ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Higgs-Dilaton Cosmology: From the Early to the Late Universe

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Outline

- ETOE
- Dilaton-Higgs Cosmology
- Higgs mass, stability, inflation and asymptotic safety
- Conclusions

An alternative to SUSY, large extra dimensions, technicolor, etc

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.

"Everything":

- neutrino masses and oscillations
- dark matter
- baryon asymmetry of the Universe
- inflation
- dark energy

Particle content of ETOE

Particles of the SM

+

graviton

+

dilaton

+

3 Majorana leptons

Symmetries of ETOE

- gauge: $SU(3) \times SU(2) \times U(1)$ – the same as in the Standard Model

Symmetries of ETOE

- Restricted coordinate transformations: TDIFF, $det[-g] = 1$ (Unimodular Gravity).

Equations of motion for Unimodular Gravity:

$$R_{\mu\nu} - \frac{1}{4} g_{\mu\nu} R = 8\pi G_N (T_{\mu\nu} - \frac{1}{4} g_{\mu\nu} T)$$

Perfect example of “degravitation" - the “$g_{\mu\nu}$" part of energy-momentum tensor does not gravitate. Solution of the “technical part" of cosmological constant problem - quartically divergent matter loops do not change the geometry. But - no solution of the “main" cosmological constant problem - why $\Lambda \ll M_P^4$? Scale invariance can help!

Symmetries of ETOE

- Exact quantum scale invariance
  - No dimensionful parameters
  - Cosmological constant is zero
  - Higgs mass is zero
  - these parameters cannot be generated radiatively, if regularisation respects this symmetry
- Scale invariance must be spontaneously broken
  - Newton constant is nonzero
  - W-mass is nonzero
  - Λ_{QCD} is nonzero

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, $\varphi^\dagger\varphi = 2h^2$):

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

Gravity part

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

For $\lambda > 0, \ \ \beta = 0$ the scale invariance can be spontaneously broken. The vacuum manifold:

$$h_0^2 = \frac{\alpha}{\lambda}\chi_0^2$$

Particles are massive, Planck constant is non-zero:

$$M_H^2 \sim M_W \sim M_t \sim M_N \propto \chi_0, \ \ M_{Pl} \sim \chi_0$$

Phenomenological requirement:

$$\alpha \sim \frac{v^2}{M_{Pl}^2} \sim 10^{-38} \lll 1$$

Absence of gravity: the only choice leading to interacting particles is $\beta = 0$. With gravity this argument is lost. Still, the choice of $\beta = 0$ will be made.

Roles of different particles

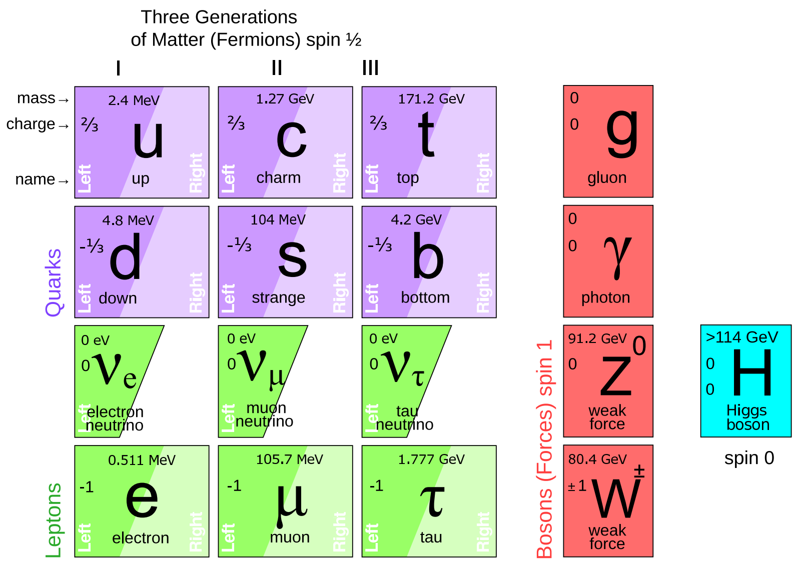
The roles of dilaton:

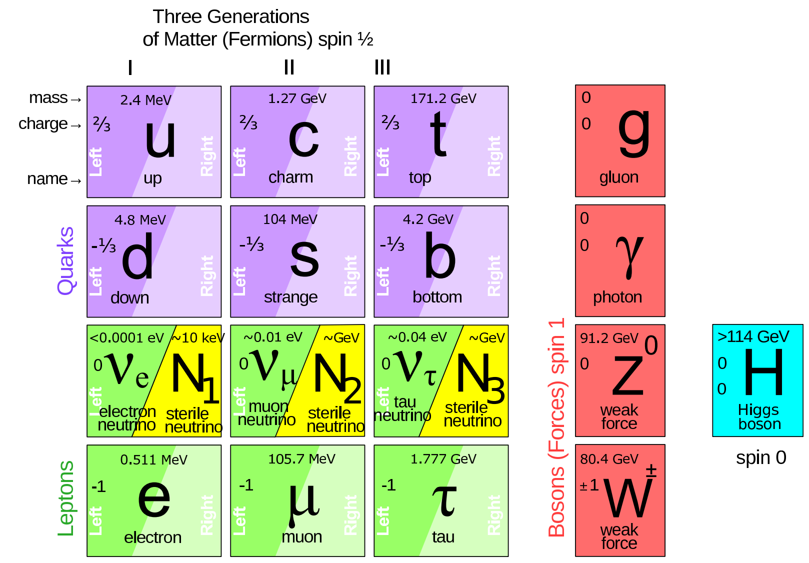
- determine the Planck mass
- give mass to the Higgs
- give masses to 3 Majorana leptons
- lead to dynamical dark energy
- Note: dilaton is a Goldstone boson of broken dilatation symmetry
  $\Longrightarrow$ only derivative couplings to matter, no fifth force!

Roles of the Higgs boson:

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

New fermions: the νMSM





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

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).

Scale invariance + unimodular gravity

Solutions of scale-invariant UG are the same as the solutions of scale-invariant GR with the action

$$S = -\int d^4x\sqrt{-g}\left[\left(\xi_\chi \chi^2 + 2\xi_h \varphi^\dagger\varphi\right)\frac{R}{2} + \Lambda + \ldots\right] \ ,$$

Physical interpretation: Einstein frame

$$g_{\mu\nu} = \Omega(x)^2 \tilde{g}_{\mu\nu} \ , \ \ (\xi_\chi \chi^2 + \xi_h h^2)\Omega^2 = M_P^2$$

Λ is not a cosmological constant, it is the strength of a peculiar potential!

