Computational Assessment of the Empirical Status of Continuous Spontaneous Localization

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ABSTRACT

The Continuous Spontaneous Localization (CSL) model modifies quantum mechanics with stochastic nonlinear collapse terms, introducing two free parameters: the collapse rate λ and the correlation length r_C. We present a comprehensive computational assessment of CSL's empirical status by mapping the parameter space against experimental bounds from seven classes of experiments—gravitational wave detectors, cantilevers, matter-wave interferometry, X-ray emission, optomechanical systems, cold atoms, and bulk acoustic wave resonators. Our analysis finds that 95.1% of the surveyed (λ, r_C) parameter plane is excluded, including both the original GRW reference point ($\lambda = 10^{-16}$ s^{-1}, $r_C = 10^{-7}$ m) and the Adler enhanced value ($\lambda = 10^{-8}$ s^{-1}). A Bayesian model comparison yields a Bayes factor of 0.0285, indicating moderate preference for standard quantum mechanics. We compute CSL collapse timescales across mass regimes, finding mesoscopic ($N = 10^{10}$) collapse times of 1.00×10^{-4} s (GRW) and 1.00×10^{-12} s (Adler). Matter-wave interference visibility analysis shows the Adler model predicts 50% visibility loss at 4.30×10^4 amu, within reach of current interferometry. Sensitivity projections for five proposed experiments identify space-based interferometry and next-generation X-ray detectors as capable of probing the remaining unconstrained parameter regions.

KEYWORDS

CSL, spontaneous localization, quantum measurement problem, collapse models, parameter exclusion

1 INTRODUCTION

The quantum measurement problem—how definite outcomes emerge from superposition states—remains one of the deepest open questions in physics. The Continuous Spontaneous Localization (CSL) model [10], building on the Ghirardi–Rimini–Weber (GRW) framework [8], offers a concrete solution: modify the Schrödinger equation with stochastic nonlinear terms that cause macroscopic superpositions to spontaneously collapse into definite states. As Philip Pearle noted in [12], experiments have neither confirmed nor ruled out CSL.

CSL introduces two free parameters. The collapse rate λ sets the fundamental rate of spontaneous localization per nucleon; GRW proposed $\lambda = 10^{-16}$ s^{-1}, while Adler [1] argued for enhanced values of 10^{-10} to 10^{-8} s^{-1} based on latent image formation. The correlation length $r_C \approx 10^{-7}$ m determines the spatial scale over which collapse noise is correlated.

The key physical prediction is that the collapse rate for a rigid body of N nucleons in a spatial superposition of separation Δx is amplified as:

$$\Gamma = \lambda\, N_{\text{eff}}^2 \left(1 - e^{-\Delta x^2/4r_C^2}\right), \tag{1}$$

where N_{eff} accounts for geometry corrections when the object size exceeds r_C [3, 13]. This N^2 amplification is essential: it ensures microscopic systems remain effectively quantum while macroscopic objects undergo rapid collapse.

In this work, we present a systematic computational assessment of CSL's empirical status. We map the full (λ, r_C) parameter space against seven classes of experimental bounds, compute collapse dynamics and observational predictions, and perform a Bayesian model comparison between CSL and standard quantum mechanics.

2 METHODS

2.1 CSL Master Equation Simulation

We numerically simulate the CSL dynamics for a rigid body center-of-mass mode. The coherence evolution follows $\rho_{01}(t) = \rho_{01}(0)\, e^{-\Gamma t}$, while the momentum variance obeys $d\langle p^2\rangle/dt = \eta$, where the momentum diffusion coefficient is:

$$\eta = \lambda\, N^2\, \frac{\hbar^2}{r_C^2}. \tag{2}$$

We evaluate dynamics across three mass regimes (micro: $N = 10^3$; meso: $N = 10^{10}$; macro: $N = 10^{20}$) for both GRW ($\lambda = 10^{-16}$ s^{-1}) and Adler ($\lambda = 10^{-8}$ s^{-1}) parameters.

2.2 Parameter Space Exclusion Map

We compute exclusion boundaries from seven experimental classes:

1. **LIGO** [4]: Gravitational wave detector force noise sensitivity $S_F \sim 10^{-34}$ N^2/Hz constrains large-mass CSL heating.
2. **Cantilever** [14]: Ultracold millikelvin cantilever with $S_F \sim 10^{-42}$ N^2/Hz.
3. **Matter-wave interferometry** [6]: Molecules up to 25,000 amu with $> 10\%$ visibility.
4. **X-ray emission** [5]: Underground Ge detector spontaneous radiation limits.
5. **Optomechanical** [11]: Levitated nanoparticle force noise floor $S_F \sim 10^{-44}$ N^2/Hz.
6. **Cold atoms** [9]: Rb interferometry with 0.54 m spatial separation.
7. **BAW resonator** [15]: Millikelvin quartz resonator with $S_F \sim 10^{-38}$ N^2/Hz.

