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Unifying inflation with the axion, dark matter, baryogenesis and the seesaw mechanism

Guillermo Ballesteros[1],* Javier Redondo[2,3],† Andreas Ringwald[4],‡ and Carlos Tamarit[5]§
[1] *Institut de Physique Théorique, Université Paris Saclay, CEA, CNRS. 91191 Gif-sur-Yvette, France*
[2] *Departamento de Física Teórica, Universidad de Zaragoza. Pedro Cerbuna 12, E-50009, Zaragoza, Spain*
[3] *Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 München, Germany*
[4] *DESY, Notkestr. 85, 22607 Hamburg, Germany and*
[5] *Institute for Particle Physics Phenomenology, Durham University South Road, DH1 3LE, United Kingdom*

A minimal extension of the Standard Model (SM) providing a complete and consistent picture of particle physics and cosmology up to the Planck scale is presented. We add to the SM three right-handed SM-singlet neutrinos, a new vector-like color triplet fermion and a complex SM singlet scalar σ whose vacuum expectation value at $\sim 10^{11}$ GeV breaks lepton number and a Peccei-Quinn symmetry simultaneously. Primordial inflation is produced by a combination of σ and the SM Higgs. Baryogenesis proceeds via thermal leptogenesis. At low energies, the model reduces to the SM, augmented by seesaw-generated neutrino masses, plus the axion, which solves the strong CP problem and accounts for the dark matter in the Universe. The model can be probed decisively by the next generation of cosmic microwave background and axion dark matter experiments.

INTRODUCTION

The Standard Model of particle physics (SM) describes with exquisite precision the interactions of all known elementary particles. In spite of intensive searches, no significant deviation from the SM has been detected in collider or other particle physics experiments. However, several long-standing problems indicate that new physics beyond the SM is needed to achieve a complete description of Nature. First of all, there is overwhelming evidence, ranging from the cosmic microwave background (CMB) to the shapes of the rotation curves of spiral galaxies, that nearly 26% of the Universe is made of yet unidentified dark matter (DM) [1]. Moreover, the SM cannot generate the primordial inflation needed to solve the horizon and flatness problems of the Universe, as well as to explain the statistically isotropic, Gaussian and nearly scale invariant fluctuations of the CMB [2]. The SM also lacks enough CP violation to explain why the Universe contains a larger fraction of baryonic matter than of antimatter. Aside from these three problems at the interface between particle physics and cosmology, the SM suffers from a variety of intrinsic naturalness issues. In particular, the neutrino masses are disparagingly smaller than any physics scale in the SM and, similarly, the strong CP problem states that the θ-parameter of quantum chromodynamics (QCD) is constrained from measurements of the neutron electric dipole moment to lie below an unexpectedly small value.

In this Letter we show that these problems may be intertwined in a remarkably simple way, with a solution pointing to a unique new physics scale around 10^{11} GeV. The SM extension we consider consists just of the KSVZ axion model [3, 4] and three right-handed (RH) heavy SM-singlet neutrinos [5]. This extra matter content was recently proposed in [6], where it was emphasized that in addition to solving the strong CP problem, providing a good dark matter candidate (the axion), explaining the origin of the small SM neutrino masses (through an induced seesaw mechanism) and the baryon asymmetry of the Universe (via thermal leptogenesis), it could also stabilize the effective potential of the SM at high energies thanks to a threshold mechanism [7, 8]. This extension also leads to successful primordial inflation by using the modulus of the KSVZ SM singlet scalar field [9]. Adding a cosmological constant to account for the present acceleration of the Universe, this Standard Model Axion Seesaw Higgs portal inflation (SMASH) model offers a self-contained description of particle physics from the electroweak scale to the Planck scale and of cosmology from inflation until today.

Although some parts of our SMASH model have been considered separately [9–21], a model incorporating all of them simultaneously had not been proposed until now. This Letter provides the most important aspects and predictions of the model. A comprehensive study of SMASH, will appear in an upcoming publication [22].

