Article

Before the Big Bang: the Apollonian Universe

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Abstract: We propose that the Big Bang does not have a singular start, but that it originates from gravitational collapse of a low density cloud that collapsed 25 Gyrs ago to form a Black Hole (BH) of mass $M \simeq 6 \times 10^{22} M_{\odot}$. The collapse continued inside the BH for 11Gyrs until the density achieves neutron degeneracy and the collapse bounces into expansion like a core collapse supernova. From observations today, this model is very similar to the standard Big Bang cosmology but there is no need for Inflation or Dark Energy (DE). The observed cosmological constant Λ is not a new form of DE, but results from the dynamics of the Big Bang expansion inside the BH event horizon $r_S = 2GM = \sqrt{3/\Lambda}$. Why our Universe has such a large mass M (or small Λ value)? If $\tau_O (\simeq 10\text{Gyr})$ is the astronomical timescale needed for observers like us to exist, we find a simple anthropic prediction, based only on gravitational collapse from Gaussian fluctuations, that the maximum probability for M is $M_O < M < 3M_O$ where $M_O = \tau_O/3G$. This agrees well with the measured values for τ_O and M in our Universe.

Keywords: cosmology; dark energy; general relativity; black holes

1. Introduction

A cosmological model predicts the background evolution, composition and structure of the observed Universe given some initial conditions. The standard cosmological model [1,2], also called ΛCDM, assumes that our Universe began in a hot Big Bang (BB) expansion at the very beginning of space-time. Such initial conditions seem to violate the classical concept of energy conservation and are very unlikely [3–6]. Our observed Hubble Horizon has a total mass energy closed to $10^{22} M_{\odot}$ in form of stars, gas, dust and Dark Matter, which according to the singular start BB model came out of (macroscopic) nothing in the form of some quantum gravity vacuum fluctuations that we can only speculate about and we will never be able to test experimentally because of the enormous energies involved ($10^{19} GeV$). There is no direct evidence that this ever occurred. The model also requires three more exotic ingredients: Inflation, Dark Matter and Dark Energy (DE), for which we have no direct evidence or understanding at any fundamental level. Despite these shortfalls, the ΛCDM model seems very successful in explaining most observations by fitting just a handful of free cosmological parameters, such as H_0 and Ω_m. We propose a new cosmological model, the Black Hole Universe (BHU) [7–9], based on well established physical concepts that can explain the same observations without the need of introducing such exotic ingredients. Recent observations show discrepancies or tensions with ΛCDM prediction in the measurements of cosmological parameters from different time-scales (see [10] for an extended review). Such tensions, if confirmed, could be supportive of the BHU model [11]. In this paper we will review the basis for the BHU in the light of addressing what was out there before. We will also present a new anthropic argument to predict the observed value for cosmic acceleration.

The BHU model corresponds to a simple exact solution to GR of a non static uniform collapsing or expanding spherical star [7,12] that also has a corresponding Newtonian solution when we account for a finite speed of light [9,13]. We argue that this BHU model matches well the observed universe for a comoving observer like us. To avoid repetition of previous papers [7,9] but provide a comprehensive review, here we combine Newtonian and GR arguments to further clarify some points of the model. It should be noted that for the Newtonian approach we use the same coordinates as in the GR solution, but to address some of this questions more carefully we should refer to events that are coordinate independent.

The fact that the universe might be generated from the inside of a BH has been studied extensively in the literature [14–19]. Most of these previous approaches involve modifications to Classical GR and will not be discussed here. There are also some simple scalar field $\varphi(x)$ examples (e.g. [16]) which presented models within the scope of a classical GR and classical field theory with a false vacuum interior. A particular case of this are Bubble or Baby Universe solutions where the BH interior is de-Sitter metric [20–27]. The BHU solution can be similar, but has some important differences. In the BHU, no surface terms (or Bubble) is needed and the matter and radiation inside are regular. In this respect the BHU is not a Bubble Universe.

In 1970´s [28,29] already proposed that the FLRW metric could be the interior of a BH. But these early proposals were not proper GR solutions, but just incomplete analogies (see [30]). The model by [31] has the same name and similar features as our BHU proposal, but it is built as a new postulate to GR and not as a solution to a classical GR problem. Our BHU solution is quite different from that of [32], who speculated that all final (e.g. BH) singularities 'bounce' or tunnel to initial singularities of new universes. Here we propose the opposite, that such mathematical singularities are not needed to explain the physical world. The solution by [33] agrees well with the one used by BHU model, but does not interpret the observed Λ as the result of BH collapse and does not consider a bounce to interpret the observed cosmic expansion. Poplawski [34] proposed the torsion in the Einstein–Cartan gravity model with Λ to generate a non singular bounce which results in a BH universe. We use instead Classical GR without Λ (it is the finite mass of the BHU the one that explains the observed effective value of Λ). The idea of a bouncing universe is also well known [34–36], but note that these previous works assume some form of Modified Gravity to avoid the initial singularity, often result in cyclic models and do not happen inside a BH. As we will see, our proposal is quite different: it is not cyclic and only uses the known laws of Physics.

