# Sterile Neutrino
## -- neutrino masses, dark matter, and baryon asymmetry --

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@ Rencontres de Moriond EW 2007

# Outline

- The νMSM
  = the "*neutrino*" Minimal Standard Model

- Dark matter

TA, Blanchet, Shaposhnikov
TA, Shaposhnikov

- Baryogenesis
- Summary

Cf. The "New" MSM
Davoudiasl, Kitano, Li, Murayama
PLB609, 117, 2005

# Motivation

The MSM fails to explain:

- Neutrino oscillations
  - Neutrinos are exactly massless
- Dark matter
  - No particle candidate for dark matter
- Baryon asymmetry
  - No mechanism to generate baryon asymmetry
  - No (strong) deviation from thermal equilibrium
  - CP violation is too small

→ go beyond the MSM !!

- A simple possibility is the νMSM

# What is the vMSM?

# Framework (νMSM)

The MSM + three right-handed neutrinos N1, N2, N3

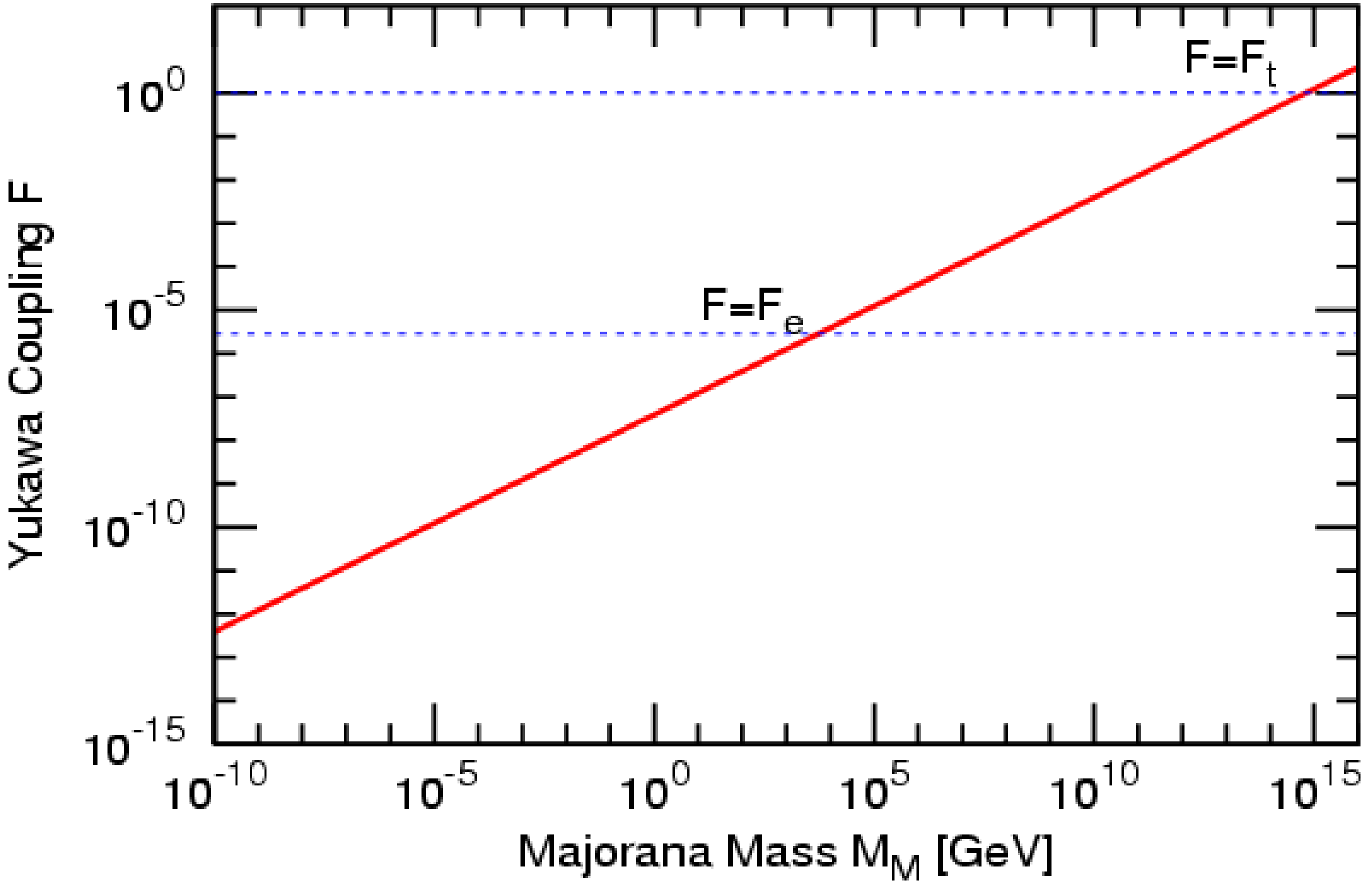
$$\mathcal{L}_{\nu\mathrm{MSM}} = \mathcal{L}_{\mathrm{MSM}} + i\overline{N}_I \partial\!\!\!/ N_I - F_{\alpha I}\overline{L}_\alpha \Phi N_I - \frac{M_I}{2}\overline{N}_I^c N_I + h.c.$$

- Dirac masses $M_D = F\langle\Phi\rangle$ and Majorana masses $M_I$

- Majorana masses are smaller than ~100 GeV
  - All parameters can potentially be determined(?)
  - Seesaw mechanism still works, if $[M_D]_{\alpha I} \ll M_I$
  - Neutrino oscillations by active neutrino mixing

# Scale of Majorana mass

$$M_\nu = -M_D^T \frac{1}{M_M} M_D \quad \Rightarrow \quad F^2 = M_M M_\nu / \langle \Phi \rangle^2$$



$$M_\nu = \sqrt{\Delta m^2_{atm}}$$

Very small Yukawa couplings!

