# Robustness of cosmic neutrino background detection in the cosmic microwave background

Viviana Niro

UAM and IFT

Madrid, 23 June, 2015

*B. Audren, E. Bellini, A. J. Cuesta, S. Gontcho A Gontcho, J. Lesgourgues, VN, M Pellejero-Ibanez, I. Pérez-Ràfols, V. Poulin, T. Tram, D. Tramonte, L. Verde,*

*JCAP 1503 (2015) 036*

# Outline

# The cosmic neutrino background

- Neutrinos decouples from matter after 2 s (∼MeV), C$\nu$B $\sim$ 100 $\nu/cm^3$
- Neutrino DM is HDM $\rightarrow$ they are not the dominant component of DM in the Universe
- First indirect confirmation of the existence of a cosmological neutrino background: adding only one extra parameter to the standard ΛCDM model, the effective number of neutrino species, $N_{\rm eff}$
- Using CMB observations, $N_{\rm eff} = 0$ is disfavoured at the level of about $17\sigma$ $\rightarrow$ indirect confirmation of the cosmic neutrino background *Planck collaboration, 2015*
- <u>But</u> departures from $N_{\rm eff}$ could be caused by any ingredient contributing to the expansion rate of the Universe in the same way as a radiation background

# The cosmic neutrino background

- free streaming particles like decoupled neutrinos leave specific signatures on the CMB, not only through their contribution to the background evolution

- effect on perturbations: their density/pressure perturbations, bulk velocity and anisotropic stress are additional sources for the gravitational potential via the Einstein equations $\rightarrow$ introduce two phenomenological parameters ($c^2_{\rm eff}$, $c^2_{\rm vis}$)

- Postulate a linear relation between isotropic pressure perturbations and density perturbations given by a squared sound speed $c^2_{\rm eff}$.
  The approach is then extended to anisotropic pressure by introducing another constant, the viscosity coefficient $c^2_{\rm vis}$.

- The CMB seems to prove that the perturbation of neutrinos are needed to explain the data
  $\Rightarrow$ Are these bounds stable when considering massive neutrinos?
  $\Rightarrow$ Could ($c^2_{\rm eff}$, $c^2_{\rm vis}$) be degenerate with other cosmological parameters, like e.g., $N_{\rm eff}$, a running of the primordial spectrum index, or the equation of state of dynamical dark energy?

# Cosmological perturbation theory

*Massless neutrinos*

$$
\begin{aligned}
(1)\quad \dot{\delta}_\nu &= -\frac{4}{3}(\theta_\nu + M_{\mathrm{continuity}})\,, \\
(2)\quad \dot{\theta}_\nu &= k^2\left(\frac{1}{4}\delta_\nu - \sigma_\nu\right) + M_{\mathrm{Euler}}\,, \\
(3)\quad \dot{F}_{\nu 2} &= 2\dot{\sigma}_\nu = \frac{8}{15}(\theta_\nu + M_{\mathrm{shear}}) - \frac{3}{5}kF_{\nu 3}\,, \\
(4)\quad \frac{2l+1}{k}\dot{F}_{\nu l} - l\dot{F}_{\nu(l-1)} &= -(l+1)F_{\nu l+1}, \quad l \geq 3\,.
\end{aligned}
$$

- $\delta$: density fluctuations, $\theta$: divergence of fluid velocity, $\sigma$: shear stress, $F_{\nu\ell}$ are the Legendre multipoles of the momentum integrated neutrino distribution function.
- (1) continuity equation, related to density contrast; (2) Euler equation; (3) anisotropic pressure/shear; (4) distribution function moments
- $(M_{\mathrm{continuity}}, M_{\mathrm{Euler}})$ refer to combination of metric perturbations, e.g. $(\dot{h}/2, 0)$ in the synchronous gauge and $(-3\dot{\phi}, k^2\psi)$ in the Newtonian gauge. $M_{\mathrm{shear}}$ is 0 in the Newtonian gauge and $(\dot{h} + 6\dot{\eta})/2$ in the synchronous gauge.

