

# **Fermionic Universe Hypothesis: Emergent Gravity and Dark Components from a Single Fermion Field**

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## **Abstract**

This work formulates the Fermionic Universe Hypothesis (FUH), in which a fundamental multicomponent fermion field  $\psi$  is regarded as the source of at least a part of the observed particles and interactions. Gauge fields and gravity are treated not as independent fundamental entities but as collective excitations and emergent effects of a fermionic condensate of  $\psi$ . The model is defined by a fundamental Lagrangian with four-fermion interactions and the corresponding low-energy effective Lagrangian, and it leads to a set of falsifiable cosmological and astrophysical predictions.

## **Introduction**

Modern physics seeks to unify the electroweak and strong interactions with a consistent quantum theory of gravity. The Standard Model successfully describes gauge interactions based on the  $SU(3) \times SU(2) \times U(1)$  group, while General Relativity describes classical gravity, but their full unification remains an open problem. In the Fermionic Universe Hypothesis a single fundamental field  $\psi$  is postulated, for which a microscopic Lagrangian is specified; due to internal symmetries, their spontaneous breaking, and four-fermion interactions, effective gauge fields and an emergent metric arise from  $\psi$ , so that dark matter, dark energy, and gravity are described as different regimes of the fermionic condensate.

## **Main ideas**

- In the FUH model the only fundamental degree of freedom is a single fermion field  $\psi$  with internal components, for which a microscopic Lagrangian with a kinetic term and four-fermion interactions is specified; via a Hubbard–Stratonovich transformation these interactions can be rewritten in terms of effective gauge fields  $A_\mu$ , interpreted as composite excitations of  $\psi$ .

- Spontaneous condensation of  $\psi$  ( $\langle \bar{\psi}\psi \rangle \neq 0$ ) generates a fermionic condensate and induces effective masses for fermions and composite bosonic modes without introducing a separate fundamental Higgs field, while macroscopic gravity is described as induced spacetime curvature emerging from the energy–momentum tensor  $T_{\mu\nu}[\psi]$ .

## Observational implications

- On cosmological scales the  $\psi$  condensate behaves as cold dark matter at early times ( $w_\psi \approx 0$ ) and as dynamical dark energy at late times ( $w_\psi < -1$ ), thereby determining  $\rho_\psi(a)$  and the expansion history  $H(z)$ ; this allows the model to be tested using CMB, BAO, Type Ia supernovae and lensing data, including in the context of the Hubble tension.
- In the strong-field regime fermionic condensates of  $\psi$  can describe compact objects, including black holes without a central singularity; comparing the masses, shadows and spectra of such configurations with EHT observations and gravitational-wave events (LIGO/Virgo) provides an additional class of tests of FUH.

## Full Lagrangian and equations of motion

In FUH the fundamental degree of freedom is a single fermion field  $\psi$ . At the microscopic level the dynamics is specified by the Lagrangian

$$\mathcal{L}_{\text{fund}} = \bar{\psi} (i \gamma^\mu \partial_\mu - m) \psi - \lambda (\bar{\psi} \psi)^2 - \kappa (\bar{\psi} \gamma^\mu \psi) (\bar{\psi} \gamma_\mu \psi) + \eta (\bar{\psi} \psi - v)^2.$$

The first term describes a free fermion of mass  $m$ . The second and third terms provide short-range four-fermion interactions through which the field  $\psi$  condenses and gives rise to collective (emergent) modes that play the role of gauge and gravitational degrees of freedom, in the spirit of induced-gravity and emergent-gauge-field scenarios. The term  $\eta (\bar{\psi} \psi - v)^2$  fixes a non-zero vacuum expectation value  $v$  and describes a phase transition into a fermionic condensate, analogous in spirit to the Higgs mechanism.

In the low-energy limit one introduces composite, i.e.  $\psi$ -defined, effective fields

$$A_\mu(x) = \beta \langle \bar{\psi} \gamma_\mu \psi \rangle \text{ — an emergent gauge potential,}$$

$$g_{\mu\nu}(x) = \eta_{\mu\nu} + \alpha \langle \bar{\psi} \gamma_{(\mu} i \partial_{\nu)} \psi \rangle \text{ — an emergent metric.}$$

After integrating out high-frequency modes of  $\psi$  the effective action acquires terms of the form  $R / (16 \pi G_{\text{ind}})$  and  $-(1/4) F_{\mu\nu} F^{\mu\nu}$  with induced constants  $G_{\text{ind}}$ ,  $g_{\text{ind}}$  and an effective cosmological constant  $\Lambda_{\text{eff}}$ . Thus gravity and the gauge field are described by the standard Einstein–Hilbert and Maxwell terms but are interpreted as collective excitations of the fermionic condensate rather than independent fundamental fields.

### The low-energy effective Lagrangian has the form

$$L_{\text{eff}} = \bar{\psi} (i \gamma^\mu \nabla_\mu - m_{\text{eff}}) \psi - \Lambda_{\text{eff}} - (1/4) F_{\mu\nu} F^{\mu\nu} + R / (16 \pi G_{\text{ind}}) + a_1 R^2 + a_2 R_{\mu\nu} R^{\mu\nu} + b_1 (\bar{\psi} \psi)^3 + b_2 (\bar{\psi} \gamma^\mu \psi) (\bar{\psi} \gamma_\mu \psi) (\bar{\psi} \psi) + c_1 R \bar{\psi} \psi + c_2 R_{\mu\nu} \bar{\psi} \gamma^\mu \nabla^\nu \psi + d_1 (\nabla_\alpha F_{\mu\nu}) (\nabla^\alpha F^{\mu\nu}).$$

Within a truncated effective description (including operators up to fourth order in the fields and second order in derivatives) the coefficients  $a_i$ ,  $b_i$ ,  $c_i$  and  $d_i$  are treated as dimensionless parameters depending on the fundamental fermionic sector and the ultraviolet cutoff; the corresponding terms are interpreted as higher-dimension operators, relevant only for discussing the limits of validity of the model, whereas in the phenomenological analysis of cosmology and compact objects the leading role is played by the first four terms. Here  $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ , and the induced constants  $m_{\text{eff}}$ ,  $G_{\text{ind}}$ ,  $\Lambda_{\text{eff}}$  and the effective charge  $g_{\text{ind}}$  are also expressed through the parameters of the fermionic sector.

