ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Rare decays, dark matter and baryon asymmetry

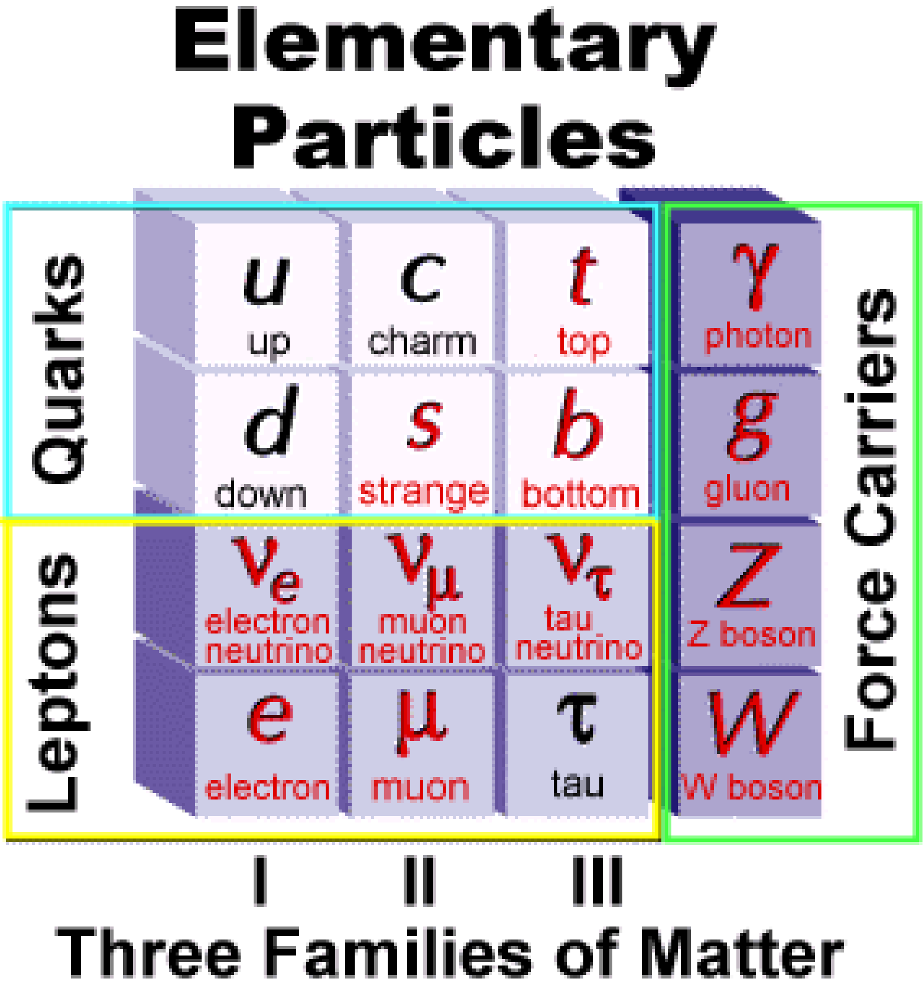
Mikhail Shaposhnikov

The New, the Rare and the Beautiful

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

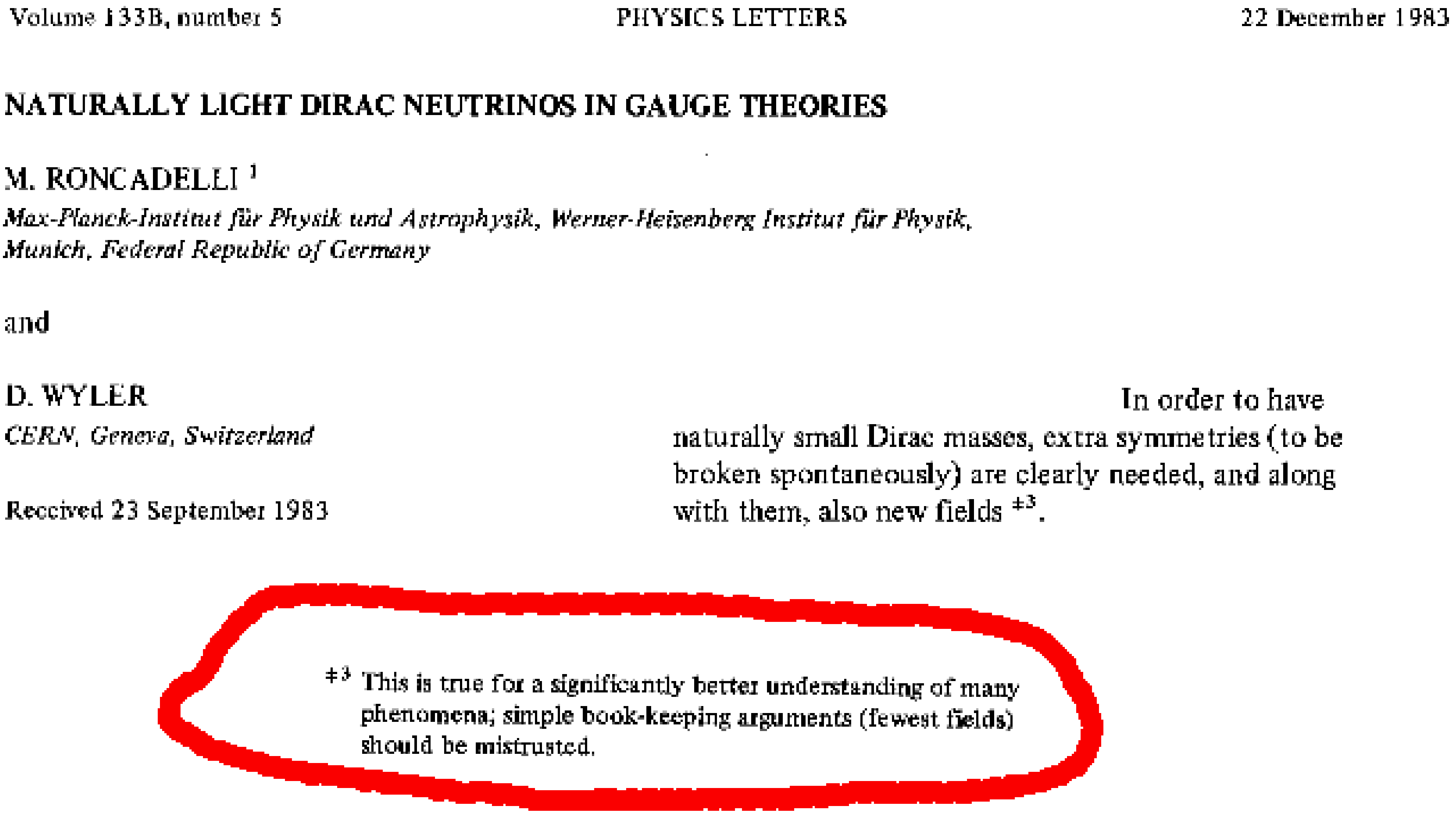


The only missing particle - the Higgs boson. It will be searched at the LHC

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.