THE SMASH MODEL

We extend the SM with a new complex singlet scalar field σ and two Weyl fermions Q and $\tilde{Q}$ in the $\mathbf{3}$ and $\bar{\mathbf{3}}$ representations of $SU(3)_c$ and with charges $-1/3$ and $1/3$ under $U(1)_Y$. With these charges, Q and $\tilde{Q}$ can decay into SM quarks, which ensures that they will not become too abundant in the early Universe. We also add three RH fermions N_i. The model is endowed with a new Peccei-Quinn (PQ) global $U(1)$

symmetry, which also plays the role of lepton number. The charges under this symmetry are: $q(1/2)$, $u(-1/2)$, $d(-1/2)$, $L(1/2)$, $N(-1/2)$, $E(-1/2)$, $Q(-1/2)$ $\tilde{Q}(-1/2)$, $\sigma(1)$; and the rest of the SM fields (e.g. the Higgs) are uncharged. The new Yukawa couplings are: $\mathcal{L} \supset -[F_{ij} L_i \epsilon H N_j + \frac{1}{2} Y_{ij} \sigma N_i N_j + y\, \tilde{Q} \sigma Q + y_{Q_d}{}_i \sigma Q d_i + h.c.]$. The two first terms realise the seesaw mechanism once σ acquires a vacuum expectation value (VEV) $\langle \sigma \rangle = v_\sigma/\sqrt{2}$, giving a neutrino mass matrix of the form $m_\nu = -F Y^{-1} F^T v^2/(\sqrt{2} v_\sigma)$, with $v = 246$ GeV. The strong CP problem is solved as in the standard KSVZ scenario, with the role of the axion decay constant, f_A, played by $v_\sigma = f_A$. Due to non-perturbative QCD effects, the angular part of $\sigma = (\rho + v_\sigma) \exp(iA/f_A)/\sqrt{2}$, the axion field A, gains a potential with an absolute minimum at $A = 0$. At energies above the QCD scale, the axion-gluon coupling is $\mathcal{L} \supset -(\alpha_s/8\pi)(A/f_A) G\tilde{G}$, solving the strong CP problem when $\langle A \rangle$ relaxes to zero. The latest lattice computation of the axion mass gives $m_A = (57.2 \pm 0.7)(10^{11}\text{GeV}/f_A)\, \mu$eV [23].

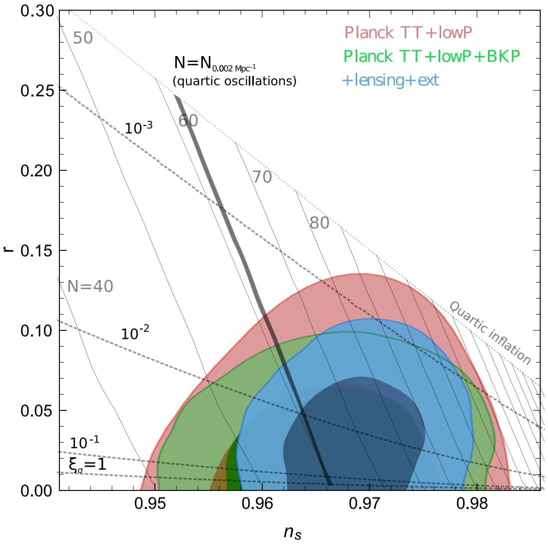

FIG. 1. The tensor-to-scalar ratio, r, vs the scalar spectral index, n_s, at $k = 0.002$ Mpc^{-1} for the SMASH inflationary potential (2), assuming $\lambda_{H\sigma} \ll \lambda_H$. The color coded contours represent current observational constraints at 68% and 95% CL from [1]. The threading of thin continuous lines indicates the number e-folds N from the time the scale $k = 0.002$ Mpc^{-1} exits the horizon to the end of inflation. Lines of constant ξ_σ are shown dotted. The thick black line takes into account the fact that after inflation the Universe enters a radiation era. The line identified as “quartic inflation” shows the prediction of N for a purely quartic monomial potential ($\xi_\sigma \to 0$), which is ruled out by the data.

