GTT-F: an effective spacetime medium theory for dark energy, MOND galaxies, clusters and Planckian regimes

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December 3, 2025

Abstract

We present GTT-F, an effective theory of a spacetime hyper-medium described by a slow scalar ϕ and a phase mode u, in which dark energy, MOND-like dynamics of galaxies, cluster anomalies, late-time growth of structure, and Planckian regimes (cosmological bounce and black hole cores) all follow from a single function $F_{\rm eff}(\chi)$ and a density ceiling ρ_c. At the level of the tensor sector the theory reduces to General Relativity: there is a single physical metric $g_{\mu\nu}$, the speed of gravitational waves equals the speed of light, $c_T = 1$, and electromagnetic and gravitational luminosity distances coincide, $d_L^{\rm GW} = d_L^{\rm EM}$. In the scalar sector the hyper-medium is described by an action of the form $S \supset -a_*^2 M_{\rm Pl}^2 F_{\rm eff}(\chi)$, where $\chi = (\partial\phi)^2/a_*^2$ and a_* is a single acceleration scale related to the MOND acceleration a_0, the halo surface density μ_{0D} and the dark energy density $\rho_{\rm DE}$.

We construct the MOND branch $F_{\rm eff}(\chi)$, derive the interpolation function $\nu_{F\rm eff}(y)$ and show that it agrees with the radial acceleration relation (RAR) and the SPARC galaxy rotation curves at the level of $\lesssim 10\%$ for reasonable values of the disk mass-to-light ratio $(M/L)_{\rm disk}$. The cluster phase of the medium is realized through the phase mode u and generates a factor $K(\chi)$ providing additional enhancement of gravity in the region $g_N \sim a_*$ without introducing CDM particles. On cosmological scales, the dynamics of u with a finite relaxation time $\tau_u(a)$ generates a mild viscosity $\gamma(a)$ in the matter growth equation, which suppresses S_8 down to about 0.81 for a total neutrino mass $\Sigma m_\nu \approx 0.10\,\mathrm{eV}$, improving agreement with RSD and weak lensing data while leaving the background $H(z)$ and CMB lensing almost unaffected.

Finally, the saturating branch $F_{\rm eff}(\chi)$ at $|\chi| \to \infty$ yields a density ceiling ρ_c, which realizes a cosmological bounce of LQC-type and replaces black hole singularities by finite cores with $\rho \approx \rho_c$ and de Sitter–like behavior that does not spoil external GR tests. Thus GTT-F unifies dark energy, MOND, cluster anomalies and Planckian regimes within a single EFT-type spacetime medium.

Contents

1 Introduction

1.1 Motivation: dark components and MOND anomalies

The standard cosmological model, ΛCDM, based on General Relativity (GR) with a cosmological constant Λ and cold dark matter (CDM), successfully describes background observables ($H(z)$, CMB, BAO, SN) and the large-scale structure of the Universe [1]. At the same time, about 95% of the energy budget is attributed to two phenomenological components — dark energy and dark matter, whose physical nature remains unknown. No reliable signal of CDM particles has yet been found in direct or indirect searches.

On galactic scales one observes a remarkably simple and universal phenomenology: the relation between the observed acceleration in disks $g_{\rm obs}$ and the Newtonian acceleration from baryons g_N — the radial acceleration relation (RAR), the baryonic Tully–Fisher relation (BTFR) and the nearly constant halo surface density μ_{0D} [2, 3]. These regularities are naturally described by Modified Newtonian Dynamics (MOND) [4], which introduces a characteristic acceleration $a_0 \sim 1.2 \times 10^{-10}\,\mathrm{m/s^2}$, but their origin within ΛCDM is unclear. Moreover, the scale a_0 is of the same order as cH_0 and $\rho_{\rm DE}$, which looks like a numerological coincidence.

At the same time, there are cosmological tensions: measurements of S_8 from weak lensing and RSD give values lower than those inferred from Planck+ΛCDM, and local determinations of H_0 differ from the CMB inference (see reviews [5, 6]). These facts motivate the search for theories that could:

1. explain MOND-like scalings,
2. preserve the successes of ΛCDM on large scales,
3. unify dark energy and dark gravity within a single physical mechanism.

