Higgs boson, neutral leptons, and cosmology

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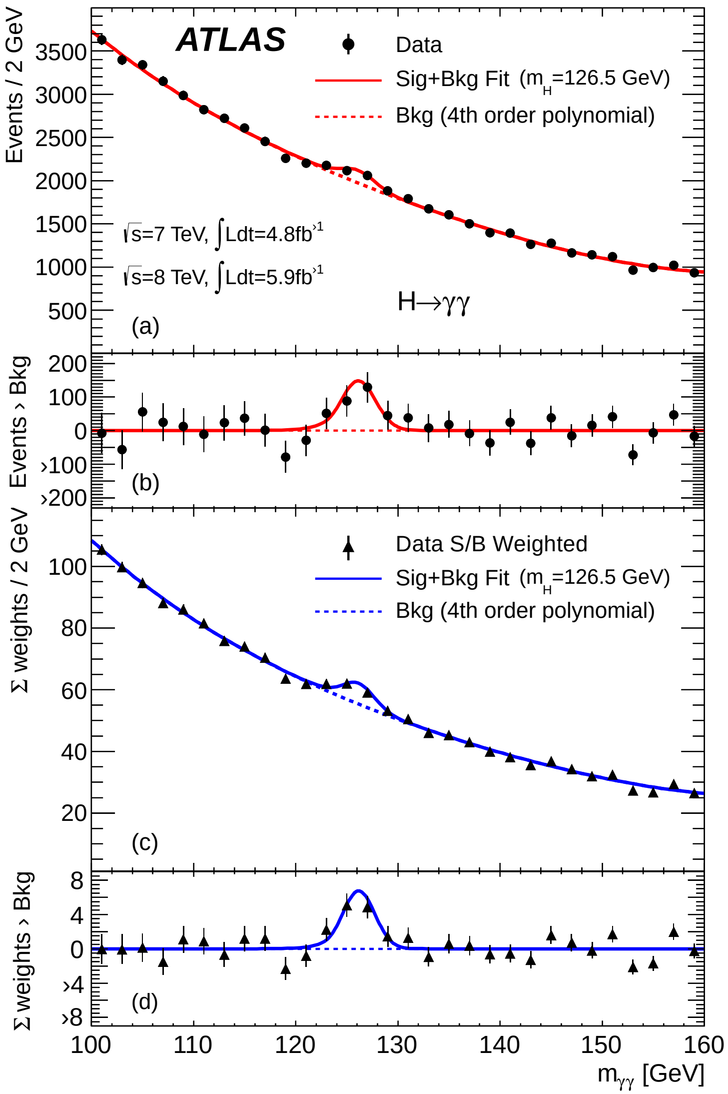
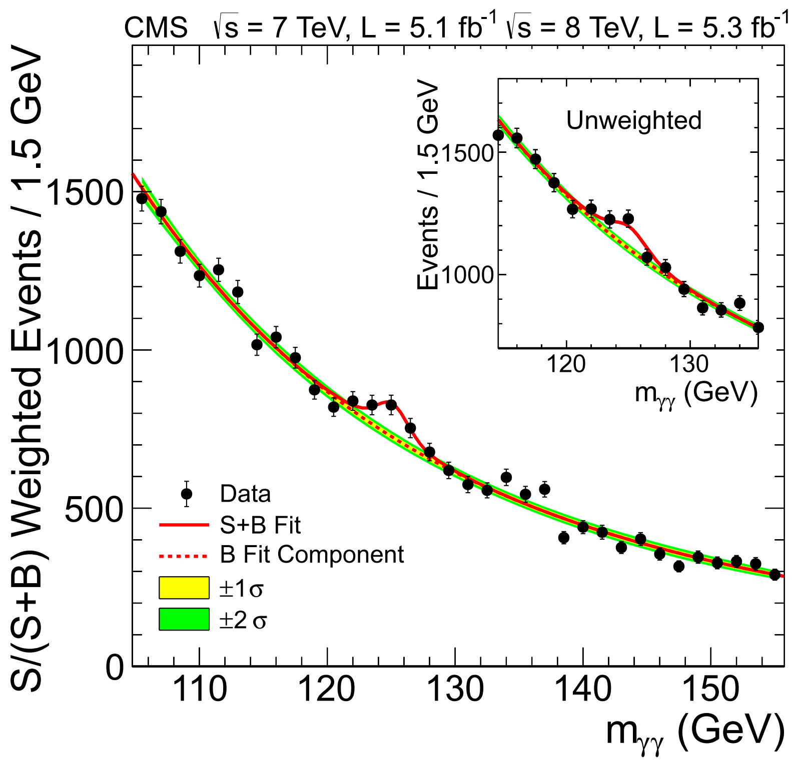
LPTHE, Paris
2 June 2014

July 4, 2012, Higgs at ATLAS and CMS



CMS



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According to CMS,

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What does it mean for high energy physics?

Higgs boson mass and the scale of new physics

Self-consistency of the SM

Within the SM the mass of the Higgs boson is an arbitrary parameter which can have any value (if all other parameters are fixed) from

$m_{\mathrm{meta}} \simeq 111$ GeV (metastability bound)

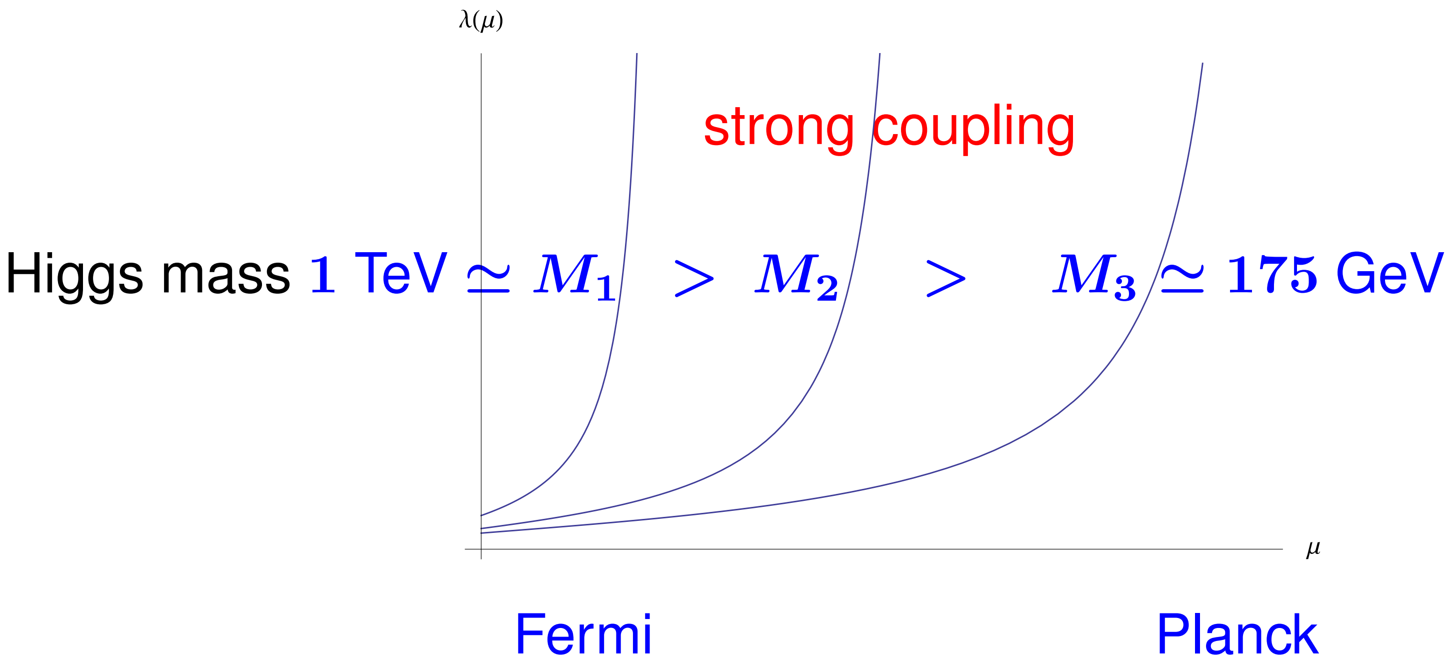
to

$m_{\mathrm{Landau}} \simeq 1$ TeV (triviality bound)

Triviality bound

L. Maiani, G. Parisi and R. Petronzio '77; Lindner '85; T. Hambye and K. Riesselmann '96;...

The Higgs boson self-coupling has a Landau pole at some energy determined by the Higgs mass. For $M_H \simeq m_{\mathbf{Landau}} \simeq 1$ TeV the position of this pole is close to the electroweak scale.



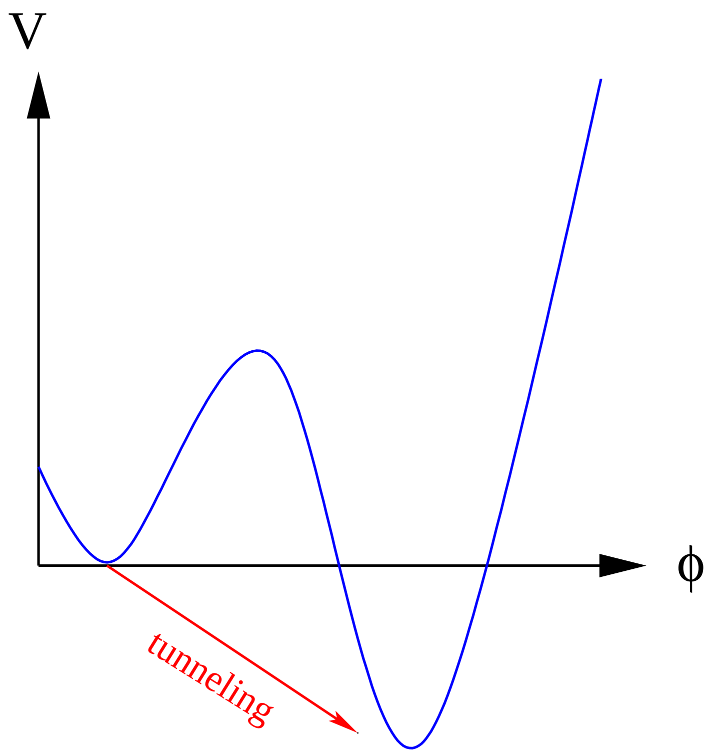
Triviality bound

If $m_H < m_{\max} \simeq 175$ GeV the Landau pole appears at energies higher than the Planck scale $E > M_P$.

