Nonthermal cosmic neutrino background

Michael Ratz

based on Phys.Rev. D92 (2015) no.12, 123006 (arXiv:1509.00481)
with: Mu–Chun Chen (UCI) and Andreas Trautner (Bonn)

(some slides stolen from Andreas' talks)

&

Kevork Abazajian, Mu–Chun Chen & M.R. (in preparation)

Erice
Italy

September 19 2017

Neutrinos vs. photons

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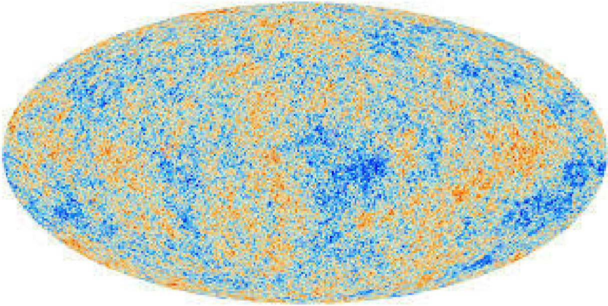

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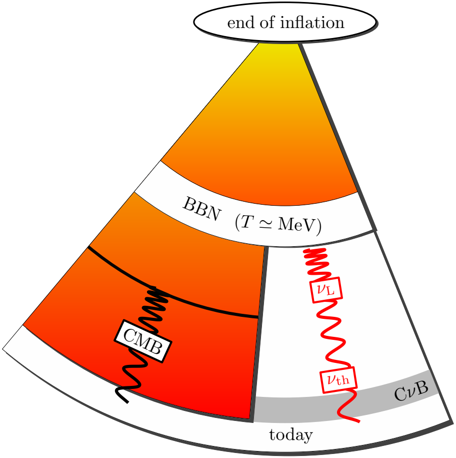
main message of this talk:

there might be more neutrinos than photons!

Standard picture



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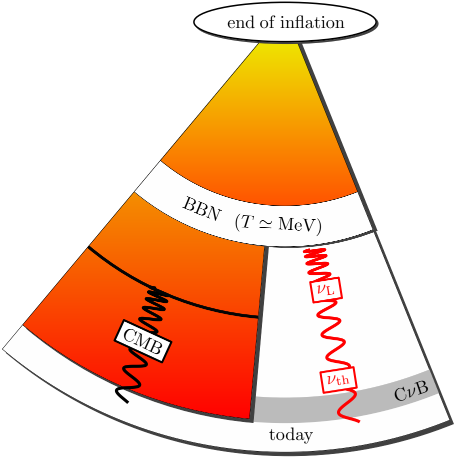

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  $T_\gamma \simeq 2.73\,\mathrm{K} \simeq 2.35 \cdot 10^{-4}\,\mathrm{eV}$
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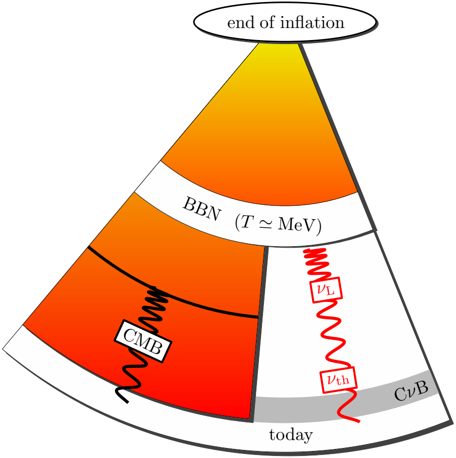

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- standard CνB (predicted)
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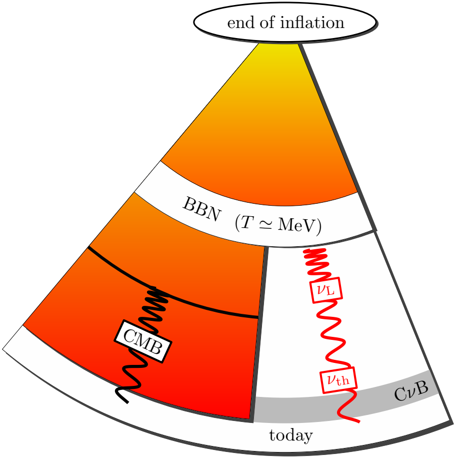

