Unified Standard Model with Emergent Gravity–Effective Field Theory (USMEG-EFT)

First Successful Unification of Gravity with the Standard Model

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Talk Outline

I. The unification problem

II. Shared foundational error

III. Proof I: canonical quantization

IV. Proof II: renormalization group

V. Proof III: BRST symmetry

VI. Convergence & EFT verdict

VII. The USMEG-EFT framework

VIII. SM–gravity unification

IX. Experimental validation

X. Applications & outlook

Three independent theoretical proofs $\Rightarrow$ one parameter-free experimental confirmation

The Unification Problem: a 60-Year Impasse

The Standard Model: three forces, electromagnetic, weak, strong $SU(3)\times SU(2)\times U(1)$, fully renormalizable, exquisitely tested.

General Relativity: Einstein–Hilbert action, classical triumph.

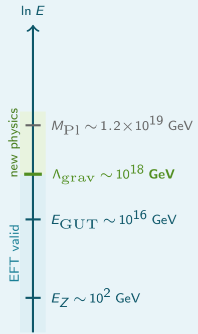
The problem: Two-loop divergences [1, 2]:

$$\Gamma^{(2)}_{\text{div}} \propto \frac{209}{2880\varepsilon}\sqrt{-g}\, R_{\mu\nu\rho\sigma} R^{\rho\sigma\alpha\beta} R_{\alpha\beta}{}^{\mu\nu}$$

These *cannot* be absorbed by renormalizing original terms in the theory.

Consequence: Gravity is not renormalizable – but what does that *actually mean?*

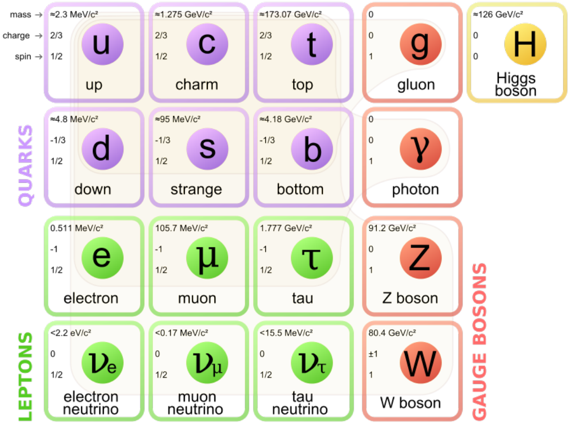
Energy scale hierarchy



The Standard Model: Our Best Description of Matter and Forces

Particle content:

- **Quarks** (6 flavours): constituents of protons, neutrons, all hadrons; carry colour charge.
- **Leptons** (6): electrons, muons, taus and their neutrinos; no colour charge.
- **Gauge bosons**: g (strong), γ, W, Z (electroweak) – force mediators.
- **Higgs boson**: scalar field giving mass via spontaneous symmetry breaking.



$$\mathcal{G}_{\rm SM} = SU(3)_c \times SU(2)_L \times U(1)_Y$$

- Fully renormalizable to all loop orders.
- Predictions verified to 10^{-12} precision (electron $g-2$, electroweak precision tests).
- Higgs discovered at CERN in 2012 at $\approx 126\,\mathrm{GeV}$.

One glaring omission: gravity is absent. The SM has no graviton partly due to non-renormalizabilty of GR.

The Energy Scale Hierarchy: Where Gravity Lives

The fine-structure constant hierarchy:

$$\alpha_s \sim 1 \quad \alpha_w \sim 10^{-2} \quad \alpha_{em} \sim 10^{-3}$$

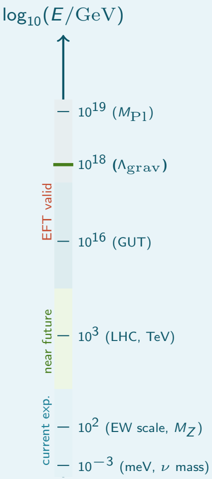
$$\alpha_G = \frac{G_N m_p^2}{\hbar c} \sim 10^{-38}$$

Gravity is 10^{38} times weaker than the strong force for elementary particles.

Physical origin: The Planck scale $M_{\mathrm{Pl}} = \sqrt{\hbar c/G_N} \approx 1.22\times 10^{19}\,\mathrm{GeV}$ sets the energy at which gravitational effects become $\mathcal{O}(1)$. Below it, gravity is suppressed by powers of $(E/M_{\mathrm{Pl}})^2$.

At the energies probed by current experiment, gravity is entirely negligible compared with the other three forces – yet it dominates the universe at macroscopic scales. This enormous gap is the **hierarchy problem** in stark relief.

