precision studies of low-scale leptogenesis and relation to dark matter[1]

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motivation

explain neutrino properties with the minimal seesaw

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

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

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

more recently: $M_I \sim 1\ldots100$ GeV $\Leftrightarrow h_\nu \sim 10^{-7}\ldots10^{-6}$

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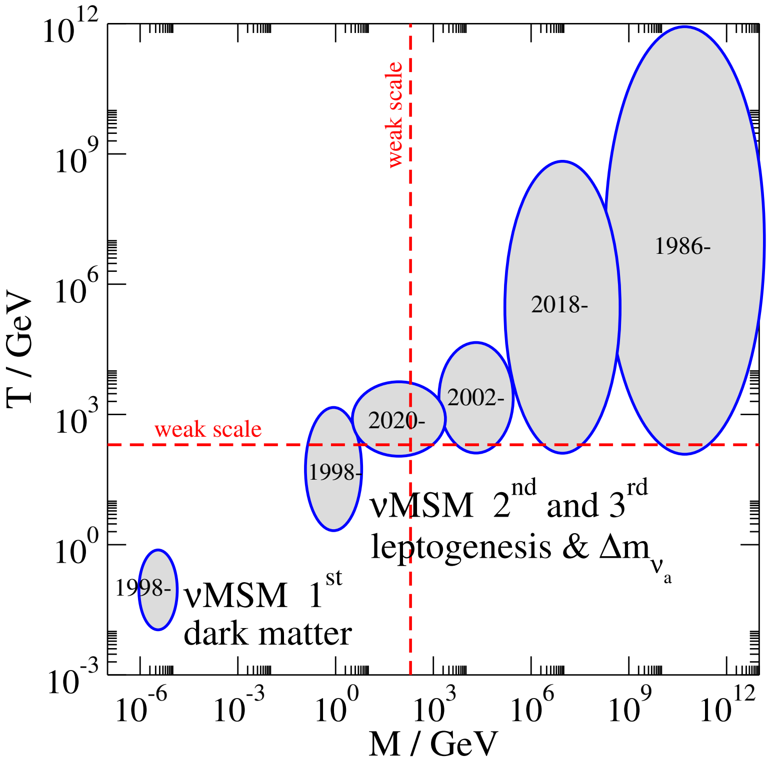
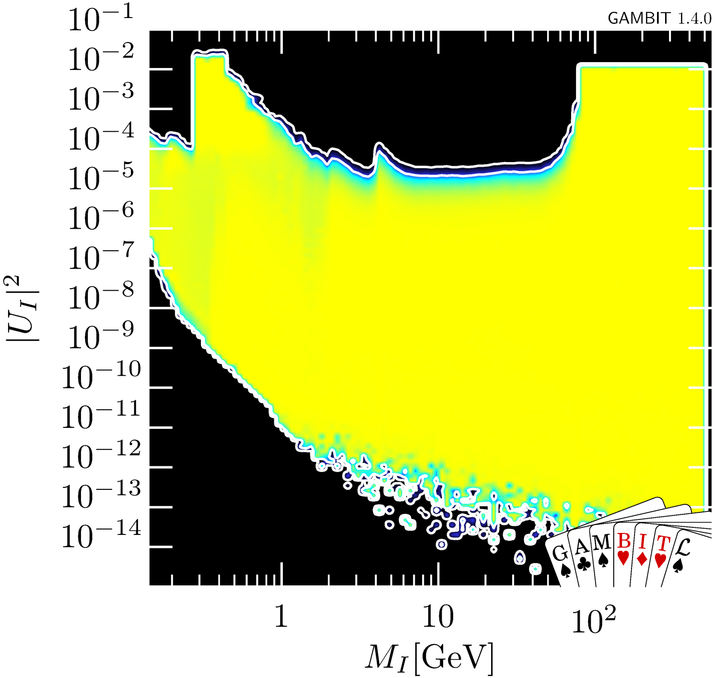
[2] P. Minkowski, *$\mu \to e\gamma$ at a Rate of One Out of 10^9 Muon Decays?*, PLB 67 (1977) 421; M. Gell-Mann, P. Ramond and R. Slansky, *Complex Spinors and Unified Theories*, 1306.4669; T. Yanagida, *Horizontal Symmetry and Masses of Neutrinos*, PTP 64 (1980) 1103

