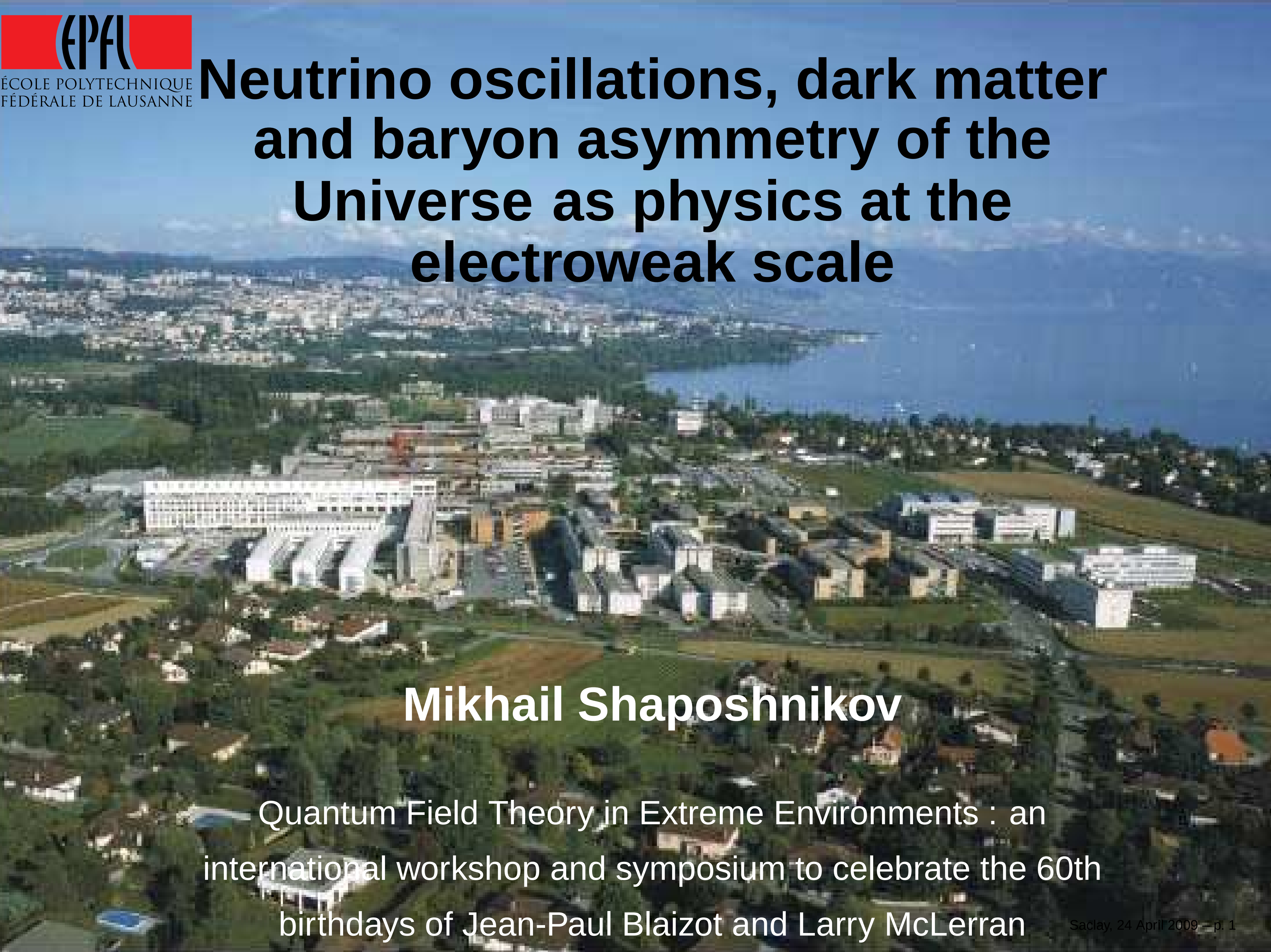

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Neutrino oscillations, dark matter and baryon asymmetry of the Universe as physics at the electroweak scale

Mikhail Shaposhnikov

Quantum Field Theory in Extreme Environments : an international workshop and symposium to celebrate the 60th birthdays of Jean-Paul Blaizot and Larry McLerran

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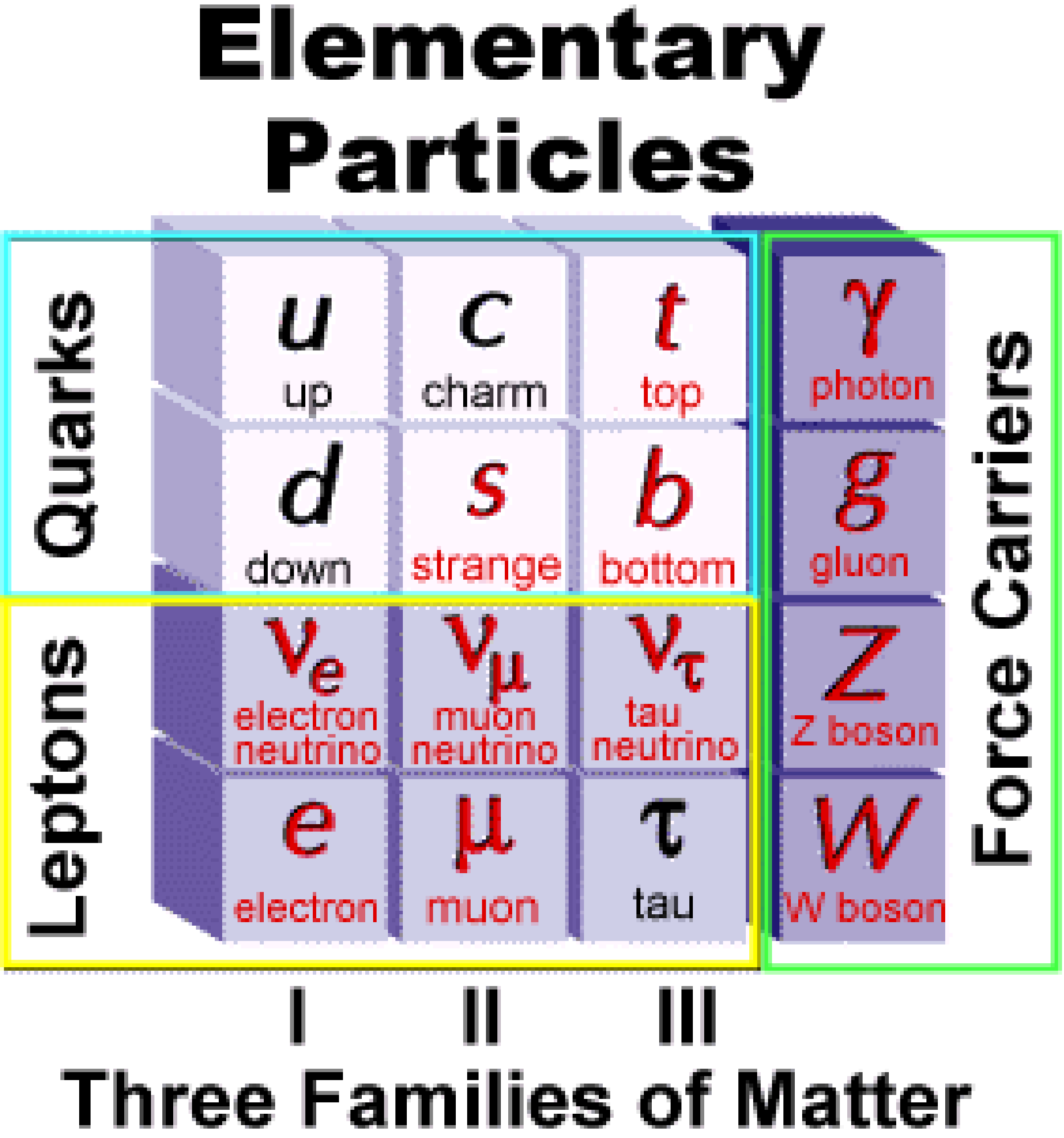
Outline

