ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Sterile Neutrinos in Cosmology

Mikhail Shaposhnikov

3rd CHIPP Swiss neutrino workshop

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Sterile Neutrinos in Cosmology
and how to find them in the Lab

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WARNING

Sterile neutrinos in this talk have nothing to do with:

- LSND
- MiniBooNE
- 3+1 Scheme
- 3+2 Scheme
- 3+3 Scheme
- ...

Aim of the talk:

to argue that the existing high intensity protons beams

NuMi beam at FNAL, CNGS beam at CERN

and future accelerator facilities

J-PARC in Japan, Project X at FNAL

can be used to search for physics beyond the Standard Model in

new dedicated experiments

Possible outcome of these new experiments

- Discover new neutrino states – massive neutral leptons

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Possible outcome of these new experiments

- Discover new neutrino states – massive neutral leptons
- Uncover the origin of neutrino masses
- Fix the pattern of neutrino mass hierarchy
- and eventually
- Discover CP-violation in neutrino sector
- Reveal the origin of baryon asymmetry of the universe and fix its sign

Guaranteed outcome of these new experiments

- Improving constraints of the couplings of new particles by several orders of magnitude

Outline

- Theoretical motivation
  - Neutrino masses
  - Dark matter
  - Baryon asymmetry of the Universe
- How to search for new leptons
- What to expect at LHC
- Conclusions

Theoretical motivation: 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:

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

$m_{atm} \simeq 0.05$ 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

Highlights

An extension of the Standard Model by three singlet fermions (the νMSM, neutrino minimal SM) 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)
- Masses of new leptons are small: they can be found experimentally.

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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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

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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,

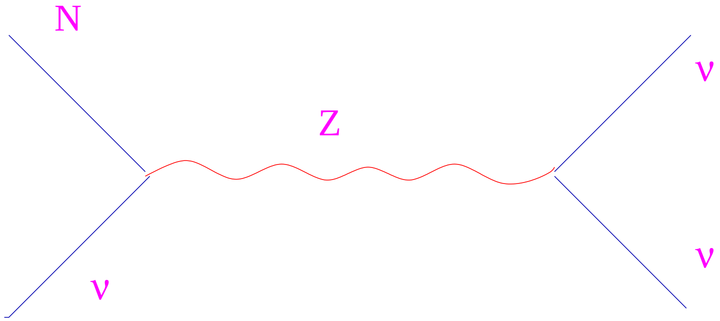
in total $(3 \times 2 + 3 \times 2 + 2 + 1 + 1) \times 3 \times 2 = 96$ fermionic and

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

Theoretical motivation: dark matter

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

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:

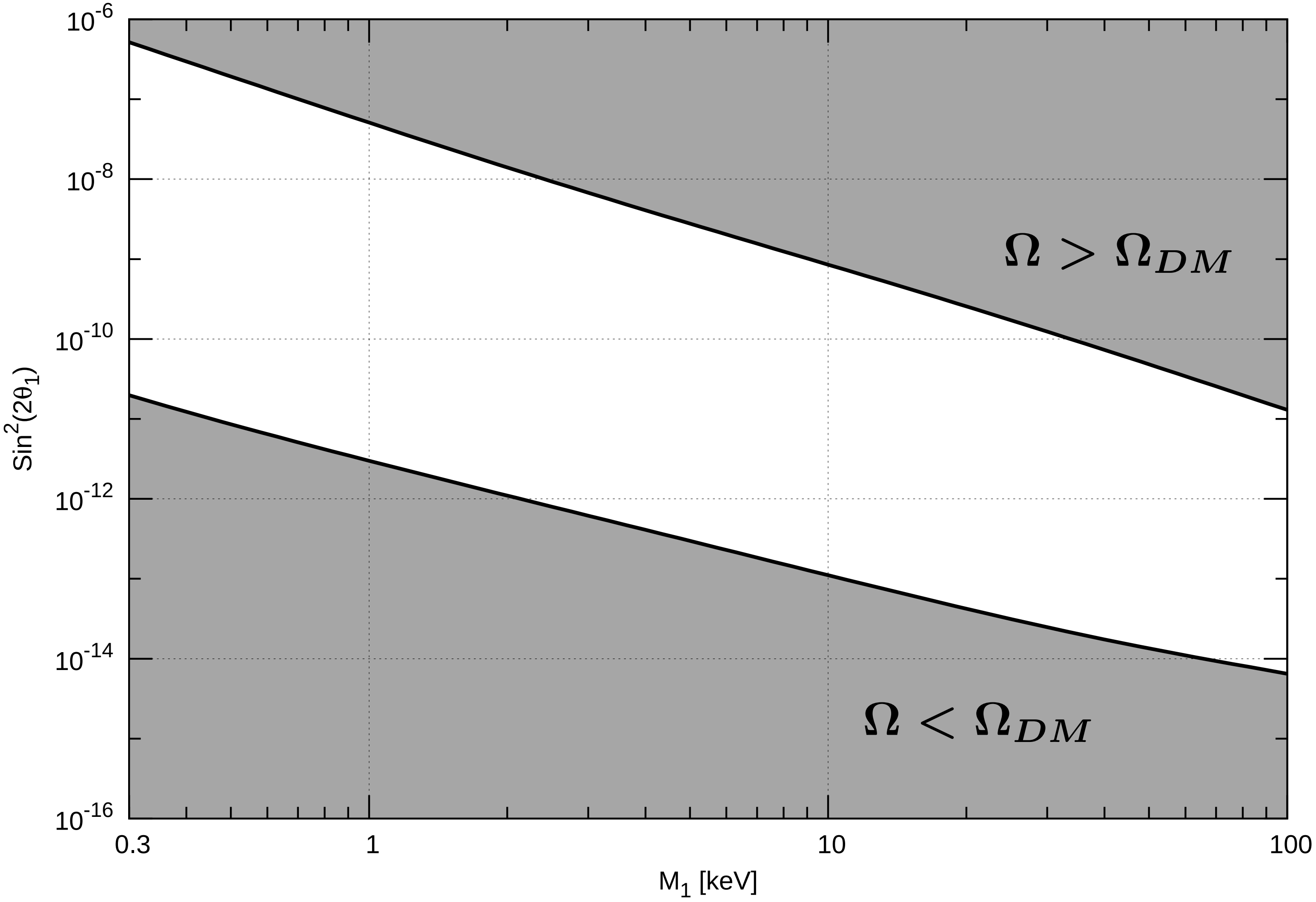
$$\tau_{N_1} = 10^{14}\,\text{years}\left(\frac{10\,\text{keV}}{M_N}\right)^5\left(\frac{10^{-8}}{\theta_1^2}\right)$$

