Information Activation Theory (IAT):
A Scalar-Field Effective Action for the Dark Sector and an Information-Theoretic Interpretation of Cosmological Expansion

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Abstract

We propose *Information Activation Theory* (IAT), an information-theoretic interpretation of cosmology formulated as a generally covariant scalar-field effective theory. A dimensionless activation field $\psi(x)$ is introduced, with canonical normalization $\phi \equiv f_\psi \psi$, and coupled minimally to gravity with optional matter couplings. We make three technical moves intended to render the proposal testable: (i) we relate the kinetic normalization scale f_ψ to the reduced Planck mass $M_{\rm Pl}$ by requiring slow variation of the potential in Planck units for late-time acceleration; (ii) we compute the small-oscillation mass $m_\phi^2 = V''(\psi_{\rm min})/f_\psi^2$ and identify parameter regimes corresponding to cold-dark-matter-like behavior and to ultralight ("fuzzy") dark matter; and (iii) we treat the Hubble-constant problem as a falsifiable target rather than a settled claim, specifying the likelihood analysis required for a skeptic-proof assessment. We emphasize that statements about the Hubble tension require joint constraints in the H_0–r_d plane and confrontation with both sound-horizon-dependent (cosmic microwave background and baryon acoustic oscillations) and sound-horizon-marginalized determinations of H_0 from large-scale structure.

1 Introduction

Landauer's principle relates logically irreversible information processing to a minimum thermodynamic cost, $E \geq k_{\rm B} T \ln 2$, for erasure at temperature T [1, 2]. Motivated by the broader program connecting gravity, horizons, and entropy [3, 4, 5, 6], IAT adopts the working postulate that information is not merely descriptive but has an associated physical accounting that can be encoded in a covariant field theory. The aim of this manuscript is to provide a *formal* presentation suitable for peer evaluation, while clearly separating established results from new hypotheses.

Positioning relative to prior work. Information-theoretic and holographic constraints in gravity and cosmology are widely discussed in the literature [4, 5, 6, 7, 8], and scalar-field descriptions of dark energy and unified dark-sector models are well developed [9, 10]. IAT proposes a particular interpretation of a scalar degree of freedom and a particular entropy-expansion coupling; the novelty therefore lies primarily in the *interpretation* and in any *new, testable predictions* beyond existing scalar-field effective theories.

2 Core Postulates and Definitions

This section should be made maximally explicit and operational.

2.1 Information activation field

We introduce a scalar field $\psi(x)$ intended to parameterize the local degree of "activation" of underlying informational degrees of freedom.

- $\psi \to 0$: high-entropy, unstructured ("noise-like") degrees of freedom.
- $\psi \to 1$: low-entropy, structured ("activated") configurations associated with stable matter-like behavior.

Operational definition (chosen for this manuscript). We take "information" to mean *coarse-grained Shannon entropy* of a specified ensemble of microstates, with base-2 logarithms so that entropy is measured in bits [11]. For a discrete distribution p_i over outcomes i, the Shannon entropy is

$$H(p) = -\sum_i p_i \log_2 p_i. \tag{1}$$

We treat $\psi(x)$ as a *dimensionless order parameter* that is monotone with a coarse-grained entropy density $s(x)$, for example $\psi \equiv 1 - s/s_{\max}$ (with the coarse-graining scale and the reference ensemble specified as part of the model). This choice avoids reliance on uncomputable notions of Kolmogorov complexity while remaining compatible with thermodynamic entropy via $S = k_B \ln 2\, H$ for appropriate coarse-graining. To be a physical theory, ψ must be tied to a measurable quantity: e.g., a coarse-grained entropy density, a relative entropy, a computational-complexity proxy, or another operationally defined information measure. (Algorithmic complexity in the strict Kolmogorov sense is not directly observable; a practical surrogate must be provided.)

2.2 Thermodynamic and holographic bounds

We will use entropy bounds in the sense of Bekenstein [7] and/or covariant bounds in the sense of Bousso [6]. For bounded systems the Bekenstein bound may be written

$$S \leq \frac{2\pi k_{\rm B} R E}{\hbar c}, \tag{2}$$

with the corresponding information-in-bits bound $I \leq \frac{2\pi R E}{\hbar c \ln 2}$.

