ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

SEWDarkM

Mikhail Shaposhnikov

Based on:

- Takehiko Asaka, Mikko Laine, M. S., JHEP 0606 (2006) 053
- Takehiko Asaka, Mikko Laine, M. S., JHEP 0701 (2007) 091
- M. S., JHEP 0808 (2008) 008
- Mikko Laine, M. S., JCAP 0806 (2008) 031

Outline

- Standard Model extension - the νMSM
- Sterile neutrino as Dark Matter
- General theory of Sterile EW DarkM production
- Results: non-resonant case
- Results: resonant case
- Conclusions

Standard Model extension

the νMSM

What is the νMSM?

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Other names used in the literature

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- ESM - Extended Standard Model, Jan Smit

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Other names used in the literature

- ESM - Extended Standard Model, Jan Smit
- See-Saw Lagrangian (normally, for $M_I \sim M_{GUT}$)

Parameter counting: the νMSM

Most general renormalizable Lagrangian

$$L_{\nu MSM} = L_{MSM} + \bar{N}_I i\partial_\mu \gamma^\mu N_I - F_{\alpha I}\, \bar{L}_\alpha N_I \Phi - \frac{M_I}{2}\, \bar{N}_I^c N_I + h.c.,$$

Extra coupling constants:

3 Majorana masses of new neutral fermions N_i,

15 new Yukawa couplings in the leptonic sector

(3 Dirac neutrino masses $M_D = F_{\alpha I} v$, 6 mixing angles and 6 CP-violating phases),

18 new parameters in total.

Require: $M_I < M_W$ (No see-saw)

Consequence: small Yukawa couplings,

$$F_{\alpha I} \sim \frac{\sqrt{m_{atm} M_I}}{v} \sim (10^{-6} - 10^{-13}),$$

here $v \simeq 174$ GeV is the VEV of the Higgs field,

$m_{atm} \simeq 0.05$ eV is the atmospheric neutrino mass difference.

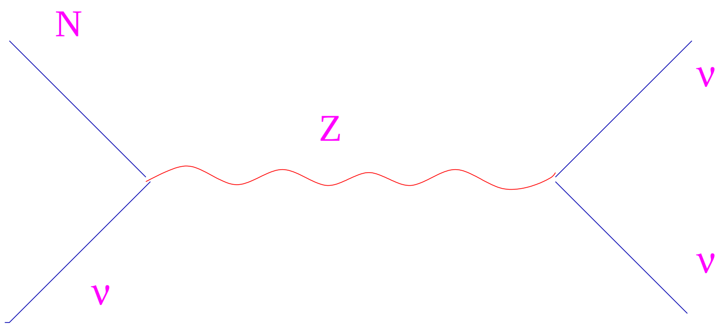
Highlights of the νMSM

- Consistent description of neutrino masses and oscillations
- Can explain baryon asymmetry of the Universe
- Can explain dark matter in the universe
- Can provide inflation
- Masses of new leptons are small: all parameters can potentially be determined experimentally

Sterile neutrino as Dark Matter

Dodelson, Widrow; Shi, Fuller; Dolgov, Hansen;
Abazajian, Fuller, Patel; Asaka, Laine, M.S.

Yukawa couplings are small $\longrightarrow$ sterile N can be very stable.



Main decay mode: $N \to 3\nu$.

Subdominant radiative decay channel: $N \to \nu\gamma$.

For one flavour:

$$\tau_{N_1} = 10^{14}\,\text{years}\left(\frac{10\,\text{keV}}{M_N}\right)^5\left(\frac{10^{-8}}{\theta_1^2}\right)$$

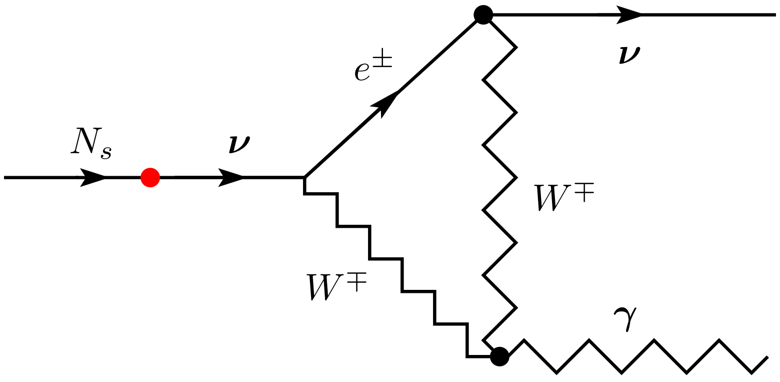
$$\theta_1 = \frac{m_D}{M_N}$$

DM particle is not stable. Main decay mode $N_1 \longrightarrow 3\nu$ is not observable.

Subdominant radiative decay channel: $N \longrightarrow \nu\gamma$.

Photon energy:

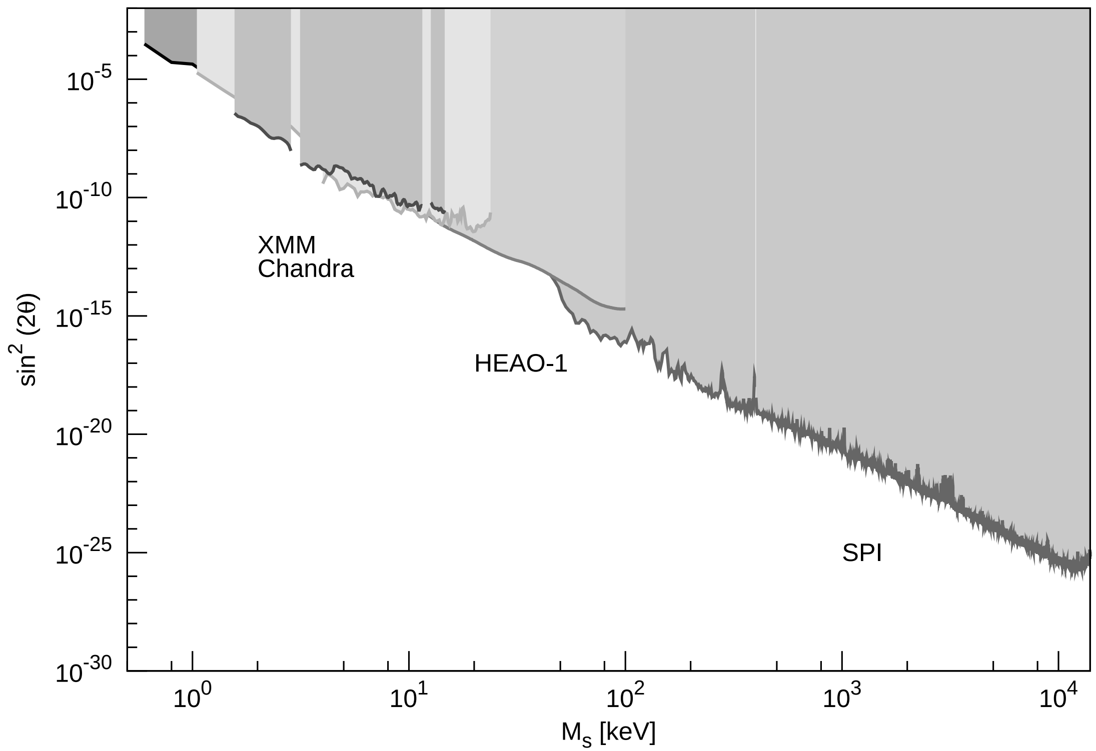
$$E_\gamma = \frac{M}{2}$$



Radiative decay width:

$$\Gamma_{\mathrm{rad}} = \frac{9\,\alpha_{\mathrm{EM}}\,G_F^2}{256\cdot 4\pi^4}\,\sin^2(2\theta)\,M_s^5$$

MW (HEAO-1): Boyarsky et al.; **Coma and Virgo clusters:** Boyarsky et al.; **LMC+MW(XMM):** Boyarsky et al.; **MW (Chandra):** Riemer-Søorensen et al.; Abazajian et al.; **M31:** Watson et al., Boyarsky et al.; **SPI:** Boyarsky et al.