- The νMSM versus the SM
- Neutrino masses
- Dark Matter
- Baryon Asymmetry
- Higgs-inflation
- Conclusions

Standard Model



the SM

There are 36 quark states: left fermionic doublets:

$(u\ ,d)_L,\ (c\ ,s)_L,\ (t\ ,b)_L$ and $u_R\ ,\ d_R,\ c_R\ ,\ s_R,\ t_R\ ,\ b_R$

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$(u\ ,d)_L,\ (c\ ,s)_L,\ (t\ ,b)_L$ and $u_R\ ,\ d_R,\ c_R\ ,\ s_R,\ t_R\ ,\ b_R$,

9 + 3 leptonic states

$(\nu_e, e)_L,\ (\nu_\mu, \mu)_L,\ (\nu_\tau, \tau)_L$ and $e_R,\quad \mu_R,\quad \tau_R$

12 $SU(3) \times SU(2) \times U(1)$ gauge bosons (8+3+1)

and one Higgs doublet,

in total $(3 \times 2 + 3 \times 2 + 2 + 1 + 0) \times 3 \times 2 = 90$ fermionic and

$(8 + 3 + 1) \times 2 + 4 = 28$ bosonic degrees of freedom

the νMSM

There are 36 quark states: left fermionic doublets:

$(u\ ,d)_L,\ (c\ ,s)_L,\ (t\ ,b)_L$ and $u_R\ ,\ d_R,\ c_R\ ,\ s_R,\ t_R\ ,\ b_R$

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$(u\ ,d)_L,\ (c\ ,s)_L,\ (t\ ,b)_L$ and $u_R\ ,\ d_R,\ c_R\ ,\ s_R,\ t_R\ ,\ b_R$,

9 + 3 leptonic states

$(\nu_e, e)_L,\ (\nu_\mu, \mu)_L,\ (\nu_\tau, \tau)_L$ and $N_D, e_R,\ N_C, \mu_R,\ N_B, \tau_R$

12 $SU(3) \times SU(2) \times U(1)$ gauge bosons (8+3+1)

and one Higgs doublet,

in total $(3 \times 2 + 3 \times 2 + 2 + 1 + 1) \times 3 \times 2 = 96$ fermionic and

$(8 + 3 + 1) \times 2 + 4 = 28$ bosonic degrees of freedom

Why the νMSM?

Because it is a minimal model which allows to address all experimentally confirmed signals in favour of physics beyond the SM:

- Consistent description of neutrino masses and oscillations
- Can explain dark matter in the Universe
- Can explain baryon asymmetry of the Universe
- Can provide inflation (as well as the Standard Model)

Neutrino masses

Neutrinos have mass. Possible origin of this mass - existence of right-handed neutrinos (singlet fermions, sterile neutrinos...) with mass M_N and Yukawa couplings to the SM leptons and the Higgs boson. See-saw formula:

$$m_\nu = -M_D \frac{1}{M_N} [M_D]^T, \quad M_D = Fv, \;\; v = 174\ \mathrm{GeV}$$

tells nothing about scale of M_N!

Popular choice: GUT see-saw

Assume that Yukawa couplings of N to the Higgs and left-handed lepton doublets is similar to those in quark or charged lepton sector (say, $F \sim 1$, as for the top quark) and find M_N from requirement that one gets correct active neutrino masses:

$$M_N \simeq \frac{F^2 v^2}{m_{atm}} \simeq 6 \times 10^{14} \text{ GeV}$$

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

GUT see-saw: problems

- Hierarchy problem: M_N is much larger than EW scale: one has to understand not only why $M_W \ll M_{Pl}$, but also why $M_W \ll M_N$ and why $M_N \ll M_{Pl}$. Three fine tunings instead of one.
- Stabilization of hierarchy - SUSY. SUGRA - gravitino production problem. Reheating temperature must be smaller than $T_{\rm reh} \lesssim 10^{10}$ GeV. Problem with leptogenesis. Extra scale - extra (4th) hierarchy problem! Why $M_N \ll M_{GUT}$?
- Unfortunately, no direct experimental verification is foreseen

Alternative: EW see-saw

Assume that the Majorana masses of N are smaller or of the same order as the mass of the Higgs boson and find Yukawa couplings from requirement that one gets correct active neutrino masses:

$$F \sim \frac{\sqrt{m_{atm} M_N}}{v} \sim (10^{-6} - 10^{-13}),$$

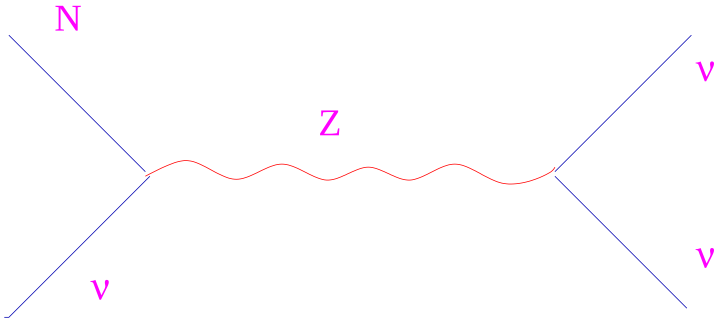
Advantages:

- No new energy scale - no new hierarchy or fine tuning problem in comparison with the Standard Model.
- Different approach to hierarchy problem

Dark matter

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

Yukawa couplings are small → sterile N can be very stable.