1.1. The local spherical metric

The most general form of a flat metric with spherical symmetry in physical or Schwarzschild (SW) coordinates (t, r, θ, ϕ) in units of $c \equiv 1$, can be written as follows:

$$ds^2 = -[1 + 2\Psi(t, r)]dt^2 + \frac{dr^2}{1 + 2\Phi(t, r)} + r^2 d\Omega^2. \quad (1)$$

The simplest approximation for a static BH is the SW metric: $2\Phi = 2\Psi = -2GM/r \equiv -r_S/r$ which corresponds to a singular point of mass M [37]. Regardless of its metric, a physical BH can be defined as an object of total mass-energy M with a radial size R that is smaller or equal to its SW radius r_S:

$$r_S = \frac{2GM}{c^2} \simeq 2.9\text{km}\frac{M}{M_\odot}. \quad (2)$$

This corresponds to a radial escape velocity $\dot{r} = c \equiv 1$. As events cannot travel faster than c, nothing can escape from inside r_S. The average energy density of a BH inside r_S is always:

$$\rho_{BH} = \frac{M}{V} = \frac{3M}{4\pi r_S^3} = \frac{3r_S^{-2}}{8\pi G} \simeq 9.8 \times 10^{-3} \left[\frac{M_\odot}{M}\right]^2 \frac{M_\odot}{\text{km}^3}. \quad (3)$$

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This value should be compared with the atomic nuclear saturation density:

$$\rho_{NS} \simeq 2 \times 10^{-4} \frac{M_\odot}{\text{km}^3} \tag{4}$$

which corresponds to the density of heavy nuclei and results from the Pauli Exclusion Principle applied to neutrons and protons. For a Neutron Star (NS) with $M \simeq 7M_\odot$, both densities are the same: $\rho_{BH} = \rho_{NS}$. This relation indicates that it is difficult to form BHs, from gravitational collapse, with masses smaller than $M \simeq 7M_\odot$, because you somehow need to first overcome Pauli Exclusion Principle. It also explains why NS are never larger than $M \simeq 7M_\odot$, as a collapsing cloud with such mass reaches BH density ρ_{BH} before it reaches ρ_{NS}. The maximum observed M for NS is closer to $M \simeq 3M_\odot$ [38], which agrees with more detailed considerations that include the equation of state estimates. Cold nuclear matter at neutron density is a major unsolved problem in modern physics [38]. Fortunately, we should be able to understand this better in the near future by using further modeling (see e.g.[39]), simulations and neutron star observations. This topic might turn our to be key to understand cosmic expansion, as we will discuss here later in §2.1.

1.2. The global FLRW metric

The Friedmann–Lemaitre–Robertson–Walker (FLRW) metric can describe a flat infinite homogeneous and isotropic space. In co-moving coordinates $\xi^\alpha = (\tau, \chi, \theta, \phi)$:

$$ds^2 = -d\tau^2 + a(\tau)^2 \left[d\chi^2 + \chi^2 d\Omega \right]. \tag{5}$$

This metric is also spherically symmetric, so it is a particular case of Eq.1. Comparing the solid angle term $d\Omega$ to Eq.1, note that the SW or physical coordinates are $r = a\chi$, which imply Hubble's law: $\dot{r} \equiv dr/d\tau = \frac{\dot{a}}{a} r \equiv Hr$. The scale factor, $a(\tau)$, gives the expansion/contraction as a function of co-moving or cosmic time τ (proper time for a co-moving observer). For a perfect fluid with density ρ and pressure p, the solution to GR field equations is well-known:

$$H^2 = \frac{8\pi G}{3} \rho = H_0^2 \left[\Omega_m a^{-3} + \Omega_R a^{-4} + \Omega_\Lambda \right], \tag{6}$$

where $\rho_c \equiv \frac{3H_0^2}{8\pi G}$ and $\Omega_X \equiv \frac{\rho_X}{\rho_c}$, where Ω_m and Ω_R represents the current ($a = 1$) matter and radiation density, respectively, and $\Omega_m + \Omega_R + \Omega_\Lambda = 1$. The effective cosmological constant term Ω_Λ results from: $\rho_\Lambda \equiv \rho_{\text{vac}} + \frac{\Lambda}{8\pi G}$ where ρ_{vac} represents the vacuum or the ground state of a scalar field: $\rho_{\text{vac}} = -p_{\text{vac}} = V(\varphi)$ with negligible kinetic energy. At any time, the expansion rate H^2 is given by ρ. Energy–mass conservation requires that $\rho \propto a^{-3(1+\omega)}$, where $\omega = p/\rho$ is the equation of state of the different components: $\omega = 0$ for matter, $\omega = 1/3$ for radiation, and $\omega = -1$ for ρ_Λ. Given $a_* = a(\tau_*)$ and $H = H_*$ at time τ_* the solution dominated by a single component with equation of state ω is:

$$a(\tau) = a_* \left[\frac{3(1+\omega)}{2} \tau H_* \right]^{\frac{2}{3(1+\omega)}} \Rightarrow r_H = \frac{3(1+\omega)}{2} \tau \tag{7}$$

for $\omega \neq -1$ and $a = a_* e^{H_*(\tau - \tau_*)}$ for $\omega = -1$. During collapse, H and τ are negative. So that $r < 0$ refers to the collapse phase and $r > 0$ to the expansion phase. The Hubble Horizon is defined as $r_H \equiv H^{-1}$. Structures that are larger than r_H cannot evolve because the time that a perturbation takes to travel that distance is larger than the expansion time. How can these structures form if they were never in causal contact? This question poses the horizon problem. In the BB model, this problem is solved by Cosmic Inflation [40–43], a period of exponential expansion that must have happened right at the beginning of time ($\tau = 10^{-30}$sec). After expanding by a factor e^{60}, Inflation leaves the universe empty and we need a mechanism to stop Inflation and to create the matter and radiation that we observe today. This is called re-heating. These components require fine-tuning and free parameters that we do not understand at a fundamental level and occur at energies ($> 10^{15}$GeV) that are out of reach from direct validation [1].

1.3. Cosmic Acceleration

Cosmic acceleration is defined as $q \equiv (\ddot{a}/a)H^{-2}$. Taking a derivative of Eq.7, we find $q = -\frac{1}{2}(1+3\omega)$, which is also valid for the case of $\omega = -1$. For regular matter, we have $\omega > 0$ so we expect the expansion to decelerate ($q < 0$). However, the latest concordant measurements from a Type Ia supernova (SN), galaxy clustering, and the Cosmic Microwave Background (CMB) all agree with DE with $\omega = -1.03 \pm 0.03$ [44], which means that the expansion ends up dominated by $q \simeq 1$. However, there is no fundamental understanding of what DE is or why $\omega \simeq -1$. This is very similar to Inflation above but at 10^{-12} GeV energy. A candidate for DE is ρ_Λ [45–48]. The value $q \simeq 1$ is also important to obtain a longer age estimate of 14 Gyr, which is needed to account for the oldest stars and to give more time for structures to grow from the CMB seeds $\delta_T \simeq 10^{-5}$ to the amplitude (and shape) we observe today [49–51].

Note how $q = 1$ implies $\omega = -1$ and therefore $\dot{H} = 0$, so that H becomes constant and all structures become super-horizon and freeze, such as in Inflation. In the physical (SW) frame of Eq.1, this corresponds to a static hypersphere (de-Sitter [52]) metric with:

$$2\Phi = 2\Psi = -\Lambda r^2/3 \equiv -\frac{r^2}{r_\Lambda^2} \equiv -r^2 H_\Lambda^2. \tag{8}$$

It also corresponds to the Steady State Universe [53,54]. We often say that the expansion accelerates but it is more physical to say that the expansion becomes asymptotically static, as proposed by Einstein [45,55] when he introduced Λ.

2. Inside a Black Hole

The density of our Universe (in Eq.6) inside its Hubble Horizon $r_H = 1/H$ corresponds to that of a BH in Eq.3. This can be easily understood, because the escape velocity (or Hubble flow) at $r = r_H$ is the speed of light: $\dot{r}_H = Hr_H = 1$. The mass inside r_H follows $r_H = 2GM$ and H^2 tends toward a constant $H_\Lambda^2 = \frac{8\pi G}{3}\rho_\Lambda = H_0^2\Omega_\Lambda$. The Universe becomes asymptotically static (in the SW frame) with a fixed radius ($r_\Lambda = H_\Lambda^{-1}$). In that limit we have a static BH with $r_S = r_\Lambda$. Consider an outgoing radial null geodesic to ∞ (i.e., the Event Horizon, [56]) starting at proper time τ from anywhere inside the FLRW metric:

$$r_* = a\int_\tau^\infty \frac{d\tau}{a(\tau)} = a\int_a^\infty \frac{d\ln a}{aH(a)} < \frac{1}{H_\Lambda} \equiv r_\Lambda \tag{9}$$

As the Hubble rate becomes constant, r_* freezes to a constant value $r_* = r_H = r_\Lambda$. We will next argue that the region inside r_Λ, where we live, corresponds to the interior of a BH. This is an unusual interpretation for a comoving observer, but is the natural interpretation for an observer not moving with the fluid.

