

# Composition-Dependent Bounds on Scalar-Field Coupling to Nuclear Decay Rates

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(Dated: March 19, 2026)

Scalar-tensor theories of gravity generically predict composition-dependent coupling of a gravitational scalar field to nuclear transition rates. We apply the Flambaum nuclear sensitivity formalism to compute isotope-specific sensitivity coefficients  $\kappa_q^{(I)}$  for eight nuclides central to the decade-long debate over reported annual modulations in decay rates. The sensitivity is driven by  $Q$ -value through  $\kappa_q \propto n/Q$ , placing  $^{32}\text{Si}$  ( $Q = 0.227$  MeV) at the top of the hierarchy. We show that existing null results constrain different regions of the  $(k_q^{\text{eff}}, \kappa_q)$  parameter space and do not exclude composition-dependent signals in untested low- $Q$  isotopes. The classic positive datasets ( $^{32}\text{Si}$  at BNL,  $^{226}\text{Ra}$  at PTB) are now understood to be dominated by environmental systematics—particularly humidity and temperature—and cannot be treated as detections. We identify  $^{187}\text{Re}$  ( $Q = 2.63$  keV,  $\kappa_q \approx 19,000$ ) and the  $^{229}\text{Th}$  nuclear clock isomer ( $K \sim 10^4$ ) as the most sensitive future targets, and propose a multi-isotope ratio test that eliminates environmental systematics while directly probing composition dependence. For the highest-sensitivity low- $Q$  isotopes, the question of whether nuclear decay rates couple to gravitational environment at the  $10^{-6}$ – $10^{-7}$  level remains experimentally open.

## I. INTRODUCTION

Between 2008 and 2012, Jenkins, Fischbach, and collaborators reported annual modulations in nuclear decay rates correlated with the Earth–Sun distance [1, 2, 4, 5]. The primary datasets—the  $^{32}\text{Si}/^{36}\text{Cl}$  ratio at Brookhaven National Laboratory (BNL) [12] and the  $^{226}\text{Ra}/^{152}\text{Eu}$  ratio at the Physikalisch-Technische Bundesanstalt (PTB) [13]—showed  $\sim 0.1\%$  annual modulations.

These claims have been extensively challenged. Pommé *et al.* [8] compiled data from 14 laboratories, finding no solar-phase oscillations at  $10^{-6}$ – $10^{-5}$  precision across multiple isotopes. Bellotti *et al.* [9] constrained  $^{137}\text{Cs}$  modulations below  $5 \times 10^{-5}$  at Gran Sasso. Cooper [6] found no anomaly in  $^{238}\text{Pu}$  aboard Cassini. Hardy *et al.* [7] set a  $\pm 0.02\%$  limit on  $^{198}\text{Au}$ . Most damagingly, Pommé *et al.* [10] showed that the original BNL  $^{32}\text{Si}$  and Ohio State  $^{36}\text{Cl}$  datasets correlate better with local dew point and temperature than with the Earth–Sun distance, identifying humidity-driven instrumental instability as the likely cause of the reported modulations.

The standard conclusion is that the Jenkins–Fischbach effect is an experimental artifact [8, 10]. We do not dispute this for the claimed  $\sim 10^{-3}$  amplitudes. However, we note that the experimental program that “disproved” the effect tested different isotopes from those originally claimed, and the null bounds span a wide range ( $10^{-6}$  to  $10^{-4}$ ) depending on isotope and technique. Scalar-tensor theories generically predict *composition-dependent* coupling [17, 18], in which different isotopes have different sensitivity to a gravitational scalar field. In such a framework, a null for isotope  $A$  does not constrain isotope  $B$ .

The purpose of this paper is not to resurrect the Jenkins–Fischbach claims. It is to develop a quantitative framework for computing isotope-specific nuclear sensitivity coefficients, to map existing null results onto the resulting parameter space, and to identify the most sensitive targets for future measurements that could detect—or definitively exclude—composition-dependent scalar coupling to nuclear decay rates at the  $10^{-6}$ – $10^{-7}$  level.