LHC: The Standard Model is weakly coupled all the way up to the Planck scale

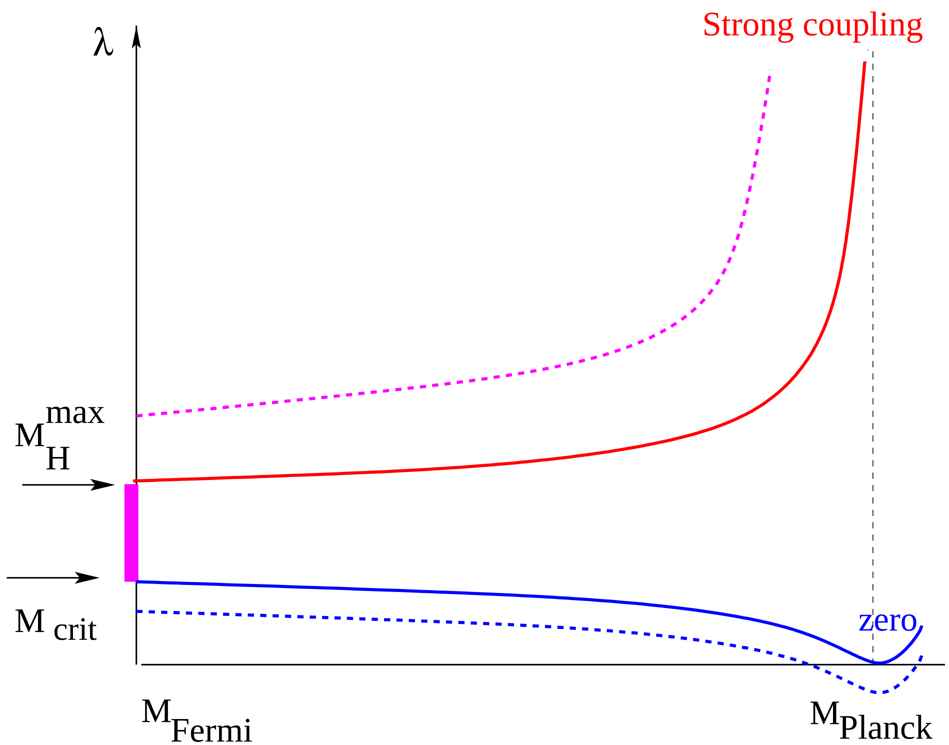
Metastability bound

Krasnikov '78, Hung '79; Politzer and Wolfram '79; Altarelli and Isidori '94; Casas, Espinosa and Quiros '94,'96;...; Ellis, Espinosa, Giudice, Hoecker, Riotto '09;...

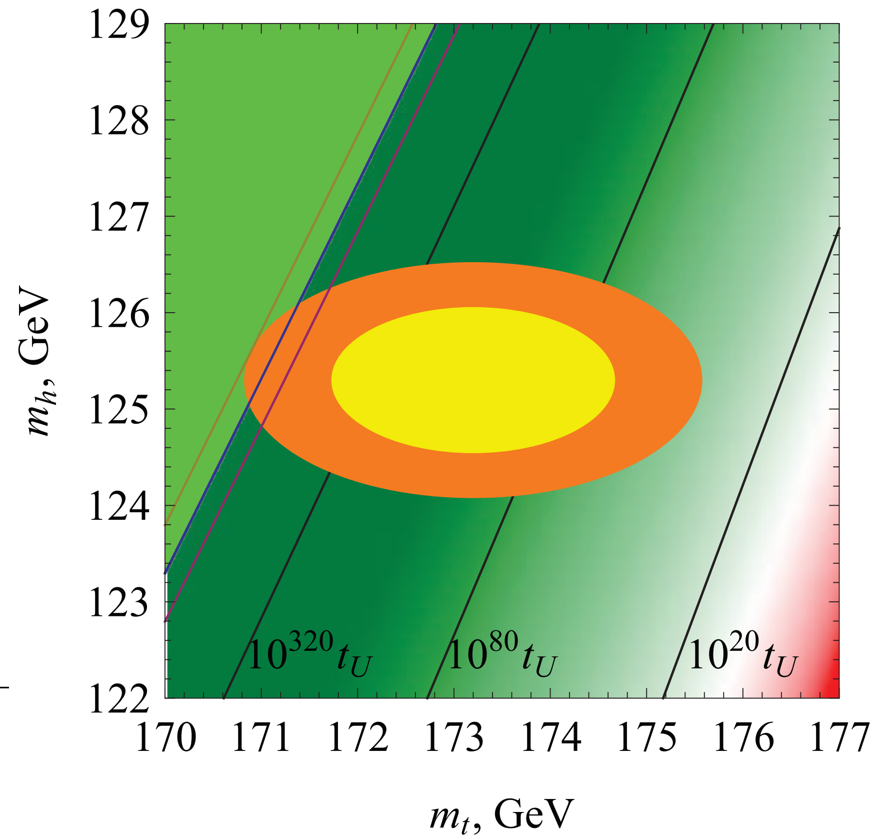


The life-time of our vacuum is smaller than the age of the Universe if $m_H < m_{\mathbf{meta}}$, with $m_{\mathbf{meta}} \simeq \mathbf{111}$ GeV Espinosa, Giudice, Riotto '07

Behaviour of the scalar self-coupling



vacuum lifetime



Metastability bound

If the Higgs mass happened to be smaller than $m_{\rm meta} \simeq 111$ GeV, we would be forced to conclude that there must be some new physics beyond the SM, which stabilizes the SM vacuum.

However, already since LEP we know that $m_H > m_{\rm meta}$ so that new physics is not needed from this point of view.

LHC: SM is a consistent effective theory all the way up to the Planck scale!

Why $M_H = \mathbf{126}$ GeV?

Higgs boson mass predictions

Though the Higgs mass cannot be predicted within the Standard Model, embedding it into larger context may fix M_H.

Compilation of 81 predictions, Thomas Schücker (as of November 2, 2010)

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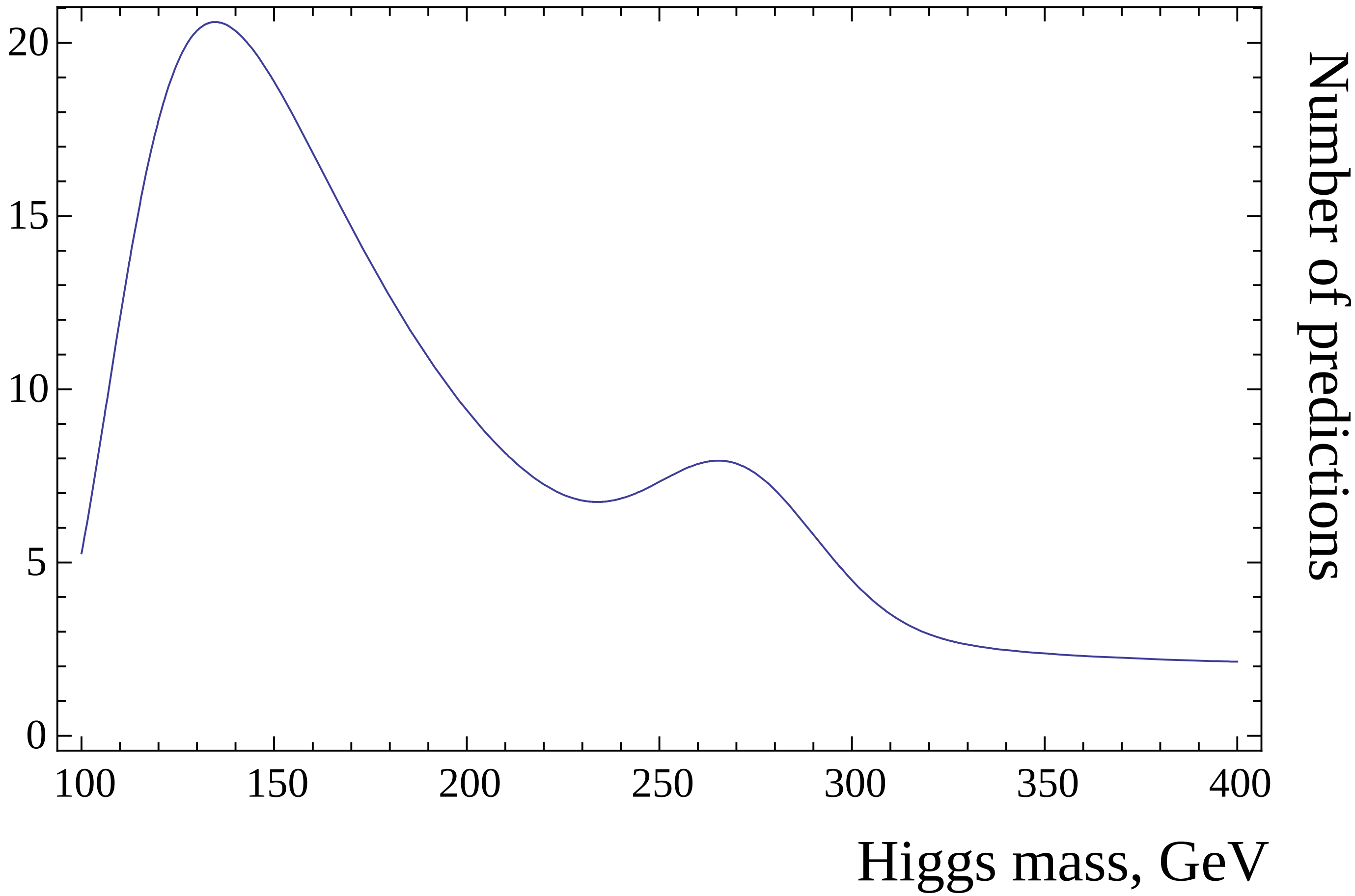
- The most precise prediction: $m_H = 161.8033989$ by NN
- The highest number of predictions by one person (NN): 12
- No predictions in intervals:
  $600 - 739,\ 781 - 1800,\ 2000 - 10^{18}$ GeV

Bayesian approach

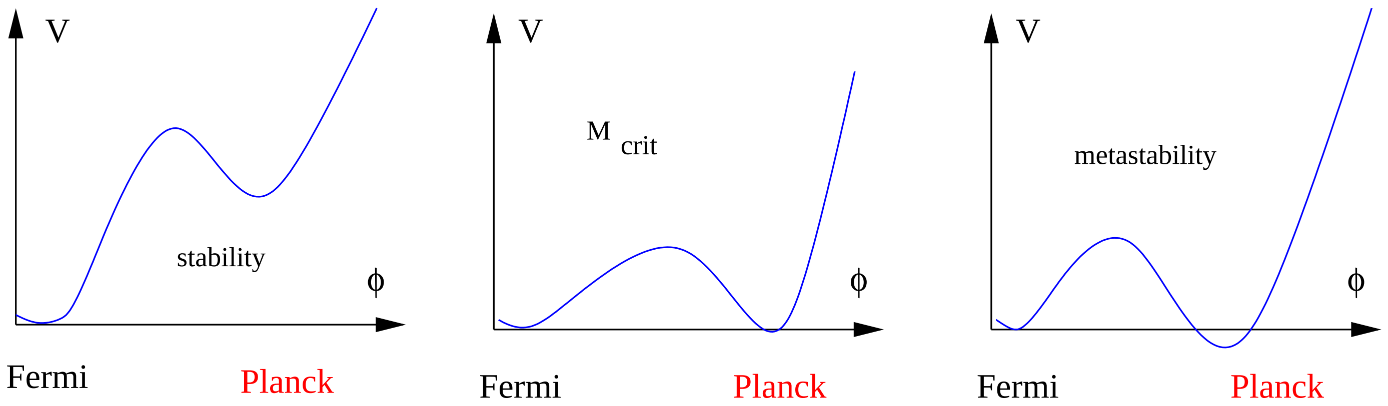
(as of November 2, 2010)



