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Pierre Sikivie and the Gift for Simple Ideas

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Abstract. I comment on the status and future prospects of the field of axion searches in the context of the seminal contributions of Pierre Sikivie.

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It was fitting to dedicate "Axions 2010" in honor of Pierre Sikivie on the occasion of his 60th birthday. Pierre possesses a rare gift for simple ideas with deep physical appeal and powerful consequences; his work has launched a large number of axion experiments around the world, and parallel theoretical efforts.

FIVE KEY CONTRIBUTIONS

Five major contributions to the field can be attributed to Pierre, described briefly below from my own perspective and recollection of these developments over the past quarter-century. References will be illustrative rather than exhaustive.

The Cosmological Significance of the Axion

Pierre's debut in the field was his realization that the Peccei-Quinn vacuum realignment mechanism for dynamically driving θ to 0 in the early universe [1] implied that axions would be created as a cold Bose gas at QCD time during the Big Bang, and that a sufficiently light axion would be an excellent dark matter candidate. The Sikivie and Abbott paper became a landmark, and has been cited roughly 500 times [2].

The Primakoff Mechanism for Detection of the Axion

Such light axions however would interact so feebly with matter and radiation as to be undetectable in ordinary experiments. Pierre's 1983 Physical Review Letter resolved the difficulty, demonstrating that within a high-Q cavity permeated by a strong magnetic field, dark-matter axions could resonantly convert to a weak but detectable microwave signal [3]. Within the same paper, he detailed how solar axions of mass O(1 eV) could be detected by their conversion to keV x-rays by the same mechanism. This paper too, has become a landmark, also having been cited some 500 times, and references to it continue unabated.

The Microwave Cavity Experiments

In addition to the conception of the microwave cavity experiment, it is important to recognize Pierre's role in the launching of the experiments themselves. Two first generation searches began not long after the publication of ref. 3, one at the University of Florida [4], and the other a Rochester-Brookhaven-Fermilab collaboration at BNL [5]. The Axion Dark Matter eXperiment (ADMX) which began in the early 1990's, reaped the experience of both pilot efforts, and is now embarking its second major upgrade [6]; Pierre has been an active collaborator throughout its history.

Axion Radiation from Topological Defects

It was realized that in addition to axion production from the vacuum realignment mechanism, axions could be radiated from topological defects, and cosmic strings in particular. The relative importance of the two mechanisms bears directly on the optimum search mass for halo axions. Sikivie and collaborators concluded that the string contribution was comparable to the vacuum realignment mechanism [7]. In contrast, the Cambridge group initially found the string contribution to be strongly dominant, implying an axion mass saturating the matter density of the universe to be in the meV rather than μeV range [8]. Eventually, as the latter's simulations were refined and corrected [9], the string and vacuum realignment estimates merged within their uncertainties, and further debate became moot.

Phase Space Structure and the High-Resolution Channel

N-body simulations of structure formation in the universe has become an industry today, but Pierre was among the first to perform analytical models of the folding of phase space to gain insight into what the signal of axionic dark matter would look like in the cavity microwave experiment [10]. This is particularly consequential insofar as in the cavity microwave experiment measures the *(total energy = mass + kinetic)* of axionic dark matter. That implies that, should axions be discovered to be the dark matter, a high resolution search could reveal potentially interesting substructure reflecting the history of the formation of the Milky Way. The University of Florida group implemented the high-resolution channel within ADMX in the late 1990's, and it has been taking and publishing data ever since.

More recently he has focused on the role and evidence of caustics in structure [11], and has been emboldened to argue that the balance of evidence now points to axions being the dominant component of dark matter [12].

COLLATERAL IMPACT OF SIKIVIE'S WORK

A measure of a truly seminal idea is the diversity of its offshoots. For those of us who attended the first workshop dedicated specifically to axions in 1989 [13], it is gratifying to see here how broad has been the impact of those original concepts.

New Physics

There was much new physics under discussion at this workshop either generalizing of the concept of the axion, e.g. Axion-Like Particles or ALPS [14], or by virtue of leveraging the techniques developed for the search for the axions, e.g. searches for holographic noise [15], chameleons [16] or paraphotons [17].

