

# Fast Radio Bursts as Probes of Six-Dimensional Spacetime Structure

## Q-Field Signatures in Dispersion Measure Statistics, Cosmic Web Tomography, and the Modified Macquart Relation

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### Abstract

Fast radio bursts (FRBs) traverse cosmological distances, accumulating dispersion measures (DM) that encode the integrated free electron density along the line of sight. We derive three independent, quantitative predictions of the 3D+3D discrete spacetime framework for FRB observables. **\*\*Channel 1:\*\*** The Q-field deepens the gravitational potential of galaxy halos through enclosed effective mass  $M_Q^{\text{eff}} \approx 5M_b$  (built up at  $r \lesssim 30$  kpc and persisting at all larger radii), modifying the CGM gas profile and predicting a host DM enhancement of  $\Delta\text{DM}_{\text{host}} \approx 8\text{--}18 \text{ pc cm}^{-3}$  for sub-critical galaxies ( $M_b < M_{\text{crit}} = 2.43 \times 10^{10} M_\odot$ ), scaling as  $\Delta\text{DM}_{\text{host}} \propto (1 + M_Q^{\text{eff}}/M_b)^{3\beta_{\text{prof}}/4}$ , where  $\beta_{\text{prof}}$  is the gas profile slope. **\*\*Channel 2:\*\*** The cosmic web periodicity at  $\lambda_{13} = 0.856$  Mpc produces a localized feature in the DM–galaxy cross-correlation function  $\xi_{\text{DM-gal}}(r)$  that is absent in  $\Lambda\text{CDM}$ , where the 1-halo/2-halo transition creates only a smooth shoulder with no preferred sub-BAO scale; detection requires  $\gtrsim 1000$  localized FRBs with foreground spectroscopic surveys, making this the most distinctive but also the most demanding channel. **\*\*Channel 3:\*\*** The dynamical dark energy equation of state  $w(z) = -1 + 1/(3H(z)\tau_\beta)$ , where  $\tau_\beta$  is the moduli activation timescale, increases  $H(z)$  at  $z > 0$ , reducing the mean Macquart relation by  $\sim 1\text{--}4\%$  at  $z = 0.5$  depending on  $\tau_\beta$  (20--100 Gyr, constrained by CMB+BAO+SN); the primary degeneracy is with  $f_{\text{IGM}}$  ( $\pm 6\%$  uncertainty), but the redshift-dependent shape discriminates: the 3D+3D signal grows from  $\sim -0.5\%$  at  $z = 0.1$  to  $\sim -2\%$  at  $z = 1.0$  while an  $f_{\text{IGM}}$  rescaling produces a flat offset at all  $z$ . All three channels produce falsifiable predictions testable with CHIME, ASKAP/CRAFT, DSA-110, and DSA-2000. We provide explicit falsification criteria for each channel.

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## 1. Introduction

### 1.1 Fast Radio Bursts as Cosmological Probes

Fast radio bursts (FRBs) are millisecond-duration radio pulses originating from extragalactic sources [1,2]. Their defining observable—the dispersion measure (DM)—quantifies the integrated column density of free electrons along the line of sight:

$$\text{DM} = \int_0^d n_e dl \quad (1.1)$$

where  $n_e$  is the free electron number density and  $d$  is the path length. For extragalactic FRBs, the observed DM decomposes into four contributions [3]:

$$\text{DM}_{\text{obs}} = \text{DM}_{\text{MW,ISM}} + \text{DM}_{\text{MW,halo}} + \text{DM}_{\text{IGM}}(z) + \frac{\text{DM}_{\text{host}}}{1+z} \quad (1.2)$$

The intergalactic medium (IGM) contribution follows the Macquart relation [3]:

$$\langle \text{DM}_{\text{IGM}}(z) \rangle = \frac{3cH_0\Omega_b f_{\text{IGM}}}{8\pi Gm_p} \int_0^z \frac{(1+z') dz'}{E(z')} \quad (1.3)$$

where  $E(z) = H(z)/H_0$  and  $f_{\text{IGM}} \approx 0.83$  is the fraction of baryons in the IGM [4]. The scatter around this mean relation encodes information about the large-scale distribution of baryons, feedback processes, and the cosmic web structure [5,6].

### 1.2 The 3D+3D Framework

The 3D+3D discrete spacetime theory proposes that spacetime has six dimensions with metric signature  $(-, +, +, +, -, -)$ , where two extra temporal dimensions  $(\tau_2, \tau_3)$  are compactified on a 2-torus  $T^2$  with canonical parameters [7,8]:

$$L_2 = 9.5 \text{ ly}, \quad L_3 = 6.0 \text{ ly}, \quad T_2 = 30 \text{ yr}, \quad T_3 = 19 \text{ yr} \quad (1.4)$$

The compactification produces scalar Q-fields  $(Q_2, Q_3)$  that modify the effective gravitational potential at galactic scales [9]:

$$V_{\text{eff}}(r) = -\frac{GM}{r} [1 + \beta_2 Q_2(r) + \beta_3 Q_3(r)] \quad (1.5)$$

with characteristic breathing scales  $\lambda_2 = 4.30 \text{ kpc}$ ,  $\lambda_3 = 11.7 \text{ kpc}$  following a golden ratio progression [10]. This framework has been validated against SPARC rotation curves (175 galaxies, zero free parameters)

[11], SLACS gravitational lensing ( $4\sigma$  detection) [12], NANOGrav pulsar timing [13], and cosmic web structure at  $\lambda_{13} = 0.856$  Mpc [14].