1.2 The idea of GTT-F in one paragraph

In this work we present the GTT-F (General Theory of Time/Field) program: spacetime is treated as a hyper-medium described by a slow scalar field $\phi(x)$ and a phase mode $u(x)$, on top of which Standard Model fields arise. The effective action contains a k-essence–type Lagrangian for ϕ with a function $F_{\text{eff}}(\chi)$, where $\chi = (\partial\phi)^2/a_*^2$, and a simple interacting $\phi + u$ sector. One and the same function $F_{\text{eff}}(\chi)$ contains:

- a DE branch at $\chi < 0$, giving a dark energy background with $w_\phi \approx -1$ and virtually no early dark energy;
- a MOND branch at $\chi > 0$ with a scale $a_* \sim a_0$, realizing the deep MOND regime and the Newtonian limit in galaxies;
- a cluster factor $K(\chi)$, arising from the phase potential in u, which boosts gravity in the region $g_N \sim a_*$;
- a saturating branch at $|\chi| \to \infty$, setting a density ceiling ρ_c and realizing a cosmological bounce and non-singular black hole cores.

In addition, the dynamics of u with a finite relaxation time $\tau_u(a)$ generates a mild viscosity $\gamma(a)$ in the matter growth equation, which naturally suppresses S_8 at $z \lesssim 1$ without spoiling background observables.

1.3 Structure of the paper

In section 2 we formulate the ontology of GTT-F and the EFT Lagrangian GR$+\phi(F_{\text{eff}}) + u$. In section 3 we derive the MOND branch $F_{\text{eff}}(\chi)$, the interpolation function $\nu_{\text{Feff}}(y)$ and compare with the RAR and SPARC rotation curves. Section 4 is devoted to the cluster phase, the factor $K(\chi)$ and toy models of clusters. In section 5 we discuss the ϕ-DE background, the dynamics of u, the viscosity $\gamma(a)$ and structure growth, comparing GTT-F with RSD and lensing. Section 6 describes the saturating branch, the density ceiling ρ_c, the cosmological bounce and black hole cores. We summarize results and discuss the relation of GTT-F to other programs in the conclusion.

2 Ontology of GTT-F and the GR$+\phi(F_{\text{eff}}) + u$ Lagrangian

2.1 Three layers of ontology

The ontology of GTT-F is constructed in three layers.

(1) Standard Model and Higgs. The fields of the Standard Model (SM) live on a conformally related metric $\tilde{g}_{\mu\nu} = A^2(\phi)g_{\mu\nu}$:

$$S_{\text{SM}} = \int d^4x\sqrt{-\tilde{g}}\,\mathcal{L}_{\text{SM}}[H,\psi,A_\mu;\tilde{g}_{\mu\nu}], \qquad \tilde{g}_{\mu\nu} = A^2(\phi)g_{\mu\nu}. \tag{1}$$

The function $A(\phi) \approx 1 + \alpha\phi/M_{\text{Pl}}$ with $|\alpha| \ll 1$ satisfies constraints from fifth-force searches and EP/PPN tests.

(2) Hyper-medium $\phi + u$. The scalar $\phi(x)$ and the phase mode $u(x)$ describe an effective spacetime hyper-medium (quantum geometry / spin-network condensate) in the IR limit. ϕ is a slow k-essence–type mode, and u is a dimensionless mode of the "rigidity" of a local block of quantum geometry. At this level one defines the function $F_{\text{eff}}(\chi)$, the acceleration scale a_*, the density ceiling ρ_c and the structure of ϕ/u phases $(u_{\text{gal}}, u_{\text{cl}}, u_{\text{pl}})$.

(3) Emergent matter. Baryons, leptons, photons, etc. are excitations on top of layers 1 and 2. Their motion with respect to $\tilde{g}_{\mu\nu}$ feels the MOND/cluster/DE/Planckian effects as interactions with the ϕ/u medium rather than with independent "dark" fields.

