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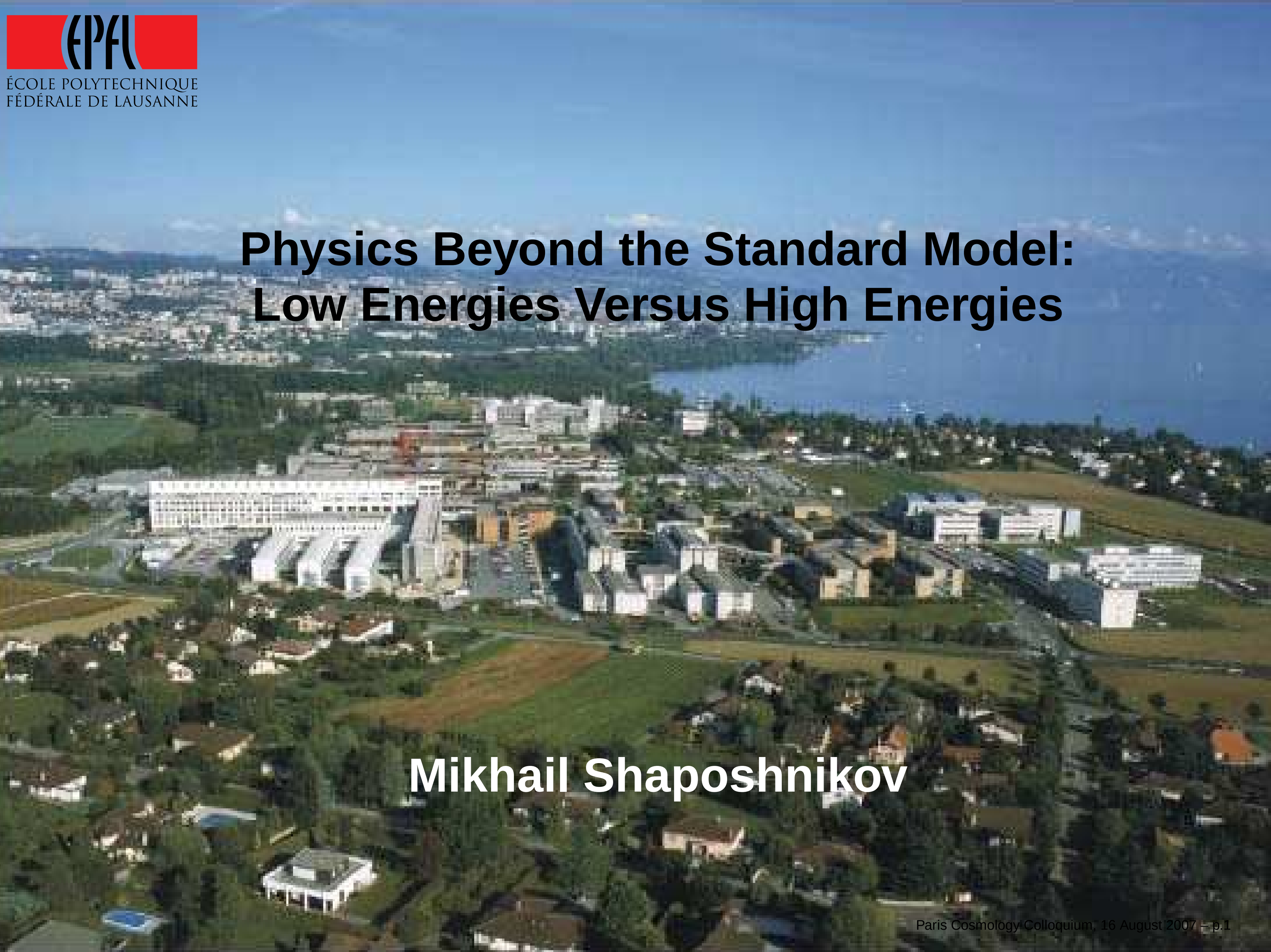

Physics Beyond the Standard Model: Low Energies Versus High Energies

Mikhail Shaposhnikov

Outline

- Why the SM must be extended?
- Do we really need an intermediate energy scale between M_W and M_{Planck}?
- The νMSM as a unified description of neutrino oscillations, dark matter, and baryon asymmetry of the Universe
- Crucial test and experiments

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Yes from field theory point of view: but only if $M_H \in [129, 189]\ \mathrm{GeV}$. Then the Landau pole is above the Planck scale and the EW symmetry breaking vacuum is stable.

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What about experiment?

Suppose that the SM is an effective field theory valid up to the Planck scale.

Low energy Lagrangian can contain all sorts of higher-dimensional SU(3)×SU(2)×U(1) invariant operators, suppressed by the Planck scale:

$$L = L_{\rm SM} + \sum_{n=5}^{\infty} \frac{O_n}{M_{Pl}^{n-4}} \,.$$

Majorana neutrino mass: from five-dimensional operator

$$O_5 = A_{\alpha\beta}\left(\bar{L}_\alpha \tilde{\phi}\right)\left(\phi^\dagger L_\beta^c\right)$$

Prediction: $m_\nu \sim v^2/M_{Pl} \simeq 10^{-6}$ eV – far away from experimental observations!

SM cannot be right all the way to M_{Pl}!

Cosmological arguments

- No particle physics candidate for Dark Matter
- No baryogenesis
- No inflation: Higgs does not work as an inflaton. The Planck scale inflation seems unlikely: the vacuum energy density during inflation is limited from above by $V_{inf} \lesssim 10^{-11} M_{Pl}^4$.
- Accelerated expansion of the Universe – dark energy.