Scale ladder



How Weak Is Gravity? A Quantitative Picture

Gravitational coupling compared with other forces:

Force	Mediator	Coupling at M_Z
Strong (QCD)	gluon	$\alpha_s \sim 0.12$
Weak	W, Z	$\alpha_w \sim 0.034$
Electromagnetic	photon	$\alpha_{em} \sim 1/128$
Gravity	**graviton**	$\boldsymbol{\alpha_G \sim 10^{-38}}$

Gravitational scattering cross section:

$$\sigma_{\rm grav} \sim G_N^2 s \sim \frac{s}{M_{\rm Pl}^4}$$

Completely undetectable at any foreseeable collider.

Yet this same tiny coupling produces ultraviolet divergences that destroy the theory at two loops.

The paradox of weakness

Weakness does not protect against non-renormalizability. The two-loop divergence [2]

$$\Gamma^{(2)}_{\rm div} \propto \frac{G_N^2}{\varepsilon} R^3$$

cannot be absorbed: no R^3 counterterm exists in the EH action, regardless of how small G_N is.

The EFT reading

Quantum corrections are suppressed by $(E/M_{\rm Pl})^2$ – the hallmark of an EFT, not a fundamental obstruction.

What Does Non-Renormalizability Actually Mean?

Classical interpretation (pre-EFT):

Infinitely many counterterms; no predictive power; the theory must be discarded.

Modern EFT interpretation (Weinberg, Wilson):

Non-renormalizability signals a finite radius of validity:

$$\mathcal{L}_{\mathrm{EFT}} = \sum_n \frac{c_n(\mu)}{\Lambda^{n-4}} \mathcal{O}_n$$

Below Λ: finitely many operators matter. Above Λ: new physics enters.

Applied to gravity:

The divergence $\propto R^3/\varepsilon$ announces GR is an EFT with cutoff $\sim M_{\mathrm{Pl}}$. It says nothing about physics below that scale.

Historical analogues

Fermi weak theory: non-renormalizable. Resolution: W/Z at 80–91 GeV.

Chiral perturbation theory: non-renormalizable. Resolution: QCD.

General relativity: non-renormalizable. Resolution: EFT breakdown at $\Lambda_{\mathrm{grav}} \sim 10^{18}\,\mathrm{GeV}$. The SM already provides the UV completion.

The critical reframing

The 60-year search for a UV completion of gravity answers a question the theory never asked. Non-renormalizability demands an EFT identification – not a UV completion.

The Deeper Problem: Ontological Incompatibility

GR is ontologically deterministic:

- Spacetime is a smooth classical 4-manifold; $g_{\mu\nu}(x)$ is a real-valued tensor – no superposition, no Hilbert space.
- $G_{\mu\nu} = 8\pi G_N T_{\mu\nu}$: deterministic PDEs with well-posed Cauchy evolution.
- The geometry itself is the dynamical variable.

The SM is ontologically probabilistic:

- Fields are operator-valued distributions on a *fixed* background spacetime.
- States live in a Hilbert space; evolution is unitary.
- The background metric is prescribed, not solved for.

The structural clash

Is the metric a c-number or an operator?

If a c-number: what sources curvature from quantum fluctuations?

If an operator: which Hilbert space, on which background?

USMEG-EFT resolution

$g_{\mu\nu} = \bar{g}_{\mu\nu} + \varkappa\phi_{\mu\nu}$: the background $\bar{g}_{\mu\nu}$ is a classical c-number; $\phi_{\mu\nu}$ is a quantum field on it. The ontological conflict is resolved by construction and enforced by the Lagrange multiplier constraint.

The unification problem is not merely technical – it is a conflict between two incompatible ontologies of physical reality.

All Quantum Gravity Major Programs Share One Assumption

The shared assumption

The full non-linear metric $g_{\mu\nu}$ is a valid fundamental quantum degree of freedom at *all* energy scales, and equivalently, that the diffeomorphism invariance of the complete non-linear theory holds quantum mechanically without bound.

String theory

Low-energy limit $\rightarrow$ full non-linear EH action, not the weak-field EFT [17].

Landscape: $\sim 10^{500}$ vacua; no confirmed 4D prediction.

Loop quantum gravity

Ashtekar variables encode the full non-linear constraint algebra [16].

Semiclassical limit and scalar constraint unsolved.

Asymptotic safety

Functional RG over *all* metric configurations – infinite gravitational phase space [14].

Gies–Knorr–Lippoldt: scheme dependence undermines UV fixed point [15].

Three independent proofs show this assumption fails for $d > 2$: the non-linear metric is not a valid quantum field above Λ_{grav}.

Once this is recognised, a consistent EFT unification follows naturally.

Proof I: Loss of General Covariance for $d > 2$

Result from canonical analysis [3, 4]:

- Second-class constraints are non-covariant under diffeomorphisms for $d > 2$.
- Constraint algebra involves *structure functions*, not structure constants:

$$\{H[N], H[M]\} = H[\mathcal{L}_N M]$$

  The right-hand side depends on the dynamical metric – the Hamiltonian manifestation of the breakdown.
- The Senjanovic path-integral fails: covariant quantization is impossible for the full theory.

