on the relation between low-scale leptogenesis and dark matter [1,2]

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[1] based on collaboration with Jacopo Ghiglieri

[2] supported by the SNF under grant 200020-168988

basic setup

focus here on a minimal model ($\tilde{\phi}$, $\ell_{\rm L} \subset$ old-SM, add $\nu_{\rm R}$)

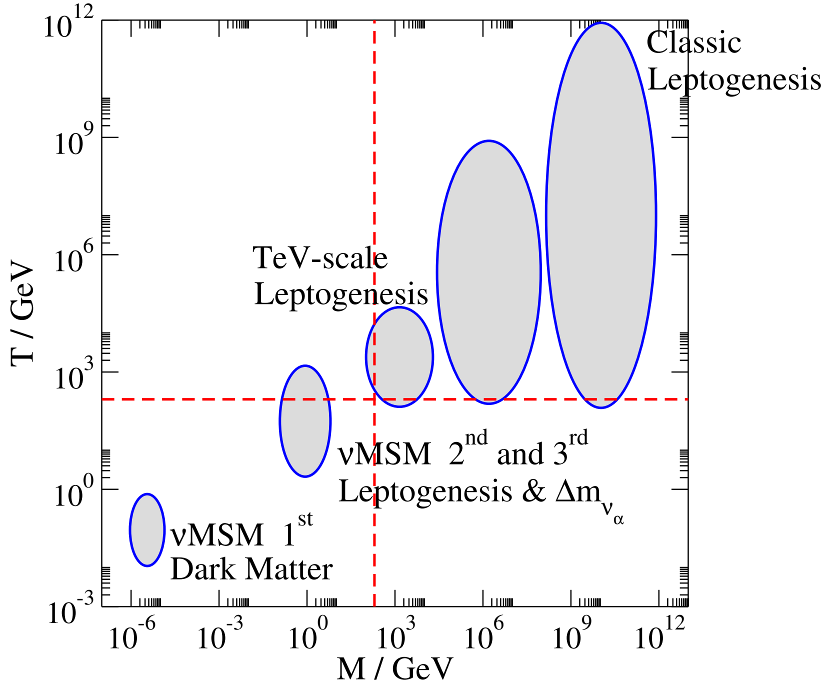
$$
\begin{aligned}
\mathcal{L}_{\text{new-SM}} \quad &\equiv \quad \mathcal{L}_{\text{old-SM}} + \bar{\nu}_{\rm R} i \partial\!\!\!/ \, \nu_{\rm R} \\
&- \quad (\bar{\nu}_{\rm R}\, \tilde{\phi}^{\dagger} h_{\nu}\, \ell_{\rm L} + \bar{\ell}_{\rm L}\, h_{\nu}^{\dagger}\, \tilde{\phi}\, \nu_{\rm R}) \\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