Relevant part of the Lagrangian (scalars + gravity) in Einstein frame:

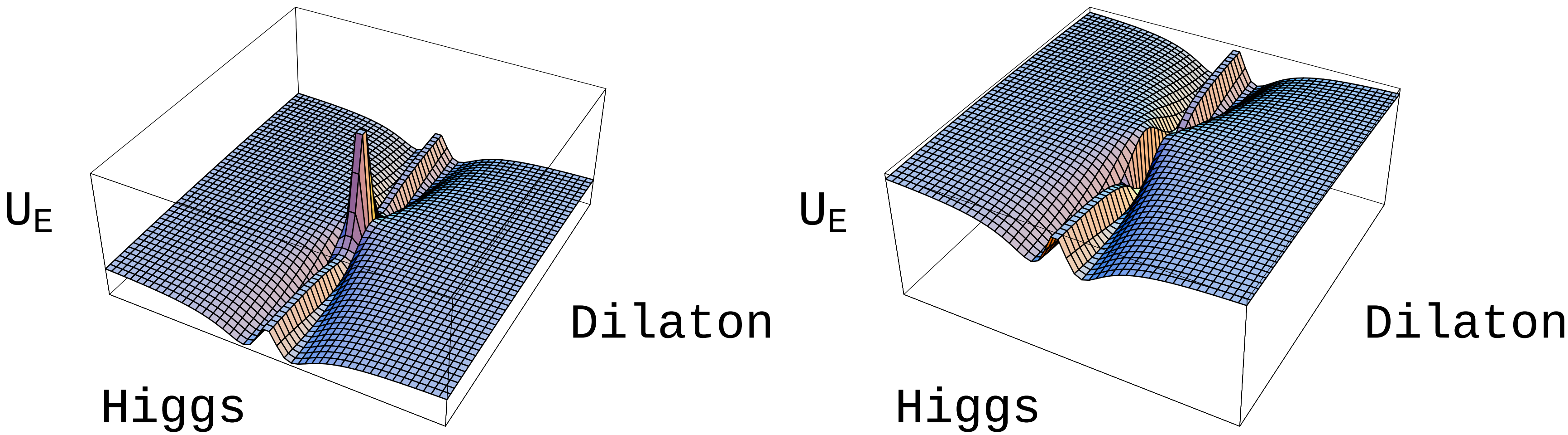
$$\mathcal{L}_E = \sqrt{-\tilde{g}}\left(-M_P^2\frac{\tilde{R}}{2} + K - U_E(h,\chi)\right) \, ,$$

K - complicated non-linear kinetic term for the scalar fields,

$$K = \Omega^2\left(\frac{1}{2}(\partial_\mu\chi)^2 + \frac{1}{2}(\partial_\mu h)^2\right) - 3M_P^2(\partial_\mu\Omega)^2 \, .$$

The Einstein-frame potential $U_E(h,\chi)$:

$$U_E(h,\chi) = M_P^4\left[\frac{\lambda\left(h^2 - \frac{\alpha}{\lambda}\chi^2\right)^2}{4(\xi_\chi\chi^2 + \xi_h h^2)^2} + \frac{\Lambda}{(\xi_\chi\chi^2 + \xi_h h^2)^2}\right] \, ,$$



Potential for the Higgs field and dilaton in the Einstein frame.

Left: $\mathbf{\Lambda > 0}$, right $\mathbf{\Lambda < 0}$.

$\mathbf{50\%}$ chance ($\mathbf{\Lambda < 0}$): inflation + late collapse

$\mathbf{50\%}$ chance ($\mathbf{\Lambda > 0}$): inflation + late acceleration

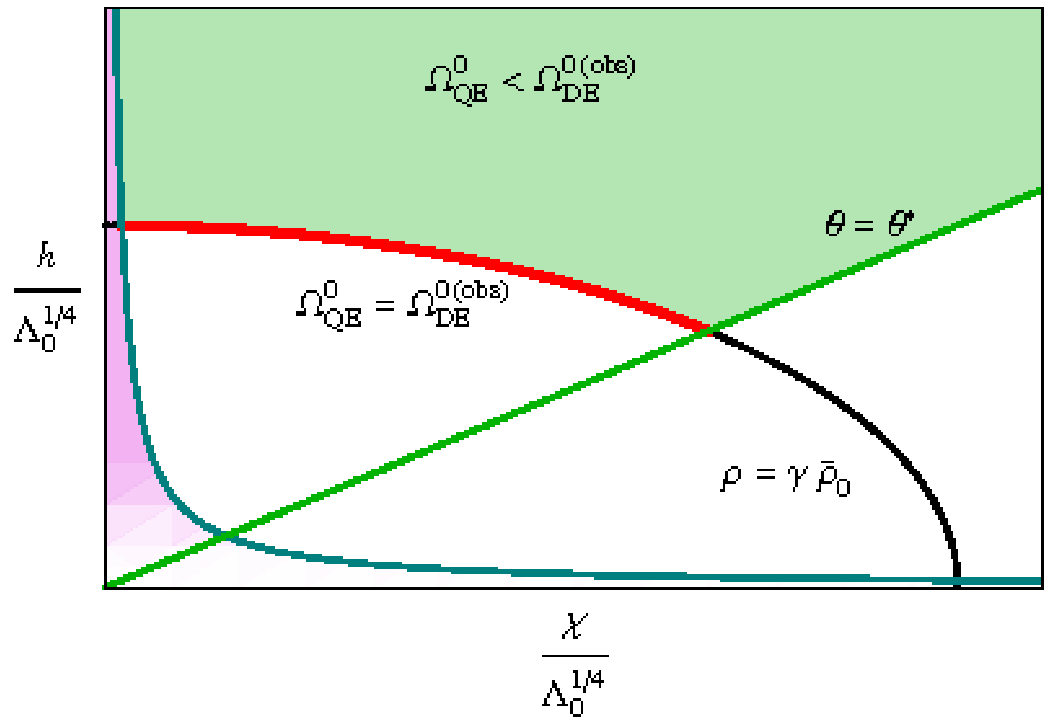
Quite amazing: the effective potential for the dilaton in Unimodular scale-invariant Gravity coincides with the one proposed by Wetterich in 1980 for run-away quintessence scalar field.

