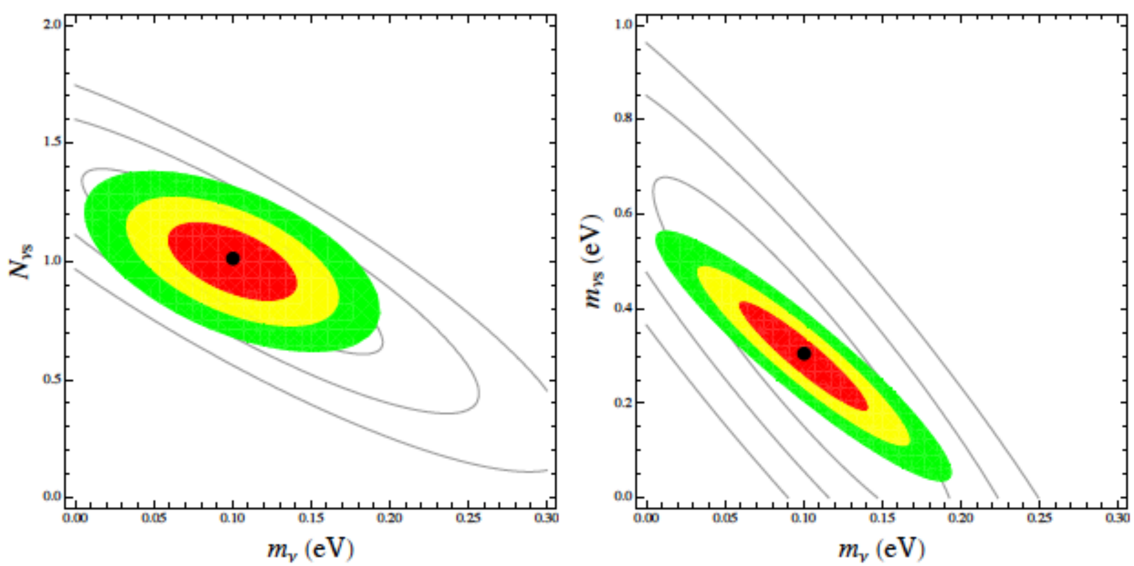
EVIDENCES FOR A STERILE NEUTRINO

$$\rightarrow \quad N_{\rm eff} = 3.046 + N_{\rm s}$$



Left: The 3 + N_s scheme, in which ordinary neutrinos are massless.
Right: The N_s +3 scheme, where the sterile state is massless and 3.046 species of ordinary neutrinos have a common mass.

[Hamann et al., PRL ,105, 181301 (2010) arXiv:1006.5276v2]



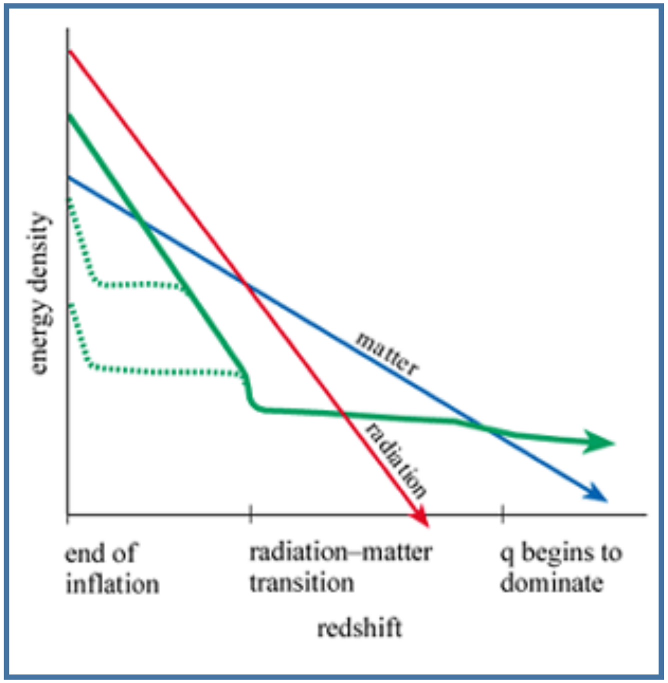
The empty (filled) contours denote the 68%, 95% and 99.73% c.l. regions for Planck plus BOSS (Euclid) data.

The neutrino parameters in the fiducial model are $N_{\nu s}$ = 1, $m_{\nu s}$ = 0.3 eV and m_ν = 0.1 eV.

[Giusarma et al. Phys.Rev.D83:115023,2011 arXiv:1102.4774]

EARLY DARK ENERGY

The dark energy contribution is assumed to be represented by a scalar field whose evolution tracks that of the dominant component of the cosmic fluid at a given time!



[See Zlatev et al, arXiv:9807002v2 [astro-ph.CO]](#)
[Ferreira and Joyce, PRD , 58, 023503 (1998)](#)

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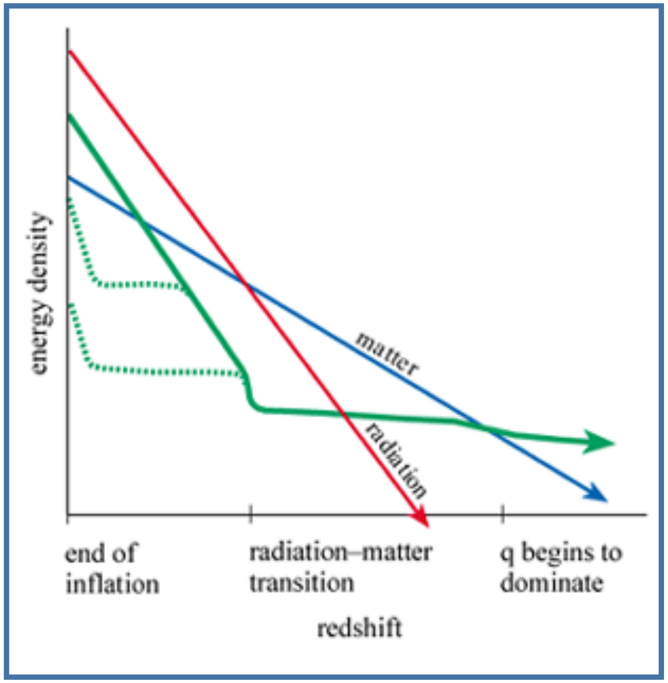
$$\Omega_{\rm de}(a) = \frac{\Omega_{\rm de}^0 - \Omega_{\rm e}\left(1 - a^{-3w_0}\right)}{\Omega_{\rm de}^0 + \Omega_m^0 a^{3w_0}} + \Omega_{\rm e}\left(1 - a^{-3w_0}\right)$$

$$w(a) = -\frac{1}{3[1 - \Omega_{\rm de}(a)]}\frac{d\ln\Omega_{\rm de}(a)}{d\ln a} + \frac{a_{eq}}{3(a + a_{eq.})}$$

