Screening Mechanisms and Local Tests of Alternative Cosmological Models

Lesson III – Testing Screened Modified Gravity

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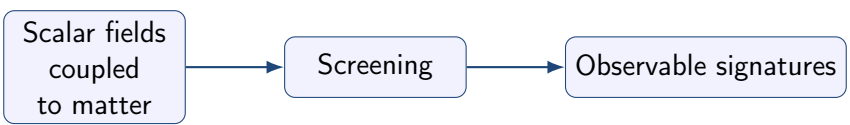
1. From Lesson II to Lesson III

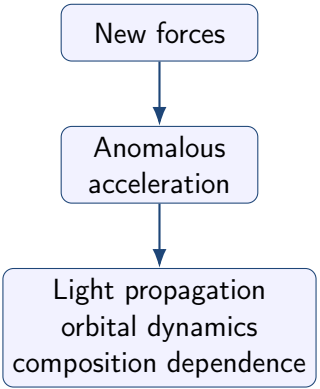
- Screening provides a mechanism for hiding extra gravitational degrees of freedom:
  1. Density screening (densities and field value)
  2. Kinetic (field gradient $X = -\frac{1}{2}(\partial\phi)^2$))
  3. Vainshtein (large second derivatives $\partial^2\phi$)
- Lesson III try to answer the following question:
  how do we know whether gravity is actually hidden?
- We move from mechanisms to observables:



What we are looking for

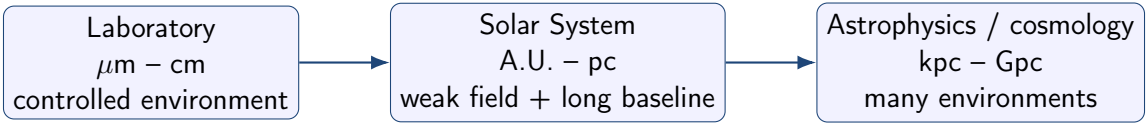
The observable signatures include:

- Deviations from the inverse-square law.
- Composition-dependent accelerations (WEP violation).
- Modified post-Newtonian parameters (γ, β, ...).
- Anomalous perihelion precession.
- Shapiro delay or light deflection shifts.
- Modified relation between dynamical and lensing potentials.



No single experiment is sufficient. Complementary tests spanning distance, density, composition and gravitational potential are required.

Probing gravity across scales



- **Laboratory** experiments access short ranges and controlled environments; sensitive to large effective masses.
- **Solar-System** observations probe weak-field relativistic gravity with long baselines and known source properties.
- **Astrophysical** systems can be partially or fully unscreened, revealing the modified force at larger scales.

Each regime probes a different combination of range, coupling strength, and screening state.

2. The fifth-force parametrisation

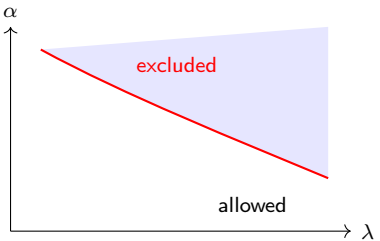
A generic extra interaction beyond Newtonian gravity is parametrised as a Yukawa correction:

$$V(r) = -\frac{G m_1 m_2}{r}\left[1 + \alpha\, e^{-r/\lambda}\right],$$

which gives a force

$$F(r) = F_N(r)\left[1 + \alpha\left(1 + \frac{r}{\lambda}\right) e^{-r/\lambda}\right].$$

- α: relative strength of the new interaction.
- λ: range (Compton wavelength of the mediator).
- $\lambda \gg r$: effectively a long-range modification.
- $\lambda \ll r$: exponential (Yukawa) suppression.



In screened theories, $\alpha_{\rm eff}$ can depend on source, environment, and geometry — the constraint is on the *screened observable*.

The screened observable

For two screened bodies A and B, the fifth force reads

$$F = F_N\left[1 + 2\beta^2\,\mathcal{S}_A\,\mathcal{S}_B\,e^{-m_{\rm eff}r}(1 + m_{\rm eff}r)\right],$$

where β is the microscopic coupling, $m_{\rm eff}$ the environmental mass, and $\mathcal{S}_{A,B}$ source-dependent screening factors.

- $\mathcal{S} \approx 1$: body unscreened, full coupling.
- $\mathcal{S} \ll 1$: body screened (e.g. thin-shell factor $3\Delta R/R$ for the chameleon).