## II. THEORETICAL FRAMEWORK

### A. Scalar-field coupling to fundamental constants

We work within a scalar-field framework in which a gravitational potential  $\psi$  couples to fundamental constants through distinct Standard Model channels [15, 17, 18]:

$$\frac{\delta\alpha}{\alpha} = k_\alpha \delta\psi, \quad \frac{\delta X_q}{X_q} = k_q \delta\psi, \quad (1)$$

where  $\alpha$  is the fine-structure constant,  $X_q \equiv m_q/\Lambda_{\text{QCD}}$ , and  $k_\alpha, k_q$  are channel coupling constants. Composition-dependent coupling is a generic feature of scalar-tensor theories [17, 18], but the numerical values of  $k_\alpha$  and  $k_q$  are model-dependent. As a concrete benchmark we adopt DFD values [15]:  $k_\alpha = \alpha^2/(2\pi) \approx 8.5 \times 10^{-6}$  and  $k_q = \alpha_s^2/(2\pi) \approx 0.035$  (with  $\alpha_s = 0.47$ ). In the bounds analysis below,  $k_q$  is treated as a free parameter; the benchmark serves only to define a target sensitivity for future experiments. For Earth’s annual orbit, the solar potential variation is

$$|\Delta\psi_\odot| = \frac{GM_\odot}{c^2} \left( \frac{1}{r_{\text{peri}}} - \frac{1}{r_{\text{aph}}} \right) = 3.30 \times 10^{-10}, \quad (2)$$

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numerically identical to  $|\Delta\Phi_\odot/c^2|$  used in LPI tests [16].

### B. Nuclear sensitivity coefficients

The fractional change in decay rate  $\lambda_I$  is

$$\frac{\delta\lambda_I}{\lambda_I} = K_I \delta\psi = (k_\alpha \kappa_\alpha^{(I)} + k_q \kappa_q^{(I)}) \delta\psi, \quad (3)$$

where  $\kappa_\alpha^{(I)}$  and  $\kappa_q^{(I)}$  encode the nuclear-physics sensitivity. Following Flambaum and collaborators [19–21]:

*a. Beta decay.* For a transition with  $Q$ -value  $Q$  and phase-space power  $n$  ( $n = 5$  allowed,  $n = 7$  first-forbidden,  $n = 9$  second-forbidden),

$$\kappa_q^{(\beta)} = n \frac{\delta E_r}{Q}, \quad (4)$$

where  $\delta E_r \approx 10$  MeV is Flambaum’s estimate for a generic nuclear level shift per unit  $\delta X_q/X_q$  [19]. The electromagnetic sensitivity is  $\kappa_\alpha^{(\beta)} = n |\Delta E_C|/Q$ , where  $\Delta E_C$  is the parent–daughter Coulomb energy difference.

The  $1/Q$  dependence is the key structural prediction: low- $Q$  transitions are dramatically more sensitive. This is the same near-degeneracy mechanism that makes the  $^{229}\text{Th}$  isomer (8.4 eV) sensitive at the  $10^4$  level [22] and the  $^{150}\text{Sm}$  compound resonance (0.1 eV) sensitive at  $10^8$  [19].

*b. Alpha decay.* The Gamow penetration factor gives  $\kappa_\alpha^{(\alpha)} = 2\pi\eta$  and  $\kappa_q^{(\alpha)} = 2\pi\eta \delta E_r/V_B$ , where  $\eta$  is the Sommerfeld parameter and  $V_B \approx 30$  MeV the barrier height.

These estimates carry systematic uncertainties of a factor  $\sim 2$ – $3$  from nuclear matrix elements not captured by the simple  $Q$ -value scaling.

### III. SENSITIVITY RANKING AND EXISTING BOUNDS

Table I presents computed sensitivity coefficients for all eight isotopes in the experimental record. Figure 1 shows the ranking graphically. Figure 2 displays the  $Q$ -value correlation.

