The effective number of neutrinos: Standard and non-standard scenarios

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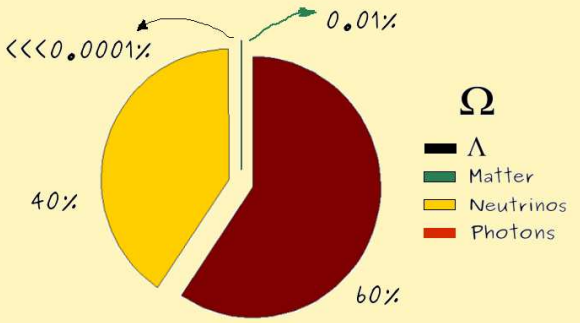
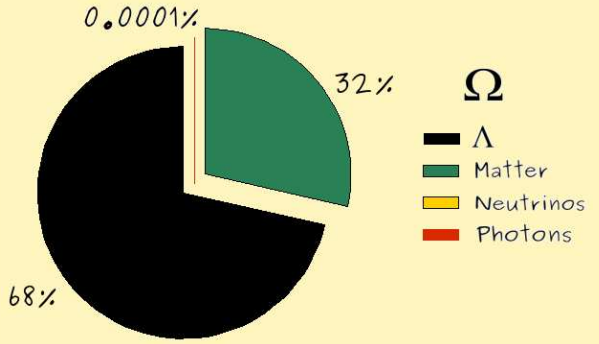
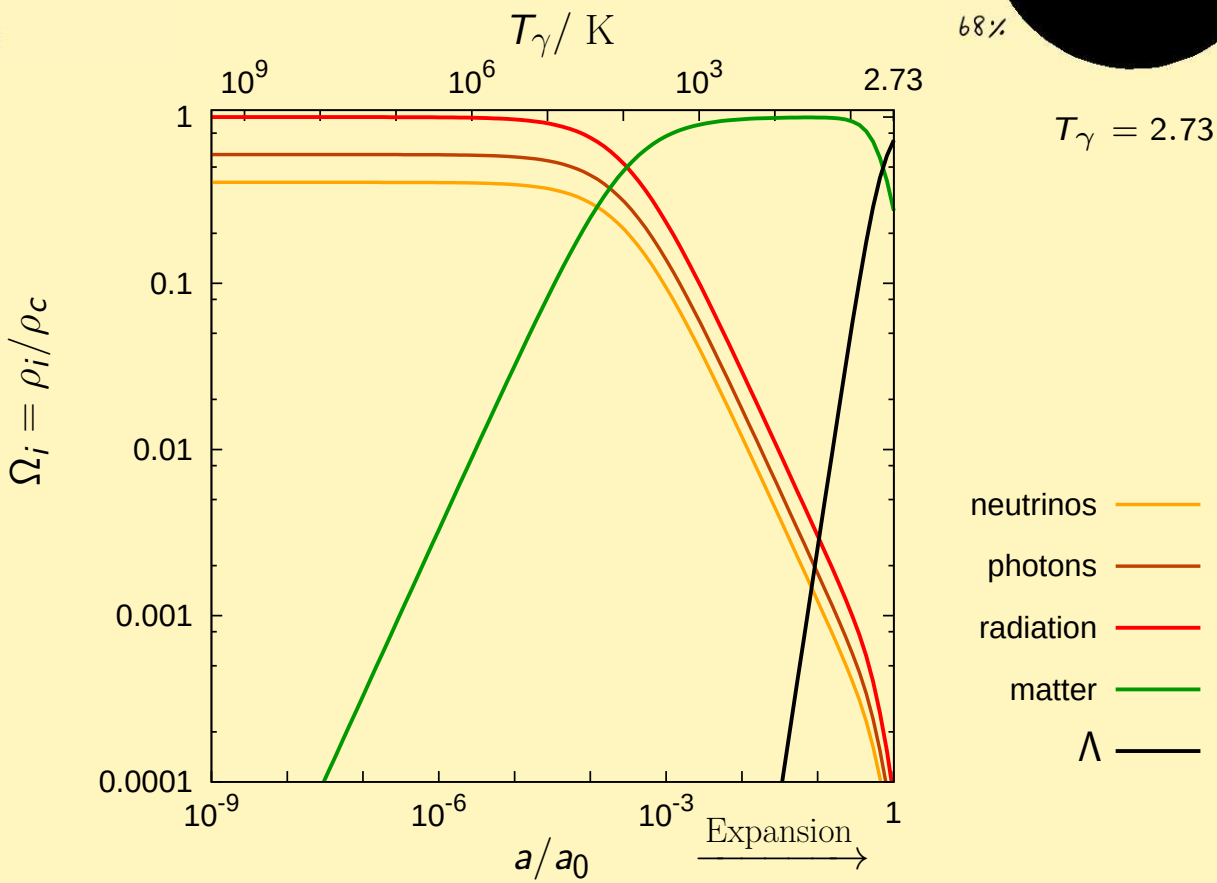
Components of the Universe



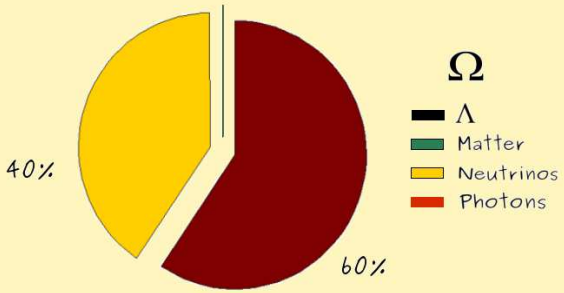
$T_\gamma = 10^8\ \mathrm{K}\ \ (8.6\,\mathrm{keV})$