Conclusion: For $d > 2$, GR cannot be a fundamental quantum theory. The weak-field regime defines the consistent EFT domain.

Exception: $d = 2$

In 2D, GR is topological. Covariance is preserved; consistent quantization is possible. The breakdown is *dimensional* in origin.

Resolution

Covariance is restored in the weak-field expansion $g_{\mu\nu} = \eta_{\mu\nu} + \varkappa\phi_{\mu\nu}$. The only regime admitting consistent quantum treatment.

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Proof I: Recovery of Covariance in the Weak-Field Limit

The breakdown of covariance localizes the valid regime precisely via the background field decompostition:

$$g_{\mu\nu} = \eta_{\mu\nu} + \varkappa\phi_{\mu\nu}$$

where $\eta_{\mu\nu}$ is the flat background; $\phi_{\mu\nu}$ represents quantum fluctuations. In this regime:

- The constraint algebra *linearizes*: structure functions reduce to structure constants on the background.
- Second-class constraints become covariant w.r.t. background diffeomorphisms.
- Senjanovic path integral is well-defined; the graviton propagator is unambiguously constructed.

Key finding (common to both formulations)

Path-integral quantization via Senjanovic's method [5] requires second-class constraints to transform covariantly under diffeomorphisms. In GR for $d > 2$ the constraint algebra closes with field-dependent structure *functions*, not structure constants – a direct proof that $g_{\mu\nu}$ is not a valid fundamental quantum field in $d > 2$.

Proof II: The Lagrange Multiplier Action

The LM method by McKeon et al. [6, 7] introduces auxiliary tensor field $\lambda^{\mu\nu}$:

$$S_{\mathrm{LM}} = S_{\mathrm{EH}} + \frac{1}{\varkappa^2} \int d^4x \sqrt{-g}\, \lambda^{\mu\nu} G_{\mu\nu}[g] \quad (1)$$

where $G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R$.

Mechanism: Path-integrating over $\lambda^{\mu\nu}$ yields $\delta[G_{\mu\nu}]$ – enforces Einstein's equations at the path-integral level.

Effect on the loop expansion:

- All *multi-loop* graviton contributions are systematically eliminated.
- Quantum gravity corrections are confined to exactly one loop.
- Newton's constant G_N does *not* run – divergences absorbed by field shifts, not coupling renormalization.

Structural constraint, not truncation – and fully general

Proof II: Logarithmic Running and the EFT Nature of GR

One-loop dimensional regularization yields the **finite** effective action [8]:

$$\Gamma^{(1)}_{\mathrm{finite}} = \frac{1}{(4\pi)^2} \ln\left(\frac{\mu}{\Lambda}\right) \int d^4x \sqrt{-\bar{g}} \left[\frac{1}{120} \bar{R}^2 + \frac{7}{20} \bar{R}_{\mu\nu} \bar{R}^{\mu\nu} \right] \tag{2}$$

The two Wilson coefficients are dimensionless,

$$c_1(\mu) = \frac{1}{(4\pi)^2} \cdot \frac{1}{120} \ln\left(\frac{\mu}{\Lambda}\right), \qquad c_2(\mu) = \frac{1}{(4\pi)^2} \cdot \frac{7}{20} \ln\left(\frac{\mu}{\Lambda}\right),$$

so their RG equations carry a *dimensionless* right-hand side:

$$\mu \frac{dc_1}{d\mu} = \frac{1}{(4\pi)^2} \cdot \frac{1}{120}, \qquad \mu \frac{dc_2}{d\mu} = \frac{1}{(4\pi)^2} \cdot \frac{7}{20}.$$

Two key signatures:

- $\ln(\mu/\Lambda)$ is *not* absorbable into G_N – it multiplies new structures $\bar{R}^2, \bar{R}_{\mu\nu}\bar{R}^{\mu\nu}$ absent from the Einstein–Hilbert action.
- No UV fixed points. For the dimensionful couplings $g_i \equiv \mu^2 c_i$,

$$\beta_1 = \frac{\mu^2}{(4\pi)^2} \frac{1}{120} + 2g_1,$$

Breakdown criterion:

When $\mu \to \Lambda_{\mathrm{grav}}$, $\ln(\mu/\Lambda) \sim \mathcal{O}(1)$ and the quantum corrections $c_i(\mu)\bar{R}^2$ become comparable to the classical EH term $M^2_{\mathrm{Pl}}\bar{R}/2$. The EFT ceases:

$$\Lambda_{\mathrm{grav}} \sim 10^{18}\,\mathrm{GeV}$$

Proof II: Mathematical Proof via the Appelquist–Carazzone Theorem

Theorem (Appelquist–Carazzone [9])

