ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

The EW scale in cosmology

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One of the old theme in cosmology:

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Understand the evolution of the Universe from its creation till the present time

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Understand the evolution of the Universe from its creation till the present time

This requires the knowledge of the theory, valid up to the scale of inflation

This new theory must explain, at least, well established experimental facts leading to the conclusion the SM is not complete:

- Neutrino masses and oscillations
- Baryon asymmetry of the Universe
- Dark matter in the Universe
- Dark energy
- Flatness and homogeneity of the Universe, related presumably to cosmological inflation

The most conservative (and thus most predictive) hypothesis:

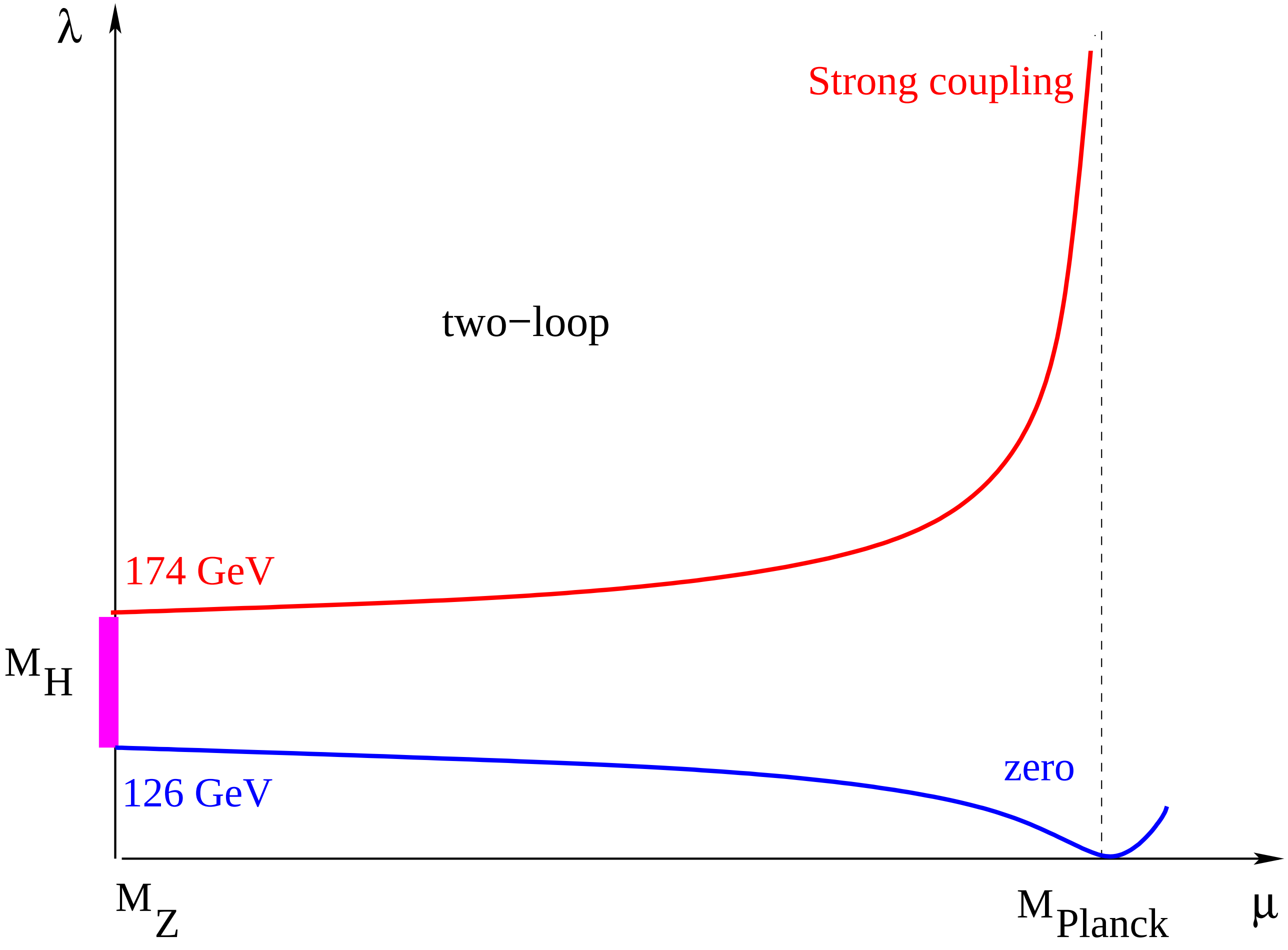
The Standard Model, minimally extended to solve the above mentioned problems, survives to the Planck scale as is.

No new scale scenario

Outline

- Higgs mass as an indication of “no new scale scenario”
- Minimal model leading to minimal solutions
- Universe evolution in “no new scale scenario”
- Challenges of “no new scale scenario”

Behaviour of the scalar self-coupling



For $m_H > m_{\rm max}$: Landau pole for energies $E = E_{\rm Landau} < M_P$ – quantum field theory is inconsistent for $E > E_{\rm Landau}$.

For $m_H < m_{\rm min}$: Electroweak vacuum is unstable: there is a lower ground state at $\phi < M_P$.

L. Maiani, G. Parisi and R. Petronzio ’77; Lindner ’85; T. Hambye and K. Riesselmann ’96; Krasnikov ’78, Hung ’79; Politzer and S. Wolfram ’79; G. Altarelli and G. Isidori ’94; J. A. Casas, J. R. Espinosa and M. Quiros ’94,’96; ...

Interval for the Higgs mass

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

$$m_{\min} = [126.3 + \frac{m_t - 171.2}{2.1} \times 4.1 - \frac{\alpha_s - 0.1176}{0.002} \times 0.6]\ \mathrm{GeV}$$

$$m_{\max} = [173.5 + \frac{m_t - 171.2}{2.1} \times 0.6 - \frac{\alpha_s - 0.118}{0.002} \times 0.1]\ \mathrm{GeV}$$

theory error in $m_{\min} \simeq \pm 2.2$ GeV.

Numbers from Bezrukov, M.S. '09, see also Ellis, Espinosa, Giudice, Hoecker, Riotto '09

Experiments and electroweak precision tests

Direct searches

LEP limit: $m_H > 114.4$ GeV, 95% C.L.

Tevatron experiments CDF and D0: the region

$158 \text{ GeV} < m_H < 175 \text{ GeV}$ is excluded, 95% C.L.

The LEP Electroweak Working Group:

The preferred value:

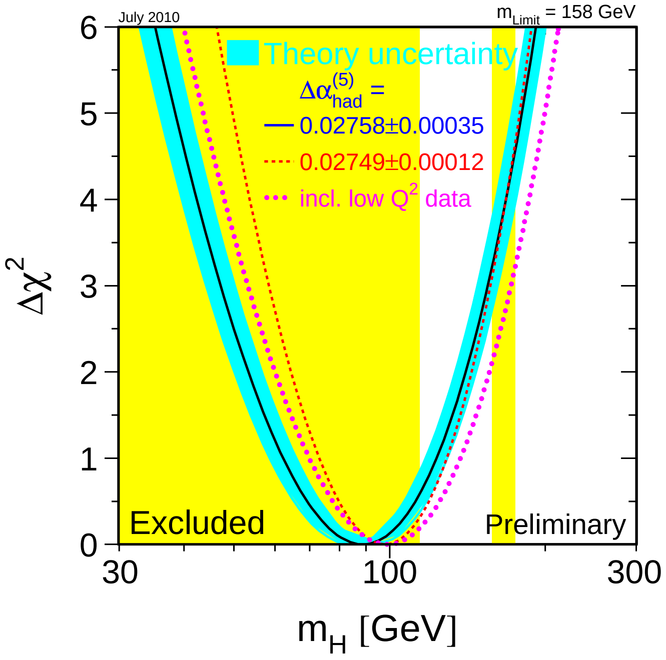
$m_H = 89^{+35}_{-26}$ GeV, 68% C.L.

Upper limit:

$m_H < 158$ GeV, one-sided 95% C.L.