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

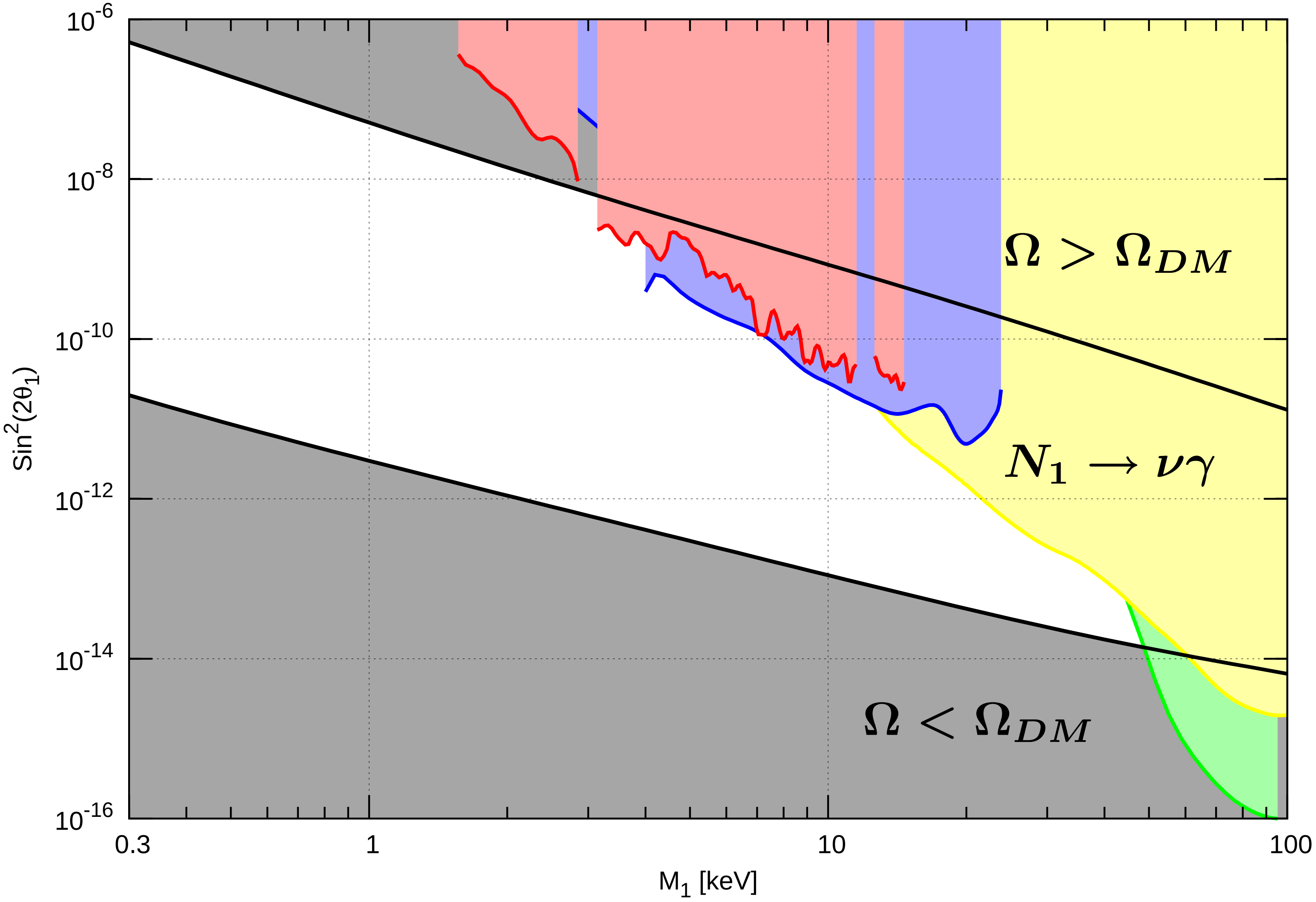
Constraints on DM sterile neutrino

- Production. N_1 are created in the early Universe in reactions $l\bar{l} \to \nu N_1, \quad q\bar{q} \to \nu N_1$ etc. We should get correct DM abundance.
- X-rays. N_1 decays radiatively, $N_1 \to \gamma\nu$, 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.

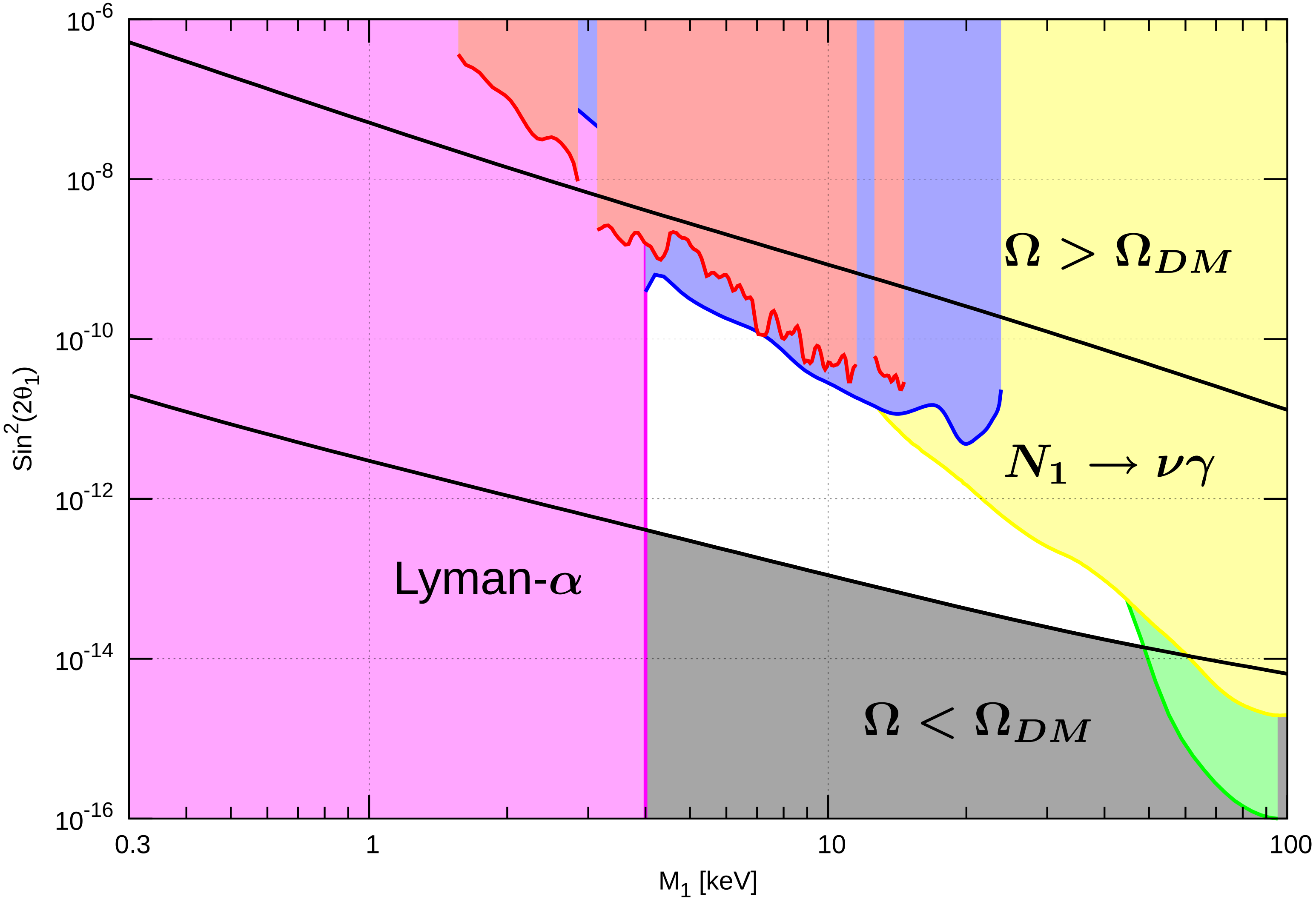
DM: production



DM: production + X-ray constraints



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



Theoretical motivation: baryon asymmetry

Asaka, M.S; Akhmedov, Rubakov, Smirnov

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

Value of baryon asymmetry

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

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

$\delta_{\mathrm{CP}} \sim 1$ 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.