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

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

For one flavour:

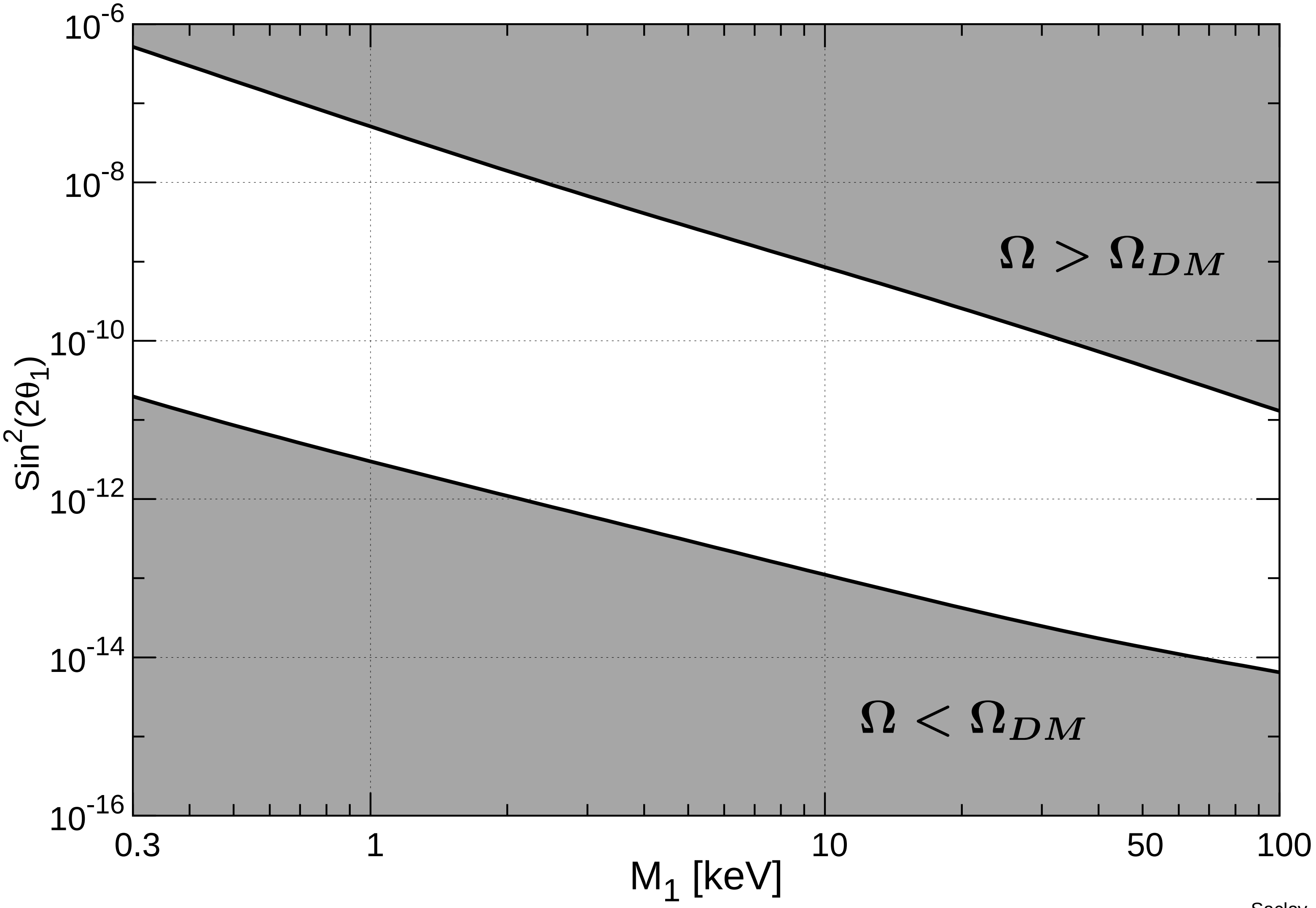
$$\tau_{N_1} = 10^{14}\,\text{years}\left(\frac{10\,\text{keV}}{M_N}\right)^5\left(\frac{10^{-8}}{\theta_1^2}\right)$$