Higgs-dilaton inflation

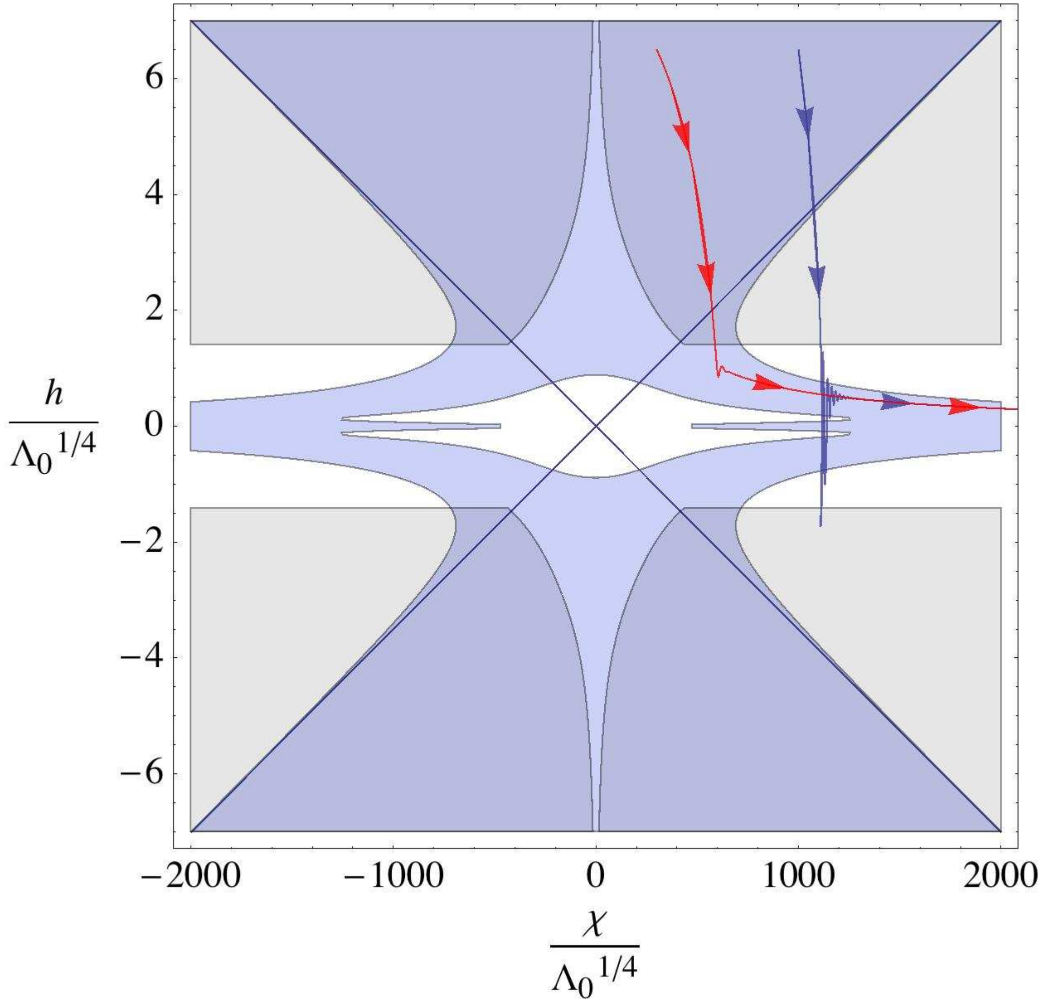
Juan García-Bellido, Javier Rubio, M.S., Daniel Zenhäusern

- Take arbitrary initial conditions for the Higgs and the dilaton
- Find the region on the $\{\chi, h\}$ plane that lead to inflation
- Find the region on the $\{\chi, h\}$ plane that lead to exit from inflation
- Find the region on the $\{\chi, h\}$ plane that lead to observed abundance of Dark Energy

Initial conditions



Trajectories



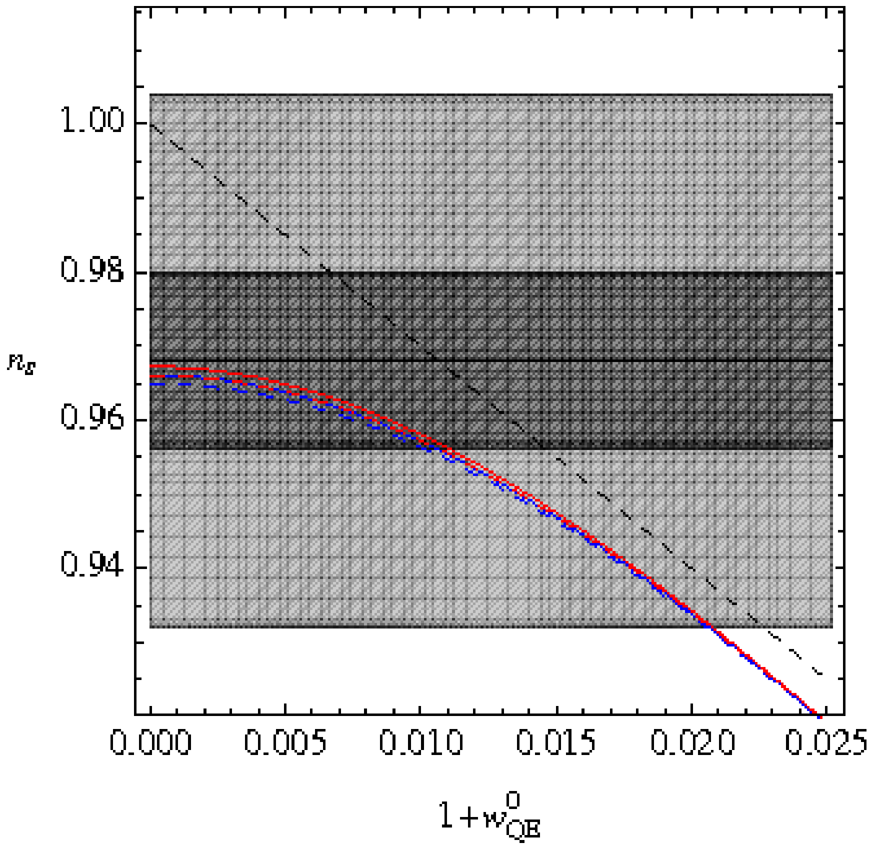
Generic semiclassical initial conditions lead to:

- the Universe, which was inflating in the past
- the Universe with the Dark Energy abundance smaller, than observed

Quantum initial state to explain the DM-DE coincidence problem?

Inflation-dark energy relation

Value of n_s is determined by ξ_h and ξ_χ, and equation of state of DE ω by $\xi_\chi \Longrightarrow n_s - \omega$ relation:



Higgs mass, stability, inflation and asymptotic safety

Radiative corrections are essential for validity of ETOE (and thus for the Higgs-dilaton cosmology). ETOE must be self-consistent up to inflationary scale. This gives a direct relation to the Higgs mass.

Definition: "$\overline{MS}$ benchmark Higgs mass M_{crit}" is defined from equations

$$\lambda(\mu_0) = 0, \quad \beta_\lambda^{\rm SM}(\mu_0) = 0$$

together with parameter μ_0, assuming that all parameters of the SM, except the Higgs mass, are fixed.

Then:

- Electroweak vacuum is stable for $M_H > M_{crit} + \Delta M_{stab}$
- Higgs or Higgs-dilaton inflation can take place at $M_H > M_{crit} + \Delta M_{infl}$
- Prediction of the Higgs mass from asymptotic safety of the SM is $M_H = M_{crit} + \Delta M_{safety}$