In a renormalizable QFT, heavy degrees of freedom with masses $M \gg \mu$ decouple, with corrections suppressed by powers of μ/M: $\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm light} + \sum_n \frac{c_n}{\Lambda^n}\mathcal{O}_n(\mu/\Lambda)$

Application to LM gravity. The suppression follows from the *dimensionless ratio* of the one-loop correction to the classical action – not from expanding the logarithm. With $S_{\rm EH} = \frac{1}{\kappa^2}\int\sqrt{-\bar{g}}\,\bar{R}$, $\kappa^2 = 16\pi G_N \sim M_{\rm Pl}^{-2}$, and $\bar{R} \sim E^2$,

$$\frac{\Gamma^{(1)}[\bar{g}]}{S_{\rm EH}[\bar{g}]} \sim \frac{\kappa^2\bar{R}}{(4\pi)^2}\ln\left(\frac{\mu}{\Lambda}\right) \sim \left(\frac{E}{M_{\rm Pl}}\right)^2 \ln\left(\frac{\mu}{\Lambda}\right).$$

The one-loop correction is the curvature-squared pair $\bar{R}^2, \bar{R}_{\mu\nu}\bar{R}^{\mu\nu}$, down by $\kappa^2\bar{R} \sim (E/M_{\rm Pl})^2$ relative to Einstein–Hilbert. The Lagrange-multiplier constraint stops the expansion at one loop, so no $\bar{R}^{\,n\geq 3}$ is generated – decoupling is a *terminated* series, not merely a suppressed one; the logarithm runs the Wilson coefficients, not a power correction. ■

What this proves:

- LM gravity is a *rigorous* EFT.
- The $\ln(\mu/\Lambda)$ is a structural EFT signature, not a renormalization artifact.

Contrast with asymptotic safety:

- AS requires $G_N(\mu)$ flow to a UV fixed point.
- In USMEG-EFT, G_N is fixed; no UV fixed point exists.

Proof III: BRST Symmetry – the Consistency Test

What is BRST symmetry?

Named after Becchi, Rouet, Stora and Tyutin, BRST symmetry is the residual symmetry left after a gauge theory is gauge-fixed for quantization. It guarantees that physical predictions never depend on the arbitrary gauge choice: in a *fundamental* theory such as Yang–Mills the one-loop action obeys $\partial\Gamma/\partial\xi = 0$ exactly, at every energy.

The test. Compute the one-loop coefficient of R^2 in two standard gauges and compare:

Gauge	β_1 (coefficient of R^2)
't Hooft–Veltman	$+\frac{1}{120}$
Goldberg	$-\frac{119}{120}$

$$\boxed{\Delta\beta_1 = \beta_1^{\mathrm{Gold}} - \beta_1^{\mathrm{tHV}} = -\frac{119}{120} - \frac{1}{120} = -1} \tag{3}$$

An order-unity difference between gauges – in Yang–Mills the same comparison gives *identically zero*. Gravity differs; the next slide shows why, and why it stays consistent below Λ_{grav}.

Proof III: Conditional Nilpotency – the EFT Reading

What the gauge dependence means. The order-unity gauge dependence established on the previous slide is the diagnostic: the unconstrained metric carries graviton modes that violate Einstein's equations, and the BRST charge is non-nilpotent on them. For a fundamental theory this would be fatal; for an effective theory it is the expected signal that the full metric is not the right quantum field.

How USMEG-EFT resolves it. The LM constraint removes exactly those off-shell modes, projecting onto the Einstein surface. There the BRST charge is nilpotent, $s^2 = 0$, and the effective action is gauge-independent: the curvature-squared coefficients become genuine, unambiguous predictions. Exact nilpotency is conditional on the constraint, which is the precise content of the EFT reading.

The decisive contrast. In the unconstrained theory the running of the curvature-squared coupling is gauge-dependent down to its sign, so the prediction is ambiguous. Under the LM constraint the effective action is gauge-independent, and Newton's constant does not run at all: the couplings are physical and unambiguous. The construction is perturbative about the classical background metric, which need not be flat, and is valid up to $\Lambda_{\mathrm{grav}} \sim 10^{18}$ GeV.

