

## **Particle Physics and Cosmology**

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#### New Trends in Particle Physics, Quantum Gravity & Cosmology

# Outline

#### Lecture 1: What are the problems and ideas for solutions?

- Structure of the Universe at large scales: flatness, horison, etc
  - Inflationary Universe
- Charge asymmetry of the Universe
  - Baryogenesis
- Rotational curves of galaxies, matter content, large scale structure
  - Particle Dark Matter

# Outline

#### Lecture 2

- The current scene: LHC and  $\Lambda$ CDM
- Vacuum meta(?) stability
- Minimal physics for inflation: Higgs as an inflaton

#### Lecture 3

- Minimal physics for neutrino masses
- Baryogenesis
- Dark Matter
- Conclusions

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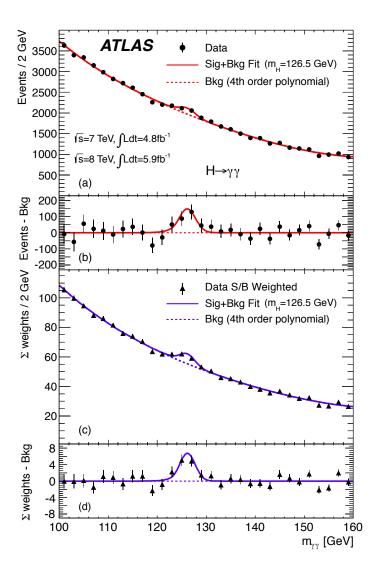
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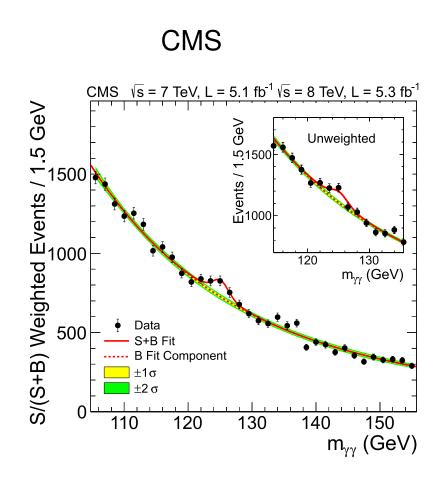
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# LHC discoveries important for Cosmology

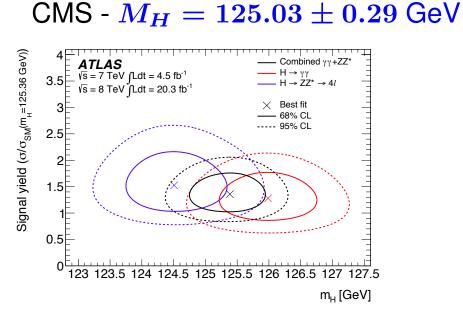
#### July 4, 2012, Higgs at ATLAS and CMS

