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

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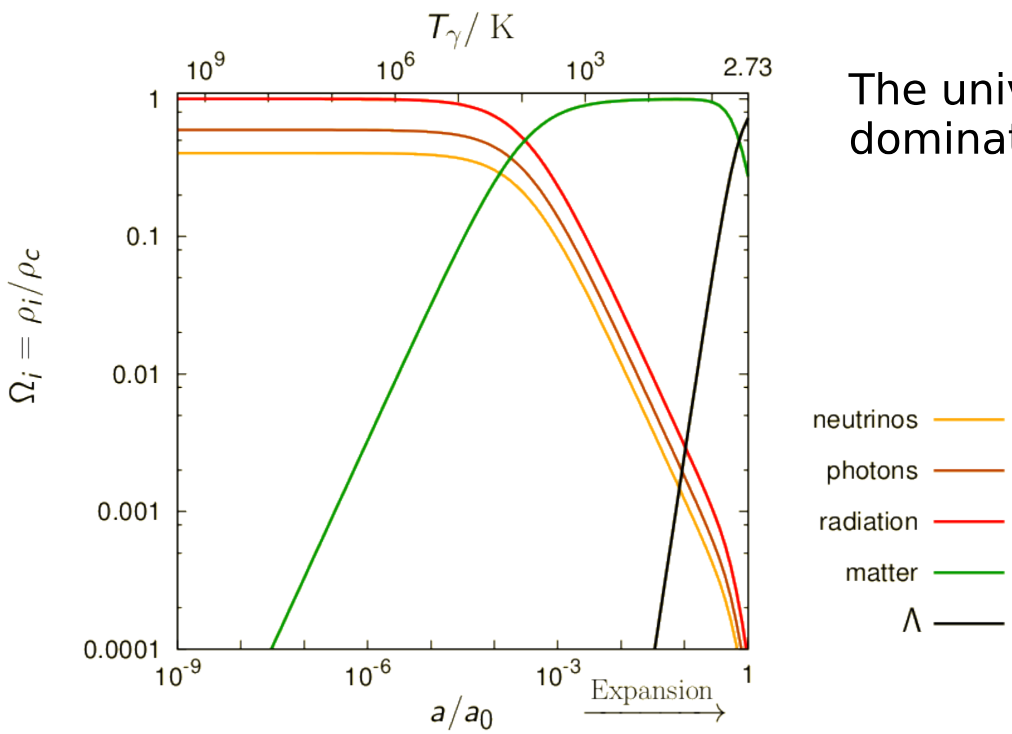
28th Texas Symposium on Relativistic Astrophysics

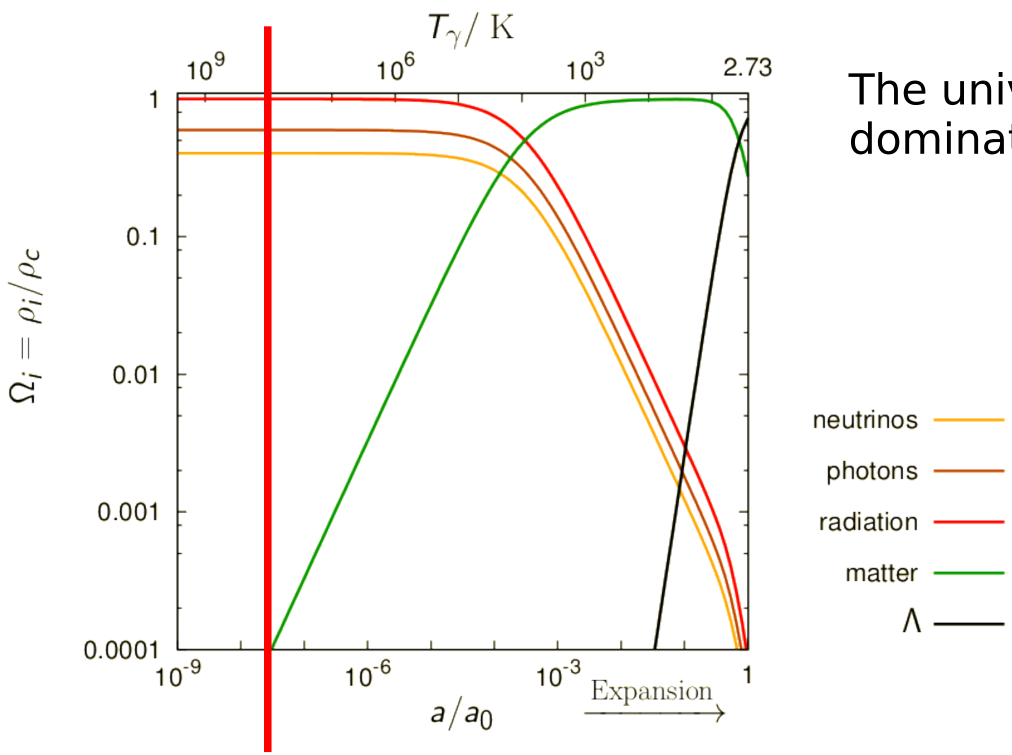
Geneva – 15th December 2015

Radiation-dominated epoch of the universe



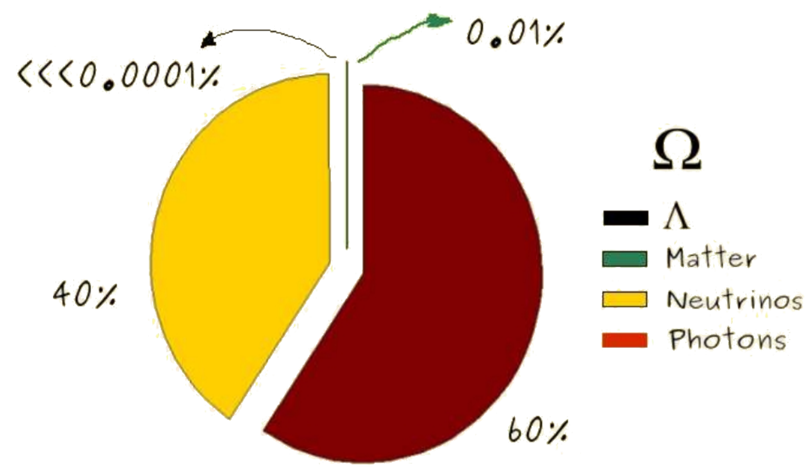
The universe has passed through epochs of domination of different components