### 1.3 Why FRBs Probe 3D+3D

FRBs are uniquely suited to test the 3D+3D framework because:

1. **They traverse multiple scale regimes:** From host galaxy ( $\sim$  kpc, where Q-fields are active) through the IGM ( $\sim$  Mpc, where cosmic web structure emerges) to cosmological distances (where  $w_0 \neq -1$  modifies  $H(z)$ ).
2. **DM is a line-of-sight integral:** Unlike rotation curves (which probe local gravitational fields) or lensing (which probes projected mass), DM integrates electron density over the full path, providing sensitivity to distributed Q-field effects.
3. **The scatter is informative:** The variance of DM at fixed  $z$  encodes the clumpiness of baryons, which is directly modified by Q-field baryon redistribution.
4. **Sample sizes are growing rapidly:** CHIME has detected  $>600$  FRBs [15], with  $>100$  localized to host galaxies [4,16]. DSA-2000 will localize thousands per year [17].

### 1.4 Paper Structure

Section 2 derives the Q-field contribution to host galaxy DM, including the radial profile and enclosed mass argument. Section 3 analyzes cosmic web periodicity signatures in DM statistics, with explicit  $\Lambda$ CDM comparison. Section 4 computes the modified Macquart relation from the 3D+3D dark energy equation of state  $w(z) = -1 + 1/(3H(z)\tau_\beta)$  and provides a quantitative degeneracy analysis with  $f_{\text{IGM}}$ ,  $H_0$ , and  $\Omega_b$ . Section 5 presents combined statistical analysis and detection forecasts. Section 6 establishes falsification criteria. Section 7 verifies Vainshtein screening consistency. Section 8 discusses results and Section 9 summarizes conclusions.

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## 2. Channel 1: Q-Field Modification of Host Galaxy DM

### 2.1 Baryon Distribution in the Q-Field Framework

In the 3D+3D framework, the effective gravitational potential binds baryons more strongly than Newtonian gravity alone [9]. For a galaxy with baryonic mass  $M_b$ , the total effective mass profile is:

$$M_{\text{eff}}(r) = M_b(r) + M_Q(r) \quad (2.1)$$

where the Q-field contribution to effective mass is:

$$M_Q(r) = \frac{\beta^2}{4\pi} \frac{M_b}{M_{\text{Pl}}^2} \int_0^r 4\pi r'^2 \rho_b(r') Q(r') dr' \quad (2.2)$$

In hydrostatic equilibrium, the baryon density profile satisfies:

$$\frac{dP}{dr} = -\frac{GM_{\text{eff}}(r)\rho_g(r)}{r^2} \quad (2.3)$$

where  $\rho_g$  is the gas density.

## 2.2 Q-Field Radial Profile and Enclosed Mass

**\*\*Critical clarification:\*\*** The ratio  $M_Q^{\text{eff}}/M_b \approx 5$  calibrated from SPARC rotation curves [11] describes the *\*enclosed\** effective mass at galactic scales ( $r \lesssim \lambda_3 \approx 12$  kpc). The Q-field profile itself—its local amplitude—decays at large radii. However, the gravitational effect depends on *\*enclosed mass\**, not local field strength.

For temporal compactification (signature  $(-, -)$ ), the static Q-field equation is:

$$\nabla^2 Q_i + m_i^2 Q_i = \frac{\beta_i \rho_b}{M_{\text{Pl}}^2} \quad (2.4)$$

where  $m_i = 2\pi/\lambda_i$ . The temporal signature yields the same sign for the  $\nabla^2$  and  $m^2$  terms, producing an **oscillatory** Green's function:

$$G(r) \sim \frac{\sin(m_i r)}{4\pi r} \quad (2.5)$$

This is fundamentally different from spatial compactification (which gives Yukawa decay  $\sim e^{-mr}/r$ ). The Q-field has long-range oscillatory behavior with a  $1/r$  envelope.

**\*\*Theorem 2.1 (Enclosed Mass Saturation).\*\*** \*The enclosed Q-field effective mass  $M_Q^{\text{eff}}(< r)$  is dominated by the inner region  $r \lesssim \text{few} \times \lambda_3$  and saturates at  $M_Q^{\text{eff}} \approx 5M_b$  for sub-critical galaxies. At larger radii, the oscillatory Q-field contributions partially cancel, adding negligible net enclosed mass.\*

**\*\*Lemma 2.1 (Mathematical bound).\*\*** \*For baryonic density  $\rho_b(r) \leq \rho_0 e^{-r/r_d}$  with disk scale  $r_d \approx 3$  kpc, the residual Q-field mass beyond radius  $R$  satisfies  $M_Q^{\text{eff}}(> R)/M_Q^{\text{eff}}(\text{total}) \leq e^{-R/r_d}[(R/r_d)^2 + 2(R/r_d) + 2]/2$ . At  $R = 30$  kpc  $= 10 r_d$ :  $\varepsilon < 2.8 \times 10^{-3}$  (i.e.,  $> 99.7\%$  enclosed). The proof uses  $|\sin(mr)/r| \leq 1/r$  (Coulomb bound on the oscillatory Green function), so the exponential decay of  $\rho_b$  dominates convergence.\*  $\square$

**Consequence for CGM:** The gravitational potential at CGM radii ( $r \sim 50\text{--}200$  kpc) is:

$$\Phi(r) = -\frac{G [M_b + M_Q^{\text{eff}}(< 30 \text{ kpc})]}{r} \approx -\frac{6 GM_b}{r} \quad (2.6)$$

The potential is  $\sim 6\times$  deeper than Newtonian at all CGM scales, despite the Q-field amplitude being locally small at  $r > 30$  kpc. This distinction—enclosed mass vs. local field—is the key physical argument.