many domains have been looked into



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



⇒ a large region to explore

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

$$
\begin{aligned}
Y_L' &= -\,\widehat{\Gamma}_L\, Y_L - \widehat{\Gamma}_{L,R}\,(Y_R - Y_{\text{eq}}) \\
Y_R' &= -\,\widehat{\Gamma}_R\,(Y_R - Y_{\text{eq}}) - \widehat{\Gamma}_{R,L}\, Y_L
\end{aligned}
$$

$\Rightarrow$ $Y_L \neq 0$ possible if $\widehat{\Gamma}_L$, $\widehat{\Gamma}_R$ “small” and $\widehat{\Gamma}_{L,R}$ “large”

$\Rightarrow$ “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

coefficients contain the physics of fast (equilibrium) modes

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

where $Q^{\pm}_{(a)} \equiv [Q_{(a+)} \pm Q_{(a-)}]/2$ and

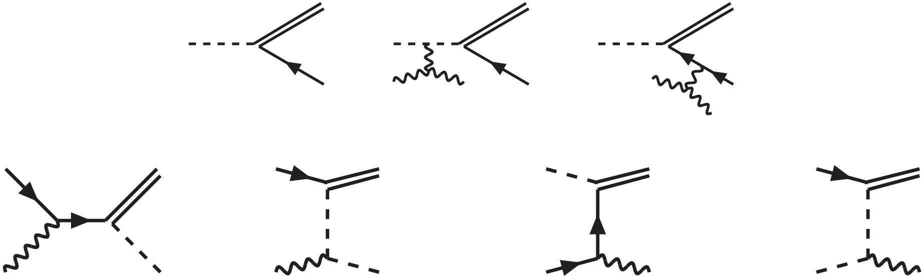
$$\underbrace{Q_{(a\tau)I}}_{\text{C-even}} + \underbrace{\bar{Q}_{(a\tau)I}}_{\text{C-odd}} \equiv \frac{\bar{u}_{\mathbf{k}\tau I} \; \mathrm{Im}\, \Pi^{\mathrm{R}}_{a}(\mathcal{K}_I) \, u_{\mathbf{k}\tau I}}{\omega_I}$$

here $u_{\mathbf{k}\tau I}$ denotes an on-shell spinor of helicity $\tau = \pm$, and

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

examples of 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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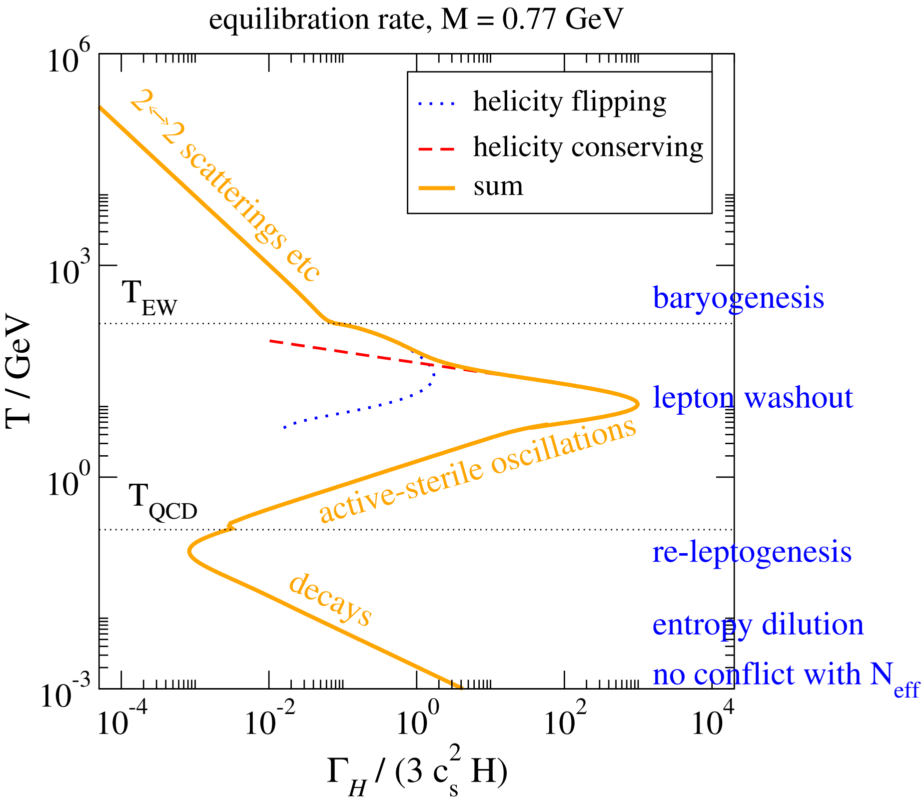
[6] originally: A. Anisimov, D. Besak and D. Bödeker, *Thermal production of relativistic Majorana neutrinos: Strong enhancement by multiple soft scattering*, 1012.3784; D. Besak and D. Bödeker, *Thermal production of ultrarelativistic right-handed neutrinos: Complete leading-order results*, 1202.1288; 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

