The QCD Mass Problem in ACT and Its Resolution: From the Yukawa Vertex to the Stress-Energy Coupling

A Working Note

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Abstract

The Mathematical Supplement derives the Anchored Causality Theory (ACT) mass-squared anchoring rate, $\Gamma_{\text{anchor}} \propto m_f^2$, from the Higgs Yukawa vertex. This note identifies a problem with that derivation: approximately 90% of the mass of a nucleon—and hence of any atom or molecule used in the isotope test—originates in QCD binding energy, not in Higgs Yukawa couplings. As written, the Yukawa-vertex derivation does not support the flagship ^{12}C/^{13}C prediction. We diagnose the root cause (the Yukawa vertex is dynamically inert in ACT's own framework), and resolve it by relocating the anchoring coupling from the Yukawa vertex to the energy-momentum tensor T^{00}: anchoring couples to *total inertial mass-energy*. For the gravitational realization of the channel, the equivalence principle then guarantees, by symmetry rather than by approximation, that QCD binding energy anchors at the same rate as Yukawa-generated mass; for the postulated universal channel, the same universality is part of the channel hypothesis rather than a theorem. The isotope prediction survives intact and is in fact sharpened: the benchmark ratio becomes a direct function of measured atomic masses, $(13.003355/12)^2 = 1.1742$—exact in the coherent long-wavelength limit, before form-factor, momentum-transfer, and bath-spectrum corrections. The Higgs field's role is clarified rather than diminished: it remains the structural enabler of mass (Layer 1), consistent with ACT's three-layer doctrine, but the anchoring vertex itself is the universal coupling of mass-energy to environmental fields. The note states honestly what this costs: ACT's mass channel is now an explicit postulate of a universal T^{00}-coupled environmental channel (with gravity as its only Standard-Model realization), rather than a derived consequence of electroweak structure.

1 The Problem

1.1 The derivation as it stands

The Mathematical Supplement (May 2026) derives the mass dependence of the anchoring rate from the Higgs Yukawa interaction. After electroweak symmetry breaking, the physical Higgs couples to a fundamental fermion f as

$$\mathcal{L}_{\text{int}} = -\frac{m_f}{v}\,\bar{f}\,h\,f, \qquad v \approx 246 \text{ GeV}, \tag{1}$$

so the vertex strength is $\propto m_f$ and the squared coupling is $\propto m_f^2$. The anchoring rate inherits this factor,

$$\Gamma_{\hat{\mathcal{O}}_{\text{bath}}} = \frac{m_f^2}{\hbar^2}\int_0^\infty d\omega\, S_{\text{bath}}(\omega)\, J_{\hat{\mathcal{O}}_{\text{bath}}}(\omega), \tag{2}$$

and the flagship prediction follows: for isotopologues of masses m_1, m_2 in identical environments, $\Gamma(m_1)/\Gamma(m_2) = (m_1/m_2)^2$.

1.2 Why the derivation fails for composite matter

Equation (1) is a statement about *fundamental fermions*. The isotope test is performed on atoms and molecules, whose mass is overwhelmingly *not* of Yukawa origin. Lattice QCD decompositions of the proton mass via the QCD energy-momentum tensor (Yang et al., *Phys. Rev. Lett.* **121**, 212001 (2018)) give, at $\overline{\text{MS}}$ scale 2 GeV, approximately:

Contribution to m_p	Fraction
Quark condensate (Yukawa-origin quark masses)	$\sim 9\%$
Quark kinetic/potential energy	$\sim 32\%$
Gluon field energy	$\sim 37\%$
QCD trace anomaly	$\sim 23\%$

About 90% of nucleon mass is confined QCD field energy. The ^{12}C–^{13}C mass difference is one neutron, ≈ 939.6 MeV, of which only $\mathcal{O}(10\text{ MeV})$ traces to the Higgs mechanism. If the anchoring coupling were literally the sum of constituent Yukawa vertices, the mass-mediated channel would see only the Yukawa-origin fraction, the predicted isotope differential would be suppressed by roughly two orders of magnitude, and—worse—it would no longer be a clean function of the total atomic masses. The 17% prediction would be unsupported by the theory's own mechanism.

