ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Neutral Leptons in Cosmology

Mikhail Shaposhnikov

BEYOND 2010, Cape Town

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Neutral Leptons in Cosmology

or New Physics Without New Energy Scale

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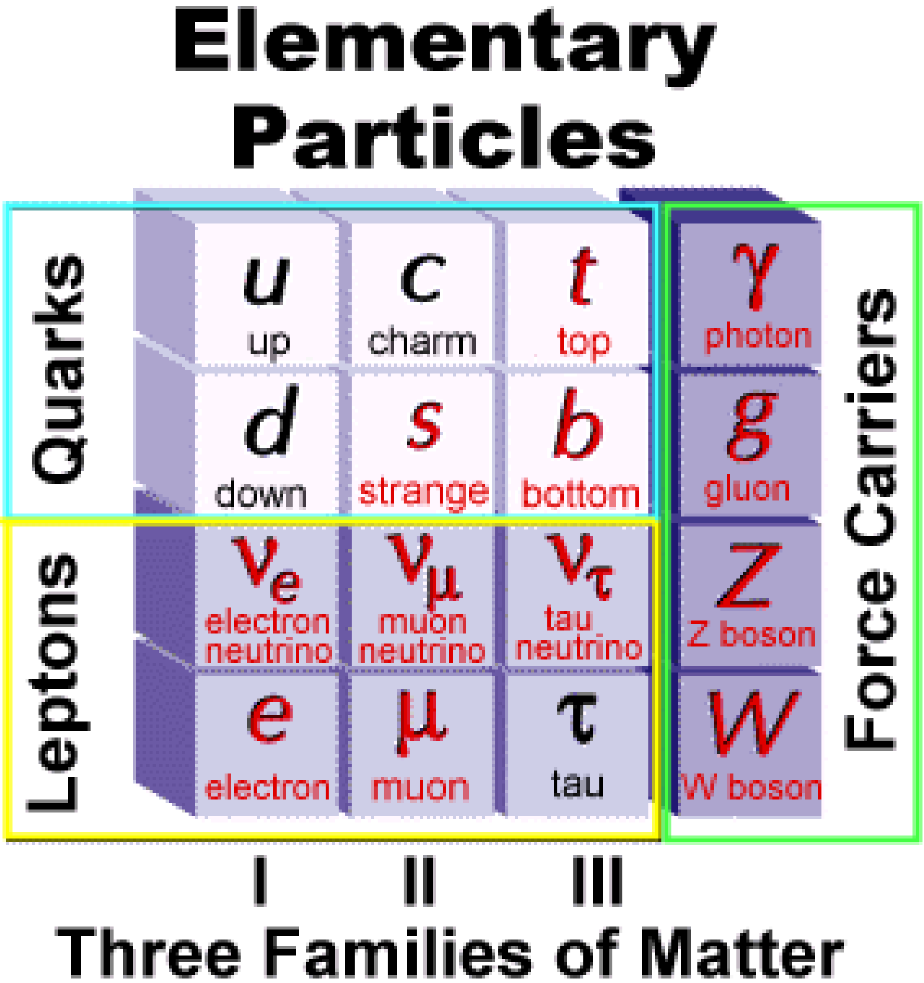
Outline

- Motivation
- Neutrino masses
- Dark Matter
- Baryon Asymmetry
- Rare decays
- Conclusions

Standard Model of particle interactions is in great shape: it agrees with all accelerator experiments



The only missing particle - the Higgs boson. It will be searched at the LHC

Still, the Standard Model cannot accommodate a number of cosmological observations and discoveries in neutrino physics, it also has a number of “fine tuning” problems from theory side.

Our strategy

- Select the most important problems to solve (may be subjective).
- Use Ockham’s razor principle: *“Frustra fit per plura quod potest fieri per pauciora”* or ”entities must not be multiplied beyond necessity”. For particle physics: entities = new hypothetical particles and new scales different from Fermi and Planck scales.

SM problems and possible solutions

Hierarchy problem: stability of the Higgs mass against radiative corrections

Possible solutions:

- Compensation of divergent diagrams by new particles at TeV scale (supersymmetry, composite Higgs boson). Consequence: new physics at LHC

SM problems and possible solutions

- New symmetry – exact, but spontaneously broken scale invariance. Higgs mass is kept small in the same way as photon mass is kept zero by gauge invariance. Consequences: validity of the SM all the way up to the Planck scale, nothing but the Higgs at LHC in the mass interval

$$m_{\min} < m_H < m_{\max}$$

$$m_{\min} = [126.3 + \frac{m_t - 171.2}{2.1} \times 4.1 - \frac{\alpha_s - 0.1176}{0.002} \times 1.5]\ \mathrm{GeV}$$

$$m_{\max} = [173.5 + \frac{m_t - 171.2}{2.1} \times 1.1 - \frac{\alpha_s - 0.1176}{0.002} \times 0.3]\ \mathrm{GeV}$$

theory error in $m_{\min} \simeq \pm 2$ GeV. Existence of massless particle – dilaton, which can play the role of Dark Energy

SM problems and possible solutions

The universe is flat, homogeneous and isotropic with high accuracy. It contained in the past small density fluctuations that lead to structure formation

Possible solution: inflation.

The inflaton (scalar particle inflating the universe) is

- new particle with the mass of the order of $\mathbf{10^{13}}$ GeV and minimal coupling to gravity

Alternative

- SM Higgs boson with non-minimal coupling to gravity

SM problems and possible solutions

Neutrino masses and oscillations

Possible solutions:

- See-saw mechanism: existence of several superheavy ($M \sim 10^{10}$ GeV) neutral leptons. Direct experimental consequences: none, as the mass is too large to be accessed

Alternative

- Existence of new leptonic flavours with masses similar to those of known quarks and leptons. Experimental consequence: possibility of direct experimental search

SM problems and possible solutions

Dark matter

Possible solutions:

- WIMPS with masses of the order of 100 GeV and roughly electroweak cross-sections (e.g. SUSY neutralino). Consequences: new particles at LHC, success of WIMP searches

Alternative

- Super-WIMPS with masses in keV region. Natural possibility: new neutral leptonic flavour with mass of few keV. Consequences: no DM candidates at LHC, failure of WIMP searches. Possibility of search through radiative processes $N \longrightarrow \nu\gamma$ which leads to existence of narrow X-ray line in direction of DM concentrations.