## 2.3 The DM\_host Enhancement: Derivation from Hydrostatic Equilibrium

The dispersion measure from the host galaxy is:

$$\text{DM}_{\text{host}} = \int_0^{R_{\text{vir}}} n_e(r) dl \quad (2.7)$$

**Derivation from first principles.** For isothermal gas at temperature  $T_{\text{gas}}$  (equivalently, velocity dispersion  $\sigma_{\text{gas}}$ ) in a gravitational potential  $\Phi(r)$ , the hydrostatic equilibrium equation is:

$$\sigma_{\text{gas}}^2 \frac{d \ln \rho_g}{dr} = -\frac{d\Phi}{dr} \quad (2.8)$$

with solution:

$$\rho_g(r) = \rho_0 \exp \left[ -\frac{\Phi(r)}{\sigma_{\text{gas}}^2} \right] \quad (2.9)$$

For an NFW-like total mass profile  $M(< r) = M_{\text{eff}} \cdot r / (r + r_s)$ , we solve Eq. (2.8) numerically for both Newtonian ( $M_{\text{eff}} = M_b$ ) and 3D+3D ( $M_{\text{eff}} = (1 + \alpha)M_b$  with  $\alpha = M_Q^{\text{eff}}/M_b \approx 5$ ) potentials.

**Self-consistent normalization:** The total gas mass is conserved between the two models (same baryons, different potential). The deeper 3D+3D potential concentrates gas toward the center, increasing  $n_e$  along lines of sight through the halo interior:

$r$ (kpc)	$n_e^{3D3D}/n_e^N$	Physical effect
5	6.5	Strong concentration
20	3.7	Enhanced retention
50	2.1	Moderate enhancement
100	1.4	Mild enhancement
200	1.0	Converges

Integrating the line-of-sight DM from 5 to 250 kpc (calibrated to  $n_e = 10^{-4} \text{ cm}^{-3}$  at 50 kpc) and applying a geometric path-length factor  $f_{\text{path}} \approx 0.5$ :

$$\text{DM}_{\text{host}}^N \approx 23 \text{ pc cm}^{-3}, \quad \text{DM}_{\text{host}}^{3D3D} \approx 40 \text{ pc cm}^{-3} \quad (2.10)$$

$$\boxed{\Delta \text{DM}_{\text{host}} \approx 17 \times f_{\text{path}} \approx 8 \text{ pc cm}^{-3} \quad (\text{fiducial sub-critical host})} \quad (2.11)$$

With the uncertainty on CGM density ( $n_e$  uncertain by factor  $\sim 2\text{--}3$ ):

$$\Delta\text{DM}_{\text{host}} \approx 5\text{--}18 \text{ pc cm}^{-3} \quad (2.12)$$

## 2.4 Mass Dependence

The Q-field enhancement depends on the host galaxy mass through the enclosed mass ratio:

$$\Delta\text{DM}_{\text{host}}(M_b) = \Delta\text{DM}_0 \times \left(1 + \frac{M_Q^{\text{eff}}(M_b)}{M_b}\right)^{3\beta_{\text{prof}}/4} \quad (2.14)$$

For sub-critical galaxies ( $M_b < M_{\text{crit}}$ ),  $M_Q^{\text{eff}}/M_b$  grows with mass (more baryonic source  $\rightarrow$  stronger Q-field). For super-critical galaxies, nonlinear saturation suppresses the growth [19]. The scaling is:

$$\Delta\text{DM}_{\text{host}} \propto M_b^{0.38} \quad (M_b < M_{\text{crit}}) \quad (2.15)$$

slightly weaker than  $M_b^{1/2}$  due to the  $3\beta/4$  exponent.

## 2.5 Comparison with $\Lambda$ CDM

In  $\Lambda$ CDM, the host DM is determined by the baryonic gas distribution in the dark matter halo potential:

$$\text{DM}_{\text{host}}^{\Lambda\text{CDM}} = \int_0^{R_{200}} n_e^{\text{NFW}}(r) dl \quad (2.16)$$

The  $\Lambda$ CDM prediction depends on the halo mass (a free parameter fitted from rotation curves or abundance matching), while the 3D+3D prediction depends on  $M_b$  alone (zero free parameters).

**Key discriminator:** In 3D+3D, the  $\text{DM}_{\text{host}}$  enhancement correlates with  $M_b$  (measured independently from luminosity), not with inferred halo mass. The predicted scaling  $\Delta\text{DM}_{\text{host}} \propto M_b^{0.38}$  is a specific, testable prediction.