INFLATION

The scalar sector of the model has the potential

$$V(H,\sigma) = \lambda_H \left(H^\dagger H - \frac{v^2}{2} \right)^2 + \lambda_\sigma \left(|\sigma|^2 - \frac{v_\sigma^2}{2} \right)^2 + 2\lambda_{H\sigma} \left(H^\dagger H - \frac{v^2}{2} \right) \left(|\sigma|^2 - \frac{v_\sigma^2}{2} \right) . \qquad (1)$$

In the unitary gauge, there are two scalar fields that could drive inflation: h, the neutral component of the Higgs doublet $H^t = (0\,, h)/\sqrt{2}$, and the modulus of the new singlet, $\rho = \sqrt{2}|\sigma|$. In the context of the SM, it was proposed in [13] that h could be the inflaton if it is non-minimally coupled to the scalar curvature R through a term $\mathcal{L} \supset -\sqrt{-g}\, \xi_H\, H^\dagger H\, R$ [24], with $\xi_H \sim 10^4$. Such a large value of ξ_H is required by the constraint $\xi_H \sim 10^5 \sqrt{\lambda_H}$ to fit the amplitude of primordial fluctuations and it implies that perturbative unitarity breaks down at the scale $\Lambda_U = M_P/\sqrt{\xi_H} \ll M_P$ [25, 26], where $M_P = 1/\sqrt{8\pi\, G}$ is the reduced Planck mass. This raises a serious difficulty for Higgs inflation, which requires Planckian values of h and an energy density of order Λ_U^2. Since new physics is expected at or below Λ_U to restore unitarity, the predictivity of Higgs inflation is lost, because the effect of this new physics on inflation is undetermined. This issue affects some completions of the SM such as the νMSM [27, 28] and the model proposed in [18]. Instead, inflation in SMASH is mostly driven by ρ, with a non-minimal coupling $2 \times 10^{-3} \lesssim \xi_\sigma \lesssim 1$. The upper bound on ξ_σ ensures that the scale of perturbative unitarity breaking is at M_P (provided that also $\xi_H \lesssim 1$), whereas the lower bound on ξ_σ corresponds to a tensor-to-scalar ratio $r \lesssim 0.07$ (as constrained by the Planck satellite and the BICEP/Keck array [1, 29]). Neglecting ξ_H, predictive slow-roll inflation in SMASH in the Einstein frame can be described by a single canonically normalized field χ with potential

$$\tilde{V}(\chi) = \frac{\lambda}{4} \rho(\chi)^4 \left(1 + \xi_\sigma \frac{\rho(\chi)^2}{M_P^2} \right)^{-2} , \qquad (2)$$

where λ can be either λ_σ or $\tilde{\lambda}_\sigma = \lambda_\sigma - \lambda_{H\sigma}^2/\lambda_H$, with the second case being possible only if $\lambda_{H\sigma} < 0$, corresponding to an inflationary valley in a mixed direction in the plane (ρ, h). The field χ is the solution of $\Omega^2\, d\chi/d\rho \simeq (b\, \Omega^2 + 6\, \xi_\sigma^2\, \rho^2/M_P^2)^{1/2}$, where $\Omega \simeq 1 + \xi_\sigma\, \rho^2/M_P^2$ is the Weyl transformation into the Einstein frame and $b = 1$ for $\lambda = \lambda_\sigma$ or $b = 1 + |\lambda_{H\sigma}/\lambda_H| \sim 1$ for $\lambda = \tilde{\lambda}_\sigma$. The value of b determines the angle in field space described by the inflationary trajectory: $h^2/\rho^2 \simeq b - 1$. The predictions in the case $\lambda = \lambda_\sigma$ (or $b \to 1$) for r vs the scalar spectral index n_s are shown in FIG. 1 for various values of ξ_σ. The running of n_s is in the ballpark of 10^{-4}–10^{-3}, which may be probed e.g. by future observations of the 21 cm emission line of Hydrogen [30]. These values of the primordial parameters are perfectly compatible with the latest CMB data, and the amount of inflation that is produced solves the horizon and flatness problems. Given the current bounds on r and n_s, fully consistent (and predictive) inflation in SMASH occurs if $10^{-13} \lesssim \lambda \lesssim 10^{-9}$.