Upper limit accounting for LEP result:

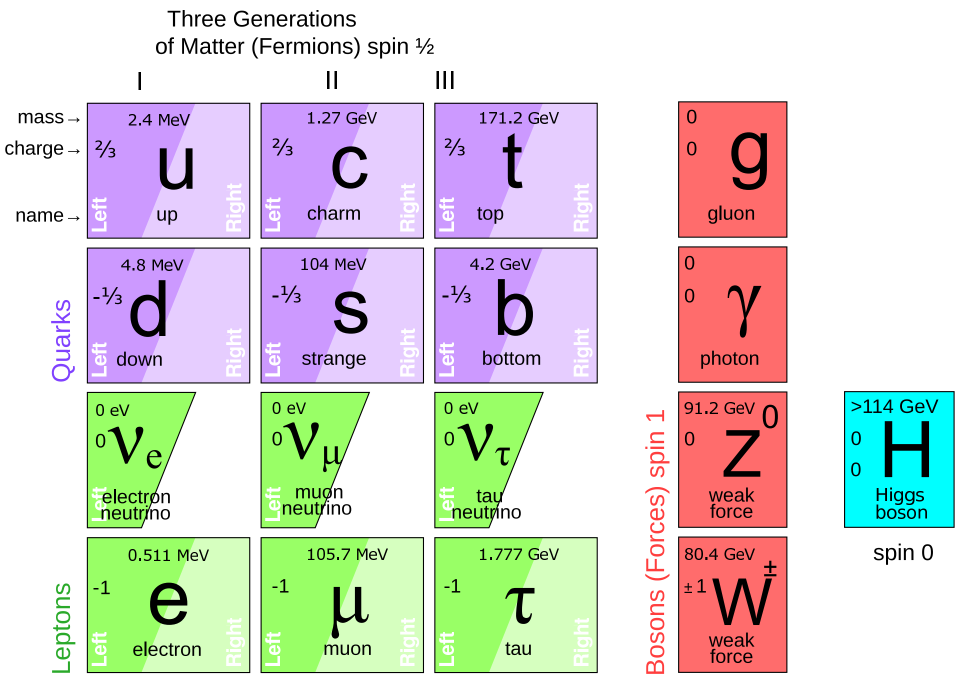
$m_H < 185$ GeV, one-sided 95% C.L.



Conclusion: SM survives to the Planck scale without any new physics added!

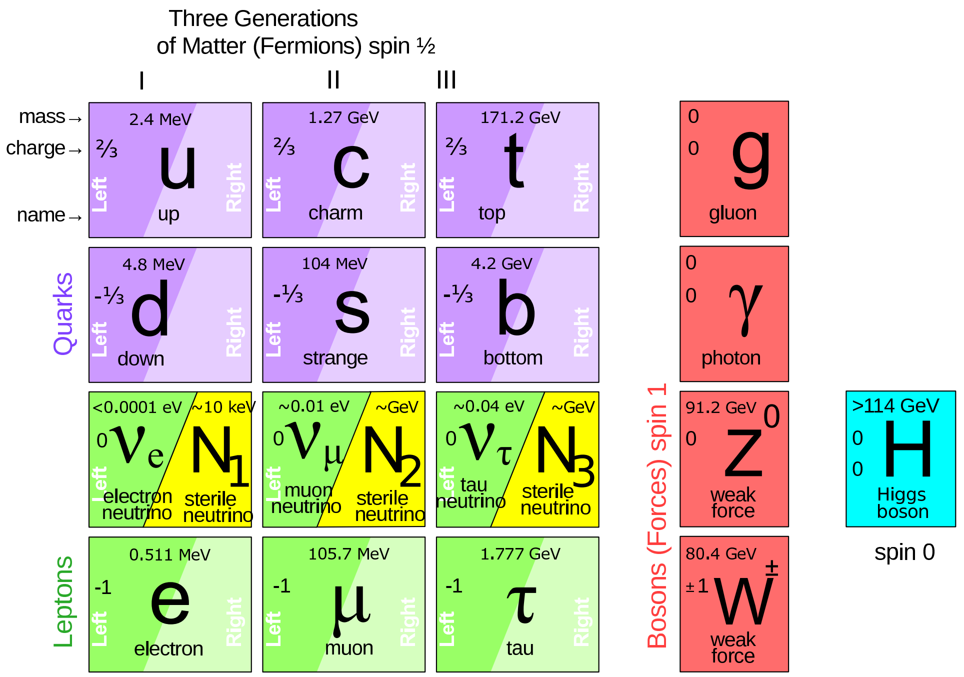
(Except for m_H between the LEP limit $\simeq \mathbf{114}$ GeV and $m_{\min} \simeq \mathbf{126}$ GeV.)

Realisation: νMSM + scale-invariant unimodular gravity



Three Generations of Matter (Fermions) spin ½

	I	II	III	Bosons (Forces) spin 1	
mass→ charge→ name→	2.4 MeV ⅔ u up	1.27 GeV ⅔ c charm	171.2 GeV ⅔ t top	0 0 g gluon	
Quarks	4.8 MeV -⅓ d down	104 MeV -⅓ s strange	4.2 GeV -⅓ b bottom	0 0 γ photon	
	0 eV 0 ν_e electron neutrino	0 eV 0 ν_μ muon neutrino	0 eV 0 ν_τ tau neutrino	91.2 GeV 0 0 Z weak force	>114 GeV 0 0 H Higgs boson
Leptons	0.511 MeV -1 e electron	105.7 MeV -1 μ muon	1.777 GeV -1 τ tau	80.4 GeV ±1 $W^\pm$ weak force	spin 0



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mass→ charge→ name→	2.4 MeV ⅔ u up	1.27 GeV ⅔ c charm	171.2 GeV ⅔ t top	0 0 g gluon	
Quarks	4.8 MeV -⅓ d down	104 MeV -⅓ s strange	4.2 GeV -⅓ b bottom	0 0 γ photon	
	<0.0001 eV 0 ν_e electron neutrino ~10 keV N_1 sterile neutrino	~0.01 eV 0 ν_μ muon neutrino ~GeV N_2 sterile neutrino	~0.04 eV 0 ν_τ tau neutrino ~GeV N_3 sterile neutrino	91.2 GeV 0 0 Z weak force	>114 GeV 0 0 H Higgs boson
Leptons	0.511 MeV -1 e electron	105.7 MeV -1 μ muon	1.777 GeV -1 τ tau	80.4 GeV ±1 $W^\pm$ weak force	spin 0

Role of N_1 with mass in keV region: dark matter

Role of $N_2,\ N_3$ 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.

Role of scale invariance and unimodular gravity: dilaton gives mass to the Higgs and $N_{1,2,3}$ and provides dynamical dark energy

Unique νMSM Lagrangian

$$\mathcal{L}_{\nu\mathrm{MSM}} = \mathcal{L}_{\mathrm{SM[M\to 0]}} + \mathcal{L}_G + \frac{1}{2}(\partial_\mu\chi)^2 - V(\varphi,\chi)$$
$$+ \left(\bar{N}_I i\gamma^\mu\partial_\mu N_I - h_{\alpha I}\,\bar{L}_\alpha N_I\tilde{\varphi} - f_I \bar{N}_I{}^c N_I\chi + \mathrm{h.c.}\right)\ ,$$

Potential (χ - dilaton, φ - Higgs, $\varphi^\dagger\varphi = 2h^2$):

$$V(\varphi,\chi) = \lambda\left(\varphi^\dagger\varphi - \frac{\alpha}{2\lambda}\chi^2\right)^2,$$

Unimodular gravity part ($det g_{\mu\nu} = -1$)

$$\mathcal{L}_G = -\left(\xi_\chi\chi^2 + 2\xi_h\varphi^\dagger\varphi\right)\frac{R}{2}\ ,$$

Choice of parameters:

$\xi_h \gg 1$ – inflation, $\xi_\chi \ll 1$ – dark energy,

$\alpha,\ h_{\alpha I} \lll 1$ – hierarchy between Fermi and Planck scales,

$$M_P^2 = \xi_\chi \frac{m_H^2}{\alpha}$$

Only one scale is relevant for cosmology: M_W !

SM problems and possible solutions

If there is new particle physics scale between the Planck scale and Fermi scale - hierarchy problem (yet another argument in favour of “no new scale scenario")

Hierarchy problem: stability of the Higgs mass against radiative corrections

Possible solutions:

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

SM problems and possible solutions

- No new particle physics scale - no loop corrections from heavy particles! Protection from gravity contributions: new symmetry – exact, but spontaneously broken scale invariance. Higgs mass is kept small due to new symmetry. Consequences: validity of the SM all the way up to the Planck scale, nothing but the Higgs at LHC in the mass interval discussed above. Existence of massless particle – dilaton, which can play the role of Dark Energy (M.S., D. Zenhausern).