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  Ade et al. (2016)
- $N_\mathrm{eff} = 3.2 \pm 0.5$
  cf. talk by M. Archidiacono

indirect evidence: $N_\mathrm{eff}^{(3\nu,\mathrm{theory})} = 3.046$

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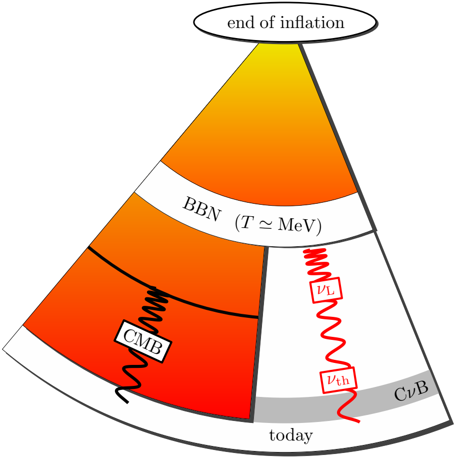

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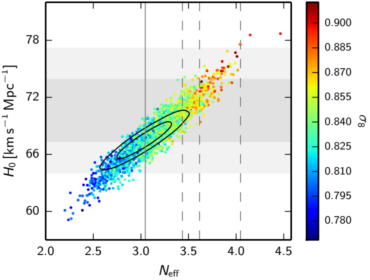

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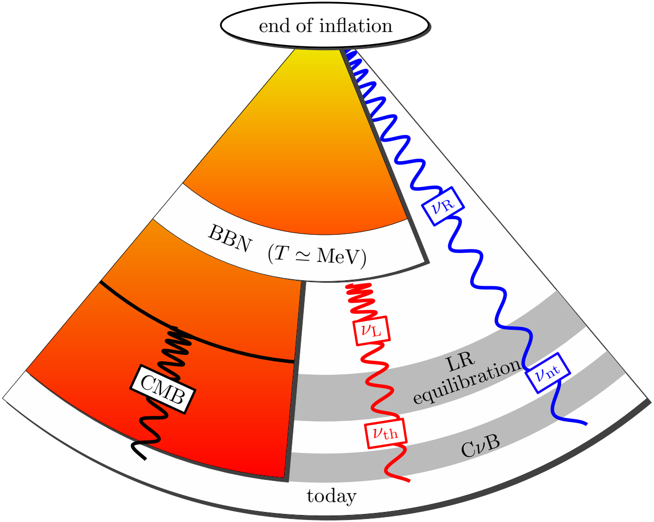
Standard picture + nonthermal Dirac neutrinos



Dirac neutrinos in the early universe

☞ **Dirac** neutrinos get their mass from the Yukawa coupling

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

☞ $m_\nu \lesssim 0.1$ eV $\curvearrowright$ singular values of $Y_\nu \lesssim 10^{-12}$

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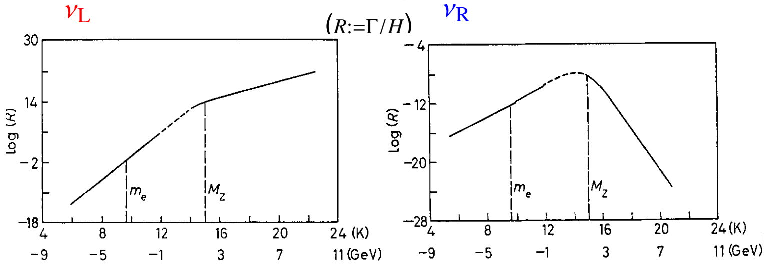
- standard CνB initially consists *only* of left–chiral neutrinos ν_L while ν_R are too weakly coupled

Antonelli, Fargion, and Konoplich (1981)



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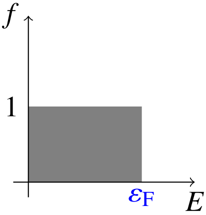
- most extreme possibility: degenerate Fermi gas
  fill ν_R states from the bottom up



ultrarelativistic approximation

$$n_{\nu_\mathrm{R}} = \frac{g}{6\pi^2}\,\varepsilon_\mathrm{F}^3$$

$$\rho_{\nu_\mathrm{R}} = \frac{g}{8\pi^2}\,\varepsilon_\mathrm{F}^4$$

$g = 2$ for spin–1/2 fermion

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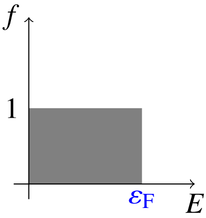
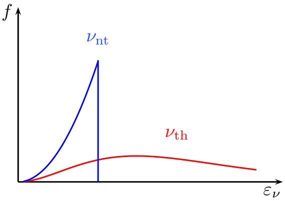
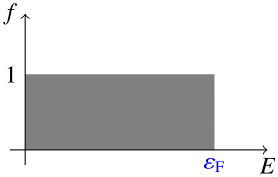