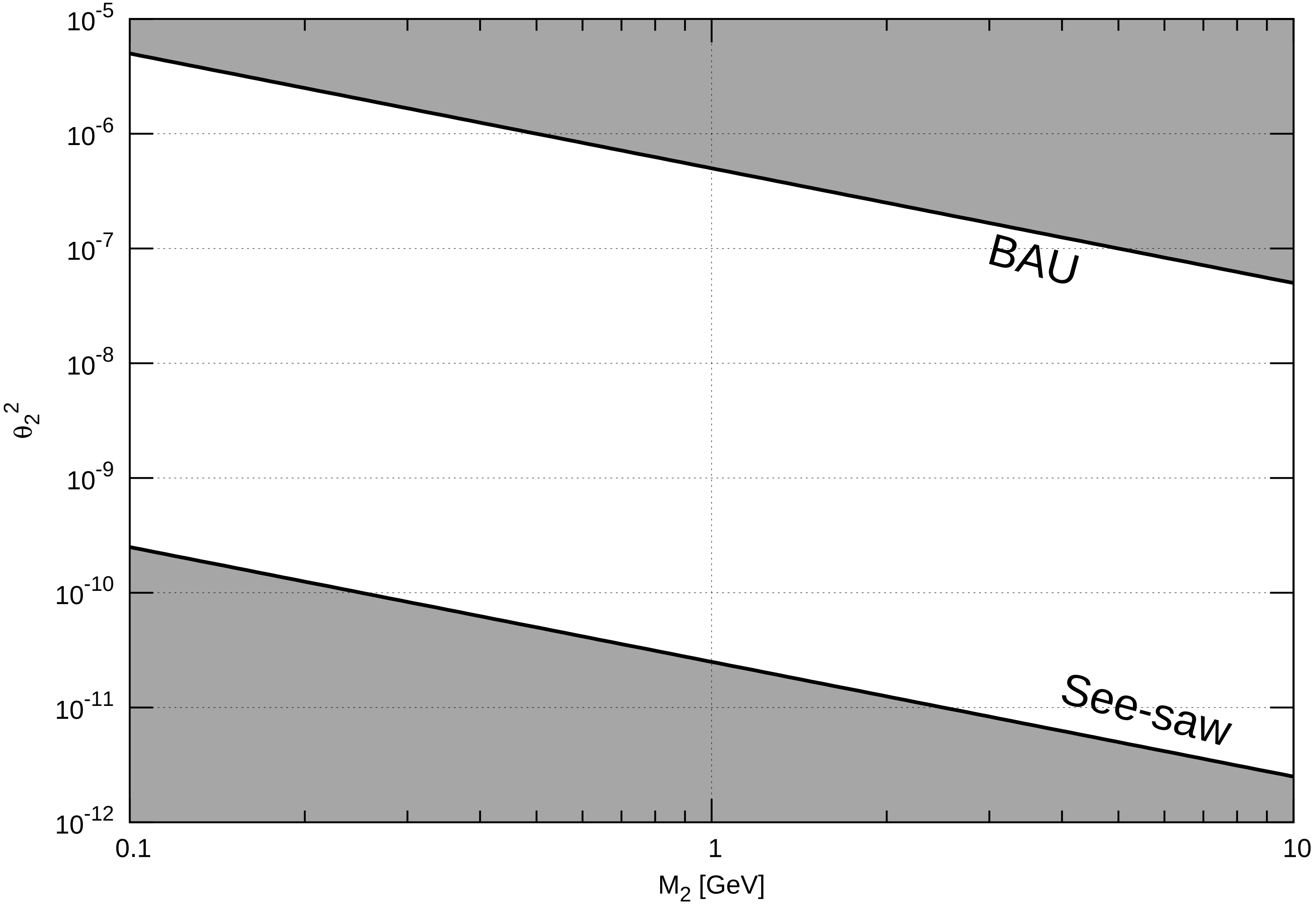
Works best if

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

Constraints on BAU sterile neutrinos

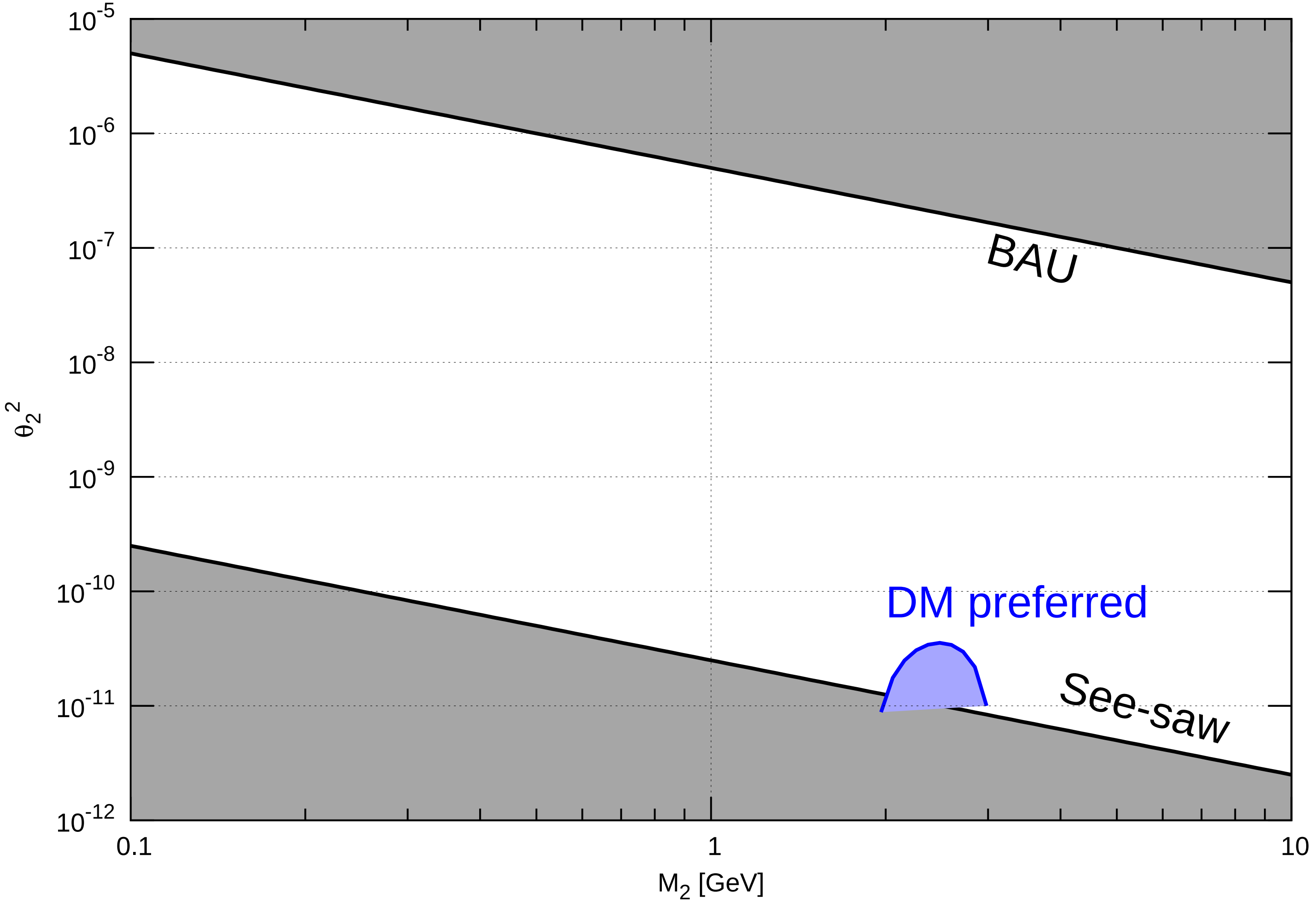
- BAU generation requires out of equilibrium: mixing angle of $N_{2,3}$ to active neutrinos cannot be too large
- Neutrino masses. Mixing angle of $N_{2,3}$ to active neutrinos cannot be too small
- Dark matter and BAU. Concentration of DM sterile neutrinos must be much larger than concentration of baryons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