New Technologies

The microwave cavity axion search drove the development of gigahertz quantum-limited SQUID amplifiers in the late 1990's [18]. Not only did they enable the upgrade of ADMX, but these SQUID amplifiers have become a key enabling technology in the emerging field of quantum computation.

New Communities

It was realized that the sensitivity of the original "light shining through walls" axion search [19] could be improved dramatically by resonant regeneration, i.e. encompassing the production and regeneration magnets with matched Fabry-Perot cavities [20]. Members of the LIGO and GEO laser interferometric gravity wave groups have now joined the effort to provide the sophisticated laser and optical technologies required for the task.

New Talent

Without question, Pierre's greatest legacy has been the large number of new researchers in the field of particle astrophysics, whose doctoral training tracing back to his own research in axions and dark matter. An informal survey indicates that, at the time of this workshop, at least 40 experimental Ph.D. theses were written around the world based on ideas tracing back to Ref. 3 (Figure 1). The number of theory Ph.D. theses was not surveyed but is surely comparable.

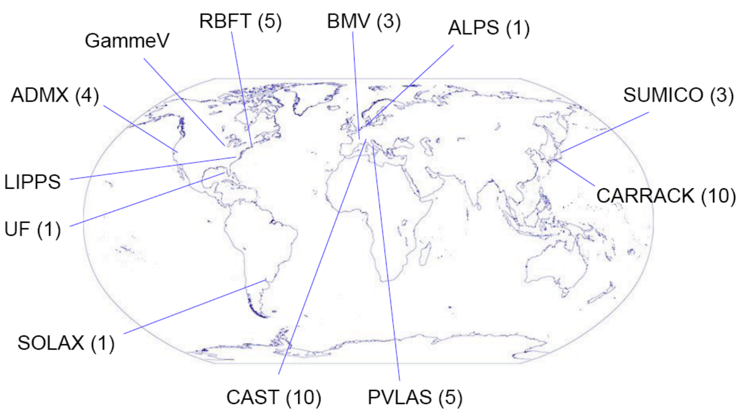

FIGURE 1. Ph.D. theses stemming from Pierre Sikivie's 1983 Physical Review Letter.

PIERRE AS PEDAGOG

The author's favorite paper of Pierre's was not a refereed journal article at all, but rather his *Physics Today* feature article "The Pool-Table Analogy with Axion Physics" [21]. This article presents a fable about a group of physics students on Mars who play pool on a table imported from Earth. The protagonist "Thinking Snookers Player" or TSP for short, ponders why a generic pool table (the underside of which he cannot see) can be placed at an arbitrary location on the Martian landscape, where the local normal and gravitational vectors have no reason to be perfectly aligned, and yet be flat to 10^{-11}, permitting an honest game of pool. TSP hypothesizes that the pool table is mounted on a pivot, stabilized by a very long pendulum, and sets about proving his hypothesis (Figure 2). Sikivie develops the analogy between the length of the pendulum and the Peccei-Quinn symmetry-breaking scale f_a, the turn-on of the gravitional potential as rocket conveying the pool table from Earth to Mars decelerates and the turn-on of the restoring potential of θ at QCD time during the Big Bang, and how miniscule relic oscillations can be detected by a high-Q tuned resonator in both situations. This lovely article gives some insight into how Pierre thinks about physics.

