Snowmass2021 - Letter of Interest

HAYSTAC – Pioneering the Quantum Frontier

Thematic Areas: (check all that apply ☐/■)

■ (IF1) Quantum Sensors
■ (CF2) Dark Matter: Wavelike

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Abstract:

HAYSTAC is a microwave cavity dark matter axion search designed as an innovation testbed and data pathfinder for the $15-50\,\mu$eV $(3.5-12\,\text{GHz})$ mass range. Commissioned in 2014 with a single Josephson Parametric Amplifier (JPA) receiver, it has operated from the beginning with a system noise temperature N_{sys} within an order of magnitude of the Standard Quantum Limit N_{SQL}. Recently the experiment has run with a dual JPA squeezed state receiver circumventing the standard quantum limit entirely, achieving a sensitivity to axions at $1.38\times$KSVZ despite its small volume $V = 1.5\,$L. Breaking the quantum barrier is a significant milestone; not only is this the first quantum-enhanced dark matter experiment ever, but together with LIGO it is only one of two experiments to have employed squeezed states to hunt for new fundamental physics. Parallel developments in microwave cavities for this frequency range have included tunable Photonic Band Gap structures, and more recently metamaterial plasmonic resonators. While maintaining its identity as a technology test bed, future operation will emphasize production running in this mass range, where a much more ambitious receiver is under development (the CEASEFIRE project) based on a squeezing and state-swapping protocol in order to best probe the wide area of open axion parameter space.

Science landscape: Since the last Snowmass in 2013, dramatic progress has been made in the fields of both axion theory and experiment, and the axion has emerged as one of the two leading Dark Matter (DM) candidates. From the perspective of axion cosmology, we need to be prepared to search over a much wider range of masses than is currently possible experimentally as some inflationary scenarios naturally allow the axion mass to be much lower than previously thought, as low as 10^{-12} eV[1;2]. On the other hand, for post-inflation PQ-symmetry breaking, predictions of the axion mass corresponding to a dark matter fraction of $\Omega_{DM} \approx 0.27$ have tightened up dramatically, with the $m_a \approx$ 15-35 μeV range now being a particularly well motivated region[3;4]. Similarly, it has been recently realized that ALP cogenesis can simultaneously explain both baryon and dark matter densities, but with photon couplings orders of magnitude stronger than for the standard QCD axion[5]. Taken together, this suggests a broad search philosophy, namely that one should cover as much of the currently available parameter space as rapidly as possible, with an eye towards an early discovery. On the experimental side, in the past several years, three experiments have now published results probing the QCD model band in the $>$ μeV range: Haloscope At Yale Sensitive To Axion Cold dark matter (HAYSTAC)[6–8], ADMX[9], and CAPP[10]. Additionally, major experiments are currently under development to search for axions of lower (ABRACADABRA[11], DM Radio[12–14], CASPEr[15]) and higher masses (MADMAX[16]).

Breaking the quantum barrier: Over the past decade, the HAYSTAC experiment has been steadily pushing the limits of quantum measurement in the search for DM axions. First funded by NSF in 2011 and later by the Heising-Simons Foundation, the HAYSTAC experiment — a collaboration of Yale, UC Berkeley, Colorado, and now Johns Hopkins — was designed to be both an innovation testbed and a data pathfinder in the 4–12 GHz range. The experiment was intended to be an agile technology platform where the latest advances in quantum measurement could be explored along with novel concepts for microwave cavities which satisfy the stringent requirements of an axion search while maintaining high figures of merit. From its inaugural data run in 2015, HAYSTAC operated with a system noise level N_{sys} within a factor of 2-3 of the standard quantum limit N_{SQL}, and is to date still the only microwave cavity axion experiment to come within an order of magnitude of N_{SQL}[6;7;17]. Going further, however; we have just recently submitted for publication our first run with a Squeezed State Receiver (SSR) which manipulates quantum states in order to circumvent the standard quantum limit entirely[8]. Breaking the quantum barrier is a significant milestone; not only is this the first quantum-enhanced DM experiment ever, but together with LIGO it is only one of two experiments to have ever employed squeezed states to search for new fundamental physics. Squeezing with other optimizations[18] have accelerated our search by a factor of ≈ 3 over the standard mode of operation. Coupled with additional experimental improvements, for our next data runs we seek to improve the scan rate by an additional factor of 4. In addition, thanks to a radical new design being developed by our Colorado/JILA collaborators we have the potential to increase this scan rate even further.