## 2.6 Observational Test

**Prediction 2.1:** For FRBs localized to host galaxies with measured stellar masses, the host DM should show a systematic mass-dependent excess compared to ISM-only models. Leung et al. (2025) find that more massive hosts show systematically *lower* DMs, consistent with stronger feedback ejecting gas. The 3D+3D prediction adds a competing retention effect, which could explain observed tension between CGM models and data.

**Required sample:**  $\sim 300$  localized FRBs with host galaxy stellar masses, to achieve  $3\sigma$  sensitivity to the predicted scaling.

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### 3. Channel 2: Cosmic Web Periodicity in DM Statistics

#### 3.1 The $\lambda_{13}$ Signature

The 3D+3D framework predicts a characteristic periodicity in the cosmic web at [14]:

$$\lambda_{13} = 0.856 \text{ Mpc} \quad (3.1)$$

This scale emerges from the harmonic coupling of the two Q-field modes through the golden ratio ladder [10]:

$$\lambda_{13} = \lambda_3 \times \phi^{n_{\text{step}}} \quad (3.2)$$

where  $n_{\text{step}} = 7$  and  $\phi = (1 + \sqrt{5})/2$ . This periodicity creates characteristic baryon density enhancements along cosmic filaments, with overdensity nodes separated by  $\sim \lambda_{13}$ .

#### 3.2 Effect on DM Statistics

An FRB at redshift  $z$  traverses a comoving distance  $d_c(z)$ . At  $z = 0.5$ :  $d_c \approx 1950 \text{ Mpc}$ , crossing  $N_\lambda \approx 2280$  intervals of  $\lambda_{13}$ . Each filament crossing contributes a DM modulation of:

$$\delta\text{DM}_{\text{per crossing}} \approx \bar{n}_e \times \delta_{\text{fil}} \times \lambda_{13} \times f_{\text{fil}} \approx 0.3 \text{ pc cm}^{-3} \quad (3.3)$$

Since the crossings have random phases along different lines of sight, the cumulative effect is incoherent noise:

$$\sigma_{\text{DM}}^{\lambda_{13}} \approx \delta\text{DM}_{\text{per crossing}} \times \sqrt{N_\lambda} \approx 0.3 \times \sqrt{2280} \approx 14 \text{ pc cm}^{-3} \quad (3.4)$$

This represents  $\sim 3\%$  of  $\langle\text{DM}_{\text{IGM}}(z = 0.5)\rangle \approx 500 \text{ pc cm}^{-3}$ , comparable to the observed fluctuation parameter  $F$  from Baptista et al. [5].

#### 3.3 The Key Prediction: Spatial Correlation Structure

The 3D+3D prediction is **not** about the total scatter amplitude (which  $\Lambda\text{CDM}$  also produces through large-scale structure) but about the **spatial correlation structure** of DM residuals.

Define the DM residual:

$$\Delta\text{DM}(z, \hat{n}) = \text{DM}_{\text{IGM}}^{\text{obs}}(z, \hat{n}) - \langle\text{DM}_{\text{IGM}}(z)\rangle \quad (3.5)$$

The cross-correlation of DM residuals with foreground galaxy density at transverse separation  $r$  is:

$$\xi_{\text{DM-gal}}(r) = \frac{\langle\Delta\text{DM} \cdot \delta_g(r)\rangle}{\sigma_{\text{DM}}\sigma_g} \quad (3.6)$$

The 3D+3D framework predicts that  $\xi_{\text{DM-gal}}(r)$  has a **localized feature** at  $r = \lambda_{13} = 0.856 \text{ Mpc}$  superimposed on the smooth large-scale correlation.

### 3.4 Explicit $\Lambda$ CDM Comparison and NoGo Argument

**\*\*Theorem 3.1 ( $\Lambda$ CDM NoGo).** **\*\*** Standard  $\Lambda$ CDM cannot produce a narrow ( $\sigma_r \lesssim 0.1$  Mpc) peak at  $r = 0.856$  Mpc in the DM-galaxy cross-correlation function  $\xi_{\text{DM-gal}}(r)$ .\*

**Proof** (by exhaustion of mechanisms):

In  $\Lambda$ CDM, the DM-galaxy cross-correlation decomposes into halo model terms [20]:

$$\xi_{\text{DM-gal}}^{\Lambda\text{CDM}}(r) = \xi_{1h}(r) + \xi_{2h}(r) \quad (3.7)$$

We examine all known mechanisms that could create structure at  $r \sim 0.856$  Mpc:

**(a) 1-halo/2-halo transition:** The 1-halo term ( $\text{NFW} \times \text{gas profile}$ ) dominates at  $r < R_{\text{vir}} \sim 200$  kpc; the 2-halo term ( $b^2 \xi_{\text{mm}}$ ) dominates at  $r > 2$  Mpc. The transition creates a smooth shoulder with minimum width  $\Delta(\log r) > 0.3$  dex, corresponding to  $\Delta r > 0.6$  Mpc. This is  $12\times$  broader than the 3D+3D prediction ( $\sigma_r = 0.05$  Mpc).

**(b) BAO residuals:** Baryon acoustic oscillations produce wiggles in  $P(k)$  at  $k \lesssim 0.3 h/\text{Mpc}$ , fully damped at  $k > 0.5 h/\text{Mpc}$ . No residual exists at  $k \sim 5 h/\text{Mpc}$  ( $r \sim 0.856$  Mpc).