#### A. What the bounds constrain

The critical observation is that existing null results constrain *different* regions of the sensitivity parameter space. We define an effective coupling  $k_q^{\text{eff}} \equiv k_q \times f_{\text{enh}}$ , where  $f_{\text{enh}} \geq 1$  absorbs any nuclear resonance enhancement beyond the generic Flambaum estimate  $\delta E_r \approx 10$  MeV. An experimental upper limit  $(\delta\lambda/\lambda)_{\text{max}}$  on isotope  $I$  constrains  $k_q^{\text{eff}} < (\delta\lambda/\lambda)_{\text{max}}/(\kappa_q^{(I)} |\Delta\psi_\odot|)$ . The existing bounds give:

### Nuclear Sensitivity Ranking

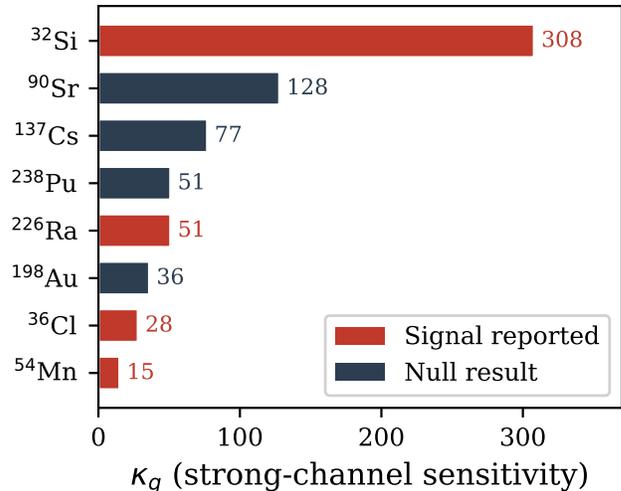


FIG. 1. Strong-channel sensitivity  $\kappa_q$  for all eight isotopes. The ranking is driven by  $Q$ -value. Note that no isotope with  $\kappa_q > 100$  has been measured with environmentally-controlled modern apparatus at  $< 10^{-5}$  sensitivity. The highest-sensitivity isotope in the experimental record ( $^{32}\text{Si}$ ) was measured with 1980s gas-counting technology in an uncontrolled environment [10, 12].

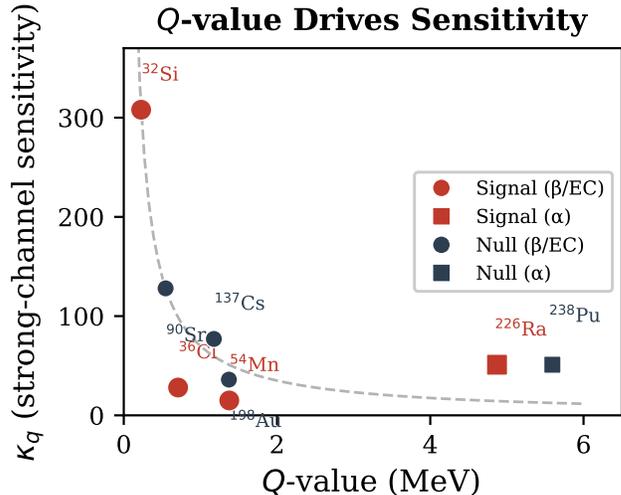


FIG. 2. Strong-channel sensitivity  $\kappa_q$  versus  $Q$ -value. Circles:  $\beta^-/\text{EC}$ ; squares:  $\alpha$ . The dashed curve shows  $\kappa_q = 7 \times 10 \text{ MeV}/Q$ . The tightest null bounds (Gran Sasso  $^{137}\text{Cs}$ , PTB  $^{90}\text{Sr}$ ) probe intermediate-sensitivity isotopes; the highest-sensitivity region ( $Q < 0.3$  MeV) remains unexplored with modern techniques.

- The Gran Sasso  $^{137}\text{Cs}$  bound ( $< 5 \times 10^{-5}$  at  $\kappa_q = 77$ ) constrains  $k_q^{\text{eff}} < 2 \times 10^3$ .
- The PTB  $^{90}\text{Sr}$  bound ( $< 8 \times 10^{-5}$  at  $\kappa_q = 128$ ) constrains  $k_q^{\text{eff}} < 2 \times 10^3$ .