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 for baryogenesis

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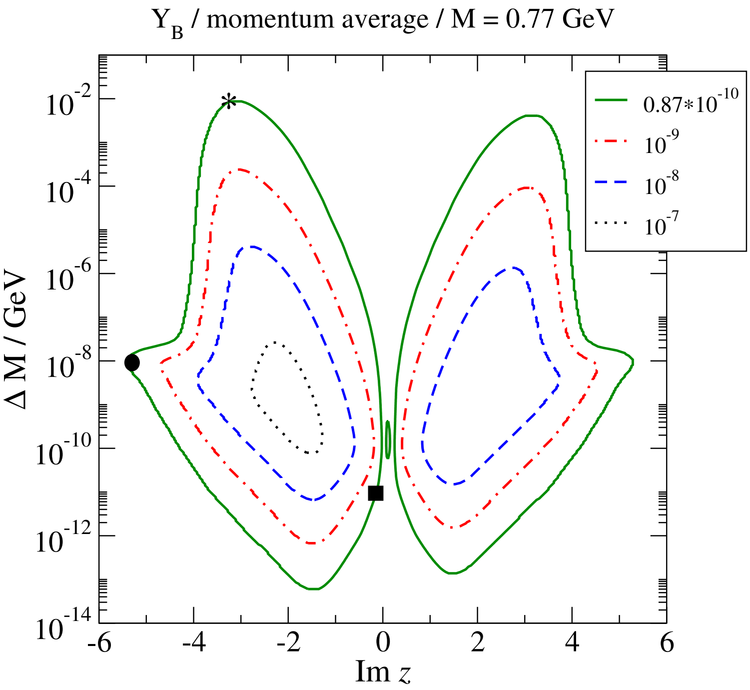
[7] J.A. Casas and A. Ibarra, *Oscillating neutrinos and* $\mu \to e\gamma$, hep-ph/0103065; generalization beyond seesaw limit: A. Donini, P. Hernández, J. López-Pavón, M. Maltoni and T. Schwetz, *The minimal 3+2 neutrino model versus oscillation anomalies*, 1205.5230

[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* ν*MSM*, 1808.10833

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



$\Rightarrow$ it works!

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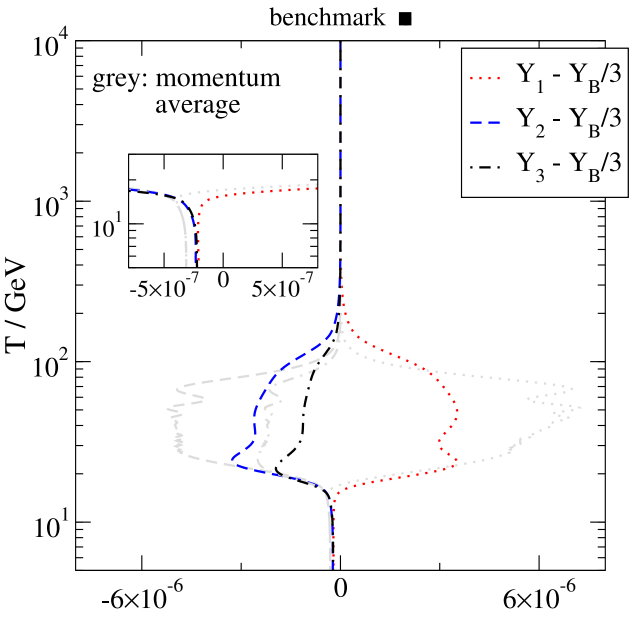
[9] J. Ghiglieri and ML, *Precision study of GeV-scale resonant leptogenesis*, 1811.01971

