towards precision studies of low-scale leptogenesis[1]

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motivation

explain known neutrino properties with minimal seesaw

$$\begin{aligned}\mathcal{L}_{\text{new-SM}} \quad &\equiv \quad \mathcal{L}_{\text{old-SM}} + \bar{\nu}_{\rm R} i \partial\!\!\!/ \, \nu_{\rm R} \\ &- \quad (\bar{\nu}_{\rm R}\, \tilde{\phi}^{\dagger} h_{\nu}\, \ell_{\rm L} + \bar{\ell}_{\rm L}\, h_{\nu}^{\dagger}\, \tilde{\phi}\, \nu_{\rm R}) \\ &- \quad \frac{1}{2}(\bar{\nu}_{\rm R}^{c} M_{\rm M} \nu_{\rm R} + \bar{\nu}_{\rm R}\, M_{\rm M}^{\dagger} \nu_{\rm R}^{c})\end{aligned}$$

singular value decomposition & field rotation

$\Rightarrow M_{\rm M} =$ diag(M_1, M_2, M_3), where $M_I \geq 0$

we assume that $\{M_I\}$ are set in increasing order

prediction: $\exists$ heavy states **and** lepton numbers are violated

there is a large parameter space to explore

if only one neutrino yukawa contributes to a given mass difference[2]

$$|\Delta m_\nu| \simeq \frac{|(h_\nu)_{Ia}|^2 v^2}{M_I}$$

traditionally: $M_I \overset{\mathrm{GUT?}}{\sim} 10^{15}$ GeV $\Leftrightarrow h_\nu \sim 1$

more recently: $M_I \sim 1...100$ GeV $\Leftrightarrow h_\nu \sim 10^{-7}...10^{-6}$

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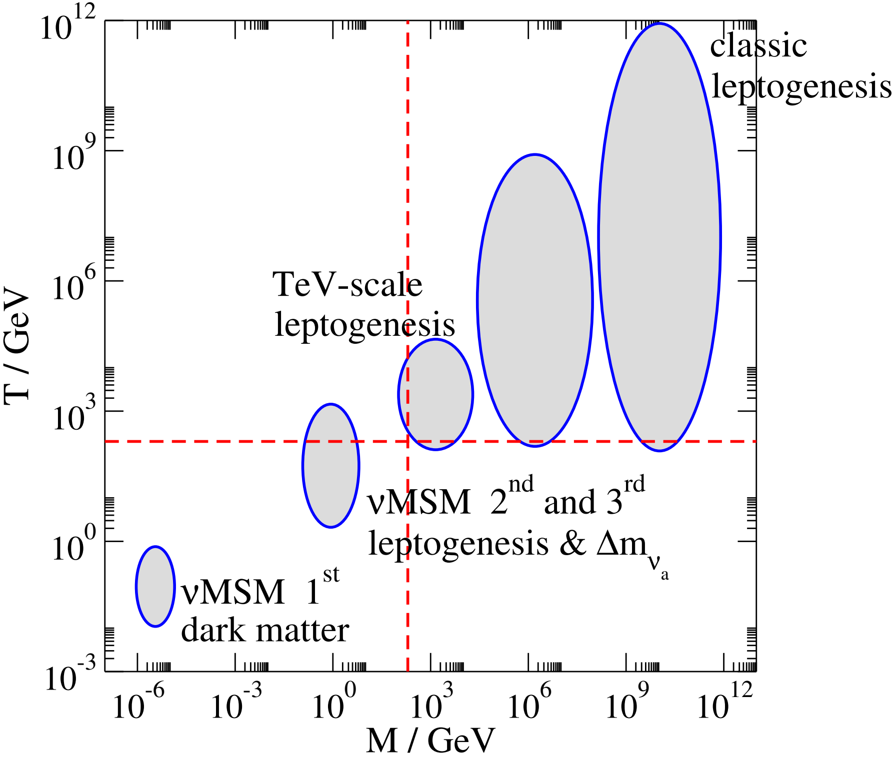
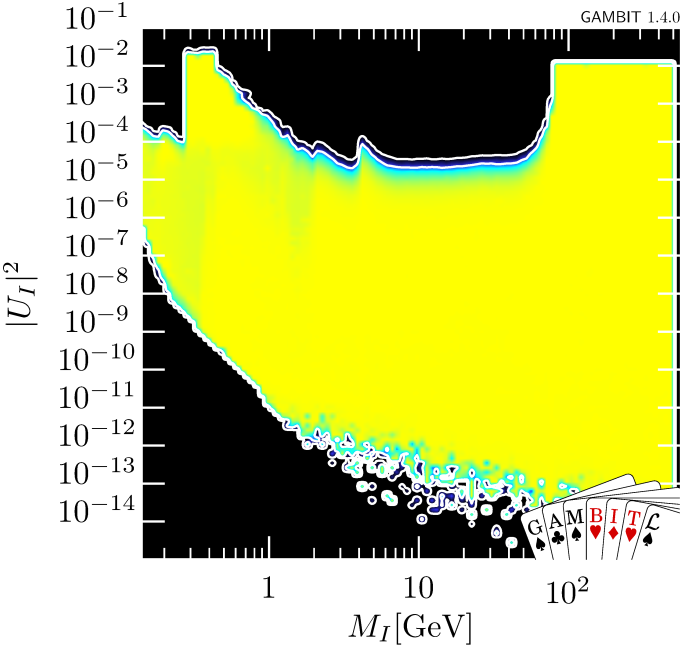
[2] P. Minkowski, *$\mu \to e\gamma$ at a Rate of One Out of 10^9 Muon Decays?*, PLB 67 (1977) 421; M. Gell-Mann, P. Ramond and R. Slansky, *Complex Spinors and Unified Theories*, 1306.4669; T. Yanagida, *Horizontal Symmetry and Masses of Neutrinos*, PTP 64 (1980) 1103