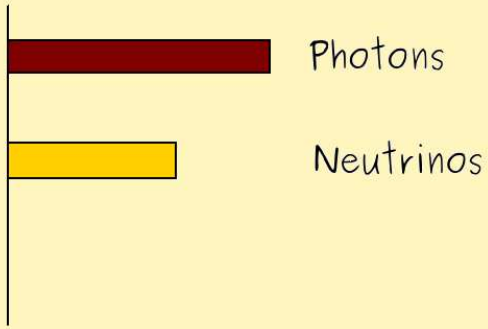
$T_\gamma = 2.73\ \mathrm{K}$



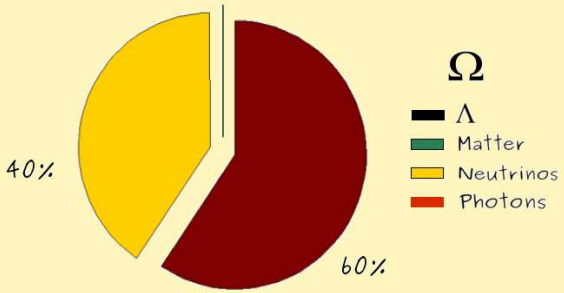
Radiation energy density in the radiation era



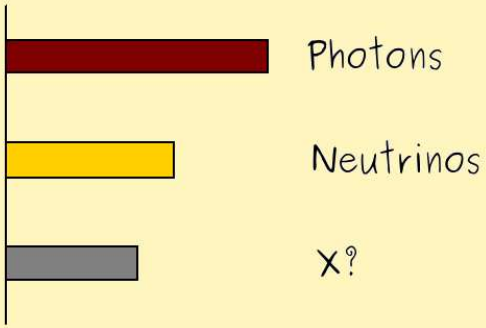
$$\rho_R = \rho_\gamma + \rho_\nu$$



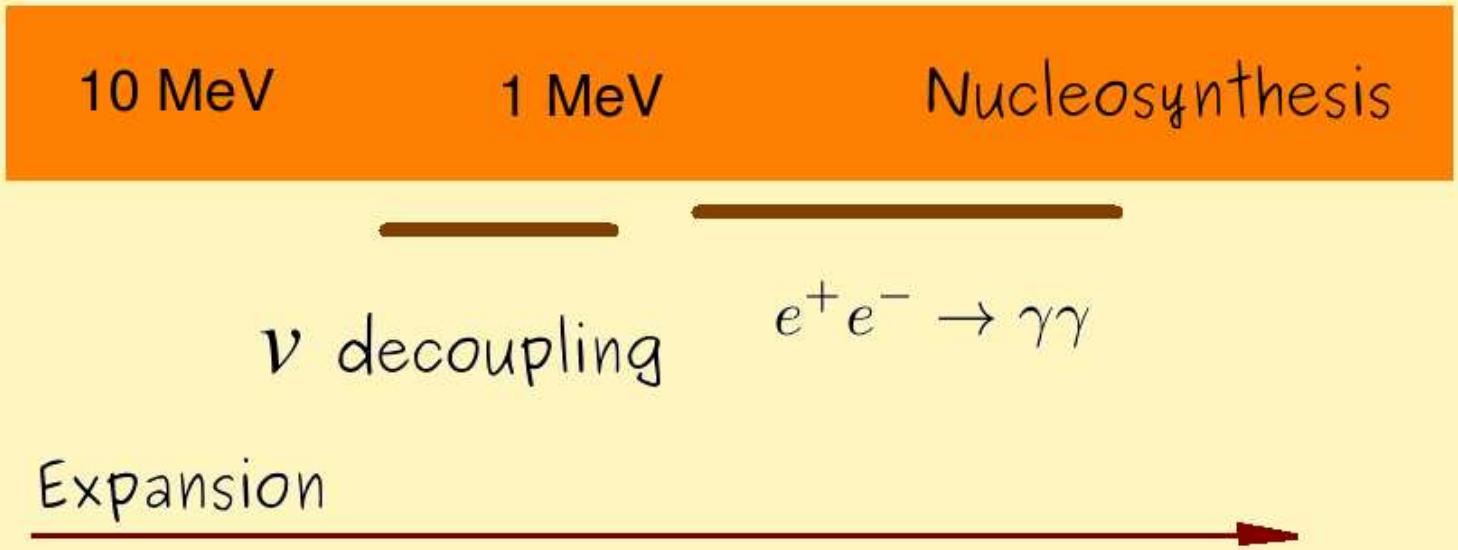
Radiation energy density in the radiation era



$$\rho_R = \rho_\gamma + \rho_\nu + \rho_X$$



ν decoupling and $e^{\pm}$ annihilations



Effective number of neutrinos

$$\rho_\nu^0 = \frac{7}{8}\left(\frac{T_\nu}{T_\gamma}\right)^4 \rho_\gamma \qquad \left.\frac{T_\nu}{T_\gamma}\right|_{\text{inst.dec.}} = \left(\frac{4}{11}\right)^{1/3}$$

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$$\rho_R = \left(1 + 3\frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\right)\rho_\gamma + \rho_X$$

Effective number of neutrinos

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

N_ν^{eff} accounts for all contributions to ρ_R different from ρ_γ

$$N_\nu^{\text{eff}} \equiv \left(\frac{\rho_R - \rho_\gamma}{\rho_{\nu_{\text{eq}}}}\right)\left(\frac{\rho_\gamma|_{\text{inst.dec.}}}{\rho_\gamma}\right)$$