*C.-P. Ma, E. Bertschinger, astro-ph/9506072*

# Introducing the $(c^2_{\rm eff}, c^2_{\rm vis})$ parameters

*Massless neutrinos*

$$
\begin{aligned}
\dot\delta_\nu &= \left(1-3c^2_{\rm eff}\right)\frac{\dot a}{a}\left(\delta_\nu+\frac{4}{k^2}\frac{\dot a}{a}\theta_\nu\right)-\frac{4}{3}(\theta_\nu+M_{\rm continuity})\,,\\
\dot\theta_\nu &= \frac{k^2}{4}(3c^2_{\rm eff})\left(\delta_\nu+\frac{4}{k^2}\frac{\dot a}{a}\theta_\nu\right)-\frac{\dot a}{a}\theta_\nu-k^2\sigma_\nu+M_{\rm Euler}\,,\\
\dot F_{\nu 2} &= 2\dot\sigma_\nu=(3c^2_{\rm vis})\frac{8}{15}(\theta_\nu+M_{\rm shear})-\frac{3}{5}kF_{\nu 3}\,,
\end{aligned}
$$

- perturbations of relativistic free-streaming species: $(c^2_{\rm eff},\, c^2_{\rm vis}) = (1/3,\, 1/3)$
  perfect relativistic fluid (isotropic pressure; $\sigma_\nu$ and all multipoles $F_{\nu\ell}$ with $\ell \geq 3$ remain zero at all times): $(c^2_{\rm eff},\, c^2_{\rm vis}) = (1/3,\, 0)$
  a scalar field: $(c^2_{\rm eff},\, c^2_{\rm vis}) = (1,\, 0)$,
  more general case: arbitrary $(c^2_{\rm eff},\, c^2_{\rm vis})$.
- assume $\hat{\delta p} = c^2_{\rm eff}\ \hat{\delta\rho}$, identify the source terms corresponding to $\hat{\delta p}$ in the continuity/Euler equation and multiply them by $(3c^2_{\rm eff})$; identify the source term for $\sigma$ in the quadrupole equation and multiply it by $(3c^2_{\rm vis})$.

*See also W. Hu, D. J. Eisenstein, M. Tegmark, M. White, astro-ph/9806362; W. Hu astro-ph/9801234; R. Trotta and A. Melchiorri, astro-ph/0412066; M. Archidiacono, E. Calabrese, A. Melchiorri, 1109.2767; M. Gerbino, E. Di Valentino, N. Said, 1304.7400 [astro-ph.CO]*

