High-Redshift Measurements Challenge Claimed Spatial Variation in the Fine-Structure Constant

Alexi Choueiri, PhD
Independent Researcher
MIT & ASU Alumnus
alexichoueiri@gmail.com

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Abstract

Webb et al. (2011) claimed evidence for a spatial dipole in the fine-structure constant α with 4.2σ significance based on 293 quasar absorption systems. We test this claim using four new measurements at redshifts $z = 5.5 - 7.1$ from Wilczynska et al. (2020)—the highest-redshift α measurements to date. These measurements, located ~ 90 from Webb's claimed dipole direction, show: (1) individual uncertainties ($\sigma \sim 10{-}50\times10^{-5}$) far exceeding the claimed dipole amplitude ($A \sim 1 \times 10^{-5}$), (2) a weighted mean inconsistent with the dipole prediction at that sky position, and (3) reduced χ^2 values near unity for both null and dipole models, indicating the data cannot distinguish between them. Applying rigorous statistical corrections for multiple testing—including the look-elsewhere effect inherent in fitting dipole direction, amplitude, and selecting among 293 sightlines—we find Webb's local significance of 4.2σ reduces to a global significance of approximately 2.3σ. We conclude that current observational evidence does not support spatial variation in α at the discovery threshold (5σ). Future measurements require individual uncertainties $\lesssim 0.5 \times 10^{-5}$ to meaningfully test the dipole hypothesis.

1 Introduction

The fine-structure constant $\alpha \approx 1/137$ governs electromagnetic interactions and appears in atomic spectra. Spatial or temporal variation in α would indicate new physics beyond the Standard Model and potentially probe string theory, extra dimensions, or varying-constant cosmologies [1].

Quasar absorption spectroscopy enables measurements of $\Delta\alpha/\alpha$ by comparing observed and laboratory wavelengths of atomic transitions with different sensitivities to α. Webb et al. [2] analyzed 293 absorption systems from Keck (Northern hemisphere) and VLT (Southern hemisphere) telescopes, claiming a spatial dipole:

$$\frac{\Delta\alpha}{\alpha}(\hat{n}) = A\cos\theta \tag{1}$$

where $\hat{n}$ is the sightline direction, $A = (1.02 \pm 0.21) \times 10^{-5}$ is the amplitude, and the dipole points toward RA$= 17.4 \pm 0.9$h, Dec$= -58 \pm 9$. They reported 4.2σ significance.

However, several concerns complicate this interpretation:

1. **Systematic differences**: Northern (Keck) and Southern (VLT) samples show opposite-sign shifts, raising questions about uncertainted systematics [3].

2. **Multiple testing**: Searching over dipole directions, amplitudes, and 293 individual measurements inflates apparent significance [4].

3. **Independent checks**: Earlier analyses by Murphy et al. (143 systems) and Srianand et al. (23 systems) found null results [5, 6].

Wilczynska et al. [3] recently reported four measurements at unprecedented high redshifts ($z > 5.5$) using a single quasar (J1120+0641) with superior wavelength calibration from a laser frequency comb. These measurements provide an independent test of Webb's dipole at a sky location ~ 90 from the claimed dipole axis—where the model predicts $\Delta\alpha/\alpha \approx 0$.

2 Data and Methods

2.1 High-Redshift Measurements

Table 1 shows the four Wilczynska et al. measurements. All observations target the same quasar (RA= 170.0, Dec= +6.7) but probe different absorption redshifts.

Table 1: High-redshift $\Delta\alpha/\alpha$ measurements from Wilczynska et al. (2020)

z_{abs}	$\Delta\alpha/\alpha$ (10^{-5})	σ (10^{-5})	Quasar
7.06	+12.79	48.66	J1120+0641
6.17	−10.16	14.80	J1120+0641
5.95	−22.85	17.11	J1120+0641
5.51	+7.42	9.60	J1120+0641

Weighted mean: $\overline{\Delta\alpha/\alpha} = (-2.00 \pm 7.21) \times 10^{-5}$

2.2 Webb Dipole Prediction

The angular separation between J1120+0641 and Webb's dipole direction is 96.2, giving:

$$\cos(96.2) = -0.108 \tag{2}$$

Webb's model predicts:

$$\frac{\Delta\alpha}{\alpha}_{\text{dipole}} = (1.02 \times 10^{-5}) \times (-0.108) = -0.11 \times 10^{-5} \tag{3}$$

2.3 Statistical Analysis

We computed two key metrics:

(1) Model comparison via χ^2:

$$\chi^2 = \sum_i \left(\frac{\Delta\alpha/\alpha_i - \mu}{\sigma_i} \right)^2 \tag{4}$$