$\theta^2 = F_{\alpha 1}^2 v^2/(2M_1^2)$

Conclusion: Yukawa couplings of DM sterile neutrino must be small, $F_{\alpha 1} \lesssim 10^{-12}$. DM sterile neutrino is always out of thermal equilibrium in the early universe.

Constraints on the mass of dark matter sterile neutrinos

Tremaine, Gunn; Lin, Faber; Hogan, Dalcanton:

Rotational curves of dwarf spheroidal galaxies: $M > 0.3$ keV.

Hansen et al, Viel et al: Lyman-α forest observations can resolve inhomogeneities on small scales and put constraints on free streaming length.

- "Generic" warm dark matter:

  Viel et al., $M > 2$ keV, 2σ, Seljak et al., $M > 2.4$ keV, 95%.

- Sterile neutrino produced in active-sterile transitions:

  Viel et al., $M > 8$ keV, 2σ

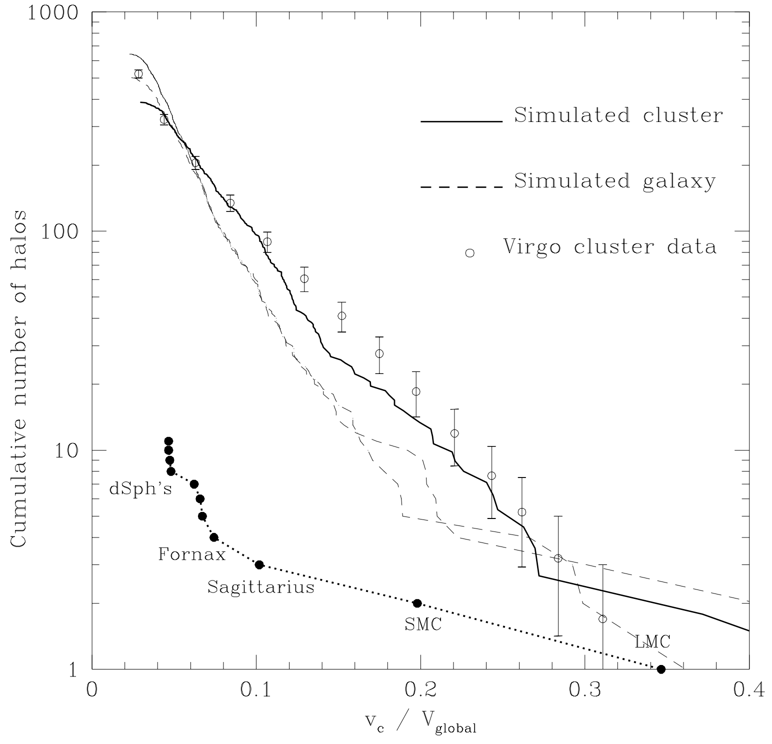
  Seljak et al., $M > 11.7$ keV, 95% and $M > 8.1$ keV, 99%.

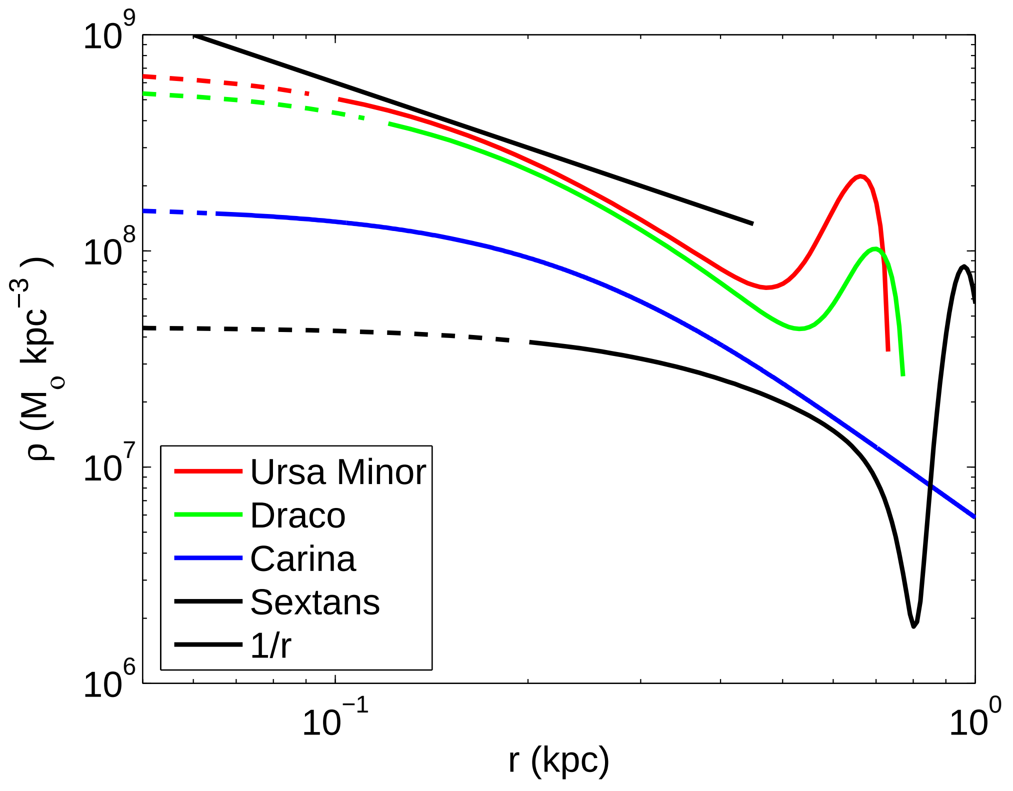
For smooth spectra the results can be rescaled as follows:

$M > M_{Ly\alpha}\left(\frac{<p_s>}{<p_a>}\right), \quad M_{Ly\alpha} = 10 - 14$ keV. For spectra appearing in other mechanisms of sterile neutrino production the simulations have never been performed.

Warm keV DM?

Potentially, warm (KeV) dark matter could solve some problems of the CDM scenario: [i] Cuspy profiles, [ii] Missing satellites problem (Bode, Ostriker, Turok; Klypin, Moore; Gilmore)





General theory of
Sterile EW DarkM production

Initial conditions for Big Bang

Assume: at some temperature $T \gg M_W$ we have:

- thermal equilibrium for all SM particles
- no singlet fermions present

Why?

- Yukawa couplings of singlet fermions are very small: reactions $N \leftrightarrow$ SM particles are out of thermal equilibrium at $T \gg M_W$.
- In the νMSM with non-minimal Higgs coupling the $Higgs \equiv inflaton$ energy goes to SM particles rather than singlet fermions. Yukawas are small!