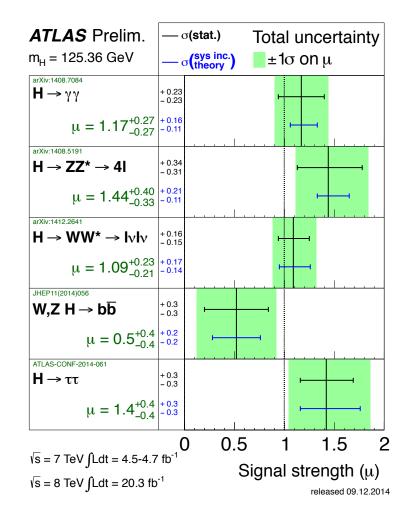




## **Higgs boson properties**

Atlas -  $M_H = 125.36 \pm 0.41$  GeV





New resonance properties are consistent with those of the Higgs

boson of the Standard Model

Schaldming, 21-26 February 2016 - p. 7

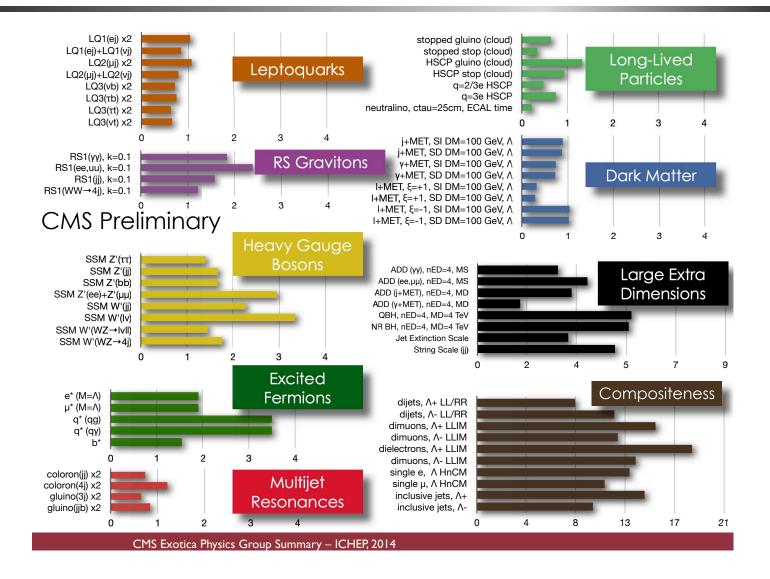
#### **Searches for new physics, SUSY**

#### ATLAS SUSY Searches\* - 95% CL Lower Limits

	Model	$e, \mu, \tau, \gamma$	Jets	$E_{\mathrm{T}}^{\mathrm{miss}}$	∫ <i>L dt</i> [fb	Mass limit	Reference
	SUGRA/CMSSM SUGRA/CMSSM SUGRA/CMSSM $i, \bar{q} \rightarrow q \tilde{x}_{1}^{0}$ $i, \bar{q} \rightarrow q \tilde{x}_{1}^{0}$ $i, \bar{q} \rightarrow q \tilde{x}_{1}^{0}$ $i, \bar{q} \rightarrow q q \tilde{x}_{1}^{0}$ $i, \bar{q} \rightarrow q q (\ell) (\bar{r} / \nu \nu ) \tilde{x}_{1}^{0}$ MSB ( $\ell$ NLSP) MSB ( $\ell$ NLSP) GM (vino NLSP) GM (ving Sur DLSP) GM (higgsino NLSP) GM (higgsino NLSP) GM (higgsino NLSP) GM (higgsino NLSP) GM (higgsino NLSP) GM (higgsino NLSP)	$\begin{matrix} 0 \\ 1  e, \mu \\ 0 \\ 0 \\ 1  e, \mu \\ 2  e, \mu \\ 2  e, \mu \\ 1 - 2  \tau + 0 - 1  \ell \\ 2  \gamma \\ 1  e, \mu + \gamma \\ \gamma \\ 2  e, \mu (Z) \\ 0 \end{matrix}$	2-6 jets 3-6 jets 7-10 jets 2-6 jets 2-6 jets 3-6 jets 0-3 jets 2-4 jets 0-2 jets 	Yes Yes Yes Yes Yes Yes Yes Yes Yes Yes	20.3 20.3 20.3 20.3 20.3 20.3 20.3 4.7 20.3 20.3 4.8 4.8 5.8 10.5	1.7 TeV         m(ij)=m(ij)           1.2 TeV         ary m(ij)           1.1 TeV         ary m(ij)           1.1 TeV         ary m(ij)           850 GeV         m(i <sup>2</sup> )=0 GeV, m(1 <sup>4</sup> gen. ij)=m(2 <sup>nd</sup> gen. ij)           1.33 TeV         m(i <sup>2</sup> )=0 GeV, m(i <sup>4</sup> )=0.5(m(i <sup>2</sup> )+m(ij))           1.18 TeV         m(i <sup>2</sup> )=200 GeV (m(i <sup>4</sup> )=0.5(m(i <sup>2</sup> )+m(ij))           1.12 TeV         m(i <sup>2</sup> )=20 GeV           1.24 TeV         tanj> 20           1.5 TeV         tanj> 20           1.28 TeV         m(i <sup>2</sup> )=50 GeV           900 GeV         m(i <sup>2</sup> )=50 GeV           690 GeV         m(i <sup>2</sup> )=50 GeV           690 GeV         m(i <sup>2</sup> )=50 GeV	1405.7875 ATLAS-CONF-2013-06: 1308.1841 1405.7875 1405.7875 ATLAS-CONF-2013-06: 1208.4688 1407.0603 ATLAS-CONF-2012-40 ATLAS-CONF-2012-41 ATLAS-CONF-2012-41 ATLAS-CONF-2012-14 ATLAS-CONF-2012-15
g g	$\rightarrow b \bar{b} \tilde{\chi}_{1}^{0}$ $\rightarrow t \bar{t} \tilde{\chi}_{1}^{0}$ $\rightarrow t \bar{t} \tilde{\chi}_{1}^{0}$ $\rightarrow b \bar{t} \tilde{\chi}_{1}^{+}$	0 0 0-1 <i>e</i> ,μ 0-1 <i>e</i> ,μ	3 b 7-10 jets 3 b 3 b	Yes Yes Yes Yes	20.1 20.3 20.1 20.1	1.25         TeV         m(k <sup>3</sup> <sub>1</sub> ).<400 GeV           1.1 TeV         m(k <sup>3</sup> <sub>1</sub> ).<450 GeV	1407.0600 1308.1841 1407.0600 1407.0600
	$ \begin{split} \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{k}_1^0 \\ \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{k}_1^+ \\ \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{k}_1^+ \\ \tilde{h}_1, \tilde{b}_1 \rightarrow b \tilde{k}_1^+ \\ \tilde{h}_1 (\text{light}), \tilde{t}_1 \rightarrow b \tilde{k}_1^0 \\ \tilde{h}_1 (\text{light}), \tilde{t}_1 \rightarrow b \tilde{k}_1^0 \\ \tilde{h}_1 (\text{nead}um), \tilde{h}_1 \rightarrow b \tilde{k}_1^0 \\ \tilde{h}_1 (\text{nead}um), \tilde{h}_1 \rightarrow b \tilde{k}_1^0 \\ \tilde{h}_1 (\text{nead}um), \tilde{h}_1 \rightarrow \tilde{k}_1^0 \\ \tilde{h}_1 (\text{nead}um), \tilde{h}_1 \rightarrow \tilde{k}_1^0 \\ \tilde{h}_1 (\text{nead}um) \tilde{h}_1 \rightarrow \tilde{h}_1 \\ \tilde{h}_1 \rightarrow \tilde{h}_1 \end{pmatrix} $	$\begin{array}{c} 0\\ 2\ e,\mu\ ({\rm SS})\\ 1\mathchar`-2\ e,\mu\\ 2\ e,\mu\\ 0\\ 1\ e,\mu\\ 0\\ 0\\ 2\ e,\mu\ (Z)\\ 3\ e,\mu\ (Z) \end{array}$	2 b 0-3 b 1-2 b 0-2 jets 2 jets 2 b 1 b 2 b 0 no-jet/c-ta 1 b 1 b	Yes Yes Yes Yes Yes Yes Yes Yes Yes Yes	20.1 20.3 4.7 20.3 20.3 20.1 20 20.1 20.3 20.3 20.3	100-620 GeV         m(t <sup>2</sup> i)-20 GeV           275-440 GeV         m(t <sup>2</sup> i)-20 GeV           110-167 GeV         m(t <sup>2</sup> i)-20 GeV           130-210 GeV         m(t <sup>2</sup> i)-20 GeV           130-210 GeV         m(t <sup>2</sup> i)-20 GeV           130-200 GeV         m(t <sup>2</sup> i)-10 GeV           150-580 GeV         m(t <sup>2</sup> i)-10 GeV           150-580 GeV         m(t <sup>2</sup> i)-10 GeV           210-640 GeV         m(t <sup>2</sup> i)-10 GeV           90-240 GeV         m(t <sup>2</sup> i)-10 GeV           150-580 GeV         m(t <sup>2</sup> i)-200 GeV           206-640 GeV         m(t <sup>2</sup> i)-10 GeV           90-240 GeV         m(t <sup>2</sup> i)-10 GeV           150-580 GeV         m(t <sup>2</sup> i)-200 GeV	1308.2631 1404.2500 1208.4305, 1209.2102 1403.4853 1403.4853 1308.2631 1407.0583 1406.1122 1407.0608 1403.5222 1403.5222