SM problems and possible solutions

Baryon asymmetry of the Universe

Possible solutions:

- Baryogenesis due to new physics above the electroweak scale. Potential consequences: new particles at LHC (for electroweak baryogenesis)

Alternative

- Baryogenesis due to new neutral leptonic flavours with masses in the region from 140 MeV up to few GeV. Experimental consequence: possibility of direct experimental search

Realisation: νMSM

SM fermions

quarks

left	u	d	c	s	t	b
right	u	d	c	s	t	b
left	ν_e	e	ν_μ	μ	ν_τ	τ
right		e		μ		τ

leptons

νMSM fermions

quarks

left	u	d	c	s	t	b
right	u	d	c	s	t	b
left	ν_e	e	ν_μ	μ	ν_τ	τ
right	N_e	e	N_μ	μ	N_τ	τ

leptons

Role of N_e with mass in keV region: dark matter

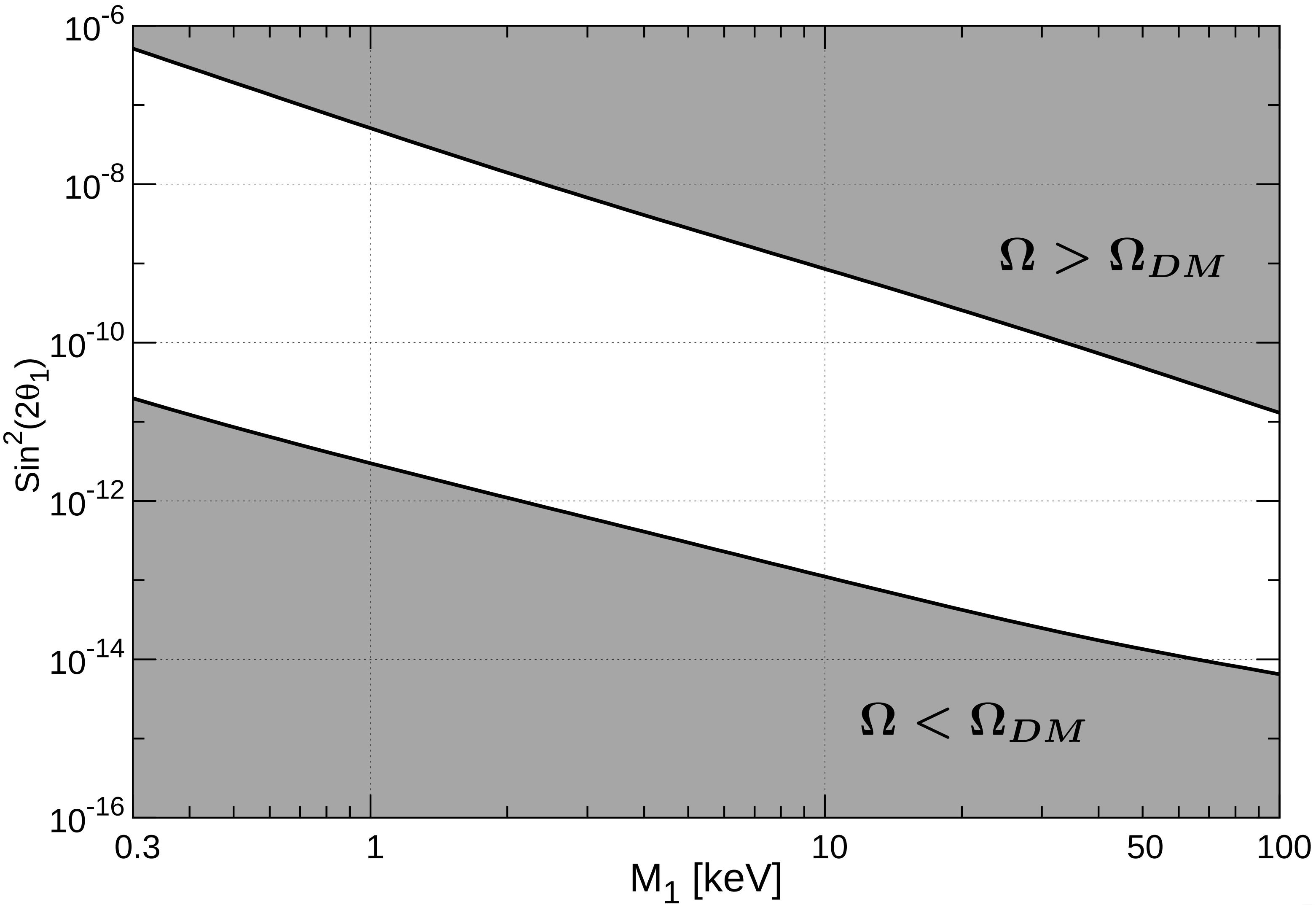
Role of $N_\mu,\ N_\tau$ with mass in 100 MeV – GeV region: “give” masses to neutrinos and produce baryon asymmetry of the Universe

Role of the Higgs: give masses to quarks, leptons, Z and W and inflate the Universe.