Bayesian “prediction” : $m_H \simeq 140$ GeV

Top and Higgs: absolute stability bound

The combination of top-quark and Higgs boson masses is very close to the stability bound of the SM vacuum* (95'), to the Higgs inflation bound** (08'), and to asymptotic safety values for M_H and M_t *** (09'):



* Froggatt, Nielsen

** Bezrukov et al, De Simone et al

*** Wetterich, MS

Computation of absolute stability bound

- Choose the renormalisation scheme for the SM: $\overline{MS}$
- Compute the effective potential $V(\phi)$ for the Standard Model in tree, one-loop, two-loop,... approximation. It will be a function of the scalar field and $\overline{MS}$ parameters $\alpha_s(\mu),\ y_t(\mu),\ \lambda(\mu)$ etc.
- Find the relation between $\overline{MS}$ parameters of the SM at low energy scale (e.g. $\mu = M_Z$ and experimentally measured quantities, such as masses of weak bosons, the Higgs and the pole top masses, etc in tree, one-loop, two-loop,... approximation.
- Make the renormalisation group improvement of the effective potential with the use of RG equations for the SM couplings in one-loop, two-loop, three-loop,... approximation.
- Find the parameters at which the effective potential has two degenerate minima:

$$V(\phi_{SM}) = V(\phi_1), \quad V'(\phi_{SM}) = V'(\phi_1) = 0,$$

Absolute stability condition

SM vacuum is absolutely stable for $y_t(173.2) < y_t^{\text{crit}}$:

$$y_t^{\text{crit}} = 0.9268 + 0.0058 \times \left[\frac{M_H - 125.9}{0.4} \times 0.2 + \frac{\alpha_s(M_Z) - 0.1184}{0.0007} \times 0.28 \right]$$

$y_t(173.2)$ - top Yukawa coupling in $\overline{\text{MS}}$- scheme at $\mu = 173.2$ GeV, $\alpha_s(M_Z)$ - strong coupling

M_{crit}: Bezrukov et al, Degrassi et al, Buttazzo et al,

theoretical uncertainty: $\delta y_t / y_t \simeq 2 \times 10^{-4}$ equivalent to changing of M_H by ~ 70 MeV, or m_t by ~ 35 MeV Buttazzo et al

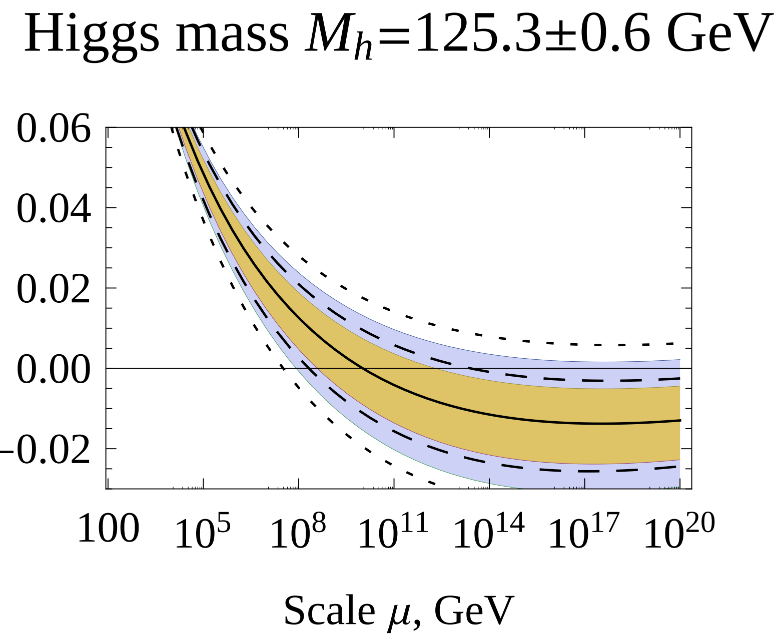
Complicated problem: - extraction of top Yukawa coupling from available data

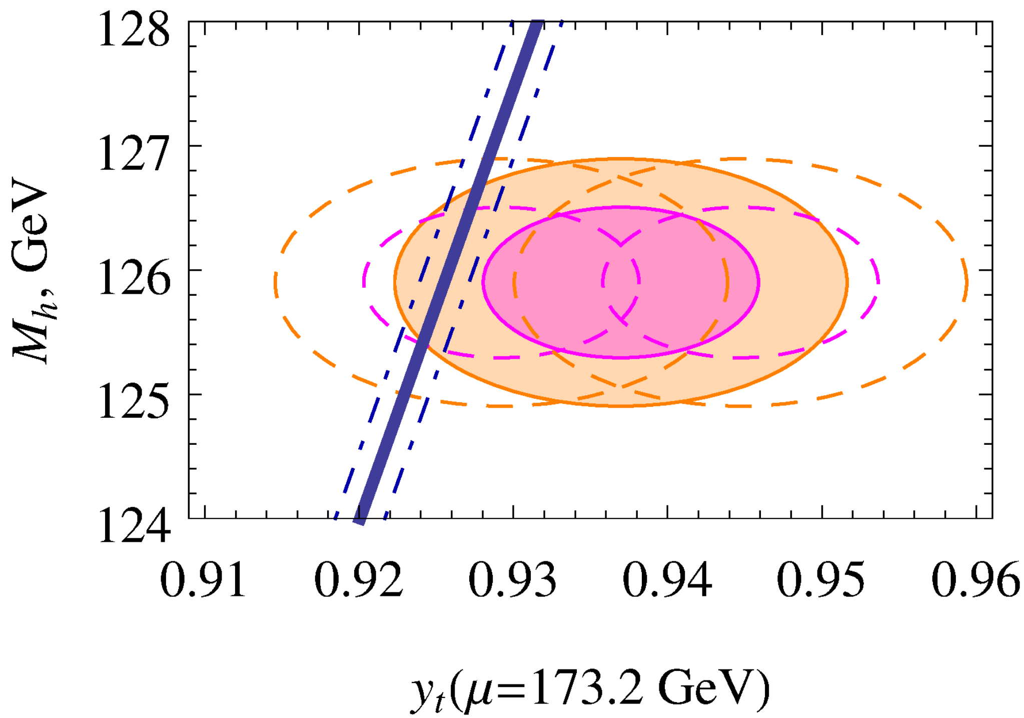
- FNAL and LHC - "Monte Carlo $\simeq$ pole ± 1 GeV " top quark mass
- top quark pole mass is not well defined theoretically: hadronisation, renormalons
- unknown higher order perturbative effects: $\mathcal{O}(\alpha_s^4)$. Estimate of Kataev and Kim: $\delta y_t / y_t \simeq -750(\alpha_s/\pi)^4 \simeq -0.0015$, corresponding to $\delta m_t \sim 300$ MeV
- unknown non-perturbative QCD effects, $\delta m_t \simeq \Lambda_{QCD} \simeq 300$ MeV , $\delta y_t / y_t \simeq 0.0015$
- 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, $\delta y_t / y_t \simeq 0.015$

Precision measurements of m_H, y_t and α_s are needed! ILC, TLEP stage of FCC.

Comparison with experiments:

Central value of $y_t(\mu_t) = 0.9361$: 1 % above the critical value 0.9268





extra errors in extraction of y_t from “Monte-Carlo” top mass are added to Tevatron - LHC combination : $M_t = 173.34 \pm 0.27 \pm 0.71$ GeV

$\alpha_s = 0.1184 \pm 0.0007$

The SM vacuum may be absolutely stable.

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Therefore, we can describe the evolution of the Universe from the very early stages, such as inflation and Big Bang, till the present days !

Role of the Higgs field in cosmology

- Can make the Universe flat, homogeneous and isotropic
- Can produce fluctuations leading to structure formation: clusters of galaxies, etc
- Can lead to Hot Big Bang
- Can play a crucial role in baryogenesis leading to charge asymmetric Universe
- Can play a crucial role in Dark Matter production

Higgs coupling to gravity

Higgs field in general must have non-minimal coupling 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,...

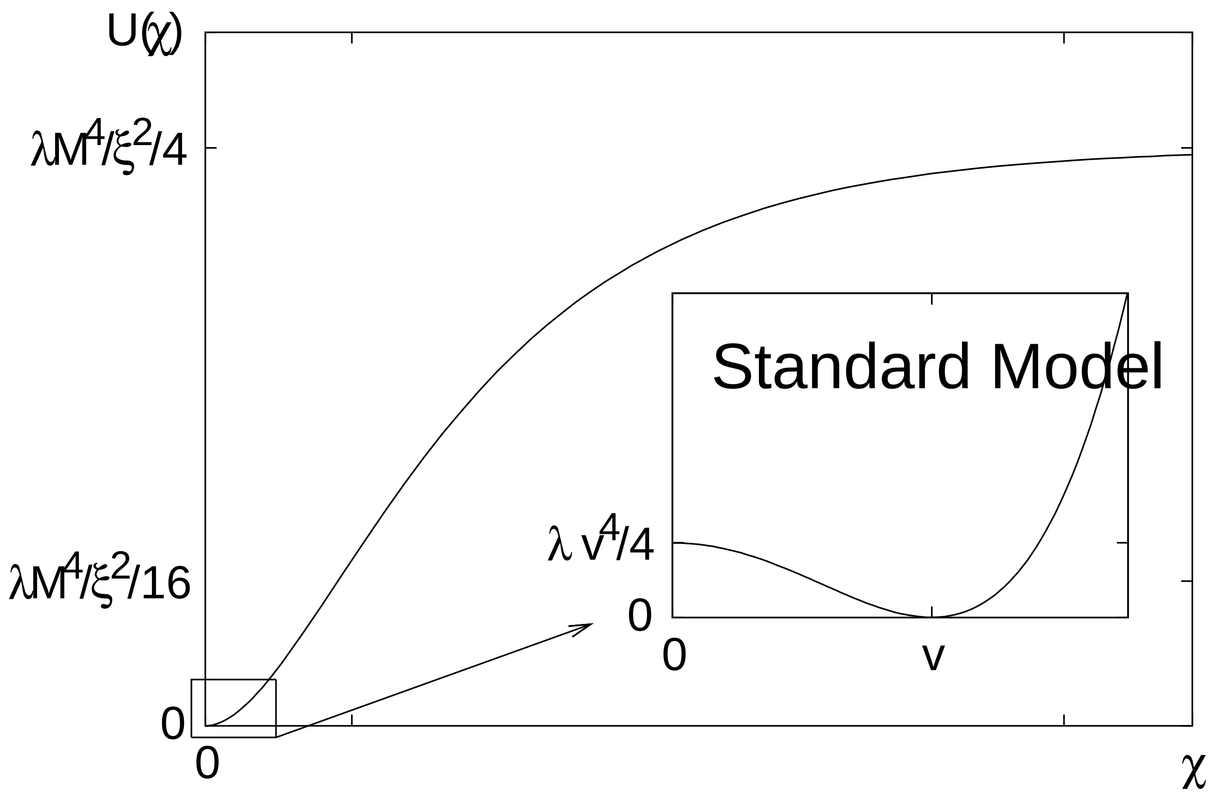
Consider large Higgs fields $h > M_P/\sqrt{\xi}$, which may have existed in the early Universe