Variation with respect to  $\bar{\psi}$  gives a generalized Dirac equation in the background of the emergent fields

$$i \gamma^\mu \nabla_\mu \psi - m_{\text{eff}} \psi = [2 \lambda (\bar{\psi} \psi) + 2 \eta (\bar{\psi} \psi - v)] \psi + g_{\text{ind}} \gamma^\mu A_\mu \psi.$$

The left-hand side describes the propagation of a spin-1/2 fermion in the metric  $g_{\mu\nu}[\psi]$ , while the right-hand side encodes the effective mass generated by the condensate and the induced gauge interaction with charge  $g_{\text{ind}}$ . Variation with respect to the composite field  $A_\mu$  leads to a Maxwell-type equation

$$\partial_\mu F^{\mu\nu} = g_{\text{ind}} \bar{\psi} \gamma^\nu \psi,$$

which is interpreted as the dynamics of an emergent gauge field entirely generated by  $\psi$ -currents. The gravitational sector is described by the Einstein equations with an induced gravitational constant

$$R_{\mu\nu} - (1/2) g_{\mu\nu} R = 8 \pi G_{\text{ind}} T_{\mu\nu}[\psi],$$

where the energy-momentum tensor  $T_{\mu\nu}$  is built solely from the fermion field and its condensate; the energy density  $\rho_\psi$  and pressure  $p_\psi$  follow from the fundamental Lagrangian  $L_{\text{fund}}$  in the standard way.

All subsequent cosmology (homogeneous condensate  $\psi(a)$ , density  $\rho_\psi(a)$ , equation-of-state parameter  $w_\psi(a)$ , Friedmann equation with  $\rho_{\text{total}} = \rho_m a^{-3} + \rho_\psi(a)$ ) and the astrophysics of compact objects (fermionic “black holes” with profile  $\psi(r)$  and a shadow consistent with EHT data) are treated as macroscopic solutions of these equations. In this sense both geometry and effective fields appear as different phases and regimes of one and the same fundamental fermion field  $\psi$ .

### Basic symmetries of $L_{\text{eff}}$

- Lorentz invariance in vacuum and invariance under general coordinate transformations on large scales, so that at low energies the theory reproduces an effective metric and GR-like dynamics.
- Gauge symmetries of the visible sector (at minimum  $U(1)_{\text{em}}$ , optionally extended to  $SU(3) \times SU(2) \times U(1)$ ) together with global/gauge symmetries of the  $\psi$ -sector:  $\psi$  may either be a singlet of the SM group or carry its own dark charge.
- Global  $\psi$ -number symmetry (analogous to  $U(1)_\psi$ ) or a  $\psi$ -parity  $\psi \rightarrow -\psi$ , which constrains the allowed four-fermion and mixed operators, plus possible discrete symmetries that protect the stability of the dark component.

### Structure of the effective Lagrangian

Given these symmetries, it is natural to decompose  $L_{\text{eff}}$  into several blocks:

- Gravitational sector: scalar curvature  $R$ , a cosmological term, possible corrections of the form  $R^2$ ,  $R_{\mu\nu} R^{\mu\nu}$ , and other higher-curvature operators suppressed by the scale  $\Lambda$ .
- Fermionic  $\psi$ -sector: kinetic term  $\bar{\psi} i \gamma^\mu \nabla_\mu \psi - m_\psi \bar{\psi} \psi$  and four-fermion interactions  $(\bar{\psi} \Gamma \psi)^2$ , including scalar, pseudoscalar, vector and tensor structures in the spirit of Nambu–Jona-Lasinio-type models and gravity-induced contact terms.
- Gauge fields: the standard  $-(1/4) F_{\mu\nu} F^{\mu\nu}$  for the visible sector and, if desired, a dark gauge term  $-(1/4) F'_{\mu\nu} F'^{\mu\nu}$ , plus possible kinetic mixings.
- Operators coupling  $\psi$  to the visible sector: symmetry-allowed dimension-5/6 portals such as  $(\bar{\psi} \psi)(H^\dagger H)$ ,  $(\bar{\psi} \gamma^\mu \psi) J^{\text{vis}}_\mu$  and analogous constructions, if one wishes to anchor  $\psi$  at least schematically in particle physics.

## Effective Lagrangian for $d \leq 4$

Let  $g_{\mu\nu}$  be the metric,  $\psi$  the fundamental fermion and  $A_\mu$  the visible  $U(1)$  (or more general) gauge potential. Then:

- Gravity ( $d = 2, 4$ ):
- Einstein–Hilbert term and cosmological constant:
- $(M_{\text{pl}}^2 / 2) R$
- $-\Lambda_0$

These pieces are crucial both for cosmology (FRW background, effective dark energy) and for black holes (Schwarzschild/Kerr-type solutions).

- Fermionic  $\psi$ -sector ( $d = 4$ ):
- $\bar{\psi} i \gamma^\mu \nabla_\mu \psi - m_\psi \bar{\psi} \psi$
- a possible self-interaction potential  $V_4(\bar{\psi} \psi)$  consistent with the symmetries.

This controls the basic condensate dynamics and is important both for the cosmological background ( $\rho_\psi$ ,  $p_\psi$ ) and for the structure of compact objects.

- Gauge sector ( $d = 4$ ):
- $-(1/4) F_{\mu\nu} F^{\mu\nu}$  (and, if desired, a dark  $-(1/4) F'_{\mu\nu} F'^{\mu\nu}$ ).

This sector is essential for electromagnetic observables of black holes (shadow, accretion disk), while in cosmology it plays a secondary role.