STABILITY

For the measured central values of the Higgs and top quark masses, the Higgs quartic coupling of the SM becomes negative at $h = \Lambda_I \sim 10^{11}$ GeV [31]. If no new physics changes this behaviour, Higgs inflation is not viable, since it requires a positive potential at Planckian field values. Moreover, the instability of the effective potential is also a problem even if another field drives inflation. This is because scalars that are light (in comparison to the Hubble scale, $\mathcal{H}$) acquire fluctuations of order $\sim N\,\mathcal{H}/2\pi$, where N is the number of e-folds before the end of inflation. They would make the Higgs tunnel into the instability region of the potential, contradicting the present electroweak vacuum [32]. Remarkably, the the Higgs portal term $\propto \lambda_{H\sigma}$ in (1) allows absolute stability (even when the corresponding low-energy SM potential would be negative if extrapolated to large h) via the threshold-stabilisation mechanism of [7, 8, 22]. In SMASH, instabilities could also originate in the ρ direction due to quantum corrections from the RH neutrinos and KSVZ fermions. For $\lambda_{H\sigma} > 0$, absolute stability requires

$$\begin{cases} \tilde{\lambda}_H, \tilde{\lambda}_\sigma > 0, & \text{for} \quad h < \sqrt{2}\Lambda_h \\ \lambda_H, \lambda_\sigma > 0, & \text{for} \quad h > \sqrt{2}\Lambda_h \end{cases}, \tag{3}$$

where we define $\Lambda_h^2 = \lambda_{H\sigma} v_\sigma^2/\lambda_H$, $\tilde{\lambda}_H = \lambda_H - \lambda_{H\sigma}^2/\lambda_\sigma$ and $\tilde{\lambda}_\sigma = \lambda_\sigma - \lambda_{H\sigma}^2/\lambda_H$. Instead, for $\lambda_{H\sigma} < 0$, the stability condition is $\tilde{\lambda}_H, \tilde{\lambda}_\sigma > 0$, for all h [33].

An analysis based on two-loop renormalization group (RG) equations for the SMASH couplings and one-loop matching with the SM [22] shows that stability can be achieved for $\delta \equiv \lambda_{H\sigma}^2/\lambda_\sigma$ between 10^{-3} and 10^{-1}, depending on m_t, see FIG. 2. The Yukawas must satisfy the bound $6y^4 + \sum Y_{ii}^4 \lesssim 16\pi^2\lambda_\sigma/\log\left(30M_P/\sqrt{2\lambda_\sigma}v_\sigma\right)$. It will prove convenient to define SMASH benchmark units:

$$\lambda_{10} = \frac{\lambda_\sigma}{10^{-10}} \quad ; \quad \delta_3 = \frac{\delta}{0.03} \quad ; \quad v_{11} = \frac{v_\sigma}{10^{11}\,\mathrm{GeV}}. \tag{4}$$

REHEATING

Understanding the properties of reheating in SMASH is essential to determine whether the PQ symmetry is restored after inflation and whether efficient baryogenesis occurs. Slow-roll inflation ends at a value of $\rho \sim \mathcal{O}(M_P)$, where the effect of ξ_σ is negligible and the inflaton starts to undergo Hubble-damped oscillations in a quartic potential, with the Universe expanding as in a radiation-dominated era, which lasts until reheating. After the latter, radiation domination continues, though driven by a bath of relativistic particles. This fixes the thick black line of FIG. 1 as the prediction for r, n_s and N in SMASH, see e.g. [34]. The line spans values of N (as a function of n_s) in the interval $\sim (60, 62)$ and its width (~ 0.8 e-folds) measures the uncertainty on the transient regime from the end of inflation to radiation domination.

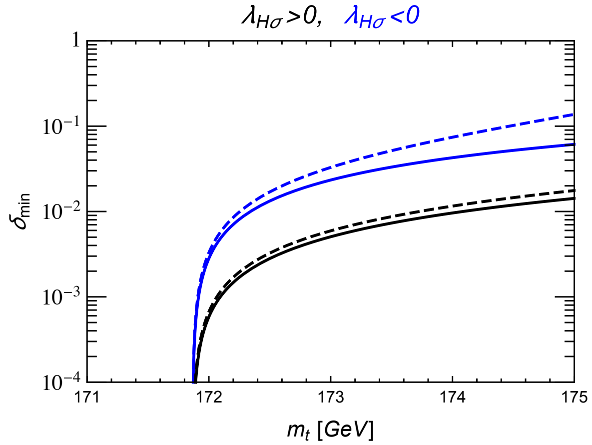

FIG. 2. Minimum value of the threshold correction to the Higgs quartic coupling, $\delta = \lambda_{H\sigma}^2/\lambda_\sigma$, for stable SMASH potentials at RG scales $\mu = m_\rho$ (solid) and $\mu = 30M_P$ (dashed), for $\lambda_{H\sigma} > 0$ (black) and $\lambda_{H\sigma} < 0$ (blue).