M. Doran and G. Robbers, JCAP 0606 (2006) [arXiv:astro-ph/0601544].



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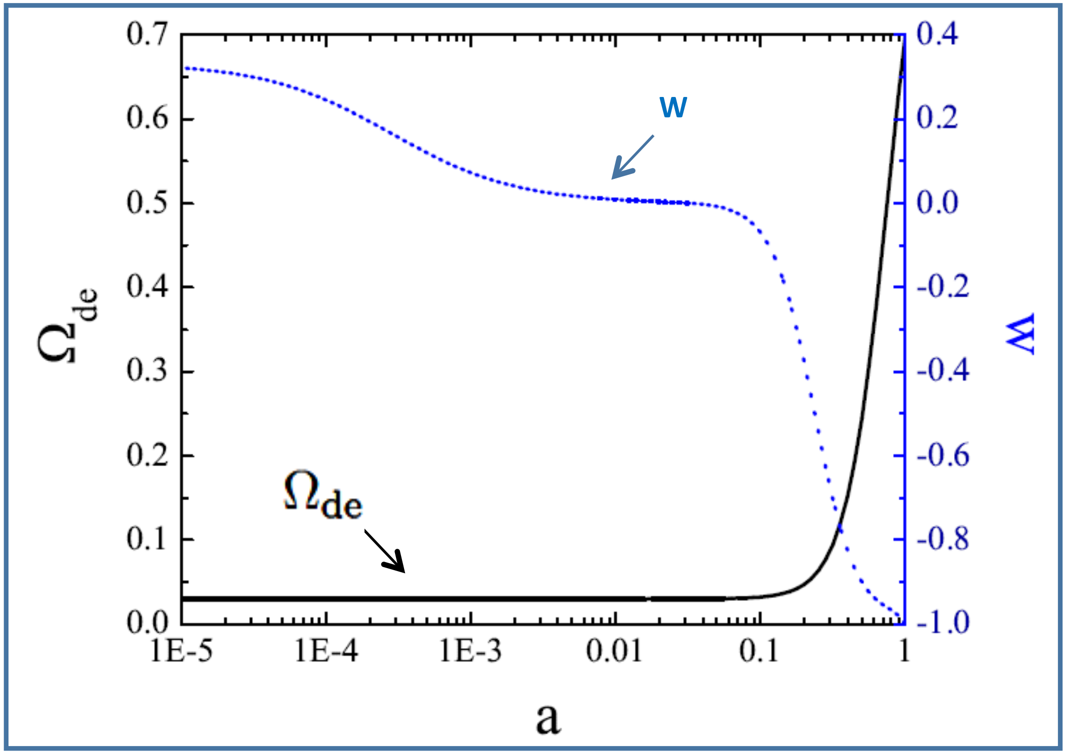

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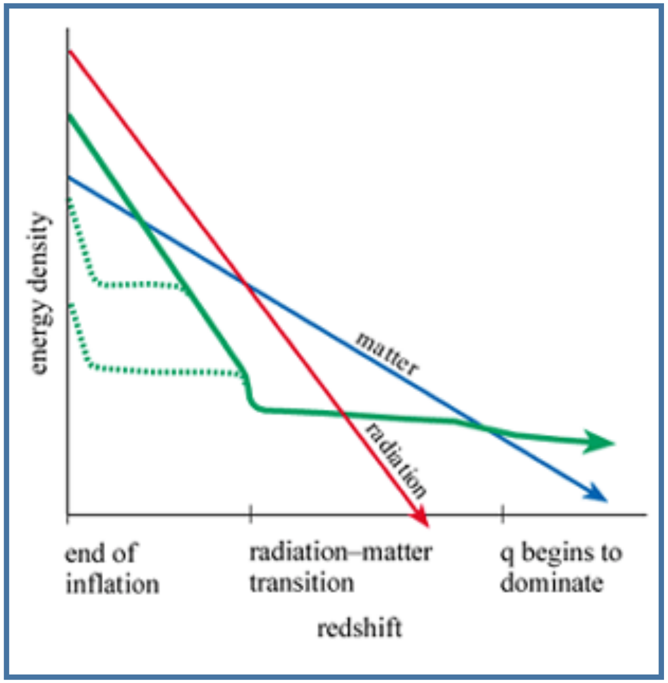

