

A Rotational–Spiral Cosmology: connecting primordial rotation, energy injection, and the Hubble tension

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The enduring discrepancy between the Hubble constant inferred from the cosmic microwave background and local observations challenges the completeness of the standard Λ CDM model. This study builds upon recent explorations of cosmic rotation, proposing a rotational-spiral cosmology that introduces a minute primordial vorticity, subtly influencing the early universe’s dynamics. By integrating the gravitational wave energy injected from primordial black hole clustering during the QCD epoch, the model enhances the effective radiation density, thereby compressing the comoving sound horizon and advancing the recombination epoch to 372,000 to 374,000 years. Quantitative analysis reveals an elevation of the CMB-inferred Hubble constant to 68.5 to 69 $\text{km s}^{-1} \text{Mpc}^{-1}$, offering a partial alignment with local measurements consistent with recent BAO constraints [1]. The framework remains compatible with Planck and CMB isotropy limits [2] and provides distinctive testable predictions, notably galaxy spin alignments detectable with DESI. This refined interpretation relies solely on general relativity, presenting a novel perspective on the Hubble tension without invoking new physics.

I. PREFACE

Observations from the James Webb Space Telescope have revealed unexpectedly mature galaxies at redshifts between 10 and 13, implying that large structures emerged within only a few hundred million years of the Big Bang. At the same time, the continuing disagreement between the Hubble constant derived from the cosmic microwave background (about $67 \text{ km s}^{-1} \text{Mpc}^{-1}$) and that obtained from local measurements (about $73 \text{ km s}^{-1} \text{Mpc}^{-1}$) challenges the completeness of the standard Λ CDM cosmology.

These findings suggest that the early universe may have evolved under conditions that allowed faster structural development and a slightly different expansion history than the conventional model assumes.

Recent observations also hint at large-scale asymmetries, including coherent galaxy rotations across scales of twenty million light-years and measurable angular-momentum correlations within cosmic filaments. These may represent faint relics of primordial vorticity, consistent with the rotational–spiral hypothesis yet within observed isotropy limits [3, 4].

The rotational–spiral cosmology presented here offers one such possibility. It proposes that the universe began with a minute but finite angular momentum, imparted by a rotating singularity, and that the formation of primordial black holes during the radiation-dominated era provided a natural mechanism for small-scale gravitational-wave energy injection. In combination, these two effects could have shortened the comoving sound horizon, advanced recombination, and led to the earlier appearance of bound structures now observed by JWST.

Within the parameter range established by Planck 2018 ($\Omega_m \approx 0.315$, $\Omega_\Lambda \approx 0.685$), this framework remains consistent with the observed isotropy of the Universe and with all major CMB and BAO constraints. It provides a coherent physical basis linking the apparent maturity

of high-redshift galaxies with the measured Hubble tension, while remaining fully compatible with the established large-scale structure of modern cosmology.

II. THEORY OVERVIEW

The rotational–spiral model proposes that the Universe originated from a rotating singularity, imparting a minute but finite angular momentum to the primordial expansion. This initial spin introduced a faint spiral structure into the geometry of space–time, a concept rooted in anisotropic cosmological models such as the Bianchi I metric. The Bianchi I spacetime, characterized by a flat Friedmann-Lemaître-Robertson-Walker (FLRW) geometry with an additional rotational component, provides a framework where the Universe retains statistical isotropy despite early rotation. The initial angular velocity is assumed to be $\omega_0 \approx 10^{-30} \text{ rad s}^{-1}$, a value sufficiently small to avoid significant deviations from isotropy, yet sufficient to seed a coherent rotational pattern.

As the Universe cooled and entered the radiation-dominated era, overdense regions began to collapse under gravity. Around $10^{-6} - 10^{-5} \text{ s}$ after the Big Bang, near the QCD phase transition, the available horizon mass ($M_H \approx c^3 t / G$) allowed the formation of long-lived, high-mass primordial black holes (PBHs). These PBHs, with characteristic masses ranging from approximately 10^{-1} to $10 M_\odot$, generated a background of gravitational waves that redshifted as radiation, slightly increasing the total relativistic energy density. This enhancement, quantified in later sections, complements the rotational dynamics and is consistent with Planck 2015 constraints on the cosmic microwave background (CMB) isotropy.

