ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

CERN

Higgs and cosmology

Mikhail Shaposhnikov

Higgs boson discovery at the LHC

Atlas - $M_H = 125.36 \pm 0.41$ GeV

CMS - $M_H = 125.03 \pm 0.29$ GeV

- New resonance properties are consistent with those of the Higgs boson of the Standard Model
- No deviations from the SM have been observed

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Therefore, we can describe the evolution of the Universe from the very early stages till the present days!

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,...

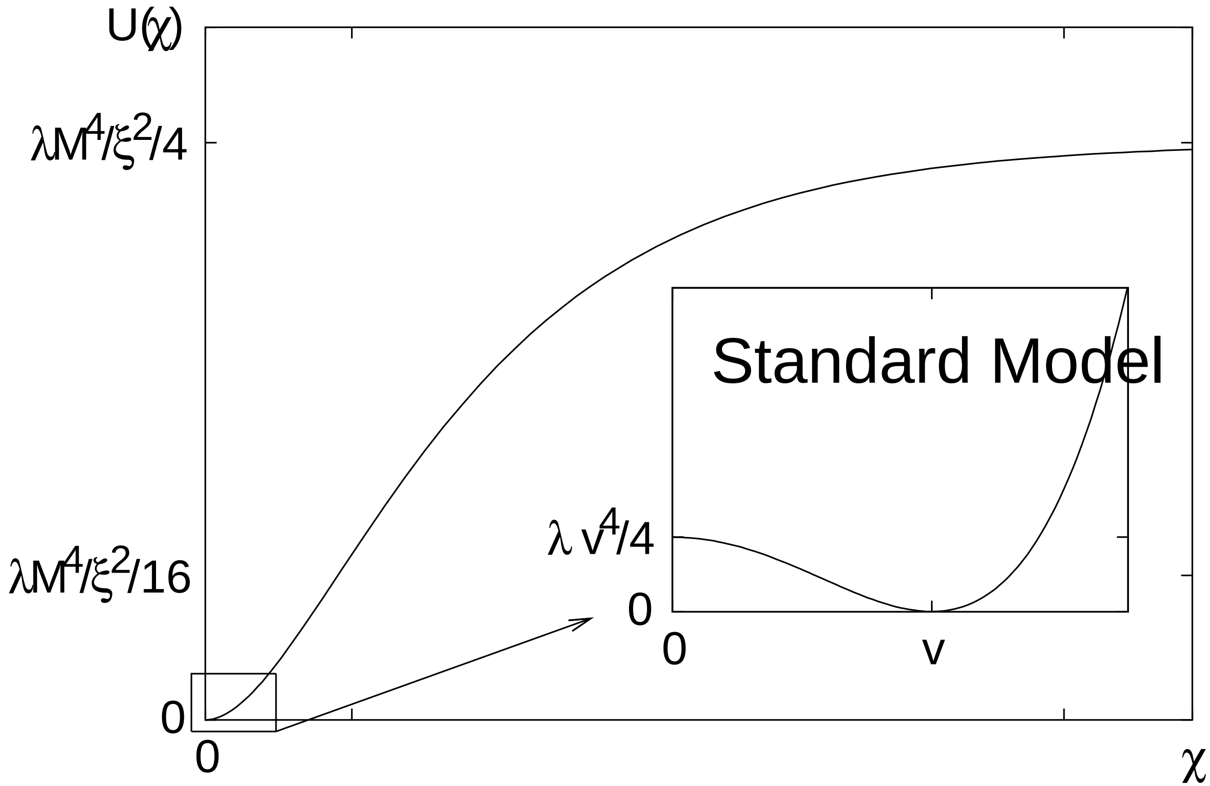
Consider large Higgs fields $h > M_P/\sqrt{\xi}$, which may have existed in the early Universe

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

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

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

Potential in Einstein frame



χ - canonically normalized scalar field in Einstein frame.

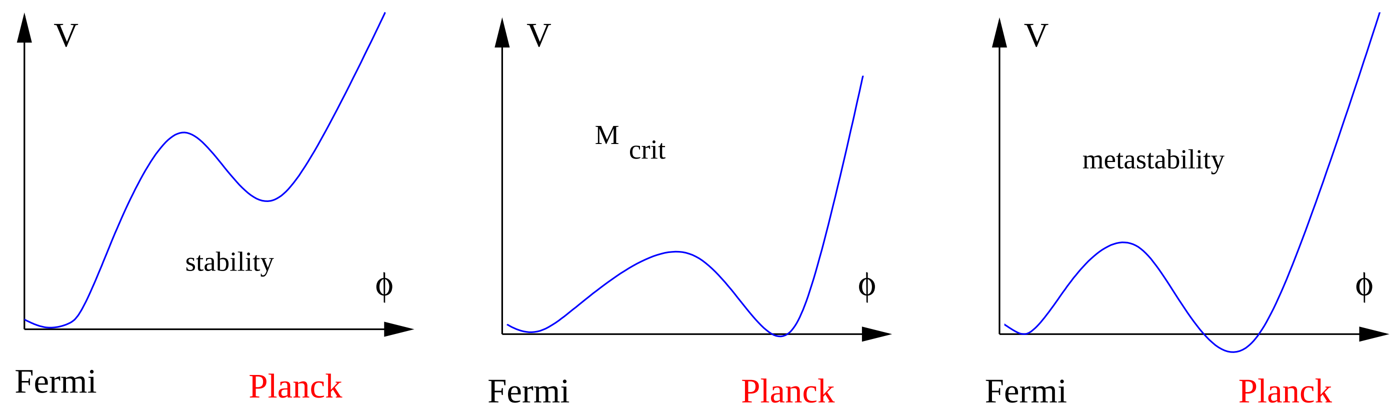
This form of the potential is universal for (Bezrukov, MS) $y_t(173.2) < y_t^{crit}$:

$$y_t^{crit} = 0.9223 + 0.00118\left(\frac{\alpha_s - 0.1184}{0.0007}\right) + 0.00085\left(\frac{M_H - 125.03}{0.3}\right) + 0.0023\left(\frac{\log\xi}{6.9}\right)$$

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

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

Numerically for $\xi = 1,\quad y_t^{crit}$ coincides with the metastability bound on the top Yukawa coupling



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, $\delta y_t/y_t \simeq 0.015$

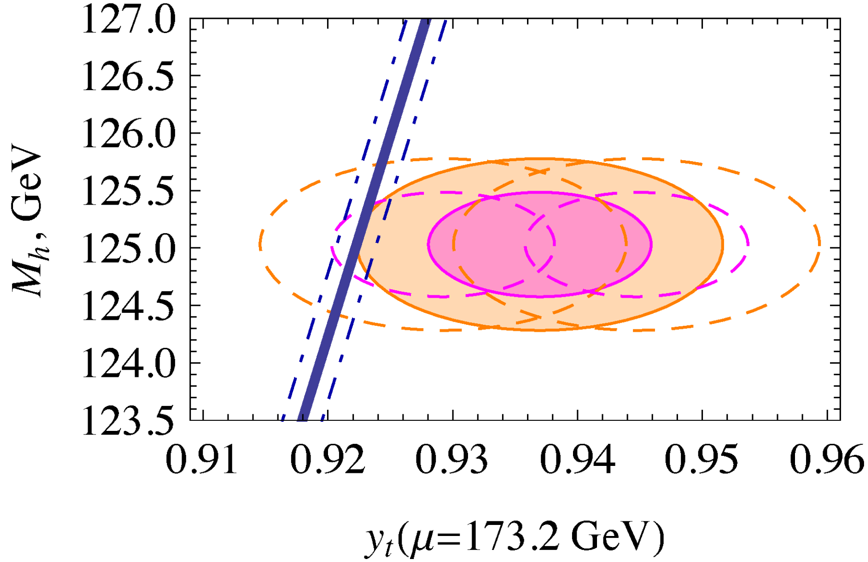
Precision measurements of m_H, y_t and α_s are needed! ILC, TLEP stage of FCC.

