ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Is there a new physics between electroweak and Planck scale ?

Mikhail Shaposhnikov

LAUNCH 09 - Heidelberg, MPIK

Yes

- proton decay yes (?)
- new physics at LHC yes (?)
- searches for DM WIMPS yes (?)
- searches for DM annihilation yes (?)
- searches for axions yes (?)

No

- proton decay no
- Higgs and nothing else at LHC
- searches for DM WIMPS no
- searches for DM annihilation no
- searches for axions no

Outline

- Is there a new physics beyond SM?
- Intermediate energy scale between M_W and M_{Planck}: pros and cons
  - Gauge couplings unification: GUTs and SUSY
  - Higgs mass hierarchy problem
  - Inflation
  - Strong CP problem
  - See-saw and neutrino masses
  - Dark matter
  - Baryogenesis
- Alternative to intermediate energy scale
- Crucial test and experiments

Why the SM must be extended?

Why the SM must be extended?

Can the stand alone Standard Model be a final theory?

Why the SM must be extended?

Can the stand alone Standard Model be a final theory?

Not from field theory point of view: it suffers from triviality problem due to Higgs self-coupling and U(1) gauge coupling!

Why the SM must be extended?

Can the stand alone Standard Model be a final theory?

Not from field theory point of view: it suffers from triviality problem due to Higgs self-coupling and U(1) gauge coupling!

Can the Standard Model as an effective field theory be valid all the way up to the Planck scale?

Why the SM must be extended?

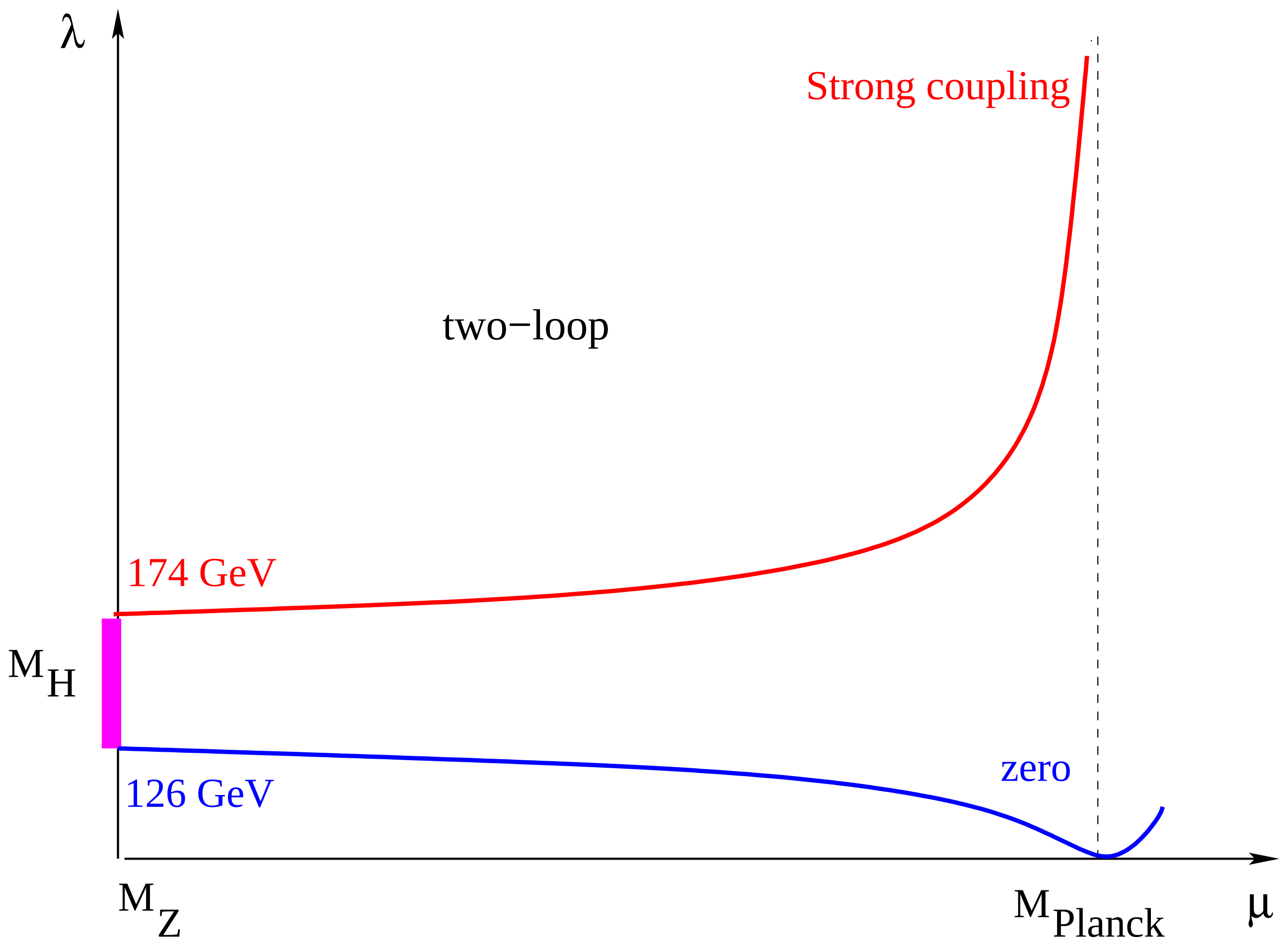
Can the stand alone Standard Model be a final theory?

Not from field theory point of view: it suffers from triviality problem due to Higgs self-coupling and U(1) gauge coupling!

Can the Standard Model as an effective field theory be valid all the way up to the Planck scale?

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

Behaviour of the scalar self-coupling



Validity of the SM

Two loop results:

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

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

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

theory error in $m_{\min} \simeq \pm 2$ GeV.