$N_{2,3}$: BAU

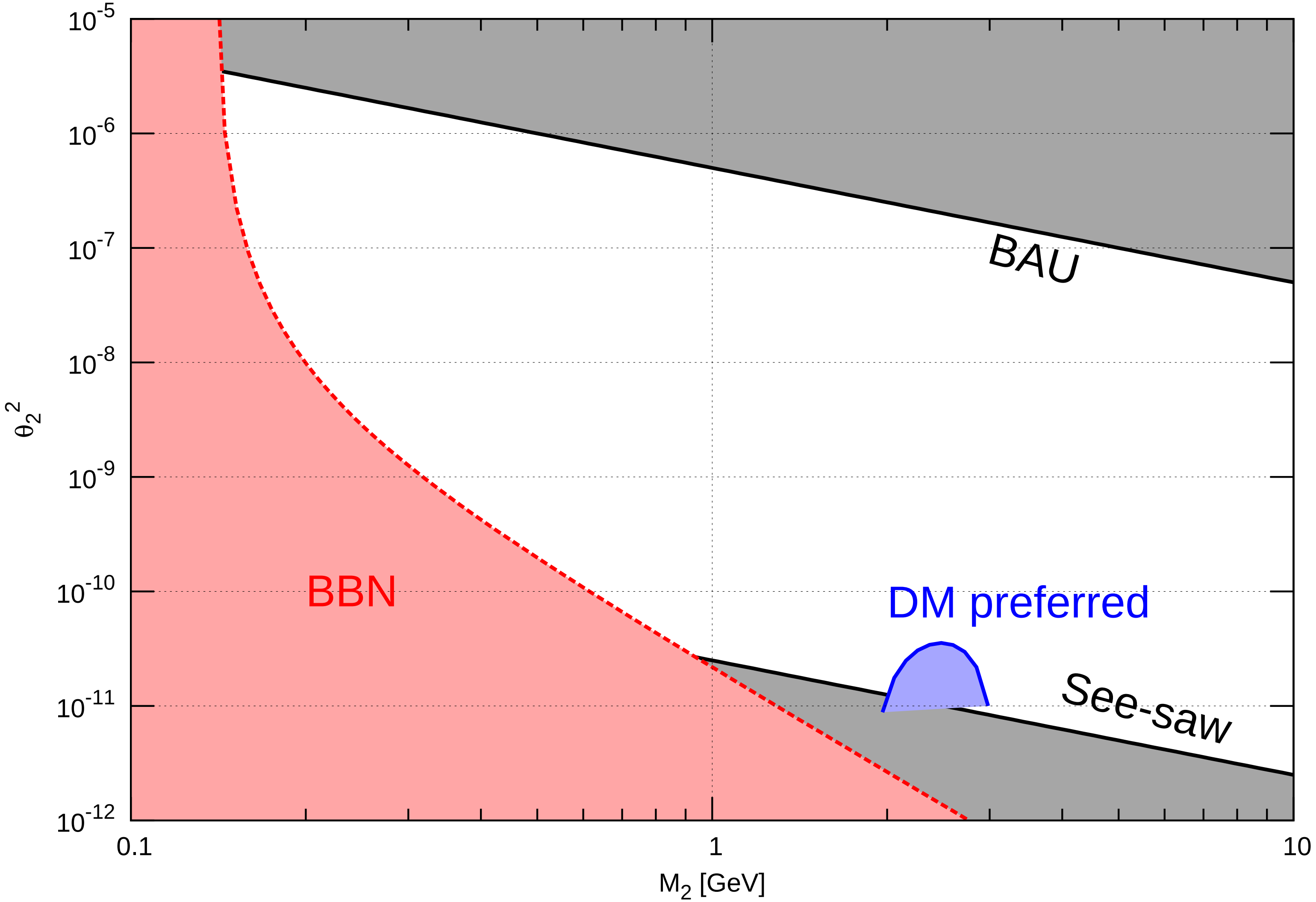


10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
θ_2^2
BAU
See-saw
0.1
1
10
M_2 [GeV]