Naturalness arguments

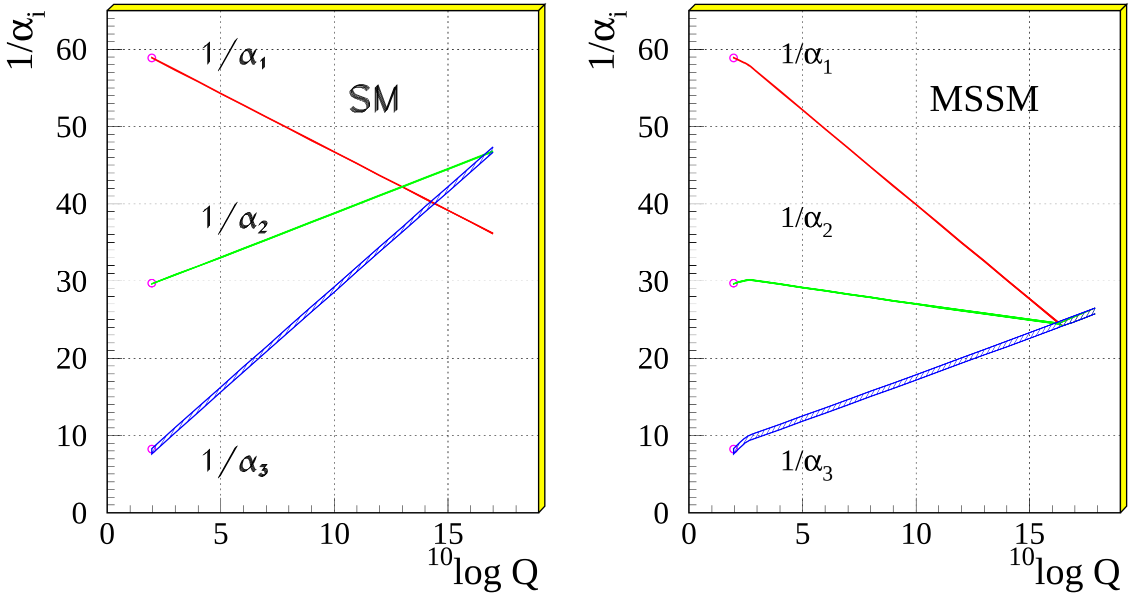
- Hierarchy: why $M_W \ll M_{Pl}$?
- Why cosmological constant is so small?
- Why CP is conserved in strong interactions? ($\theta_{QCD} \ll 1$)
- Why $m_e \ll m_t$?
- ...

Overwhelming point of view: these problems should find their solution by physics beyond the SM which contains some intermediate energy scale

$$M_W < M_{new} < M_{Planck}$$

Gauge coupling unification: the three couplings of the SM intersect with each other at three points scattered between $\mathbf{10^{13}}$ and $\mathbf{10^{17}}$ GeV – indication for Grand Unification at $M_{GUT} \sim \mathbf{10^{16}}$ GeV (?)

The constants of the SM do not meet at the same point: there must exist one more intermediate threshold for new physics between the GUT scale and the electroweak scale, chosen in such a way that all the three constants do intersect at the same point – indication for low energy supersymmetry (?)



Ways out

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Gauge coupling unification at M_{Pl}! (Hill, 1984; Shafi and Wetterich, 1984...)

Take any GUT and add $4+n,\ n \geq 1$ dimensional operators like

$$\mathrm{Tr}\left[F^2\Phi^n\right]/M_{Pl}^n$$

If $\langle\Phi\rangle \sim M_{Pl}$ higher dimensional operators can shift the crossing point to M_{Pl}– unification of gravity with other forces!

Inflation: Take the simplest quadratic potential

$$V(\chi) = \frac{1}{2} m_\chi^2 \chi^2 \; .$$

It fits very well the CMB data with $m_\chi \sim 10^{13}$ GeV.

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New scale? Not necessarily:

The CBM constraints the inflaton potential (single field inflation) only for $\chi \sim M_{Pl}$ and tells nothing about the structure of $V(\chi)$ near its minimum! Inflaton may be very light whereas large V_{inf} may come from its self-interactions. Even a pure $\beta\chi^4$ potential (massless inflaton) provides a reasonable fit to the WMAP data with just 3σ off the central values for inflationary parameters (can be corrected by a slight modification of the potential at $\chi \sim M_{Pl}$ by higher dimensional operators or by allowing non-minimal coupling.)

Strong CP-problem: Invisible axion solution to strong CP-problem: Peccei-Quinn scale is bounded from above and below by cosmology and astrophysics to be in the region $\mathbf{10^8}$ GeV $\lesssim M_{PQ} \lesssim \mathbf{10^{12}}$ GeV.

Intermediate scale appears again?

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Intermediate scale appears again? Not necessarily:

If extra dimensions have topology such that the mapping

$$\mathbf{D - dim\ Space} \rightarrow \boldsymbol{S_3}$$

is trivial no $\boldsymbol{\theta}$ angle exists! Planck scale compactification is sufficient - the solution to the strong CP-problem may occur at $\boldsymbol{M_{Pl}}$ (Khlebnikov, M.S., 1988, 2004)

Neutrino masses - the see-saw argument: add to the Lagrangian of the Standard Model a dimension five operator

$$A_{\alpha\beta}\left(\bar{L}_\alpha\tilde{\phi}\right)\left(\phi^\dagger L^c_\beta\right)$$

suppressed by an (unknown a-priory) mass parameter Λ and find it then from the requirement that this term gives the correct active neutrino masses. One gets:

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

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Not necessarily - will discus later!

Thermal leptogenesis: Out of equilibrium and conversion to baryon asymmetry conditions:

$$M_W < T_{decay} < M_N$$

Constraint on the decay Yukawa coupling $\Gamma_{\rm tot} \simeq f^2 M_N$:

$$\frac{M_W^2}{M_N M^*} < f^2 < \frac{M_N}{M^*}, \quad M^* \simeq 10^{18}{\rm GeV}$$

Baryon asymmetry for non-degenerate case ($\Delta M_{ij} \sim M_k$):

$$\frac{n_B}{s} \sim 10^{-3} f^2 \simeq 10^{-10}$$

for $f^2 \sim 10^{-7}$; works for $M_N > 10^{11}$ GeV.