**\*\* (c) Baryonic feedback:** **\*\*** AGN feedback suppresses  $P(k)$  smoothly at  $k \sim 1\text{--}10 h/\text{Mpc}$  by 5–20% (EAGLE [26], BAHAMAS [27], Flamingo [28] simulations). This is a \*smooth suppression\*, not a peak.

**\*\* (d) Halo exclusion:** **\*\*** Creates a \*suppression\* (wrong sign) at  $k \sim 2\pi/R_{\text{vir}}$ , and the scale depends on the halo mass function (broad). Cannot produce a narrow peak.

**(e) Galaxy assembly bias:** Modifies clustering amplitude, but does not create preferred scales.  $\square$

The key discriminator is **feature width**: the 3D+3D prediction is a peak at  $0.856 \pm 0.05$  Mpc ( $\sigma_r/r = 6\%$ ), while the narrowest possible  $\Lambda$ CDM feature (1h-2h transition) has  $\sigma_r/r > 30\%$ . No published hydrodynamical simulation produces a narrow feature at this scale.

**\*\*Theorem 3.2 (Fourier NoGo).** **\*\*** The Fourier uncertainty principle provides an independent proof. A feature in  $\xi(r)$  with width  $\sigma_r = 0.05$  Mpc requires  $P(k)$  to contain structure spanning  $\Delta k \geq 1/(2\sigma_r) = 10 \text{ Mpc}^{-1}$  around  $k_0 = 2\pi/0.856 \approx 7.3 \text{ Mpc}^{-1}$ . In  $\Lambda$ CDM,  $P(k)$  is smooth at these scales (effective index  $n_{\text{eff}} \approx -2.7$  with  $|dn_{\text{eff}}/d \ln k| < 0.5$ ), so the minimum achievable feature width is  $\sigma_r^{\text{min}} \approx 0.3\text{--}0.5$  Mpc ( $6\text{--}10\times$  broader). Furthermore, BAO wiggles—the only oscillatory feature in  $P(k)$ —are damped by  $\exp(-k^2/k_D^2)$  with  $k_D \approx 0.15 \text{ Mpc}^{-1}$ , giving zero residual at  $k = 7.3 \text{ Mpc}^{-1}$ .\*  $\square$

**Observational test:** Fit  $\xi_{\text{DM-gal}}(r)$  with a smooth halo model plus an optional Gaussian peak:

$$\xi_{\text{model}}(r) = \xi_{\text{halo}}(r) + A \exp \left[ -\frac{(r - \lambda_{13})^2}{2\sigma_\lambda^2} \right] \quad (3.8)$$

Test whether  $A > 0$  at significant confidence.



### 3.5 Statistical Feasibility

With  $N_{\text{FRB}}$  localized FRBs and a foreground spectroscopic galaxy survey (DESI-like,  $n_{\text{gal}} \sim 0.01 \text{ Mpc}^{-3}$ ), the number of FRB-galaxy pairs in a shell at  $r \sim 0.856 \text{ Mpc}$  is:

$$N_{\text{pairs}} \approx N_{\text{FRB}} \times n_{\text{gal}} \times 4\pi r^2 \Delta r \times d_c \quad (3.9)$$

$N_{\text{FRB}}$	$N_{\text{pairs}}$	SNR (for $A = 0.02$ )
100	$\sim 10^3$	$\sim 0.6\sigma$
500	$\sim 5 \times 10^3$	$\sim 1.4\sigma$
1000	$\sim 10^4$	$\sim 2.0\sigma$
5000	$\sim 5 \times 10^4$	$\sim 4.5\sigma$

**Honest assessment:** Channel 2 is the most distinctive prediction but also the most demanding observationally. A  $3\sigma$  detection requires  $\sim 2000$ – $3000$  localized FRBs with foreground spectroscopic surveys, likely achievable with DSA-2000 by  $\sim 2030$ .

## 4. Channel 3: Modified Macquart Relation from Dynamical Dark Energy

### 4.1 The 3D+3D Dark Energy Equation of State

In the 3D+3D framework, dark energy arises from the time-dependent activation of the third temporal dimension  $\tau_3$ , governed by the metric coefficient  $\beta(t)$  [21,22]. The exponential activation model gives [22]:

$$\beta(t) = \beta_{\text{max}} \left( 1 - e^{-t/\tau_\beta} \right) \quad (4.1)$$

The equation of state follows directly:

$$\boxed{w(z) = -1 + \frac{1}{3H(z)\tau_\beta}} \quad (4.2)$$

At  $z = 0$ :

$$w_0 = -1 + \frac{1}{3H_0\tau_\beta} \quad (4.3)$$

**Key properties of this formula:**

- $w > -1$  at all redshifts (no phantom crossing) — a falsifiable prediction
- $w(z) \rightarrow -1$  as  $z \rightarrow \infty$  ( $\Lambda$ CDM recovered at high redshift)
- $w$  deviates most from  $-1$  at  $z = 0$  (late-time effect)
- The single parameter  $\tau_\beta$  controls all dark energy phenomenology

## 4.2 Observational Constraints on $\tau_\beta$

The timescale  $\tau_\beta$  is constrained by cosmological data. We perform a self-consistent analysis requiring: (i) CMB acoustic scale  $\theta_* = r_s/D_A(z_*)$  preserved, (ii)  $\Omega_m h^2 = 0.143$  (CMB peak heights), (iii) BAO  $D_V(z)/r_s$  compatible at  $< 3\sigma$ , (iv) SN distance moduli compatible at  $< 3\sigma$ .

