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Cosmology: theory

Mikhail Shaposhnikov

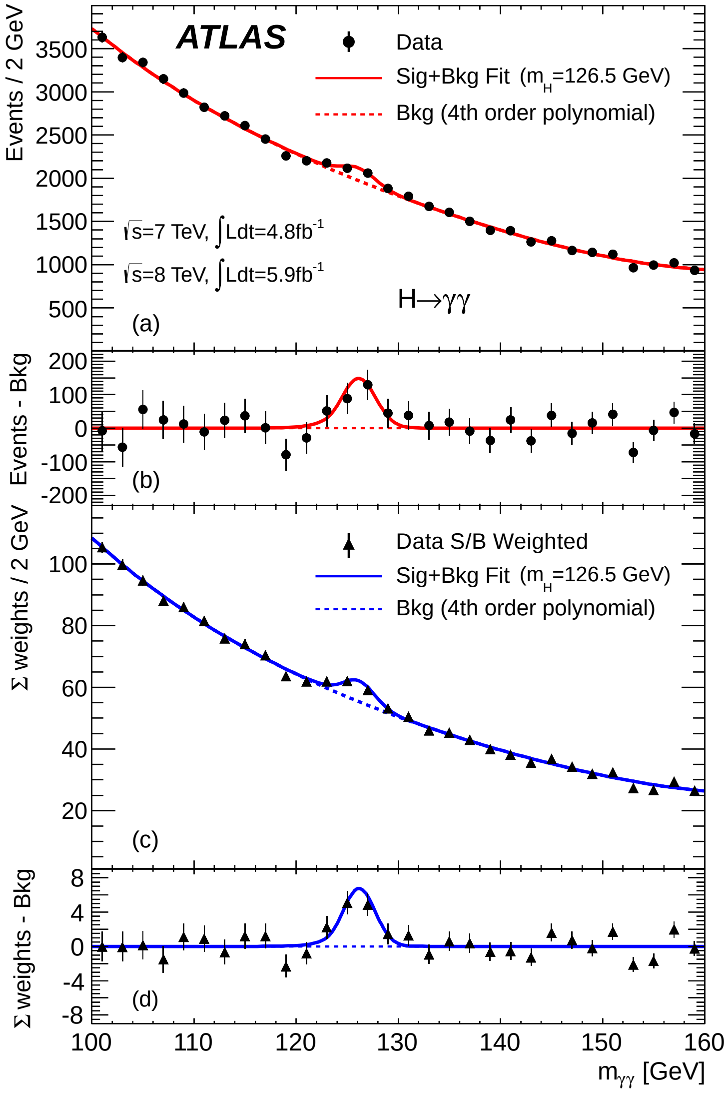
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Will not cover: Dark energy, quintessence, non-Gaussian inflationary perturbations, cosmological magnetic fields, sterile neutrinos, primordial nucleosynthesis, string cosmology, quantum gravity, massive gravity, galileons, chameleons, radion cosmology, modified gravity, f(R) gravity, Hořava-Lifshitz gravity, Landscape and Multiverse, holographic cosmology ...

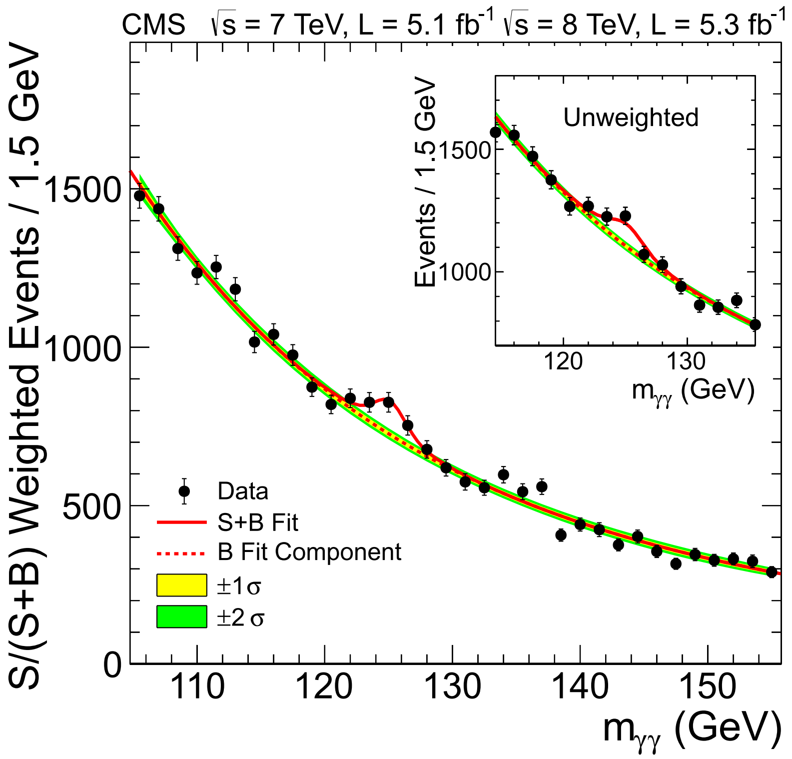
Outline

- Mass of the Higgs boson and cosmology
- Inflation
- Baryogenesis and dark matter in view of LHC results
- Neutrino masses, dark radiation
- Conclusions

July 4, 2012, Higgs at ATLAS and CMS



CMS



$$M_H = 125 - 126 \text{ GeV}$$

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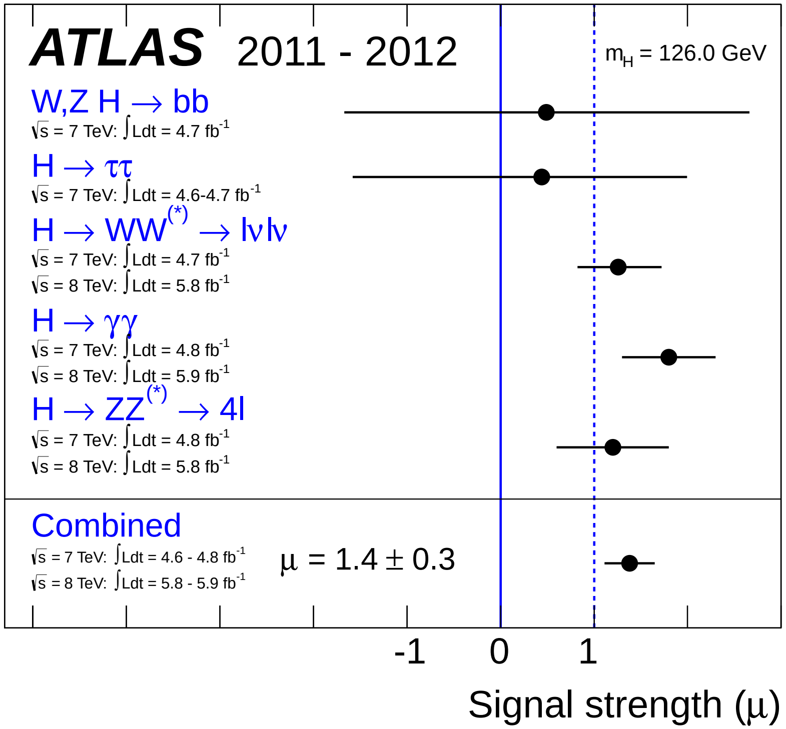
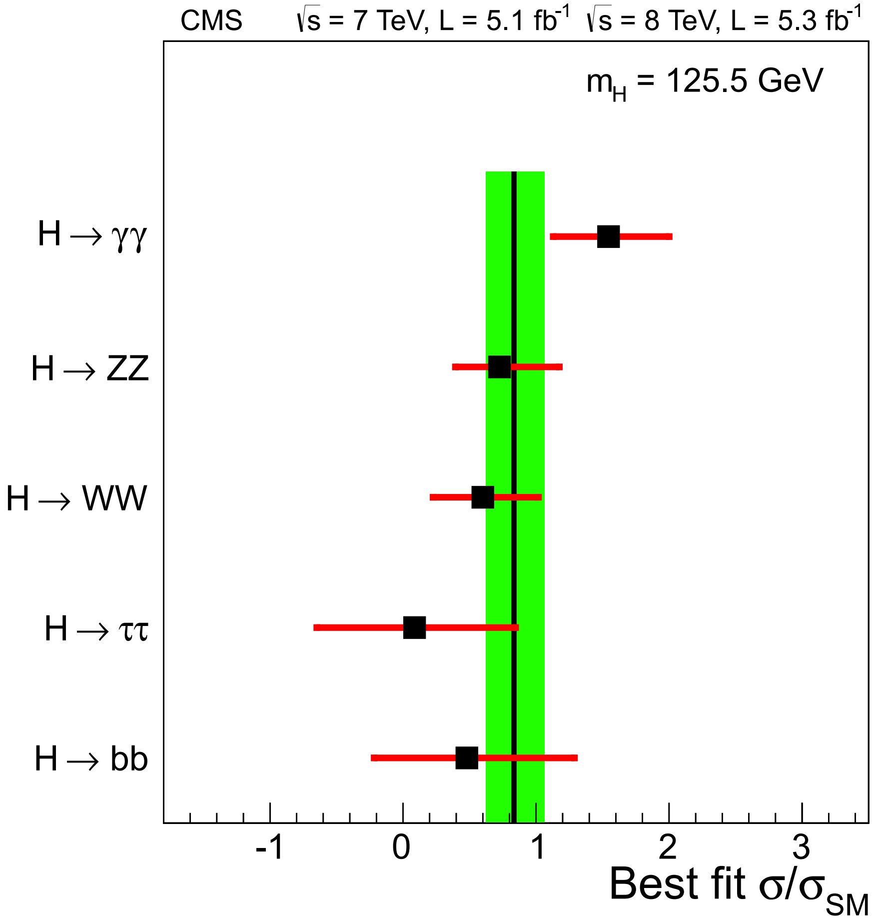
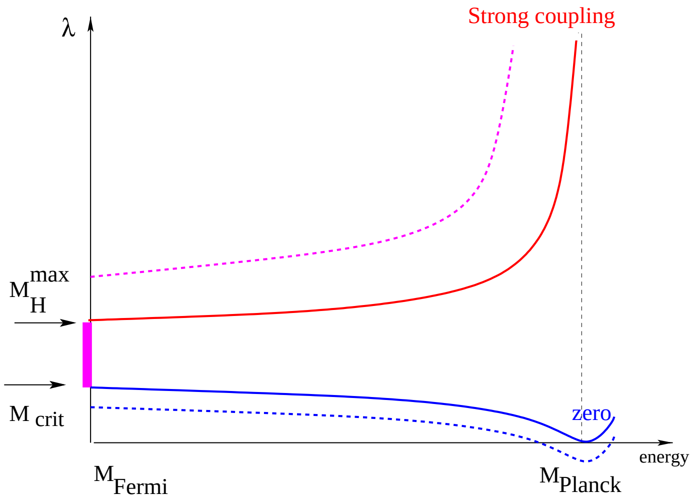
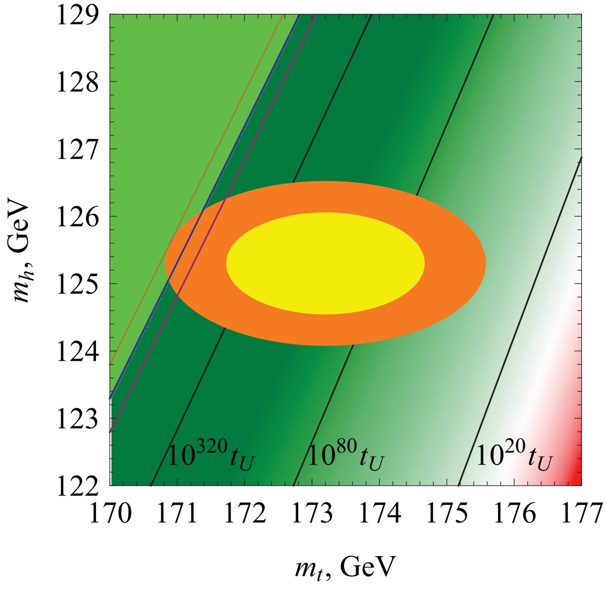