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

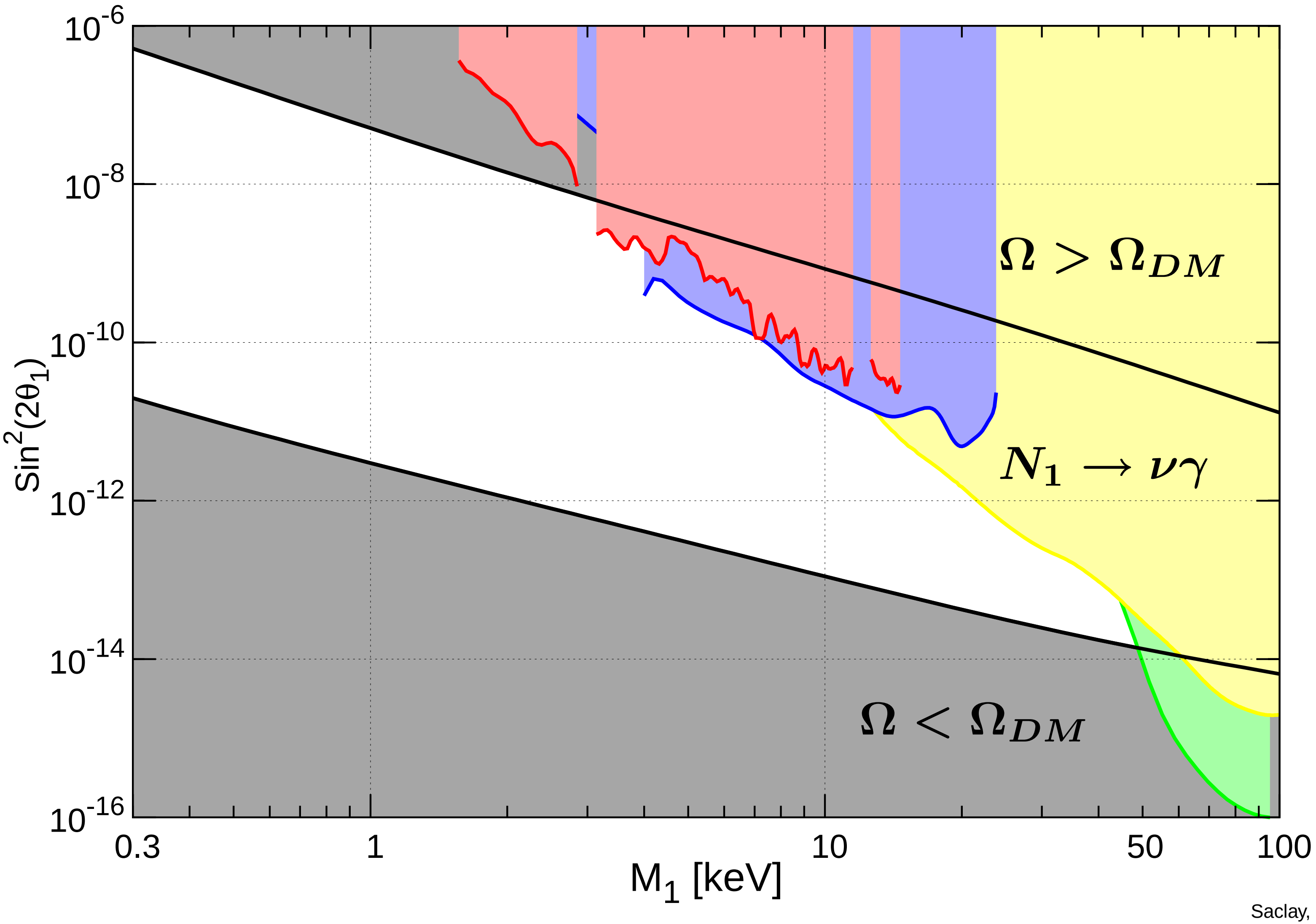
Constraints on DM sterile neutrino

- Production. N_1 are created in the early Universe in reactions $l\bar{l} \longrightarrow \nu N_1, \;\; q\bar{q} \longrightarrow \nu N_1$ etc. We should get correct DM abundance.
- X-rays. N_1 decays radiatively, $N_1 \longrightarrow \gamma\nu$, producing a narrow line which can be detected. This line has not been seen (yet).
- Structure formation. If N_1 is too light it may have considerable free streaming length and erase fluctuations on small scales. This can be checked by the study of Lyman-α forest spectra of distant quasars.

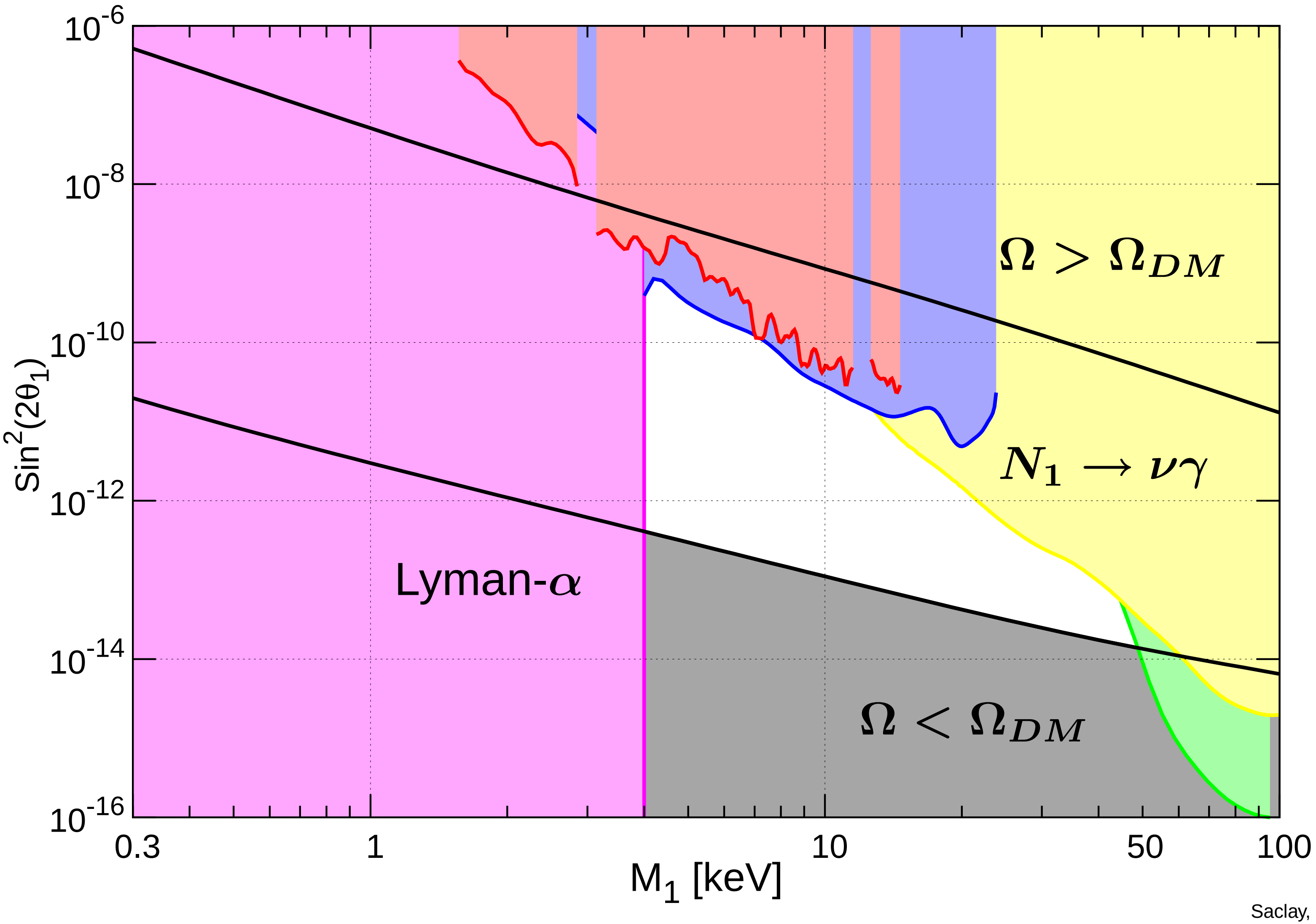
DM: production



DM: production + X-ray constraints



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



Baryon asymmetry

Leptogenesis via sterile neutrino oscillations

(Asaka, M.S; Akhmedov, Rubakov, Smirnov)