3 Effective Action and Field Equations

A generally covariant effective action is proposed:

$$S = \int d^4x \sqrt{-g} \left[\frac{c^3}{16\pi G} R - \frac{f_\psi^2}{2} g^{\mu\nu} (\partial_\mu \psi)(\partial_\nu \psi) - V(\psi) + \mathcal{L}_{\rm m}(g_{\mu\nu}, \Psi_{\rm m}; \psi) \right], \tag{3}$$

where f_ψ is an energy scale introduced so that ψ may be treated as dimensionless while keeping the action dimensionally consistent. (Equivalently one may define a canonically normalized field $\phi \equiv f_\psi \psi$.)

3.1 Canonical normalization and the scale f_ψ

Because ψ is taken to be dimensionless, we introduce an energy scale f_ψ so that the kinetic term has the correct dimensions. Defining the canonically normalized field

$$\phi \equiv f_\psi\, \psi, \tag{4}$$

the scalar sector becomes the standard form $-\frac{1}{2}(\partial \phi)^2 - V(\phi)$, where $V(\phi) \equiv V(\psi = \phi/f_\psi)$.

It is also convenient to rewrite the gravitational term using the reduced Planck mass $M_{\rm Pl} \equiv (8\pi G)^{-1/2}$, so that

$$\frac{c^3}{16\pi G}R = \frac{M_{\rm Pl}^2 c^3}{2} R. \tag{5}$$

Why $f_\psi \sim M_{\rm Pl}$ is a natural expectation in dark-energy-like regimes. If ϕ drives late-time acceleration (quintessence-like behavior), then the potential must be sufficiently flat in Planck units. A standard measure is the potential slow-roll parameter

$$\epsilon_V \equiv \frac{M_{\rm Pl}^2}{2}\left(\frac{V'_\phi}{V}\right)^2, \tag{6}$$

where $V'_\phi \equiv dV/d\phi$. Since $V'_\phi = (1/f_\psi)\, V'_\psi$, we obtain

$$\epsilon_V = \frac{M_{\rm Pl}^2}{2f_\psi^2}\left(\frac{V'_\psi}{V}\right)^2. \tag{7}$$

If $V(\psi)$ varies by $\mathcal{O}(1)$ over excursions $\Delta\psi \sim \mathcal{O}(1)$, then $|V'_\psi|/V \sim \mathcal{O}(1)$ and Eq. (7) implies $\epsilon_V \sim M_{\rm Pl}^2/(2f_\psi^2)$. Requiring $\epsilon_V \ll 1$ for sustained acceleration therefore suggests $f_\psi \gtrsim M_{\rm Pl}$ (and often $f_\psi \gg M_{\rm Pl}$ for very $w \approx -1$) [9].

3.2 Activation potential

A symmetry-breaking potential may be used as a working model:

$$V(\psi) = V_0 + \frac{\lambda}{4}\left(\psi^2 - \psi_0^2\right)^2, \tag{8}$$

where V_0 can act as an effective cosmological constant term and the remaining structure can support matter-like or defect-like configurations depending on parameters.

3.3 Equations of motion

Varying (3) yields Einstein's equation with total stress-energy, plus the scalar equation of motion. These should be derived explicitly and displayed here.

4 Cosmology

Adopt a Friedmann–Lemaître–Robertson–Walker metric and derive the modified Friedmann equations. Define the effective energy density and pressure contributed by ψ, then identify conditions under which:

- ψ behaves as pressureless matter ($w \approx 0$),
- ψ behaves as vacuum energy ($w \approx -1$),

and compare to standard scalar-field dark energy (quintessence) and unified dark matter models [9, 10].

5 Hubble Constant and Sound-Horizon Constraints

5.1 Status of the H_0 and r_d tensions

In the base Λ cold dark matter (ΛCDM) model, the Planck cosmic microwave background analysis implies a Hubble constant $H_0 \simeq 67.4 \pm 0.5$ km s^{-1} Mpc^{-1} [12]. Distance-ladder measurements anchored by Cepheids and Type Ia supernovae (SH0ES) report $H_0 \simeq 73.04 \pm 1.04$ km s^{-1} Mpc^{-1} [13]. This discrepancy is commonly referred to as the *Hubble tension*.

Assuming independent Gaussian uncertainties, the nominal discrepancy between the above central values can be summarized by

$$T_{H_0} \equiv \frac{|H_0^{(\mathrm{late})} - H_0^{(\mathrm{early})}|}{\sqrt{\sigma_{\mathrm{late}}^2 + \sigma_{\mathrm{early}}^2}}, \tag{9}$$

which yields $T_{H_0} \approx 4.9$ for the Planck–SH0ES pair using the quoted uncertainties [12, 13].

It is closely related to the *sound-horizon* tension because baryon acoustic oscillation (BAO) constraints strongly couple H_0 to the sound horizon at the drag epoch r_d (often entering as $H_0 r_d$), motivating analyses that track both quantities jointly [14, 15].