TABLE I. Nuclear sensitivity coefficients and existing experimental bounds. The predicted modulation  $\delta\lambda/\lambda = K_I |\Delta\psi_\odot|$  uses  $k_\alpha = 8.5 \times 10^{-6}$  and  $k_q = 0.035$  as a DFD-motivated benchmark (not a generic scalar-tensor prediction; see text). Experimental bounds are upper limits from the references cited; the  $^{32}\text{Si}$  and  $^{226}\text{Ra}$  entries list the *claimed* amplitudes, which are now attributed to environmental systematics [10, 11].

Isotope	Decay type	$Q$ (MeV)	$\kappa_q$	Baseline $\delta\lambda/\lambda$	Expt. bound	Status	Source
$^{32}\text{Si}$	$\beta^-$ , 1st forb. uniq.	0.227	308	$3.6 \times 10^{-9}$	$\sim 10^{-3}$ (syst.) <sup>†</sup>	Artifact	[10]
$^{90}\text{Sr}$	$\beta^-$ , 1st forb. uniq.	0.546	128	$1.5 \times 10^{-9}$	$< 8 \times 10^{-5}$	Null	[8]
$^{137}\text{Cs}$	$\beta^-$ , 2nd forbidden	1.176	77	$8.9 \times 10^{-10}$	$< 5 \times 10^{-5}$	Null	[9]
$^{226}\text{Ra}$	$\alpha$	4.871	51	$5.9 \times 10^{-10}$	$\sim 10^{-3}$ (syst.) <sup>†</sup>	Artifact	[10]
$^{238}\text{Pu}$	$\alpha$	5.593	51	$5.9 \times 10^{-10}$	$< 3 \times 10^{-4}$	Null	[6]
$^{198}\text{Au}$	$\beta^-$ , allowed	1.372	36	$4.2 \times 10^{-10}$	$< 2 \times 10^{-4}$	Null	[7]
$^{36}\text{Cl}$	$\beta^-$ , 2nd forbidden	0.709	28	$3.3 \times 10^{-10}$	$\sim 5 \times 10^{-4}$ (syst.) <sup>†</sup>	Artifact	[10]
$^{54}\text{Mn}$	EC, allowed	1.377	15	$1.7 \times 10^{-10}$	Not bounded <sup>‡</sup>	Open	[2]

<sup>†</sup>Claimed detection, now attributed to humidity/temperature systematics by Pommé *et al.* [10, 11].

<sup>‡</sup>The  $^{54}\text{Mn}$  flare-precursor claim [2] is a single event; later searches found no flare–decay correlation for other isotopes [3]. Not a robust bound.

- The Cassini  $^{238}\text{Pu}$  bound ( $< 3 \times 10^{-4}$  at  $\kappa_q = 51$ ) constrains  $k_q^{\text{eff}} < 2 \times 10^4$ .

None of these constrain  $k_q^{\text{eff}}$  below  $\sim 10^3$ . A measurement of  $^{32}\text{Si}$  ( $\kappa_q = 308$ ) at  $10^{-6}$  would constrain  $k_q^{\text{eff}} < 10$ , pushing into the theoretically interesting regime for the first time. A measurement of  $^{187}\text{Re}$  ( $\kappa_q \approx 19,000$ ) at  $10^{-6}$  would constrain  $k_q^{\text{eff}} < 0.2$ —directly probing the benchmark coupling scale adopted in this framework.

## B. The status of the original positive claims

The original BNL  $^{32}\text{Si}$  and Ohio State  $^{36}\text{Cl}$  datasets, which launched the entire debate, are now understood to be contaminated by environmental systematics. Pommé *et al.* [10] showed that the  $^{32}\text{Si}$  decay rate variations inversely correlate with dew point at a nearby weather station, and that similar humidity-driven effects explain the  $^{36}\text{Cl}$  data. Pommé and Pelczar [11] extended this analysis to  $^{90}\text{Sr}/^{90}\text{Y}$  and  $^{60}\text{Co}$ , finding humidity correlations in those datasets as well. The PTB  $^{226}\text{Ra}$  data were originally ratioed against  $^{152}\text{Eu}$ , a technique that Schrader [14] showed is sensitive to measurement-technique choices.