# Dark matter in the νMSM

# Dark Matter

**Candidate:** lightest sterile neutrino N1 with ~keV mass

Dodelson, Widrow / Shi, Fuller / Dolgov, Hansen / Abazajian, Fuller, Patel

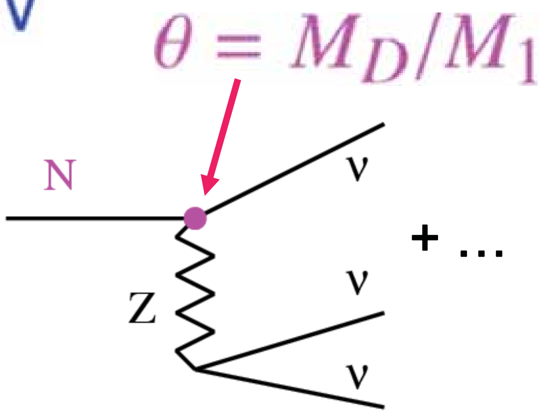
**Requirements:**

- Its lifetime is longer than the age of the universe
  - $\tau > t_U \sim 10^{17}$ sec
- It explains dark matter density
  - $\Omega_{dm} h^2 \simeq 0.1$
- It avoids cosmological constraints
  - Bounds from X-ray and Ly-alpha forest observations

# Decays of sterile neutrino

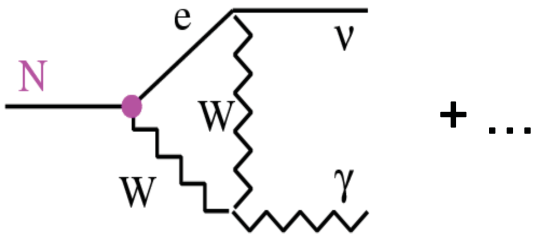
**N1 is not completely stable particle !**

- Dominant decay: $N_1 \to 3\nu$ for $M_1 \sim$ keV
- Lifetime can be very long
  - $\tau_{N_1} \simeq 5 \cdot 10^{26}\mathrm{sec}\left(\frac{\mathrm{keV}}{M_1}\right)^5\left(\frac{10^{-8}}{\theta^2}\right)$

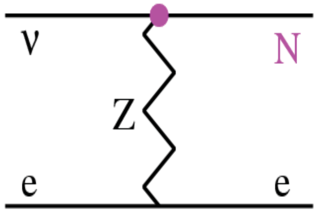


**N1 is not completely dark !**

- Subdominant decay: $N_1 \to \nu + \gamma$
- Branching ratio is small
  - $\mathbf{Br} = 27\alpha_{\mathrm{em}}/8\pi$
- But, severely restricted from X-ray observations



# Production of sterile neutrino



Dodelson-Widrow scenario:

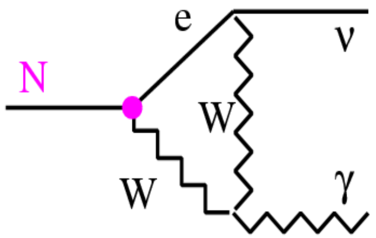
- N1 is not thermalized
- Production via active-sterile neutrino oscillations
- Dominant production at $T_* \simeq 100\mathrm{MeV}\,(M_1/\mathrm{keV})^{1/3}$

Recently, we improve the estimate of the abundance

- Use kinetic equation for density matrix
- Study "hadronic uncertainties" in detail:
  - Hadronic contributions to production rate
  - QCD equation of state (time-temp. relation)

TA, Laine, Shaposhnikov JHEP06 ('06) 053 [hep-ph/0606209]
TA, Laine, Shaposhnikov [hep-ph/0612182]

# Constraints from X-rays



Radiative decays of sterile neutrino DM

- feature in X-ray background spectrum
- line X-ray from clusters, galaxies, dwarf galaxies…
  - TEST for sterile neutrino DM!
  - No signal → Upper bound on mixing angle !

Dolgov, Hansen / Abazajian, Fuller, Tucker
Boyarsky, Neronov, Ruchayskiy, Shaposhnikov
Boyarsky, Neronov, Ruchayskiy, Shaposhnikov
Boyarsky, Neronov, Ruchayskiy, Shaposhnikov, Tkachev
Riemer-Sorensen, Hansen, Pedersen
Watson, Beacom, Yuksel, Walker
Boyarsky, Ruchayskiy, Markevitch
Riemer-Sorensen, Pedersen, Hansen, Dahle
Abazajian, Markevitch, Koushiappas, Hickox
Boyarsky, Herder, Neronov, Ruchayskiy

# Constraints from structure formation

Light sterile neutrino = WDM $\lambda_{\rm FS} \sim {\rm Mpc}\left(\frac{\rm keV}{M_1}\right)\frac{\langle|\mathbf{q}_{\rm s}|\rangle}{\langle|\mathbf{q}_{\rm a}|\rangle}$

- Erase structures on smaller scales
- Lower bound on mass $M_1 > \frac{\langle|\mathbf{q}_{\rm s}|\rangle}{\langle|\mathbf{q}_{\rm a}|\rangle} M_0$

From Ly-$\alpha$ forest observations

$M_0 \simeq 14.4{\rm keV}$ Seljak, Makarov, McDonald, Trac '06

$M_0 \simeq 10{\rm keV}$ Viel, Lesgourgues, Haehnelt, Matarresse, Riotto '06

We find: $\frac{\langle|\mathbf{q}_{\rm s}|\rangle}{\langle|\mathbf{q}_{\rm a}|\rangle} \simeq 0.8$ for $M_1 \simeq 10{\rm keV}$

➡ $M_1 \gtrsim 11.6\,{\rm keV}$ (SMMT), $8\,{\rm keV}$ (VLHMR)