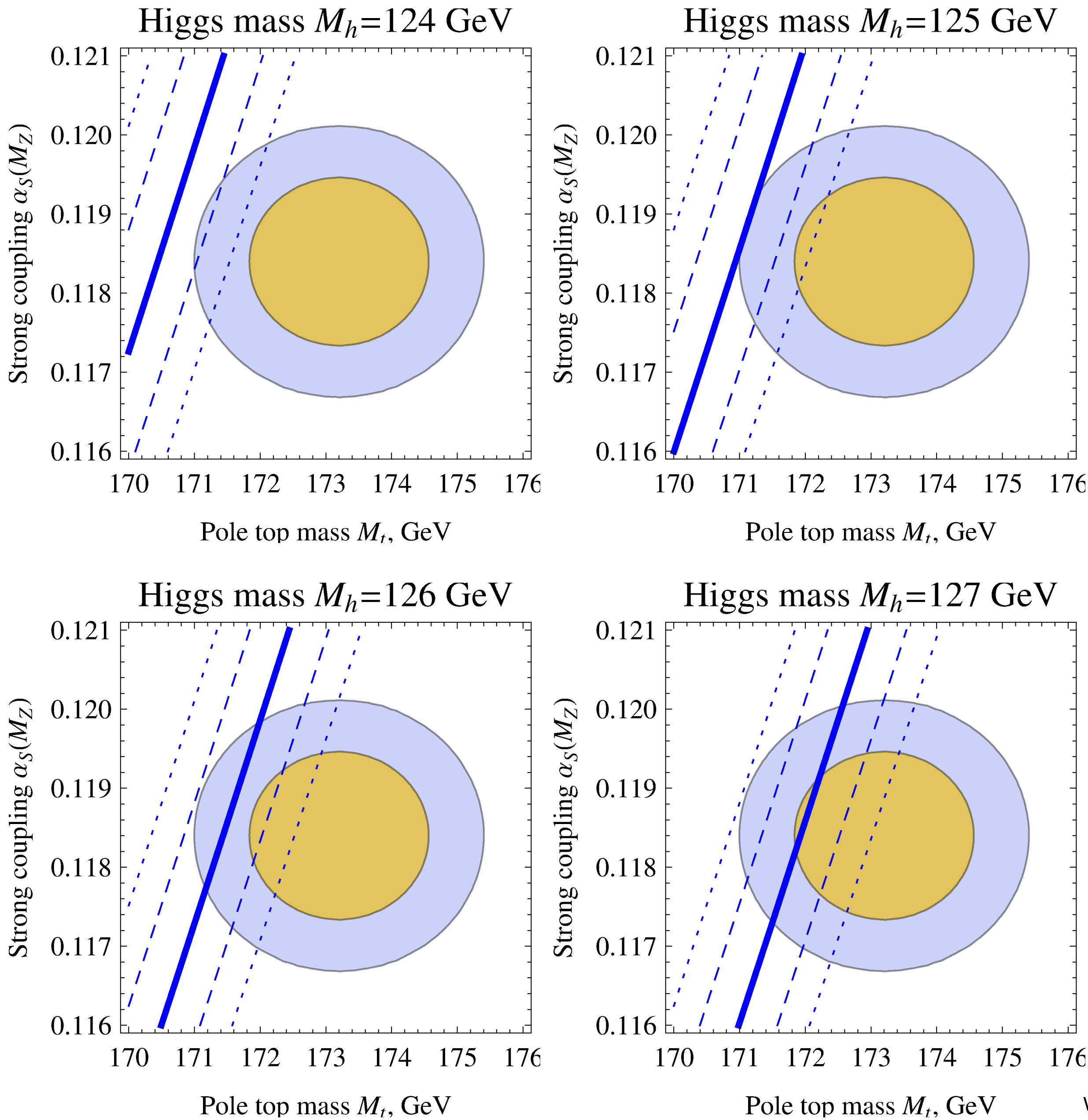
All ΔM_I are small (few hundred MeV).

Value of M_{crit} as of 2009 (one-loop matching at the EW scale and 2-loop running up to high energy scale):

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

Theoretical uncertainties: ± 2.5 GeV (different sources are summed quadratically) or ± 5 GeV (different sources are summed linearly).

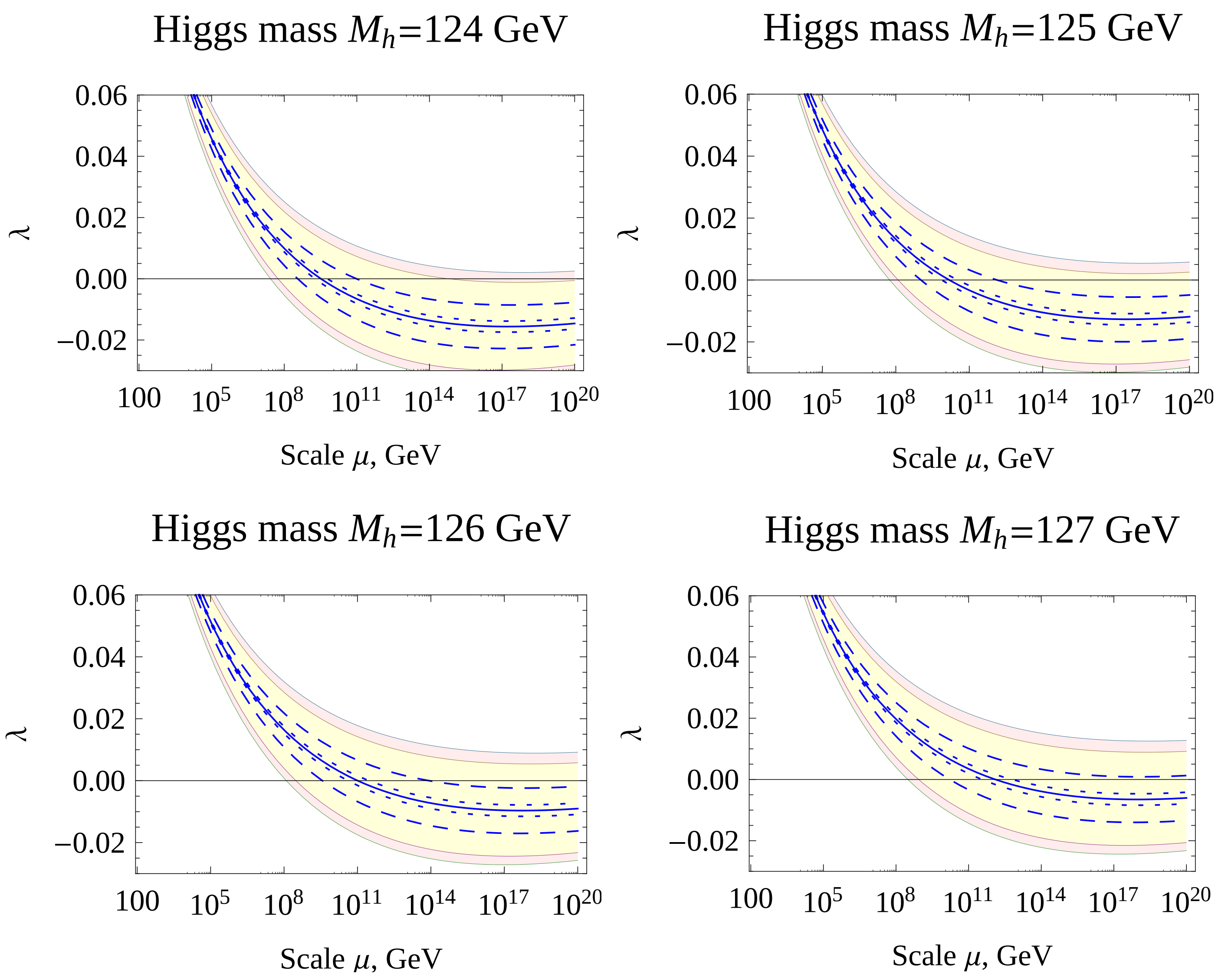
Updated computation of M_H (Bezrukov, Kalmykov, Kniel, M.S.), incorporating $\mathcal{O}(\alpha\alpha_s)$ two-loop matching and 3-loop running of coupling constants (Chetyrkin, Zoller)