The evolution of the rotational component follows from the conservation of angular momentum, expressed as $j = r^2 \omega = \text{constant}$, where j is the specific angular mo-

mentum, r is the comoving radius, and ω is the angular velocity. As the Universe expands, the scale factor a increases, leading to a damping of the rotational velocity proportional to a^{-2} . This relationship can be derived by considering the expansion dynamics, where $r \propto a$, so $\omega \propto j/r^2 \propto a^{-2}$. The rapid inflation that followed the singularity, typically spanning 50 to 60 e-folds, played a crucial role in diluting the rotational shear, ensuring compatibility with the observed isotropy of the CMB. The shear tensor, initially non-zero due to rotation, is reduced by a factor of $\exp(-60)$ during inflation, aligning with constraints from modern cosmological data.

This damped vorticity, with $\omega/H \lesssim 10^{-9}$ at the present epoch, remains consistent with Planck 2015 limits on large-scale vorticity in Bianchi VII_h models. The model assumes that the initial rotational energy is redistributed into the large-scale structure, potentially influencing galaxy formation and alignment patterns, a hypothesis supported by recent observations of coherent spins in cosmic filaments. The spiral geometry, though faint, suggests a topological imprint that could manifest as subtle anisotropies, detectable through future surveys such as Euclid or DESI.

The interplay between rotation and the GW energy injection from PBHs, as introduced above, forms a dual mechanism that enhances the radiation-like component without altering the fundamental Λ CDM parameters at late times. This synergy preserves the overall isotropy, as the GW contribution is isotropic on large scales, while the rotational damping ensures that local vorticity remains below observational thresholds. This framework provides a novel approach to linking primordial conditions to current observational tensions, setting the stage for the quantitative analysis in subsequent sections.

III. COMPATIBILITY WITH EXISTING MODELS

The rotational–spiral model remains fully consistent with the Λ CDM framework and with the observed isotropy of the CMB. Its rotational component obeys $j = r^2\omega = \text{constant}$, giving $\omega \propto a^{-2}$, so any primordial rotation is rapidly damped as the Universe expands.

Early constraints on universal rotation suggested $\omega/H_0 \lesssim 10^{-13}$ [5], while modern *Planck* 2015 limits refine this to $\omega/H_0 \lesssim 10^{-9}$ [6], consistent with the model’s damped vorticity. At the present epoch, the dimensionless rotational pitch $p = \omega/H$ is expected to be $< 10^{-9}$, in agreement with *Planck* limits on large-scale vorticity. The model therefore introduces no measurable anisotropy beyond current observational bounds.

Rotational damping and gravitational-wave energy injection operate as complementary processes: the first describes the natural decline of vorticity, and the second represents a small, radiation-like enhancement of the cosmic fluid. Acting together, they stabilise the large-scale geometry without altering Λ CDM parameters at

late times.

This minute rotational component satisfies all current CMB isotropy tests [2], confirming that $\omega/H \lesssim 10^{-9}$. The resulting geometry remains statistically isotropic but allows small-scale spin coherence that may manifest in galaxy-alignment data.

IV. PRIMORDIAL BLACK HOLES AS SOURCES OF RADIATION-LIKE ENERGY

Primordial black holes (PBHs) provide a natural physical channel through which the early universe could release a small fraction of its energy as gravitational radiation while remaining globally isotropic. Formed near the QCD epoch, around 10^{-6} – 10^{-5} s after the Big Bang with a critical temperature $T_c \approx 150$ MeV, these compact objects acted as localised sources of curvature and gravitational waves within the expanding radiation field [7].

The gravitational collapse of these overdense regions into PBHs converted kinetic and potential energy into compact curvature and gravitational-wave emission. As the Universe expanded, PBHs did not simply remain static: some merged or orbited within clusters, generating a stochastic background of gravitational waves that spread evenly across space. This produced a small but measurable increase in the mean radiation density—equivalent to a modest enhancement of the effective relativistic degrees of freedom.

This enhancement can be expressed as

$$\rho_{\text{eff}} = (1 + f_{\text{rad}}) \rho_{\text{std}}, \quad (1)$$

where $f_{\text{rad}} \approx 0.03$ – 0.04 represents the fractional excess of radiation energy. A small change of this magnitude slightly accelerates the early expansion rate and shortens the comoving sound horizon. The first-order relationships are

$$\frac{\Delta H}{H} \approx +\frac{1}{2}f_{\text{rad}}, \quad \frac{\Delta r_s}{r_s} \approx -\frac{1}{2}f_{\text{rad}}, \quad (2)$$

showing how even a few per cent increase in radiation density can measurably shift the early-Universe timeline.

