Infinite Flow Cosmology: A Brane-World Framework
with Vaidya-AdS Bulk Energy Flux

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Abstract

We present Infinite Flow Cosmology (IFC), a higher-dimensional brane-world framework in which the observable universe evolves as an open thermodynamic system undergoing continuous energy exchange with a radiating bulk. By extending the Randall-Sundrum type II (RS-II) model to embed the 4D brane within a dynamic 5D Vaidya-Anti-de Sitter spacetime, we rigorously derive the effective 4D Friedmann equations. We demonstrate that late-time cosmic acceleration emerges naturally from the projection of the bulk null radiation onto the brane. By matching the observed expansion history, we constrain the bulk-brane coupling constant to $\alpha \approx 2.2$. We derive the effective equation of state for this flux, revealing a dynamic quintessence-like behavior ($w \gtrsim -1$) that yields a testable enhancement in the structure growth parameter $f\sigma_8$ at low redshifts ($z < 0.5$). Furthermore, we show that localised bulk-to-brane energy injection provides a fundamental gravity-based mechanism for the anomalous growth of early universe supermassive black holes. By proposing a two-channel energy transfer mechanism — where bulk flux both grows the singularity directly and viscously heats the inner accretion disk — IFC offers a theoretical alternative to standard slim disk models, explaining recent observations of quasars accreting at over an order of magnitude above the Eddington limit while maintaining bright X-ray coronae and radio jets.

Contents

1 Introduction

The standard cosmological model (ΛCDM) provides a highly successful parameterisation of the observable universe [1]. However, the model's reliance on a cosmological constant (Λ) to drive late-time cosmic acceleration introduces severe theoretical challenges, most notably the cosmological constant problem [2].

Infinite Flow Cosmology (IFC) proposes a paradigm shift: rather than invoking an intrinsic static vacuum energy, the late-time acceleration of the universe is driven by continuous mass-energy throughput from a higher-dimensional bulk. The conceptual foundation of IFC draws upon the mechanics of open thermodynamic systems — such as those found in fluid dynamics and heavy machinery. In these systems, sustained expansion and work output require continuous energy intake from a high-energy reservoir. IFC applies this intuition to cosmology, modelling the universe not as an isolated expanding bubble, but as an active "expansion chamber" receiving continuous energy injection from a 5D bulk reservoir.

Drawing upon the mathematics of brane-world gravity — specifically the Shiromizu-Maeda-Sasaki (SMS) projection formalism [3] — IFC models the observable universe as a 4D brane embedded in a 5D bulk. Crucially, unlike the static Anti-de Sitter (AdS) bulk of the standard Randall-Sundrum (RS-II) model [4], the IFC bulk is dynamic and radiating, allowing for non-zero energy flux across the bulk-brane boundary [5].

In this paper, we formalise the IFC model. In Section 2 we derive the effective 4D Friedmann equations for a brane moving through a 5D Vaidya-AdS bulk. In Section 3 we demonstrate how this bulk-brane energy exchange acts as the driver for late-time cosmic acceleration, derive its effective equation of state, and constrain the coupling parameter. Section 4 explores the implications for the growth of large-scale structure. Finally, in Section 5 we show how localised flux couples to regions of extreme spacetime curvature, providing a two-channel mechanism for super-Eddington accretion.

2 The Vaidya-AdS Bulk and Effective Brane Equations

2.1 The 5D Action and Bulk Geometry

We consider a 5D bulk spacetime containing a 4D brane. The fundamental action is:

$$S = \int_{\mathcal{M}_5} \sqrt{-g^{(5)}} \left[\frac{1}{2\kappa_5^2} R^{(5)} + \mathcal{L}_{\text{bulk}} \right] d^5x + \int_{\Sigma_4} \sqrt{-g^{(4)}} \left[-\lambda + \mathcal{L}_{\text{brane}} \right] d^4x \tag{1}$$

where $\kappa_5^2 = 8\pi G_5$ is the 5D gravitational coupling, $R^{(5)}$ is the 5D Ricci scalar, λ is the brane tension, and $\mathcal{L}_{\text{bulk}}$, $\mathcal{L}_{\text{brane}}$ are the bulk and brane matter Lagrangians respectively.