Do not compare the bare coupling β directly with an experimental bound. Always compare the screened observable.

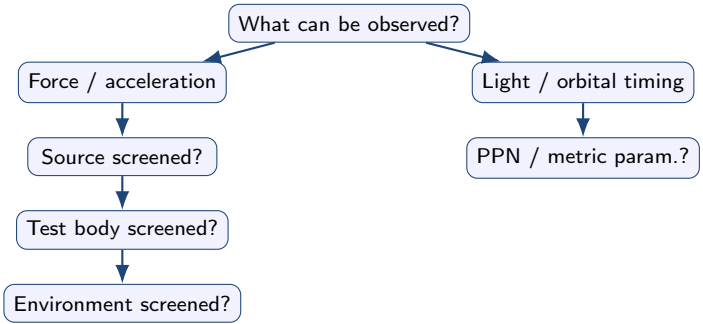
What does a null result actually mean?

A null measurement can arise from:

1. The new interaction is genuinely absent.
2. The coupling is intrinsically small ($\beta \ll 1$).
3. The interaction is too short-ranged ($\lambda \ll r_{\rm expt}$).
4. The **source body is screened** ($\mathcal{S}_A \ll 1$).
5. The **test body is screened** ($\mathcal{S}_B \ll 1$).
6. The experiment operates in a **screened environment** ($m_{\rm eff} \to \infty$ locally).
7. The observable is insensitive to the modified degree of freedom.

A null result is a constraint on a model's screened prediction, not automatically a proof that the new degree of freedom does not exist.

Screening-aware experimental decision tree



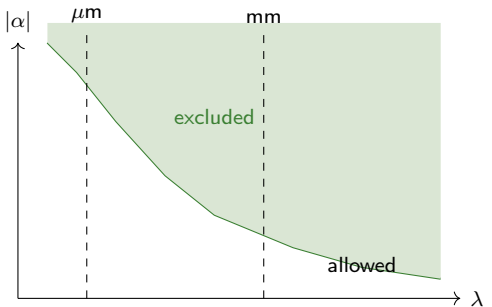
- Identify the observable and the experiment.
- Determine the screening state of source, test body, and environment.
- Compute the **screened prediction** for that configuration.
- Compare with the experimental residual.

Only after answering all three screening questions can the bare coupling be compared with data.

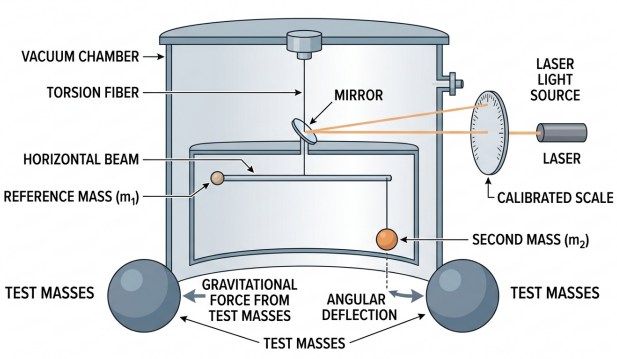
3. Laboratory tests: inverse-square law

Torsion balances measure deviations from $F(r) = F_N\left[1 + \alpha\left(1 + \frac{r}{\lambda}\right) e^{-r/\lambda}\right]$; no signal observed, giving $\alpha(\lambda) < \alpha_{\max}(\lambda)$.

- **Eöt-Wash**: source and test masses designed to suppress Newtonian background and enhance new-force sensitivity.
- Current: $|\alpha| \lesssim 10^{-2}$ for $\lambda \sim 20\,\mu$m–1 mm.
- Backgrounds: EM, thermal, seismic, Casimir must be controlled.
- **Screened:** source develops thin shell ($\mathcal{S} \propto 3\Delta R/R \ll 1$), relaxing the bound on β.



3.1 Torsion balance: working principle



- Torsion fiber suspends a beam with test masses.
- Source masses exert a differential gravitational torque.
- Mirror + laser detects deflections of $\sim 10^{-9}$ rad.
- Vacuum chamber suppresses air and Casimir effects.
- Leading constraints on new short-range gravity and WEP violation.

3.2 Casimir forces: background and opportunity

At sub-millimeter and micron scales, quantum vacuum (Casimir) forces become significant: $F_C(d) \propto -\hbar c\, A/d^4$ (parallel plates).