The Higgs field not only gives particles their masses $\propto h$, but also determines the gravity interaction strength:

$M_P^{\rm eff} = \sqrt{M_P^2 + \xi h^2} \propto h$

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

Potential in Einstein frame



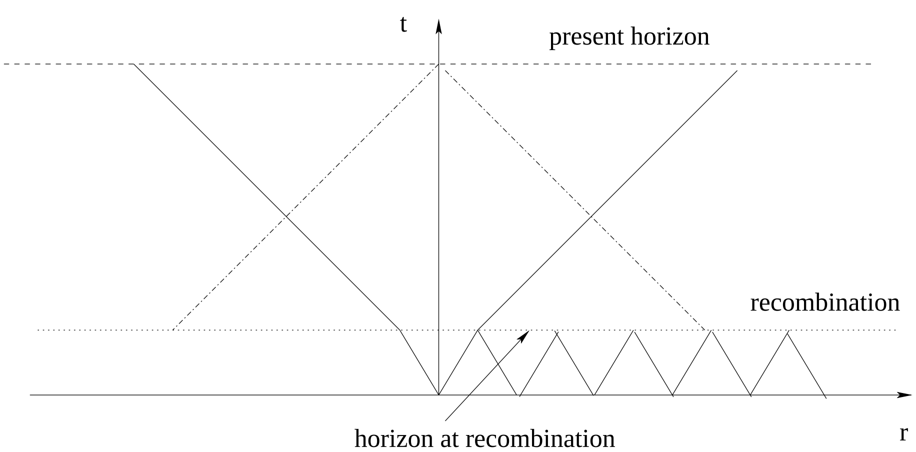
χ - canonically normalised scalar field in Einstein frame.

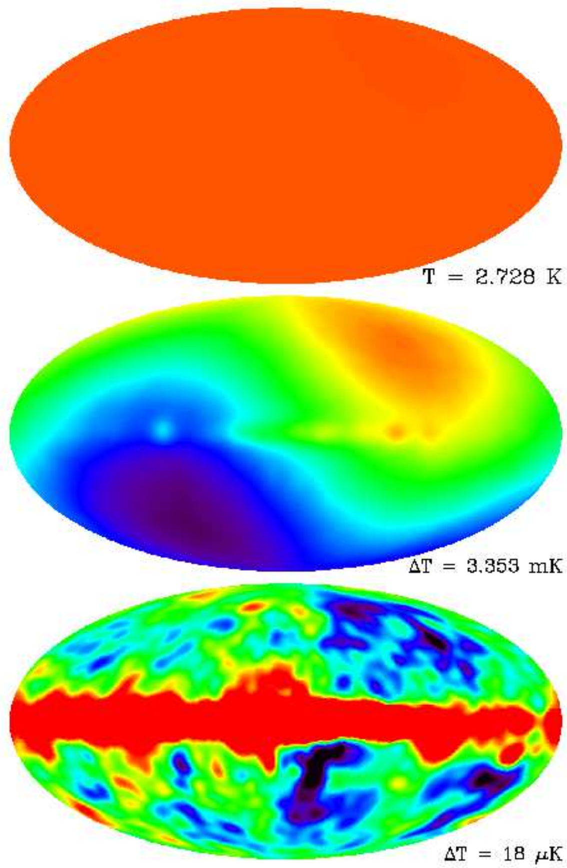
This form of the potential is universal for $y_t(173.2) < y_t^{\text{crit}}$

Cosmological inflation

Important cosmological problems

Horizon problem: Why the universe is so uniform and isotropic?



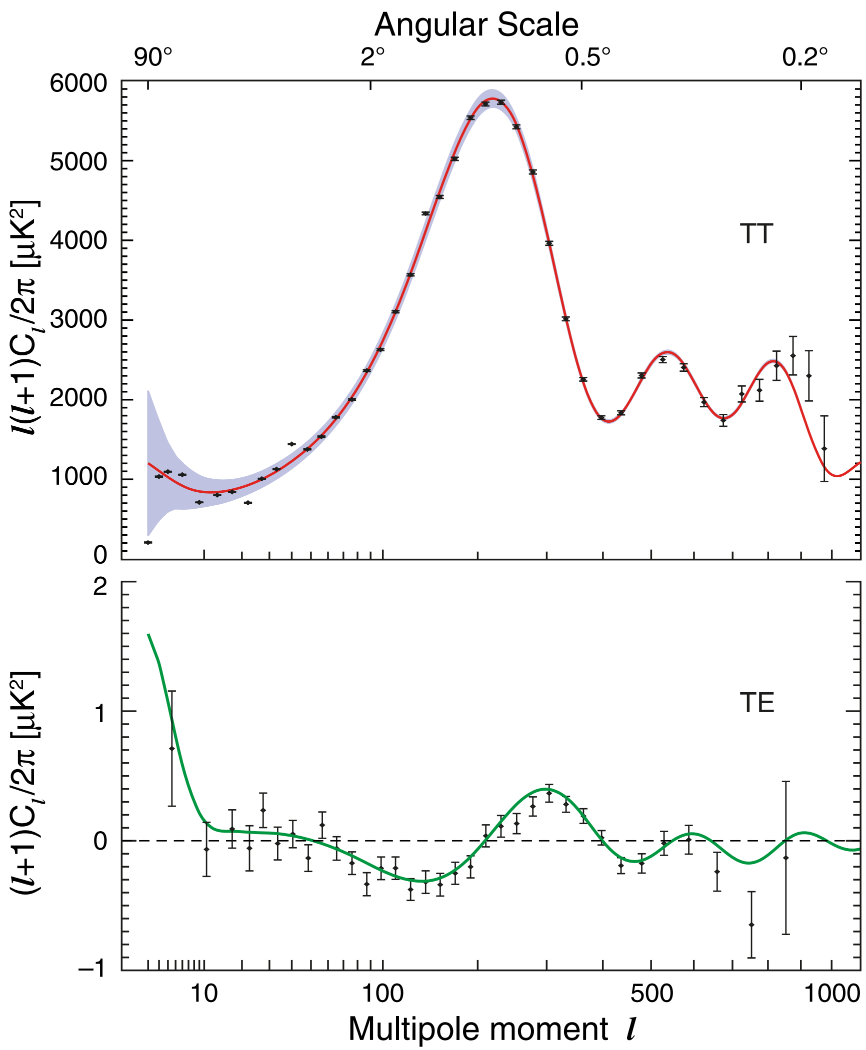


Expected fluctuations at $\theta \sim 1^o$:

$\delta T/T \sim 1$.

Observed fluctuations: $\delta T/T \sim 1O^{-5}$

Structure formation problem: What is the origin of cosmological perturbations and why their spectrum is almost scale-invariant?

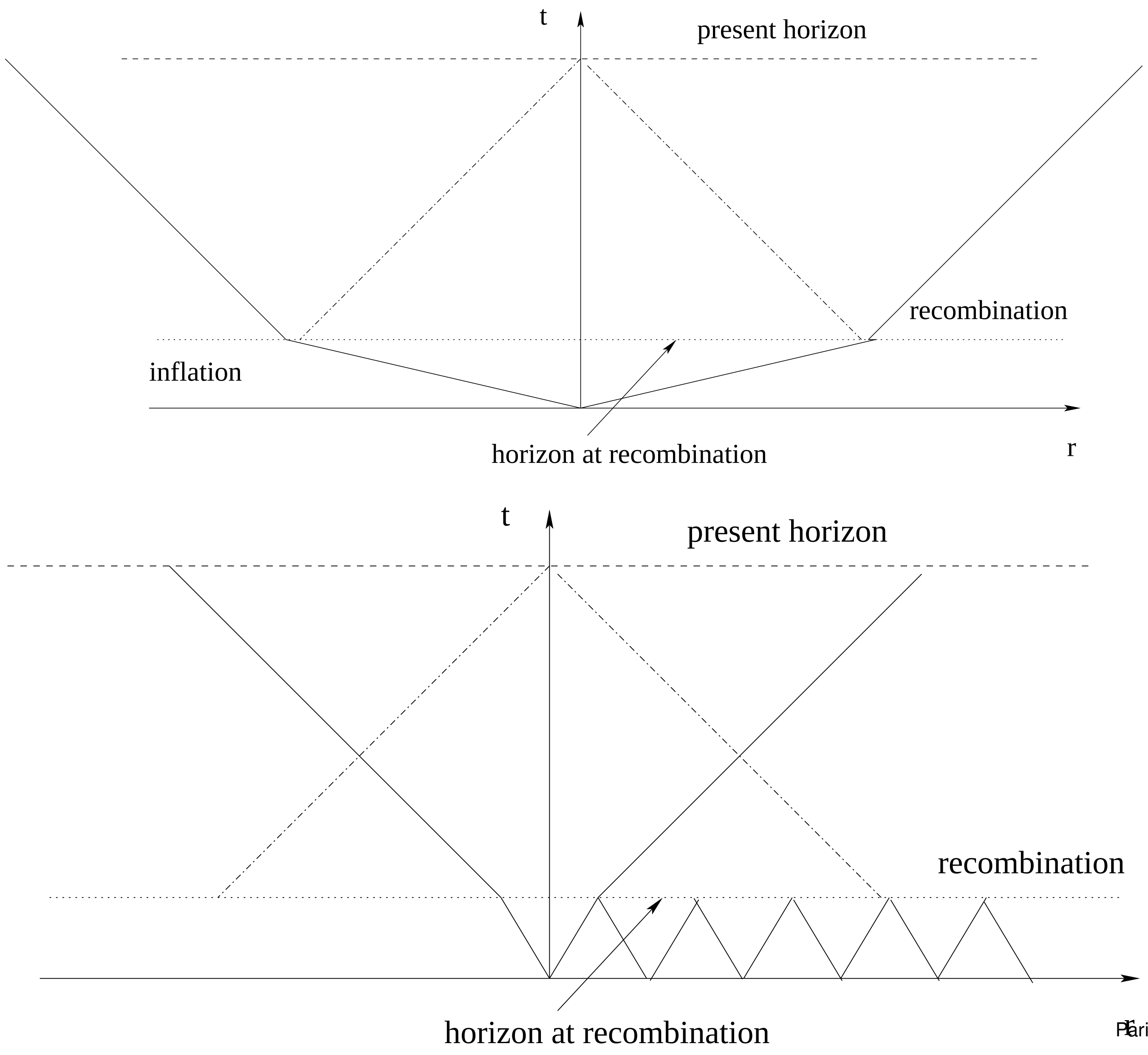


Sakharov peaks

Flatness problem: Why $\Omega_M + \Omega_\Lambda + \Omega_{\mathbf{rad}}$ is so close to 1 now and was immensely close to 1 in the past?