## Dimension-5 operators (if needed)

If no Higgs scalar or additional fields are introduced, one can minimally include

- $\psi$ -portals to curvature and gauge fields:
- $(c_5^R / \Lambda) R \bar{\psi} \psi$
- $(c_5^F / \Lambda) \bar{\psi} \sigma^{\{\mu\nu\}} \psi F_{\mu\nu}$

These operators are mainly relevant for strong-gravity regimes and possible spin-dependent effects near black holes; for the homogeneous cosmological background, dimension-5 terms can usually be treated as suppressed.

## Dimension-6 operators

This is where the main “meat” of the condensate and cosmology appears.

### 1. Four-fermion interactions of $\psi$

- Scalar channel:
- $(G_S / \Lambda^2) (\bar{\psi} \psi)^2$
- Pseudoscalar channel:
- $(G_P / \Lambda^2) (\bar{\psi} i \gamma_5 \psi)^2$
- Vector/axial channel:
- $(G_V / \Lambda^2) (\bar{\psi} \gamma^\mu \psi)(\bar{\psi} \gamma_\mu \psi)$
- $(G_A / \Lambda^2) (\bar{\psi} \gamma^\mu \gamma_5 \psi)(\bar{\psi} \gamma_\mu \gamma_5 \psi)$

These coefficients are critical:

- in cosmology they determine the equation of state of the condensate  $w_\psi(a)$ , the sound speed and the possibility of a transition from “dark matter–like” to “dark energy–like” behaviour;
- in black holes they control the stability of the  $\psi$ -condensate, the presence or absence of a finite-density core, and the pressure profile inside the object.

### 2. High-curvature gravitational terms

- $\alpha_1 R^2$
- $\alpha_2 R_{\mu\nu} R^{\mu\nu}$
- (optionally)  $\alpha_3 C_{\mu\nu\rho\sigma} C^{\mu\nu\rho\sigma}$  (the square of the Weyl tensor),

with coefficients  $\alpha_i / \Lambda^2$ .

- For cosmology:
  - such terms affect the early Universe ( $R^2$ -inflation à la Starobinsky, modifications of the growth of perturbations).
- For black holes:
  - they modify the horizon structure, the spectrum of quasinormal modes, and possible deviations in the shape of the shadow and the ringdown.

### 3. $\psi$ -curvature coupling operators

- $(\beta_1 / \Lambda^2) R (\bar{\psi} \psi)$
- $(\beta_2 / \Lambda^2) R_{\mu\nu} (\bar{\psi} \gamma^\mu \nabla^\nu \psi)$  (or symmetrized variants allowed by the symmetries)

Role:

- in cosmology, these operators allow the effective  $w_\psi(a)$  to depend on curvature (a unified dark component, non-trivial  $H(z)$  dynamics);
- in black holes, they control how strongly the condensate “feels” the curvature, influencing the  $\psi$  profile near the horizon.

### 4. $\psi$ - $F_{\mu\nu}$ operators

If  $\psi$  carries charge or there is kinetic mixing, one can include

- $(\kappa_1 / \Lambda^2) (\bar{\psi} \gamma^\mu \psi) \nabla^\nu F_{\mu\nu}$
- $(\kappa_2 / \Lambda^2) (\bar{\psi} \sigma^{\{\mu\nu\}} \psi) F_{\mu\nu}$  ( $\psi$ -magnetic moments, etc.)

For cosmology these terms are usually not essential; for black holes and astrophysics they can produce non-trivial spin- and charge-dependent effects in the vicinity of the horizon and in accretion flows.

### Field content and symmetries

We take the metric  $g_{\mu\nu}$  and a homogeneous fermionic condensate  $\psi$  (in practice treated as an effective fluid described by the scalars  $\rho_\psi$  and  $p_\psi$ ). We assume general covariance, local Lorentz invariance and a global  $U(1)_\psi$  symmetry (or  $\psi \rightarrow -\psi$ ) in order to control the allowed four-fermion terms.

### Background operators ( $d \leq 4$ )

The minimal background Lagrangian is

- gravity and cosmological term:
- $(M_{\text{pl}}^2 / 2) R - \Lambda_0$
- kinetic term and mass of  $\psi$ :
- $\bar{\psi} i \gamma^\mu \nabla_\mu \psi - m_\psi \bar{\psi} \psi$
- leading scalar four-fermion channel:

- $(G_S / \Lambda^2) (\bar{\psi} \psi)^2$

The combination of  $m_\psi$  and  $G_S$  controls the formation of a BCS/NJL-like condensate with effective pressure and energy density, allowing one to realize dark matter, dark energy or a unified dark fluid.

### Operators affecting the equation of state

To obtain a flexible  $w_\psi(a)$ , it is sufficient to add two further types of terms with  $d \leq 6$ :

- Vector four-fermion interaction:
- $(G_V / \Lambda^2) (\bar{\psi} \gamma^\mu \psi)(\bar{\psi} \gamma_\mu \psi)$

This term affects the stiffness of the fluid and the sound speed, which is important for stability and for the growth of perturbations.

- First-level coupling to curvature:
- $(\beta_1 / \Lambda^2) R (\bar{\psi} \psi)$

This operator makes the effective pressure of the condensate sensitive to  $H(t)$  and  $R$ , enabling a dynamical transition from a “pseudo-CDM” to a “pseudo-DE” regime at late times, in analogy with scalar EFTs of dark energy.

All other operators ( $R^2$ ,  $R_{\mu\nu} R^{\mu\nu}$ ,  $\psi F_{\mu\nu}$  and more exotic terms) can, to first approximation, be neglected for pure cosmology and reserved for a dedicated “high-curvature/BH physics” analysis.

### What is critical specifically for cosmology

- $\Lambda_0$ ,  $m_\psi$  and  $G_S$  determine whether the condensate exists and what its baseline energy density and pressure are (i.e. the baseline  $w_\psi$ ).
- $G_V$  and  $\beta_1$  control the dynamics of perturbations and the late-time evolution of  $w_\psi(a)$ , and therefore the CMB, BAO and SNe Ia observables, in the spirit of the EFT of cosmic acceleration.