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
- 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

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

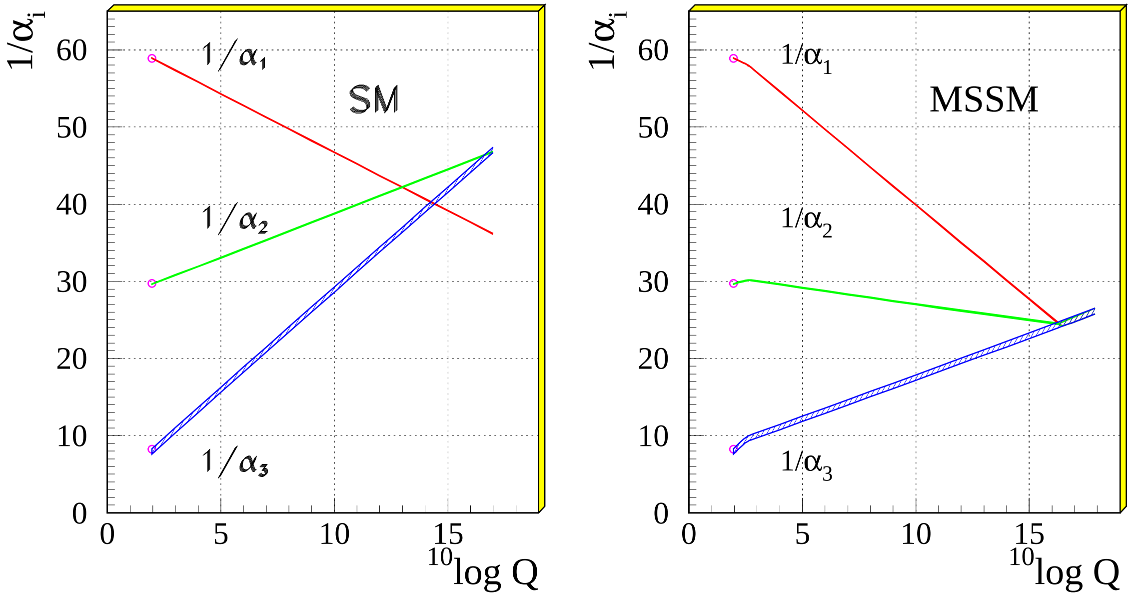
Intermediate energy scale between M_W and M_{Planck}: pros and cons

Intermediate energy scale between M_W and M_{Planck}: pros and cons

Gauge couplings unification: GUTs and SUSY

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

Possibility No 1:

Ways out

Possibility No 1:

The standard model gauge couplings evolve and do not meet at the same point.

Ways out

Possibility No 1:

The standard model gauge couplings evolve and do not meet at the same point.

This is an indication that there is no Grand unification.

Possibility No 2

Ways out

Possibility No 1:

The standard model gauge couplings evolve and do not meet at the same point.

This is an indication that there is no Grand unification.

Possibility No 2

Gauge coupling unification at M_{Pl}! (Hill, 1984; Shafi and Wetterich, 1984..., Calmet et al, 2009)

Ways out

Possibility No 1:

The standard model gauge couplings evolve and do not meet at the same point.

This is an indication that there is no Grand unification.

Possibility No 2

Gauge coupling unification at M_{Pl}! (Hill, 1984; Shafi and Wetterich, 1984..., Calmet et al, 2009)

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

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

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

Higgs mass hierarchy problem

Actually, two different problems:

- 1. Why $M_W \ll M_{Planck}$?
- 2. Quantum corrections to the Higgs mass M_H are (from power counting) quadratically divergent. What is the mechanism of their cancellation? Naturalness problem.

Only the second problem will be discussed.

Quadratic divergences

One can hear often: since the quantum corrections M_H diverge as Λ^2, one must introduce new physics which cancels these divergences, and that new physics should appear close to the EW scale.

Quadratic divergences

One can hear often: since the quantum corrections M_H diverge as Λ^2, one must introduce new physics which cancels these divergences, and that new physics should appear close to the EW scale.

Apply this argument to the vacuum energy ϵ_{vac}(quartically divergent): necessity of new physics at energies larger than $\epsilon_{vac}^{1/4} \simeq 10^{-3}$ eV?

Quadratic divergences

One can hear often: since the quantum corrections M_H diverge as Λ^2, one must introduce new physics which cancels these divergences, and that new physics should appear close to the EW scale.

Apply this argument to the vacuum energy ϵ_{vac}(quartically divergent): necessity of new physics at energies larger than $\epsilon_{vac}^{1/4} \simeq 10^{-3}$ eV?

Since this is not observed, we should either conclude that the case of quartic divergences is very much different from the case of quadratic divergences, or accept that this type of logic can be wrong.

Quadratic divergences

One can hear often: since the quantum corrections M_H diverge as Λ^2, one must introduce new physics which cancels these divergences, and that new physics should appear close to the EW scale.

Apply this argument to the vacuum energy ϵ_{vac}(quartically divergent): necessity of new physics at energies larger than $\epsilon_{vac}^{1/4} \simeq 10^{-3}$ eV?

Since this is not observed, we should either conclude that the case of quartic divergences is very much different from the case of quadratic divergences, or accept that this type of logic can be wrong.

In fact, besides the problem of Landau pole, the EW theory itself is known to be a perfectly valid theory without any new physics!

Naturalness and GUTs

Suppose that there is an intermediate high energy GUT scale, $M_{GUT} \ll M_{Planck}$. Then one has to choose carefully counter-terms up to $N \simeq \log(M_{GUT}^2/M_W^2)/\log(\pi/\alpha_W) \simeq 13$ loop level to get $M_H \ll M_{GUT}$! This is enormous fine-tuning and is an argument for existing of new physics right above the EW scale.

Possible solution:

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

Naturalness without GUTs

Suppose that there are no GUTs or unification happens at the Planck scale.

- Easy “solution” to the problem of quadratic divergences: since we do not know what happens at the Planck scale, Planck mass cannot be considered as a *field-theoretical* cut-off (or as a mass of some particle in dimensional regularisation). Consequence: Nothing but the Higgs at the LHC in the mass interval $m_{\mathbf{min}} < m_H < m_{\mathbf{max}}$.