  Asymptotic safety prediction (M.S., C. Wetterich):

$$m_H = \left[126.3 + \frac{m_t - 171.2}{2.1} \times 4.1 - \frac{\alpha_s - 0.1176}{0.002} \times 1.5 \pm 2.2\right] \mathrm{GeV}$$

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 10^{13} GeV and minimal coupling to gravity

Alternative (Bezrukov, M.S)

- 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

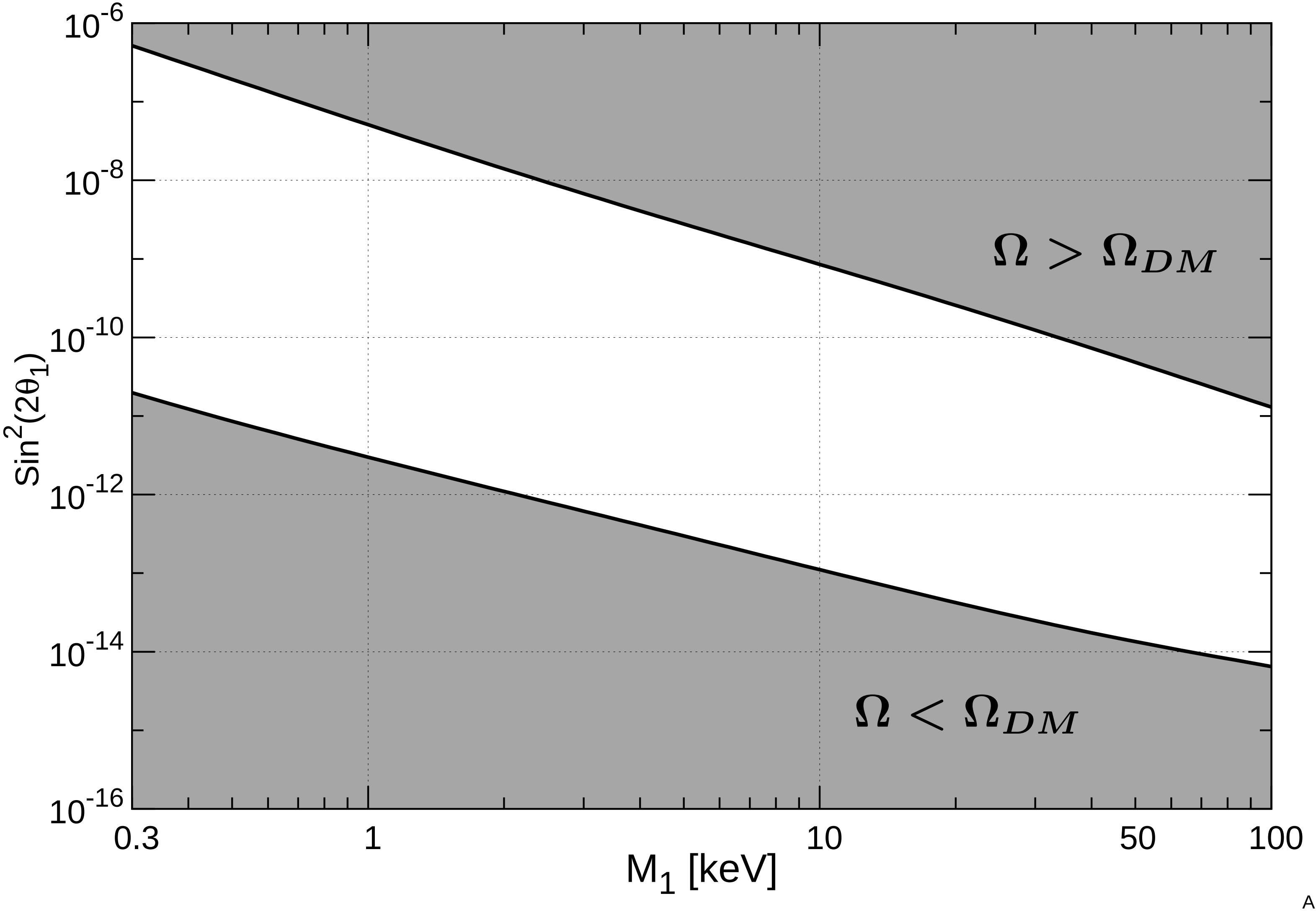
Alternative

- 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 $N \to \nu\gamma$ which leads to existence of narrow X-ray line in direction of DM concentrations.

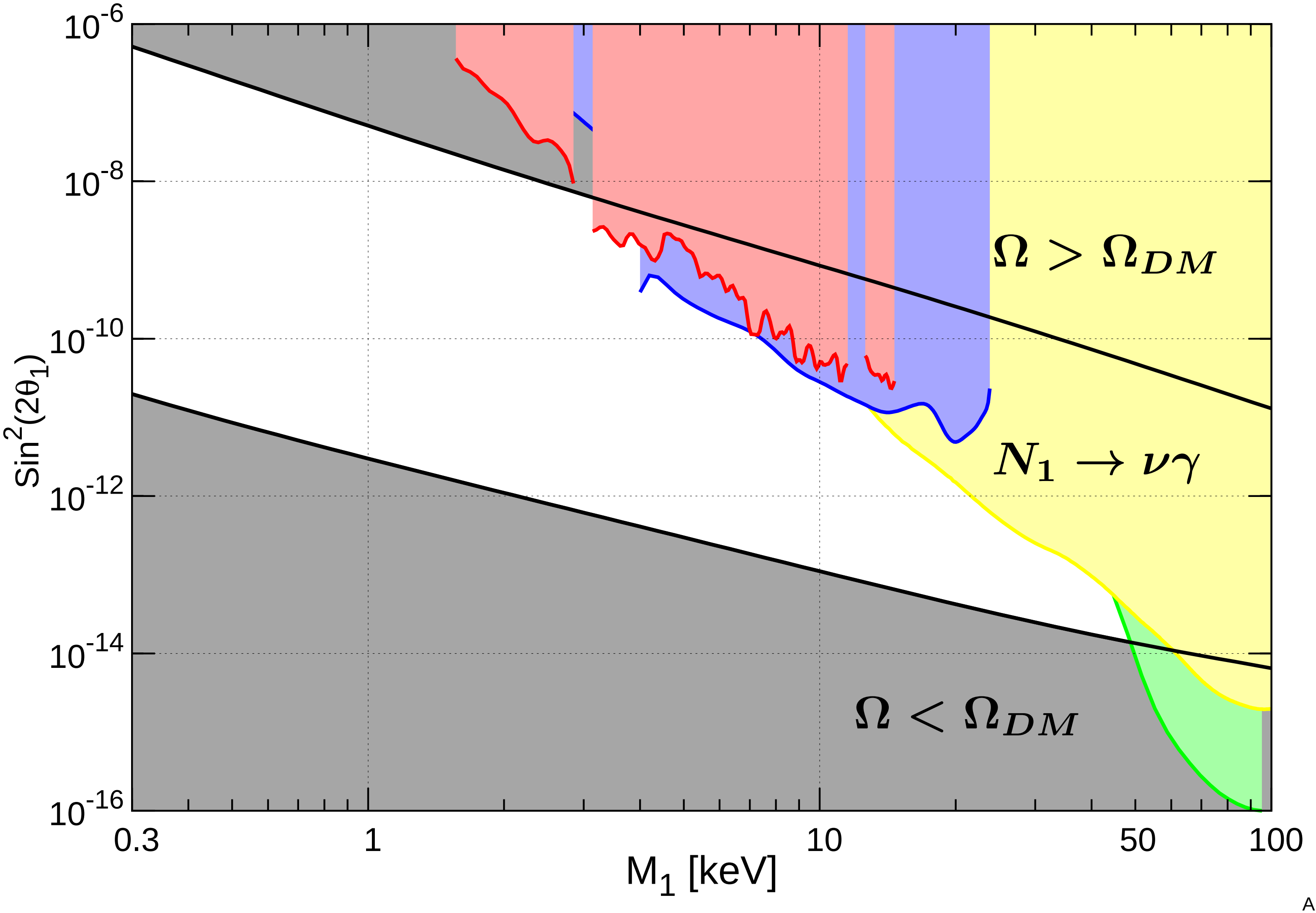
Constraints on DM sterile neutrino

- 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.