many (if not all) domains have been looked into



the low mass range is motivated at least by falsifibility[3]



⇒ a large fraction can be explored in future (see other talks)

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[3] for a review of current status see e.g. M. Chrzaszcz *et al*, *A frequentist analysis of three right-handed neutrinos with GAMBIT*, 1908.02302

general framework

classic leptogenesis: non-equilibrium in two variables [4]

consider $Y_R \simeq e_R/(Ms)$ and lepton asymmetry $Y_L \equiv n_L/s$

defining $\widehat\Gamma \equiv \Gamma/(3c_s^2 H)$, $x \equiv \ln(T_{\rm max}/T)$, $Y' \equiv {\rm d}Y/{\rm d}x$:

$$\begin{aligned} Y_L' &= -\,\widehat\Gamma_L\, Y_L - \widehat\Gamma_{L,R}\,(Y_R - Y_{\rm eq}) \\ Y_R' &= -\,\widehat\Gamma_R\,(Y_R - Y_{\rm eq}) - \widehat\Gamma_{R,L}\, Y_L \end{aligned}$$

$\Rightarrow$ $Y_L \neq 0$ can be generated if $Y_R \neq Y_{\rm eq}$ and $\widehat\Gamma_L$ is not huge

$\Rightarrow$ “sphaleron equilibrium”, $Y_B + Y_L \simeq 0$, then produces Y_B

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[4] M. Fukugita, T. Yanagida, *Baryogenesis Without Grand Unification*, PLB 174 (1986) 45; for current status, see D. Bödeker and M. Wörmann, *Non-relativistic leptogenesis*, 1311.2593; D. Bödeker and M. Sangel, *Lepton asymmetry rate from quantum field theory: NLO in the hierarchical limit*, 1702.02155

low-scale leptogenesis involves more "slow" variables[5]

