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A common origin for baryons and dark matter

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The origin of the baryon asymmetry of the Universe (BAU) and the nature of dark matter are two of the most challenging problems in cosmology. We propose a scenario in which the gravitational collapse of large inhomogeneities at the quark-hadron epoch generates both the baryon asymmetry and dark matter in the form of primordial black holes (PBHs). This is due to the sudden drop in radiation pressure during the transition from a quark-gluon plasma to non-relativistic hadrons. The collapse to a PBH is induced by fluctuations of a light spectator scalar field in rare regions and is accompanied by the violent expulsion of surrounding material, which might be regarded as a sort of “primordial supernova”. The acceleration of protons to relativistic speeds provides the ingredients for efficient baryogenesis around the collapsing regions and its subsequent propagation to the rest of the Universe. This scenario naturally explains why the observed BAU is of order the PBH collapse fraction and why the baryons and dark matter have comparable densities. The predicted PBH mass distribution ranges from sub-solar to several hundred solar masses. This is compatible with current observational constraints and could explain the rate, mass and low spin of the black hole mergers detected by LIGO-Virgo. Future observations will soon be able to test this scenario.

Keywords: baryon asymmetry, dark matter, primordial black holes, quark-hadron transition

Introduction. The first LIGO-Virgo detection [1] of gravitational waves from the coalescence of two very massive black holes has triggered renewed interest in primordial black holes (PBHs) as dark matter (DM) [2]. Their abundance and mass distribution has intrigued both cosmologists and particle physicists [3]. If the PBHs were generated in the early radiation-dominated Universe from the gravitational collapse of large curvature fluctuations, then they would have formed shortly after falling within the Hubble horizon with a mass

$$M_{\text{PBH}} \simeq 0.5 \gamma g_*(T)^{-1/2} (T/\text{GeV})^{-2} M \quad . \quad (1)$$

Here γ is the fraction of the Hubble horizon mass ending up in the black hole (with $\gamma \lesssim 1$ in general and $\gamma \approx 0.2$ in a simplified analysis [4]), T is the temperature of the background Universe and $g_*(T)$ is the number of degrees of freedom then. M_{PBH} is of order the Chandrasekhar mass, $M_{\text{Ch}} \approx 1.4 M_\odot$, for PBHs forming at the Quantum Chromodynamics (QCD) scale, $\Lambda_{\text{QCD}} \approx 200$ MeV. At this temperature, quarks and gluons form baryons (protons and neutrons) and mesons (pions) and the number of relativistic degrees of freedom drops abruptly. Also the sound speed dips, exponentially enhancing the collapse probability for any large curvature fluctuation that enter the horizon then [5]. The fraction of domains undergoing collapse is necessarily tiny, even if the PBHs provide all the DM. However, because they are non-relativistic, their density dilutes more slowly than the surrounding radiation until they dominate the expansion of the Universe at matter-radiation equality.

The sudden gravitational collapse of the mass within the Hubble horizon at the QCD epoch releases a large amount of entropy and generates a relativistically expanding shock-wave, with an effective temperature well above that of the surrounding plasma. Such high density *hot spots* might be regarded as *primordial supernovae* and provide the out-of-equilibrium conditions required to generate a baryon asymmetry through the well-known electroweak sphaleron transitions responsible for Higgs windings around the electroweak (EW) vacuum [6]. In this process, the charge-parity (CP) symmetry violation of the standard model of particle physics suffices to generate a local baryon-to-photon ratio of order one or larger. The hot spots are separated by many horizon scales (thousands of kilometers) at the time of formation, while there is initially no matter-antimatter asymmetry in the rest of the Universe. However, since the baryons are relativistic at formation, they propagate away from the hot spots at the speed of light and become homogeneously distributed well before big bang nucleosynthesis. The large initial local baryon asymmetry is thus diluted to the tiny observed global BAU.

