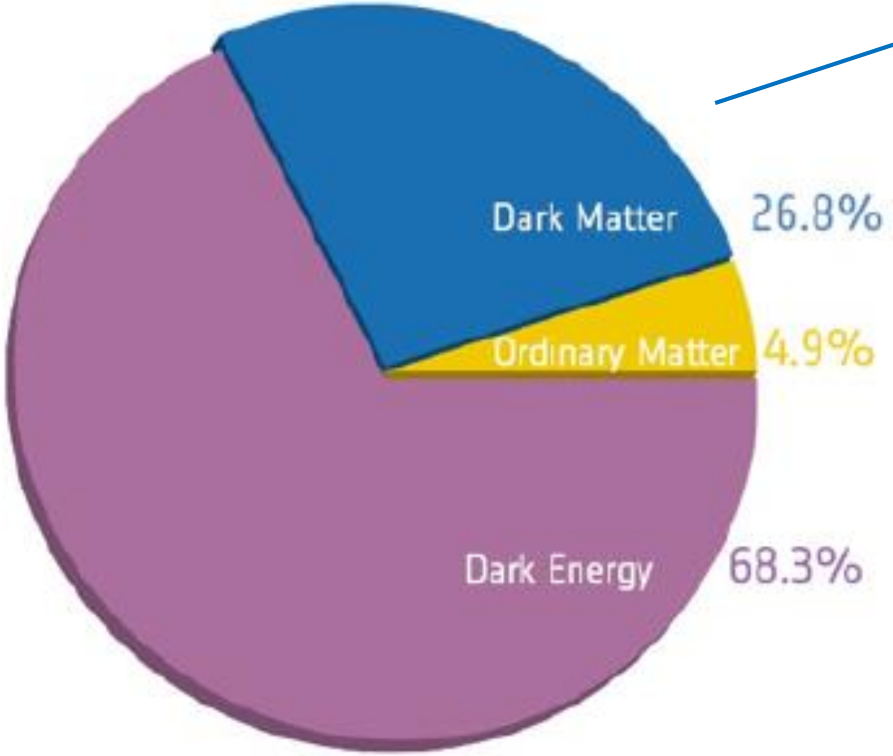
Leptogenesis and Dark Matter in Low Energy See-Saw

MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK
HEIDELBERG



Originated by unknown mechanism

$$\eta \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma} \approx 6 \times 10^{-10}$$

Originated from a Baryon Asymmetry

Extension of the SM with RH/sterile neutrinos

Baryogenesis through Leptogenesis:

Production of the lepton asymmetry through decay or oscillation processes, converted into baryon asymmetry by Sphaleron processes.

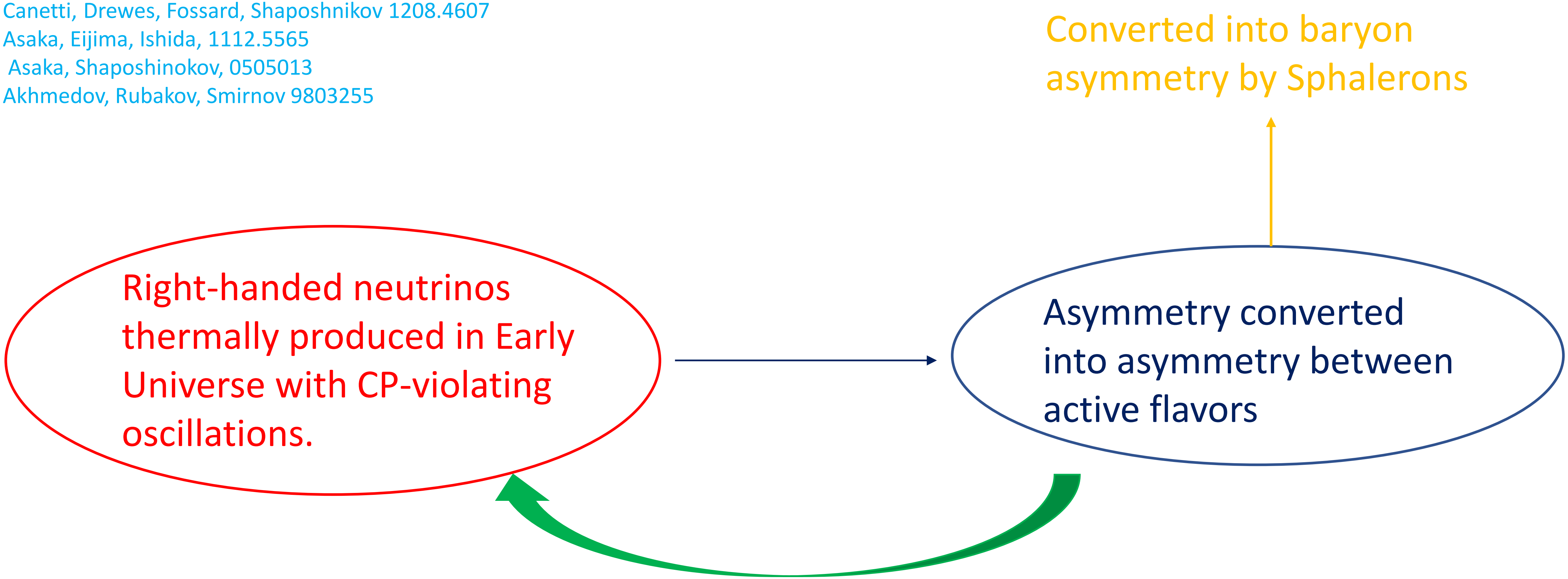
DM as sterile neutrinos (typically KeV scale):

Different production mechanisms possible.

