Solar System and Atomic Clock Bounds on Locally Coupled Swampland Scalars

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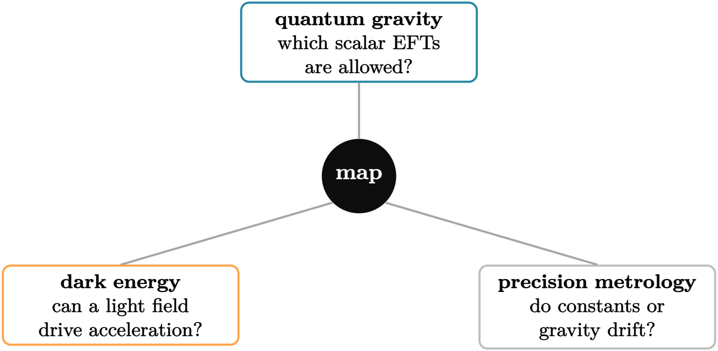
: Albert Einstein

Fields and Clocks

- Suppose a scalar field is cosmic enough to help accelerate the Universe. Can it really be invisible to a clock on Earth?
- The answer depends on a geometric object: the direction in microscopic coupling space along which the scalar moves.
- A light field has a trajectory, say $\phi(t)$. Two transitions are compared, and we get a dimensionless frequency ratio.
- The clock is not a scalar field speedometer. It does not tell us $\dot{\phi}$, it rather gives a product of the motion and the difference between the two transitions' sensitivities to the couplings.

Three Old Questions



What we show

- The local observables are correlated projections of one microscopic visible sector coupling vector.
- The answer depends on a geometric object: the direction in microscopic coupling space along which the scalar moves.
- For directions that are locally visible, unscreened, and slowly accelerating today, the permitted scalar motion is so small that visible matter coupling alone has great difficulty producing an order-one de Sitter gradient.
- The escape directions *can be named*.

What we don't show

- We do not derive any universal bound $|x| < 10^{-2}$.
- We do not provide an experimental test of the global Distance Conjecture.
- We do not falsify the refined de Sitter conjecture (we certainly do not rule out string theory *yet*).

This is true:

Conditional results are not weak results. On the contrary, a conditional claim is pretty informative.

The Potential in the Potential is immense

- Swampland gradients (c, η) and distances are in a field space.
- The gradient norm formed with the field space metric is invariant. In our local single field problem, we transform to the Einstein frame and canonically normalize the scalar.

$$\boxed{\begin{array}{c} V_{,\phi}/V \\ \text{coordinate dependent} \end{array}} \xrightarrow{\text{normalize}} \boxed{\begin{array}{c} M_{\mathrm{Pl}}|\nabla_\phi|/V \\ \text{canonical} \end{array}}$$

Frame changes

Jordan frame

$F(\Phi)\tilde{R}$

matter parameters $q_a(\Phi)$

$$\xrightarrow[\text{field space arc length}]{g^E_{\mu\nu} = F\tilde{g}_{\mu\nu}}$$

canonical Einstein frame

$R - (\nabla\phi)^2$

$V(\phi) = U/F^2$

for
local matter couplings

for
$c, \eta,$ distances

Canonical Normalization

$$\left(\frac{d\phi}{d\Phi}\right)^2 = \frac{K_J(\Phi)}{F(\Phi)} + \frac{3M_{\mathrm{Pl}}^2}{2}\left(\frac{F_{,\Phi}}{F}\right)^2$$

- This also tells us what the multifield generalization would require. We would replace the single derivative by a covariant gradient norm and the scalar η by eigenvalues of the covariant Hessian. Our paper is the local one dimensional projection of that more general geometry.

The Swampland Variables

$$c = M_{\mathrm{Pl}} \frac{V_{,\phi}}{V} \qquad \text{(gradient magnitude)}$$

$$\eta = M_{\mathrm{Pl}}^2 \frac{V_{,\phi\phi}}{V} \qquad \text{(signed curvature)}$$

- The original de Sitter proposal asks for a lower bound $c \geq c_*$ with a conjectural coefficient often described as order one. The refined alternative permits a small gradient if there is an order one tachyonic Hessian direction, here $\eta \lesssim -c'_*$.