The main LHC result: SM is a consistent effective theory all the way up to the Planck scale

- No signs of new physics beyond the SM are seen
- $M_H < 175$ GeV : SM is a weakly coupled theory up to Planck energies
- $M_H > 111$ GeV: Our EW vacuum is stable or metastable with a lifetime greatly exceeding the Universe age. Espinosa et al





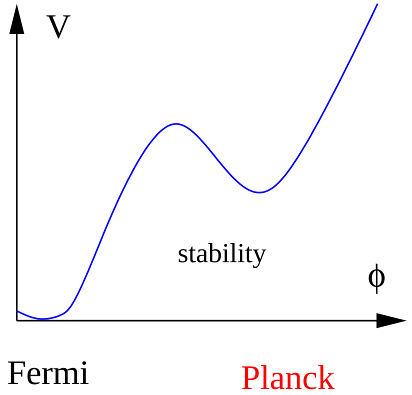
At the same time, the mass of the Higgs boson is very close to the stability bound on the Higgs mass* (95'), to the Higgs inflation bound** (08'), and to asymptotic safety value for M_H*** (09'):

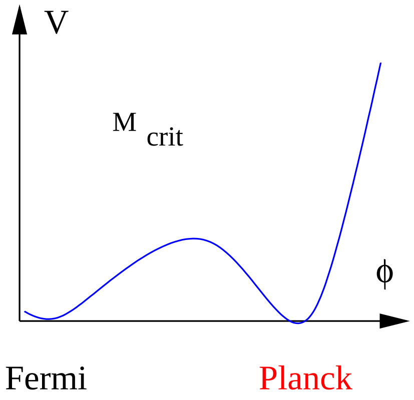
$$M_{crit} = \left[129.3 + \frac{y_t(M_t) - 0.9361}{0.0058} \times 2.0 - \frac{\alpha_s(M_Z) - 0.1184}{0.0007} \times 0.5\right] \mathrm{GeV}$$

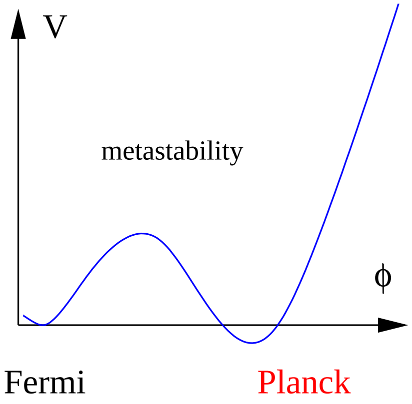
$y_t(M_t)$ - top Yukawa in $\overline{\mathrm{MS}}$ scheme

Matching at EW scale	Central value	theor. error
Bezrukov et al, $\mathcal{O}(\alpha\alpha_s)$	129.4 GeV	1.0 GeV
Degrassi et al, $\mathcal{O}(\alpha\alpha_s, y_t^2\alpha_s, \lambda^2, \lambda\alpha_s)$	129.6 GeV	0.7 GeV
Buttazzo et al, complete 2-loop	129.3 GeV	0.07 GeV

Chetyrkin et al, Mihaila et al, Bednyakov et al, 3 loop running to high energies







* Froggatt, Nielsen

** Bezrukov et al, De Simone et al

*** Wetterich, MS

What does it mean for cosmology?

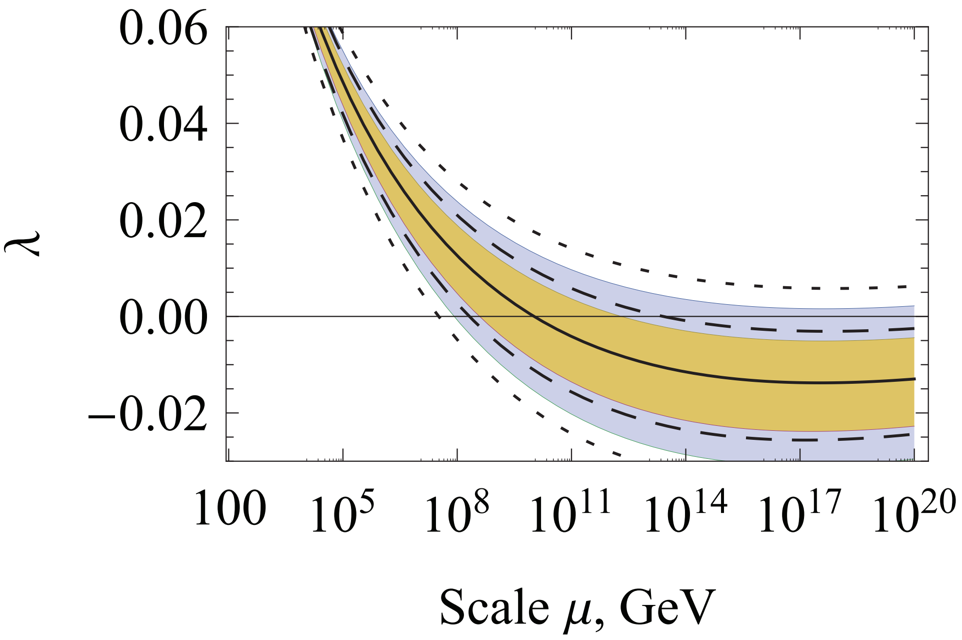
Two possibilities

- Higgs self coupling crosses zero at energy scale $M_\lambda \ll M_P$. M_λ can be as “small” as 10^8 GeV.
  - The Universe after inflation finds itself in our vacuum, reheating temperature is below M_λ. Example - R^2 inflation Gorbunov, Panin;....
  - Some kind of new physics makes our vacuum unique. Giudice et al,Hyun Min Lee, Lebedev et al, Barroso et al, Baek et al., Datta et al., Anchordoqui et al.,...

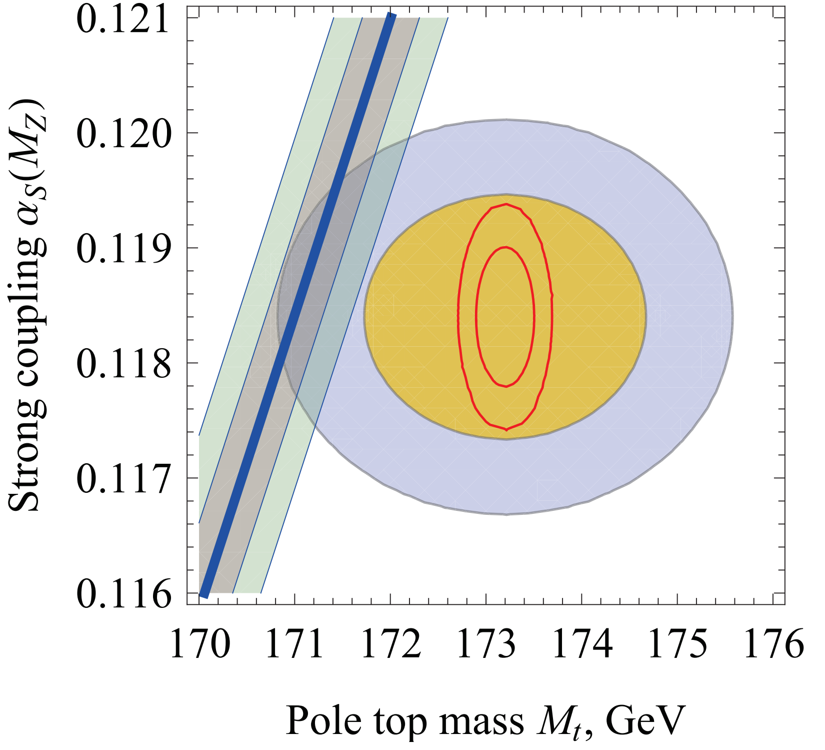
or

- Higgs self coupling never crosses zero or does that close to the Planck scale. Then no new physics at high energies is needed.

We do not know which possibility is realised!



Higgs mass M_h=125.3±0.6 GeV



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errors in y_t: theory + experiment

Tevatron: $M_t = 173.2 \pm 0.51 \pm 0.71$ GeV

ATLAS and CMS: $M_t = 173.4 \pm 0.4 \pm 0.9$ GeV

$\alpha_s = 0.1184 \pm 0.0007$

Main uncertainty - top Yukawa coupling.

- Perturbation theory, $\mathcal{O}(\alpha_s^4)$. Estimate of Kataev and Kim: $\delta y_t/y_t \simeq -750(\alpha_s/\pi)^4 \simeq -0.0015$, $\delta M_{crit} \simeq -0.5$ GeV
- Non-perturbative QCD effects, $\delta M_t \simeq \pm\Lambda_{QCD} \simeq \pm 300$ MeV, $\delta M_{crit} \simeq \pm 0.6$ GeV
- 1 GeV experimental error in M_t leads to 2 GeV error in M_{crit}.
- Alekhin et al. Theoretically clean is the extraction of y_t from $t\bar{t}$ cross-section. However, the experimental errors in $p\bar{p} \to t\bar{t} + X$ are quite large, leading to $\delta M_t \simeq \pm 2.8$ GeV, $\delta M_{crit} \simeq \pm 5.6$ GeV.