- $Y_L \to$ flavour asymmetries $Y_a - \frac{1}{3} Y_B$, $a \in \{e, \mu, \tau\}$
- $Y_R \to$ density matrices $\rho_{IJ}(k, \pm)$, $\pm \equiv$ helicity

it is convenient to employ helicity symmetries and asymmetries

$$\rho^{\pm} \equiv \frac{\rho(k,+) \pm \rho(k,-)}{2}$$

redshift $k_T \equiv \frac{k(T_{\text{min}})\, a(T_{\text{min}})}{a(T)}$, energies $\omega_T \equiv \sqrt{k_T^2 + M_I^2}$

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[5] original ideas were put forward by E.K. Akhmedov, V.A. Rubakov and A.Y. Smirnov, *Baryogenesis via neutrino oscillations*, hep-ph/9803255, and T. Asaka and M. Shaposhnikov, *The νMSM, dark matter and baryon asymmetry of the universe*, hep-ph/0505013; general formalism is similar to G. Sigl and G. Raffelt, *General kinetic description of relativistic mixed neutrinos*, NPB 406 (1993) 423

evolution equation for lepton asymmetries

$$\begin{aligned} Y_a' - \frac{Y_B'}{3} \quad = \quad & \frac{4}{s} \int_{\mathbf{k}_T} \mathrm{Tr}\{\, n_\mathrm{F}'(\omega_T) \; \underbrace{\widehat{A}^+_{(a)}}_{\propto \{\mu_a\}} \\ & \qquad + [\, \rho^+ - n_\mathrm{F}(\omega_T) \,] \, \underbrace{\widehat{B}^+_{(a)}}_{\text{C-odd}} \\ & \qquad + \rho^- \; \underbrace{\widehat{B}^-_{(a)}}_{\text{C-even}} \; \} \end{aligned}$$

1st term: washout term (“equilibration” *viz.* $\widehat{\Gamma}_L$)

2nd term: source from helicity-symmetric non-equilibrium

3rd term: source from helicity-asymmetric non-equilibrium

like in EFT, coefficients contain the physics of fast modes

$$\Pi^{\rm R}_a(\mathcal{K}) \equiv \int_X e^{i\tilde{K}\cdot X} \, \langle (\tilde{\phi}^\dagger \ell_a)(X) \, (\bar{\ell}_a \tilde{\phi})(0) \rangle \Big|_{k_n - i\mu_a \to -i[\omega + i0^+]}$$

denoting by $u_{\mathbf{k}\tau I}$ an on-shell spinor of helicity $\tau = \pm$, we need

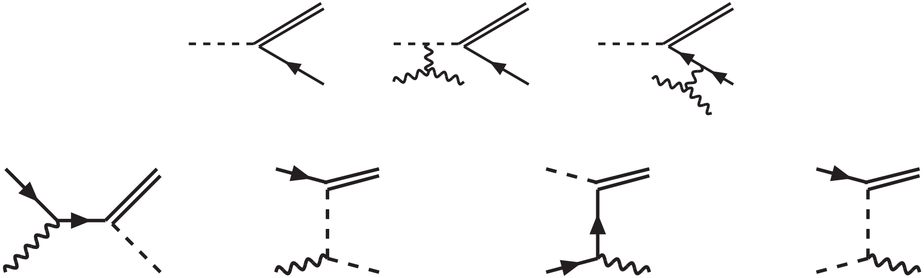
$$\frac{\bar{u}_{\mathbf{k}\tau I} \; {\rm Im}\, \Pi^{\rm R}_a(\mathcal{K}_I) \, u_{\mathbf{k}\tau I}}{\omega_I} \equiv \underbrace{Q_{(a\tau)I}}_{\text{C-even}} + \underbrace{\bar{Q}_{(a\tau)I}}_{\text{C-odd}}$$

denoting $Q^{\pm}_{(a)} \; \equiv \; [Q_{(a+)} \pm Q_{(a-)}]/2$ yields

$$A^{+}_{(a)II} = \mu_a \, {\rm Re}(h_{Ia} h^{*}_{Ia}) \, Q^{+}_{(a)I}$$

examples of “direct” processes contributing to $\mathrm{Im}\,\Pi^{\mathrm{R}}_{a}$

by optical theorem $\mathrm{Im}\,\mathcal{A} \Leftrightarrow \mathcal{A}^{*}\mathcal{A}$, e.g.