In practice, much of the model dependence enters through r_d because BAO measurements constrain ratios of distances to a standard ruler; in many late-time combinations one effectively measures a product close to $H_0 r_d$ rather than H_0 alone [14, 15]. As an order-of-magnitude guide, raising H_0 from 67.4 to 73.0 km s^{-1} Mpc^{-1} at fixed $H_0 r_d$ would require a reduction of r_d by a factor $\simeq 67.4/73.0 \approx 0.92$ (i.e., $\sim 8\%$), motivating early-time mechanisms that reduce the sound horizon.

A key development is the emergence of *sound-horizon-marginalized* (or "sound-horizon-free") determinations of H_0 from large-scale structure combined with cosmic microwave background lensing and uncalibrated supernovae. Using DESI data, Zaborowski *et al.* report a sub-3% sound-horizon-marginalized constraint with central values near $H_0 \sim 67$–68 km s^{-1} Mpc^{-1}, remaining in multi-σ tension with SH0ES [16].

Using the representative value $H_0 \simeq 67.9 \pm 2.0$ km s^{-1} Mpc^{-1} quoted in [16], the discrepancy relative to SH0ES is reduced to the ~ 2–3σ level, consistent with their reported range.

More recently, a DESI-DR1 analysis reports determinations that move toward intermediate values and argues that the data no longer show the Hubble tension *independently* of the sound horizon at high confidence [17]. These results sharpen the requirement for any proposed "resolution": it must be confronted not only with CMB and BAO (which depend on the sound horizon) but also with sound-horizon-marginalized large-scale-structure inferences.

5.2 What a viable IAT mechanism must accomplish

From a model-building standpoint there are two broad pathways to shift the inferred H_0:

1. **Early-time modifications** that reduce r_d (or r_s), allowing CMB/BAO-inferred values of H_0 to increase at fixed angular scales. Early dark energy (EDE) is a canonical example [18]. However, it has been argued that reducing the sound horizon *alone* is generally insufficient to fully reconcile all datasets [19].

2. **Late-time modifications** to the expansion history (e.g., evolving dark energy equation of state), which can move distance-ladder inferences without changing r_d, but must remain consistent with BAO and supernova distance measurements.

IAT, as formulated here, can in principle realize *both* pathways, depending on the choice of potential $V(\psi)$ and any additional information-capacity constraint imposed on the background evolution.

5.3 Quantitative program: likelihood analysis and decision criteria

A skeptic-proof claim about the Hubble tension requires a quantitative inference pipeline. We therefore specify the minimal analysis that must accompany any strong statement:

1. **Background and perturbations:** implement the IAT scalar sector in a Boltzmann code (e.g., `CLASS` or `CAMB`) by evolving ϕ in an expanding background and including linear perturbations (ensuring no ghost or gradient instabilities).

2. **Data combinations:** fit to Planck 2018 CMB likelihoods, BAO data (including DESI), and Type Ia supernova compilations; include SH0ES as an optional external prior for late-time calibration [12, 13].

3. **Sound-horizon-marginalized tests:** additionally confront the model with H_0 determinations designed to remove sound-horizon information (e.g., DESI-based analyses) [16, 17].

4. **Decision criteria:** report (i) the posterior for H_0 under joint early+late datasets, (ii) the posterior for r_d, (iii) goodness-of-fit relative to ΛCDM, and (iv) Bayesian evidence where feasible. A working definition of "tension alleviation" is that posteriors derived from early-time and late-time data overlap at $\lesssim 1$–2σ under the same model assumptions.

In the absence of this pipeline, we treat the Hubble tension as a *prediction target and falsifiability lever*, not as a resolved problem.

6 Parameter Inference Framework

This section specifies the analysis pipeline required to confront IAT with cosmological data, with the explicit goal of enabling a skeptic-proof assessment of any claim to alleviate the Hubble tension. In practice, the question "does the model resolve the tension?" is answered only by joint likelihood analyses over standard datasets and by reporting the resulting posterior distributions for H_0, r_d, and correlated parameters (e.g., Ω_m and S_8).

6.1 Theory engine and sampling framework

We perform parameter inference using the `Cobaya` Bayesian analysis framework [20], coupled to the Boltzmann solver `CLASS` [21, 22]. Cobaya provides a modular interface to cosmological theory codes (including CLASS) and to a suite of commonly used likelihoods, while caching intermediate results and organizing parameter blocks to improve sampling efficiency [20]. CLASS computes background evolution, linear perturbations, and observable predictions for the cosmic microwave background (CMB) and large-scale structure (LSS) for a given set of cosmological parameters [21, 22].