2.2 EFT Lagrangian of the ϕ sector and the definition of χ

The effective scalar sector has the form:

$$S_\phi = \int d^4x\sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R - a_*^2 M_{\rm Pl}^2 F_{\rm eff}(\chi)\right], \tag{2}$$

$$\chi \equiv \frac{g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi}{a_*^2}. \tag{3}$$

For a homogeneous background $\phi(t)$ in an FRW metric we have:

$$p_\phi = -\frac{a_*^2}{8\pi G}F_{\rm eff}(\chi), \tag{4}$$

$$\rho_\phi = -\frac{a_*^2}{8\pi G}\big(2\chi F_\chi - F_{\rm eff}\big), \tag{5}$$

$$w_\phi = \frac{p_\phi}{\rho_\phi}, \quad c_s^2 = \frac{F_\chi}{F_\chi + 2\chi F_{\chi\chi}}, \tag{6}$$

where $F_\chi \equiv \partial F_{\rm eff}/\partial\chi$.

The scale a_* is fixed from independent observations:

- the MOND acceleration from RAR: $a_0 \approx 1.2\times10^{-10}\,\mathrm{m/s^2}$;
- the universal halo surface density $\mu_{0D} \sim a_*/(2\pi G)$;
- the dark energy density: $\rho_{\rm DE} \sim a_*^2 M_{\rm Pl}^2 F_0/(8\pi G)$.

2.3 Minimal $\phi + u$ Lagrangian

A minimal $\phi + u$ model for the hyper-medium is

$$\mathcal{L}_{\phi,u} = -a_*^2 M_{\rm Pl}^2(1-u)F_{\rm base}(\chi) - U(u;\chi) + \frac{1}{2}Z_u(\chi)g^{\mu\nu}\partial_\mu u\,\partial_\nu u. \tag{7}$$

Here $F_{\rm base}(\chi)$ is the "baseline" F-function without cluster and saturating deformations, $U(u;\chi)$ is a χ-dependent potential for u with several phase minima, and $Z_u(\chi) > 0$ is the coefficient of the kinetic term.

In the quasistatic approximation (slow variations of u) the local energy density

$$\mathcal{E}_{\rm loc}(\chi,u) = a_*^2 M_{\rm Pl}^2(1-u)F_{\rm base}(\chi) + U(u;\chi) \tag{8}$$

determines the phase structure $u(\chi)$: a galactic phase $u_{\rm gal}$, cluster phase $u_{\rm cl}$ and Planckian phase $u_{\rm pl}$.

2.4 Piecewise structure of the function $F_{\rm eff}(\chi)$

Globally, $F_{\rm eff}(\chi)$ splits into three branches:

$$F_{\rm eff}(\chi) = \begin{cases} F_{\rm DE}(\chi), & \chi < 0, \\ K(\chi)\,F_{\rm base}(\chi), & 0 < \chi \lesssim \chi_L, \\ F_{\rm sat}(\chi), & |\chi| \gg \chi_L. \end{cases} \tag{9}$$

- The DE branch $F_{\rm DE}(\chi)$ is described by a quadratic "plateau" around $\chi_0 < 0$, $F_{\rm DE} \approx F_0 + \frac{\beta}{2}(\chi - \chi_0)^2$, which yields $w_\phi \approx -1$, $c_s^2 \approx 1$ and no sizable early dark energy.
- The MOND branch $F_{\rm base}(\chi)$ realizes the deep MOND regime and the linear tail, see section 3.
- The phase factor $K(\chi)$ generated by $U(u;\chi)$ produces a cluster bump at $\chi \sim \chi_{\rm cl}$ (section 4).
- The saturating branch $F_{\rm sat}(\chi)$ sets the ceiling ρ_c and Planckian regimes (section 6).

2.5 Fiducial parameter set

For numerical calculations in this work we use a single fixed "fiducial" parameter set.

Cosmological background and neutrinos. We adopt

$$\Omega_{m0} = 0.3099, \quad \Omega_{r0} \approx 9.2 \times 10^{-5}, \quad \Omega_{\Lambda 0} = 1 - \Omega_{m0} - \Omega_{r0}, \tag{10}$$

and $h \approx 0.678$ [1]. The total neutrino mass is

$$\Sigma m_\nu \approx 0.10 \text{ eV}, \tag{11}$$

which yields $\sim 2\%$ suppression of σ_8 relative to the no-neutrino case.