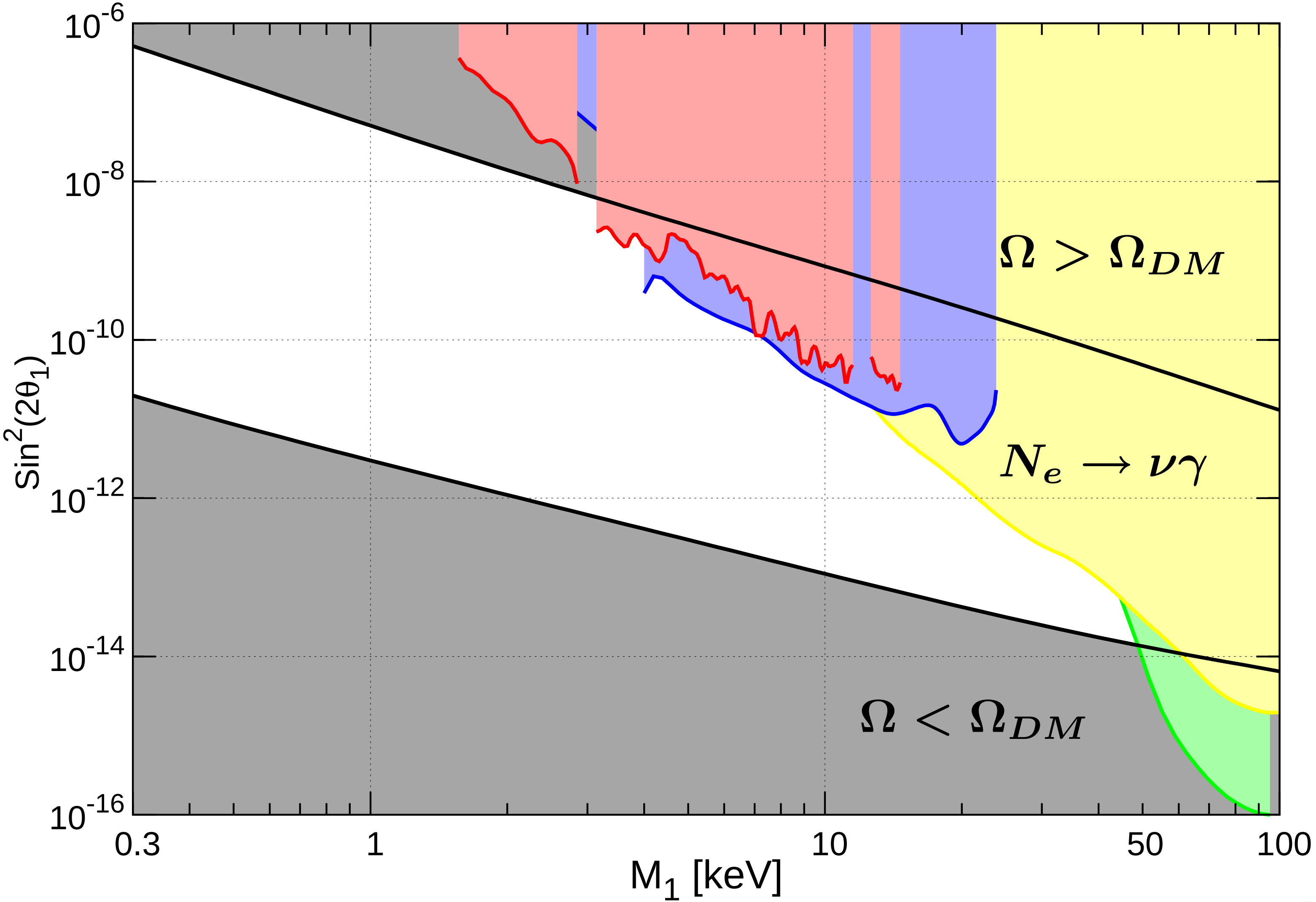
Constraints on DM sterile neutrino

- Production. N_e are created in the early Universe in reactions $l\bar{l} \to \nu N_e, \;\; q\bar{q} \to \nu N_e$ etc. We should get correct DM abundance.
- X-rays. N_e decays radiatively, $N_e \to \gamma\nu$, producing a narrow line which can be detected. This line has not been seen (yet).
- Structure formation. If N_e 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.