6.2 Likelihoods and datasets

We adopt the following baseline likelihood set, chosen to directly target late-time expansion constraints and the H_0–r_d degeneracy:

- **CMB anisotropies (Planck 2018):** We use the Planck 2018 likelihoods (including the official `clik` likelihoods where applicable) for temperature and polarization power spectra, and optionally the Planck CMB lensing likelihood [12, 23].

- **BAO (DESI DR1):** We use DESI Year-1 BAO measurements as implemented in the Cobaya internal likelihood `bao.desi_2024_bao_all`, corresponding to the DESI 2024 BAO cosmology analysis [24, 25].

- **Type Ia supernovae (Pantheon+):** We use the Pantheon+ supernova likelihood (without SH0ES calibration) as implemented in `sn.pantheonplus` [26, 27].

For robustness checks and for clearer interpretation of the "sound-horizon tension", we additionally consider: (i) alternative BAO compilations (e.g. SDSS DR12/DR16 likelihoods available in Cobaya [25]), (ii) inclusion of external priors (e.g. big-bang nucleosynthesis priors on ω_b), and (iii) "sound-horizon-free" constraints on H_0 from large-scale structure, e.g. sound-horizon-marginalized DESI full-shape analyses [16].

6.3 Model hierarchy analyzed

Because the full IAT microphysics is still being developed, we analyze a hierarchy of models to separate empirical requirements from theoretical implementation details:

1. **ΛCDM (baseline):** six-parameter flat ΛCDM.

2. **w_0–w_aCDM (phenomenological proxy):** a time-varying dark-energy equation of state parameterized as $w(a) = w_0 + w_a(1 - a)$, used as a controlled proxy for IAT-induced deviations in the expansion history. This layer determines *what* late-time expansion behavior the data prefer.

3. **IAT effective model:** a minimal IAT-inspired parameterization that maps the information-expansion coupling to an effective $w(z)$ or directly to $H(z)$ via a small number of parameters (e.g., a late-time transition redshift and amplitude). This layer is used to test whether IAT can reproduce the phenomenology required by the data with fewer degrees of freedom.

4. **IAT field-theory realization (future work):** a canonical scalar-field realization with potential $V(\psi)$ and normalization f_ψ, evolved self-consistently at background and perturbation level. This is the end goal for a definitive test, but it requires a fully specified operational definition of $S_{\rm tot}$ and its coupling to ψ.

6.4 Priors and sampling

Unless otherwise stated, we use broad, conservative priors consistent with common practice in CMB+LSS analyses, and we report them explicitly in the released configuration files. Sampling is performed with Markov chain Monte Carlo (MCMC) in Cobaya [20]. We run multiple independent chains and require standard convergence diagnostics (e.g. Gelman–Rubin $R - 1 < 0.01$ for all sampled parameters) before quoting posteriors. Where model comparison is required, we additionally compute Bayesian evidences using nested sampling (e.g. PolyChord) and report Bayes factors relative to ΛCDM.

6.5 What constitutes "alleviation" of the Hubble tension

We do not treat the Hubble tension as a single number, but as a set of consistency checks across dataset combinations. A model is said to *alleviate* the tension only if it simultaneously satisfies:

1. **Posterior shift:** the CMB+BAO+SN posterior for H_0 shifts toward local-distance-ladder determinations (e.g. SH0ES) *without* producing significant degradation in the global goodness-of-fit compared with ΛCDM.

2. **Sound-horizon consistency:** the inferred sound horizon r_d and the BAO observables remain consistent with DESI BAO constraints [24], and the model remains consistent with sound-horizon-marginalized constraints where applicable [16].

3. **No new tensions:** the model does not induce unacceptable shifts in other well-constrained derived parameters (e.g. S_8) when CMB lensing and other LSS constraints are included.

All chains, configuration files, and derived-parameter tables required to reproduce the analysis are to be released with the manuscript.

7 Dark Matter as "Inert Information"

A mathematically standard route for a scalar field to reproduce cold-dark-matter phenomenology is through *coherent oscillations about a potential minimum.* When the potential is approximately quadratic, $V(\phi) \simeq \frac{1}{2}m_\phi^2(\phi - \phi_{\rm min})^2$, the oscillating field behaves as a pressureless fluid on timescales long compared to the oscillation period, with mean equation of state $\langle w \rangle \approx 0$ [28].

