Screening Mechanisms and Local Tests of Alternative Cosmological Models

Lesson IV – Where Can Modified Gravity Survive? Astrophysics, Strong Fields, and Cosmology

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1. From Lesson III to Lesson IV

Lesson III: local tests probe specific ranges of density, potential and curvature.

If MG is screened in the Solar System, where can it still be observed?

L. I: Why hide? → L. II: How to hide? → L. III: Local tests → L. IV: Where survives?

- Screening is not equally efficient in all environments.
- Astrophysical systems span enormous ranges of ρ, Φ_N, curvature.
- A null local test constrains that regime only.

State	Signal	Role
Screened	$\Delta\mathcal{O} \simeq 0$	almost null test
Partial	$0 < \Delta\mathcal{O}$	**transition**
Unscreened	$\Delta\mathcal{O} \simeq$ max	often excluded

Signal migrates to where screening weakens.

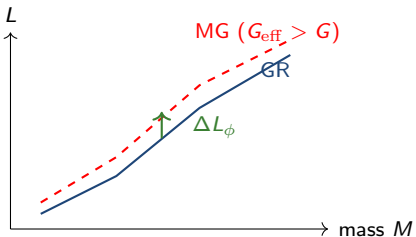
2. Stars as laboratories of modified gravity

A scalar field modifies the force balance:

$$dP/dr = -\rho[GM/r^2 + a_\phi], \quad a_\phi \simeq 2\beta^2 S(r)\, GM/r^2$$

Screening factor $S(r)$:

- $S \ll 1$: GR-like star.
- $0 < S < 1$: partially modified.
- $S \simeq 1$: strongly modified.



Consequences:

- modified hydrostatic equilibrium,
- shifted central temperature,
- altered mass–radius–luminosity relation,
- different main-sequence lifetime,
- modified evolutionary tracks.

Stellar populations: a hierarchy of tests

Stars provide a *population* of test masses with systematically varying screening state.

Object	M	Φ_N/c^2	**Screening**	**Observable**
Brown dwarf	$< 0.08 M_\odot$	$\sim 10^{-6}$	partial	$M_{\rm min}$ (H burning)
Low-mass star	0.1–$0.5 M_\odot$	$\sim 10^{-6}$	partial	L–M relation
Solar-type	$1 M_\odot$	2×10^{-6}	partial–screened	H-R diagram
RGB/TRGB	1–$2 M_\odot$	10^{-6}–10^{-4}	varies	TRGB luminosity
White dwarf	0.5–$1.4 M_\odot$	$\sim 10^{-4}$	intermediate	M–R relation
Neutron star	$\sim 1.4 M_\odot$	~ 0.2	compactness	scalarization

A screened theory predicts a "characteristic pattern" across the stellar sequence, not a single universal correction.

Minimum mass for hydrogen burning

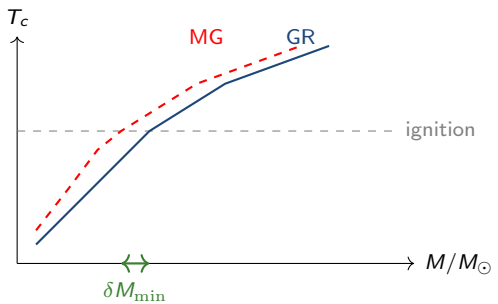
A clean stellar test is the **minimum mass for sustained H burning** $M_{\rm min}$.
In GR: $M_{\rm min} \simeq 0.08\,M_\odot$ (pp-chain ignition).
In scalar-tensor gravity:

$$M_{\rm min} \propto G_{\rm eff}^{-3/2} M_{\rm Pl}^3 .$$

Enhanced $G_{\rm eff}$ lowers the ignition mass; reduced $G_{\rm eff}$ raises it.

Observable: the stellar/sub-stellar boundary in mass functions of nearby star-forming regions constrains $G_{\rm eff}$ directly.

Hydrogen burning in low-mass stars is therefore a sensitive probe of scalar-tensor theories in the partial-screening regime.