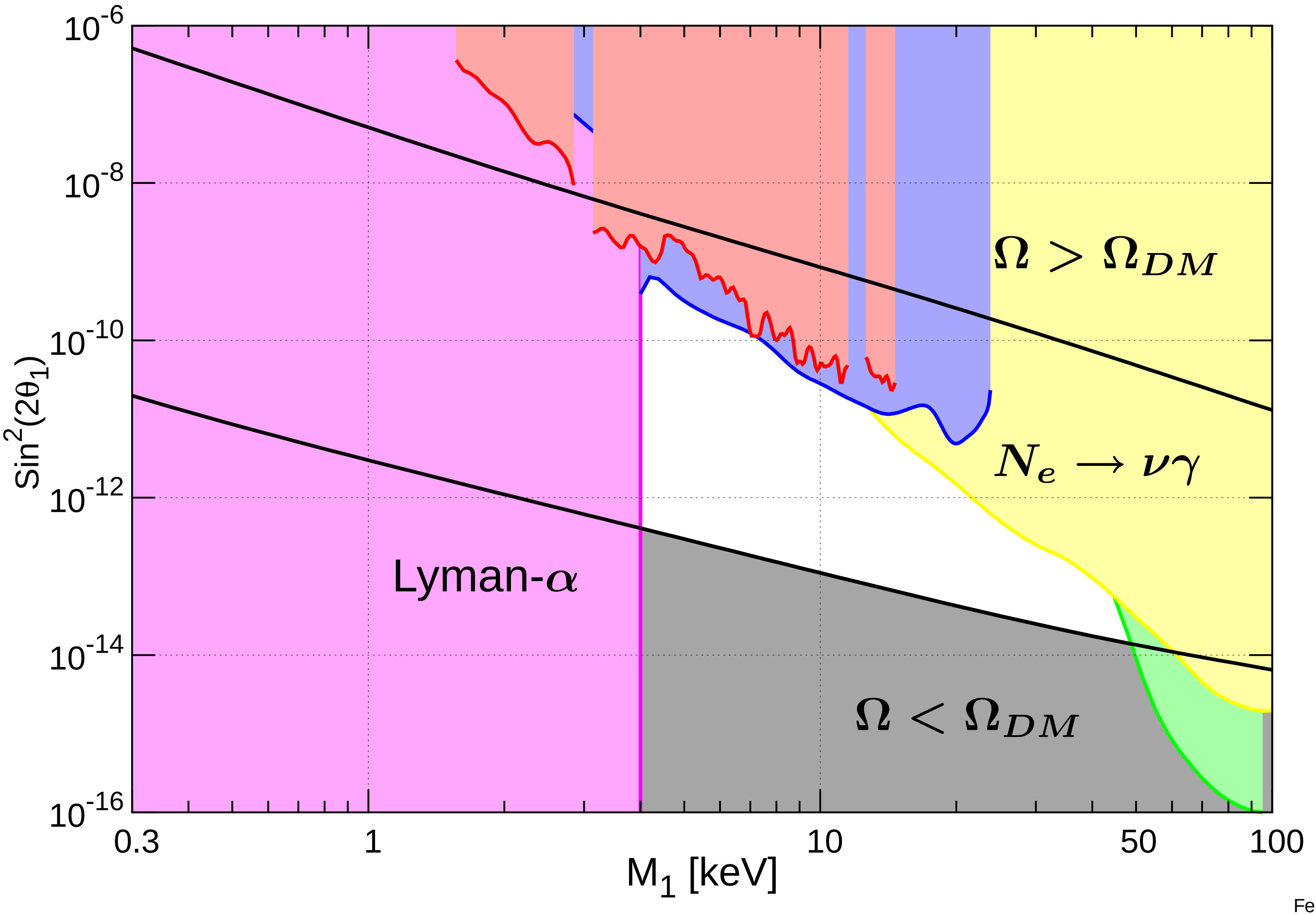
DM: production



DM: production + X-ray constraints



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



Direct experimental test: astrophysics

Over the last years restrictions on sterile neutrino parameters were improved by several orders of magnitude.

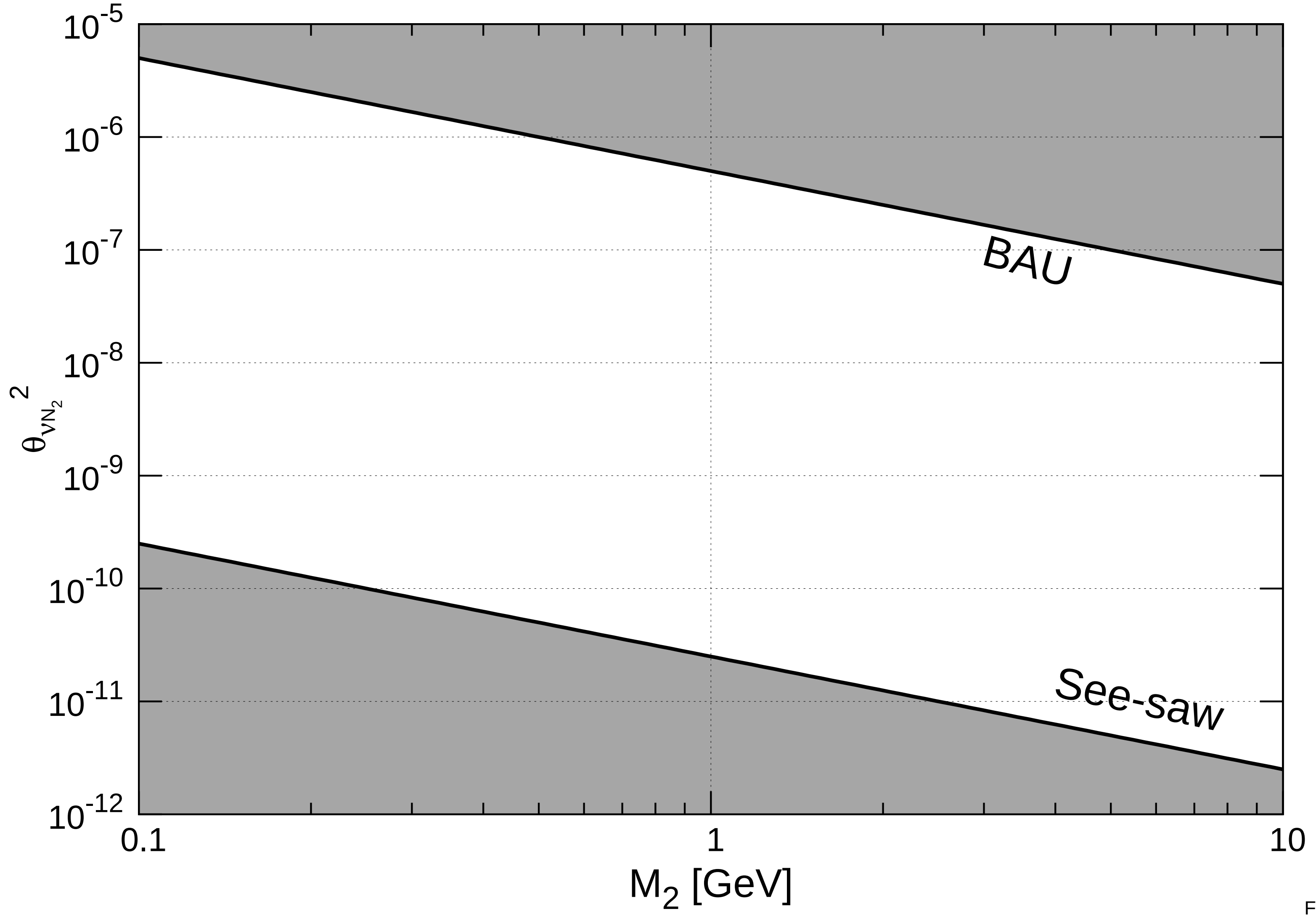
The new data from *Chandra* and *XMM-Newton* can hardly improve constraints by more than a factor $\mathbf{10}$. One needs:

- Improvement of spectral resolution up to the natural line width ($\boldsymbol{\Delta E/E \sim 10^{-3}}$).
- FoV $\mathbf{\sim 1^\circ}$ (size of a dSph).
- Wide energy scan, from $\boldsymbol{\mathcal{O}(100)}$ eV to $\boldsymbol{\mathcal{O}(10)}$ MeV.