The ratio of the energy densities of matter and radiation (relativistic species) at any time is

$$\frac{\Omega_{\text{M}}}{\Omega_{\text{R}}} = \frac{\Omega_{\text{B}} + \Omega_{\text{DM}}}{\Omega_{\text{R}}} \simeq \frac{1700}{g_*(z)} \frac{1 + \chi}{1 + z} \quad , \quad (2)$$

where $\chi \equiv \Omega_{\text{DM}}/\Omega_{\text{B}} \approx 5$ is the ratio of the DM and baryonic densities. At PBH formation, the fraction of

domains that collapse is

$$\beta = \frac{\Omega_{\text{PBH}}}{\Omega_{\text{R}}} = f_{\text{PBH}} \frac{\chi \Omega_{\text{B}}}{\Omega_{\text{R}}} \simeq f_{\text{PBH}} \frac{\chi \eta}{g_*(T)} \frac{0.7 \text{ GeV}}{T}, \quad (3)$$

where $f_{\text{PBH}} \equiv \Omega_{\text{PBH}}/\Omega_{\text{DM}}$ is the fraction of the DM in PBHs and $\eta = n_{\text{B}}/n_{\gamma} = 6 \times 10^{-10}$ is the observed BAU. Therefore, for PBH formation at the QCD epoch, we have $\beta \sim \eta \sim 10^{-9}$ if PBHs constitute *all* the DM. This relationship suggests that baryogenesis is somehow linked with PBH formation and that the smallness of the BAU reflects the rarity of the Hubble domains that collapse. Here we present a brief outline of a scenario with these features and derive the expected PBH mass distribution. A more detailed description of our proposal - including the mechanism for generating curvature fluctuations via a spectator field and the various fine-tunings involved - can be found in a companion paper [7].

The quark-hadron transition. In order for PBHs to form at the QCD epoch one needs large curvature fluctuations to enter the horizon at the right time for relativistic particles to undergo gravitational collapse. One might fine-tune the inflationary dynamics (e.g. using the late plateau arising in critical Higgs inflation [8]) to produce a peak in the power spectrum of curvature fluctuations at the solar-mass scale with an amplitude several orders of magnitude larger than at the CMB scale [9]. Large non-Gaussianity might further enhance the probability of gravitational collapse [12]. However, such a fine-tuned peak is not required in our scenario because the sound speed drops abruptly by 30% during the QCD transition due to the creation of non-relativistic protons and neutrons from quarks and gluons [10]. This means that the radiation pressure, which usually prevents the collapse of mild inhomogeneities, suddenly drops, lowering the critical curvature ζ_c needed for PBH formation. Since the probability of collapse is exponentially sensitive to ζ_c [4], they can form more easily. We need just a billionth of the domains to collapse to PBHs to explain all the DM. As explained later, this condition could be met in our Universe without enhancing the power spectrum of curvature fluctuations or any other parameter fine-tuning.

Electroweak baryogenesis at the QCD epoch. The gravitational collapse at the QCD epoch of an horizon-sized ball of radiation into a solar-mass black hole would be an extremely violent process, with particles acquiring energies a thousand times their rest mass from the gravitational potential energy released by the collapse. As shown by simulations of PBH formation in spherical symmetry by Musco et al. [11], energy and momentum conservation imply that particles which do not fall into the black hole are driven out as a shock-wave towards the surrounding plasma. This is similar to the shock-wave that ejects the outer layers of a star when it explodes as a supernova, except that the surrounding plasma is much denser in the early Universe context, allowing higher energy interactions. In particular, the effective temperature

of the “hot spot” is above that of EW sphaleron transitions, inducing local windings of the Higgs field around the EW vacuum. Through the chiral anomaly, such topological configurations are equivalent to the creation of baryon number [13]. Since the surrounding plasma (initially beyond the Hubble domain that collapsed to form a PBH) is much cooler, and the far-from-equilibrium conditions ensure that further sphaleron transitions cannot wash out the local baryon asymmetry.

This means that all of the Sakharov conditions [14] for producing the matter-antimatter asymmetry are met. However, the asymmetry generated can be much larger than in the usual cosmological scenario. This is because the effective CP violation in the standard model (SM) is strongly temperature-dependent ($\delta_{\text{CP}} \propto T^{-12}$), and the amount coming from the CKM matrix [15] is enough for the local baryon-to-photon ratio to exceed one. Subsequently the impulse of the shock-wave will drive baryons from the hot spot around each PBH to the rest of the Universe, thereby diluting the global baryon-to-photon ratio to the observed value, $\eta \sim 10^{-9}$.

