Non-thermal cosmic neutrino background

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based on arXiv:1509.00481
with: Mu–Chun Chen (UCI) and Michael Ratz (TUM).

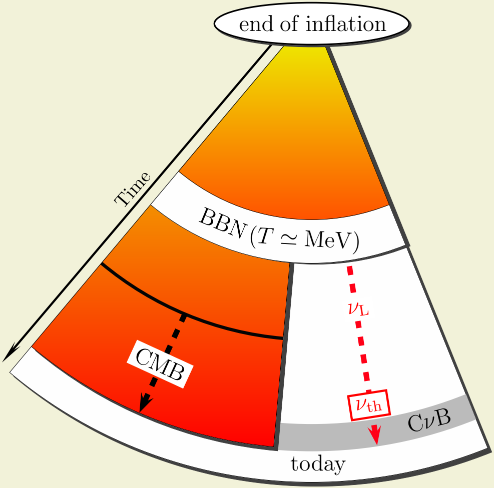
DESY Theory WS

01.10.15

Outline

- Review of CMB and thermal CνB
- Idea of a non-thermal neutrino background
- Constraints from $N_{\rm eff}$ $\Rightarrow$ maximal relic density
- Detection prospects
- Possible origin: inflationary preheating
- Conclusion

Standard picture



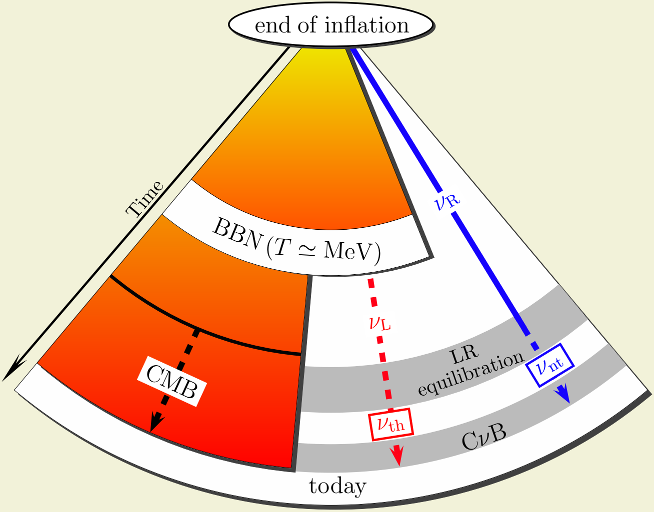
- CMB
  $t_\mathrm{dec} \sim 3.8 \cdot 10^5\,\mathrm{a}$

  today:
  $T_\gamma = 2.73\,\mathrm{K} \simeq 2.35 \cdot 10^{-4}\,\mathrm{eV}$
  $n_\gamma = 410\,\mathrm{cm}^{-3}$

- standard CνB
  $t_\mathrm{dec} \sim 1\,\mathrm{s}\ (T_\mathrm{dec} \sim 1\,\mathrm{MeV})$

  today:
  $T_{\nu_\mathrm{L}} = T_\gamma \cdot (4/11)^{1/3} \sim 1.95\,\mathrm{K}$
  $n_{\nu_\mathrm{L}} \sim 336\,\mathrm{cm}^{-3}$

Standard picture + non-thermal Dirac Neutrinos



Standard picture

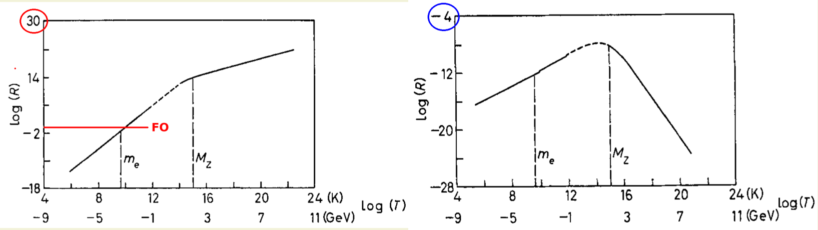
Let's assume **Dirac** neutrinos

$$\mathscr{L}_\nu \;=\; Y_\nu^{ij} \begin{pmatrix} \overline{e}^i_{\mathrm{L}} \\ \overline{\nu}^i_{\mathrm{L}} \end{pmatrix} \cdot \widetilde{H}\, {\nu_{\mathrm{R}}}^j + \mathrm{h.c.}\;.$$