$\tau_\beta$ (Gyr)	$w_0$	$w_a$ (CPL)	$H_0$ (km/s/Mpc)	$\Omega_m$	BAO $z = 0.5$	SN $\Delta\mu$	Status
10	-0.52	-0.53	58.4	0.42	+3.5%	+0.12 mag	Excluded
20	-0.76	-0.27	62.7	0.36	+1.6%	+0.06 mag	Consistent
30	-0.84	-0.18	64.2	0.35	+1.0%	+0.04 mag	Consistent
50	-0.90	-0.11	65.5	0.33	+0.6%	+0.02 mag	Consistent
100	-0.95	-0.05	66.5	0.32	+0.2%	+0.01 mag	Consistent

Combined cosmological data constrain  $\tau_\beta \gtrsim 20$  Gyr, corresponding to  $w_0 \lesssim -0.76$ . DESI DR2 BAO data combined with CMB (Planck) and Type Ia supernovae (Union3/DES5) show evidence for  $w_0 \neq -1$  at  $\sim 2.5$ -- $4.2\sigma$  depending on the dataset combination and the dark energy parameterization used [29]. Note that BAO-only constraints are weaker ( $\sim 2\sigma$ ), while the strongest evidence ( $\sim 4\sigma$ ) appears in DESI+CMB+SN combinations using the CPL parameterization, where phantom crossing ( $w < -1$  at some redshifts) is preferred. Since the 3D+3D framework forbids phantom crossing by construction ( $w > -1$  always), the precise level of agreement depends on which DESI dataset combination is used. The **observationally allowed range** is:

$$\boxed{20 \lesssim \tau_\beta \lesssim 100 \text{ Gyr}, \quad -0.95 \lesssim w_0 \lesssim -0.76} \quad (4.4)$$

**Edison Mode note:** Earlier versions of this paper used  $\tau_\beta = 10$  Gyr ( $w_0 = -0.52$ ) from galactic screening scale matching. This value is excluded by combined CMB+BAO+SN data, as correctly identified by independent verification [30]. The formula Eq. (4.2) remains valid; only the numerical value of  $\tau_\beta$  requires revision. The galactic screening timescale and the cosmological activation timescale may differ, with  $\tau_\beta^{\text{cosmo}} > \tau_\beta^{\text{galactic}}$ .

## 4.3 Modified Macquart Relation

With  $w(z)$  from Eq. (4.2), the exact Hubble rate is:

$$E^2(z) = \Omega_m(1+z)^3 + \Omega_{\text{DE}} \exp \left( 3 \int_0^z \frac{1+w(z')}{1+z'} dz' \right) \quad (4.5)$$

where  $w(z') = -1 + 1/(3H(z')\tau_\beta)$  from Eq. (4.2). This is the exact 3D+3D prediction, not a CPL approximation. The  $w_a$  values in Table 4.2 are effective CPL mappings provided for comparison with survey analyses that report constraints in the  $(w_0, w_a)$  plane; the underlying theory is fully specified by a single parameter  $\tau_\beta$ .

The predicted FRB DM deviation from  $\Lambda$ CDM at fixed cosmological parameters:

$z$	$\delta\text{DM} (\tau_\beta = 30)$	$\delta\text{DM} (\tau_\beta = 50)$	$\delta\text{DM} (\tau_\beta = 100)$
0.1	−0.8%	−0.5%	−0.2%
0.3	−1.9%	−1.1%	−0.6%
0.5	−2.6%	−1.6%	−0.8%
1.0	−3.4%	−2.0%	−1.0%
1.5	−3.5%	−2.0%	−1.0%
2.0	−3.3%	−1.9%	−0.9%

#### 4.4 Degeneracy Analysis

The primary degeneracy remains with  $f_{\text{IGM}}$ . However, the **shape discriminator** is robust across the allowed  $\tau_\beta$  range:

$$\frac{\delta(z=1.0)}{\delta(z=0.1)} \approx 4.5\text{--}4.9 \quad (3\text{D}+3\text{D}) \quad \text{vs.} \quad 1.00 \quad (f_{\text{IGM}} \text{ shift}) \quad (4.6)$$

A flat rescaling of  $f_{\text{IGM}}$ ,  $H_0$ , or  $\Omega_b$  produces a constant fractional offset at all  $z$ . The 3D+3D signal grows from  $\sim -0.5\%$  at  $z = 0.1$  to  $\sim -2\%$  at  $z = 1.0$ , regardless of  $\tau_\beta$ .

#### 4.5 Detection Forecast

For the allowed range  $\tau_\beta = 20\text{--}100$  Gyr:

$\tau_\beta$ (Gyr)	Signal at $z = 0.5$	$N_{\text{FRB}}$ for $3\sigma$
20	−3.6%	$\sim 500$
50	−1.6%	$\sim 2500$
100	−0.8%	$\sim 10000$

DSA-2000 ( $\sim 10^4$  localized FRBs) can probe the full allowed range.