- Casimir forces can **mimic or mask** a short-range modification of gravity.
- Precision experiments require accurate modelling of surface roughness, patch potentials, and geometry.
- The same environment that enables a sensitive measurement can also affect the screening state.
- **Opportunity:** Casimir geometries can be engineered to enhance or suppress the scalar field — a *screening switch*.

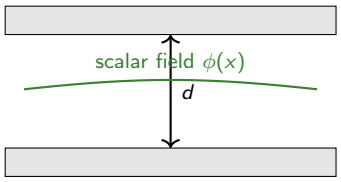


plate geometry

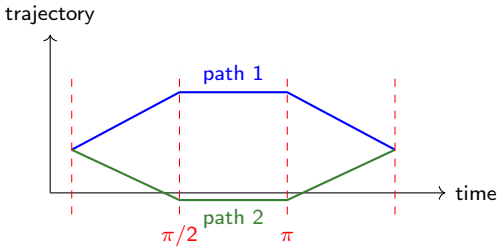
3.3 Atom interferometry: principle

Laser pulses split, redirect, and recombine atomic matter waves. The accumulated phase is sensitive to accelerations:

$$\Delta\phi = \vec{k}_{\text{eff}} \cdot \vec{a}\, T^2,$$

where T is the pulse separation and $\vec{k}_{\text{eff}}$ the effective wave vector and $\vec{a}$ acceleration (in GR g if the Earth is the gravitational source).

- A fifth-force acceleration a_ϕ shifts the phase by $\delta\phi = k_{\text{eff}}\, a_\phi\, T^2$.
- Source masses placed near the atomic trajectories generate a controllable gravitational signal.
- Changing the vacuum pressure or source geometry changes the screening state — allowing a *screening-sensitive* search.
- Current sensitivity: $a_\phi \lesssim 10^{-8}\, g$.



3.5 Laboratory tests: summary

Experiment	**Observable**	**Range**	**Best constraint**
Torsion balance (ISL)	force residual	μm – mm	$\lvert\alpha\rvert \lesssim 10^{-2}$
Torsion balance (WEP)	Eötvös η	lab	$\eta \lesssim 10^{-13}$
Casimir experiment	force at short range	$< 10\,\mu$m	geometry dependent
Atom interferometry	phase shift	cm – m	$a_\phi \lesssim 10^{-8}\,g$

- Sensitivity increases with proximity and mass of source.
- Screened theories predict **environment-dependent signals**: varying the experimental conditions is a signature of screening.
- Agreement with GR at lab scales does not exclude a scalar with $m_{\rm eff} \gg (\mathrm{mm})^{-1}$.

4. The Equivalence Principle

Weak Equivalence Principle (WEP): all freely falling test bodies have the same acceleration, independent of composition.

$$\eta_{AB} = \frac{2(a_A - a_B)}{a_A + a_B} \quad \text{(Eötvös parameter)}$$

GR predicts $\eta_{AB} = 0$ exactly.

Strong Equivalence Principle (SEP): extends universality to gravitational self-energy and local gravitational experiments.

- In GR with minimally coupled matter, WEP follows from universal metric coupling.
- A scalar coupled differently to different materials produces composition-dependent accelerations.
- Scalar-tensor theories can violate SEP even if WEP is approximately respected.
- Screening can suppress WEP violation locally, but may not fully eliminate it.

WEP violation in screened theories

In a scalar-tensor theory, each species i couples with strength β_i. The acceleration of body A in a scalar gradient $\nabla\phi$ is:

$$a_A = \frac{\beta_A}{M_{\rm Pl}}\nabla\phi \quad \text{(unscreened)}$$

For a **screened** body, the effective coupling is suppressed:

$$\tilde{\beta}_A = \beta_A\,\mathcal{S}_A, \qquad \mathcal{S}_A = 3\frac{\Delta R_A}{R_A} \ll 1.$$

The Eötvös parameter between two screened bodies becomes:

$$\eta_{AB} \approx 2\frac{\tilde{\beta}_A - \tilde{\beta}_B}{\tilde{\beta}_A + \tilde{\beta}_B}\cdot\frac{F_\phi}{F_N}.$$

Test	**Best** η
Eöt-Wash (Be,Ti)	$\lesssim 10^{-13}$
MICROSCOPE (Ti,Pt)	1.5×10^{-15}
LLR (Earth,Moon)	$\lesssim 2.4\times10^{-14}$

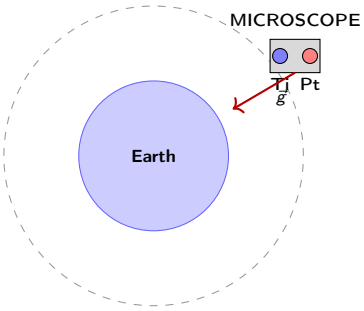
4.1 MICROSCOPE: Space-Based WEP Test

The MICROSCOPE mission (CNES) tested the Weak Equivalence Principle in Earth orbit using titanium and platinum test cylinders.