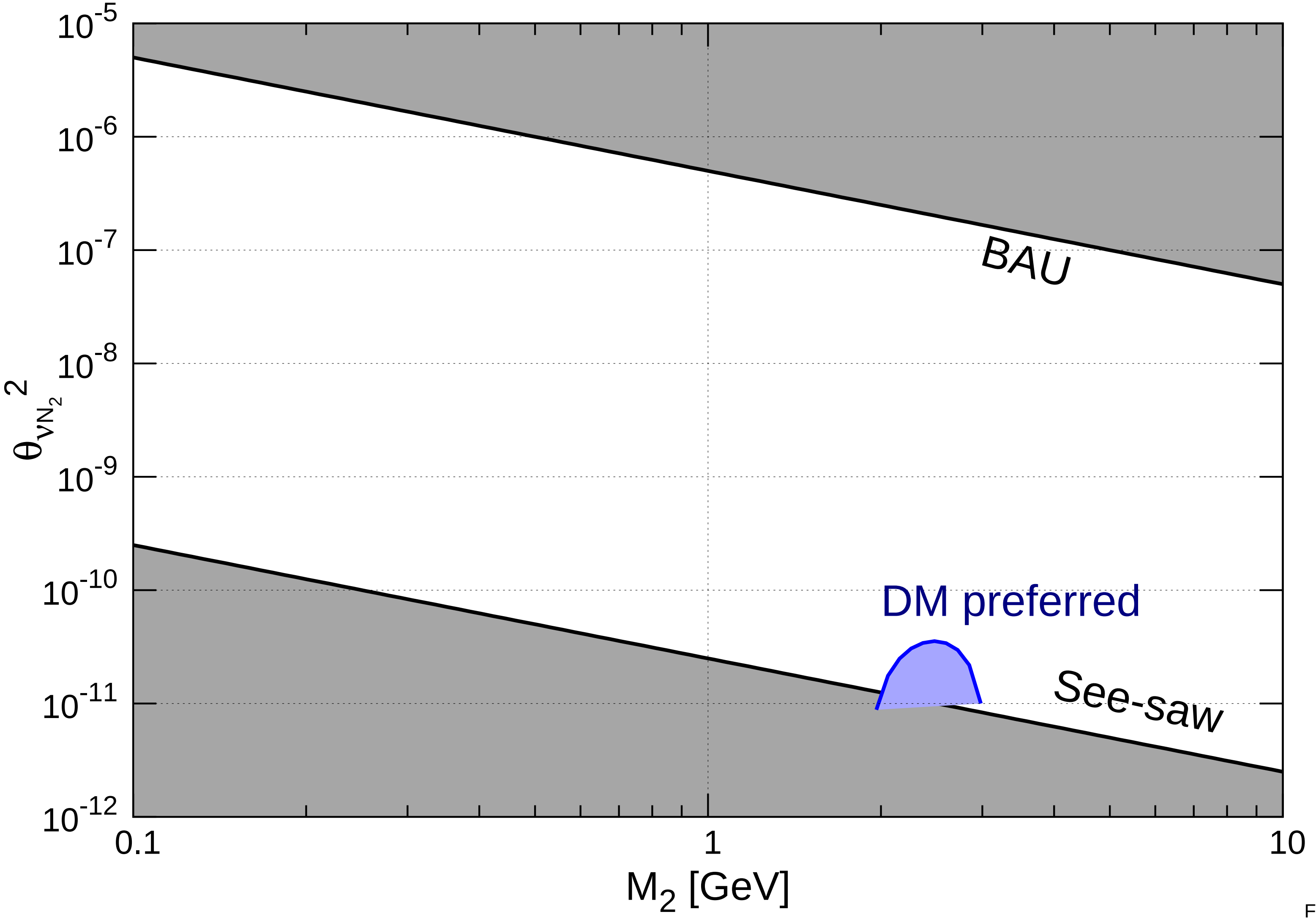
Constraints on BAU Majorana fermions

- BAU generation requires out of equilibrium: mixing angle of $N_{\mu,\tau}$ to active neutrinos cannot be too large
- Neutrino masses. Mixing angle of $N_{\mu,\tau}$ 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 $N_{\mu,\tau}$ must not spoil Big Bang Nucleosynthesis
- Experiment. $N_{\mu,\tau}$ have not been seen (yet).

