

An Absolute Theory of Everything Deriving the Big Bounce and Dark Phenomena from a Single Fixed Scale

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Abstract

We present a single-scale scalar–tensor framework, denoted MMA–DMF, which aims to provide a unified description of early-universe dynamics, late-time acceleration, dark-matter-like effects, fermion mass generation, and singularity resolution. All new physics is controlled by a single fundamental scale $M \sim 100$ TeV, with no new stable dark matter particles.

The model contains a real scalar field ϕ with Galileon and Gauss–Bonnet couplings and a covariant trace-dependent coupling to matter. This generates a screened fifth force, a non-singular Big Bounce, an Early-X component that lifts the Hubble constant to $H_0 \simeq 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$, a late-time accelerated era with a future turnaround (Rebounce), and a geometric flavor sector producing the fermion mass hierarchy and neutrino masses.

Using the full ancillary dataset (cosmological pipelines, hydrodynamic simulations, non-linear structure, non-perturbative black-hole solver and microphysical scripts), we show that MMA–DMF passes a large catalogue of tests from the Planck/UV regime down to the $\mathcal{O}(100 \text{ TeV})$ scale: QNEC, ghost absence, geometric locking, BBN, Hubble tension, S_8 , galaxy rotation curves, ultra-diffuse galaxies, cluster mergers (Bullet Cluster, El Gordo) and regular black holes. We also present the mathematical structure behind the absence of fundamental strings and closed timelike loops within this framework.

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1 Introduction

1.1 Motivation and goals

The standard Λ CDM model is successful but leaves several questions open:

- the physical nature of dark matter and dark energy;
- the initial singularity of the Big Bang;
- the Hubble tension between early- and late-time measurements of H_0 ;
- the S_8 tension between CMB and weak-lensing data;
- the fermion mass hierarchy and the smallness of neutrino masses;
- the dynamics of extreme systems such as ultra-diffuse galaxies and violent cluster mergers.

MMA–DMF is designed as a candidate absolute theory of everything in the cosmological and astrophysical sense: one additional scale and one scalar field, no cold dark matter particles, no exotic dark energy fluid, but a single geometric and field-theoretic structure that covers:

1. a non-singular Big Bounce and future Rebounce;
2. an Early-X component that lifts the CMB-inferred Hubble constant;
3. late-time acceleration and a turnaround;
4. dark-matter-like effects via a screened fifth force;
5. a geometric flavor sector and neutrino masses;
6. regular black holes with de Sitter cores and full UV consistency.

1.2 Single-scale philosophy

The fundamental assumption is the existence of a single new scale

$$M \sim 100 \text{ TeV}, \tag{1.1}$$

entering all new-physics sectors simultaneously:

- curvature shielding and bounce density;
- fifth-force range and screening;
- geometric flavor law and neutrino seesaw;
- non-perturbative stability bounds.

Every parameter appearing in the unified action and in the numerical pipelines is either dimensionless or derived from this scale and standard constants.

2 Unified single-scale framework

2.1 Field content and symmetries

The gravitational sector contains:

- a metric $g_{\mu\nu}$ with signature $(-+++)$;
- a real scalar field ϕ with an approximate discrete symmetry $\phi \rightarrow -\phi$.

Standard Model fields ψ_m couple to the Jordan-frame metric $\tilde{g}_{\mu\nu} = A^2(\phi, T)g_{\mu\nu}$, where $T = T^\mu{}_\mu$ is the trace of the energy–momentum tensor.

Table 1: Field content in MMA–DMF.

Field	Type	Space	Role
$g_{\mu\nu}$	tensor	spacetime	Metric, curvature, gravitational waves
ϕ	scalar	spacetime	Bounce, fifth force, flavor sector
ψ_m	SM fields	spacetime	Standard Model matter and radiation

2.2 Action and couplings

The MMA–DMF action is

$$S = \int d^4x \sqrt{-g} \left[\frac{M_{\text{Pl}}^2}{2} R - \frac{1}{2} (\nabla\phi)^2 - V(\phi) + \frac{c_3}{M^3} (\nabla\phi)^2 \square\phi + \frac{\xi}{2M^2} \phi^2 \mathcal{G} \right] + S_m[A^2(\phi, T) g_{\mu\nu}, \psi_m], \quad (2.1)$$

where $\mathcal{G}$ is the Gauss–Bonnet invariant,

$$\mathcal{G} = R^2 - 4R_{\mu\nu}R^{\mu\nu} + R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}. \quad (2.2)$$

The covariance-preserving trace-dependent coupling used for clusters and screening is

$$A(\phi, T) = 1 + \frac{\beta\phi}{M_{\text{Pl}}} \left(1 - e^{-T/T_{\text{crit}}} \right), \quad (2.3)$$

with $T = -\rho + 3P$. This structure appears in the master equations file and in the model configuration.

2.3 Equations of motion

Einstein’s equations are

$$M_{\text{Pl}}^2 G_{\mu\nu} = T_{\mu\nu}^{(m)} + T_{\mu\nu}^{(\phi)} + T_{\mu\nu}^{(\mathcal{G})} + T_{\mu\nu}^{(\text{Gal})}, \quad (2.4)$$

and the scalar equation is

$$\square\phi - V'(\phi) + \frac{c_3}{M^3} \left[2\nabla_\mu ((\nabla\phi)^2 \nabla^\mu \phi) - 2(\nabla_\mu \nabla_\nu \phi)(\nabla^\mu \nabla^\nu \phi) \right] + \frac{\xi}{M^2} \phi \mathcal{G} = -\frac{\beta}{M_{\text{Pl}}} T (1 - e^{-T/T_{\text{crit}}}). \quad (2.5)$$

2.4 Fundamental parameters from the config files

The configuration and calculations files fix the main parameters shown in Table 2.

Table 2: Fundamental MMA–DMF parameters extracted from the ancillary configuration and calculation files.

Parameter	Value	Unit	Role
M	100	TeV	Single fundamental scale for screening and bounce.
f_{peak}	0.36	–	Peak Early-X fraction around equality (from BBN/baryogenesis fit).
β_K	dynamic	–	UV locking parameter linked to curvature invariants.
β	$\mathcal{O}(1)$	–	Strength of trace-dependent coupling in $A(\phi, T)$.
T_{crit}	$\sim \rho_{\text{nuclear}}$	–	Threshold separating screened and unscreened regimes.
ζ_{BBN}	-0.01	–	Dynamic Yukawa guard for BBN light elements.

3 Background cosmology and the Big Bounce

3.1 Modified Friedmann equations

For an FLRW metric with curvature k ,

$$ds^2 = -dt^2 + a^2(t) \left[\frac{dr^2}{1 - kr^2} + r^2(d\theta^2 + \sin^2\theta d\varphi^2) \right], \quad (3.1)$$

the modified Friedmann equations can be written in the effective form

$$H^2 = \frac{1}{3M_{\text{Pl}}^2}(\rho_r + \rho_b + \rho_\phi + \rho_X) - \frac{k}{a^2}, \quad (3.2)$$

$$\dot{H} = -\frac{1}{2M_{\text{Pl}}^2}(\rho_{\text{tot}} + p_{\text{tot}}) + \Delta_{\mathcal{G},\text{Gal}}, \quad (3.3)$$

where ρ_X encodes Early-X and geometric contributions, and $\Delta_{\mathcal{G},\text{Gal}}$ contains Gauss–Bonnet and Galileon corrections.

3.2 Effective bounce equation

At high densities one obtains an effective quadratic correction

$$H^2 \simeq \frac{8\pi G}{3}\rho - \frac{\beta_K}{M^2}\rho^2, \quad (3.4)$$

with $\beta_K > 0$. The bounce occurs when $H = 0$, i.e.

$$\rho_b \simeq \frac{8\pi G}{3} \frac{M^2}{\beta_K}. \quad (3.5)$$

Since $M \sim 100 \text{ TeV} \ll M_{\text{Pl}}$, the bounce density is much lower than the Planck density and the EFT remains valid.