Cepheid variables and the distance ladder

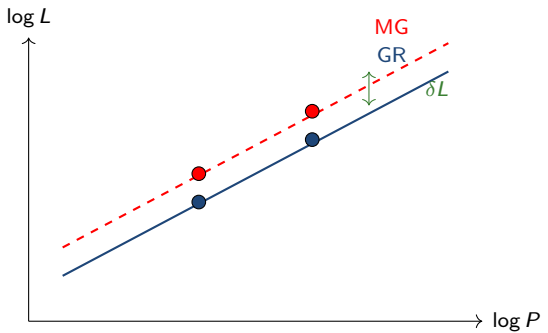
Cepheids link P, L, M, R through the period–luminosity (P–L) relation.

If MG changes stellar structure:

- The P–L relation shifts by δL_ϕ.
- Inferred distances change: $d \propto L^{1/2}$.
- Cosmological inferences (H_0, etc.) are affected.

Key strategy (Jain, Vikram & Sakstein 2013): compare Cepheids in screened environments (calibrators) with those in unscreened dwarfs (targets).

Propagation: stellar physics → shifted P–L → biased distance → cosmological inference.



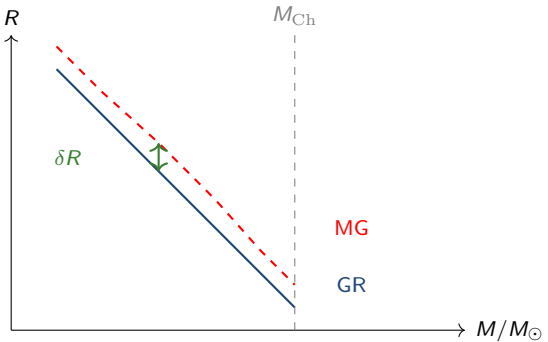
Red giants, TRGB, and white dwarfs

Tip of the RGB (TRGB):

- Degenerate He ignition provides a precise luminosity standard.
- Modified gravity shifts the ignition threshold: $M_{\rm TRGB} \propto G_{\rm eff}^{-\alpha}$.
- Testable with resolved stellar populations in nearby galaxies.

White dwarfs (WDs): $\Phi_N \sim 10^{-4}$. Probes:

- M–R relation: shifted by scalar pressure.
- Chandrasekhar mass: $M_{\rm Ch} \propto G_{\rm eff}^{-3/2}$.
- Screening transition across the mass–radius sequence.



3. Galaxies as laboratories

Rotation curves:

$$v_c^2/r = GM(<r)/r^2 + a_\phi(r) \Rightarrow v_c^2 = v_{\rm GR}^2 + \Delta v_\phi^2$$

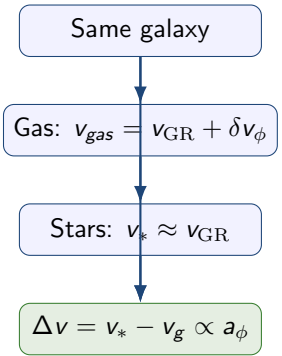
A modified force changes the baryonic-to-dynamical mass relation.

Dwarf galaxies are ideal: $|\Phi_N| \ll 1 \Rightarrow$ less screened.

- Large thin-shell fraction $\Delta R/R$.
- Often in low-density environments.
- Large possible fifth-force fraction.

Caveat: dynamical anomaly alone $\neq$ modified gravity; baryonic physics must be controlled.

Screened stars and unscreened gas respond differently to a_ϕ:



Environmental screening and differential tests

A galaxy can be screened by its own potential **or** by its environment:

$$\Phi_{\rm eff} \sim \Phi_{\rm self} + \Phi_{\rm environment}.$$

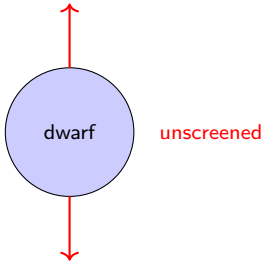
$$\boxed{\text{isolated galaxy} \neq \text{satellite galaxy}}$$

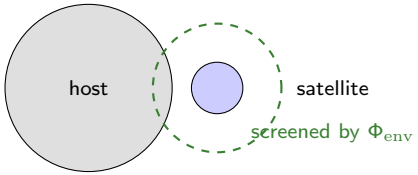
Environmental dependence is an *observable prediction*.