# Parameter space

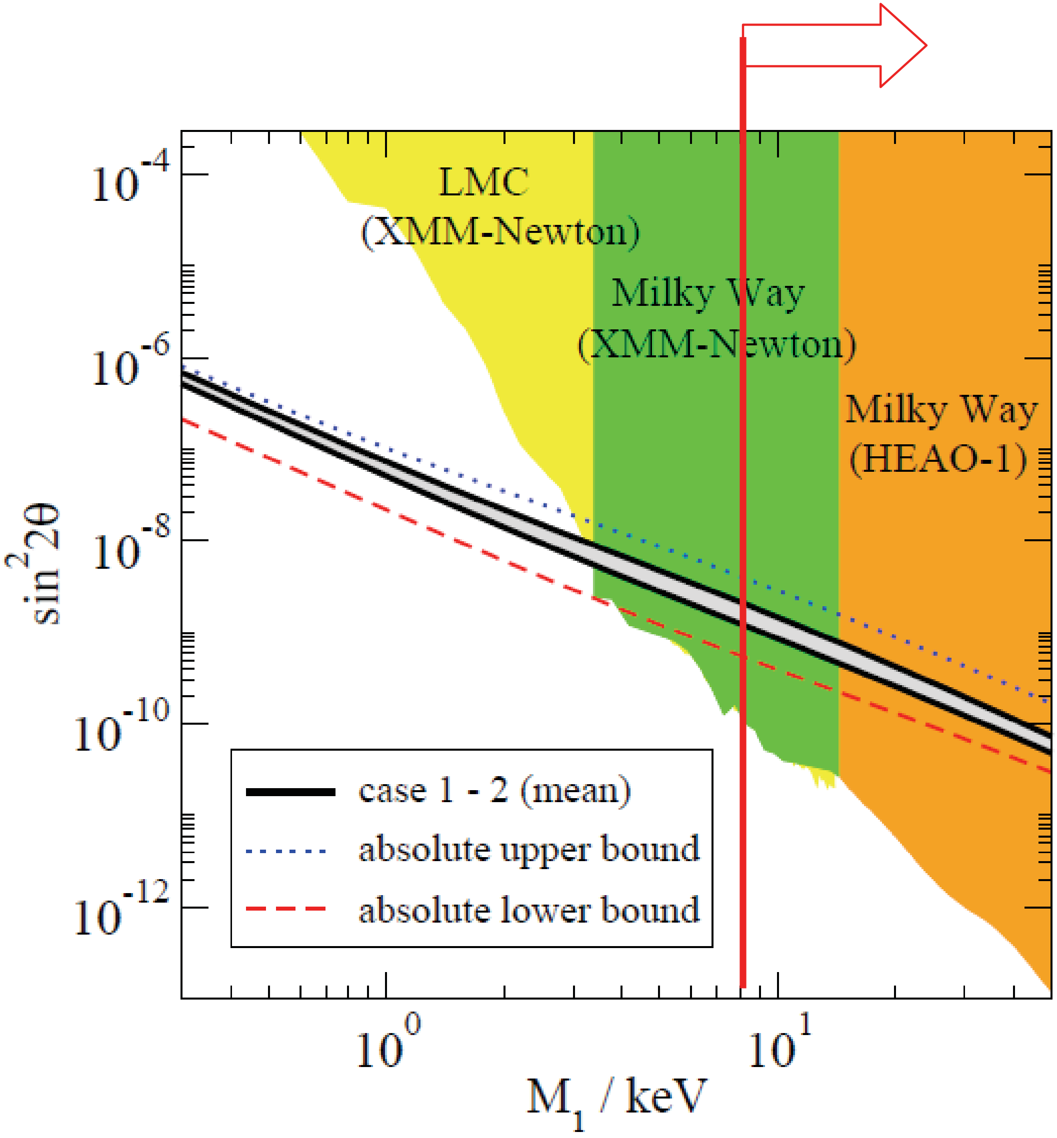
**X-ray constraint:**

$M_1 \lesssim (3.5)\ \ 6\ \ \text{keV}$

**Ly-alpha constraint:**

$M_1 \gtrsim 11.6\text{keV}\quad \text{(SMMT)}$

$M_1 \gtrsim 8\text{keV}\quad \text{(VLHMR)}$



X-ray constraints from

**Boyarsky, Neronov, Ruchayskiy, Shaposhnikov, Tkachev (astro-ph/0603660)**
**Boyarsky, Nevalainen, Ruchayskiy (astro-ph/0610961)**

# Fate of sterile neutrino DM

Dodelson-Widrow scenario assumes:

- No initial abundance at T ~ 1GeV
- No new interaction at E < 1GeV
- Charge asymmetries smaller than baryon asymmetry
- No low reheating, i.e. RD universe starts T>1GeV

Sterile neutrino DM is still possible, when

- Large lepton asymmetry (Shi-Fuller)
  - resonant production via active-sterile oscillations
- Production via decays of Inflaton/Scalar (Shaposhnikov, Tkachev / Kusenko)
- Dimension-five operator (Anisimov's talk)
- . . .

# Baryogenesis in the νMSM

# Baryon asymmetry

Baryogenesis conditions: (Sakharov)

- Baryon (Lepton) number violation
  - B+L violation by sphaleron (T>~100GeV)
  - L violation due to Majorana masses
- C and CP violations
  - 1 CP phase in quark sector
  - 6 CP phases in neutrino sector
- Out of equilibrium
  - Sterile neutrino can be out-of-equilibrium

Scenarios:

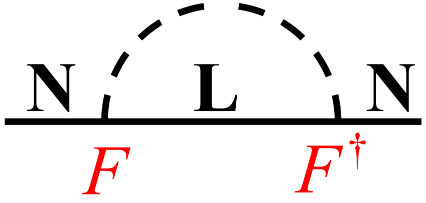
- Leptogenesis (Fukugita, Yanagida) ←NO
- Baryogenesis via sterile neutrino oscillations ←YES!

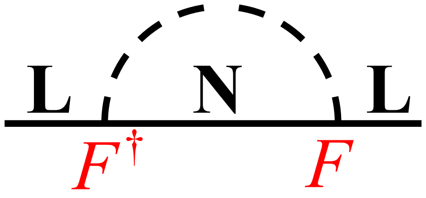
# Baryogenesis via neutrino oscillations

Akhmedov, Rubakov, Smirnov '98

Idea:

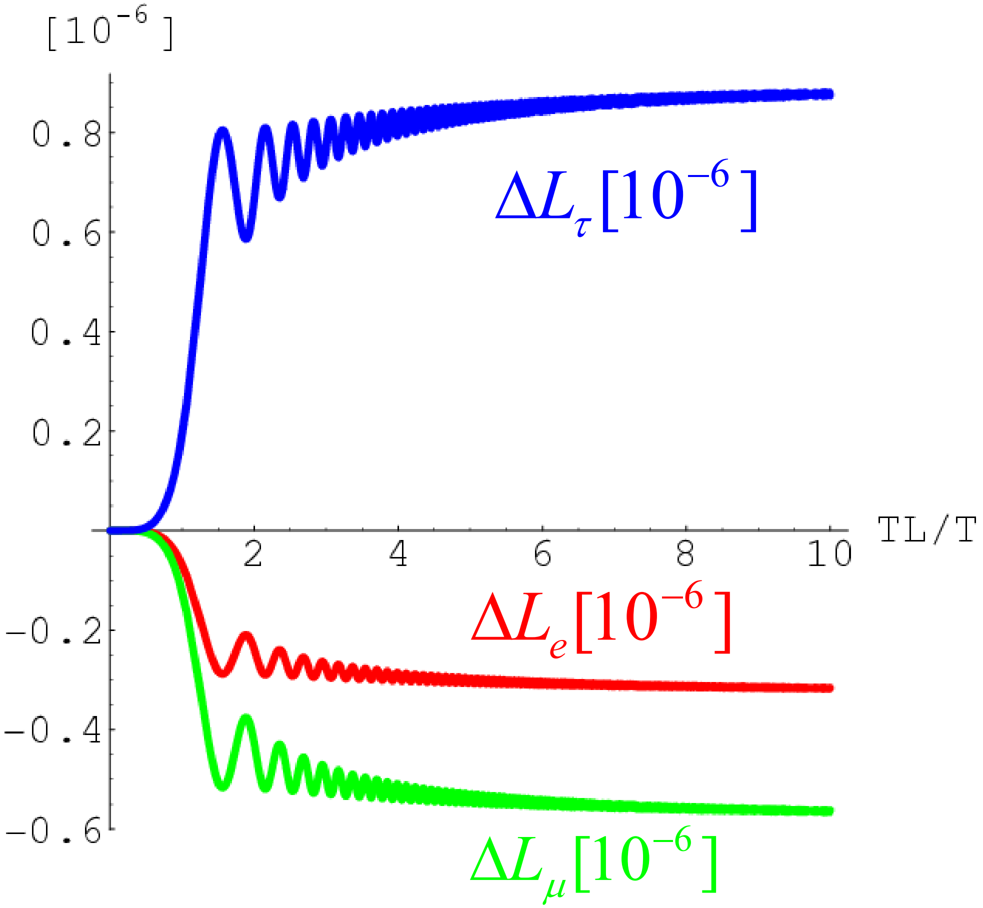
- Heavier sterile neutrinos are created and oscillate together with CP violations
- No generation of total lepton asymmetry, since Majorana masses are small ($M_I << T$)
- Lepton asymmetry is *distributed* between active and sterile sectors
- Asymmetry of active sector is partially transferred into baryon asymmetry



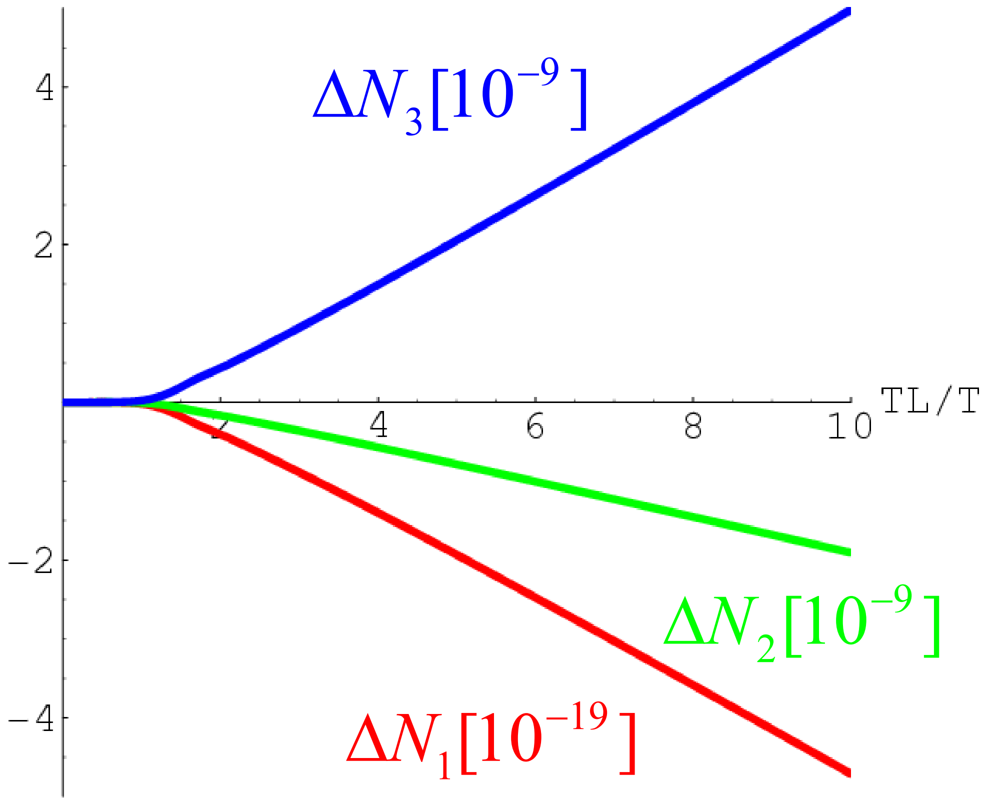


# Evolution of flavor asymmetries

## Active sector

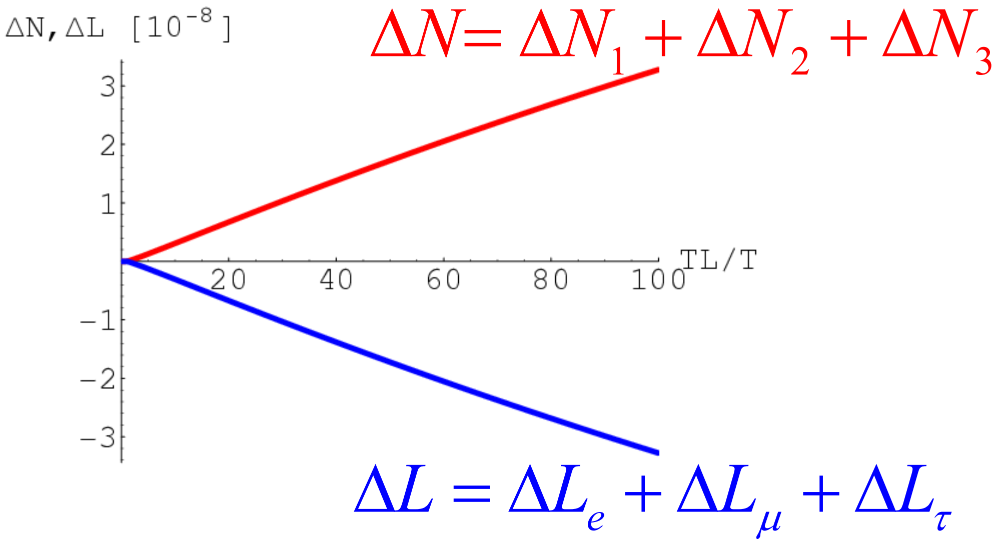


## Sterile sector



$T_L \sim 10^4\,\mathrm{GeV}$

# Baryon asymmetry of the universe



$\Delta N = \Delta N_1 + \Delta N_2 + \Delta N_3$

$\Delta L = \Delta L_e + \Delta L_\mu + \Delta L_\tau$

**Asymmetry in active sector is partially converted into baryon asymmetry**

$$\Delta B = -\frac{28}{79}\Delta L \neq 0$$

**(Kuzmin, Rubakov, Shaposhnikov)**

$$\frac{n_B}{s} \simeq 2\times 10^{-10}\ \delta_{CP}\left(\frac{10^{-5}}{\Delta M_{32}^2 / M_3^2}\right)^{2/3}\left(\frac{M_3}{10\mathrm{GeV}}\right)^{5/3}$$

$$\left(n_B / s\right)_{\mathrm{OBS}} \sim 10^{-10}$$

- **Heavier sterile neutrinos are quasi-degenerate**

$$1\mathrm{GeV} < M_2, M_3 < 17\mathrm{GeV}$$

**BBN** → **Out-of-equilibrium**

# Summary

The MSM + three right-handed neutrinos ($\nu$MSM)