What is outside r_Λ? In the limit of empty space outside, Birkhoff's Theorem (see [57,58]) tells us that the metric outside should be SW metric [59]. This solution can also be verified using Israel's junction conditions (see below). So, no signal from inside r_Λ can reach outside and we have SW metric outside with a total mass inside given by:

$$M = \rho_\Lambda \int_0^{r_\Lambda} 4\pi r^2 dr = \frac{r_\Lambda}{2G} \tag{10}$$

where $r \equiv a\chi$ in the FLRW metric. This is pretty much the definition of a BH. The FLRW metric with Λ is a BH as seeing from outside. This also provides a fundamental

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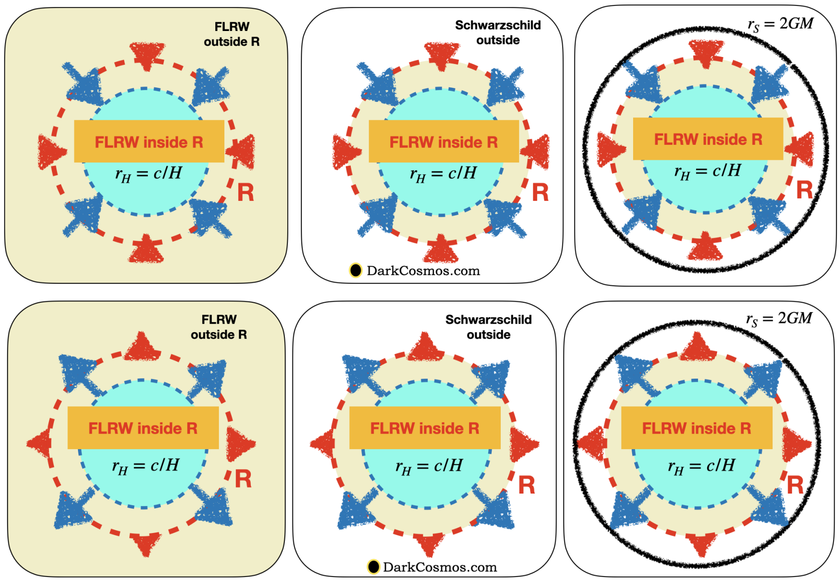

Figure 1. The FLRW metric can be used to model an infinite universe (left), collapsing (top) or expanding (bottom), and a cloud of finite mass M and size $R(\tau)$ (red circle) in empty space (middle) or inside its SW radius $r_S = 2GM$ (right). In the BHU, cosmic expansion originated with the freefall of a FLRW cloud (top middle) that collapsed into a BH (top right) and later bounced into expansion (bottom right), trapped inside r_S, which results in cosmic acceleration. The Hubble Horizon $r_H = H^{-1}$ (blue circle) moves faster than R, so that perturbations become super-horizon during collapse and re-enter during expansion, solving the horizon problem without Inflation.

interpretation for Λ, which is just given by the SW mass inside [8]. For $\Omega_\Lambda \simeq 0.7$ and $H_0 \simeq 70$ km/s/Mpc we have:

$$r_S = H_0^{-1}\Omega_\Lambda^{-1/2} \simeq 1.6 \times 10^{23} km \ \ ; \ \ M = \frac{r_S}{2G} \simeq 6 \times 10^{22} M_\odot \tag{11}$$

This interpretation can formally break global homogeneity for the large background (on scales larger than r_Λ), but this is needed if we want causality. Homogeneity is inconsistent with a causal origin [59,60], the same way that a BB out of nothing is inconsistent with Energy conservation.

2.1. The FLRW cloud

We can arrive at the same conclusion (that we live inside a BH) from a different perspective. The FLRW solution and metric can also be used to describe a local spherical homogeneous cloud of variable radius R and fix mass M, which collapses or expands in freefall. Based on Gauss law (or the corollary to Birkhoff's theorem [57]) each sphere $r < R$ evolves with independence of what is outside $r > R$. This is only valid for a system with spherical symmetry. As a consequence, the local FLRW solution is also a valid solution in GR [13]. A radial shell at $r = R$ is in free fall under the gravity of M, so that the potential energy $-\Phi = GM/R$ must equal kinetic energy $-\Phi = K = \dot{R}^2/2$. Because R follows the FLRW solution we have that $\dot{R} = HR$, which results in $GM/R = H^2R^2/2$ or:

$$R = [r_H^2 r_S]^{1/3} \tag{12}$$

In GR this is equivalent to matching the SW metric ($\Phi = -GM/R$ in Eq.1) to the FLRW (or de-Sitter metric in Eq,8). Using Israel conditions [61], one can show [7,9] that the physical radius coordinate R of the FLRW cloud follows the same Eq.12 as in the Newtonian solution.

For a regular star $R > r_S$ so the expansion is subluminar $R < r_H$. The static solution requires the famous $R > 9/8 r_S$ Buchdahl bound [62]. But it is clear that our Universe has

$R > r_H$ (we observe super-horizon scales in the CMB) which requires $R < r_S$ in Eq.12: i.e. we are inside our own BH!