4.6 Falsification Criteria

Channel 3 falsification requires observation of **any one** of:

- 1.  $w < -1$  (phantom crossing) detected at  $> 5\sigma \Rightarrow$  fundamental 3D+3D prediction violated
- 2.  $w_0 = -1.00 \pm 0.02$  established with high significance  $\Rightarrow$  no moduli dynamics
- 3. FRB shape ratio  $\delta(z = 1)/\delta(z = 0.1)$  consistent with 1.00 (flat) at  $> 3\sigma$  with  $N > 2000 \Rightarrow$  no  $w(z)$  evolution of predicted form

5. Combined Statistical Analysis

5.1 Summary of Predictions

Channel	Observable	3D+3D Prediction	$\Lambda$ CDM Prediction	Scale	Required $N_{\text{FRB}}$
1 (Host)	$\Delta\text{DM}_{\text{host}}(M_b)$	$\propto M_b^{0.38}, 5\text{--}18\text{ pc cm}^{-3}$	No $M_b$ scaling	kpc	$\sim 300$
2 (Web)	$\xi_{\text{DM-gal}}(r)$	Peak at $\lambda_{13} = 0.856\text{ Mpc}$	Smooth 1h/2h shoulder	Mpc	$\sim 2000$
3 (H(z))	$\langle\text{DM}(z)\rangle$	$-4.8\%$ at $z = 0.5$ , shape grows with $z$	Macquart ( $w = -1$ )	Gpc	$\sim 500$

5.2 Detection Timeline

Sample Size	Source	Timeline	Ch. 1	Ch. 2	Ch. 3
$\sim 100$ localized	CHIME + ASKAP	2025	$1\sigma$ hint	—	$<1\sigma$
$\sim 300$ localized	+ DSA-110	2026–27	$3\sigma$	$<1\sigma$	$2\sigma$
$\sim 1000$ localized	DSA-2000 early	2028–29	$>5\sigma$	$2\sigma$	$5\sigma$
$\sim 5000$ localized	DSA-2000 full	2030+	$>5\sigma$	$4\sigma$	$>5\sigma$

5.3 Systematic Uncertainties

**DM\_MW subtraction:** Models NE2001 [23] and YMW16 [24] differ by  $\sim 20\text{--}50\text{ pc cm}^{-3}$  in some directions. This is a systematic floor for all channels.

**DM\_host estimation:** Requires either scattering time measurements [6] or host galaxy modeling. Uncertainty:  $\sim 30\text{--}50 \text{ pc cm}^{-3}$  per FRB.

**Selection effects:** FRBs with high DM are easier to identify as extragalactic. The CHIME injection system [15] provides a well-characterized selection function.

**Mitigation:** Channel 3 is least affected because it relies on the *mean trend* and its *shape*, not absolute values. Channel 2 uses *relative correlations*, reducing sensitivity to absolute DM calibration.

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## 6. Falsification Criteria

### 6.1 Channel 1 Falsification

IF: No correlation between  $\Delta\text{DM}_{\text{host}}$  and  $M_b$  at  $> 3\sigma$  with  $N > 300$

THEN: Channel 1 prediction falsified (6.1)

### 6.2 Channel 2 Falsification

IF:  $\xi_{\text{DM-gal}}(r)$  consistent with smooth halo model (no peak at  $0.856 \pm 0.10 \text{ Mpc}$ )

AND:  $N_{\text{FRB}} > 2000$  with foreground spectroscopic survey overlap

THEN: Channel 2 prediction falsified (6.2)

### 6.3 Channel 3 Falsification

IF: The ratio  $\delta(z = 1)/\delta(z = 0.1) = 1.0 \pm 0.5$  (consistent with flat)

AND:  $N_{\text{FRB}} > 500$  spanning  $z = 0.1\text{--}2.0$

THEN: Channel 3 shape prediction falsified (6.3)

Equivalently: if  $w_0 = -1.00 \pm 0.08$  from FRBs alone, the 3D+3D dark energy prediction is excluded.

### 6.4 Complete Falsification

If all three channels simultaneously show null results with the sample sizes specified above, the framework's FRB sector predictions are comprehensively falsified. However, failure of individual channels does not falsify

the core framework, since the primary predictions (rotation curves, lensing, PTA) are independent.

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## 7. Vainshtein Screening Consistency Check

### 7.1 Scale Hierarchy

The Vainshtein radius for a Milky Way–mass galaxy is  $r_V \sim 2600 \text{ ly} \approx 0.80 \text{ kpc}$  [25]. The relevant scales for FRB physics are:

Scale	$r/r_V$	Q-field active?	Relevant channel
ISM ( $r < 1 \text{ kpc}$ )	$\sim 1$	Transition	DM_host (inner)
CGM ( $r \sim 10\text{--}200 \text{ kpc}$ )	$\gg 1$	Yes, fully	DM_host (outer)
IGM ( $r \sim \text{Mpc}$ )	$\gg 1$	Yes, fully	DM_IGM, cosmic web
Cosmological	N/A	Moduli dynamics	$H(z)$ modification

The Q-field is fully active at all scales relevant for FRB dispersion.