$\tilde{\chi}_{1}^{\dagger}$ $\tilde{\chi}_{1}^{\dagger}$ $\tilde{\chi}_{1}^{\dagger}$	$\begin{array}{l} & R \tilde{\ell}_{LR}, \tilde{\ell} \rightarrow \ell \tilde{\chi}_{1}^{0} \\ & \tilde{\chi}_{1}, \tilde{\chi}_{1}^{+} \rightarrow \tilde{\ell} \nu (\ell \tilde{\nu}) \\ & \tilde{\chi}_{1}^{-} \tilde{\chi}_{1}^{+} \rightarrow \tilde{\nu} \nu (\tau \tilde{\nu}) \\ & \tilde{\chi}_{2}^{0} \rightarrow \tilde{\ell}_{L} \nu \tilde{\ell}_{L} \ell (\tilde{\nu} \nu), \ell \tilde{\nu} \tilde{\ell}_{L} \ell (\tilde{\nu} \nu) \\ & \tilde{\chi}_{2}^{0} \rightarrow W \tilde{\chi}_{1}^{0} Z \tilde{\nu} \\ & \tilde{\chi}_{2}^{0} \rightarrow W \tilde{\chi}_{1}^{0} L \tilde{\chi}_{1}^{0} \\ & \tilde{\chi}_{3}^{0}, \tilde{\chi}_{23} \rightarrow \tilde{\ell}_{R} \ell \end{array}$	2 e,μ 2 e,μ 2 τ 3 e,μ 2-3 e,μ 1 e,μ 4 e,μ	0 0 - 0 2 <i>b</i> 0	Yes Yes Yes Yes Yes Yes Yes	20.3 20.3 20.3 20.3 20.3 20.3 20.3 20.3	90-325 GeV         m(t <sup>2</sup> ) <sub>1</sub> )=0 GeV           140-465 GeV         m(t <sup>2</sup> ) <sub>1</sub> )=0 GeV, m(t <sup>2</sup> , ν)=0.5(m(t <sup>2</sup> ) <sub>1</sub> )=m(t <sup>2</sup> ) <sub>1</sub> )           100-350 GeV         m(t <sup>2</sup> ) <sub>1</sub> )=0 GeV, m(t <sup>2</sup> , ν)=0.5(m(t <sup>2</sup> ) <sub>1</sub> )=m(t <sup>2</sup> ) <sub>1</sub> )           700 GeV         m(t <sup>2</sup> ) <sub>1</sub> =m(t <sup>2</sup> ) <sub>2</sub> ), m(t <sup>2</sup> ) <sub>1</sub> =0, m(t <sup>2</sup> )=m(t <sup>2</sup> ) <sub>1</sub> )           420 GeV         m(t <sup>2</sup> ) <sub>1</sub> =m(t <sup>2</sup> ) <sub>2</sub> ), m(t <sup>2</sup> ) <sub>1</sub> =0, sleptons decoupled           285 GeV         m(t <sup>2</sup> ) <sub>1</sub> =m(t <sup>2</sup> ) <sub>2</sub> ), m(t <sup>2</sup> ) <sub>1</sub> =0, m(t <sup>2</sup> )=m(t <sup>2</sup> ) <sub>1</sub> )           620 GeV         m(t <sup>2</sup> ) <sub>2</sub> =m(t <sup>2</sup> ) <sub>2</sub> ), m(t <sup>2</sup> ) <sub>1</sub> =0, m(t <sup>2</sup> ) <sub>1</sub> =m(t <sup>2</sup> ) <sub>1</sub> )	1403.5294 1403.5294 1407.0350 1402.7029 1403.5294, 1402.7029 ATLAS-CONF-2013-09: 1405.5086
Darticles IS IS 15	rect $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$ able, stopped $\tilde{g}$ R-hadron MSB, stable $\tilde{\tau}, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}(\tilde{e}, \tilde{\mu}) + \tau(e, \mu)$ MSB, $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$ , long-lived $\tilde{\chi}_1^0$	Disapp. trk 0 $\mu$ ) 1-2 $\mu$ 2 $\gamma$ 1 $\mu$ , displ. vtx	1 jet 1-5 jets - -	Yes Yes Yes	20.3 27.9 15.9 4.7 20.3	270 GeV         m(k <sup>2</sup> <sub>1</sub> )=h(k <sup>0</sup> <sub>1</sub> )=160 MeV, r(k <sup>2</sup> <sub>1</sub> )=0.2 ns           832 GeV         m(k <sup>2</sup> <sub>1</sub> )=100 GeV, 10 µs <r(k<sup>2)=100 geV, 10 µs <r(k<sup>2)&lt;1000 s</r(k<sup></r(k<sup>	ATLAS-CONF-2013-069 1310.6584 ATLAS-CONF-2013-058 1304.6310 ATLAS-CONF-2013-092
LF Bi $\tilde{\chi}_{1}^{+}$ $\tilde{g}^{-}$	$ \begin{array}{l} \nabla pp \rightarrow \tilde{\mathbf{v}}_{\tau} + X, \tilde{\mathbf{v}}_{\tau} \rightarrow e + \mu \\ \nabla pp \rightarrow \tilde{\mathbf{v}}_{\tau} + X, \tilde{\mathbf{v}}_{\tau} \rightarrow e(\mu) + \tau \\ \text{linear RPV CMSSM} \\ \tilde{\lambda}_{1}^{-}, \tilde{\lambda}_{1}^{+} \rightarrow W \tilde{\lambda}_{1}^{0}, \tilde{\lambda}_{1}^{0} \rightarrow e \tilde{\nu}_{\mu}, e \mu \tilde{\nu}_{e} \\ \tilde{\chi}_{1}^{-}, \tilde{\chi}_{1}^{+} \rightarrow W \tilde{\lambda}_{1}^{0}, \tilde{\lambda}_{1}^{0} \rightarrow \tau \tau \tilde{\nu}_{e}, e \tau \tilde{\nu}_{\tau} \\ q q q \\ \tilde{\eta}_{1}(t, \tilde{t}_{1}) \rightarrow b s \end{array} $	$\begin{array}{c} 2 \ e, \mu \\ 1 \ e, \mu + \tau \\ 2 \ e, \mu \ (\text{SS}) \\ 4 \ e, \mu \\ 3 \ e, \mu + \tau \\ 0 \\ 2 \ e, \mu \ (\text{SS}) \end{array}$	- 0-3 b - - 6-7 jets 0-3 b	Yes Yes Yes Yes	4.6 4.6 20.3 20.3 20.3 20.3 20.3 20.3	1.61 TeV         J <sub>511</sub> =0.0, J <sub>132</sub> =0.05           1.1 TeV         J <sub>311</sub> =0.10, J <sub>132</sub> =0.05           1.1 TeV         J <sub>311</sub> =0.10, J <sub>132</sub> =0.05           1.35 TeV         m(ij)=m(ij), cr <sub>LSP</sub> <1 mm	1212.1272 1212.1272 1404.2500 1405.5086 1405.5086 ATLAS-CONF-2013-09 1404.250
D So	calar gluon pair, sgluon $\rightarrow q\bar{q}$ calar gluon pair, sgluon $\rightarrow t\bar{t}$ IMP interaction (D5, Dirac $\chi$ )	0 2 <i>e</i> , <i>µ</i> (SS) 0	4 jets 2 b mono-jet	- Yes Yes	4.6 14.3 10.5	n 100-287 GeV incl. limit from 1110.2693 a 350-800 GeV m(χ)<80 GeV, limit of<687 GeV for D8	1210.4826 ATLAS-CONF-2013-05 ATLAS-CONF-2012-14