- Lightest sterile neutrino ~10keV can be dark matter candidate
  - The simplest Dodelson-Widrow scenario conflicts with X-ray and Ly-alpha constraints
  - Some other production mechanism is needed
- Heavier sterile neutrinos can be responsible to baryon asymmetry of the universe
  - Baryogenesis via neutrino oscillations (not leptogenesis)

# Three sterile neutrinos

We may call as "dark", "clear" and "bright"

- Dark, $N_D$: Lightest one
  - Dark matter (production?)
  - $M \sim keV$, $F < 10^{-12}$, $\theta < 10^{-4}$

- Clear and Bright, $N_C$ and $N_B$: Heavier ones
  - Baryon asymmetry
  - Neutrino oscillations
  - $M \sim 1-10GeV$, $F \sim 10^{-7}$, $\theta \sim 10^{-6}$

# Neutrino masses

**Seesaw mechanism:** Dirac masses >> Majorana masses

$$\begin{pmatrix} 0 & M_D \\ M_D^T & M_M \end{pmatrix} \Rightarrow \begin{pmatrix} M_\nu & 0 \\ 0 & M_M \end{pmatrix} \qquad M_\nu = -M_D^T \frac{1}{M_M} M_D$$

- Active neutrinos

$$\nu_1,\ \nu_2,\ \nu_3\ (m_1 \le m_2 \le m_3) \qquad U^T M_\nu U = diag(m_1, m_2, m_3)$$

- Sterile neutrinos

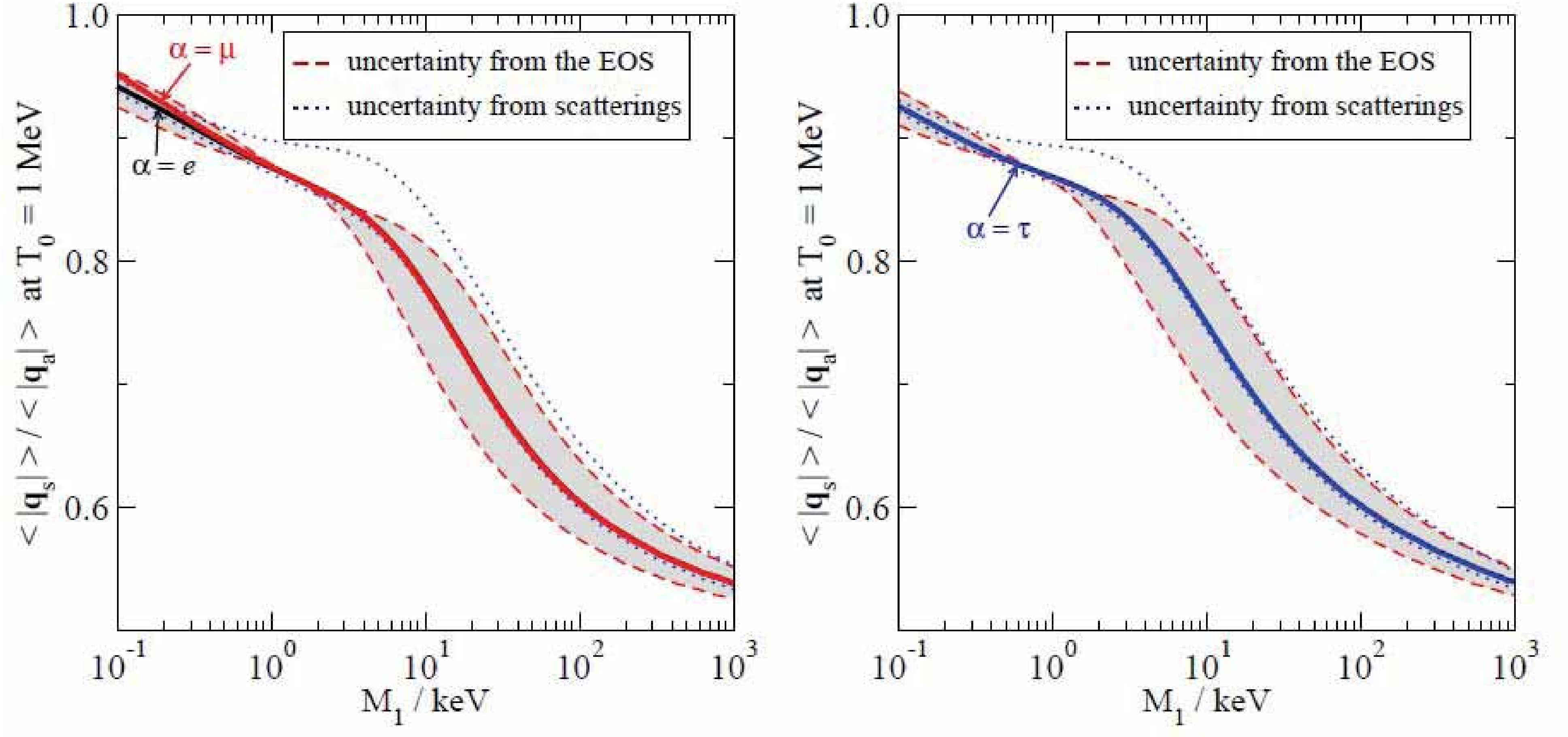
$$N_1,\ N_2,\ N_3\ (M_1 \le M_2 \le M_3) \qquad M_M = diag(M_1, M_2, M_3)$$