singular value decomposition & field rotation

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

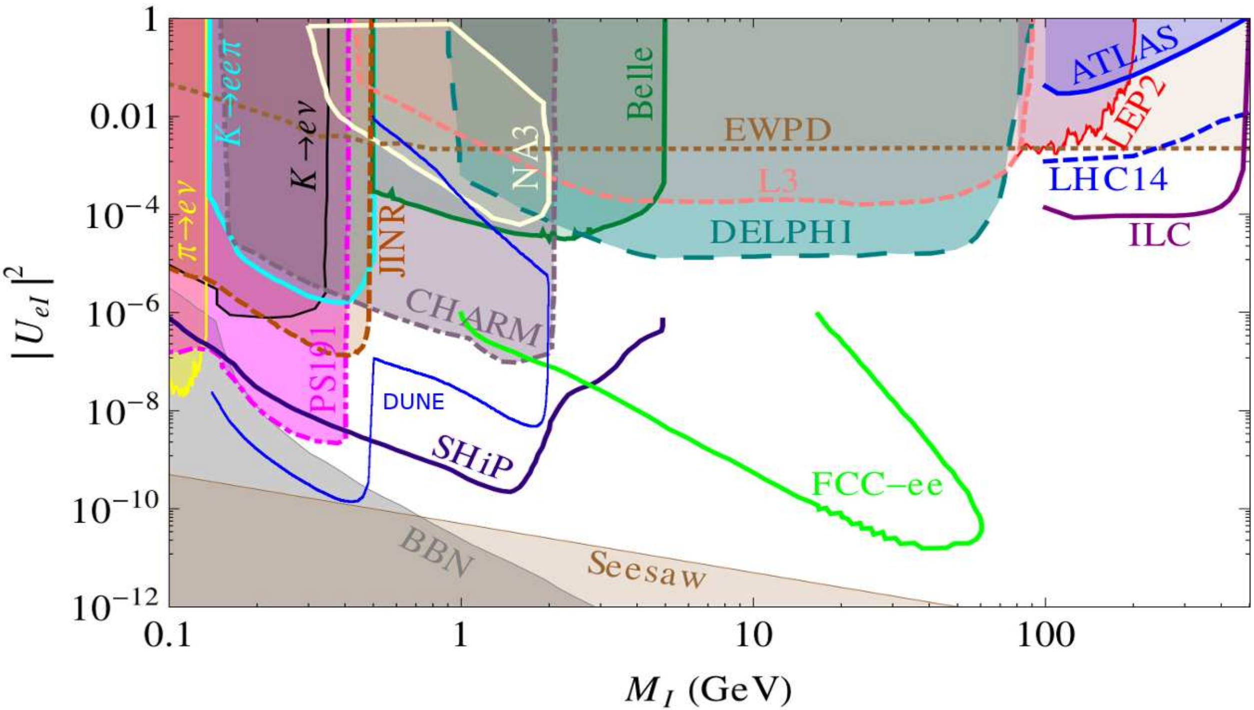
consider the situation $M_1 \sim$ keV, $M_{2,3} \sim$ GeV, with $M_{2,3}$ generating the active neutrino mass differences and mixings

a broad range of M_I could be of cosmological interest [3]



3 the low-mass range has been popularized by T. Asaka and M. Shaposhnikov, *The νMSM, dark matter and baryon asymmetry of the universe*, hep-ph/0505013

recently many new searches proposed for the GeV range[4]



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[4] ...; I. Krasnov, *On DUNE prospects in the search for sterile neutrinos*, 1902.06099; I. Boiarska et al, *Probing baryon asymmetry of the Universe at LHC and SHiP*, 1902.04535; P. Ballett et al, *Heavy Neutral Leptons ... at the DUNE Near Detector* , 1905.00284; ...

convenient parametrization of neutrino yukawas[5]

$$M \equiv \begin{pmatrix} M_2 & 0 \\ 0 & M_3 \end{pmatrix} , \quad R \equiv \begin{pmatrix} \cos z & \sin z \\ -\sin z & \cos z \end{pmatrix} , \quad z \in \mathbb{C} ,$$

$$P_{\rm NH} \equiv \begin{pmatrix} 0 & e^{-i\phi_1} & 0 \\ 0 & 0 & 1 \end{pmatrix} , \quad P_{\sf IH} \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\phi_1} & 0 \end{pmatrix}$$

$$\Rightarrow \boxed{h_\nu = -i\sqrt{M}\, R\, P \underbrace{\sqrt{m_\nu}\, V^\dagger}_{\text{data}} \frac{\sqrt{2}}{v}}$$

[5] 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

start with a benchmark ($*$) from a previous scan:[6]

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

"inverted hierarchy"

not excluded, could be discovered, produces baryon asymmetry!

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[6] P. Hernández, M. Kekic, J. López-Pavón, J. Racker and J. Salvado, *Testable Baryogenesis in Seesaw Models*, 1606.06719

baryogenesis via resonant leptogenesis

basic variables [7]

- $n_L \rightarrow$ flavour asymmetries $n_a - \frac{n_B}{3}$, $a \in \{e, \mu, \tau\}$

- $n_R \rightarrow$ density matrices $\rho_{IJ}(k, \pm)$, $I, J \in \{2, 3\}$

employ "yields" ($Y_a \equiv \frac{n_a}{s}$) and helicity-symmetrized density matrices $\rho^{\pm} \equiv [\rho(k,+) \pm \rho(k,-)]/2$

cosmological evolution tracked through $x \equiv \ln(\frac{T_{\text{max}}}{T})$
redshift tracked through co-moving momentum $k_T \equiv k\,\frac{a(T_{\text{min}})}{a(T)}$

number densities $\Leftrightarrow$ chemical potentials: $n_a = \partial p / \partial \mu_a$