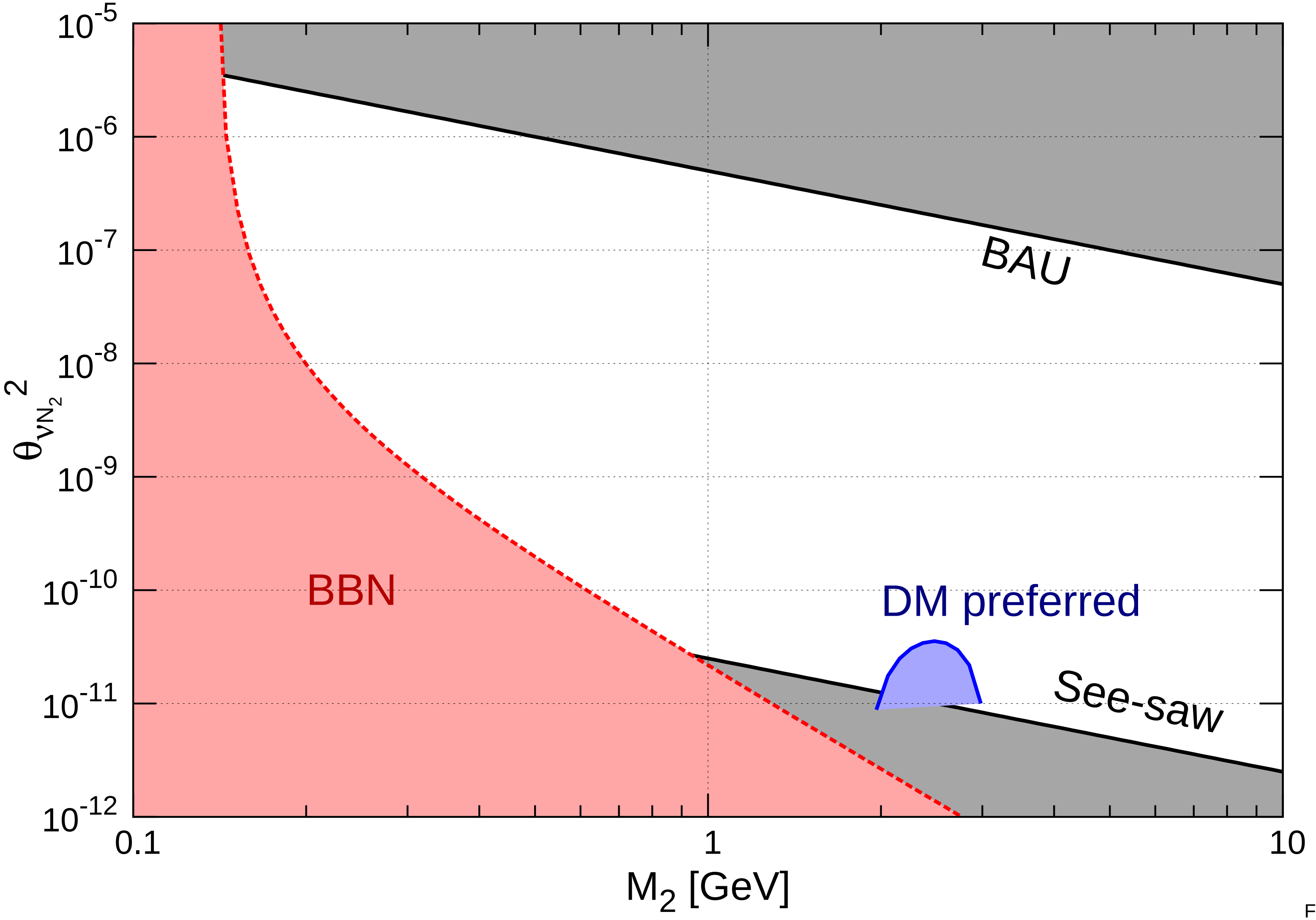
$N_{\mu,\tau}$: BAU


10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
$\theta_{\nu N_2}^2$
BAU
See-saw
0.1
1
10
M_2 [GeV]