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## 8. Discussion

### 8.1 Comparison with Previous Observational Results

Hsu et al. (2025) [6] found statistical evidence that cosmological baryonic fluctuations correlate with foreground galaxy number density on scales  $\lesssim 6 \text{ Mpc}$ , qualitatively consistent with the 3D+3D prediction. The reported scale (6 Mpc) is larger than  $\lambda_{13} = 0.856 \text{ Mpc}$ , which may reflect the limited angular resolution of photometric galaxy catalogs used, or the fact that the  $\lambda_{13}$  feature is embedded in a broader correlation that extends to larger scales through the harmonic ladder.

### 8.2 Synergy with DESI and Euclid

The FRB predictions are synergistic with pre-registered predictions for DESI and Euclid [14]: DESI will measure  $\lambda_{13}$  in the galaxy correlation function; Euclid weak lensing maps will trace the cosmic web at  $\sim \text{Mpc}$  scales. Cross-correlation of these with FRB DM residuals provides independent validation.

### 8.3 Model-Independent Value

All three channels can be tested without assuming the full 3D+3D framework. Channel 1 tests whether DM\_host correlates with baryonic mass; Channel 2 tests for spatial structure at sub-Mpc scales; Channel 3 tests  $w_0$  through the DM– $z$  shape. The 3D+3D framework provides specific quantitative predictions, but the tests have broader value for constraining baryon physics and dark energy.

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## 9. Conclusions

We have derived three independent, quantitative predictions of the 3D+3D framework for Fast Radio Burst observables:

1. **Host Galaxy DM Enhancement** (Section 2): The Q-field creates an enclosed effective mass  $M_Q^{\text{eff}} \approx 5M_b$  in the inner  $\sim 30$  kpc, deepening the gravitational potential at all CGM radii. This modifies the gas profile, predicting  $\Delta\text{DM}_{\text{host}} \approx 5\text{--}18 \text{ pc cm}^{-3}$  scaling as  $M_b^{0.38}$ . Testable with  $\sim 300$  localized FRBs.
2. **Cosmic Web Periodicity** (Section 3): The  $\lambda_{13} = 0.856$  Mpc periodicity should produce a localized feature in the DM-galaxy cross-correlation, absent in  $\Lambda\text{CDM}$  where the 1-halo/2-halo transition is smooth. This is the most distinctive channel but requires  $\gtrsim 2000$  FRBs with foreground spectroscopic surveys.
3. **Modified Macquart Relation** (Section 4): dynamical dark energy with  $w(z) = -1 + 1/(3H(z)\tau_\beta)$  yields  $\sim 1\text{--}4\%$  suppression at  $z = 0.5$  for the allowed range  $\tau_\beta = 20\text{--}100$  Gyr. The primary degeneracy ( $f_{\text{IGM}}$ ) is broken by the redshift-dependent shape: the 3D+3D signal grows with  $z$  while parameter rescalings produce flat offsets. Testable with  $\sim 500$  FRBs spanning  $z = 0.1\text{--}2.0$ .

All predictions are falsifiable, pre-registered before the relevant data become available, and independent of the framework's other validated predictions. The combination of CHIME/FRB, ASKAP/CRAFT, DSA-110, and DSA-2000 will provide sufficient data for definitive tests by  $\sim 2028\text{--}2030$ .

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## Appendix A: Response to Referee Concerns

This version (v1.1) addresses three specific technical concerns raised during peer review:

**\*\*Concern 1 (Section 2.2):\*\*** "Is  $M_Q/M_b = 5$  transferable from SPARC (kpc) to CGM scales (100 kpc)?" — The key insight is that  $M_Q^{\text{eff}}$  is an *enclosed* mass that saturates at  $\sim 30$  kpc. The gravitational potential at CGM radii depends on this enclosed mass, not on the local Q-field amplitude. The potential is  $\sim 6\times$  deeper than Newtonian at all  $r > 30$  kpc.

**\*\*Concern 2 (Section 3.4):\*\*** "Does  $\Lambda\text{CDM}$  already produce structure at  $\sim 1$  Mpc?" — The  $\Lambda\text{CDM}$  power spectrum at  $k \sim 5 \text{ h/Mpc}$  is featureless. The 1-halo/2-halo transition creates a smooth shoulder in  $\xi(r)$ , not a peak at a specific scale. A localized peak at exactly  $0.856 \pm 0.05$  Mpc would be anomalous in  $\Lambda\text{CDM}$ .

**\*\*Concern 3 (Section 4.5–4.6):\*\*** "How degenerate is the Macquart signal with  $f_{\text{IGM}}$ ?" —  $f_{\text{IGM}}$  ( $\pm 6\%$  uncertainty) is the dominant degeneracy. However, an  $f_{\text{IGM}}$  rescaling produces a *flat* offset at all  $z$ , while the 3D+3D  $w(z)$  produces a *growing* offset, with shape ratio  $\delta(z=1)/\delta(z=0.1) \approx 4.5\text{--}4.9$  across the allowed  $\tau_\beta$  range vs. 1.00 provides clean discrimination.

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### Edison Mode:

*"The sign error caught in v1.0 Red Team, and the three referee corrections in v1.1, are exactly why we verify everything numerically. Not 10,000 ways that don't work—just careful derivation meeting careful checking."*

— S. Calzighetti & Lucy, 2026

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— End of Paper —