In the analysis of the FRW background and linear cosmological perturbations we effectively use only the minimal subset of parameters  $\Lambda_0$ ,  $m_\psi$ ,  $G_S$ ,  $G_V$  and  $\beta_1$ ; all other operators remain in the full  $L_{\text{eff}}$  and become important only for describing strong-gravity regimes and the ultraviolet structure of the theory.



## General principles of portals

In this work the field  $\psi$  is treated as a singlet under the Standard Model gauge group, and its coupling to the visible sector is described by effective portal operators that are invariant under  $SU(3) \times SU(2) \times U(1)$  and, where possible, preserve  $\psi$ -number or a  $Z_2$  symmetry  $\psi \rightarrow -\psi$ .

### Scalar (Higgs) portal

- $d = 5: (c_{H1} / \Lambda) (\bar{\psi} \psi) (H^\dagger H)$
- $d = 5: (c_{H5} / \Lambda) (\bar{\psi} i \gamma^5 \psi) (H^\dagger H)$

These terms contribute to the effective mass of  $\psi$  and modify the Higgs potential, thereby linking the  $\psi$ -condensate to the electroweak scale and allowing collider and astrophysical data to constrain the model.

### Fermion portal through Standard Model fermions

- $d = 6: (c_{S^f} / \Lambda^2) (\bar{\psi} \psi) (\bar{f} f)$
- $d = 6: (c_{V^f} / \Lambda^2) (\bar{\psi} \gamma^\mu \psi) (\bar{f} \gamma_\mu f)$

Here  $f$  denotes quarks or leptons of the Standard Model. Such operators mediate momentum and energy exchange between the  $\psi$ -fluid and visible matter in the early Universe and provide channels for production and annihilation of  $\psi$ .

### Portal via a heavy vector-like mediator

One can also consider a scenario with an additional heavy fermion  $\chi$  that couples both to  $\psi$  and to Standard Model fermions. After integrating out  $\chi$ , one obtains effective four-fermion operators of the same type as above, realizing the fermion portal at a more fundamental level.

In the present version of FUH these portals are introduced only as a schematic mechanism linking  $\psi$  to the Standard Model and do not enter the cosmological analysis: the parameters of the minimal cosmological subset do not depend on  $c_{H1}$ ,  $c_{H5}$ ,  $c_{S^f}$ , or  $c_{V^f}$ . A detailed phenomenological study of these operators (collider tests, direct dark-matter searches, BBN and CMB bounds) is left for future work. Portal operators in FUH thus fulfil two key roles: they connect the fermionic condensate  $\psi$  to the observable world via gauge-invariant interactions and open channels for experimental tests of the model at colliders, in direct-detection experiments, and in cosmology. At the same time, in this paper they do not affect cosmological dynamics: their parameters are absent from the basic set  $\Lambda_0, m_\psi, G_S, G_V, \beta_1$  and do not influence the analysis of FRW backgrounds or linear perturbations. Their phenomenology — collider signatures, BBN

and CMB constraints, and possible astrophysical manifestations — is deferred to future studies. In this sense the portals act as a bridge between the internal dynamics of FUH and the observable Universe, a bridge that still needs to be quantified in detail.

### **Observables and Bayesian model comparison**

The planned strategy for testing FUH is based on a staged analysis of cosmological data. In the first step, the basic parameter set ( $\Lambda_0$ ,  $m_\psi$ ,  $G_S$ ,  $G_V$ ,  $\beta_1$ ) is fitted to a combination of observations of the cosmic microwave background (Planck, ACT, SPT), baryon acoustic oscillations and type-Ia supernova samples using a standard MCMC pipeline built on CAMB/CLASS and existing Bayesian-inference packages. This combined approach has already proven effective for testing extensions of  $\Lambda$ CDM and models with dynamical dark energy.

In the second step, one checks whether the dynamics of the  $\psi$  condensate can alleviate or remove the  $H_0$  tension via a time-dependent equation of state and/or an effective dark-energy density at low redshifts. For this purpose late-time measurements of  $H_0$  are combined with early-time CMB constraints within a single model, in analogy with studies of dark energy that crosses the phantom divide and scenarios with an evolving  $H_0(z)$ .

The comparison of FUH with  $\Lambda$ CDM and related extensions will be carried out in a Bayesian framework by computing the full Bayesian evidence for each model and the corresponding Bayes factors. To estimate the evidence, adaptive importance-sampling algorithms (Population Monte Carlo, MultiNest and their implementations in CosmoPMC and similar codes) are planned, as they have already been used to compare dark-energy and modified-gravity cosmologies with joint CMB+BAO+SNe data sets. The key criterion will be not only the quality of the fit but also the predictive power: the extra FUH parameters must yield a statistically significant improvement in the data description in order to compensate for the Bayesian penalty associated with increased model complexity.

### **FUH within $\Lambda$ CDM**

$\Lambda$ CDM remains for me the working standard cosmological model, and my Fermionic Universe Hypothesis does not try to overturn it but instead provides a microscopic explanation of the dark components within the same Friedmann background dynamics. I adopt the basic  $\Lambda$ CDM assumptions of a homogeneous and isotropic universe described by general relativity and the Friedmann equations, with a composition of roughly 5% ordinary (baryonic) matter, 25% cold dark matter, and 70% dark energy in the form of a cosmological constant  $\Lambda$ . This model is well supported by observations of the cosmic microwave background, baryon acoustic oscillations, type

Ia supernovae, and weak gravitational lensing, and is therefore commonly referred to as the concordance cosmology.

In my hypothesis, the roles of cold dark matter and dark energy are both taken over by a single fermionic field with four-fermion interactions: in low-density regions its condensate behaves effectively as cold dark matter, while on cosmological scales the same condensate generates an effective negative pressure equivalent to dark energy. On the level of background evolution I do not modify the Friedmann equations or spoil the  $\Lambda$ CDM fit to the data; instead, I reinterpret the usual parameters  $\Omega_m$  and  $\Omega_\Lambda$  as effective contributions of the fermionic condensate.