PBHs thus act not as static energy sinks but as transient conversion mechanisms, transforming a minute fraction of local gravitational energy into radiation. Over cosmic time these black holes gradually released energy through gravitational waves—a process occurring naturally within general relativity and requiring no new physics. The total mass involved, estimated at $\sim 10^{10} M_\odot$ distributed across many comoving regions, suggests that PBHs played a temporary but important role. This energy release complements the rotational damping of primordial vorticity discussed earlier, forming a balanced dual mechanism. Acting together, these effects help stabilise the expanding geometry, keeping it consistent with the standard Λ CDM framework while offering a fresh physical interpretation of early-Universe evolution.

V. QUANTITATIVE MODELLING OF GW INJECTION AND ROTATIONAL EFFECTS

A quantitative estimate of the radiation-like energy fraction associated with primordial black hole (PBH) formation can be obtained by treating the resulting gravitational-wave (GW) background as an additional radiation component. During the QCD epoch, approximately $t \approx 10^{-6}$ – 10^{-5} s with a critical temperature $T_c \approx 150$ MeV, density fluctuations of order unity on horizon scales allowed the collapse of regions with characteristic masses $M_{\text{PBH}} \approx 10^{-1}$ – $10 M_\odot$. The subsequent clustering and binary interactions of these PBHs produced a stochastic GW background that redshifts as radiation, contributing a fractional excess f_{rad} to the total relativistic energy density.

Following standard estimates for GW production from PBH clustering [8–10], the energy density of the resulting background can be approximated as

$$\Omega_{\text{GW}} h^2 \approx (f_{\text{PBH}})^2 \left(\frac{M_{\text{PBH}}}{M_{\text{Pl}}} \right)^{5/3} \left(\frac{t_{\text{form}}}{t_{\text{Pl}}} \right)^{-1/3}. \quad (3)$$

For a cumulative PBH mass of approximately $10^{10} M_\odot$ distributed over $\sim 10^6$ horizon volumes, the fractional abundance f_{PBH} lies between 10^{-9} and 10^{-8} , yielding $f_{\text{rad}} = \Omega_{\text{GW}}/\Omega_{\text{rad}} \approx 0.03$ – 0.04 . Because the GW energy density redshifts as $\rho_{\text{GW}} \propto a^{-4}$, it behaves as a radiation component and thus contributes to the effective relativistic degrees of freedom.

The corresponding increase in relativistic degrees of freedom can be written as

$$\Delta N_{\text{eff}} \simeq 7.4 f_{\text{rad}}, \quad (4)$$

where the numerical factor reflects the photon–baryon coupling and temperature dependence during the radiation-dominated era. For $f_{\text{rad}} = 0.03$ – 0.04 , this gives $\Delta N_{\text{eff}} \approx 0.2$ – 0.3 , consistent with joint BBN–CMB constraints on light, electromagnetically coupled relics [11].

To first order in the radiation era, the Hubble parameter is modified as

$$H^2 = \frac{8\pi G}{3} (1 + f_{\text{rad}}) \rho_{\text{std}}, \quad (5)$$

leading to the simple scaling relations

$$\frac{\Delta H}{H} \approx +\frac{1}{2} f_{\text{rad}}, \quad \frac{\Delta r_s}{r_s} \approx -\frac{1}{2} f_{\text{rad}}. \quad (6)$$

For $f_{\text{rad}} = 0.03$ – 0.04 , the comoving sound horizon shortens from ≈ 147 Mpc in the standard Λ CDM model to ≈ 142 – 144 Mpc. The recombination time, which scales inversely with H , becomes about $t_{\text{rec}} \approx 374,000$ yr, with $f_{\text{rad}} \approx 0.1$ giving $t_{\text{rec}} \approx 340,000$ yr—close to the BBN limit where $\Delta N_{\text{eff}} \lesssim 0.6$.

The adjustments implied by $f_{\text{rad}} = 0.03$ – 0.04 raise the CMB-inferred Hubble constant $H_{0,\text{CMB}}$ from ≈ 67.4 to

f_{rad}	ΔN_{eff}	r_s (Mpc)	t_{rec} (kyr)	$H_{0,\text{CMB}}$ ($\text{km s}^{-1} \text{Mpc}^{-1}$)
0.00	0.0	147	380	67.4
0.03	≈ 0.2	144	374	68.4
0.04	≈ 0.3	142	372	68.7
0.10	≈ 0.6	137	359	70.1 (upper bound)

TABLE I. Sensitivity of key cosmological parameters to f_{rad} .

≈ 68.5 – $69 \text{ km s}^{-1} \text{Mpc}^{-1}$, narrowing the tension with local measurements. Boltzmann-code checks using CLASS indicate negligible distortion in the CMB power spectrum for $\Delta N_{\text{eff}} \lesssim 0.3$, supporting the model’s compatibility with current data.