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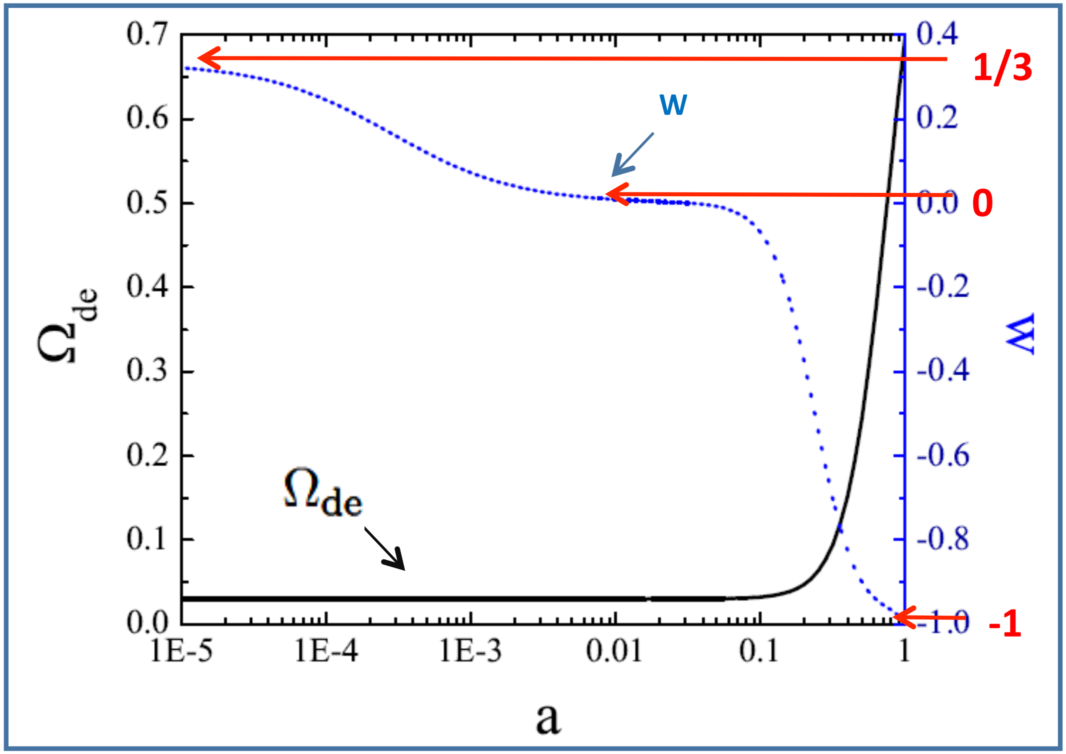
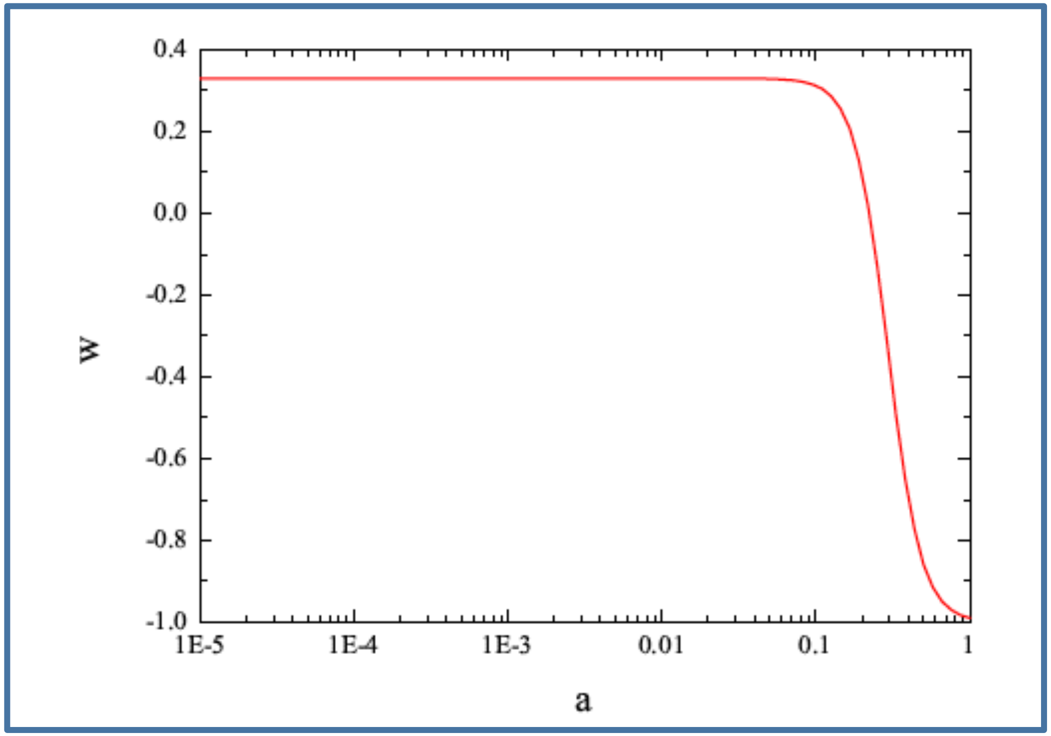


BAROTROPIC DARK ENERGY

$$w = [c_s^2 B a^{-3(1+c_s^2)} - 1]/[B a^{-3(1+c_s^2)} + 1] \ ,$$

$$B = (1 + w_0)/(c_s^2 - w_0)$$



See Sherrer R.J. PRD, 73, (2006), arXiv:0509890 [astro-ph]
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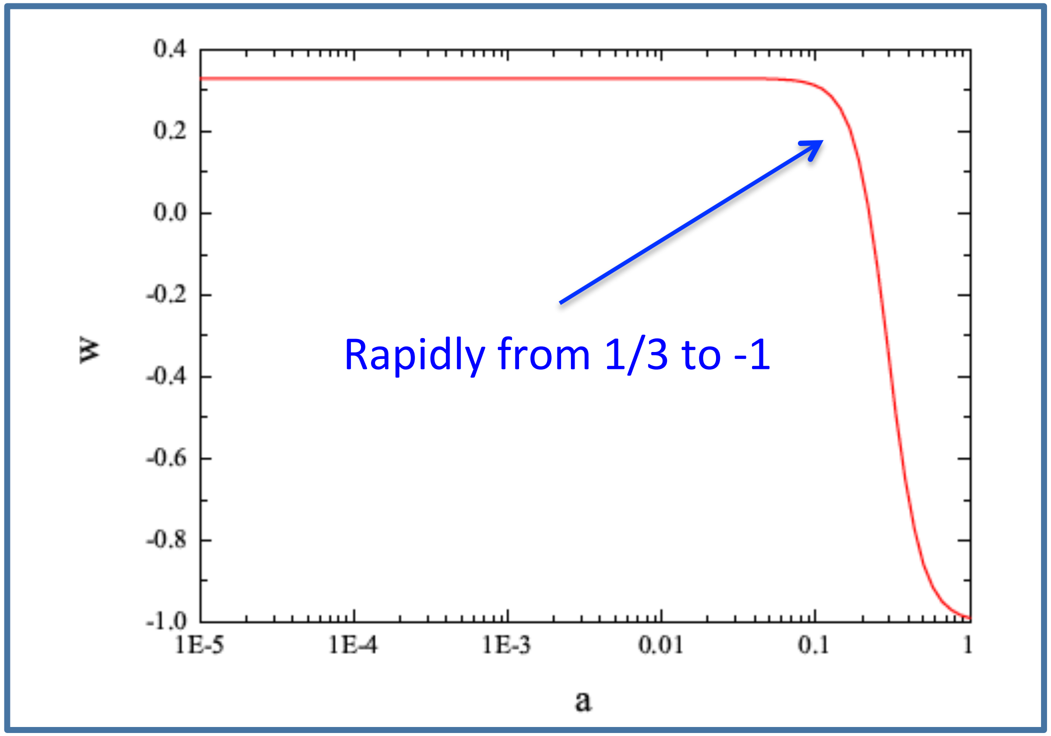