Let us estimate the energy available for the process of hot spot electroweak baryogenesis (HSEWB). Energy conservation implies that the change in kinetic energy due to the collapse of matter within the Hubble radius, d_H , down to the Schwarzschild radius of the PBH, $R_S = 2GM_{\text{PBH}}/c^2 = \gamma d_H$, is

$$\Delta K \simeq \left(\frac{1}{\gamma} - 1 \right) M_{\text{H}} = \left(\frac{1 - \gamma}{\gamma^2} \right) M_{\text{PBH}}. \quad (4)$$

Note that the smaller the value of γ , the more compact the resulting PBH and the larger the kinetic energy of ejected particles. To estimate the energy acquired per proton E_0 in the expanding shell, we note that the number density of protons between the QCD transition and proton freeze-out ($20 \text{ MeV} < T < 200 \text{ MeV}$) is that of a non-relativistic species,

$$n_{\text{p}}(x) = 1.59 \times 10^{40} x^{-3/2} e^{-x} \text{ cm}^{-3}, \quad (5)$$

with $x \equiv m_{\text{p}}/T$. Therefore

$$E_0 = \frac{\Delta K}{n_{\text{p}} \Delta V} \simeq 100 g_*(x) x^{-5/2} e^x \text{ GeV}, \quad (6)$$

where $\Delta V \equiv V_{\text{H}} - V_{\text{PBH}}$ is the difference between the Hubble and PBH volumes. We have used $\gamma = 0.2$ as a conservative estimate but note that E_0 scales as $(\gamma + \gamma^2 + \gamma^3)^{-1}$. At the same time, the density of the relativistic plasma surrounding the collapse horizon is huge, $n_{\text{gas}}(x) = 1.64 \times 10^{41} x^{-3} \text{ cm}^{-3}$, so it behaves like a wall for the escaping relativistic protons.

For a PBH formed at $T \approx 140 \text{ MeV}$, the energy released and thus effective temperature is given by

$$\Delta K = \frac{3}{2} N_{\text{p}} k_{\text{B}} T_{\text{eff}} \Rightarrow k_{\text{B}} T_{\text{eff}} = \frac{2}{3} E_0 \simeq 5 \text{ TeV}, \quad (7)$$

which is well above the sphaleron barrier and thus the sphaleron transition rate per unit volume at this temperature is $\Gamma_{\text{sph}} \sim \alpha_W^4 T_{\text{eff}}^4$ [13]. The ultra-relativistic partons (here mainly protons) produce jets that heat up the surrounding plasma and induce a baryon asymmetry [6]

$$\eta \simeq \frac{7n_B}{s} \simeq \frac{7n_{\text{par}}}{s} \times \Gamma_{\text{sph}}(T_{\text{eff}}) V_H \Delta t \times \delta_{\text{CP}}, \quad (8)$$

where n_{par} is the number density of the partons (here protons and antiprotons), $\Delta t \sim 2 \times 10^{-5} \text{ s}$ ($200 \text{ MeV}/T$)² is the duration of the sphaleron process and the standard model CP violation parameter is [13]

$$\delta_{\text{CP}}(T) = 3 \times 10^{-5} (20.4 \text{ GeV}/T)^{12}. \quad (9)$$

The entropy density in the thermalized plasma surrounding each PBH is $s = (2\pi^2/45) g_{*S} T_{\text{th}}^3$ at temperatures $T_{\text{th}} \ll T_{\text{eff}}$; this quenches the sphaleron transitions and prevents baryon washout. The production of baryons is thus very efficient for $x \gtrsim 5$, giving $n_B \gtrsim n_\gamma$ or $\eta \gtrsim 1$ locally. Note, however, that one cannot produce significantly more baryons than photons since they are soon brought into equilibrium with the rest of the plasma via standard model interactions. The dynamical process is actually rather complicated [16] and will require further investigation.

This maximal BAU is then diluted as the protons propagate from the hot spots to the rest of the Universe. If the PBHs provide all the dark matter ($f_{\text{PBH}} = 1$), one requires $\beta \sim 10^{-9}$, and the distance between hot spots is then $d \sim \beta^{-1/3} d_H(t_{\text{QCD}}) \sim 3000 \text{ km}$, or 0.01 light-seconds. Moving at the speed of light, protons uniformly distribute the original baryon asymmetry to the rest of the Universe well before primordial nucleosynthesis ($t_{\text{BBN}} \sim 1 - 180 \text{ s}$), thus diluting the initial baryon asymmetry and explaining the relation $\eta \sim \beta$.