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[7] original ideas put forward by E.K. Akhmedov, V.A. Rubakov and A.Y. Smirnov, *Baryogenesis via neutrino oscillations*, hep-ph/9803255

evolution equation for lepton asymmetries

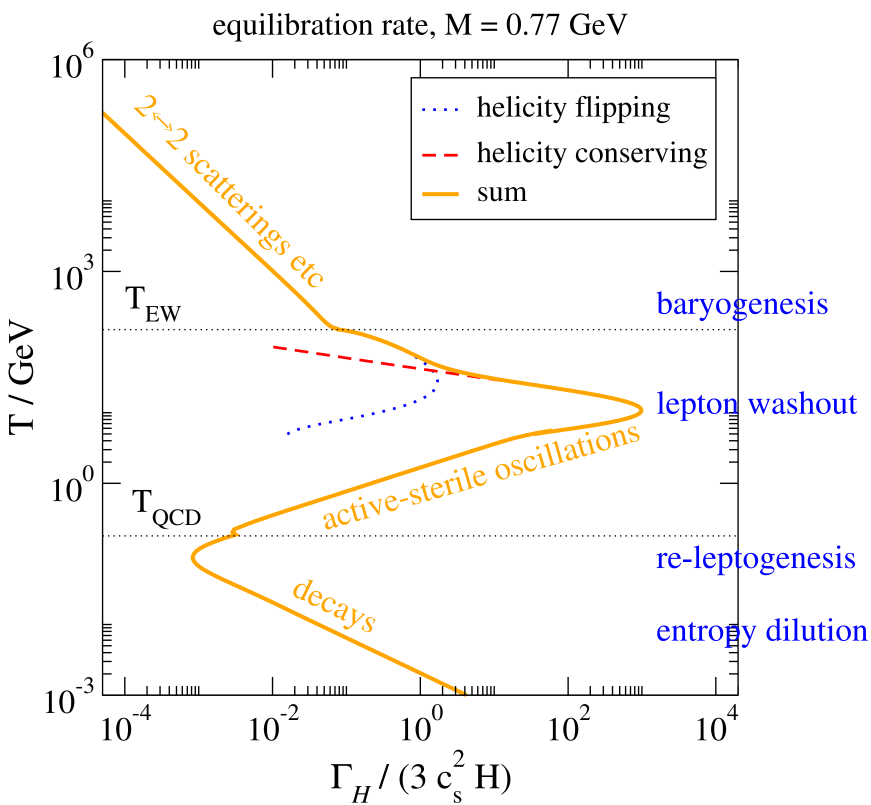
$$
\begin{aligned}
Y_a' - \frac{Y_B'}{3} \quad = \quad & \frac{4}{s} \int_{\mathbf{k}_T} \mathrm{Tr}\Big\{ -n_\mathsf{F}(\omega_T)[1-n_\mathsf{F}(\omega_T)]\, \widehat{A}^{+}_{(a)} \\
& + [\, \rho^{+} - n_\mathsf{F}(\omega_T)\,]\, \widehat{B}^{+}_{(a)} \\
& + \rho^{-}\, \widehat{B}^{-}_{(a)} \;\Big\}
\end{aligned}
$$