\*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1 or theoretical signal cross section uncertainty.

#### **Searches for new physics, exotics**



#### **Determination of top quark mass**

Monte Carlo mass:  $m_t = 172.38 \pm 0.10 \pm 0.65~{
m GeV}$ 

	19.7 fb <sup>-1</sup> (8 TeV) + 5.1 fb <sup>-1</sup> (7 TeV)
CMS Preliminary	
CMS 2010, dilepton	175.5 ± 4.6 ± 4.6 GeV
JHEP 07 (2011) 049, 36 pb <sup>-1</sup>	(value ± stat ± syst)
CMS 2010, lepton+jets	173.1 ± 2.1 ± 2.6 GeV
PAS TOP-10-009, 36 pb <sup>-1</sup>	(value ± stat ± syst)
CMS 2011, dilepton	172.5 ± 0.4 ± 1.4 GeV
EPJC 72 (2012) 2202, 5.0 fb <sup>-1</sup>	(value ± stat ± syst)
CMS 2011, lepton+jets	173.5 ± 0.4 ± 1.0 GeV
JHEP 12 (2012) 105, 5.0 fb <sup>-1</sup>	(value ± stat ± syst)
CMS 2011, all-hadronic	173.5 ± 0.7 ± 1.2 GeV
EPJ C74 (2014) 2758, 3.5 fb <sup>-1</sup>	(value ± stat ± syst)
CMS 2012, lepton+jets	172.0 ± 0.1 ± 0.7 GeV
PAS TOP-14-001, 19.7 fb <sup>-1</sup>	(value ± stat ± syst)
CMS 2012, all-hadronic	172.1 ± 0.3 ± 0.8 GeV
PAS TOP-14-002, 18.2 fb <sup>-1</sup>	(value ± stat ± syst)
CMS 2012, dilepton	172.5 ± 0.2 ± 1.4 GeV
PAS TOP-14-010, 19.7 fb <sup>-1</sup>	(value ± stat ± syst)
CMS combination	172.38 ± 0.10 ± 0.65 GeV
September 2014	(value ± stat ± syst)
Tevatron combination	174.34 ± 0.37 ± 0.52 GeV
July 2014 arXiv:1407.2682	(value ± stat ± syst)
World combination March 2014	173.34 ± 0.27 ± 0.71 GeV
ATLAS, CDF, CMS, D0	(value ± stat ± syst)
165 170	175 180
	m <sub>t</sub> [GeV]

#### **Summary of the LHC findings**

The Standard Model in now complete: the last particle - Higgs boson, predicted by the SM, has been found

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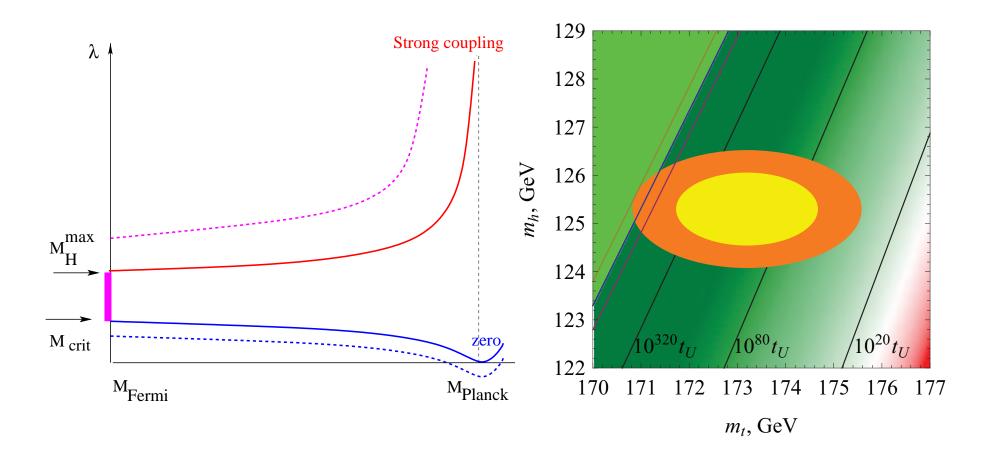
- The Standard Model in now complete: the last particle Higgs boson, predicted by the SM, has been found
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### **Summary of the LHC findings**

- The Standard Model in now complete: the last particle Higgs boson, predicted by the SM, has been found
- No deviations from the SM have been observed (750 diphoton excess?)
- The masses of the top quark and of the Higgs boson, the Nature has chosen, make the SM a self-consistent effective field theory all the way up to the Planck scale  $114 \text{ GeV} < m_H < 175 \text{ GeV}$

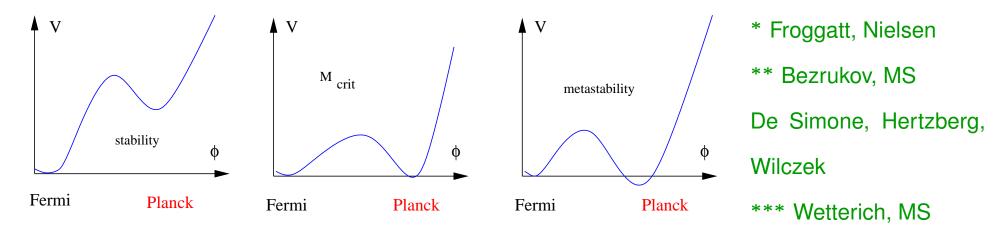
#### Behaviour of the scalar self-coupling