Precision measurements of m_H, y_t and α_s are needed.

I will concentrate on the second, most conservative option - no new physics between the Fermi scale and the Planck scale.

- Inflation?
- Baryogenesis?
- Dark matter?

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For inflation we better have some bosonic field, which drives it. At last, the Higgs boson has been discovered! Can it make the Universe flat, homogeneous, and isotropic, and produce the necessary spectrum of fluctuations for structure formation?

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Yes: Higgs inflation

Bezrukov, MS

non-minimal coupling of Higgs field to gravity

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

Jordan, Feynman, Brans, Dicke,...

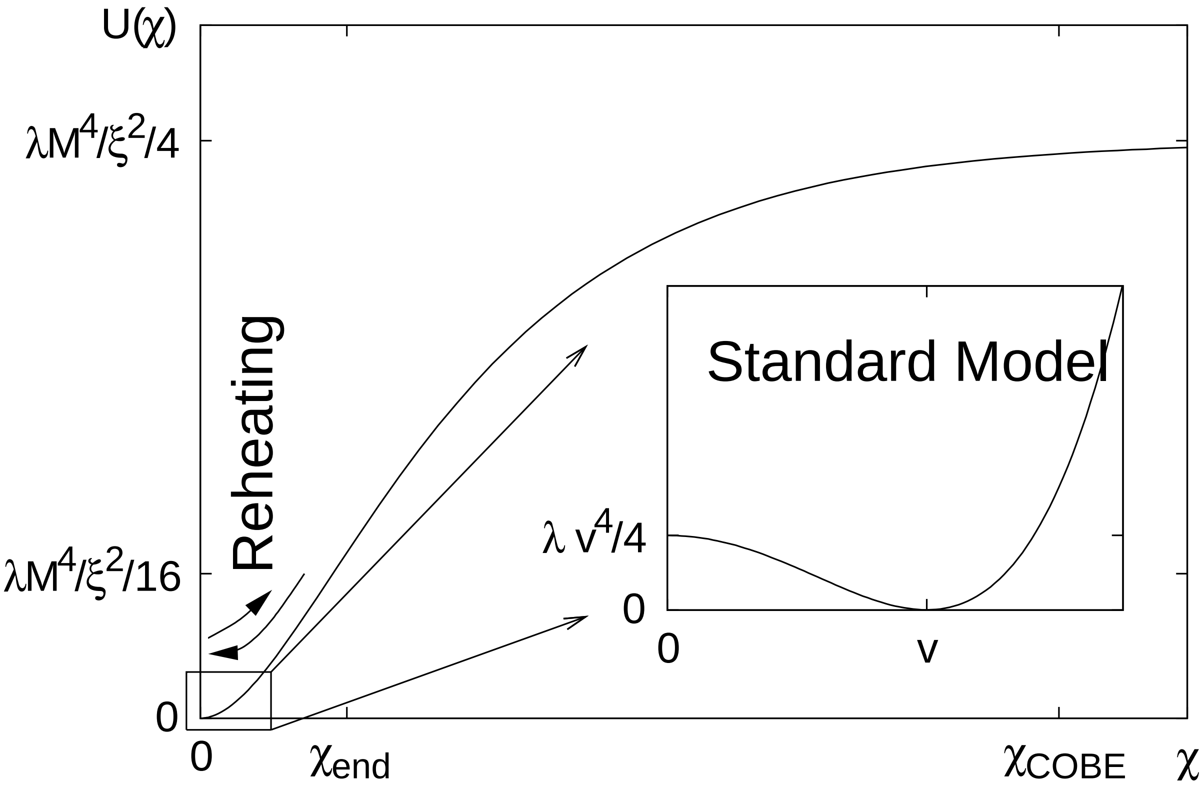
Consider large Higgs fields h.

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

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

Existence of effective flat direction, necessary for successful inflation.

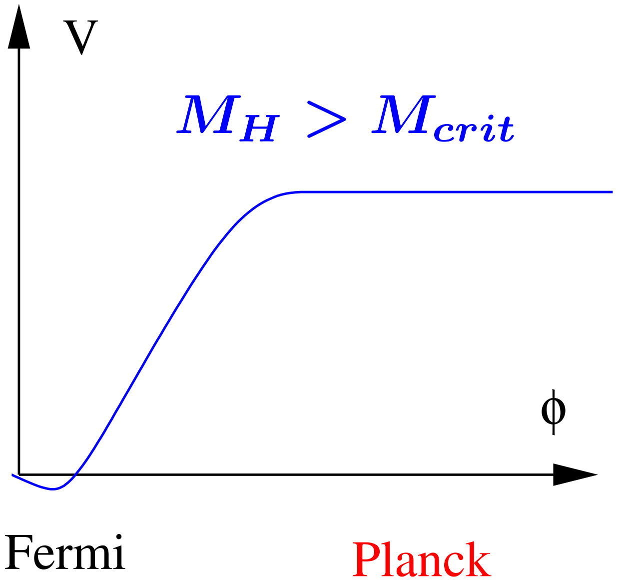
Potential in Einstein frame

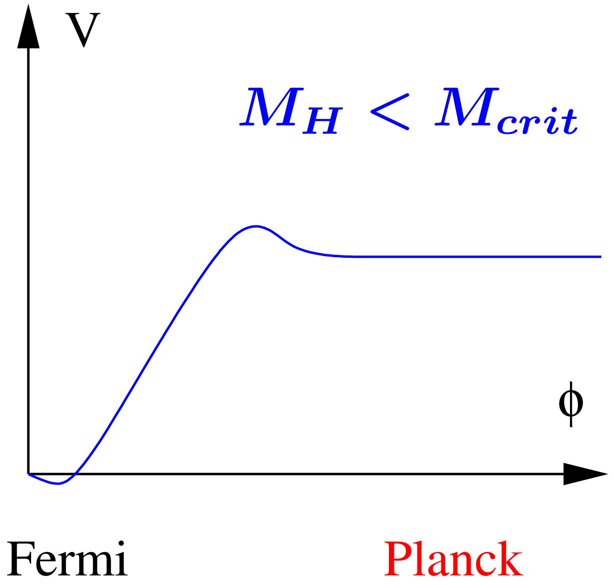


χ - canonically normalized scalar field in Einstein frame.

Inflation and the Higgs mass

Radiative corrections to inflationary potential: Higgs inflation works only for $\boldsymbol{\lambda(M_P/\sqrt{\xi}) > 0}$. Numerically, $\boldsymbol{M_H > M_{crit}}$ with extra theoretical uncertainty of $\boldsymbol{\delta M_H \sim}$ 1 GeV.





Analysis of higher dimensional operators and radiative corrections: Higgs inflation occurs in the weak coupling regime and is self-consistent. Bezrukov et al

Inflaton potential and observations

If inflaton potential is known one can make predictions and compare them with observations.

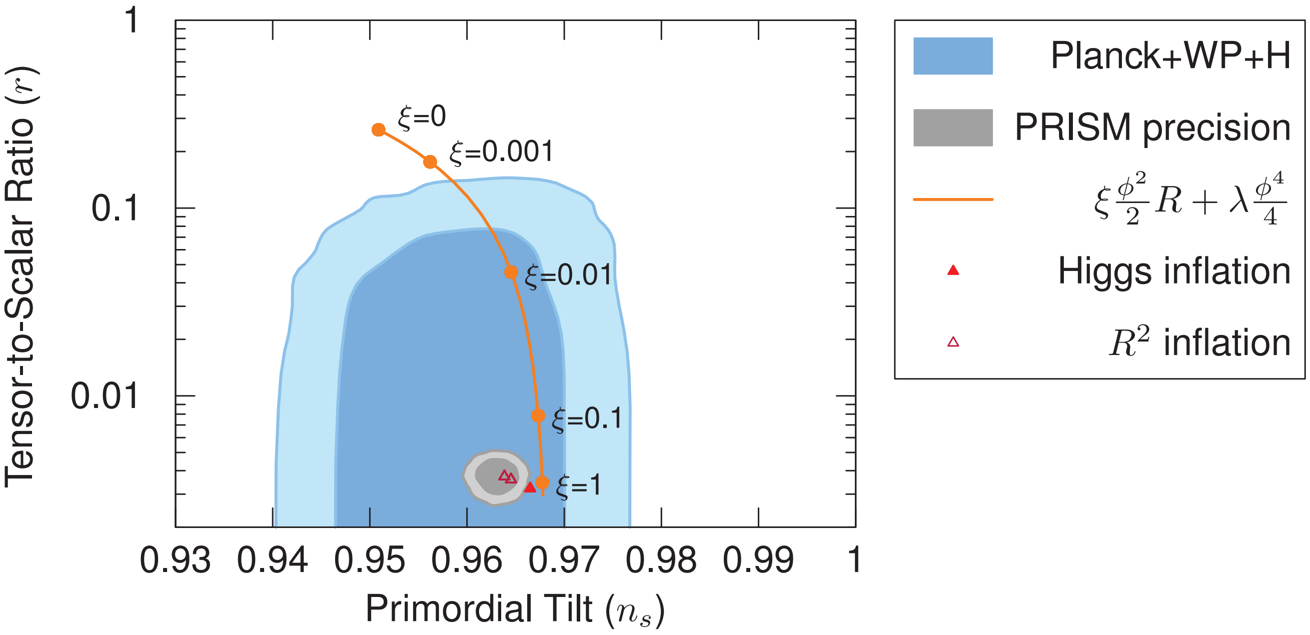
- $\delta T/T$ at the WMAP normalization scale $\sim \mathbf{500}$ Mpc.
- The value of spectral index n_s of scalar density perturbations

$$\left\langle \frac{\delta T(x)}{T}\frac{\delta T(y)}{T} \right\rangle \propto \int \frac{d^3k}{k^3} e^{ik(x-y)} k^{n_s-1}$$

- The amplitude of tensor perturbations $r = \frac{\delta\rho_s}{\delta\rho_t}$

These numbers can be extracted from WMAP observations of cosmic microwave background. Higgs inflation: one new parameter, $\xi \Longrightarrow$ two predictions. From WMAP normalization $\xi \sim \mathbf{700}$.