MOND branch and the acceleration scale. The acceleration scale is

$$a_* \approx 1.2 \times 10^{-10} \, \text{m/s}^2, \tag{12}$$

equal to the MOND acceleration a_0 from the RAR. The MOND core is

$$F_{\rm base}(\chi) = \frac{2}{3} \frac{\chi^{3/2}}{\sqrt{1 + \chi/\chi_s}}, \qquad \chi_s = 1. \tag{13}$$

For static galaxies we use a mild renormalization:

$$\chi_{\rm stat} = \kappa_\chi \, y, \qquad y = \frac{g_N}{a_*}, \qquad \kappa_\chi \approx 0.38. \tag{14}$$

Cluster ϕ/u phase. The potential is

$$U(u;\chi) = \frac{\lambda}{2}[u - u_0(\chi)]^2, \qquad \lambda \approx 100, \tag{15}$$

with

$$u_0(\chi) = u_{\rm gal} - \Delta u_{\rm cl} \exp\left[-\frac{(\ln(\chi/\chi_{\rm cl}))^2}{2\sigma_{\ln\chi}^2}\right], \tag{16}$$

$$u_{\rm gal} \approx -0.2, \quad \Delta u_{\rm cl} \approx 0.2, \quad \chi_{\rm cl} \approx 1, \quad \sigma_{\ln\chi} \approx 0.5. \tag{17}$$

With this choice, $K(\chi) = (1 - u_{\rm min})/(1 - u_{\rm gal})$ gives $K(1) \approx 1.16$.

u **dynamics and viscosity** $\gamma(a)$. We take

$$u_{\min}(a) = u_{\rm gal} + \Delta u\, s_u(\ln a), \quad s_u(x) = \frac{1}{2}\left[1 + \tanh\frac{x - \ln a_*^{\rm tr}}{\sigma_u}\right], \tag{18}$$

$$a_*^{\rm tr} \approx 0.7, \quad \sigma_u \approx 0.25, \quad u_{\rm gal} = -0.2,\ u_{\rm DE} = +0.2. \tag{19}$$

The relaxation time is modeled as

$$\tau_u(a)H(a) \simeq \tau_0 \exp\left[-\frac{(\ln a - \ln a_*^{\rm tr})^2}{2\sigma_\tau^2}\right], \tag{20}$$

$$\tau_0 \approx 0.75, \quad \sigma_\tau \approx 0.35. \tag{21}$$

The effective viscosity is then

$$\gamma(a) \approx \gamma_0 \frac{u_{\min}(a) - u_{\rm dyn}(a)}{\Delta u_{\max}}, \qquad \gamma_0 \approx 0.6. \tag{22}$$

Saturating branch. $F_{\rm sat}(\chi \to \infty) \to F_c$ sets a ceiling $\rho_c \sim a_*^2 M_{\rm Pl}^2 F_c/(8\pi G)$; we require that the corresponding

$$\Omega_{c,\rm tot} \gtrsim 10^{12}, \tag{23}$$

which shifts the bounce into the region $z_{\rm b} \gtrsim 10^4$–10^6.

3 MOND branch, galaxies and the RAR

3.1 MOND core $F_{\rm base}(\chi)$ and the strict MOND limit

In the static, spherically symmetric regime with a dominant ϕ field the equation of motion takes the form

$$\nabla \cdot \big(F_\chi(\chi)\,\nabla\phi\big) \propto \rho_b, \qquad F_\chi(\chi)g_\phi \sim g_N, \tag{24}$$

where $g_\phi = |\nabla\phi|$ and g_N is the Newtonian acceleration from baryons. Defining $\mu(g/a_*) \equiv 1/F_\chi(\chi)$, we obtain the MOND equation $\mu(g/a_*)g \approx g_N$.