We therefore treat the original  $\sim 10^{-3}$  claims as artifacts. The question we address is not whether those specific signals were real, but whether composition-dependent scalar coupling at the  $10^{-6}$ – $10^{-7}$  level—below all existing bounds—could exist and how it would be detected.

## IV. QUALITATIVE FEATURES OF SCALAR COUPLING

If a scalar-field coupling to nuclear decay rates exists at any level, several qualitative features follow from the

framework:

1. **Phase:** Maximum rate at perihelion (deepest  $\psi$ ). This is a generic prediction of any solar-potential coupling.
2. **Periodicity:** Annual from  $1/r_{\oplus-\odot}$ . Sub-annual periodicities (e.g., 33-day) would require asphericity in the solar mass distribution, which is speculative.
3. **Composition dependence:** Different isotopes couple differently through  $K_I = k_\alpha \kappa_\alpha^{(I)} + k_q \kappa_q^{(I)}$ . This is the central testable prediction and has not been directly probed.
4. **Scalar mechanism:** The coupling proceeds through  $\psi$ , not through neutrinos. This resolves the mechanistic difficulties of the original neutrino hypothesis [1].

We note that the 33-day periodicity claimed by Sturrock *et al.* [5] and the  $^{54}\text{Mn}$  flare-precursor event [2] are suggestive but not established. Later searches found no correlation between major solar flares and decay rates in monitored isotopes [3], and the 33-day signal in the BNL data may be an artifact of the same environmental contamination that produces the annual modulation [10]. We do not treat these as confirmed features.

## V. THE AMPLITUDE LANDSCAPE

Figure 3 shows the amplitude landscape. Three regimes are relevant:

**Above  $10^{-4}$ :** Excluded for all tested isotopes. The original  $\sim 10^{-3}$  claims are environmental artifacts [10].

**$10^{-5}$ – $10^{-4}$ :** Excluded for  $^{137}\text{Cs}$ ,  $^{90}\text{Sr}$ , and  $^{198}\text{Au}$ . Not excluded for  $^{32}\text{Si}$ ,  $^{36}\text{Cl}$ , or any isotope with  $\kappa_q > 200$ , because these have never been measured with adequate environmental control at this sensitivity.

### Amplitude Gap: Three Scenarios

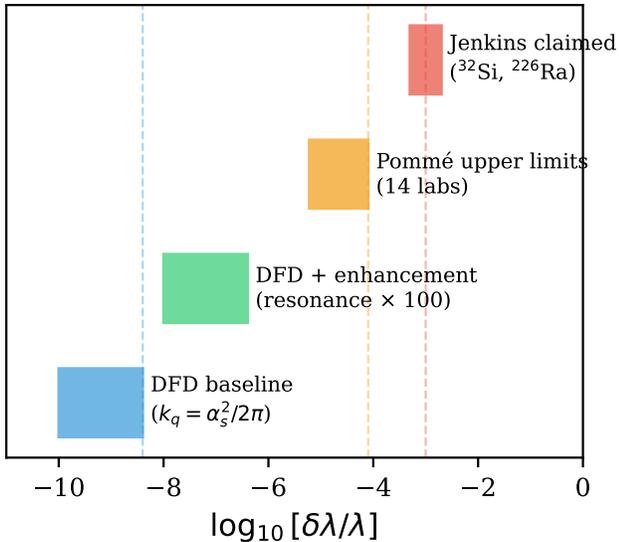


FIG. 3. Amplitude landscape for annual decay-rate modulation. Red: original Jenkins claims (now attributed to systematics). Orange: tightest existing null bounds (Pommé, Gran Sasso). Blue: baseline scalar-coupling prediction with  $k_q = \alpha_s^2/(2\pi)$ . Green: prediction with nuclear resonance enhancement ( $\times 100$ ). The experimentally unexplored window between  $10^{-7}$  and  $10^{-5}$  is where a composition-dependent signal could reside.

**Below  $10^{-5}$ :** Unexplored for all isotopes in the dataset. This is the regime where baseline scalar-coupling predictions ( $10^{-9}$ – $10^{-7}$ ) and modestly enhanced predictions ( $10^{-7}$ – $10^{-5}$ ) reside.