Thus, we can understand the FLRW in the usual comoving frame or in the SW frame, not moving with the fluid. We call this a frame duality. In the SW frame of Eq.1, this local FLRW solution corresponds to $2\Phi = -H^2r^2$ for $r < R$ (and $2\Phi = -r_S/r$ for $r > R$), which for the static case is a well known solution for a BH interior [63]. This frame duality can be understood as a Lorentz contraction $\gamma = 1/\sqrt{1-\dot{r}^2}$ where the velocity $\dot{r}$ is given by the Hubble law: $\dot{r} = Hr$, which results from the change of variables: $r = a\chi$. An observer in the SW frame, not moving with the fluid, sees the moving fluid element $ad\chi$ contracted by the Lorentz factor γ: $ad\chi \Rightarrow \gamma dr$, which explains how you can get $2\Phi = -H^2r^2$ in Eq.1 from Eq.5 [7]. For $\omega = p = 0$, R in Eq.12 follows a time-like geodesic in freefall with constant $\chi = R/a = r_S/a_{BH}$. For $\omega \neq 0$, $R = r_*$ follows the null geodesic in Eq.9. Compared with Eq.7, R grows slower than r_H so perturbations become super-horizon during collapse and re-enter during expansion, solving the horizon problem without the need of Inflation, as explain in Fig.1 (see also [35]).

3. The Black Hole Universe (BHU)

So our FLRW cloud seems to be now expanding, but inside its BH event horizon. How did this happen? Here we give a possible explanation that, if correct, indicates that there was something already out there before the BB.

3.1. The Big Bounce conjecture

- Our local FLRW cloud must first collapse to formed a BH. Before it collapse, the density of such a large cloud was so small that radiation escaped the cloud, so that $p = 0$ ($\omega = 0$). Radial co-moving shells of matter are in free-fall collapse and continuously passes $R = r_S$ inside its own BH horizon. We take τ_* in Eq.7 as the time τ_{BH} (a_{BH}) when $r_H = -r_S$, i.e. when the BH forms. Recall that $r < 0$ refers to the collapse phase in Eq.7, but collapse and expansion are not symmetric because the event horizon is not symmetric: it allows matter to fall in but not to get out. This is key to the BHU model. We then find that the BH forms at time $r_H = -r_S$:

$$\tau_{BH} = \tau_* = -\frac{2}{3(1+\omega)} r_S \simeq -11\text{Gyrs}, \tag{13}$$

  i.e. before $\tau = 0$ (the BB) or 25Gyr ago.
- The collapse continues inside until it reaches nuclear saturation (GeV) in Eq.4. The Hubble radius corresponding to Eq.4 is only few km and contains a few solar masses. So the collapse mass and scale is similar to that the interior of a regular collapsing star. Higher densities can not be reached because of Pauli Exclusion Principle. This indicates that the collapse must be halted by neutron degeneracy pressure, causing the implosion to rebound as it happens in stars [64]. Other bouncing mechanism have been proposed [34–36], but they assume modifications to Classical GR.
- The different Hubble size regions within the BHU explode in sync because (ignoring small scale fluctuations) the background density is approximately the same everywhere in the collapsing FLRW cloud. The collapse energy ($H < 0$) bounces into approximately uniformed expansion ($H > 0$). Radiation, baryons, Neutron Stars or primordial Black Holes (PBHs) could result from each Hubble size region as compact remnants that can make up all or part of Dark Matter Ω_m. Such compact remnants do not necessarily disrupt Nucleosynthesis or CMB recombination, as long as they are not too large [65,66]. The bounce must produce the right amount of diffuse baryons per photon ($\eta = n_B/n_\gamma \simeq 6 \times 10^{-10}$) so that Nucleosynthesis generates the observed primordial element abundance [67]. This will also give the right temperature for the observed CMB recombination physics.

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3.2. Comparison with Inflation

Cosmic Inflation speculates that reheating after inflation produces the right number of baryons per photon ($\eta = n_B/n_\gamma \simeq 6 \times 10^{-10}$) to match Nucleosynthesis and CMB recombination. The simplest models of Inflation also predict adiabatic scale invariant fluctuations (given by an overall amplitude δ_T and slope n_S) in general agreement with current observations [1]. But note that the actual parameters that are fitted to observations ($\delta_T \sim 10^{-5}$, $n_S \sim 1$, $\eta \sim 10^{-9}$ or $\Omega_m/\Omega_B \sim 4$) are not fundamental predictions of Inflation, but free parameters of the ΛCDM model.