Standard neutrinos only

$N_\nu^{\text{eff}} \approx 3$

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$N_\nu^{\rm eff}$ accounts for all contributions to ρ_R different from ρ_γ

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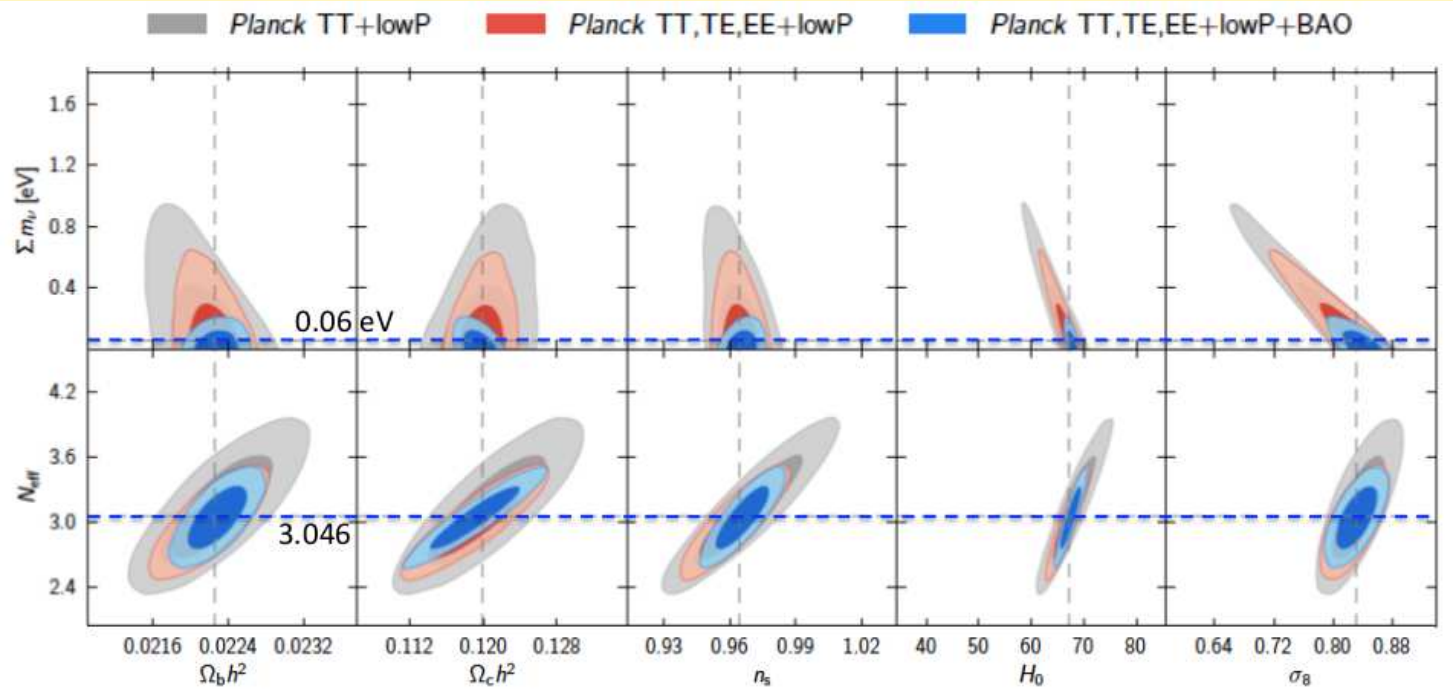
Standard neutrinos only

$N_\nu^{\rm eff} \approx 3$

Not to be confused with the number of neutrino generations

Measured value



$N_\nu^{\rm eff} = 3.13 \pm 0.32$ *Planck* TT + lowP
$N_\nu^{\rm eff} = 3.15 \pm 0.23$ *Planck* TT + lowP + BAO
$N_\nu^{\rm eff} = 2.99 \pm 0.20$ *Planck* TT,TE,EE + lowP
$N_\nu^{\rm eff} = 3.04 \pm 0.18$ *Planck* TT,TE,EE + lowP + BAO

All 68 % C.L.