Statistical physics formulation

Find $\mathbf{TrN}\hat{\rho}(\mathbf{t})$ where density matrix $\hat{\rho}(t)$ satisfies:

$$i\frac{\mathrm{d}\hat{\rho}(t)}{\mathrm{d}t} = [\hat{H}, \hat{\rho}(t)]$$

$\hat{H}$ - total Hamiltonian. Initial condition:

$$\hat{\rho}(0) = \hat{\rho}_{\text{SM}} \otimes |0\rangle\langle 0|$$

where $\hat{\rho}_{\text{SM}} = Z^{-1}_{\text{SM}} \exp(-\beta \hat{H}_{\text{SM}})$, $\beta \equiv 1/T$, is the equilibrium MSM density matrix at a temperature T, and $|0\rangle$ is the vacuum state for sterile neutrinos.

Master formula

DM sterile neutrinos are never in thermal equilibrium

$\Downarrow$

Kinetic equations are not necessary: one can use perturbation theory on Yukawa coupling !

Result in the lowest order of perturbation theory:

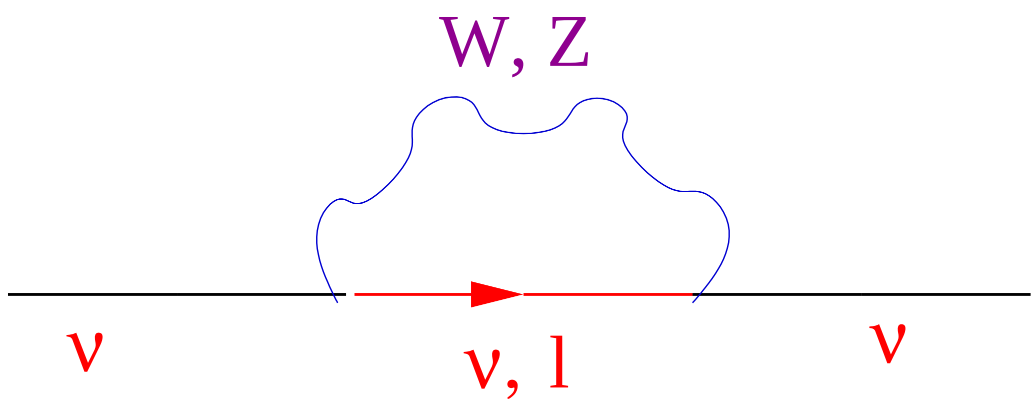
$$\frac{\mathrm{d}N_I(x,\vec{q})}{\mathrm{d}^4x\,\mathrm{d}^3\vec{q}} = \frac{2n_F(q^0)}{(2\pi)^3 2q^0}\sum_{\alpha=1}^{3}|M_D|^2_{\alpha I}\mathrm{tr}\left\{\not{Q}\,\mathrm{a_L}\left[\rho_{\alpha\alpha}(-\mathrm{Q})+\rho_{\alpha\alpha}(\mathrm{Q})\right]\mathrm{a_R}\right\}$$

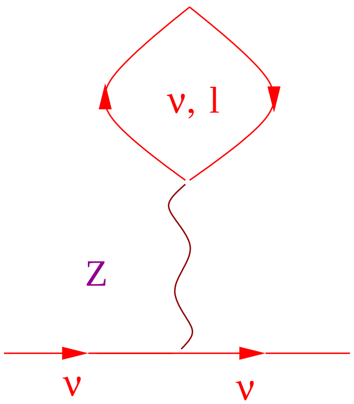
$$a_{L,R} = \frac{1}{2}(1 \pm \gamma_5)$$

Spectral function

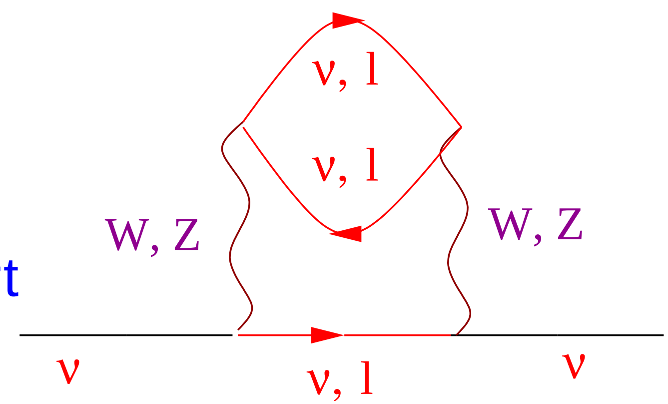
$$\rho_{\alpha\beta}(Q) \equiv \int \mathrm{d}t\, \mathrm{d}^3\vec{x}\, e^{iQ\cdot x} \left\langle \frac{1}{2}\left\{\hat{\nu}_\alpha(x), \hat{\bar{\nu}}_\beta(0)\right\}\right\rangle$$

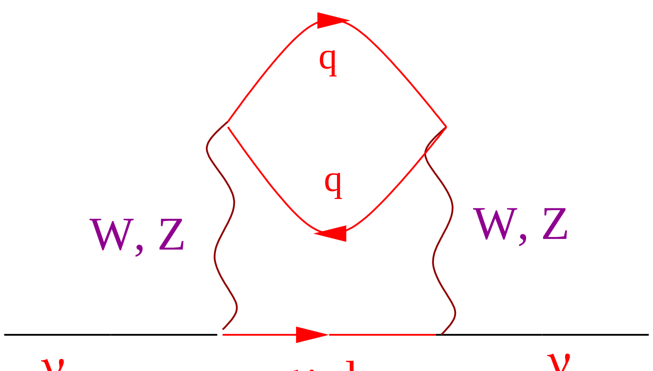
Real part





Imaginary part





Challenge: production temperature of sterile neutrinos:

$$T \sim 130 \left(\frac{M_I}{1\ \mathrm{keV}}\right)^{1/3}\ \mathrm{MeV}$$

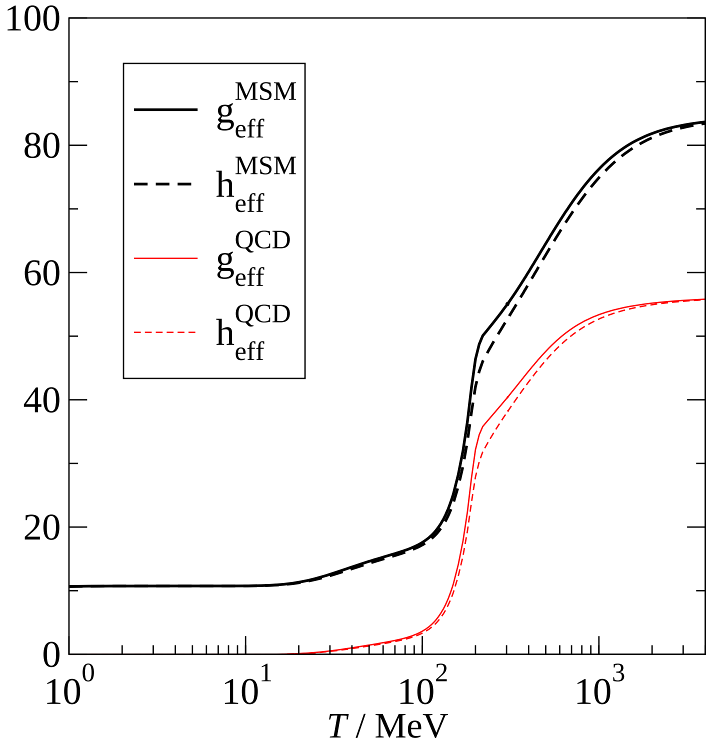
QCD interactions are strong!