Radiation-dominated epoch of the universe



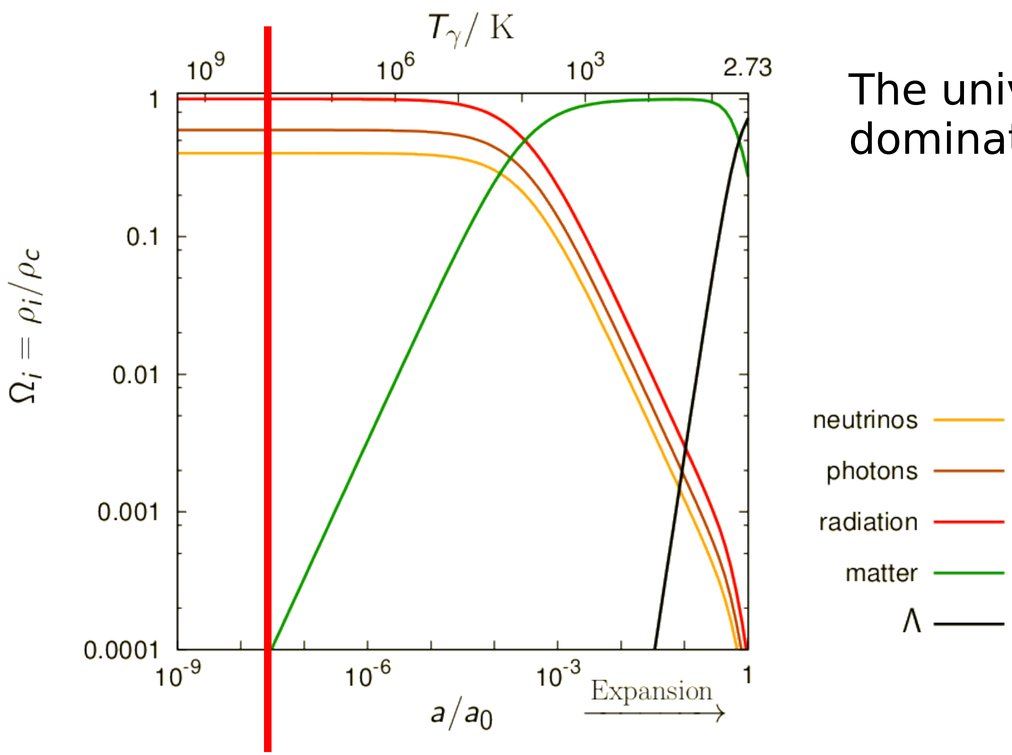
The universe has passed through epochs of domination of different components

During the radiation-dominated era



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

Radiation-dominated epoch of the universe



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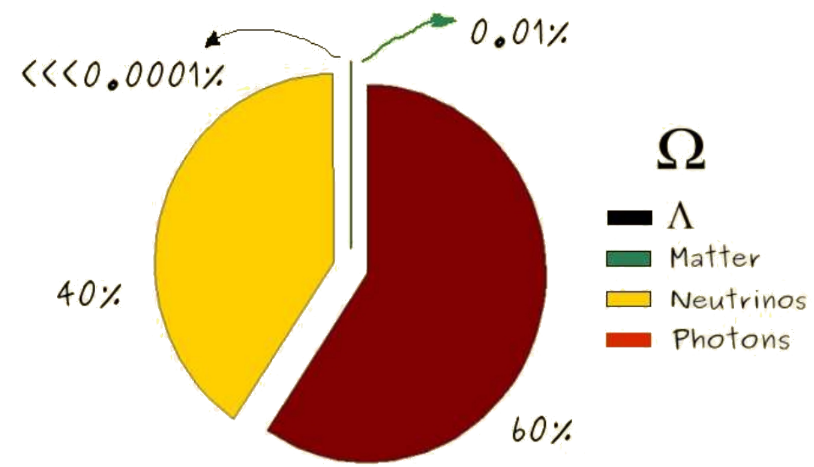
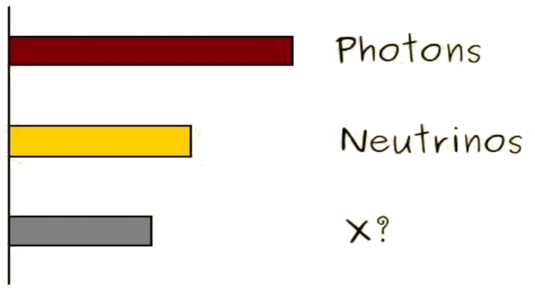
During the radiation-dominated era





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

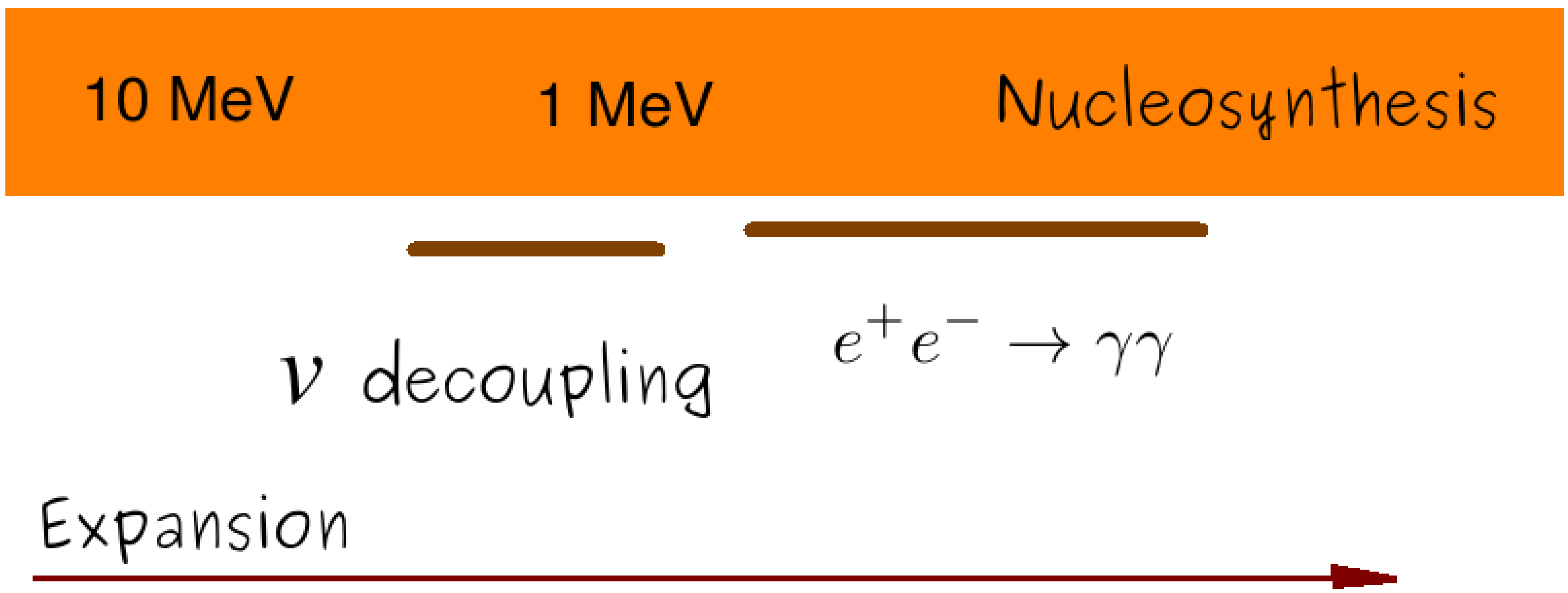
Neutrino decoupling and e^+e^- annihilations