A strategy

- Select the most important problems to solve (may be subjective).
- Use Ockham’s razor principle: ”entities must not be multiplied beyond necessity”. For particle physics: entities = new hypothetical particles.



Volume 133B, number 5 PHYSICS LETTERS 22 December 1983

NATURALLY LIGHT DIRAC NEUTRINOS IN GAUGE THEORIES

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Received 23 September 1983

In order to have naturally small Dirac masses, extra symmetries (to be broken spontaneously) are clearly needed, and along with them, also new fields ‡3.

‡3 This is true for a significantly better understanding of many phenomena; simple book-keeping arguments (fewest fields) should be mistrusted.

Experimental evidence in favour of new physics

- 0.511 MeV annihilation line in the direction of the Galaxy center
- Baryon asymmetry of the Universe
- Cosmological inflation
- DAMA annual modulations
- Dark energy
- Dark matter in the Universe
- Discrepancy between experiment and the theory prediction of anomalous magnetic moment of muon
- Egret gamma-ray excess
- Heidelberg neutrinoless double β decays
- LSND anomaly (light sterile neutrino?)
- MiniBooNE anomaly (excess of low energy events)
- Neutrino masses and oscillations
- Origin of high energy cosmic rays
- Pamela positron excess
- Pulsar-kick velocities
- ...

Confirmed experimental evidence in favour of new physics

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Fine-tuning problems

- Cosmological constant problem: Why $\epsilon_{vac}/M_{Pl}^4 \lll 1$?
- Hierarchy problem: Why $M_W/M_{Pl} \ll 1$?
- Stability of the Higgs mass against radiative corrections.
- Strong CP-problem: Why $\theta_{QCD} \ll 1$?
- Fermion mass matrix: Why $m_e \ll m_t$?
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Will concentrate on:

- Neutrino masses and oscillations
- Dark matter
- Baryon asymmetry of the Universe
- Inflation

New dedicated experiments
in flavour physics

The νMSM

Neutrino masses and oscillations, Dark matter, and Baryon asymmetry of the Universe can be explained if the Standard Model is extended in a minimal way by adding 3 right-handed neutrinos (other names: Majorana fermions, singlet leptons, neutral fermions)

$$\text{SM} \quad \Rightarrow \quad \nu\text{MSM}$$

νMSM = Neutrino Minimal Standard Model

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

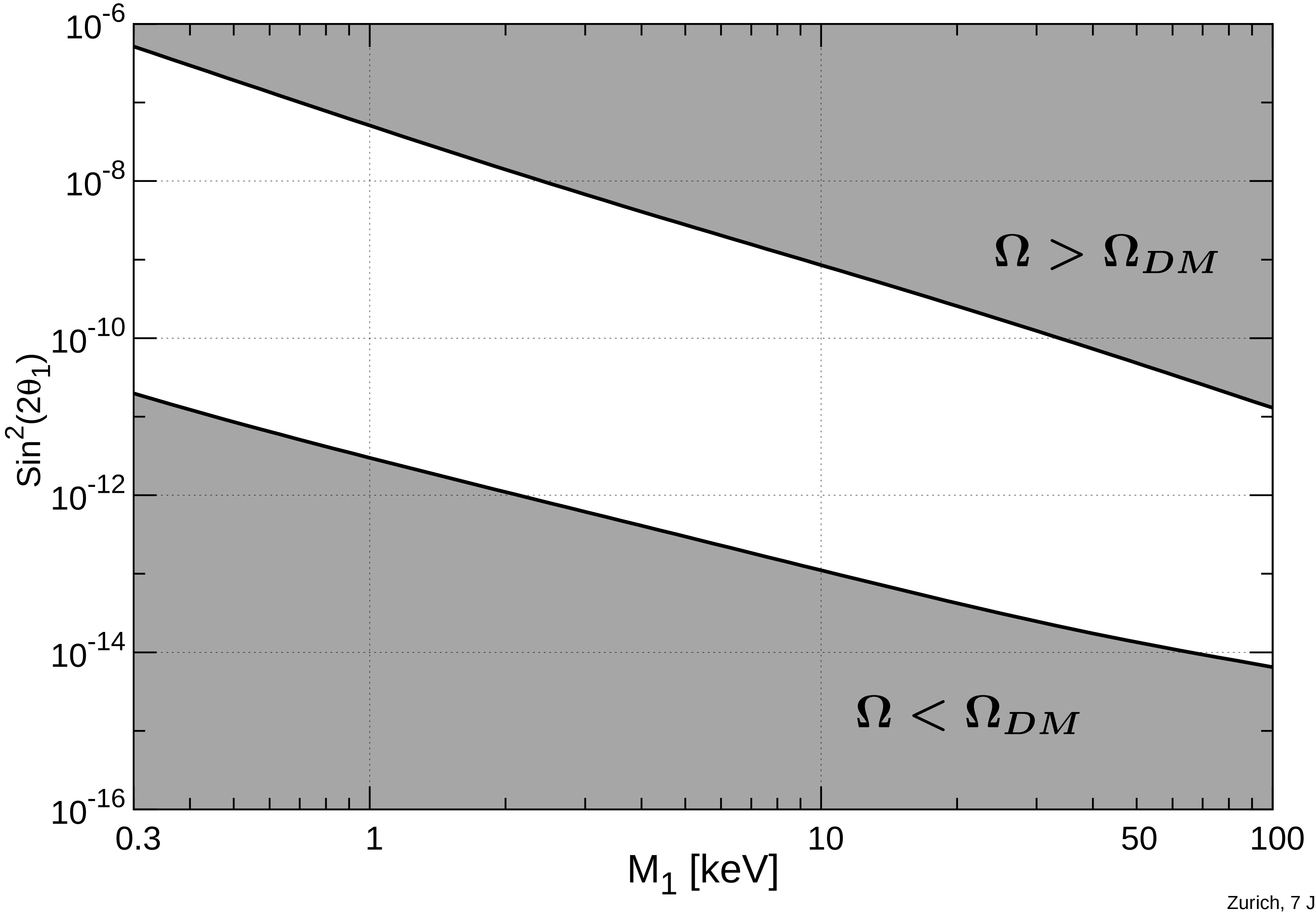
Role of $N_\mu,\ N_\tau$ with mass in 100 MeV – GeV region: “give” masses to neutrinos and produce baryon asymmetry of the Universe

Automatic electric charge quantisation without Grand Unification: from requirement of gravitational and gauge anomalies cancellation.