Planck+ΛCDM $\Longrightarrow m_\nu \lesssim \mathcal{O}(0.1)\,\mathrm{eV} \iff \mathrm{E.V.}(Y_\nu) \lesssim 10^{-12}$

Note: Standard CνB initially consists only of left–chiral ($\equiv$left–handed) neutrinos. ν_{R} are too weakly coupled!

ν_{L} ν_{R}



$(R := \Gamma/H)$

[Antonelli, Fargion, Konoplich '81]

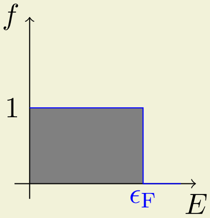
Non-thermal background

$\Gamma_{\nu_{\rm R}} \ll H$ implies:

- **No thermal production** of $\nu_{\rm R}$, but also
- **No thermalization** of existing abundance of $\nu_{\rm R}$!

$\curvearrowright$ <u>Assume</u> that there **is** a non–thermal abundance of $\nu_{\rm R}$**...**

Easiest thing to do:
Fill $\nu_{\rm R}$ states from the bottom up $\Longleftrightarrow$ degenerate Fermi gas.



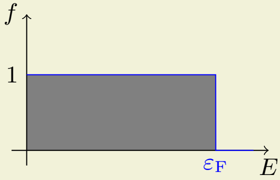
$$n_{\nu_{\rm R}} = \frac{g}{6\pi^2}\,\varepsilon_{\rm F}^3$$
$$\rho_{\nu_{\rm R}} = \frac{g}{8\pi^2}\,\varepsilon_{\rm F}^4$$

(ultrarelativistic approx.)

($g = 2$ for a Weyl fermion)

Evolution of the non-thermal background

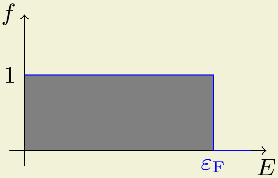
$$n_{\nu_{\mathrm{R}}}(T) \;=\; n_{\nu_{\mathrm{R}}}(T_{\mathrm{RH}}) \cdot \left(\frac{R(T_{\mathrm{RH}})}{R(T)}\right)^3$$



Evolution of the non-thermal background

$$n_{\nu_\mathrm{R}}(T) \;=\; \frac{g\,\xi^3}{6\,\pi^2}\,\frac{g_{*\mathrm{S}}(T)}{g_{*\mathrm{S}}(T_\mathrm{RH})}\,T^3$$

$$\xi := \varepsilon_\mathrm{F}/T_\mathrm{RH}$$



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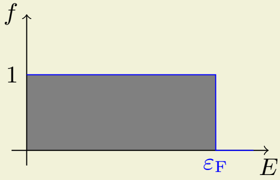
$$\varepsilon_\mathrm{F}(T) \propto T$$



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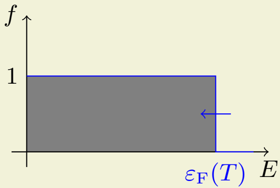

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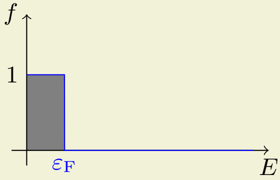

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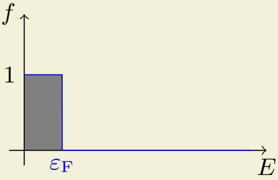

$$\frac{n_{\nu_\mathrm{R}}(T_\gamma)}{n_\gamma} \;=\; \frac{g\,\xi^3}{12\,\zeta(3)}\;\frac{g_{*\mathrm{S}}(T_\gamma)}{g_{*\mathrm{S}}(T_\mathrm{RH})}$$

$$\Delta N_\mathrm{eff}^{(\nu_\mathrm{R})} \;=\; \frac{8}{7}\;\frac{30}{8\,\pi^4}\;\frac{g\,\xi^4}{2}\;\left(\frac{g_{*\mathrm{S}}(T_\mathrm{BBN})}{g_{*\mathrm{S}}(T_\mathrm{RH})}\right)^{4/3}$$