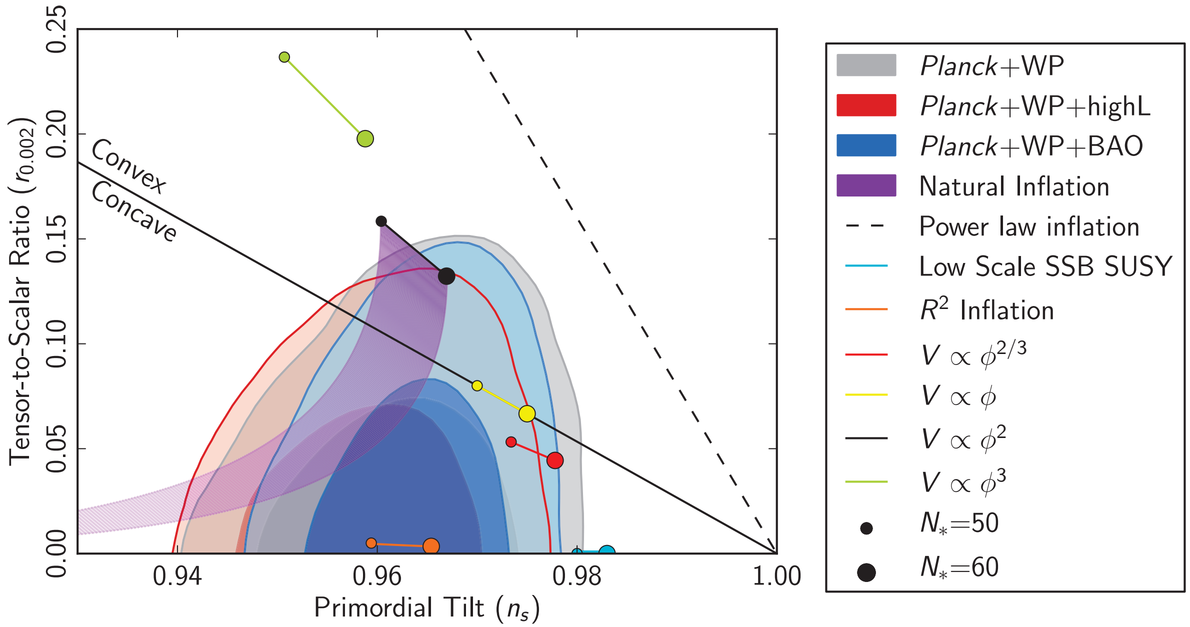
CMB parameters—spectrum and tensor modes



- Higgs inflation - no new particles, $T_{reh}\sim 10^{13-14}$ GeV, $N\simeq 58$
- Small non-minimal coupling ξ : light inflaton. Gorbunov, Bezrukov
- Large or small ξ: conformal supergravity. Einhorn et al, Ferrara et al, Kallosh, Linde,...

Perturbations are Gaussian, in accordance with Planck. Rosset, parallel sect.

Other models



- R^2 inflaton - scalaron with mass $\sim 3 \times 10^{13}$ GeV, $T_{reh} \sim 3 \times 10^9$ GeV, $N \simeq 54$. Starobinsky; Chibisov, Mukhanov; Vilenkin; Gorbunov et al.,...
- R^2 inflation in SUGRA. Kallosh, Linde; Ellis et al., Starobinsky, Ketov; Farakos et al., Buchmuller et al.,...

Baryon asymmetry of the Universe I

Popular mechanism for baryogenesis:

- Electroweak baryogenesis. Idea (Cohen, Kaplan, Nelson): at high temperatures we are in the symmetric phase of the EW theory. During the universe cooling the first order EW phase transition (PT) goes through nucleation of bubbles of the new (Higgs) phase. Scattering of different particles on the domain walls leads to separation of baryon number and due to sphalerons to baryon asymmetry.

Challenged, but still possible in the MSSM: light stop is required for first order EW phase transition. Curtin et al, Cohen et al, Carena et al, Morrissey et al,...

Baryon asymmetry of the Universe II

Another popular mechanism for baryogenesis:

- Thermal leptogenesis. Idea (Fukugita, Yanagida): superheavy Majorana leptons with the mass $\sim 10^{10}$ GeV decay and produce lepton asymmetry, which is converted to baryon asymmetry by sphalerons.

Necessity of heavy particles $\Longrightarrow$ large radiative corrections to the Higgs mass (hierarchy problem) $\Longrightarrow$ SUSY at the electroweak scale. However, no signs of SUSY are seen... Way out: resonant leptogenesis with degenerate Majorana leptons with masses 1 TeV Pilaftsis et al

Thermal leptogenesis cannot be disproved, but will be fine tuned without new physics at Fermi scale

So, if the next LHC runs will confirm the SM, popular mechanisms for baryogenesis will be disfavored.

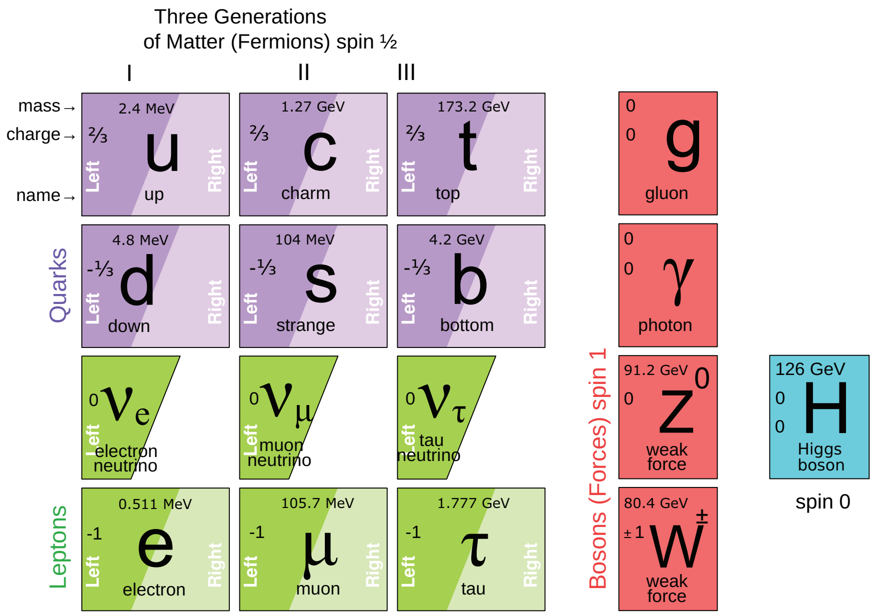
How the baryon asymmetry of the Universe has emerged?

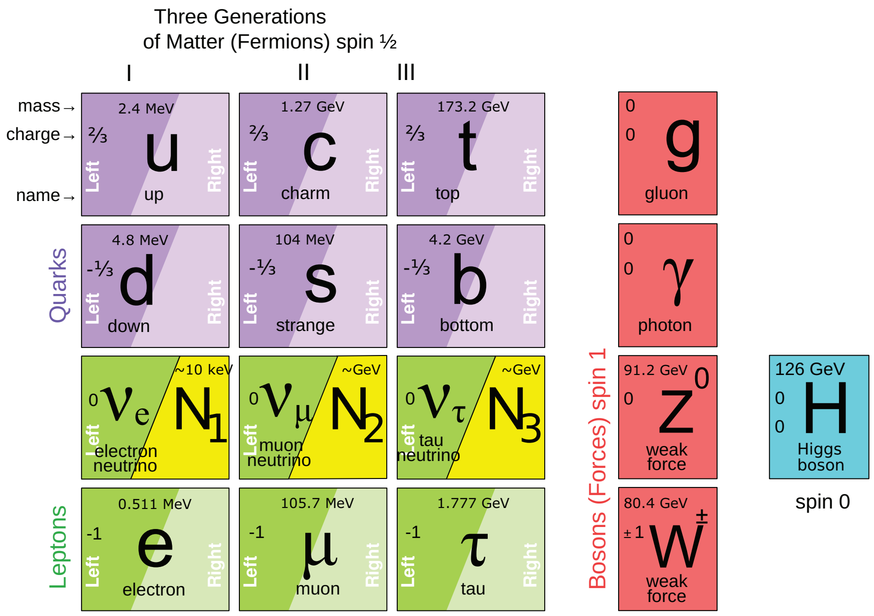
Dark matter

Most popular DM candidate: WIMP, associated with new physics solving the hierarchy problem at the electroweak scale. If no new physics is discovered at the LHC, this candidate is not that attractive anymore...

What is the Dark matter particle?

A possible answer: the νMSM





Role of N_1 with mass in keV region: dark matter. Search - with the use of X-ray telescopes

Role of $N_2,\ N_3$ with mass in 100 MeV – GeV region: “give” masses to neutrinos and produce baryon asymmetry of the Universe. Search - intensity and precision frontier, SPS at CERN.

See Ruchayskiy, EPS HEP parallel session

Dark radiation, neutrino masses

Light particles of the Standard Model: 3 neutrinos and a photon.

Prediction of the number of relativistic degrees of freedom (photon is not included) in terms of “effective number of neutrino species”

$$N_{eff} = 3.046$$

Deviation from 3 is due to non-instantaneous decoupling and finite temperature effects.

Lower bound on the sum of neutrino masses, from neutrino oscillations:

$$\sum m_\nu > 0.06 \text{ eV} \qquad \sum m_\nu > 0.1 \text{ eV}$$

normal hierarchy   inverted hierarchy

Both quantities can be limited by cosmological observations (CMB, BAO,...)