$1 \leftrightarrow 2$ require “lpm” resummation, a nice field-theory problem[6]

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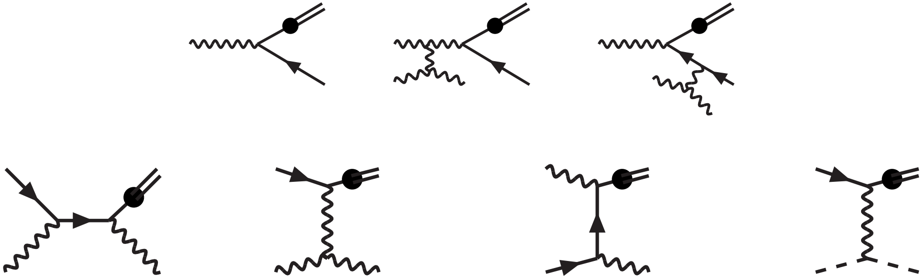
[6] originally: A. Anisimov, D. Besak and D. Bödeker, *Thermal production of relativistic Majorana neutrinos: Strong enhancement by multiple soft scattering*, 1012.3784; D. Besak and D. Bödeker, *Thermal production of ultrarelativistic right-handed neutrinos: Complete leading-order results*, 1202.1288; resolved into helicity channels and generalized to broken phase and finite chemical potentials: J. Ghiglieri and ML, *Neutrino dynamics below the electroweak crossover*, 1605.07720; *GeV-scale hot sterile neutrino oscillations: a derivation of evolution equations*, 1703.06087

examples of “indirect” processes contributing to $\mathrm{Im}\,\Pi_a^{\mathrm{R}}$

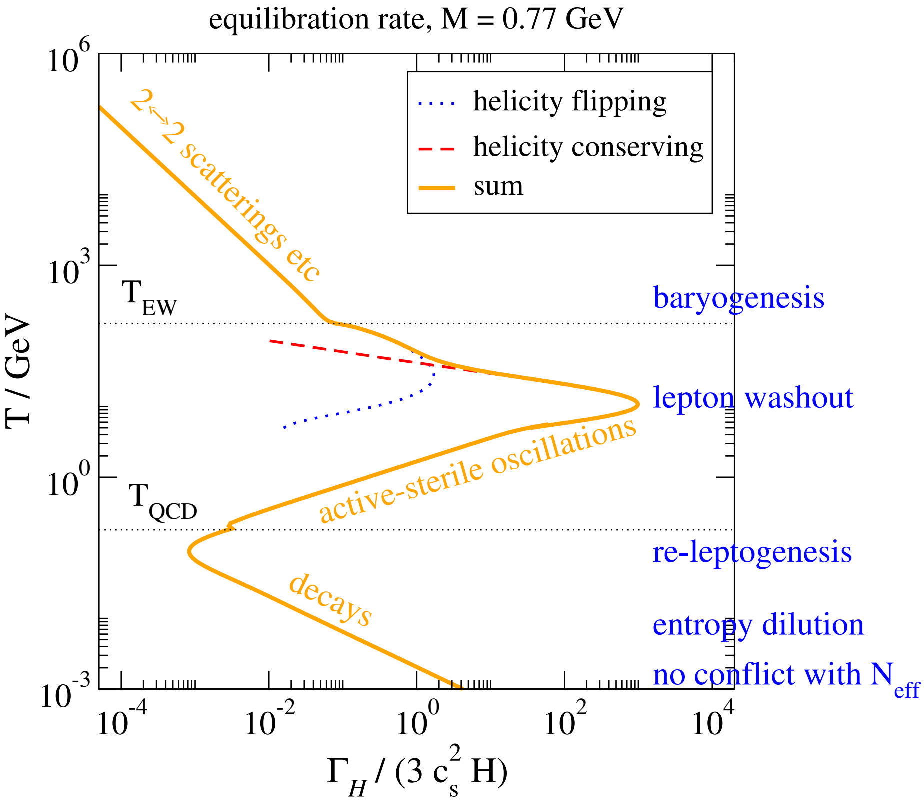
here ● indicates a higgs vev, i.e. active-sterile oscillation