Comparison with experiments for $\xi = 1$:

If the Monte Carlo mass is identified with the pole mass and theoretical uncertainties in the pole mass are disregarded, then

$y_t(173.2) = 0.937$ - 1.6 % above the critical value 0.922 : $1 - 3\,\sigma$ away from the boundary, if systematic uncertainties are included

Stable EW vacuum $\Longleftarrow$ $\Longrightarrow$ meta-stable EW vacuum



Tevatron - LHC combination : $M_t = 173.34 \pm 0.27 \pm 0.71$ GeV

CMS Higgs mass value : $M_H = 125.03 \pm 0.3$ GeV

$\alpha_s = 0.1184 \pm 0.0007$

The SM vacuum may be absolutely stable, and potential for the Higgs field may be flat at large values of h

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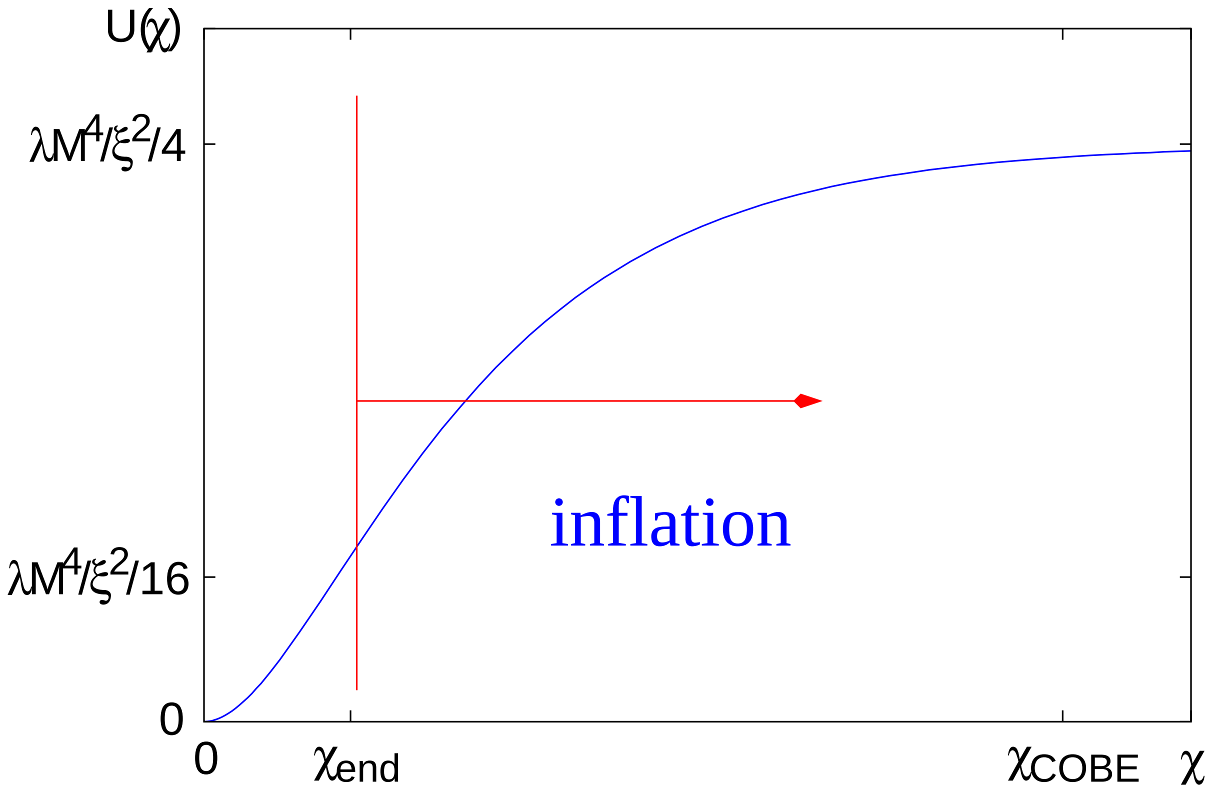
Inflation, Big Bang - all in the framework of the Standard Model!