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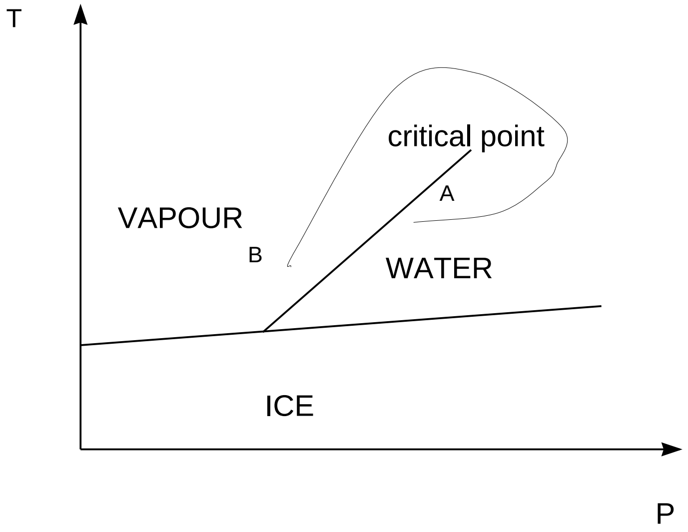
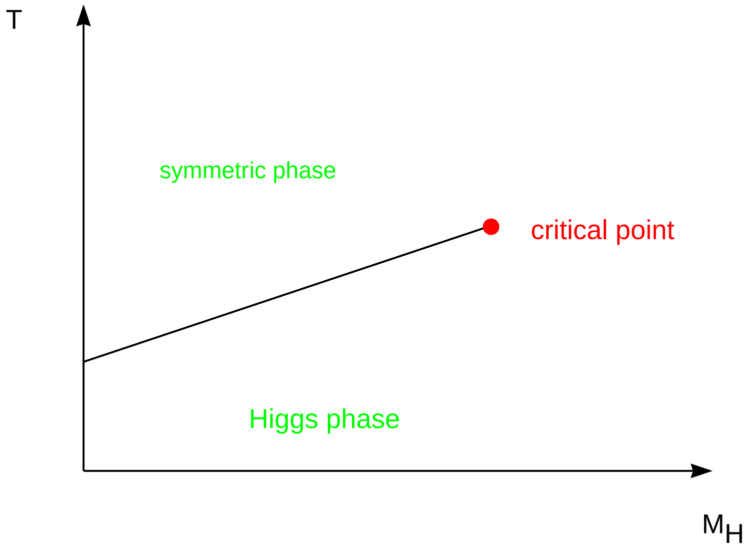


Typical condensed matter phase diagram (pressure versus temperature)



Electroweak theory

$\langle\phi^\dagger\phi\rangle \ll (250GeV)^2$

$T = 109.2 \pm 0.8GeV,$

$M_H = 72.3 \pm 0.7GeV$

$\langle\phi^\dagger\phi\rangle_{T=0} \sim (250\ \mathrm{GeV})^2$

To make first order EW phase transition: add new physics right above the EW scale.

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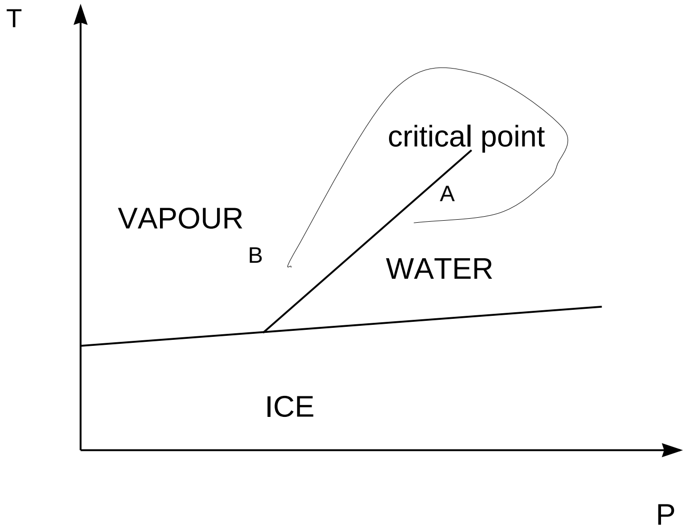

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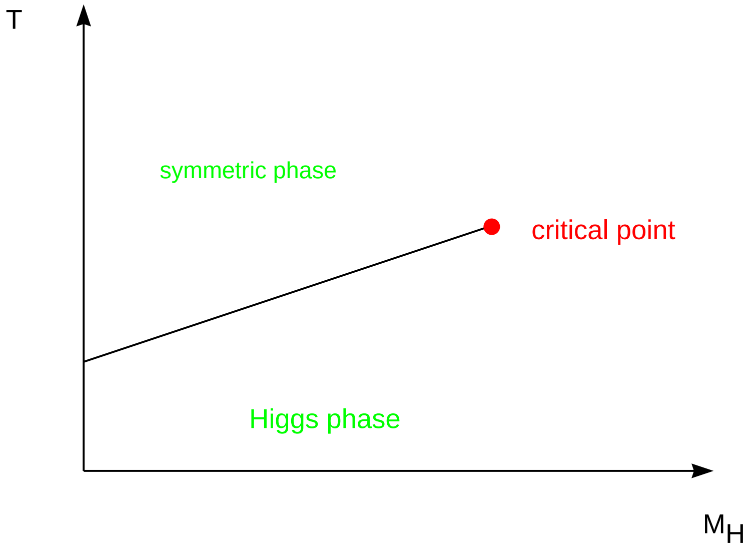

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Not necessarily - will discus later!

Dark matter from WIMPS: annihilation cross-section related to the scale $M \sim 100$ GeV gives roughly the right DM abundance.

New physics right above the EW scale?

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New physics right above the EW scale?

Not necessarily: This argument is based on the specific processes the dark matter can be created and destroyed and thus is not valid in general.

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- A minimal extention of the standard model, called νMSM, is a viable effective field theory up to the Planck scale
- the νMSM = MSM + three right-handed singlet fermions

the SM

There are 36 quark states: left fermionic doublets:

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

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9 + 3 leptonic states

$\boldsymbol{(\nu_e, e)_L,\ (\nu_\mu, \mu)_L,\ (\nu_\tau, \tau)_L}$ and $\boldsymbol{e_R,}$ $\boldsymbol{\mu_R,}$ $\boldsymbol{\tau_R}$

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

and one Higgs doublet,

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

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

the νMSM

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$(\nu_e, e)_L,\ (\nu_\mu, \mu)_L,\ (\nu_\tau, \tau)_L$ 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

Parameter counting: the νMSM

Most general renormalizable Lagrangian

$$L_{\nu MSM} = L_{MSM} + \bar{N}_I i\partial_\mu \gamma^\mu N_I - F_{\alpha I}\, \bar{L}_\alpha N_I \Phi - \frac{M_I}{2}\, \bar{N}_I^c N_I + h.c.,$$

Extra coupling constants:

3 Majorana masses of new neutral fermions N_i,

15 new Yukawa couplings in the leptonic sector

(3 Dirac neutrino masses $M_D = F_{\alpha I} v$, 6 mixing angles and 6 CP-violating phases),

18 new parameters in total.