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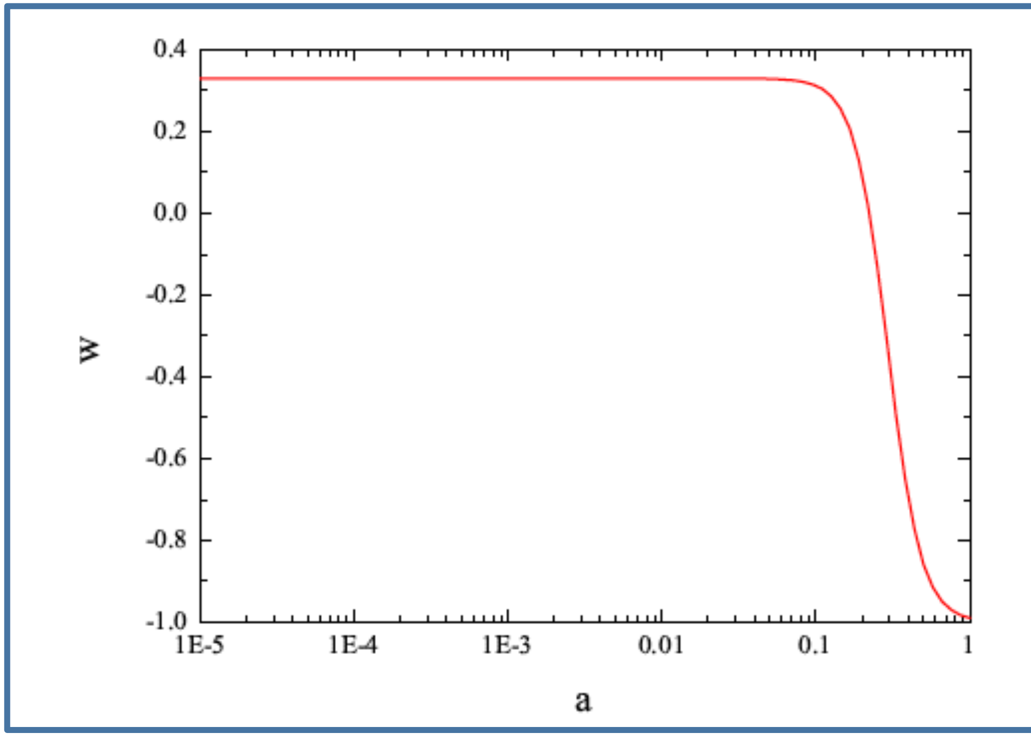
$c^2{}_s = 1/3$



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$$\rho_{\text{baro}}(a) = \rho_\infty + C\rho_{r,0} a^{-4} \ ,$$

$$\rho_\infty = (3H_0^2/8\pi G)(1 - \Omega_m - C\Omega_{r,0})$$

$$C = \Omega_e^B/(1-\Omega_e^B)$$

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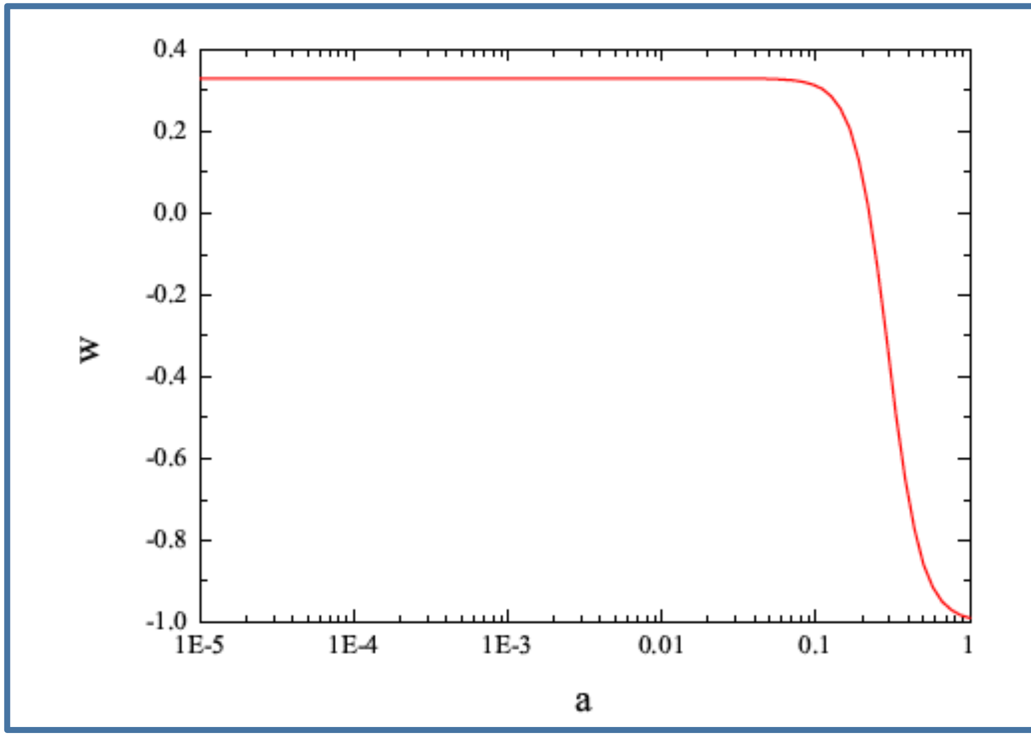