Differential test strategy:

$$\Delta\mathcal{O} = \mathcal{O}_{\rm isolated} - \mathcal{O}_{\rm env.\ screened}.$$

Same class of object + different environment = controlled comparison.



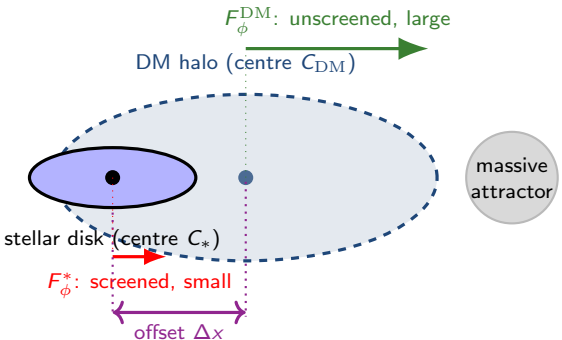


Galaxy morphology: offset tests

In many screened theories, DM (unscreened) and baryons (screened) feel different accelerations: $a_{\rm DM} \neq a_{\rm stars} \Rightarrow$ offset between stellar and DM distributions.

Observational signatures:

- Offset between stellar light peak and dynamical centre.
- Galactic warps and lopsidedness.
- Asymmetric star formation rates.



Morphological distortions from asymmetric scalar force (massive attractor)
Morphology constrains screened gravity independently of kinematics (Desmond & Ferreira, 2020)

4. Large Scale Structure and Galaxy clusters

- Lensing vs dynamics
- Galaxy cluster counts
- Growth of structure:
  - G_{eff} and $f\sigma_8$
  - RSD and growth rate
- Weak lensing

These effects and their modified gravity extensions were covered in Susana's lecture today!!!

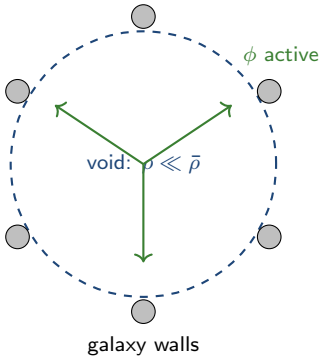
Cosmic voids

Voids represent the opposite environmental regime:

$$\rho_{\rm void} \ll \bar{\rho} \Rightarrow \text{screening weakens} \Rightarrow \phi \text{ becomes active.}$$

Void observables:

- void density profiles and sizes,
- void abundance (number counts),
- galaxy velocities around voids (RSD),
- weak lensing by voids,
- void–galaxy cross-correlations,
- ISW effect from voids.



Challenge: separate modified gravity from nonlinear bias and galaxy-formation effects.

5. Astrophysical systematics: the main challenge

Astrophysical tests are powerful but not clean laboratories.

Galaxy-scale systematics:

- Baryonic feedback (AGN, supernovae).
- Galaxy bias and assembly bias.
- Intrinsic alignments in weak lensing.
- Stellar population uncertainty.

Cluster-scale systematics:

- Gas temperature calibration.
- Non-thermal pressure support.
- Triaxiality and projection effects.
- Mass–observable scatter.

Mitigation strategies:

- Use multiple tracers (stars, gas, lensing).
- Compare objects in different environments (environmental controls).
- Exploit scale and redshift dependence.
- Joint fits with galaxy formation simulations.

A modified-gravity inference is only as reliable as the systematic control. The cleanest tests use observables that are theoretically well understood and environmentally controlled.

6. From weak fields to compact objects

The compactness parameter:

$$\epsilon = \frac{GM}{Rc^2}$$

SS tests probe $\varepsilon \sim 10^{-6}$: PN approximation valid, screening is environmental depending on the mechanism.
Moving to compact objects changes physics *qualitatively*:

- $\varepsilon_{\rm NS} \sim 0.2$: GR nonlinearities are $\mathcal{O}(1)$.
- Scalar profile inside the star: nonlinear, not perturbative.
- Compact object develops scalar charge with *no external source* — absent in weak-field screening.