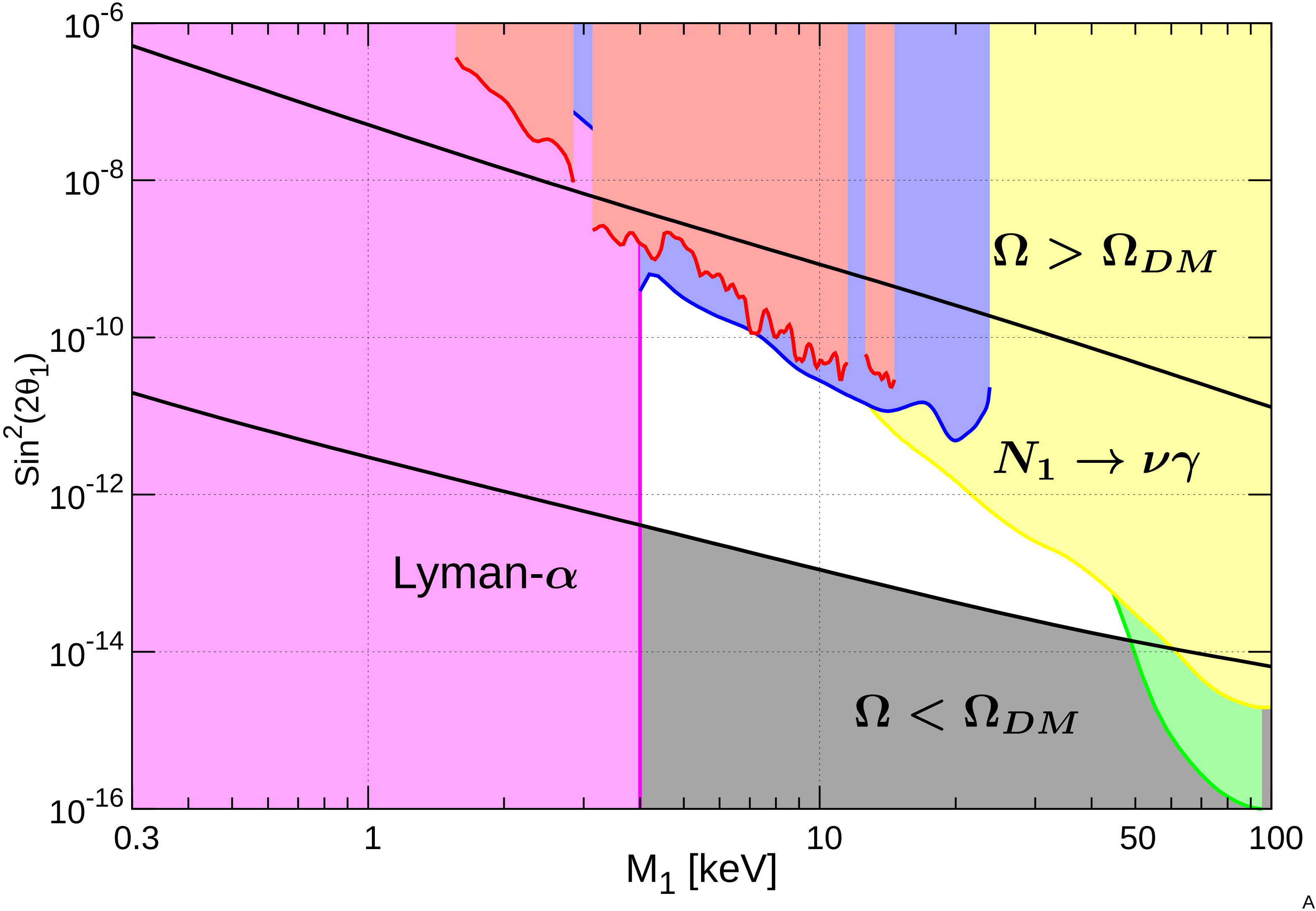
DM: production



DM: production + X-ray constraints



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



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)

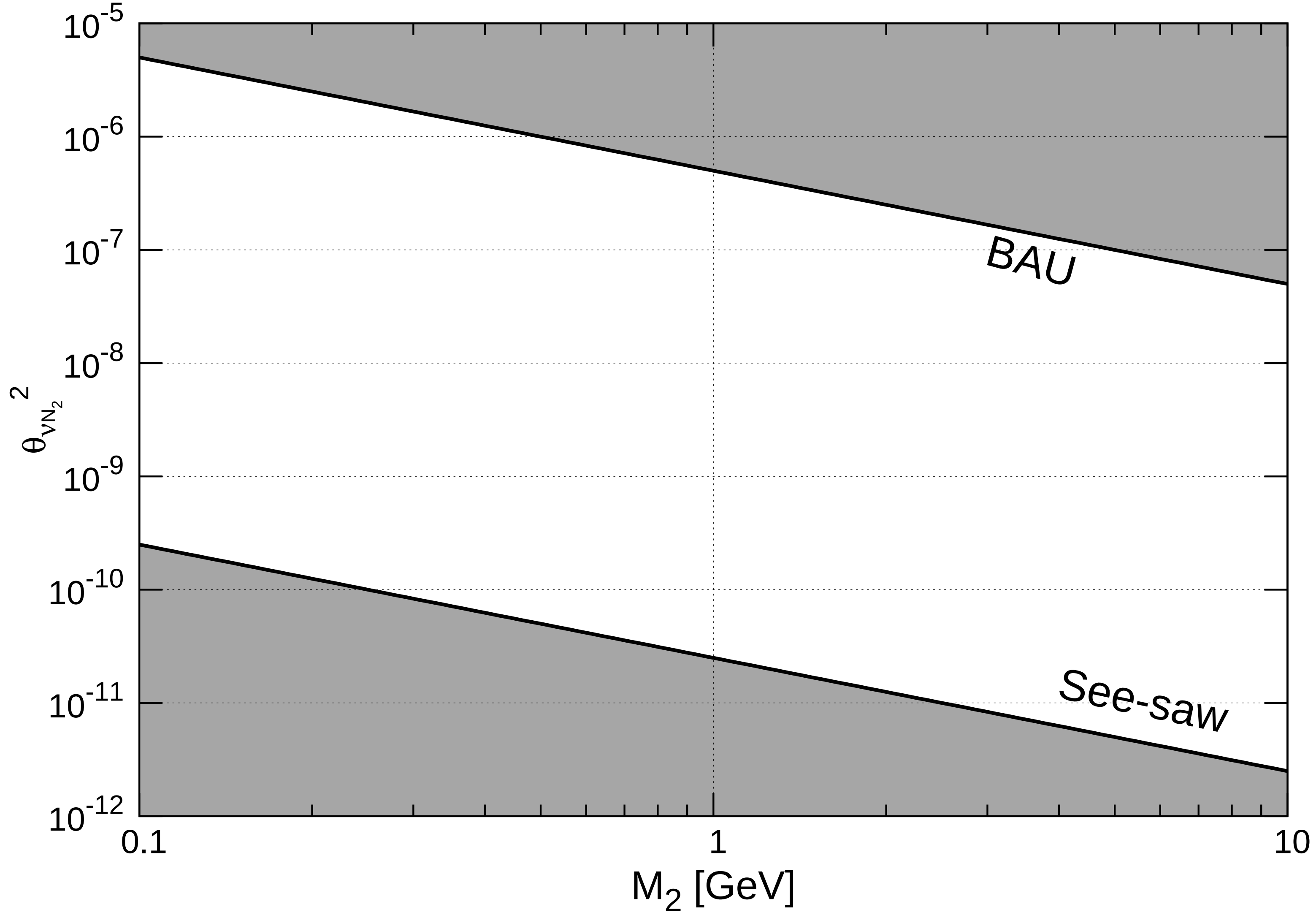
Alternative

- 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

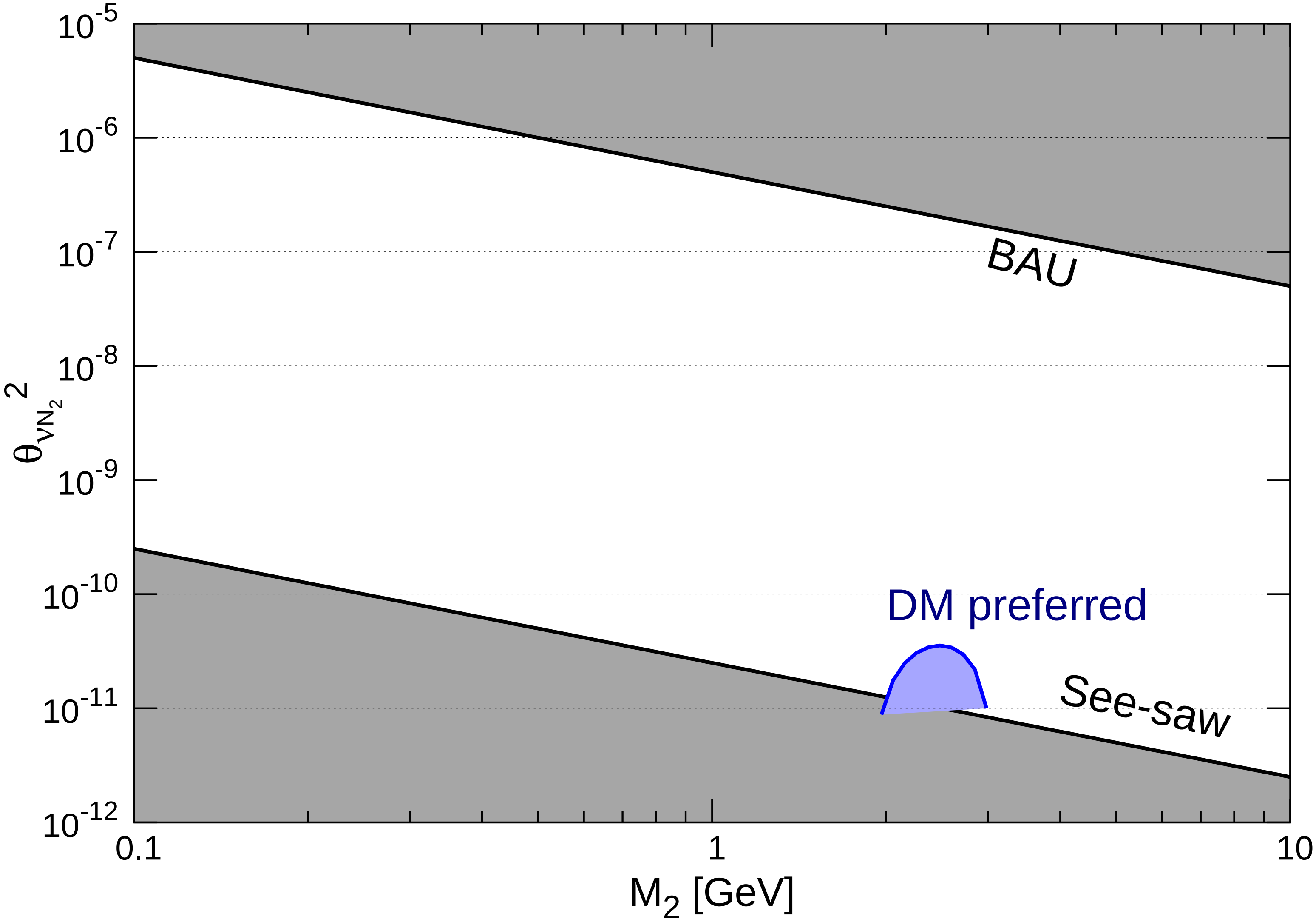
Constraints on BAU Majorana fermions

- 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).