A differential clock

- Take two atomic transitions, I and J. Each frequency depends on dimensionless microscopic parameters like the fine structure constant, mass ratios, nuclear quantities, and so on. The vector $\mathbf{d}$ tells us how those parameters respond to a unit displacement of the canonical scalar. The measureable quantity is

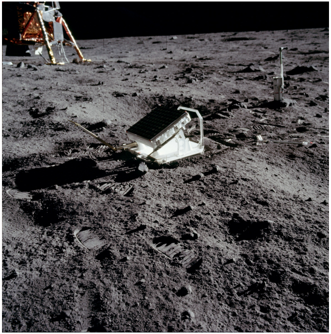
$$D_{IJ} \equiv \frac{d}{dt} \ln \frac{\nu_I}{\nu_J} = H_0 x \Delta k_{IJ}(\mathbf{d})$$

$$x \equiv \frac{\dot{\phi}_0}{H_0 M_{\mathrm{Pl}}}$$

- If $\Delta k_{IJ}(\mathbf{d}) = 0$, the clock pair is blind even when $x \neq 0$.

Lunar Ranging

The Apollo 11 retroreflector was placed on the Moon in July 1969. More than half a century later, pulses sent from Earth still turn that object into a test of whether gravity drifts.



: The Apollo 11 retroreflector

Lunar Ranging

- Lunar Laser Ranging constrains the time dependence of the gravitational coupling. After direct scalar exchange corrections are either modelled separately or subleading in the derivative

$$\frac{\dot{G}}{G} \simeq -H_0 \, d_F \, x$$

$$x \equiv \frac{\dot{\phi}_0}{H_0 M_{\rm Pl}}$$

- Again, the instrument constrains a product. If d_F is tiny, the same bound says very little about the speed of the scalar.

Free fall and Shapiro delay

- For equivalence principle tests, a source, say S, attracts two test bodies call A and B. The leading Eötvös signal is $(\alpha_A - \alpha_B)\alpha_S$.
- For a post-Newtonian measurement such as Cassini's radio link test, the relevant approximation depends mainly on the source charge. In the universal limit

$$\gamma_{\mathrm{PPN}} - 1 \sim \frac{-2\alpha_S^2}{1+\alpha_S^2}$$

- These are not the same projection. The universal part cancels in $\alpha_A - \alpha_B$, so a leading differential free fall test may be blind to a common rescaling. But that universal charge remains in α_S, where a post-Newtonian measurement can see it. Cassini measured the frequency shift of radio photons passing close to the Sun and obtained $\gamma = 1 + (2.1 \pm 2.3) \times 10^{-5}$. The number constrains a source dependent scalar charge.

Experimental Tests

1961	1969	2003	2008
Brans–Dicke G dynamical	Apollo 11 retroreflector	Cassini $\gamma - 1 \sim 10^{-5}$	Optical clocks 10^{-17}

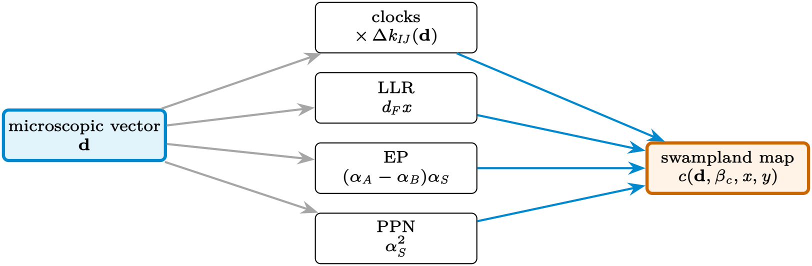
The instrument changed; the question stayed:

Which combination of fields and couplings moved?

One Microscopic Vector

$$\mathbf{d} = (\, d_f\,,\, d_g\,,\, d_e\,,\, d_{m_e}\,,\, d_{\hat{m}}\,,\, d_{\delta m}\,,\, \cdots\,)$$

Microscopic Map to Swampland Variables



The coupling consistent bridge

$$c(\mathbf{d},\beta_c,x,y)=\left|\frac{\Omega_{b,0}}{\Omega_{\mathrm{DE},0}}\beta_m(\mathbf{d})+\frac{\Omega_{c,0}}{\Omega_{\mathrm{DE},0}}\beta_c-\frac{x}{\Omega_{\mathrm{DE},0}}-\frac{y}{3\Omega_{\mathrm{DE},0}}\right|$$

- The first term is the visible baryonic source. Its coupling β_m is derived from the same $\mathbf{d}$ constrained by clocks, PPN, and equivalence principle tests.
- The second term is an independent cold dark matter source unless universality is imposed. The third term is the present field velocity. The fourth is the acceleration nuisance direction.