A theory can pass all SS tests and still show large deviations at $\varepsilon \sim 0.2$.

System	ϵ	Regime
Earth	7×10^{-10}	Newtonian
Sun	2×10^{-6}	weak-field GR
White dwarf	$\sim 10^{-4}$	intermediate
Neutron star	~ 0.2	strong field
Black hole	~ 0.5	extreme

Binary pulsars and post-Keplerian tests

Pulsar timing provides extremely precise measurements of post-Keplerian (PK) parameters: P_b, e, $\dot{P}_b$, $\dot{\omega}$, $\gamma_{\rm PK}$, r, s.

In GR, 5 PK parameters depend only on (m_1, m_2):

PK parameter	Physical effect	PN order
$\dot{\omega}$	periastron advance	1PN
$\gamma_{\rm PK}$	time dilation + grav. redshift	1PN
r, s	Shapiro delay	1PN
$\dot{P}_b$	orbital decay (GW emission)	2.5PN

With 5 PK parameters and 2 unknowns: **3 independent tests**. Consistency of all pairs is the test. That is, with two observed parameters, m_1 and m_2 are determined. Then, the GR prediction of other parameter can be calculated and compared it with the observable value.

Dipolar gravitational radiation

- **GR:** gravitational dipole $\propto$ total momentum (conserved) $\Rightarrow$ no dipolar radiation. Lowest multipole: quadrupole at order $(v/c)^5$.
- **Scalar-tensor:** each body acquires charge $\alpha_A \equiv \partial \ln m_A/\partial\phi$. If $\alpha_A \neq \alpha_B$, the scalar dipole oscillates $\Rightarrow$ dipolar radiation at order $(v/c)^3$. The rate of energy loss is

$$\dot{E}_{\rm dip} = -\frac{G\mu^2}{6c^3}(\alpha_A - \alpha_B)^2 \left(\frac{2\pi}{P_b}\right)^2 .$$

  being $\mu = m_1 m_2/(m_1 + m_2)$ the reduced mass.

Given that

$$\frac{\dot{E}_{\rm dip}}{\dot{E}^{\rm GR}_{\rm quad}} \sim \frac{(\alpha_A - \alpha_B)^2}{(v/c)^2}.$$

For orbital velocities $v/c \sim 10^{-3}$, dipole radiation is amplified by $(c/v)^2 \sim 10^6$ relative to the quadrupole term.

Binary pulsars are therefore exceptionally sensitive to even minute differences in scalar charges.

Dipolar gravitational radiation (cont)

The dipolar signal $\propto (\alpha_A - \alpha_B)^2$ is maximised when the two bodies have *very different* scalar charges.

System	$\alpha_A - \alpha_B$	Dipole signal
NS–NS (same mass)	≈ 0	suppressed
NS–NS (diff. mass)	small	small
NS–WD	**large**	**maximum**
NS–BH (future)	unknown	unknown

Why NS–WD:

- NS: $\varepsilon_{\rm NS} \sim 0.2$, $\alpha_{\rm NS}$ large (strong-field, near scalarization threshold).
- WD: $\varepsilon_{\rm WD} \sim 10^{-4}$, $\alpha_{\rm WD} \approx \alpha_0$ (weak-field, constrained by SS tests to be tiny).
- Difference $|\alpha_{\rm NS} - \alpha_{\rm WD}|$ is maximised.

Current best constraints:

- PSR J1738+0333 (NS–WD): $|\dot{E}_{\rm dip}/\dot{E}_{\rm quad}| < 3 \times 10^{-4}$.
- PSR J0348+0432 (NS–WD, $M_{\rm NS} = 2.01 M_\odot$): tests near scalarization threshold.
- PSR J1012+5307 (NS–WD): constrains $\dot{G}/G < 10^{-12}$ yr^{-1}.