Instantaneous decoupling approximation:

1) Neutrinos decouple completely

2) e^+e^- annihilate

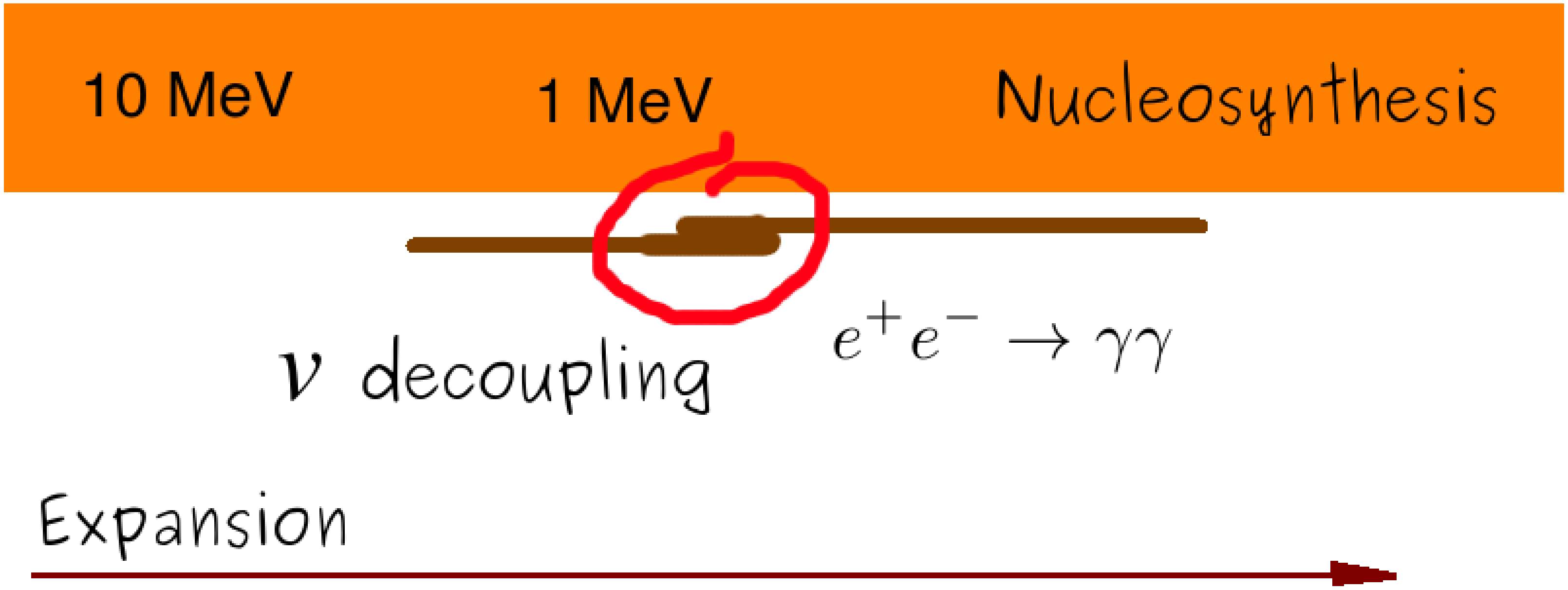
$$\left.\frac{T_\nu}{T_\gamma}\right|_{\mathrm{inst.dec.}} = \left(\frac{4}{11}\right)^{1/3}$$



Neutrino decoupling and e^+e^- annihilations

Beyond the Instantaneous decoupling approximation:

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



Effective number of neutrinos

N_{eff} accounts for any contribution to radiation other than photons

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

Another definition

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

Standard scenario: only neutrinos → $N_{eff} \approx 3$

Measured value:

$N_{eff} = 3.04 \pm 0.18$ (68% C.L.)