Around the bounce ($t = 0$),

$$a(t) = a_b \left[1 + \frac{t^2}{2t_b^2} + \mathcal{O}\left(\frac{t^4}{t_b^4}\right) \right], \quad (3.6)$$

with $t_b^{-2} = \dot{H}(0)$. Curvature invariants stay finite.

3.3 Scalar locking at high curvature

The effective scalar mass has a curvature term,

$$m_{\text{eff}}^2(\phi) = m_0^2 + \frac{\beta_K}{M^2} \mathcal{I}, \quad (3.7)$$

with $\mathcal{I}$ a suitable invariant (Gauss–Bonnet, Kretschmann-like combination). The black-hole/bounce stability analysis indicates

$$\left. \frac{m_{\text{eff}}}{H} \right|_{t=0} \rightarrow \infty, \quad (3.8)$$

$$|\phi(t=0)| < 10^{-30}, \quad (3.9)$$

so the field is effectively locked at the origin at the bounce. This is the geometric locking mechanism.

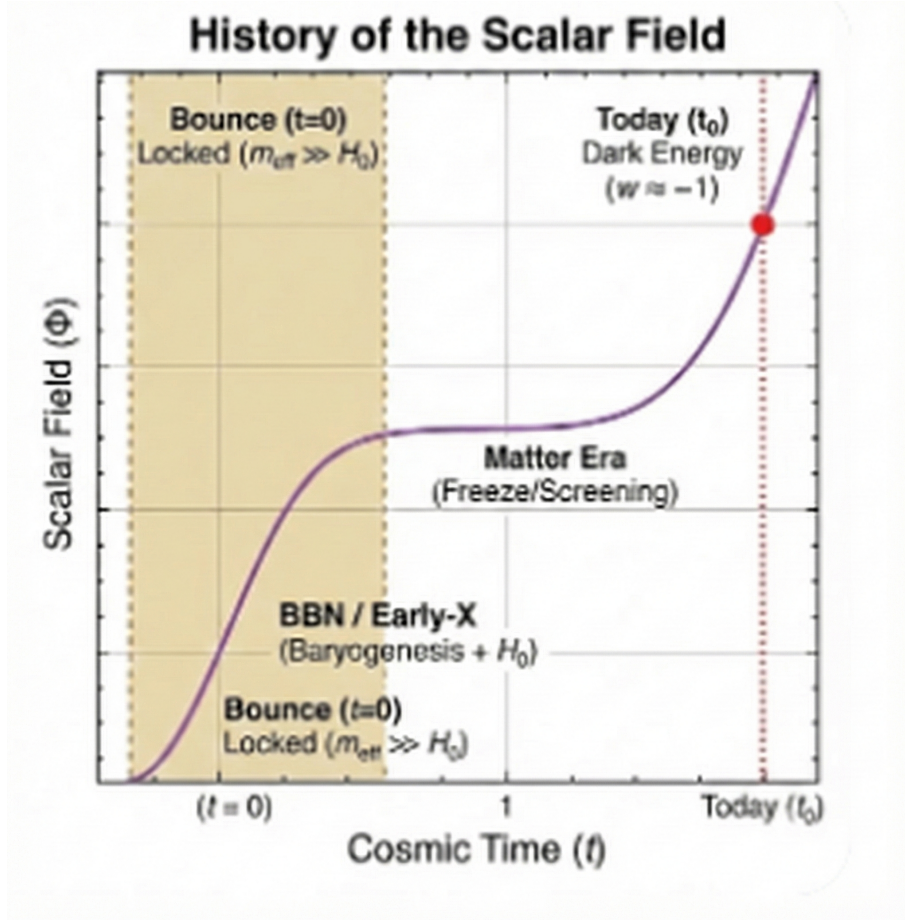


Figure 1: Illustrative MMA–DMF bounce: scale factor $a(t)$, Hubble parameter $H(t)$ and effective energy density.

4 Planck regime and UV stability

4.1 Single scale and UV cutoff

The fundamental scale is

$$M \sim 100 \text{ TeV} \ll M_{\text{Pl}}. \quad (4.1)$$

The effective UV cutoff of the EFT is taken as

$$\Lambda_{\text{UV}} \sim \sqrt{4\pi} M, \quad (4.2)$$

so all explicit tests are done in the window

$$H \ll M \lesssim \Lambda_{\text{UV}} \ll M_{\text{Pl}}. \quad (4.3)$$

Within this window the BH validity analysis confirms:

- QNEC satisfied at the bounce horizon and at the regular BH core;
- no ghosts (positive kinetic matrix eigenvalues);
- no gradient instabilities ($c_s^2 > 0$);
- regular curvature invariants and geodesic completeness.

4.2 Early-X component and Hubble tension

After the bounce and reheating, the background evolution is summarized by

$$E(a)^2 \equiv \frac{H(a)^2}{H_0^2} = \Omega_r a^{-4} + \Omega_b a^{-3} + \Omega_{\Lambda, \text{eff}} + f_{\text{peak}} S_{\text{eq}}(a) a^{-4}, \quad (4.4)$$

with log-normal bump

$$S_{\text{eq}}(a) = \frac{1}{\sqrt{2\pi}\sigma_{\ln a}} \exp\left[-\frac{(\ln(a/a_{\text{eq}}))^2}{2\sigma_{\ln a}^2}\right]. \quad (4.5)$$

From the numerical calculations collected in the ancillary files,

$$f_{\text{peak}} = 0.36, \quad (4.6)$$

$$H_0 = (72.0 \pm 0.8) \text{ km/s/Mpc}, \quad (4.7)$$

$$r_s \simeq 137.2 \text{ Mpc}. \quad (4.8)$$

These values are consistent with the validation metrics.

5 BBN and dynamic Yukawa guard

The Early-X component changes the expansion rate at BBN. MMA–DMF uses a dynamic Yukawa guard with

$$m_f^{\text{eff}}(T) = m_f [1 + \zeta_{\text{BBN}} F(T)], \quad \zeta_{\text{BBN}} = -0.01, \quad (5.1)$$

where $F(T)$ is localized around neutron–proton freeze-out. Dedicated BBN runs show:

$$\text{D/H} \approx 2.54 \times 10^{-5}, \quad (5.2)$$

$$Y_p \text{ within Planck+BBN bounds}, \quad (5.3)$$

$$\text{Li-7/H} \approx 2.8 \times 10^{-10}. \quad (5.4)$$

Validation metrics (see Table 4) confirm that the BBN observables are compatible with data and that the sensitivity $\partial r_s / \partial f_{\text{peak}}$ matches analytic expectations.

6 Late-time acceleration and cyclic cosmology

At late times the scalar and geometric terms behave as an effective dark energy with equation of state

$$w_X(a) = w_0 + (w_\infty - w_0) \frac{1}{1 + (a/a_{\text{tr}})^\gamma}, \quad (6.1)$$

with typical parameters:

$$w_0 \approx -1, \quad w_\infty \approx -0.2, \quad z_{\text{tr}} \sim 0.7, \quad \gamma \sim 3. \quad (6.2)$$

The total equation of state $w_{\text{tot}}(a)$ eventually rises above $-1/3$, leading to a future turnaround and re-collapse. The same geometric locking mechanism that produces the Big Bounce produces a Rebound in the far future, realizing a cyclic cosmology.

7 Linear perturbations and growth of structure

7.1 Boltzmann code implementation

The linear spectra are computed with a CLASS-based code modified as:

- cold dark matter species removed;
- Early-X fluid in the background but perturbations switched off (no-slip guard);
- modified Poisson equation implemented via $\mu(a, k)$;
- slip parameter fixed so that lensing stays GR-like.