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

Cosmological inflation

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



- Makes the Universe flat, homogeneous and isotropic
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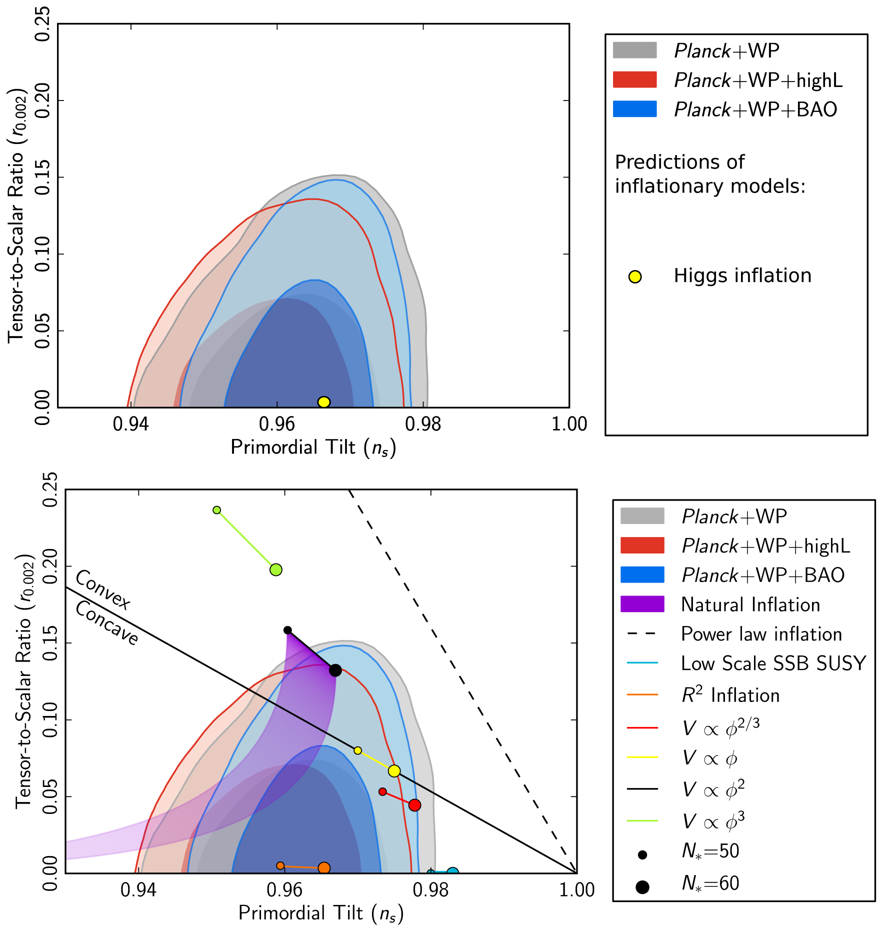
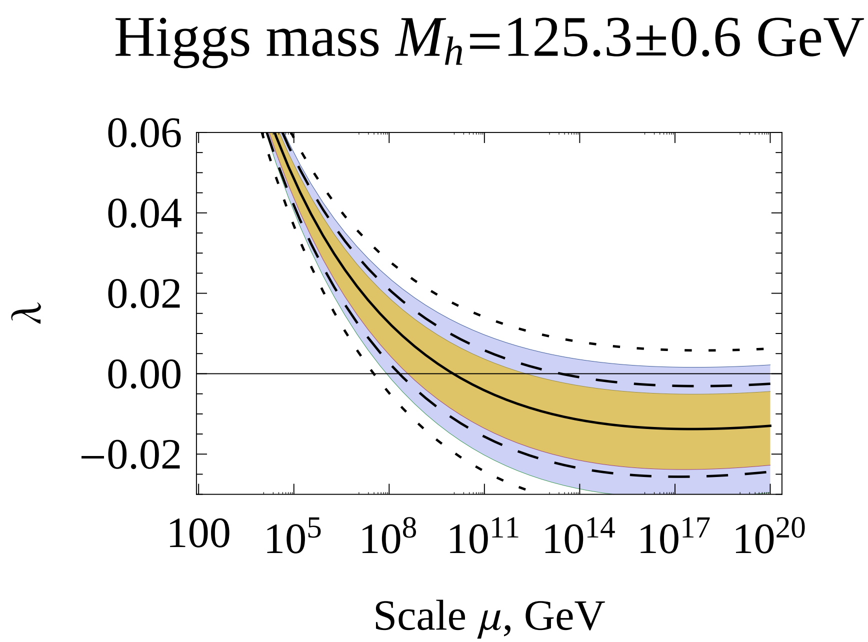
CMB parameters - spectrum and tensor modes, $\xi \gtrsim 1000$



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

Critical point

Behaviour of λ:



$$\lambda(z) = \lambda_0 + b\,(\log z)^2\,,\quad z = \frac{\mu}{qM_P},\quad M_P = 2.44 \times 10^{18}\text{GeV}$$

Numerically $\lambda_0 \ll 1,\ \ q \sim 1,\ \ b \simeq 2.3 \times 10^{-5}$.

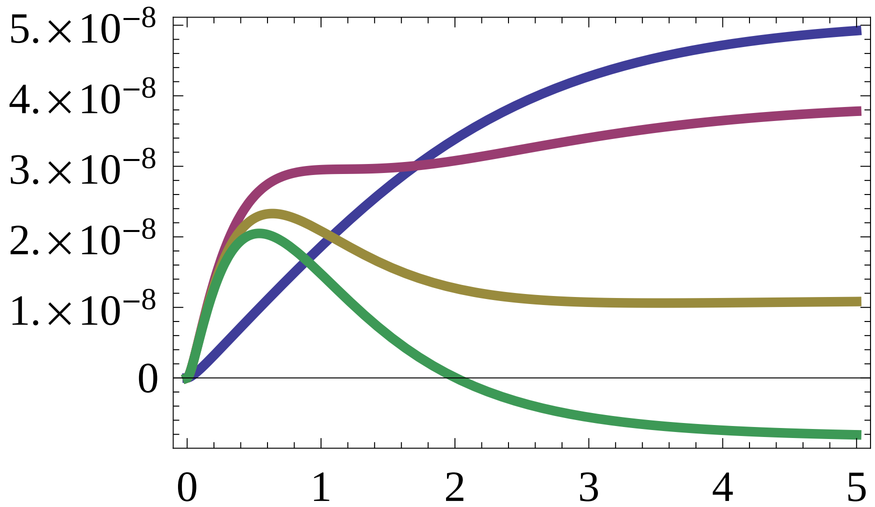
Effective potential

$$U(\chi) \simeq \frac{\lambda(z')}{4\xi^2}\bar{\mu}^4\,,\quad z' = \frac{\bar{\mu}}{\kappa M_P},\quad \bar{\mu}^2 = M_P^2\left(1 - e^{-\frac{2\chi}{\sqrt{6}M_P}}\right)$$

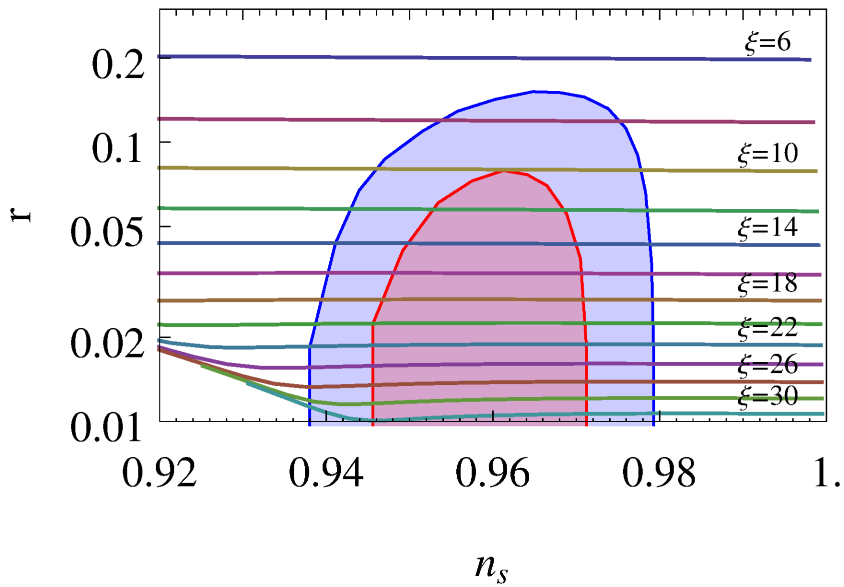
The parameter μ that optimises the convergence of the perturbation theory is related to $\bar{\mu}$ as