- Lepton number violation: $\boldsymbol{N_{2,3} \leftrightarrow \nu}$
- Baryon number violation: electroweak anomaly, sphalerons
- CP - violation: Dirac and Majorana phases in $\boldsymbol{N_{2,3} - \nu}$ interactions
- Arrow of time: $\boldsymbol{N_{2,3}}$ are out of thermal equilibrium for small Yukawa couplings

Value of baryon asymmetry

$$\frac{n_B}{s} \simeq 1.7 \cdot 10^{-10}\, \delta_{\mathrm{CP}} \left(\frac{10^{-5}}{\Delta M_{32}^2 / M_3^2} \right)^{\frac{2}{3}} \left(\frac{M_3}{10\mathrm{GeV}} \right)^{\frac{5}{3}} .$$

$$\begin{aligned} \delta_{\mathrm{CP}} &= 4 s_{R23} c_{R23} \Big[s_{L12} s_{L13} c_{L13} \big((c_{L23}^4 + s_{L23}^4) c_{L13}^2 - s_{L13}^2 \big) \cdot \sin(\delta_L + \alpha_2) \\ &\quad + c_{L12} c_{L13}^3 s_{L23} c_{L23} \left(c_{L23}^2 - s_{L23}^2 \right) \cdot \sin\alpha_2 \Big] . \end{aligned}$$

$\delta_{\mathrm{CP}} \sim 1$ may be consistent with observed ν oscillations.

Nontrivial requirement: $|M_2 - M_3| \ll M_{2,3}$, i.e. heavier neutrinos must be degenerate in mass.

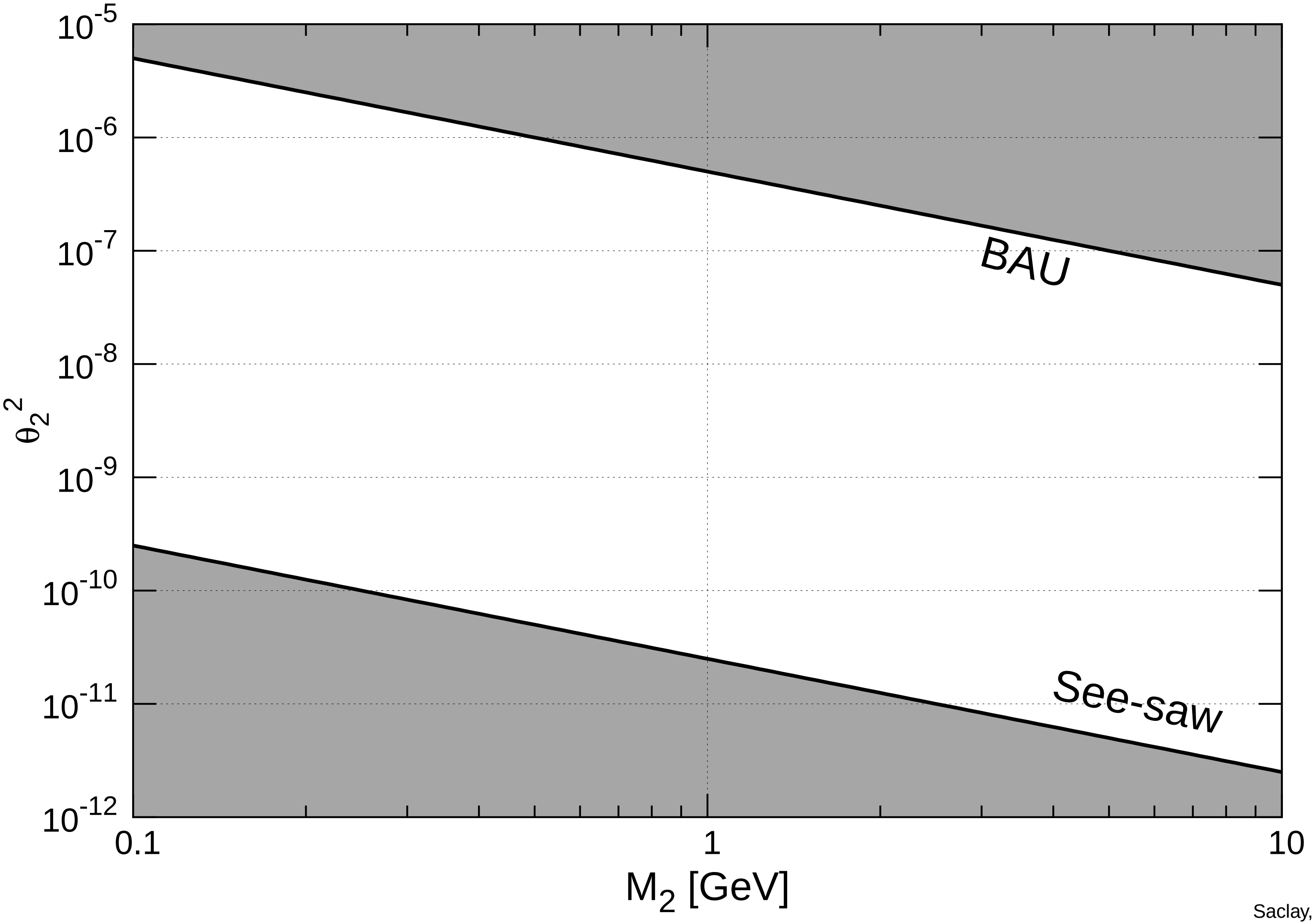
Works best if

$$M_2^2 - M_3^2 \sim T_W^3 / M_0 \simeq 4\,(\mathrm{keV})^2, \;\; |\mathrm{M}_2^2 - \mathrm{M}_3^2| \sim \mathrm{M}_1^2 \;\; ???$$