The rotational damping, governed by $\omega \propto a^{-2}$, remains an independent process, but it may enhance GW production by 10 to 20 percent through anisotropic collapse of overdense regions. Together, these effects provide a complementary mechanism that operates entirely within the framework of general relativity, offering a refined understanding of the early Universe’s dynamics.

A secondary coupling arises between rotation and PBH clustering: regions with non-zero vorticity experience anisotropic collapse, which may enhance the quadrupole moment and thus potentially increase the efficiency of GW emission. This effect can be modelled by a small multiplicative correction to the stochastic background amplitude,

$$\Omega_{\text{GW}}^{\text{rot}} \simeq \Omega_{\text{GW}} (1 + \kappa \omega/H), \quad (7)$$

where $\kappa \approx 0.1$ – 0.2 quantifies the anisotropic enhancement derived from rotating-collapse simulations [9, 12]. In practice, this corresponds to a possible 10–20% increase in GW yield within the allowed rotational limits, pending further simulations to confirm the effect.

Having established the quantitative energy balance and its effect on key cosmological parameters, we now examine where this redistributed mass–energy resides in comoving space.

VI. BLACK HOLES BEYOND OBSERVATIONAL LIMITS

The model predicts that roughly 60–80 per cent of the total black-hole mass budget, around $10^{10} M_\odot$, becomes redistributed toward outer comoving regions through slow angular-momentum transport, analogous to viscous diffusion in accretion discs. This process, though speculative and observationally unconstrained beyond $z \gtrsim 2$, implies a subtle energy redistribution that preserves the Universe’s isotropy and sustains its faint spiral geometry, with $\omega/H \approx 10^{-9}$. No modification to general relativity or to the Λ CDM framework is required to maintain this residual structure.

This redistribution likely arises from rotational dynamics, where angular-momentum transfer, reminiscent of

vortices in hydrodynamic models [12], drives PBHs outward. Such behaviour finds qualitative support in N -body simulations of PBH clustering [13], which can be adapted to rotating cosmologies and show outward migration in rotating fields. The idea also echoes Gödel-like centrifugal effects [14], where rotation tends to push mass radially. Moreover, if the Universe extends beyond the observable horizon—estimated to be at least 250 times larger [15]—the presence of additional outer mass naturally strengthens this distribution, aligning with the model’s predictions.

VII. COUNTERARGUMENTS AND TOLERANCES

The rotational–spiral model introduces a modest early-time increase in radiation from PBH-sourced gravitational waves, coupled with a global rotation that diminishes as the Universe expands. The following sections outline potential challenges and how the model remains compatible with current observations.

A. PBH Formation Epoch and Persistence

The horizon mass, scaling with time as $M_H \sim c^3 t / G$, allows sub-solar seeds ($\sim 10^{-2}$ – $10^{-1} M_\odot$) to form at $t \approx 10^{-6}$ s, growing to solar or tens-of-solar-mass objects by 10^{-5} – 10^{-4} s, all well above the Hawking evaporation threshold ($\sim 10^{12}$ – 10^{15} g) [7]. The model assumes a total PBH mass budget of about $10^{10} M_\odot$, stable across formation times within this range. Early PBHs, forming around 10^{-6} s, would have interacted with both radiation and vorticity, while later ones dispersed, contributing to the cumulative mass total.

B. Seed Mass versus Number Density

Gravitational-wave injection and angular-momentum coupling depend on PBH density, ρ_{BH} , through $\dot{J}_{\text{sink}} \propto \rho_{\text{BH}} C(\sigma, \omega)$. Exchanging a few solar-mass PBHs for many sub-solar ones leaves the total density approximately constant, so the overall impact on the expansion rate and sound horizon remains unchanged.

C. Energy Injection Fraction and Early Dynamics

PBH formation and the resulting gravitational waves add a few per cent to the early Universe’s radiation density, expressed as $\rho_{\text{eff}} = (1 + f_{\text{rad}}) \rho_{\text{std}}$. This increase raises the expansion rate ($\Delta H / H \approx +\frac{1}{2} f_{\text{rad}}$) and shortens the sound horizon ($\Delta r_s / r_s \approx -\frac{1}{2} f_{\text{rad}}$), bringing the CMB-inferred Hubble constant closer to local measurements. Values up to $f_{\text{rad}} \approx 0.05$ remain compatible with

current observations, although higher values would begin to conflict with CMB data [15].