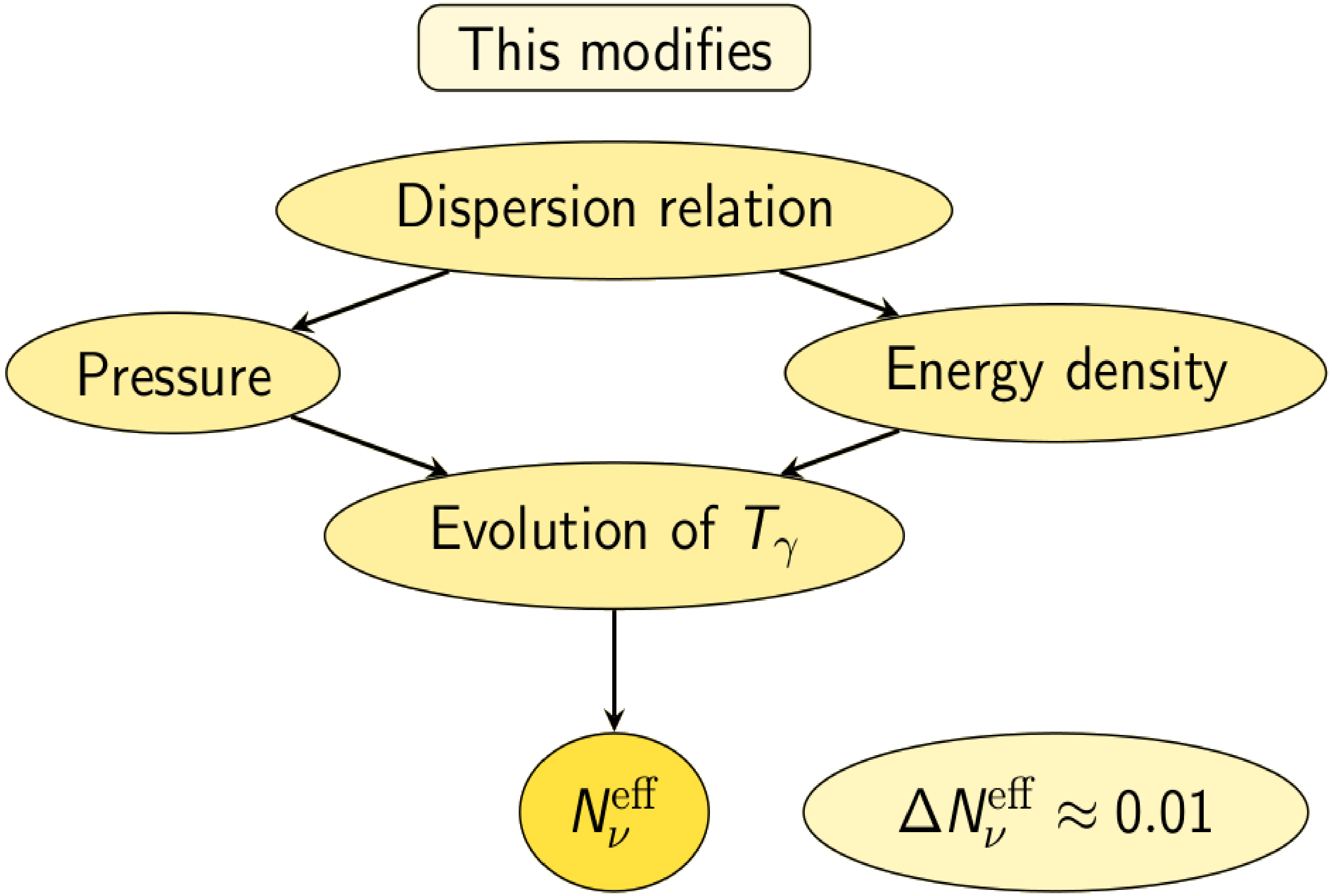
Planck TT,TE,EE+lowP+BAO

Deviation from $N_{eff} = 3$ due only to neutrinos

- Neutrino decoupling is not complete when e^+e^- annihilate
- Finite temperature QED corrections
- Non-Standard neutrino-electron Interactions (NSI)
- Very Low-Reheating scenarios ($N_{eff} < 3$)

Finite temperature QED corrections

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



Neutrino decoupling not complete when e± annihilate

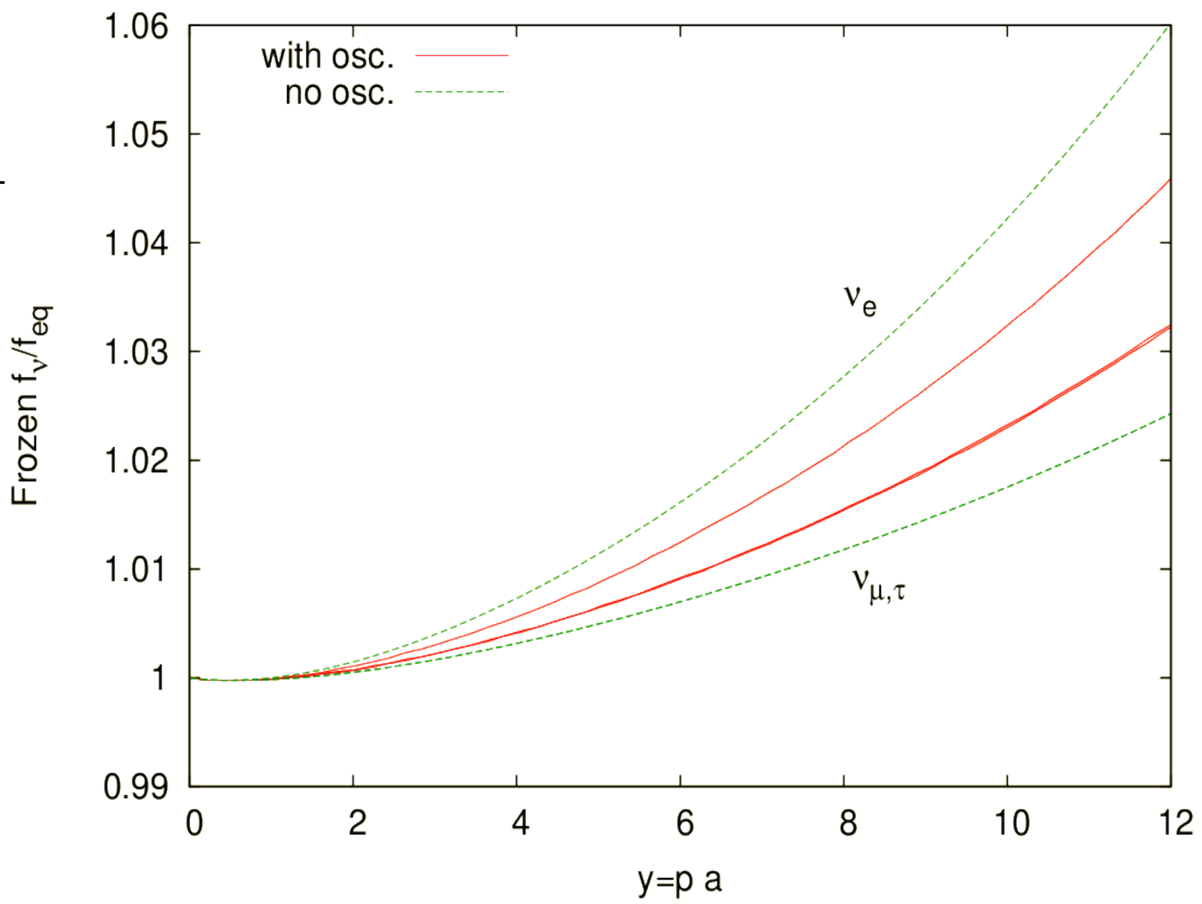
→ Deviation of f_ν from equilibrium

Main source of deviation

- Interactions with e^- and e^+

Also important

- Neutrino oscillations
- Neutrino self-interactions



Neutrino decoupling not complete when e± annihilate

→ Computing the deviation from equilibrium

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 $I_{coll} \neq 0$

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

Neutrino decoupling not complete when e± annihilate

→ Collision integrals treatment

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

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

- 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 off-diagonal terms of the density matrix**