Baryons and total matter carry different weights

$$c(\mathbf{d}, \beta_c, x, y) = \left| \frac{\Omega_{b,0}}{\Omega_{\mathrm{DE},0}} \beta_m(\mathbf{d}) + \frac{\Omega_{c,0}}{\Omega_{\mathrm{DE},0}} \beta_c - \frac{x}{\Omega_{\mathrm{DE},0}} - \frac{y}{3\Omega_{\mathrm{DE},0}} \right|$$

- The source term depends on which matter sector couples to the field. For the conservative visible sector case, local tests constrain only baryons, giving a weight $\Omega_{b,0}/\Omega_{\mathrm{DE},0} = 0.0715$.
- If a universal matter coupling is assumed, baryons and cold dark matter share the same coupling, and the weight becomes $\Omega_{m,0}/\Omega_{\mathrm{DE},0} = 0.4599$, about $6.4\times$ larger.
- This enhances the cosmological source but also exposes the same coupling to Solar System, post-Newtonian, and fifth force constraints, making the dark matter contribution experimentally testable.

Visible and dark couplings are independent

$\beta_m(\mathbf{d})$
visible; locally projected

β_c
dark; locally unmeasured

Setting $\beta_c = \beta_m$ is a model assumption, not a consequence of clocks, LLR, PPN, or EP.

Acceleration is an unconstrained nuisance direction

- We define
$$y \equiv \frac{\ddot{\phi}_0}{H_0^2 M_{\rm Pl}}$$
Solving the scalar equation of motion for the potential slope gives the contribution
$$-\frac{y}{3\Omega_{\rm DE,0}}$$
- Atomic clocks constrain a velocity projection, not the acceleration. LLR constrains $d_F x$. PPN and equivalence principle tests constrain spatial source and composition charges. None of these experiments directly constrains y.
- Hence, any bound such as $|y| \leq y_{\rm max}$ is a dynamical prior, not an experimental result. In particular, the slow acceleration limit $|y| \ll |x|$ is an assumption.

A large acceleration reopens the gradient map

- If y is allowed to be large, it can mimic a large present potential slope even when x and the visible sector couplings remain small, broadening the allowed gradient map.

The Velocity Ceiling

- The clock data produce $x_{\rm clk}(\mathbf{d})$, which is the allowed drift divided by the sensitivity projection for each clock pair. LLR produces $\epsilon_G/|d_F|$. The combined local ceiling is their minimum:

$$|x| \le x_{\max}(\mathbf{d}) = \min\left[x_{\rm clk}(\mathbf{d}), \frac{\epsilon_G}{|d_F|}\right].$$

- For a direction with appreciable clock sensitivity, representative drift limits can yield $x_{\max} \sim 10^{-2}$. That is the ultra slow regime emphasized in the paper. Along a clock null direction with small d_F, the ceiling can be much weaker and cosmological energy density or equation of state bounds may dominate instead.

Three directions show why 10^{-2} is not universal

Direction	What sees it	What follows
$d_e = 10^{-6}$	Clock pair with $\lvert\Delta K_\alpha\rvert \sim 1$	$x_{\text{clk}} \sim 10^{-2}$
Universal rescaling	Leading clock and differential EP responses vanish	PPN still sees residual universal charge
$d_F = 10^{-3}$ only	Clocks are blind; LLR measures $d_F x$	$\lvert x\rvert \lesssim \mathcal{O}(10)$ for $\epsilon_G \sim 10^{-2}$

Screening?

- The microscopic basis determines which Standard Model operators the scalar couples to. Screening is governed by nonlinear dynamics, the scalar potential, and the environmental background.
- In chameleon, symmetron, and environmental dilaton models, the local field value, effective mass, coupling, and body charge depend on density. Observables involve screened quantities such as $x_{\mathrm{loc}}\Delta_k$ or $(d_F x)_{\mathrm{loc}}$.
- In Vainshtein or kinetic screening, spatial fifth forces can be suppressed while cosmological evolution remains unscreened. Constraints from observables (e.g., $\dot{G}/G$ or clock drift) are model dependent.