D. Early-Universe Harmony

The energy injection associated with PBH formation during the QCD epoch slightly modifies early expansion without disturbing Big Bang Nucleosynthesis (BBN). The corresponding increase in effective neutrino species, $\Delta N_{\text{eff}} \approx 0.2$ – 0.3 , remains well within the empirical limit of 0.6 and consistent with light-element abundances [11]. At the same time, the global rotation, decaying as $\omega \propto a^{-2}$, keeps the CMB isotropic with $\omega / H < 10^{-10}$, consistent with *Planck* limits [15]. The additional gravitational waves from PBHs also help smooth shear anisotropies, maintaining large-scale uniformity.

E. Stochastic Gravitational-Wave Background

The predicted energy fraction implies a present-day GW background with $\Omega_{\text{GW}} h^2 \lesssim 10^{-10}$ – 10^{-9} at nHz frequencies, remaining below current detection thresholds for NANOGrav and LIGO/Virgo [16], but potentially observable with future instruments such as LISA.

F. Microlensing and Compact-Object Counts

Most of the PBH mass budget, approximately 70–80%, resides in outer regions beyond $z > 2$, roughly 3 – 4×10^4 Mpc from us, placing it outside present microlensing and GW-detection ranges. The inner fraction remains consistent with microlensing limits requiring $f_{\text{PBH}} < 10^{-3}$ [17].

G. BAO, Sound Horizon, and Distance-Ladder Consistency

A sound-horizon reduction of roughly $-\frac{1}{2} f_{\text{rad}}$ (3–4%) fits comfortably within CMB, BAO, and supernova constraints, maintaining consistency with the Λ CDM model [1, 18]. While previous studies have shown that reducing the sound horizon alone cannot fully resolve the Hubble tension [18], the present model’s additional rotational and gravitational-wave contributions are supported by recent BAO measurements that confirm the adjusted scale [1].

H. Structure Formation and Early Massive Galaxies

This framework naturally accommodates the emergence of galaxies with $M \approx 10^9 M_\odot$ at redshifts $z \approx$

10–13, consistent with JWST detections and without overproducing later structures [19].

I. SMBH Demographics and Late-Time Black-Hole Budget

A total PBH mass of $\sim 10^{10} M_{\odot}$ matches the observed local supermassive black hole density, approximately $10^5 M_{\odot} \text{Mpc}^{-3}$, without producing an excess [20].

J. Parameter Degeneracies and Alternatives

While early-dark-energy models can also modify the sound horizon, the present approach combines rotational damping with early-time GW energy injection, offering distinct observational signatures and parameter degeneracies.

K. Relation to Other Rotating Cosmologies

Recent analyses of rotation-only cosmological models [21] indicate that pure background vorticity provides only a limited reduction of the Hubble tension under CMB constraints. Rotation on its own, however, produces changes in the expansion history that are at least an order of magnitude too small to account for the observed ΔH_0 ; the coupling with early-time GW energy injection is therefore essential to achieve the required magnitude while remaining consistent with isotropy constraints. The current model thus extends this scenario by combining the damped rotational component with PBH-driven gravitational-wave energy injection, yielding a composite mechanism consistent with Λ CDM bounds.

L. Compatibility with Standard Cosmology

Overall, the model remains compatible with Λ CDM when $f_{\text{rad}} \approx 0.03\text{--}0.04$ and $\Delta N_{\text{eff}} \approx 0.2\text{--}0.3$, values consistent with BBN–CMB constraints [11]. The resulting shift in recombination time to 340 000–370 000 yr stays within established observational tolerances.

VIII. CONCLUSION

This work presents a rotational–spiral cosmology in which a small primordial angular momentum and a brief period of gravitational-wave energy injection during the radiation era together influenced the evolution of the early universe. The model accounts for both the unexpectedly early formation of massive galaxies and the apparent tension between CMB-derived and locally measured values of the Hubble constant.

A modest enhancement of about 3–4% in the early radiation density, associated with PBH formation and gravitational-wave emission near the QCD epoch, shortens the comoving sound horizon and advances recombination to roughly 340 000–370 000 years after the Big Bang. The same process naturally accelerates structure formation while preserving isotropy and the overall Λ CDM dynamics.

Forthcoming surveys such as Euclid, LSST, DESI, and Roman will provide an opportunity to test this framework observationally. Coherent spin alignments detected across scales exceeding 20 Mpc would offer potential evidence for residual cosmic vorticity. The model therefore offers a minimal, observationally testable refinement of the early universe’s rotational and radiative history, operating entirely within established physics and without the need for new fundamental parameters.

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