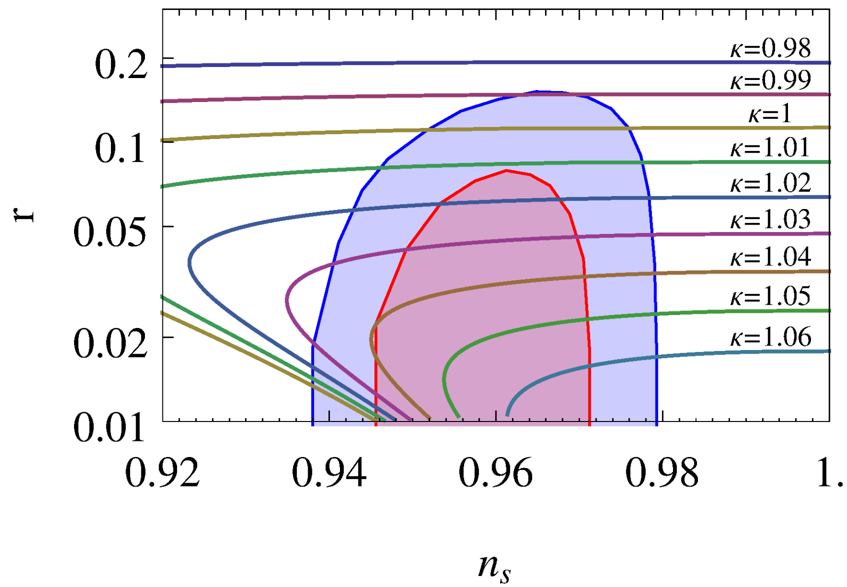
$$\mu^2 = \alpha^2\frac{y_t(\mu)^2}{2}\frac{\bar{\mu}^2}{\xi(\mu)}\,,\quad \alpha \simeq 0.6$$

Behaviour of effective potential for $\lambda_0 \simeq b/16$:



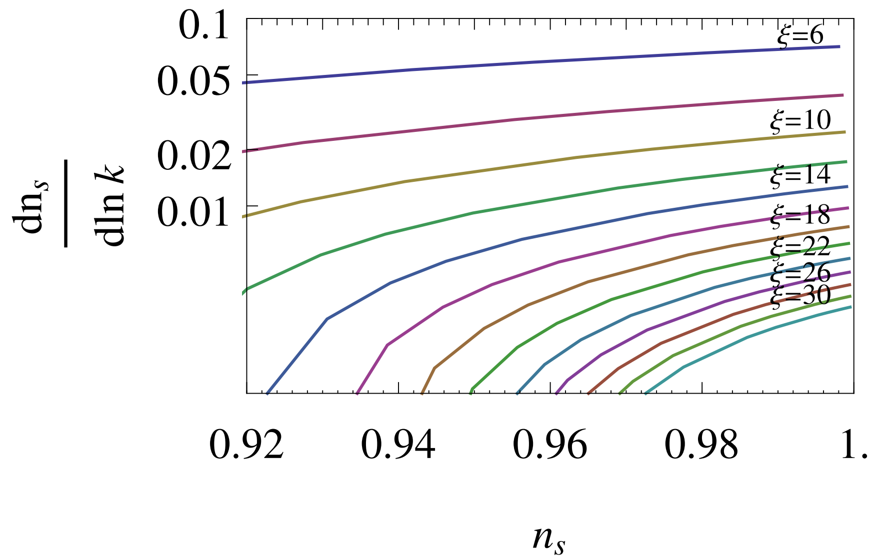
The inflationary indexes

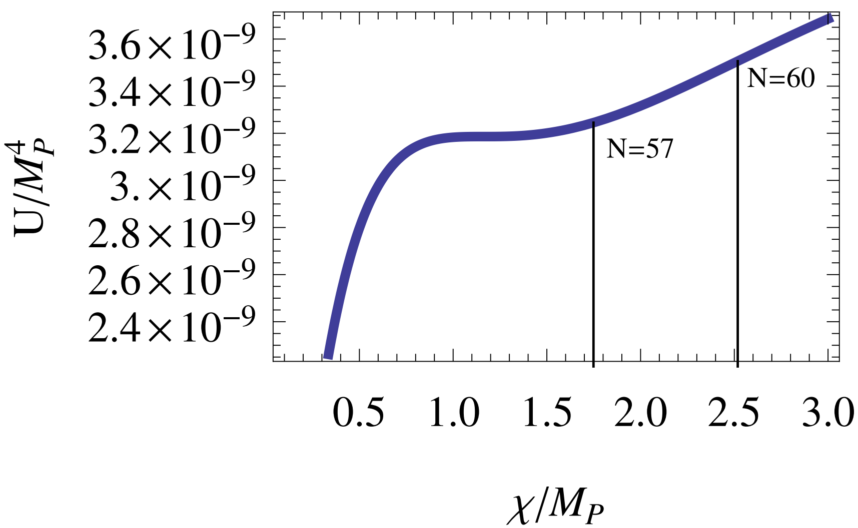




r can be large! BICEP 2?