The DM-to-baryon ratio, $\chi \sim 5$, can also be explained in this scenario: most of PBHs are formed during or after the sudden drop of the sound-speed during the QCD transition, when the parton energies are high enough to produce a strong baryon asymmetry. χ is thus given by the ratio of the black hole mass and the ejected mass, which is $\chi \approx \gamma/(1 - \gamma) \approx 5$ if $\gamma \approx 0.8$. Lower values of γ could nevertheless be accommodated if the temperature below which protons acquire enough energy to drive the baryon-producing sphaleron transitions is reduced, $T \lesssim 100 \text{ MeV}$, so that only the massive PBHs formed at later time contribute to the BAU. The scenario is represented qualitatively in Fig. 1.

The origin of the large curvature fluctuations. The softening of the equation of state during the quark-hadron transition boosts the formation of stellar-mass PBHs but does not alleviate the need for large curvature fluctuations. We propose that before or during the QCD epoch, a light stochastic spectator field [17] induces in rare regions an extra curvature fluctuation, above the

threshold required for PBH formation. The spectator field is a curvaton; its quantum fluctuations during inflation permeate all space but its energy density is subdominant during both inflation and the period after reheating. This field remains frozen during the radiation era ($m \ll H$) until its potential energy density (at the top of its potential) starts to dominate the total density of the Universe. At this point, the spectator field in the still super-horizon regions triggers a second brief period of inflation, generating local non-linear curvature fluctuations which later reenter the horizon and collapse to form PBHs. In the rest of the Universe, the field rolls quickly towards the bottom of the potential and its fluctuations do not significantly impact the expansion. This means that the curvature fluctuations remain Gaussian, at the same level as those observed in the CMB, unaffected by the dynamics of the spectator field, and do not form PBHs. There are no isocurvature modes on cosmological scales, because the quantum fluctuations of both the inflaton and spectator fields scale with the Hubble rate during inflation, thereby correlating the large-scale curvature fluctuations with the PBH and baryon fluctuations.

A natural candidate for the light spectator field is the QCD axion. Its existence is well-motivated, providing a robust solution to the strong CP problem. We assume that the associated Peccei-Quinn symmetry is spontaneously broken before inflation. The axion potential at temperatures below a few GeV is

$$V(a) = m_a^{\text{eff}}(T)^2 f_a^2 [1 + \cos(a/f_a)], \quad (10)$$

where $m_a^{\text{eff}}(T) = m_a (T/T_c)^{-7/2}$ for $T \gtrsim T_c \sim 100 \text{ MeV}$ but is constant and equal to the zero-temperature mass m_a otherwise [18]. For the QCD axion there is a relation between mass and decay constant, $m_a f_a \simeq (75 \text{ MeV})^2$. Therefore, the axion will dominate the energy density of the Universe at temperatures below

$$T \approx (60 m_a^2 f_a^2 / \pi^2 g_*)^{1/4} \approx 80 \text{ MeV}, \quad (11)$$

but it already starts rolling down the hill from the rms value generated during inflation, $a_{\text{ini}} \ll f_a$, at $T \sim \text{GeV}$.

In most regions, this only marginally impacts the expansion rate, but in a few rare patches where the field lies exactly in the slow-roll region, it produces a short period of inflation until slow-roll ends at $a_{\text{end}} \simeq 8\sqrt{\pi} f_a^2 / M_{\text{P}}$ where M_{P} is the Planck mass. The second inflationary period can last slightly more than one e-fold, which produces $\mathcal{O}(1)$ curvature fluctuations, according to the stochastic δN formalism [19]. The probability of collapse depends on the mean value of the axion (curvaton) field in our Hubble patch but it can be around 10^{-9} , as required, if $f_a \gtrsim 10^{17} \text{ GeV}$.

The PBH mass distribution. This is shown in Fig. 2 and is a concrete prediction of our scenario. In the general curvaton case, shown by the lower curves for $\gamma = 0.2$