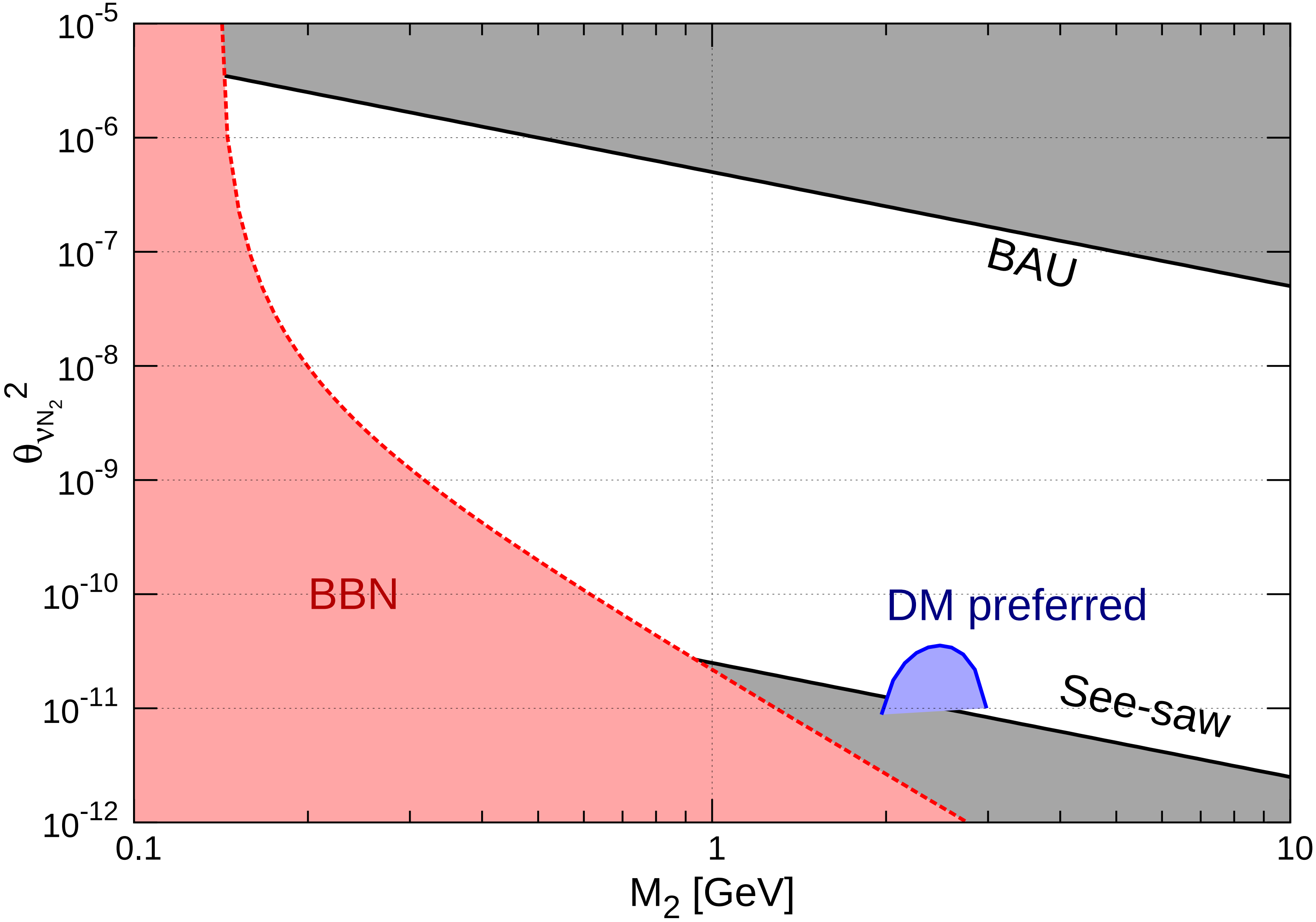
$N_{2,3}$: BAU


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

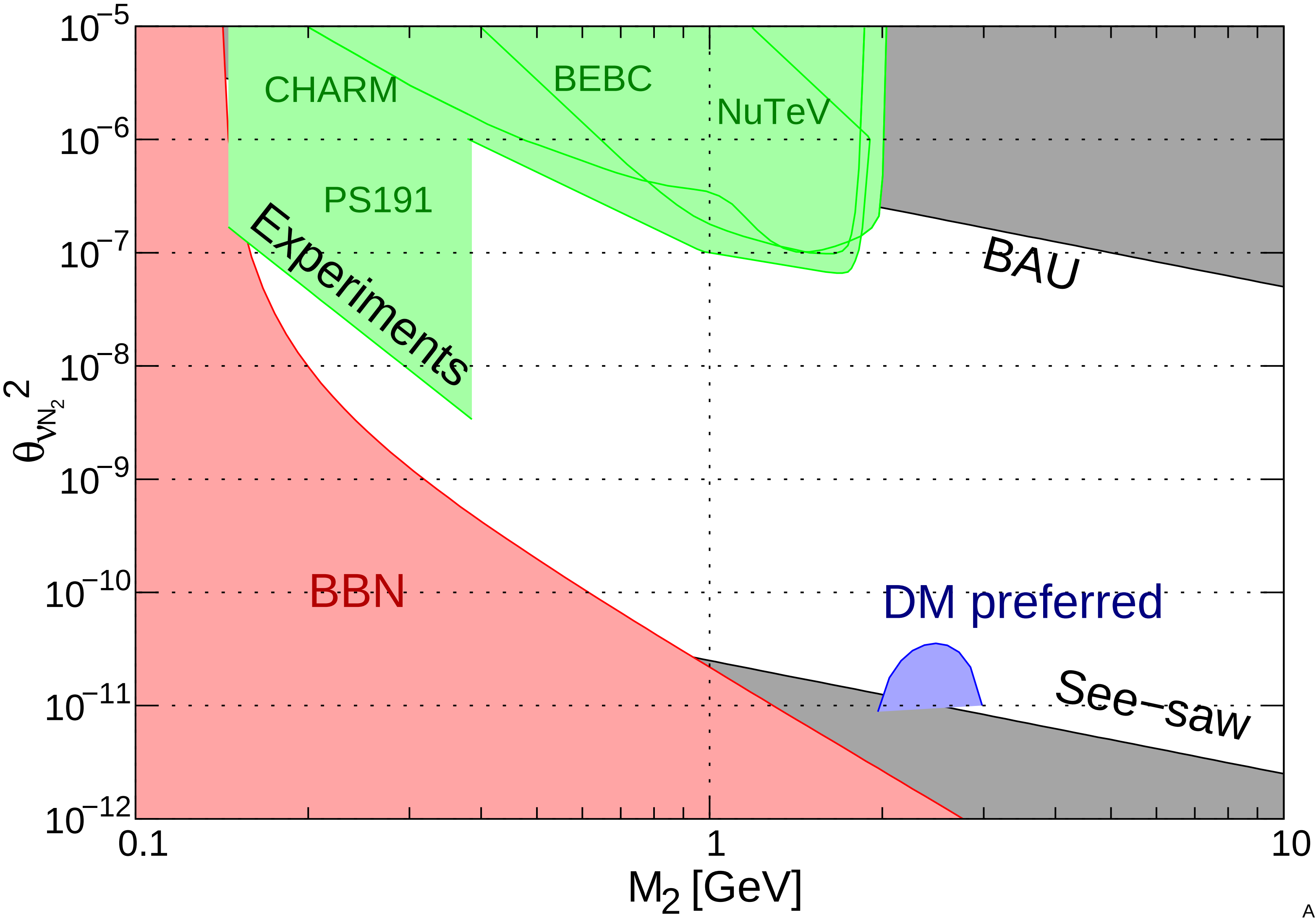
$N_{2,3}$: BAU + DM


10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12
θ_νN2^2
0.1
1
10
M_2 [GeV]
BAU
DM preferred
See-saw