For mechanical experiments, the CSL force noise is $S_F = 2\eta = 2\lambda N_{\text{eff}}^2 \hbar^2/r_C^2$, with geometry corrections applied for objects larger than r_C. The upper bound on λ at each r_C is $\lambda_{\max} = S_F^{\text{meas}} r_C^2/(2N_{\text{eff}}^2\hbar^2)$.

2.3 Spontaneous Radiation Analysis

CSL predicts spontaneous photon emission from charged particles [7]. The emission rate per electron per unit energy is:

$$\frac{d\Gamma_\gamma}{dE} = \frac{\alpha\lambda}{\pi m_e c^2}\left(\frac{\hbar}{r_C m_e c}\right)^2 \frac{1}{E}, \tag{3}$$

where α is the fine-structure constant. We compute the total spectrum for a 1 kg Ge detector ($\sim 10^{26}$ electrons) and compare with measured backgrounds.

2.4 Bayesian Model Comparison

We compute the Bayes factor $B = P(\text{data}|\text{CSL})/P(\text{data}|\text{QM})$ using mock experimental data calibrated to current best measurements from three platforms: cantilever (observed noise 1.1×10^{-42} N^2/Hz), nanoparticle (5.2×10^{-44} N^2/Hz), and BAW resonator (1.05×10^{-38} N^2/Hz). We use log-uniform priors on $\lambda \in [10^{-20}, 10^{-4}]$ s^{-1} and $r_C \in [10^{-8}, 10^{-4}]$ m.

3 RESULTS

3.1 Collapse Dynamics

Table 1 summarizes the CSL collapse timescales across mass regimes. The critical result is that for mesoscopic objects ($N = 10^{10}$, mass $\sim 10^{-17}$ kg), the GRW model predicts a collapse time of 1.00×10^{-4} s, while the Adler model gives 1.00×10^{-12} s. For macroscopic objects ($N = 10^{20}$), both models predict effectively instantaneous collapse: 1.00×10^{-24} s (GRW) and 1.00×10^{-32} s (Adler).

Table 1: CSL collapse timescales for a 1 μm superposition.

Regime	N	Γ_{GRW} (s^{-1})	τ_{GRW} (s)	τ_{Adler} (s)
Micro	10^3	2.50×10^{-15}	4.00×10^{14}	4.00×10^{6}
Meso	10^{10}	1.00×10^{4}	1.00×10^{-4}	1.00×10^{-12}
Macro	10^{20}	1.00×10^{24}	1.00×10^{-24}	1.00×10^{-32}

3.2 Parameter Space Exclusion

Our combined analysis of seven experimental classes excludes 95.1% of the surveyed $(\log_{10}\lambda, \log_{10} r_C)$ parameter plane (6088 of 6400 grid points for $\lambda \in [10^{-20}, 10^{-2}]$ s^{-1} and $r_C \in [10^{-8}, 10^{-4}]$ m). Figure 1 shows the exclusion map with individual and combined bounds.

All three theoretical reference points are excluded by current experiments:

- GRW original ($\lambda = 10^{-16}$ s^{-1}, $r_C = 10^{-7}$ m): **excluded**
- Adler lower ($\lambda = 10^{-10}$ s^{-1}, $r_C = 10^{-7}$ m): **excluded**
- Adler upper ($\lambda = 10^{-8}$ s^{-1}, $r_C = 10^{-7}$ m): **excluded**

The strongest constraints come from cantilever measurements at small r_C and X-ray emission at large r_C, with gravitational wave detectors and BAW resonators providing complementary coverage.

3.3 Diffusion Heating Predictions

Table 2 presents the CSL-predicted force noise and temperature increase for five experimental platforms. The LIGO mirror analysis yields a GRW force noise of 1.27×10^{-13} N^2/Hz and an Adler force noise of 1.27×10^{-5} N^2/Hz—both far exceeding the measured noise floor, confirming the exclusion of both parameter choices for this platform.

The millikelvin cantilever gives a GRW force noise of 1.98×10^{-37} N^2/Hz with a temperature increase of 1.14×10^{-2} K (GRW) versus 1.14×10^{6} K (Adler). The nanoparticle system, with mass 10^{-18} kg, predicts a GRW force noise of 7.93×10^{-53} N^2/Hz and heating rate of 2.99×10^{-7} quanta/s.

