Primordial Black Hole production in Critical Higgs Inflation

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Primordial Black Holes (PBH) arise naturally from high peaks in the curvature power spectrum of near-inflection-point single-field inflation, and could constitute today the dominant component of the dark matter in the universe. In this letter we explore the possibility that a broad spectrum of PBH is formed in models of Critical Higgs Inflation (CHI), where the quasi-inflection point is related to the near-critical value of the RGE running of both the Higgs self-coupling $\lambda(\mu)$ and its non-minimal coupling to gravity $\xi(\mu)$. We show that the peak in the matter spectrum arises at sufficiently small scales that it passes all the observational constraints from the cosmic microwave background (CMB) and large scale structure (LSS) observations. The CMB spectrum at large scales is in agreement with Planck-2015 data, $A_s^2 = 2.1 \times 10^{-9}$, $n_s = 0.957$, $r = 0.028$, $dn_s/d\ln k = -0.00144$. The relatively large tensor-to-scalar ratio may be detected soon with B-mode polarization experiments. Moreover, the model predicts a lognormal PBH broad-mass distribution peaked at $\mu_{\rm PBH} = 4 \times 10^{-11}\, M_\odot$, with dispersion $\sigma_{\rm PBH} = 1.4$, which is consistent with the present constraints on PBH and may eventually be discovered with microlensing experiments. The stochastic background of gravitational waves coming from the unresolved black-hole-binary (BHB) mergings could also be detected by LISA or PTA. Furthermore, the parameters of the CHI model correspond to a Standard Model Higgs self-coupling running, given by $\lambda_0 = 1.2\times 10^{-6}$ and $b_\lambda = 0.9\times 10^{-5}$ near the critical point, and a running non-minimal coupling, with $\xi_0 = 21$ and $b_\xi = 40.6$, while the critical Higgs value is $\kappa^2\mu^2 = 0.0226$. These values are consistent, within 2σ, with the measured Higgs parameters at the LHC. Future measurements of the PBH mass spectrum will allow us to determine the SM couplings of the Higgs and their running from the electroweak scale to almost the Planck scale.

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Introduction. The first direct detection of gravitational waves (GW) by LIGO has initiated a new era of astronomy [1] and opened the possibility to test the nature of dark matter, specially if its dominant component is primordial black holes (PBH) [2]. These massive black holes could arise in the early universe from the gravitational collapse of matter/radiation on large-amplitude curvature fluctuations generated during inflation [3, 4]. All that is required is a super-slow-roll period (i.e. a plateau feature in the potential) during which the inflaton quantum fluctuations get amplified and produce a peak in the spatial curvature power spectrum [5]. The mass and spin distribution of the subsequently produced PBH then depends on the details of the inflationary dynamics. Its detection and characterization by LIGO, VIRGO and future GW detectors will allow us to open a new window into the physics of the early universe.

The nature of the inflaton field responsible for the initial acceleration of the universe is still unknown. Observations of the temperature and polarization anisotropies in the cosmic microwave background (CMB) suggests a special inflaton dynamics, dominated by a flat plateau on large scales [6]. Such type of potentials arise naturally in models of Higgs Inflation [7], where the scalar field responsible for inflation is the Higgs boson of the Standard Model (SM) of Particle Physics, with its usual couplings to ordinary matter (gauge fields, quarks and leptons), plus a new non-minimal coupling ξ to gravity. This economical scenario not only passes all solar system and CMB observational constraints, but also predicts a small tensor-to-scalar ratio and a large reheating temperature [8].

It has recently been realized [9] that the running of the Higgs self-coupling to large energy scales, via the renormalization group equations (RGE) within the 2σ SM values, could lead to a critical point $\phi_c = \mu$, with $\lambda(\mu) = \beta_\lambda(\mu) = 0$, where $\lambda(\phi)$ has a minimum. This induces an extra feature in the inflationary potential that could lead to a brief plateau of super-slow-roll conditions at scales much smaller than those of the CMB, giving rise to a large peak in the matter power spectrum, and thus to copious production of PBH.