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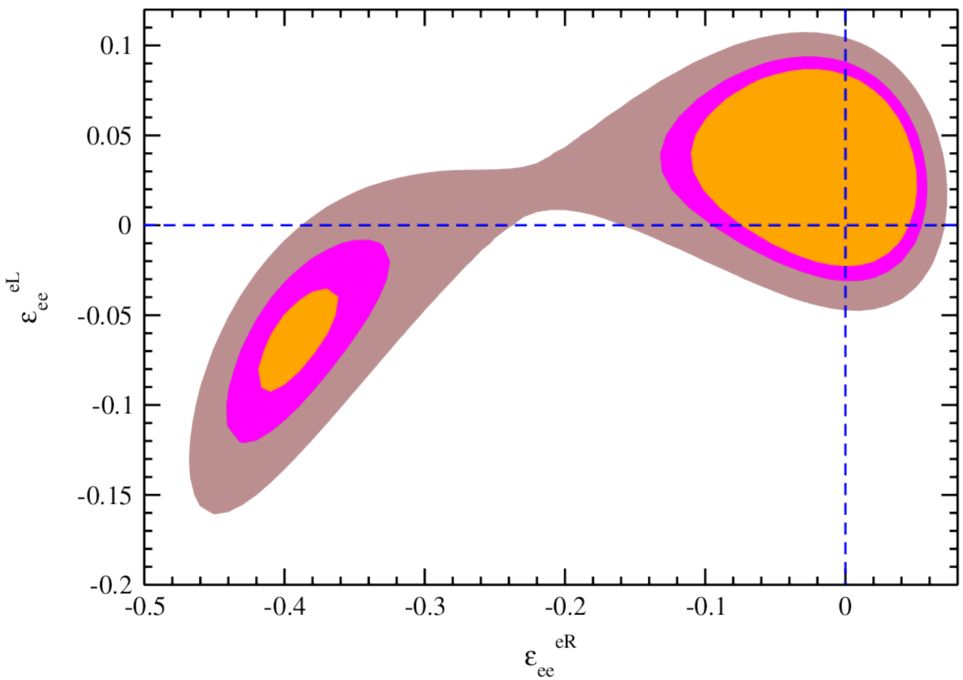
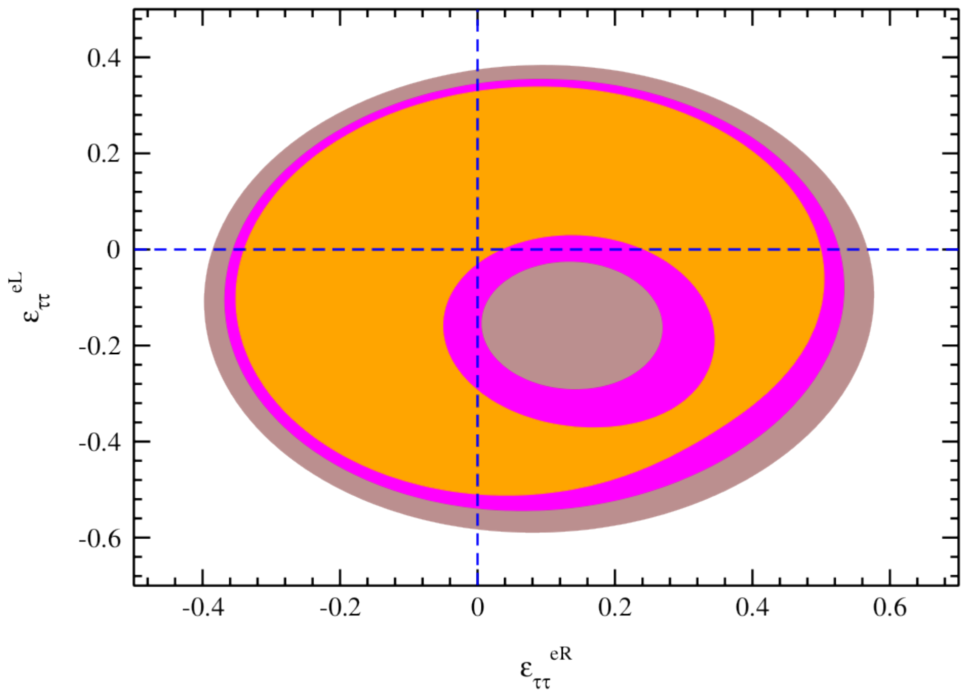
N_{eff} = 3.044