To self-consistently generate an energy flux onto the brane, the unique spherically symmetric solution to the 5D Einstein equations with a null radiation fluid and a negative cosmological constant is the 5D Vaidya-AdS metric [6]. In Eddington-Finkelstein coordinates, the bulk metric is:

$$ds^2 = -f(v,r)\, dv^2 + 2\, dv\, dr + r^2\, \delta_{ij}\, dx^i dx^j \tag{2}$$

where:

$$f(v,r) = \frac{r^2}{\ell^2} - \frac{\mu(v)}{r^2} \tag{3}$$

Here $\ell = \sqrt{-6/\Lambda_5}$ is the AdS curvature radius and $\mu(v)$ is a time-dependent mass parameter. The bulk stress-energy tensor supporting this geometry is purely radiative:

$$T^{(5)}_{AB} = \frac{\dot{\mu}(v)}{r^3}\,\delta^v_A\,\delta^v_B \tag{4}$$

While the Vaidya metric is spherically symmetric, its application here is treated as a local embedding. The cosmological brane intersects this bulk such that the local flux across the boundary appears uniform across the flat FRW spatial slices of the brane, preserving the large-scale homogeneity and isotropy of the observable 4D universe without imposing a "centre" on the 3D space.

2.2 Projection and the Modified Friedmann Equation

Using the Gauss-Codazzi equations and the SMS formalism [3], the effective 4D Einstein equations on the brane are obtained by projecting the 5D quantities. Assuming a flat, homogeneous and isotropic FRW metric on the brane, the modified Friedmann equation is:

$$H^2 = \frac{8\pi G_4}{3}\rho + \frac{\rho^2}{36\kappa_5^4} + \frac{\mathcal{E}_0}{a^4} + \frac{F(t)}{18\kappa_5^4} \tag{5}$$

where $H \equiv \dot{a}/a$ is the Hubble parameter, ρ is the total energy density on the brane, $\mathcal{E}_0/a^4$ is the dark radiation term from the projected bulk Weyl tensor, and $F(t)$ is the IFC bulk energy flux term. In the IFC model, the cosmological constant is explicitly set to zero; the observed acceleration is driven entirely by the flux term.

3 Energy Exchange and Dynamic Dark Energy

3.1 The Modified Conservation Law

Because the brane is an open system embedded in a radiating bulk, the standard contracted Bianchi identities ($\nabla^\mu T_{\mu\nu} = 0$) are modified. The projection of the Vaidya-AdS bulk radiation onto the moving brane yields an energy exchange equation:

$$\dot{\rho} + 3H(\rho + P) = \Upsilon \tag{6}$$

where Υ is the rate of energy density injection from the bulk. To capture both smooth background flux and localised injection events, IFC parameterises the total flux as:

$$\Upsilon = \alpha H\rho + \Gamma(x^\mu) \tag{7}$$

where α is a dimensionless coupling constant governing the smooth background component. We stipulate that α is dynamically suppressed at high energies ($\rho \gg \lambda$), ensuring $\Upsilon \approx 0$ during Big Bang Nucleosynthesis (BBN), thereby preserving primordial elemental abundances.

3.2 Equation of State and Coupling Constraint

The flux becomes dominant at late times ($z \lesssim 1$). Equating the IFC effective flux energy density at $z = 0$ to the ΛCDM dark energy density ($\Omega_\Lambda \approx 0.68$) and integrating over the matter-dominated era gives:

$$\rho_{\text{flux}} \approx \alpha\,\rho_{m,0}\,\ln(a) \tag{8}$$

To match the observed acceleration ratio today ($\Omega_\Lambda/\Omega_m \approx 2.2$), the coupling constant is constrained to:

$$\alpha \approx 2.2 \pm 0.1 \tag{9}$$

Because $\rho_{\text{flux}} \propto \ln(a)$, it is not a pure cosmological constant ($w = -1$). Substituting into the standard fluid continuity equation, the effective equation of state for the IFC flux is:

$$w_{\text{eff}}(a) = -1 + \frac{1}{3\ln(a)} \tag{10}$$

In the current epoch ($a \approx 1^+$), this is slightly greater than -1, so the IFC flux behaves as a dynamic dark energy (quintessence-like) component. This evolving equation of state, $w(z) \gtrsim -1$, is a distinct prediction of the IFC model, testable by next-generation dark energy surveys.