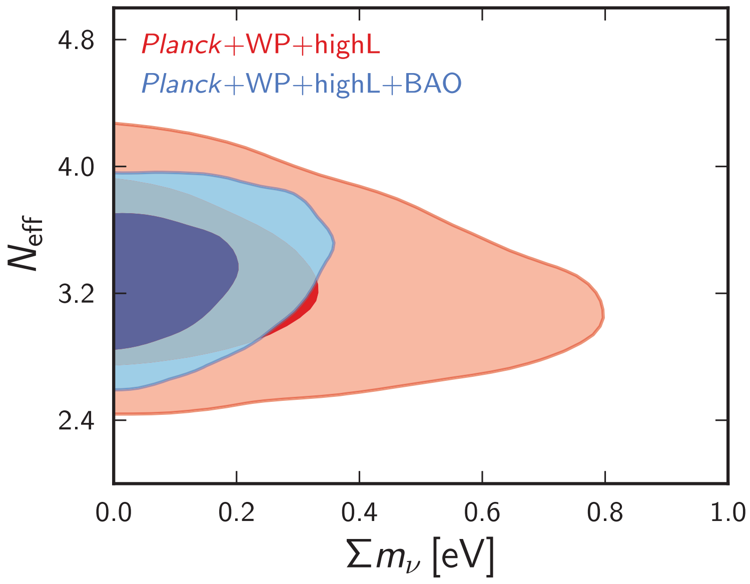
Planck numbers (CMB + BAO):

$$\sum m_\nu < 0.23\ \text{eV}, \qquad N_{eff} = 3.30 \pm 0.27$$

but results depend on the dataset used (± WMAP polarisation, high resolution CMB from ACT and SPT)

Consistent with the Standard Model, but cannot rule out new physics, which can potentially change N_{eff}:

- light $\sim$ 1 eV sterile neutrinos
- quintessence, dilaton
- relic gravitational waves
- new particle decays during BBN
- ...



Conclusions

Wish list

In addition to the traditional goals of HEP experiments for cosmology (WIMPS, axions, new physics above the Fermi scale, light sterile neutrinos,...):

- Higgs mass with highest possible precision (LHC, $\mathbf{200}$ MeV?)
- Top Yukawa coupling with accuracy $\mathbf{5 \times 10^{-4}}$ ($\boldsymbol{\delta M_t \simeq} \mathbf{100}$ MeV) (LHC? future e^+e^- collider?)
- $\boldsymbol{\alpha_s}$ with uncertainty $\boldsymbol{\delta\alpha_s \simeq} \mathbf{2 \times 10^{-4}}$

Stability of EW vacuum? Higgs inflation? Asymptotic safety?

- Search for new particles producing baryon asymmetry of the Universe (below the Fermi scale, possible experiment at CERN-SPS?)

Wish list, cont

Cosmological and astrophysical experiments, which can elucidate the structure of the underlying theory.

To test Higgs inflation, and to distinguish it from R^2 inflation and other models:

- Precision in spectral index n_s of scalar perturbations at the level of 10^{-3} (PRISM?)
- Determination of tensor-to-scalar ratio down to values $r \simeq 0.003$ (COrE, PRISM?)
- Determination of the running of the spectral index $dn_s/dlogk$ down to values 5×10^{-4} (SKA?).

Equation of state of dark energy, to check the predictions of different dynamical DE models (quintessence, Higgs-dilaton, etc)

- $\omega = P/V$, with accuracy of 1% (Euclid?)

Wish list, cont

Dark radiation, neutrino masses

- Neutrino masses from cosmology down to $\sum m_\nu \simeq 0.05$ eV, to reach the lower bound (Planck+Euclid?)
- Accuracy in determination of effective number of massless degrees of freedom below ~ 0.04, to check the SM prediction 3.046 (Planck+Euclid?).

Dark matter

- Search for radiative decays of DM particles $N \to \gamma\nu$, alternative to WIMPS or axions with the help of high resolution X-ray telescopes.

*Prism: Polarized Radiation Imaging and Spectroscopy Mission
*DES: The Dark Energy Survey
*SKA: The Square Kilometer Array
*COrE: The Cosmic Origins Explorer

Back up slides

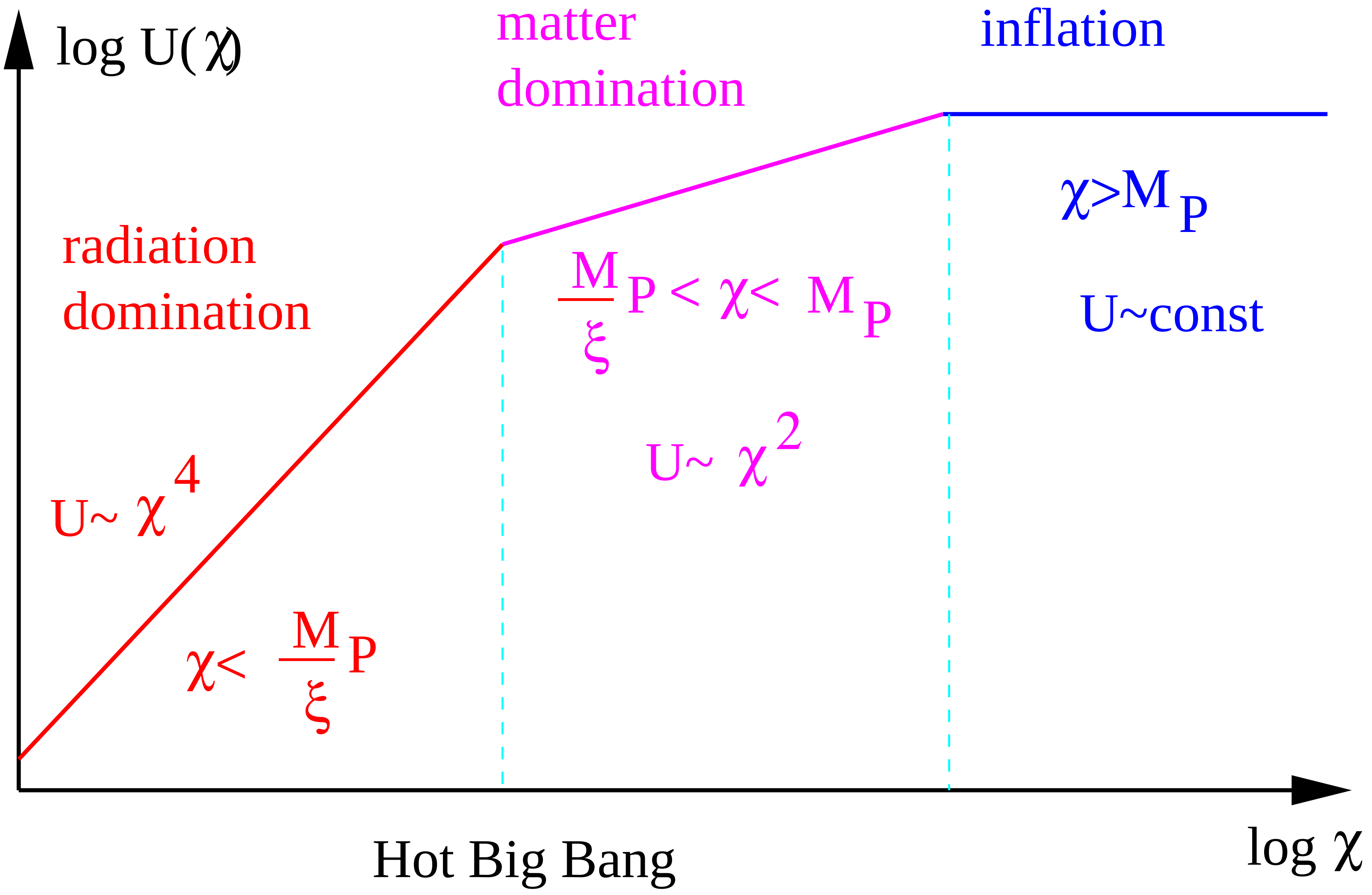
Life after Higgs inflation

Two different stages:

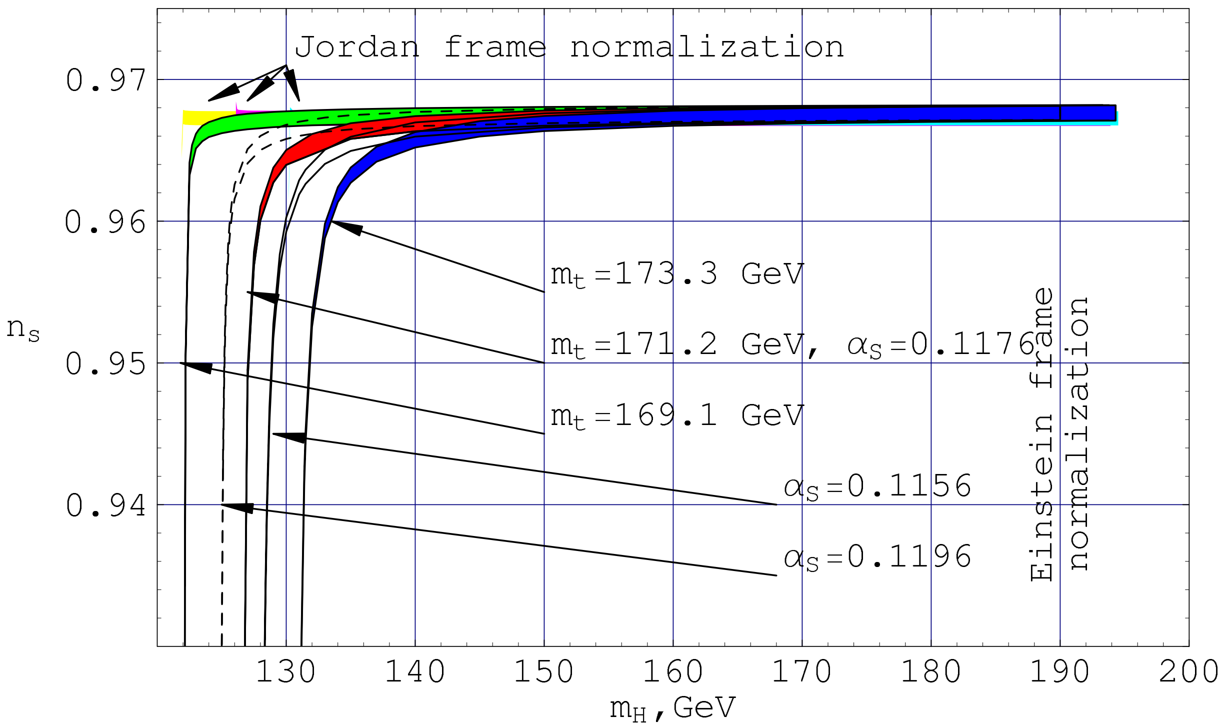
- For scalar field $M_P > \chi > \frac{M_P}{\xi}$ the potential for χ is essentially *quadratic*, $m_\chi^2 \sim \lambda M_P^2/\xi^2$. Exponential expansion of the Universe is changed to the power low, corresponding to matter domination. Particle creation takes place when χ passes through zero.
- After $\mathcal{O}(\xi)$ oscillations the scalar field reaches $\chi \simeq \frac{M_P}{\xi}$. The energy is transferred to other fields of the SM, and the radiation-dominated epoch starts,