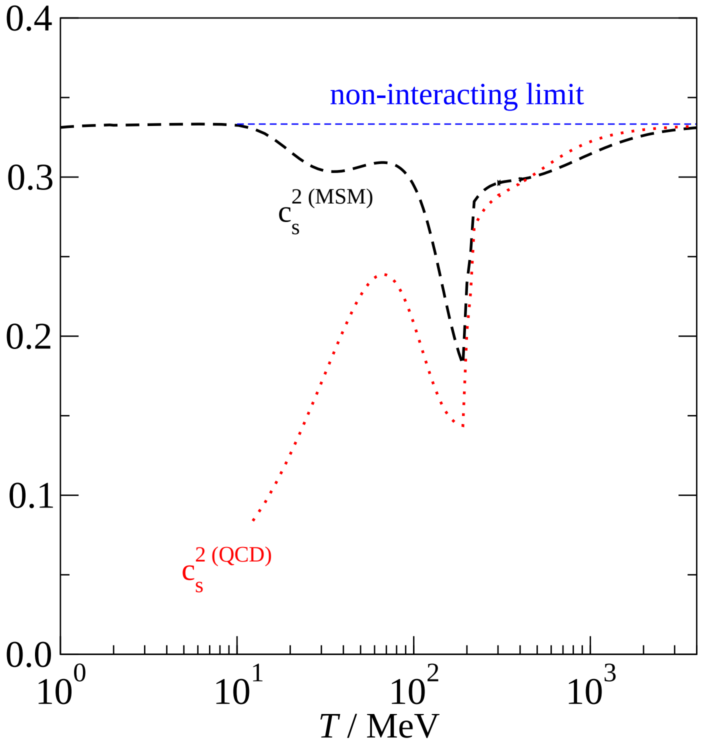
The problem can be solved if one knows:

- equation of state at temperatures 10 MeV - 1 GeV
- real time correlators of vector and axial vector hadronic currents in this temperature range

Equation of state

Method: use a gas of hadronic resonances at low temperatures; the most advanced (up to resummed 4-loop level weak-coupling) results at high temperatures; and an interpolation thereof at intermediate temperatures





Scattering: imaginary part

- $T \gg \Lambda_{QCD}$: use quarks
- $T \ll \Lambda_{QCD}$: use hadrons
- Conservative upper bound on hadronic contribution: use free quarks at all temperatures
- Conservative lower bound on hadronic contribution: put $N_c = 0$
- Phenomenological mean value:

$$N_c \to N_c \frac{h_{eff}^{QCD}(T)}{58}$$

Yet another parameter: leptonic asymmetry

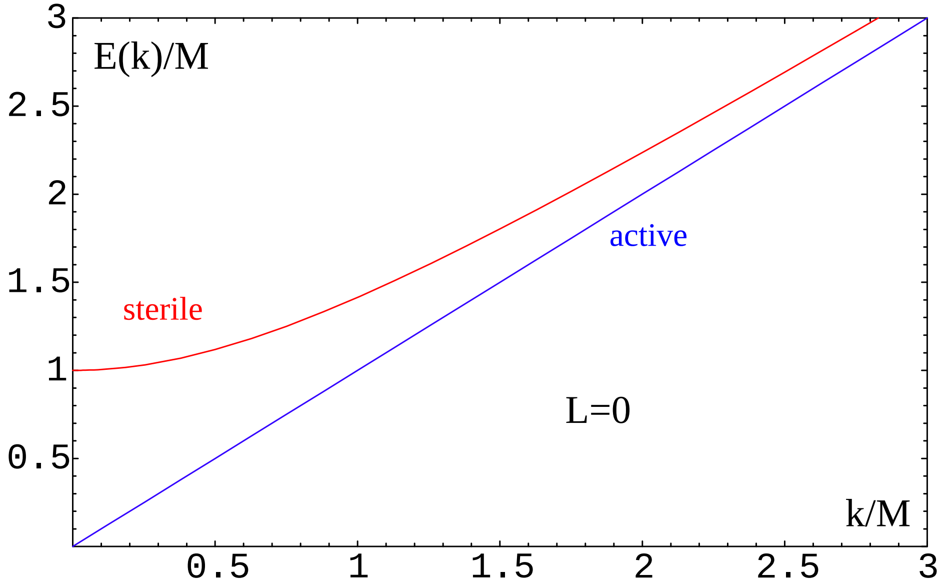
$$\Delta_L = \frac{(n_L - \bar{n}_L)}{(n_L + \bar{n}_L)}$$

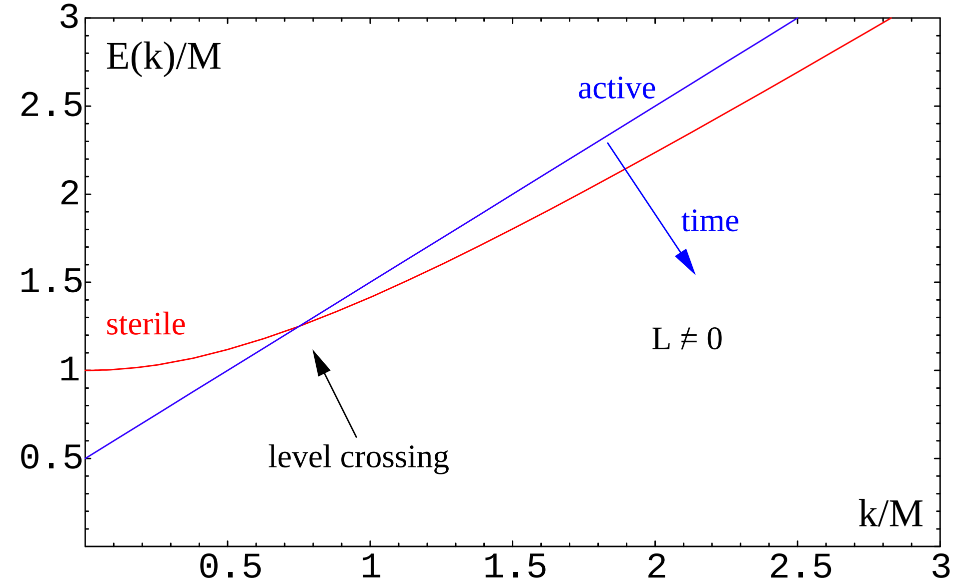
in the QCD epoch

- Lepton asymmetry is created in reactions with heavier singlet fermions of the νMSM, $\Delta_L \lesssim 0.2$
- Constraints from BBN on Δ_L are weak

Non-resonant and resonant production

Dispersional relations for active and sterile neutrinos (from leal part)