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DR

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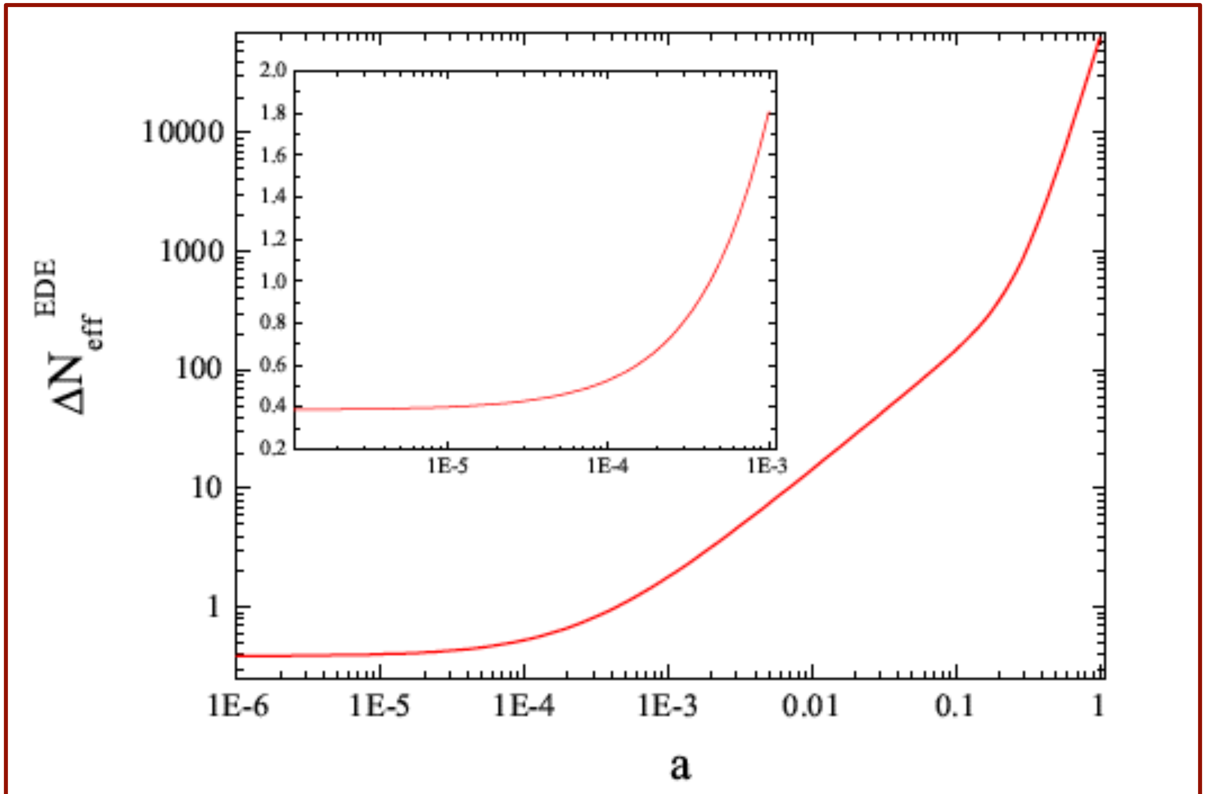
RELATIVISTIC DEGREES OF FREEDOM

$$N_{\rm eff} = N_{\rm eff}^{\nu} + \Delta N_{\rm eff}^{EDE} + \Delta N_{\rm eff}^{B}$$

$$\Delta N_{\rm eff}^{EDE}(a) = \left[\frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\right]^{-1} \frac{\rho_{de}(a)}{\rho_\gamma(a)} \quad , \quad \Delta N_{\rm eff}^{EDE}(a \ll a_{eq}) = 7.44 \frac{\Omega_{\rm e}}{1-\Omega_{\rm e}}$$



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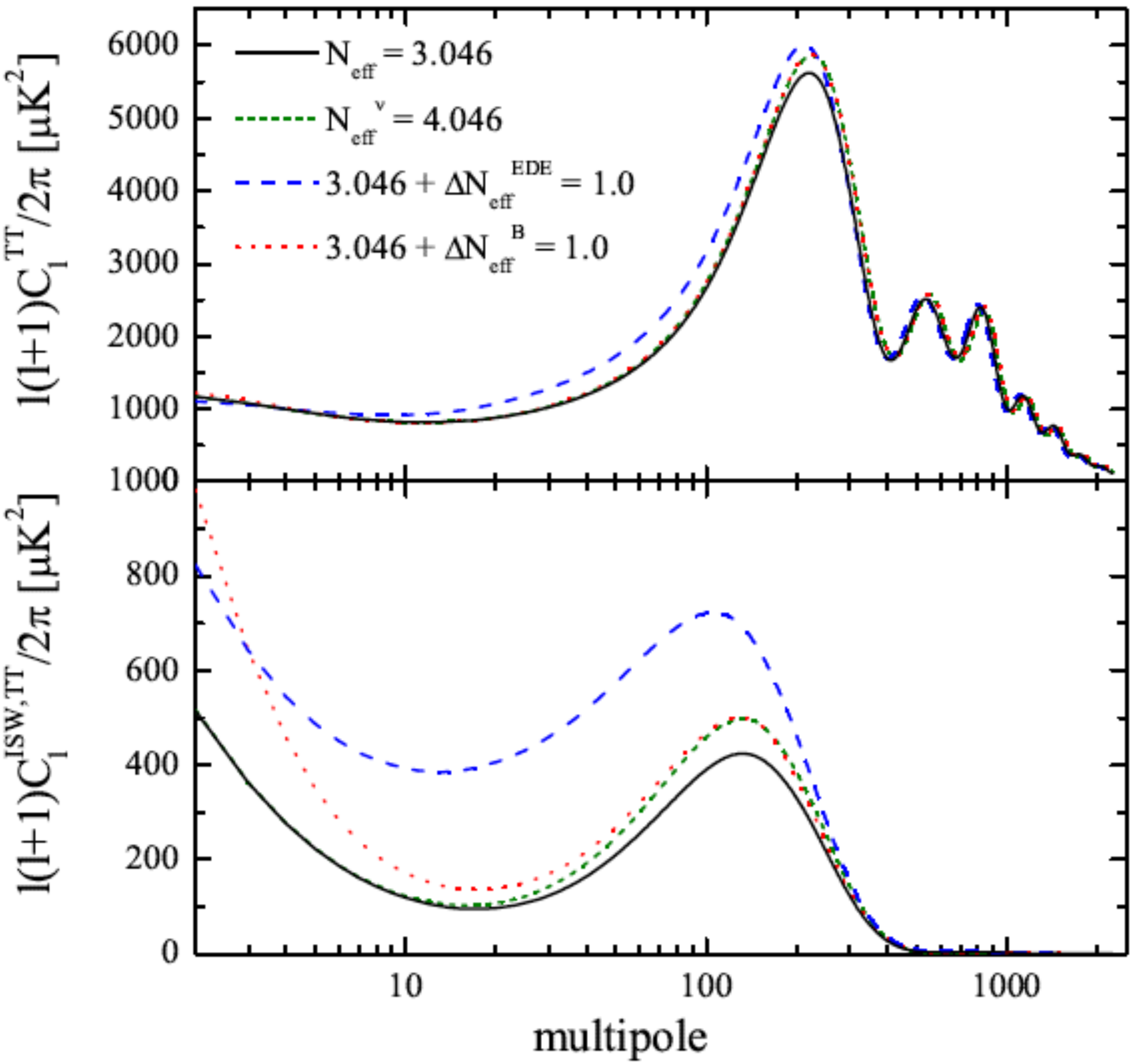
CMB INFORMATIONS