The choice of scales of the νMSM

Require: $M_I < M_W$ (No see-saw)

There is no indication of the existence of GUT scale from neutrino oscillations!

Consequence: small Yukawa couplings,

$$F_{\alpha I} \sim \frac{\sqrt{m_{atm} M_I}}{v} \sim (10^{-6} - 10^{-13}),$$

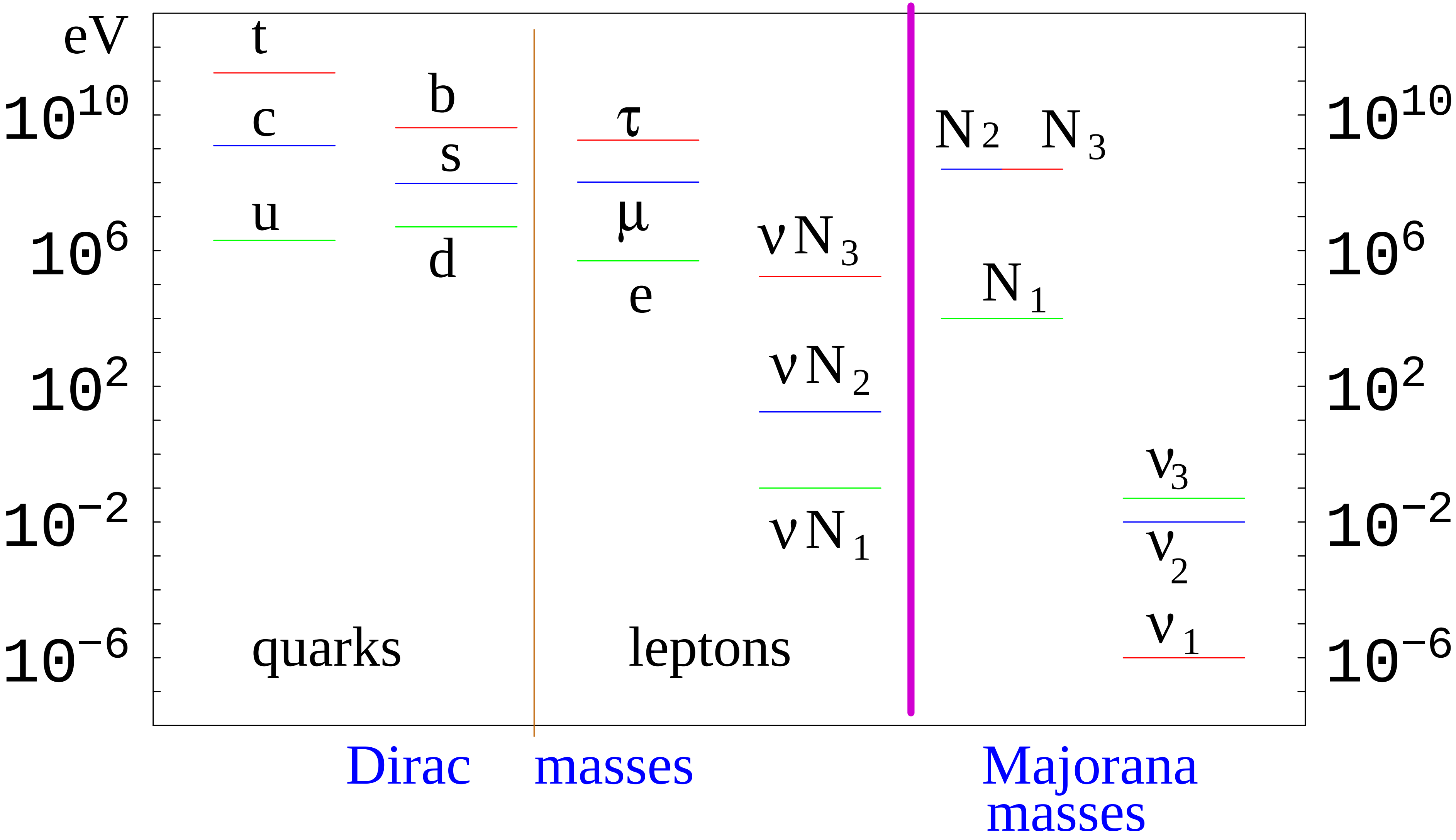
here $v \simeq 174$ GeV is the VEV of the Higgs field,

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

Highlights of the νMSM

- Consistent description of neutrino masses and oscillations.
- Can explain dark matter in the Universe.
- Can explain baryon asymmetry of the Universe.
- Charge quantization from requirement of cancellation of gauge and gravitational anomalies. (Not true for the SM !)
- Masses of new leptons are small: all parameters can potentially be determined experimentally!
- Prediction of the negative result of the MiniBooNE experiment.
- Astrophysical applications: talks by Alex Kusenko and Peter Biermann

The spectrum of the νMSM

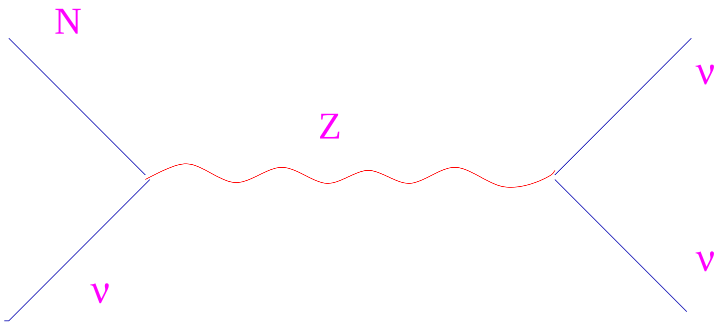


DM candidate: the lightest sterile neutrino

Dodelson, Widrow; Shi, Fuller; Dolgov, Hansen; Abazajian, Fuller, Patel

Interaction strength is very small

→ sterile N can be very stable.