Two attempted rescues fail or fall short:

(a) Effective Higgs–nucleon coupling. One might replace the constituent-quark Yukawa sum with the effective Higgs–nucleon vertex $g_{hNN} = f_N\, m_N/v$, $f_N \approx 0.3$, familiar from dark-matter direct detection, in which heavy-quark loops couple the Higgs to the gluon condensate. This restores *approximate* proportionality of coupling to total nucleon mass. But it inherits two defects. First, f_N is a hadronic matrix element, not exactly universal: it differs between proton and neutron and is blind to nuclear binding energy (~ 7–8 MeV per nucleon, which differs between ^{12}C and ^{13}C). The composition-independence of the prediction would hold only approximately, to uncontrolled hadronic accuracy. Second—decisively—it does not address the deeper problem of §2.

(b) Restriction to fundamental fermions. ACT could retreat to claiming m^2 scaling only for elementary particles. This is internally consistent but empirically sterile: there is no practical interferometric mass-comparison experiment on isolated fundamental fermions in identical environments. The flagship test would be lost.

2 Diagnosis: The Yukawa Vertex Is Dynamically Inert

The deeper issue is structural, and ACT's own three-layer doctrine already contains it. The Supplement correctly states that the Higgs field is *not* the bath: the Higgs boson is gapped at 125 GeV, with correlation time $\sim 10^{-26}$ s, and contributes no infrared modes to the quantum Brownian motion kernels. All dynamical decoherence is carried by environmental gauge fields, phonons, and thermal modes. But then the Yukawa vertex (1), which connects matter to the *Higgs* field, never appears in the influence functional at all. No Higgs propagator enters the noise kernel $N(\tau)$ or the dissipation kernel $\gamma(\tau)$. A vertex that does not enter the Schwinger–Keldysh effective action cannot lend its coupling constant to the anchoring rate. The m_f^2 prefactor in Eq. (2) was inherited from a vertex that does no dynamical work—a residue, we suggest, of the earlier (corrected) Higgs-as-bath picture.

What *does* enter the kernels is the inertial mass m in the system's kinetic term $\hat{p}^2/2m$: it controls wavepacket dispersion, recoil, and current histories. But these dynamical entries of mass are channel-specific and do not produce a universal m^2. For example, heavier wavepackets disperse *more slowly* ($\sigma_x(t) \sim \hbar t/m\sigma_0$), making them *less* distinguishable to position-monitoring environments—a negative mass dependence; collisional (Joos–Zeh) rates are governed by scattering cross sections, nearly independent of the heavy particle's mass; electromagnetic channels couple to *charge*, which is identical between isotopologues. A universal m^2 scaling cannot be assembled from dynamical mass dependences. It can only come from a coupling constant at the vertex that is itself proportional to mass.

The question that decides the theory is therefore: *to what conserved quantity does the anchoring environment couple?*

3 Resolution: Anchoring Couples to the Stress-Energy Tensor

3.1 The coupling

There is exactly one current in physics that is (i) proportional to total inertial mass-energy, (ii) exactly composition-blind, counting QCD binding energy, Yukawa mass, nuclear binding, and thermal excitation identically, and (iii) conserved as a matter of principle: the energy-momentum tensor $T^{\mu\nu}$. We therefore replace the Yukawa vertex as the origin of the anchoring coupling with

$$H_{\text{int}} = \int d^3x \, T^{00}(x) \, \Phi_{\text{env}}(x, t), \tag{3}$$

where Φ_{env} is the environmental field component that couples to mass-energy density. For a system localized near position $\hat{x}$ with total rest energy Mc^2, the gradient expansion of (3) gives

$$H_{\text{int}} \approx Mc^2 \, \Phi_{\text{env}}(0, t) \; + \; Mc^2 \, \hat{x} \cdot \nabla \Phi_{\text{env}}(0, t) \; + \; \cdots \tag{4}$$

The first term is a global phase; the second is precisely the QBM form $H_{\text{int}} = \hat{\mathcal{O}} \otimes \hat{X}$ of the Supplement, with system operator $\hat{\mathcal{O}} = \hat{x}$ and coupling constant proportional to M. The anchoring rate of the Supplement's Eq. (20) is then reproduced with one substitution:

$$\boxed{\Gamma_{\hat{\mathcal{O}}_{\text{bath}}} = \frac{M^2}{\hbar^2} \int_0^\infty d\omega \; S_{\text{bath}}(\omega) \, J_{\hat{\mathcal{O}}_{\text{bath}}}(\omega), \qquad M = \text{total inertial mass},} \tag{5}$$

where M now includes QCD field energy, trace anomaly, nuclear and chemical binding—everything that gravitates and everything that resists acceleration. The M^2 appears for the same structural reason as before (squared coupling at the vertex), but the vertex is now one that actually appears in the influence functional.