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



⇒ relation to resonant sterile neutrino dark matter production?

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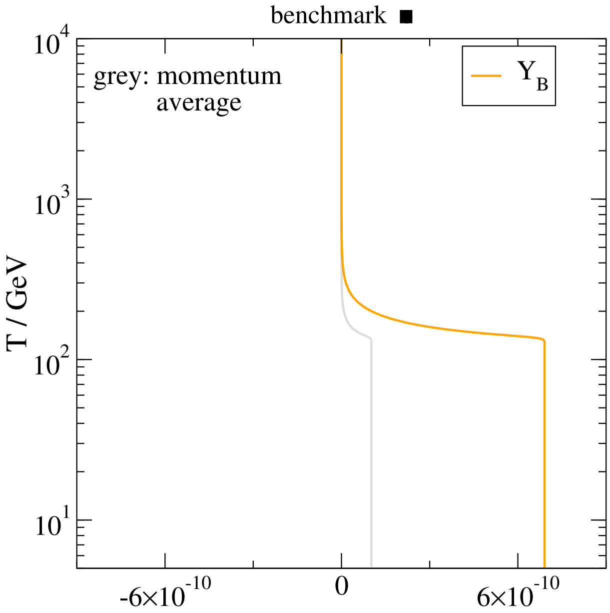
[10] see also S. Eijima and M. Shaposhnikov, *Fermion number violating effects in low scale leptogenesis*, 1703.06085

how precise are such results?

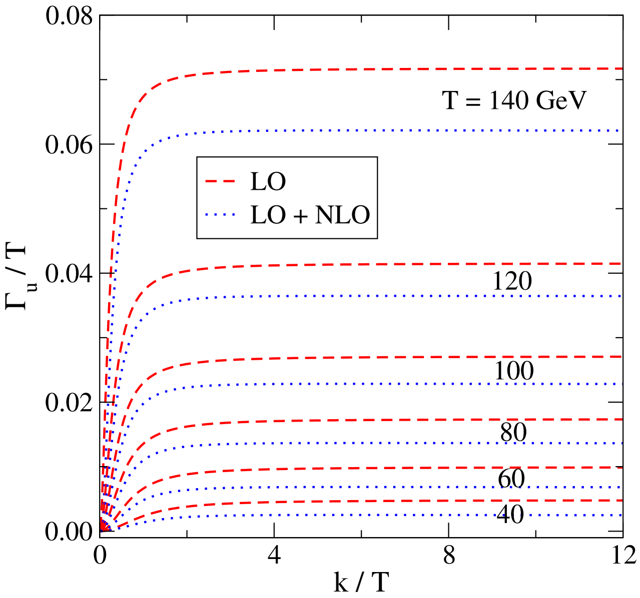
effect of kinetic non-equilibrium



$\Rightarrow$ uncertainties of $\mathcal{O}(1)$ but normally much less

how precise are such results?

computing coefficients at NLO [11]