Neutron stars and spontaneous scalarization

Spontaneous scalarization Damour & Esposito-Farèse, 1993 ($A(\phi) = e^{\beta_0 \phi^2 / 2M_{\rm Pl}^2}$): $\phi = 0$ becomes *unstable* inside sufficiently compact stars. The coupling of ϕ to the trace of the stress-energy tensor T generates a negative effective mass squared. A nonzero scalar spontaneously develops above a threshold compactness. This is qualitatively different from environmental screening: the compact object *itself* triggers the scalar.

NS compactness: $\epsilon_{\rm NS} \sim 0.2$.

Possible effects:

- modified mass–radius relation,
- scalar profiles inside the star,
- altered orbital dynamics,
- additional radiation channels,
- modified merger waveforms.

7. Gravitational waves as a new window

Modified gravity can affect GWs through multiple independent channels:

1. Modified GW generation
2. Propagation speed and damping
3. Additional polarizations
4. GW luminosity distance d_L^{GW}

GW170817 gives $|c_T/c - 1| < 10^{-15}$, ruling out large Horndeski subclasses.

Even when $c_T = c$ is satisfied, modified gravity can still affect **generation, damping, polarizations, and d_L^{GW}**. Screening of local fifth forces $\neq$ absence of GW effects. GW observations are therefore a complementary strong-field and cosmological probe.

Channel 1: Modified GW generation

In GR, radiation is dominated by the **quadrupole**.
In scalar-tensor theories, additional channels open:

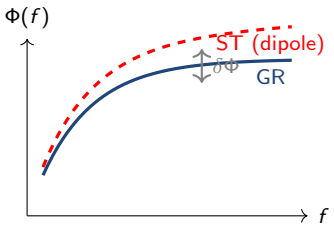
Dipolar ($\alpha_A \neq \alpha_B$): $\dot{E}_{\rm dip} \propto (\alpha_A - \alpha_B)^2 (v/c)^3$. Enters 2 PN orders below quadrupole: dominant at low v.

Monopolar: if total scalar charge changes during inspiral (dynamical scalarization), a scalar burst is emitted.

Modified $G_{\rm GW}$: effective Newton constant for GW generation can differ from $G_{\rm matter}$.

GW phasing $\Phi(f)$: accumulates over $\sim 10^4$ orbital cycles. Extra energy loss from dipole radiation accelerates the inspiral, producing fewer cycles than GR predicts and a detectable phase shift $\delta\Phi$.

$$\frac{d\Phi}{df} \propto \frac{1}{\dot{E}_{\rm quad} + \dot{E}_{\rm dip} + \ldots}$$



Channel 2: Propagation speed and Channel 3: Polarizations

GW speed c_T

In Horndeski theory, tensor modes propagate at:

$$c_T^2 = 1 + \frac{2XG_{4X}}{G_4 - 2XG_{4X}}.$$

GW170817 + GRB 170817A:

$|c_T/c - 1| < 10^{-15}$ (time delay < 1.7 s over ~ 40 Mpc).

$\Rightarrow$ $G_{4X} \approx 0$, $G_5 \approx 0$: large subclasses of Horndeski excluded.

Surviving subclass: $G_4 = G_4(\phi)$ only. This single measurement did more to constrain MG theories than decades of cosmological data.

Extra polarization modes

Mode	Helicity	Source
h_+, $h_\times$	± 2	GR
h_x, h_y	± 1	vector fields
h_b (breathing)	0	scalar-tensor
h_L (longit.)	0	massive gravity

$h_b \propto (\alpha_A - \alpha_B)$: the scalar breathing mode produces an isotropic expansion and contraction transverse to the propagation direction.

Requires ≥ 3 non-coplanar detectors to disentangle modes. Einstein Telescope (triangular) can resolve all 6 independently.

Null result in polarization content at ET constrains $|\alpha_A - \alpha_B|$ down to $\lesssim 10^{-3}$.

Channel 4: GW luminosity distance and standard sirens

GR: $d_L^{\rm GW} = d_L^{\rm EM}$

In MG the tensor equation gets extra damping from $\alpha_M \equiv d\ln M_*^2/d\ln a$ (running Planck mass):

$$d_L^{\rm GW} = d_L^{\rm EM}\exp\left(-\tfrac{1}{2}\int_0^z \frac{\alpha_M}{1+z'}dz'\right).$$

Parametrized as:

$$\frac{d_L^{\rm GW}}{d_L^{\rm EM}} = \Xi_0 + \frac{1-\Xi_0}{(1+z)^n}, \quad \Xi_0 = 1 \text{ (GR)}.$$

$\Xi_0 \neq 1 \Rightarrow$ running Planck mass in tensor sector.