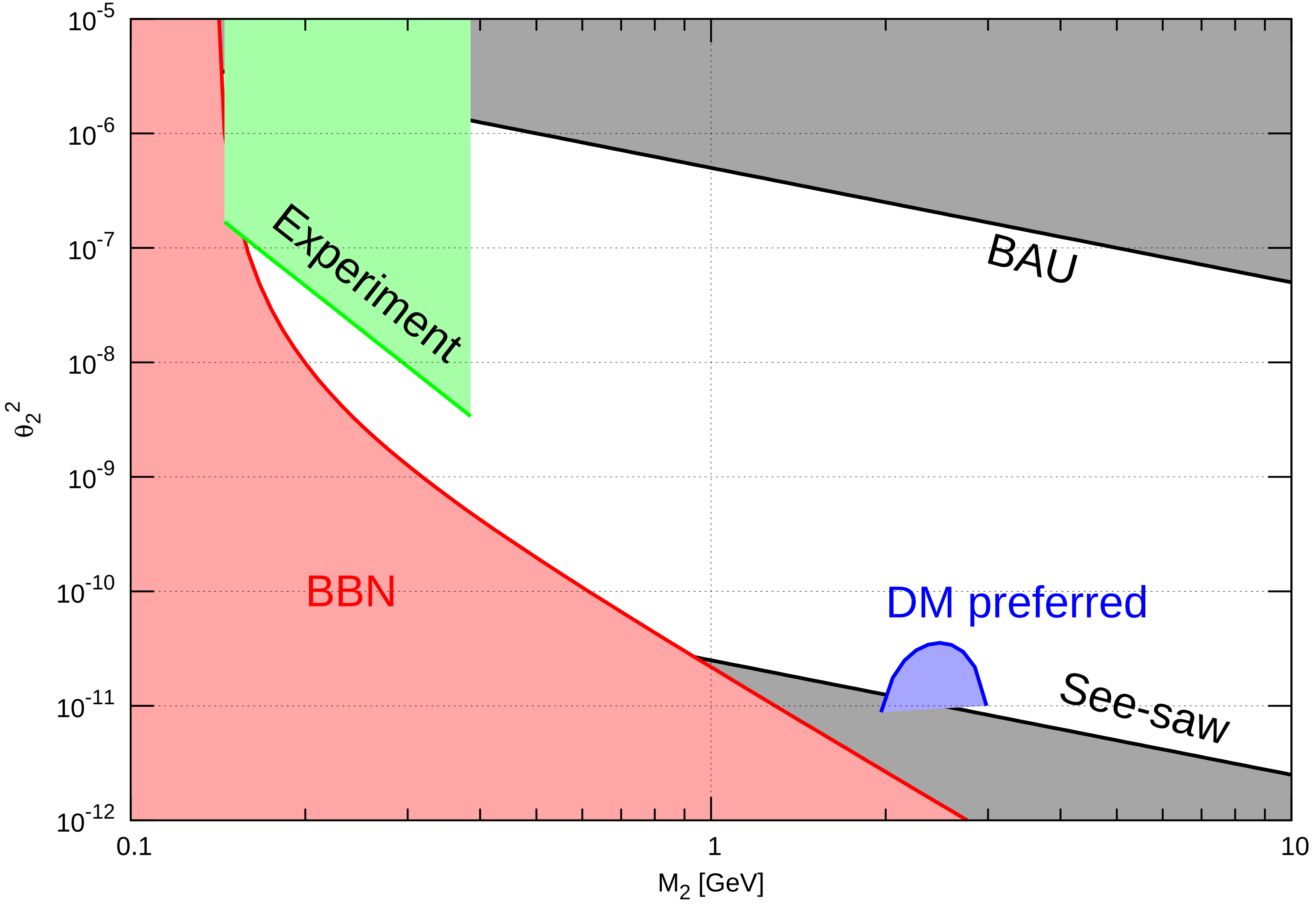
$N_{2,3}$: BAU + DM


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

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



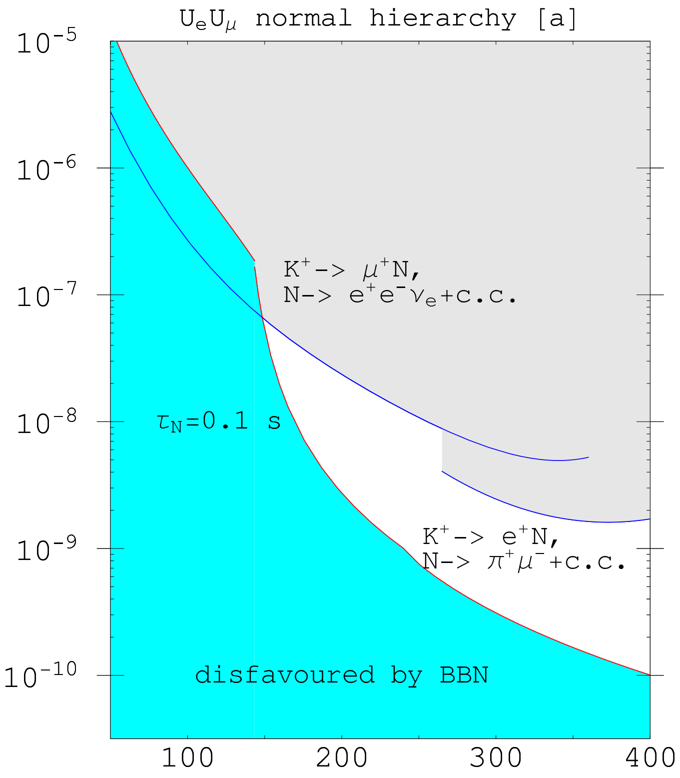
$N_{2,3}$: BAU + DM + BBN + Experiment

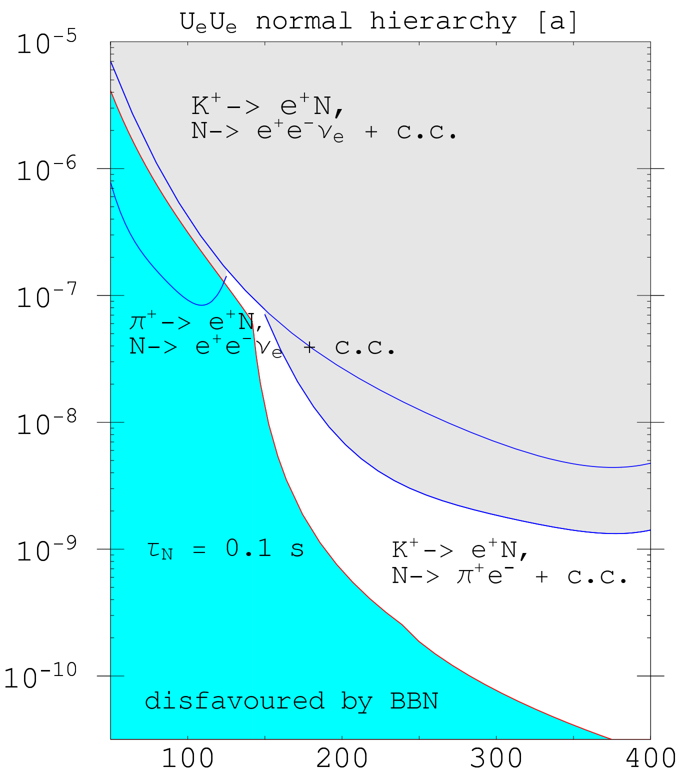


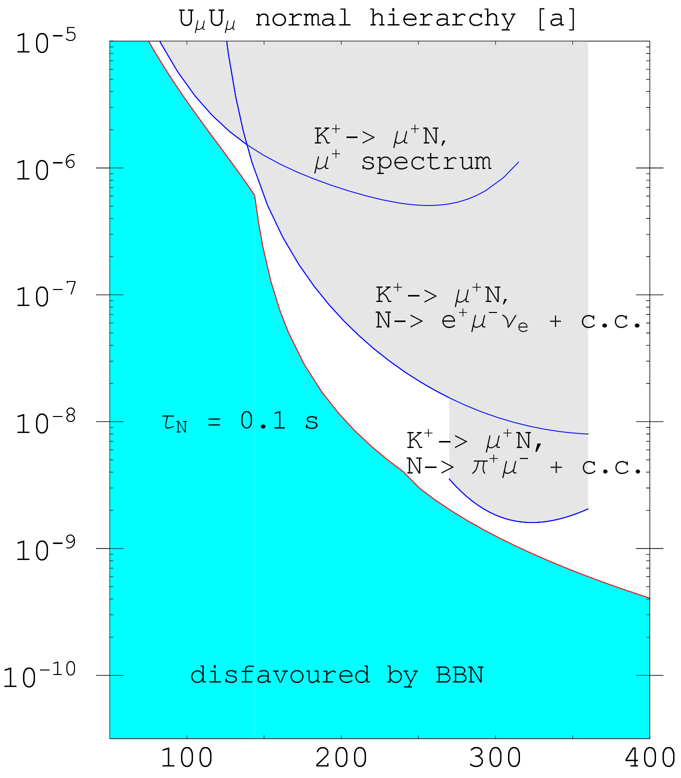
Previous searches

- T. Yamazaki *et al.*, “Search for heavy neutrinos in kaon decay”, 1984
- M. Daum *et al.* “The KARMEN time anomaly: Search for a neutral particle of mass 33.9-MeV in pion decay”, 2000
- A. Vaitaitis *et al.* [NuTeV Collaboration], “Search for neutral heavy leptons in a high-energy neutrino beam”, 1999
- P. Astier *et al.* [NOMAD Collaboration], “Search for heavy neutrinos mixing with tau neutrinos”, 2001
- P. Achard *et al.* [L3 Collaboration], “Search for heavy neutral and charged leptons in e+ e- annihilation at LEP”, 2001
- G. Bernardi *et al.*, “Search For Neutrino Decay”, 1986;
  “Further Limits On Heavy Neutrino Couplings”, 1988

CERN PS191 experiment, F. Vannucci (1988)







Conclusion: $M_{2,3} > 140$ MeV

Summary of predictions from cosmology

Robust:

- Absolute values of the active neutrino masses (Asaka, Blanchet, M.S.): $m_1 \leq \mathcal{O}(10^{-5})$ 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, $140\ \mathrm{MeV} < M_{2,3} \lesssim M_W$,