Non-Standard neutrino-electron Interactions

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





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

3.040 ≤ Neff ≤ 3.059

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

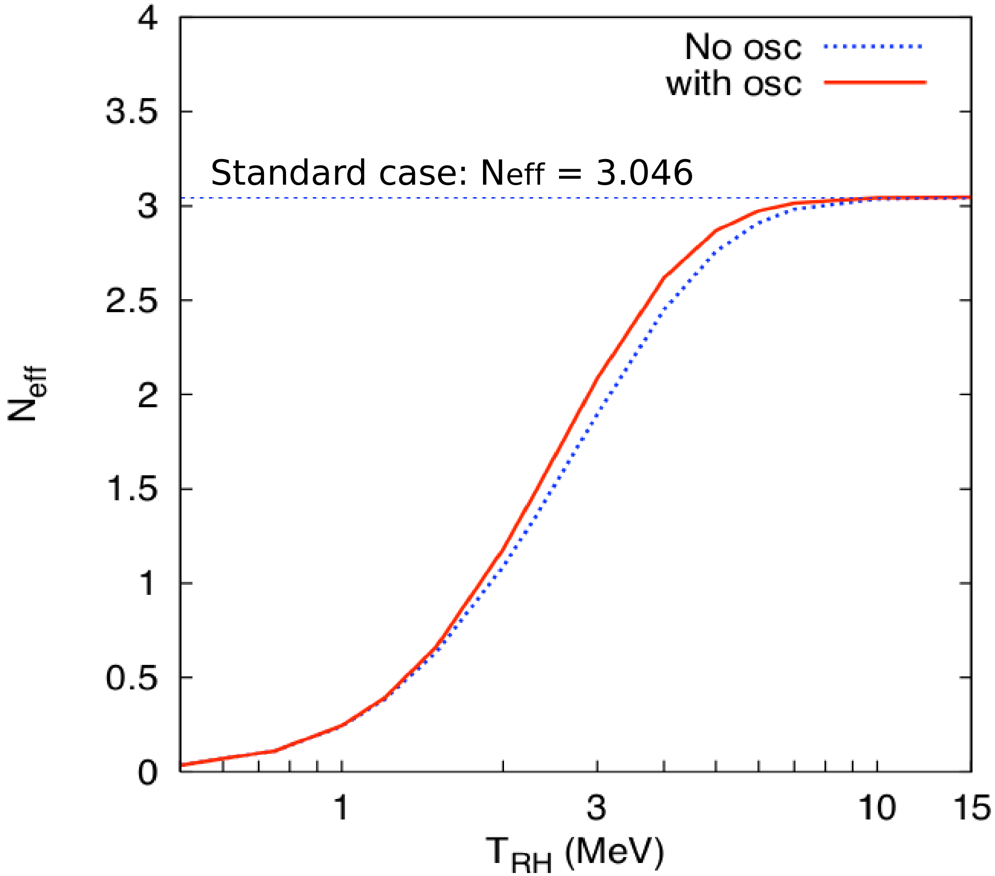
Very Low-Reheating scenarios

The last radiation-dominated era of the universe usually arises from the decaying of a massive particle, a process known as **reheating**

In the specific scenario where the so-called **reheating temperature** is as low as $T_{RH} \sim$ few MeV, neutrinos do not have time to thermalize.

This affects their contribution to the radiation content of the universe

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



P. F. de Salas *et al* (2015)

PRD *in press* (arXiv:1511.00672)

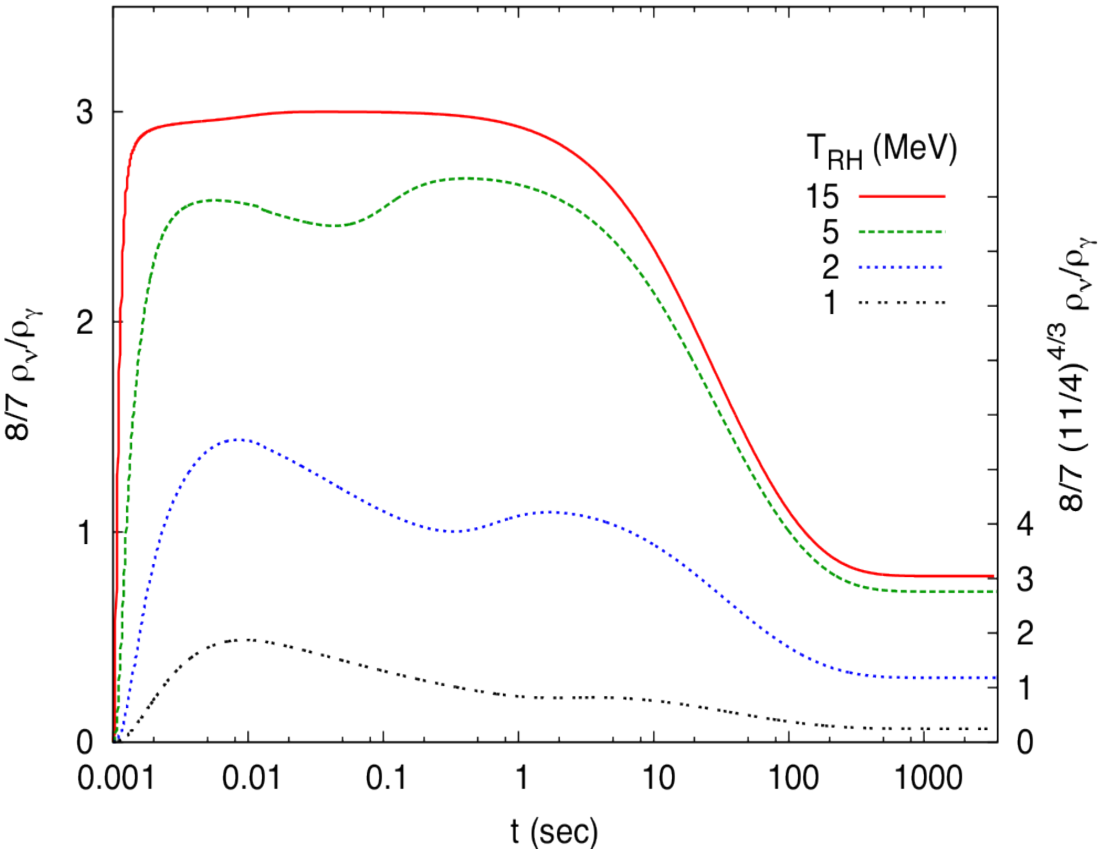
Very Low-Reheating scenarios

→ Neutrino production in LR scenarios

- We assume a massive particle ϕ decaying into relativistic particles other than neutrinos

$$\Gamma_\phi = 3H(T_{\rm RH})$$

- Neutrinos will be populated via weak interactions with charged leptons



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Conclusions and results

Standard scenario

→ Neutrinos only

$N_{eff} = 3.044$

Non-Standard Interaction (NSI) scenario

→ neutrino-electron NSI

$3.040 \leq N_{eff} \leq 3.059$

No significant possible deviation from the standard case

Low-Reheating scenarios

→ Bound from BBN (95% C.L.)

$$T_{\rm RH} \geq 4.1\,{\rm MeV}$$

→ Bound from CMB (95% C.L.)