Neutrino mixing in charged current

$$\nu_\alpha = U_{\alpha a}\ \nu_a + \Theta_{\alpha I}\ N_I^c \qquad \Theta_{\alpha I} = (M_D)_{\alpha I} / M_I \ll 1$$

$$(\alpha = e, \mu, \tau) \qquad (a = 1,2,3)$$

# Averaged momentum



We find: $\frac{\langle|\mathbf{q}_s|\rangle}{\langle|\mathbf{q}_a|\rangle} \simeq 0.8$ for $M_1 \simeq 10$keV

$M_1 \gtrsim 11.6$keV (SMMT)
$M_1 \gtrsim 8$keV (VLHMR)

# Neutrino Yukawa coupling constants

$$F = K_L \cdot P_\alpha \cdot F_d \cdot K_R^\dagger \cdot P_\beta$$

$$F_d = \mathrm{diag}(f_1, f_{2,} f_3)$$

$$P_\alpha = \mathrm{diag}(e^{i\alpha_1}, e^{i\alpha_2}, 1),\ P_\beta = \mathrm{diag}(e^{i\beta_1}, e^{i\beta_2}, 1)$$

$$K_L = \begin{pmatrix} 1 & & \\ & c_{L23} & s_{L23} \\ & -s_{L23} & c_{L23} \end{pmatrix} \begin{pmatrix} c_{L13} & & s_{L13}e^{-i\delta_L} \\ & 1 & \\ -s_{L13}e^{i\delta_L} & & c_{L13} \end{pmatrix} \begin{pmatrix} c_{L12} & s_{L12} & \\ -s_{L12} & c_{L12} & \\ & & 1 \end{pmatrix}$$

$$K_R = \begin{pmatrix} 1 & & \\ & c_{R23} & s_{R23} \\ & -s_{R23} & c_{R23} \end{pmatrix} \begin{pmatrix} c_{R13} & & s_{R13}e^{-i\delta_R} \\ & 1 & \\ -s_{R13}e^{i\delta_R} & & c_{R13} \end{pmatrix} \begin{pmatrix} c_{R12} & s_{R12} & \\ -s_{R12} & c_{R12} & \\ & & 1 \end{pmatrix}$$

# Implication to active neutrino masses

## The lightest active neutrino mass

$$m_{\nu_1} \lesssim \sum_{\alpha=e,\mu,\tau} \frac{|M_D|^2_{\alpha 1}}{M_1}$$

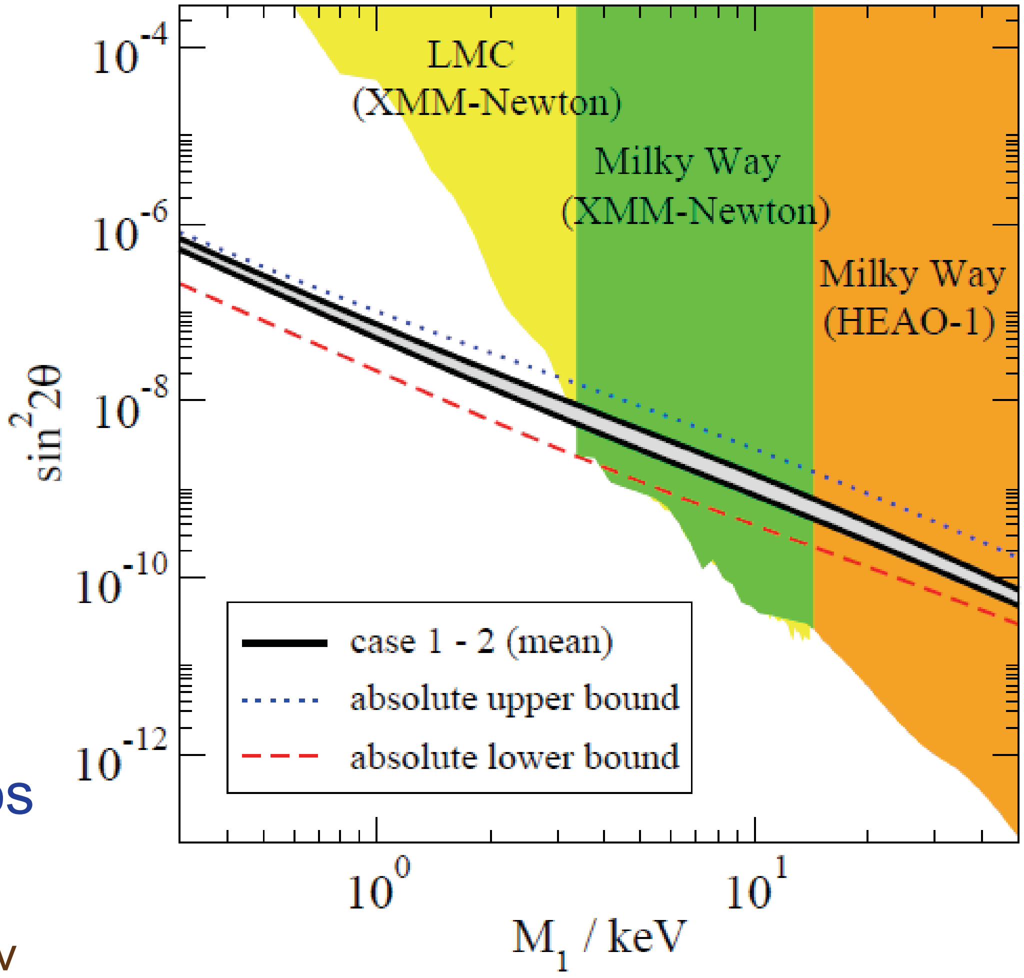
$$\simeq 2 \cdot 10^{-5}\mathrm{eV}\left(\frac{\mathrm{keV}}{M_1}\right)$$