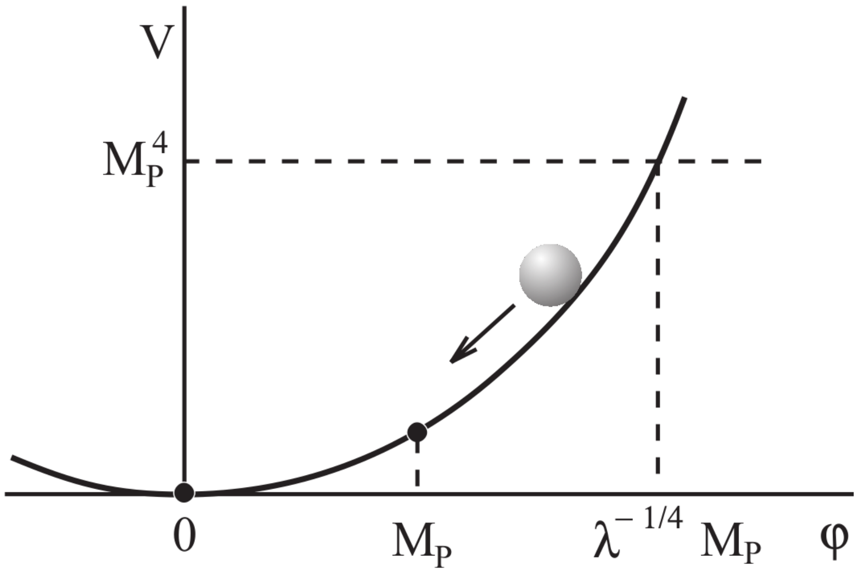
Naturalness without GUTs

- 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 the LHC. Existence of new massless particle – dilaton, which can play the role of dynamical Dark Energy. Cosmological constant is zero. Dilaton – Goldstone boson of the broken scale invariance. It has only derivative couplings to matter, "gives" mass to the Higgs boson and determines the Planck mass via non-minimal coupling to gravity.

Scale-invariant renormalization procedure:

Zenhäusern, M.S; Englert, Truffin, Gastmans, 1976

Inflation



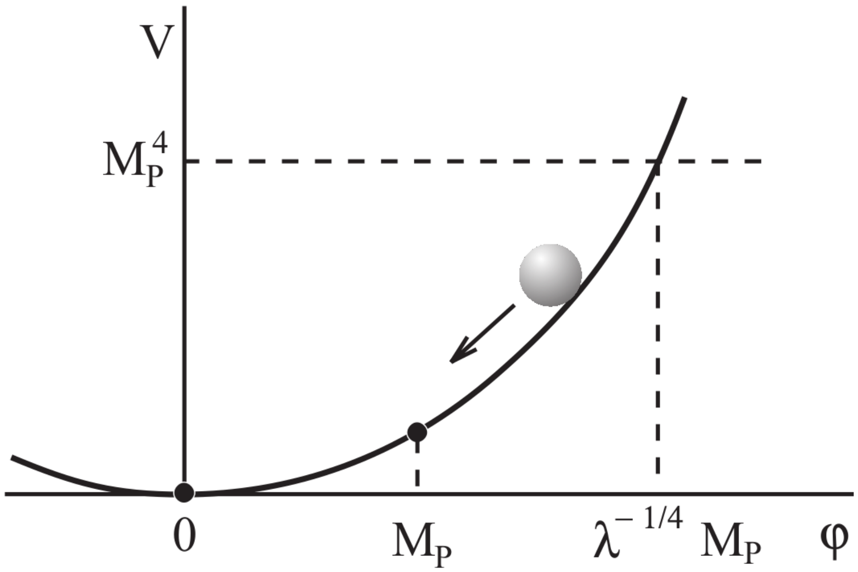
Required for inflation: (to get $\delta T/T \sim 10^{-5}$)

- quartic coupling constant $\lambda \sim 10^{-13}$
- mass $m \sim 10^{13}$ GeV,

Present in the Standard Model: Higgs boson

- $\lambda \sim 1$, $m_H \sim 100$ GeV
- $\delta T/T \sim 1$

Inflation



Required for inflation: (to get $\delta T/T \sim 10^{-5}$)

- quartic coupling constant $\lambda \sim 10^{-13}$
- mass $m \sim 10^{13}$ GeV,

Present in the Standard Model: Higgs boson

- $\lambda \sim 1$, $m_H \sim 100$ GeV
- $\delta T/T \sim 1$

New physics is required?

No - these conclusions are based on a theory with minimal coupling of scalar to gravity!:

$$S=\int d^4x\sqrt{-g}\left\{-\frac{M^2}{2}R+g_{\mu\nu}\frac{\partial^\mu h\partial^\nu h}{2}-\frac{\lambda}{4}\left(h^2-v^2\right)^2\right\}$$

Extra term, necessary for renormalizability:

non-minimal coupling of scalar to gravity

$$\Delta S=\int d^4x\sqrt{-g}\left\{-\frac{\xi h^2}{2}R\right\}$$

Feynman, Brans, Dicke,...

Standard Model Higgs boson as inflaton

Bezrukov, MS

Consider large Higgs fields h.

- Gravity strength: $M_P^{\text{eff}} = \sqrt{M_P^2 + \xi h^2} \propto h$
- All particle masses are $\propto h$

For $h > \frac{M_P}{\xi}$ (classical) physics is the same (M_W/M_P^{eff} does not depend on h)!