Mechanism for SM neutrino mass generation

ARS Leptogenesis

Hernandez, Kekic, Lopez-Pavon, Racker, Salvado 1606.06719
Canetti, Drewes, Fossard, Shaposhnikov 1208.4607
Asaka, Eijima, Ishida, 1112.5565
Asaka, Shaposhinokov, 0505013
Akhmedov, Rubakov, Smirnov 9803255



Converted into baryon asymmetry by Sphalerons

Right-handed neutrinos thermally produced in Early Universe with CP-violating oscillations.

Asymmetry converted into asymmetry between active flavors

Asymmetry in the active sector acts as background potential and enhances the asymmetry in the RH sector

The total lepton asymmetry in the active and new neutrino sector is null.

Degeneracy removed for leptogenesis from 3 (or more) neutrinos

Drewes and Garbrecht 1206.5537

Minimal version of ARS leptogenesis requires a pair of nearly mass degenerate neutrinos.

Additional LNV processes might be relevant

Eijima, Shaposhnikov 1703.06085
Hambye, Teresi 1606.00017
Eijima, Shaposhnikov, Timiryasov 1808.10833

ARS requires GeV (O(10) at most) scale neutrinos. Low energy neutrino mass mechanism required.

Model Setup

$$-\mathcal{L}_{m_\nu} = n_L^T\, C\, \mathcal{M}\, n_L + \text{h.c.}$$

Linear+Inverse See-Saw

$$n_L \equiv (\nu_L^e, \nu_L^\mu, \nu_L^\tau, N_R^{1\,c}, N_R^{2\,c})^T$$

L-conserving

$$\mathcal{M}^{(\nu)} = \begin{pmatrix} 0 & Yv/\sqrt{2} & \epsilon Y'v/\sqrt{2} \\ Yv/\sqrt{2} & 0 & \Lambda \\ \epsilon Y'v/\sqrt{2} & \Lambda & \xi\Lambda \end{pmatrix}$$

L-violating

L-conserving

L-violating

Inverse See-Saw

(2) Right handed

(2-3) Sterile

$$n_L \equiv (\nu_L^e,\, \nu_L^\mu,\, \nu_L^\tau,\, \nu_{R,i}{}^c, s_j)^T$$

L-conserving

$$\mathcal{M} \equiv \begin{pmatrix} 0 & d & 0 \\ d^T & 0 & n \\ 0 & n^T & \xi\Lambda \end{pmatrix}$$

L-violating

$$m_{\text{PD}} \simeq n \simeq \Lambda$$

$$\Delta m^2_{\text{PD}} = M_2^2 - M_1^2 = 2\xi\Lambda^2$$

If $\#s > \#\nu_R$ DM candidate present

$$m_{\text{DM}} \simeq \xi\Lambda$$

Boltzmann Equations

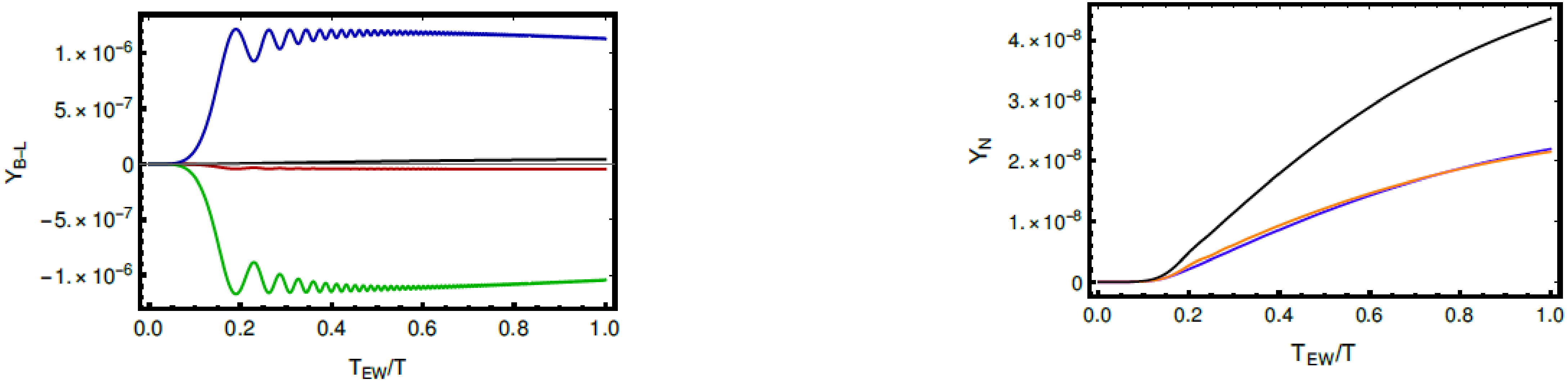
$$\frac{dR_N}{dt} = -\,i\,[\langle H\rangle, R_N] - \frac{1}{2}\langle\gamma^{(0)}\rangle\left\{F^\dagger F, R_N - I\right\} - \frac{1}{2}\langle\gamma^{(1b)}\rangle\left\{F^\dagger \mu_L F, R_N\right\} + \langle\gamma^{(1a)}\rangle F^\dagger \mu_L F$$