- Tremaine-Gunn bound:

$$M_1 \gtrsim 0.3\mathrm{keV}$$

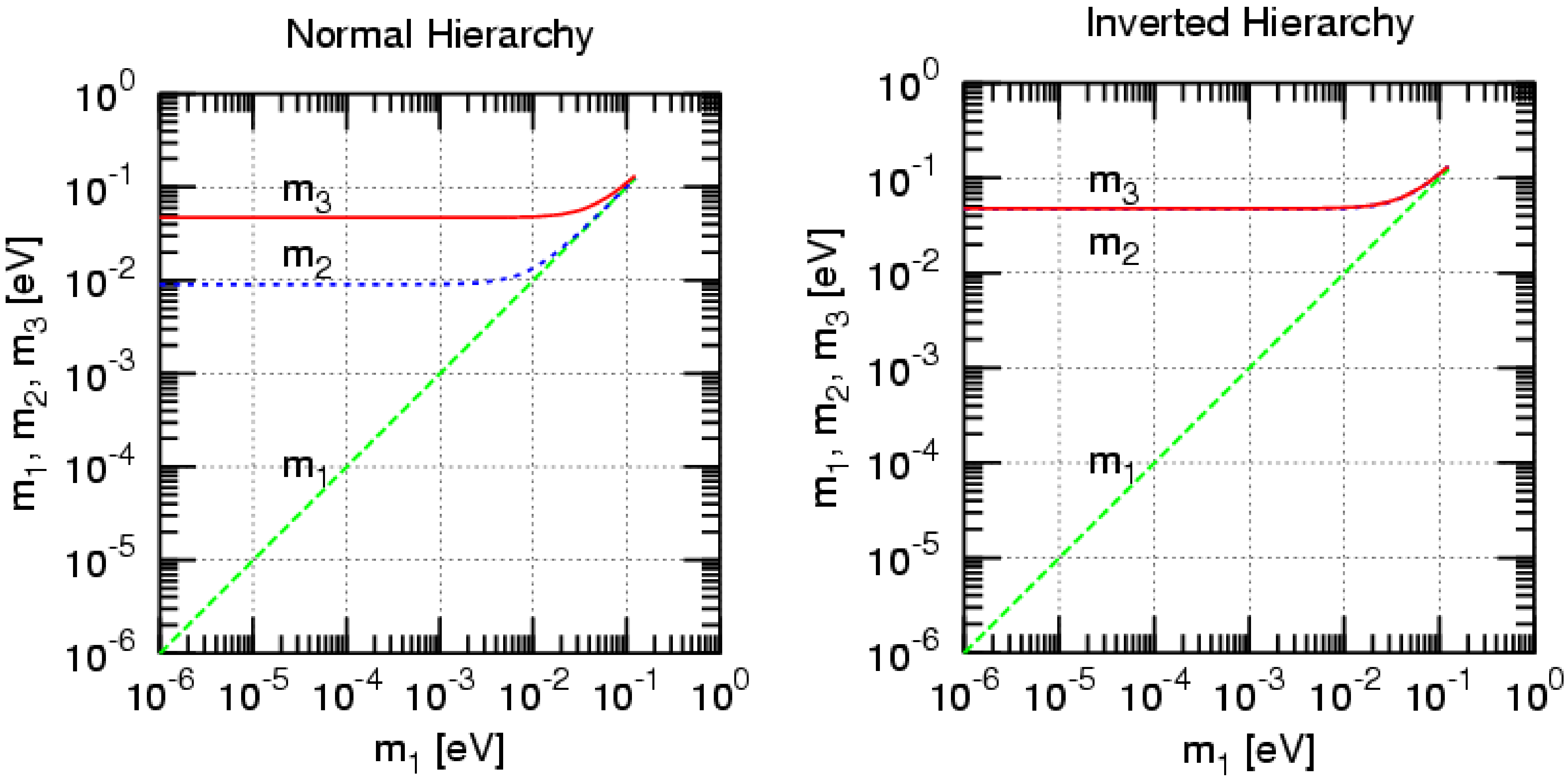
➡ $m_{\nu_1} \lesssim 7 \cdot 10^{-5}$ eV

➡ exclude the degenerate masses of active neutrinos



TA, Blanchet, Shaposhnikov

# Active neutrino masses



Normal Hierarchy

Inverted Hierarchy

# Entropy dilution

TA, Kusenko, Shaposhnikov

**Decays of heavier sterile neutrinos can produce entropy by $S \lesssim 30$ within the νMSM**

- Bound from overclosure: $\sin^2(2\theta) < f(M_1) \cdot S$
- Bound from X-rays: does not change
- Bound from Ly-α: $M_1 > \frac{\langle|\mathbf{q}_s|\rangle}{\langle|\mathbf{q}_a|\rangle} M_0 \cdot S^{-1/3}$

■ Allowed region opens

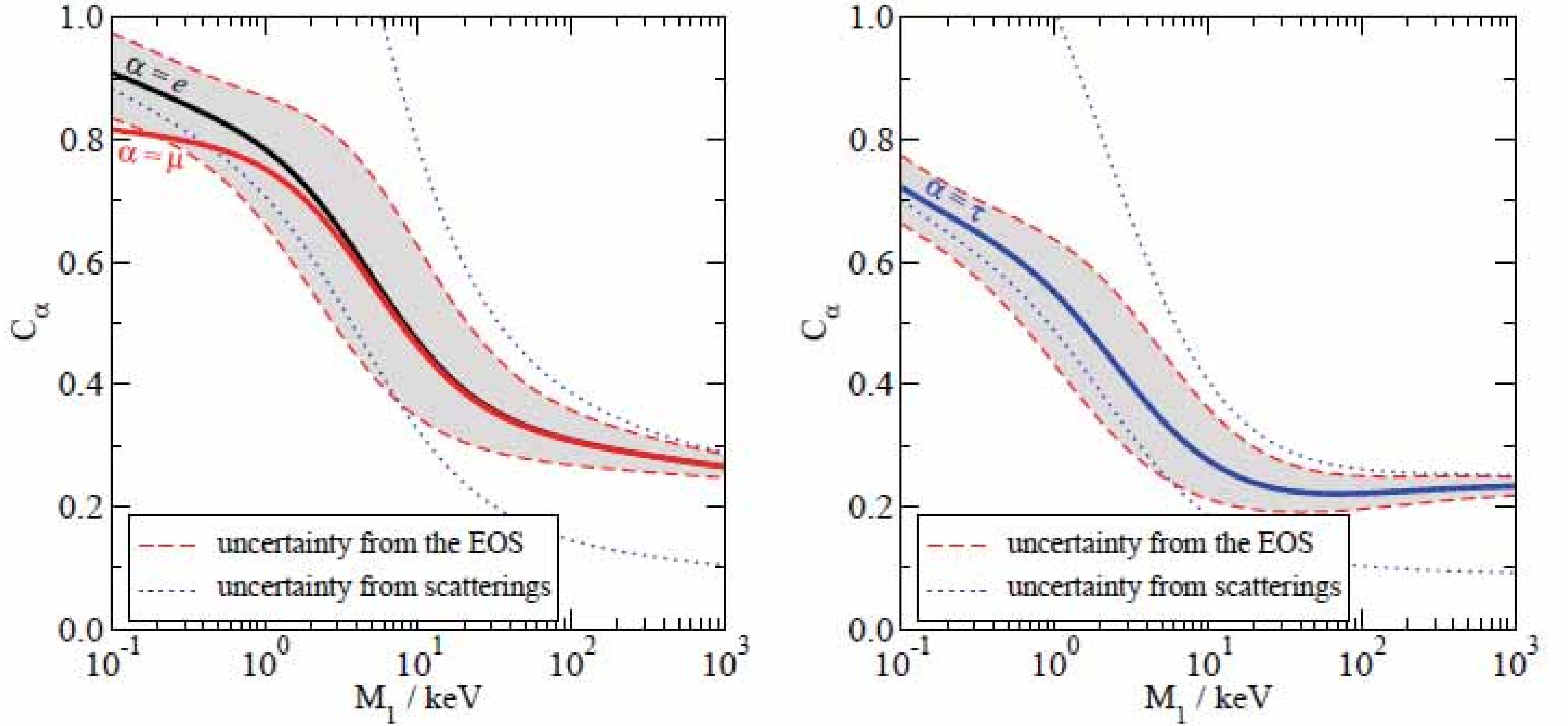
$$S \gtrsim 155\,, \quad (M_1 \lesssim 1.5\text{keV}, \ \sin^2(2\theta) < 1.9 \cdot 10^{-6})$$