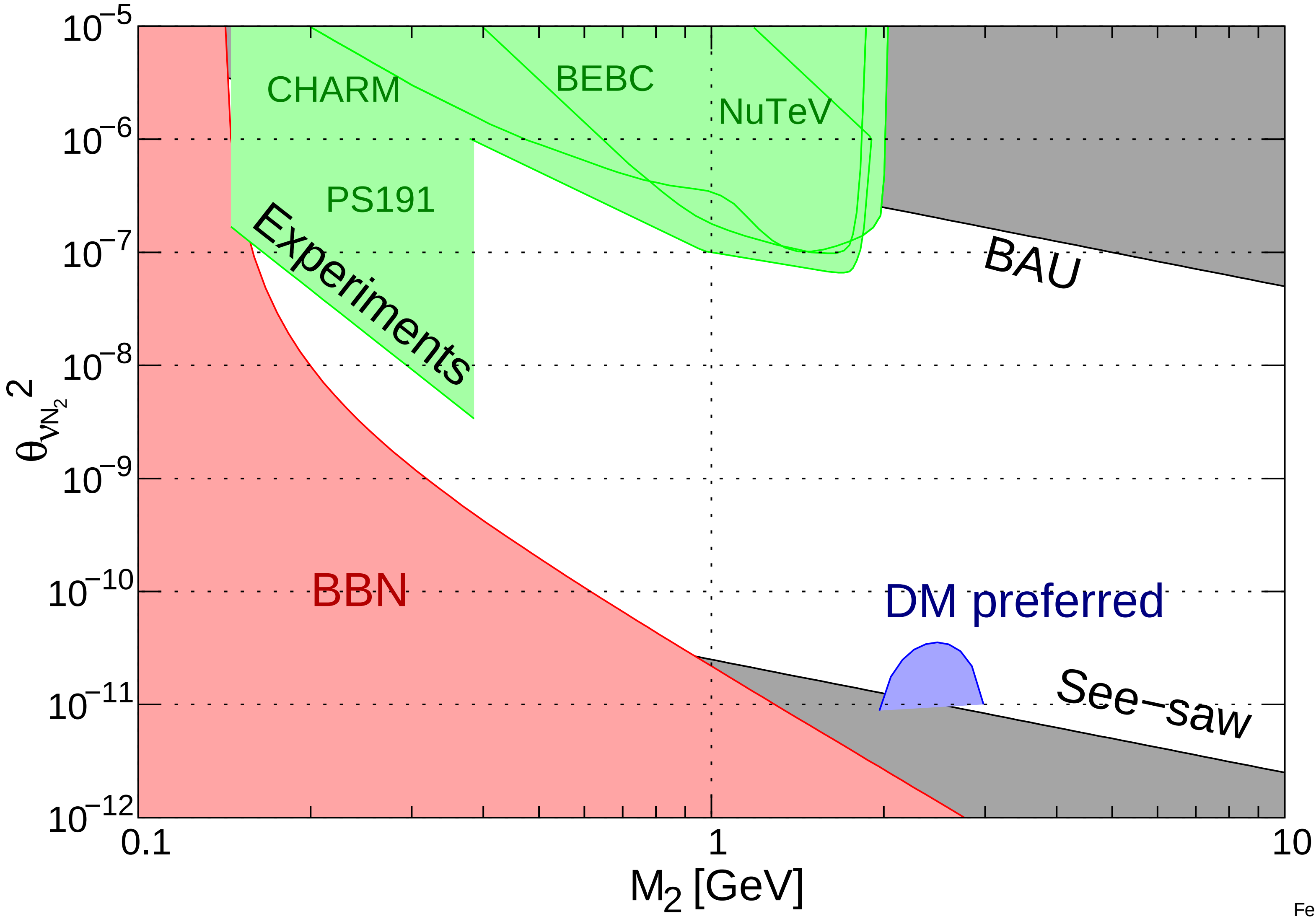
$N_{\mu,\tau}$: BAU + DM



$N_{\mu,\tau}$: BAU + DM + BBN



$N_{\mu,\tau}$: BAU + DM + BBN + Experiment

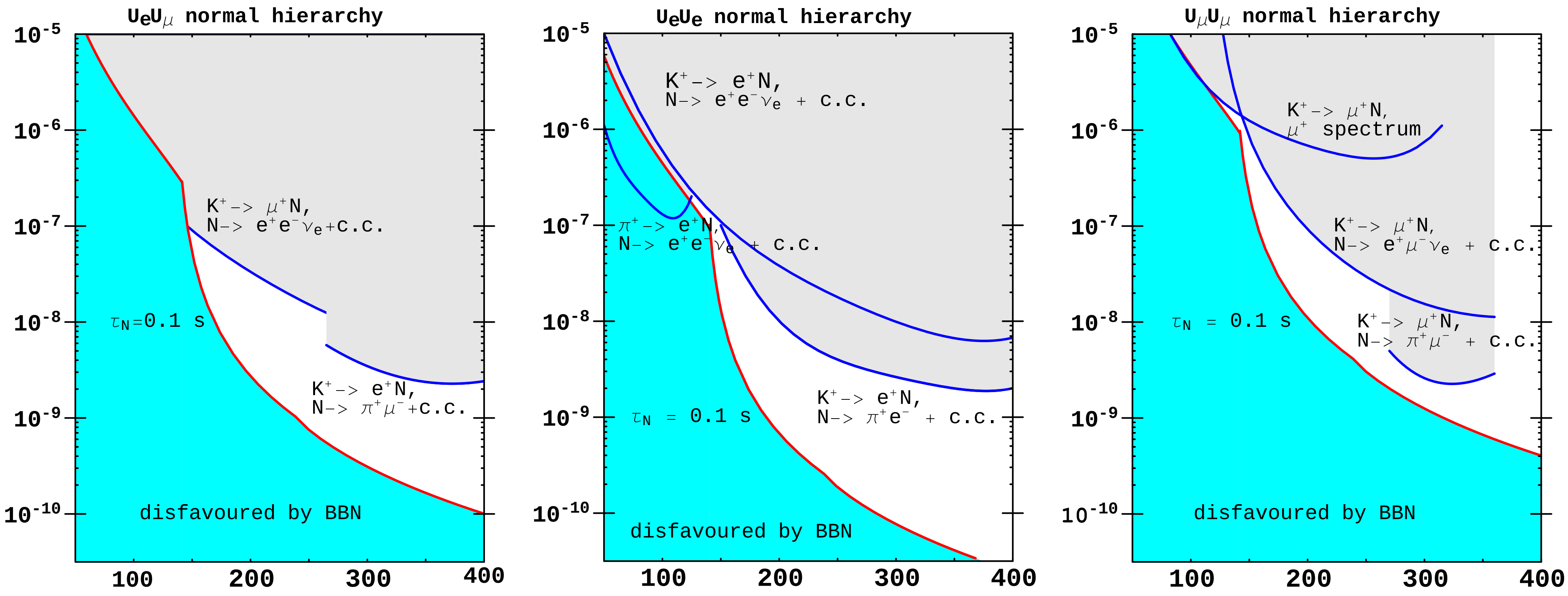


Direct experimental tests: rare decays

Previous searches at CERN

- A. M. Cooper-Sarkar *et al.* [WA66 Collaboration] “Search For Heavy Neutrino Decays In The Bebc Beam Dump Experiment”, 1985
- J. Dorenbosch *et al.* [CHARM Collaboration] “A search for decays of heavy neutrinos in the mass range 0.5-GeV to 2.8-GeV”, 1985
- G. Bernardi *et al.* [PS191 Collaboration], “Search For Neutrino Decay”, 1986;
  “Further Limits On Heavy Neutrino Couplings”, 1988
- 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

CERN PS191 experiment, 1988



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

Experimental signatures 1

Challenge - from baryon asymmetry: $\theta^2 \lesssim 5 \times 10^{-7} \left(\frac{\mathrm{GeV}}{M}\right)$

- Peak from 2-body decay and missing energy signal from 3-body decays of K, D and B mesons (sensitivity θ^2)

  Example:

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

  Similar for charm and beauty.

  - $M_N < M_K$: KLOE, NA62, E787
  - $M_K < M_N < M_D$: charm and τ factories, CLEO
  - $M_N < M_B$: B-factories (planned luminosity is not enough to get into cosmologically interesting region)

Experimental signatures 2

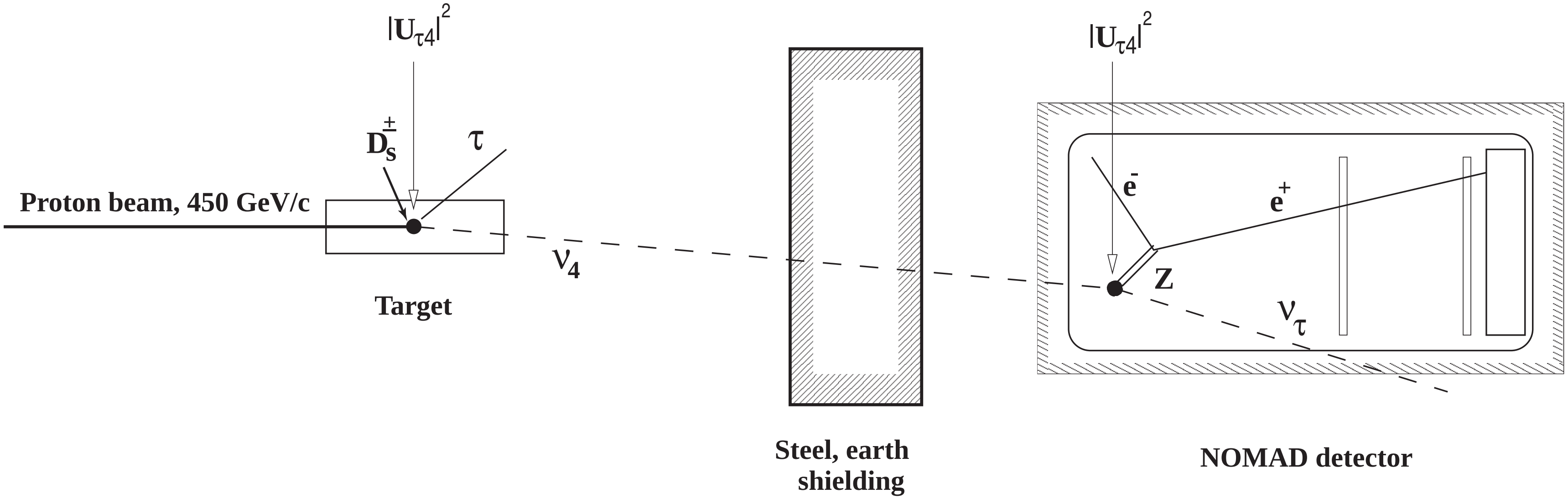
- Two charged tracks from a common vertex, decay processes $N \to \mu^+\mu^-\nu$, etc. (sensitivity $\theta^4 = \theta^2 \times \theta^2$)