Non-resonant transitions $\nu \to N_1$

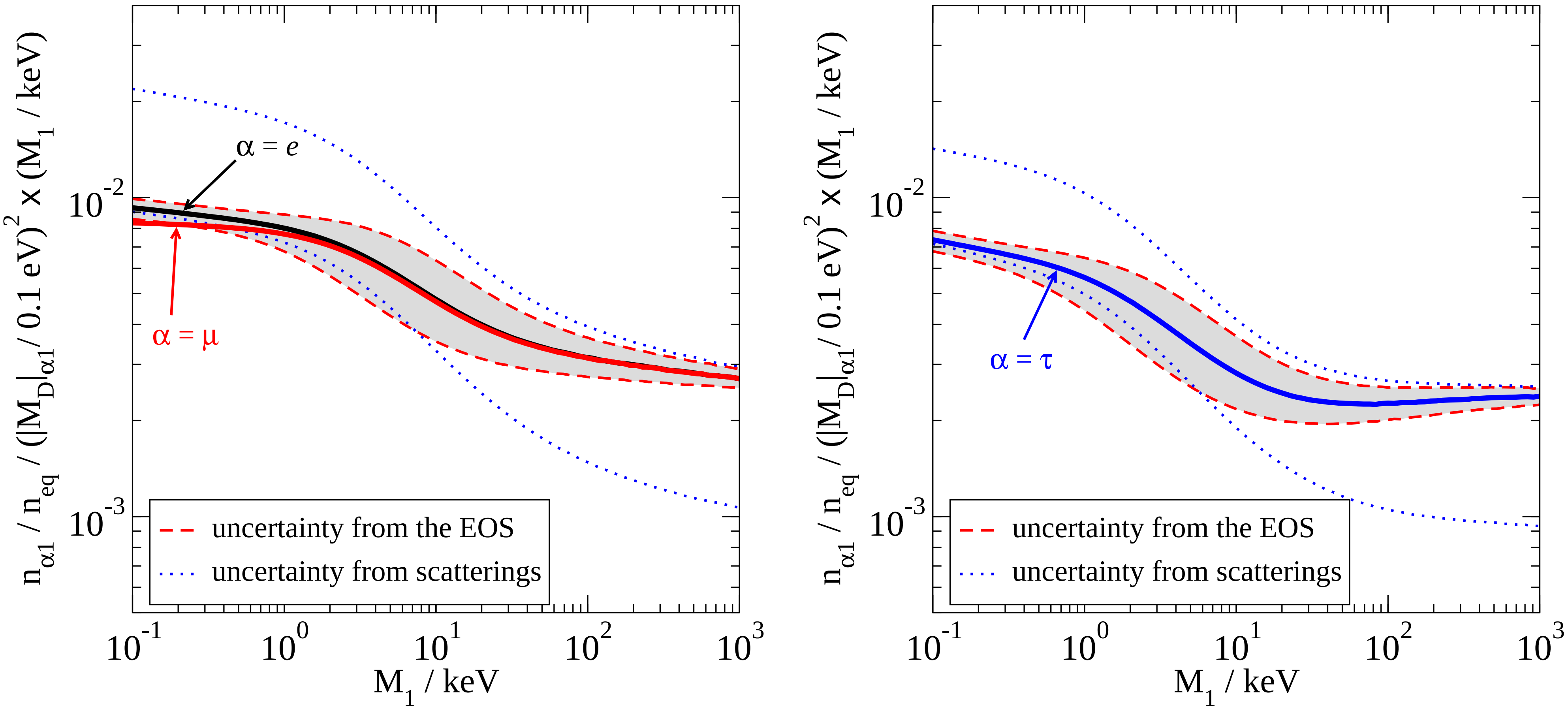
$L = 0$

Resonant transitions

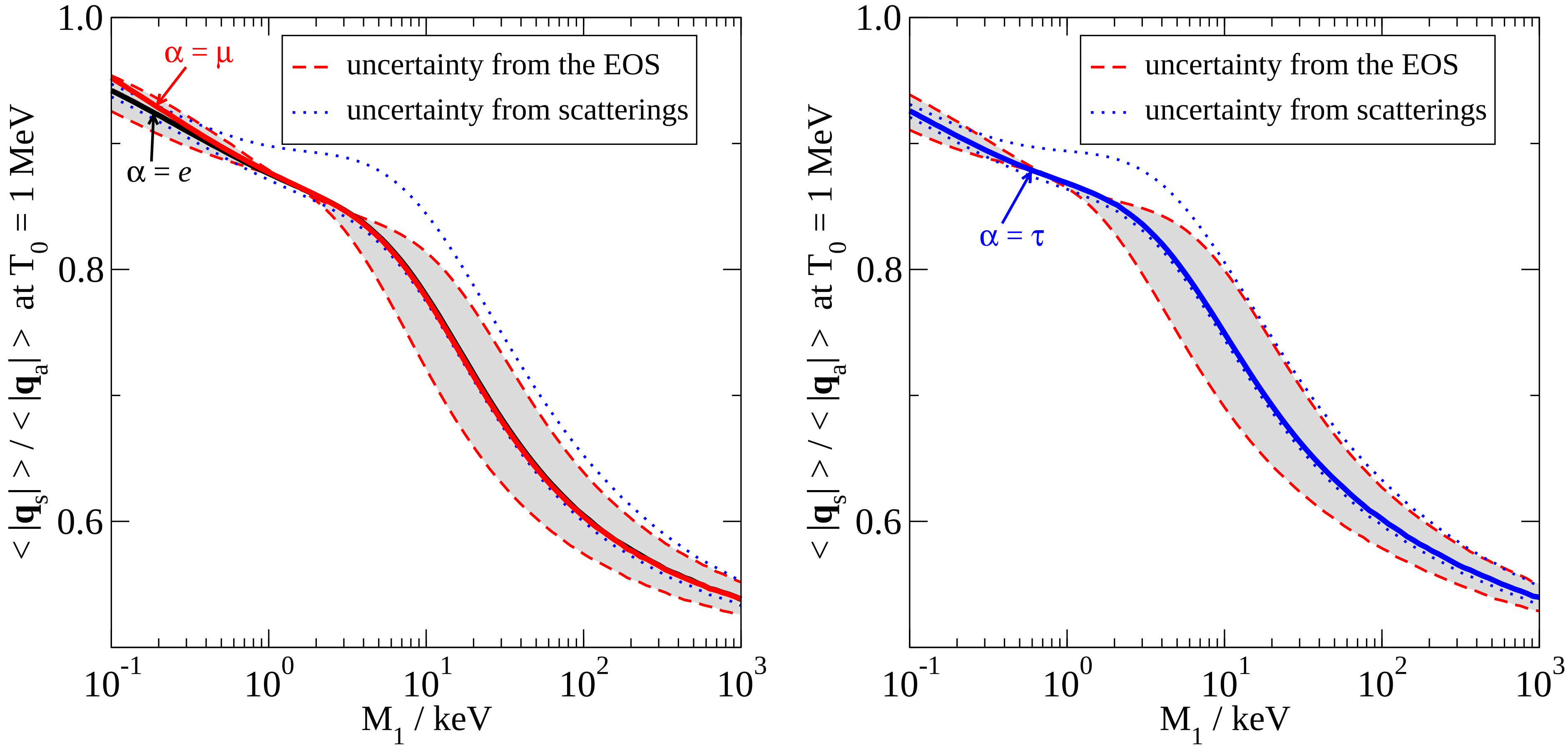
$L \neq 0$

Results: non-resonant case

Dark matter abundance



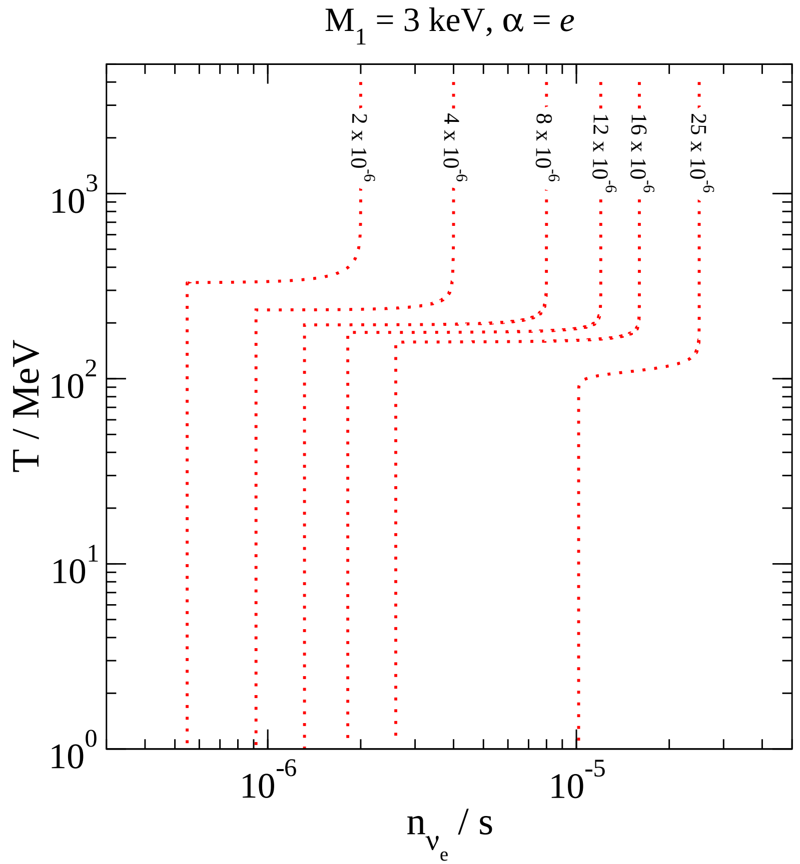