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

Lifetime:

$$\tau_{N_1} = 5\times 10^{26}\,\text{sec}\left(\frac{1\ \text{keV}}{M}\right)^5\left(\frac{10^{-8}}{\theta^2}\right)$$

$$\theta = \frac{m_D}{M}$$

Constraints on the mass of dark matter sterile neutrinos

Tremaine, Gunn; Lin, Faber; Hogan, Dalcanton:

Rotational curves of dwarf spheroidal galaxies: $M > 0.3$ keV.

Hansen et al, Viel et al: Lyman-α forest observations can resolve inhomogeneities on small scales and put constraints on free streaming length.

- “Generic” warm dark matter:

  Viel et al., $M > 2$ keV, 2σ, Seljak et al., $M > 2.4$ keV, 95%.

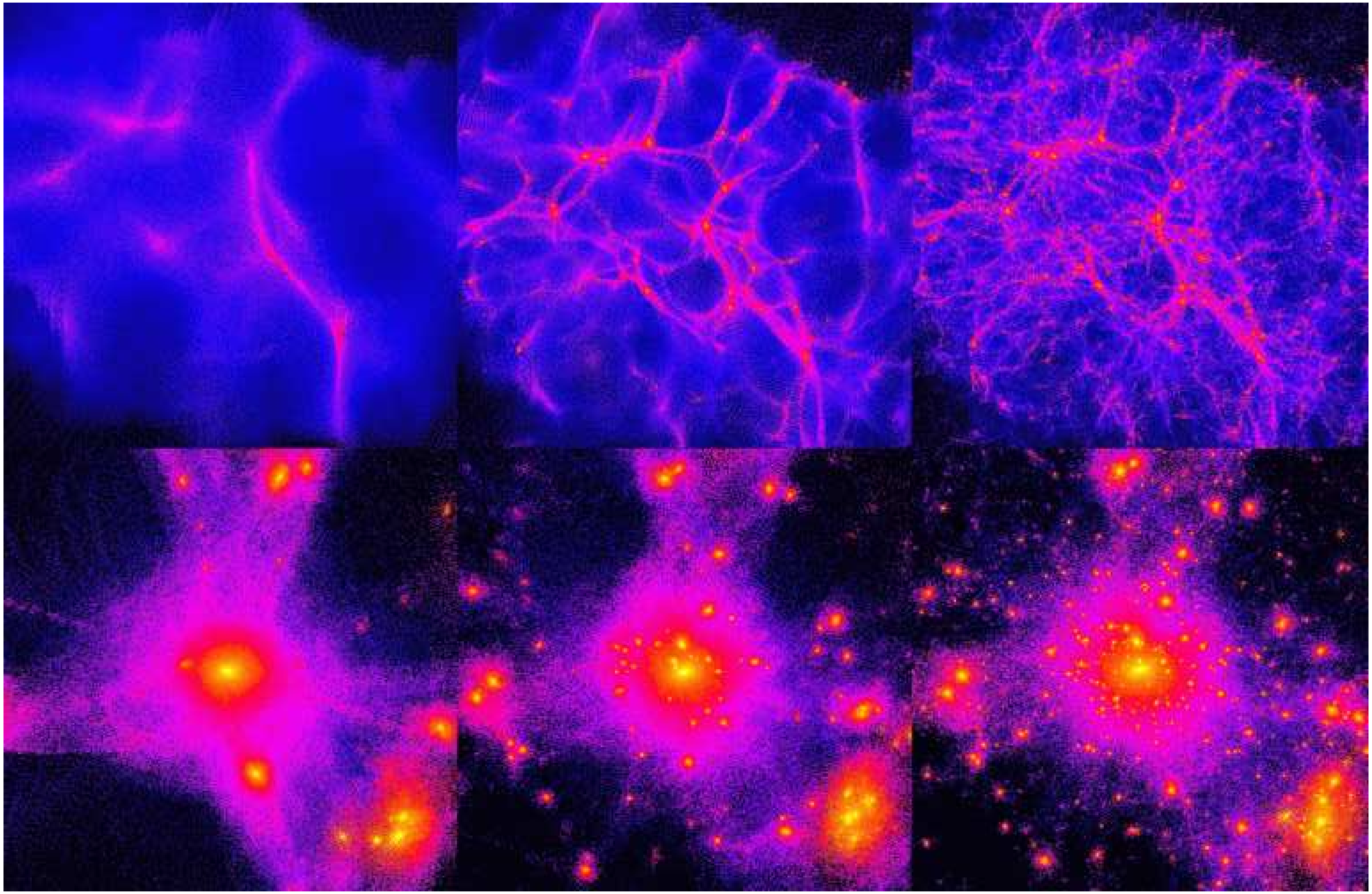
- Sterile neutrino produced in active-sterile transitions:

  Viel et al., $M > 8$ keV, 2σ

  Seljak et al., $M > 11.7$ keV, 95% and $M > 8.1$ keV, 99%.

For spectra appearing in other mechanisms of sterile neutrino production the simulations have never been performed.