1st term: washout term ("equilibration") $\propto \{\mu_a\}$

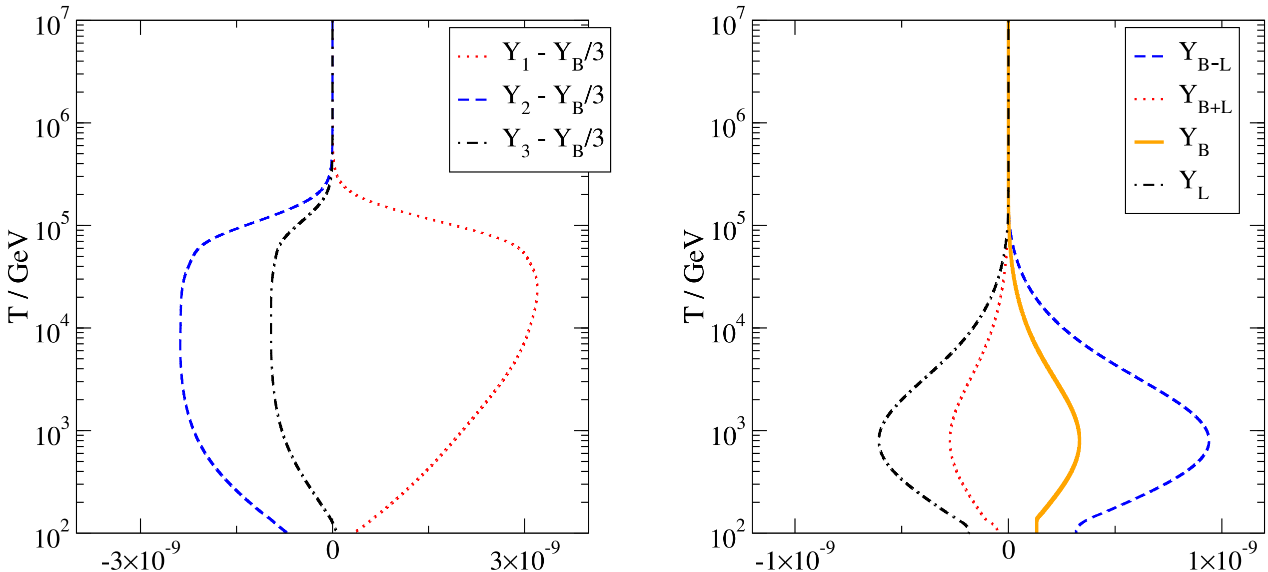
2nd term: source from helicity-symmetric non-equilibrium

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

normalized equilibration rate (part of $\widehat{A}^{+}_{(a)}$)



evolution of lepton asymmetries for benchmark $(*)$



final Y_B gets fixed when sphalerons freeze out at $T \sim 130$ GeV[8]

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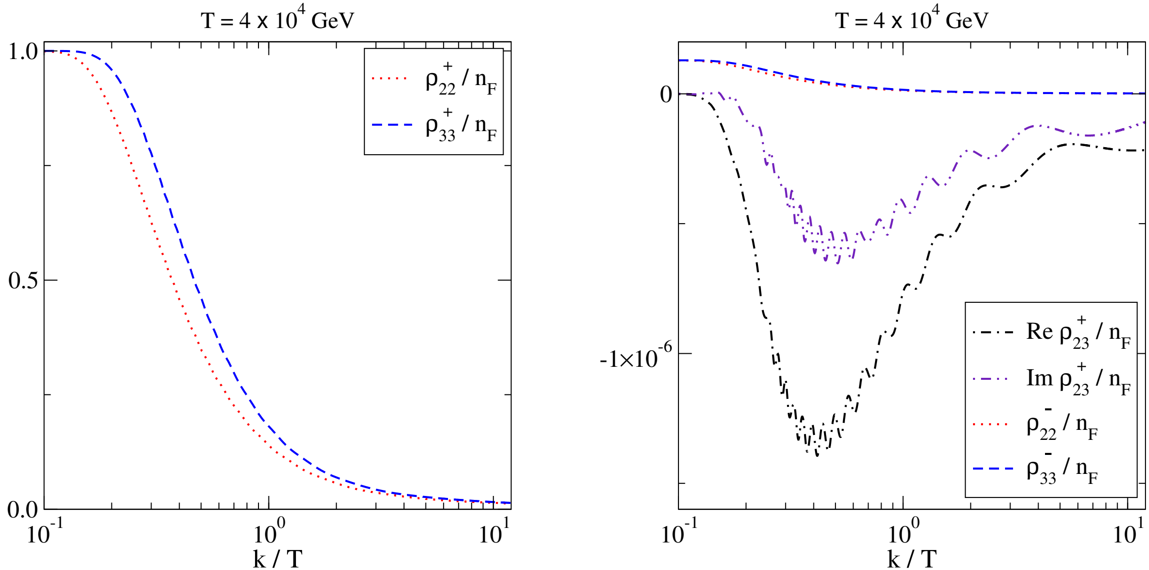
[8] M. D'Onofrio, K. Rummukainen and A. Tranberg, *Sphaleron Rate in the Minimal Standard Model*, 1404.3565