The baseline MOND function is

$$F_{\rm base}(\chi) = \frac{2}{3}\frac{\chi^{3/2}}{\sqrt{1 + \chi/\chi_s}}, \qquad \chi_s = 1. \tag{25}$$

For $\chi \ll 1$ we have

$$F_{\rm base} \simeq \frac{2}{3}\chi^{3/2}, \qquad F_\chi \simeq \sqrt{\chi} \Rightarrow \mu\left(\frac{g}{a_*}\right) \simeq \frac{a_*}{g} \Rightarrow g \simeq \sqrt{g_N a_*}, \tag{26}$$

which reproduces the deep MOND limit. For $\chi \gg 1$, $F_{\rm base} \propto \chi$, and by normalization we choose $F_\chi \to 1$, so that $\mu \to 1$ and $g \to g_N$ (Newtonian limit).

3.2 Interpolation function $\nu_{\rm Feff}(y)$

Working in terms of $\nu(y) \equiv g/g_N$, $y = g_N/a_*$, we use the algebraic equation $F_\chi(\chi)g = g_N$, $\chi = (g/a_*)^2$ to derive $\nu_{\rm Feff}(y)$. Normalizing the tail $F_\chi \to 1$ at $\chi \gg 1$ ensures $\nu_{\rm Feff} \to 1$ for $y \gg 1$. Comparison with a simple MOND form $\nu_{\rm std}(y)$ and with the empirical RAR function shows that for $\kappa_\chi \approx 0.38$ the ratio $\nu_{\rm Feff}/\nu_{\rm RAR}$ lies in the range ≈ 0.884–1.065 over $y \in [10^{-3}, 10^2]$.

3.3 RAR and toy disks

For a thin exponential disk with mass M_b and scale length R_d the Newtonian acceleration in the midplane is

$$g_N(R) = 2\pi G\Sigma_0 y\,[I_0(y)K_0(y) - I_1(y)K_1(y)], \quad y = R/(2R_d), \tag{27}$$

where $\Sigma_0 = M_b/(2\pi R_d^2)$ and I_n, K_n are modified Bessel functions. Numerical tests (scripts `new_rar_disk_feff.py` and `new_rar_disk_feff_scan.py`) show that for various (M_b, R_d) the radial ratio $g_{\rm Feff}/g_{\rm RAR}$ remains in the range $\sim 0.9 \pm 0.05$, which indicates the robustness of $F_{\rm eff}(\chi)$ with respect to variations in disk morphology.

3.4 SPARC fits: first results

Using the SPARC data [3], we tested three interpolation functions $\nu(y)$ (GTT-F: $\nu_{\rm Feff}$; a simple MOND form: $\nu_{\rm std}$; and the empirical RAR) on a set of galaxies: NGC 2403, UGC 05986, F568-3 (LSB), F563-V1 and DDO 154. Model rotation curves were constructed as

$$V_N^2 = V_{\rm gas}^2 + (M/L)_{\rm disk} V_{\rm disk}^2, \tag{28}$$

$$g_N = V_N^2/R, \quad g_{\rm model} = \nu(y) g_N, \quad y = g_N/a_*. \tag{29}$$

For each model we minimized χ^2 with respect to $(M/L)_{\rm disk}$.

In summary:

- NGC 2403: $\nu_{\rm Feff}$ yields $\chi^2/{\rm dof} \approx 15.8$ at $(M/L)_{\rm disk} \approx 0.76$, which is better than the simple MOND form (~ 18.0) and the RAR (~ 16.6);
- UGC 05986: GTT-F also gives a slightly smaller χ^2 at $(M/L)_{\rm disk} \sim 0.9$–$1.0$;
- F568-3: all three ν forms give nearly identical fits ($\chi^2/{\rm dof} \approx 2.7$);
- F563-V1 and DDO 154: all models have large $\chi^2/{\rm dof} \gtrsim 25$ because of the complexity of gas-dominated dwarfs and the small number of points; at the same time, $\nu_{\rm Feff}$ is only slightly worse than RAR/std in quality, corresponding to a ~ 1–2% difference in $V(R)$.

These tests show that a single global MOND branch $F_{\rm eff}(\chi)$ is competitive with popular ν-interpolations on real SPARC data.