Average sterile neutrino momentum



Results: resonant case

Transfer of asymmetry to DM

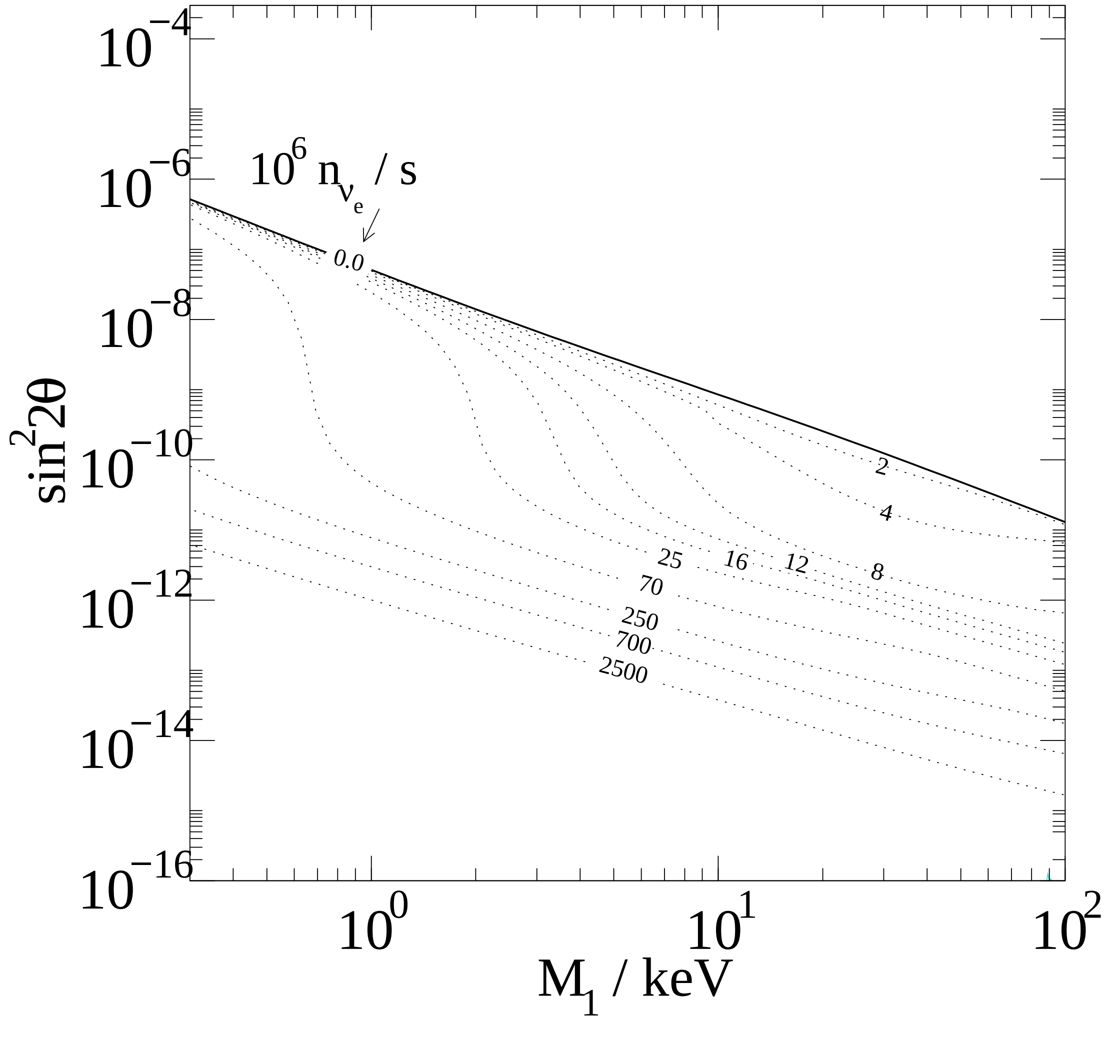
Large fraction of lepton asymmetry is transferred to DM



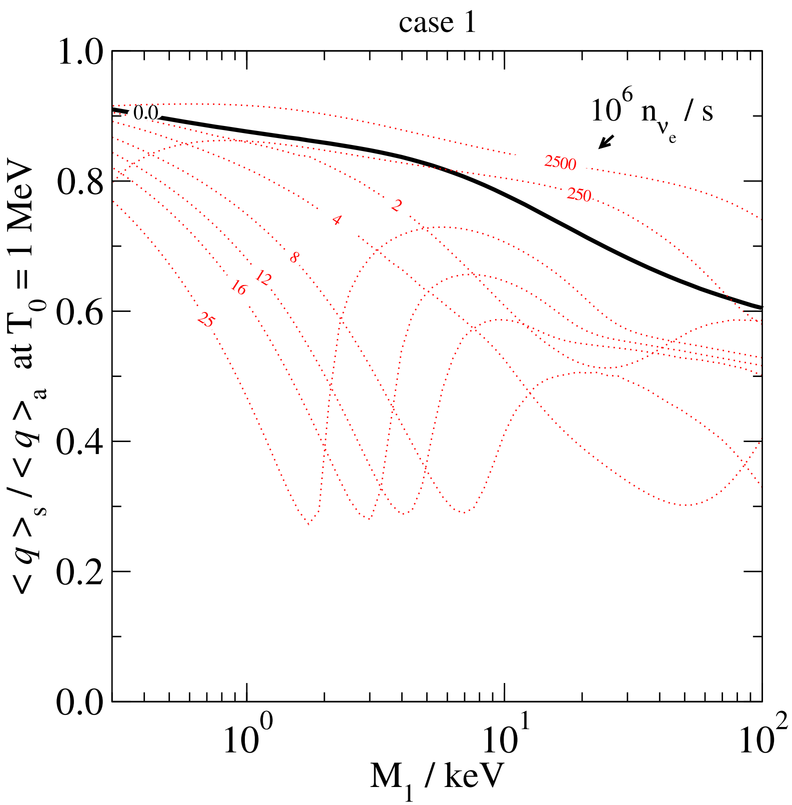
Common origin of DM and baryon asymmetry!