In the BHU, the Big Bounce replaces the role of reheating and gives rise to η (diffused baryons to photons) and Ω_m/Ω_B (compact to diffused baryons). The collapse and bounce can also generate the initial spectrum of fluctuations needed to explain the observed cosmic structures ($\delta_T \sim 10^{-5}$ and $n_S \sim 1$). Gravitational instability [68–70] allows perturbations δ to grow causally during the collapse phase but they quickly exit r_H as the collapse approaches $\tau = 0$. Such causally disconnected regions will therefore have slightly different Ω_m and H_0 at the time close to the Big Bounce (10^{-4}s). These regions correspond to super-horizon perturbations in the CMB that re-enter r_H during the expansion given rise to the structures that we see today in Cosmic Maps (see Fig.1 and the text at the end of previous section).

Because R is always finite, we expect a cut-off in the spectrum of perturbations. This is at odds with the simplest prediction of Inflation. Recent anomalies in measurements of cosmological parameters over very large super-horizon scales agree better with the BHU predictions than with Inflation [10] and indicate that fluctuations are not adiabatic, as predicted by Inflation. This again could provide evidence for the Big Bounce, which is an out of equilibrium process.

This new model is speculative, the same way Inflation is speculative. The main difference is that Inflation happens at energies that we will never be able to test, whereas the core collapse bounce in the BHU can be modeled and tested using classical physics and the same Nuclear Astrophysics (and observations) that we use to understand Neutron stars, pulsars or core collapsed supernovae. Further work is needed to show this. This work could potentially explain from first principles some key cosmological observations, like η, δ_T or Ω_m/Ω_B, which are currently fixed as free parameters of the ΛCDM model.

3.3. Trapped Inside a Black Hole

A comoving observer sees the Hubble law of Eq.6 from anywhere inside but the background is not isotropic for $R > r_S$ in Eq.12 unless you are at the center. Once the FLRW cloud collapses to become a BH, nothing can escape out of the event horizon r_S, so the condition $p = 0$ at the horizon $r = r_* = R$ is automatically fulfilled, even when in the last stages of the collapse part of the energy could transformed into heat ($p \neq 0$). The GR field equations change for an expanding FLRW cloud inside a BH because r_S becomes a boundary in the Hilbert action [8]: r_S behaves like a Λ term ($\Lambda = 3/r_S^2$), despite having $\Lambda = 0$ to start with. A co-moving observer anywhere inside such a local FLRW cloud has no way to distinguish it from an infinite FLRW universe. We can understand this curious behavior in the dual frame by considering radial null events ($ds^2 = 0$) connecting $(0, r_0)$ with (t, r) in de-Sitter metric Eq.8, which follow:

$$r = r_\Lambda \frac{r_\Lambda + r_0 - (r_\Lambda - r_0)e^{-2t/r_\Lambda}}{r_\Lambda + r_0 + (r_\Lambda - r_0)e^{-2t/r_\Lambda}}. \tag{14}$$

It takes $t = \infty$ to reach $r = r_\Lambda$ from any point inside, no matter where r_0 is. This agrees with Eq.9. The homogeneous solution seems to have larger symmetry (more killing vectors) than the FLRW cloud, but this is not the case when we have Λ or when we are inside a BH (which is equivalent). This is apparent in de-Sitter metric, which can be expressed as a homogeneous expanding FLRW metric of Eq.5 with $H = H_\Lambda$ or as a static hypersphere of

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Eq.8 (see also [71]). Another consequence of these properties is that even if we are not close to the center of our BHU we can not measure any background anisotropies.

4. The Apollonian Universe

If the Big Bounce idea is correct, what was there before our BHU collapsed? We will assume here that there are other BHUs and regular matter within a larger space-time that we call the Apollonian Universe. This has to be a much larger space-time but we assume that it is otherwise similar to ours: a uniform background with energy density $\bar{\rho}$ with an initially Gaussian distribution of small fluctuations δ, so that $\rho = \bar{\rho}(1+\delta)$. We don't know the initial particle composition of the Apollonian Universe, but we can assume that it is similar to the one in our BHU. For weakly interacting, collisionless dark matter (CDM), the hierarchical gravitational collapse leads to dense dark matter halos and not to collapsing BHs. This is the case even if the CDM that we observe today does not correspond to a new exotic particle but is made of compact objects with regular matter (like stellar BHs and Neutron stars). BHs could still form inside CDM halos. So compact objects could correspond to halos with smaller BHs or just regular BHs.

By its definition, gravity dominates for masses above the Jeans mass $M > M_J$. For such large masses, we can then use the Press-Schechter formalism [72] to predict the number of collapsed objects $dn(M)$ of a given mass M. For scale-free power spectrum $n = 0$ (scalar spectral index $n_S = 1$), close to the one inside our BHU at the largest scales:

$$\frac{dn(M)}{dM} = \sqrt{\frac{1}{\pi}} \left(\frac{M}{M_*}\right)^{1/2} \exp\left(-\frac{M}{M_*}\right) \frac{\bar{\rho}}{M^2} \tag{15}$$

where M_* is corresponds to the gravitational collapse non-linear transition scale. This corresponds to the case of white noise ($n = 0$). More generally for different spectral indexes n, we have $(M/M_*)^{(n+3)/6}$. This result can be understood as the abundace of peaks in a Gaussian field [73]. The important point to notice is that large collapsed objects are exponentially suppressed for $M > M_*$. The typical value of M_* increases with time. The value today corresponds to a cluster mass: $M_* \simeq 10^{14} M_\odot$ but was lower in the past.