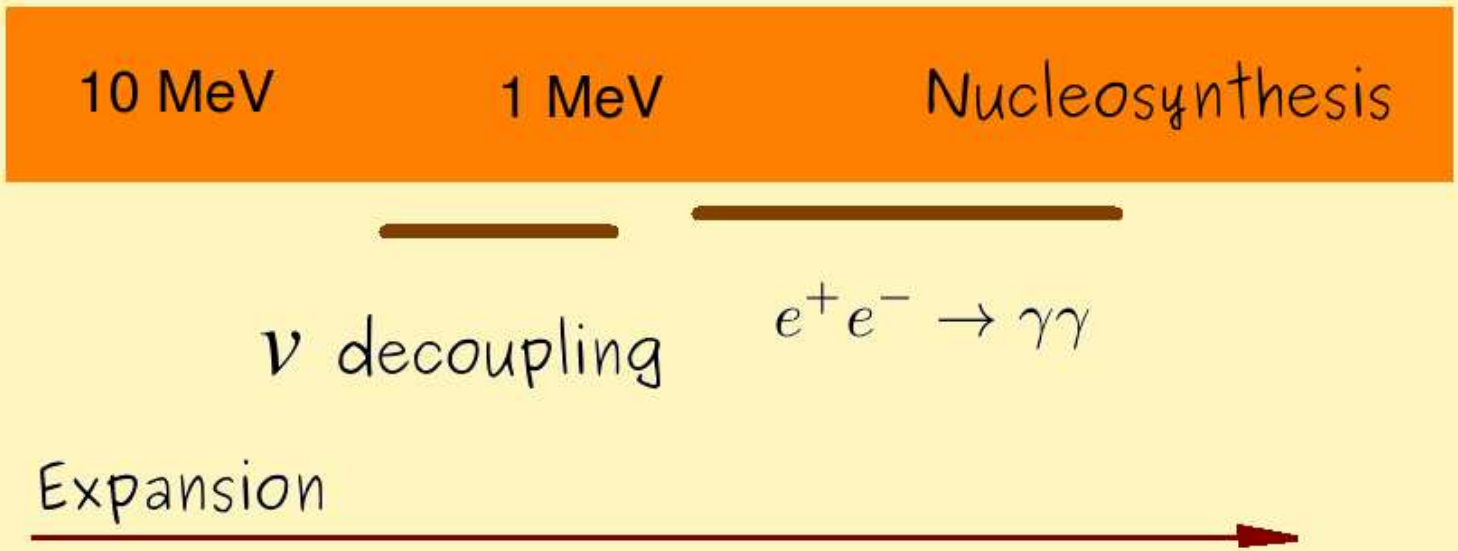
Planck collaboration,
arXiv:1502.01589

Deviation from $N_\nu^{\rm eff} = 3$ due only to neutrinos

- Neutrinos not completely decoupled when $e^\pm$ annihilate
- Finite temperature QED corrections
- Non-Standard Interactions (NSI)
- Low reheating scenarios

Beyond the instantaneous decoupling approximation

- ν decoupling and $e^{\pm}$ annihilations were not fully disconnected
- After $e^{\pm}$ annihilations $f_\nu = f_\nu^{\rm eq} + \delta f_{\nu_\alpha}$ and $T_\gamma < T_\gamma|_{\rm inst.dec.}$



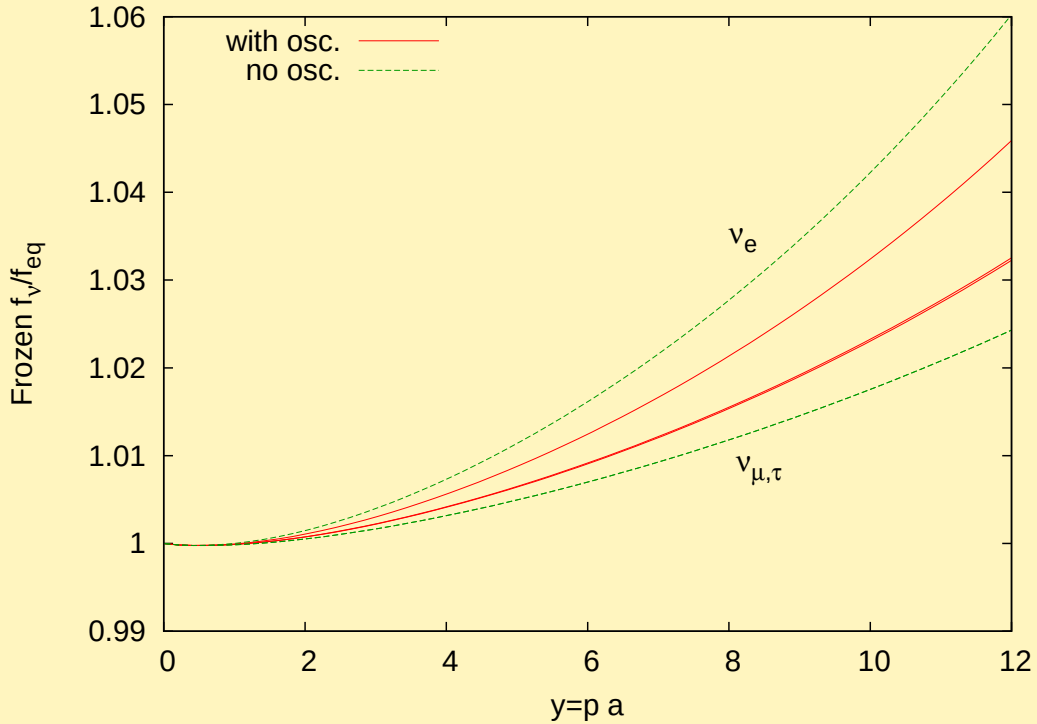
Deviation of f_ν from equilibrium

Main source of deviation

- Interaction with $e^{\pm}$

Also important

- ν oscillations
- ν self-interactions



Computing the deviation from f_{eq}

- Density matrix formalism

$$\varrho_p = \begin{pmatrix} f_{\nu_e} & A & B \\ A^* & f_{\nu_\mu} & C \\ B^* & C^* & f_{\nu_\tau} \end{pmatrix}$$

f_ν: occupational numbers

A, B, C: phase information, non-zero if oscillations are considered

- Solve Boltzmann equations with $I_{\mathrm{coll}} \neq 0$

$$(\partial_t - Hp\partial_p)\,\varrho_p = -i\frac{1}{2p}\left[\left(\mathbb{M}_F - 2p\frac{8\sqrt{2}G_F p}{3m_W^2}\rho_e \underline{\underline{\varepsilon}}\right), \varrho_p\right] + I_{\mathrm{coll}}\left[\varrho_p\right]$$