[EC et al.,Phys. Rev. D 83 (2011) 123504, arXiv:1103.4132](https://arxiv.org/abs/1103.4132)

CONSTRAINTS ON EDE AND N^{ν}_{eff}

	WMAP7 + ACBAR + QUAD + ACT + SDSS-DR7 + HST			
Model:	$N^{\nu}_{\rm eff} = 3.046$		$N^{\nu}_{\rm eff}$ **varying**	
	$c_{\rm s}^2 = c_{\rm vis}^2 = 1/3$	$c_{\rm s}^2 = 1, c_{\rm vis}^2 = 0$	$c_{\rm s}^2 = c_{\rm vis}^2 = 1/3$	$c_{\rm s}^2 = 1, c_{\rm vis}^2 = 0$
Parameter				
$\Omega_b h^2$	0.02218 ± 0.00044	0.02232 ± 0.00044	0.02238 ± 0.00047	0.02259 ± 0.00048
$\Omega_c h^2$	0.1178 ± 0.0039	0.1163 ± 0.0038	0.138 ± 0.012	0.139 ± 0.011
H_0	68.2 ± 1.7	67.8 ± 1.6	72.5 ± 2.8	72.4 ± 2.7
n_s	0.971 ± 0.013	0.964 ± 0.011	0.988 ± 0.015	0.986 ± 0.015
$t_0/$ Gyr	13.71 ± 0.30	13.83 ± 0.29	12.91 ± 0.48	12.94 ± 0.48
$N^{\nu}_{\rm eff}$	3.046	3.046	4.37 ± 0.76	4.49 ± 0.72
Ω_e	< 0.043	< 0.024	< 0.039	< 0.020
$\Delta N^{EDE}_{\rm eff}(a_{\rm BBN})$	< 0.34	< 0.18	< 0.32	< 0.18
Y_p	0.2504 ± 0.0013	0.2495 ± 0.0008	0.2661 ± 0.0078	0.2667 ± 0.0080

TABLE I: Best-fit values and 68% confidence errors on cosmological parameters using the current cosmological data. For Ω_e and $\Delta N^{EDE}_{\rm eff}(a_{\rm BBN})$, EDE density and the contribution to the RDOF from EDE at the BBN epoch respectively, the upper bounds at 95% c.l. are reported. See text for other details.

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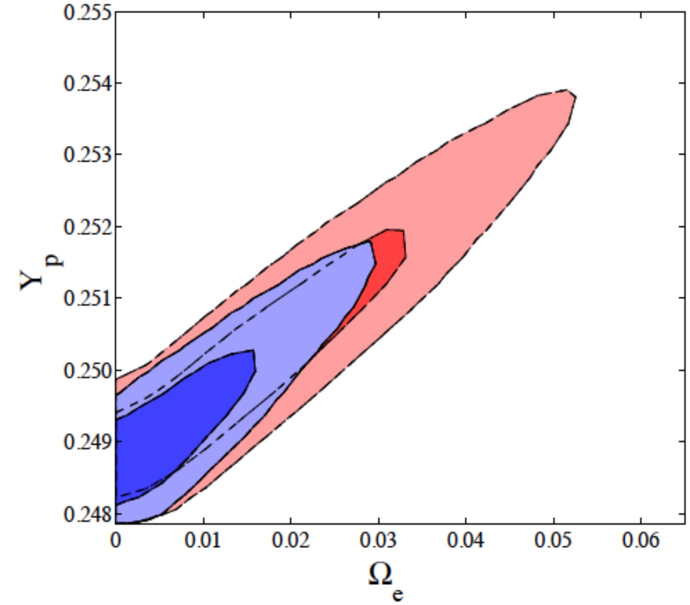
Since the early dark energy enhances the expansion rate during the BBN, it allows for a higher primordial Helium mass fraction according to $\Delta Yp \simeq 0.013(N_{eff} - 3)$



Current measurements seems to prefer a larger value for Yp, Yp=0.2561±0.0108 or Yp=0.2565±0.0010(stat.)±0.0050(syst.). These results are off by ~1.5 sigma from the expectations of standard BBN but introducing EDE acts to alleviate this tension.

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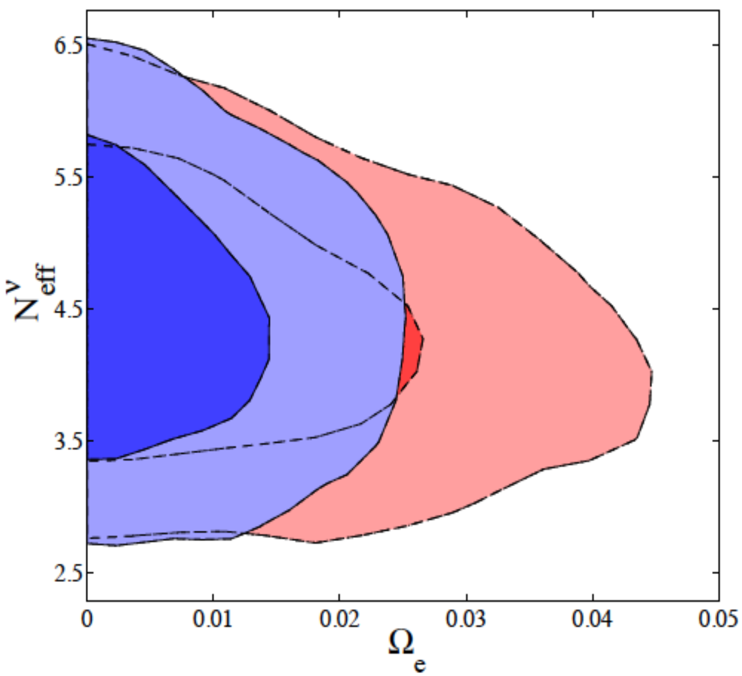
CONSTRAINTS ON EDE AND N^{ν}_{eff}

When also N_{eff} is varying, the constraints on Ω_e are practically unaffected by the inclusion of extra RDOF and vice versa. From our analysis we found that sterile neutrinos are preferred.