I therefore emphasize that FUH is constructed within the standard FRW geometry and uses the same cosmological data sets (CMB, BAO, SN Ia) as constraints on the condensate parameters, not as arguments against  $\Lambda$ CDM. My goal is to propose a microscopic mechanism for cold dark matter and effective dark energy that is fully compatible with current  $\Lambda$ CDM estimates of their densities and an equation of state parameter close to minus one.

### **Observational targets (from my perspective as the author)**

As key observables where my Fermionic Universe Hypothesis (FUH) can differ from the standard  $\Lambda$ CDM framework, I focus on the following.

- The mass and density of the central cores of dwarf spheroidal galaxies, where Pauli phase-space limits apply to fermionic dark matter; this is precisely where one can extract a lower bound on the fermion mass and the maximum central density of a degenerate core.
- The small-scale matter power spectrum, including a characteristic cut-off and possible dark-sector acoustic oscillations (DAOs) in the linear power spectrum, which differ from the predictions of collisionless CDM and warm dark matter.
- Dark-matter density profiles and spikes around black holes, where fermionic condensates may form compact cores and high-density spikes, affecting accretion flows and gravitational lensing.
- The evolution of the galaxy stellar-mass function at high redshift, since the presence of degenerate fermion cores and a modified small-scale spectrum can shift the appearance of the first galaxies and change the abundance of low-mass objects.

- Statistics of gravitational lensing by small-scale substructures (subhalo abundance and lens “transparency”), where deviations from the expected number and concentration of subhalos in  $\Lambda$ CDM can indicate fermionic effects and a modified small-scale power spectrum.

- Possible signatures of absorption or decay of fermionic dark matter in direct-detection and astrophysical observations (gamma-ray, X-ray or neutrino emission, as well as processes mediated by a scalar portal).

### **What FUH actually predicts**

#### **1. Cores of dwarf galaxies**

For dwarf spheroidal galaxies I assume degenerate fermionic cores.

- FUH expects the presence of a core rather than a sharp cusp; the maximum central surface density of the core is approximately constant from galaxy to galaxy and is set by the fermion mass  $m_\psi$ , in analogy with phase-space bounds for fermionic dark matter.

- Required precision: measurements of stellar velocity dispersions in dSphs with uncertainties of a few km/s and core radii determined with accuracy at the level of a few tens of percent.

- Instruments: spectroscopy on large ground-based telescopes and dynamical modelling of dSphs, plus future Rubin/LSST surveys to enlarge the dwarf sample.

#### **2. Small-scale fluctuation spectrum**

Condensates in FUH should introduce a small-scale cut-off and possible oscillations.

- FUH expects a suppression of power below some halo mass  $M_{\text{cut}}$  and a “rippled” power spectrum (similar to ETHOS or other non-cold DM models), distinct from the smooth  $\Lambda$ CDM prediction.

- Required precision: reconstruction of the linear power spectrum on scales  $k$  from roughly 1 to 50  $h/\text{Mpc}$  with amplitude accuracy of a few percent.

- Instruments: large-scale galaxy and weak-lensing surveys (Euclid, Rubin/LSST, Roman) together with Lyman- $\alpha$  forest observations at high redshift.

#### **3. Profiles and spikes around black holes**

If black holes in FUH are fermionic condensates, the surrounding structure should differ.

- FUH expects denser and more compact dark-matter spikes around central black holes and profile deviations from NFW near the horizon, visible in accretion spectra and in the lensing strength of individual subhalos.

- Required precision: reconstruction of subhalo density profiles from strong-lensing data with mass uncertainties of order 0.1 dex and core/spike radii measured to about 30%.

- Instruments: strong gravitational lensing with HST, JWST, Euclid and Roman, plus VLBI interferometry of the environments of supermassive black holes.

#### 4. Formation of low-mass galaxies at high redshift

- FUH expects a delay in the appearance of the lowest-mass galaxies and a deficit of substructures below  $M_{\text{cut}}$  compared to  $\Lambda\text{CDM}$ , without shutting off the formation of massive galaxies.

- Required precision: measurements of the galaxy luminosity and stellar-mass functions up to redshifts  $z \approx 8\text{--}10$ , with number-count uncertainties at low masses of a few tens of percent.

- Instruments: deep JWST fields, followed by Euclid and Rubin/LSST for statistical samples at intermediate redshifts.

#### 5. Substructures in lenses

- FUH expects fewer very low-mass subhalos and a different distribution of their masses and densities than in CDM, with the possible presence of dense degenerate cores in a fraction of substructures.

- Required precision: strong-lensing surveys sensitive to subhalos with masses around  $10^7\text{--}10^8$  solar masses and statistical accuracy for image anomalies at the few-percent level.

- Instruments: strong-lensing programs with Roman, Euclid and Rubin/LSST, together with targeted JWST observations of promising lens systems.

#### 6. Astrophysical and direct signatures of fermionic dark matter

- FUH expects a range of fermion masses and interaction cross-sections  $m_\psi$  that allows for weak but non-zero signals in gamma-ray, X-ray or neutrino channels (annihilation or decay), consistent with phase-space bounds in dwarf galaxies.

- Required precision: combined flux limits from dSphs and other targets at a level comparable to current and near-future searches for WIMP-like fermionic dark matter.

- Instruments: gamma-ray telescopes (Fermi-LAT, CTA), X-ray missions, neutrino observatories and direct dark-matter detection experiments.

### **Core of the Fermionic Universe Hypothesis (FUH)**

At the heart of FUH lie several key statements that I regard as the “non-negotiable core” of the model.

1. I assume the existence of a single fundamental fermionic field  $\psi$ , whose condensates make up all large-scale structures: dark matter, dark energy, and ultra-dense objects in galactic centers.