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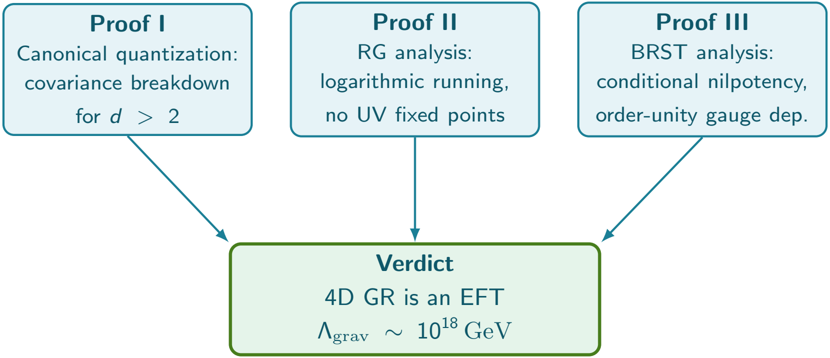
Convergence of Three Independent Proofs



Each proof uses entirely different mathematical tools (Dirac constraint analysis, heat kernel RG, BRST algebra).

All three converge on the same breakdown scale. This *independent* convergence provides extremely strong evidence.

USMEG-EFT: The Gravity-SM Unified Action

$$S_{\rm USMEG} = \underbrace{S_{\rm EH}}_{\text{gravity}} + \underbrace{S_{\rm LM}}_{\text{constraint}} + \underbrace{S_{\rm SM}}_{\text{Standard Model}} + \underbrace{S_{\rm int}}_{\text{coupling}} \tag{4}$$

$$S_{\rm EH+LM} = \frac{1}{2\varkappa^2}\int d^4x\sqrt{-g}[R + \lambda^{\mu\nu}G_{\mu\nu}]$$

$$S_{\rm SM} = \int d^4x\sqrt{-g}\left[-\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + \bar{\psi}_f i\gamma^\mu D_\mu\psi_f + |D_\mu H|^2 - V(H)\right]$$

- The LM field $\lambda^{\mu\nu}$ operates on quantum fluctuations around a *general curved background* – not restricted to flat space.
- $S_{\rm int}$ contains gravitational interactions from minimal coupling plus dimension-six SMEFT operators preserving $SU(3) \times SU(2) \times U(1)$.
- Newton's constant G_N does not run; the theory is renormalizable for $\mu < \Lambda_{\rm grav}$.

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SM–Gravity Coupling: Sector-by-Sector Analysis

The $\delta[G_{\mu\nu}]$ constraint produces a structurally *asymmetric* coupling – by first principles [12, 8]:

Gauge sector: one-loop gravitational corrections

$$S_{\rm int}^{\rm gauge} = \frac{\varkappa}{2}\int d^4x\sqrt{-\bar{g}}\; h^{\mu\nu}\, T_{\mu\nu}^{\rm gauge}$$

Corrections arise from *internal gauge boson propagators* coupling to external graviton legs through $T_{\mu\nu}^{\rm gauge}$, governed by $S_{\rm SM}$ and outside the scope of $\delta[G_{\mu\nu}]$:

$$\Delta\Gamma \supset \frac{\varkappa^2 \ln(\mu/\Lambda)}{(4\pi)^2}\int \sqrt{-\bar{g}}\,\alpha_i F^a_{\mu\nu} F^{a\mu\rho}\bar{R}^{\nu}{}_{\rho}$$

Fermion & Higgs sectors

$$S_{\rm int}^{\rm f} = \frac{\varkappa}{2}\int d^4x\sqrt{-\bar{g}}\; h^{\mu\nu}\, T_{\mu\nu}^{\rm f}$$

Present: SM loop corrections to the graviton–fermion vertex $\Gamma_{h\bar{\psi}\psi}$ from internal gauge boson and fermion lines – these are governed by $S_{\rm SM}$ and survive.

Absent at all orders: any diagram with a *virtual graviton internal line*. $\delta[G_{\mu\nu}]$ projects these out exactly, since the on-shell locus $\mathcal{G}^{(1)}_{\mu\nu}[\bar{g};\phi] = 0$ has measure zero in $\mathbb{R}^4$.

The precise asymmetry

Gauge sector: internal gauge boson loops generate gravitational operator corrections – no virtual graviton needed.

Fermion/Higgs sector: SM loops dress the graviton–matter vertex in the standard way; what is *absent* is any correction from a virtual graviton on an internal line at any loop order. No new non-renormalizable gravitational structures are ever generated in any sector.

Gravitational–Gauge Sector Corrections: Loop Structure

The one-loop gravitational correction to the gauge sector takes the form:

$$\Delta\Gamma^{(1)}_{\rm gauge} = \frac{\varkappa^2 \ln(\mu/\Lambda)}{(4\pi)^2} \int d^4x \sqrt{-\bar{g}} \left[\alpha_1(\mu)\, F^a_{\mu\nu} F^{a\mu\nu} \bar{R} + \alpha_2(\mu)\, F^a_{\mu\nu} F^{a\mu\rho} \bar{R}^\nu{}_\rho\right]$$

where the Wilson coefficients $\alpha_i(\mu)$ carry explicit μ-dependence from nested SM gauge loops.