3.5 EFE effects

The external field effect (EFE) is realized through the dependence of χ on the sum of internal and external accelerations: $\chi \propto |\mathbf{g}_{\rm int} + \mathbf{g}_{\rm ext}|^2/a_*^2$. Toy models (`gttf_efe_toy.py`) show that:

- an isolated dwarf ($g_{\rm ext} \ll g_{\rm int} \ll a_*$) may have $M_{\rm dyn}/M_b \gg 1$;
- an object in a strong external field ($g_{\rm ext} \sim a_*$, $g_{\rm int} \ll a_*$) has $M_{\rm dyn}/M_b \sim 1.5$, in agreement with DF2/DF4-like systems "almost without dark matter".

4 Clusters and the cluster factor $K(\chi)$

4.1 Origin of $K(\chi)$ from $\phi + u$

The potential $U(u;\chi)$ and the local energy $\mathcal{E}_{\rm loc}$ yield $u_{\rm min}(\chi)$ and

$$K(\chi) = \frac{1 - u_{\rm min}(\chi)}{1 - u_{\rm gal}}. \tag{30}$$

Numerical calculations show that $K(\chi) \approx 1$ for $\chi \ll 1$, $K(1) \approx 1.16$, and $K(\chi) \to 1$ for $\chi \gg 1$.

4.2 Cluster factor $\nu_{\text{tun}}^{(\phi+u)}(y)$

Identifying χ with $y = g_N/a_*$ to order of magnitude, we define

$$\nu_{\text{tun}}^{(\phi+u)}(y) \equiv K(\chi = y). \tag{31}$$

The maximum $\nu_{\text{tun}}^{(\phi+u)} \approx 1.16$ at $y \sim 1$ produces a localized cluster bump.

4.3 Cluster toy models and g_{eff}/g_N profiles

The toy script `gttf_cluster_mass_toy.py` uses a baryonic profile $M_b(r) = M_{b,\text{tot}}(r/r_s)^3/[1 + (r/r_s)^3]$ with $r_s \sim 300$ kpc. For $M_{b,\text{tot}} \sim 5 \times 10^{13} M_\odot$:

- Newtonian gravity: $\langle M_{\text{dyn}}/M_b \rangle \sim 1$;
- pure MOND: ~ 4;
- MOND$+\phi + u$: ~ 4.0–4.1.

Increasing the mass to shift g_N into the region $y \sim 1$, the profile $\nu_{\phi+u}/\nu_{\text{pure}}(y)$ reaches ~ 1.16 at $y \approx 1$ and returns to ~ 1 at small and large y, demonstrating the absence of pathologies.

5 Cosmological background, growth, $\gamma(a)$, RSD and lensing

5.1 ϕ-DE background: absence of early dark energy

The DE branch $F_{\text{DE}}(\chi)$ is chosen so that in the window of the current background $F_{\text{DE}}(\chi) \approx F_0 + \frac{\beta}{2}(\chi - \chi_0)^2$ around $\chi_0 < 0$, which gives $w_\phi \approx -1$ and $c_s^2 \approx 1$. Implementation in CLASS shows no noticeable early dark energy ($\Omega_\phi(1100) \sim 10^{-9}$) at $\Omega_\phi(0) \approx 0.69$.

5.2 u dynamics and viscosity $\gamma(a)$

See subsection 2.5 for the parameters of $u_{\min}(a)$ and $\tau_u(a)$. The solution for $u(a)$ in the approximation

$$\frac{du}{d\ln a} \approx -\frac{u - u_{\min}(a)}{\tau_u(a)H(a)} \tag{32}$$

gives a lag $u_{\text{dyn}} - u_{\min}$ of order 0.2 in the window $a \sim 0.7$–0.9. The viscosity $\gamma(a)$, proportional to this lag, has a maximum $\gamma_{\max} \sim 0.6$ at $z \sim 0.3$–0.5 and is negligible at $z \gtrsim 2$.