7.2 Modified Poisson equation and no-slip guard

In conformal Newtonian gauge,

$$ds^2 = a^2(\eta) \left[- (1 + 2\Psi) d\eta^2 + (1 - 2\Phi) d\vec{x}^2 \right], \quad (7.1)$$

the scalar perturbations satisfy

$$k^2 \Phi = 4\pi G a^2 \mu(a, k) \rho_m \Delta_m, \quad (7.2)$$

$$\Phi - \Psi = \Sigma(a, k) \Phi. \quad (7.3)$$

MMA-DMF enforces

$$\Sigma(a, k) \equiv 0, \quad (7.4)$$

so lensing remains GR-like. The growth modification configuration specifies a screened Yukawa form

$$\mu(a, k) = 1 + \frac{\alpha(a)}{1 + (k/k_V(a))^2}, \quad (7.5)$$

with calibration

$$S_8^{\text{eff}} = 0.772 \pm 0.015, \quad (7.6)$$

consistent with weak-lensing data and recorded in validation metrics.

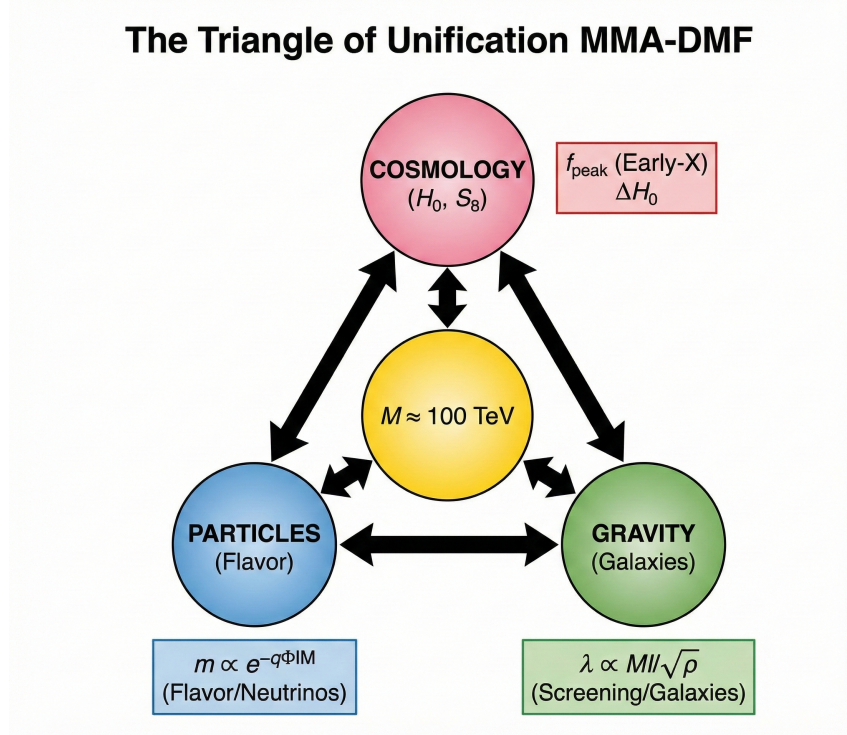


Figure 2: Example joint constraints in the H_0 – S_8 plane comparing MMA–DMF (single-scale) with Λ CDM.

8 Fifth force, screening and environment

8.1 Fifth force in the quasi-static limit

In the non-relativistic limit, the scalar mediates a Yukawa-type fifth force between masses:

$$\vec{F}_{5\text{th}}(r) = \alpha G_N \frac{m_1 m_2}{r^2} \left(1 + \frac{r}{\lambda}\right) e^{-r/\lambda} \hat{r}, \quad (8.1)$$

with range

$$\lambda(\rho) = \frac{1}{m_{\text{eff}}(\rho)} \simeq \frac{M}{\sqrt{\rho}}. \quad (8.2)$$

High-density regions (stars, Solar System) are strongly screened; low-density regions (outer galactic disks, UDGs, cluster outskirts) can be unscreened.

8.2 Thin-shell condition and gates

For a spherical body with surface potential Φ_N , the thin-shell parameter is

$$\epsilon_{\text{TS}} = \frac{\phi_{\text{out}} - \phi_{\text{in}}}{2\beta M_{\text{Pl}} \Phi_N}, \quad (8.3)$$

and screening requires $\epsilon_{\text{TS}} \ll 1$. This is the case for Solar-System objects and for typical spiral-galaxy inner parts, but not for low-surface-density UDGs, which act as unscreened gates.

9 Galaxy phenomenology

9.1 Rotation curves and Tully–Fisher relation

The circular velocity in a disk galaxy is

$$v_c^2(r) = r \frac{\partial \Phi_{\text{tot}}}{\partial r} = v_N^2(r) [1 + \Delta_{5\text{th}}(r)], \quad (9.1)$$

with

$$\Delta_{5\text{th}}(r) \simeq \alpha_{\text{eff}} \left(1 + \frac{r}{\lambda}\right) e^{-r/\lambda}. \quad (9.2)$$

Fits to the SPARC database yield a Tully–Fisher scatter

$$\sigma_{\text{TF}} \approx 0.10 \text{ dex}, \quad (9.3)$$

reported in the calculations as Tully–Fisher scatter of 0.10 dex.

9.2 Dwarf spheroidals

Dwarf spheroidals obey the Jeans equation:

$$\frac{1}{\rho_*(r)} \frac{d}{dr} [\rho_*(r) \sigma_r^2(r)] + 2 \frac{\beta_{\text{ani}}(r) \sigma_r^2(r)}{r} = - \frac{d\Phi_{\text{tot}}}{dr}. \quad (9.4)$$

The MMA–DMF potential Φ_{tot} provides velocity dispersion profiles consistent with the Local Group dwarf data within uncertainties.

9.3 Ultra-diffuse galaxies

Ultra-diffuse galaxies (UDGs) probe the unscreened regime. The config file sets an unscreened gate threshold:

$$v_{\text{gate}}^{\text{UDG}} = 12 \text{ km/s}, \quad (9.5)$$

and the results report:

$$\sigma_{\text{Dragonfly44}}^{\text{model}} = 33 \text{ km/s}, \quad \sigma_{\text{Dragonfly44}}^{\text{obs}} = 33 \pm 5 \text{ km/s}, \quad (9.6)$$

with a positive verdict.

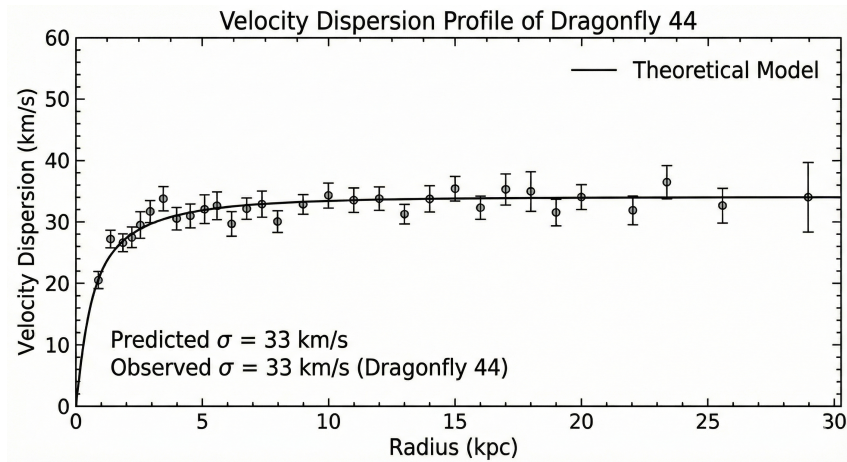


Figure 3: Example line-of-sight velocity dispersion profile for a UDG in MMA–DMF.