All this requires enormous fine-tuning of initial conditions (at the Planck scale?) if the Universe was dominated by matter or radiation all the time!

Solution: Inflation = accelerated Universe expansion in the past



Mechanism: scalar field dynamics

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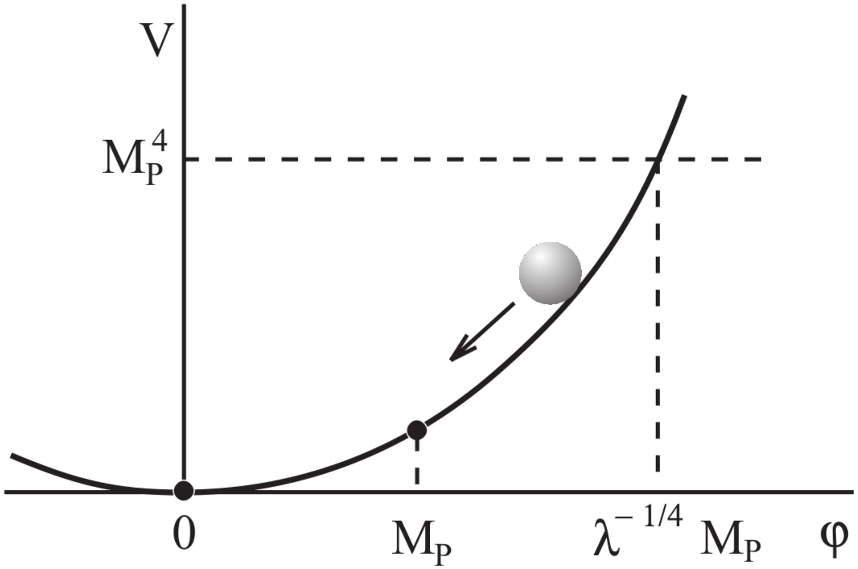
Why scalar?

- Vector - breaking of Lorentz symmetry
- Fermion - bilinear combinations are equivalent to scalar fields
- Uniform scalar condensate has an equation of state of cosmological constant and leads to exponential universe expansion.

"Standard" chaotic inflation

$$V(\phi) \quad = \quad \frac{1}{2}m^2\phi^2 \;+\; \frac{\lambda}{4}\phi^4$$



Almost flat potential for large scalar fields is needed! Linde

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
- $\delta T/T \sim 1$

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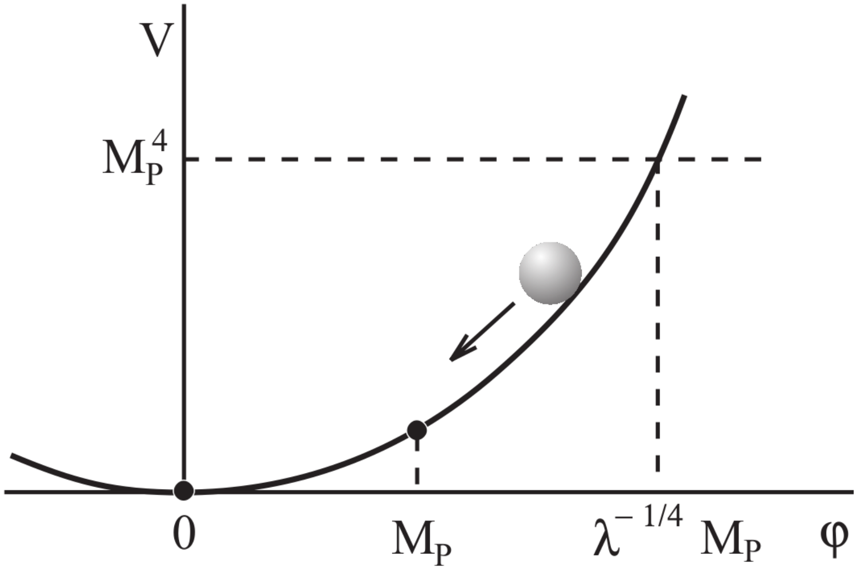

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- $\delta T/T \sim 1$

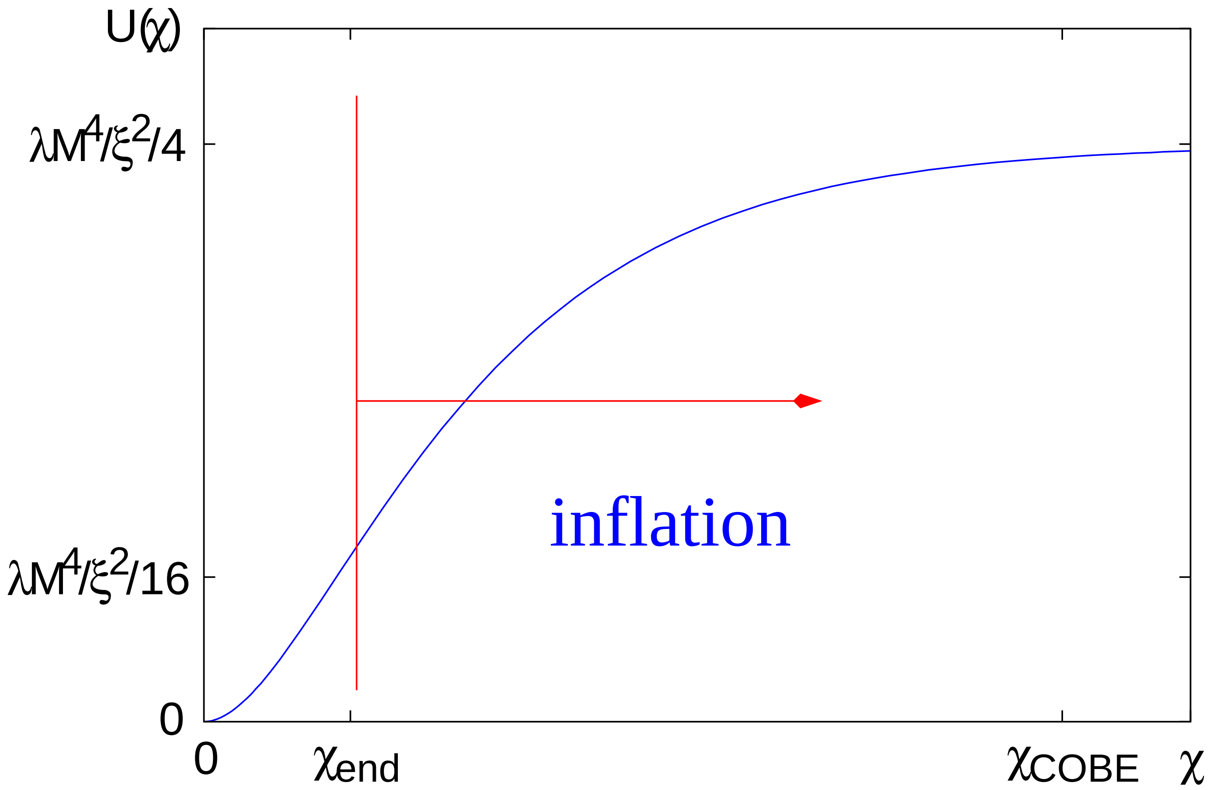
New physics is required?

No!

No!

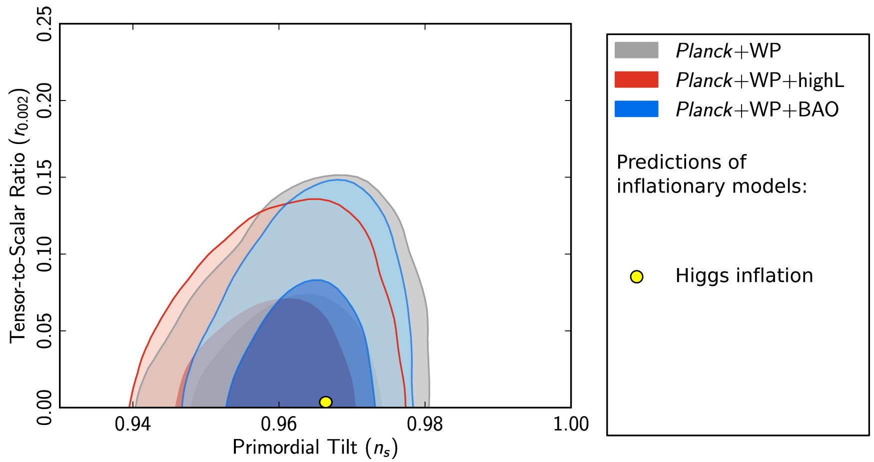
The Higgs boson of the Standard Model can inflate the Universe due to non-minimal coupling to gravity

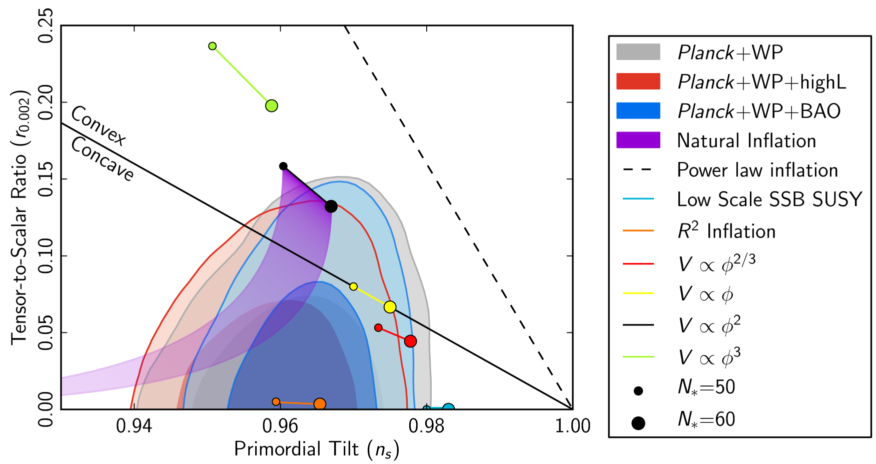
Stage 1: Cosmological Higgs inflation, $h > \frac{M_P}{\sqrt{\xi}}$, slow roll of the Higgs field