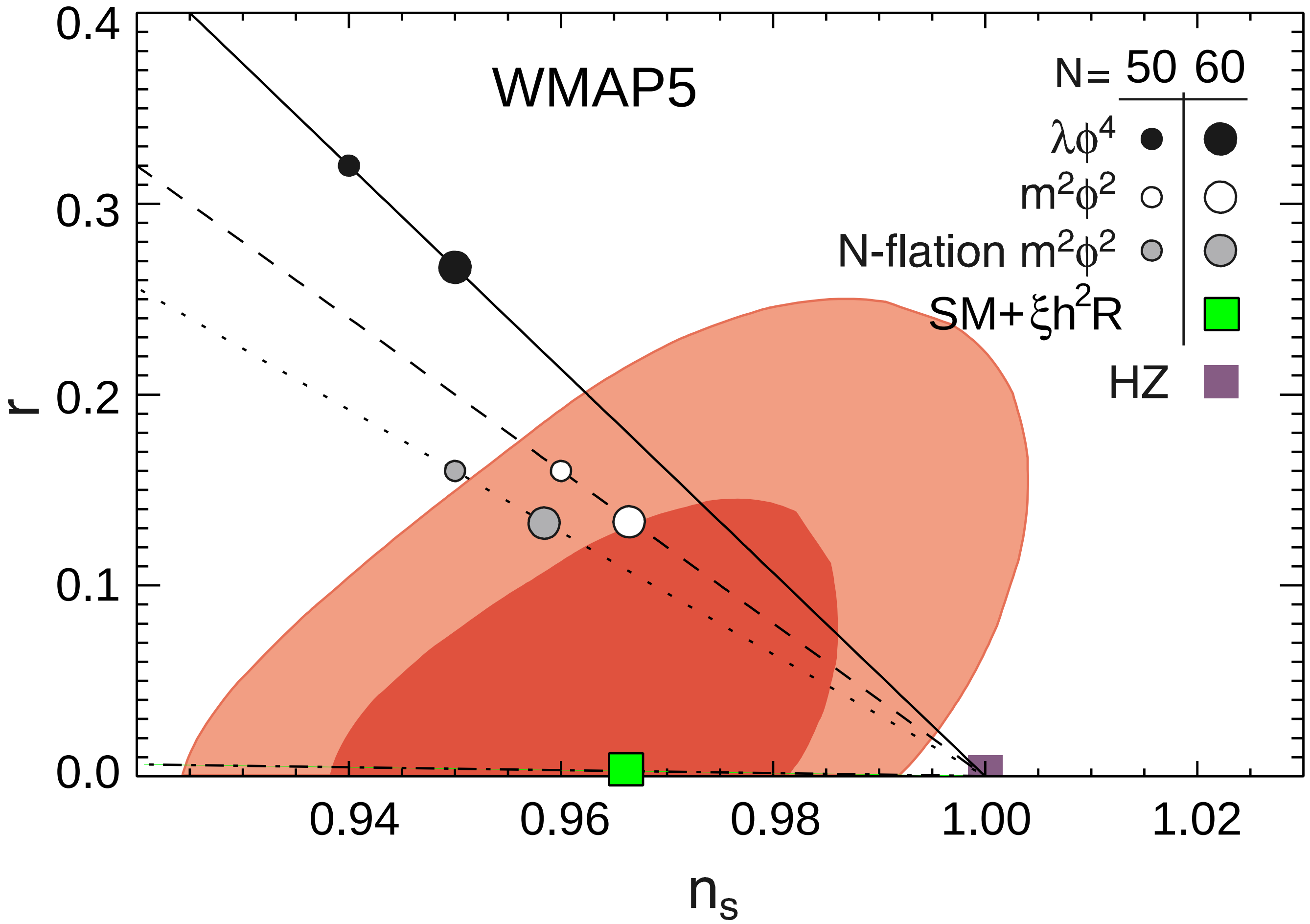
Existence of effective flat direction, necessary for successful inflation.

Higgs inflation works for

$$126\ \text{GeV} < M_H < 194\ \text{GeV}$$

and large $\xi = 800 - 10^5$, depending on the Higgs mass.

CMB parameters—spectrum and tensor modes



Light inflaton

Suppose that large non-minimal coupling to gravity ξ is forbidden because of some reason. Do we need an intermediate energy scale?

Light inflaton

Suppose that large non-minimal coupling to gravity ξ is forbidden because of some reason. Do we need an intermediate energy scale?

Not necessarily: The CMB 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 $m_{inf} < M_H$ 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 allowing non-minimal coupling $\xi \sim 10^{-3}$).

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 10^8 GeV $\lesssim M_{PQ} \lesssim 10^{12}$ GeV.

Intermediate scale appears again?

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 10^8 GeV $\lesssim M_{PQ} \lesssim 10^{12}$ GeV.

Intermediate scale appears again? Not necessarily:

Strong CP-problem is essentially related to the topology of space. It appears only if the space is continuous and has non-trivial topological mapping onto 3-sphere.

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 10^8 GeV $\lesssim M_{PQ} \lesssim 10^{12}$ GeV.

Intermediate scale appears again? Not necessarily:

Strong CP-problem is essentially related to the topology of space. It appears only if the space is continuous and has non-trivial topological mapping onto 3-sphere.

Is there space at all at short distances if gravity is included?

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 10^8 GeV $\lesssim M_{PQ} \lesssim 10^{12}$ GeV.

Intermediate scale appears again? Not necessarily:

Strong CP-problem is essentially related to the topology of space. It appears only if the space is continuous and has non-trivial topological mapping onto 3-sphere.

Is there space at all at short distances if gravity is included?

Is the topology of space always non-trivial?

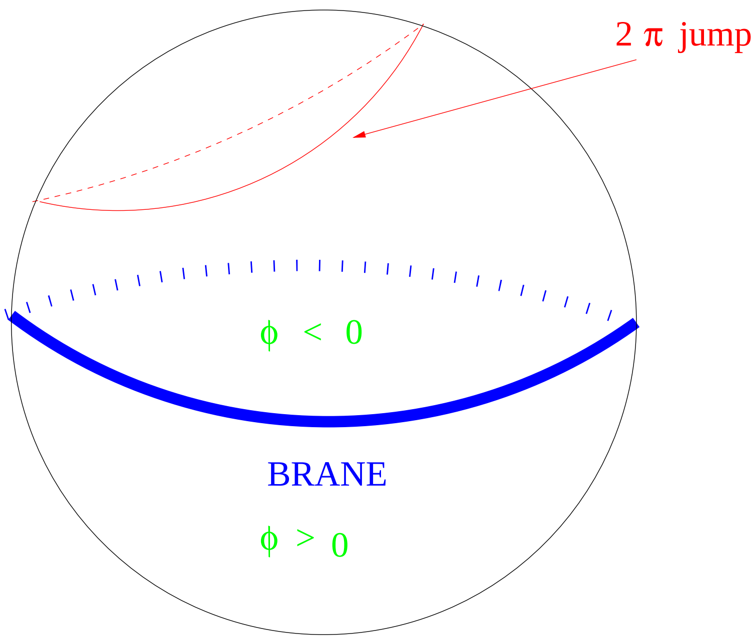
Topology

If extra dimensions have topology such that the mapping

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

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

$2 + 1$ U(1) example, brane-world



Maxwell equations do not admit existence of source-less static electric field.