We recall that for $\lambda_{H\sigma} < 0$ the inflaton has a Higgs component, whereas for $\lambda_{H\sigma} > 0$ the inflaton is just ρ, the modulus of σ. In any case, during the first ~ 14 oscillations, the fluctuations of σ grow very fast by parametric resonance until the PQ symmetry is restored non-thermally as in [35]. Only if v_σ were larger than $\sim 10^{-2}M_P$ there would not be enough time for the fluctuations of σ to grow and the PQ symmetry would not be restored by nonthermal effects, but such high values of v_σ are ruled out by CMB axion isocurvature constraints [9].

Parametric resonant production of Higgs fluctuations (particles) produced during inflaton crossings ($\tilde{V}(\rho) = 0$) is quenched by the large value of the Higgs self-coupling [36] (and their fast enough decay into $t\bar{t}$ and gauge bosons for $\lambda_{H\sigma} > 0$). Gauge bosons are produced in the same way if the inflaton has a Higgs component, i.e. if $\lambda_{H\sigma} < 0$. In this case, resonant production is prevented by fast decays into light quarks and leptons, but the mass of the gauge bosons does not stop oscillating at the onset of the non-thermal PQ restoration (in contrast to the Higgs mass in purely σ-inflation, $\lambda_{H\sigma} > 0$) and the accumulated particle production can dominate reheating, as we explain below. RH neutrinos and $Q, \tilde{Q}$ are also produced during this preheating stage but their occupation numbers stay low.

For $\lambda_{H\sigma} > 0$, reheating takes place when the inflaton fluctuations decay after the spontaneous PQ symmetry breaking at $\langle\rho\rangle \sim v_\sigma$. The corresponding temperature can be estimated as $T_R \sim 10^7\,\mathrm{GeV}\,v_{11}\lambda_{10}^{3/8}\delta_3^{-1/8}$. However, for the benchmark values (4) of SMASH there is typically an excessive amount of dark radiation stored in relativistic axions. They are copiously produced during reheating and remain decoupled in the case of such a low reheating temperature [37], leading to a significant increase $\Delta N_\nu^{\rm eff} \sim 0.96\,(\delta_3 v_{11}/\lambda_{10})^{-1/6}$ of the effective number of relativistic neutrino species beyond the SM value $N_\nu^{\rm eff}(\mathrm{SM}) = 3.046$ [38]. This is strongly constrained ($N_\nu^{\rm eff} = 3.04 \pm 0.18$ at 68% CL) by CMB and baryon acoustic oscillation data [1].

This problem does not arise for $\lambda_{H\sigma} < 0$. As anticipated before, in this case the background can produce fast-decaying weak gauge bosons, leading to a steady growth of the density of their decay products. When these light particles thermalise, they can produce additional gauge bosons. These gain energy from the background as their mass increases, and transfer it to the light particles when decaying. Using Boltzmann equations with thermal and non-thermal sources, and accounting for the energy loss of the background, we can estimate the reheating temperature by finding the time at which the energy densities of the inflaton and the thermal bath are equal. The reheating temperature turns out to be $\sim 10^{10}$ GeV for $\delta \sim 0.05$ (see FIG. 2) and $\tilde{\lambda}_\sigma \sim 10^{-10}$ (which satisfy the requirements for stability and inflation). Such temperature ensures a thermal restoration of the PQ symmetry for the relevant region of parameter space, since the critical temperature T_c of the PQ phase transition goes as $T_c/v_\sigma \simeq 2\sqrt{6\lambda_\sigma}/\sqrt{8(\lambda_\sigma + \lambda_{H\sigma}) + \sum_i Y_{ii}^2 + 6y^2}$. As we mentioned above, in this case there is no dark radiation problem; the corresponding increase in the effective number of relativistic neutrino species is just $\triangle N_\nu^{\rm eff} \simeq 0.03$, assuming $g_*(T_A^{\rm dec}) = 427/4$ relativistic degrees of freedom at thermal axion decoupling, $T_A^{\rm dec} \simeq 2 \times 10^9$ $\mathrm{GeV}\,v_{11}^{2.246}$ [37, 39, 40]. This small value of $\Delta N_{\rm eff}$ could be probed with future CMB polarization experiments [41, 42].