Small x consequences

- The equation of state becomes

$$1 + w_0 = \frac{x^2}{2\Omega_{\mathrm{DE},0}}$$

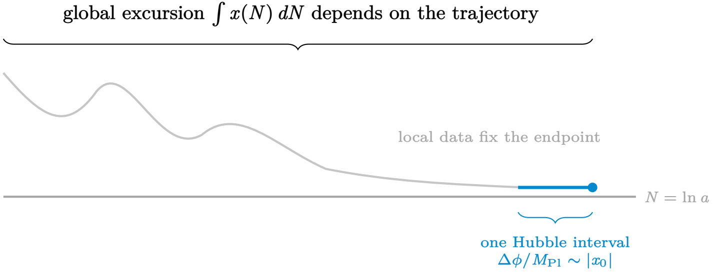
- If a locally visible direction really has $|x| \lesssim 10^{-2}$ and $\Omega_{\mathrm{DE},0} \simeq 0.685$, then $1 + w_0$ is below roughly 5×10^{-5}. The present equation of state is extraordinarily close to minus one.
- For a general $P(X, \phi)$ theory, the relation acquires the factor P_X evaluated on the background. The clock relation is indeed unchanged.

$$1 + w_0 = \frac{P_X x^2}{2\Omega_{\mathrm{DE},0}}$$

A small endpoint step is not a global distance test

- Over approximately one present Hubble interval, the displacement is
$$\frac{\Delta\phi_{H_0}}{M_{\mathrm{Pl}}} \sim |x_0|$$
Thus, a visible direction with $|x_0| \lesssim 10^{-2}$ moves only a small local step today.
- The Distance Conjecture concerns the accumulated controlled field space distance over an extended trajectory. This quantity is given by the integral
$$\frac{\Delta\phi}{M_{\mathrm{Pl}}} = \int x(N)\, dN$$
A field can be nearly frozen at present while still having traversed a distance of order unity or larger at earlier times.

The endpoint does not reconstruct the trajectory



Only dynamics give the history

$$\frac{d\phi}{dN} = M_{\rm Pl}\, x, \qquad \frac{dx}{dN} = -\left(3 + \frac{d\ln H}{dN}\right)x - \frac{V_{,\phi}}{H^2 M_{\rm Pl}} + 3\sum_I \beta_I(\phi)\Omega_I.$$

local endpoint (ϕ_0, x_0) → choose $V,\ \beta_I,\ H(N)$ → integrate backward in $N = \ln a$ → global distance $\int x(N)\, dN$

- Local experiments provide boundary conditions, not the preceding trajectory.
- Only a specified potential, coupling model, and background turn the endpoint into a global Distance Conjecture test.

The gradient is percent scale

$$\beta_c = 0, \quad |\beta_m| \ll 1$$
$$|y| \ll |x|, \quad |x| \lesssim 10^{-2}$$

$$c \simeq \left| \frac{\Omega_b}{\Omega_{\mathrm{DE}}} \beta_m - \frac{x}{\Omega_{\mathrm{DE}}} \right|$$
$$c \text{ naturally } \lesssim \text{ few} \times 10^{-2}$$

- This is not a direct measurement of c.
- It is the scale generated by the present equation of motion on an explicitly declared slice of theory space.

Visible matter cannot manufacture an order one gradient

$$|\beta|_{\rm req} \simeq \frac{\Omega_{\rm DE,0}\, c_\star - x_{\rm max}}{\Omega_{\rm source}}, \qquad x_{\rm max} = 10^{-2}.$$

	$c_\star = 1$	$c_\star = 0.1$
visible baryons, $\Omega_{\rm source} = \Omega_b$	**13.8**	**1.19**
universal matter, $\Omega_{\rm source} = \Omega_m$	2.14	0.19

These are enormous unscreened visible charges compared with the Solar System scale of at most a few $\times 10^{-3}$ in the universal long range limit.

Universality helps and hurts?

It helps

$$\frac{\Omega_m}{\Omega_{\mathrm{DE}}} = 0.4599, \qquad \frac{\Omega_b}{\Omega_{\mathrm{DE}}} = 0.0715$$

$$\frac{0.4599}{0.0715} \simeq 6.4.$$

The homogeneous matter source is stronger for the same coupling.