Evolution of the nonthermal background

$$n_{\nu_\mathrm{R}}(T) \;=\; n_{\nu_\mathrm{R}}(T_\mathrm{RH})\cdot\left(\frac{a(T_\mathrm{RH})}{\underbrace{a(T)}_{\text{scale factor}}}\right)^3$$



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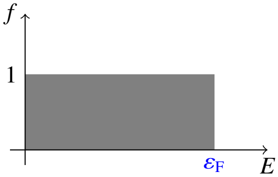
$$n_{\nu_\mathrm{R}}(T) = \frac{g\,\xi^3}{6\,\pi^2}\,\frac{g_{*S}(T)}{g_{*S}(T_\mathrm{RH)}}\,T^3$$

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



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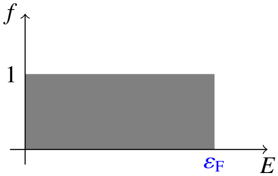

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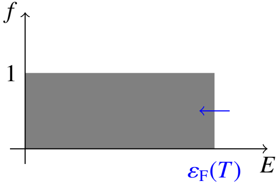

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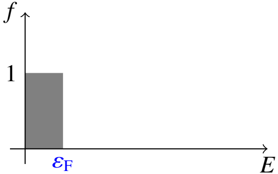

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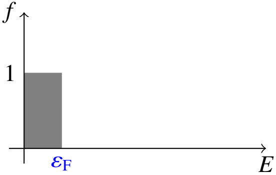

$$\frac{n_{\nu_\mathrm{R}}(T_\gamma)}{n_\gamma} = \frac{g\,\xi^3}{12\,\zeta(3)}\,\frac{g_{*\mathrm{S}}(T_\gamma)}{g_{*\mathrm{S}}(T_\mathrm{RH})} \quad \& \quad \Delta N_\mathrm{eff}^{(\nu_\mathrm{R})} = \frac{8}{7}\,\frac{30}{8\,\pi^4}\,\frac{g\,\xi^4}{2}\left(\frac{g_{*\mathrm{S}}(T_\mathrm{BBN})}{g_{*\mathrm{S}}(T_\mathrm{RH})}\right)^{4/3}$$

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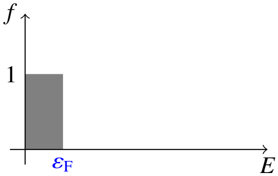

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maximal number of nonthermal neutrinos:

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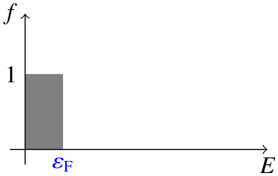

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Planck: $\Delta N_\mathrm{eff} = 0.2 \pm 0.5$

How to look for relic neutrinos

Direct detection of CνB on earth

☞ proposal: capture ν's with tritium $^3\mathrm{H}$

Weinberg (1962)

$$\beta\ \text{decay: } {}^3\mathrm{H} \to {}^3\mathrm{He}^+ + \mathrm{e}^- + \overline{\nu}_\mathrm{e}$$

Direct detection of CνB on earth

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Weinberg (1962)

$$\begin{tikzcd}
 & {}^3\mathrm{H} \rightarrow {}^3\mathrm{He}^+ + \mathrm{e}^- + & \bar{\nu}_\mathrm{e} \arrow[dll, bend right] \\
\nu_\mathrm{e} & + {}^3\mathrm{H} \rightarrow {}^3\mathrm{He}^+ + \boxed{\mathrm{e}^-} & \leftarrow \text{measure spectrum}
\end{tikzcd}$$

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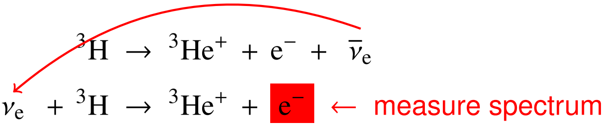
Weinberg (1962)



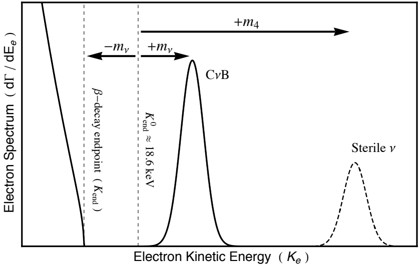
$$^3\mathrm{H} \rightarrow {}^3\mathrm{He}^+ + e^- + \bar{\nu}_e$$

$$\nu_e + {}^3\mathrm{H} \rightarrow {}^3\mathrm{He}^+ + \boxed{e^-} \leftarrow$$

measure spectrum

- $\langle E_\mathrm{kin}^{\nu_\mathrm{th}} \rangle_\mathrm{today} \approx 1.7 \cdot 10^{-4}\,\mathrm{eV}$
- $\Delta m_{12}^2 \approx 7.5 \cdot 10^{-5}\,\mathrm{eV}^2$
  $\Delta m_{13}^2 \approx 2.5 \cdot 10^{-3}\,\mathrm{eV}^2$