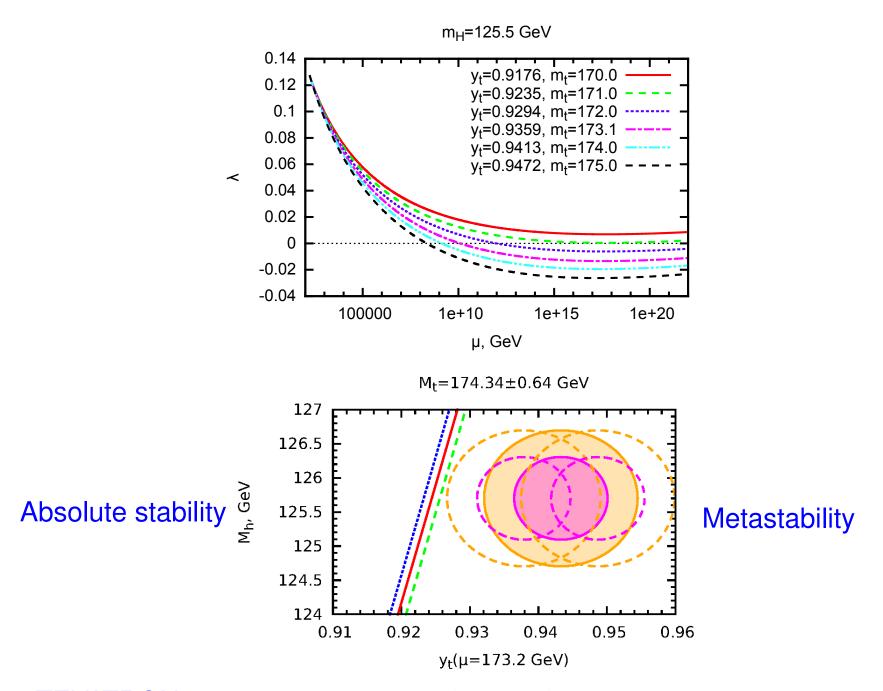
#### vacuum lifetime



# Vacuum (meta?)stability

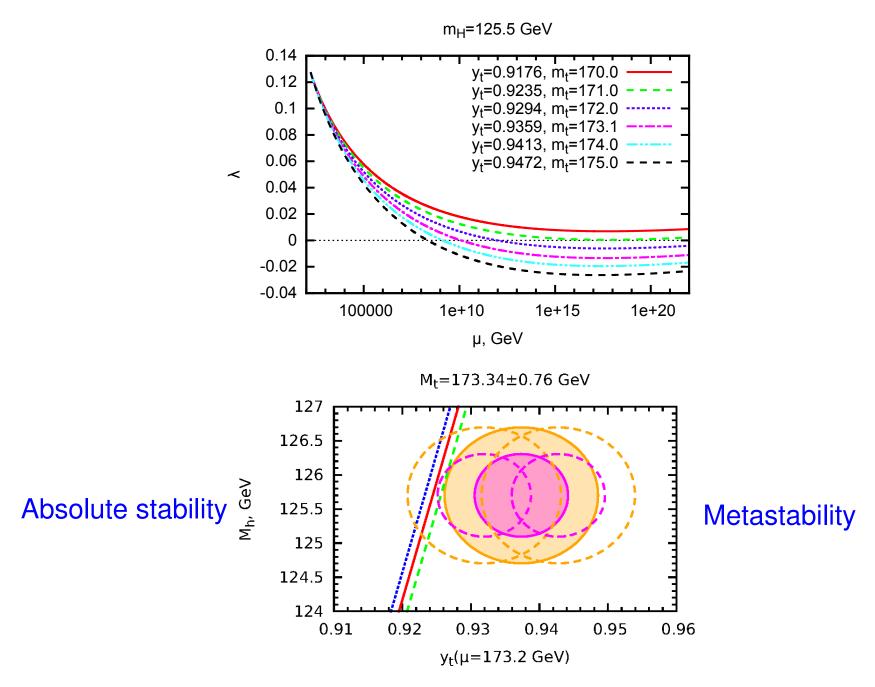
Important fact: The combination of top-quark and Higgs boson masses is very close to the stability bound of the SM vacuum\* (95'), to the Higgs inflation bound\*\* (08'), and to asymptotic safety values for  $M_H$ and  $M_t$  \*\*\* (09'):



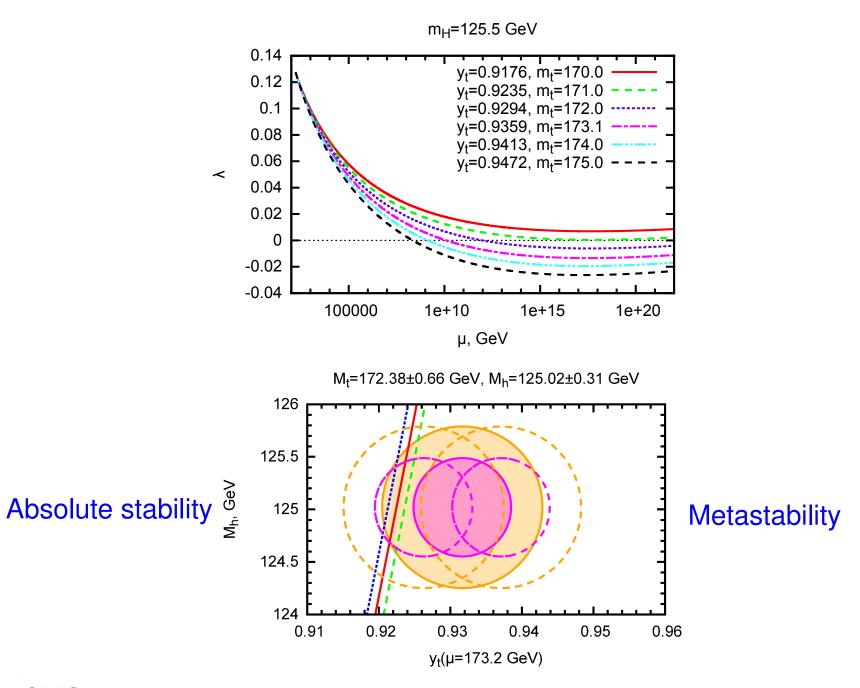


TEVATRON 2014:  $m_t = 174.34 \pm 0.37 \pm 0.52~{
m GeV}$ 

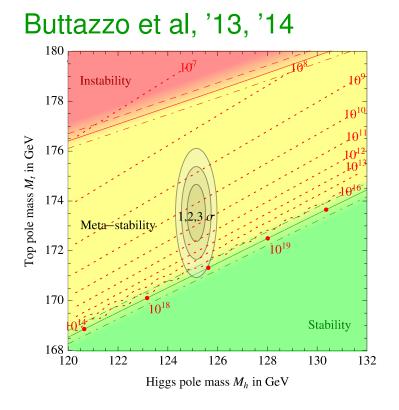
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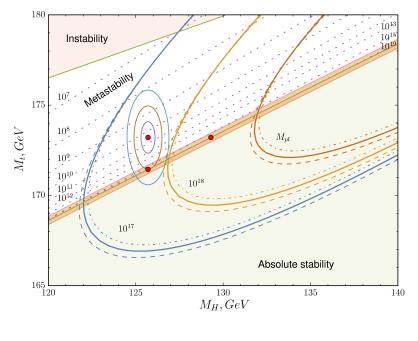
PDG 2014:  $m_t = 173.34 \pm 0.27 \pm 0.71~{
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m GeV}$ 