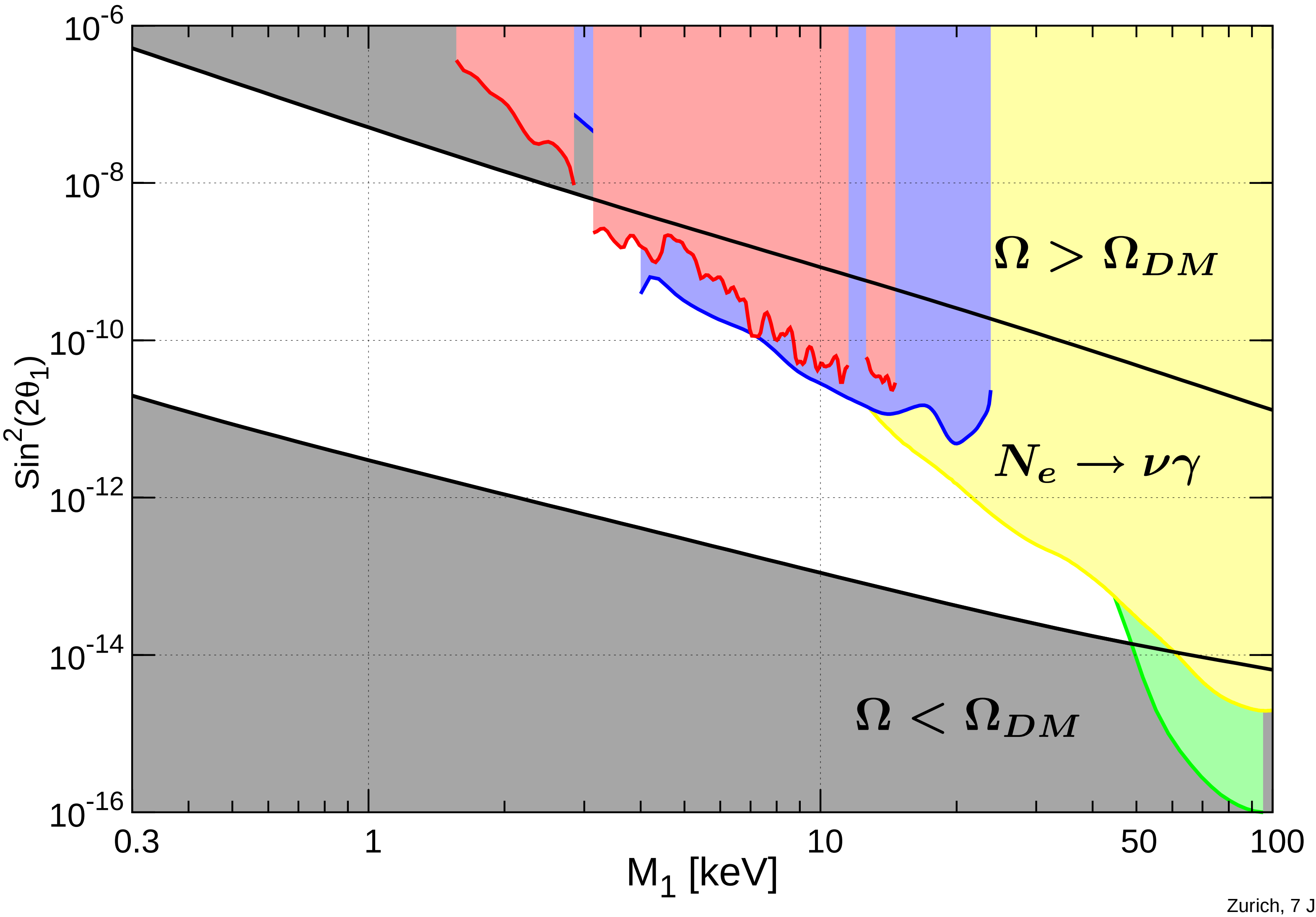
Constraints on DM sterile neutrino

- **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.