Collision integrals treatment

When oscillations are added we need to solve 9 collision integrals, one for each real entry of ϱ_p

$$I_{\rm coll} \propto \frac{1}{E_1}\int (2\pi)^4 \delta^{(4)}(p_1+p_2-p_3-p_4) F(f_{e^\pm}, \varrho, G^{R,L}) S |\mathcal{M}|^2_{12\to 34} \prod_{i=2}^{4} \frac{d^3\vec{p}_i}{2E_i(2\pi)^3}$$

- Reduce analytically from 9 to 2 integrals
- Solve numerically with a grid on the incoming neutrino momentum
- **We do not consider damping factors for the processes**

$N_\nu^{\rm eff} > 3$ (neutrinos only)

Standard case

$N_\nu^{\rm eff} = 3.044$

Non-Standard neutrino-electron Interactions

$$\mathcal{L}_{\rm NSI}^{\alpha\beta} = -2\sqrt{2} G_F \sum_P \epsilon_{\alpha\beta}^P \left(\bar{\nu}_\alpha \gamma^\mu L \nu_\beta\right) \left(\bar{e} \gamma_\mu P e\right)$$

$3.040 \leq N_\nu^{\rm eff} \leq 3.059$

$$\begin{cases} \epsilon_{ee}^R = -0.42 \\ \epsilon_{ee}^L = -0.09 \end{cases} \qquad \begin{cases} \epsilon_{\tau\tau}^R = 0.37 \\ \epsilon_{\tau\tau}^L = -0.37 \end{cases}$$

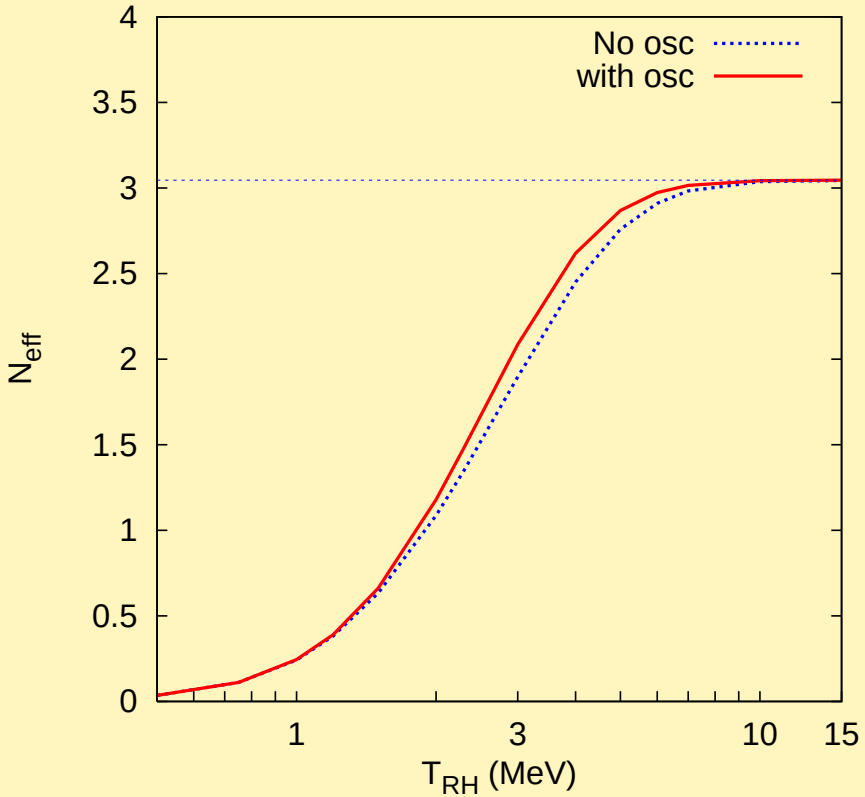
Mangano et al 2005,
Mangano et al 2006,
P.F. de Salas & S. Pastor, in preparation

D.V. Forero & M.M. Guzzo 2011

$N_\nu^{\rm eff} < 3$?

Low-Reheating scenarios

If $T_{RH} < 10\,\mathrm{MeV}$ interactions are not enough to have standard neutrinos in eq.



Stronger bound

(from CMB – 95 % C.L.)

$$N_\nu^{\rm eff} \geq 2.81$$

P. F. de Salas et al,
arXiv:1511.00672

S. Hannestad 2004
K. Ichikawa et al 2005

Conclusions

- Measurements in cosmology are getting more and more precise.

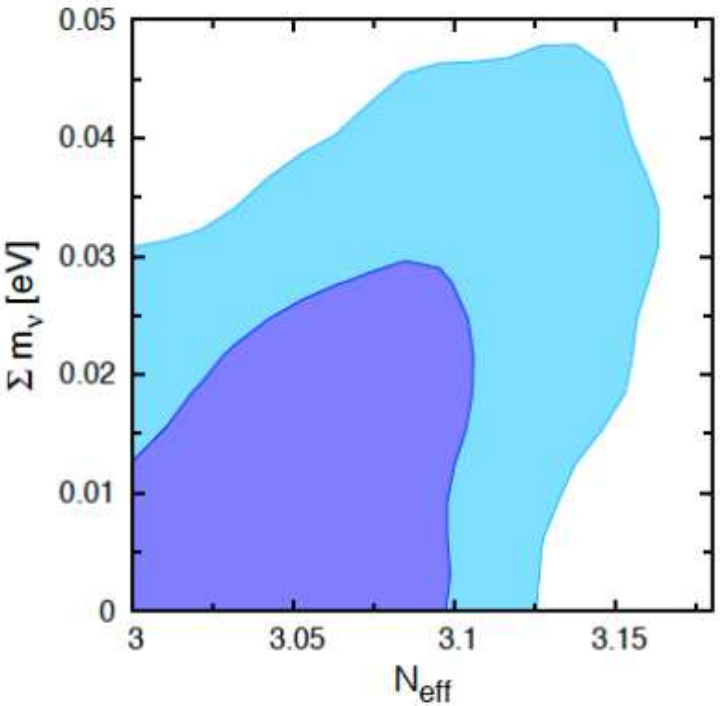
- In the Standard case (neutrinos only) $N_\nu^{\rm eff} = 3.044$, and in presence of Non-Standard Interactions with electrons $3.040 < N_\nu^{\rm eff} < 3.059$