Innovative data analysis strategies: In addition, HAYSTAC has led a push in the axion direct detection community for improved data processing and statistical analysis. In 2017[19], HAYSTAC standardized the use of maximum-likelihood estimation throughout the data processing and optimized the spectral filtering used across all haloscope searches. In doing so, we provided the first codification of haloscope analysis protocols since 2001[20], during which time these protocols have evolved significantly. Practices pioneered by HAYSTAC have since been adopted by all other QCD axion-sensitive haloscopes[10;21]. In 2020, HAYSTAC optimized the framework commonly used for statistical inference in axion direct detection, allowing for conservative results reported with 30-50% faster effective scan rates, and more flexible stopping criteria, which aided our most recent data run[8;18]. This novel framework has since been used advantageously in an ALP DM search conducted using existing data from the JILA eEDM experiment and extending 17 orders of magnitude lower in mass than the QCD axions that HAYSTAC targets[22].

Future plans: While we will continue to advance technology both on the receiver and cavity fronts, at the same time HAYSTAC will now additionally function as a data production experiment aiming to search much of the 15-30 μeV (3.5-8.0 GHz) range. Ideally, the experiment will upgrade to a Nb_3Sn magnet as soon as possible, improving the scan rate $R \propto B^2 V$ of 10 and enable coverage of the 30-50 μeV (8.0-12 GHz) range. While there are multiple paths to quantum enhancement[23], we argue that squeezing is by far the most practical and feasible in the near term - indeed it has already delivered science results. The current SSR design is broadly tunable and has a clear path for continuous improvements. While the collaboration now comprises four institutions with Johns Hopkins (where former HAYSTAC postdoc D. H. Speller is now faculty), expanding by one new group may be warranted to ensure adequate depth in both operations and analysis, for a data production and technology R&D experiment.

State of the R&D: The question should be asked whether extensions of the present SSR, and a possible next generation squeezer of greatly enhanced capability and its incorporation into the HAYSTAC experiment is well supported by both the technology and the R&D. Concerning the current platform, the Josephson Parametric Amplifiers (JPAs) and microwave cavities for the 3.5-8.0 GHz phase are already in hand and ready for deployment. For the 8.0-12.0 GHz operation, the current JPA design is satisfactory; but some of the conventional microwave components in the receiver will need to be modified for use at higher frequencies. In regard to the microwave cavities, extensions of the current design[24] look promising and R&D is underway. The Berkeley group has studied tunable resonators based on Photonic Band Gap structures to eliminate the forest of intruder TE modes which mix with the TM modes of interest, eroding frequency coverage. This has been the bane of all cavity schemes to extend their dynamical range upward in frequency. The state of cavity R&D has already produced several interesting results with engineering prototypes of actual cavities to be manufactured and tested in the coming year.
The one R&D program which is considered moderate risk is the development of a next-generation squeezing and state swapping protocol to achieve very large squeezing factors currently limited by losses in the circulator. The Colorado group is therefore pursuing an architecture that does not require a circulator, under the banner of the CEASEFIRE project[25] with a bench demonstration that could be ready in two-four years and integration into HAYSTAC soon thereafter.

Yale's Initiative in Quantum Science: Quantum science and advanced instrumentation development for fundamental research have been identified as the top priorities in Yale's science initiative[1]. Yale University is also one of the leading partners in the recently announced DOE "Co-design Center for Quantum Advantage " [2]. Over the coming years, Yale will be developing a Physics Science and Engineering Building adjacent to the current Wright Laboratory including a state-of-the-art Advanced Instrumentation Development Center, fabrication facilities, cleanrooms and technical staff to support Yale's initiative in this field[3]. The building will provide new laboratory space for the HAYSTAC experiment by 2023 and enable research and production on quantum devices. Together with the historic strength of the Yale quantum sciences group this will represent a focal point for the East Coast comparable to NIST Boulder. The new HAYSTAC lab will have a closed-loop LHe system supporting all low-temperature operations in the lab, including the Nb_3Sn magnet we hope to procure for HAYSTAC. This development represents an opportunity for Yale to become a national center for quantum-enhanced dark matter research. This new facility also represents an excellent future resource for all upcoming HAYSTAC runs.

Long-range R&D: HAYSTAC will continue to promote and follow the R&D on a quantum non-demolition Rydberg atom single-quantum detector, being led by R. Maruyama (as discussed in the LOI submitted to IF1/CF2). While this is potentially an exceedingly powerful strategy for axion searches, this is long-range R&D, and the pathway for integration into HAYSTAC remains an open question.

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[1] University Science Strategy Committee Report

[2] "Yale scientists to help lead national quantum center" - Yale News August 2020

[3] University Wide Academic Priorities

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