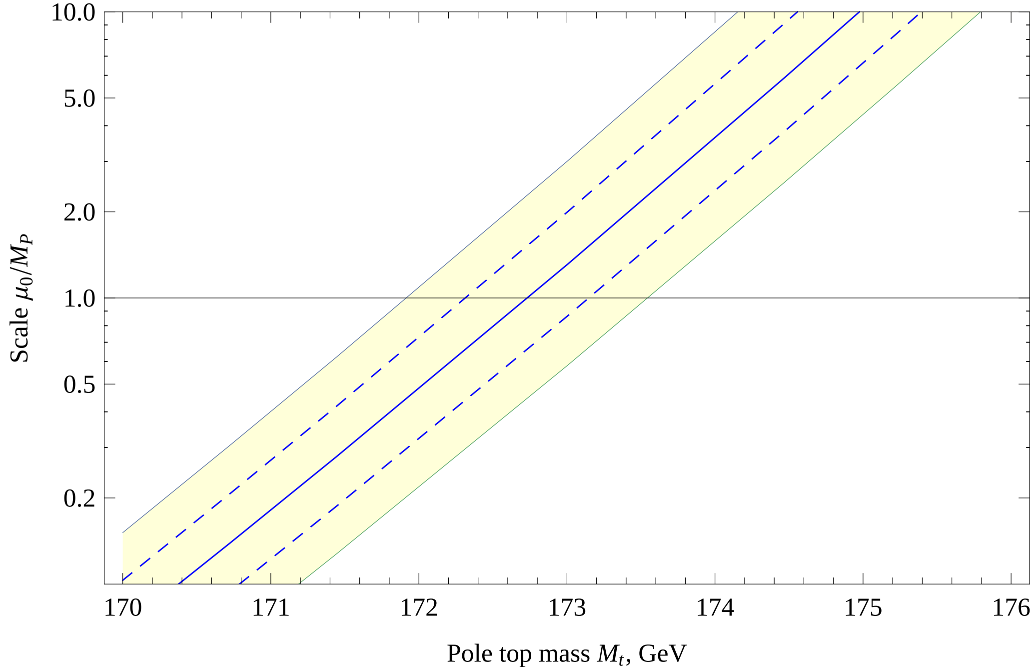
To decrease uncertainty: (the LHC accuracy can be as small as $\mathbf{200}$ MeV!)

- Compute two-loop $\mathcal{O}(\alpha^2)$ corrections to pole - $\overline{\mathrm{M}S}$ matching for the Higgs mass and top masses.
- If done, the theoretical uncertainty can be reduced to $\sim \mathbf{0.5-1}$ GeV, due to irremovable non-perturbative contribution $\sim \Lambda_{QCD}$ to top quark mass.
- Measure better t-quark mass (present error in m_H due to this uncertainty is $\simeq 4$ GeV at 2σ level): construct t-quark factory – e^+e^- or $\mu^+\mu^-$ linear collider with energy $\simeq \mathbf{200 \times 200}$ GeV - proposal for the European high energy strategy committee
- Measure better α_s (present error in m_H due to this uncertainty is $\simeq 1$ GeV at 2σ level)

Behaviour of the Higgs self-coupling



Scale from equations: $\boldsymbol{\lambda(\mu_0) = 0}$ and $\boldsymbol{\beta_\lambda^{\mathrm{SM}}(\mu_0) = 0}$



μ_0 determined by the EW physics gives the Planck scale!

Numerical coincidence?

Fermi scale is determined by the Planck scale (or vice versa)?

Possible explanation - asymptotic safety of the SM+gravity

Conclusions. ETOE gives:

- Dynamical origin of all mass scales
- Hierarchy problem gets a different meaning - an alternative (to SUSY, techicolor, little Higgs or large extra dimensions) solution of it may be possible.
- Cosmological constant problem acquires another formulation.
- Natural chaotic cosmological inflation
- Low energy sector contains a massless dilaton
- There is Dark Energy even without cosmological constant
- There is direct relation between inflation and DE equation of state
- Agreement with LHC indications of the Higgs existence and of absence of evidence of new physics right above the EW scale

Problems to solve

- Though the stability of the electroweak scale against quantum corrections may be achieved, it is unclear *why* the electroweak scale is so much smaller than the Planck scale (or why $\zeta \lll 1$).

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- High energy limit

If the Higgs, and nothing else are found at LHC, we need a $t-\bar{t}$ factory - $e^+ - e^-$ or $\mu^+ - \mu^-$ accelerator with energy $\simeq 200 \times 200$ GeV, to study in detail the properties of the Higgs and t-quark, to approach the Planck scale.

Based on works with

- Takehiko Asaka, Niigata U.
- Fedor Bezrukov, Connecticut U.
- Steve Blanchet, EPFL
- Diego Blas, CERN
- Alexey Boyarsky, Leiden
- Laurent Canetti, EPFL
- Marco Drewes, Aachen U.
- Juan Garcia-Bellido, Madrid U.
- Dmitry Gorbunov, INR Moscow
- Mikhail Kalmykov, Hamburg U.
- Bernd Kniel, Hamburg U.
- Mikko Laine, Bern U.
- Amaury Magnin, EPFL
- Andrii Neronov, Versoix
- Javie Rubio, EPFL
- Oleg Ruchayskiy, CERN
- Sergei Sibiryakov, INR Moscow
- Igor Tkachev, INR Moscow
- Christof Wetterich, Heidelberg U.
- Daniel Zenhausern, EPFL

Back up slides

Towards to Physics at All Scales

If gravity (Weinberg, M. Reuter)

and the Standard Model (M.S., Wetterich)

are asymptotically safe then

ETOE may appear to be a fundamental theory

To be true: all the couplings of the SM must be asymptotically safe or asymptotically free

Problem for:

- U(1) gauge coupling g_1, $\mu \frac{dg_1}{d\mu} = \beta_1^{\rm SM} = \frac{41}{96\pi^2} g_1^3$
- Scalar self-coupling λ, $\mu \frac{d\lambda}{d\mu} = \beta_\lambda^{\rm SM} =$

$$= \frac{1}{16\pi^2}\left[(24\lambda + 12h^2 - 9(g_2^2 + \frac{1}{3}g_1^2))\lambda - 6h^4 + \frac{9}{8}g_2^4 + \frac{3}{8}g_1^4 + \frac{3}{4}g_2^2 g_1^2\right]$$

- Fermion Yukawa couplings, t-quark in particular h, $\mu \frac{dh}{d\mu} = \beta_h^{\rm SM} =$

$$= \frac{h}{16\pi^2}\left[\frac{9}{2}h^2 - 8g_3^2 - \frac{9}{4}g_2^2 - \frac{17}{12}g_1^2\right]$$

Landau pole behaviour

Gravity contribution to RG running

Let x_j is a SM coupling. Gravity contribution to RG:

$$\mu\frac{dx_j}{d\mu} = \beta_j^{\rm SM} + \beta_j^{grav} \ .$$

On dimensional grounds

$$\beta_j^{grav} = \frac{a_j}{8\pi}\frac{\mu^2}{M_P^2(\mu)}x_j \ .$$

where

$$M_P^2(\mu) = M_P^2 + 2\xi_0\mu^2 \ ,$$

with $M_P = (8\pi G_N)^{-1/2} = 2.4\times 10^{18}$ GeV, $\xi_0 \approx 0.024$
from a numerical solution of FRGE

Remarks

- The couplings are not in $\overline{\mathrm{M}S}$ scheme
- The couplings are not in MOM scheme
- Pretty vague definition based on physical scattering amplitudes at large momentum transfer - never actually worked out in details

Thus, computations of a_j are ambiguous and controversial.