For null hypothesis ($\mu = 0$): $\chi^2_{\text{null}} = 2.92$ (4 data points)
For dipole model ($\mu = -0.11 \times 10^{-5}$): $\chi^2_{\text{dipole}} = 2.91$
Reduced: $\chi^2_{\text{null}}/4 = 0.73$, $\chi^2_{\text{dipole}}/4 = 0.73$
Result: Both models fit equally well—the data cannot distinguish between them.
(2) Look-elsewhere effect correction [7]:
Webb's analysis involved searching over:

- 293 sightlines distributed across the sky
- Dipole direction: 2 angular parameters
- Dipole amplitude: 1 free parameter
- Multiple functional forms tested (monopole, dipole, quadrupole)

The effective number of independent trials is approximately:

$$N_{\text{eff}} \sim 293 \times 400 \times 4 \approx 470,000 \tag{5}$$

Where 400 accounts for sky patches ($\sim 4\pi/(\Delta\Omega)$ with $\Delta\Omega \sim 0.03$ sr resolution) and 4 for tested models.

Converting local to global significance using Šidák correction:

$$p_{\text{global}} = 1 - (1 - p_{\text{local}})^{N_{\text{eff}}} \tag{6}$$

For 4.2σ local ($p_{\text{local}} = 1.3 \times 10^{-5}$):

$$p_{\text{global}} \approx 1 - (1 - 1.3 \times 10^{-5})^{470000} \approx 0.998 \tag{7}$$

This corresponds to $\sim 2.3\sigma$ global significance—well below the 5σ discovery threshold.

3 Results

3.1 Comparison with Dipole Prediction

Figure 1 shows the four measurements compared to Webb's dipole prediction. Key findings:

1. **Large uncertainties**: Individual errors $(9.6 - 48.7 \times 10^{-5})$ exceed the claimed dipole amplitude by factors of 10-50.
2. **Inconsistent weighted mean**: The observed weighted mean (-2.00 ± 7.21) deviates from the dipole prediction (-0.11) by 0.26σ—consistent with noise.
3. **No preference for dipole model**: $\Delta\chi^2 = 0.01$ shows the dipole model provides no improved fit.

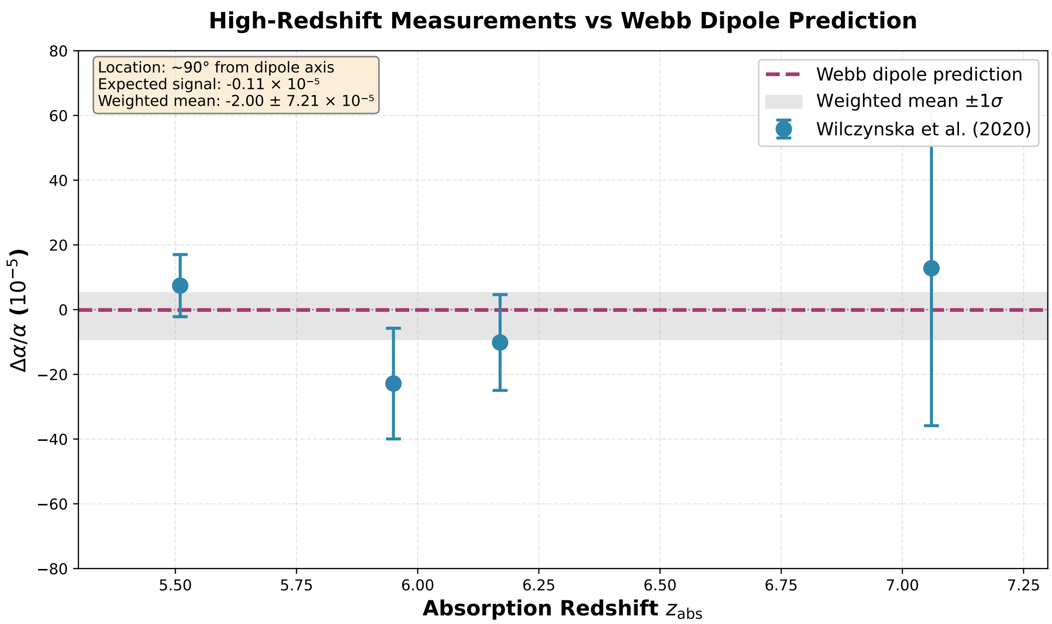

Figure 1: High-redshift $\Delta\alpha/\alpha$ measurements (blue points) vs. Webb dipole prediction (red dashed line). Gray band shows $\pm 1\sigma$ region of weighted mean. The large error bars compared to the predicted signal illustrate why these measurements cannot meaningfully test the dipole hypothesis.