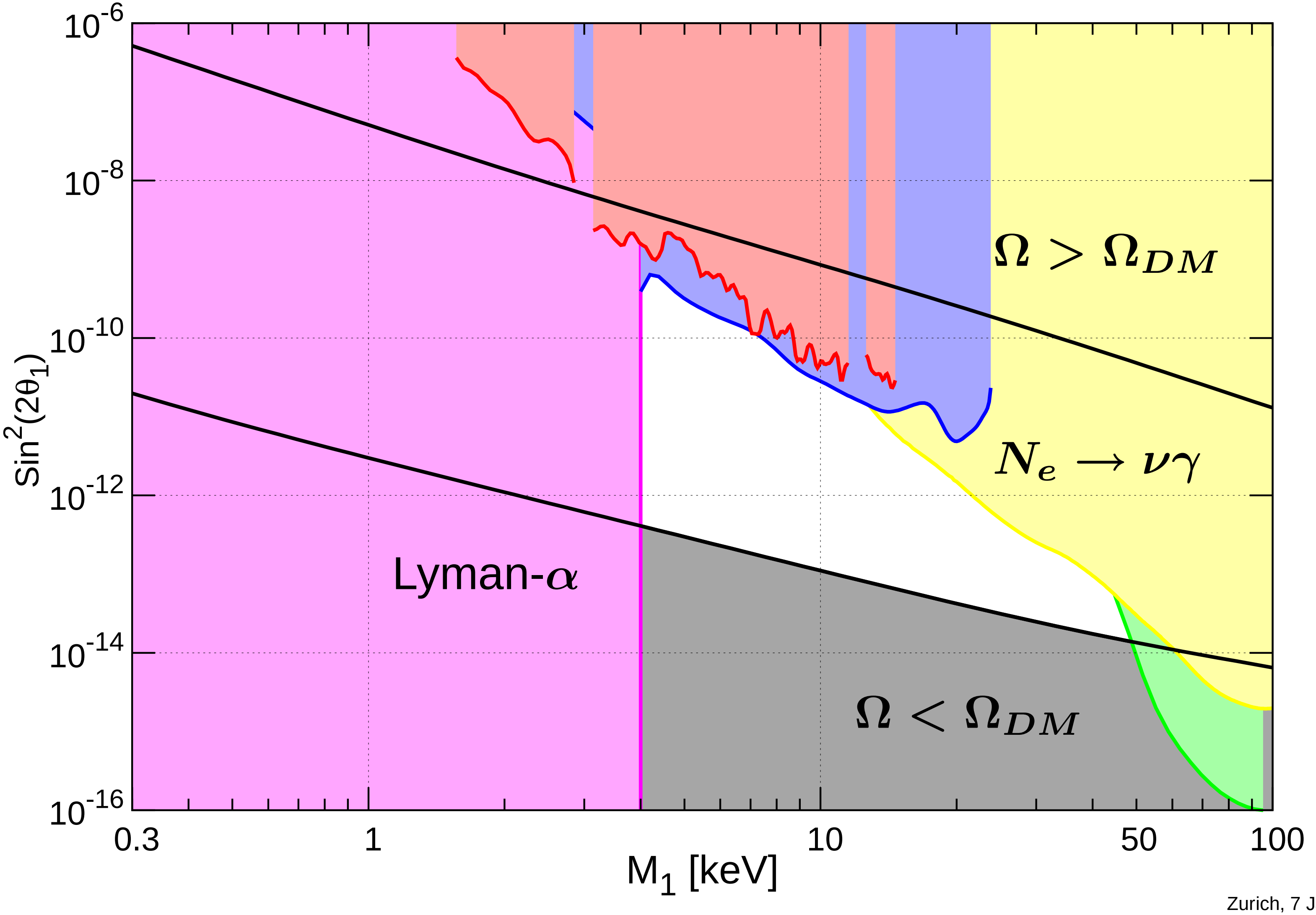
DM: production



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.

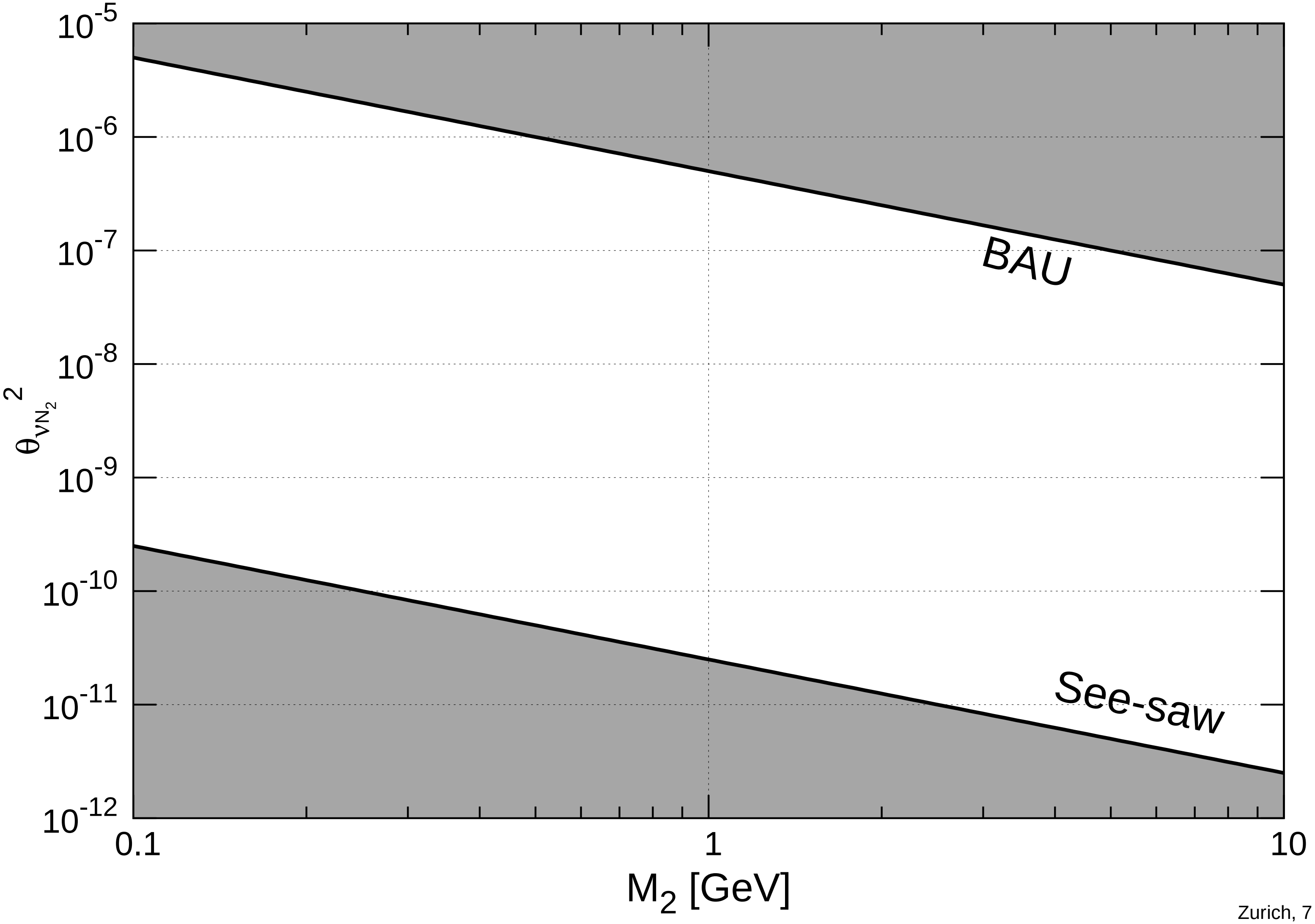
The new data from *Chandra* and *XMM-Newton* can hardly improve constraints by more than a factor $\mathbf{10}$. One needs:

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

Constraints on BAU Majorana fermions

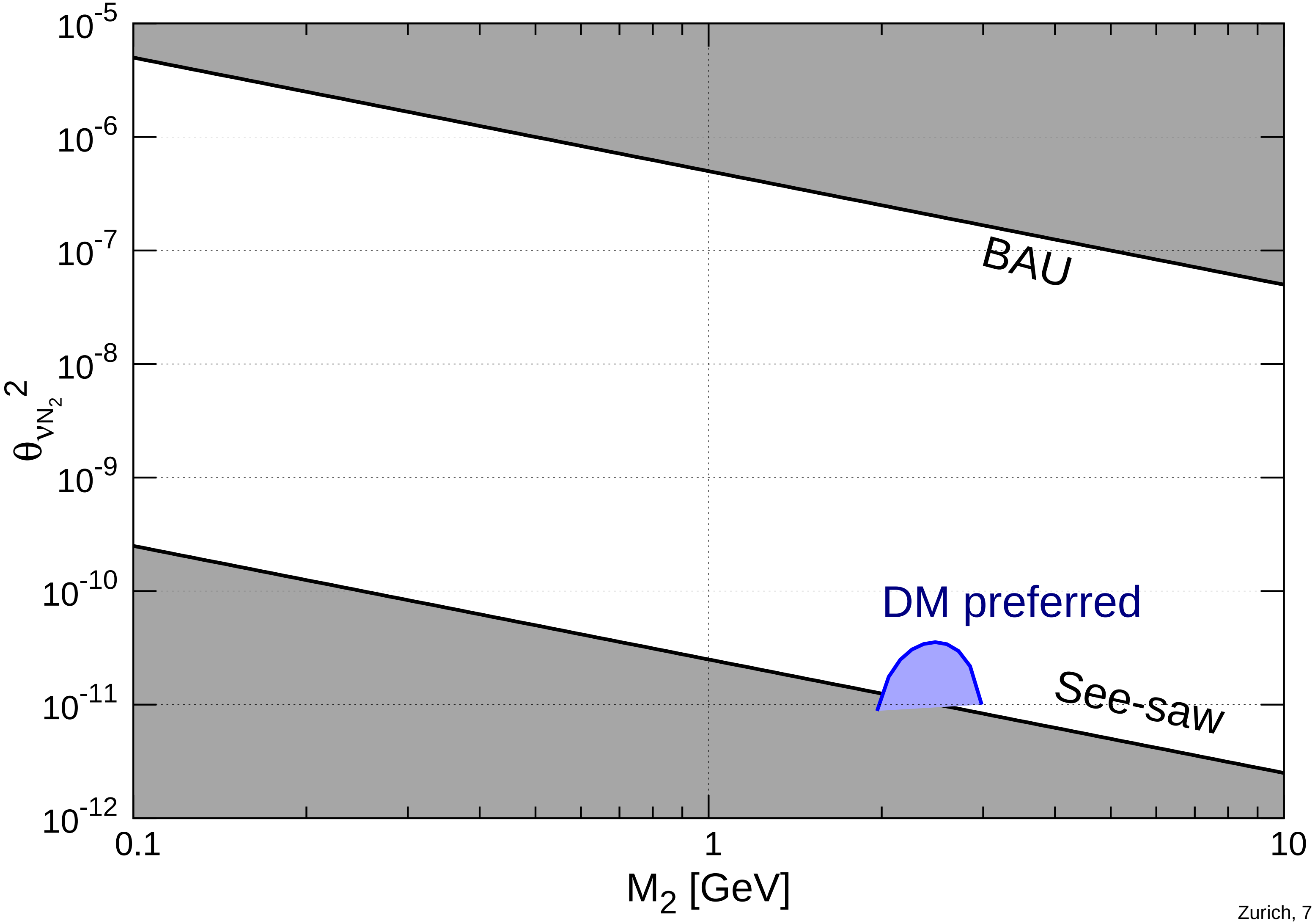
- BAU generation requires out of equilibrium: mixing angle of $N_{\mu,\tau}$ to active neutrinos cannot be too large
- Neutrino masses. Mixing angle of $N_{\mu,\tau}$ to active neutrinos cannot be too small
- Dark matter and BAU. Concentration of DM sterile neutrinos must be much larger than concentration 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

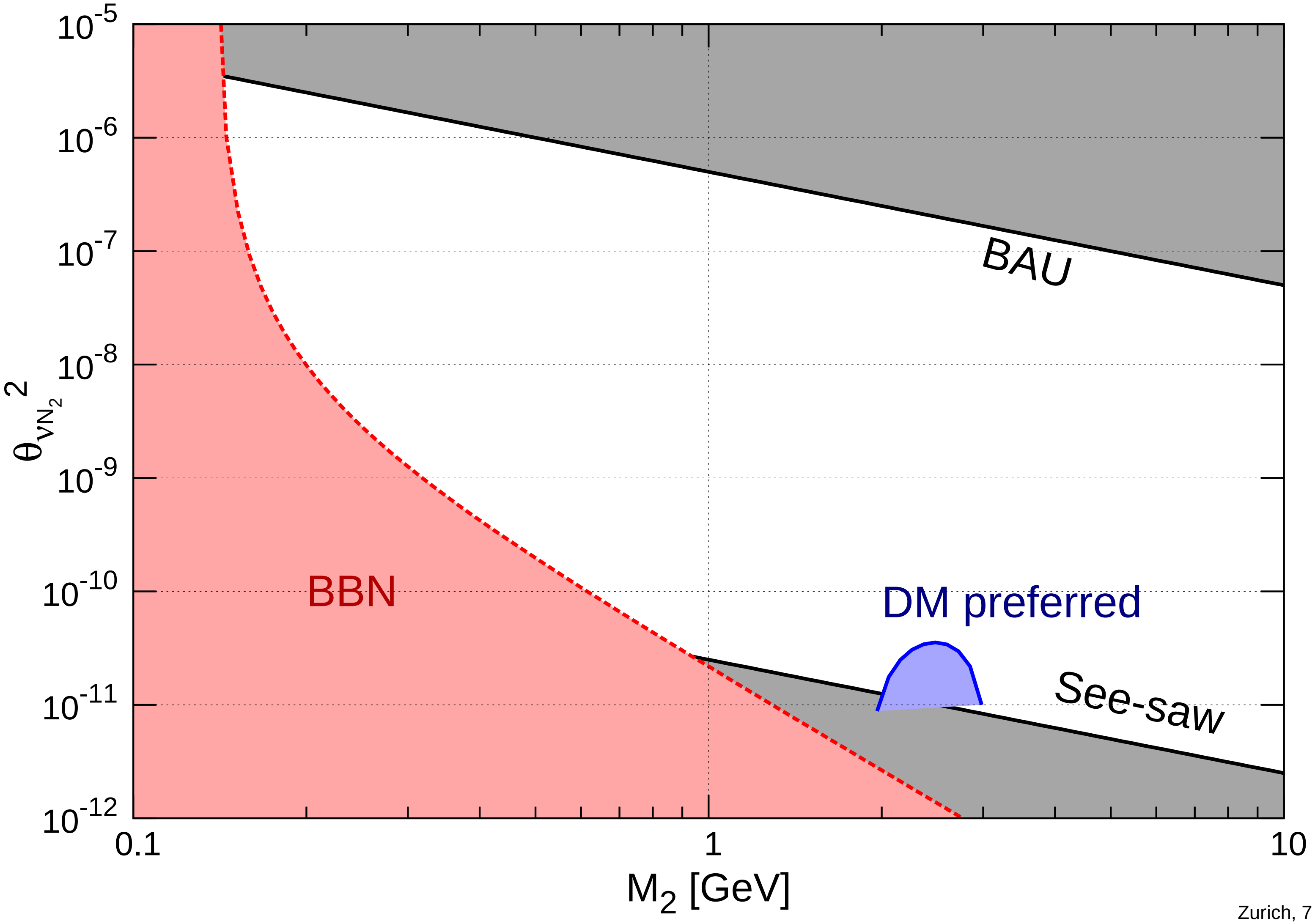


10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
$\theta_{\nu N_2}^{\ 2}$
BAU
See-saw
0.1
1
10
M_2 [GeV]