#### Bednyakov et al, '15

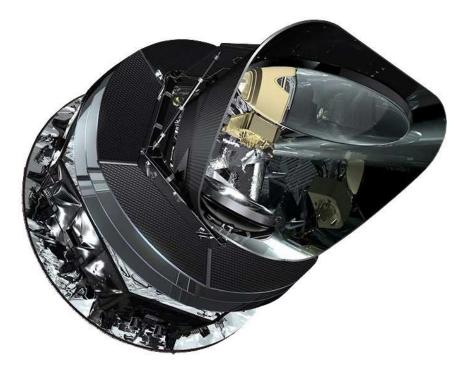


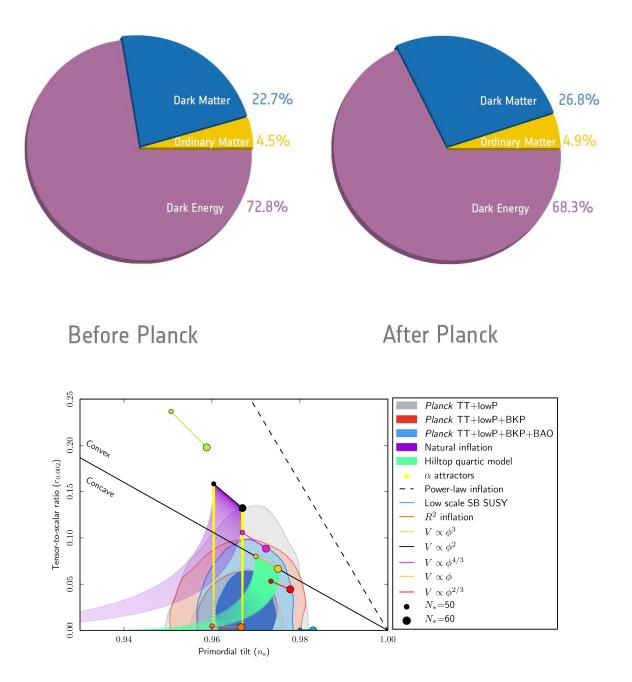
Vacuum is unstable at  $2.8\sigma$ 

Vacuum is unstable at  $1.3\sigma$ 

Main uncertainty: top Yukawa coupling, relation between the MC mass and the top Yukawa coupling allows for  $\pm 1$  GeV in  $M_{top}$ . Alekhin et al, Frixione et al.

# Planck results





# The message from Planck: The Standard $\Lambda$ CDM model is in a very good agreement with the data

- No primordial non-Gaussianities are observed
- One-field inflationary models agree well with Planck
- No physics beyond Standard  $\Lambda$ CDM is observed

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- Most of the matter in the universe is dark : no particle physics candidate in the SM
- Neutrino masses and oscillations, absent in the Standard Model
- The Universe expansion at present is accelerating. Is this simply a tiny cosmological constant or something more complicated?

How to reconcile the evidence for new physics without spoiling the success of the Standard Model and Standard ΛCDM?

# Inflation

# Inflation

Ockham's razor in action, 3 step logic:

# Inflation

- Ockham's razor in action, 3 step logic:
- For inflation we better have scalar field

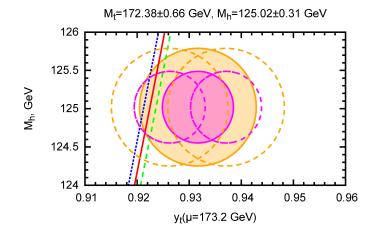
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- Ockham's razor in action, 3 step logic:
- For inflation we better have scalar field
- The Higgs boson was predicted by the SM and finally has been discovered
- Let's use it for inflation!

# Higgs inflation near the critical line



# **Higgs Inflation, no loops**

Higgs field in general must have non-minimal coupling to gravity:

$$S_G=\int d^4x\sqrt{-g}iggl\{-rac{M_P^2}{2}R-rac{m{\xi}h^2}{2}Riggr\}$$

Jordan, Feynman, Brans, Dicke,...

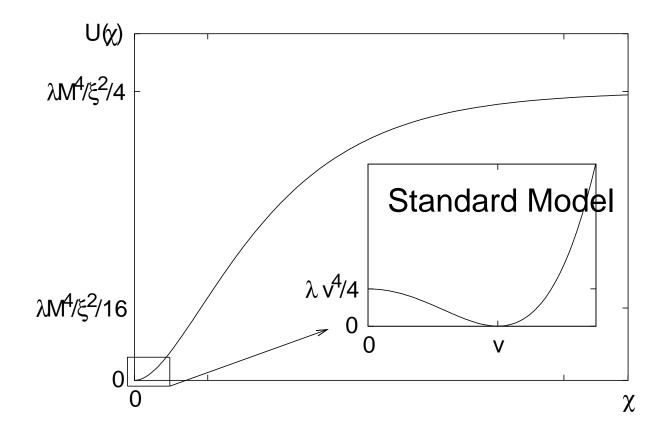
Consider large Higgs fields  $h > M_P / \sqrt{\xi}$ , which may have existed in the early Universe

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

 $M_{_{m P}}^{
m eff}=\sqrt{M_{_{m P}}^2+\xi h^2}\propto h$ 

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

# Potential in Einstein frame

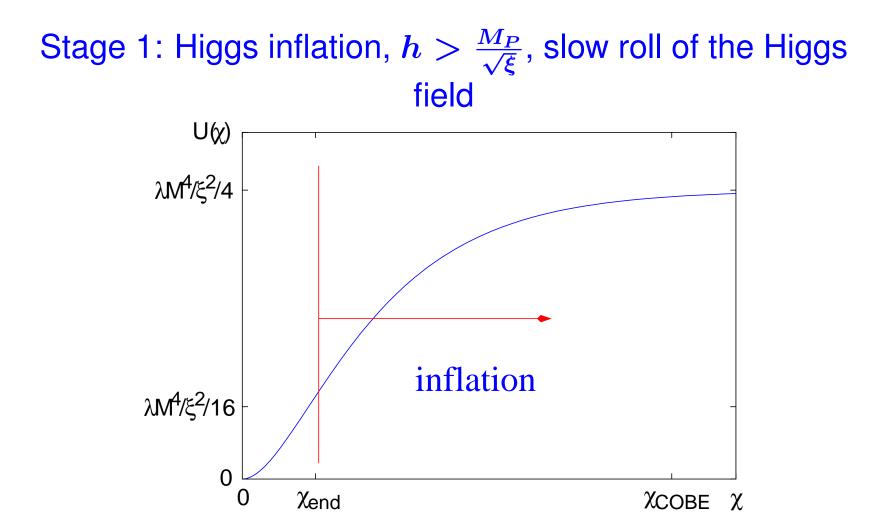


 $\chi$  - canonically normalized scalar field in Einstein frame.

# Potential for the Higgs field may be flat at large values of *h*: Linde chaotic inflation

Potential for the Higgs field may be flat at large values of *h*: Linde chaotic inflation

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



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

# **Slow roll stage**

COBE normalization  $U/\epsilon = (0.0276 M_P)^4$  gives

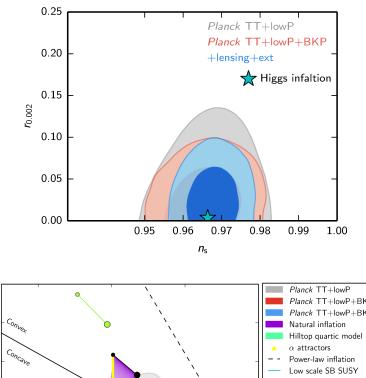
$$\xi\simeq\sqrt{rac{\lambda}{3}}rac{N_{
m COBE}}{0.027^2}\simeq47000\sqrt{\lambda}=47000rac{m_H}{\sqrt{2}v}$$