$$\frac{d\mu_{\Delta_\alpha}}{dt} = -\frac{9\zeta(3)}{2N_D\,\pi^2}\left\{\langle\gamma^{(0)}\rangle\left(FR_NF^\dagger - F^*R_{\bar N}F^T\right) - 2\langle\gamma^{(1a)}\rangle\mu_L FF^\dagger \; + \langle\gamma^{(1b)}\rangle\mu_L\left(FR_NF^\dagger + F^*R_{\bar N}F^T\right)\right\}_{\alpha\alpha}$$

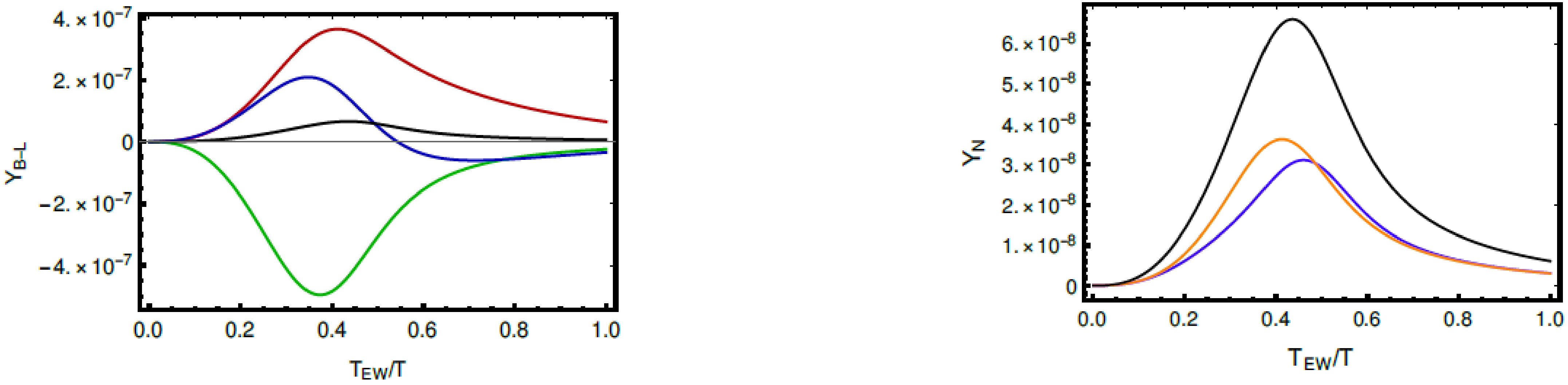
$$\mu_{L_\alpha} = A_{\alpha\beta}\mu_{\Delta_\beta} \qquad\qquad A = \frac{1}{711}\begin{pmatrix} -221 & 16 & 16 \\ 16 & -221 & 16 \\ 16 & 16 & -221 \end{pmatrix}$$

$$\langle\gamma^{(i)}\rangle = A_i\left[c^{(i)}_{\rm LPM} + y_t^2 c^{(i)}_Q + (3g^2 + g'^2)\left(c^{(i)}_V - \ln(3g^2+g'^2)\right)\right] \qquad \langle\gamma(T)\rangle = \frac{\int d^3p\,\gamma(p,T)\,f^0_F(p/T)}{\int d^3p\,f^0_F(p/T)}$$