in terms of active neutrino matter potential b and width Γ_u:

$$Q_{(a-)I} + \bar{Q}_{(a-)I}\Big|^{\text{indirect}} \approx \frac{v^2 M_I^2 \Gamma_u}{2[(M_I^2 + 2\omega_I b)^2 + (\omega_I \Gamma_u)^2]}$$

example of a rate: $\Gamma_H \equiv \sum_{a,I=2,3} |h_{Ia}|^2 \langle Q^+_{(a)I} \rangle_{\mathbf{k}_T}$



sample results

parametrization[7]

$$h_\nu = -i\sqrt{M}\,R(z)\,P_H(\phi_1)\,\underbrace{\sqrt{m_\nu}\,V^\dagger}_{\text{data}}\,\frac{\sqrt{2}}{v}$$

two-flavour benchmark $(*)$ from a previous scan:[8]

$$\begin{aligned} M_2 &= 0.7688\,\text{GeV}\,, \quad M_3 = 0.7776\,\text{GeV}\,, \\ z &= 2.444 - i3.285\,, \\ \phi_1 &= -1.857\,, \quad \delta = -2.199\,, \quad H = \text{inverted} \end{aligned}$$

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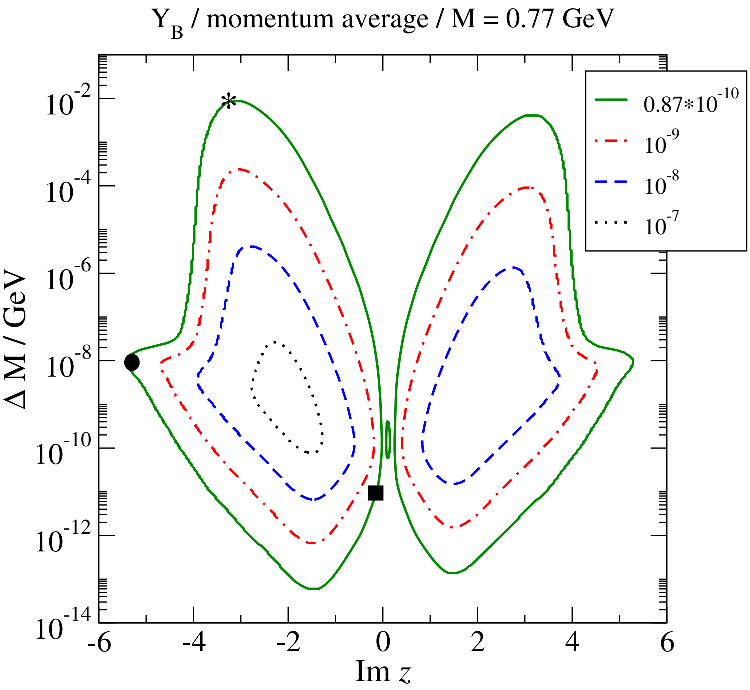
[7] J.A. Casas and A. Ibarra, *Oscillating neutrinos and $\mu \to e\gamma$*, hep-ph/0103065; generalization beyond seesaw limit: A. Donini, P. Hernández, J. López-Pavón, M. Maltoni and T. Schwetz, *The minimal 3+2 neutrino model versus oscillation anomalies*, 1205.5230

[8] P. Hernández, M. Kekic, J. López-Pavón, J. Racker and J. Salvado, *Testable Baryogenesis in Seesaw Models*, 1606.06719; another extensive scan in S. Eijima, M. Shaposhnikov and I. Timiryasov, *Parameter space of baryogenesis in the νMSM*, 1808.10833

a partial scan of Y_B at $T \sim 100$ GeV[9]



⇒ it works!