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

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

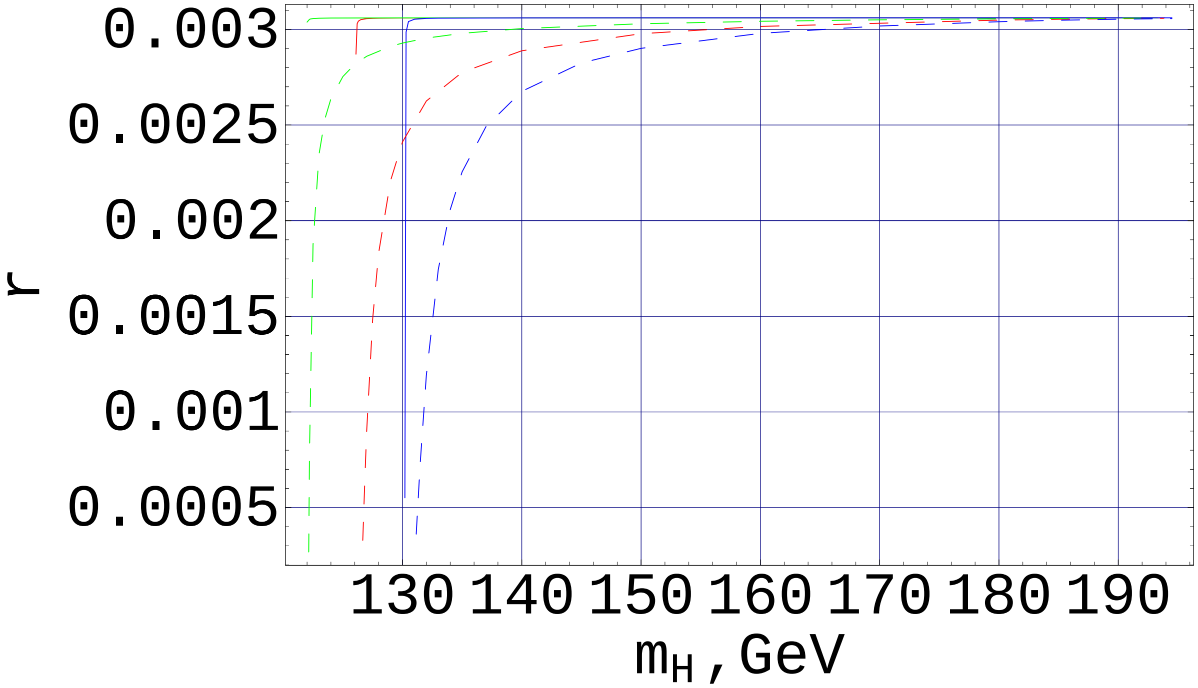

log U(χ)
matter domination
inflation
$\chi > M_P$
radiation domination
$\frac{M_P}{\xi} < \chi < M_P$
U~const
$U \sim \chi^2$
$U \sim \chi^4$
$\chi < \frac{M_P}{\xi}$
Hot Big Bang
log χ

Two-loop results



Nearly horizontal coloured stripes correspond to the normalization prescription I. Green, red, and blue stripes give the result with normalization prescription II for different $\boldsymbol{m_t}$ and $\boldsymbol{\alpha_s = 0.1176}$, two white regions correspond to different $\boldsymbol{\alpha_s}$ and $\boldsymbol{m_t = 171.2\mathrm{GeV}}$. The width of the stripes corresponds to changing the number of e-foldings between 58 and 60, or approximately one order of magnitude in reheating temperature.

Two-loop results

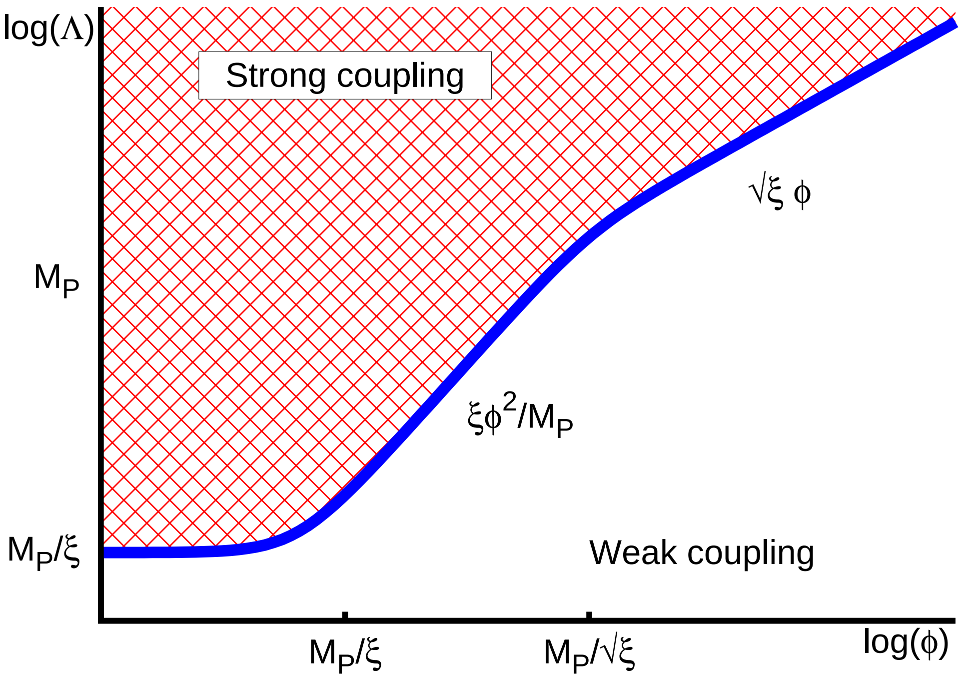


Tensor-to-scalar ratio r depending on the Higgs mass m_H, calculated with the RG enhanced effective potential. Nearly horizontal solid lines correspond to the normalization prescription I. Green, red, and blue dashed lines give the result with normalization prescription II for $m_t = 169.1, 171.2, 173.3$ GeV. Dependence on the number of e-foldings is very small.

Summary of predictions

- Certain interval for the Higgs mass, $m_{\rm min} < M_H < m_{\rm max}$
- $n_s = 0.968, \;\; r = 0.003$, for scale-invariant regularisation
- $n_s < 0.968, \;\; r < 0.003$, for scale-noninvariant regularisation
- Gaussian perturbations

Higgs-dependent cutoff

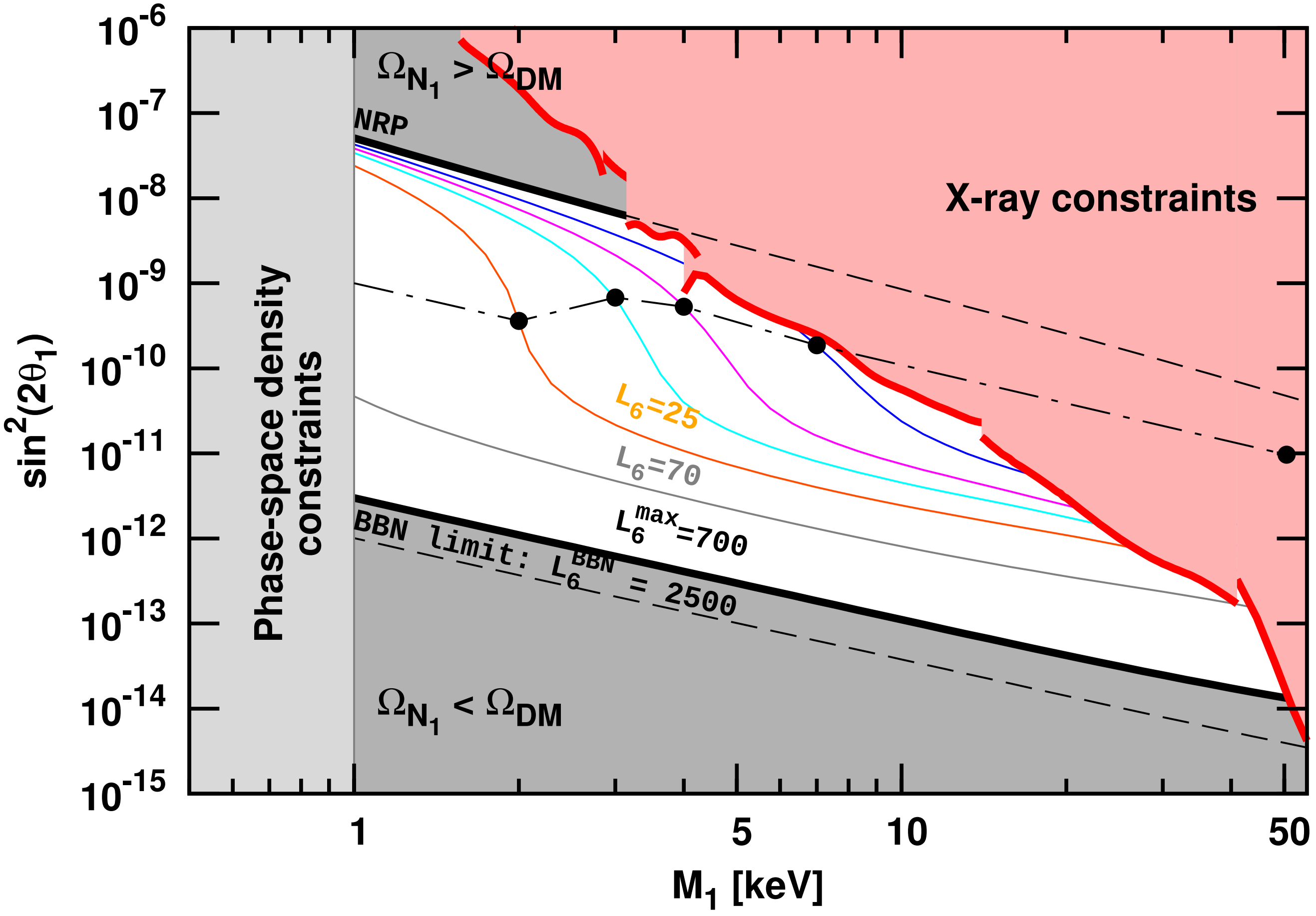


Cutoff is higher than the relevant dynamical scales throughout the whole history of the Universe, including the inflationary epoch and reheating!!

The Higgs-inflation is self-consistent.