We assume that the probability of having observers like us increases linearly with time for $\tau > \tau_O$ and is zero for $\tau < \tau_O$. So τ_O is the astronomical time needed for observers like us to exist. Its value must be close to $\tau_O \simeq 13$Gyrs, corresponding to the age of our galaxy [74], which is only about 3 times the age of our planet: 4.5Gyr [75]. The BH collapse time in Eq.13 is proportional to M, so that a large mass $M \simeq 6 \times 10^{22} M_\odot$ in Eq.11 has a typical collapse time of $\tau \simeq 11$Gyr in Eq.13. The expansion time is longer because of the acceleration caused by the BH event horizon, but during de-Sitter phase the Hubble horizon shrinks and structure formation halts. So in practice, the relevant timescale is the one given by matter domination ($\omega \simeq 0$) in Eq.13: $\tau = 4GM/3$.

We express M in terms of Δ: $M = M_O(1+\Delta)$, where $M_O = 3\tau_O/4G$ is the BH mass corresponding to τ_O in Eq.13. The anthropic probability $P(\Delta)$ that an observer lives inside a BH of such mass is then:

$$P(\Delta) \propto \frac{n(M)}{n(M_O)}\Delta = (1+\Delta)^{-3/2}\,\Delta\,\exp\left(-\frac{M_O}{M_*}\Delta\right) \quad \text{for} \quad \Delta > 0. \tag{16}$$

We have divided $n(M)$ in Eq.15 by $n(M_O)$ because we are interested in the relative number of BHs above the ones with the minimal mass M_O. Fig.2 shows Eq.16 for some values of M_O/M_*. For $M_O \gg M_*$ the probability is dominated by the exponential suppression and $P(\Delta)$ peaks around $\Delta = 0$. This means that most observers will live in a BH with mass M_O. So an accurate estimation of τ_O provides a prediction for M_O and therefore a prediction for $r_S = 2GM_O$ and $\Lambda = 3/r_S^2$, in agreement with the values measured in our BHU. For $M_O \simeq M_*$ the probability $P(\Delta)$ peaks around $\Delta = 1$, which predicts that most observers live in BHs which are two times M_O. For $M_O \ll M_*$ the result is independent of M_* and the peak is at $\Delta = 2$. Thus, regardless of M_*, the maximum probability corresponds to

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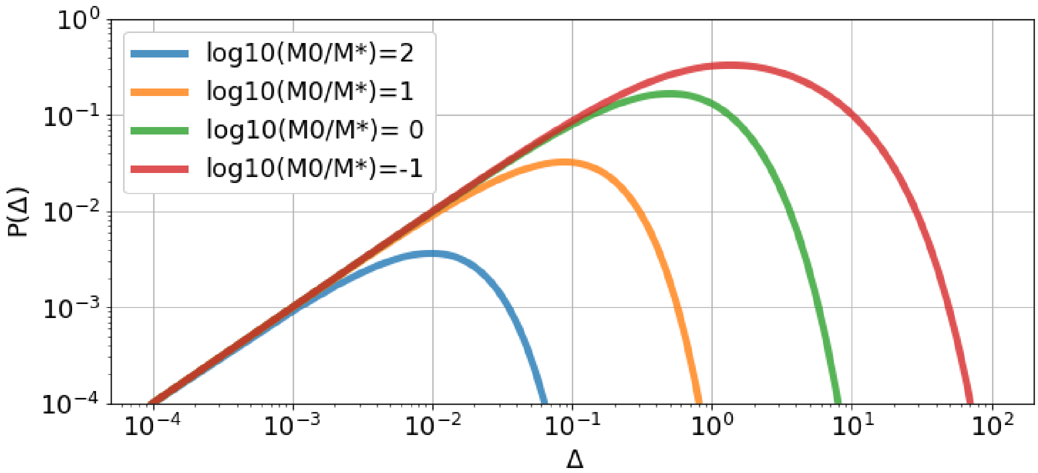

Figure 2. Anthropic probability $P(\Delta)$ in Eq.16 for different values of M_O/M_*. This corresponds to the probability for an observer like us to be in a BH of mass $M = M_O(1+\Delta)$. M_O corresponds to the minimum time $\tau_O \simeq 10$Gyr needed for a galaxy and planet like ours to form. M_* is the non-linear mass scale. Regardless of M_*, the maximum in $P(\Delta)$ is always within $0 < \Delta < 2$ or $M_O < M < 3M_O$.

observers in a BH with mass $M_O < M < 3M_O$ or collapse times $\tau_O < \tau < 3\tau_O$, which is very consistent with the measurements in our Universe for τ_O and M in Eq.11. In terms of Λ this corresponds to $\Lambda_O/9 < \Lambda < \Lambda_O$, where Λ_O is the value corresponding to M_O or τ_O.