- **Drag-free control:** Maintained an ultra-quiet free-fall environment.
- **Measurement:** Differential acceleration vs. orbital phase.
- **Final Result** (Touboul et al. 2022):

$$\eta(\mathrm{Ti}, \mathrm{Pt}) = [-1.5 \pm 2.3_{\mathrm{stat}} \pm 1.5_{\mathrm{syst}}] \times 10^{-15}$$

- No WEP violation at 10^{-15} level ($\sim 100\times$ improvement over ground tests).



Space Advantages

- Reduced seismic noise.
- Continuous, longer integration time.
- Low-density ambient environment.

5. Solar-System gravity: PPN framework

The parameterised post-Newtonian (PPN) formalism describes the weak-field, slow-motion metric as an expansion in gravitational potential:

$$g_{00} = -1 + 2U - 2\beta U^2 + \mathcal{O}(\epsilon^3), \qquad g_{ij} = (1 + 2\gamma U)\delta_{ij} + \mathcal{O}(\epsilon^2).$$

The remaining PPN parameters enter at higher post-Newtonian orders and account for moving sources, internal energy, and preferred-frame or preferred-location effects.

Parameter	Physical meaning	GR
γ	spatial curvature per unit U	1
β	nonlinearity of gravity	1
$\alpha_1, \alpha_2, \alpha_3$	preferred-frame effects	0
ξ	preferred-location effects	0
$\zeta_1, \zeta_2, \zeta_3, \zeta_4$	violations of E-M cons	0

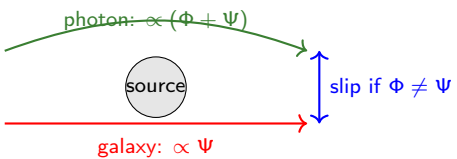
- γ controls **light deflection** and **Shapiro delay**.
- β controls **perihelion precession** and nonlinear gravity.
- Any scalar field sourced by matter generically shifts γ and β.

The gravitational slip: lensing vs dynamics

In GR with negligible anisotropic stress, the two metric potentials are equal: $\Phi \simeq \Psi$. A scalar field with non-minimal coupling introduces a **gravitational slip**:

$$\eta_{\rm slip}(k, a) = \frac{\Phi}{\Psi} \neq 1.$$

- **Non-relativistic matter** (galaxies, planets) moves along geodesics of Ψ: dynamics probe Ψ.
- **Photons** are deflected by $(\Phi + \Psi)/2$: lensing probes $\Phi + \Psi$.
- Comparing galaxy velocities (from redshift-space distortions) with weak lensing maps reveals $\eta_{\rm slip}$.
- In the Solar System, the Cassini measurement of γ directly constrains the slip at A.U. scales.



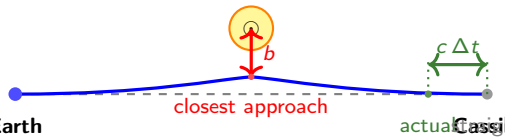
5.1 Shapiro time delay and Cassini experiment

Shapiro delay (1964): signal near a massive body is delayed. From PPN metric coordinate light speed can be reduced to: $dr/dt \simeq c[1-(1+\gamma)U/c^2] < c$.
Integrating Earth↔spacecraft:

$$\Delta t_{\rm Shapiro} = \frac{2(1+\gamma)GM_\odot}{c^3} \ln \frac{4r_\oplus r_{\rm sc}}{b^2}$$

Cassini measures the fractional Doppler shift induced by the changing impact parameter b as Earth and the spacecraft moved. This $\dot{b}/b$ in conjunction allows to estimate γ

$$\boxed{\gamma - 1 = (2.1 \pm 2.3) \times 10^{-5}.}$$



b: Sun-to-path distance at closest approach.
$c\Delta t$: extra distance actual signal still has to travel when the straight-path wavefront reaches Cassini.
$r_\oplus$:Earth-Sun's distance
r_{SC}: Sun-Cassini distance