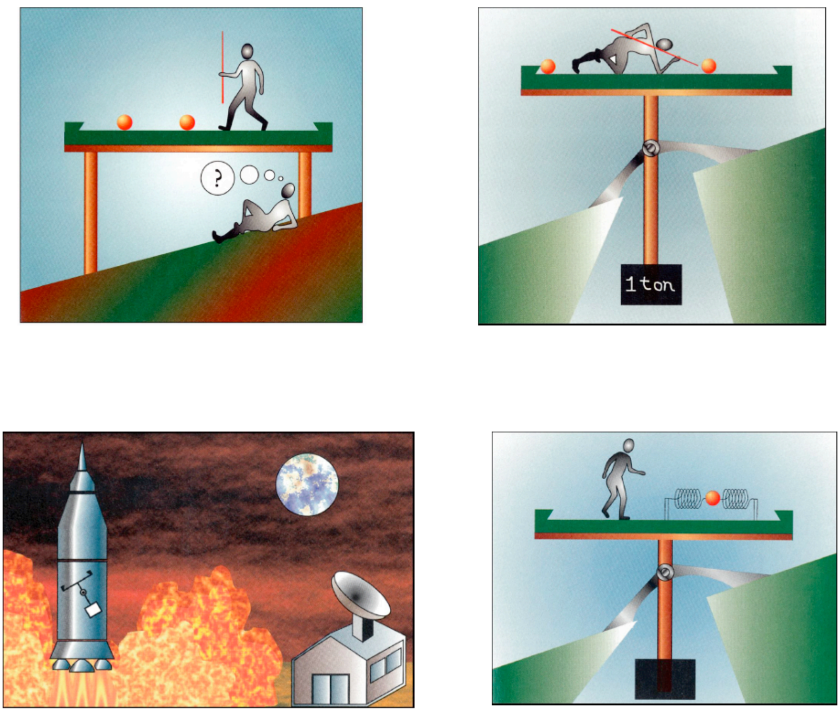

FIGURE 2. Illustrations from Sikivie's "The Pool-Table Analogy with Axion Physics" [21].

PERSONAL REFLECTIONS ON THE FIELD

This workshop has also been an opportunity to assess where we have got to in our search for the axion along the lines suggested by Pierre, and how we may best bring our search to a successful conclusion. Along the way, we may discover some new things not envisioned by Peccei, Quinn, Weinberg and Wilczek, including perhaps some of the related physics we have heard about, such as chameleons and paraphotons.

Figure 3 depicts the plane of the axion-photon coupling vs. axion mass; it is a useful, if somewhat notional representation of the global picture of theory and all disparate types of experiments. It focuses the mind is to categorize the various experiments according to the power of $g \equiv g_{a\gamma\gamma}$ of their measurable signals; a little reflection leads to the conclusion that it is difficult (if not impossible) to push any purely laboratory experiment down to the P-Q axion. This having been said, let me comment on what I believe are the two best prospects for discovery.

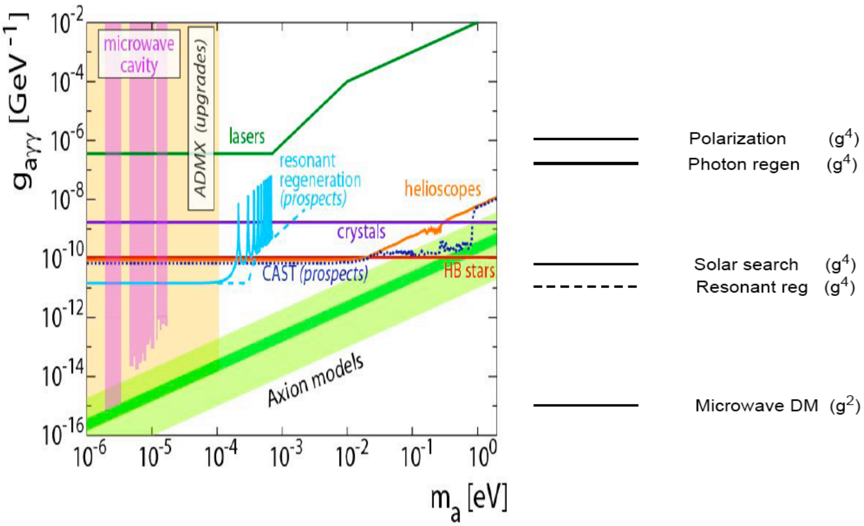

FIGURE 3. The plane of axion-photon coupling and axion mass. Shown also are various classes of experiments, categorized by the dependence of their signal on powers of $g \equiv g_{a\gamma\gamma}$.

Only the microwave cavity experiment, which goes as g^2, has demonstrated sensitivity to Peccei-Quinn axions in a region of mass and coupling which has not as yet been excluded by astrophysics. It does, of course, rely on the assumption that axions constitute the dark matter of our halo, but a sufficiently light axion would almost necessarily be cosmologically significant. It is also a tuning experiment, and progress in mass range covered by ADMX has been slow. However the invention and implementation of quantum-limited SQUIDs in ADMX, coupled with the future upgrade of a dilution refrigerator promises significant improvement in scanning speed.