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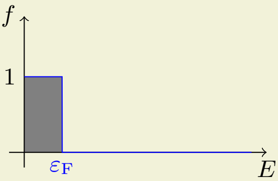

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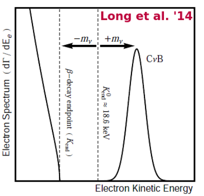
$$\Delta N_{\mathrm{eff}} \lesssim 0.7 \quad \Longrightarrow \quad n_{\nu_{\mathrm{R}}}(T_\gamma) \lesssim 0.53\,n_\gamma \approx 217\,\mathrm{cm}^{-3}$$

Planck: $\Delta N_{\mathrm{eff}} = 0.2 \pm 0.5 \;\; (95\%\mathrm{CL})$ [Ade et al.'15]

Detection of the non-thermal background

PTOLEMY collaboration: proposal to measure CνB. [Betts et al.'13]
Capture of relic neutrinos via inverse β-decay



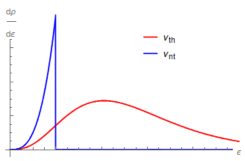
$$\nu_e + n \to p + e^- .$$

- relic ν's are **non–relativistic**

$\Rightarrow$ Chiralities mix via the mass term; $\nu_{\rm L} \to \nu_{\rm th}$, $\nu_{\rm R} \to \nu_{\rm nt}$
(**Helicity**, not chirality is conserved)

- Thermal and non–thermal neutrinos **in**distinguishable by experiment with resolution $\mathcal{O}(0.1)\,\mathrm{eV}$.

$$\langle E_{\nu_{\rm nt}} \rangle \lesssim \langle E_{\nu_{\rm th}} \rangle \ll m_\nu \lesssim \mathcal{O}(0.1)\,\mathrm{eV} .$$



$\Rightarrow$ Non-thermal neutrinos give irreducible contribution to CνB measurement.

Detection of the non-thermal background

- Proposal: [Long, Lunardini, Sabancilar '14]
  Distinguish Dirac vs. Majorana ν's by different CνB count rate
  $$\Gamma^{\mathrm{M}} \;=\; 2\,\Gamma^{\mathrm{D}} \;\approx\; 8\,\mathrm{yr}^{-1}\;.$$
- If there are non–thermal neutrinos, the count rate Γ^{D} could be enhanced by up to $\sim 64\%$.

$\Rightarrow$ Distinction could be inconclusive with low statistics.

Other effects:

- Relic neutrino clustering $\Rightarrow \mathcal{O}(1)$ factor. [Ringwald, Wong '04]
- SM extensions with Dirac neutrinos: ν_R could also be thermally coupled. eg. [Anchordoqui, Goldberg, Steigman '12], [Solaguren-Beascoa, Gonzalez-Garcia '12]
  Maximal enhancement in this case: $\sim 28\%$. [Zhang&Zhou '15]

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Ingredients:

- Inflation (chaotic, hybrid,...), e.g. $V(\phi) \sim m_\phi^2 \phi^2$
- Inflaton coupling to fermion field $\lambda\,\phi\,\overline{\Psi}\Psi$.

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Theory of fermionic preheating

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... In an expanding universe, parametric excitation of fermions is stochastic. Created fermions very quickly, within tens of inflaton oscillations, fill up a sphere of radius $\simeq q^{1/4}$ in momentum space. ...