density matrices manifest kinetic non-equilibrium

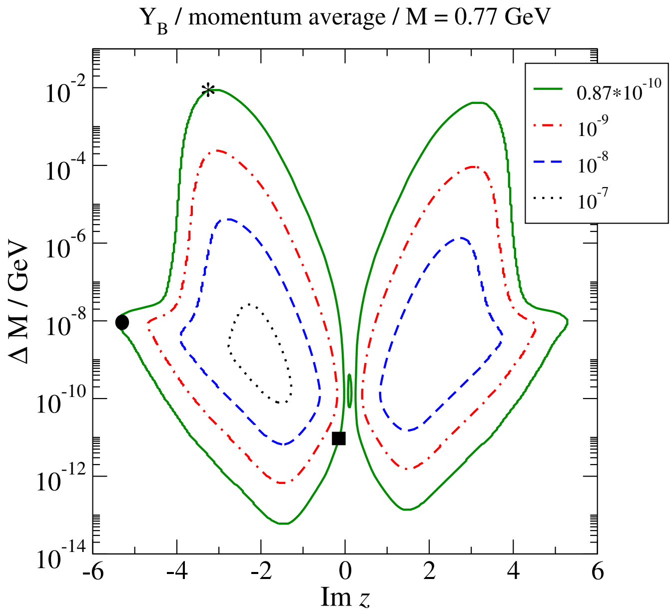


accounting for this we find $\sim 50\%$ increase over a previous study

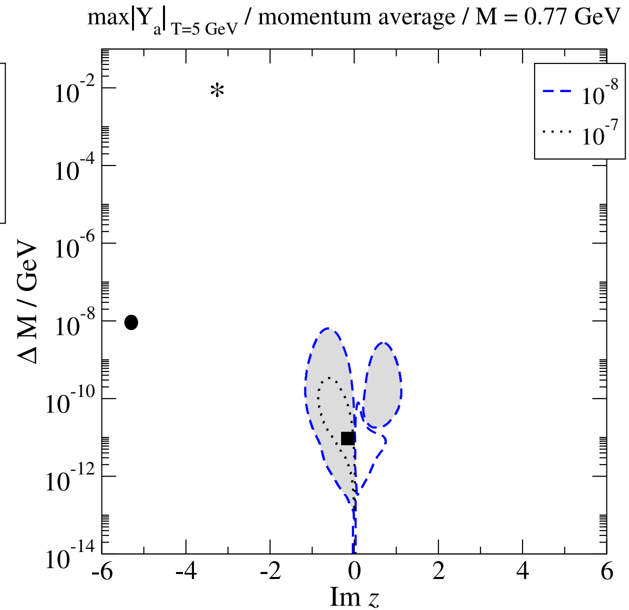
but conclusion is confirmed: baryogenesis works!

generation of low-T lepton asymmetries

push previous benchmark ($*$) towards more degeneracy[9]