#### Connection of $\xi$ and the Higgs mass!

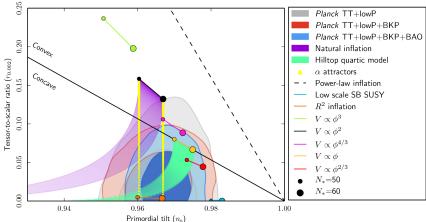
Number of e-folds of inflation at the moment  $h_N$  is  $N \simeq \frac{6}{8} \frac{h_N^2 - h_{end}^2}{M_P^2/\xi}$ Slow roll ends at  $\chi_{end} \simeq M_P$ ; and "begins" at  $\chi_{60} \simeq 5M_P$ 

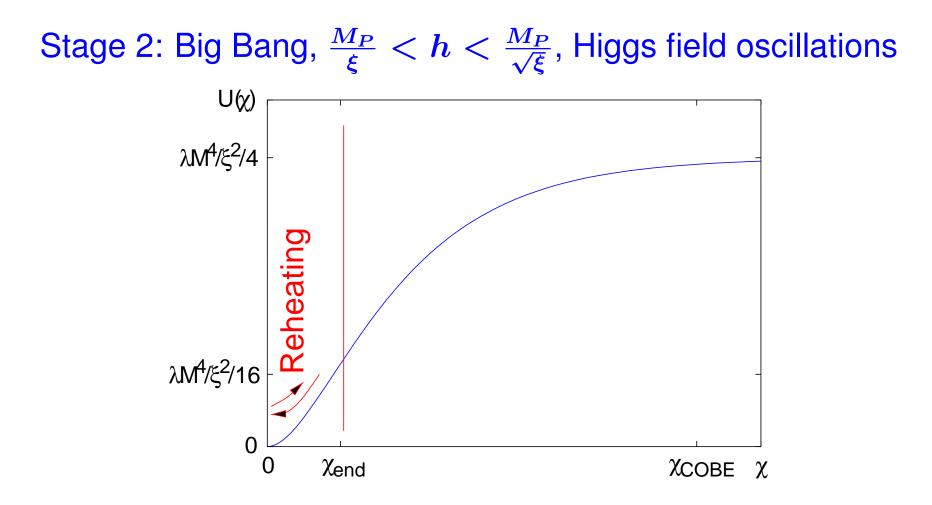
$$egin{aligned} \epsilon &= rac{M_P^2}{2} \left(rac{dU/d\chi}{U}
ight)^2, & \eta &= M_P^2 rac{d^2 U/d\chi^2}{U} \ n_s &= 1-6\epsilon+2\eta, & r = 16\epsilon \end{aligned}$$

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



#### $n_s = 0.97, \ r = 0.003$





- All particles of the Standard Model are produced
- Coherent Higgs field disappears
- The Universe is heated up to  $T \propto M_P / \xi \sim 10^{14} \, \text{GeV}$

(i) Add to the theory all higher-dimensional operators, suppressed by the Planck scale. This kills all large field inflationary models (not the Higgs inflation, if the Planck suppressed operators are added in Jordan frame, but also Higgs inflation, if done in the Einstein frame)

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(ii) Self-consistent approach to Higgs inflation: compute the onset of strong coupling  $\Lambda$  ("UV cutoff") by considering tree high energy scattering amplitudes Burgess, Lee, Trott ; Barbon and Espinosa in the Higgs-dependent background Bezrukov, Magnin, M.S., Sibiryakov; Ferrara, Kallosh, Linde, A. Marrani, Van Proeyen and add higher-dimensional operators suppressed by this cutoff.

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(iii) The most minimal setup: add to Lagrangian all counter-terms necessary to make the theory finite with all constant parts having the same structure as counter-terms. Bezrukov, Magnin, MS, Sibiryakov

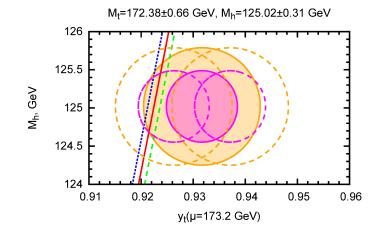
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Radiative corrections, different approaches: Barvinsky, Kamenshchik, Starobinsky; Bezrukov, MS; De Simone, Hertzberg, Wilczek; George, Mooij, Postma,...

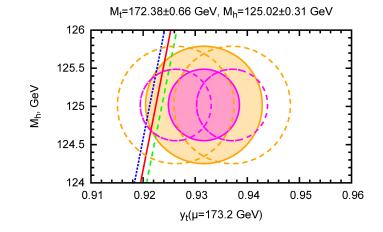
# Higgs inflation: $y_t < y_t^{ ext{crit}}$



# The same story as the Higgs inflation at the tree level.

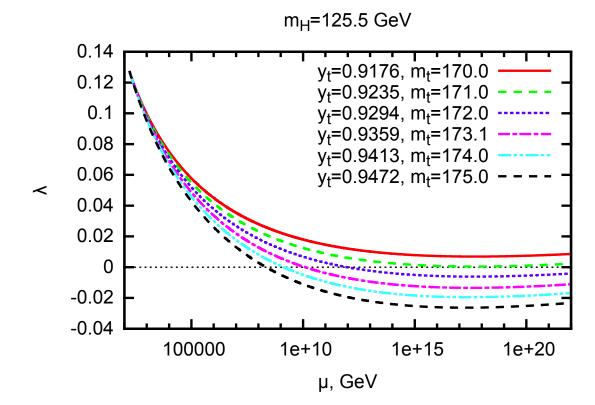
# Critical Higgs inflation: $y_t pprox y_t^{ ext{crit}}$

## Extreme fine tuning of the Higgs and top quark masses



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

Behaviour of  $\lambda$ :



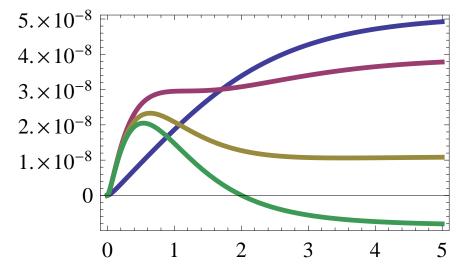
## **Effective potential**

$$U(\chi) \simeq rac{\lambda(z')}{4\xi^2} ar{\mu}^4 \;, \; z' = rac{ar{\mu}}{\kappa M_P}, \; ar{\mu}^2 = M_P^2 \left(1 - e^{-rac{2\chi}{\sqrt{6}M_P}}
ight)$$

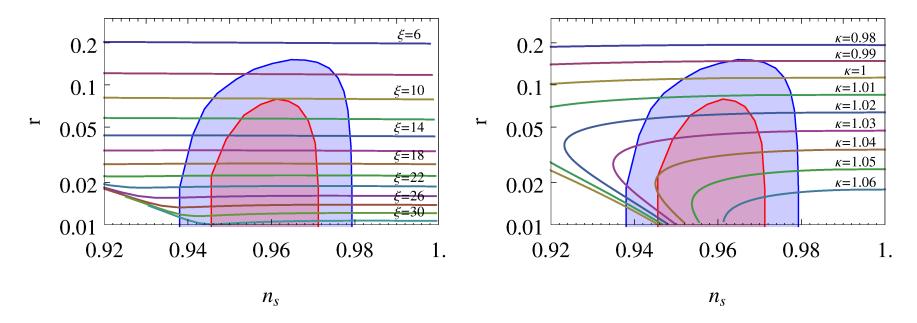
The parameter  $\mu$  that optimises the convergence of the perturbation theory is related to  $\bar{\mu}$  as

$$\mu^2 = lpha^2 rac{y_t(\mu)^2}{2} rac{ar{\mu}^2}{\xi(\mu)} \,, \;\; lpha \simeq 0.6$$

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



# The inflationary indexes

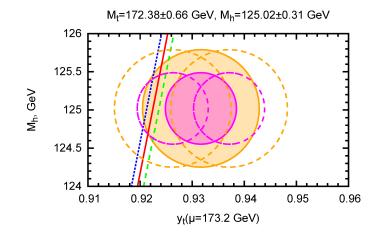


#### *r* can be large!

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.