# Introducing the $(c^2_{\rm eff}, c^2_{\rm vis})$ parameters

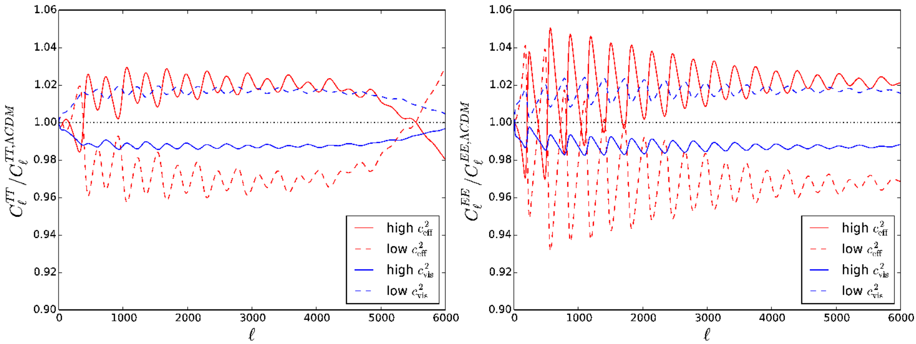
*Massive neutrinos*

$$
\begin{aligned}
\dot\Psi_0 &= \frac{\dot a}{a}\left(1-3c^2_{\rm eff}\right)\frac{q^2}{\epsilon^2}\left[\Psi_0 + 3\frac{\dot a}{a}\frac{5p-\tilde p}{\rho+p}\frac{\epsilon}{kq}\Psi_1\right] - \frac{qk}{\epsilon}\Psi_1 + \frac{1}{3}M_{\rm continuity}\frac{d\ln f_0}{d\ln q}\ , \\
\dot\Psi_1 &= c^2_{\rm eff}\frac{qk}{\epsilon}\left[\Psi_0 + 3\frac{\dot a}{a}\frac{5p-\tilde p}{\rho+p}\frac{\epsilon}{qk}\Psi_1\right] - \frac{\dot a}{a}\frac{5p-\tilde p}{\rho+p}\Psi_1 - \frac{2}{3}\frac{qk}{\epsilon}\Psi_2 - \frac{\epsilon}{3qk}M_{\rm euler}\frac{d\ln f_0}{d\ln q}\ , \\
\dot\Psi_2 &= \frac{qk}{5\epsilon}\left(6c^2_{\rm vis}\Psi_1 - 3\Psi_3\right) - 3c^2_{\rm vis}\frac{2}{15}M_{\rm shear}\frac{d\ln f_0}{d\ln q}\ .
\end{aligned}
$$

- In the case of light relics experiencing a non-relativistic transition such as massive neutrinos, the Boltzmann equation cannot be integrated over momentum, and one must solve one hierarchy per momentum bin.
- The previous parametrisation can be extended to the case of light relics experiencing a non-relativistic transition such as massive neutrinos $\Rightarrow$ obtain a modified Boltzmann hierarchy for each momentum $q$.
- $f_0$: unperturbed phase space distribution function; $\Psi_l$: $l$th Legendre component of perturbation to $f_0$     *C.-P. Ma, E. Bertschinger, astro-ph/9506072*

# Impact of $(c^2_{\rm eff}, c^2_{\rm vis})$ on CMB

CMB power spectra of our four models with non-standard values of $c^2_{\rm eff}$ and $c^2_{\rm vis}$, normalised to the reference model with $c^2_{\rm eff} = c^2_{\rm vis} = 1/3$.




CMB power spectrum multipoles for the temperature and $E$-mode polarisation. Solid (dashed) red lines correspond to a $c^2_{\rm eff}$ of 0.36 (0.30), solid (dashed) blue lines correspond to a $c^2_{\rm vis}$ of 0.36 (0.30).

# Impact of $(c_{\rm eff}^2, c_{\rm vis}^2)$ on CMB

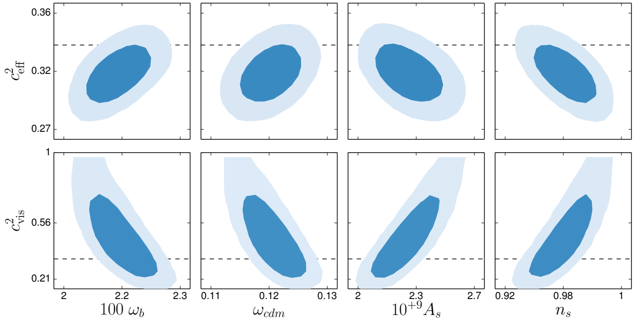
In the polarisation power spectrum:

- the change in *amplitude* is similar to the one in the temperature power spectrum
- but the *shift* in the position of the peaks is more clear: for polarisation there is no contribution from Doppler effects

  $\Rightarrow$ strong oscillations in the ratios

# Degeneracies

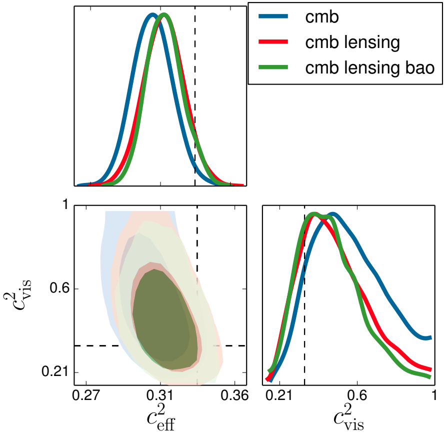
Degeneracies between the parameters ($c^2_{\rm vis}$, $c^2_{\rm eff}$) and the parameters $\omega_b$, $\omega_{cdm}$, $A_s$ and $n_s$ (CMB+lensing data).