+ ACT + SDSS-DR7 + HST

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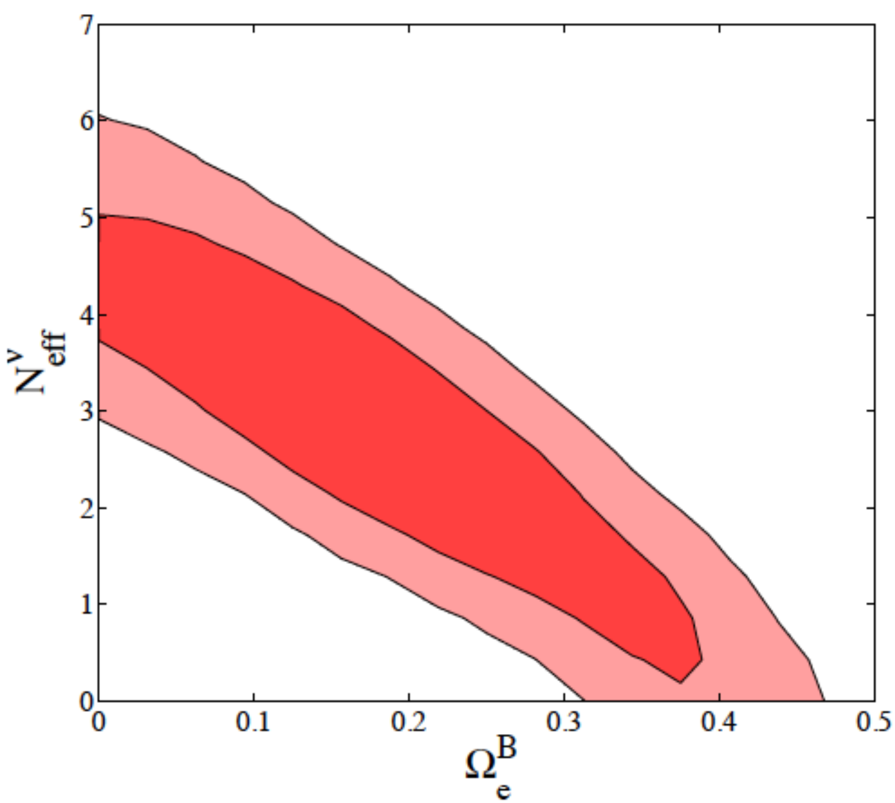
CONSTRAINTS ON BAROTROPIC DE AND N^{ν}_{eff}

The barotropic model strongly alters the constraints on N^{ν}_{eff} and a non-negligible presence of the dark radiation part of the barotropic dark energy at recombination could not only bring the constraints on N^{ν}_{eff} back in agreement with the standard value of N^{ν}_{eff} = 3.046 but even erase the current claim for a neutrino background from CMB data!

Parameter	WMAP7+ACBAR+QUAD + ACT+SDSS-DR7+HST
$\Omega_b h^2$	0.02209 ± 0.00055
$\Omega_c h^2$	0.135 ± 0.012
H_0	71.1 ± 2.8
n_s	0.986 ± 0.015
$t_0/$ Gyr	13.18 ± 0.51
$N^{\nu}_{\rm eff}$	< 5.1
Ω^B_e	< 0.37
$\Delta N^B_{\rm eff}$	< 2.8
Y_p	0.2649 ± 0.0084



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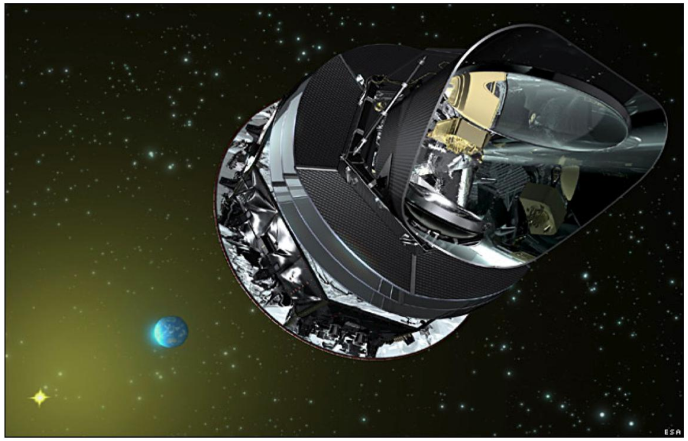
PLANCK FORECASTS



$$F_{ij} \equiv \langle -\frac{\partial^2 ln\mathcal{L}}{\partial p_i \partial p_j} \rangle_{p_0}$$

$$F_{ij}^{\text{CMB}} = \sum_{l=2}^{l_{\max}} \sum_{\alpha,\beta} \frac{\partial C_l^{\alpha}}{\partial p_i} (\text{Cov}_l)^{-1}_{\alpha\beta} \frac{\partial C_l^{\beta}}{\partial p_i},$$