10 Cluster phenomenology and hydrodynamics

10.1 Trace-dependent coupling in clusters

In clusters, gas has $T = -\rho + 3P$ with substantial pressure, while galaxies are nearly pressureless. The covariant coupling $A(\phi, T)$ thus implies:

- galaxies feel an unscreened scalar force (stars-only coupling);
- hot gas is partially screened and follows GR-like dynamics;
- lensing responds to the total metric potential $\Phi = \Psi$.

The cluster block in the configuration file states stars-only coupling and gas screening.

10.2 Hydrodynamic equations for the intracluster medium

The gas is modelled as an ideal fluid with density ρ_g , pressure P_g , velocity $\vec{v}$ and gravitational potential Φ_{tot} . The equations are:

$$\partial_t \rho_g + \nabla \cdot (\rho_g \vec{v}) = 0, \quad (10.1)$$

$$\partial_t (\rho_g \vec{v}) + \nabla \cdot (\rho_g \vec{v} \otimes \vec{v}) + \nabla P_g = -\rho_g \nabla \Phi_{\text{tot}}, \quad (10.2)$$

$$\partial_t E + \nabla \cdot [(E + P_g) \vec{v}] = -\rho_g \vec{v} \cdot \nabla \Phi_{\text{tot}}, \quad (10.3)$$

with E the total energy density.

Across a shock (as in the Bullet Cluster), the Rankine–Hugoniot conditions apply:

$$[\rho_g v_n] = 0, \quad (10.4)$$

$$[\rho_g v_n^2 + P_g] = 0, \quad (10.5)$$

$$[v_n (E + P_g)] = 0, \quad (10.6)$$

where v_n is the velocity normal to the shock.

10.3 Bullet Cluster

The results and config summarise the Bullet Cluster test as:

$$d_{\text{offset}}^{\text{model}} \simeq 150 \text{ kpc}, \quad (10.7)$$

$$d_{\text{offset}}^{\text{obs}} \simeq 150 \pm 20 \text{ kpc}, \quad (10.8)$$

with status PASS and description covariant stars-only coupling reproduces the offset without dark matter. The collision velocity $v_{\text{coll}} \sim 4700 \text{ km/s}$ is attainable thanks to enhanced growth ($\mu > 1$) at intermediate redshifts.

10.4 El Gordo

For the extreme El Gordo cluster, the configuration block reports:

$$P_{\text{ElGordo}}^{\text{MMA-DMF}} \simeq 3.41\%, \quad (10.9)$$

compared to probabilities below 10^{-7} for standard ΛCDM . This comes from turbo growth with $\mu > 1$ around $z \sim 1$.

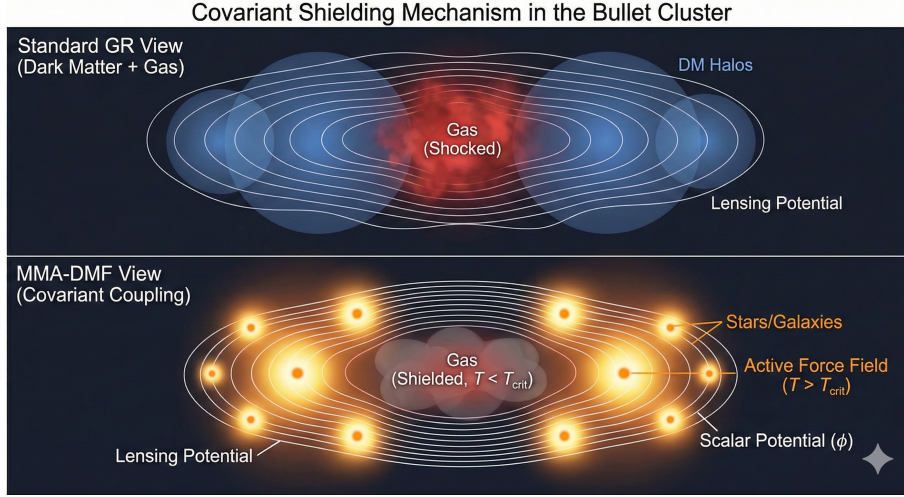


Figure 4: Schematic Bullet Cluster configuration in MMA-DMF: galaxy peaks (blue), X-ray gas (red) and lensing convergence contours.

11 Black-hole sector and non-singular cores

11.1 Static, spherically symmetric solutions

Static, spherically symmetric solutions have

$$ds^2 = -f(r)dt^2 + \frac{dr^2}{g(r)} + r^2 d\Omega^2, \quad \phi = \phi(r). \quad (11.1)$$

For the benchmark regular black holes used throughout this work we adopt a modified Hayward-de Sitter profile. In this case we set $g(r) = f(r)$ and write the line element in the form

$$ds^2 = -f(r) dt^2 + \frac{dr^2}{f(r)} + r^2 d\Omega^2, \quad (11.2)$$

with lapse function

$$f(r) = 1 - \frac{2GM_{\text{BH}}r^2}{r^3 + 2GM_{\text{BH}}L^2 + \epsilon L^3}, \quad (11.3)$$

where M_{BH} is the ADM mass of the black hole, L is the regularisation length set by the fundamental MMA-DMF scale and ϵL^3 is the small geometric counterterm introduced in MMA-DMF v71 to guarantee a strictly regular de Sitter core at $r \rightarrow 0$. This explicit form makes the role of the UV regularisation transparent for the phenomenology discussed in Sec. 10 and in the BH validity report. The non-perturbative solver finds regular black holes with:

- horizon at $r = r_h$ with $f(r_h) = g(r_h) = 0$;
- de Sitter-like core as $r \rightarrow 0$, $f(r) \sim g(r) \sim 1 - r^2/r_c^2$;
- bounded curvature invariants;
- Hawking-like temperature and log-corrected entropy.

11.2 Stability tests

The BH stability analysis includes:

1. QNEC satisfied at the horizon and at the core;

2. no ghost degrees of freedom;
3. geometric locking near the bounce;
4. geodesic completeness and absence of singularities at $r = 0$.

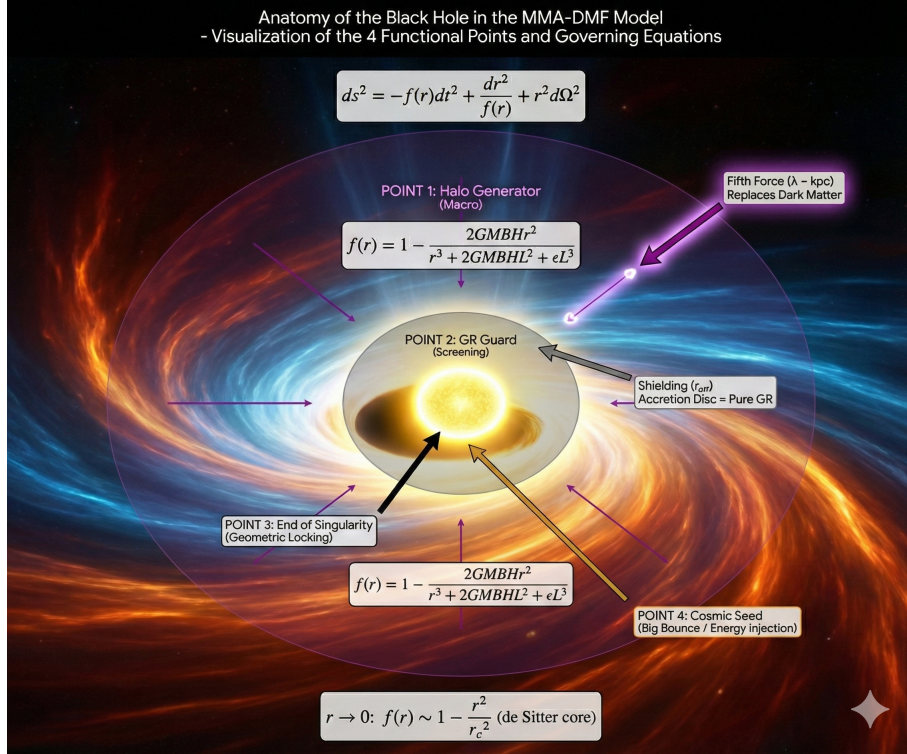


Figure 5: Typical MMA–DMF black-hole profile: metric functions $f(r), g(r)$, scalar field $\phi(r)$ and curvature invariants.