Critical Higgs Inflation, CMB and Particle Physics. In this letter, we explore this critical Higgs scenario, taking into account both the RGE running of the Higgs self-coupling and its non-minimal coupling to gravity [10]. The action of the Higgs-inflaton model is given by

$$S=\int d^4x\sqrt{g}\left[\left(\frac{1}{2\kappa^2}+\frac{\xi(\phi)}{2}\phi^2\right)R-\frac{1}{2}(\partial\phi)^2-\frac{1}{4}\lambda(\phi)\phi^4\right]$$

with the running of the couplings parametrized by

$$\lambda(\phi) \;=\; \lambda_0 + b_\lambda \ln^2(\phi/\mu)\,, \tag{1}$$

$$\xi(\phi) \;=\; \xi_0 + b_\xi \ln(\phi/\mu)\,, \tag{2}$$

around the critical point $\phi = \mu$. Here $\kappa^2 \equiv 8\pi G$.

After a standard metric and scalar field redefinition, the effective inflationary potential becomes

$$V(x) = \frac{V_0\,(1 + a\,\ln^2 x)\,x^4}{(1 + c\,(1 + b\,\ln x)\,x^2)^2}\,, \tag{3}$$

with $V_0 = \lambda_0\mu^4/4$, $a = b_\lambda/\lambda_0$, $b = b_\xi/\xi_0$ and $c = \xi_0\,\kappa^2\mu^2$. The potential has a flat plateau $V(x) \simeq V_0\,a/(b\,c)^2$ at large values of the field $x = \phi/\mu$, see Fig. 1. This region will be responsible for the nice properties of the CMB anisotropies near x_{65}. It also has a short secondary plateau around the critical point, $\phi \simeq \mu$, where the inflaton-Higgs suffers super-slow-roll and induces a large peak in the curvature power spectrum. This second plateau is induced by a near-inflection point at $x = x_c$, where $V'(x_c) \simeq 0$, $V''(x_c) \simeq 0$. As a consequence, the number of e-folds has a sharp jump at that point, ΔN, plus a slow rise towards larger field values, corresponding to CMB scales. This potential and power spectrum is very similar to the one recently discussed in Ref. [5]. Following this reference, we have computed the tensor-to-scalar ratio, the scalar spectral index and its running at those scales, as well as the height of the peak at the critical point as a function of the model parameters.

The choice we have made is to parametrize the model in terms of the height and width of the peak in the power spectrum, see Fig. 1. The heigh of the peak relative to the amplitude at CMB scales (A_s^2) is controlled by the closeness of x_c to a true inflection point, $V'(x_c) = V''(x_c) = 0$. The width is determined by the jump in the number of e-folds, ΔN. There will be a true inflection point at x_c if $a(x_c,\,c) = 4/(1 + c\,x_c^2 + 2\ln x_c - 4\ln^2 x_c)$ and $b(x_c,\,c) = 2(1 + c\,x_c^2 + 4\ln x_c - 4\ln^2 x_c)/(c\,x_c^2(1 + c\,x_c^2 + 2\ln x_c - 4\ln^2 x_c))$. Thus, a near-inflection can be characterized by $a \to a(x_c,\,c)$ and $b \to (1-\beta)\,b(x_c,\,c)$. Then, the relative height of the peak will be proportional to β^{-1} and $\Delta N \propto \beta^{-1/2}$. Fixing β and ΔN, we compute the rest of parameters as a function of just two $(x_c,\,c)$, which we vary satisfying the 2σ CMB constraints.

We have studied the main CMB observables (the scalar spectral index n_s, its running, $\alpha_s = dn_s/d\ln k$, and the tensor-to-scalar ratio r), as a function of $(x_c,\,c)$, for different heights and widths of the power spectrum. We find that, for each β and ΔN, there are many choices of $(x_c,\,c)$ that give rise to valid cosmologies. In order to study the PBH production, we have chosen a reference one, $\beta = 7\times10^{-5}$, $\Delta N = 32$ and $(x_c,\,c) = (0.78, 0.48)$, for which the CMB parameters are $n_s = 0.9566$, $r = 0.028$ and $\alpha_s = -0.00144$, perfectly within the 2σ limits of Planck 2015 [6].