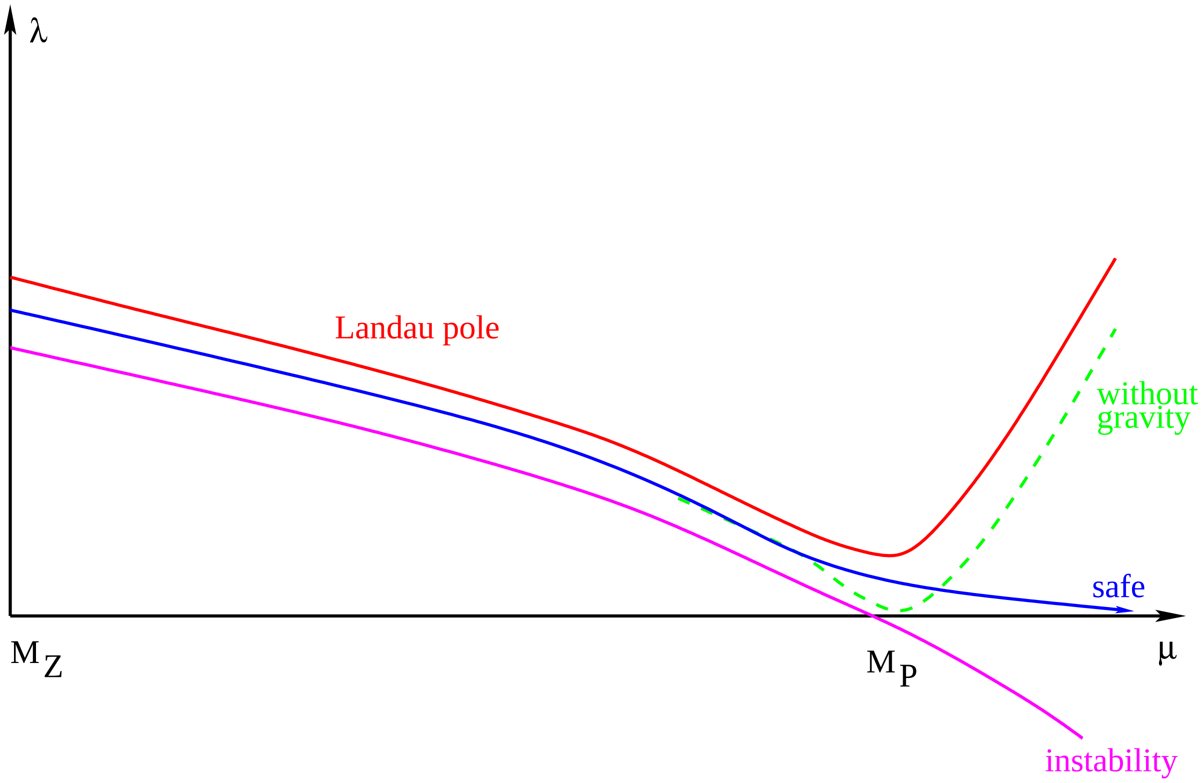
Still, even without exact knowledge of a_j a lot can be said about the Higgs mass

Robinson and Wilczek ’05, Pietrykowski ’06, Toms ’07&’08, Ebert, Plefka and Rodigast ’07, Narain and Percacci ’09, Daum, Harst and Reuter ’09, Zanusso et al ’09, ...

- Most works get for gauge couplings a universal value $a_1 = a_2 = a_3 < 0$: U(1) gauge coupling get asymptotically free in asymptotically safe gravity
- $a_\lambda \simeq 2.6 > 0$ according to Percacci and Narain ’03 for scalar theory coupled to gravity
- $a_h >< 0$?? The case $a_h > 0$ is not phenomenologically acceptable - only massless fermions are admitted

Suppose that indeed $a_1 < 0,\ a_h < 0,\ a_\lambda > 0$. Then the Higgs mass can be predicted (number as of 2009):

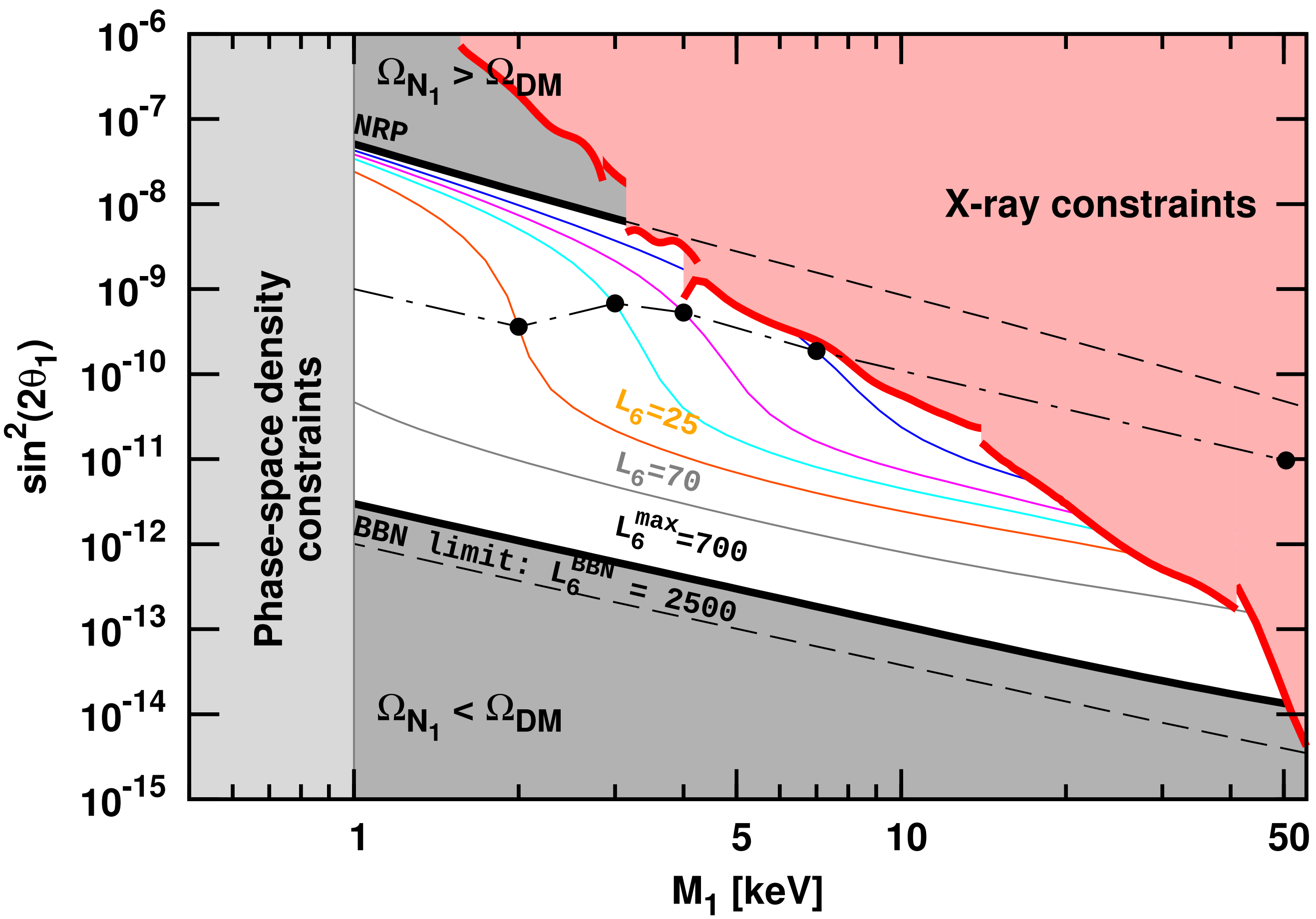
$$m_{\mathrm{H}} = [126.3 + \frac{m_t - 171.2}{2.1} \times 4.1 - \frac{\alpha_s - 0.1176}{0.002} \times 1.5]\ \mathrm{GeV}\ ,$$



Possible understanding of the amazing fact that $\lambda(M_P) = 0$ and $\beta_\lambda^{\mathrm{SM}}(M_P) = 0$ simultaneously at the Planck scale.