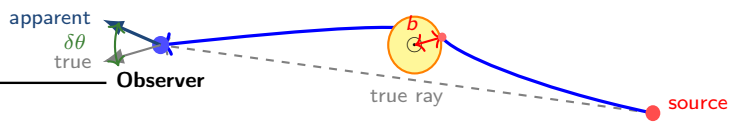
5.2 Light deflection

Derivation. Photons follow null geodesics; the effective refractive index is $n = 1 + (1+\gamma)U/c^2$. Integrating the transverse gradient:

$$\delta\theta = \frac{1+\gamma}{2}\,\frac{4GM_\odot}{c^2 b} = \frac{1+\gamma}{2} \times 1.75'' \left(\frac{R_\odot}{b}\right)$$

Experimental progress:

Measurement	Year	$\gamma - 1$
Eddington (optical)	1919	0 ± 0.3
Radio interferometry	1975	0.007 ± 0.009
VLBI (astrometry)	2004	-0.0002 ± 0.0003

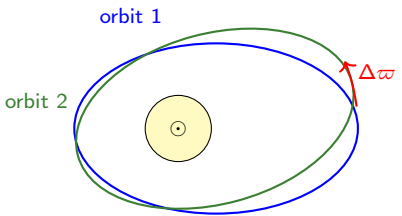


5.3 The PPN parameter β: nonlinear gravity

The parameter β measures the nonlinearity of gravitational superposition. It enters the perihelion precession:

$$\dot{\varpi} = \frac{(2 + 2\gamma - \beta)}{3} \frac{6\pi G M_\odot}{a(1-e^2)c^2 T}.$$

- For Mercury: $\dot{\varpi}_{\rm GR} = 42.98''/\text{century}$.
- Current bound from planetary ephemerides and LLR: $\beta - 1 = (0.0 \pm 1.1) \times 10^{-4}$.
- In scalar-tensor theories: $\beta - 1 = -\beta_{\rm ST}^2 \dot{\beta}_{\rm ST}/(1+\beta_{\rm ST}^2)^2$, with $\beta_{\rm ST} = M_{\rm Pl}\, d\ln A/d\phi$.



5.4 PPN beyond γ and β: preferred-frame effects

The full PPN expansion includes parameters beyond γ and β.

Preferred-frame effects (α_1, α_2):

- Theory not Lorentz-invariant $\Rightarrow \alpha_1 \neq 0$.
- Scalar with preferred rest frame $\Rightarrow$ anisotropy.
- Tested: perihelion anisotropy, binary pulsars.
- Bounds: $|\alpha_1| < 10^{-4}$, $|\alpha_2| < 10^{-7}$.

Preferred-location effects (ξ):

- Local experiments depend on gravitational environment.
- Related to LPI: $\alpha_{\rm EM} = \alpha_{\rm EM}(\phi)$.
- Tested with atomic clocks.

Parameter	GR	Best bound
$\gamma - 1$	0	2×10^{-5}
$\beta - 1$	0	10^{-4}
α_1	0	10^{-4}
α_2	0	10^{-7}
ξ	0	10^{-3}
ζ_1	0	2×10^{-2}

Ref.: Will, Living Rev. Relativ. 17, 4 (2014).

5.5 Planetary ephemerides

Modern solar-system ephemerides (e.g. DE430, INPOP) fit millions of observations simultaneously:

- Planetary positions and velocities.
- Radar ranging to planets and spacecraft.
- Spacecraft tracking (Pioneer, Cassini, MESSENGER, etc.).
- Astrometric observations of asteroids.

A tiny anomalous acceleration $a_{\mathrm{MG}} \sim \alpha G M_\odot r^{-2} e^{-r/\lambda}$ accumulated over many orbits produces a measurable residual.

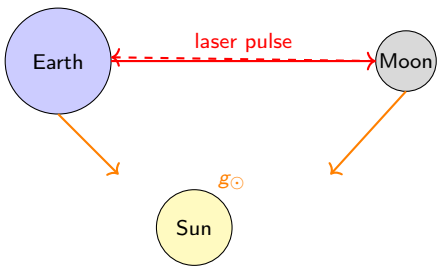
- Global fits constrain $a_{\mathrm{MG}} \lesssim 10^{-13}\,\mathrm{m/s^2}$ in the inner Solar System.
- Agreement across planets and long time spans amplifies sensitivity.