We present in Fig. 2 the results in the $(n_s,\,r)$-plane. The parameter space is consistent with CMB anisotropies, and at the same time induces a large peak in the power spectrum at small scales, that will later give rise to PBH through gravitational collapse upon reentry [3]. The peak can be parametrized by the ratio $\mathcal{P}_\mathcal{R}(x_c)/\mathcal{P}_\mathcal{R}(x_{65})$ of the amplitude of the fluctuations

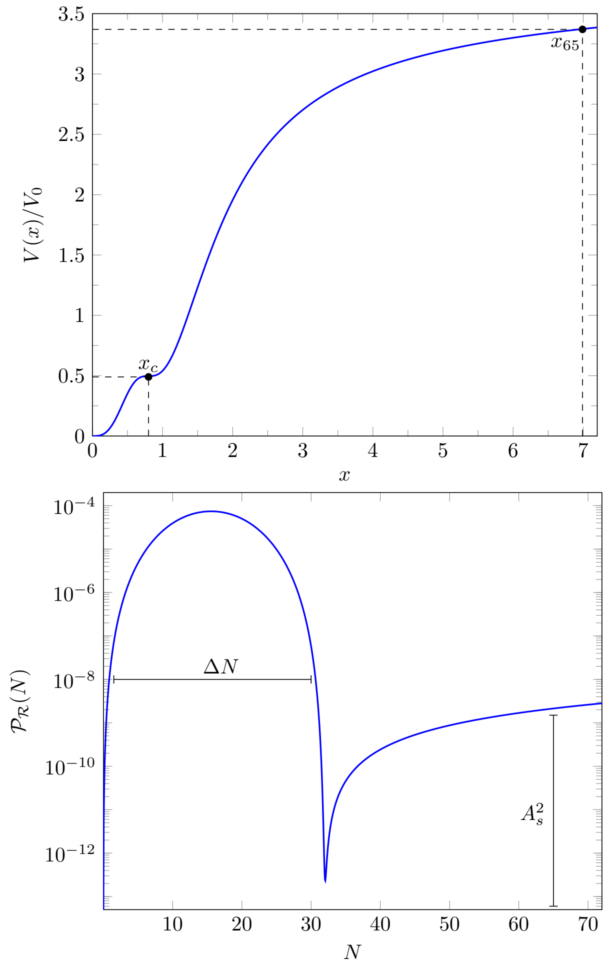

FIG. 1: Top panel: The CHI model potential. Bottom panel: The curvature power spectrum $\mathcal{P}_\mathcal{R}(N)$. The large and broad peak at small scales ($N < \Delta N$) is responsible for PBH production over a wide range of masses.

around the near-inflection point x_c over the one at the inflationary plateau x_{65}, which we find to be greater than 10^4 in the whole range of Fig. 2.

Since in this economical model, the inflaton is the Higgs of the Standard Model, the connection with particle physics is direct, and we can derive the couplings of the model, which will depend on the concrete parameter choice. For instance, we show in color in Fig. 2 the values of the non-minimal coupling ξ at CMB scales. For our reference values, we find that $\lambda_0 = 1.195\times10^{-6}$, $\xi_0 = 21$, $\kappa^2\mu^2 = 0.0226$, $b_\lambda = 0.9\times10^{-5}$ and $b_\xi = 40.6$. These values are consistent, within 2σ, with the measured Higgs parameters at the LHC. Future measurements of the PBH mass spectrum will allow us to determine the SM couplings of the Higgs and their RGE running from the EW scale to almost the Planck scale. A detailed analysis of the compatibility of these coefficients with the predictions of the SM non-minimally coupled to gravity requires further work (in progress).