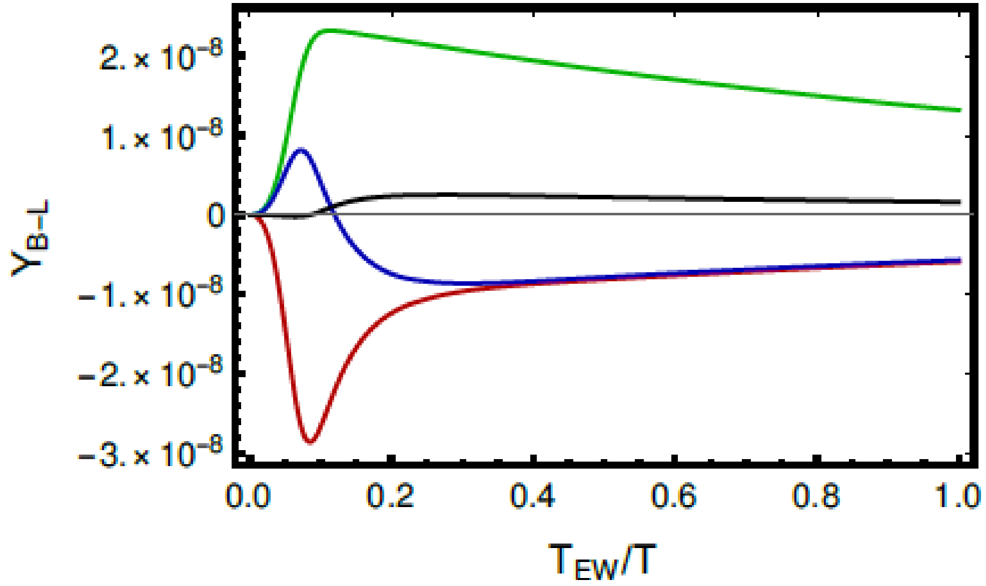
Weak wash out solution

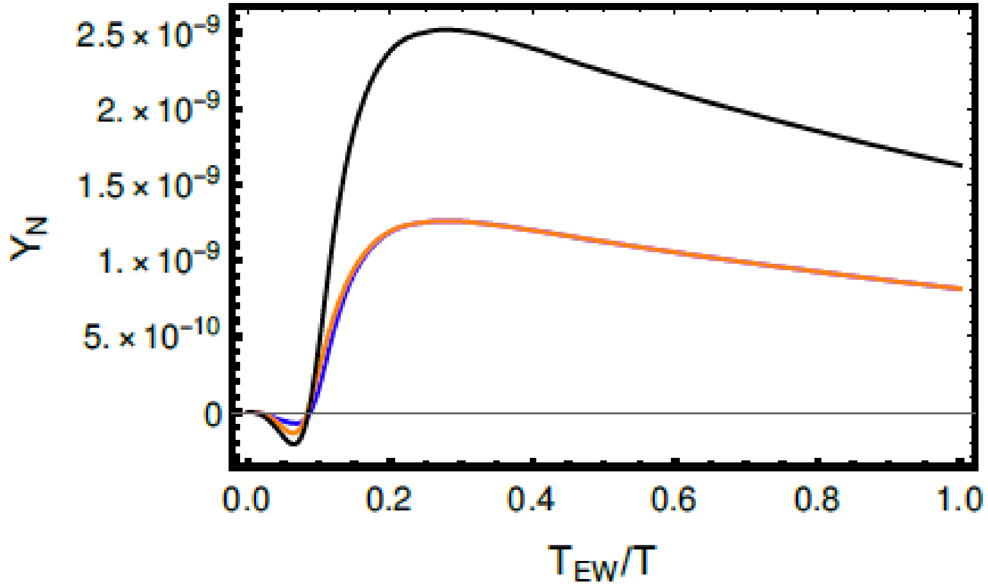


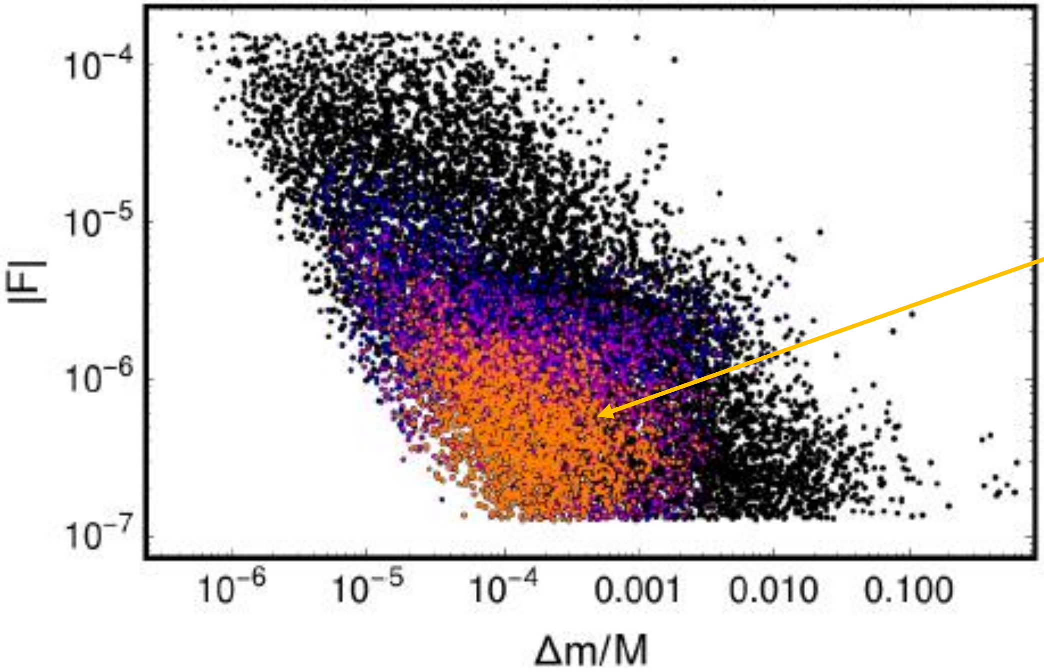
Strong wash out solution



Solution of hierarchical Yukawas (ISS(2,2))