GW luminosity distance and standard sirens (cont)

How to measure Ξ_0:

1. GW amplitude $\Rightarrow d_L^{\rm GW}$.
2. EM counterpart + spectroscopy $\Rightarrow$ redshift $z \Rightarrow d_L^{\rm EM}$ assuming a cosmological model.
   - Using ΛCDM $d_L^{EM}(z)$, Ξ_0 isolates modifications to GW propagation ($\alpha_M \neq 0$), assuming ΛCDM expansion
   - Estimating $d_L^{\rm EM}(z)$ using an alternative cosmology, Ξ_0 becomes degenerate with cosmological parameters; breaking this degeneracy requires a joint analysis combining GW standard sirens with CMB, BAO and SNe Ia.

The ppE framework: model-independent GW tests

The **ppE framework** (Yunes & Pretorius 2009) is the GW analogue of PPN for Solar-System tests. Deviations of the amplitud A and the phase Ψ from GR written as:

$$\tilde{h}(f) = A_{\rm GR}(1+\alpha u^a)e^{i[\Psi_{\rm GR}+\beta u^b]}, \quad u = (\pi \mathcal{M} f)^{1/3}.$$

The parameters (α, a) describe amplitude corrections, while (β, b) characterize phase corrections; specific theories predict definite values for then

Theory	b	Main effect
Scalar-tensor (dipole)	$-7/3$	inspiral phase shift
Massive graviton	$+1$	low-f dispersion
Lorentz violation	variable	freq.-dep. phase
Extra dimensions	$-13/3$	amplitude + phase

Why ppE is powerful:

- Theory-agnostic: no model assumed.
- $\beta \neq 0$ at power b: identifies the theory.
- Dipole ($b = -7/3$) below GR quadrupole ($b = -5/3$): inspiral is far more sensitive.

LIGO O3: no GR departures, $|\beta| \lesssim 10^{-3}$ at dipolar order.

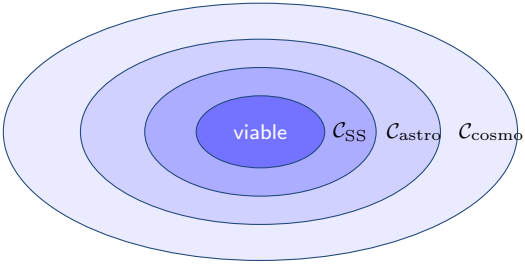
8. Multi-scale consistency: the viability intersection

A viable theory must satisfy simultaneously:

$$\mathcal{C}_{\text{lab}} \cap \mathcal{C}_{\text{SS}} \cap \mathcal{C}_{\text{astro}} \cap \mathcal{C}_{\text{strong}} \cap \mathcal{C}_{\text{cosmo}} \neq \varnothing.$$

Each $\mathcal{C}$ is the region allowed by a class of observations. The intersection is the real target of model building.

- Different experiments constrain the same parameter space from different directions.
- Adding a new observable shrinks the allowed region.
- A theory is viable only when *all* constraints are satisfied with a single parameter set.



Why $H(z)$ is not enough

A modified-gravity model can mimic the background expansion $H(z) \simeq H_{\rm GR}(z)$ while changing the perturbation sector:

$$G_{\rm eff}(k,a) \neq G, \qquad \eta(k,a) \neq 1.$$

background degeneracy $\not\Rightarrow$ perturbation degeneracy.

Test	What it probes
$H(z)$ (BAO, SNIa)	background
$f\sigma_8$ (RSD)	growth ($G_{\rm eff}$)
WL power spectrum	$G_{\rm eff} + \eta$
ISW, CMB lensing	$\Phi + \Psi$ integrated
Cluster counts	$G_{\rm eff}$ (nonlinear)

Only a combined analysis of background + growth + lensing can break the degeneracy. This is why modern surveys measure all three simultaneously.