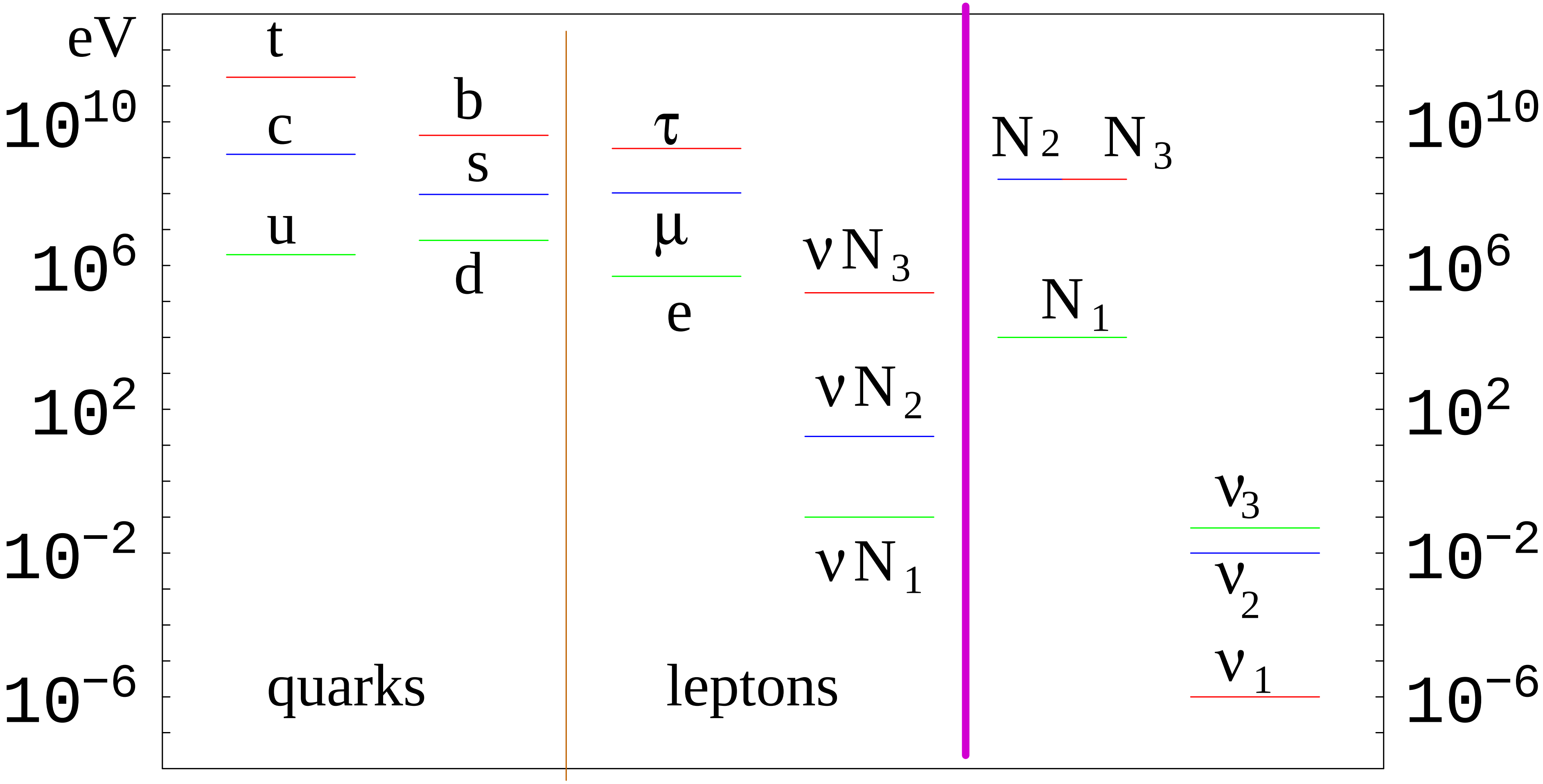
  $\delta M < 800 m_{atm} \left(\frac{M}{\mathrm{GeV}}\right)^2$

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%

The spectrum of the νMSM



Dirac masses

Majorana masses

How to search for new leptons: laboratory

- Missing energy signal in $K,\ D$ and B decays (θ^2 effect)

  Example:

$$K^+ \rightarrow \mu^+ N, \quad M_N^2 = (p_K - p_\mu)^2 \neq 0$$

Similar for charm and beauty.

  - $M_N < M_K$: KLOE, NA48, E787
  - $M_K < M_N < 1$ GeV: charm and τ factories
  - $M_N < M_B$: B-factories (planned luminosity is not enough)

How to search for new leptons: laboratory

- Decay processes $N \to \mu^+\mu^-\nu$, etc ("nothing"$\to \mu^+\mu^-$) (θ^4 effect)

  First step: proton beam dump, creation of N in decays of $K,\ D$ or B mesons

  Second step: search for decays of N in a near detector, to collect all Ns.

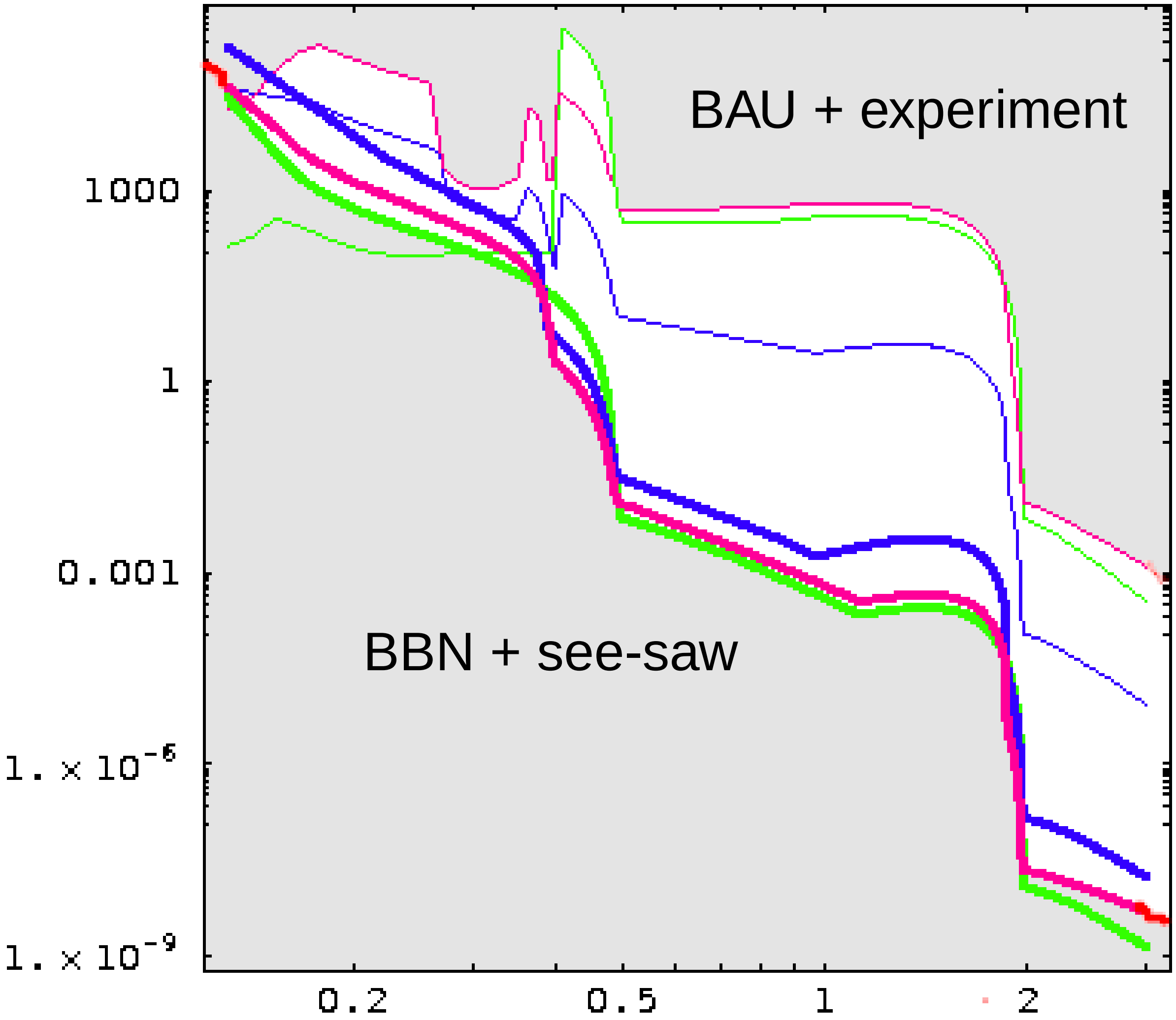
  - $M_N < M_K$: Any intense source of K-mesons (e.g. from proton targets of MiniBooNE, NuMi, CNGS, T2K)
  - $M_N < M_D$: NuMi or CNGS or T2K beam + near detector
  - $M_N < M_B$: Project X (?) + near detector
  - $M_N > M_B$: extremely difficult