Brane-world compactification, $S^2 \longrightarrow U(1) = S^1$ - trivial mapping $\longrightarrow$ no N-vacua $\longrightarrow$ no θ vacua.

Extra dimensions are not seen if we live on a brane.

Major ingredients:

(i) compactness of the space

(ii) non-factorizable geometry

See-saw and neutrino masses

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:

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

Intermediate scale again?

See-saw and neutrino masses

Add to the Lagrangian of the Standard Model a dimension five operator

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

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:

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

Intermediate scale again?

Not necessarily - will discus later!

Baryogenesis

Thermal leptogenesis: Out of equilibrium and conversion to baryon asymmetry conditions: $M_W < T_{decay} < M_N$ Constraint on the decay Yukawa coupling $\Gamma_{\rm tot} \simeq f^2 M_N$:

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

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.

Intermediate scale again?

Baryogenesis

Thermal leptogenesis: Out of equilibrium and conversion to baryon asymmetry conditions: $M_W < T_{decay} < M_N$ Constraint on the decay Yukawa coupling $\Gamma_{\rm tot} \simeq f^2 M_N$:

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

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

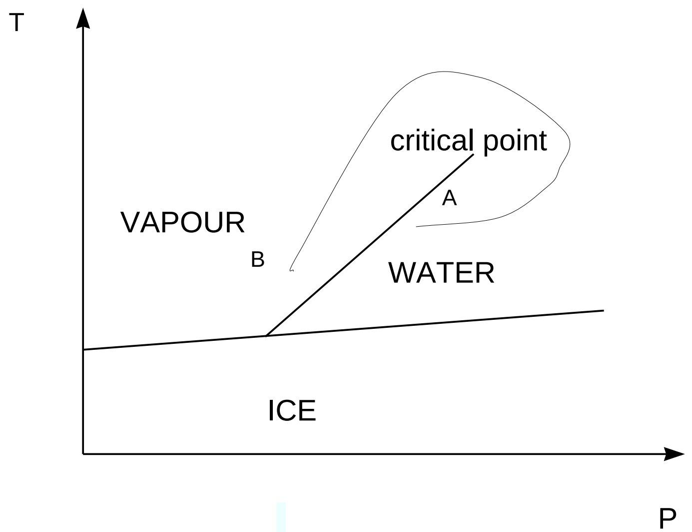
$$\frac{n_B}{s} \sim 10^{-3} f^2 \simeq 10^{-10}$$

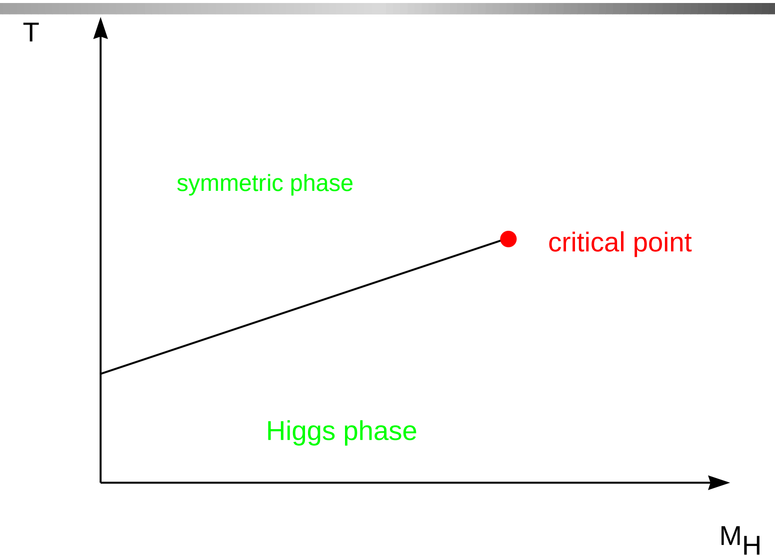
for $f^2 \sim 10^{-7}$; works for $M_N > 10^{11}$ GeV.

Intermediate scale again?

Not necessarily - will discus later!

Electroweak baryogenesis





Typical condensed matter phase diagram (pressure versus temperature)