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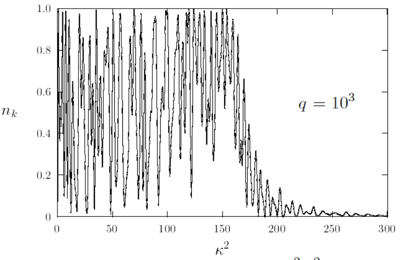


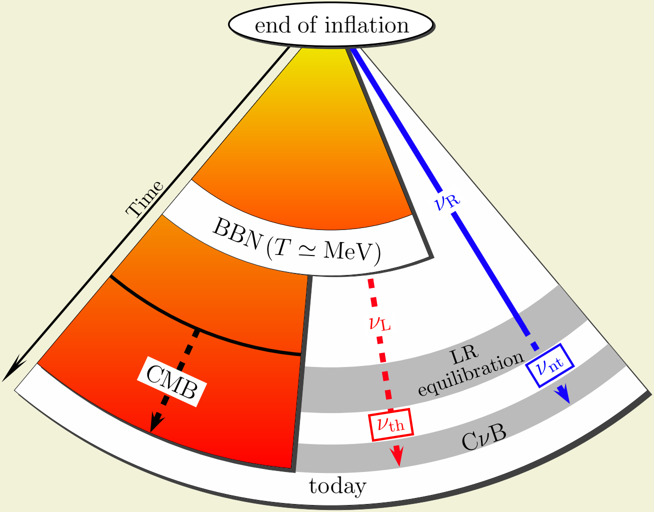
occupation number of fermions in $m_\phi^2\phi^2$-inflation after 50 inflaton oscillations

[Greene&Kofman '00]

$$q \;:= \lambda^2\,\phi_0^2/m_\phi^2$$

$$\varepsilon_{\mathrm{F}} \;\sim q^{1/4}\,m_\phi$$

Summary

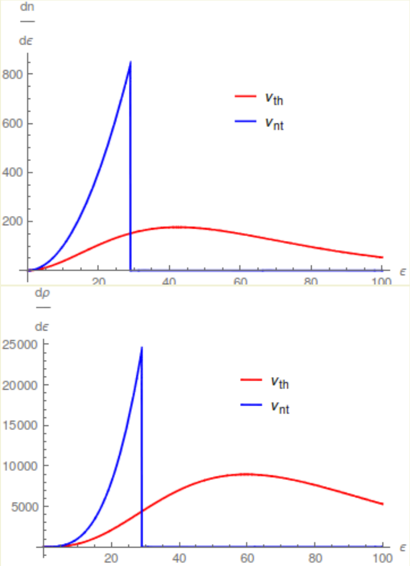


- non–thermal CνB: $t_\text{creation} \sim t_\text{infl.}$; Today: $n_{\nu_\text{nt}} \lesssim 217\,\text{cm}^{-3}$.

Thank You!

Backup slides

Evolution of Spectra



Relic density

$$\frac{n_{\nu_{\mathrm{nt}}}}{n_\gamma} \approx 1.2\,\frac{g_{*\mathrm{S}}(T_\gamma)}{g_{*\mathrm{S}}(T_{\mathrm{BBN}})}\,\eta^{1/4}\,g^{1/4}\,\left(\Delta N_{\mathrm{eff}}^{(\nu_\mathrm{R})}\right)^{3/4}\;.$$

η: filling factor of Fermi-gas

Production mechanism

In our case we need a coupling

$$\mathscr{L} \supset \lambda \phi \overline{\nu_{\mathrm{R}}{}^{\mathcal{C}}} \nu_{\mathrm{R}} + \text{h.c.}\ .$$

Neglecting spacial expansion, but for $\sim$realistic ξ:

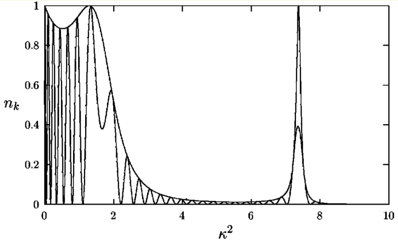


FIG. 2. The occupation number of fermions in $m_\phi^2 \phi^2$ theory as a function of κ^2 after 10 inflaton oscillations for resonance parameter $q = 10$.

[Greene&Kofman '00]

Reheating of the SM: via perturbative decay of ϕ, or $\phi^2 H^2$ coupling and the "scalar" parametric resonance.

[Brandenberger&Traschen '90]
[Kofman, Linde, Starobinsky '94]

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