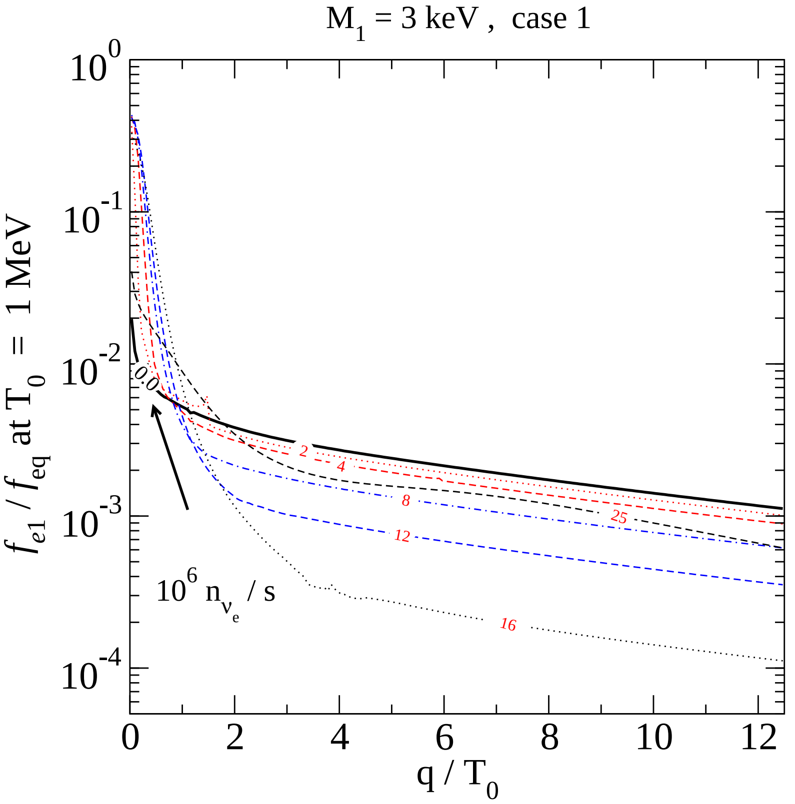
Explanation why $\Omega_{DM} \sim \Omega_B$?