Electroweak theory

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

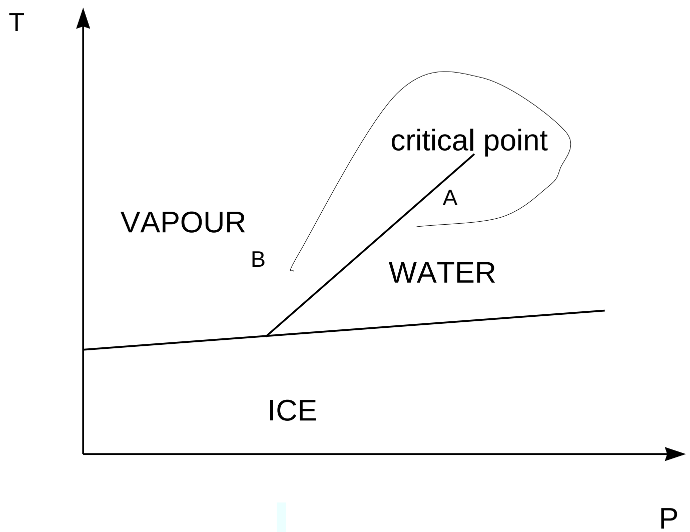
$T = 109.2 \pm 0.8 GeV,$

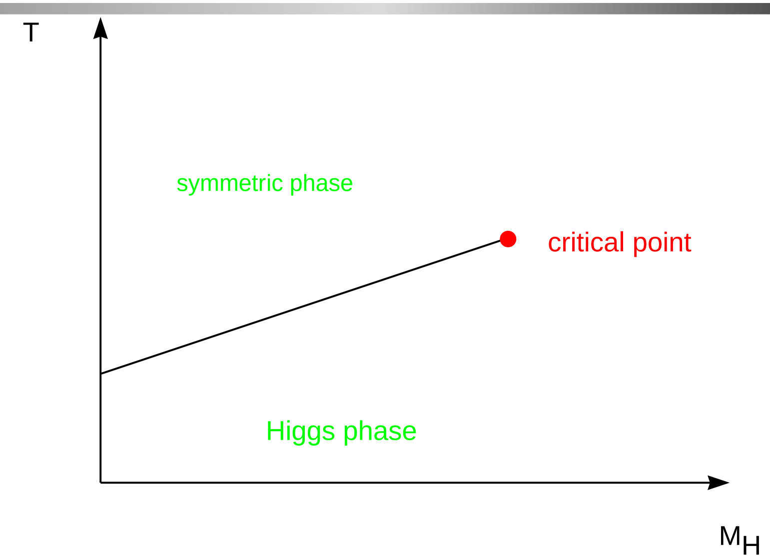
$M_H = 72.3 \pm 0.7 GeV$

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

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

Electroweak baryogenesis





Typical condensed matter phase diagram (pressure versus temperature)

Electroweak theory

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

$T = 109.2 \pm 0.8 GeV,$

$M_H = 72.3 \pm 0.7 GeV$

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

To make first order EW phase transition: add new physics right above the EW scale. Not necessarily - will discus later!

Dark matter

WIMPS: annihilation cross-section related to the scale $M \sim \mathbf{100}$ GeV gives roughly the right DM abundance.

New physics right above the EW scale?

Dark matter

WIMPS: annihilation cross-section related to the scale $M \sim \mathbf{100}$ GeV gives roughly the right DM abundance.

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.

An alternative to intermediate energy scale

E

T

O

E

An alternative to intermediate energy scale

Effective

Theory

Of

Everything

Definitions

"Effective": valid up to the Planck scale, quantum gravity problem is not addressed. No new particles heavier than the Higgs boson.

May be even fundamental, if gravity is "asymptotically safe" (S. Weinberg '79, M. Reuter '98)

"Everything": neutrino masses and oscillations, Dark matter, baryon asymmetry of the Universe, inflation, stability of the Higgs mass against radiative corrections, absence of cosmological constant, presence of Dark energy.

Particle content of ETOE

Particles of the SM + graviton + dilaton + 3 Majorana leptons

The roles of dilaton

- determine the Planck mass
- give mass to the Higgs
- give masses to 3 Majorana leptons
- realise exact, but spontaneously broken scale invariance leading to
  - stability of the Higgs mass against radiative corrections
  - absence of cosmological constant
  - presence of dynamical dark energy

New fermions: the 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

Lagrangian of ETOE

Scale-invariant Lagrangian

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

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

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

Gravity part

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

Symmetries of ETOE

- gauge: SU(3)×SU(2)×U(1) – the same as in the Standard Model
- Restricted coordinate transformations: TDIFF, $det[-g] = 1$ (Unimodular gravity). This is essential for existence of dark energy
- Exact, but spontaneously broken scale invariance, leading to massless dilaton

Role of the Higgs boson:

- give masses to fermions and vector bosons of the SM
- provide inflation

The couplings of the νMSM

Particle physics part, accessible to low energy experiments: the νMSM. Mass scales of the νMSM:

$M_I < M_W$ (No see-saw)

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.

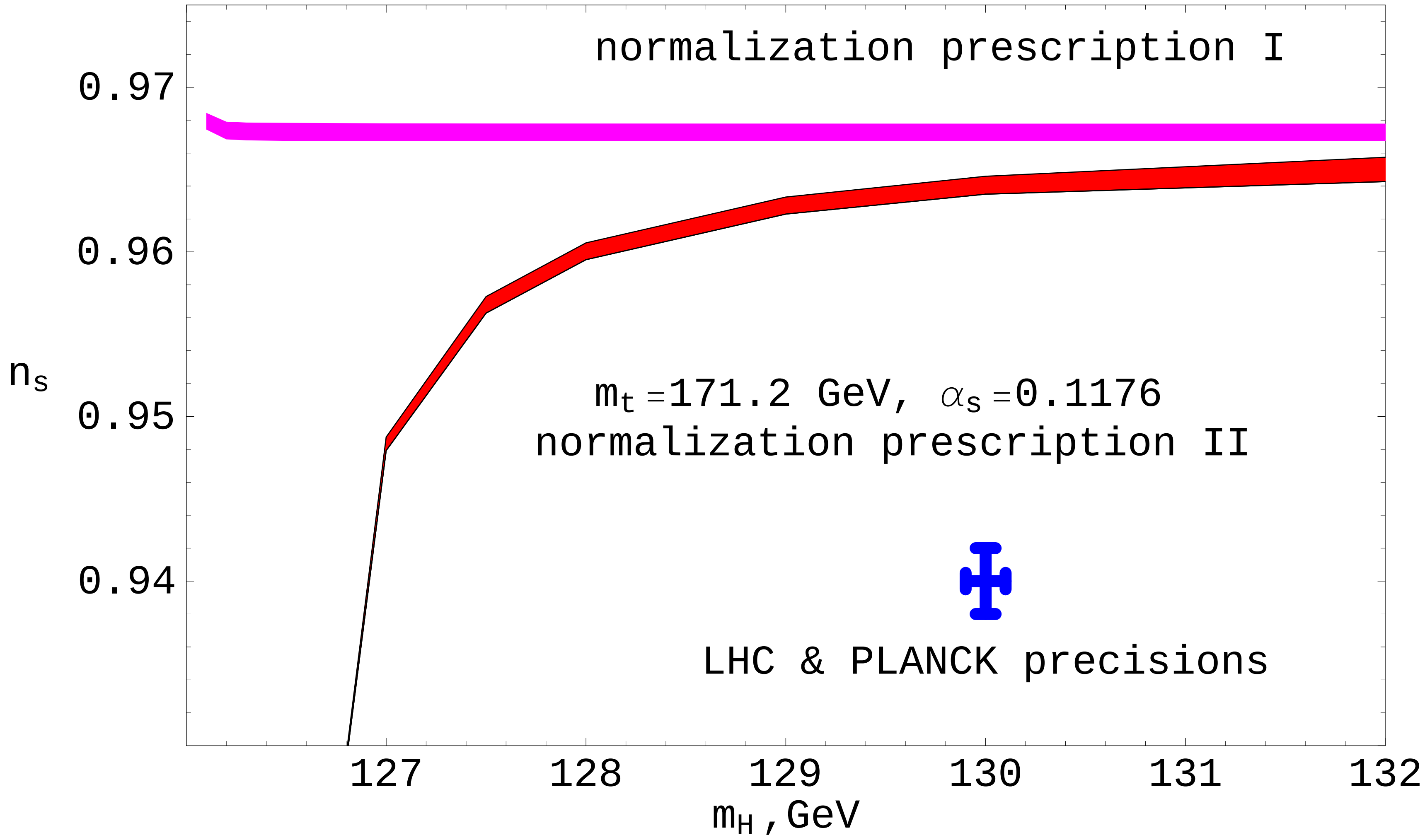
Small Yukawas are also necessary for stability of dark matter and baryogenesis (out of equilibrium at the EW temperature).