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

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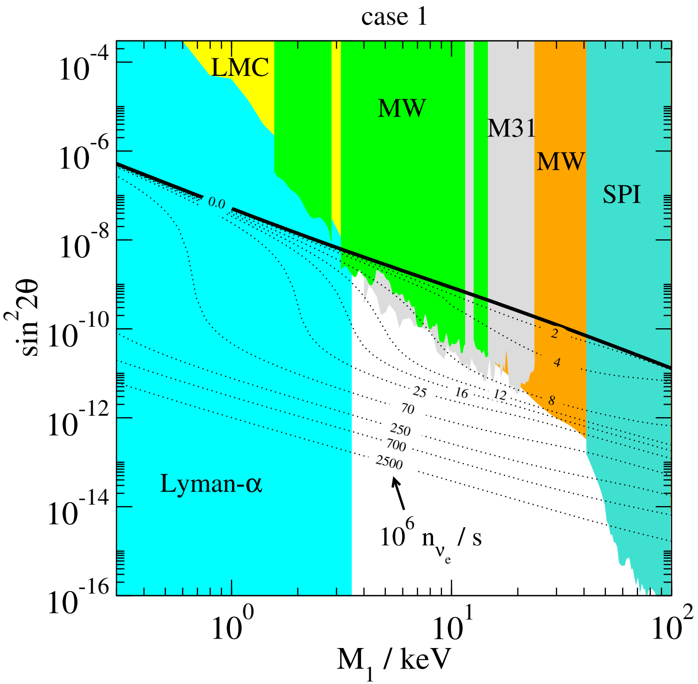
[11] G. Jackson and ML, *A thermal neutrino interaction rate at NLO*, 1910.12880

resonant dark matter production

large Y_a permits for resonant sterile neutrino production[12]



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[12] X.-D. Shi and G.M. Fuller, *A New dark matter candidate: Nonthermal sterile neutrinos*, astro-ph/9810076; ML and M. Shaposhnikov, *Sterile neutrino dark matter as a consequence of νMSM-induced lepton asymmetry*, 0804.4543; ... ; D. Bödeker and A. Klaus, *Sterile neutrino dark matter: Impact of active-neutrino opacities*, 2005.03039

inspired by supposed detection,[13] consider modern setup[14]

1 light flavour ($\overset{?}{\Rightarrow}$ dm), 2 heavy flavours ($\overset{!}{\Rightarrow}$ Δm_ν, n_B), three lepton asymmetries, helicities, momentum dependence

obtain $|Y_a|$ from dynamics, **not** by hand

parameters of light flavour: $M_1 = 7$ keV, $\sin^2(2\theta) = 2 \times 10^{-10}$

maximal effect: all light yukawas equal $|h_{1a}| \simeq 1.6 \times 10^{-13}$

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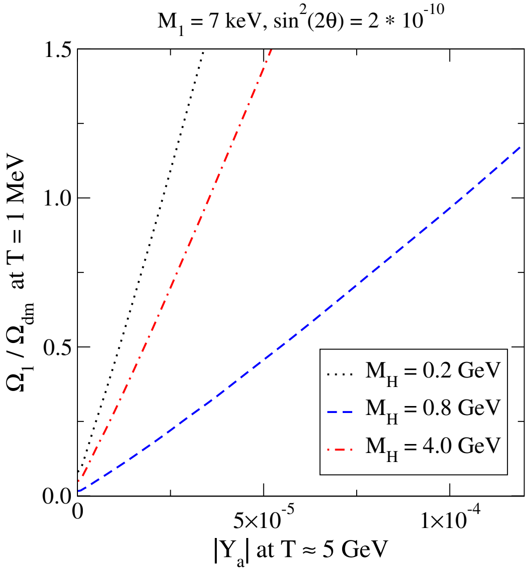
[13] E. Bulbul *et al*, *Detection of An Unidentified Emission Line in the Stacked X-ray spectrum of Galaxy Clusters*, 1402.2301; A. Boyarsky *et al*, *An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster*, 1402.4119