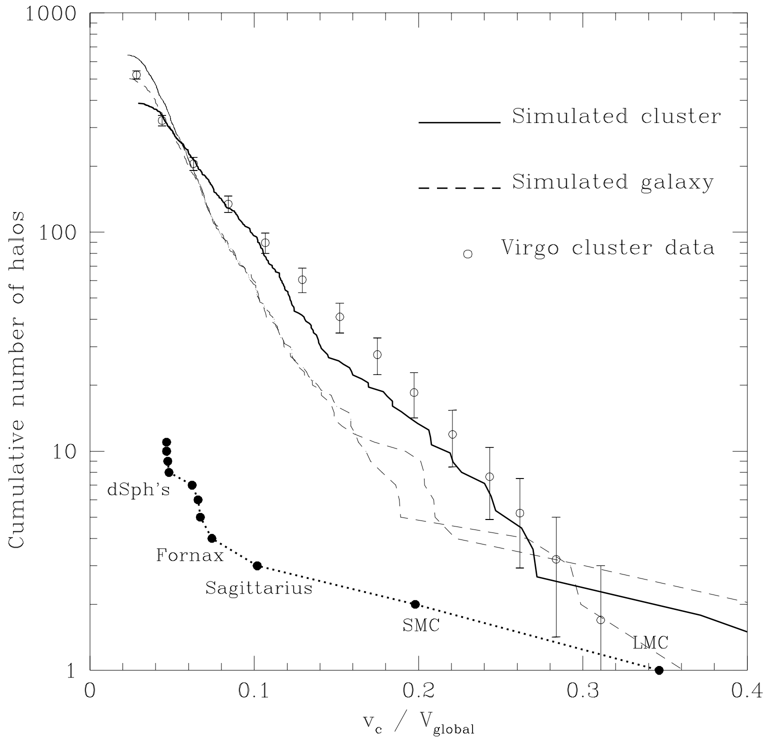
Hot DM Warm DM Cold DM

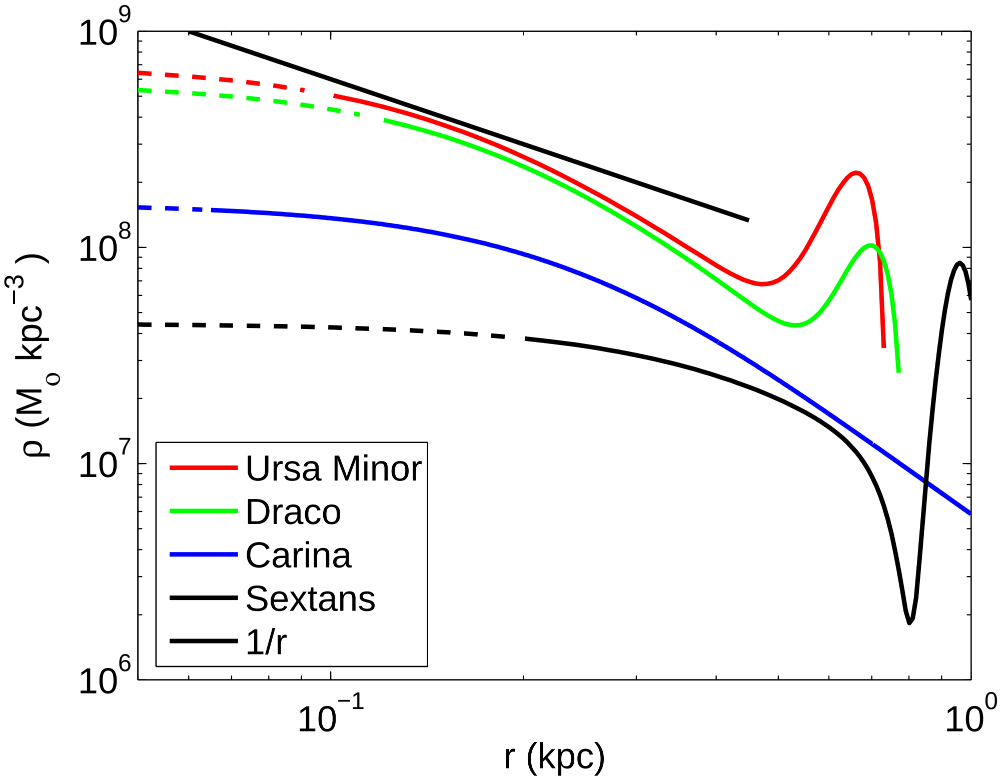


Ben Moore simulations

Warm versus Cold

Potentially, warm dark matter could solve some problems of the CDM scenario: [i] Cuspy profiles, [ii] Missing satellites problem (Bode, Ostriker, Turok; Klypin, Moore; Gilmore)





Cosmological production of sterile neutrinos

- Via active-sterile neutrino oscillations (Dodelson, Widrow)
  Most probably, this is ruled out: the required Yukawa coupling is too large to be consistent with X-ray and Lyman-α constraints.
- Via resonant active-sterile neutrino oscillations in the presence of lepton asymmetries (Shi, Fuller). Works well for sterile neutrinos in keV range.
- In inflaton (or any neutral scalar) decays (M.S., Tkachev). Can produce sterile neutrinos up to the mass of few MeV.

Baryon asymmetry

Baryon and lepton numbers are not conserved in the νMSM.

Lepton number: due to Majorana neutrino masses. Can be neglected for $M_I < M_W$. Rate of B non-conservation:

$$\Gamma \sim \begin{cases} \exp(-\frac{4\pi}{\alpha_W}) \sim 10^{-160}, & T = 0 \\ \exp\left(-\frac{M_{sph}}{T}\right), & T < M_W \\ (\alpha_W)^5 T^4, & T > M_W \end{cases}$$

These reactions are in thermal equilibrium for

$$100 \text{ GeV} < T < (\alpha_W)^5 M_{Pl} \sim 10^{12} \text{ GeV}$$

Baryon asymmetry

CP is non-conserved in the νMSM:

6 CP-violating phases in the lepton sector and

1 Kobayashi-Maskawa phase in the quark sector.

Deviations from thermal equilibrium:

there is no electroweak phase transition with allowed value for the Higgs mass.

$$\Downarrow$$

The only possible reason for non-equilibrium - sterile neutrinos.

Baryon asymmetry

Akhmedov, Rubakov, Smirnov

Asaka,MS

Idea - sterile neutrino oscillations as a source of baryon asymmetry.

Qualitatively:

- Sterile neutrino are created in the early Universe and oscillate in a coherent way with CP-breaking.
- The total lepton number is zero but gets unevenly distributed between active and sterile neutrinos.
- The lepton number of active left-handed neutrinos is transferred to baryons due to equilibrium sphaleron processes.