- Makes the Universe flat, homogeneous and isotropic
- Produces fluctuations leading to structure formation: clusters of galaxies, etc

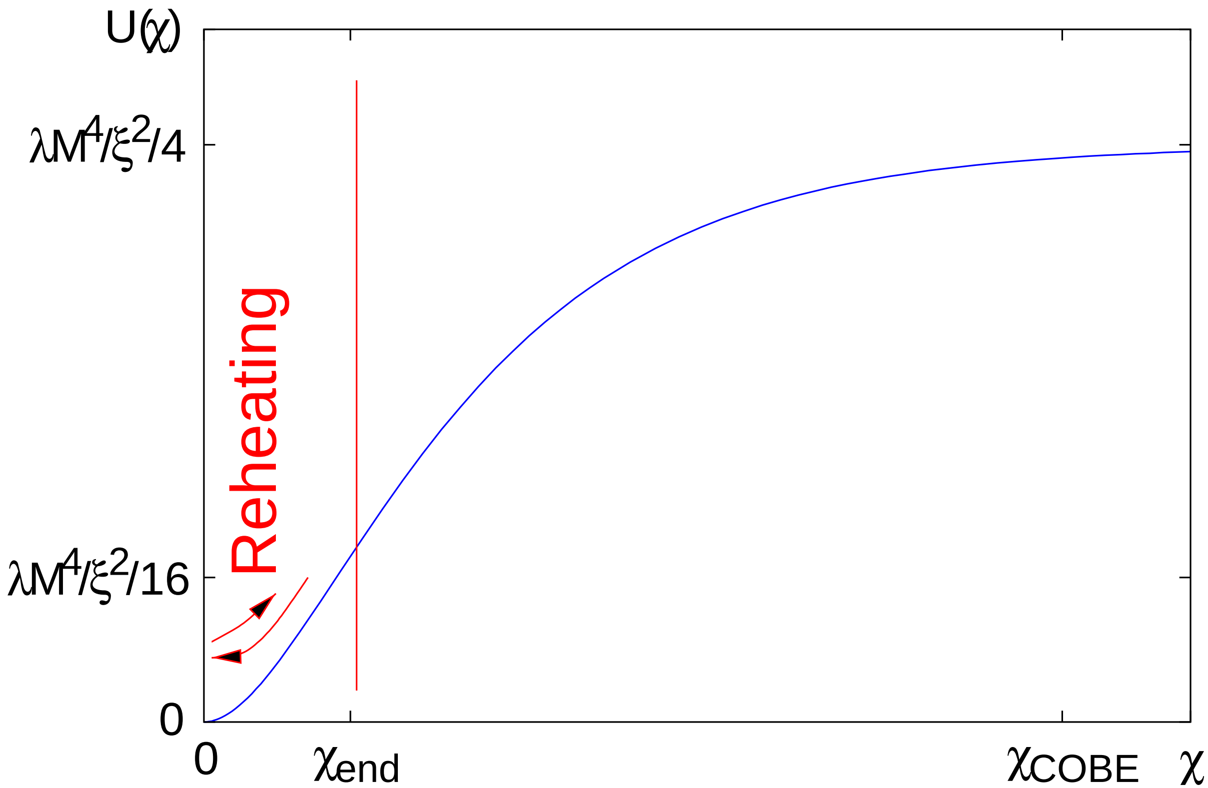
CMB parameters - spectrum and tensor modes, $\xi \gtrsim 1000$





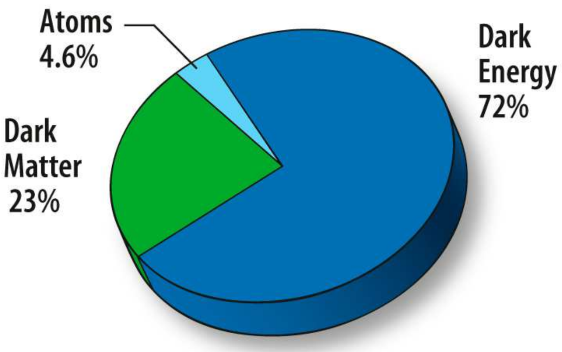
For M_H very close to M_{crit} : critical Higgs inflation - tensor-to-scalar ratio can be large, $\xi \sim 10$

Stage 2: Big Bang, $\frac{M_P}{\xi} < h < \frac{M_P}{\sqrt{\xi}}$, Higgs field oscillations

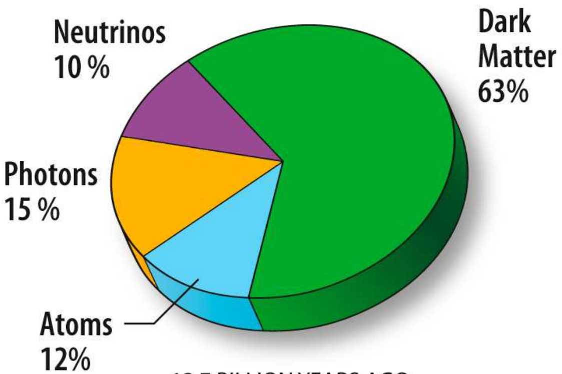


- All particles of the Standard Model are produced
- Coherent Higgs field disappears
- The Universe is heated up to $T \propto M_P/\xi \sim (3-15) \times 10^{13}$ GeV

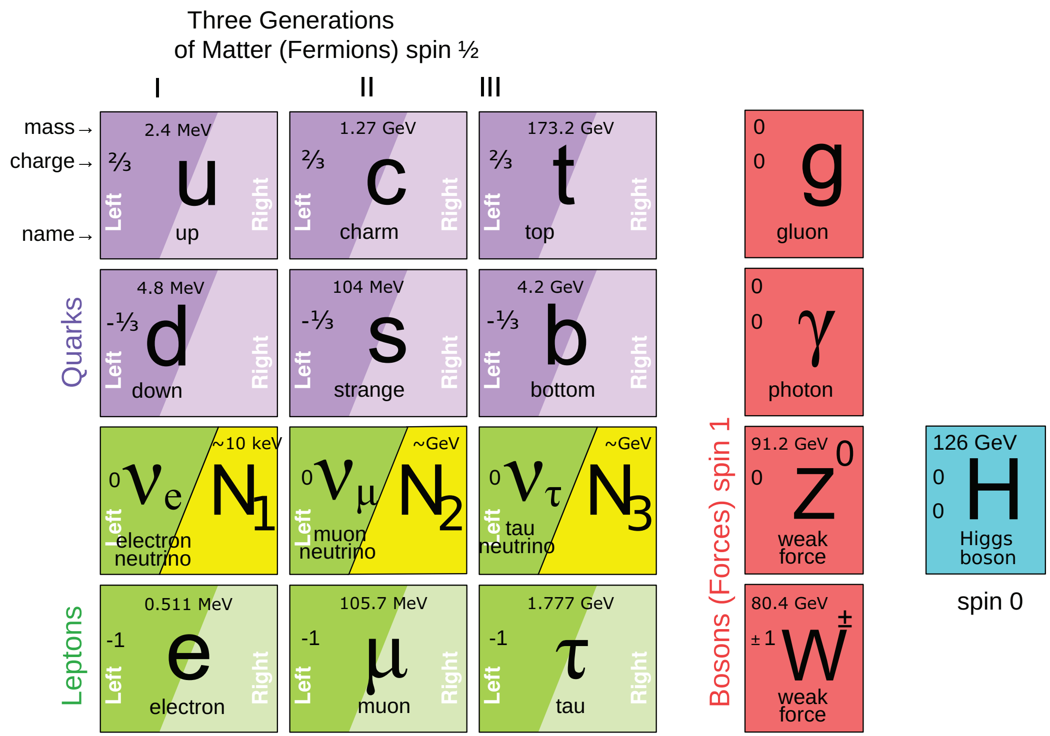
For further discussion, we need to go beyond the Standard Model, which cannot explain matter-antimatter asymmetry of the Universe and dark matter. The Neutrino Minimal Standard Model - νMSM will be used.



TODAY



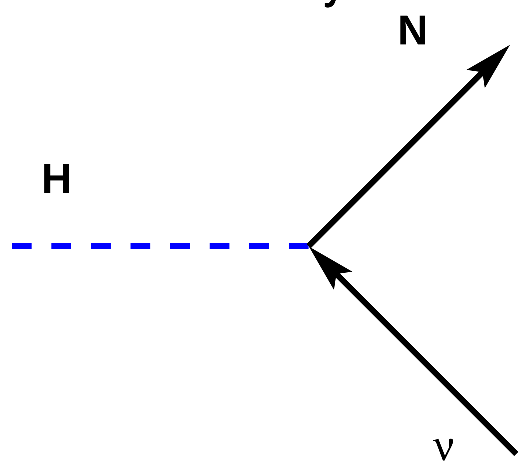
13.7 BILLION YEARS AGO
(Universe 380,000 years old)



Three new particles

- heavy neutral leptons - HNL
- with masses from keV to GeV
- explain in addition neutrino masses and oscillations

Heavy neutral leptons interact with the Higgs boson via Yukawa interactions - exactly in the same way other fermions do:



$F_{\alpha I}\,\bar{L}_\alpha N_I \tilde{H}$

These interactions lead to

- active neutrino masses due to GeV scale see-saw
- creation of matter-antimatter asymmetry at temperatures $T \sim 100$ GeV
- to dark matter production at $T \sim 100$ MeV