It is also interesting to note that this CHI scenario

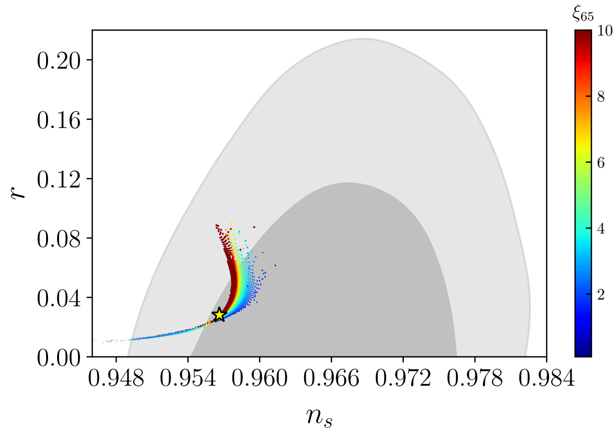

FIG. 2: Predictions in the plane (n_s, r) of CHI with a large peak in the spectrum ($\beta = 7 \times 10^{-5}$ and $\Delta N = 32$). The color bar codes the value of the non-minimal coupling $\xi_{65} = \xi(\phi_{65})$ at CMB scales. The contours represent the 1 and 2σ Planck constraints for models with variable n_s, $dn_s/d\ln k$ and r, obtained from the Planck Legacy Archive. The star corresponds to the reference parameter choice (x_c, c) = (0.78, 0.48).

predicts an amplitude of tensor modes that lies within the target range of present and next-generation B-mode experiments [11]. Moreover, the large amplitude of curvature fluctuations a few e-folds before the end of inflation, see Fig. 1, may induce a significantly inhomogeneous reheating upon reentry, which could have important consequences for the reheating temperature and possibly also for the production of PBH and gravitational waves at preheating, see e.g. [12]. In particular, we find that the energy density at the end of inflation is $\rho_{\rm end} = 2.8 \times 10^{63}$ GeV and the estimated reheating temperature, $T_{\rm rh} = 3 \times 10^{15}$ GeV, is relatively high.

Production of PBHs and DM. We use the Press-Schechter formalism of gravitational collapse to compute the probability that a given horizon-sized volume forms a PBH when a large curvature fluctuation reenters the horizon during the radiation era, and not even radiation pressure can prevent collapse [13]. The mass of the PBH at formation is essentially given by the mass within the horizon at the time of reentry. In our case, for the large, flat and wide peak in $\mathcal{P}_{\mathcal{R}}(k)$ at small scales, see Fig. 1, one finds a lognormal distribution of masses for PBH,

$$P(M) = \frac{A\,\mu}{M\,\sqrt{2\pi\sigma^2}}\,\exp\left(-\frac{\ln^2(M/\mu)}{2\sigma^2}\right)\,.$$

The distribution of PBHs at equality is fully characterized by the physics of inflation, its evolution during radiation domination and the evaporation due to Hawking radiation. We find that for the chosen parameters PBHs constitute the total DM at equality, i.e. $\Omega_{\rm PBH}^{\rm eq} = 0.42$.

From equality to present times, the mass distribution will shift to higher masses due to merging and accretion. In this CHI scenario, there is a very wide and flat peak in the matter spectrum at small scales. This means that PBHs will cluster in very dense environments, which can significantly increase the frequency of black-hole-binary mergers. In order to exactly determine the mass distribution of PBHs today, one would have to solve the non-linear evolution with a N-body simulation. Following Ref. [14], we estimate the growth in PBH masses by a factor 10^7, although it could be significantly larger. In this case, we find that the mean of the lognormal distribution corresponds today to approximately $\mu_{\rm PBH} \simeq 4 \times 10^{-11}\, M_\odot$ and the lognormal dispersion to $\sigma_{\rm PBH} \simeq 1.4$. Therefore, Dark Matter is dominated today by *light* PBH with masses in the range from 10^{-13} to $10^{-9}\, M_\odot$, between the size of large asteroids and small planets like Pluto. This low-mass range of PBH produced in the CHI scenario passes all observational constraints without difficulty, see Fig. 3. The fact that the scenario predicts a very wide mass range helps, since it can achieve $\Omega_{\rm DM} = \Omega_{\rm PBH}$ in an integrated way, without having to saturate the bound at any given mass scale. On the other hand, these *light* PBH are difficult to detect with FermiLAT via femtolensing of gamma ray bursts (GRB) [15]. It is going to be a challenge even with microlensing experiments of distant quasars [16].