3.2 Composition-independence is now exact, not approximate

The equivalence principle guarantees that inertial mass equals gravitational mass—i.e., that T^{00} counts all forms of internal energy identically—to the precision of the best Eötvös-type experiments. The MICROSCOPE final results (*Phys. Rev. Lett.* **129**, 121102 (2022)) bound composition-dependent violations at the 10^{-15} level. Under the coupling (3) in its gravitational realization, the isotope benchmark is therefore protected by a symmetry, not by a hadronic approximation (for the postulated universal channel, this universality is hypothesis, not theorem): the ratio

$$\frac{\Gamma(^{13}\mathrm{C})}{\Gamma(^{12}\mathrm{C})} = \left(\frac{M_{13}}{M_{12}}\right)^2 = \left(\frac{13.003355}{12.000000}\right)^2 = 1.1742 \tag{6}$$

is now an exact function of *measured atomic masses*—a stronger and cleaner statement than the original $(13/12)^2 = 1.174$, which implicitly assumed integer nucleon-number scaling (a CSL habit, not an ACT necessity).

3.3 The differential protocol as a channel filter

The reframing sorts the decoherence channels cleanly:

- **Charge-coupled channels** (photon scattering, blackbody, van der Waals, collisional): couple to j^μ_{EM}, polarizability, and cross sections—identical between isotopologues to high accuracy. These constitute Γ_{bkg} and *cancel* in the differential measurement.
- **Mass-coupled channel** (Eq. (3)): couples to T^{00}—differs between isotopologues exactly as M^2. This is the surviving signal.

The isotope experiment is thus not merely a noise-subtraction trick: it is a *projector onto the T^{00}-coupled channel*. Any residual differential signal, after charge-coupled systematics are controlled, is a direct measurement of the universal mass-energy coupling α_{eff}. This sharpens the experimental logic of the Supplement's Sec. 4 without changing its design.

3.4 The role of the Higgs, clarified

This resolution does not diminish the Higgs field's place in ACT; it completes the correction that the three-layer framework began. The Higgs remains **Layer 1, structural**: it generates the masses of the fundamental fermions, without which there are no stable bound states, no rest frames, no proper time, and nothing for T^{00} to accumulate. But the Higgs was never the bath (Layer 2), and—we now make explicit—it is not the anchoring vertex either. The anchoring vertex is the universal coupling of accumulated mass-energy to the environment. One sentence summarizes the revised doctrine:

> *The Higgs makes mass possible; QCD makes most of it; T^{00} is what anchors.*

4 Two Realizations of the T^{00} Channel

Equation (3) requires an environmental field that couples to mass-energy. Within established physics there is exactly one: gravity. ACT can take either of two positions, and this note recommends stating both explicitly in the manuscripts.

Variant G (gravitational bath). Φ_{env} is the gravitational potential sourced by environmental matter and its thermal fluctuations. This variant is maximally conservative—no new fields—and connects ACT to an existing literature with exactly the required structure: the Diósi–Penrose rate $\Gamma_{\mathrm{DP}} \sim GM^2 f(\text{geometry})/\hbar$ scales as M^2 in total mass, and gravitational time-dilation dephasing (Pikovski et al., *Nature Physics* **11**, 668 (2015)) couples to total internal energy, i.e., to T^{00}. These works serve as existence proofs that T^{00}-coupled decoherence channels are theoretically well-formed and automatically composition-blind. The cost: gravitational rates are calculable and small, and the parameter-free Diósi–Penrose model is already strongly constrained by underground radiation-emission searches (Donadi et al., *Nature Physics* **17**, 74 (2021)). ACT's Variant G differs from DP—it is fluctuation-dissipation consistent and predicts no spontaneous radiation at the DP rate—but a referee will require this distinction to be worked out quantitatively before Variant G can claim to evade the Donadi bound.