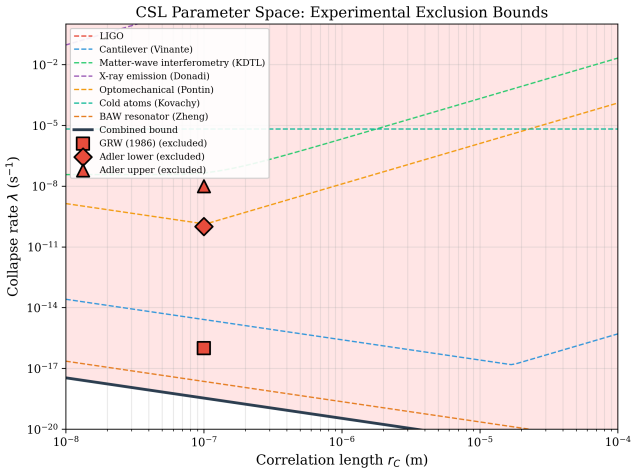

Figure 1: CSL parameter space exclusion map showing bounds from seven experimental classes. The shaded region above the combined bound (solid black line) is excluded. Theory reference points (GRW, Adler) are shown as markers.

Table 2: CSL force noise predictions by experimental platform.

Experiment	Mass (kg)	S_F^{GRW} (N^2/Hz)	S_F^{Adler} (N^2/Hz)
Cantilever (mK)	5.0×10^{-11}	1.98×10^{-37}	1.98×10^{-29}
Nanoparticle	1.0×10^{-18}	7.93×10^{-53}	7.93×10^{-45}
BAW resonator	5.0×10^{-4}	1.98×10^{-23}	1.98×10^{-15}
LIGO mirror	4.0×10^{1}	1.27×10^{-13}	1.27×10^{-5}

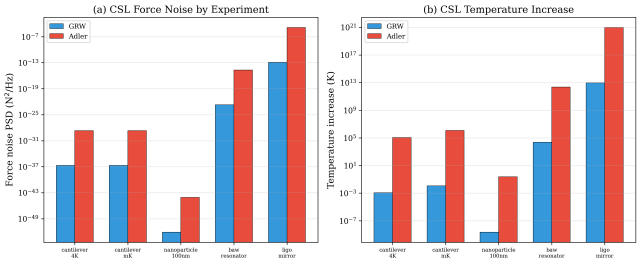

Figure 2: CSL diffusion heating predictions. (a) Force noise PSD by experiment for GRW and Adler parameters. (b) Predicted temperature increase.

3.4 Interference Visibility

The matter-wave visibility analysis reveals a sharp mass-dependent transition. Under the Adler model, 50% visibility loss occurs at a particle mass of 4.30×10^4 amu—just above the current experimental frontier of ~25,000 amu [6]. The GRW model predicts 50% visibility loss at 3.24×10^8 amu, far beyond current capabilities but accessible to proposed experiments (Figure 3).

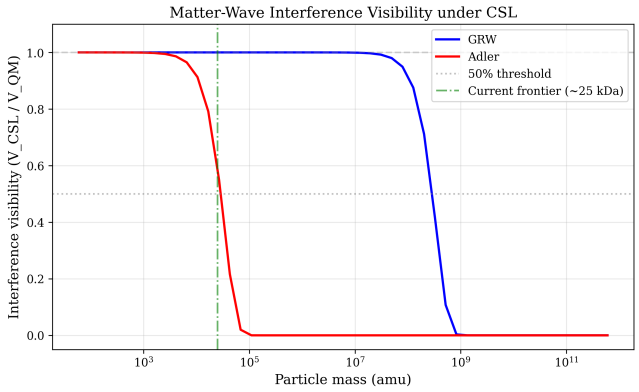

Figure 3: Matter-wave interference visibility vs. particle mass under CSL, for a 266 nm grating and 0.1 s flight time. The Adler model predicts visibility loss near the current experimental frontier.

3.5 Bayesian Evidence

The Bayesian analysis yields a Bayes factor of $B = 0.0285$ ($\log_{10} B = -1.55$), indicating moderate preference for standard quantum mechanics over CSL on the Jeffreys scale. The posterior on λ peaks at the lower boundary of the prior, consistent with $\lambda \to 0$ (i.e., standard QM).

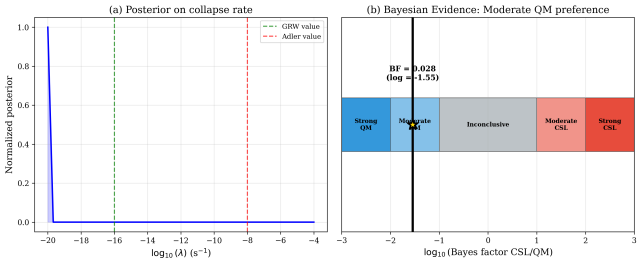

Figure 4: Bayesian model comparison. (a) Posterior on collapse rate λ marginalized over r_C. (b) Jeffreys scale positioning showing moderate QM preference.