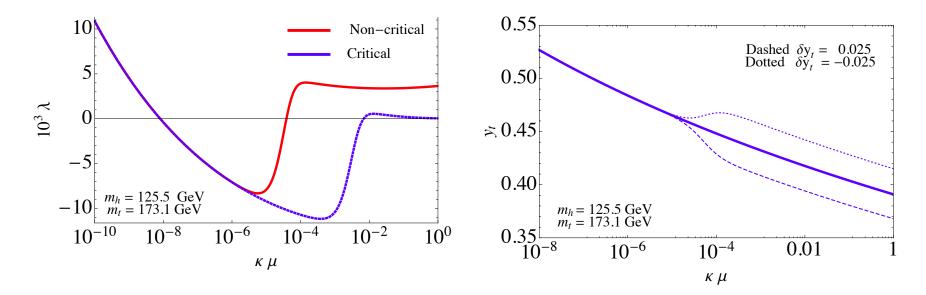
# Living beyond the edge: Higgs inflation and vacuum metastability, $y_t > y_t^{crit}$



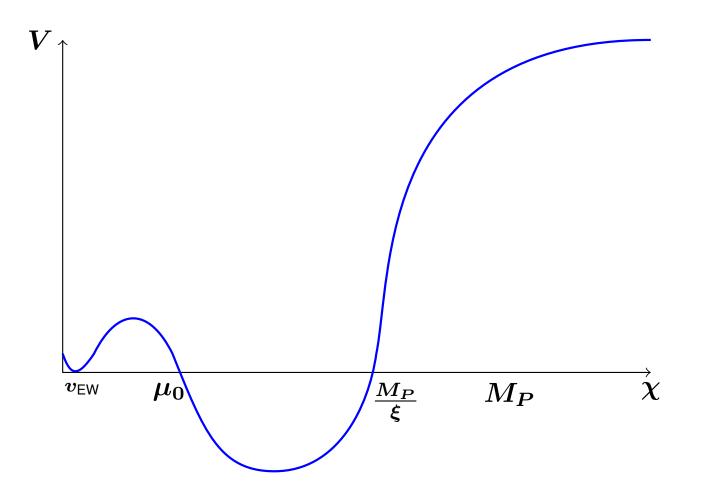
### Bezrukov, Rubio, MS

Renormalisation of the SM coupling constants at the scale  $M_P/\xi$ : "jumps" of  $\lambda$  and  $y_t$  controlled by UV completion of the SM, which cannot be found from low-energy observables of the SM Bezrukov, Magnin, MS., Sibiryakov

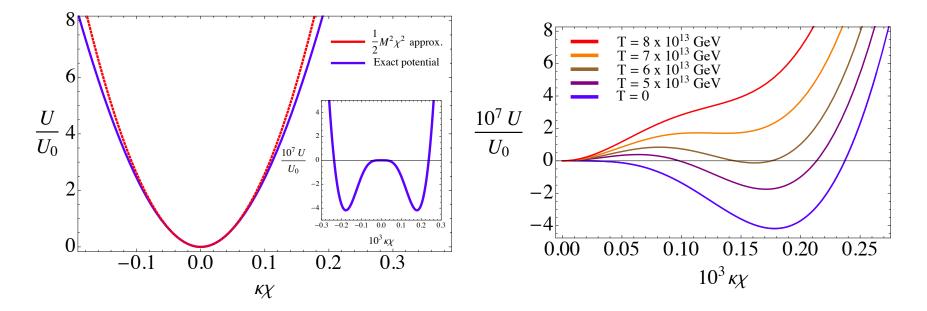
 $\lambda(M_P/\xi)$  is small due to cancellations between fermionic and bosonic loops:  $\delta\lambda$  can be of the order of  $\lambda$ 



# **Higgs potential**



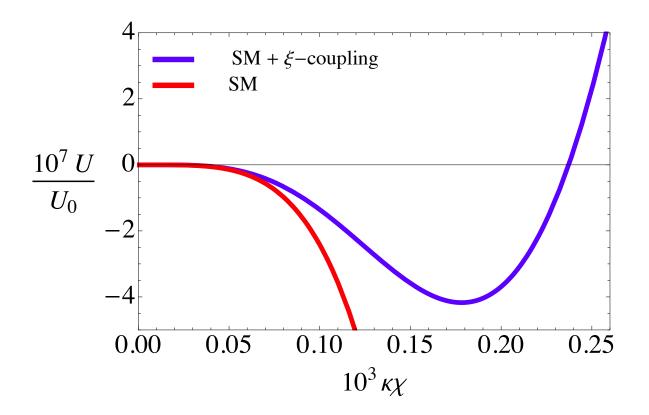
## **Symmetry restoration**



Reheating temperature  $T_R\simeq 2 imes 10^{14}~{
m GeV}>T_+\simeq 7 imes 10^{13}~{
m GeV},$  $T_c=6 imes 10^{13}~{
m GeV}$ 

## (Meta) stability of false vacuum

Computation for SM: Espinosa, Giudice, Riotto



Predictions for critical indexes  $n_s$  and r are the same as for non-critical Higgs inflation

 $n_s = 0.97, \ r = 0.003$ 

# Critical Higgs inflation at $y_t > y_t^{crit}$ ?

Critical Higgs inflation : small  $\xi \sim 10$  - the depth of the large Higgs value vacuum is comparable with the energy stored in the Higgs after inflation: the required reheating temperature is too large,  $T_+ \simeq 10^{16}$  GeV and cannot be achieved.

- Higgs boson of the Standard Model can make the universe flat, homogeneous and isotropic, and can lead to primordial perturbations needed for structure formation
- The Higgs inflation can take place both for absolutely stable and metastable vacuum, with universal predictions  $n_s = 0.97, \ r = 0.003 \text{ for a wide range of parameters}$
- For critical Higgs inflation corresponding to  $y_t \approx y_t^{\text{crit}}$   $n_s$  and rcan be substantially different from these values