$\Rightarrow$ $c^2_{\rm eff}$ and $c^2_{\rm vis}$ parametersa are degenerate with combinations of $\omega_b$, $\omega_{cdm}$, $n_s$ and $A_s$

# Degeneracies

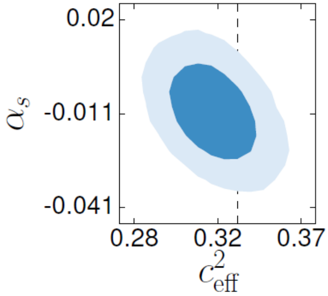
Constraints in the $(c^2_{\rm vis}, c^2_{\rm eff})$ plane for combination of CMB, CMB+lensing and CMB+lensing+BAO data.




$\Rightarrow$ $c^2_{\rm eff}$ and $c^2_{\rm vis}$ parameters are anti-correlated

# Degeneracies

Constraints on ($c^2_{\rm vis}$, $c^2_{\rm eff}$) and the running spectral index $\alpha_s$ for CMB+lensing data




$\Rightarrow$ small anti-correlation between $c^2_{\rm eff}$ and the running of the primordial spectrum tilt $\alpha_s \equiv dn_s/d\log k$, but $c^2_{\rm eff}$ is compatible with the standard value of $1/3$ and $\alpha_s$ is consistent with 0

# Robustness of C$\nu$B evidence

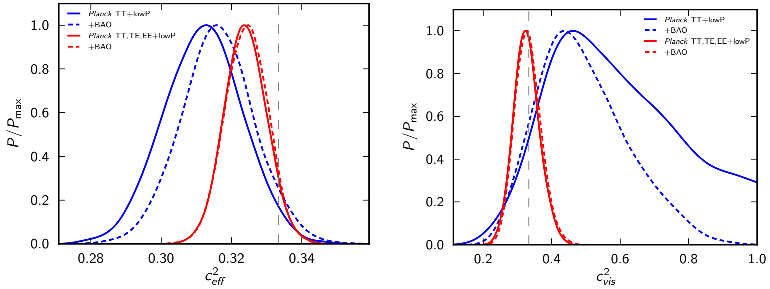
- $\Lambda$CDM$+c^2_{\rm eff}+c^2_{\rm vis}$: The standard values $(c^2_{\rm eff},\ c^2_{\rm vis})$ are always well within the 95% confidence intervals
  $\Rightarrow$ the data gives no indication of exotic physics, but further evidence in favour of the detection of the C$\nu$B.

- The bounds on the parameters of the $\Lambda$CDM model are significantly broader than in the base $\Lambda$CDM case
  $\Rightarrow$ polarization data can help break these degeneracies. Measurements of the shape of the matter power spectrum should also greatly help to lift the $\{n_s,\ c^2_{\rm eff},\ c^2_{\rm vis}\}$ degeneracies.

- The $(c^2_{\rm eff},\ c^2_{\rm vis})$ constraints are robust to the addition of extra cosmological parameters
  no degeneracy between $c^2_{\rm eff}+c^2_{\rm vis}$ and the total neutrino mass $M_\nu \equiv \sum m_\nu$, the effective number of relativistic species $N_{\rm eff}$ and the dark energy equation of state parameter $w$. There is a slight anti-correlation between $\alpha_s$ and $c^2_{\rm eff}$.