Crucial tests and experiments

Experiments, which will be done anyway

- Unitarity of PMNS neutrino mixing matrix:
  θ_{13}, $\theta_{23} - \pi/4$, type of neutrino mass hierarchy, Dirac CP-violating phase
- Absolute neutrino mass. The νMSM prediction: $m_1 \lesssim 10^{-5}$ eV (from DM). Then $m_2 \simeq 5 \cdot 10^{-2}$eV, $m_3 \simeq 9 \cdot 10^{-3}$eV or $m_{2,3} \simeq 5 \cdot 10^{-2}$ eV.
  (Double β decay, Bezrukov)
  Normal hierarchy: $1.3 \text{ meV} < m_{\beta\beta} < 3.4 \text{ meV}$
  Inverted hierarchy: $13 \text{ meV} < m_{\beta\beta} < 50 \text{ meV}$
- Crucial experimental test - the LHC, precise determination of the Higgs mass, $\Delta M_H \simeq 200$ MeV
- Crucial cosmological test - precise measurements of cosmological parameters n_s, r, $\Delta n_s \simeq 0.004$, the dark energy equation of state

Experimental precision



New dedicated experiments

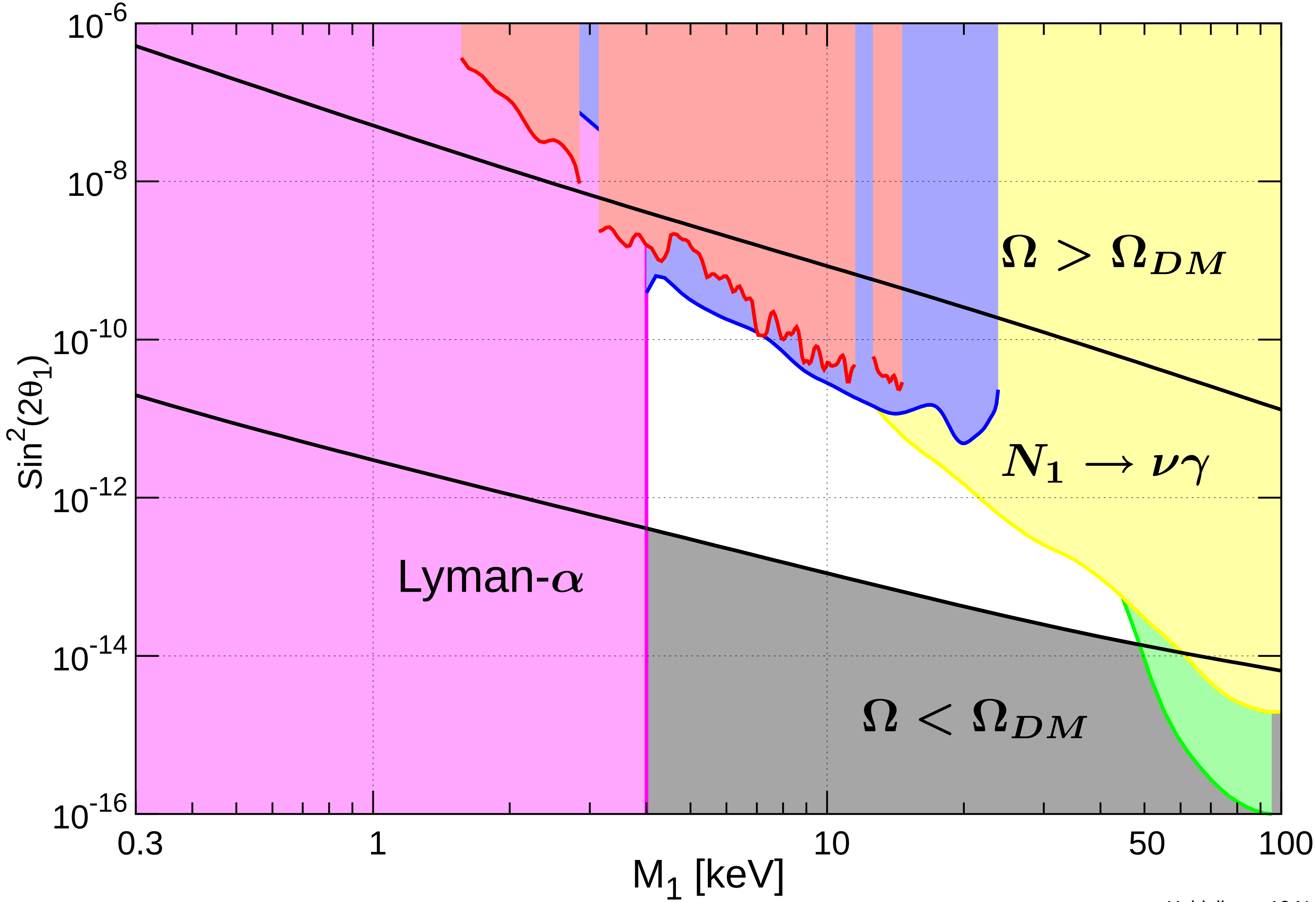
Search for N_e

X-ray telescopes similar to *Chandra* or *XMM-Newton* but with better energy resolution: narrow X-ray line from decay $N_e \to \nu\gamma$

One needs:

- Improvement of spectral resolution up to the natural line width ($\Delta E/E \sim 10^{-3}$).
- FoV $\sim 1^\circ$ (size of a dwarf galaxies).
- Wide energy scan, from $\mathcal{O}(100)$ eV to $\mathcal{O}(50)$ keV.