5.6 Lunar Laser Ranging (LLR)

Retroreflectors placed on the Moon during Apollo missions allow the Earth–Moon distance to be measured with millimetre precision via laser pulse timing.

What LLR tests:

- Orbital dynamics: anomalous accelerations or long-range forces.
- Weak Equivalence Principle
- Strong Equivalence Principle via the Nordtvedt effect.
- Time variation of G: $\dot{G}/G \lesssim 10^{-13}\,\mathrm{yr}^{-1}$.
- Preferred-frame effects (α_1, α_2).



Current precision:

- Distance: $\sim$ 1–2 mm over 384 000 km.
- $|\eta_{WEP}| \lesssim 2.4 \times 10^{-14}$.

The Nordtvedt effect and SEP

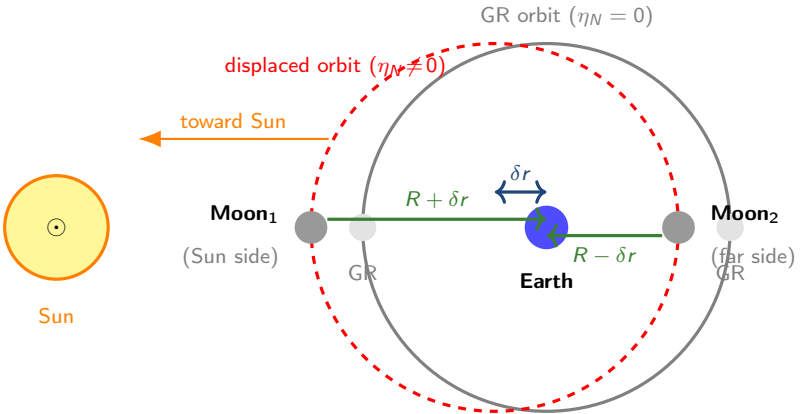
If gravitational self-energy contributes differently to gravitational and inertial mass, the Earth and Moon fall toward the Sun at slightly different rates:

$$\left.\frac{m_g}{m_i}\right|_{\text{body}} = 1 + \eta_N \frac{E_{\text{grav}}}{mc^2}.$$

This produces a **polarisation** of the lunar orbit: $\delta r \approx \eta_N \times 13\,\text{m} \cos(\omega_{\text{synodic}} t)$.

- Earth has larger fractional self-energy: $E_{\text{grav}}/mc^2\big|_{\oplus} \approx 4.6 \times 10^{-10}$.
- Moon has smaller self-energy.
- A difference in free-fall rates gives a characteristic monthly signal in LLR data.
- PPN: $\eta_N = 4\beta - \gamma - 3 - \frac{10}{3}\xi - \ldots$
- LLR result: $\eta_N = (-0.6 \pm 5.2) \times 10^{-4}$ (Williams et al. 2004).

The Nordtvedt effect and SEP (cont)



LLR measures $r_{\mathrm{EM}}(t)$:

$$r_{\mathrm{EM}}(t) \approx R + \delta r \cos(\omega_{\mathrm{syn}} t)$$

$$\delta r = \eta_N \times 13\,\mathrm{m}$$

5.7 Time variation of G and scalar-tensor theories

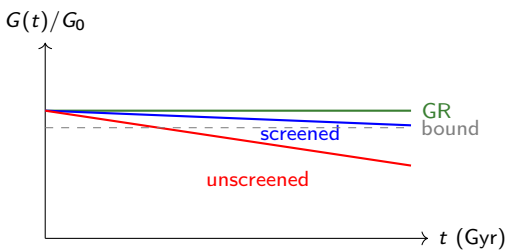
A cosmologically evolving scalar field can produce a secular drift of G:

$$\dot{G}/G \approx -2\dot{\phi}\, d\ln A/d\phi$$

Current bounds:

- LLR (Williams et al. 2004): $\dot{G}/G = (-0.7 \pm 3.8) \times 10^{-13}\,\mathrm{yr}^{-1}$.
- Helioseismology: $|\dot{G}/G| \lesssim 2 \times 10^{-12}\,\mathrm{yr}^{-1}$.
- Pulsar timing: $|\dot{G}/G| \lesssim 10^{-12}\,\mathrm{yr}^{-1}$.
- BBN: $|\Delta G/G| \lesssim 0.1$ at $z \sim 10^9$.