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 $l\bar{l} \to \nu N_1, \quad q\bar{q} \to \nu N_1$ 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 $\Omega_{\rm fov} \ll 1$)

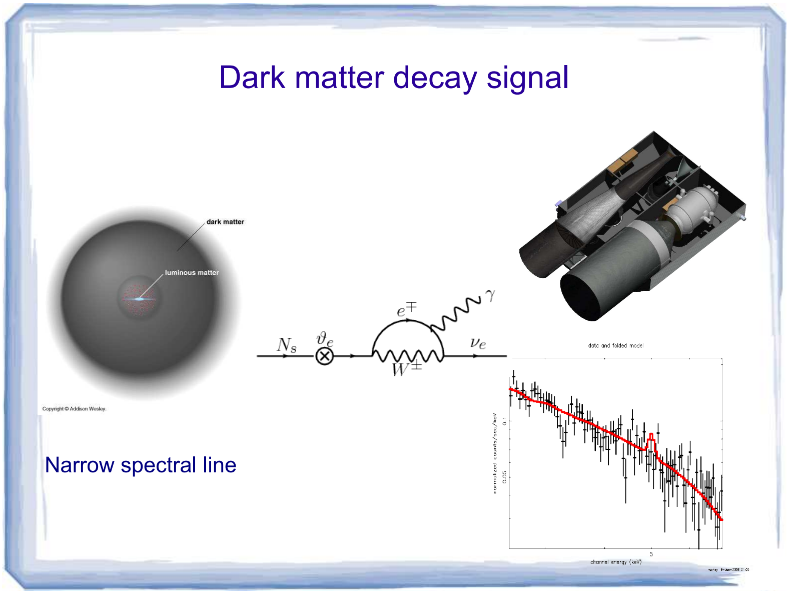
Strategy: Use X-ray telescopes (such as Chandra and XMM Newton) to look for a narrow γ line against astrophysical background. Choose astrophysical objects for which:

- 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 !

Search for N_1

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.

Prediction: active neutrino masses

Asaka, Blanchet, M.S: The minimal number of sterile neutrinos, which can explain the dark matter in the Universe and neutrino oscillations, is $\mathcal{N} = 3$. Only one sterile neutrino can be the dark matter. Lightest active neutrino:

$$m_1 \leq 2 \cdot 10^{-3}\ \text{eV}.$$

Normal hierarchy:

$$m_2 = [9.05^{+0.2}_{-0.1}] \cdot 10^{-3}\text{eV} \simeq \sqrt{\Delta m^2_{solar}}\ ,$$
$$m_3 = [4.8^{+0.6}_{-0.5}] \cdot 10^{-2}\text{eV} \simeq \sqrt{\Delta m^2_{atm}}\ ,$$

Inverted hierarchy: $m_{2,3} = [4.7^{+0.6}_{-0.5}] \cdot 10^{-2}$ eV .

Prediction: neutrinoless double β decay

F. Bezrukov: Effective Majorana mass $m_{\beta\beta}$

Normal hierarchy: $\mathbf{1.3\ meV} < m_{\beta\beta} < \mathbf{3.4\ meV}$

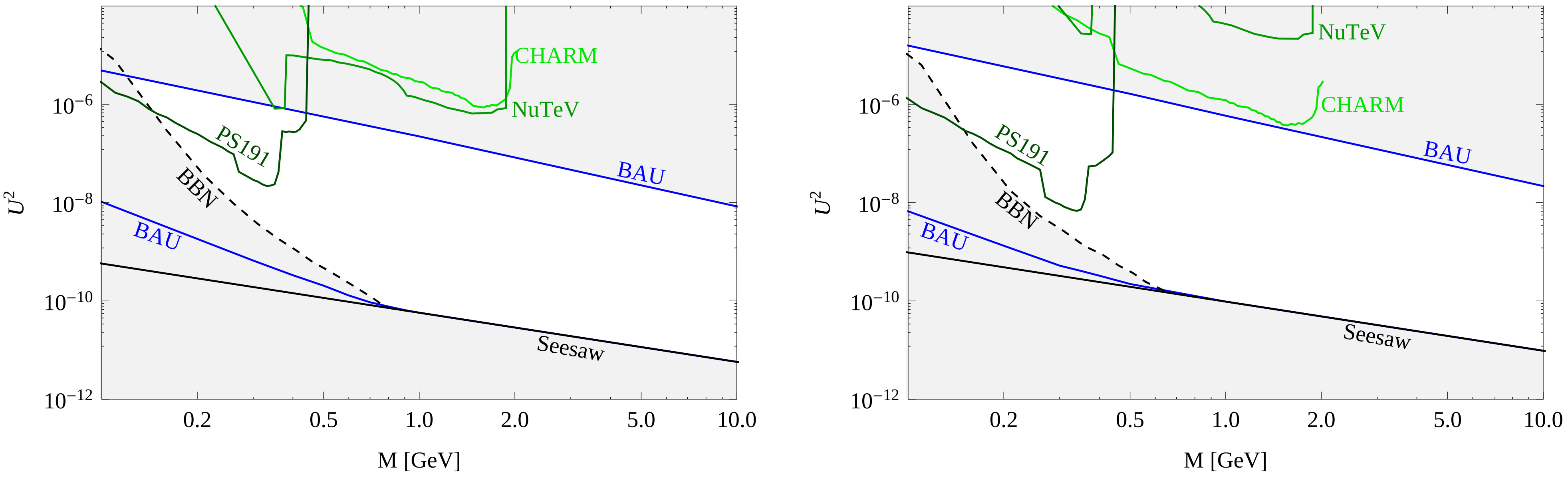
Inverted hierarchy: $\mathbf{13\ meV} < m_{\beta\beta} < \mathbf{50\ meV}$

Knowing $m_{\beta\beta}$ experimentally will allow to fix Majorana CP-violating phases in neutrino mass matrix, provided θ_{13} and Dirac phase δ are known.

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, from the see-saw formula, from the big bang nucleosynthesis and experimental searches. Left panel - normal hierarchy, right panel - inverted hierarchy.

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 $U^4 = U^2 \times U^2$)

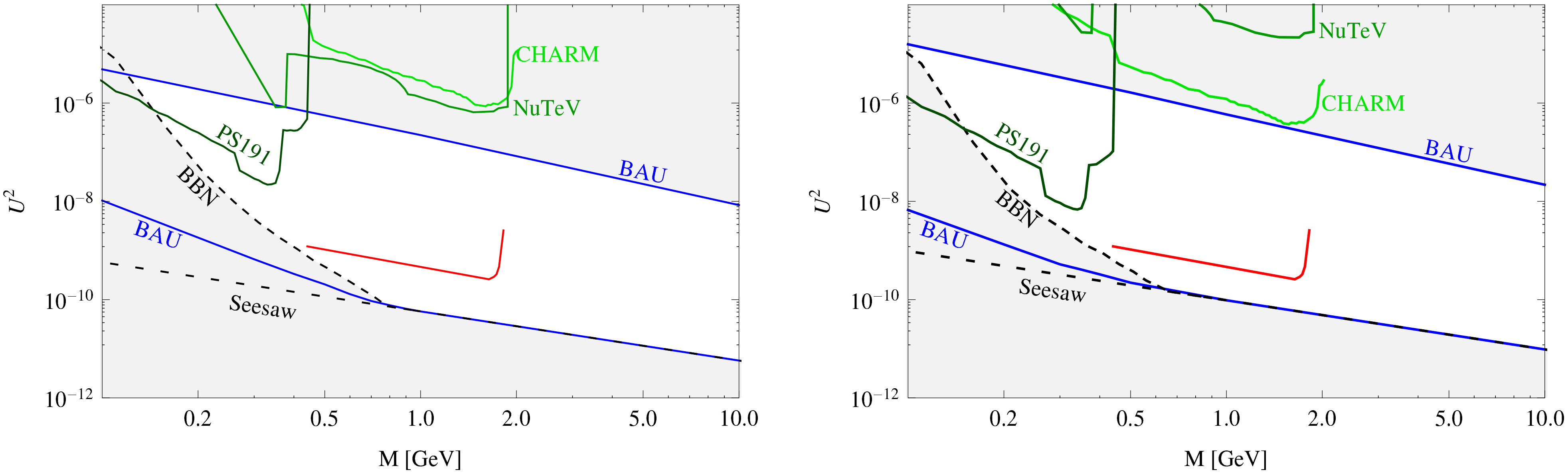
  First step: proton beam dump, creation of N in decays of $K,\ D$ or B mesons: U^2

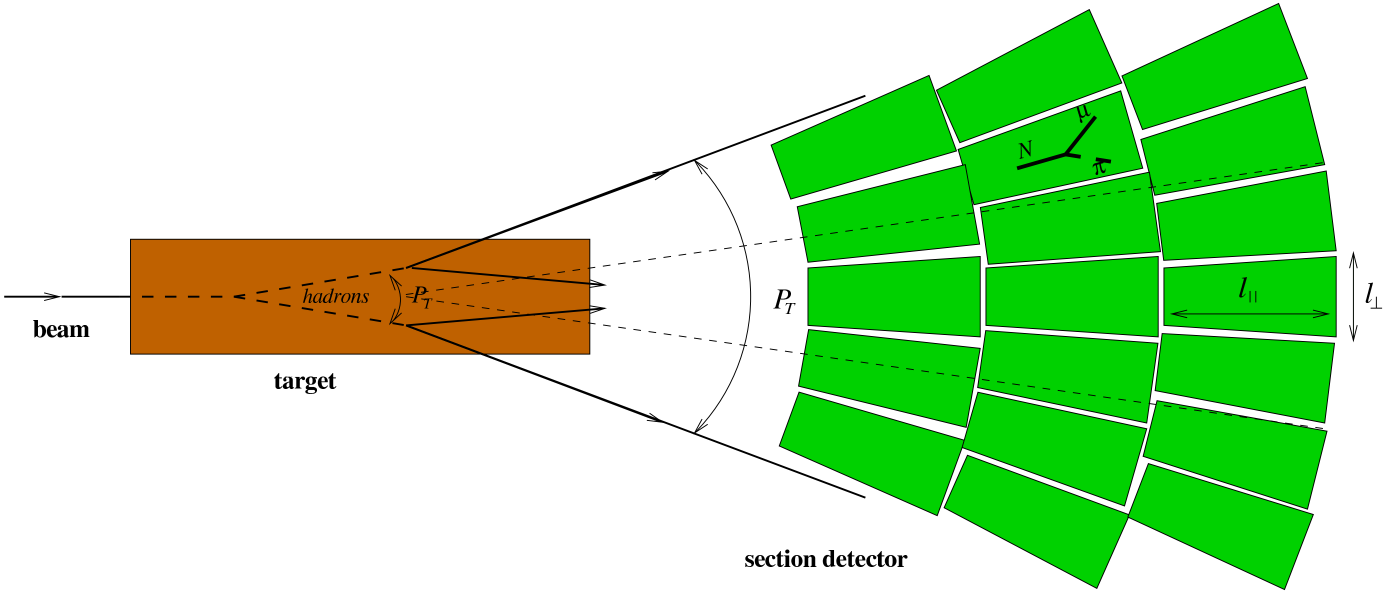
  Second step: search for decays of N in a near detector, to collect all Ns: U^2