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



Search for $N_\mu,\ N_\tau$

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

- 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
  - $M_N < M_B$: (super) B-factories

Search for $N_\mu,\ N_\tau$

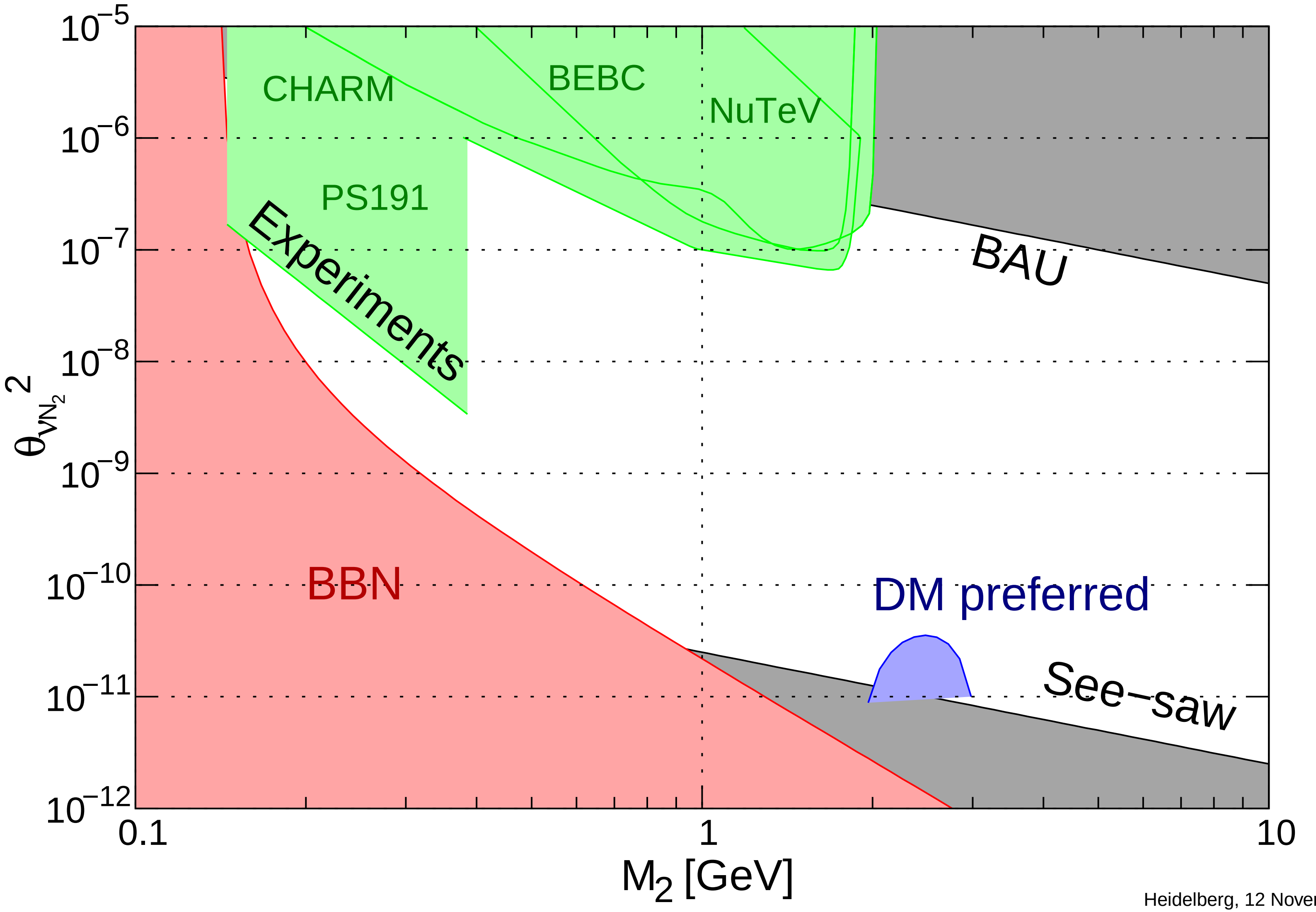
- Two charged tracks from a common vertex, decay processes $N \to \mu^+\mu^-\nu$, etc. (sensitivity $\theta^4 = \theta^2 \times \theta^2$)

  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
  - $M_N < M_D$: CERN SPS beam + near detector
  - $M_N < M_B$: Project X (?) + near detector
  - $M_N > M_B$: extremely difficult

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



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 can happen due to non-minimal coupling of the Higgs to gravity or due to existence of light inflaton
- Stability of the Higgs mass against radiative corrections may be due to quantum scale invariance, rather than existence of new particles right above the EW scale
- inflation, neutrino masses, dark matter and baryogenesis can all be explained by the particles with the masses below the electroweak scale
- The minimal model dealing with many drawbacks of the SM requires 4 new particles - the dilaton and 3 Majorana neutrinos
- There are plenty of experiments which can confirm or reject the minimal model

Collaborators

- Takehiko Asaka, Niigata U.
- Fedor Bezrukov, MPI Heidelberg
- Steve Blanchet, Maryland U.
- Alexey Boyarsky, EPFL
- Dmitry Gorbunov, INR Moscow
- Mikko Laine, Bielefeld U.
- Amaury Magnin, EPFL
- Andrei Neronov, Versoix
- Oleg Ruchayskiy, EPFL
- Igor Tkachev, INR Moscow
- Daniel Zenhausern, EPFL