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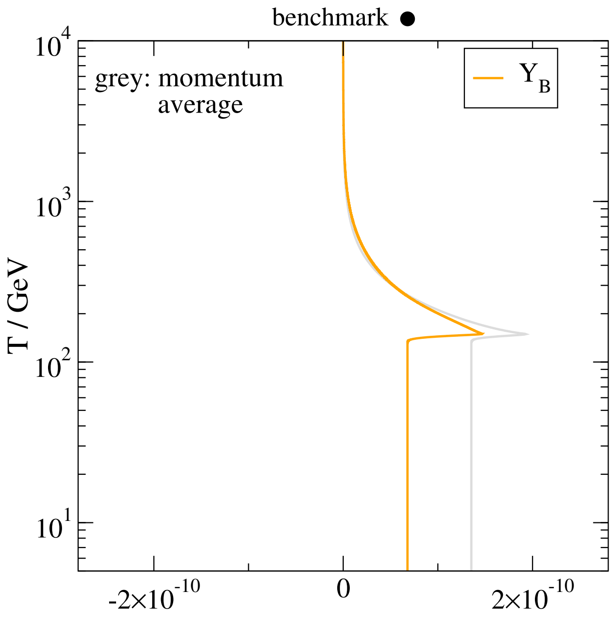
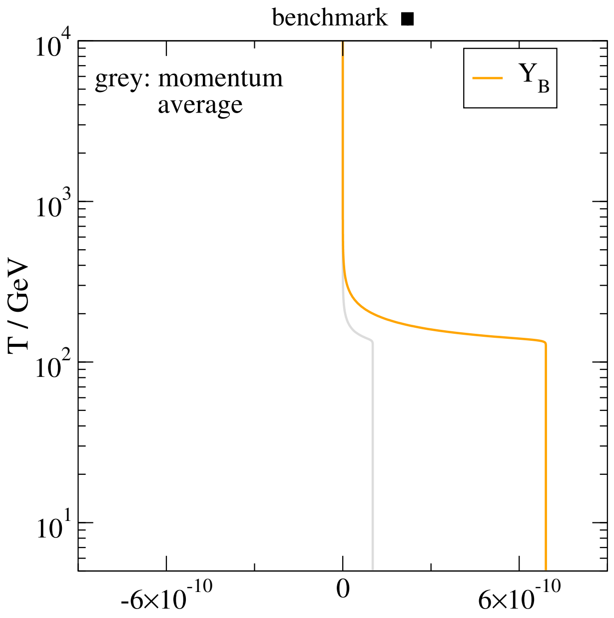
[9] J. Ghiglieri and ML, *Precision study of GeV-scale resonant leptogenesis*, 1811.01971