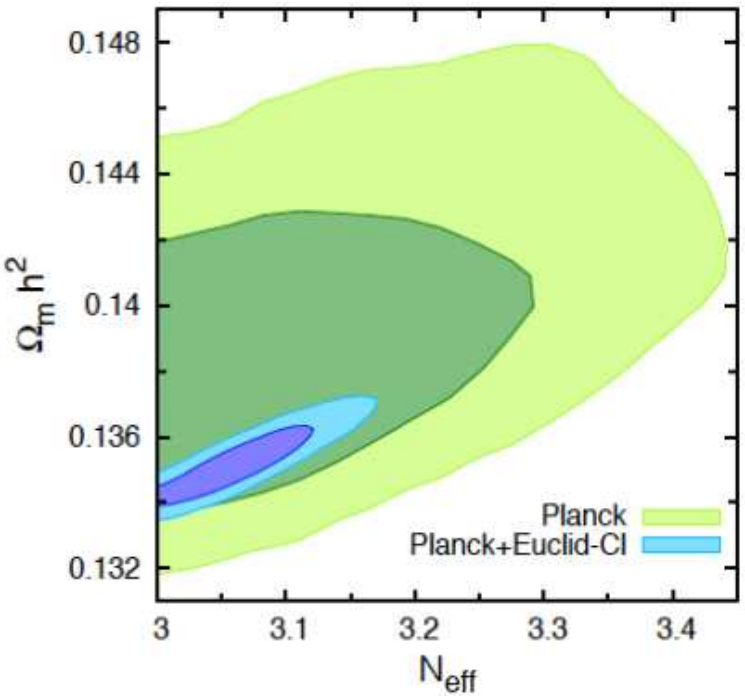
- $N_\nu^{\rm eff} < 3$ is also possible in low reheating scenarios. Most stringent bound $N_\nu^{\rm eff} \geq 2.81$

Backup

Future sensitivities to N_{eff} and Σm_ν

Example of forecast: PLANCK + Euclid-like photometric galaxy cluster survey





Data		Planck+Euclid-Cl	
Model		wCDM+m_ν+$N_{\rm eff}$	ΛCDM+m_ν+$N_{\rm eff}$+$\Omega_{\rm k}$
$\sum m_\nu$ [eV]	68% CL	< 0.024	< 0.024
	95% CL	< 0.046	< 0.046
$N_{\rm eff}$	95% CL	< 3.16	< 3.17

M.C.A. Cerbolini et al, JCAP 06 (2013) 020 [arXiv:1303.4550]

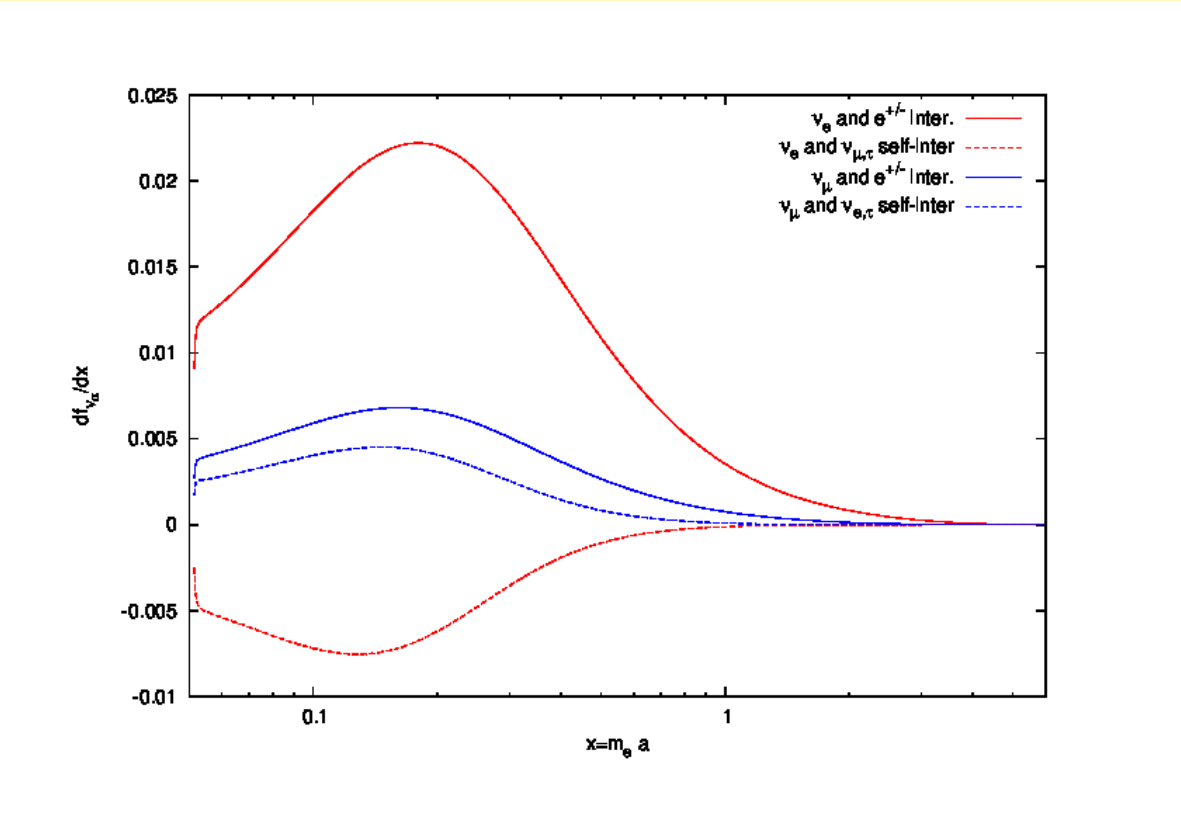
$N_\nu^{\rm eff}$ and $\sum m_\nu$ simultaneously constraint