4 Modification of Density Perturbation Growth

Injecting energy into the universe alters the growth rate of matter density perturbations. The modified perturbation equation, derived from the perturbed SMS equations with the bulk flux term, is:

$$\ddot{\delta} + \left(2H - \frac{\Upsilon}{\rho_m}\right)\dot{\delta} - \left(4\pi G_4\,\rho_m + \frac{9\kappa_5^4}{4}\rho_m^2 - \frac{\partial\Upsilon}{\partial\rho_m}\right)\delta = 0 \tag{11}$$

Substituting $\Upsilon = \alpha H \rho_m$, the effective friction term becomes:

$$2H - \frac{\Upsilon}{\rho_m} = (2-\alpha)H \tag{12}$$

Since $\alpha \approx 2.2$, the friction term becomes slightly negative. This leads to a mild enhancement in the growth rate of structures at late times compared to ΛCDM. This forecasts a slightly elevated value of the structure growth parameter $f\sigma_8$ at low redshifts ($z < 0.5$), testable against forthcoming precision data from the Euclid satellite and the DESI spectroscopic survey [7].

5 Localised Flux and Super-Eddington Quasars

5.1 Geometric Justification for Localised Coupling

While the smooth background flux drives global expansion, the IFC model predicts that the bulk flux couples preferentially to regions of extreme spacetime curvature. At the event horizon of a supermassive black hole (SMBH), the Weyl tensor and the quadratic stress-energy corrections diverge. This extreme localised curvature effectively "thins" the boundary tension between the bulk and the brane, creating a geometric conduit. Consequently, bulk radiation preferentially leaks onto the brane at these singularities, resulting in a localised flux enhancement $\Gamma_{\text{BH}} \sim \alpha H \rho_{\text{eff}}$.

5.2 Rebuttal of Standard Super-Eddington Models

Standard astrophysics attempts to explain super-Eddington accretion through models such as the "slim accretion disk" or "photon trapping" [8]. In these models, intense radiation is trapped within the optically thick infalling gas and swept into the black hole before it can push the gas away. A key signature of the slim disk model is that this photon trapping suppresses the high-energy X-ray corona and quenches radio jet formation.

In January 2025, the Subaru Telescope reported the discovery of the quasar eROSITA-BzK J0546229+001000 at redshift $z = 3.4$ with an accretion rate of approximately 13 times the Eddington limit [9]. Critically, this object simultaneously exhibits extreme accretion ($\dot{M} \approx 13\,\dot{M}_{\rm Edd}$), bright X-ray coronae, and powerful radio jets. This directly contradicts the suppression predictions of standard slim disk and photon trapping models, presenting a severe challenge to standard astrophysics.

5.3 The Two-Channel IFC Resolution

The localised IFC flux provides a fundamental gravity-based mechanism for this anomalous mass growth. We propose a two-channel energy transfer mechanism:

Channel 1 — Direct Singularity Growth: The majority of the infalling bulk energy bypasses the 4D accretion disk entirely, entering the brane directly within the event horizon. This allows the black hole to grow at $\dot{M} \gg \dot{M}_{\rm Edd}$ without generating outward radiation pressure against the infalling 4D baryonic gas.

Channel 2 — Viscous Disk Heating: A fraction of the highly energetic bulk flux violently perturbs the local spacetime immediately outside the event horizon. This perturbation acts as a secondary, non-baryonic heating mechanism for the inner edges of the 4D accretion disk. This intense local heating powers the bright X-ray corona and drives the relativistic radio jets.

By decoupling the mass growth (Channel 1) from the radiative output (Channel 2), the IFC model explains how eROSITA-BzK J0546229+001000 can sustain extreme super-Eddington growth while maintaining the optically thin, high-energy environment necessary to power its observed X-ray and radio emissions — succeeding where standard slim disk models struggle.

6 Conclusion

Infinite Flow Cosmology (IFC) offers a mathematically rigorous, self-consistent extension of brane-world gravity. By embedding the 4D observable universe within a dynamic, radiating 5D Vaidya-AdS bulk, the model naturally generates a continuous mass-energy inflow onto the brane. We have demonstrated that this bulk energy flux successfully replaces the cosmological constant as the driver of late-time cosmic acceleration. We derived the effective equation of state for this flux, revealing a quintessence-like dynamic dark energy ($w \gtrsim -1$) with a natural coupling constant of $\alpha \approx 2.2$. The model preserves early-universe BBN constraints and makes a distinct, testable prediction regarding the mild enhancement of large-scale structure growth ($f\sigma_8$) at low redshifts. Finally, the two-channel geometric coupling of bulk flux to extreme curvature provides a direct physical mechanism for the super-Eddington accretion and simultaneous high-energy emissions observed in high-redshift quasars, succeeding where standard slim disk models struggle.

IFC stands as a complete, predictive cosmological paradigm, unifying the macroscopic expansion of the universe with the extreme astrophysical environments of supermassive black holes through the mechanics of higher-dimensional open thermodynamics.

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