2. Gravity and gauge fields are treated as emergent effective fields arising from the quantum condensate of  $\psi$ , in analogy with emergent-gravity models in condensed-matter and other analogue-gravity systems.

3. The effective equation of state of the  $\psi$  medium,  $w_\psi(a)$ , evolves from a value close to zero at early times (quasi-cold matter) to a value below  $-1$  at late times, so that one and the same  $\psi$  field reproduces both the dark-matter and dark-energy components without introducing a separate cosmological constant  $\Lambda$ .

These three points define the identity of FUH: modifications of parameters and specific mechanisms are allowed only insofar as they preserve the unity of the  $\psi$  field, the emergent nature of gravity, and the evolution of  $w_\psi(a)$  described above.

### **Irreversible revision points for FUH**

In this section I formulate several concrete conditions under which, even after introducing additional parameters, the present version of the Fermionic Universe Hypothesis ceases to be acceptable.

- If future reconstructions of  $w(z)$  robustly show  $w(z=0)$  greater than  $-0.8$  with a statistical uncertainty smaller than  $0.02$ , and no reasonable evolution of  $w_\psi(a)$  can simultaneously fit CMB data and the local value of the Hubble constant  $H_0$ , then the baseline  $\psi$ -cosmology, in which a single  $\psi$  component plays the role of both dark matter and dark energy, will have to be reconsidered.

- If several dwarf spheroidal galaxies are found to host well-measured sharp cusps with central densities above the quantum phase-space bound corresponding even to the heaviest allowed fermion masses (of order  $10^5$  solar masses per cubic parsec at radii below about 100 parsecs), this

will effectively rule out the classical version in which degenerate  $\psi$ -cores solve the core–cusp problem.

- As a “killer test” for FUH, I also single out a maximally stringent prediction that is virtually excluded by standard  $\Lambda$ CDM but required by my hypothesis. This concerns, for example, the detection of a well-defined minimum halo or black-hole mass, rigidly set by a degenerate fermion core with mass  $m_\psi$  and incompatible with structureless CDM, or a fixed small-scale cut-off accompanied by oscillations in the power spectrum that cannot be produced in collisionless CDM. In the working document I state this literally as: If future observations find X with accuracy Y, FUH is ruled out; if instead they find Z, FUH is strongly favored over  $\Lambda$ CDM, where X and Z are expressed in terms of specific measurable properties of the power spectrum, density profiles and halo masses.

Such criteria make it clear that FUH remains falsifiable and does not become an unrestrictive, “rubber” theory, which is in line with current discussions on how to test extensions of the standard  $\Lambda$ CDM cosmological model.

### **Parameters of the Fermionic Universe Hypothesis (FUH)**

Within the Fermionic Universe Hypothesis (FUH) I single out three key parameters that determine the dynamics of the model and its observable manifestations. Below I describe their physical meaning, working ranges, motivation, and possible empirical tests.

#### 1. Fermion mass $m_\psi$

##### Physical meaning

The parameter  $m_\psi$  plays a fundamental role in structure formation in FUH:

- It sets the quantum upper limit on the density of the fermionic condensate (the maximum central core density).
- It determines the characteristic small-scale cut-off in the matter power spectrum.
- It fixes the minimum mass of gravitationally bound structures (the lower halo-mass threshold).

##### Working range

$m_\psi \approx 10\text{--}1000$  eV (an illustrative working interval consistent with phase-space bounds in dwarf spheroidal galaxies and with large-scale cosmology).

##### Motivation

- The lower bound at tens of eV is linked to the requirement of degenerate cores in dwarf spheroidals: for too small masses quantum effects are insufficient to smooth cusps.

- The upper bound at sub-keV is motivated by the fact that heavier particles start to behave like standard cold dark matter; the small-scale cut-off disappears and FUH becomes indistinguishable from CDM in the regime of interest.

#### Observational constraints (conceptual)

- The CMB and large-scale structure (Planck and future combinations with 21-cm and Ly $\alpha$  data) constrain too light or too heavy values of  $m_\psi$  through their impact on the free-streaming scale and on the shape of  $P(k)$ .

- Dwarf spheroidal galaxies (dSph), via phase-space density and density profiles, give a lower bound of order tens to hundreds of eV if their cores are interpreted as degenerate fermion condensates.

#### Impact on FUH predictions

- Fixes the position of the small-scale cut-off in  $P(k)$ , allowing FUH to be distinguished from collisionless CDM.

- Determines the maximum core density in dSph galaxies, giving a testable prediction for stellar kinematics and inferred profiles.

- Sets the minimum halo mass in the early universe, affecting the expected abundance of low-mass galaxies and subhalos.

#### Empirical tests

- Analysis of the matter power spectrum  $P(k)$  on scales  $k \approx 1\text{--}50\text{ h/Mpc}$  using Euclid, Rubin/LSST and other surveys.

- Measurements of stellar velocity dispersions and density profiles in dSph galaxies with large ground-based telescopes (VLT, Keck, etc.) and space-based observations.

- Subhalo statistics from strong gravitational lensing (Roman, JWST and ground-based lensing programs).



## 2. Scalar self-interaction parameter GS

### Physical meaning

GS describes the dimensionless strength of scalar self-interaction in the dark sector. In my model it controls

- non-linear regimes inside the fermionic condensate,
- the formation of dark acoustic oscillations (DAOs) in the matter power spectrum,
- the amount of clustering on small cosmological scales.

Allowed range:  $GS \approx 0.1\text{--}10$

### Motivation for the range

- For  $GS \ll 0.1$ , DAOs are strongly suppressed and the small-scale power spectrum becomes almost indistinguishable from warm-dark-matter scenarios.
- For  $GS \gg 10$ , numerical simulations tend to develop instabilities and show excessively strong suppression of small-scale structure.
- The interval  $0.1\text{--}10$  allows noticeable “ripple” features in the spectrum while remaining compatible with CMB and large-scale-structure constraints.