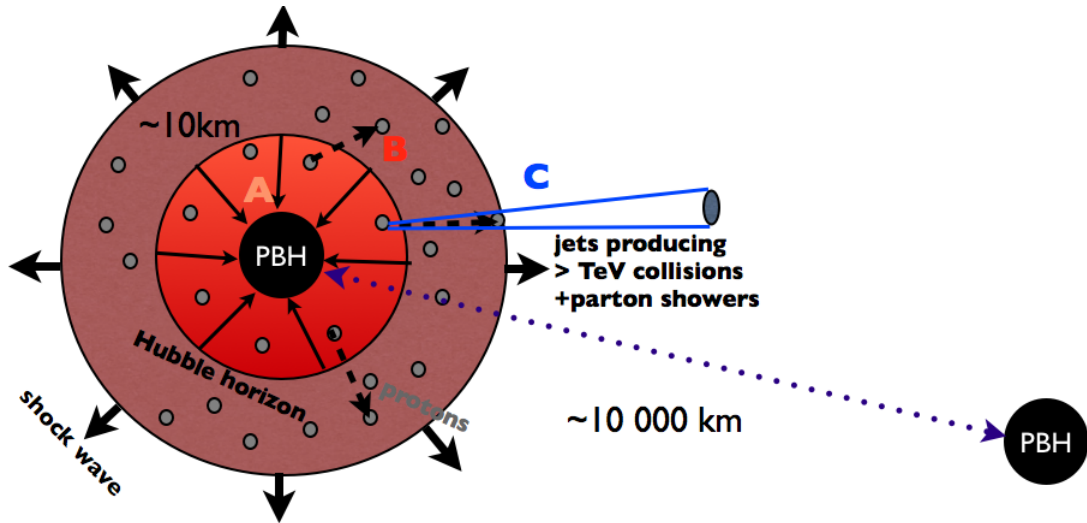


FIG. 1: Qualitative representation of the three steps in our scenario. (A) Gravitational collapse to a PBH of the curvature fluctuation at horizon re-entry. (B) Sphaleron transition in hot spot around the PBH, producing $\eta \gtrsim \mathcal{O}(1)$ locally through EW baryogenesis. (C) Propagation of baryons to rest of Universe through jets, resulting in the observed BAU with $\eta \sim 10^{-9}$.

(solid lines) and $\gamma = 0.8$ (dotted lines), the largest density is associated with the horizon mass when protons become non-relativistic at $T \sim \Lambda_{\text{QCD}}$ and we have seen that this is of order the Chandrasekhar mass ($1.4 M_{\odot}$). Then there is a small plateau associated with the temperature $T \sim m_{\pi}$ at which pions become non-relativistic. This also slightly changes the sound-speed and corresponds to $M \sim 30 M_{\odot}$, which may explain why LIGO-Virgo find so many black holes with that mass. At later times, the relativistic degrees of freedom again dominate the expansion of the Universe, so the PBH mass distribution declines quickly at larger masses, evading all the present constraints.

If the spectator field is the QCD axion, since its mass turns on abruptly, the PBH production is strongly suppressed at temperatures above T_c . Therefore the PBH mass distribution is naturally cut-off on sub-solar masses, as shown by the top curves in Fig. 2. This could explain the observed lack of subsolar microlenses, whose significance is still debated [20]. In both cases, the majority of PBHs are in the $0.1 - 10 M_{\odot}$ range and no more than a few percent of the DM density is made of heavier PBHs. Such a distribution passes the various constraints on the abundance of massive PBHs [21]. The second peak in the distribution might explain the mass, rates and low spins of the black hole mergers detected so far by LIGO-Virgo. This is very different than the distribution expected for stellar black holes, which should exhibit a gap in the range $2 - 5 M_{\odot}$ and be suppressed above $80 M_{\odot}$ [22]. It is intriguing that an excess of dark microlensing events in this mass range has recently been reported from OGLE and Gaia observations of the Galactic bulge [23].

In the near future, further LIGO-Virgo observations, upcoming microlensing and supernova lensing sur-

veys, and a series of other electromagnetic probes [24] should determine the mass spectrum of coalescing black holes [25] sufficiently well to test our scenario. In particular, LIGO-Virgo might confirm both the “proton” peak and the “pion” plateau at tens of solar masses.

Addressing the fine-tunings. Our scenario naturally links the PBH abundance to the baryon abundance and the BAU to the PBH collapse fraction ($\eta \sim \beta$). The spectator field mechanism for producing the required curvature fluctuations also avoids the need for a fine-tuned peak in the power spectrum, which has long been considered a major drawback of PBH scenarios. One still needs fine-tuning of the mean field value to produce the observed values of η and β (i.e. $\sim 10^{-9}$). However, the stochasticity of the field during inflation (if it lasted for more than 60 e-folds) ensures that Hubble volumes exist with all possible field values and this means that one can explain the fine-tuning by invoking a single anthropic selection argument.