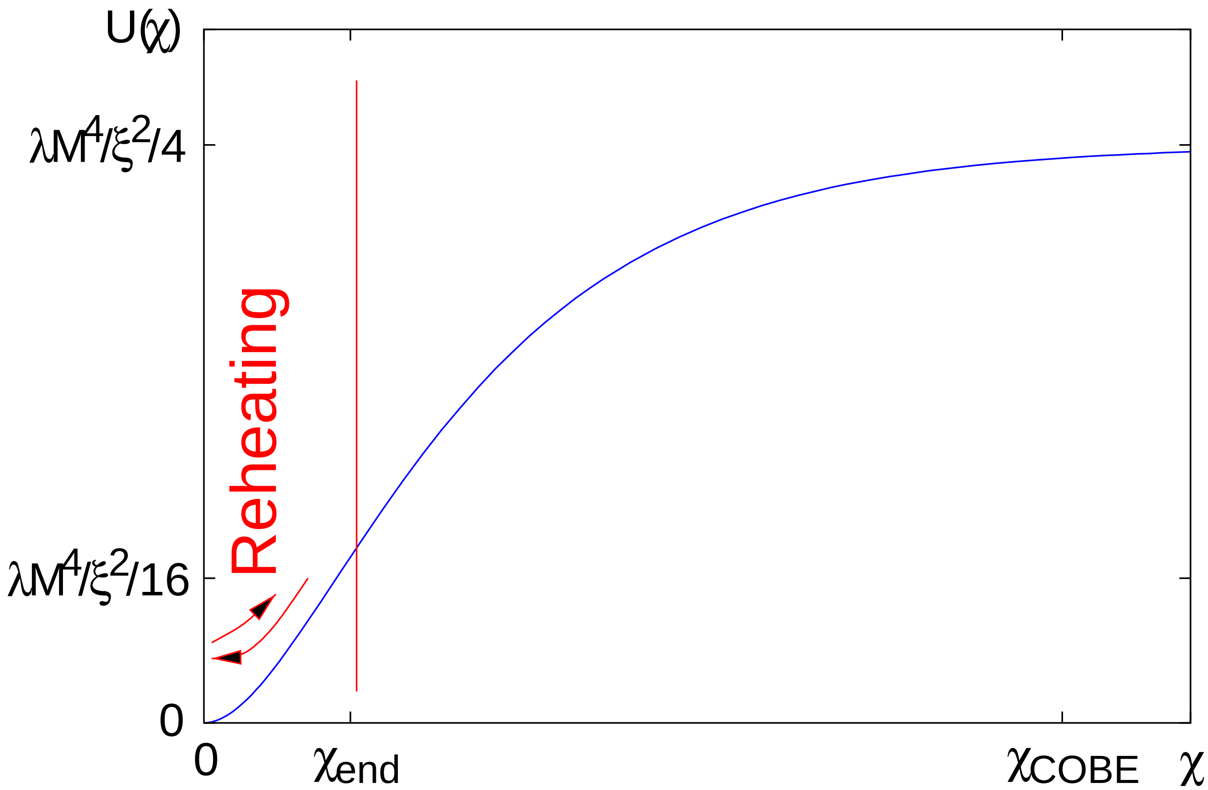
see also Hamada, Kawai, Oda and Park





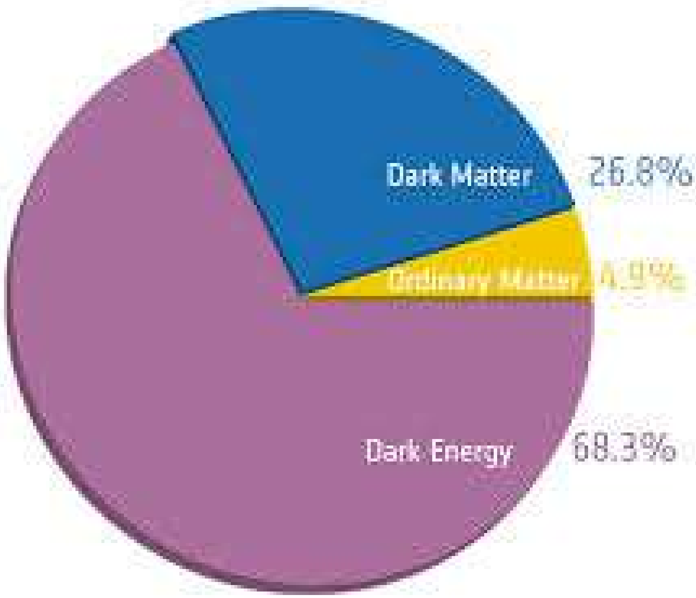
Critical Higgs inflation only works if both Higgs and top quark masses are close to their experimental values.

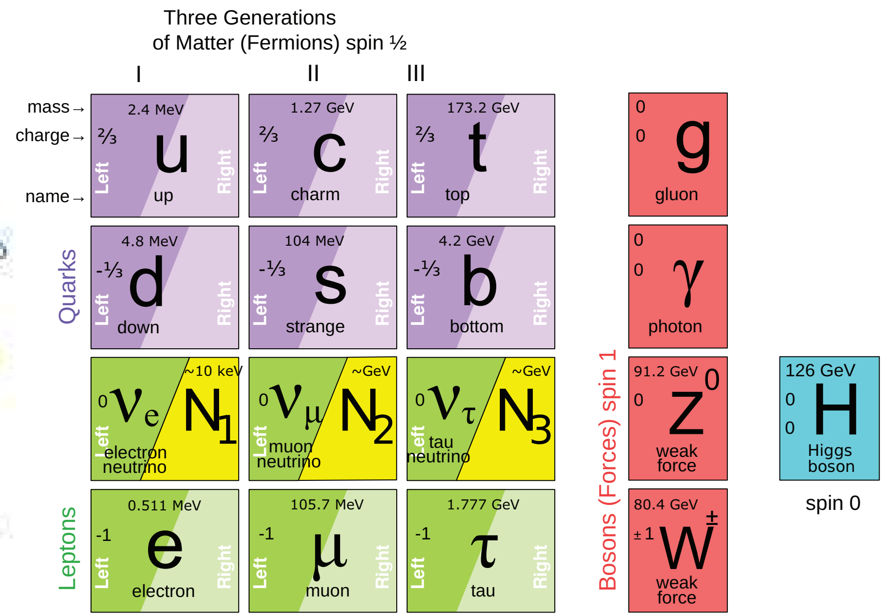
Stage 2: Big Bang, $\frac{M_P}{\xi} < h < \frac{M_P}{\sqrt{\xi}}$, Higgs field oscillations



- 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

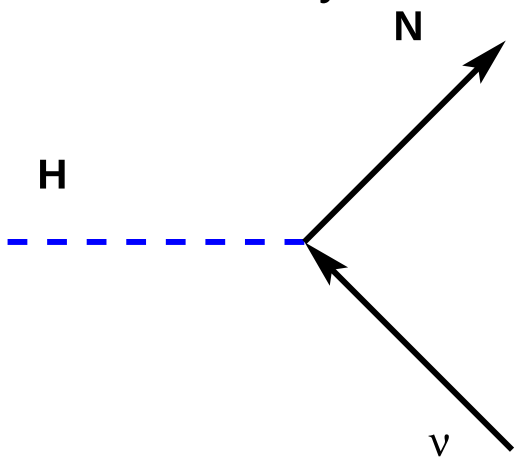
For further discussion, we need to go beyond the Standard Model, which cannot explain matter-antimatter asymmetry of the Universe and dark matter. The Neutrino Minimal Standard Model - νMSM will be used.





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

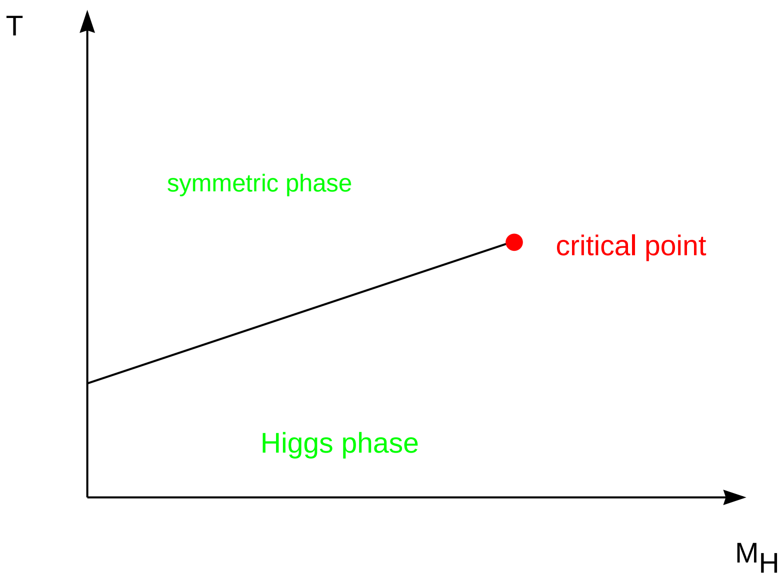
Stage 3: Baryogenesis

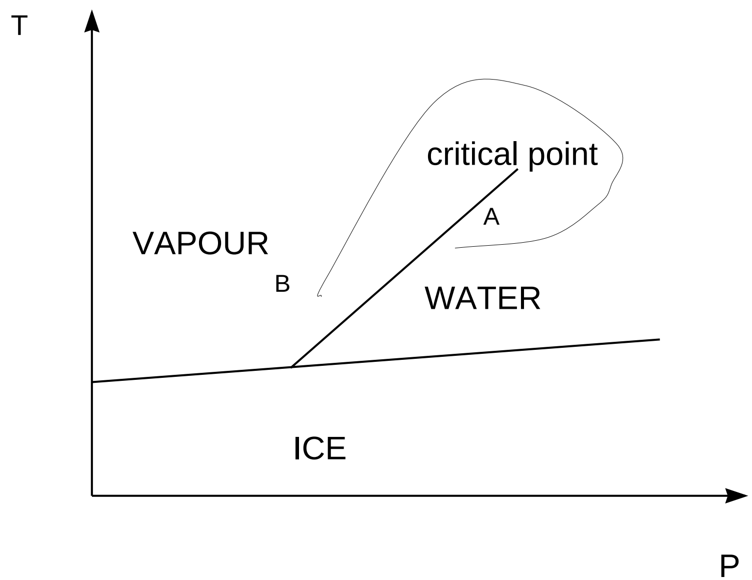
- Nothing essentially interesting happens between 10^3 GeV $< T < 10^{13}$ GeV: all SM elementary particles are nearly in thermal equilibrium.
- Heavy neutral leptons $N_{2,3}$ are out of equilibrium. They are created in interaction with the Higgs boson $H \leftrightarrow N\nu, \;\; t\bar{t} \leftrightarrow N\nu$, 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