Moreover, the PBH mass range is too small to be directly detected with AdvLIGO [1]. The typical amplitude of inspiralling BHB is well below the sensitivity of present and future GW interferometers in the kHz region. However, the unresolved GW emission from BHB merging since equality could induce a significant stochastic background at LISA and PTA scales, depending on the width of the lognormal mass distribution [17]. The actual amplitude depends on the merger rate, τ_m, which can be significantly larger for *light* PBH, see [18],

$$h^2\,\Omega_{\rm GW}(f) = 8 \times 10^{-15}\;\tau_m\, f^{2/3}({\rm Hz})\,\mu^{5/3}(M_\odot)\,R(\sigma)\,,$$

where $R(\sigma)$ is an exponentially growing function of $\sigma_{\rm PBH}$.

Conclusions. In this letter we have explored the possibility that the Standard Model Higgs, with a non-minimal coupling to gravity, may have acted as the inflaton in the early universe, and produced all of the dark matter in the present universe from quantum fluctuations, that reentered the horizon as huge curvature perturbations, which then collapsed to form black holes much before primordial nucleosynthesis. Taking into account the RGE running of both the Higgs self-coupling λ and the non-minimal coupling to gravity ξ, we find regions of parameter space allowed by the Standard Model for which the inflaton-Higgs potential acquires a second plateau at smaller scales, around the critical point $\lambda(\mu) \simeq \beta_\lambda(\mu) = 0$. This plateau gives a super-slow-roll evolution of the Higgs, inducing a high peak in the curvature power spectrum which is almost flat and very broad, lasting for many e-folds. When those fluctuations reenter the horizon during the radiation era they

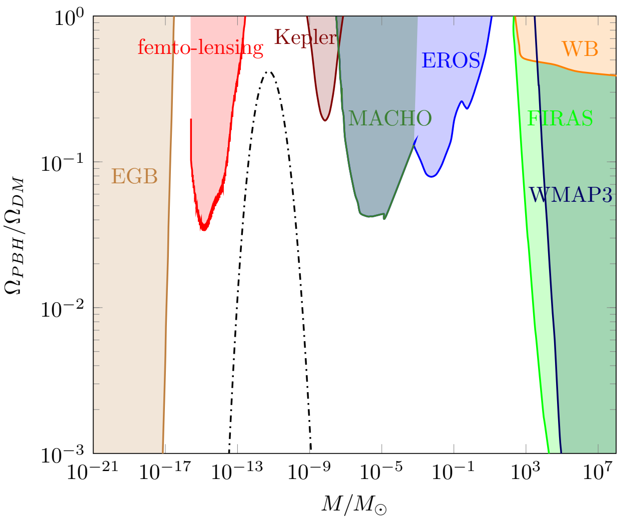

FIG. 3: Present constraints on PBH from Extragalactic Gamma Background (EGB), femto-lensing of GRB, microlensing (Kepler, MACHO and EROS), Wide Binaries (WB) and the CMB (FIRAS and WMAP3). The low-mass primordial black holes (dashed-dotted line) produced in Critical Higgs Inflation could comprise all of the dark matter and still pass all the constraints. See Ref. [19, 20] for a review on the different constraints.