$$\Rightarrow \quad \sigma_{p_i} \geq \sqrt{(F^{-1})_{ii}}$$

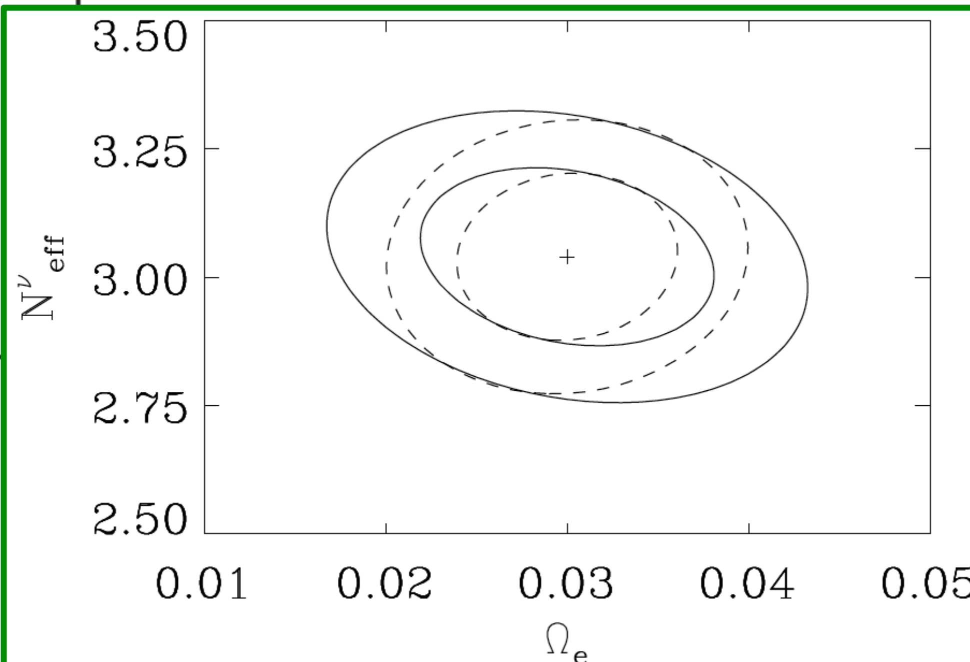
Experiment	Channel[GHz]	FWHM	$\sigma_T[\mu K]$	$\sigma_P[\mu K]$
Planck	143	7.1'	6.0	11.4
$f_{\text{sky}} = 0.85$	100	10.0'	6.8	10.9
	70	14.0'	12.8	18.3

[Planck Collaboration], arXiv:astro-ph/0604069.

PLANCK FORECASTS

		Planck 1-σ uncertainty	
Model:		$c_s^2 = c_{vis}^2 = 1/3$	$c_s^2 = 1, c_{vis}^2 = 0$
Parameter	Fiducial		
$\Omega_b h^2$	0.02258	0.00016	0.00014
$\Omega_c h^2$	0.1109	0.0018	0.0017
τ	0.0880	0.0020	0.0022
H_0	71.0	8.5	8.8
n_s	0.9630	0.0046	0.0044
N_{eff}^{ν}	3.046	0.11	0.11
w_0	−0.95	0.24	0.24
Ω_e	0.030	0.005	0.004
c_s^2	0.33	0.047	–
c_{vis}^2	0.33	0.13	–
c_s^2	1.00	–	0.34
c_{vis}^2	0	–	0.11

Stringent limits on relativistic degrees of freedom and very little impact from EDE.



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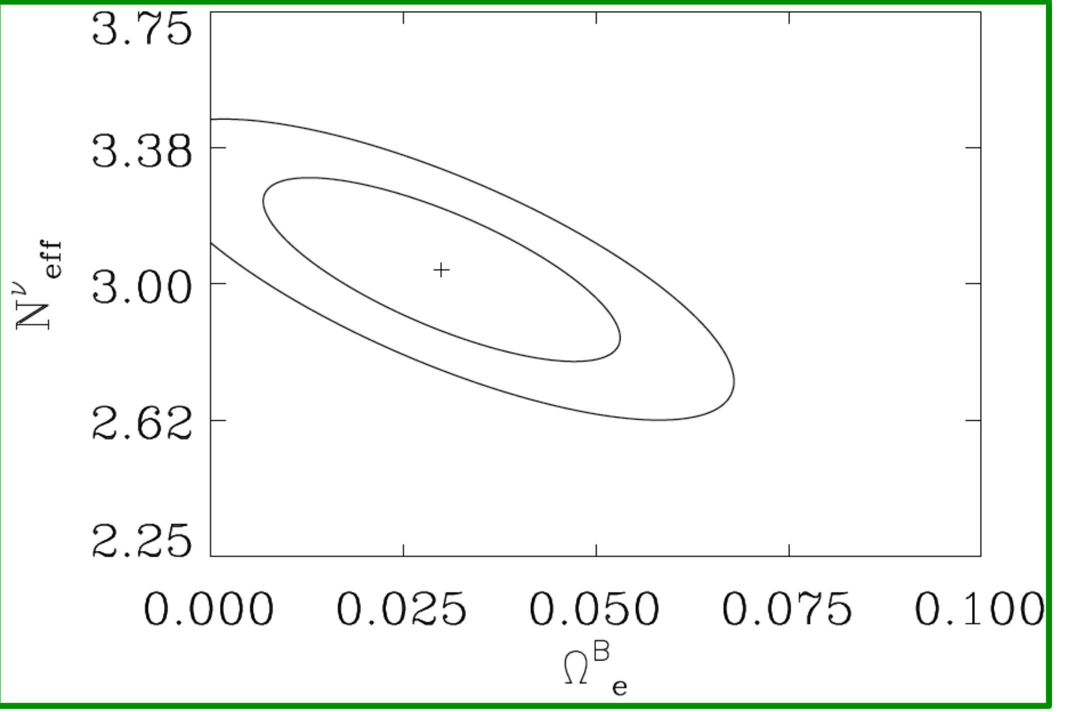
PLANCK FORECASTS

	Planck $1-\sigma$ uncertainty
Model:	$c_s^2 = c_{vis}^2 = 1/3$

Parameter	Fiducial	
$\Omega_b h^2$	0.02258	0.00013
$\Omega_c h^2$	0.1109	0.0019
τ	0.0880	0.0022
H_0	71.00	0.88
n_s	0.9630	0.0041
N_{eff}^{ν}	3.046	0.17
w_0	−0.95	0.041
Ω_e^B	0.030	0.015
c_s^2	0.33	0.045
c_{vis}^2	0.33	0.17

A degeneracy is still present and we have weaker bound than in the EDE scenario.



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CONCLUSIONS

- ✓ We have studied the nature of the relativistic excess highlighted by current data focusing on an interplay between neutrinos and dark energy.

- ✓ We have seen that in a EDE scenario we still have a preference for a sterile neutrino at about two standard deviations.

- ✓ In the Barotropic DE scenario, N^{ν}_{eff} can be in perfect agreement with the standard value.

- ✓ Planck could shed light…