DARK MATTER

For $\lambda_{H\sigma} > 0$, the PQ symmetry is restored non-thermally after inflation and then spontaneously broken again before reheating. On the other hand, for $\lambda_{H\sigma} < 0$ and efficient reheating, the restoration and breaking are thermal. In the phase transition, which happens at a critical temperature $T_c \gtrsim \lambda_\sigma^{1/4} v_\sigma$, a network of cosmic strings is formed. Its evolution leads to a low-momentum population of axions that together with those arising from the realignment mechanism [43–45] constitute the dark matter in SMASH. Requiring that all the DM is made of axions restricts the symmetry breaking scale to the range

$$3 \times 10^{10}\,\mathrm{GeV} \lesssim v_\sigma \lesssim 1.2 \times 10^{11}\,\mathrm{GeV}, \tag{5}$$

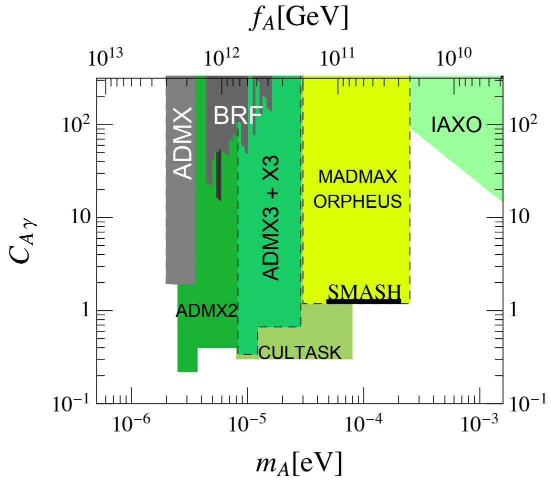

FIG. 3. SMASH predictions for the axion-photon coupling (thick solid horizontal line) with current bounds on axion DM (ADMX,BRF) and prospects for next generation axion dark matter experiments, such as ADMX2(3) [54], CULTASK [50], MADMAX [51], ORPHEUS [52], X3 [55], and the helioscope IAXO [56].

which translates into the mass window

$$50\,\mu\mathrm{eV} \lesssim m_A \lesssim 200\,\mu\mathrm{eV}, \tag{6}$$

updating the results of [46] with the latest axion mass data [23]. The main uncertainty now arises from the string contribution [46, 47], which is expected to be diminished in the near future [48, 49]. Importantly, the SMASH axion mass window (6) will be probed in the upcoming decade by axion dark matter direct detection experiments such as CULTASK [50], MADMAX [51], and ORPHEUS [52], see also [23, 53] and FIG. 3 for our estimates of their future sensitivity.

BARYOGENESIS

The origin of the baryon asymmetry of the Universe is explained in SMASH from thermal leptogenesis [57]. This requires massive RH neutrinos acquiring equilibrium abundances and then decaying when production rates become Boltzmann suppressed. If $\lambda_{H\sigma} < 0$, then $T_R > T_c$ for stable models in the DM window (5). The RH neutrinos become massive after the PQ phase transition, and those with masses $M_i < T_c$ retain an equilibrium abundance. The stability bound on the Yukawas Y_{ii} enforces $T_c > M_1$, so that at least the lightest RH neutrino stays in equilibrium. Moreover, the annihilations of the RH neutrinos tend to be suppressed with respect to their decays. This allows for vanilla leptogenesis from the decays of a single RH neutrino, which demands $M_1 \gtrsim 5 \times 10^8$ GeV [58, 59]. However, for v_σ as in (5), this is just borderline compatible with stability. Nevertheless, leptogenesis can occur with a mild resonant enhancement [60] for a less hierarchical RH neutrino spectrum, which relaxes the stability bound and ensures that all the RH neutrinos remain in equilibrium after the phase transitions.

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[*] guillermo.ballesteros@cea.fr
[†] jredondo@unizar.es
[‡] andreas.ringwald@desy.de
[§] carlos.tamarit@durham.ac.uk

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