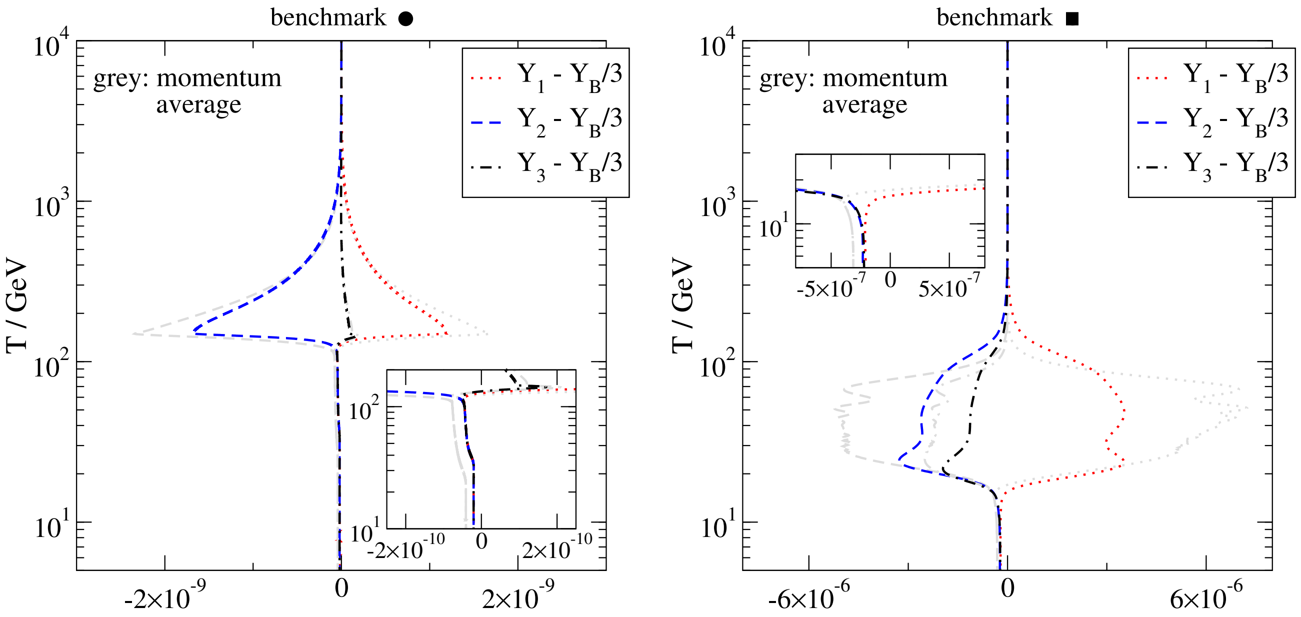
effect of kinetic non-equilibrium





$\Rightarrow$ uncertainties of $\mathcal{O}(1)$

$Y_a - \frac{1}{3}Y_B$ could be much larger than Y_B [10]



⇒ relation to resonant sterile neutrino dark matter production?

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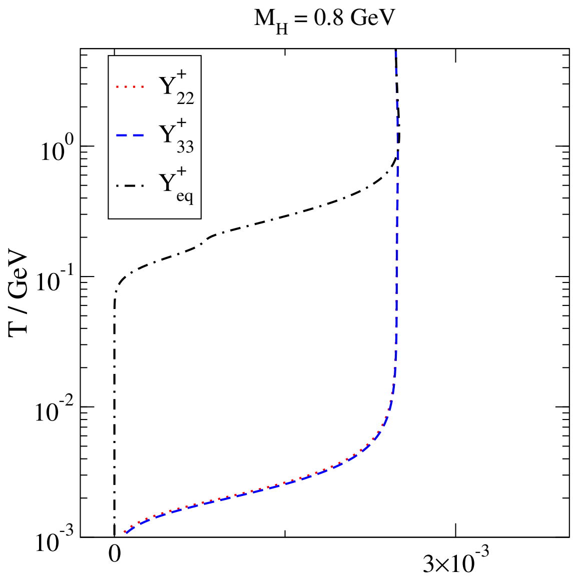
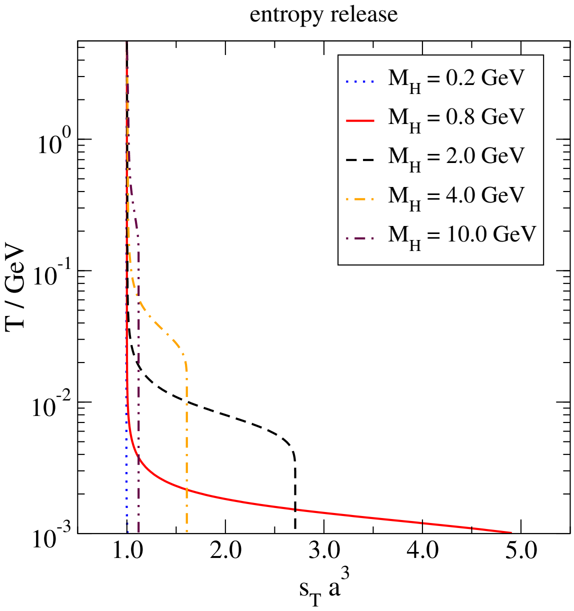
[10] see also S. Eijima and M. Shaposhnikov, *Fermion number violating effects in low scale leptogenesis*, 1703.06085

entropy release at low T[11]