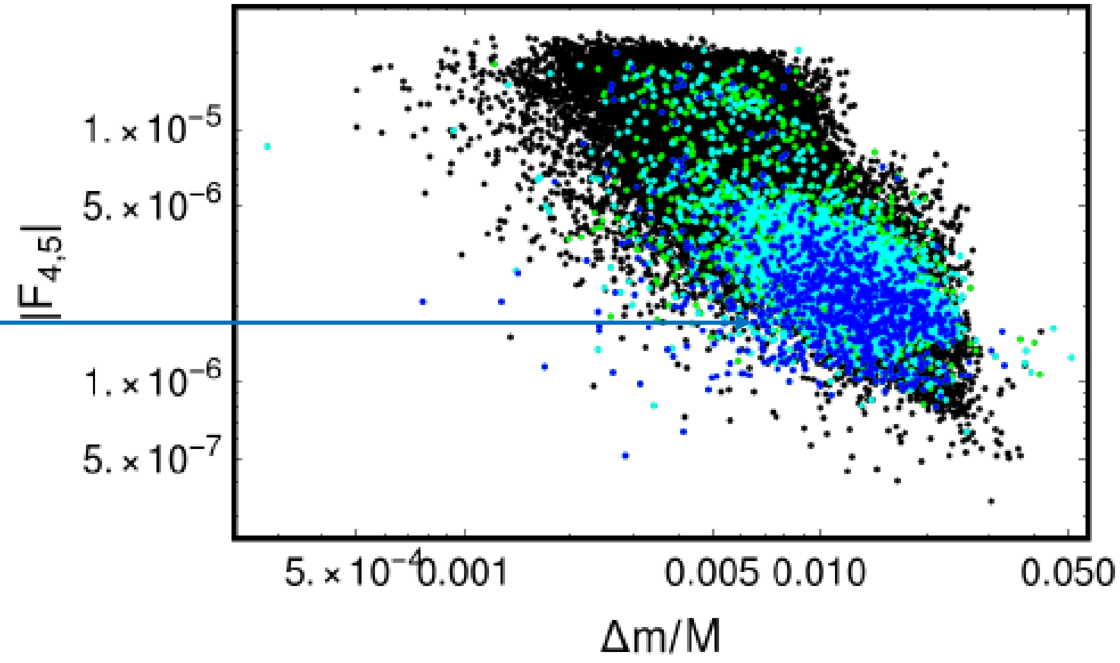


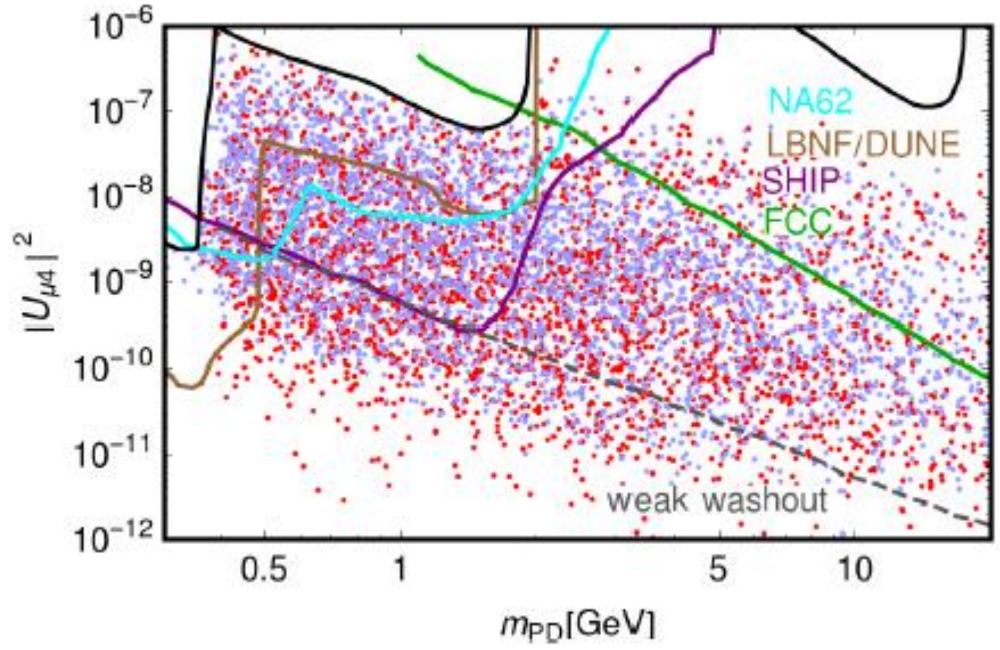




Linear+Inverse See-Saw

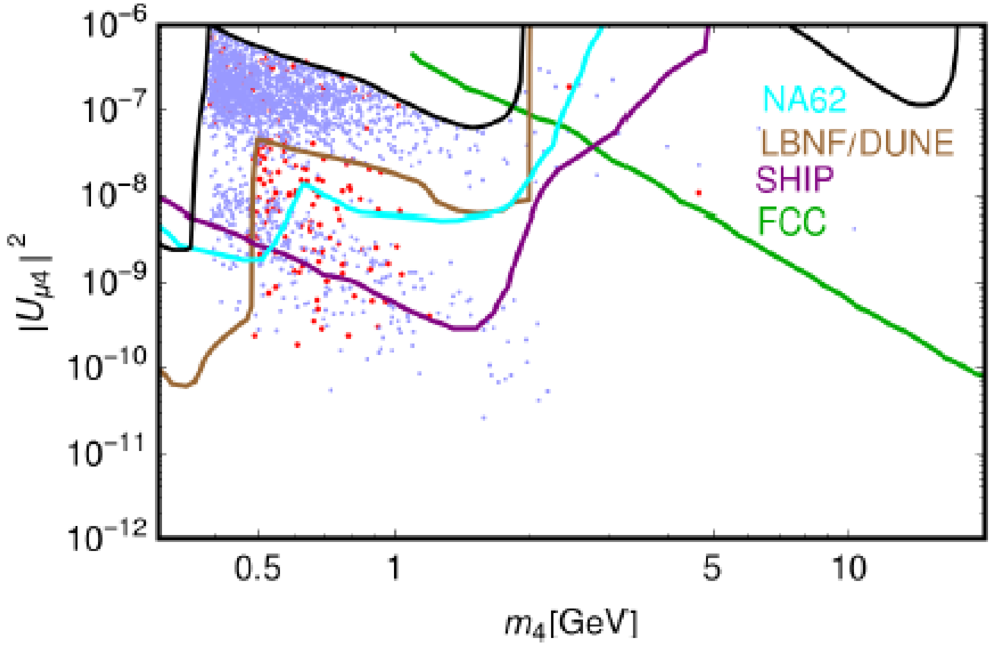
Inverse See-Saw