The key point is that the highest-sensitivity isotopes ( $^{32}\text{Si}$ ,  $^{90}\text{Sr}$ ) have never been measured at the  $10^{-6}$  level with modern environmentally-controlled apparatus. The tightest bounds come from intermediate-sensitivity isotopes ( $^{137}\text{Cs}$ ,  $^{198}\text{Au}$ ). The parameter space for composition-dependent coupling in low- $Q$  transitions at amplitudes below current isotope-specific bounds remains open.

## VI. CONNECTION TO ATOMIC CLOCK TESTS

The same multi-channel coupling structure applies at the atomic scale. Atomic clock comparisons searching for annual modulation of frequency ratios in the solar gravitational potential constrain the coupling constants  $k_\alpha$  and  $k_c$  (composition-dependent) [16].

The most stringent constraint on  $\alpha$ -coupling to gravity comes from the PTB  $\text{Yb}^+$  E3/E2 measurement by Filzinger *et al.* [27], who searched for oscillations in the E3/E2 frequency ratio at periods set by ultralight dark matter candidates and also improved limits on coupling of  $\alpha$  to gravitational potential. From their long-term

E3/E2 dataset they report  $c^2\alpha^{-1} d\alpha/d\Phi = (-2.4 \pm 3.0) \times 10^{-9}$ , corresponding to  $|k_\alpha| \lesssim 5 \times 10^{-9}$  at  $2\sigma$ . Because both transitions occur in the same ion, composition-dependent effects cancel, making this a clean probe of the  $\alpha$ -channel alone.

Cross-species comparisons (e.g., Cs/Sr, H/Cs) probe a *different* combination of couplings:  $k_\alpha \Delta\kappa_\alpha + k_c \Delta C$ . If composition-dependent coupling exists, it would appear in cross-species ratios but vanish in same-ion comparisons—a distinctive pattern. The Cs/Sr channel, with  $\Delta\kappa_\alpha = 2.77$  [25, 26], offers the largest  $\alpha$ -lever arm among operational clock pairs and has not been searched for annual solar-potential modulation at the required sensitivity.

This establishes a structural parallel: the nuclear sensitivity hierarchy ( $\kappa_q^{(I)}$  varying by isotope) mirrors the atomic sensitivity hierarchy ( $\kappa_\alpha^{(i)}$  varying by species). Both predict composition dependence as the distinguishing signature. We include this discussion not because the atomic-clock bounds enter the nuclear-sector derivation, but because the same coupling structure and the same annual  $\Delta\psi_\odot$  connect the two sectors, and progress in either informs the other.

## VII. DECISIVE FUTURE TESTS

We identify five measurements that would either detect or definitively constrain composition-dependent scalar coupling at the benchmark scale:

1.  **$^{187}\text{Re}$**  ( $Q = 2.64$  keV [24],  $\beta^-$ ,  $t_{1/2} = 4.12 \times 10^{10}$  yr [24]): The lowest  $Q$ -value of any known  $\beta$  emitter gives  $\kappa_q \approx 19,000$ . A half-life measurement at fractional precision  $10^{-6}$ , repeated at different orbital phases, would constrain  $k_q^{\text{eff}} < 0.2$ —directly probing the theoretically interesting regime. The long half-life makes direct counting impractical, but calorimetric techniques (as developed for KATRIN-type experiments) or mass-spectrometric approaches may be feasible.
2.  **$^{229}\text{Th}$  nuclear clock:** The 8.4 eV isomeric transition achieves Flambaum’s enhancement  $K \sim 10^4$  [22]. Recent observation of the radiative decay [23] and ongoing efforts toward direct laser excitation make this platform increasingly realistic. Once operational at  $10^{-18}$  fractional precision, it constrains  $k_q$  to  $\sim 10^{-4}$ , four orders of magnitude beyond any existing nuclear-sector bound.
3.  **$^{32}\text{Si}$  remeasurement:** Repeating the BNL measurement with modern pulse-counting apparatus in a temperature- and humidity-controlled environment at  $10^{-6}$  sensitivity. This directly addresses the Pommé critique [10]: if the modulation persists when environmental systematics are eliminated, it is physical; if it vanishes, the debate is closed for this isotope.