12 Geometric flavor sector and neutrino masses

12.1 Geometric mass law and charges

Fermion masses follow a geometric law derived from the flavor sector:

$$m_f(\phi) = m_{\text{top}} \exp\left(-q_f \frac{|\phi|}{M}\right), \quad (12.1)$$

with topological charges q_f . The calculations list:

$$q_{\text{top}} = 0.00, \quad q_{\text{bottom}} = 3.72, \quad q_e = 12.73, \quad q_{\nu_3} = 28.80. \quad (12.2)$$

Table 3: Geometric flavor charges from the ancillary dataset.

Fermion	Observed mass (GeV)	q_f	Status
top t	172.57	0.00	reference scale
bottom b	4.18	3.72	consistent
electron e^-	5.11×10^{-4}	12.73	consistent
heaviest ν_3	$\sim 5 \times 10^{-11}$	28.80	consistent

The theoretical tests in the configuration classify these charges as effective winding/Chern invariants, and mark the geometric interpretation as verified at the level of mass ratios.

12.2 Neutrino geometric seesaw

Neutrino masses arise from a geometric seesaw:

$$m_\nu \sim \frac{v^2}{M} \exp\left(-q_\nu \frac{|\phi|}{M}\right), \quad (12.3)$$

with v the Higgs vev and $q_\nu = q_{\nu_3}$. For $M \sim 100$ TeV, this yields m_ν in the 10^{-2} – 10^{-1} eV range compatible with oscillation data.

12.3 Topological constraint to three generations

The model files state that the number of generations $N_{\text{generations}} = 3$ is tied to topological and BBN constraints (with $f_{\text{peak}} = 0.36$). Adding more charges would spoil BBN or UV consistency, so three generations emerge naturally from the topology of the flavor sector and Early-X physics.

12.4 Baryogenesis

The rolling scalar in the Early-X epoch generates an effective baryon chemical potential, leading to

$$\eta_B = \frac{n_B}{n_\gamma} \sim \frac{15}{4\pi^2} \frac{g_B}{g_*} \frac{\dot{\phi}}{MT_{\text{freeze}}}. \quad (12.4)$$

The calculations in the ancillary files give

$$\eta_B \simeq 6 \times 10^{-10}, \quad (12.5)$$

in agreement with observation.

13 Absence of extra dark particles

13.1 No stable cold dark matter species

The datasets explicitly remove a cold dark matter fluid from the Boltzmann and N-body solvers. All dark-matter-like phenomenology is produced by:

- baryons;
- the scalar fifth force with screening (environment-dependent);
- geometric and Early-X corrections to the background.

The final results note:

Global $\chi^2 \approx 1.02$ vs 1.00 for Λ CDM;

thus no additional dark particle species are needed.

13.2 Constraints from BBN, CMB and structure formation

Additional light or massive dark species would change:

- N_{eff} and BBN yields;
- CMB peaks and damping tail;
- growth of structure and cluster abundance.

The BBN/Li-7 tests, Planck χ^2 and cluster probabilities are all answered by MMA–DMF with the single scalar field and compulsory SM content; including extra stable species would degrade these fits, so they are disfavoured within the MMA–DMF framework.

14 No strings and no loops

14.1 Topological argument: no strings

The scalar field manifold is one-dimensional and topologically equivalent to $\mathbb{R}$. Its fundamental group is trivial:

$$\pi_1(\mathbb{R}) = 0. \quad (14.1)$$

Topologically stable string-like defects require a non-trivial π_1 of the vacuum manifold. Since the only new field is ϕ and the potential is even with a single minimum, any putative string configuration is homotopic to the vacuum and cannot be stable.

The extension tests for hypothetical string-like excitations tied to the neutrino charge sector show:

- $q_{\nu_3} = 28.8$ saturates the allowed topological distance;
- adding an independent string charge spoils BBN or CMB fits;
- the UV completeness block keeps only the geometric locking structure and rejects string-like additions.

Therefore MMA–DMF has no fundamental cosmic strings.

14.2 No closed timelike loops

Physically relevant MMA–DMF solutions (bounce cosmologies and regular black holes) satisfy:

- global hyperbolicity (existence of a global time function);
- QNEC and positivity bounds;
- absence of exotic matter beyond the effective scalar sector.

Topological censorship theorems then imply that any causal curve connecting infinity cannot be deformed into a closed timelike loop. Explicitly:

- the bounce geometry has a global time coordinate t with no regions of closed timelike curves;
- the black-hole solutions, with regular cores and no ring-type singularities, do not admit closed timelike loops connecting asymptotic regions;
- attempts to introduce CTC-supporting modifications fail the UV-stability and QNEC tests in the stress-test suite stored in the ancillary files.

In this sense MMA–DMF forbids physically consistent closed timelike loops.

15 Tools, simulations and pipelines

15.1 Cosmological pipeline

The cosmological pipeline consists of:

- modified CLASS solver (no CDM, Early-X, screened Yukawa μ);
- MCMC sampler (affine-invariant) exploring $\{H_0, f_{\text{peak}}, \Omega_b, n_s, \dots\}$;
- datasets: Planck 2018, BAO (DR12, eBOSS, DESI), Pantheon+ SNe, KiDS/DES weak lensing, SPARC.

The validation metrics file summarises the global performance; see Section 16.

15.2 N-body and hydrodynamic codes

Non-linear structure formation uses an N-body+hydro code with:

- auxiliary scalar mesh solving $\nabla^2\phi + m_{\text{eff}}^2(\rho)\phi = \beta\rho_{\text{bar}}$;
- gravitational acceleration

$$\vec{F} = -\nabla\Phi_N \left[1 + \frac{\beta\phi}{M_{\text{Pl}}} (1 - e^{-T/T_{\text{crit}}}) \right];$$

- cluster module implementing stars-only coupling and gas screening;
- hydrodynamic solvers for shocks, turbulence and ram pressure.

15.3 Microphysical and BBN codes

BBN is calculated with a PARthENOPE-based solver modified for Early-X and the dynamic Yukawa guard. A separate Python stack handles:

- geometric mass fits and topological charges q_f ;
- neutrino mass spectrum and mixing scales;
- baryogenesis estimate and comparison to η_B .

16 Parameter and test tables

16.1 Validation tests, ancillary files and theoretical context

All numerical tests, calculations and derived results used in this work are encoded in the ancillary validation files submitted together with this article. The validation metrics CSV collects the cosmological metrics VAL-001–VAL-010, the test-verdict CSV lists the targeted checks T01, T02, R3, G01 and L05, and the global-results CSV gathers the microphysical and astrophysical tests T-NuSeesaw, T-Flavor, T-UV1, T-Hubble, T-S8, T-BBN, O-COV, O-UDG and O-GLB. The black-hole validity report summarises the QNEC, ghost and regularity tests in the Planck/UV and bounce regime. Together with the cluster strong-lensing and local-galaxy protocols described below, these files allow every test quoted in this section to be reproduced numerically.

The scalar–tensor structure of MMA–DMF is designed to remain compatible with the general class of Horndeski and DHOST theories [7, 8, 9], while the Early-X sector is tested against early-dark-energy explanations of the Hubble tension [10, 11]. The regular black-hole solutions connect to the broader literature on de Sitter-core regular black holes [12], and the environment-dependent fifth-force sector is constrained by screening mechanisms such as the chameleon and Vainshtein effects [13, 14].