MINERνA, NuSOnG, HiResMν

Number of N-decays in near detector, CNGS

5 m long detector

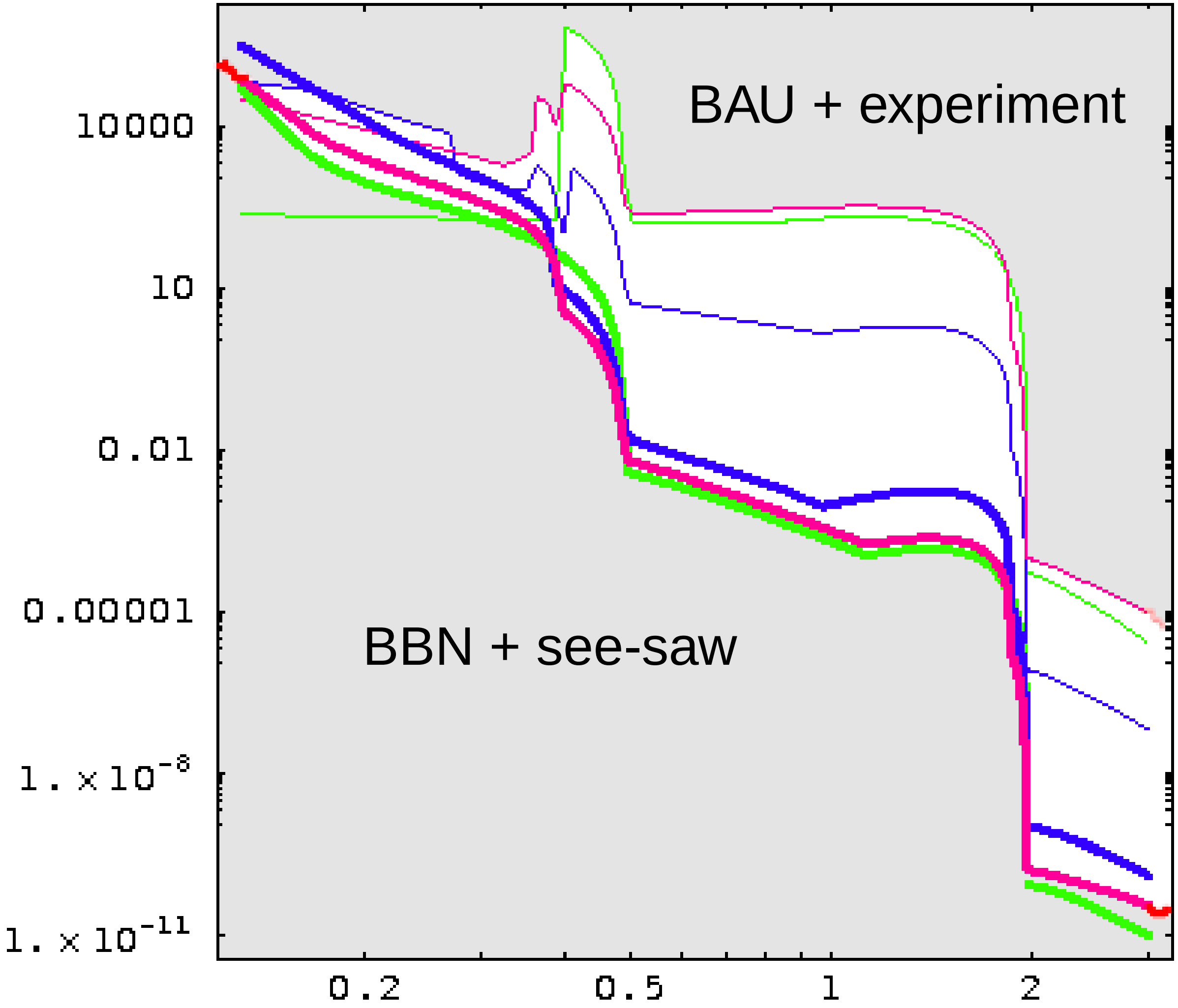
1 year of observations



Number of N-decays in near detector, NuMi

5 m long detector

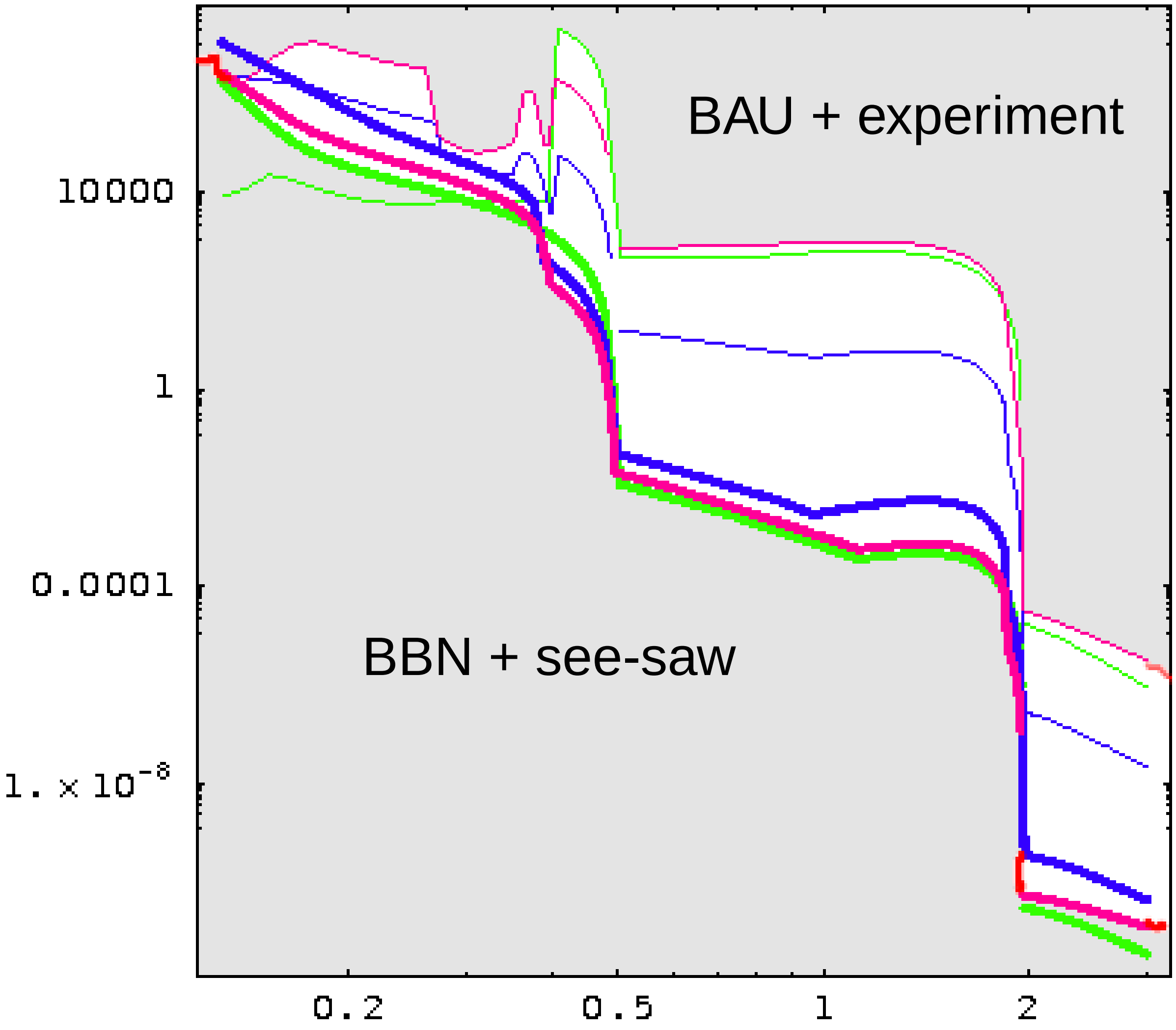
1 year of observations



Number of N-decays in near detector, JPARC

5 m long detector

1 year of observations



What to expect at LHC?

Couplings of $\boldsymbol{N_{2,3}}$ are too small to see them at LHC, however:

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Important condition for the $\boldsymbol{\nu}$MSM to solve the SM problems:
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What to expect at LHC?

Couplings of $N_{2,3}$ are too small to see them at LHC, however:

Important condition for the νMSM to solve the SM problems:
its validity up to the Planck scale.

Prediction for LHC: nothing but the Higgs in the mass interval

$$M_H \in [129, 189] \;\; \mathrm{GeV}$$

Consistency of the νMSM and SM as effective theory