collapse to form primordial black holes with masses in the range 10^{-13} to 10^{-9} $M_\odot$, which evade all the present constraints on PBH [19, 20]. Some of these PBH may evaporate before equality; the rest will act as seeds for galactic structures [4] and initiate reionization at high redshift [21]. Such a high peak in the matter power spectrum occurs at so small scales that there are no significant constraints coming from large scale structures. This scenario of *light* PBH could explain the missing satellite problem, as well as the large mass-to-light ratios found in dwarf spheroidals [4, 22], and has no conflict with Fermi-LAT gamma-ray observations. A possible direct detection could come from microlensing events by Kepler on distant quasars [16]. Alternatively, the stochastic background of gravitational waves from the merging of light black hole binaries in the dense clusters after equality could be detectable by LISA or PTA [17, 18]. Moreover, this CHI scenario also has distinctive features, such as large fluctuations at the end of inflation that may lead to a phase of inhomogeneous reheating.

But, more importantly, the PBH-CHI scenario opens a new portal to test fundamental physics above the LHC scale. The RGE running of the SM Higgs couplings, from the electroweak scale to almost the Planck scale, may contribute to our understanding of the stability of the electroweak vacuum and, moreover, to constrain new physics beyond the Standard Model of Particle Physics.

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[1] B. P. Abbott *et al.*, Phys. Rev. Lett. **116**, 061102 (2016).
[2] S. Bird *et al.*, Phys. Rev. Lett. **116**, 201301 (2016); S. Clesse and J. García-Bellido, Phys. Dark Univ. **10**, 002 (2016); M. Sasaki *et al.*, Phys. Rev. Lett. **117**, 061101 (2016).
[3] J. García-Bellido, A. D. Linde and D. Wands, Phys. Rev. D **54**, 6040 (1996).
[4] S. Clesse and J. García-Bellido, Phys. Rev. D **92**, 023524 (2015).
[5] J. García-Bellido and E. Ruiz Morales, "Primordial black holes from single-field models of inflation," arXiv:1702.03901, to appear in JCAP.
[6] P. A. R. Ade *et al.* [Planck Collaboration], Astron. Astrophys. **594**, A20 (2016)
[7] F. L. Bezrukov and M. Shaposhnikov, Phys. Lett. B **659**, 703 (2008).
[8] J. García-Bellido, D. G. Figueroa and J. Rubio, Phys. Rev. D **79**, 063531 (2009).
[9] F. Bezrukov and M. Shaposhnikov, Phys. Lett. B **734**, 249 (2014).
[10] M. Herranen, T. Markkanen, S. Nurmi and A. Rajantie, Phys. Rev. Lett. **115**, 241301 (2015).
[11] BICEP/Keck Collaboration `http://bicepkeck.org/`; ACT Collaboration `http://act.princeton.edu/`; Simons Array Collaboration `http://simonsobservatory.org/`; LiteBird Collaboration `http://litebird.jp/`.
[12] J. García-Bellido and D. G. Figueroa, Phys. Rev. Lett. **98**, 061302 (2007).
[13] T. Harada, C. M. Yoo and K. Kohri, Phys. Rev. D **88**, 084051 (2013).
[14] J. R. Chisholm, Phys. Rev. D **73**, 083504 (2006).
[15] A. Barnacka, J. F. Glicenstein and R. Moderski, Phys. Rev. D **86**, 043001 (2012).
[16] K. Griest, M. J. Lehner, A. M. Cieplak and B. Jain, Phys. Rev. Lett. **107**, 231101 (2011).
[17] S. Clesse and J. García-Bellido, "Detecting the gravitational wave background from primordial black hole dark matter," arXiv:1610.08479 [astro-ph.CO].
[18] N. Bartolo *et al.*, JCAP **1612**, 026 (2016).
[19] J. García-Bellido, "Massive Primordial Black Holes as Dark Matter and their detection with Gravitational Waves," arXiv:1702.08275, to appear in the Proceedings of the XIth LISA Symposium, Zürich (2016).
[20] B. Carr, F. Kuhnel and M. Sandstad, Phys. Rev. D **94**, 083504 (2016).
[21] A. Kashlinsky, Astrophys. J. **823**, L25 (2016).
[22] T. S. Li *et al.* [DES Collaboration], Astrophys. J. **838**, 8 (2017).