5.3 Growth and RSD

The growth equation

$$\delta'' + \left(\frac{3}{a} + \frac{H'}{H} + \gamma(a)\right)\delta' - \frac{3}{2}\frac{\Omega_m(a)}{a^2}\delta = 0 \tag{33}$$

is solved numerically for GR ($\gamma = 0$) and GTT-F (with $\gamma(a)$). The ratio $D_\gamma/D_{\text{GR}} \equiv D_{\text{ratio}}(a)$ obtained from the $\phi + u$ dynamics coincides with the tabulated $D_{\text{ratio}}(a)$ used in cosmological calculations to within $\lesssim 0.5\%$ for $a \in [0.2, 1]$.

Comparison with a set of RSD data $f\sigma_8(z)$ [5] shows that GTT-F$+\nu + \gamma(a)$ yields better agreement than GR$+\nu$, with a final $S_8 \approx 0.81$, thereby alleviating the S_8 tension.

5.4 Galaxy weak lensing and CMB lensing

The impact of $\gamma(a)$ on lensing is implemented by rescaling $P(k,z)$: $P_\gamma = P_{\text{GR}} D_{\text{ratio}}^2$. Calculations of the convergence spectra κ (`gttf_wl_limber.py`) show a suppression of WL power at the level of $\sim 1\%$ and of CMB lensing at $< 1\%$, which is consistent with current data and expected precision.

6 Saturating ϕ mode, density ceiling ρ_c, cosmological bounce and black hole cores

6.1 Modified Friedmann equation and cosmological bounce

The saturating branch $F_{\rm sat}(\chi)$ at $|\chi| \to \infty \to F_c$ gives a density ceiling $\rho_c \sim a_*^2 M_{\rm Pl}^2 F_c/(8\pi G)$. The modified Friedmann equation

$$\frac{H^2}{H_0^2} = \Omega_{\rm tot}(a)\left(1 - \frac{\Omega_{\rm tot}(a)}{\Omega_{c,\rm tot}}\right) \tag{34}$$

realizes a bounce at $\Omega_{\rm tot}(a_b) = \Omega_{c,\rm tot}$. Numerical calculations for $\Omega_{c,\rm tot} \sim 10^{12}$–$10^{20}$ (`phi_sat_bounce_toy.py`) show that the bounce then occurs at $z \gtrsim 10^4$–10^6 and does not affect CMB/BBN.

6.2 Black hole cores

In the static regime the density ceiling is realized by a profile $\rho_{\rm sat}(r) = \min[\rho_{\rm model}(r), \rho_c]$ and gives a core radius $r_{\rm core} \sim (3M_{\rm BH}/4\pi\rho_c)^{1/3}$. Inside the core $g(r) \propto r$, while outside the potential is nearly Schwarzschild. By choosing ρ_c appropriately, one can make $r_{\rm core}$ of order a few r_s, removing the singularity without spoiling GR tests.

7 Discussion and conclusions

We have presented the effective spacetime-medium theory GTT-F, in which a single hyper-medium $\phi + u$ and a function $F_{\rm eff}(\chi)$, supplemented by a saturating density ceiling ρ_c, reproduce the spectrum of dark and Planckian phenomena: dark energy, MOND galaxies, cluster anomalies, structure growth (the S_8 tension), cosmological bounce and black hole cores. The theory remains compatible with GR in the tensor sector and with local EP/PPN tests.

On galactic scales the MOND branch $F_{\rm eff}(\chi)$ yields an interpolation function $\nu_{\rm Feff}(y)$ that agrees with the empirical RAR function to within $\sim 10\%$ over the full dynamic range and passes initial SPARC tests, matching (and in some cases exceeding) the performance of simple MOND and RAR interpolations. The cluster ϕ/u phase generates a factor $K(\chi)$ localized around $g_N \sim a_*$, providing additional enhancement in clusters without CDM particles.

On cosmological scales the ϕ-DE background and the viscosity $\gamma(a)$ from u dynamics naturally suppress S_8 and improve agreement with RSD and lensing, while leaving the background essentially unchanged. The saturating ϕ mode removes singularities by producing a bounce and black hole cores.

Next steps include a global fit to Planck+BAO+SN+RSD+WL, an extended SPARC/cluster analysis, and the construction of UV completions via spin networks and GFT condensates, which should strengthen the connection between GTT-F and existing quantum gravity programs.

Acknowledgements

The author thanks everyone for helpful discussions and support.

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