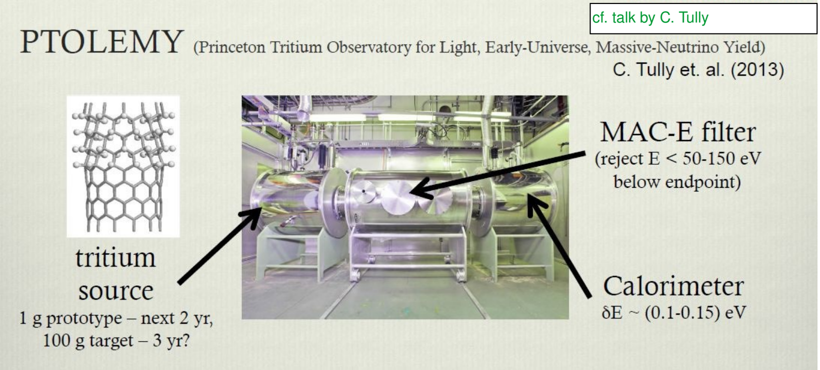
↷ at least two species are nonrelativistic!



Long, Lunardini, and Sabancilar (2014)

Experimental proposal

cf. talk by C. Tully



PTOLEMY (Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield)

C. Tully et. al. (2013)

tritium source

1 g prototype – next 2 yr,
100 g target – 3 yr?

MAC-E filter
(reject E < 50-150 eV
below endpoint)

Calorimeter
$\delta E \sim (0.1\text{-}0.15)$ eV

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☞ expected rate: 8–23 events per 100 g tritium and year for Majorana neutrinos

de Salas, Gariazzo, Lesgourgues, and Pastor (2017)

depends on DM halo & absolute ν mass

Dirac vs. Majorana

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$$\Gamma_{\mathrm{C}\nu\mathrm{B}}^{\mathrm{Majorana}} = \mathbf{2} \cdot \Gamma_{\mathrm{C}\nu\mathrm{B}}^{\mathrm{Dirac}} \approx \frac{8-23}{\mathrm{yr}^{-1} \cdot 100\,\mathrm{g}}$$

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- ☞ local ν density higher than average

Ringwald and Wong (2004) ; de Salas, Gariazzo, Lesgourgues, and Pastor (2017)

e.g. $\Gamma_{\mathrm{C}\nu\mathrm{B}}^{\mathrm{Majorana}} \approx 23\,\mathrm{yr}^{-1}/100\,\mathrm{g}$ for $m_\nu = 150\,\mathrm{meV}$

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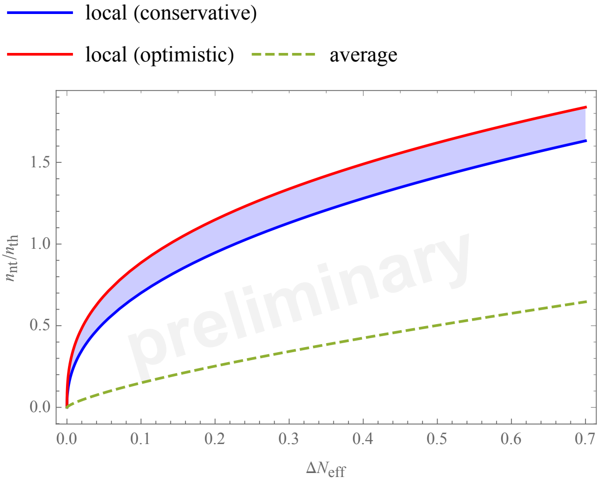

Abazajian, Chen & M.R. (to appear)

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bottom–line:

discrimination between Dirac and Majorana through measurement of relic neutrinos may be impossible

Is there an appropriate ν_R production mechanism?