Why partial screening is the most informative regime

State	Information content
Fully screened	null test only
Partially screened	**transition info**
Fully unscreened	often excluded

A partially screened system:

- satisfies Solar-System bounds;
- produces a detectable astrophysical signal;
- probes the *screening transition* directly.

Environmental dependence as a prediction: $\mathcal{O} = \mathcal{O}(\text{internal}, \text{environment})$.
Key strategy: same class of object, different environment:

- isolated vs satellite galaxies;
- Cepheids in screened vs unscreened hosts;
- NS–WD vs NS–NS binaries;
- low-density vs high-density regions.

9. Where can modified gravity survive?

Look where screening is weakest.

Window	Key systems	Primary mechanism
Low-potential galaxies	dwarfs, isolated	chameleon, symmetron
Low-density envir.	voids	environmental
Stellar populations	low-mass, TRGB, WDs	potential / thin-shell
Compact objects	NS, WD sequences	compactness
Strong-field	binary pulsars	scalar charge
Nonlinear structure	N-body, halos	all mechanisms
GW propagation	standard sirens	tensor sector
GW generation	inspiral waveform	dipole, extra DOF

What would constitute a convincing model?

A compelling MG signature should show:

1. **theoretically predicted** dependence on environment;
2. **consistency** across independent observables;
3. **robustness** to astrophysical systematics;
4. **compatibility** with Solar-System bounds;
5. coherent parameter inference.

Viability is a multi-scale consistency problem.

Key takeaways: Lesson IV

1. A null Solar-System test does not exclude all astrophysical signatures.
2. **Partially screened** systems are the most informative: they probe the screening transition directly.
3. **Stars** probe modified stellar structure; Cepheids and TRGB propagate the effect into distance measurements.
4. **Dwarf and isolated galaxies** probe low-potential regimes; differential tests reduce systematics.
5. **Voids** probe low-density environments where scalar forces are least suppressed.
6. **Binary pulsars** constrain dipolar radiation and scalar charges in the strong-field regime.
7. **Neutron stars** can trigger spontaneous scalarization —a qualitatively new phenomenon absent in weak-field tests.
8. **Gravitational waves** probe generation, additional polarizations, and a possible $d_L^{\mathrm{GW}}/d_L^{\mathrm{EM}} \neq 1$.
9. Astrophysical systematics are part of the gravity test.
10. **Viability is a multi-scale consistency requirement.**

The complete logic of the course

Lesson I: Why must modified gravity hide? Extra DOF $\Rightarrow$ fifth forces $\Rightarrow$ screening needed

↓

Lesson II: How can it hide? Chameleon, symmetron, dilaton, Vainshtein, K-mouflage, $f(R)$

↓

Lesson III: How do we test the hiding? Lab, Solar System, EP, PPN, LLR, MICROSCOPE

↓

Lesson IV: Where can an observable window remain? Stars, galaxies, voids, pulsars, NS, GWs

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Summary: where can modified gravity survive?

Regime	**Key probe**	**Screened?**	**Leading ref.**
Stars ($M_{\min}$, P–L)	Cepheids, RGB tip	partial	Sakstein (2015), Jain et al. (2013)
White dwarfs	M–R relation	intermediate	Sakstein et al. (2025)
Dwarf galaxies	dynamics, lensing	partial–unscr.	Jain et al. (2013)
Voids	galaxy flows, ISW	very weak	Clifton et al. (2012)
Clusters + lensing	$\eta = \Phi/\Psi$	env. dep.	Clifton et al. (2012)
$f\sigma_8$ + WL	$Q(k,a)$, $\eta(k,a)$	scale dep.	Koyama (2016)
Binary pulsars	dipole $\dot{P}_b$	compactness	Freire & Wex (2024)
Neutron stars	scalarization	threshold	Damour & EF (1993)
GW generation	ppE, waveform	theory dep.	Yunes et al. (2025)
Standard sirens	$d_L^{\rm GW}/d_L^{\rm EM}$	propagation	Belgacem et al. (2018)