5. Discussion and Conclusion

We propose that cosmic expansion originated from the collapse of a cloud in an existing background. We assume that such background is flat with $k = 0$ and $\Lambda = 0$, as in empty space. The field equations of GR are local and they do not change k or Λ because these are global topological quantities which are not altered by the presence of matter. We should therefore adopt the most simple topology, that of empty space, unless we find some evidence or good reason to the contrary. The so call flatness problem, that is solved by Inflation, is only a problem if the BB singularity creates curvature. In the BHU model the singularity is avoided at GeV (i.e. the energy corresponding to the nuclear saturation density in Eq.4), well before Quantum Gravity effects (10^{19} GeV), so we do not expect a global curvature or Λ in this model's background. There is therefore no flatness problem that needs to be solved.

In nature, we never observe cold regular matter with densities larger than that of an atomic nuclei in Eq.4. This is due to Pauli Exclusion Principle in Quantum Mechanics, which prevents fermions from occupying the same quantum state. We propose here that, when the collapse reaches nuclear saturation density, it bounces back, as it happens in a supernova core collapse. The bounce happens at times and energy densities that are many orders of magnitudes away from Inflation or Planck times. Thus, Quantum Gravity or Inflation are not needed to understand cosmic expansion or the monopole problem [41]. Further work is needed to understand the details of such a Big Bounce: to estimate the perturbations, composition, and fraction of compact and diffuse remnants that resulted from the bounce. This could explain from first principles some of the free parameters in the ΛCDM model, as shown in Table 1 of [9] and described in §3.

The Big Bounce could provide a uniform start for the BB, solving the horizon problem (see Fig.1): super-horizon perturbations during collapse (and bounce) seed structure (BAO and galaxies) as they re-enter r_H during expansion. The main differences with Inflation are the origin of those perturbations and the existence of a cutoff in the spectrum of fluctuations given by R in Eq.12. Such a cutoff has recently been measured in CMB maps [9,76–78]. Galaxy maps are also able to measure this signal [79,80] which could also appear as a dipole [81]. The existence of such super-horizon perturbations could be related to the tension in measurements of the cosmological parameters from different cosmic scaletimes [10,82–85], which have similar variations in cosmological parameters to the measured CMB cutoff anomalies reported in [10].

The BH collapse time in Eq.13 is proportional to M, so that a large mass $M \simeq 6 \times 10^{22} M_\odot$ in Eq.11 is just the right one to allow enough time for galaxies and planets to form before de-Sitter phase dominates. This provides an anthropic explanation [51,86] as to why we live inside such a large BH or why $\Lambda = 3/r_S^2$ is so small. According to Eq.16 (see also Fig.2) the maximum probability corresponds to observers that appear in BHs with $\Lambda_O/9 < \Lambda < \Lambda_O$, where $\Lambda_O = 4/(3\tau_O^2)$ is the value corresponding to $r_S \simeq 3\tau_O/2$ in Eq.13 for the minimum time τ_O needed for observers to exit. If we assume that this time τ agrees with the age of our galaxy we find good agreement between this prediction and the estimated Λ measurements. These arguments neglect global rotation of the FLRW cloud (or the BHU). Such rotation could slow down the expansion rate (see Appendix C in [9]) and play some role in the bounce and collapse time.

The BHU solution can also be used to understand the interior of regular (stellar or galactic) BHs. Such BHs could just be made of regular (baryonic) collapsing matter, but will not have time to form regular galaxies or stars inside because within seconds of the bounce, the internal dynamics becomes dominated by de-Sitter phase caused by their event horizon mass. The bounce proposed here, based in Quantum Mechanics, could avoid both the BH and the BB singularities [87,88]. The BHU also eludes the entropy paradox [4] in a similar way as that proposed by Penrose [5]. The difference is that the BHU does not require new laws (infinite conformal re-scaling) or cyclic repetition. Our expansion will end up trapped and static inside a larger and older universe, possibly containing other BHUs.

Funding: This work was partially supported by grants from Spain PGC2018-102021-B-100 and Unidad de Excelencia María de Maeztu CEX2020-001058-M and from European Union LACEGAL 734374 and EWC 776247. IEEC is funded by Generalitat de Catalunya.

Data Availability Statement: No new data is presented.

Acknowledgments: Thanks to Valerio Faraoni, Samir Mathur, Diego Blas and Ivan Agullo for comments on the draft.

Conflicts of Interest: The author declares no conflict of interest.

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