Maiani, Parisi, Petronzio;
Krasnikov;Politzer, Wolfram

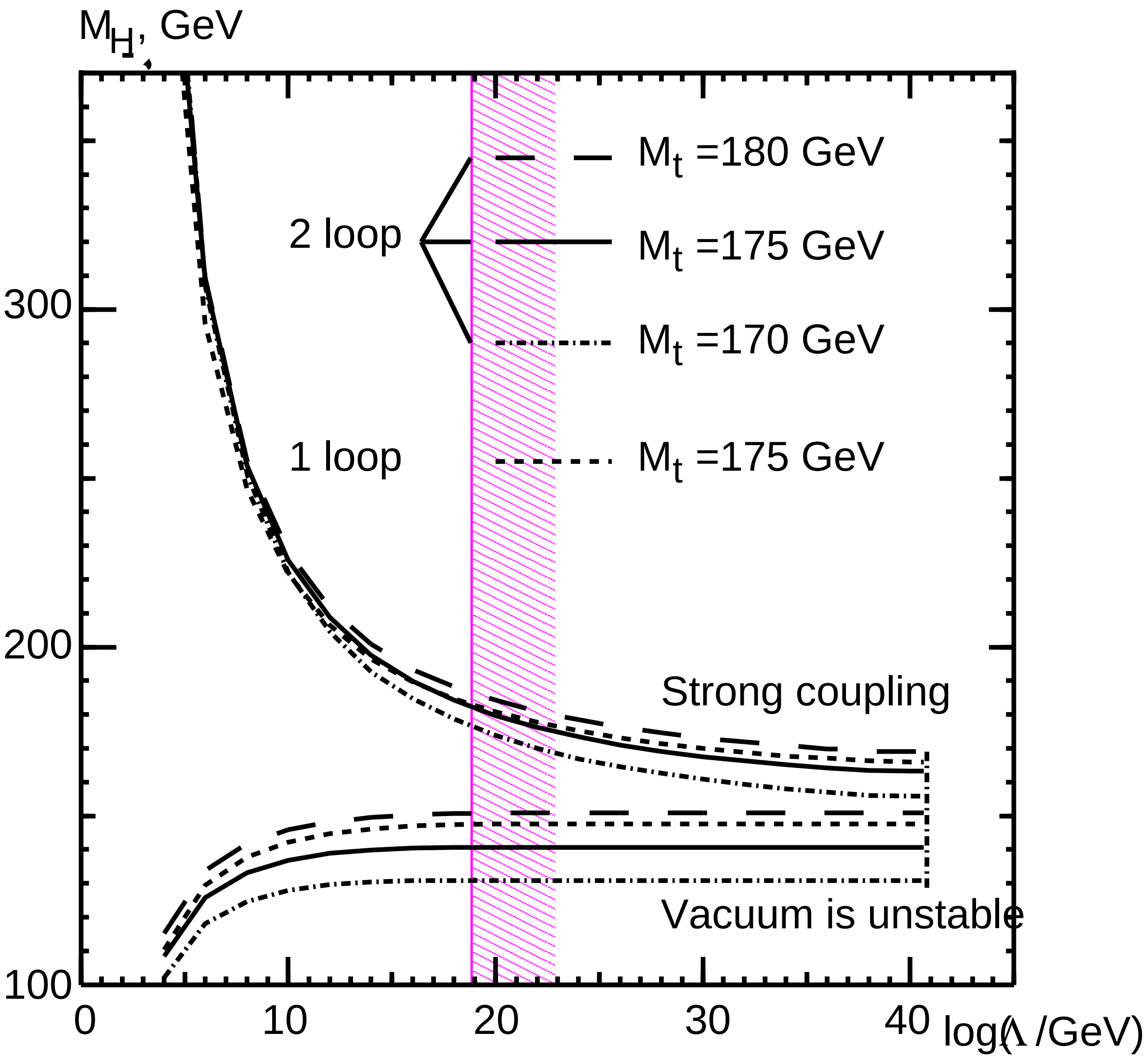

Figure: from Pirogov
and Zenin, arXiv:hep-ph/9808396

Conclusions

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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
- It can be searched for with the use of existing intensive proton beams at CERN, FNAL and planned neutrino facilities in Japan, for neutral fermion masses up to $\mathbf{2}$ GeV
- The search of singlet fermions in the mass interval $\mathbf{2-5}$ GeV would require a considerable increase of the intensity of proton accelerators or the detailed analysis of kinematics of more than $\mathbf{10^{11}}$ B-meson decays.

  Intensity versus high energy for new physics!

Conclusions

- Dark matter search: high resolution and wide field of view X-ray spectrometer in Space looking at narrow photon line in direction of dwarf galaxies

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Collaborators:

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