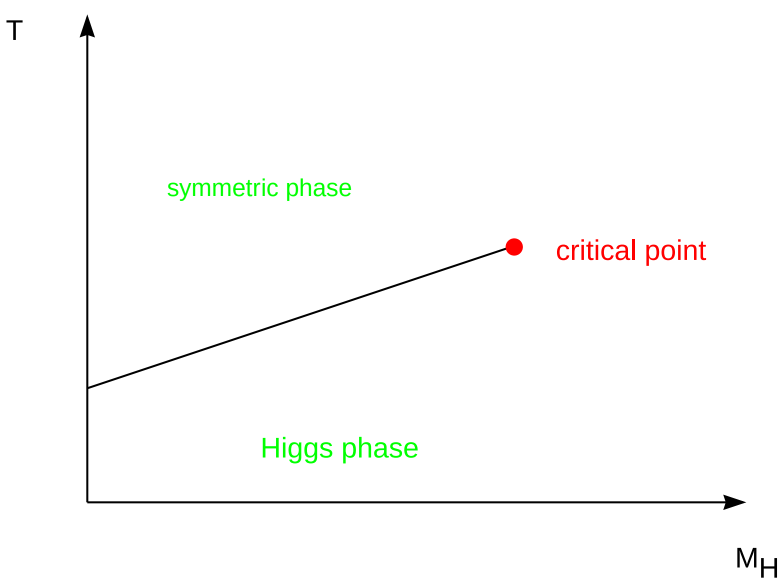
Stage 3: Baryogenesis

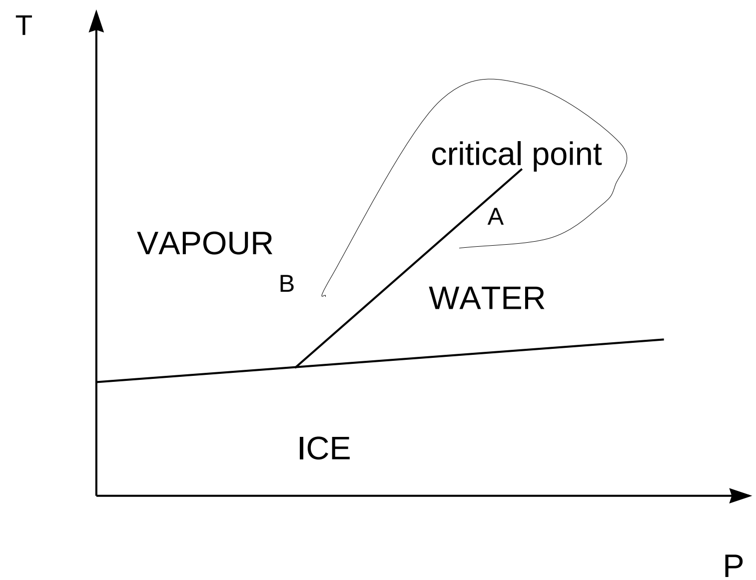
- Nothing essentially interesting happens between 10^3 GeV $< T < 10^{13}$ GeV: all SM elementary particles are nearly in thermal equilibrium.
- Heavy neutral leptons $N_{2,3}$ are out of equilibrium. They are created in interaction with the Higgs boson $H \leftrightarrow N\nu,\ \ t\bar{t} \leftrightarrow N\nu$, etc
- CP- violation in these reactions lead to lepton asymmetry of the Universe
- Electroweak baryon number violation due to SM sphalerons convert lepton asymmetry to baryon asymmetry of the Universe
- These processes freeze out at $T \simeq 140$ GeV

Electroweak cross-over

No phase transition in the electroweak theory for Higgs masses larger than 73 GeV the Higgs field vacuum expectation value smoothly grows from small values up to 250 GeV. The crossover temperature

$$T_c \simeq v \left(\frac{M_H^2}{M_H^2 + M_W^2 + M_Z^2/2 + m_t^2} \right)^{\frac{1}{2}} \simeq 160\ GeV$$





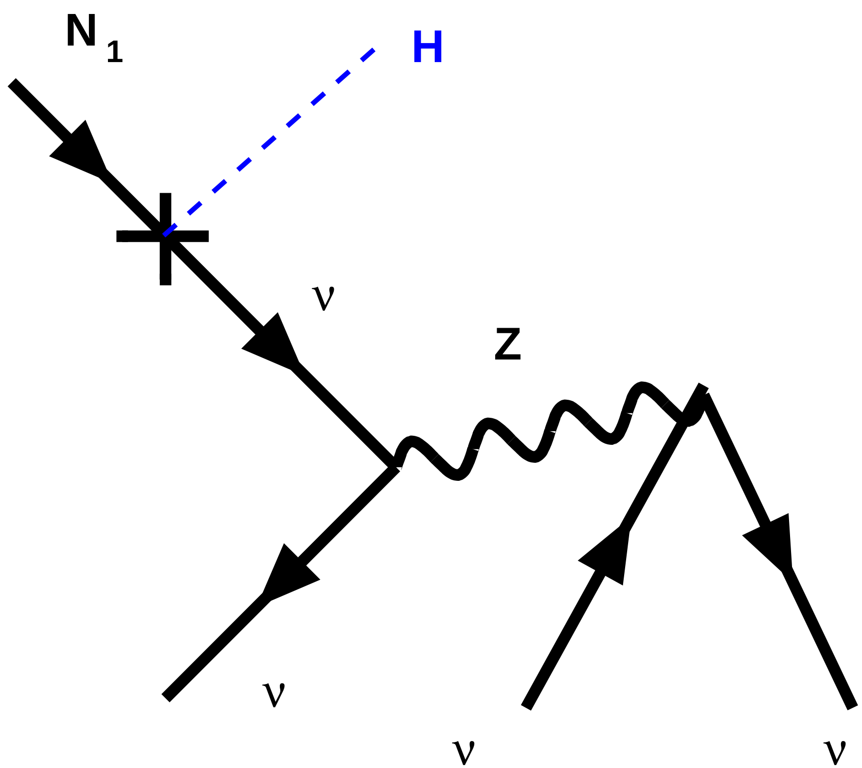
$$T^{crit} = 109.2 \pm 0.8\ GeV$$

$$M_H^{crit} = 72.3 \pm 0.7\ GeV$$

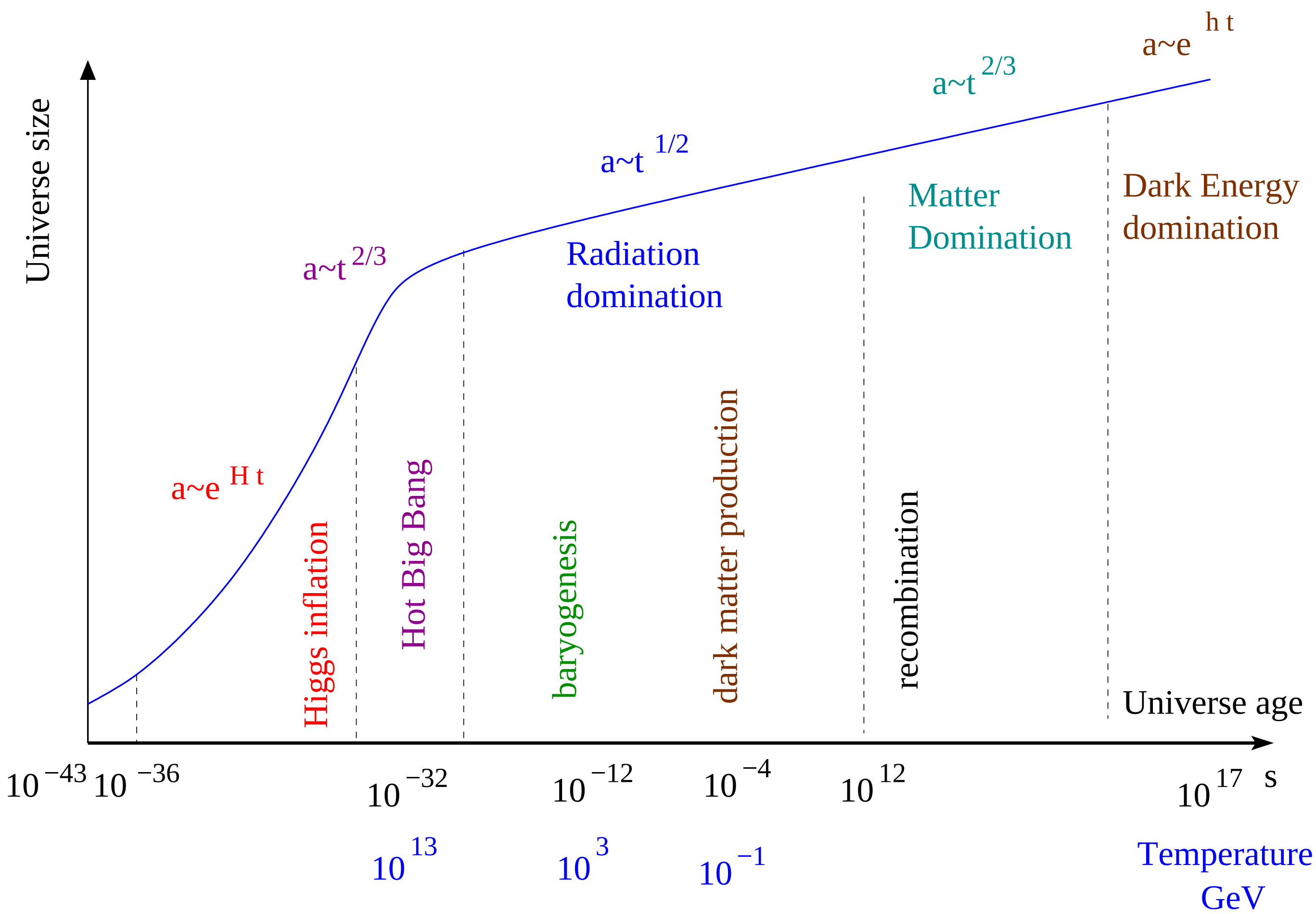
Stage 4: Dark matter production

Production temperature of Dark matter HNL via processes like $l\bar{l} \to \nu N_1$:

$$T \sim 130 \left(\frac{M_I}{1\ \mathrm{keV}} \right)^{1/3} \text{ MeV}$$



History of the Universe



Crucial experiments to confirm or to rule out this picture

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, $\Delta n_s \simeq 0.004$

New dedicated experiments

High energy frontier

Construction of t-quark factory – e^+e^- or $\mu^+\mu^-$ linear collider with energy $\simeq 200 \times 200$ GeV.