  First step: proton beam dump, creation of N in decays of $K,\ D$ or B mesons: θ^2

  Second step: search for decays of N in a near detector, to collect all Ns: θ^2

  - $M_N < M_K$: Any intense source of K-mesons (e.g. from proton targets of PS or SPS.)
  - $M_N < M_D$: SPS beam + near detector
  - $M_N < M_B$: Very high intensity p-accelerator (E $\sim$ 1TeV) + near detector
  - $M_N > M_B$: extremely difficult

$N_{2,3}$ production and decays



Type on neutrino mass hierarchy - from branching ratios of $N_{2,3}$ decays to e, μ, τ.

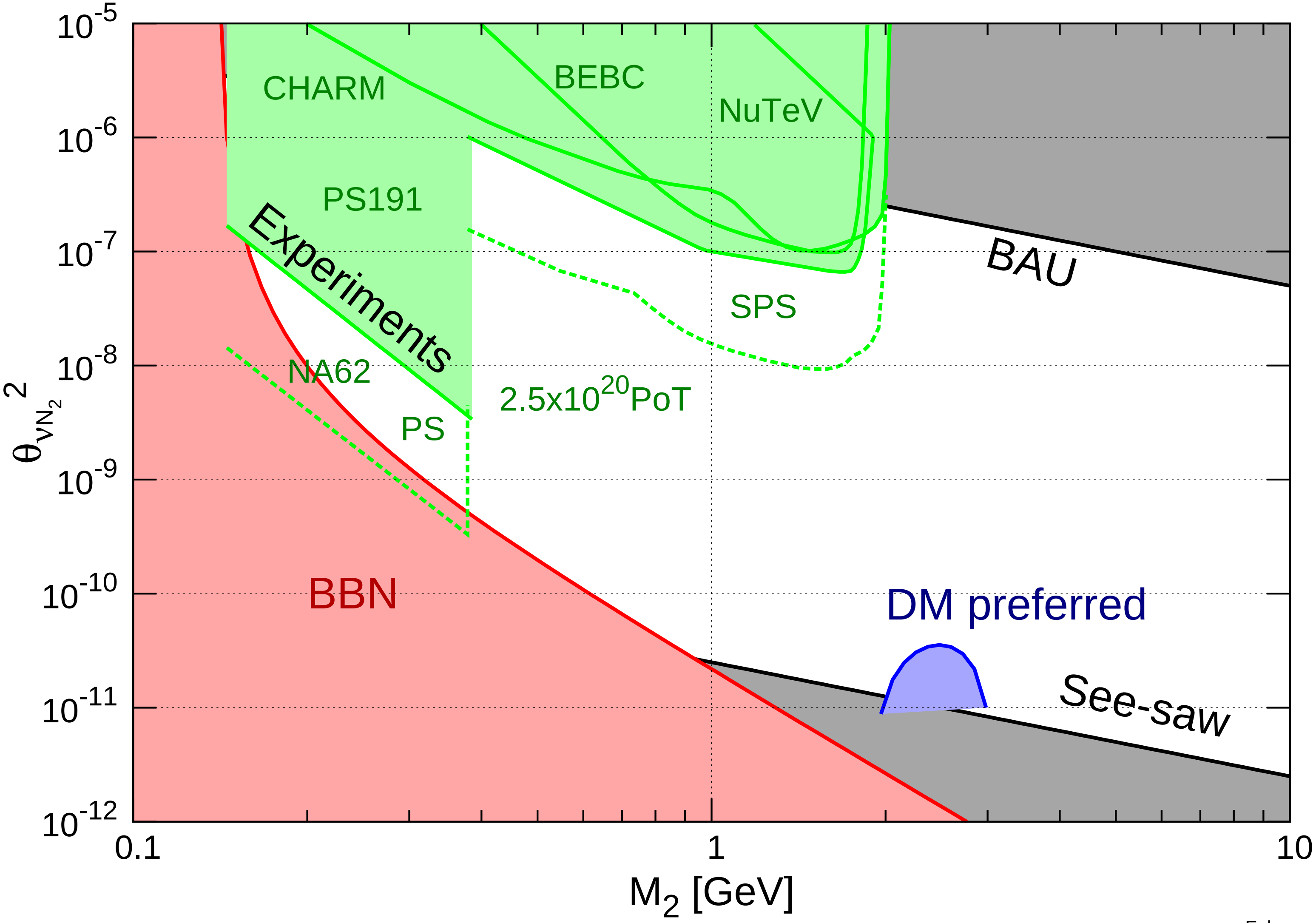
CP asymmetry can be as large as 1% - from BAU and DM

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

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
- Search for new physics: very high intensity proton accelerators, very high intensity B or charm factories, rather than high energy colliders. SPS at CERN is a very good opportunity. Prediction: no new physics at LHC (except Higgs), ILC or muon collider.


CHARM
BEBC
NuTeV
PS191
Experiments
BAU
SPS
NA62
PS
2.5x10^20 PoT
BBN
DM preferred
See-saw
$\theta_{\nu N_2}^2$
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
0.1
1
10
M_2 [GeV]