What $\delta[G_{\mu\nu}]$ removes

Any diagram with a *virtual graviton internal line* – metric quantum $\phi_{\mu\nu}$ integrated over $\mathcal{D}g_{\mu\nu}$ – is projected out at every loop order. The on-shell locus $\mathcal{G}^{(1)}_{\mu\nu}[\bar{g};\phi] = 0$ has measure zero in $\mathbb{R}^4$; generic loop momenta are eliminated exactly. This removes Goroff-Sagnotti-type R^3 divergences and all their higher-loop analogues.

What $\delta[G_{\mu\nu}]$ cannot reach

Nested gauge boson loops dressing the internal gauge propagator are integrated over $\mathcal{D}A_\mu$, governed by $S_{\rm SM}$ alone. No metric quantum appears on internal lines; $\delta[G_{\mu\nu}]$ has no jurisdiction. These loops renormalize $\alpha_i(\mu)$ through standard SM RG running – the same physics that runs g_s, g_W, g_Y in the pure SM, now feeding into the coefficient of a mixed gravitational-gauge operator.

Why this is benign: no new non-renormalizable structures

Nested gauge loops dress the *coefficient* of an operator already present, they do not generate new operator structures. No R^3, R^4, or other unabsorbable gravitational divergences are reintroduced. The theory remains renormalizable below $\Lambda_{\rm grav}$ because $\delta[G_{\mu\nu}]$ guarantees that no virtual graviton ever appears on an internal line at any order, which is the unique source of the dangerous non-renormalizability.

Experimental Validation I: the Graviton Polarization Prediction

The prediction, stated before any data:

The LM constraint leads to the transverse-traceless (TT) condition:

$$N_{\text{dof}}^{\text{grav}} = \boxed{2} \quad \text{(exactly two TT polarization states)}$$

Parameter-free and discrete – admits no continuous adjustment.

What makes this remarkable:

- Not a bound on a continuous parameter – a discrete integer.
- The count 2 is determined by the LM constraint structure alone.
- Every competing theory predicts a *different* integer.

The corrected graviton propagator

$$\Delta_{\mu\nu,\rho\sigma}(k) = \frac{i}{k^2 + i\varepsilon}\left[P^{(2)}_{\mu\nu,\rho\sigma} - \tfrac{1}{2}P^{(0)}_{\mu\nu,\rho\sigma}\right]\left(1 + \frac{\varkappa^2}{16\pi^2}\ln\frac{k^2}{\Lambda^2_{\text{grav}}}\right)$$

Only spin-2 (h_+, $h_\times$) modes propagate. Scalar, vector, longitudinal, and breathing modes are *absent in the theory*.

Experimental Validation II: LIGO-Virgo-KAGRA Confirmation

Observational verdict: Across dozens of GW detections (GW150914, GW170817, GW190521, full GWTC catalogs):

$$h_{ij}^{TT}(t,\vec{x}) = h_{+}(t - z/c)\, e_{ij}^{+} + h_{\times}(t - z/c)\, e_{ij}^{\times}$$

No evidence for additional polarizations at $> 99\%$ confidence against scalar, tensor or vector content.

Theory	Pred. polarizations	LVK consistent?
USMEG-EFT	**2 (TT only)**	**YES**
Einstein–Cartan + propagating torsion	up to 6	**NO**
Massive gravity (dRGT)	5	**NO**
$f(R)$ gravity	3 (TT + scalar breathing)	**NO**
Scalar-tensor (Brans-Dicke, Horndeski)	3	**NO**
Bimetric gravity	up to 7	**NO**

Additional constraint from GW170817 + GRB 170817A: Consistent with the massless graviton of USMEG-EFT: $m_g < 1.76 \times 10^{-23}\,\mathrm{eV}/c^2 \quad (90\%\,\mathrm{C.L.})$

Experimental Validation III: GW Phase Corrections and Future Tests

Gravitational wave phase corrections:

$$\Phi_{\mathrm{GW}}(f) = \Phi_{\mathrm{GR}}(f) + \delta\Phi_{\mathrm{quantum}}, \qquad \delta\Phi_{\mathrm{quantum}} = \frac{\varkappa^2}{16\pi^2} \ln\left(\frac{f}{f_{\mathrm{Pl}}}\right) \times \frac{3}{128}\left(\frac{GM_c\pi f}{c^3}\right)^{-5/3}$$

For NS binary ($M_c = 1.2\,M_\odot$, $f = 100\,\mathrm{Hz}$): $\delta\Phi/\Phi_{\mathrm{GR}} \sim 10^{-37}$.

High-energy scattering:

$$\left.\frac{\delta\sigma}{\sigma}\right|_{e^+e^-\to\mu^+\mu^-} = \frac{G_N s}{8\pi^2} \ln\frac{\sqrt{s}}{\Lambda_{\mathrm{grav}}}$$

For $\sqrt{s} = 100\,\mathrm{TeV}$: $\delta\sigma/\sigma \approx -9.8\times 10^{-12}$.