The argument is discussed in Ref. [7] and depends on the fact that only a small fraction of patches will have the PBH and baryon abundance required for galaxies to form. In most others, the field is too far from the slow-roll region to produce either PBHs or baryons. Such patches lead to radiation universes without any DM or matter-antimatter asymmetry. In other (much rarer) patches, PBHs are produced too copiously, leading to rapid accretion of most of the baryons, as might have happened in ultra-faint-dwarf galaxies. This anthropic selection effect may therefore explain the observed value of η and β . The connection between the rareness of the PBHs, responsible for later matter-domination, and subsequent structure formation is an important feature of our scenario.

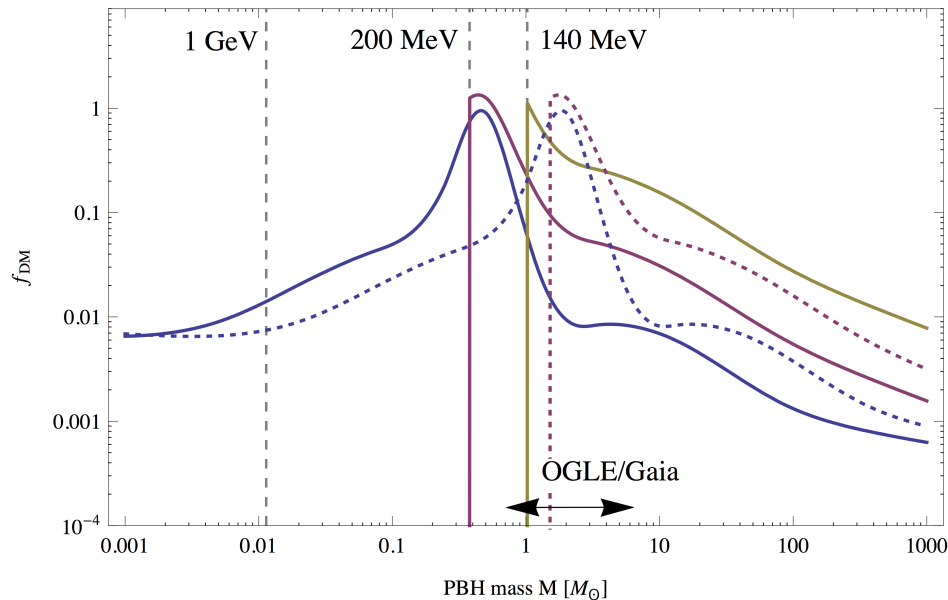


FIG. 2: PBH mass functions, $f_{\text{PBH}} \equiv (d\rho_{\text{PBH}}/d \ln M)/\rho_{\text{DM}}$, for different curvaton models and for a collapse efficiency $\gamma = 0.2$ (solid) and $\gamma = 0.8$ (dotted), the integrated PBH abundance corresponding to the dark matter density in all cases. The vertical (grey) lines correspond to the temperature at PBH formation (assuming $\gamma = 0.2$). The top curves apply if the curvaton is identified with the QCD axion, with $T_c \simeq 200$ MeV (red) and $T_c \simeq 140$ MeV (yellow), assuming $f_a = 0.15 M_p$, but the value of f_a only marginally impacts the shape of the distribution. In these cases PBH formation at $T \gtrsim T_c$ is suppressed, which induces a sharp lower cut-off in the distribution. The blue curve applies for a more general curvaton field. The double arrow indicates the peak in the number of dark lenses from combined OGLE and Gaia microlensing observations [23].

Conclusions. It is well known that the early Universe can be used as a probe of fundamental physics at very high energies. The production of the BAU through CP-violating processes is one example of this, the usual assumption being that new high-energy physics generates the baryon asymmetry everywhere simultaneously via out-of-equilibrium particle decays or first-order phase transitions. However, in our scenario, the BAU is generated in local hot spots through the violent process of PBH formation at the QCD transition, this being triggered by the sudden drop in the radiation pressure and the presence of large amplitude curvature fluctuations. The only CP violation needed is that of the Standard Model and the same regions which generate the baryon asymmetry also produce PBHs with a density comparable to that of the baryons.

A full analysis of the non-linear dynamics of gravitational collapse and out-of-equilibrium baryogenesis will require detailed numerical simulations. Future particle physics experiments with ultra-high-density heavy ion collisions in the 100 TeV range [26] may be able to explore the high-energy sphaleron transitions invoked by our proposal. Note that our model does not preclude some baryogenesis occurring at an earlier epoch, providing the associated value of η is much less than 10^{-9} .