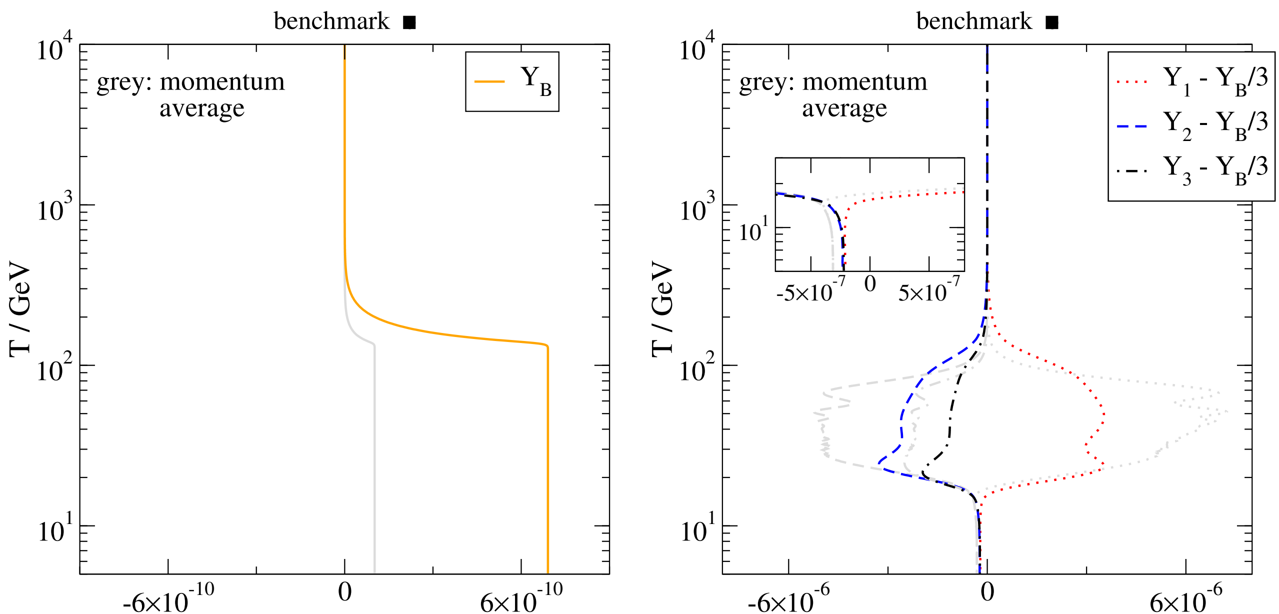
final Y_B



Y_a at $T = 1$ GeV

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

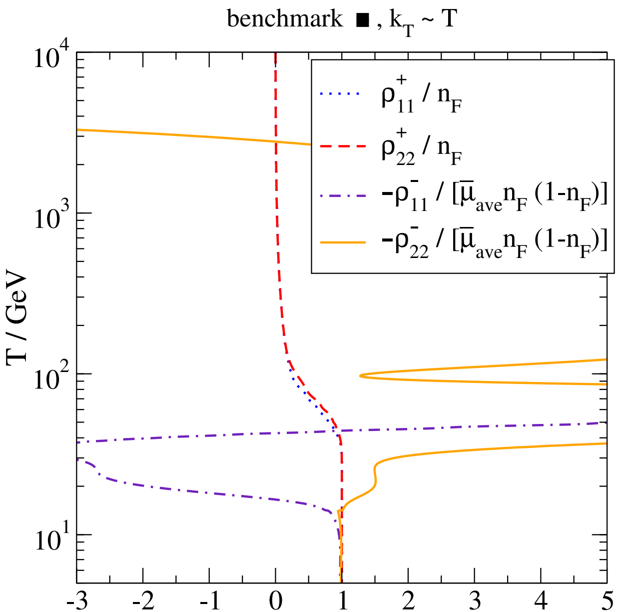
the case with minimal yukawas / weak washout

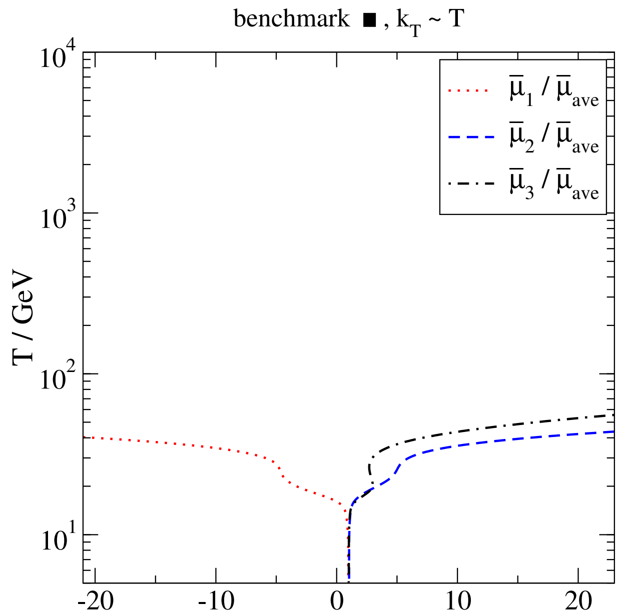


⇒ despite washout, a remnant lepton asymmetry is left over

⇒ the value is "large": $|Y_a| \sim 3 \times 10^{-7} \approx 3 \times 10^3\, Y_B$