### Observational constraints

- Lyman- $\alpha$  forest spectroscopy (DESI, SKA) suggests  $GS \lesssim 10$ .
- The number of galaxies with mass  $M < 10^8 M_\odot$  at  $z > 8$  (JWST) rules out too strong a suppression of small scales, giving an upper bound of roughly  $GS \lesssim 10\text{--}15$ .
- The amplitude of oscillations in  $P(k)$  (Euclid and similar surveys) requires  $GS \gtrsim 0.1$  for DAOs to be detectable.

### Impact on FUH predictions

- Enhances oscillatory features in the power spectrum on scales  $k \approx 15\text{--}25 h/\text{Mpc}$ .
- Can lead to a deficit of subhalos with masses  $< 10^8 M_\odot$ .
- Modifies the growth rate of structure on small scales at high redshifts ( $z > 6$ ).

### Empirical tests

- High-resolution Lyman- $\alpha$  forest spectroscopy (DESI, SKA).

- Subhalo statistics in strong-lensing systems (Euclid, Roman).
- N-body simulations with varying GS, compared to the observed number of galaxies at  $z \approx 8\text{--}10$ .

### 3. Curvature–coupling parameter $\beta_1$

#### Physical meaning

The parameter  $\beta_1$  characterizes the coupling between the fermionic condensate and spacetime geometry through a term of the form  $\mathcal{L} \supset \beta_1 R(\bar{\psi}\psi)$ . Its main effects are:

- It controls the evolution of the equation of state  $w_\psi(a)$ , from  $\approx 0$  in the early universe to values below  $-1$  at late times.
- It introduces corrections to GR in the vicinity of black holes.
- It modifies the growth of density perturbations at very high redshifts ( $z \gtrsim 1000$ )

#### Working range

$$\beta_1 \approx 0.01\text{--}1 \text{ MPlanck}^{-2}.$$

#### Motivation

- For  $\beta_1 \ll 0.01$  the associated effects become negligible, and FUH effectively reduces to  $\Lambda$ CDM with  $\psi$  behaving as a standard CDM component.
- For  $\beta_1 \gtrsim 1$  the model conflicts with current bounds on deviations from GR derived from gravitational-wave data and black-hole shadow observations.
- The interval  $0.01\text{--}1$  allows the desired evolution of  $w_\psi(z)$  while remaining within present gravitational tests.

#### Observational constraints

- Gravitational waves (LIGO/Virgo and future detectors):  $\beta_1 \lesssim 1 \text{ MPlanck}^{-2}$  from constraints on the speed and damping of the waves.
- Black-hole shadows (EHT and follow-up VLBI observations):  $\beta_1 \lesssim 0.5 \text{ MPlanck}^{-2}$  from the measured radius and shape of the shadow.
- Reconstruction of  $w(z)$  from combined CMB + SN Ia + BAO data requires a deviation from zero, giving a lower bound of roughly  $\beta_1 \gtrsim 0.01$ .

### Impact on FUH predictions

- Enables the transition from quasi-cold matter ( $w \approx 0$ ) to “super-dark” energy ( $w < -1$ ) without an explicit cosmological constant  $\Lambda$ .
- Predicts small deviations from the Kerr metric in the immediate vicinity of black-hole horizons.
- Affects the growth of perturbations in the early universe ( $z \gtrsim 1000$ ), potentially leaving imprints in CMB parameters and in primordial nucleosynthesis.

### Empirical tests

- Joint reconstruction of  $w(z)$  using Planck (CMB), SN Ia and BAO data.
- High-resolution observations of black-hole shadows with EHT and future VLBI projects.
- Tests of GR in the strong-field regime with LISA and observations of compact binaries / double pulsars.

### A concise table

Parameter	Physical meaning	Acceptable range	Verification method
$m_\psi$	Fermion mass. Sets the quantum upper limit on condensate density and the characteristic cut-off scale in the matter power spectrum.	10-1000 eV	1) Position of the small-scale cut-off $k_{\text{cut}}$ in the power spectrum ( $h/\text{Mpc}$ ); 2) Central density of dwarf-spheroidal cores ( $M_\odot/\text{pc}^3$ ).
GS	Dimensionless strength of scalar self-interaction. Affects the presence and amplitude of DAOs and small-scale clustering.	0,1-10	1) Amplitude of DAO wiggles ADAO in $P(k)$ at $k \approx 15\text{--}25$ $h/\text{Mpc}$ ; 2) Number of subhalos with mass $< 10^8 M_\odot$ inferred from strong-lensing analyses.
$\beta_1$	Coupling of the $\psi$ condensate to spacetime curvature (in units of the inverse reduced Planck mass squared). Controls the evolution of $w_\psi(a)$ and possible deviations from GR near black holes.	0,01-1	1) Evolution of $w_\psi(z)$ in the range $z \approx 0\text{--}2$ ; 2) Angular radius of black-hole shadows measured by EHT-like observations ( $\mu\text{as}$ ).

## Comparison with alternative approaches

- String theory: considers one-dimensional fundamental objects (strings) living in a space with extra dimensions; gauge fields and gravity are embedded in a single string dynamics, but a fermion field does not play a singled-out role as a universal building block, in contrast to FUH.
- Loop quantum gravity: quantizes the geometry of spacetime itself and yields a discrete spectrum of geometric quantities without introducing a new fundamental matter field; in FUH, by contrast, geometry is treated as emergent, generated by the condensate of  $\psi$ .
- Extra-dimension models: explain hierarchies and the structure of interactions through the geometry of extra dimensions and typically predict new bosons and Kaluza–Klein excitations; FUH instead relies on a single fermion field and its condensation, without introducing additional dimensions or elementary bosonic degrees of freedom.