# Recent Planck results on $c^2_{\rm eff}$ and $c^2_{\rm vis}$

1D posterior distributions for the neutrino perturbation parameters $c^2_{\rm eff}$ and $c^2_{\rm vis}$




| Parameters | TT+TE+EE+lowP | TT+TE+EE+lowP+BAO |
|---|---|---|
| $c^2_{\rm eff}$ | $0.3240 \pm 0.0060$ | $0.3242 \pm 0.0059$ |
| $c^2_{\rm vis}$ | $0.327 \pm 0.037$ | $0.331 \pm 0.037$ |

*Planck collaboration, 2015*

strong evidence for neutrino anisotropies with the standard values $c^2_{\rm vis} = 1/3$ and $c^2_{\rm eff} = 1/3$. A vanishing value of $c^2_{\rm vis}$ is excluded at more than 95 % level from the Planck temperature data, about $9\,\sigma$ when Planck polarization data are included.

# Conclusions

- Already with Planck 2013 data release and WMAP low $\ell$ polarisation data alone or in combination with BAO, we can conclude that these parameters are not significantly degenerate with any other
$\Rightarrow$ the detection of the anisotropies of the cosmic neutrino background is robust.

- we are in the era of precision cosmology
$\Rightarrow$ strong evidence for C$\nu$B!

# BACKUP SLIDES

# Cosmological perturbation theory

*Massive neutrinos*

$$\begin{aligned}
\dot{\Psi}_0 &= -\frac{qk}{\epsilon}\Psi_1 + \frac{1}{3}M_{\mathrm{continuity}}\frac{d\ln f_0}{d\ln q} \,, \\
\dot{\Psi}_1 &= \frac{qk}{3\,\epsilon}(\Psi_0 - 2\Psi_2) - \frac{\epsilon}{3qk}M_{\mathrm{euler}}\frac{d\ln f_0}{d\ln q} \,, \\
\dot{\Psi}_2 &= \frac{qk}{5\epsilon}(2\Psi_1 - 3\Psi_3) - \frac{2}{15}M_{\mathrm{shear}}\frac{d\ln f_0}{d\ln q} \,.
\end{aligned}$$

- In the case of light relics experiencing a non-relativistic transition such as massive neutrinos, the Boltzmann equation cannot be integrated over momentum, and one must solve one hierarchy per momentum bin.
- $f_0$: unperturbed phase space distribution function; $\Psi_l$: $l$th Legendre component of perturbation to $f_0$ *C.-P. Ma, E. Bertschinger, astro-ph/9506072*

# Impact of $(c^2_{\rm eff}, c^2_{\rm vis})$ on CMB

- The CMB is sensitive to neutrino perturbations through gravitational interactions

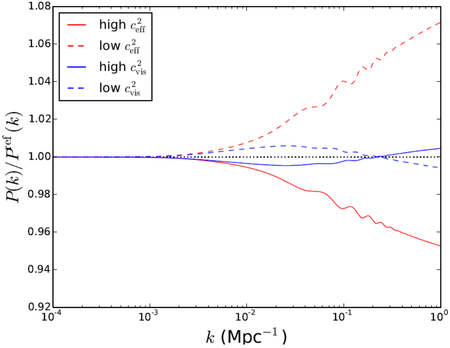
- In the temperature power spectrum, effect of $c^2_{\rm eff}$ and $c^2_{\rm vis}$: change in the amplitude of the spectrum, caused by different amounts of gravitational boosting.

  lower $c^2_{\rm eff}$: more density contrast in the neutrino species (perturbations grow as power law of the scale factor above the sound-horizon, $s_{\rm eff} = \int c_{\rm eff}\, d\tau$), the metric fluctuations decay more slowly near SH crossing, the boosting of photon perturbations is reduced and the amplitude of the CMB fluctuations is lower.

  lower $c^2_{\rm vis}$: the neutrino anisotropic stress is smaller at the time when the gravitational boosting of photon fluctuations is relevant, and this results in larger fluctuations (boost the amplitude of the CMB acustic peaks $\rightarrow$ this can be compensate by lower value of $n_s$).

- In the polarisation power spectrum: effects similar to those present in the temperature power spectrum

# Impact of $(c_{\rm eff}^2, c_{\rm vis}^2)$ on $P(k)$




While $c_{\rm vis}^2$ effects are within 1%, we find that $c_{\rm eff}^2$ can cause changes of several percent already at $k = 0.2$ Mpc$^{-1}$ for the values we have studied.
$\Rightarrow$ Forthcoming large-scale structure surveys have in principle the statistical power to measure sub-percent effects on these scales.