remarkably, the system settles into a "fixed point" at low T



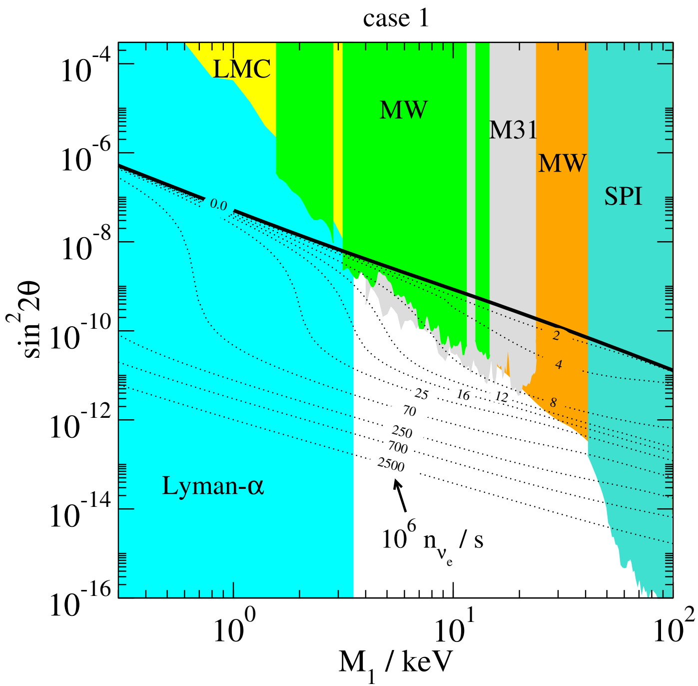


$\Rightarrow$ helicity asymmetries balance against lepton asymmetries

$\Rightarrow$ flavour equilibrium even at $T \gg 10$ MeV

resonant dark matter production

large Y_a permits for resonant sterile neutrino production[10]



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[10] 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

inspired by supposed detection,[11] consider modern setup[12]

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

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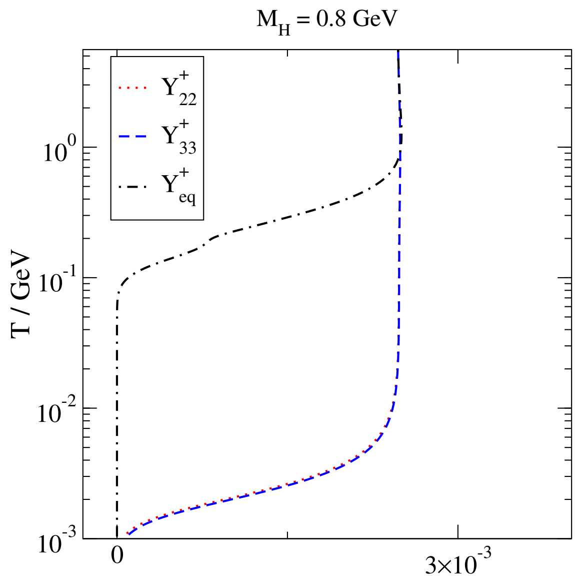
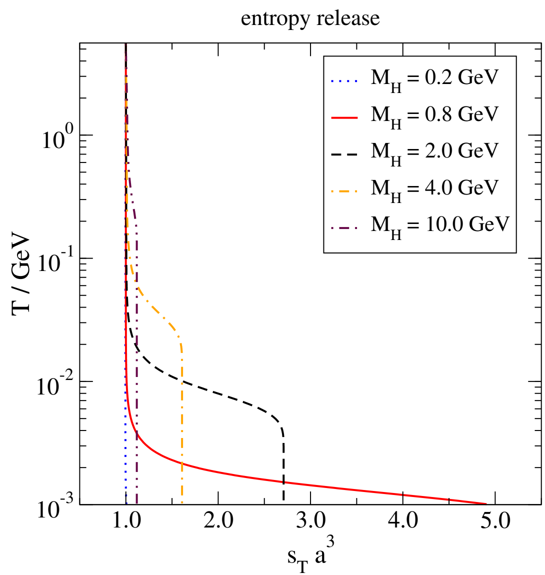
[11] E. Bulbul *et al*, *Detection of An Unidentified Emission Line in the Stacked X-ray spectrum of Galaxy Clusters*, 1402.2301; A. Boyarsky *et al*, *An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster*, 1402.4119