Screened theories: in the thin-shell regime the scalar rolls very slowly, suppressing $\dot{G}/G$ to well below observational bounds.



5.8 Solar-System tests: review of observables

Observable	Experiment	GR prediction	Best result	Probes
$\gamma - 1$	Cassini	0	2.1×10^{-5}	Φ vs Ψ (lensing)
$\beta - 1$	Ephemerides	0	$\sim 10^{-4}$	nonlinear gravity
$\dot{\varpi}_{\rm anom}$	Mercury/LLR	0	$\sim 0.5''$/cen.	force law
η_N	LLR	0	5×10^{-4}	SEP / self-energy
η_{WEP}	LLR	0	2×10^{-14}	WEP
$\dot{G}/G$	LLR	0	10^{-13}/yr	G time variation
$\eta_{\rm WEP}$	MICROSCOPE	0	10^{-15}	composition dep.

- Each observable probes a different sector of the theory.
- Screening affects each constraint differently.
- Joint constraints are much more powerful than individual ones.

6. Screening-aware interpretation of experiments

For each Solar-System or laboratory test, a complete analysis requires:

1. **Field configuration:** what is the scalar field profile generated by the source in its environment?
2. **Source screening:** is the source body (Sun, Earth, attractor mass, ...) screened?
3. **Test-body screening:** does the test body (planet, Moon, atom, ...) have a suppressed scalar charge?
4. **Propagation environment:** what is $m_{\rm eff}$ along the signal or trajectory path?
5. **Effective observable:** what charge, metric perturbation, or force reaches the detector?

Remember Do not compare the **bare coupling** β directly with an experimental bound.
Compare the **screened observable**.

The role of the environment

A screened scalar field (like chameleons or symmetron) depends on: $\rho_{\rm local}, \rho_{\rm env}, \Phi_N$, geometry .

- A vacuum chamber ($\rho \sim 10^{-6}\,{\rm g/cm^3}$) is not equivalent to interplanetary space ($\rho \sim 10^{-24}\,{\rm g/cm^3}$).
- A laboratory source can be screened while the test particle is not, suppressing the observable force even for large β.
- The Milky Way galactic potential can affect the screening state of stellar and sub-galactic objects.
- Changing the experimental environment is itself a diagnostic: an environment-dependent signal is a *qualitative* signature of screening.

Environmental control is part of the theory test. The screening prediction changes with ambient density.

7. Degeneracies and systematic effects

Not every discrepancy signals modified gravity.

Astrophysical / instrumental:

- Baryonic feedback can alter galaxy dynamics.
- Stellar populations affect mass-to-light ratios.
- Plasma effects can mimic small forces.
- Ephemeris systematics from correlated observations.
- Instrumental biases in torsion-balance readout.

Theory side:

- Different mechanisms can produce similar signatures.
- A single deviation is not sufficient; cross-checks across multiple tests are required.
- Ghosts, instabilities, strong-coupling must be checked independently.

A gravity test must model the relevant astrophysical and instrumental backgrounds before attributing a residual to modified gravity.

8. Screening is necessary, not sufficient

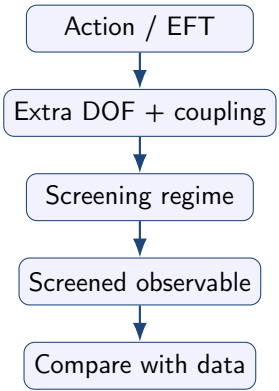
A theory may satisfy all local fifth-force and Solar-System bounds and still fail because of:

- **Ghosts or gradient instabilities** in the scalar sector.
- **Strong-coupling problems** at short distances.
- **Incorrect gravitational-wave propagation:** GW170817 requires $|c_T/c - 1| < 10^{-15}$, ruling out large Horndeski subclasses.
- **Cosmological instabilities** in the background evolution.
- **Excessive modifications** of structure growth or disagreement with lensing surveys.
- **Expansion history** inconsistencies with CMB or BAO.

Viability requires a global consistency check across theory stability, local tests, and large-scale observations.

Model-to-data workflow

1. Specify the modified-gravity action.
2. Derive the extra degree of freedom and coupling.
3. Determine the screening regime for each environment.
4. Compute the observable (force, γ, Nordtvedt parameter, ...) in that regime.
5. Include experimental geometry and systematic effects.
6. Compare prediction with data.
7. Propagate the constraint to other scales and environments.