☞ e.g. fermionic preheating

Greene and Kofman (1999)
Baacke, Heitmann, and Patzold (1998)

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- ☞ large amounts of ν_R get produced during inflation and get ‘cooled down’ afterwards

Summary & outlook

☺ neutrinos might be more abundant than photons!

	t_{creation}	N_{eff}	relic density
ν_{th}	$t_{\text{BBN}} \sim 1\,\text{s}$	3.046	$n_{\nu_{\text{th}}} \approx 336\,\text{cm}^{-3}$
ν_{nt}	$t_{\text{infl.}}$	$\lesssim 0.7$	$n_{\nu_{\text{nt}}} \lesssim 217\,\text{cm}^{-3}$
γ	$t \simeq 3.8 \cdot 10^5\,\text{a}$	$16/7$	$n_\gamma \approx 412\,\text{cm}^{-3}$

$(n_{\nu_{\text{nt}}} \lesssim 84\,\text{cm}^{-3}$ for $\Delta N_{\text{eff}} = 0.2)$

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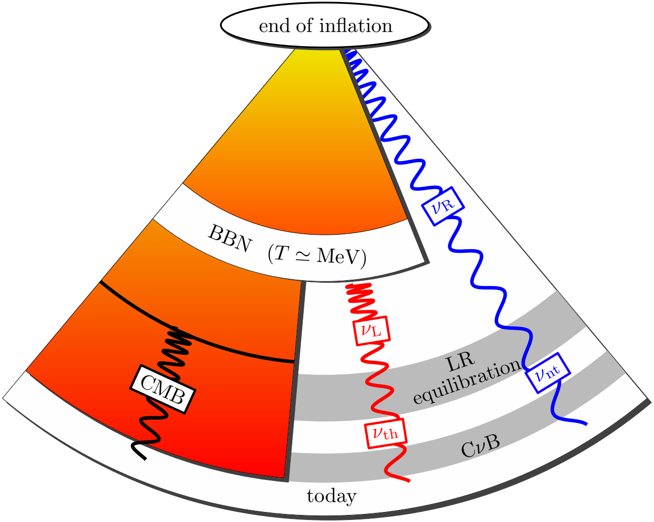
- 😑 nonthermal neutrinos may spoil the distinction between Dirac and Majorana
- 😎 nonthermal neutrinos directly probe the universe at the stage of inflation

Standard picture + nonthermal Dirac neutrinos



Backup slides

Fermionic preheating

☞ ingredients

Greene and Kofman (1999)
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✓ massive scalar field ϕ such as inflaton w/ $\mathscr{V}(\phi) \sim \dfrac{m_\phi^2}{2}\phi^2$

✓ coupling to fermions $\lambda\,\phi\,\overline{\Psi}\Psi$

Fermionic preheating

☞ ingredients

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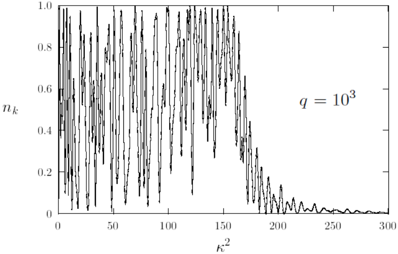
- ✓ coupling to fermions $\lambda\,\phi\,\overline{\Psi}\Psi$
- ↷ (nonperturbative) “parametric resonance” effect:



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

Greene and Kofman (1999)

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

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

$$\frac{q^{1/4}}{2} \;\sim\; \frac{\varepsilon_\mathrm{F}}{T_\mathrm{RH}} \;=\; \xi \;\lesssim\; 3$$

▸ back

Nonthermal ν_R production mechanism

- to produce nonthermal ν_R one needs a coupling

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

- Majorana mass term forbidden by e.g. $\mathbb{Z}_4^L$ Witten (2001)
- reheating of the SM via perturbative decay of ϕ, or $\phi^2 H^2$ coupling and the "scalar" parametric resonance
Kofman, Linde, and Starobinsky (1994) ; Traschen and Brandenberger (1990)

▸ back

Discriminate thermal from nonthermal relic neutrinos?

☞ obvious difference: spectrum?

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☞ annual modulation?
due to different mean velocity

Lisanti, Safdi, and Tully (2014)

$$\langle v_{\mathrm{C}\nu\mathrm{B},\,\mathrm{nt}}\rangle = 572\,(1+z)\left(\frac{0.1\,\mathrm{eV}}{m_\nu}\right)\left(\frac{\Delta N_{\mathrm{eff}}^{(\nu_\mathrm{R})}}{0.7}\right)^{1/4}\mathrm{km\,s}^{-1}$$

$$\langle v_{\mathrm{C}\nu\mathrm{B},\,\mathrm{th}}\rangle = 1580\,(1+z)\left(\frac{0.1\,\mathrm{eV}}{m_\nu}\right)\mathrm{km\,s}^{-1}$$

redshift

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☞ however, this would require $\mathcal{O}\left(10^{6}\right)$ recorded events

▸ back

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