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

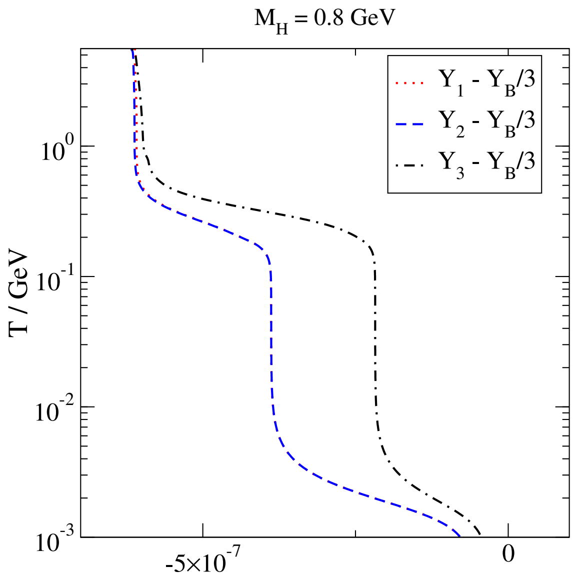
entropy dilution[13] from out-of-equilibrium decays of $M_{2,3}$

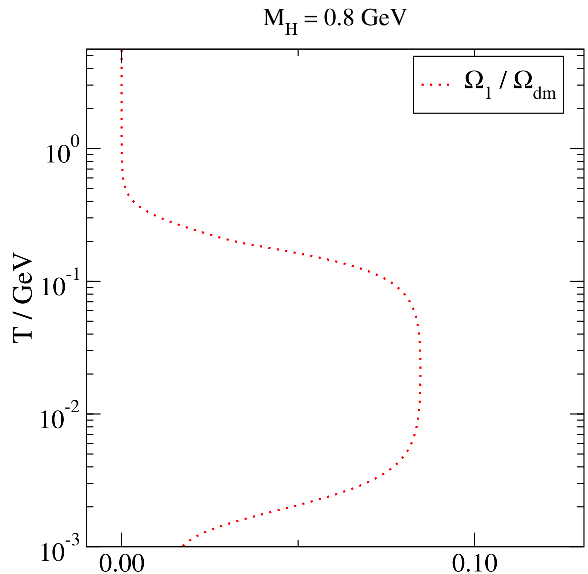




[13] e.g. R.J. Scherrer and M.S. Turner, *Decaying particles do not "heat up" the Universe*, PRD 31 (1985) 681

initial lepton asymmetries partly convert to dark matter

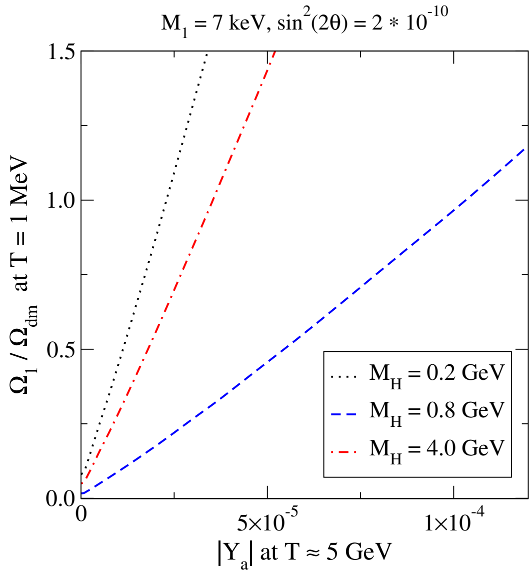




$\Rightarrow$ entropy dilution is substantial for these parameters

$\Rightarrow$ final abundance remains below 10%

$\Omega_1 \approx \Omega_{\text{dm}}$ obtained only if $|Y_a|$ larger by $\sim 10^2$



$\Rightarrow$ differences between M_H due to entropy release

$\Rightarrow$ is $|Y_a| \sim \times 10^{3\ldots4}\, Y_B$ a glass half full or empty?

summary & what's next

$\Rightarrow$ baryogenesis through GeV-scale resonant leptogenesis works

$\Rightarrow$ theoretical uncertainties hopefully below 50% level

$\Rightarrow$ $\exists$ remarkable stationary state with large lepton asymmetries

$\Rightarrow$ yet producing $\Omega_{\rm dm}$ difficult within SHiP range $M_{2,3} \lesssim 5$ GeV

$\Rightarrow$ larger masses $M_{2,3} \gtrsim 10$ GeV remain to be explored

$\Rightarrow$ it has also become popular to modify the model slightly