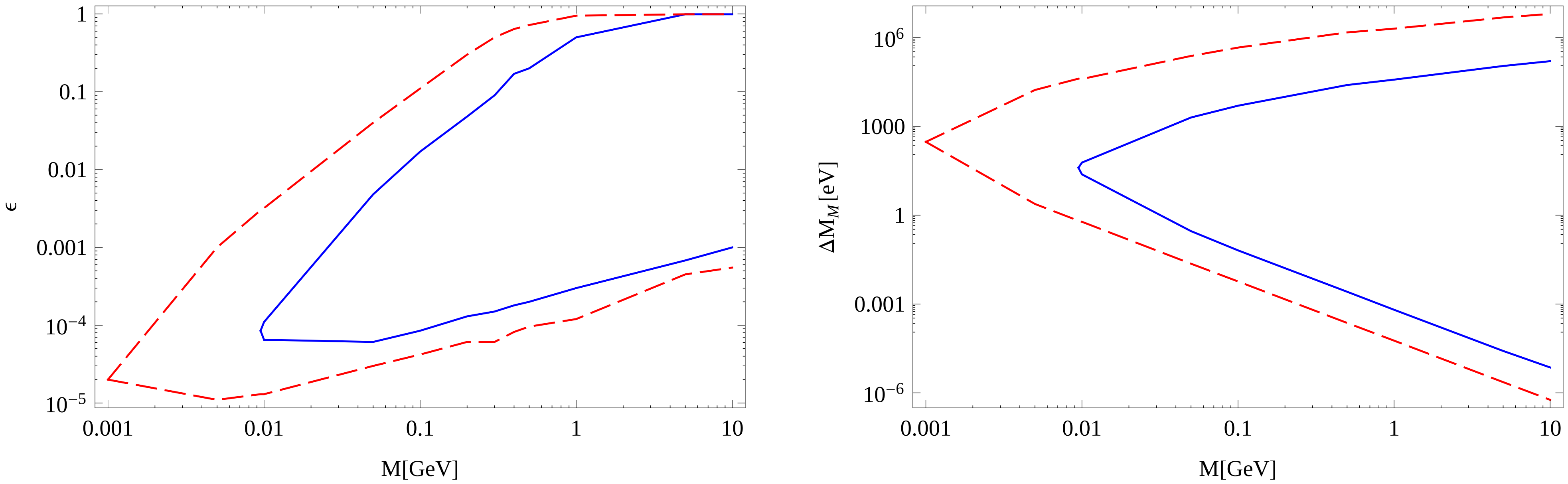
$N_{2,3}$: BAU + DM + BBN



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

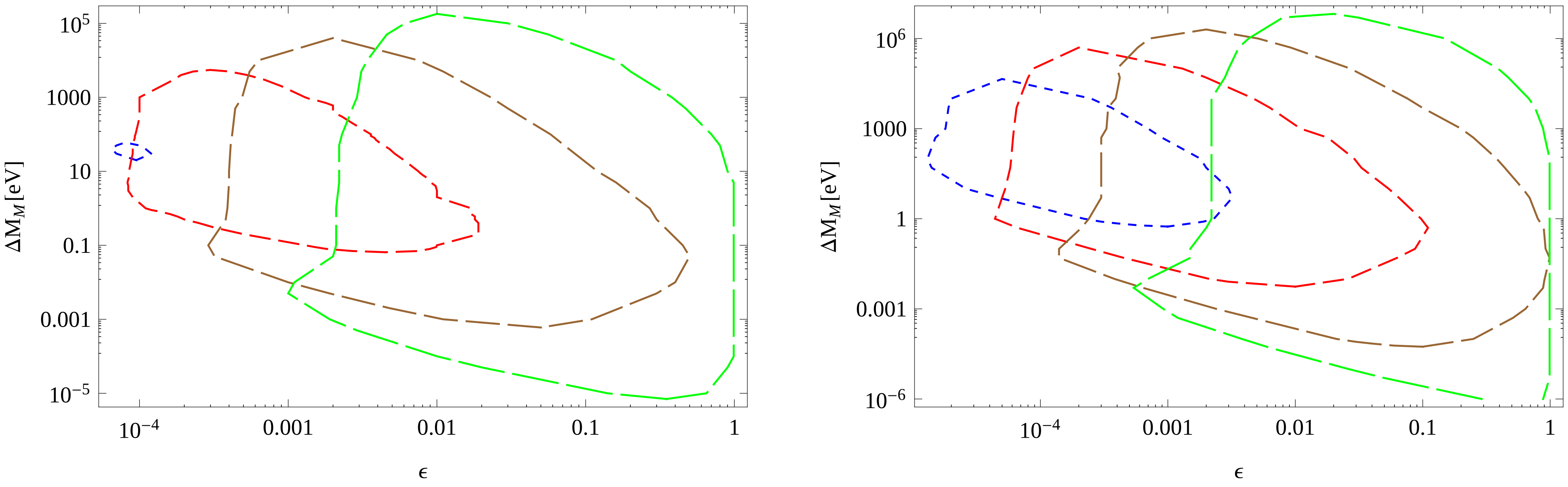


Canetti, M.S.

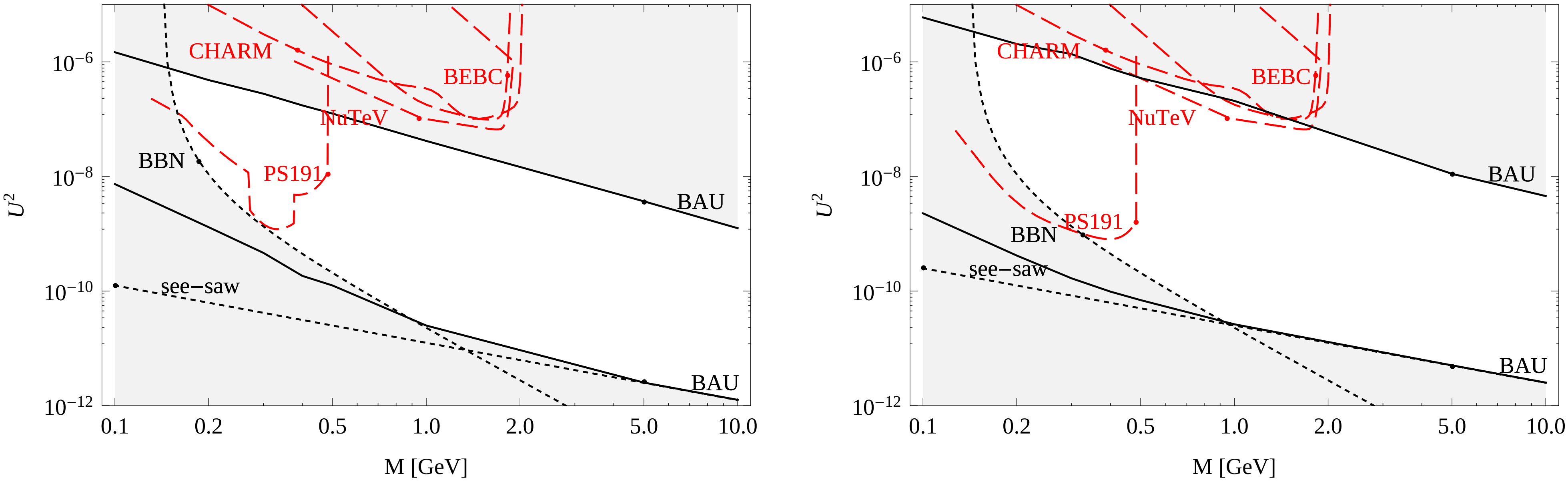


Values of ϵ - M (left panel) and ΔM_M - M (right panel) that leads to the observed baryon asymmetry for the normal hierarchy and for the inverted one. Degeneracy $\Delta M_M \ll M$ is required for resonant baryon asymmetry generation.

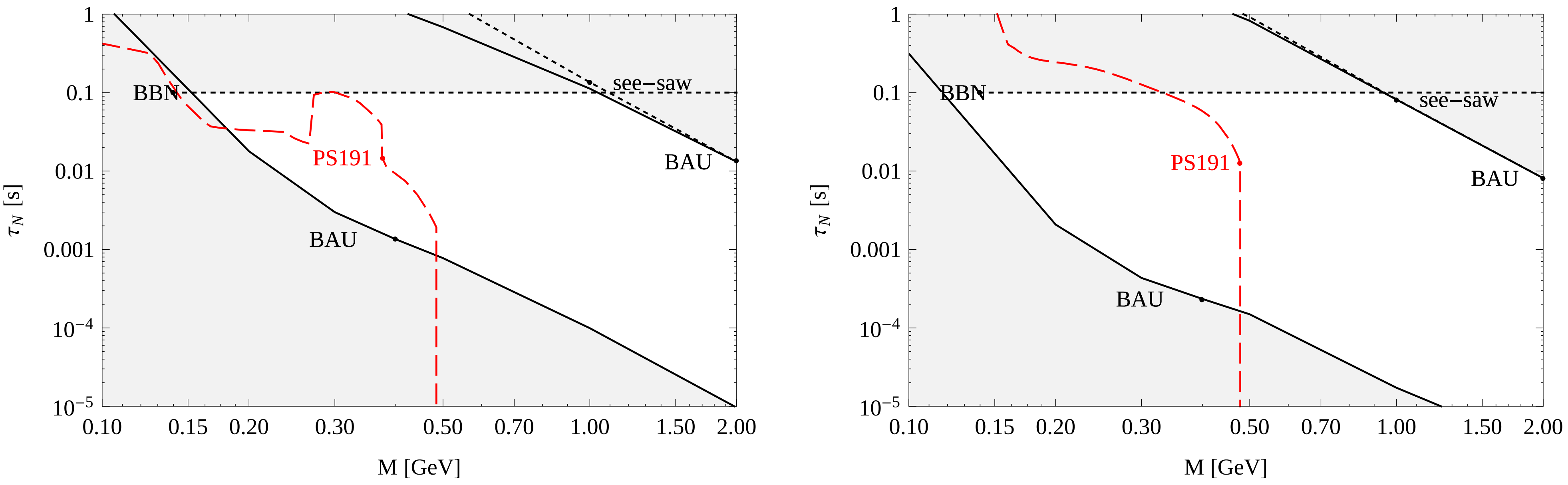
$$\epsilon = \frac{coupling\ of\ N_2}{coupling\ of\ N_3}$$