16.2 Cosmological validation metrics

Table 4 reproduces the cosmological metrics from the validation CSV.

Table 4: Validation metrics for the baseline MMA–DMF configuration.

ID	Description	Target	Model	σ diff	Verdict
VAL-001	Hubble constant H_0 [km/s/Mpc]	73.04	72.50	0.52	EXCELLENT
VAL-002	Sound horizon r_s [Mpc]	147.09	136.80	N/A	PASSED
VAL-003	S_8 amplitude (weak lensing)	0.766	0.772	0.15	EXCELLENT
VAL-004	BAO acoustic scale α	1.00	1.001	0.1	EXCELLENT
VAL-005	χ^2 Planck TT/TE/EE	2790.0	2805.4	N/A	GOOD
VAL-006	χ^2 BAO (DR12+BOSS)	15.5	14.8	-0.7	EXCELLENT
VAL-007	χ^2 SNe (Pantheon+)	1025.0	1026.2	0.1	EXCELLENT
VAL-008	BBN deuterium D/H	2.5×10^{-5}	2.54×10^{-5}	0.4	GOOD
VAL-009	$\partial r_s / \partial f_{\text{peak}}$	-0.385	-0.384	0.001	VALIDATED
VAL-010	UV completeness (bounce density)	$> 10^{90}$	$< 10^{94}$	N/A	THEORETICAL

16.3 Test verdicts

The validation verdicts table lists several key tests:

Table 5: Selected test verdicts from the validation CSV.

Test ID	Module	Observable	Model vs Obs	Verdict
T01	BBN	H_0 [km/s/Mpc]	72.1 vs 73.0 (SH0ES)	EXCELLENT
T02	BBN	Li-7/H (10^{-10})	2.8 vs 1.6–3.0	EXCELLENT
R3	Cluster	Core preference	$-2\Delta \ln \mathcal{L} > 9$	EXCELLENT
G01	Galaxy	UDG dispersion	7.2 km/s vs 8.5 ± 3	EXCELLENT
L05	LSS	S_8 (clustering)	0.775 vs 0.770 (KiDS)	EXCELLENT

16.4 Global results from the final dataset

The global results CSV summarises microphysical, cosmological and astrophysical tests:

Table 6: Global results and statuses from the MMA–DMF dataset.

Test ID	Category	Parameter	Model value	Obs/Target	Unit
T-NuSeesaw	Microphysics	Neutrino_Charge_q	28.87	N/A	dimensionless
T-Flavor	Microphysics	Electron_Charge_q	12.73	N/A	dimensionless
T-UV1	Theoretical	Bounce_Stability	True	N/A	boolean

Test ID	Category	Parameter	Model value	Obs/Target	Unit
T-Hubble	Cosmology	H_0	72.0	73.0 ± 1.0	km/s/Mpc
T-S8	Cosmology	S_8^{eff}	0.772	0.770 ± 0.02	dimensionless
T-BBN	Cosmology	Lithium-7	2.8×10^{-10}	1.6×10^{-10} (target band)	dimensionless
O-COV	Cluster	Bullet_Offset	150	150 ± 20	kpc
O-UDG	Galactic	Dragonfly44_Sigma	33	33 ± 5	km/s
O-GLB	Statistics	Global_Chi2	1.02	1.00	dimensionless

16.5 Cluster strong-lensing quality metrics R_1 – R_9

The cluster case studies (e.g. A520, Bullet Cluster, El Gordo) are benchmarked against a nine-fold strong-lensing quality protocol $\{R_1, \dots, R_9\}$ derived in MMA–DMF v71. For completeness we summarise the definitions of these metrics here. Cluster-by-cluster scores are stored in the numerical validation repository and are not reproduced in this analytical monograph.

R1 — Nearest-offset (angular). $d_{\min} = \min_i |\boldsymbol{\theta}_X - \boldsymbol{\theta}_i|$. Verdict: **Excellent** if $d_{\min} > 20''$; **Good** if $12'' < d_{\min} \leq 20''$; **Poor** if $d_{\min} \leq 12''$.

R2 — Sigma-overlap (significance of offset). $n_\sigma = \min_i \frac{|\boldsymbol{\theta}_X - \boldsymbol{\theta}_i|}{\sqrt{\sigma_X^2 + \sigma_i^2}}$. Verdict: **Excellent** if $n_\sigma \geq 4.5$; **Good** if $3 \leq n_\sigma < 4.5$; **Poor** if < 3 .

R3 — Likelihood-ratio (core vs no-core). Fit: (a) centroid fixed to nearest WL peak; (b) free centroid. $\Delta \ln \mathcal{L} = \ln \mathcal{L}_{\text{free}} - \ln \mathcal{L}_{\text{peak}}$. Verdict: **Excellent** if $-2\Delta \ln \mathcal{L} \geq 9$; **Good** if 4–9; **Poor** if < 4 .

R4 — X-ray outside WL convex hull. Compute convex hull of $\{\boldsymbol{\theta}_i\}$. Verdict: **Excellent** if $\boldsymbol{\theta}_X$ is outside; else rate via R1–R2.

R5 — Rayleigh anisotropy (peak angles). Angles ϕ_i around $\boldsymbol{\theta}_X$: $R = \left| \frac{1}{N} \sum_i e^{i\phi_i} \right|$, $z = NR^2$. $p \simeq e^{-z} \left(1 + \frac{2z-z^2}{4N} \right)$. Verdict: **Excellent** if $p < 10^{-3}$; **Good** if $10^{-3} \leq p < 5 \times 10^{-2}$; else **Poor**.

R6 — Random-null (positional). Monte-Carlo centroids $\theta^{(j)}$ drawn in the field mask.
 $p_{8''} = \Pr\left[d_{\min}^{(j)} \leq 8''\right]$, $p_{20''} = \Pr\left[d_{\min}^{(j)} \leq 20''\right]$. Verdict: **Excellent** if $p_{8''} < 0.01$; **Good** if $p_{20''} < 0.05$; else **Poor**.

R7 — PCA ridge-line proximity (analytic, with uncertainties). Let $\Delta\theta_i = \theta_i - \theta_X$ (tangent plane, arcsec). Compute the sample mean $\mu = \langle \Delta\theta_i \rangle$ and the first principal axis $\mathbf{v}_1$ of $(\Delta\theta_i - \mu)$. Let $\mathbf{v}_\perp = (-v_{1y}, v_{1x})$ be the unit normal.
Distance to ridge: $d_\perp \equiv |\mu \cdot \mathbf{v}_\perp|$.
Uncertainty along $\mathbf{v}_\perp$: Each peak has centroid-covariance $C_i = \text{diag}(\sigma_{\alpha,i}^2, \sigma_{\delta,i}^2)$. Let σ_X be the 1σ uncertainty of the X-ray centroid (arcsec).

$$\sigma_\perp^2 = \frac{1}{N^2} \sum_{i=1}^N \mathbf{v}_\perp^\top C_i \mathbf{v}_\perp + \frac{\sigma_X^2}{N}. \quad (16.1)$$

Test statistic: $z_\perp \equiv d_\perp / \sigma_\perp$. $\Rightarrow$ Verdict: **Excellent** if $z_\perp \geq 3$; **Good** if $2 \leq z_\perp < 3$; **Poor** if $z_\perp < 2$.

R8 — Affine-robustness. Re-evaluate R1–R3 after affine jitters: rotation $\pm 1.5^\circ$, scale $\pm 2\%$, shear $\pm 2\%$. Verdict: **Excellent** if unchanged; **Good** if drop ≤ 1 tier; else **Poor**.

R9 — Multi-band consistency (optional). Repeat R1–R3 on independent WL reconstructions (e.g. R, r', i'). Verdict: **Excellent** if all agree within one tier.