$$\begin{cases} N_\nu^{\rm eff} = 3.2 \pm 0.5 \\ \sum m_\nu < 0.32\,{\rm eV} \end{cases}$$

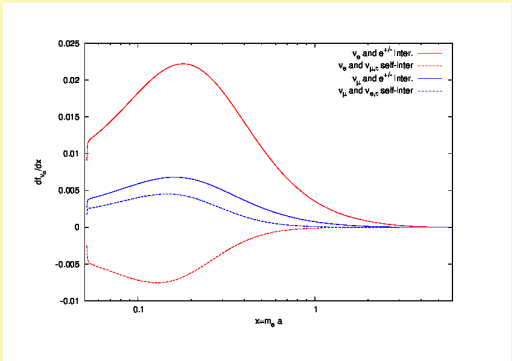
95 % *Planck* TT + lowP + lensing + BAO

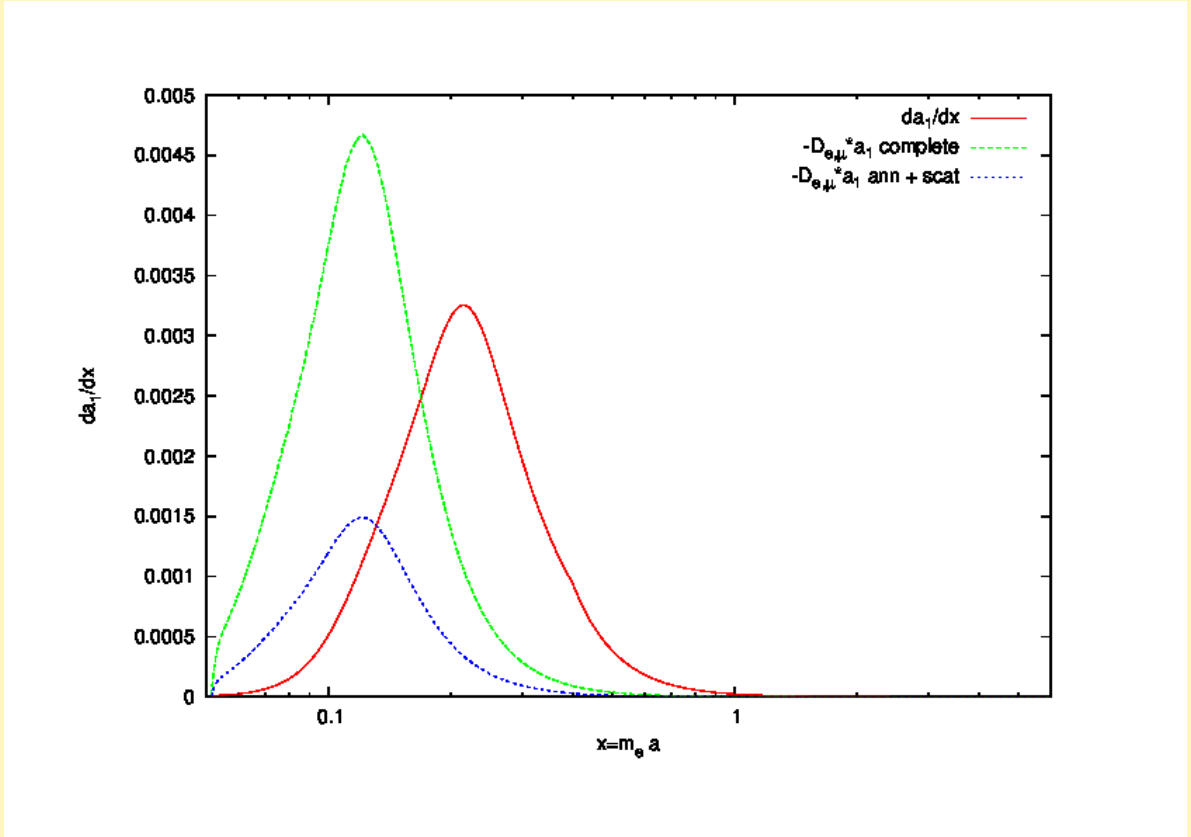
Planck collaboration, arXiv:1502.01589

Why not to consider damping factors



Why not to consider damping factors





Evolution equations

Comoving variables

$$x = m_e R(t), \qquad y = pR(t), \qquad z = T_\gamma R(t)$$

$R(t) = \frac{1}{T_\nu} = \frac{1}{T_\gamma}$ at high temperatures

Boltzmann equations

$$(\partial_t - Hp\partial_p)\,\varrho_p = -i\frac{1}{2p}\left[\left(\mathbb{M}_F - 2p\frac{8\sqrt{2}G_F p}{3m_W^2}\rho_e\underline{\underline{\varepsilon}}\right), \varrho_p\right] + \mathcal{I}\left[\varrho_p\right]$$