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

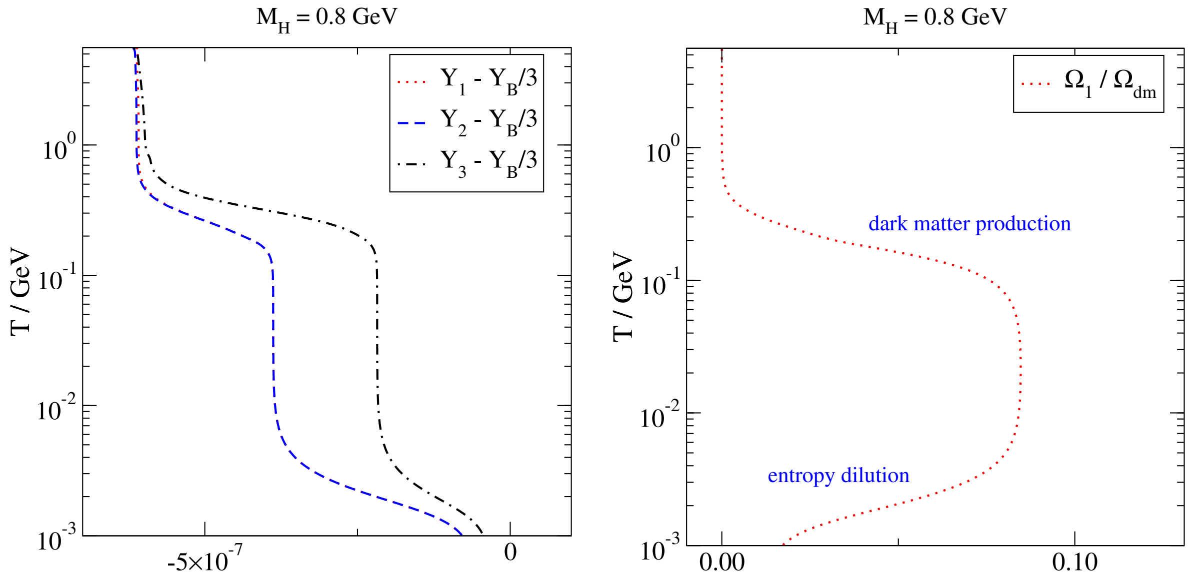
$\Omega_1 \approx \Omega_{\mathbf{dm}}$ can be obtained only if $|Y_a| \sim 10^{-5\ldots-4}$



⇒ differences between M_H are due to entropy release

⇒ where could the factor $|Y_a|/|Y_B| \sim 10^5$ come from?

generic $|Y_a|$: only partial conversion to dark matter



⇒ entropy dilution is substantial for these parameters

⇒ final abundance remains below 10%

to do better need a "coincidence"[15]

at dm production, oscillation rate should be ∼ Hubble rate

$$\langle \widehat{H}_\lambda \rangle \;\equiv\; \left|\text{eigenvalue}\left(\langle \mathrm{diag}(\widehat{\omega}_2, \widehat{\omega}_3) - \widehat{H}_H^+ \rangle_1 - \frac{\mathbb{1}}{2}(\text{trace})\right)\right|$$

at dm production, interaction rate should be ∼ Hubble rate

$$\langle \widehat{\Gamma}_H \rangle \equiv \sum_a \sum_{I=2,3} |h_{Ia}|^2 \langle \widehat{Q}^+_{(a)I} \rangle$$

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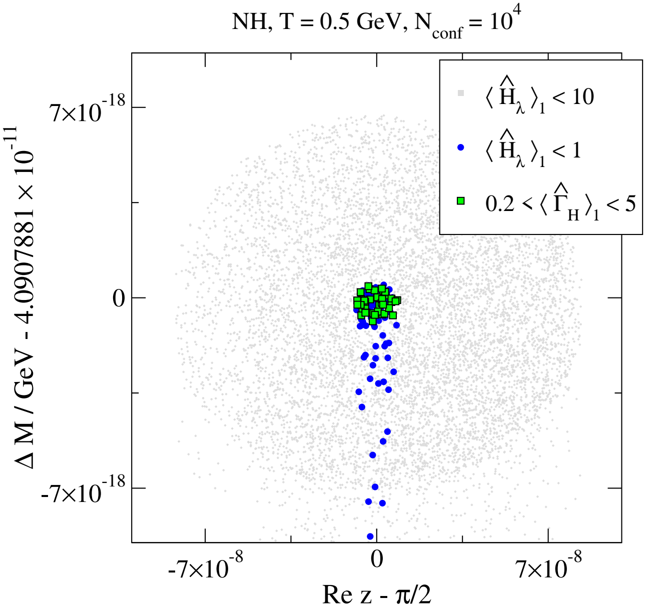
[15] L. Canetti *et al, Dark Matter, Baryogenesis and Neutrino Oscillations from Right Handed Neutrinos*, 1208.4607.