$\Rightarrow$ asymmetries may be diluted by $\mathcal{O}(1)$ (depends on $|h_\nu|^2$)

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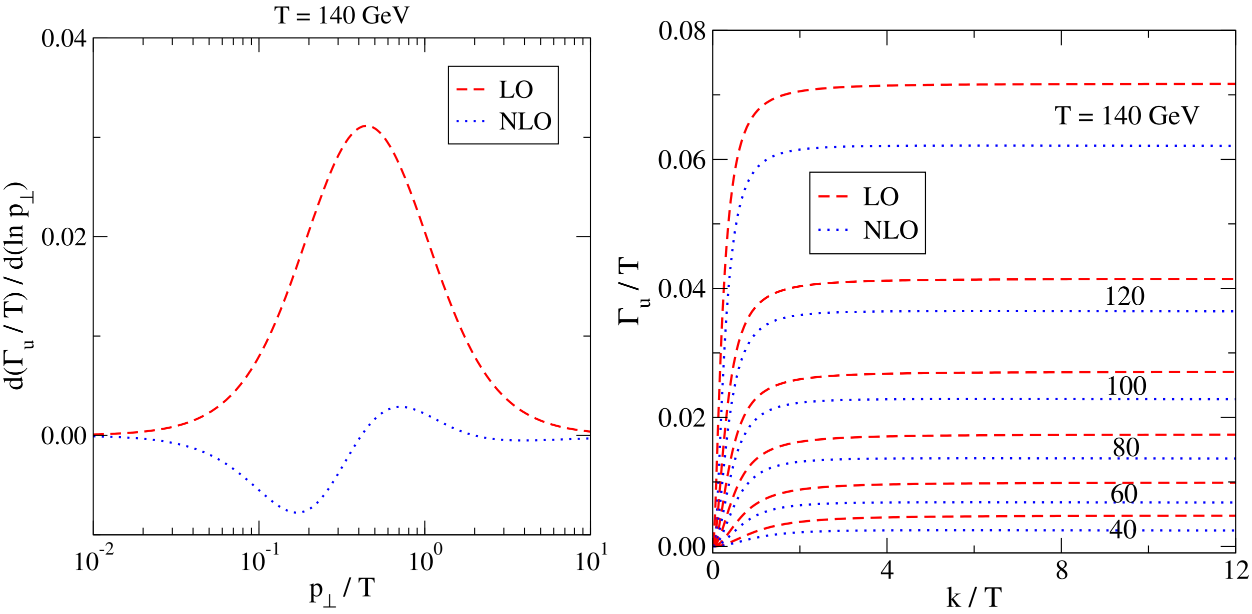
[11] J. Ghiglieri and ML, *Sterile neutrino dark matter via GeV-scale leptogenesis?*, 1905.08814

test uncertainties by computing coefficients at NLO[12]



⇒ uncertainties of $\mathcal{O}(15\%)$

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[12] G. Jackson and ML, *in preparation*

summary

$\Rightarrow$ baryogenesis is possible with $\gtrsim$ 0.1 GeV sterile neutrinos

$\Rightarrow$ model building $\sim$ not much (?), thermal physics $\sim$ fun

$\Rightarrow$ theoretical uncertainties $\lesssim 50\%$ by now

$\Rightarrow$ lepton asymmetries may be larger than baryon asymmetry

$\Rightarrow$ experimental search expected to become an active field