## Limitations and scope of the present version of FUH

In this work a minimal version of the Fermionic Universe Hypothesis is considered, based on the fundamental Lagrangian  $L_{\text{fund}}$  for a single fermion field  $\psi$  and its emergent gravitational and gauge degrees of freedom described by the effective Lagrangian  $L_{\text{eff}}$ . Additional speculative ingredients, such as specific TeV-scale resonances, detailed predictions for the  $m_p/m_e$  ratio, modifications of an effective  $G_{\text{eff}}$  depending on local density, and dedicated scenarios for dark matter and dark energy built on FCP-like states, are not used in the present version of the model and are left outside the scope of the analysis. The focus is on formulating a fermionic effective field theory with higher-dimension operators, discussing its consistency as an effective theory (with a finite ultraviolet cutoff), and outlining a programme of observational tests in cosmology and the astrophysics of compact objects.

## Black holes in the Fermionic Universe Hypothesis

In FUH, black holes are treated as highly concentrated condensates of the fermion field  $\psi$ , where the local energy density  $\rho_\psi$  becomes very large and produces strong spacetime curvature; the dense state is generated by four-fermion interactions, while the macroscopic properties are described by an emergent metric  $g_{\mu\nu}[\psi]$ . In this picture the  $\psi$  condensate enhances the effective attraction and forms a region with radius of order  $r_s \approx 2GM/c^2$ , whose interior structure is a stable “fermion lump” of finite density, and the entropy is naturally expressed as  $S \approx A/4$  due to the quantum degrees of freedom of  $\psi$  on the horizon.

This approach aims to relate singularity avoidance and the information paradox to the quantum state of the condensate instead of a classical point, and to obtain testable effects: small deviations in the structure of accretion disks, emission spectra, and ring images/shadows of black holes (EHT, LIGO/Virgo) compared to standard Kerr solutions in GR.

### **Connection to the Hubble tension and ACT DR6**

In the Fermionic Universe Hypothesis the large-scale dynamics is governed by a single fermion field  $\psi$ : dark matter and dark energy are interpreted as different phases of its condensate with equation of state  $w_\psi(a) = p_\psi / \rho_\psi$ . At early times the condensate behaves like cold dark matter ( $w_\psi \approx 0$ ), while at late times it acquires negative pressure ( $w_\psi < -1$ ) and drives accelerated expansion.

This framework is proposed as an alternative to extended  $\Lambda$ CDM models that add separate components or modify gravity in a purely phenomenological way. Recent analyses of the final ACT DR6 data set show that many such extensions fit the high-precision CMB temperature and polarization spectra poorly, while simultaneously reinforcing the Hubble tension:  $H_0$  inferred from early-Universe data and from local measurements remains inconsistent, and simple tweaks of  $\Lambda$ CDM do not resolve this discrepancy.

In FUH there is no separate early-dark-energy episode and no new fields beyond the standard content: the same  $\psi$  condensate that sources structure formation also provides the late-time vacuum-like component. The pressure  $p_\psi$  and density  $\rho_\psi$  are determined by microscopic self-interaction, so the expansion history  $H(z)$  becomes an emergent property of the fermionic fluid. By construction the model can mimic  $\Lambda$ CDM at high redshift (remaining compatible with ACT, Planck, and SPT CMB data) while allowing controlled deviations at low  $z$ , precisely where the Hubble tension appears.

This sets up a concrete testing programme. Once an explicit form of  $w_\psi(a)$  is derived from the microphysics, the model can be implemented in standard Boltzmann codes such as CAMB or CLASS to compute CMB spectra, baryon acoustic oscillations, supernova distance–redshift relations, and the growth of structure. The key criteria are: preserving agreement with ACT DR6 constraints on CMB spectra and lensing, and at the same time yielding a somewhat higher late-time value of  $H_0$  than the  $\Lambda$ CDM estimate from the CMB, without conflicting with BAO and SNe Ia data. In this sense, the new ACT results do not rule out FUH but rather narrow the space of viable extensions and point towards models in which cosmic acceleration and dark matter emerge from a single microscopic fermion field  $\psi$ .

## Observational tests of the Fermionic Universe Hypothesis

In FUH a single fermion field  $\psi$  plays the role of both dark matter and dark energy: in the early Universe it behaves like almost cold matter ( $w_\psi \approx 0$ ), while at late times it behaves like dark energy with  $w_\psi < -1$ , determining  $\rho_\psi(a)$  and  $H(z)$ .

Test plan:

- Introduce a parametrization of  $w_\psi(a)$  and a small set of field parameters (mass, self-interaction).
- Replace “CDM +  $\Lambda$ ” by  $\psi$  in CAMB or CLASS and compute the CMB spectrum,  $H(z)$ , and the growth of structure.
- Compare with Planck, ACT DR6, BAO, SNe Ia, and lensing data and check whether  $\psi$ -cosmology can preserve the precise CMB fit and at the same time naturally raise the local  $H_0$ , alleviating the Hubble tension.

Additionally, one can model accretion flows and shadows of  $\psi$ -cores and compare them with EHT observations and LIGO/Virgo signals; successfully reproducing masses, shadows, and spectra at the level of classical black holes would be a strong argument in favour of the fermionic picture.

## Conclusion

The Fermionic Universe Hypothesis (FUH) treats dark matter, dark energy and gravity as emergent phenomena of a single fermion field  $\psi$ , whose condensate generates gauge fields and an effective spacetime metric as collective low-energy excitations. On cosmological scales this condensate behaves like cold dark matter at early times and like dynamical dark energy at late times, so one component is constrained simultaneously by CMB, BAO, SN Ia and lensing data, including the regime relevant for the Hubble tension. In this sense FUH acts as a minimal microscopic completion of the  $\Lambda$ CDM background rather than a competing cosmology, tying the microphysics of  $\psi$  directly to  $H(z)$ ,  $w(a)$  and small-scale structure. In the strong-field regime it predicts nonsingular black-hole-like objects with fermionic cores, whose shadows and gravitational-wave signals can be tested with EHT, VLBI and LIGO/Virgo, making FUH a quantitatively falsifiable single-field alternative to the standard  $\Lambda$ CDM + GR description of the dark sector.

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