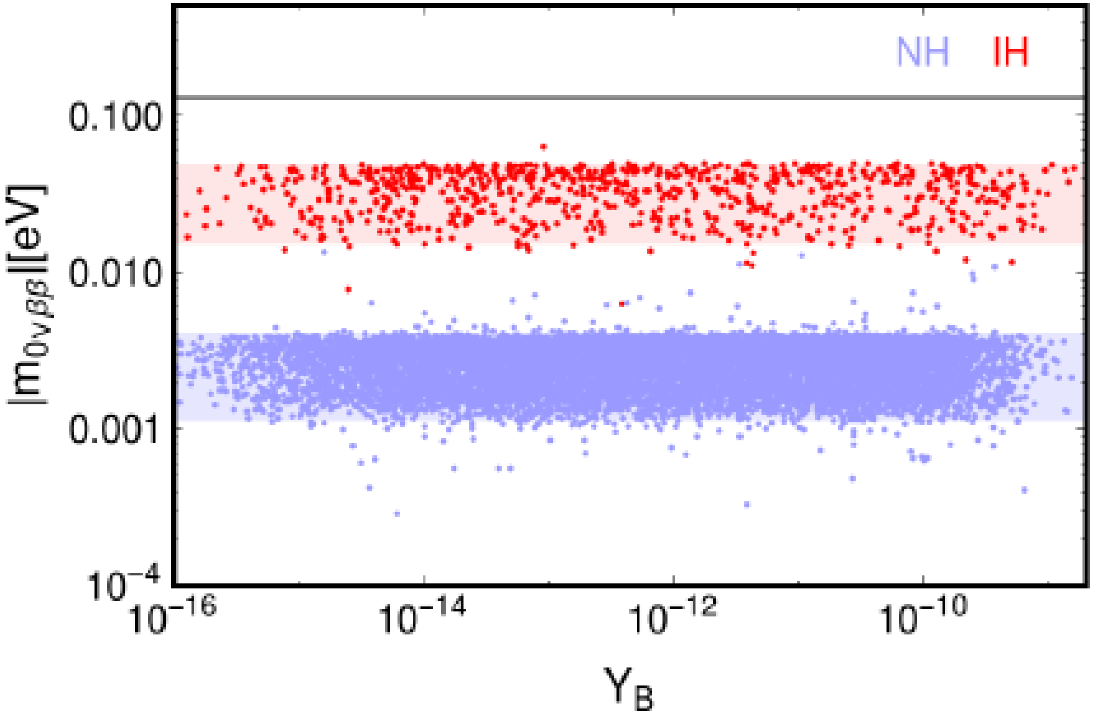
Linear+Inverse See-Saw

Inverse See-Saw

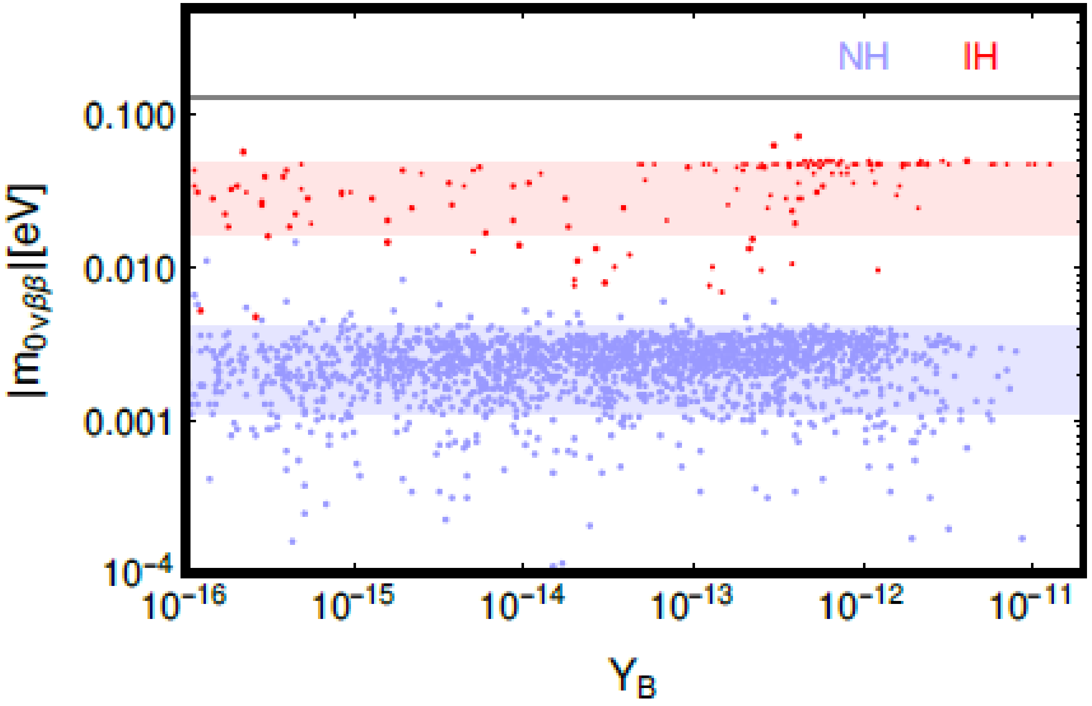


Double beta decay

ISS(2,2)

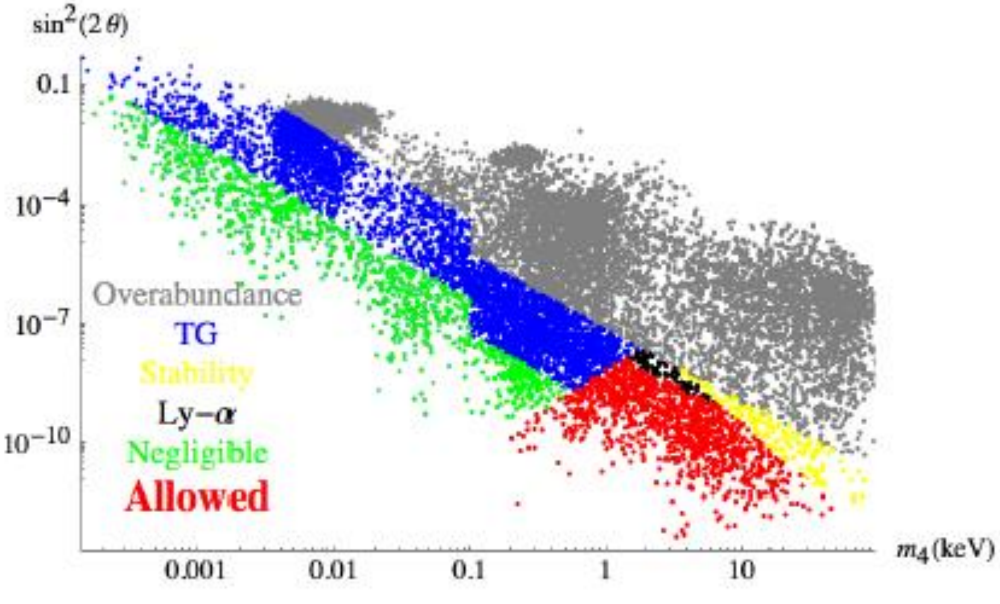