Continuity equation

$$x\frac{d\bar{\rho}}{dx} = \bar{\rho} - 3\bar{P} \quad {}_{(\bar{\rho},\bar{P}\ \text{comoving})} \longrightarrow \frac{dz}{dx}$$

Density matrix

$$\varrho_p = \begin{pmatrix} f_{\nu_e} & a_1 + ia_2 & b_1 + ib_2 \\ a_1 - ia_2 & f_{\nu_\mu} & c_1 + ic_2 \\ b_1 - ib_2 & c_1 - ic_2 & f_{\nu_\tau} \end{pmatrix}$$

f_ν: occupational numbers

a_i, b_i, c_i: phase information

Non-Standard Interactions (NSI)

Oscillation matrix

$$\underline{\underline{\varepsilon}} = \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau} & \epsilon_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix} \qquad \epsilon_{\alpha\beta} = \epsilon^R_{\alpha\beta} + \epsilon^L_{\alpha\beta}$$

Coupling matrices

$$G^L = \begin{pmatrix} g_L + \epsilon^L_{ee} & \epsilon^L_{e\mu} & \epsilon^L_{e\tau} \\ \epsilon^L_{e\mu} & \tilde{g}_L + \epsilon^L_{\mu\mu} & \epsilon^L_{\mu\tau} \\ \epsilon^L_{e\tau} & \epsilon^L_{\mu\tau} & \tilde{g}_L + \epsilon^L_{\tau\tau} \end{pmatrix} \qquad G^R = \begin{pmatrix} g_R + \epsilon^R_{ee} & \epsilon^R_{e\mu} & \epsilon^R_{e\tau} \\ \epsilon^R_{e\mu} & g_R + \epsilon^R_{\mu\mu} & \epsilon^R_{\mu\tau} \\ \epsilon^R_{e\tau} & \epsilon^R_{\mu\tau} & g_R + \epsilon^R_{\tau\tau} \end{pmatrix}$$

Collision integrals

Scattering processes with $e^{\pm}$

$$\mathcal{I}_{\nu e^{\pm}\to\nu e^{\pm}} = \frac{1}{2}\frac{2^5 G_F^2}{2|\vec{p}_1|}\int \frac{d^3\vec{p}_2}{(2\pi)^3 2E_2}\frac{d^3\vec{p}_3}{(2\pi)^3 2|\vec{p}_3|}\frac{d^3\vec{p}_4}{(2\pi)^3 2E_4}(2\pi)^4\delta^{(4)}(p_1+p_2-p_3-p_4)$$
$$\times\Big\{4(p_1\cdot p_4)(p_2\cdot p_3)F^{RR}_{scatt}(\nu^{(1)},e^{(2)},\nu^{(3)},e^{(4)}) + 4(p_1\cdot p_2)(p_3\cdot p_4)F^{LL}_{scatt}(\nu^{(1)},e^{(2)},\nu^{(3)},e^{(4)})$$
$$-2(p_1\cdot p_3)m_e^2\left(F^{RL}_{scatt}(\nu^{(1)},e^{(2)},\nu^{(3)},e^{(4)}) + F^{LR}_{scatt}(\nu^{(1)},e^{(2)},\nu^{(3)},e^{(4)})\right)\Big\}$$

$$F^{ab}_{scatt}(\nu^{(1)},e^{(2)},\nu^{(3)},e^{(4)}) = f_4(1-f_2)G^a\varrho_3 G^b(1-\varrho_1) - f_2(1-f_4)\varrho_1 G^b(1-\varrho_3)G^a + \text{h.c.}$$

Collision integrals

Annihilation process

$$\mathcal{I}_{\nu\bar{\nu}\to e^- e^+} = \frac{1}{2}\frac{2^5 G_F^2}{2|\vec{p}_1|}\int \frac{d^3\vec{p}_2}{(2\pi)^3 2|\vec{p}_2|}\frac{d^3\vec{p}_3}{(2\pi)^3 2E_3}\frac{d^3\vec{p}_4}{(2\pi)^3 2E_4}(2\pi)^4\delta^{(4)}(p_1+p_2-p_3-p_4)$$
$$\times\Big\{4(p_1\cdot p_4)(p_2\cdot p_3)F^{LL}_{annih}(\nu^{(1)},\bar{\nu}^{(2)},e^{(3)},\bar{e}^{(4)}) + 4(p_1\cdot p_3)(p_2\cdot p_4)F^{RR}_{annih}(\nu^{(1)},\bar{\nu}^{(2)},e^{(3)},\bar{e}^{(4)})$$
$$+ 2(p_1\cdot p_2)m_e^2\left(F^{RL}_{annih}(\nu^{(1)},\bar{\nu}^{(2)},e^{(3)},\bar{e}^{(4)}) + F^{LR}_{annih}(\nu^{(1)},\bar{\nu}^{(2)},e^{(3)},\bar{e}^{(4)})\right)\Big\}$$

$$F^{ab}_{annih}(\nu^{(1)},\bar{\nu}^{(2)},e^{(3)},\bar{e}^{(4)}) = f_3\bar{f}_4 G^a(1-\bar{\varrho}_2)G^b(1-\varrho_1) - (1-f_3)(1-\bar{f}_4)\varrho_1 G^b\bar{\varrho}_2 G^a + \text{h.c.}$$

Finite temperature QED corrections

- Particles are in a thermal bath with a temperature T
- Photons and electrons acquire an additional effective mass