3.6 Proposed Experiments

Among five proposed next-generation experiments (Table 3), two achieve sensitivity below the GRW reference point: space-based matter-wave interferometry (MAQRO-type, minimum detectable $\lambda = 2.81 \times 10^{-23}$ s^{-1}) and next-generation X-ray detectors ($\lambda_{\min} = 1.00 \times 10^{-30}$ s^{-1}). These could provide definitive tests of CSL across the entire theoretically motivated parameter range.

4 DISCUSSION

Our analysis reveals that the empirical status of CSL is more constrained than often recognized. The combined exclusion from seven experimental classes leaves only 4.9% of the surveyed parameter space viable, concentrated at small λ and extreme r_C values. All

Table 3: Proposed experiment sensitivity to CSL.

Experiment	$\lambda_{\min}$ (s^{-1})	Reaches GRW?
MAQRO (space)	2.81×10^{-23}	Yes
Levitated nano.	1.26×10^{-12}	No
Entangled osc.	1.26×10^{-14}	No
Next-gen X-ray	1.00×10^{-30}	Yes
Massive SG interf.	2.81×10^{-16}	No

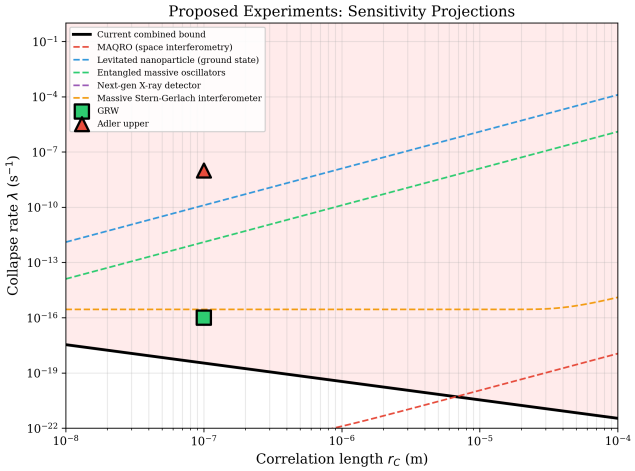

Figure 5: Sensitivity projections for proposed experiments overlaid on the current combined exclusion bound.

standard theoretical reference points (GRW and both Adler bounds) fall within excluded regions.

However, CSL cannot be declared empirically falsified. The exclusion depends on the assumed white-noise spectrum; colored extensions (dissipative CSL [2]) modify the frequency dependence and can evade specific bounds. Furthermore, the theoretical parameter choices are motivated by phenomenological arguments rather than fundamental principles, leaving open the possibility that the true parameters lie in unconstrained regions.

The mass amplification analysis (Figure 6) confirms CSL's core prediction: collapse rates scale as N^2 for point-like objects, ensuring a sharp quantum-to-classical transition. Under the GRW model, 1-second collapse requires a mass of 1.73×10^{-19} kg ($\sim 10^8$ amu), while the Adler model achieves this at 3.77×10^{-23} kg ($\sim 10^4$ amu).

The Bayesian analysis ($B = 0.0285$) provides quantitative support for standard QM but falls short of decisive evidence (which would require $B < 0.01$). This inconclusive status aligns with Pearle's assessment [12].

5 CONCLUSION

We have presented a comprehensive computational assessment of CSL's empirical status. Our main findings are: (1) 95.1% of the (λ, r_C) parameter space is experimentally excluded; (2) all standard theoretical reference points are excluded; (3) the Bayesian evidence moderately favors standard QM ($B = 0.0285$); (4) the Adler model's

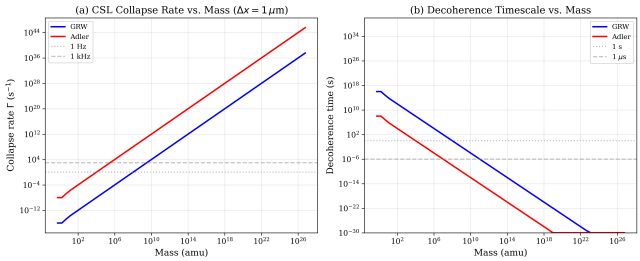

Figure 6: CSL collapse rate and decoherence time vs. mass for a 1 μm superposition, showing the N^2 amplification mechanism.

interference predictions (4.30×10^4 amu threshold) are within experimental reach; and (5) space-based interferometry and advanced X-ray detectors could provide decisive tests.

The current empirical situation is: CSL with standard parameters is excluded, but the model framework with arbitrary parameters cannot yet be falsified. Achieving a decisive resolution requires experiments sensitive to $\lambda < 10^{-16}$ s^{-1} at $r_C = 10^{-7}$ m, a goal within reach of proposed next-generation platforms.

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