ISS(2,3)

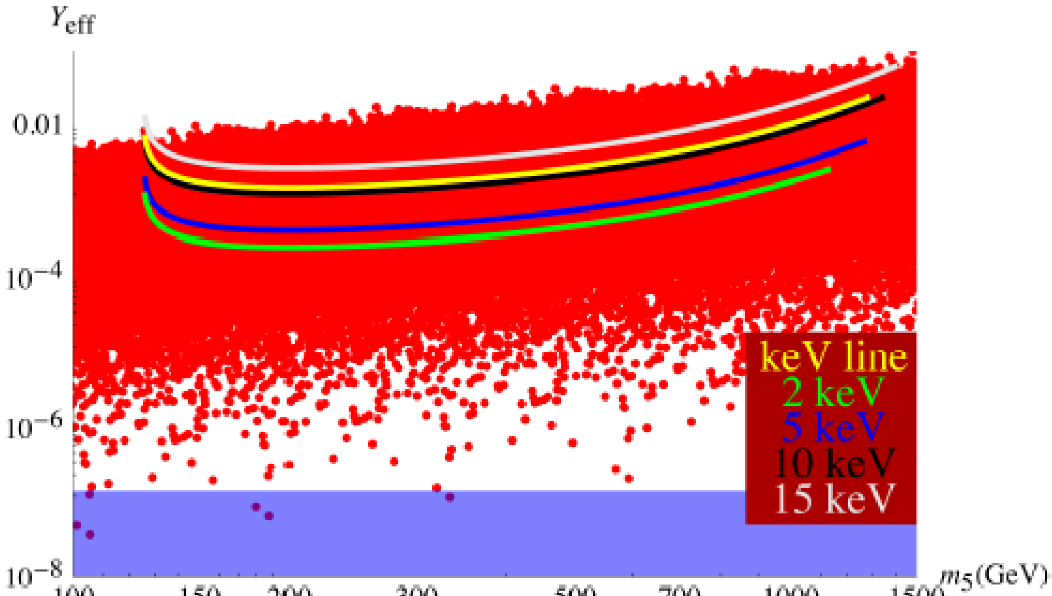


Connection with DM

Production of DM from oscillation (DW/Shi-Fuller) strongly constrained experimentally.