Kinetics of sterile neutrinos

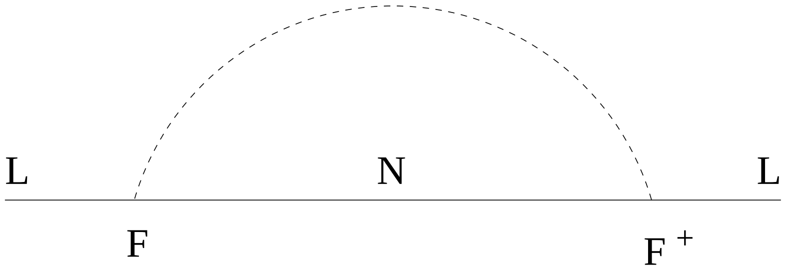
Asaka,MS

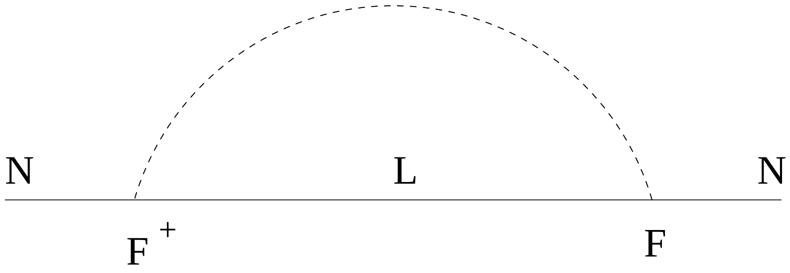
Facts to take into account:

(i) Coherence of sterile neutrino interactions → density matrix ρ_{NN} rather than concentrations.

(ii) Oscillations, creation and destruction of sterile and active neutrinos.

(iii) Dynamical asymmetries in active neutrinos and charged leptons.





Value of BAU

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

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

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

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

Inflation

A possibility to have inflation: add real scalar field, the inflaton χ. To reduce the number of parameters: suppose that inflaton-νMSM couplings are scale invariant on the classical level:

$$\mathcal{L}_{\nu\mathrm{MSM}} \to \mathcal{L}_{\nu\mathrm{MSM[M\to 0]}} + \frac{1}{2}(\partial_\mu \chi)^2 - \frac{f_I}{2}\,\bar{N_I}^c N_I \chi + \mathrm{h.c.} - \mathrm{V}(\Phi, \chi)\,.$$

Higgs-Inflaton potential:

$$V(\Phi, \chi) = \lambda\left(\Phi^\dagger\Phi - \frac{\alpha}{\lambda}\chi^2\right)^2 + \frac{\beta}{4}\chi^4 - \frac{1}{2}m_\chi^2\chi^2,$$

Chaotic inflation:

$$\beta \simeq 10^{-13}, \quad \alpha \lesssim 10^{-7}, \quad f_I \lesssim 10^{-3}$$

Electroweak symmetry breaking:

$$\langle \chi \rangle \neq 0 \rightarrow M_H \neq 0, \;\; M_I \neq 0$$

For $\alpha > \beta$ inflaton mass is smaller than the Higgs mass, $m_I < M_H$.

Sterile neutrino production in inflaton decays

Inflaton with mass $m_I > 300$ MeV is in thermal equilibrium thanks to reactions $\chi \leftrightarrow e^\dagger e,\ \chi \leftrightarrow \mu^\dagger \mu$ down to $T < m_I$.

Sterile neutrino abundance due to inflaton decays: $\chi \to NN$:

$$\Omega_s \simeq \frac{0.26 f(m_I)}{S} \frac{\Gamma M_0 m_s}{m_I^2 \times 12\ \mathrm{eV}} \frac{2\pi\zeta(5)}{\zeta(3)}\ ,$$

For $m_I \sim 300$ MeV the correct Ω_s is obtained for $m_s \sim 16 - 20$ keV.

For $m_I \sim 100$ GeV the correct Ω_s is obtained for $m_s \sim \mathcal{O}(10)$ MeV.

Conclusions

None of the arguments in favour of existence of the intermediate energy scale really requires it:

- gauge coupling unification and solution of the strong CP-problem can both occur at the Planck scale
- inflation, neutrino masses, dark matter and baryogenesis can all be explained by the particles with the masses below the electroweak scale