  - $M_N < M_K$: Any intense source of K-mesons (e.g. from proton targets of PS.)
  - $M_N < M_D$: Best option: SPS beam + near dedicated detector
  - $M_N < M_B$: Project X (?) + near detector
  - $M_N > M_B$: extremely difficult

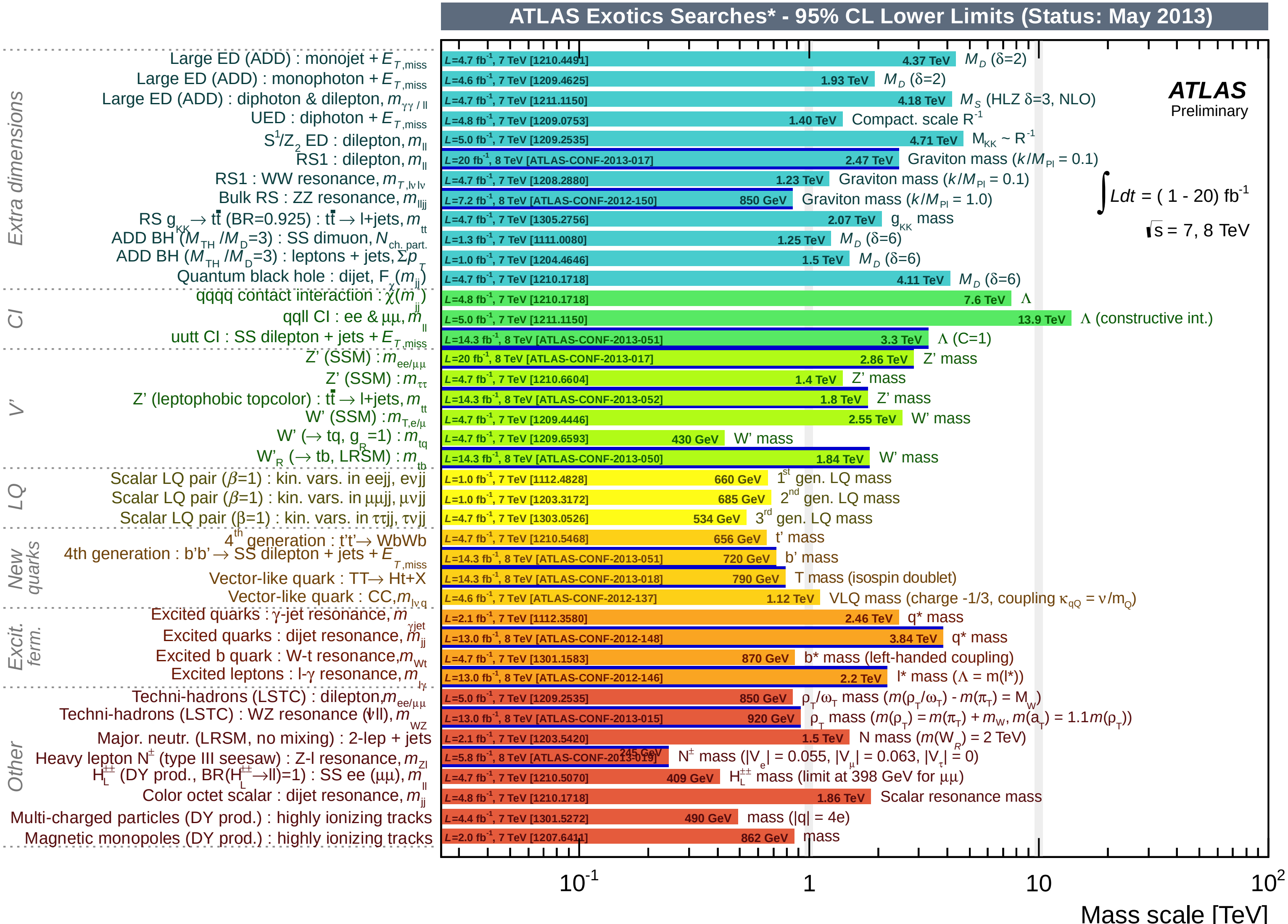
Search for $N_2, \; N_3$

Challenge - from baryon asymmetry: $\theta^2 \lesssim 5 \times 10^{-7} \left(\frac{\text{GeV}}{M}\right)$ CERN SPS is the best existing machine to uncover new physics below the electroweak scale. For $l \sim 100$ m detector.

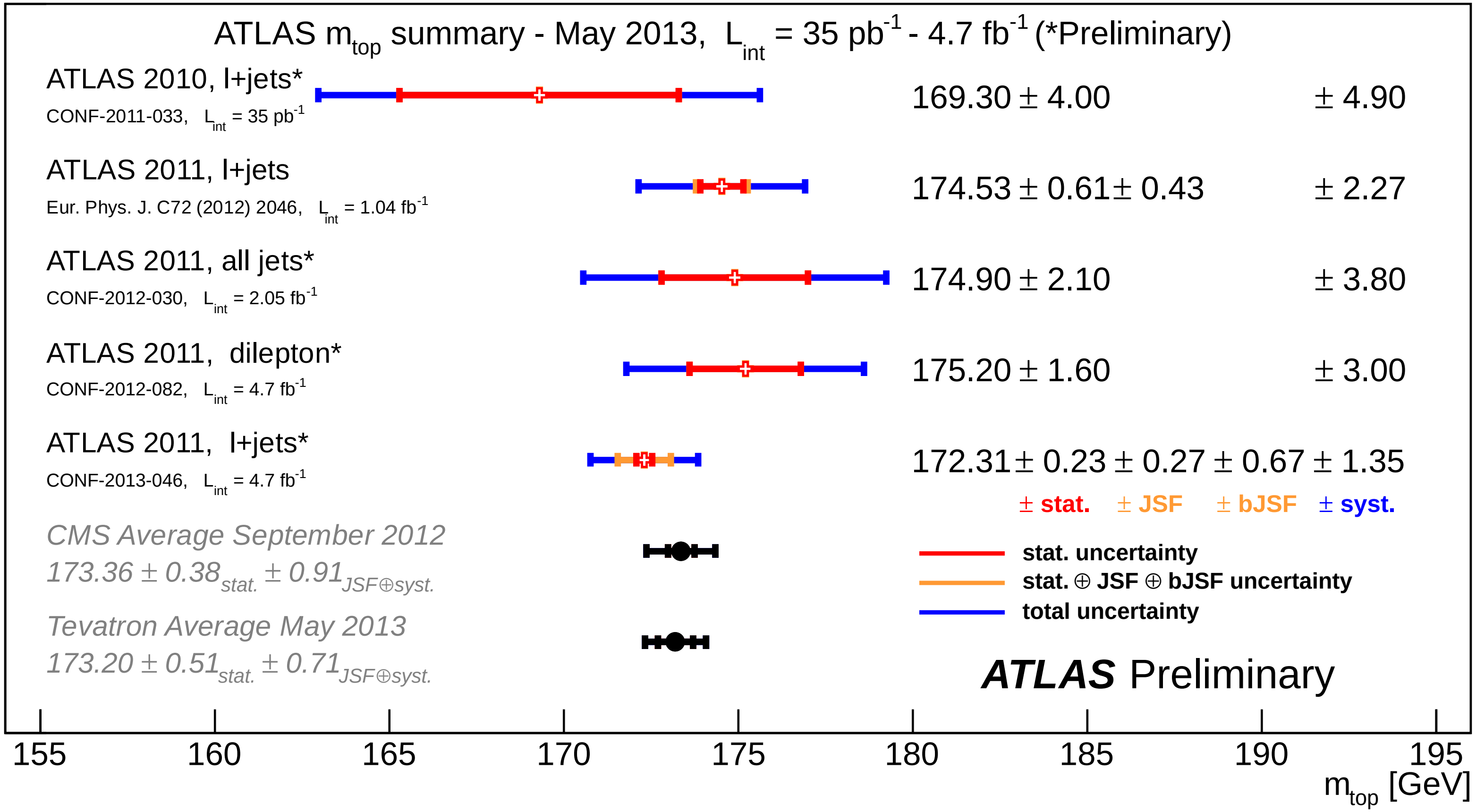




Sketch of the possible experiment at SPS



*Only a selection of the available mass limits on new states or phenomena shown


ATLAS m_{top} summary - May 2013, L_{int} = 35 pb^{-1} - 4.7 fb^{-1} (*Preliminary)
ATLAS 2010, l+jets*
CONF-2011-033, L_{int} = 35 pb^{-1}
169.30 ± 4.00 ± 4.90
ATLAS 2011, l+jets
Eur. Phys. J. C72 (2012) 2046, L_{int} = 1.04 fb^{-1}
174.53 ± 0.61 ± 0.43 ± 2.27
ATLAS 2011, all jets*
CONF-2012-030, L_{int} = 2.05 fb^{-1}
174.90 ± 2.10 ± 3.80
ATLAS 2011, dilepton*
CONF-2012-082, L_{int} = 4.7 fb^{-1}
175.20 ± 1.60 ± 3.00
ATLAS 2011, l+jets*
CONF-2013-046, L_{int} = 4.7 fb^{-1}
172.31 ± 0.23 ± 0.27 ± 0.67 ± 1.35
± stat. ± JSF ± bJSF ± syst.
CMS Average September 2012
173.36 ± $0.38_{stat.}$ ± $0.71_{JSF\oplus syst.}$
Tevatron Average May 2013
173.20 ± $0.51_{stat.}$ ± $0.71_{JSF\oplus syst.}$
stat. uncertainty
stat. ⊕ JSF ⊕ bJSF uncertainty
total uncertainty
ATLAS Preliminary
155
160
165
170
175
180
185
190
195
m_{top} [GeV]