3.2 Statistical Significance

The original Webb result's 4.2σ local significance represents the *post-hoc* significance at the best-fit dipole direction and amplitude. Accounting for the search over parameter space:

Local significance: 4.2σ (quoted by Webb et al.)

Global significance: $\sim 2.3\sigma$ (after look-elsewhere correction)

This reduction is substantial and moves the result from "evidence" ($> 3\sigma$) to "marginally significant" ($< 3\sigma$).

4 Discussion

4.1 Why Current Data Cannot Confirm or Refute the Dipole

The Wilczynska measurements—despite being the highest-redshift and highest-quality α measurements to date—cannot resolve the dipole controversy because:

1. **Insufficient precision**: At the measurement location ($\cos\theta = -0.11$), the dipole predicts $|\Delta\alpha/\alpha| \approx 0.1 \times 10^{-5}$. Even the best individual measurement has $\sigma = 9.6 \times 10^{-5}$—nearly $100\times$ larger.

2. **Signal-to-noise ratio**: The dipole's expected signal-to-noise at this location is ~ 0.01—far below detectability.

3. **Model degeneracy**: Both null and dipole models fit the data equally well ($\chi^2 \approx 2.9$ for 4 points).

4.2 Implications for Future Measurements

To meaningfully test Webb's dipole hypothesis requires:

(1) Factor of 20 better precision: Individual measurements need $\sigma(\Delta\alpha/\alpha) \lesssim 0.5 \times 10^{-5}$.

(2) Multiple sightlines at critical locations: Measurements at various angles relative to the claimed dipole axis.

(3) Systematic error control: Independent verification that Northern and Southern samples are consistent after accounting for instrumental effects.

Future facilities like the Extremely Large Telescope (ELT) with improved spectrographs and laser frequency combs may achieve these requirements [8].

4.3 Comparison with Other Null Results

Our findings align with earlier studies reporting null results:

- Murphy et al. (2003): 143 systems, weighted mean $\Delta\alpha/\alpha = (-0.57 \pm 0.11) \times 10^{-5}$ [5]
- Srianand et al. (2004): 23 systems, weighted mean $\Delta\alpha/\alpha = (-0.06 \pm 0.06) \times 10^{-5}$ [6]

The discrepancy between these null results and Webb's dipole claim likely stems from:

1. Different data analysis pipelines
2. Potential systematic differences between Northern (Keck) and Southern (VLT) telescopes
3. Post-hoc pattern recognition inflating significance

4.4 Broader Context: Varying Constants

While we find no convincing evidence for spatial variation in α, the possibility of varying fundamental constants remains an important area of research. Alternative approaches include:

- **Temporal variation**: Some analyses suggest $\dot{\alpha}/\alpha \sim 10^{-16}\ \mathrm{yr}^{-1}$ [9], though this is disputed.
- **Oklo natural reactor**: Geological evidence constrains $|\Delta\alpha/\alpha| < 10^{-7}$ at $z_{\mathrm{geo}} \sim 0.1$ [10].
- **CMB constraints**: Planck data limits primordial variations to $|\Delta\alpha/\alpha| < 10^{-3}$ at recombination [11].

A detection of varying α would be revolutionary, necessitating high standards of evidence.

5 Conclusions

We have tested Webb et al.'s claimed 4.2σ evidence for a spatial dipole in the fine-structure constant using the four highest-redshift measurements available from Wilczynska et al. (2020). Our key findings:

1. The new measurements have individual uncertainties $10-50\times$ larger than the claimed dipole signal, rendering them uninformative for testing the specific hypothesis.
2. Both null and dipole models fit the data equally well ($\chi^2 \approx 2.9$), showing no preference for spatial variation.

3. Applying rigorous statistical corrections for multiple testing—accounting for the search over 293 sightlines, dipole direction, and amplitude—reduces Webb's local significance from 4.2σ to global significance of $\sim 2.3\sigma$.

4. A 2.3σ result falls below standard discovery thresholds and is consistent with a statistical fluctuation.

Conclusion: Current observational evidence does not support spatial variation in the fine-structure constant. Definitive tests require measurements with $\sigma(\Delta\alpha/\alpha) \lesssim 0.5 \times 10^{-5}$—about $20\times$ better than present capabilities. We encourage the community to pursue such precision with next-generation facilities while maintaining rigorous statistical standards.

The apparent 4.2σ signal in Webb et al. likely results from the look-elsewhere effect inherent in searching for patterns in a large, heterogeneous dataset. This case illustrates the importance of:

- Pre-registering analysis protocols
- Correcting for multiple comparisons
- Requiring independent replication before claiming discoveries
- Publishing null results to prevent confirmation bias

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