Constraints on DM sterile neutrino N_1

- Stability. N_1 must have a lifetime larger than that of the Universe
- Production. N_1 are created in the early Universe in reactions $l\bar{l} \to \nu N_1, \;\; q\bar{q} \to \nu N_1$ etc. We should get correct DM abundance
- 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 and structure of dwarf galaxies
- X-rays. N_1 decays radiatively, $N_1 \to \gamma\nu$, producing a narrow line which can be detected by X-ray telescopes (such as Chandra or XMM-Newton). This line has not been seen yet



Important: DM sterile neutrino production requires the presence of large, $\Delta L/L > 2 \times 10^{-3}$ lepton asymmetry at temperature $T \sim 100$ MeV. It can only be produced in the νMSM.

How to find DM sterile neutrino?

Boyarsky et al: Flux from DM decay $N_1 \to \nu\gamma$:

$$F_{\rm dm} = \frac{\Gamma_{\rm rad} M_{\rm dm}^{\rm fov}}{8\pi D_L^2} \approx \frac{\Gamma_{\rm rad}\Omega_{\rm fov}}{8\pi} I, \quad I = \int_{\text{line of sight}} \rho_{\rm dm}(r)\,dr$$

(Valid for small redshifts $z \ll 1$, and small fields of view $\Omega_{\rm fov} \ll 1$)

Strategy: Use X-ray telescopes (such as Chandra and XMM Newton) to look for a narrow γ line against astrophysical background. Choose astrophysical objects for which:

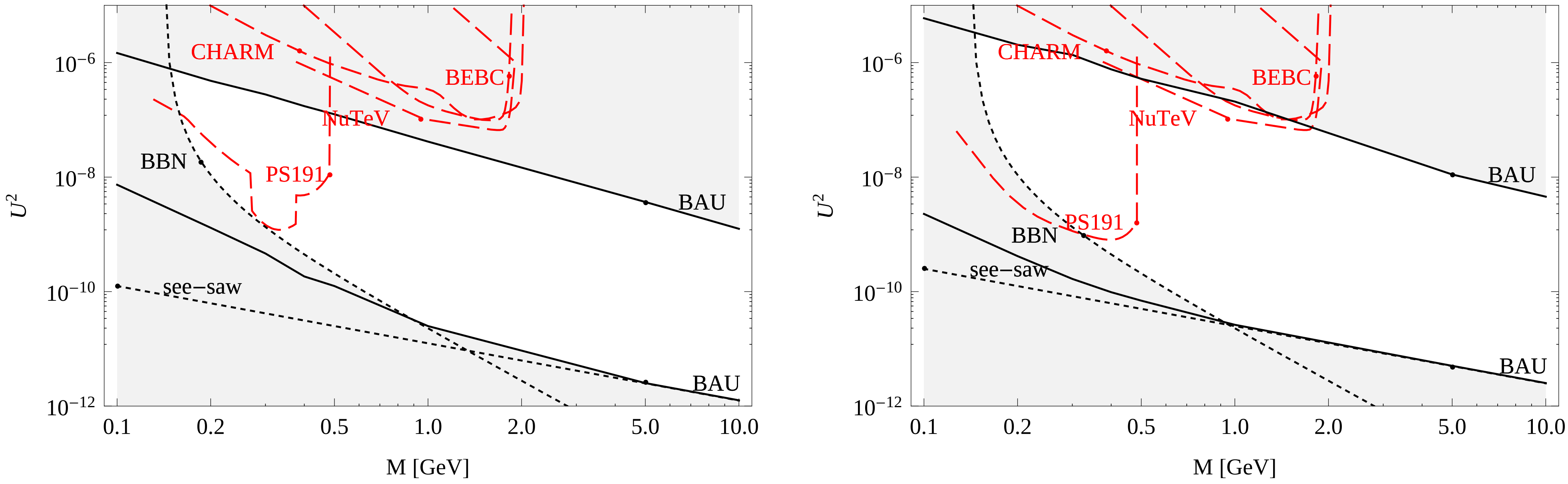
- The value of line of sight DM density integral I is maximal
- The X-ray background is minimal

$\Longrightarrow$ Look at Milky Way and dwarf satellite galaxies !

Constraints on BAU sterile neutrinos $N_{2,3}$

Baryon asymmetry generation: CP-violation in neutrino sector+singlet fermion oscillations+sphalerons

- BAU generation requires out of equilibrium: mixing angle of $\boldsymbol{N_{2,3}}$ to active neutrinos cannot be too large
- Neutrino masses. Mixing angle of $\boldsymbol{N_{2,3}}$ to active neutrinos cannot be too small
- BBN. Decays of $\boldsymbol{N_{2,3}}$ must not spoil Big Bang Nucleosynthesis
- Experiment. $\boldsymbol{N_{2,3}}$ have not been seen yet



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. Gorbunov, M.S., Canetti

Experimental signatures - 1

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

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

  Example:

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

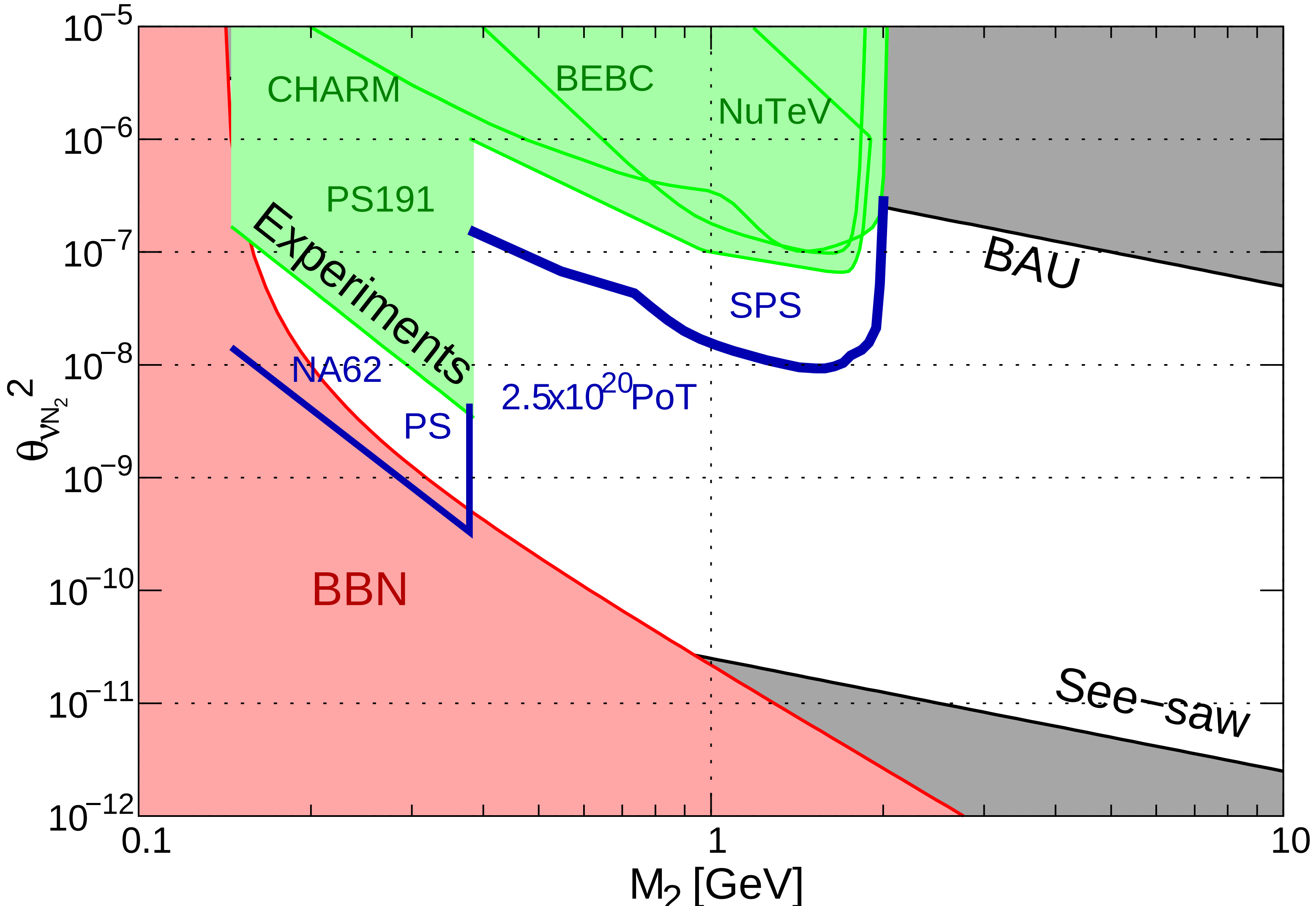
  Similar for charm and beauty.

  - $M_N < M_K$: NA62
  - $M_K < M_N < M_D$: charm and τ factories
  - $M_N < M_B$: 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 $U^4 = U^2 \times U^2$)
  First step: proton beam dump, creation of N in decays of $K,\ D$ or B mesons: U^2
  Second step: search for decays of N in a near detector, to collect all Ns: U^2
  - $M_N < M_K$: Any intense source of K-mesons (e.g. from proton targets of PS.)
  - $M_N < M_D$: Best option: SPS beam + near detector
  - $M_N < M_B$: Project X (?) + near detector
  - $M_N > M_B$: extremely difficult

CERN SPS is the best existing machine to uncover new physics below the electroweak scale. Sensitivity is proportional to total delivered protons on target.



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.*, “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

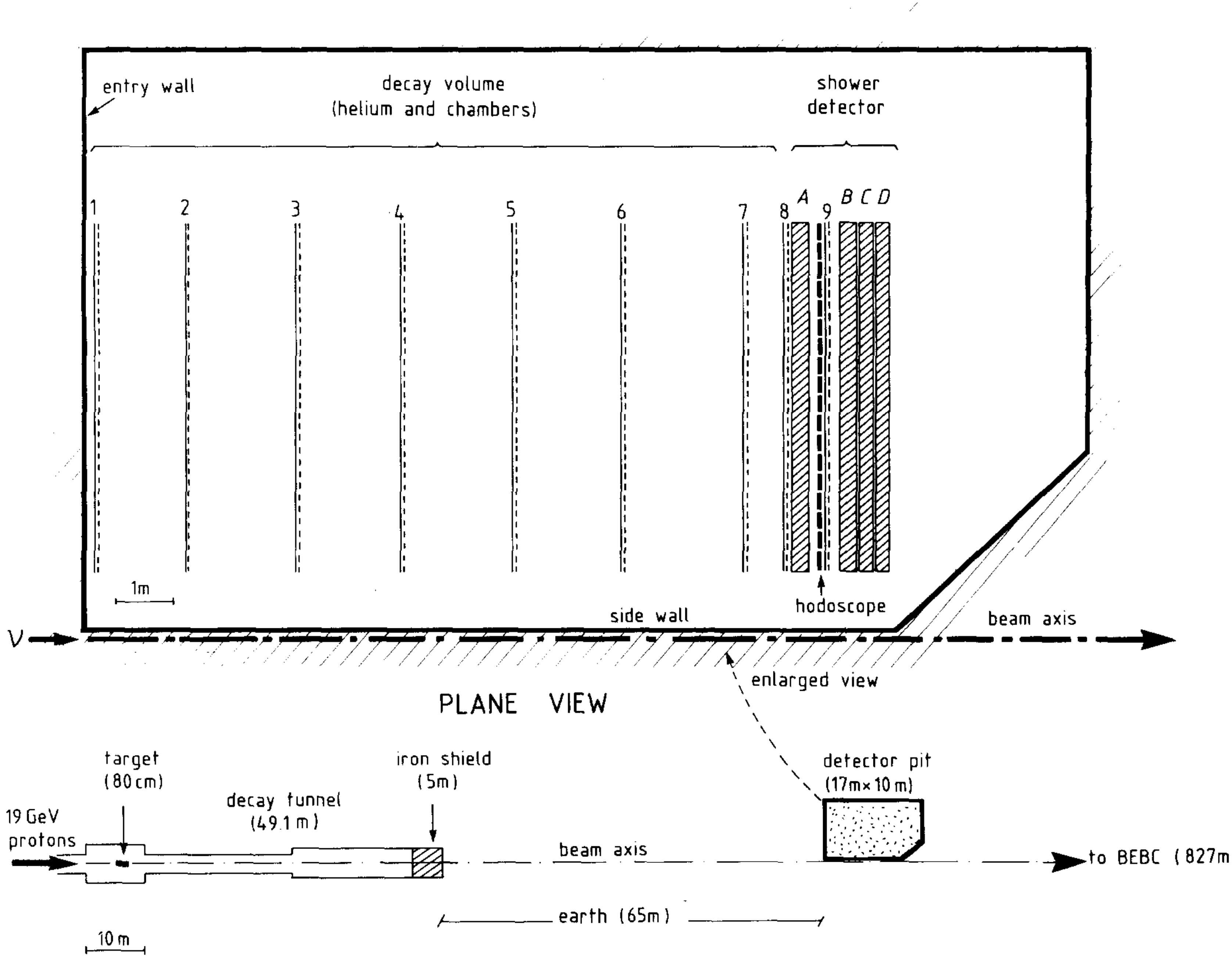


Fig. 1. Beam and layout of the detector.