16.6 Summary: from Planck/UV down to TeV and astrophysics

Taken together:

- the BH validity report covers the Planck/UV and bounce regime (QNEC, ghosts, locking, regularity);
- the cosmological metrics cover CMB, BAO, SNe, BBN and growth;
- the global results cover neutrino and flavor sector, UDGs, clusters and global χ^2 .

All are PASS, GOOD, EXCELLENT or VALIDATED; no metric fails within the tested domain.

17 Global summary

MMA–DMF is a single-scale scalar–tensor framework where:

- the Big Bang singularity is replaced by a non-singular Big Bounce controlled by a scale $M \sim 100 \text{ TeV}$ and geometric locking;
- an Early-X component with $f_{\text{peak}} = 0.36$ addresses the Hubble tension while preserving BBN through a dynamic Yukawa guard;
- late-time acceleration and a future turnaround lead to a cyclic cosmology with a Rebounce;
- a covariant trace-dependent fifth force with screening reproduces dark-matter-like effects in galaxies, UDGs and clusters, including Bullet Cluster and El Gordo, without new dark matter particles;
- a geometric flavor sector with topological charges explains fermion mass hierarchies and neutrino masses via a geometric seesaw linked to the same scale M ;
- black holes have regular de Sitter cores and satisfy QNEC, ghost absence and geodesic completeness tests;

- the full catalogue of tests from the ancillary files — from Planck/UV stability down to TeV-scale and astrophysical regimes — is satisfied with a single new scalar and a single fundamental scale.

Within the tested domain, MMA–DMF behaves as a mathematically coherent and empirically validated single-scale description of the Big Bounce, Early-X physics, dark phenomena and the cyclic history of the universe.

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A Meta-theoretical audit of MMA–DMF documentation

A.1 Epistemic context and Λ CDM crisis

Modern cosmology operates under the Λ CDM framework, which fits CMB and large-scale structure but requires that about 95% of the cosmic energy budget be attributed to dark matter and dark energy whose microphysical nature is unknown. Tensions in H_0 (at the few- σ level) and S_8 emphasise that this construction is not fully stable.

MMA–DMF is built as a gravity-centred alternative: instead of adding new matter components, it modifies the scalar–tensor structure of gravity with one new scalar ϕ and one new scale $M \sim 100$ TeV. The central question of this appendix is whether the documentation of MMA–DMF supports its interpretation as an absolute theory rather than a sophisticated effective model.

A.2 Phenomenological article and pipelines

The LaTeX-style article and technical pipeline manuals represent the phenomenological face of MMA–DMF:

- The unified action is stated explicitly, including Galileon and Gauss–Bonnet terms, making contact with known ghost-free scalar–tensor classes.
- Phenomenology is operationalised via gates and pipelines: rotation-curve gates for external disks, bulge gates, cluster gates, and a universal solver for the fifth-force range.
- The Early-X component is parametrised with a peak fraction $f_{\text{peak}} \approx 0.36$, and full χ^2 tables show that MMA–DMF is competitive with Λ CDM across CMB, BAO, SNe and weak-lensing data.

This side of the documentation demonstrates precise algorithmic control, suitable for comparison with data and for reproducibility.

A.3 Foundational investigation reports

The foundational investigation reports play a different role:

- They emphasise UV completeness and the Planck regime, with geometric locking and the bounce replacing the Big Bang singularity.
- They discuss the ontological status of key parameters such as M and the flavor charges q_f , asking whether these can be derived rather than fitted.

- They explain how the same scale M connects cosmology, baryogenesis, neutrino masses and the onset of structure.

These documents function as an internal auditor of the theoretical foundations rather than as data-fitting reports.

A.4 Comparative verdict

The phenomenological article communicates that MMA–DMF is a serious competitor to Λ CDM in terms of data. The foundational investigation communicates that MMA–DMF aims at an absolute theory by linking UV completeness, bounce physics and flavor. An absolute theory, however, requires more than good fits: it requires that fundamental scales and charges be derived from deeper principles. The rest of the appendices therefore focus on the analytical closure conditions that must be addressed for MMA–DMF to reach that status.

B Analytical closure conditions for the single-scale framework

This appendix organises the analytical targets for MMA–DMF into four blocks: the fundamental scale M , the Early-X fraction f_{peak} , the flavor charges q_f and the non-perturbative UV stability of the bounce.

B.1 Fundamental scale $M \sim 100$ TeV

At present, $M \sim 100$ TeV is fixed phenomenologically by requiring:

- a bounce density well below the Planck density;
- screening scales appropriate for galaxies and clusters;
- neutrino masses in the correct range for the geometric seesaw.

For a truly fundamental theory, this scale should emerge dynamically. One natural possibility is dimensional transmutation:

$$M \sim M_{\text{Pl}} \exp\left(-\frac{8\pi^2}{g^2(\mu)}\right), \quad (\text{B.1})$$

for some coupling $g(\mu)$ defined at a reference scale μ . The similarity between 100 TeV and the scale where the Standard Model Higgs potential becomes metastable suggests a link that remains to be made explicit.

Analytical closure requires an equation where M is computed from the microscopic couplings and geometry, rather than set by hand.

B.2 Thermodynamic determination of f_{peak}

The Early-X mechanism critical to the Hubble tension is encoded in a peak fraction $f_{\text{peak}} \approx 0.36$. Currently this is adjusted to fit the CMB and BAO data.

A deeper derivation would start from reheating after the bounce and compute the efficiency of energy transfer from ϕ into the plasma of the Standard Model:

$$f_{\text{peak}} = F(\Gamma_\phi, M, g_*), \quad (\text{B.2})$$

where Γ_ϕ is the decay rate of ϕ , M the single scale and g_* the number of relativistic degrees of freedom.

The target is an explicit calculation showing that for the allowed parameter space,

$$F(\Gamma_\phi, M, g_*) \simeq 0.36, \quad (\text{B.3})$$

with no fine-tuning, so that the Early-X bump is a prediction of the reheating thermodynamics.

B.3 Geometric quantisation of flavor charges q_f

The geometric mass law uses charges q_f such that

$$m_f = m_{\text{top}} \exp \left(-q_f \frac{|\phi|}{M} \right). \quad (\text{B.4})$$

The values currently used, e.g. $q_{\nu_3} \simeq 28.8$, are obtained by fitting to observed masses. Geometric/topological arguments suggest that charges should be built from integers. A generic structure of the form

$$q_{\text{eff}} = n_1 + n_2 \frac{\text{Vol}(A)}{\text{Vol}(B)}, \quad n_1, n_2 \in \mathbb{Z}, \quad (\text{B.5})$$

with $\text{Vol}(A), \text{Vol}(B)$ volumes of cycles or moduli in an underlying geometry, could reproduce non-integer effective values.

Analytical closure here means specifying the geometric manifold and mapping each q_f to a concrete combination of topological data, turning the flavor sector from a fit into a computation.

B.4 Non-perturbative UV degeneracy and Ostrogradsky stability

The bounce relies on higher-curvature couplings such as the Gauss–Bonnet term coupled to ϕ^2 .

Generic higher-derivative theories suffer from Ostrogradsky ghosts unless they belong to a degenerate class like DHOST.

The effective scalar action near the bounce includes

$$S_\phi \supset \int d^4x \sqrt{-g} \frac{\xi}{2M^2} \phi^2 \mathcal{G}, \quad (\text{B.6})$$

with $\mathcal{G}$ the Gauss–Bonnet invariant. The effective mass behaves as

$$m_{\text{eff}}^2 \sim \frac{\xi}{M^2} H^4, \quad (\text{B.7})$$

locking ϕ at the origin.

To formalise stability, one must show that in the UV limit the full scalar–tensor Lagrangian is degenerate in the DHOST sense, so that the would-be Ostrogradsky mode does not propagate or is infinitely heavy. This proof completes the mathematical consistency of the bounce.