Constraints on BAU sterile neutrinos

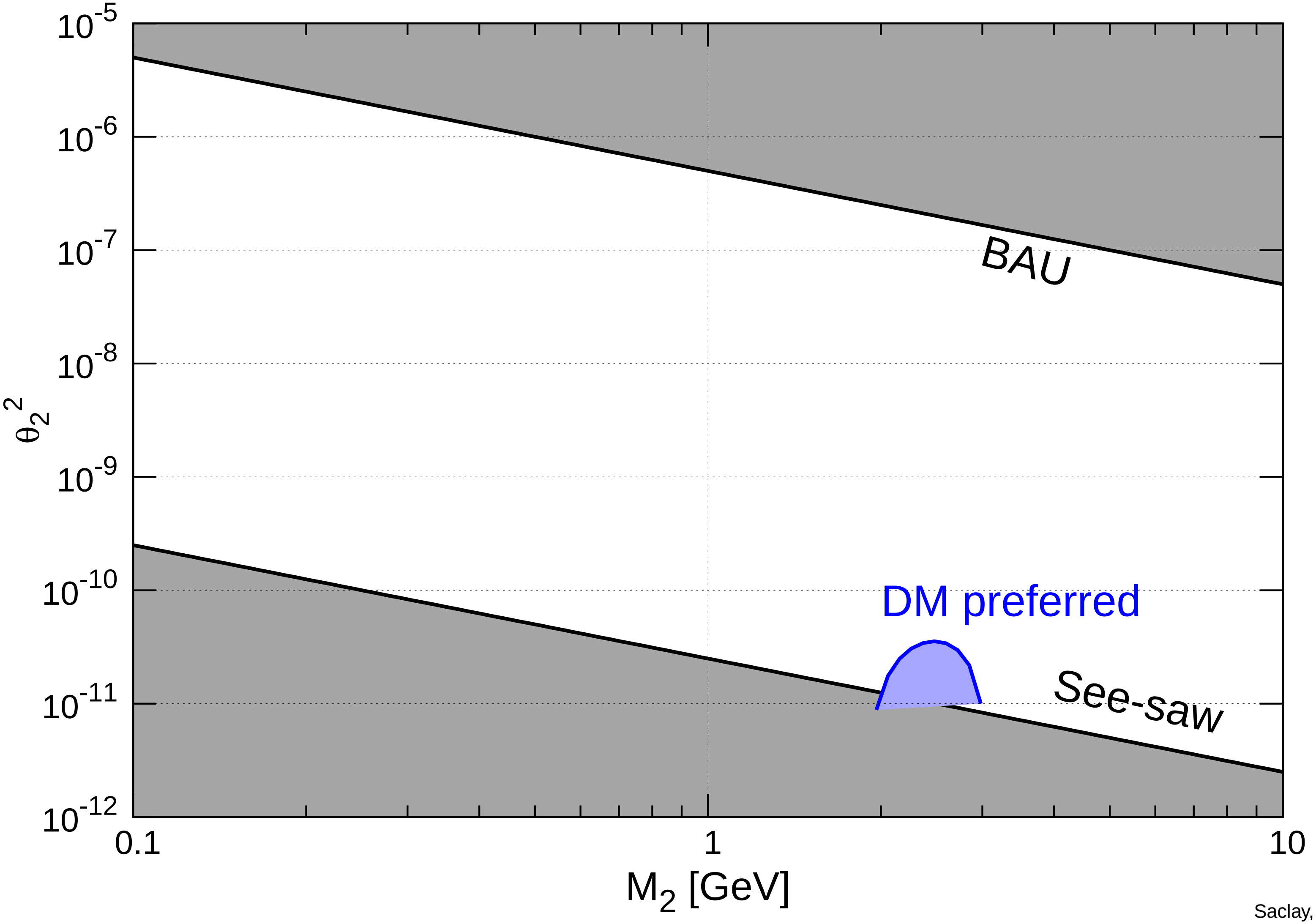
- BAU generation requires out of equilibrium: mixing angle of $\boldsymbol{N_{2,3}}$ to active neutrinos cannot be too large
- Neutrino masses. Mixing angle of $\boldsymbol{N_{2,3}}$ to active neutrinos cannot be too small
- Dark matter and BAU. Concentration of DM sterile neutrinos must be much larger than concentration of baryons
- BBN. Decays of $\boldsymbol{N_{2,3}}$ must not spoil Big Bang Nucleosynthesis
- Experiment. $\boldsymbol{N_{2,3}}$ have not been seen (yet).

$N_{2,3}$: BAU



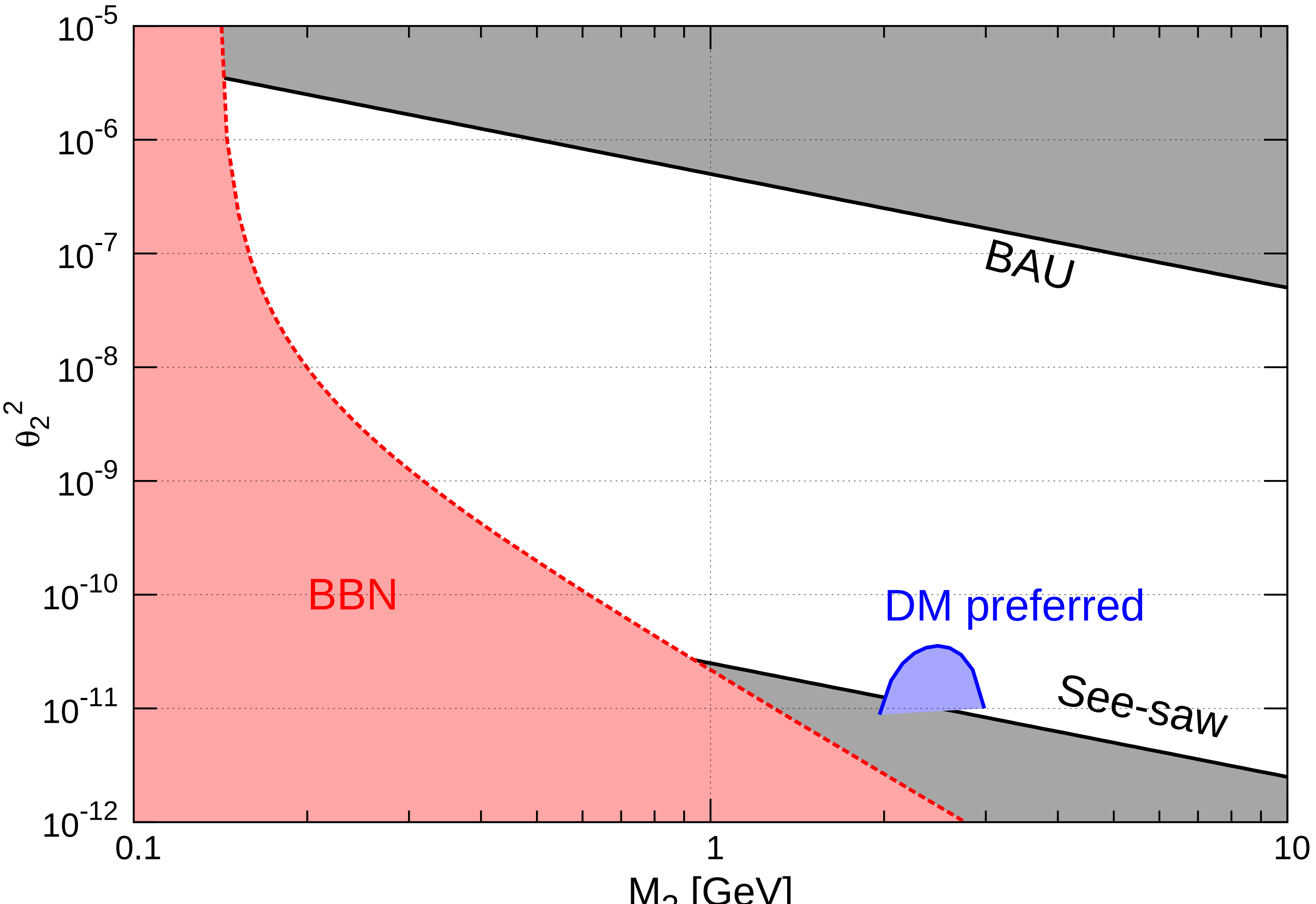
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
θ_2^2
BAU
See-saw
0.1
1
10
M_2 [GeV]