4. **Multi-isotope ratio test:** Simultaneously monitoring two isotopes with different  $\kappa_q$  in the same detector or facility. The ratio of any annual modulations should equal  $K_A/K_B$  if the coupling is real, and zero if both signals are environmental artifacts (which affect both equally). This eliminates systematics by design and directly probes composition dependence.
5. **Cross-species atomic clock campaign:** A dedicated search for annual modulation of the Cs/Sr or Rb/Sr frequency ratio over a full orbital cycle, analyzed specifically for solar-potential correlation. A detection would establish the composition-dependent coupling at the atomic scale; a null at the  $10^{-6}$  level constrains  $k_c \Delta C$  below existing bounds.

## VIII. DISCUSSION

### A. What is and is not claimed

We do *not* claim that the original Jenkins–Fischbach signals are real. The Pommé dew-point analysis [10, 11] provides a compelling environmental explanation for the BNL and Ohio State datasets, and the PTB data are similarly suspect [14].

What we do claim is: (i) Scalar-tensor theories predict composition-dependent coupling as a generic feature, not a special case. (ii) The Flambaum formalism provides a quantitative hierarchy of nuclear sensitivities driven by  $Q$ -value. (iii) Existing null results constrain intermediate-sensitivity isotopes but leave the highest-sensitivity region ( $\kappa_q > 200$ ) unexplored at better than  $10^{-4}$ . (iv) Specific future measurements ( $^{187}\text{Re}$ ,  $^{229}\text{Th}$ ,  $^{32}\text{Si}$  remeasurement, multi-isotope ratio) can probe the benchmark coupling scale for the first time.

### B. Falsification criteria

The framework of composition-dependent scalar coupling to nuclear decay rates is falsified if: (a)  $^{32}\text{Si}$  shows no modulation at  $10^{-6}$  sensitivity with modern apparatus, *and* (b)  $^{187}\text{Re}$  shows no effect at  $10^{-6}$ , *and* (c) the

$^{229}\text{Th}$  nuclear clock shows no anomalous annual shift at  $10^{-18}$  precision. Individually, each null constrains  $k_q^{\text{eff}}$ ; collectively, they would exclude composition-dependent coupling at the benchmark scale and below.

## IX. CONCLUSION

The decade-long debate over solar-modulated nuclear decay rates has been largely settled at the phenomenological level: the original  $\sim 10^{-3}$  signals are almost certainly environmental artifacts. But the *theoretical* question—whether nuclear decay rates couple to gravitational environment through composition-dependent scalar fields—remains open for the highest-sensitivity low- $Q$  isotopes at amplitudes below current isotope-specific bounds, because the experimental program that closed the debate tested different isotopes at sensitivities ( $10^{-5}$ – $10^{-4}$ ) that do not probe the benchmark coupling scale ( $10^{-7}$ – $10^{-6}$ ) in the most sensitive transitions.

The Flambaum nuclear sensitivity formalism provides a rigorous hierarchy:  $\kappa_q \propto n/Q$ , with  $^{32}\text{Si}$ ,  $^{187}\text{Re}$ , and  $^{229}\text{Th}$  at the top. The decisive next step is not to reanalyze old data, but to perform new measurements of the highest-sensitivity isotopes with environmentally-controlled modern apparatus. The multi-isotope ratio test we propose eliminates systematics by design and directly probes the composition-dependent signature that distinguishes scalar coupling from environmental contamination.

If the coupling exists at the benchmark scale, the  $^{229}\text{Th}$  nuclear clock will find it. If it does not, the same measurements will set the most stringent bounds on scalar-field coupling to nuclear structure ever achieved. Either outcome advances fundamental physics.

## ACKNOWLEDGMENTS

We acknowledge V. V. Flambaum for the nuclear sensitivity framework upon which the isotope-specific calculations rely, J. H. Jenkins and E. Fischbach for identifying the anomaly that motivated this analysis, and S. Pommé and collaborators for the rigorous environmental reanalyses that clarified the status of the original datasets.

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