Variant U (universal postulated channel). Φ_{env} is a T^{00}-coupled environmental channel whose strength α_{eff} is not fixed by gravity and is to be measured. This is ACT's distinctive physical postulate. Its epistemic status should be stated plainly: like CSL's (λ_0, r_C), α_{eff} is a free parameter; *unlike* CSL, the channel is constructed within the Schwinger–Keldysh formalism with noise and dissipation paired by the fluctuation-dissipation theorem, so it conserves energy in the appropriate limit and predicts a sharp, parameter-free *ratio* (6) even while the absolute rate is unknown.

Stage 1 of the experimental program (a differential bound at current sensitivity) constrains α_{eff} under Variant U and tests the quantitative escape of Variant G simultaneously.

5 What This Changes in the Manuscripts

1. **Math Supplement, Sec. 1.2(iii) ("Mass-mediated interaction"):** Replace the Yukawa vertex (1) as the origin of the coupling with the T^{00} coupling (3); retain the Yukawa discussion as the Layer-1 structural account of why fundamental fermions are massive. Replace $m_f^2 \to M^2$ in Eqs. (8) and (20) and in the boxed master equation's rate.
2. **Math Supplement, Sec. 3:** Replace $(13/12)^2$ with the exact atomic-mass ratio (6); add the channel-filter framing of the differential protocol.
3. **FoP manuscript (ACT v2.0):** Revise the mechanism chapter accordingly; add the Variant G / Variant U distinction and the Donadi-bound discussion. Soften "derived from electroweak structure" to "constructed within the Schwinger–Keldysh formalism with one universal coupling to be measured."
4. **PRL Letter:** The prediction table gains a line: CSL scales with nucleon number N; ACT scales with total inertial mass M — distinguishable in principle via species where M/N differs (binding-energy gradients across the nuclear chart), a second-generation discriminator beyond the isotope test.
5. **Born rule section:** Unchanged. The M^2 factors cancel between same-species outcomes exactly as before.

6 Honest Accounting

What is gained: the flagship prediction is rescued from a derivation that could not support it, the composition-independence of the isotope ratio is promoted from hadronic approximation to exact symmetry protection, the prediction becomes an exact function of measured masses, the three-layer doctrine becomes fully self-consistent (no inert vertex doing phantom work), and a new second-generation discriminator (mass vs. nucleon number) appears for free.

What is conceded: ACT's mass channel is not a parameter-free consequence of the Standard Model. Variant G is established physics but quantitatively threatened by existing constraints until the FDT distinction from Diósi–Penrose is computed; Variant U is honest new physics with one free coupling. The slogan "ACT completes QFT without adding anything" must be refined to: *ACT adds the minimal universal channel consistent with the fluctuation-dissipation theorem—one coupling constant, one exact ratio prediction, falsifiable in two stages.* That is a weaker rhetorical claim and a stronger scientific one.

Summary

1. **Problem:** $\sim 90\%$ of atomic mass is QCD field energy; the Yukawa-vertex derivation of $\Gamma \propto m^2$ does not transfer to composite matter, and the vertex never enters the influence functional in any case.

2. **Resolution:** the anchoring coupling is to T^{00}—total inertial mass-energy. $\Gamma \propto M^2$ with M the measured mass; composition-independence is guaranteed by the equivalence principle (MICROSCOPE, 10^{-15}) for the gravitational realization, and is part of the channel hypothesis for the postulated universal channel.

3. **Prediction:** $\Gamma(^{13}\text{C})/\Gamma(^{12}\text{C}) = (13.003355/12)^2 = 1.1742$, now exact in atomic masses; differential protocol unchanged and reinterpreted as a projector onto the mass channel.

4. **Higgs:** structural Layer 1 only — *the Higgs makes mass possible; QCD makes most of it; T^{00} is what anchors.*

5. **Cost, stated plainly:** one universal coupling α_{eff} is postulated (Variant U) or identified with gravity and must then evade the Donadi bound (Variant G).