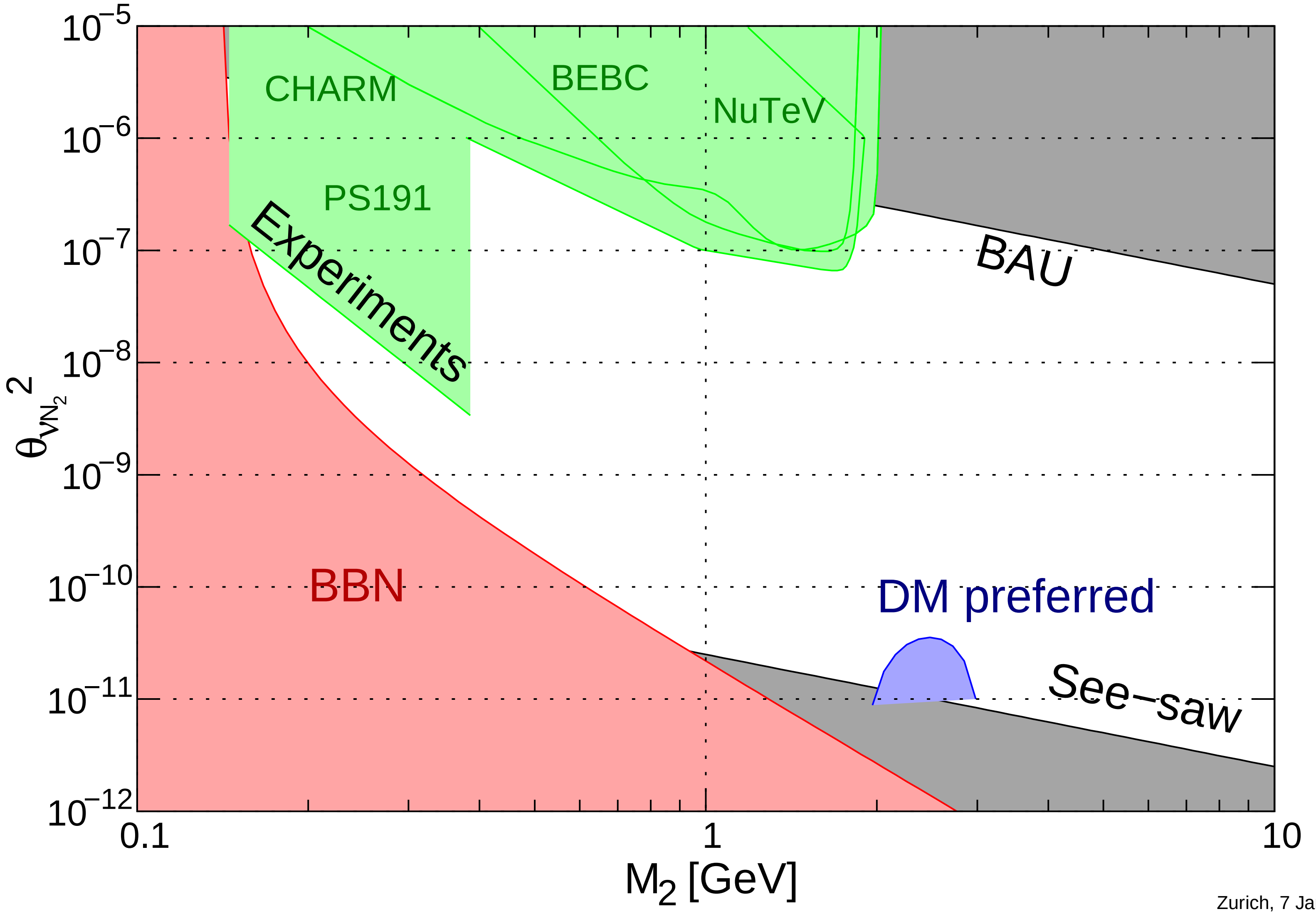
$N_{\mu,\tau}$: BAU + DM



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



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

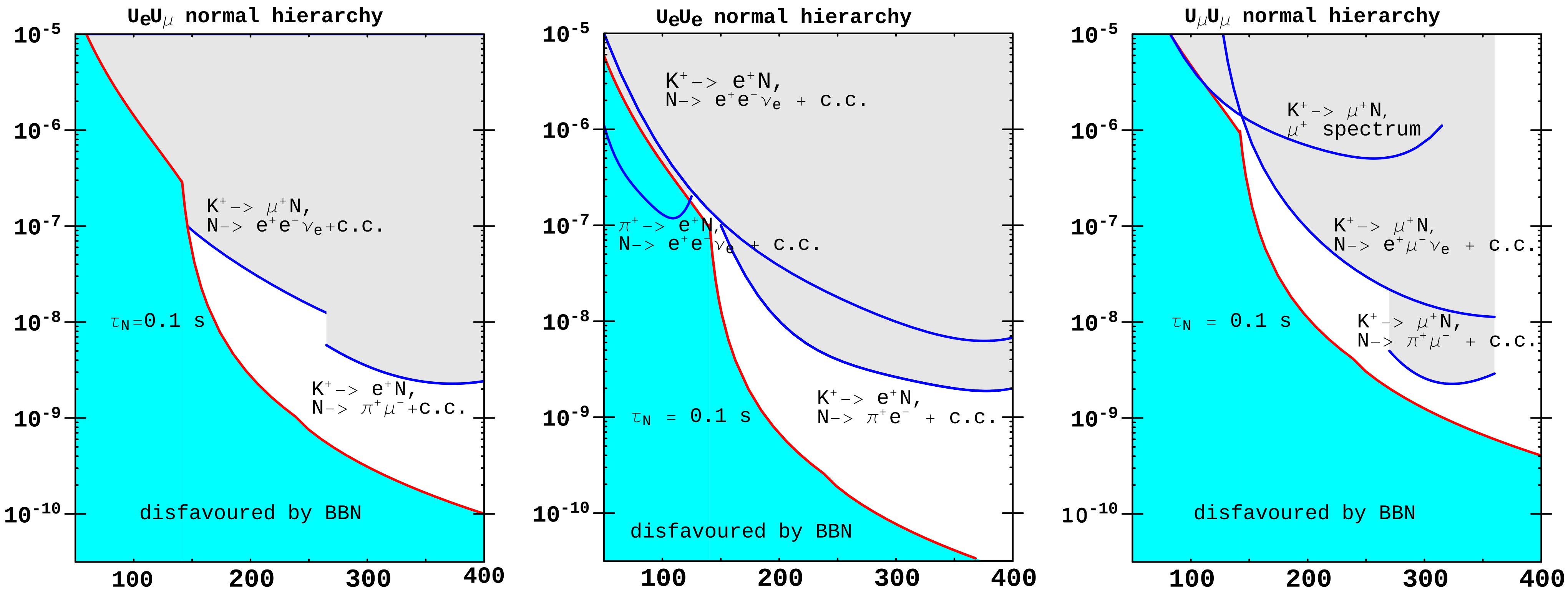


Direct experimental tests: rare decays

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

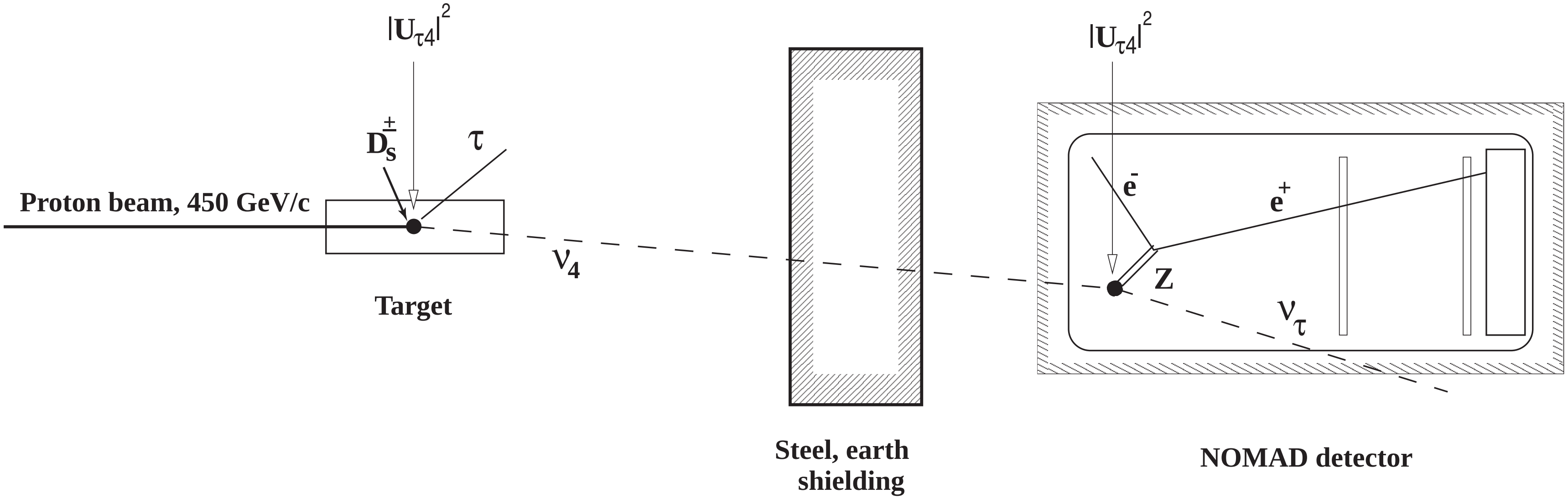