$$\text{for } \ M_1 \gtrsim 8\text{keV} \cdot S^{-1/3} \quad \text{(VLHMR)}$$

- Such rate cannot be obtained within the νMSM
- Sterile neutrino dark-matter cannot be realized within the νMSM, if we apply the current Ly-α constraints !!

# Relic density of sterile neutrino

$$\Omega_{N_1} h^2 = 0.11 \sum_{\alpha=e,\mu,\tau} C_\alpha(M_1) \left( \frac{|M_D|_{\alpha 1}}{0.1\text{eV}} \right)^2$$



$$\Omega_{N_1} = \Omega_{\mathrm{DM}} \Rightarrow |M_D|_{\alpha I} \sim 0.1 \text{ eV}, \quad |F_{\alpha I}| \sim 10^{-12}$$

# Upper bound on mixing angle

**We find** $C_e > C_\mu > C_\tau$

- The case 1:

  the largest abundance

  the strongest bound

  $|M_D|_{e1} \neq 0$

  $|M_D|_{\mu 1} = |M_D|_{\tau 1} = 0$

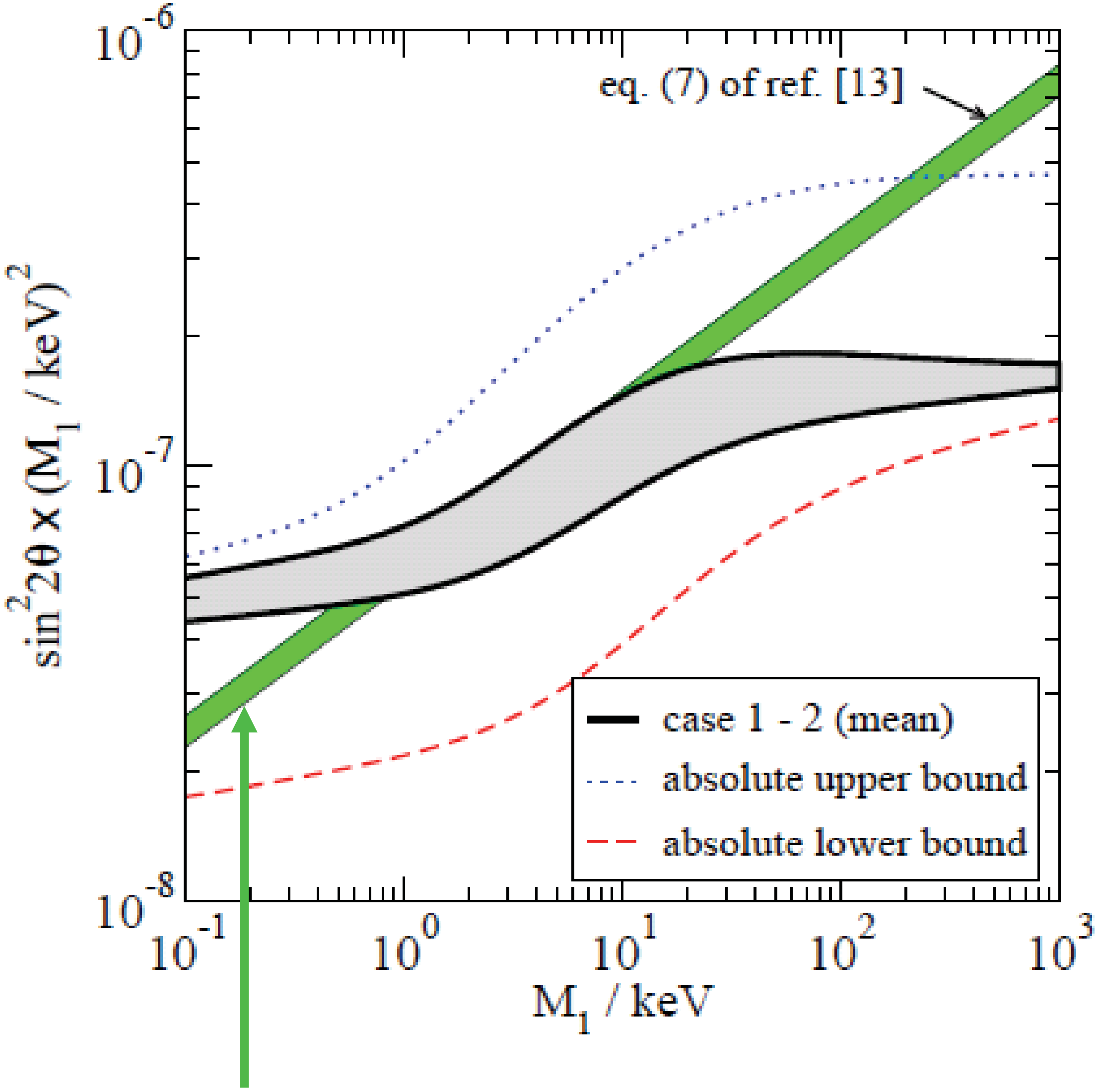
- The case 2:

  the smallest abundance

  the weakest bound

  $|M_D|_{\tau 1} \neq 0$

  $|M_D|_{e1} = |M_D|_{\mu 1} = 0$



Abazajian: Phys.Rev. D73 ('06) 063506

$\Omega_{\mathrm{DM}} = 0.2\,, \quad T_c = 150 - 200\mathrm{MeV}$