7.1 Scalar mass and oscillation frequency

For $\phi = f_\psi \psi$, the small-oscillation mass is

$$m_\phi^2 = \left.\frac{d^2V(\phi)}{d\phi^2}\right|_{\phi_{\rm min}} = \frac{1}{f_\psi^2}\left.\frac{d^2V(\psi)}{d\psi^2}\right|_{\psi_{\rm min}}. \tag{10}$$

For the symmetry-breaking quartic working model $V(\psi) = V_0 + \frac{\lambda}{4}(\psi^2 - \psi_0^2)^2$, one finds $V''(\psi_0) = 2\lambda\psi_0^2$ and hence

$$m_\phi^2 = \frac{2\lambda\psi_0^2}{f_\psi^2}. \tag{11}$$

The physical oscillation frequency is $\omega \simeq m_\phi c^2/\hbar$.

7.2 Fuzzy versus cold regimes

If $m_\phi \sim 10^{-22}$ eV, the field exhibits wave-like behavior on kiloparsec scales and can suppress small-scale structure ("fuzzy" dark matter) [29, 30]. If m_ϕ is much larger, the de Broglie wavelength becomes negligible on astrophysical scales and the model approaches cold-dark-matter behavior. Therefore, cosmological and galactic data constrain the combination of potential parameters and normalization f_ψ through Eqs. (10)–(11).

7.3 Interpretation in IAT language

In IAT terms, the "inert information" component corresponds to high coarse-grained Shannon entropy configurations (small ψ) that nevertheless carry energy density in ϕ and contribute to the gravitational stress-energy. Electromagnetic darkness follows if couplings to the Standard Model are absent or sufficiently suppressed.

8 Dark Energy as Vacuum Information Pressure

IAT interprets accelerated expansion as an effective negative pressure associated with entropy growth subject to holographic/information-capacity bounds. Connect this proposal to existing "entropic" or holographic-expansion ideas where relevant (e.g., emergent cosmic space / holographic equipartition) and state precisely which entropy is meant (horizon entropy, matter entropy, coarse-grained entropy, etc.).

9 Planck Constant and Expansion

The draft conjectures that the constancy of Planck's constant is tied to expansion via an information-capacity constraint. To make this publishable, this section should:

- specify whether h (or $\hbar$) is taken as fundamental and constant, or predicted to vary;
- avoid circularity (entropy bounds already contain $\hbar$);
- derive a quantitative relation for $H(t)$ in terms of a well-defined entropy production rate in a specified region (e.g., a causal diamond or apparent-horizon volume).

A proposed phenomenological relation is

$$H(t) \equiv \frac{\dot{a}}{a} \approx \gamma \frac{\dot{S}_{\rm tot}}{S_{\rm tot}}, \tag{12}$$

where γ is dimensionless. This should be derived (or clearly labeled as an ansatz) and then tested against observational expansion histories.

Relation to the Hubble tension. Any claim that an information-capacity or entropy-production constraint *resolves* the Hubble tension must be assessed in the joint H_0–r_d parameter space and confronted with both sound-horizon-dependent (CMB/BAO) and sound-horizon-marginalized constraints. Recent DESI-based analyses provide precisely such sound-horizon-marginalized determinations of H_0, placing strong demands on early-time solutions that act only by reducing the sound horizon [16, 17]. Accordingly, we interpret the entropy–expansion ansatz as a phenomenological ingredient whose viability must be established by likelihood-based inference (Sec. 5).

10 Experimental and Observational Signatures

Provide quantitative predictions and (where possible) order-of-magnitude estimates.

10.1 Local "high information density" experiments

The draft suggests that dense computational or data-storage systems might source measurable anomalies. To be credible, compute the predicted magnitude relative to known effects (mass-energy equivalence, thermal dissipation, electromagnetic systematics) and propose a feasible experimental protocol.

10.2 Cosmological tests

List decisive tests: background expansion $H(z)$, cosmic microwave background anisotropies, baryon acoustic oscillations, weak lensing, galaxy rotation curves, cluster masses, and structure growth.

11 Discussion

Summarize what is new relative to existing scalar-field and entropic/holographic approaches, and list open theoretical issues (well-posedness, stability, causality, renormalization, and observational constraints).

12 Conclusion

IAT offers an information-centered interpretation of the dark sector and of cosmological expansion, framed as a covariant scalar-field effective theory with an additional information-theoretic constraint. The next steps are (i) operationally defining ψ, (ii) deriving and solving the cosmological dynamics, and (iii) identifying falsifiable predictions distinct from existing models.

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