- Two charged tracks from a common vertex, decay processes $N \to \mu^+\mu^-\nu$, etc. (sensitivity $\theta^4 = \theta^2 \times \theta^2$)

  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.)
  - $M_N < M_D$: SPS or PS2 beam + near detector
  - $M_N < M_B$: Project X (?) + 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 $e,\ \mu, \tau$.

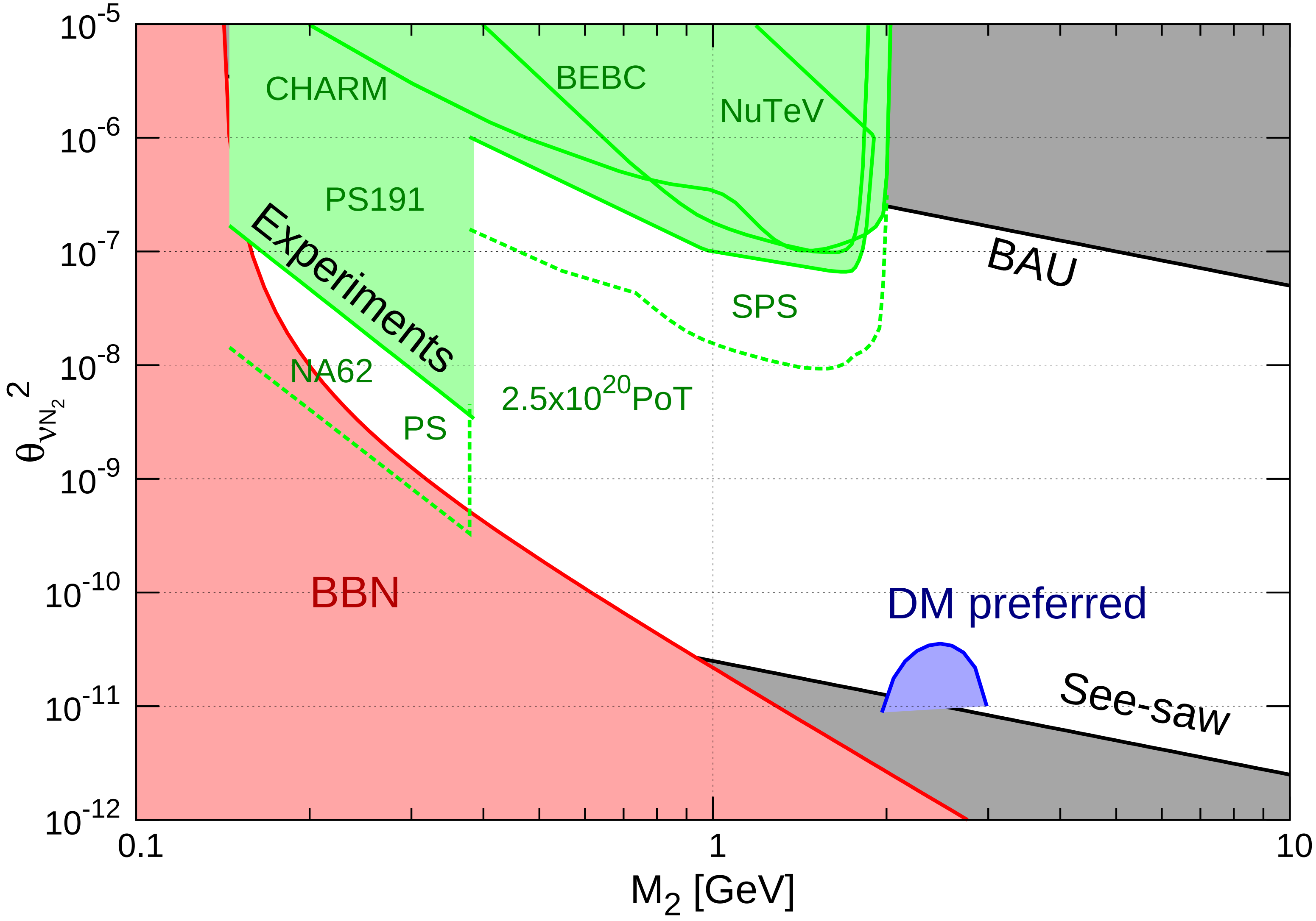
CP asymmetry can be as large as 1% - from BAU and DM