$$T_{\rm RH} \geq 4.7\,{\rm MeV}$$
$$T_{\rm RH} \geq 4.4\,{\rm MeV}$$

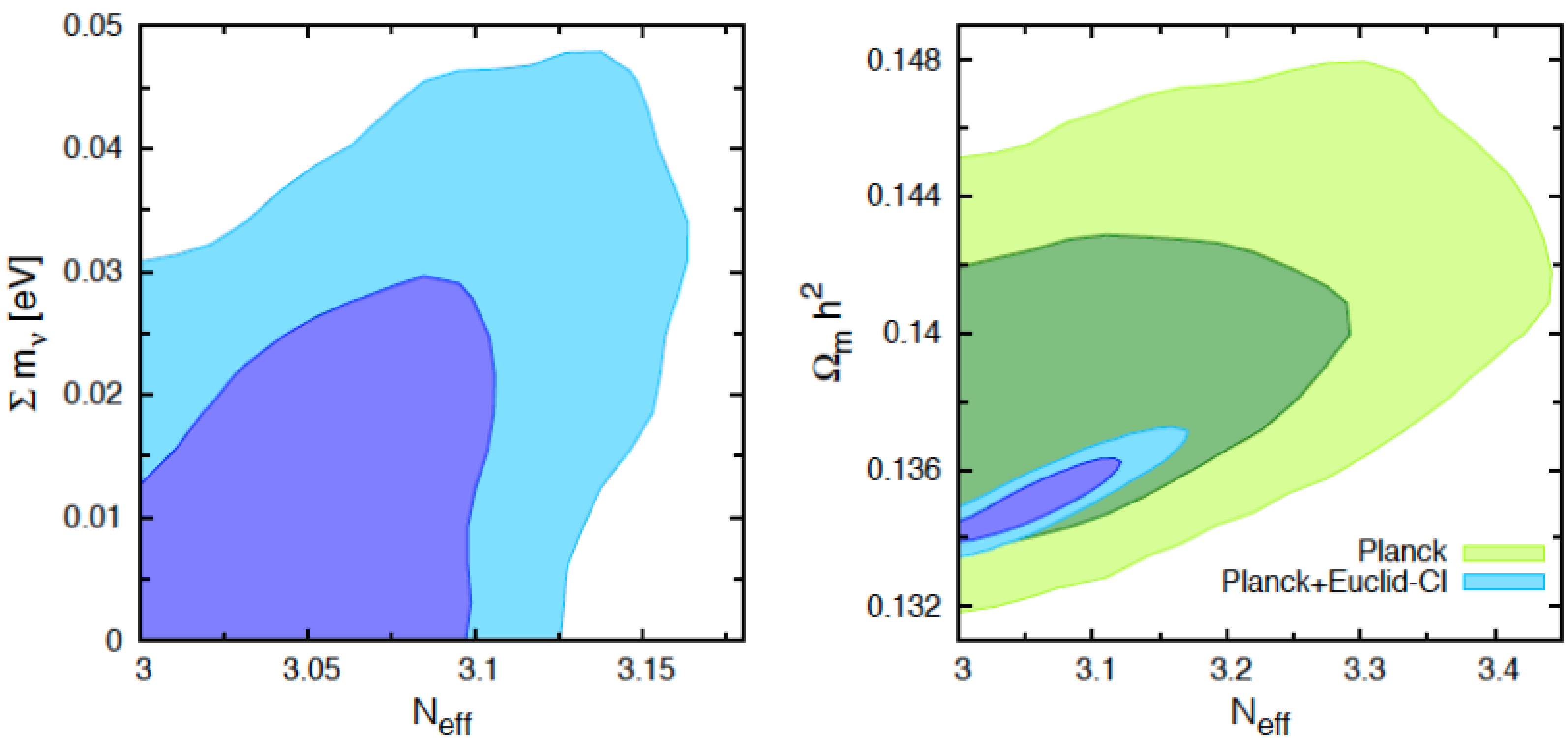
Can be interpreted as →

$$N_{\rm eff} \geq 2.81 \quad ({\rm PlanckTT} + {\rm lowP})$$
$$N_{\rm eff} \geq 2.75 \quad ({\rm PlanckTTTEEE} + {\rm lowP})$$

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$+m_\nu+N_{\rm eff}$	ΛCDM$+m_\nu+N_{\rm eff}+\Omega_{\rm k}$
$\sum m_\nu$ [eV]	68% CL	< 0.024	< 0.024
	95% CL	< 0.046	< 0.046
$N_{\rm eff}$	95% CL	< 3.16	< 3.17

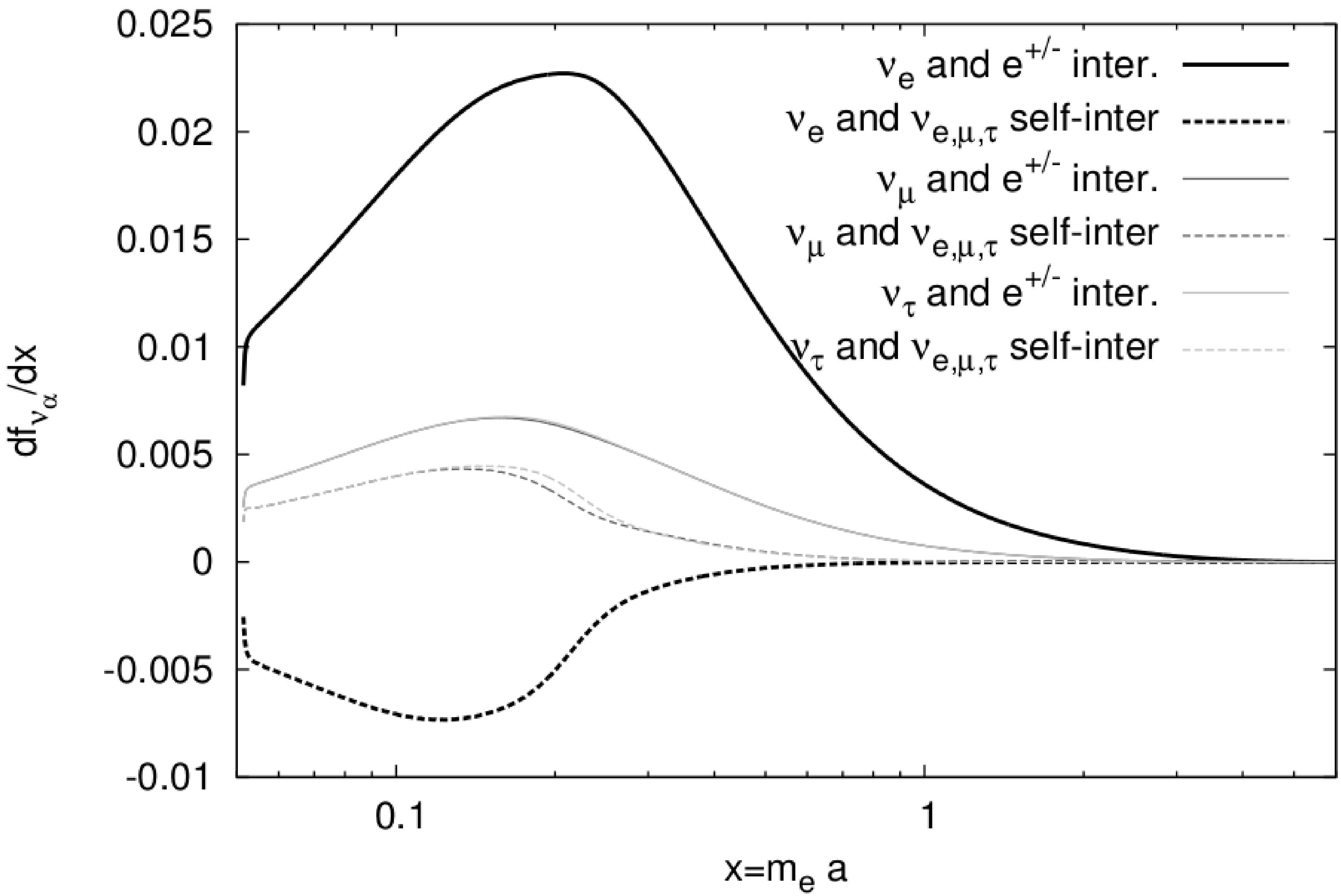
M.C.A. Cerbolini et al, JCAP 06 (2013) 020 [arXiv:1303.4550]