$N_{2,3}$: BAU + DM

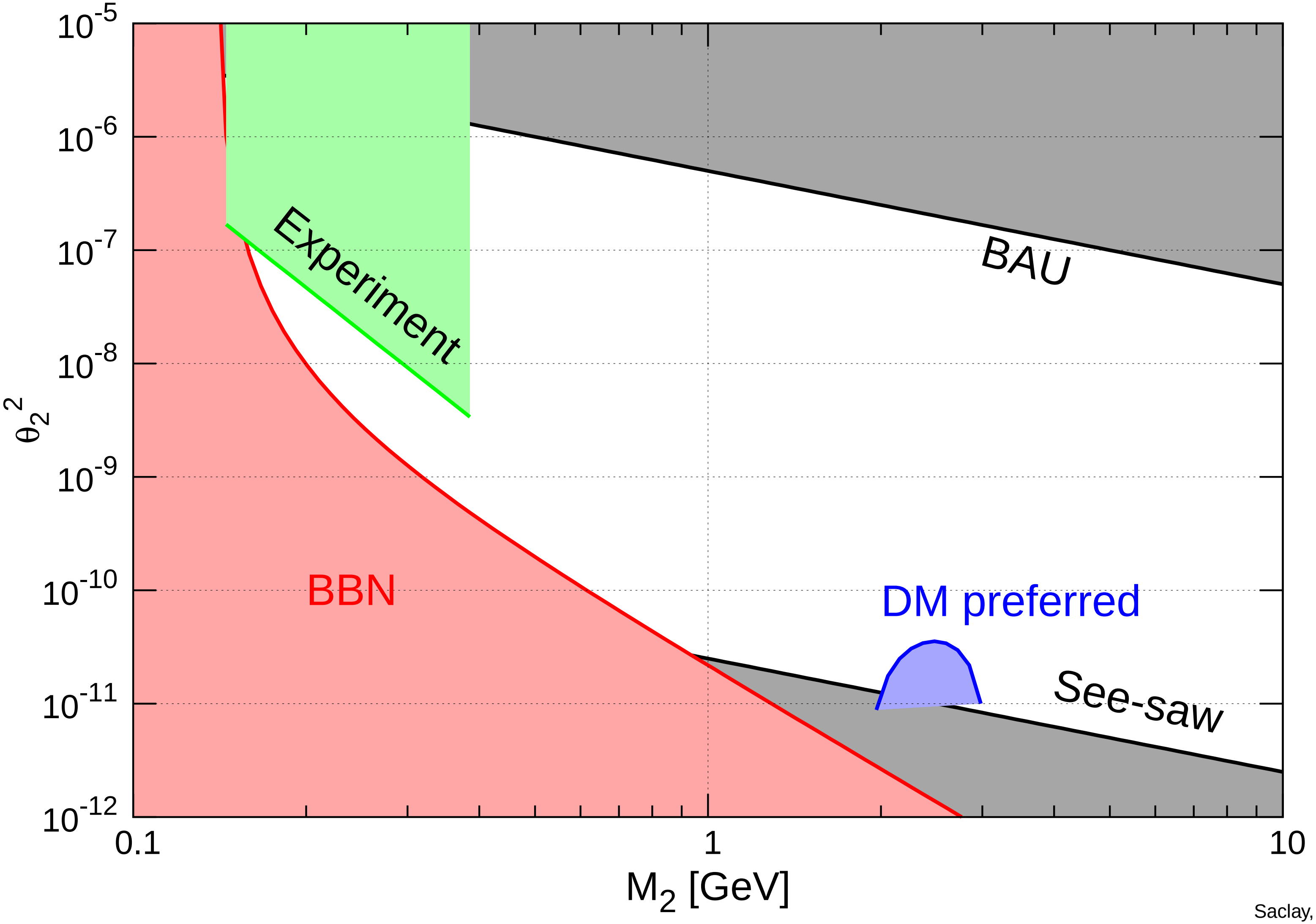


10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
θ_2^2
BAU
DM preferred
See-saw
0.1
1
10
M_2 [GeV]

$N_{2,3}$: BAU + DM + BBN



$N_{2,3}$: BAU + DM + BBN + Experiment



Summary of predictions from cosmology

Robust:

- Absolute values of the active neutrino masses (Asaka, Blanchet, M.S.; Smit): $m_1 \leq \mathcal{O}(10^{-5})$ eV

  Normal hierarchy: $m_2 \simeq \sqrt{\Delta m^2_{solar}} \simeq 9 \cdot 10^{-3}$ eV ,

  $m_3 \simeq \sqrt{\Delta m^2_{atm}} \simeq 5 \cdot 10^{-2}$ eV ,

  Inverted hierarchy: $m_{2,3} \simeq \sqrt{\Delta m^2_{atm}} \simeq 5 \cdot 10^{-2}$ eV .