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
- The estimates based on PS191, BEBC and CHARM results show that the experiments with a sensitivity in mixing strength θ^2 improved by a factor more than 10 are feasible. The coverage of significant amount of parameter space would require from CERN a delivery of more than 10^{20} POTs



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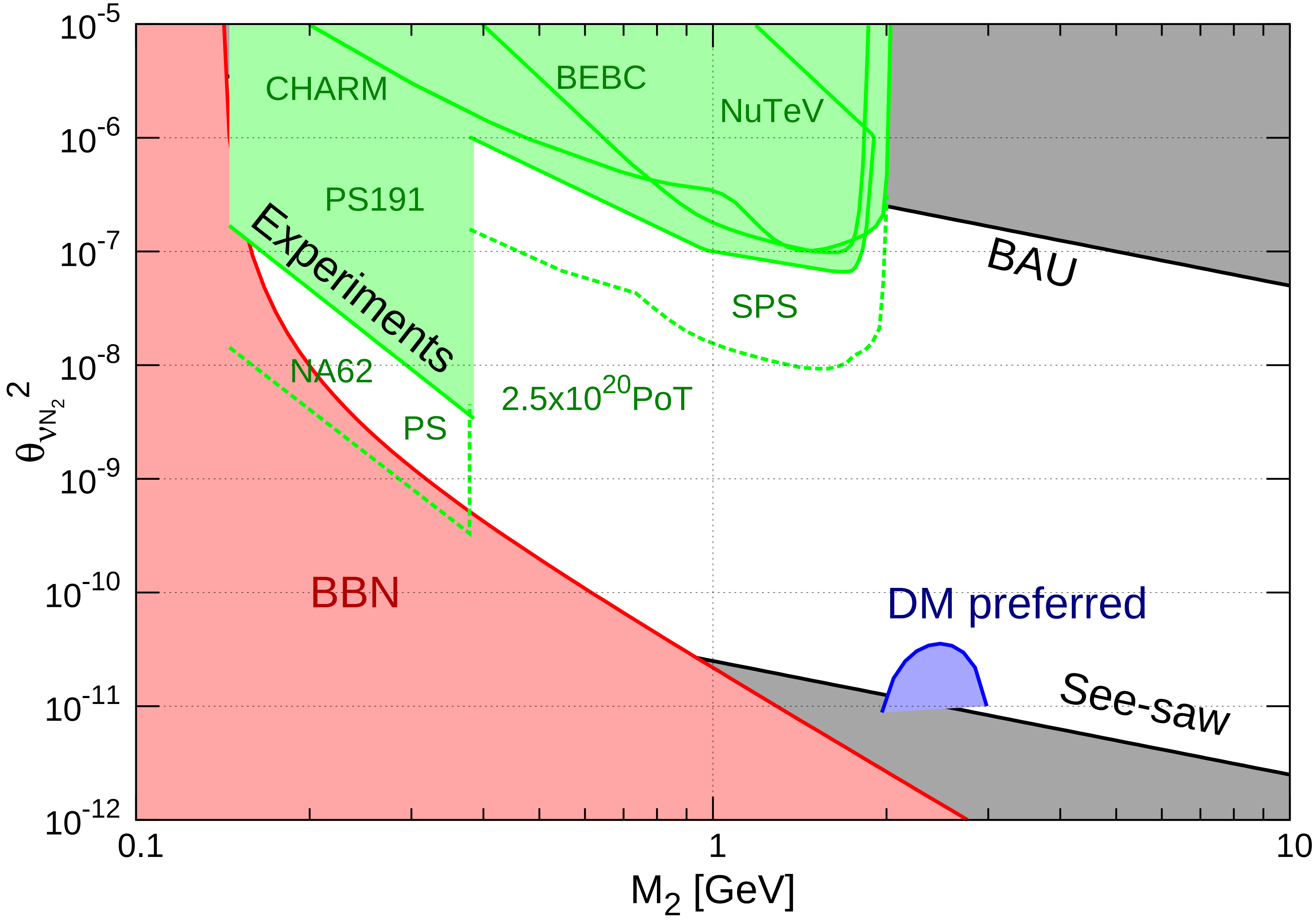
10^{-9}
10^{-10}
10^{-11}
10^{-12}
$\theta_{\nu N_2}^2$
0.1
1
10
M_2 [GeV]
CHARM
BEBC
NuTeV
PS191
Experiments
BAU
SPS
NA62
PS
2.5×10^{20}PoT
BBN
DM preferred
See-saw



The efforts for performing the dedicated experiments, pioneered by CERN almost 25 year ago, are well justified, and, hopefully, may lead these searches to the happy end.

νMSM prediction for LHC

Cosmological inflation from the Higgs of the Standard Model

(Bezrukov, MS):

Nothing but the SM Higgs in the mass interval $M_H \in [m_{min}, m_{max}]$

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

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

Theoretical uncertainty ± 2.2 GeV.

If gravity is asymptotically safe, then (MS, Wetterich): $M_H = m_{min}$