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





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

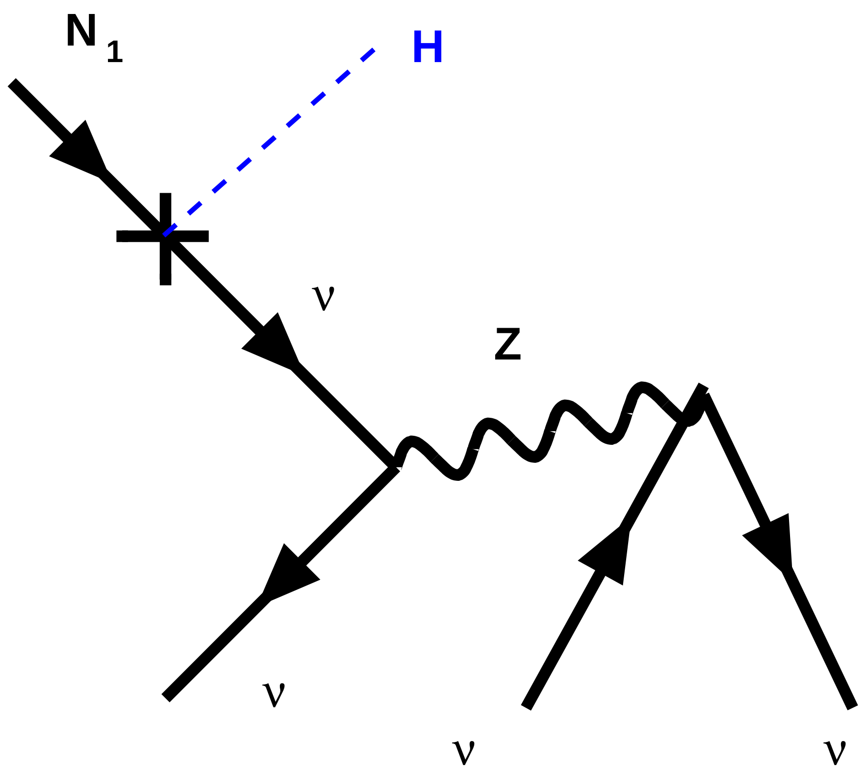
$$M_H^{crit} = 72.3 \pm 0.7\ GeV$$

Stage 4: Dark matter production

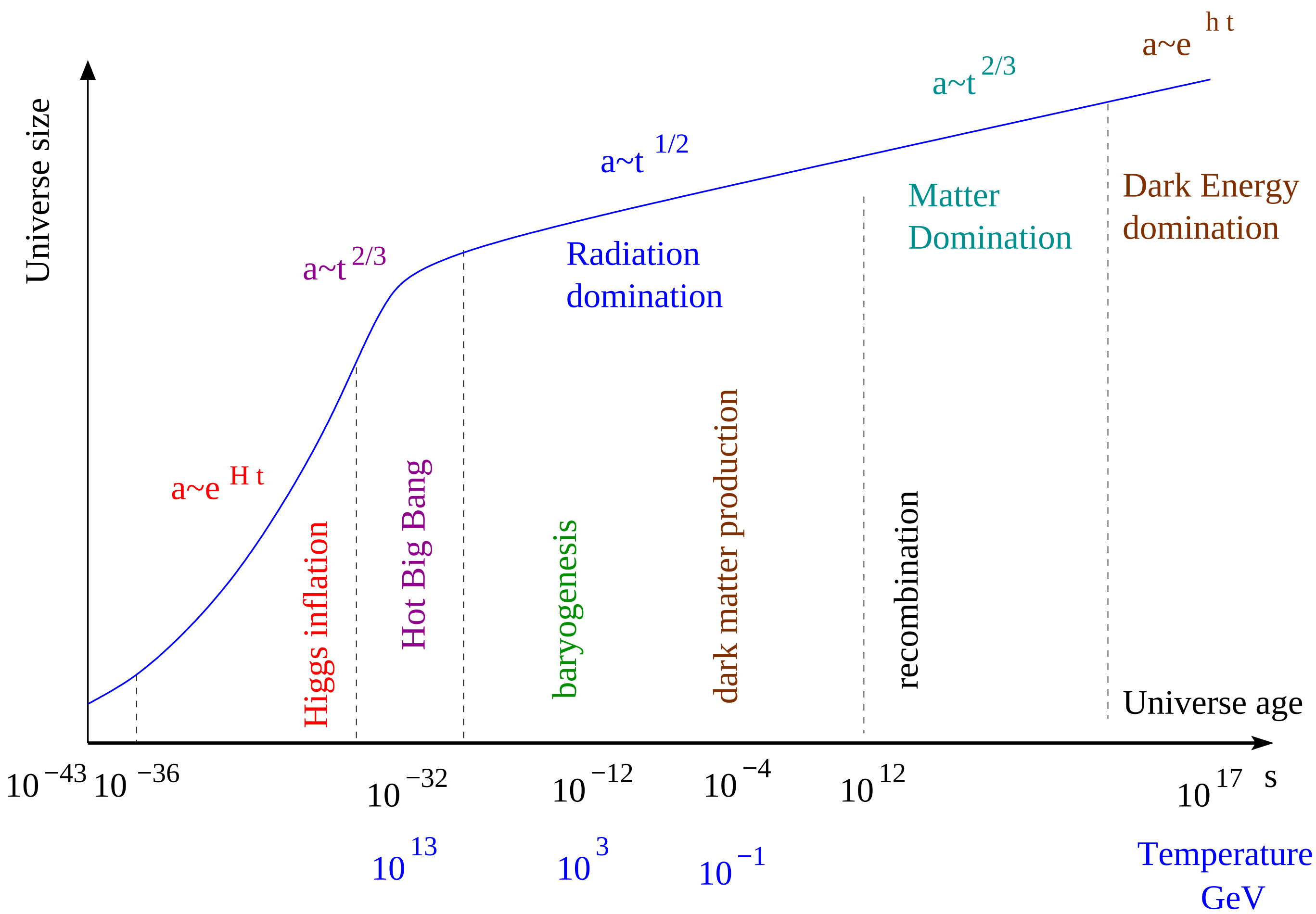
Production temperature of Dark matter HNL via processes like

$l\bar{l} \to \nu N_1$:

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



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:
  $\theta_{13}, \theta_{23} - \pi/4$, 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 $n_s, \ r$