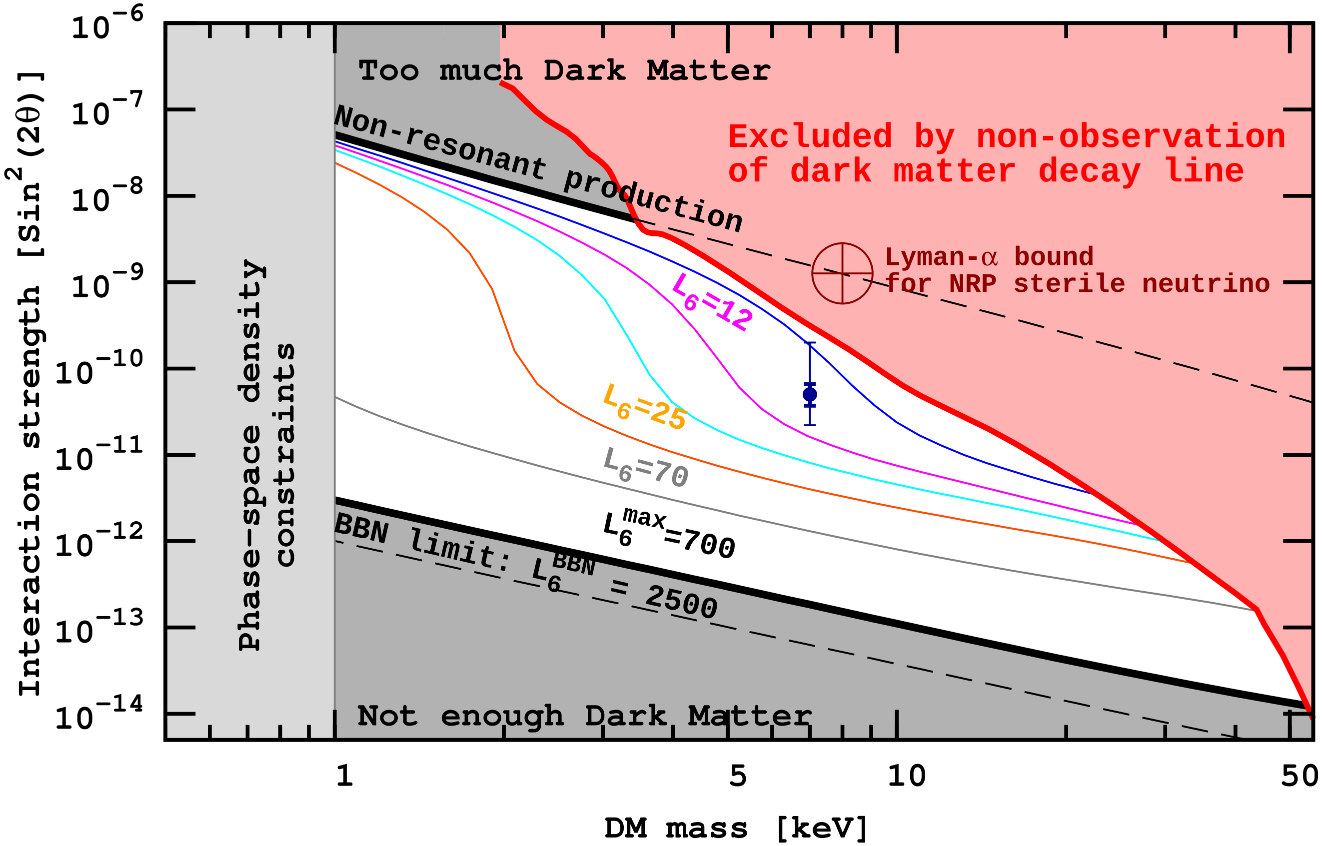
Precise measurement of top and Higgs masses, to elucidate the relation between the electroweak and Planck scales.

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.



Detection of An Unidentified Emission Line in the Stacked X-ray spectrum of Galaxy Clusters. E. Bulbul, M. Markevitch, A. Foster, R. K. Smith, M. Loewenstein, S. W. Randall. e-Print: arXiv:1402.2301

An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster. A. Boyarsky , O. Ruchayskiy, D. Iakubovskyi, J. Franse. e-Print: arXiv:1402.4119

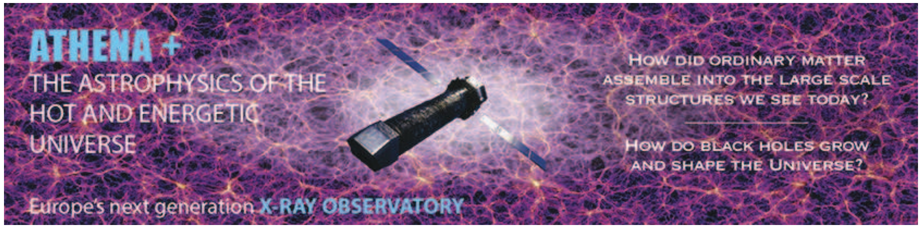
Searches for HNL in space

- Has been previously searched with *XMM-Newton, Chandra, Suzaku, INTEGRAL*
- Spectral resolution is not enough (required $\Delta E/E \sim 10^{-3}$)
- Proposed/planned X-ray missions with sufficient spectral resolution:

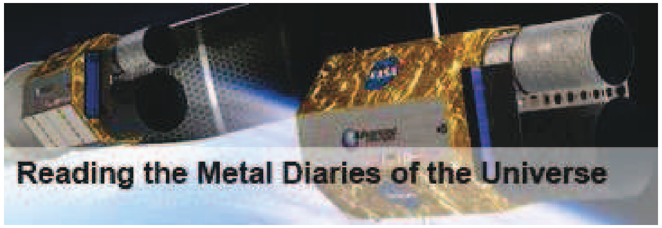
Astro-H

LOFT

Athena+



Origin/Xenia

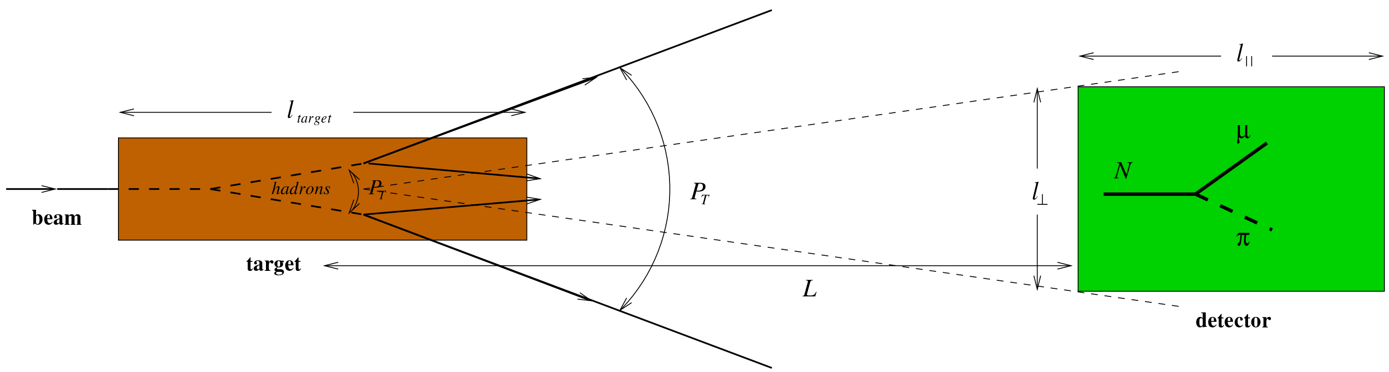


Search for $N_2,\ N_3$

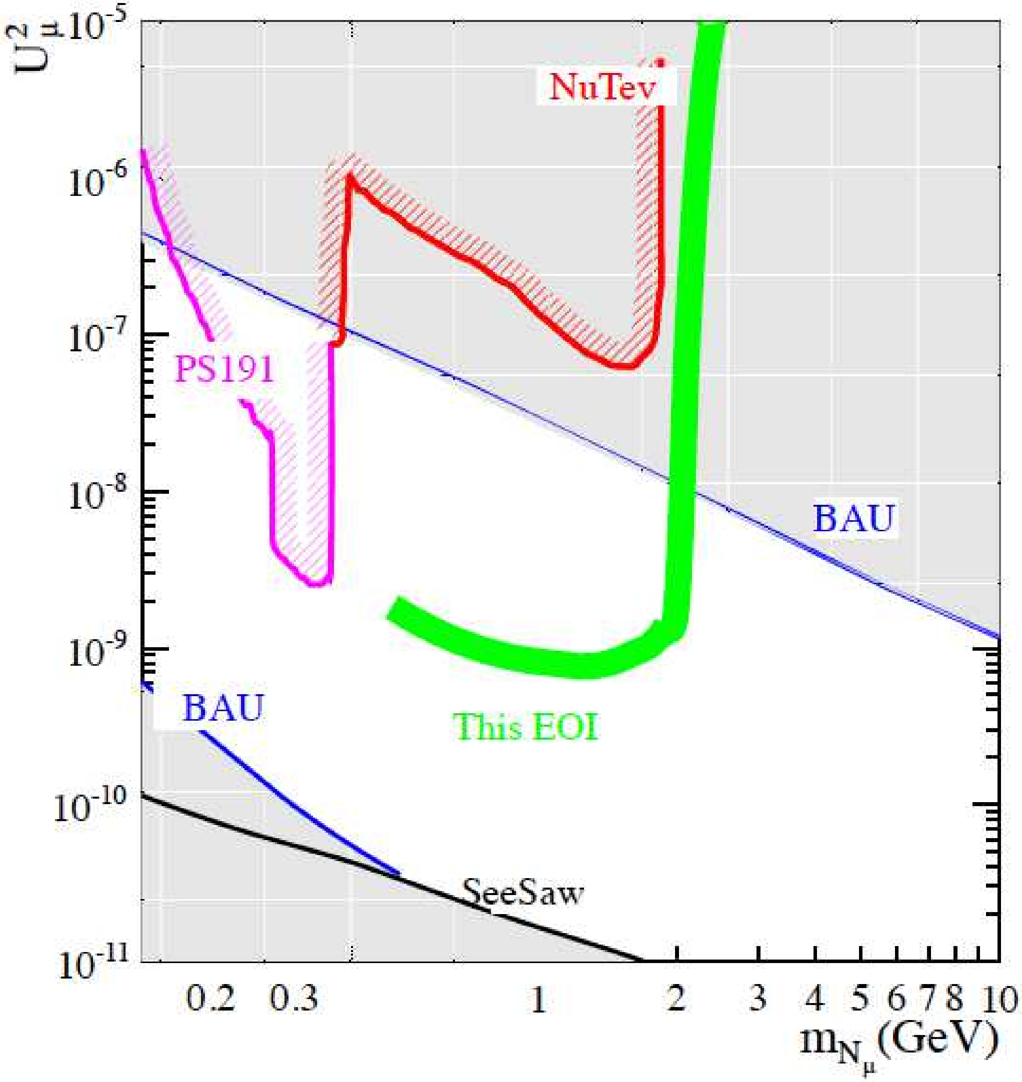
- Challenge: for baryon asymmetry generation the heavy neutral leptons must be very weakly coupled, to satisfy the Sakharov condition of out-of-equilibrium

Proposal to Search for Heavy Neutral Leptons at the SPS arXiv:1310.1762: general purpose beam dump facility for investigation of the hidden sector

W. Bonivento, A. Boyarsky, H. Dijkstra, U. Egede, M. Ferro-Luzzi, B. Goddard, A. Golutvin, D. Gorbunov, R. Jacobsson, J. Panman, M. Patel, O. Ruchayskiy, T. Ruf, N. Serra, M. Shaposhnikov, D. Treille



Sensitivity



Conclusions

- The Standard Model Higgs field can play an important role in cosmology:
  - It can make the Universe flat, homogeneous and isotropic
  - Quantum fluctuations of the Higgs field can lead to structure formation
  - Coherent oscillations of the Higgs field can make the Hot Big Bang and produce all the matter in the Universe
- Neutral leptons can solve the SM problems:
  - Explain neutrino masses and oscillations
  - Lead to baryogenesis
  - Explain dark matter in the Universe
- There are plenty of experiments which can confirm or reject the minimal model