having such a coincidence requires fine-tuning[16]



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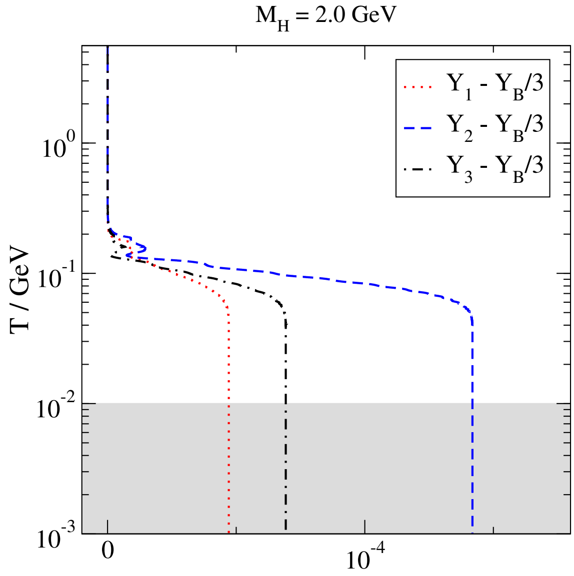
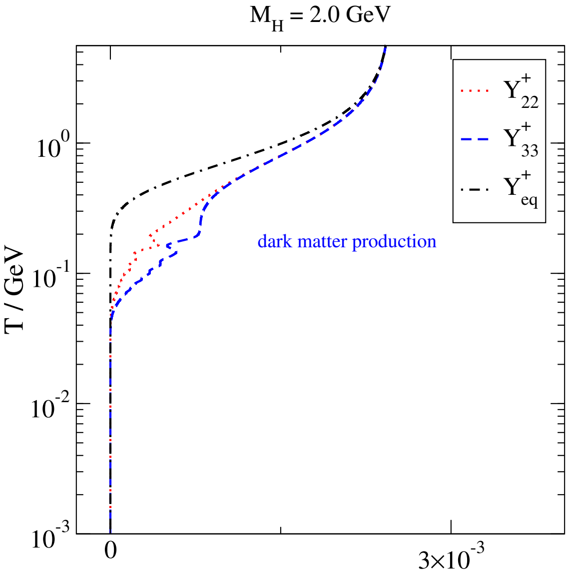
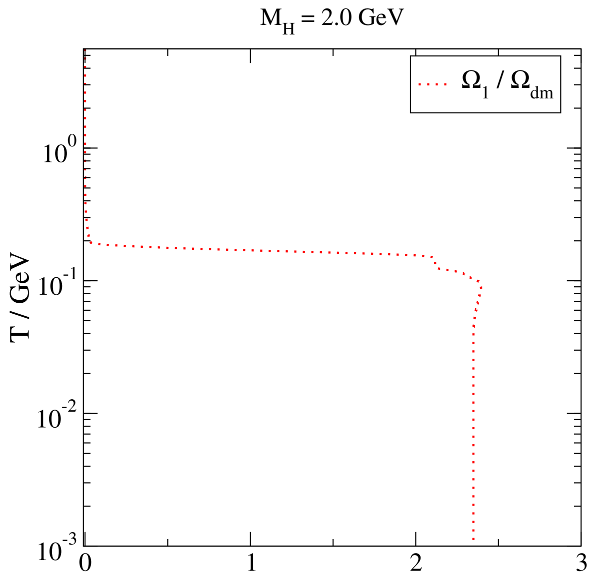
[16] J. Ghiglieri and ML, *Sterile neutrino dark matter via coinciding resonances*, 2004.10766

picking a point from the center, large $|Y_a|$ is possible





proof of existence: this gives more than enough of dm



code for spectra:[17] `https://zenodo.org/record/3938597`

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[17] J. Ghiglieri and ML, *Improved determination of sterile neutrino dark matter spectrum*, 1506.06752

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

$\Rightarrow$ connection to dark matter exists but strongly constrained

$\Rightarrow$ experimental search could/should become an active field