Path to observability:

- **Now:** polarization count confirmed.
- **Near term:** Einstein Telescope, Cosmic Explorer.
- **Future:** FCC/ILC at 100 TeV.
- **Also:** Tobar et al. gravito-phononic graviton sensing [23].

Competing Approaches: A Shared Foundational Error

All major programs fail for the same reason: assumption of infinite gravitational phase space.

Asymptotic safety [14, 15]:

- Requires $G_N(\mu)$ to flow to a non-Gaussian UV fixed point.
- Three proofs show no such fixed point is physically realizable.
- Gies–Knorr–Lippoldt: fixed point is scheme-dependent.
- Realistic SM matter coupling remains problematic.

String theory [17]:

- Low-energy limit $\rightarrow$ full non-linear EH action.
- Landscape prevents concrete 4D predictions.

Loop quantum gravity [16]:

- Full non-linear constraints imposed quantum mechanically.
- Scalar constraint (dynamics) unsolved in $d = 4$.
- Semiclassical limit not demonstrated in full generality.

Einstein–Cartan theory [18]:

- Torsion introduces additional propagating modes.
- Excluded by LVK polarization data at $> 99\%$ confidence.
- Quantization far more involved than EH.

Novel Result: Gravity as an Emergent Phenomenon

The standard assumption (all competing programs):

Gravity is a *fundamental* interaction to be quantized – the graviton is a primary degree of freedom alongside quarks and gauge bosons.

What USMEG-EFT establishes instead:

The three independent proofs do not merely show GR is an EFT. They show that classical spacetime geometry itself is an emergent, low-energy phenomenon.

- The background $\bar{g}_{\mu\nu}$ is a *condensate*: a classical expectation value of quantum gravitational fluctuations $\langle\phi_{\mu\nu}\rangle$ below $\Lambda_{\rm grav}$.
- The Einstein–Hilbert action is the leading term of an effective action.
- Newton's constant G_N does not run: it is a property of the emergent geometry.
- The EFT breakdown at $\Lambda_{\rm grav}$ is where new physics enters – it is where classical space-time geometry *ceases to exist*.

The emergent hierarchy

Quantum energy epoch
$T > \Lambda_{\rm grav}$: no geometry

PSEP transition
at $T \sim \Lambda_{\rm grav}$
geometry condenses

Emergent classical GR
$\bar{g}_{\mu\nu} = \langle\phi_{\mu\nu}\rangle$

SM + gravity EFT
valid for $\mu < \Lambda_{\rm grav}$

Why this is novel

No other program derives emergent geometry from a renormalizable EFT constraint with a *parameter-free experimental confirmation.*

Cosmological Implications

Cosmological constant problem:

Finite phase space provides a natural cutoff:

$$\rho_{\mathrm{vac}}^{\mathrm{cutoff}} \sim \Lambda_{\mathrm{grav}}^4 \sim 10^{72}\,\mathrm{GeV}^4$$

vs. naive Planck estimate $\sim 10^{76}\,\mathrm{GeV}^4$ – four orders of magnitude suppression.

Inflationary cosmology:

The EFT boundary precludes trans-Planckian field excursions. Inflation models requiring super-Λ_{grav} ranges require re-examination.

Hubble tension:

Late-time EFT corrections to dark energy may contribute to the H_0 discrepancy – under active investigation.

Primordial black holes:

BHs with $M < M_{\mathrm{min}}$ could not have formed as geometric objects. Evaporating PBHs leave non-geometric remnants – potential dark matter candidates.

Emergent spacetime (PSEP):

The Principle of Spatial Energy Potentiality proposes that spatial energy is more fundamental than classical geometry, which condenses from the quantum vacuum below Λ_{grav}.

Application: The Principle of Spatial Energy Potentiality (PSEP)

The pre-temporal state: The universe begins as a 3D spatial manifold Σ with a *pure energy functional* – no time, no kinetic terms:

$$E[\phi] = \int_{\Sigma} d^3x \left[\tfrac{1}{2}(\nabla\phi)^2 + V(\phi)\right]$$

No $(\partial\phi/\partial t)^2$ at tree level; the Wheeler–DeWitt equation is timeless, so time must emerge. PSEP provides the mechanism.

How time emerges: One-loop corrections along an auxiliary Parisi–Wu parameter *generate* a kinetic term with renormalized coefficient

$$A_{\rm ren} = \frac{[V'''(\phi)]^2}{32\pi^2[V''(\phi)]^2} \ln\left(\frac{V''(\phi)}{\mu^2}\right).$$

Time emerges once $A_{\rm ren} \geq M_P^{-2}$, a **first-order phase transition** from the spatial to the spacetime phase. The only prerequisite is $V''' \neq 0$, satisfied by any non-quadratic potential.