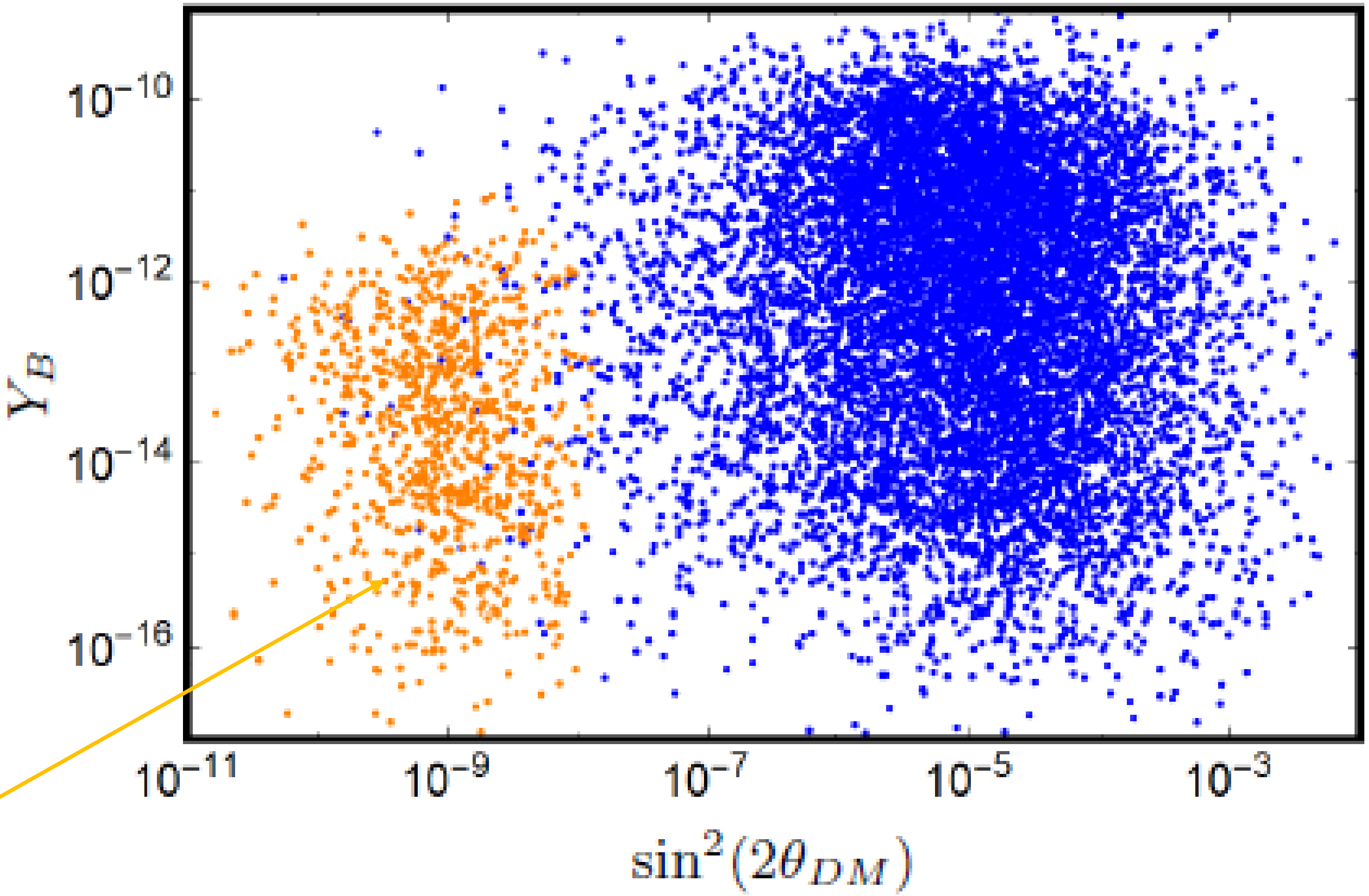


A. Abada, G. A., M. Lucente 1406.6556



DM might be produced from freeze-in decay of a heavy neutrino

$$\Omega_{\rm DM}h^2 = 1.1\cdot 10^7 \sum_\alpha C_\alpha(m_{\rm DM})\,|\mathcal{U}_{\alpha 4}|^2 \left(\frac{m_{\rm DM}}{\rm keV}\right)^2 \simeq 0.3\left(\frac{\sin^2 2\theta_{\rm DM}}{10^{-8}}\right)\left(\frac{m_{\rm DM}}{10\,{\rm keV}}\right)^2$$



Points with potentially viable DM

Conclusions

Leptogenesis from sterile-active neutrino oscillation is a viable mechanism for the generation of the baryon asymmetry of the Universe.

It can be naturally embedded in See-Saw models with tiny violation of the Lepton Number.

Parameter space of viable leptogenesis can be tested by next future facilities.