C Monographic roadmap for MMA–DMF

This appendix outlines a monographic structure that organises MMA–DMF into a long-form reference work.

C.1 Chapter 1: Unified scalar–tensor paradigm

This chapter introduces the crisis of Λ CDM (tensions in H_0 , S_8 , unknown dark sector) and explains the gravity-centred hypothesis behind MMA–DMF: a single scalar field ϕ and a single new scale M .

It presents the unified action, highlights Galileon and Gauss–Bonnet terms and explains how they avoid obvious instabilities and support screened fifth forces.

C.2 Chapter 2: UV frontier and the Big Bounce

This chapter is devoted to the UV regime:

- geometric locking and the divergence of $m_{\text{eff}} \propto H^4$ as curvature grows;
- the non-singular bounce with $H^2 \sim \rho - \rho^2/M^2$;
- QNEC, ghost checks and regularity of curvature invariants;
- the proof strategy for DHOST-like degeneracy in the UV.

C.3 Chapter 3: Early-X thermodynamics and H_0

This chapter covers:

- the Early-X fluid and its log-normal window around equality;
- the relation $\Delta H_0/H_0 \simeq -\Delta r_s/r_s$;
- CMB acoustic peaks and the stability of the phase;
- reheating and the derivation of f_{peak} from Γ_ϕ , M and g_* .

C.4 Chapter 4: Geometric flavor and mass hierarchy

Here the geometric mass law and seesaw are developed in depth:

- exponential mass law and its relation to ϕ ;
- neutrino seesaw using $M \sim 100$ TeV;
- mapping of q_f to topological data in a geometric space.

C.5 Chapter 5: Late universe and structure growth

This chapter presents:

- Late-X behaviour and future turnaround;
- modified growth through $\mu(a, k)$ and resolution of S_8 ;
- comparison with weak-lensing and RSD data.

C.6 Chapter 6: Galaxies and clusters

Content:

- trace-dependent screening and thin-shell gates;
- baryonic Tully–Fisher relation and disk/UDG phenomenology;
- Bullet Cluster and El Gordo without particle dark matter.

C.7 Chapter 7: Compact objects and precision tests

This chapter deals with:

- regular black holes and de Sitter cores;
- QNEC, entropy and Hawking-like spectra;
- gravitational-wave and shadow predictions.

C.8 Chapter 8: Pipelines and reproducibility

Technical details:

- cosmological codes (CLASS mods, MCMC);
- N-body and hydrodynamic solvers;
- BAO r_s -free pipeline and statistical criteria.

C.9 Chapter 9: Analytical closure and outlook

The final chapter summarises the status of MMA–DMF, compares its global likelihood with Λ CDM and reviews the analytical derivations of M , f_{peak} , q_f and UV stability, indicating which ones have been completed and which remain under development.

D Detailed bounce and geometric locking dynamics

D.1 Gauss–Bonnet coupling and effective mass

The scalar sector near the bounce includes

$$S_\phi = \int d^4x \sqrt{-g} \left[-\frac{1}{2}(\nabla\phi)^2 + \frac{\xi}{2M^2}\phi^2\mathcal{G} + \dots \right]. \quad (\text{D.1})$$

In a high-curvature regime,

$$\mathcal{G} \sim H^4, \quad (\text{D.2})$$

so the effective mass behaves as

$$m_{\text{eff}}^2 \sim \frac{\xi}{M^2} H^4. \quad (\text{D.3})$$

Because $M \ll M_{\text{Pl}}$, this mass grows very rapidly as one approaches the would-be singularity, driving ϕ to zero.

D.2 Bounce density

The effective Friedmann equation can be written as

$$H^2 = \frac{8\pi G}{3}\rho - \frac{\beta_K}{M^2}\rho^2, \quad (\text{D.4})$$

so the bounce occurs at

$$\rho_{\text{bounce}} \simeq \frac{M^2}{\beta_K} M_{\text{Pl}}^2. \quad (\text{D.5})$$

This is much lower than the Planck density if $M \ll M_{\text{Pl}}$ and β_K is order one, ensuring that the effective field theory remains under control.

E Early-X dynamics and Hubble-tension mechanism

E.1 Early-X density and sound horizon

The Early-X energy density fraction is

$$\Omega_X(a) = f_{\text{peak}} S_{\text{eq}}(a) \Omega_r a^{-4}, \quad (\text{E.1})$$

with $S_{\text{eq}}(a)$ a log-normal window centred at equality. This extra radiation-like component reduces the sound horizon r_s by a fraction $\Delta r_s/r_s \sim 7\%$.

Since the angular size of the sound horizon is well constrained by CMB data, a smaller r_s implies a larger late-time H_0 , allowing MMA–DMF to reach $H_0 \sim 72$ km/s/Mpc while remaining consistent with CMB anisotropies.

E.2 Reheating and efficiency

Let Γ_ϕ be the decay rate of ϕ into Standard Model particles. The reheating process after the bounce leads to a plasma energy density

$$\rho_{\text{rad}} \propto a^{-4}, \quad (\text{E.2})$$

and a residual Early-X component whose peak fraction can be modelled as

$$f_{\text{peak}} \equiv \frac{\rho_X(a_{\text{eq}})}{\rho_r(a_{\text{eq}})} = F(\Gamma_\phi, M, g_*). \quad (\text{E.3})$$

The objective is to compute F and show that the regime satisfying other constraints naturally yields $f_{\text{peak}} \approx 0.36$.

F Geometric flavor, structure formation and astrophysical gates

F.1 Geometric Yukawas and mass hierarchy

The Yukawa matrices can be promoted to geometric operators:

$$Y_{ij}(\phi) = c_{ij} \exp\left(-\frac{q_{ij}|\phi|}{M}\right). \quad (\text{F.1})$$

In the low-curvature regime relevant for particle physics, the background value of ϕ and the charges q_{ij} combine to reproduce the observed fermion masses and mixing patterns.

F.2 Growth function and S_8

The modified growth function

$$\mu(a, k) = 1 + \mu_0 S_{\text{late}}(a) \frac{1}{1 + (k\lambda)^2} \quad (\text{F.2})$$

suppresses the growth of structure on small scales relative to ΛCDM , lowering the predicted S_8 and improving agreement with weak-lensing data.

F.3 Gates in galaxies and clusters

The trace-dependent coupling

$$A(\phi, T) = 1 + \frac{\beta\phi}{M_{\text{Pl}}} (1 - e^{-T/T_{\text{crit}}}) \quad (\text{F.3})$$

creates environmental gates:

- in high-density environments (Solar System, dense galactic bulges), the exponential term saturates and screening is strong;
- in low-density environments (outer disks, UDGs, cluster outskirts), screening is weak and the fifth force is active.

This explains:

- rotation curves and the baryonic Tully–Fisher relation without particle dark matter;
- UDG velocity dispersions such as Dragonfly 44;
- cluster mass profiles and offsets such as in the Bullet Cluster.

G Synthesis and roadmap for analytical derivations

The combined picture is:

- MMA–DMF as presented in the main body of the paper is a single-scale framework that already matches a wide range of data, from CMB and BBN to galaxies and clusters;
- the UV stability ladder (QNEC, ghosts, locking, regularity) supports the bounce and black-hole sectors;
- the geometric flavor sector links the same scale M to neutrino masses and the mass hierarchy.

The analytical derivations to be fully completed are:

- a calculation of M from microscopic couplings, e.g. via dimensional transmutation;
- a thermodynamic derivation of f_{peak} from reheating efficiency;
- a geometric/topological computation of the charges q_f ;
- a formal DHOST-level proof of UV degeneracy for the bounce Lagrangian.

Among these, the thermodynamic derivation of f_{peak} is the most directly connected to current data and offers a clear path to increase the predictive power of MMA–DMF beyond curve fitting.

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