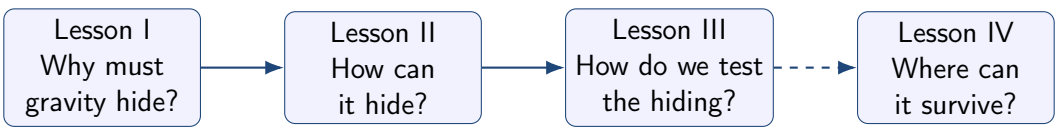
Do not import a bound derived for an unscreened model into a screened theory without re-deriving the screened observable.

9. The central message

A null local test does not mean that modified gravity is absent.

- It may mean that the theory is **screened** in the tested regime.
- The prediction is therefore not simply "GR + a small constant correction".
- The observable depends on the **nonlinear environment**: density, gravitational potential, source size, and geometry.

Test the screened prediction, not the bare theory.



10. Summary: local tests of screened modified gravity

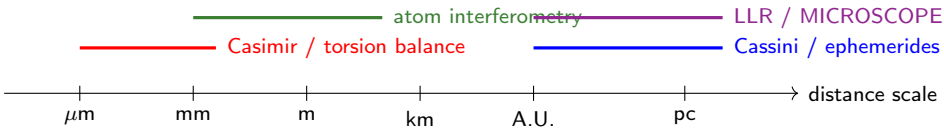
Category	**Key experiments**	**Screened signature**
ISL / short range	Eöt-Wash torsion balance	thin-shell suppression
	Casimir / atom interferom.	environment-dependent
WEP	MICROSCOPE	composition $\times$ screening
SEP	LLR (Nordtvedt)	self-energy $\times$ screening
PPN γ	Cassini Shapiro delay	$\Delta R_\odot/R_\odot \ll 1$
Perihelion	Mercury / ephemerides	Yukawa at A.U. scale
Orbital dynamics	LLR / ranging	anomalous acceleration
(Lesson IV)	*Dwarf galaxies, stars*	*partial screening*
	GW170817 / LISA	*c_T, extra polarisations*

Comparing local tests: sensitivity and screening

Test	**Range**	**Screened?**	β **sensitivity**	**Key limitation**
ISL torsion balance	μm–mm	source screened	$\lesssim 10^{-2}$	Casimir background
Atom interferometry	cm–m	env. tunable	$\lesssim 10^{-1}$	finite vacuum
Eötvös / MICROSCOPE	lab / orbit	test body screened	$\lesssim 10^{-6}$	systematic effects
LLR (Nordtvedt)	384 000 km	partial (Moon)	$\lesssim 10^{-4}$	lunar model
Cassini γ	A.U.	Sun screened	$\lesssim 10^{-3}$	single measurement
Ephemerides	A.U.	source screened	$\lesssim 10^{-5}$	ephemeris correl.

- No single test covers all of parameter space.
- Screening *weakens* some bounds but also creates *characteristic patterns* across tests.
- A consistent picture requires that the screened prediction satisfies **all** constraints simultaneously.

Laboratory vs Solar System: complementarity



- Short-range tests probe screening at high ambient density; the scalar is typically more massive.
- Solar-System tests probe long-range fields in a low-density environment; the scalar can be light and long-ranged.
- Agreement at one scale does **not** guarantee agreement at another — this is the essence of screening.

11. Future prospects: next-generation local tests

Experiment	Target	Improvement	Timeline
MICROSCOPE-2	WEP (η)	$\times 10$ over MICROSCOPE	$\sim$2030
STE-QUEST	WEP (atom interf.)	10^{-17} level	$\sim$2030s
GRACE-FO / GRACE-C	G drift, orbits	improved ranging	now
BepiColombo	Mercury PPN	γ, β at 10^{-6}	$\sim$2026+
LISA Pathfinder/LISA	GW + c_T	screened tensor modes	$\sim$2035
SKA (pulsar timing)	$\dot{G}/G$, SEP	10^{-15} yr^{-1}	$\sim$2030s

- **BepiColombo** (ESA/JAXA): Mercury orbiter will measure γ and β at the 10^{-6} level, a factor ~ 20 beyond Cassini.
- **STE-QUEST**: atom-interferometry WEP test in space, sensitive to composition-dependent scalar forces at 10^{-17}.
- **SKA**: pulsar timing arrays will probe $\dot{G}/G$ and dipolar gravitational radiation — a unique signature of scalar-tensor theories.

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