$T > \Lambda_{\rm grav}$: Quantum energy epoch

No classical spacetime; pre-temporal $\Psi[\phi]$ with no time dependence.

$T \sim \Lambda_{\rm grav}$: PSEP transition

First-order phase transition: loop-generated kinetic terms exceed M_P^{-2}. Classical geometry condenses; USMEG-EFT activates.

$T \ll \Lambda_{\rm grav}$: EFT cosmology

Emergent R^2 drives Starobinsky inflation.

Singularity resolution ($V^{1/4} \sim 10^{16}$ GeV): $R/M_P^2 \sim 1.1\times10^{-9}$, $K/M_P^4 \sim 2.2\times10^{-19}$ – finite at all scales; no $t \to 0$ limit.

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Unified Starobinsky Potential and CMB Predictions

The connection: The USMEG-EFT one-loop action (2) naturally contains R^2:

$$\Gamma^{(1)} \supset \frac{1}{120(4\pi)^2} \ln\left(\frac{\mu}{\Lambda}\right) \int \sqrt{-g}\, R^2\, d^4x$$

Combined with the EH term, this *is* the **Starobinsky action**:

$$S_{\rm Star} = \frac{M_{\rm Pl}^2}{2} \int d^4x \sqrt{-g}\left(R + \frac{R^2}{6M^2}\right)$$

Einstein-frame inflation potential:

$$V(\varphi) = \frac{3M^2 M_{\rm Pl}^2}{4}\left(1 - e^{-\sqrt{2/3}\,\varphi/M_{\rm Pl}}\right)^2$$

CMB predictions ($N \approx 60$ e-foldings):

	USMEG-EFT	Planck 2018
n_s	$1 - \frac{2}{N} \approx 0.967$	0.965 ± 0.004
r	$\frac{12}{N^2} \approx 0.003$	< 0.036

Key: The R^2 coefficient $\frac{1}{120}$ is fixed by the one-loop calculation. Once mass M is set by COBE/Planck normalization, n_s and r follow from the potential shape alone.

The Starobinsky potential is a *consequence* of USMEG-EFT – not an independent assumption.

Extensions: Neutrino Sector, Graviton Sensing, and Future Work

νSMEFT extension [21]:

Extending USMEG-EFT to include Dirac and Majorana neutrino masses. Gravitationally corrected RGEs for the neutrino sector:

$$\mu \frac{d\kappa_\nu}{d\mu} = \beta_\nu^{\mathrm{SM}} + \delta\beta_\nu^{\mathrm{grav}}$$

Corrections to leptogenesis rates and mixing angles are calculable and potentially observable via cosmological probes.

UV/IR mixing (JCAP reinterpretation):

A 20-year arc from the 2005 JCAP paper [22] – UV/IR mixing as a consequence of the EFT boundary.

Graviton quantum sensing [23]:

Tobar et al.'s gravito-phononic proposal connects directly to the USMEG-EFT graviton propagator. MS in preparation.

Published record:

- Chishtie, CJP **101**, 347 (2023)
- Chishtie, CJP **103**, 1 (2025) DOI:10.1139/cjp-2025-0083
- Chishtie, *Symmetry* **18**, 140 (2026) DOI:10.3390/sym18010140
- Chishtie, MPLA (2026) – Krein/LM equivalence & GW polarization DOI:10.1142/S0217732326500719
- Chishtie, *Phys. Lett. B* **877**, 140499 (2026) – PSEP DOI:10.1016/j.physletb.2026.140499

Conclusions

1. **Three independent proofs** establish that 4D GR is an EFT with breakdown scale $\Lambda_{\mathrm{grav}} \sim 10^{18}\,\mathrm{GeV}$:
   - Canonical quantization: covariance breaks down for $d > 2$.
   - RG analysis: logarithmic running, no UV fixed points.
   - BRST analysis: order-unity gauge dependence signals conditional nilpotency.
2. **The Lagrange multiplier construction** provides the unique consistent and exact one-loop quantum correction – the basis of USMEG-EFT.
3. **Unification with the Standard Model** is achieved: a fully renormalizable EFT of all known interactions, valid below Λ_{grav}, with sector-specific gravitational coupling structure.
4. **Parameter-free experimental confirmation:** exactly two graviton polarization modes confirmed by LVK across dozens of detections. Every competing approach predicts more – all excluded.
5. **Future work:** Theory development BSM & Higgs Physics, Experimental verification from quantum sensing, Cosmology - Other scenarios besides PSEP emergent spacetime, UV/IR mixing, dark energy, late universe times, further comparison with Planck 2018 CMB data.

Thanks for your attention! Open to questions and collaborations!

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