# Impact of $(c^2_{\rm eff}, c^2_{\rm vis})$ on $P(k)$

Effect on matter power spectrum:

- smaller $c^2_{\rm eff}$, $|\delta_\nu|$ starts growing a bit earlier and from a slightly larger equilibrium value; the ratio $\delta_\nu/\delta_{CDM}$ at a given scale and time is larger
- CDM and baryon collapse at a slightly faster rate and the small-scale matter power spectrum is enhanced

# Results

Constraints from CMB+lensing data on the values of the cosmological parameters for the $\Lambda$CDM$+c^2_{\rm eff}+c^2_{\rm vis}+..$ models. We report the 95% C.L. upper limit for the total neutrino mass $M_\nu$, the mean values and $1\sigma$ ranges for all the other parameters.

| **CMB + lensing** | | | | | |
|---|---|---|---|---|---|
| Parameter | $+N_{\rm eff}$ | $+m_\nu$ | $+w$ | $+\ \alpha_s$ | $+\ N_{\rm eff}\ +\ m_\nu$ |
| $100\ \omega_b$ | $2.174^{+0.057}_{-0.055}$ | $2.124^{+0.048}_{-0.056}$ | $2.179^{+0.052}_{-0.056}$ | $2.180^{+0.050}_{-0.056}$ | $2.136^{+0.060}_{-0.068}$ |
| $\omega_{cdm}$ | $0.1181^{+0.0054}_{-0.0051}$ | $0.1186^{+0.0037}_{-0.0036}$ | $0.1164^{+0.0037}_{-0.0035}$ | $0.1163 \pm 0.0035$ | $0.1184 \pm 0.0055$ |
| $H_0$ | $68.3 \pm 1.1$ | $63.7^{+4.1}_{-2.6}$ | $85.5^{+14.0}_{-4.5}$ | $68.3^{+1.1}_{-1.2}$ | $65.4^{+4.0}_{-4.2}$ |
| $10^{+9} A_s$ | $2.34^{+0.12}_{-0.16}$ | $2.36 \pm 0.13$ | $2.27^{+0.12}_{-0.15}$ | $2.35^{+0.13}_{-0.15}$ | $2.39 \pm 0.14$ |
| $n_s$ | $0.991^{+0.024}_{-0.025}$ | $0.981^{+0.020}_{-0.018}$ | $0.979^{+0.022}_{-0.021}$ | $0.980^{+0.022}_{-0.019}$ | $0.987^{+0.025}_{-0.022}$ |
| $\tau_{reio}$ | $0.093^{+0.013}_{-0.015}$ | $0.093^{+0.013}_{-0.014}$ | $0.088^{+0.012}_{-0.014}$ | $0.095^{+0.013}_{-0.016}$ | $0.094^{+0.013}_{-0.016}$ |
| $c^2_{\rm eff}$ | $0.314 \pm 0.013$ | $0.309^{+0.013}_{-0.014}$ | $0.318^{+0.013}_{-0.014}$ | $0.320^{+0.014}_{-0.016}$ | $0.312^{+0.014}_{-0.013}$ |
| $c^2_{\rm vis}$ | $0.49^{+0.11}_{-0.21}$ | $0.51^{+0.14}_{-0.19}$ | $0.46^{+0.11}_{-0.23}$ | $0.50^{+0.13}_{-0.22}$ | $0.56^{+0.14}_{-0.24}$ |
| $N_{\rm eff}$ | $3.22^{+0.32}_{-0.37}$ | – | – | – | $3.17^{+0.34}_{-0.37}$ |
| $M_\nu$ [eV] | – | $< 1.03$ | – | – | $< 1.05$ |
| $w$ | – | – | $-1.49^{+0.18}_{-0.38}$ | – | – |
| $\alpha_s$ | – | – | – | $-0.010 \pm 0.010$ | – |