

## Mapping the ALPs: A Naturalness Map for Axions and ALPs

The axion solution to the strong CP problem is only as robust as the Peccei-Quinn symmetry it relies on, and quantum gravity is expected to break it. We quantify the resulting axion quality problem using principled measures of fine-tuning, and show that the cost is severe. For the QCD axion to account for the observed dark matter, Planck-suppressed symmetry-breaking operators must be absent up to mass dimension  $d \geq 12$ ; the naturalness penalty for failing to realize this protection can exceed a Bayes factor of  $10^{10}$ . Extending the analysis to generic axion-like particles, we map the axion mass-decay constant plane by the degree of UV protection required, and find that large portions of the sensitivity reach of laboratory experiments are already fine-tuned at the part-per-million level or worse. We argue that quality, not mass, is the central naturalness question for the axion program.

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