Dark matter abundance

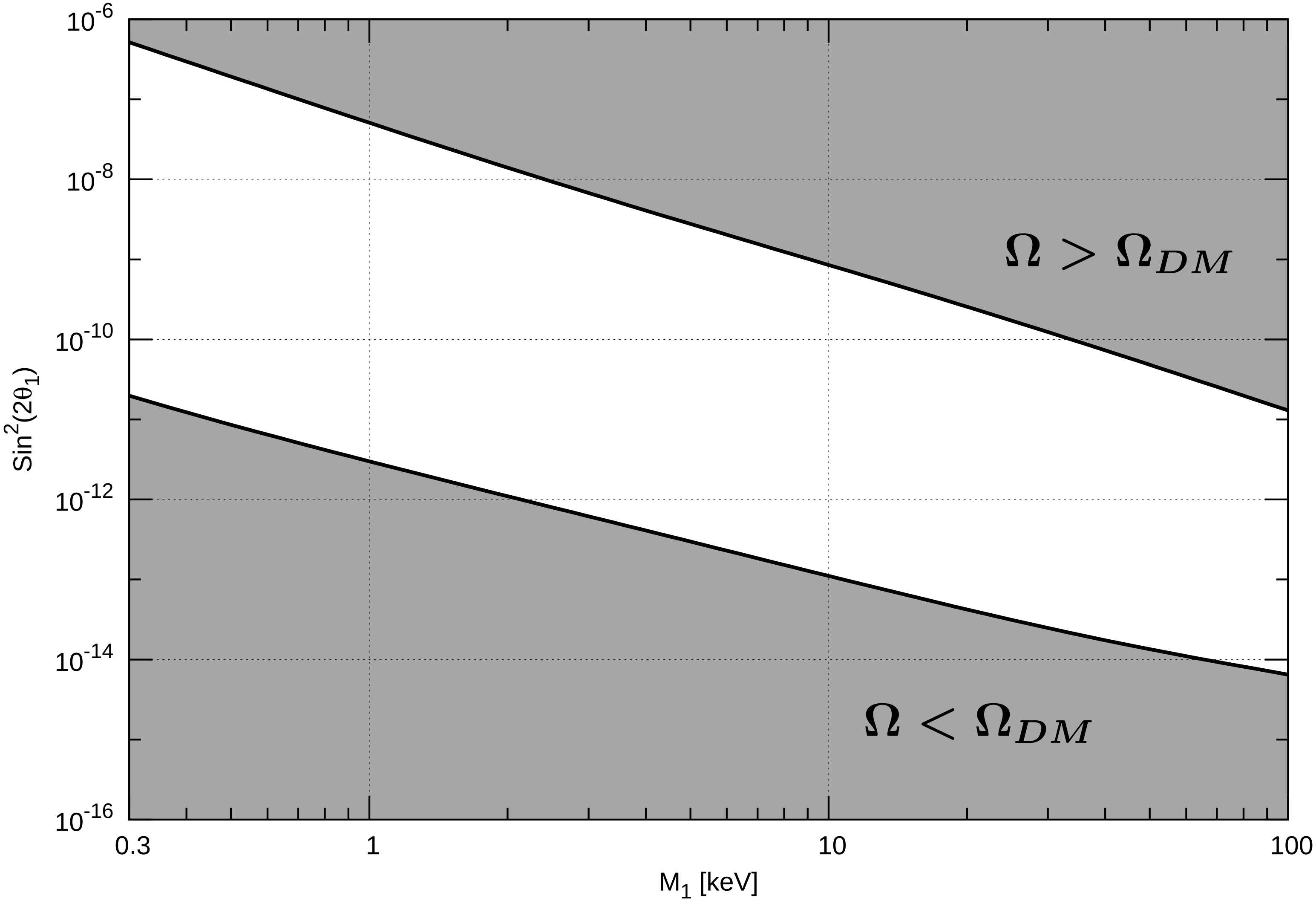


Momentum distribution of DM

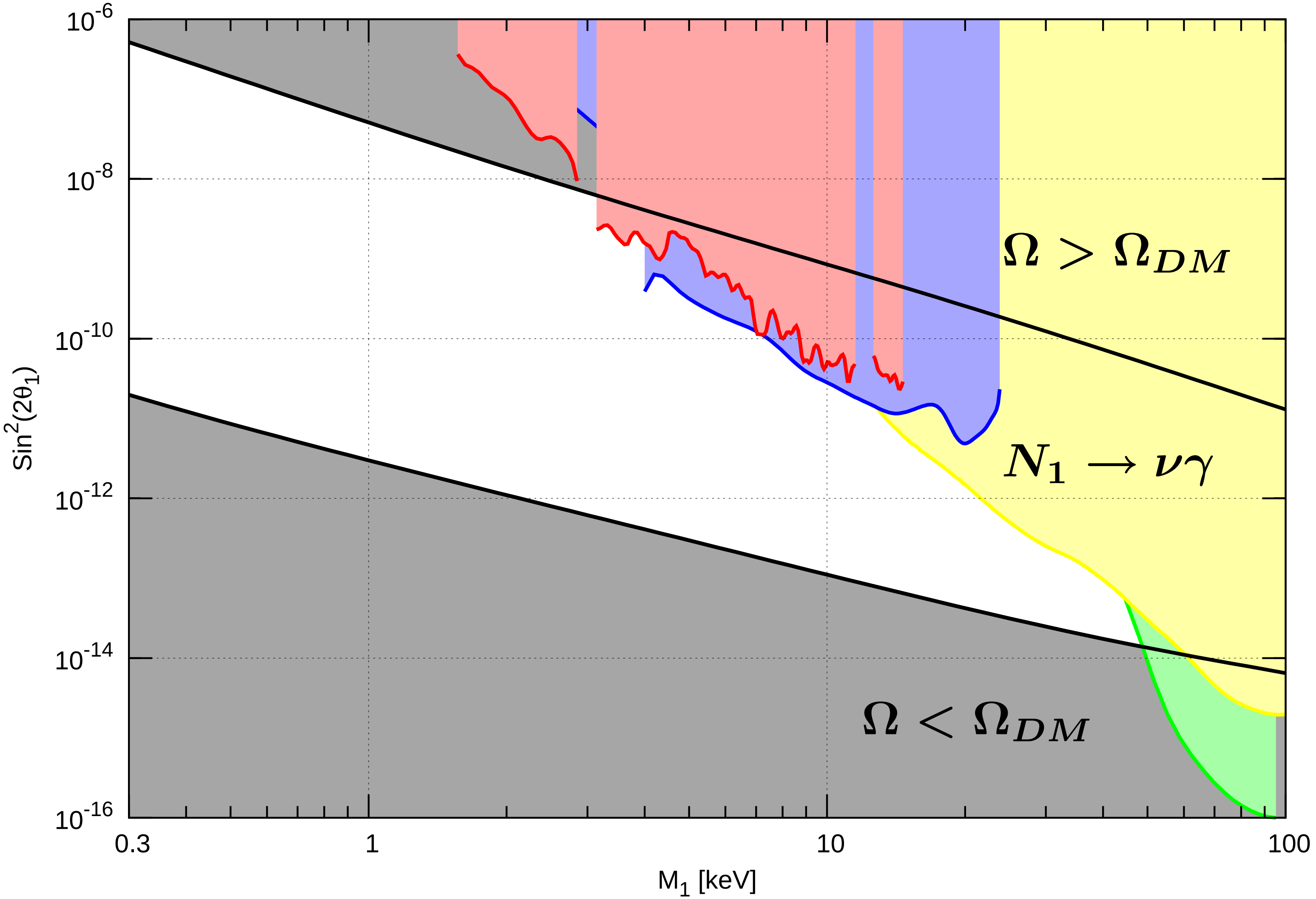




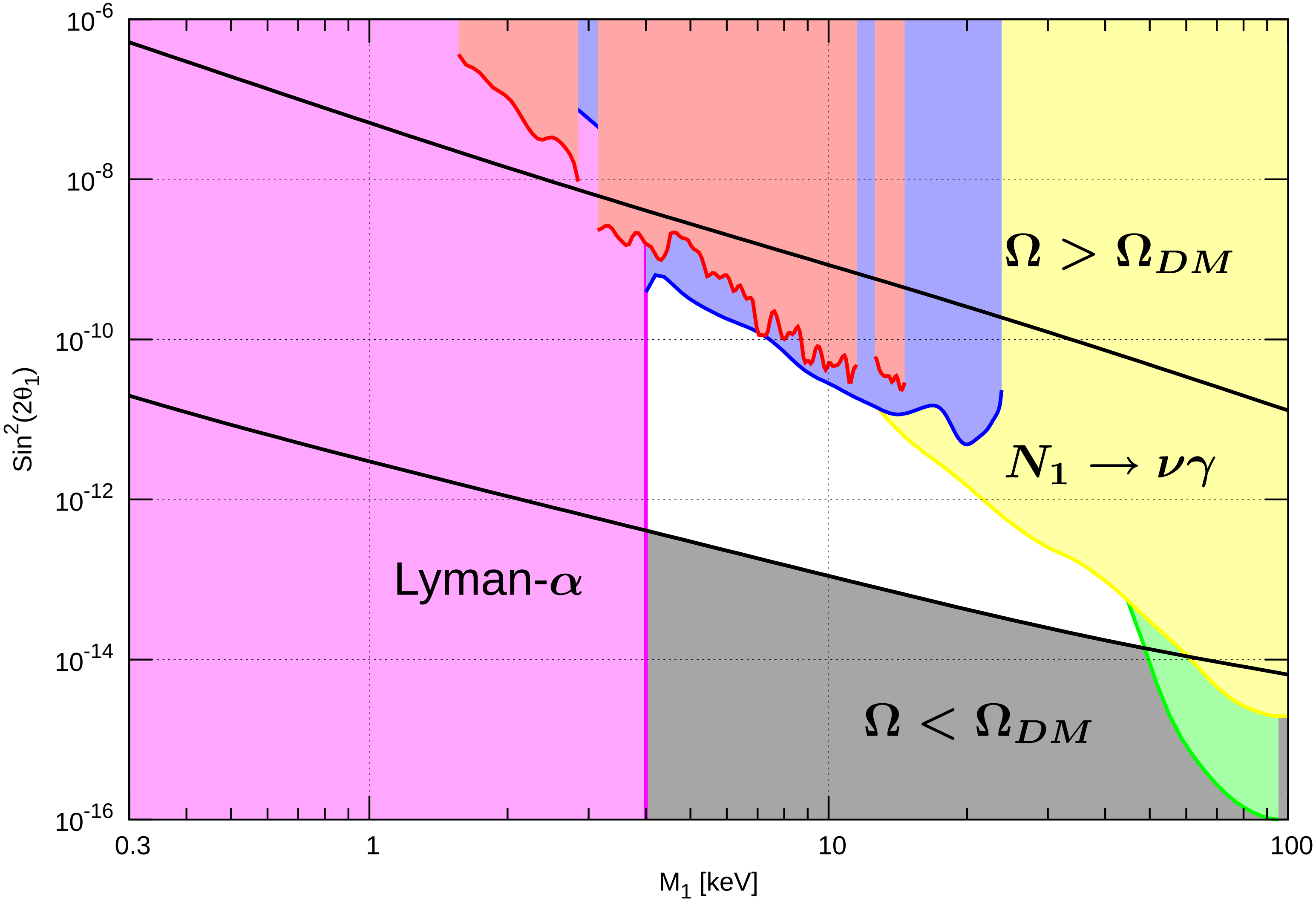
DM: production



DM: production + X-ray constraints



DM: production + X-ray constraints + Lyman-α bounds



Summary of constraints:

- Minimal low temperature leptonic asymmetry: $\Delta \simeq 2 \times 10^{-3}$
- Dark matter sterile neutrino mass: $4\ \mathrm{keV} < M_1 < 50$ keV (Lyman-α constraints on the mass of DM sterile neutrino are weaker by a factor of 3)
- Dark matter sterile neutrino mixing angle: $2 \times 10^{-15} < \theta_1^2 < 2 \times 10^{-10}$

Conclusions

- Sterile neutrino is an interesting (warm) DM candidate which
  - may solve (ease) the problem of cuspy profiles of CDM
  - may solve (ease) the problem of missing satellite dwarfs
  - may be searched experimentally in X-rays
- Computation of sterile neutrino DM abundance provides an interesting and non-trivial example of equilibrium and non-equilibrium finite T field theory
- High T QCD physics plays an important role