- Effective Majorana mass for neutrinoless double beta decay (Bezrukov)

  Normal hierarchy: $1.3\ \mathrm{meV} < m_{\beta\beta} < 3.4\ \mathrm{meV}$

  Inverted hierarchy: $13\ \mathrm{meV} < m_{\beta\beta} < 50\ \mathrm{meV}$

- $M_1 > 0.3$ keV, $140\ \mathrm{MeV} < M_{2,3} \lesssim M_W$,

  $\delta M < 800 m_{atm} \left(\frac{M}{\mathrm{GeV}}\right)^2$

Summary of predictions from cosmology

Depend on initial condition for Big Bang (no sterile neutrinos at the beginning)

- Dark matter sterile neutrino mass: $4\ \mathrm{keV} < \mathrm{M}_1 < 50$ keV
- Dark matter sterile neutrino mixing angle: $2 \times 10^{-15} < \theta_1^2 < 2 \times 10^{-10}$
- $M_2 \sim 2$ GeV, $\Delta M \lesssim 10^{-4} m_{atm}$, $\theta_2^2 \simeq 10^{-11}$
- CP asymmetry in $N_{2,3}$ decays is on the level of 1%

Higgs-inflation

Idea:

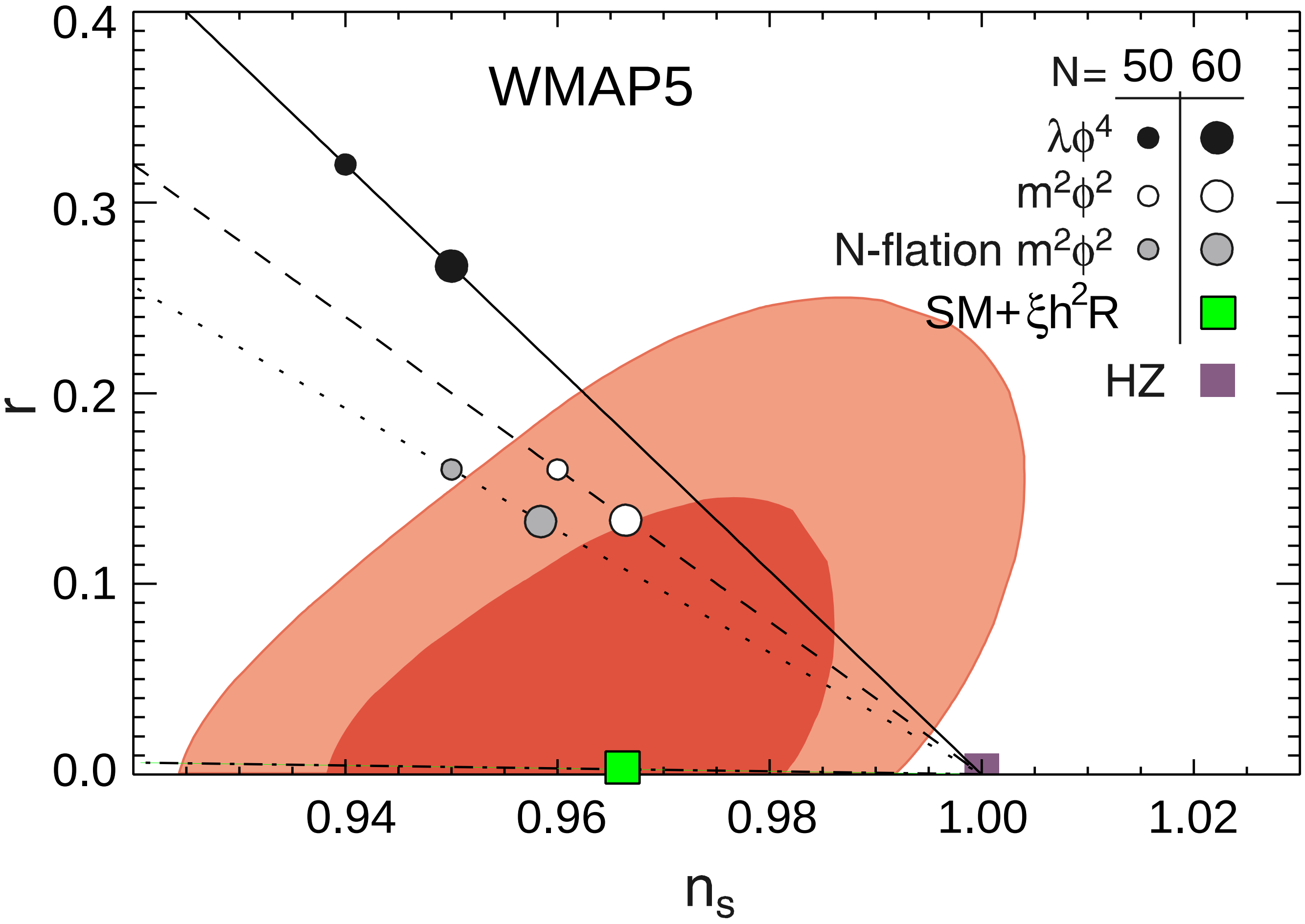
non-minimal coupling of scalar to gravity

$$\Delta S = \int d^4x\sqrt{-g}\left\{-\frac{\xi h^2}{2}R\right\}$$

Feynman, Brans, Dicke,...

If $\xi \sim 10^3 - 10^4$ - Higgs field of the SM inflates the universe and produces the required spectrum of primordial fluctuations:

CMB parameters—spectrum and tensor modes



Cosmological constraint on the Higgs mass

2 loop computation

$$m_{\min} = [126.1 + \frac{m_t - 171.2}{2.1} \times 4.1 - \frac{\alpha_s - 0.1176}{0.002} \times 0.6]\ \text{GeV}\ ,$$

$$m_{\max} = [193.9 + \frac{m_t - 171.2}{2.1} \times 0.6 - \frac{\alpha_s - 0.1176}{0.002} \times 0.1]\ \text{GeV}\ .$$

Also: A. De Simone, M. Hertzberg and F. Wilczek

Conclusions

- New physics, responsible for neutrino masses and mixings, for dark matter, and for baryon asymmetry of the universe may hide itself below the EW scale
- New dedicated experiments in particle physics and cosmology are needed to uncover this physics

Collaborators

- Takehiko Asaka (Niigata U.)
- Fedor Bezrukov (MPI, Heidelberg)
- Steve Blanchet (Maryland U.)
- Alexey Boyarsky (ETH, Zurich)
- Dmitry Gorbunov (INR, Moscow)
- Mikko Laine (Bielefeld U.)
- Amaury Magnin (EPFL, Lausanne)
- Andrei Neronov (Geneva U.)
- Oleg Ruchayskiy (EPFL, Lausanne)
- Igor Tkachev (INR, Moscow)

What new particles of the νMSM cannot explain

- origin of high energy cosmic rays
- existence of $\mathbf{0.511}$ MeV annihilation line in the direction of the Galaxy center
- pulsar-kick velocities
- discrepancy between experiment and the theory prediction of anomalous magnetic moment of muon
- LSND anomaly
- MiniBooNE anomaly
- Heidelberg neutrinoless double $\boldsymbol{\beta}$ decays
- DAMA annual modulations
- Egret gamma-ray excess
- Pamela positron excess