N_{eff} and Σm_ν simultaneous constraint

$$\begin{cases} N_\nu^{\mathrm{eff}} = 3.2 \pm 0.5 \\ \sum m_\nu < 0.32\,\mathrm{eV} \end{cases} \qquad 95\,\%\ \textit{Planck}\ \mathrm{TT} + \mathrm{lowP} + \mathrm{lensing} + \mathrm{BAO}$$

Planck collaboration, arXiv:1502.01589

Why not to consider damping factors



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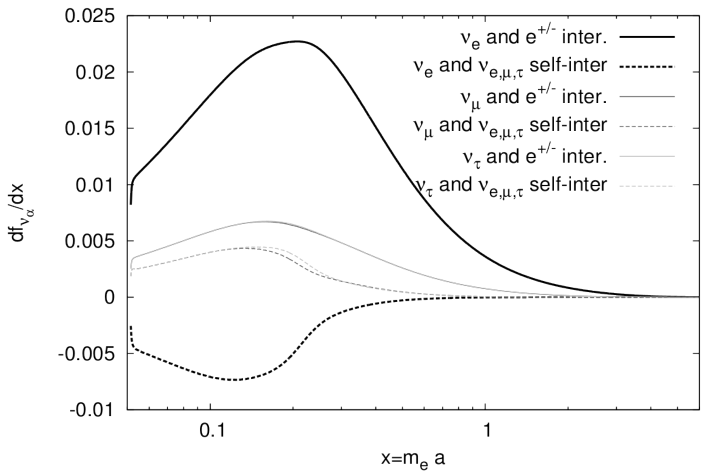

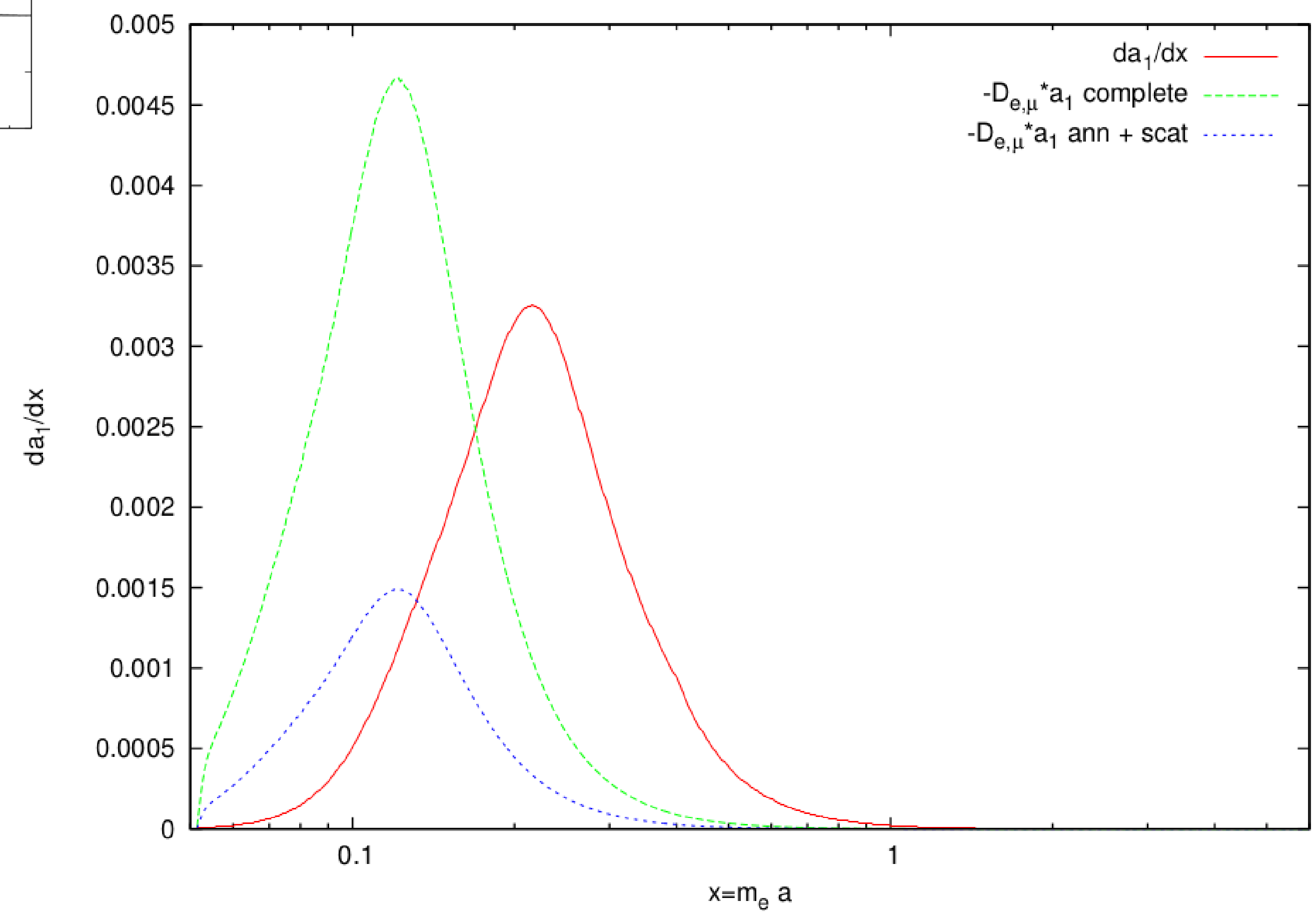

Non-Standard Interactions (NSI)

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 $e^{\pm}$

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

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

Collision integrals

Annihilation process

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

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