Values of $\boldsymbol{\Delta M_M}$ and $\boldsymbol{\epsilon}$ that lead to the observed baryon asymmetry for different singlet fermion masses, $\boldsymbol{M = 10}$ MeV, $\mathbf{100}$ MeV, $\mathbf{1}$ GeV, and $\mathbf{10}$ GeV. Left panel - normal hierarchy, right panel - inverted hierarchy.



Constraints on U^2 coming from the baryon asymmetry of the Universe (solid lines), from the see-saw formula (dotted line) and from the big bang nucleosynthesis (dotted line). Experimental searched regions are in red - dashed lines. Left panel - normal hierarchy, right panel - inverted hierarchy.

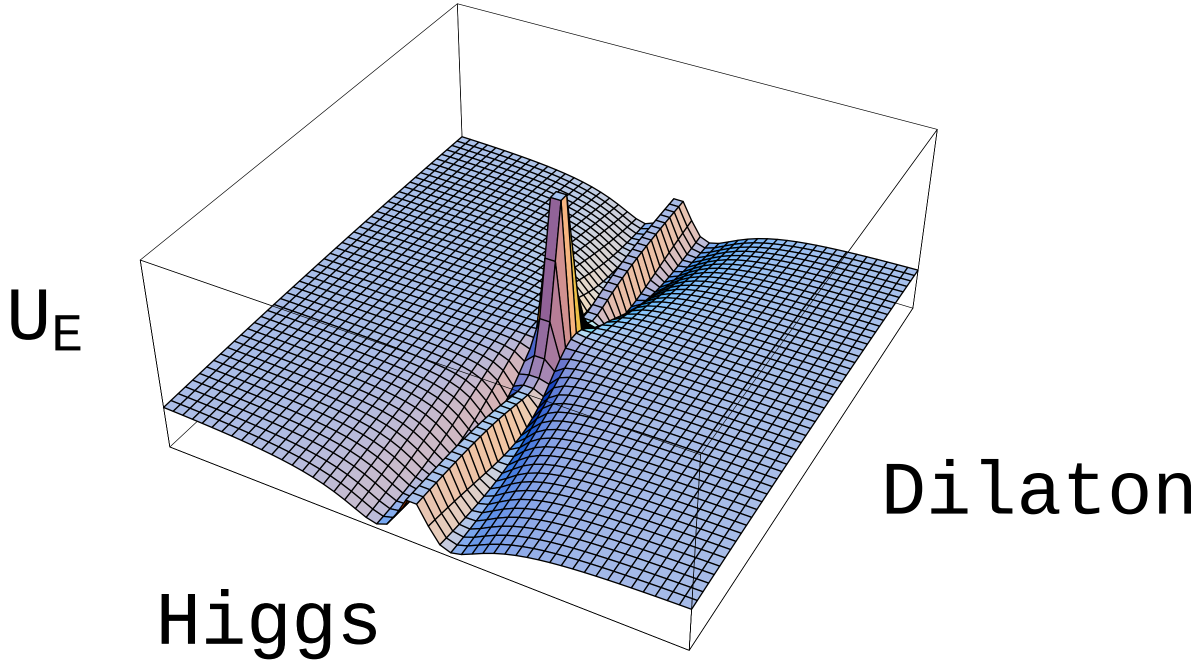


Constraints on the lifetime τ_N coming from the baryon asymmetry of the Universe (solid lines), from the see-saw formula (dotted line) and from the big bang nucleosynthesis (dotted line). Experimental constraints from PS 191 are shown in red - dashed lines. Left panel - normal hierarchy, right panel - inverted hierarchy.

Universe evolution in “no new scale scenario”

Stage 1: inflation and Big Bang

Chaotic initial condition: fields χ and h are away from their equilibrium values. Potential is flat due to non-minimal Higgs coupling to gravity



Higgs field driven inflation

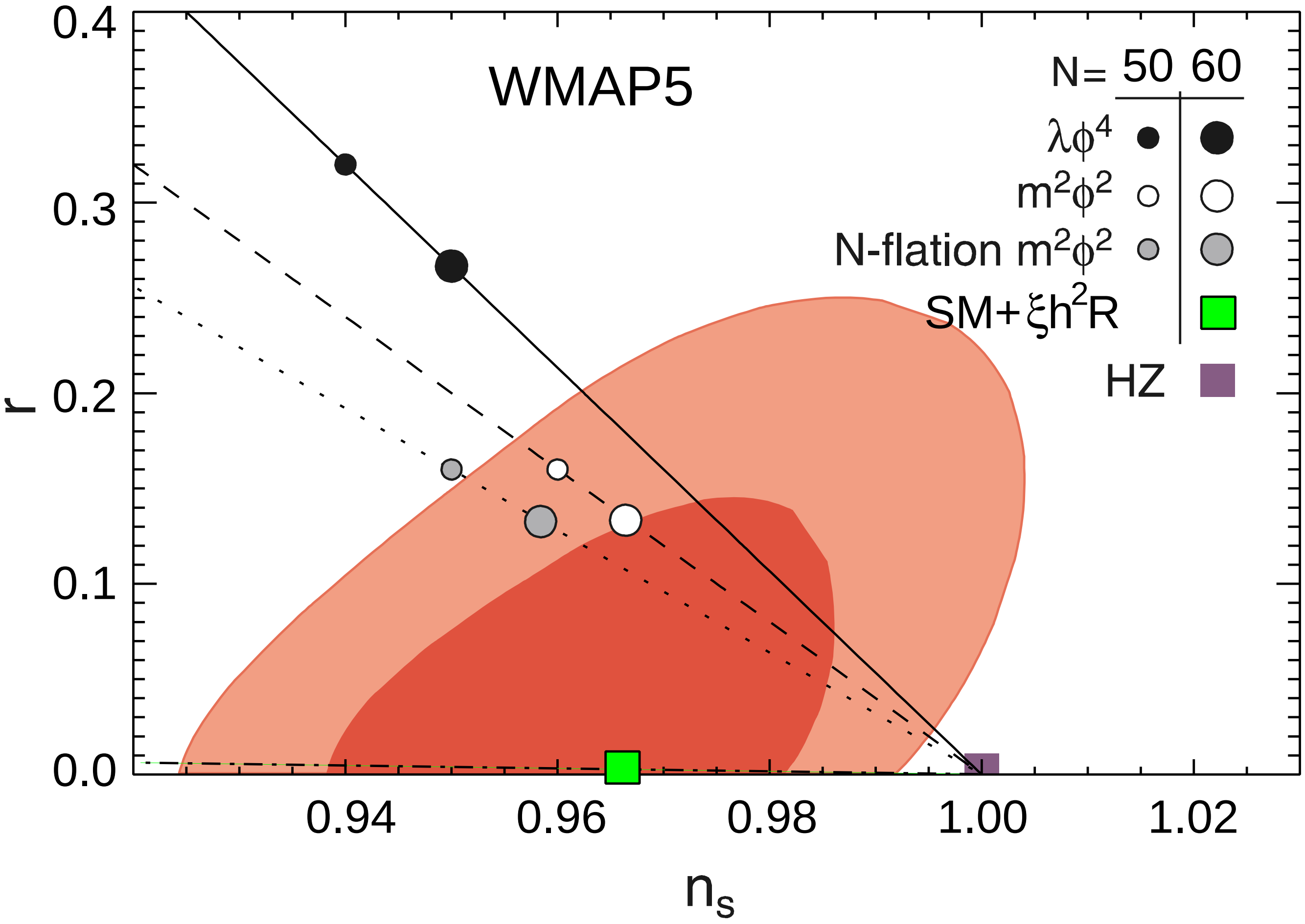
Three different periods:

- For scalar field $\phi > \frac{M_P}{\sqrt{\xi_h}}$ the potential is essentially *flat*. Exponential expansion of the Universe.
- For scalar field $\frac{M_P}{\sqrt{\xi_h}} > \phi > \frac{M_P}{\xi_h}$ the potential is essentially *quadratic*. Exponential expansion of the Universe is changed to the power low, corresponding to matter domination. Particle creation takes place when ϕ passes through zero.
- After $\mathcal{O}(\xi_h)$ oscillations the scalar field reaches $\phi \simeq \frac{M_P}{\xi}$. The energy is transferred to other fields of the SM, and the radiation-dominated epoch starts,

$$T_r \simeq (3.3 - 8.3) \times 10^{13}\ \text{GeV}.$$

Bezrukov, Gorbunov, M.S., J. Garcia-Bellido, D. G. Figueroa, J. Rubio

CMB parameters—spectrum and tensor modes



Universe evolution in “no new scale scenario”

Stage 2: Baryogenesis, $T \sim EW\ scale$

N_2, N_3 with masses of ~ 1 GeV oscillate and produce lepton asymmetry, transferred to baryon asymmetry due to electroweak anomaly. Depending on parameters, this occurs at $T \sim 200 - 10^4$ GeV

Stage 3: Dark matter production, $T \sim 100$ MeV

Dark matter sterile neutrino N_1 with mass ~ 10 keV is produced in active-sterile transitions, which can be enhanced due to lepton asymmetry generation in $N_2,\ N_3$ decays

Universe evolution in “no new scale scenario”

Stage 4: Dark energy domination

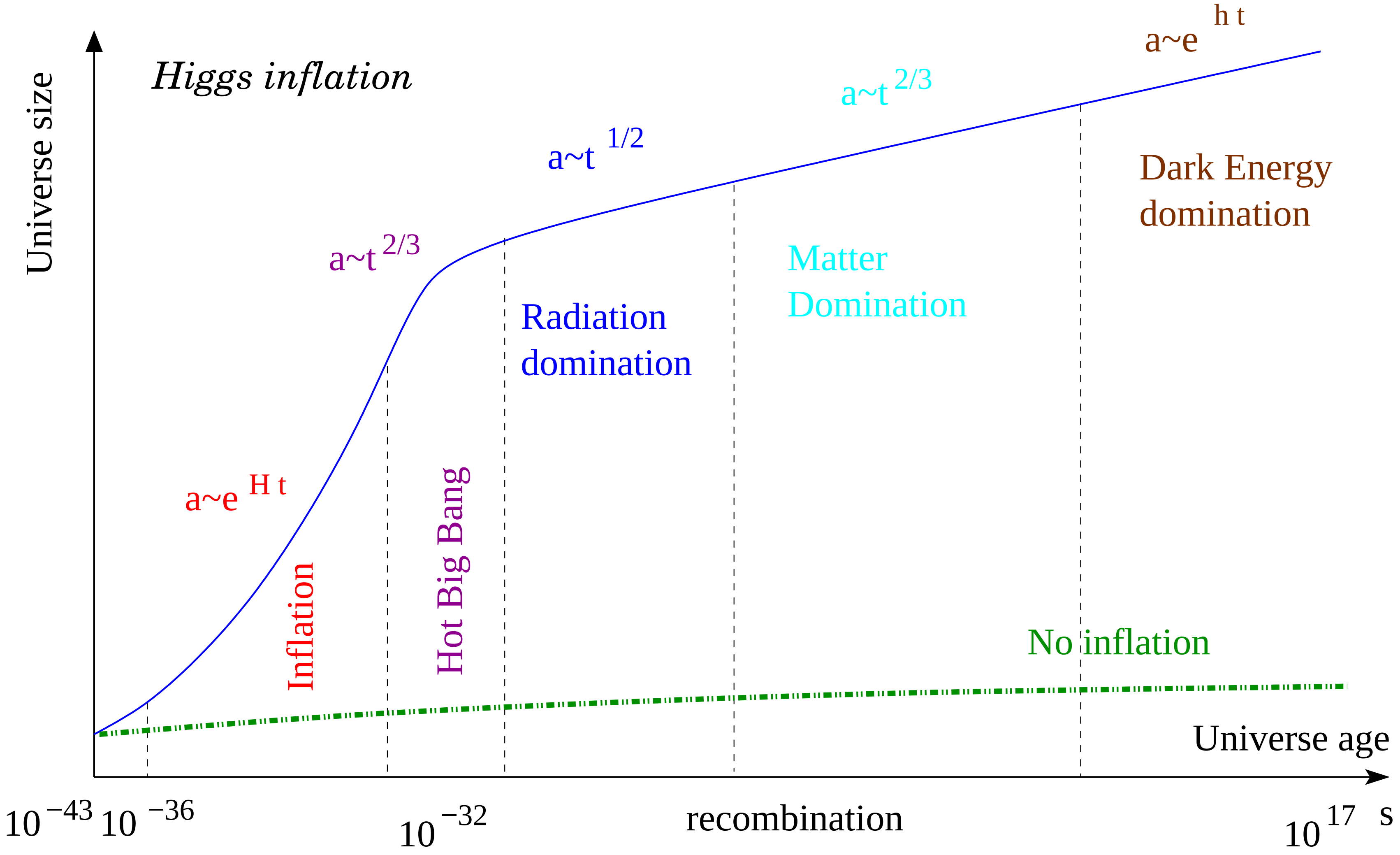
Late time evolution of dilaton ρ along the valley, related to χ as

$$\chi = M_P \exp\left(\frac{\gamma\rho}{4M_P}\right), \quad \gamma = \frac{4}{\sqrt{6 + \frac{1}{\xi_\chi}}} .$$

Potential: Wetterich; Ratra, Peebles

$$U_\rho = \frac{\Lambda}{\xi_\chi^2} \exp\left(-\frac{\gamma\rho}{M_P}\right) .$$

Λ - parameter coming from unimodular gravity. From observed equation of state: $0 < \xi_\chi < 0.09$. Result: equation of state parameter $\omega = P/E$ for dark energy must be different from that of the cosmological constant, but $\omega < -1$ is not allowed.


Higgs inflation
Universe size
$a \sim e^{h\,t}$
$a \sim t^{2/3}$
$a \sim t^{1/2}$
Dark Energy domination
$a \sim t^{2/3}$
Matter Domination
Radiation domination
$a \sim e^{H\,t}$
Hot Big Bang
Inflation
No inflation
Universe age
10^{-43} 10^{-36}
10^{-32}
recombination
10^{17} s

Challenges of “no new scale scenario”

Theoretical problems

- Higgs inflation requires large non-minimal coupling of the Higgs field to Ricci scalar, $\xi H^2 R$, $\xi \sim 10^3 - 10^5$. This leads to strong coupling at energies $E > \Lambda(H)$, where $\Lambda(H)$ is the background-dependent cutoff. Though Higgs inflation was shown to be self-consistent (Bezrukov, Magnin, M.S. Sibiryakov), the UV completion, if any, of the SM in this energy domain remains obscure.
- Though the hierarchies of the masses and mass splittings of singlet fermions, required by phenomenology, are “natural” in technical sense and can be a consequence of slightly broken U(1) leptonic symmetry, their origin remains unexplained
- We are still far from precise computation (with controllable error bars) of baryon and lepton asymmetries in the νMSM.
- Quantum scale invariance and gravity
- ...

"Easy" to rule out: one of the predictions - no new physics above the EW scale (e.g. SUSY, composite Higgs, large extra dimensions, WIMPS, etc., etc.), except the Higgs boson in the specific mass interval. Will be checked at LHC. None of the "3σ" indications of new physics fit to the νMSM:

- Fermilab (CDF): W +jj, peak at $\simeq 144$ GeV; 4.4.2011
- Fermilab (CDF): forward-backward asymmetry in top quark production, 4.1.2011
- Fermilab (D0): anomalous like-sign dimuon charge asymmetry; May 16, 2010
- Fermilab (MiniBooNE): event excess in the search for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations, July 7, 2010
- Fermilab (MiniBooNE): unexplained excess of electron-like events from a 1-GeV neutrino beam, December 11, 2008
- PAMELA: cosmic-ray positron excess
- DAMA: annual modulation of the counting rate
- The reactor neutrino anomaly (G. Menton et al, arXiv:1101.2755)
- Heidelberg neutrinoless double β decay
- Discrepancy between experiment and the theory prediction of anomalous magnetic moment of muon
- ...

Difficult to confirm directly: new dedicated experiments are needed!

Search for νMSM new physics:

- Decays of singlet fermions $N_{2,3}$ created in fixed target experiments with the use of CERN SPS proton beam (or similar, like X-project at FNAL), e.g. $N_{2,3} \to \pi^+\mu^-$.
- precision study of kinematics of K, charm and beauty mesons, e.g. $K^+ \to \pi^+ N_{2,3}$ at very high intensity B or charm factories
- X-rays from decays of Dark Matter neutrinos $N_1 \to \nu\gamma$: X-ray spectrometer in Space with good energy resolution $\delta E/E \sim 10^{-3} - 10^{-4}$ getting signals from our Galaxy and its Dwarf satellites.
- How to find massless dilaton? Due to its Goldstone character, it has only derivative couplings to matter suppressed by the Planck scale and thus is not a subject to 5th force constraints.