It hurts

The same β now charges the Sun, ordinary test bodies, and dark matter.

$$|\beta| \lesssim \text{few} \times 10^{-3}$$

$$0.4599\,|\beta| \sim 10^{-3} \ll 1.$$

PPN and fifth-force tests expose the coupling that cosmology wanted to use.

Universality removes the dark sector as an independent escape direction.

Trades for hilltop proximity

$$V(\phi) \simeq V_0 \left[1 - \frac{|\eta|}{2}\left(\frac{\phi - \phi_h}{M_{\rm Pl}}\right)^2\right], \qquad \lambda_+(|\eta|) = \frac{-3 + \sqrt{9 + 12\Omega_{\rm DE,0}|\eta|}}{2}.$$

Generic growing mode

$$|x| \simeq \lambda_+ \frac{|\phi_0 - \phi_h|}{M_{\rm Pl}}$$

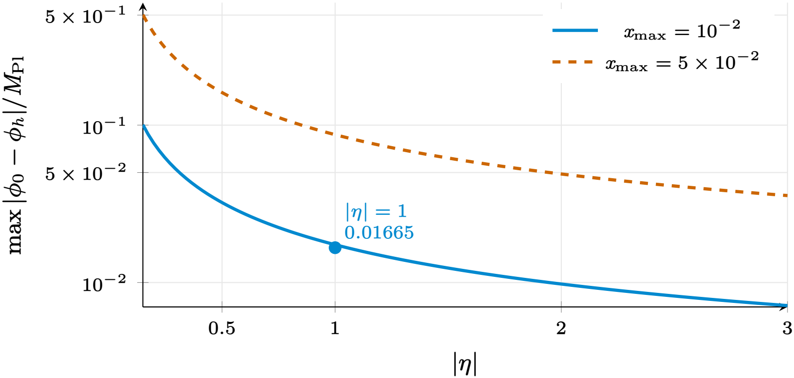
$\xrightarrow{\text{local ceiling}}$

Direction epen-
dent proximity

$$\frac{|\phi_0 - \phi_h|}{M_{\rm Pl}} \lesssim \frac{x_{\max}(\mathbf{d})}{\lambda_+(|\eta|)}$$

- The refined conjecture permits tachyonic curvature but it does not fix the present displacement or mode amplitudes.

Order one curvature bounds



At $|\eta| = 1$, $\lambda_+ = 0.6007$ and $10^{-2}/\lambda_+ = 0.01665$.

Hilltops

one canonical field
visible, unscreened coupling direction
generic growing-mode branch

→

small present
hilltop displacement

- This is a consistency and naturalness constraint on that realization.
- It can be relaxed by tuned growing/decaying amplitudes, screening, a locally weak direction, a different potential history, or multifield dynamics.
- The refined conjecture itself predicts neither today's displacement nor the relative mode amplitudes.

The likelihood is future likely

$$\chi^2_{\text{loc}}(\mathbf{d}, x) = \chi^2_{\text{clk}} + \chi^2_{\text{EP}} + \chi^2_{\text{PPN}} + \chi^2_{\dot{G}/G}.$$

sample one pair $(\mathbf{d}, x)$ → predict jointly clocks, EP, PPN, $\dot{G}/G$ → build local posterior with co-variance → add (β_c, y, V) map to $(c, \eta, \ldots)$

- Atomic sensitivities, isotope dependent charges, source composition, and experimental covariance must enter before a numerical allowed region is claimed.

The escape directions are a research program

- **Screening:** Which local observable is suppressed?
- **Dark coupling β_c:** Which cosmological data constrain it?
- **Local null direction:** Which clock or material closes the null space?
- **Acceleration y:** Which dynamics keeps it large today?
- **Mode tuning:** How precisely must growing and decaying modes cancel?
- **Beyond one canonical field:** Which part of the map changes?

Once loopholes are named as directions, they stop being rhetoric and become calculations.

Yes.

By being **screened**, **dark coupled**, **locally null**, or **dynamically atypical**.

But on an unscreened, locally visible, canonical dark energy direction, clocks, LLR, EP, and PPN make the present motion ultra slow. With no independent dark coupling and no large acceleration, the gradient naturally remains at the percent scale.

Local precision experiments constrain **coupling weighted directions of scalar motion**.

In the unscreened, locally visible, single field regime, visible matter coupling alone has great difficulty producing an order one de Sitter gradient.

Thank you!