All the dark matter in our proposal is made of PBHs with a mass distribution which peaks around a solar

mass. This passes the current observational constraints on the PBH abundance, once the large uncertainties on lensing constraints are taken into account. However, accurate predictions of the PBH mass function will require numerical investigations of the stochastic dynamics of the curvaton, both during and after inflation, for different spectator fields. If LIGO-Virgo interferometers over the next few years can determine the mass distribution of the coalescing black holes, this will allow a comparison with the predictions of Fig. 2.

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- [1] B. P. Abbott *et al.* (LVC Collaboration), Phys. Rev. Lett. **116**, 061102 (2016).
- [2] S. Bird, I. Cholis, J.B. Muñoz, Y. Ali-Haïmoud, M. Kamionkowski, E.D. Kovetz, A. Raccanelli and A.G. Riess, Phys. Rev. Lett. **116**, 201301 (2016); S. Clesse and J. García-Bellido, Phys. Dark Univ. **15**, 142 (2017); M. Sasaki, T. Suyama, T. Tanaka and S. Yokoyama, Phys. Rev. Lett. **117**, 061101 (2016).
- [3] B. J. Carr, F. Kühnel and M. Sandstat, Phys. Rev. D. **94**, 044029 (2016); J. García-Bellido, J. Phys. Conf. Ser. **840**, 012032 (2017).
- [4] B. J. Carr, Astrophys. J. **201**, 1 (1975).
- [5] K. Jedamzik, Phys. Rev. D **55**, 5871 (1997); C. T. Byrnes, M. Hindmarsh, S. Young and M. R. S. Hawkins, JCAP **1808**, 041 (2018).
- [6] T. Asaka, D. Grigoriev, V. Kuzmin and M. Shaposhnikov, Phys. Rev. Lett. **92**, 101303 (2004).
- [7] B. Carr, S. Clesse and J. García-Bellido, 1904.02129.
- [8] J. M. Ezquiaga, J. García-Bellido and E. Ruiz Morales, Phys. Lett. B **776**, 345 (2018).
- [9] S. Clesse and J. García-Bellido, Phys. Rev. D **92**, 023524 (2015).
- [10] T. Bhattacharya *et al.*, Phys. Rev. Lett. **113**, 082001 (2014).
- [11] I. Musco and J. C. Miller, Class. Quant. Grav. **30**, 145009 (2013).
- [12] J. M. Ezquiaga and J. García-Bellido, JCAP **1808**, 018 (2018).
- [13] M. Shaposhnikov, “Baryogenesis,” NATO Sci. Ser. C **555**, 397 (2000).
- [14] A. D. Sakharov, JETP Sov. Phys. Lett. **5**, 24 (1967).
- [15] M. Tanabashi *et al.* [Particle Data Group], Phys. Rev. D **98**, no. 3, 030001 (2018).
- [16] A. Kurkela and G. D. Moore, JHEP **1112**, 044 (2011).
- [17] R. J. Hardwick, V. Vennin, C. T. Byrnes, J. Torrado and D. Wands, JCAP **1710**, 018 (2017).
- [18] F. Ferrer, E. Masso, G. Panico, O. Pujolas and F. Rompineve, Phys. Rev. Lett. **122**, 101301 (2019).
- [19] R. J. Hardwick, V. Vennin, C. T. Byrnes, J. Torrado and D. Wands, JCAP **1710** (2017) 018
- [20] J. Calcino, J. García-Bellido and T. M. Davis, MNRAS **479**, 2889 (2018), J. García-Bellido and S. Clesse, Phys. Dark Univ. **19** (2018) 144 A. M. Green, Phys. Rev. D **96** (2017) 043020, M. R. S. Hawkins, Mon. Not. Roy. Astron. Soc. **415** (2011) 2744, M. R. S. Hawkins, Astron. Astrophys. **575** (2015) A107
- [21] B. J. Carr, F. Kühnel and M. Sandstat, Phys. Rev. D. **94**, 044029 (2016).
- [22] K. Belczynski, D. E. Holz, T. Bulik and R. O’Shaughnessy, Nature **534**, 512 (2016).
- [23] L. Wyrzykowski and I. Mandel, arXiv:1904.07789
- [24] A. Kashlinsky *et al.*, arXiv:1903.04424
- [25] B. P. Abbott *et al.* (LVC Collaboration), 1811.12940
- [26] J. Ellis, K. Sakurai and M. Spannowsky, JHEP **1605**, 085 (2016).