New dedicated experiments

High energy frontier

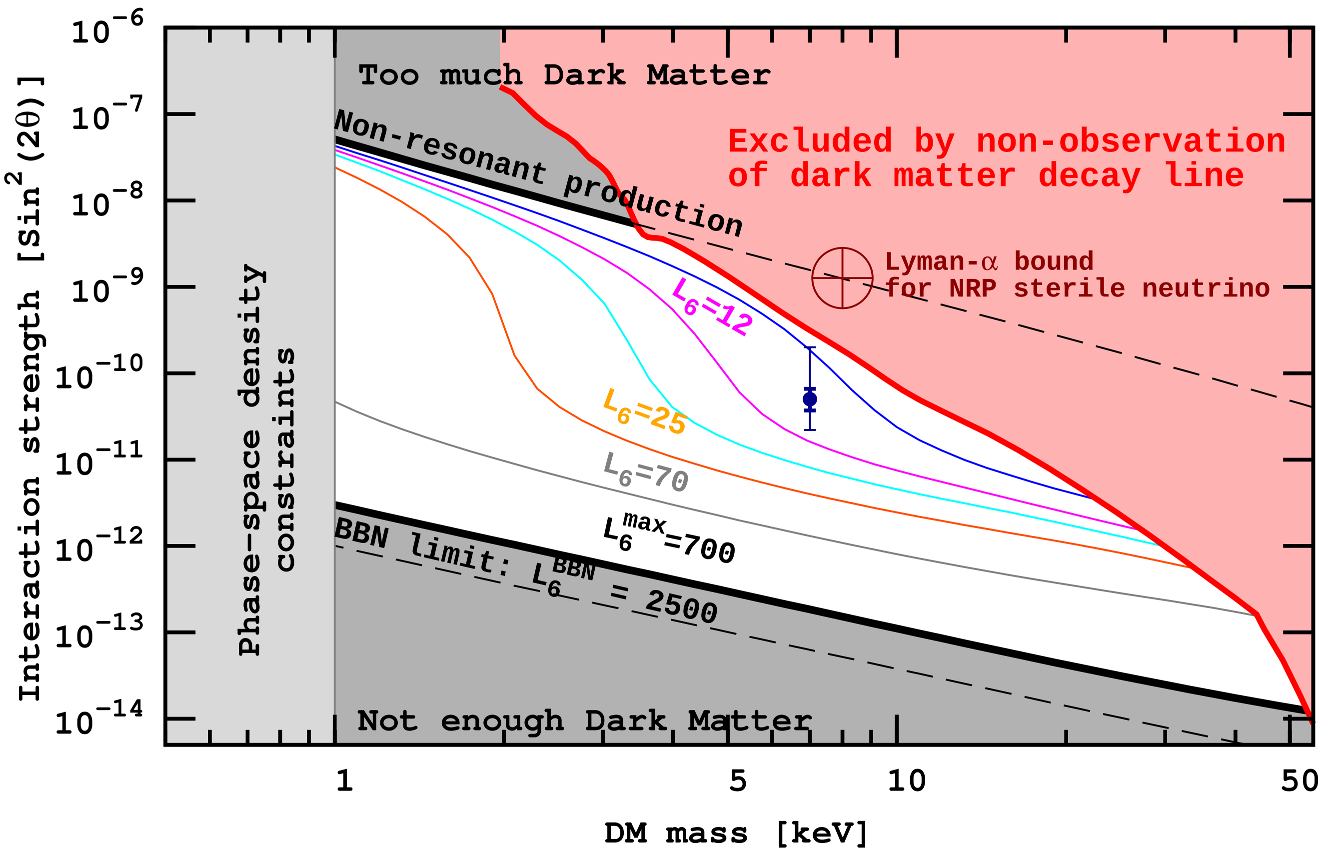
Construction of t-quark factory – e^+e^- or $\mu^+\mu^-$ linear collider with energy $\simeq 200 \times 200$ GeV.

Precise measurement of top and Higgs masses, to elucidate the stability of the EW vacuum and possibility of Higgs inflation.

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

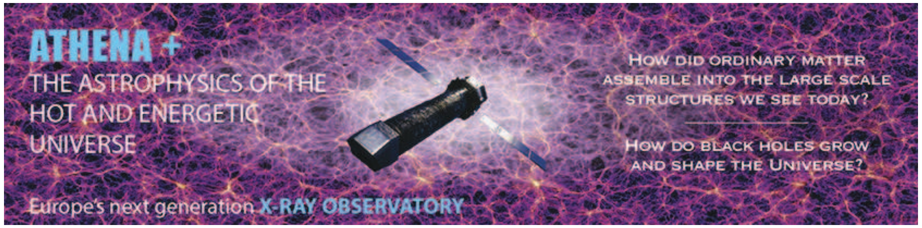
Searches for HNL in space

- 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:

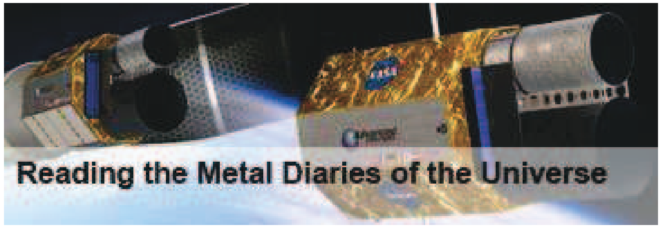
Astro-H

LOFT

Athena+



Origin/Xenia

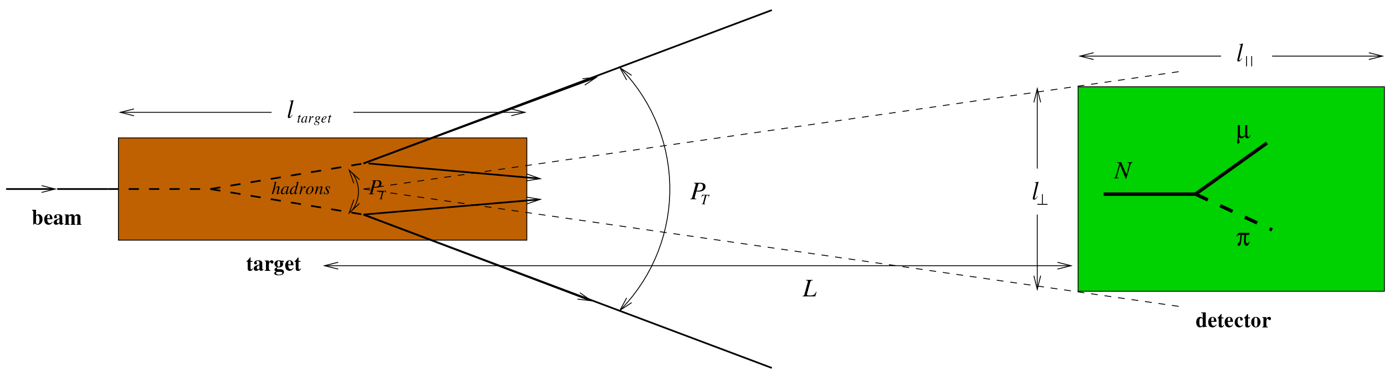


Search for $N_2, \; N_3$

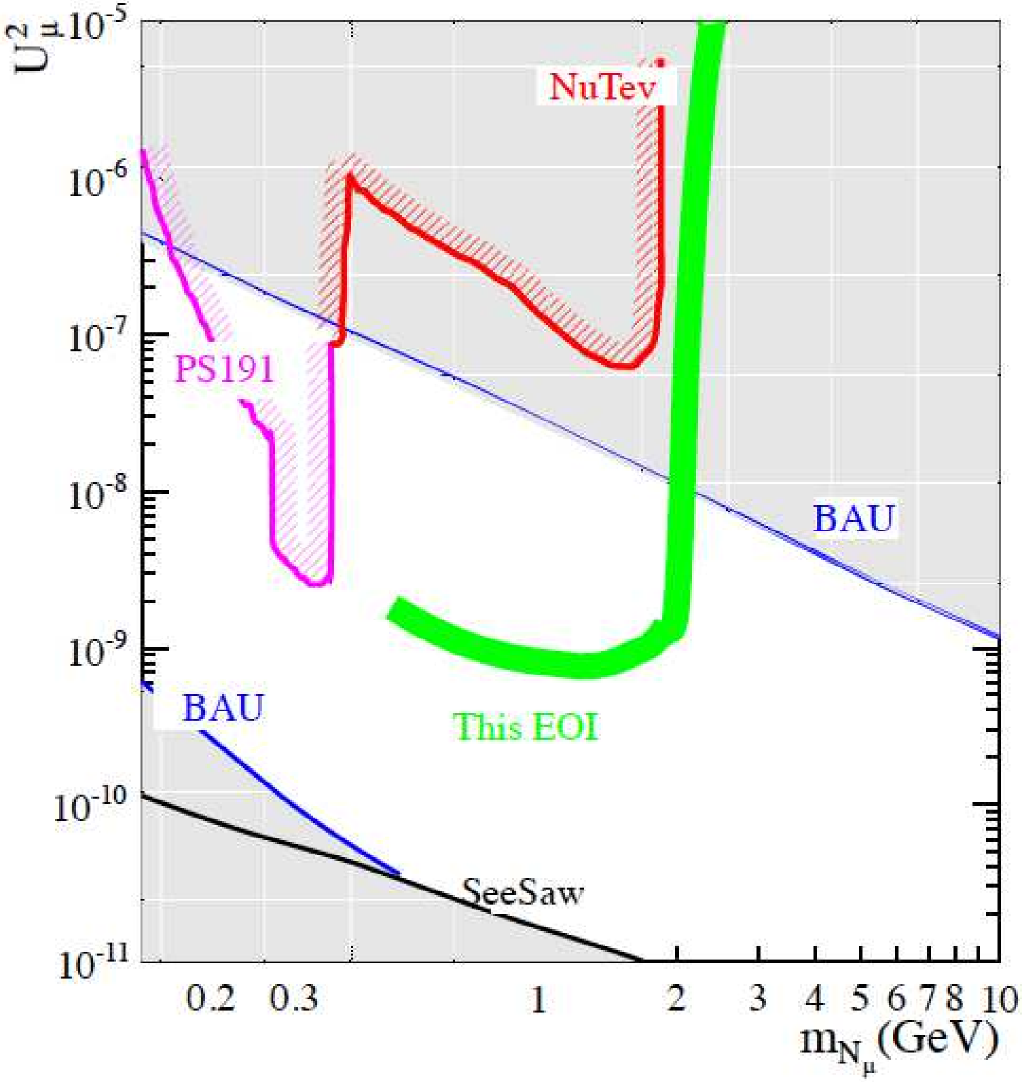
- Challenge: for baryon asymmetry generation the heavy neutral leptons must be very weakly coupled, to satisfy the Sakharov condition of out-of-equilibrium

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

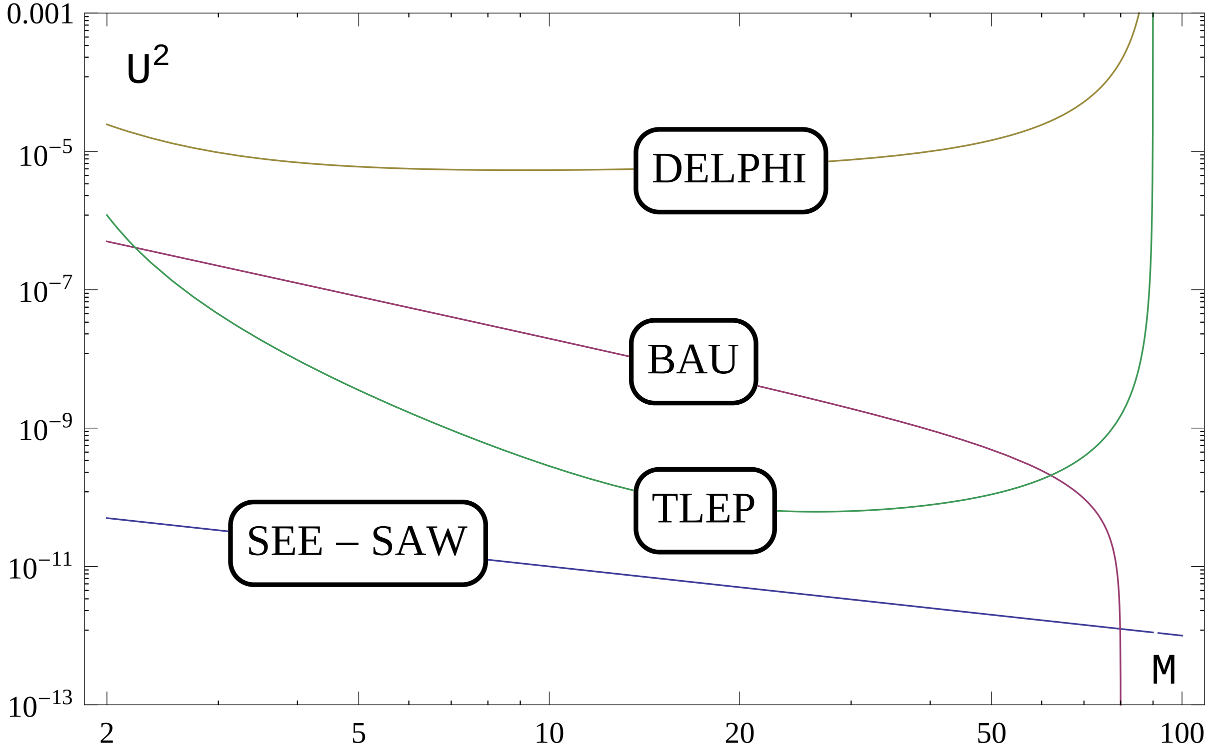


Fixed target SPS: SHIP



FCC-ee for 10^{12} Z

very preliminary



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
- Real and virtual Higgs boson can play a crucial role in baryogenesis leading to charge asymmetric Universe
- Dark Matter production may come about as an effect of mixing between neutrinos and heavy neutral leptons, induced by the Higgs field
- A number of new experiments is needed to reveal the “secret” couplings of the Higgs boson