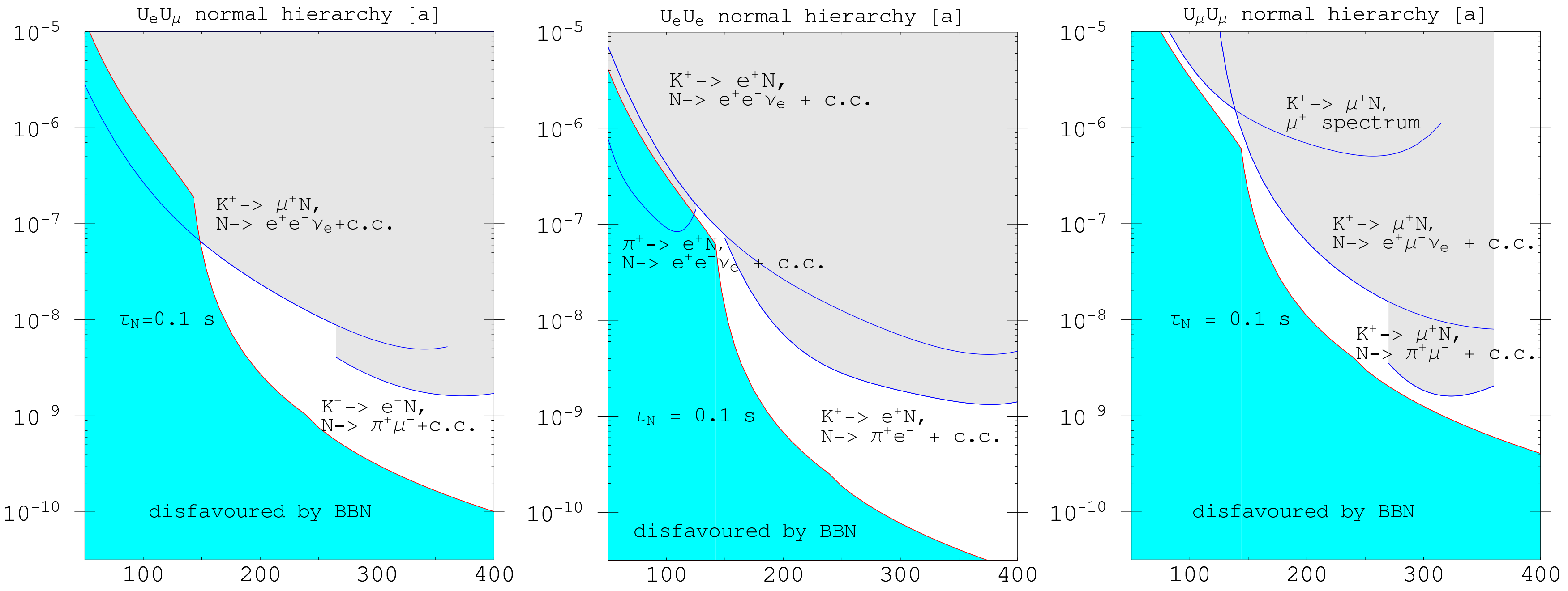
Crucial test and experiments

Particle Physics

- LHC: nothing but the Higgs with the mass in the window $M_H \in [129, 189]$ GeV
- ILC: No new physics at the ILC
- No sign of proton decay or neutron-antineutron oscillations
- Spectrum of active neutrino masses must be hierarchical, with $m_1 \ll m_{sol}$
- Two other masses are fixed to be $m_3 = [4.8^{+0.6}_{-0.5}] \cdot 10^{-2}$ eV and $m_2 = [9.05^{+0.2}_{-0.1}] \cdot 10^{-3}$eV ($[4.7^{+0.6}_{-0.5}] \cdot 10^{-2}$eV) in the normal (inverted) hierarchy
- Existence of two almost degenerate weakly coupled singlet leptons, $M_N < 20$ GeV, $\Delta M/M < 10^{-5}$, $10^{-11}\left(\frac{\text{GeV}}{M}\right) < \theta^2 < 10^{-8}\left(\frac{\text{GeV}}{M}\right)^2$
- Missing energy signal in $K,\ D,\ \tau$ and B decays

Experimental and BBN constraints

CERN PS191 experiment (1988)



Astrophysics

- X-rays from decays of Dark Matter neutrinos $N \to \nu\gamma$: 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
- WIMP and axion searches: nothing

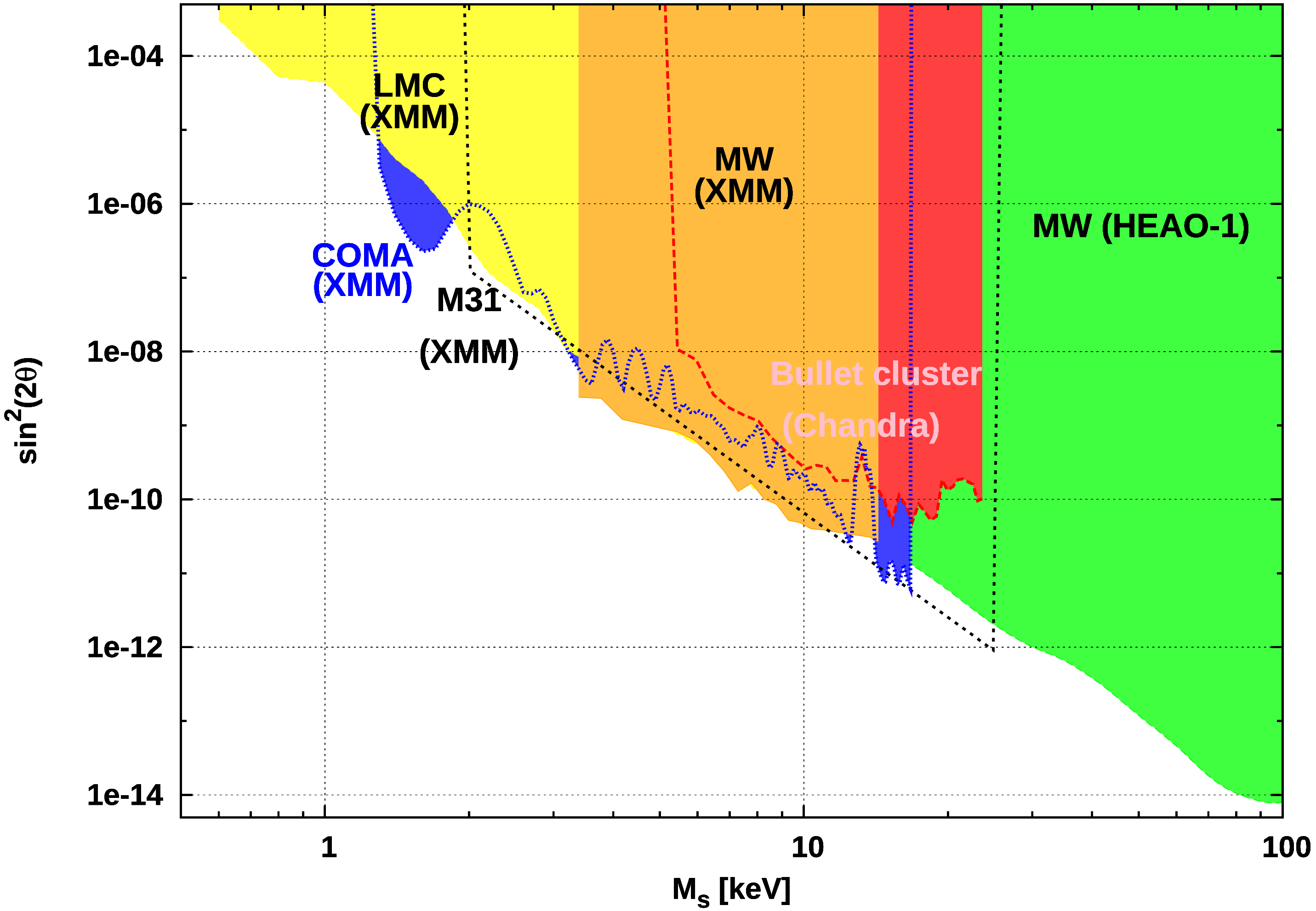
MW (HEAO-1): Boyarsky et al. 2005

Coma and Virgo clusters: Boyarsky et al.

LMC+MW(XMM): Boyarsky et al.

MW (Chandra): Riemer-Søorensen et al.; Abazajian et al.

M31: Watson et al.



Fine print: all results subject to intrinsic factor ~ 2 uncertainty!