Recently there has been the development of a detailed design for a resonant regeneration experiment (a "light shining through walls" experiment, resonantly enhanced with matched Fabry-Perot cavities) which could improve the CAST limits by an order of magnitude [20]; collaborations centered at FNAL and DESY are actively building up such efforts. While unlikely to reach the Peccei-Quinn axion, in light of how significant an advance in sensitivity it is capable of, however, it should be pursued vigorously.

The flourishing of new searches for axions and axion-like particles has been gratifying, with much new know-how and talent coming to the field. However, my counsel would be that the time has come for a strategic merging of efforts around two major campaigns, one in the microwave search for dark matter axions, and the other around a resonant regeneration experiment, with as long a magnet string as feasible. Both done properly will require a significant increase in resources, for which the funding agencies will require such convergence of manpower. Our counterparts in the WIMP dark matter community have already begun the process of national and international merging of efforts, and to good effect.

New ideas will always be needed however, and Pierre Sikivie can certainly be counted upon to continue providing intellectual leadership to the enterprise.

REFERENCES

1. R. Peccei and H. Quinn, *Phys. Rev. Lett.* **38**, 1440 (1977); and *Phys. Rev. D* **16**, 1791 (1977).
2. L. Abbott and P. Sikivie, *Phys. Lett. B* **120**, 133 (1983).
3. P. Sikivie, *Phys. Rev. Lett.* **51**, 1415 (1983). Erratum. *Phys. Rev. Lett.* **52**, 695 (1984); P. Sikivie, *Phys. Rev. D* **40**, 2988 (1985).
4. C. Hagmann et al., *Phys. Rev. D* **42**, 1297 (1990).
5. S. DePanfilis et al., *Phys. Rev. Lett.* **59**, 839 (1987); W. Wuensch et al., *Phys. Rev. D* **40**, 3153 (1989).
6. S.J. Asztalos et al., *Phys. Rev. Lett.* **104**, 041301 (2010), and refs. within.
7. C. Hagmann and P. Sikivie, *Nucl. Phys. B* **363**, 247 (1991).
8. R.A. Battye and E.P.S. Shellard, *Phys. Rev. Lett.* **73**, 2954 (1994).
9. Erratum ibid., **76**, 2203 (1996); R.A. Battye and E.P.S. Shellard, *Nucl. Phys. B* **423**, 260 (1994).
10. P. Sikivie and J.R. Ipser, *Phys. Lett. B* **291**, 288 (1992); P. Sikivie, I.I. Tkachev and Y. Wang, *Phys. Rev. Lett.* **75**, 2911 (1995).
11. P. Sikivie, *Phys. Lett. B* **432**, 139 (1998); P. Sikivie, *Phys. Rev. D* **60**, 063501 (1999); P. Sikivie, *Phys. Lett. B* **567**, 1 (2003).
12. P. Sikivie, "The Case for Axion Dark Matter", arXiv:1003.2426v1 (2010).
13. *Proceedings of the Workshop on Cosmic Axions* (Brookhaven National Laboratory, April 13-14, 1989) edited by C. Jones and A. Melissinos, Singapore:World Scientific.
14. K. Ehret et al., *Phys. Lett. B* **689**, 149 (2010) and refs. within.
15. C.J. Hogan, *Phys. Rev. D* **77**, 104031 (2008).
16. See e.g. G. Rybka et al., arXiv:1004.5160v1 (2010), and refs. within.
17. M. Goodsell, J. Jaeckel, J. Redondo, and A. Ringwald, *Journal of High Energy Physics* **11**, 027 (2009); J. Jaeckel and A. Ringwald, *Phys. Lett. B* **659**, 509 (2008).
18. M. Mück et al. *App. Phys. Lett.* **72**, 2885 (1998); M. Mück et al. *App. Phys. Lett.* **75**, 3545 (1999).
19. K. van Bibber et al., *Phys. Rev. Lett.* **59**, 759 (1987).
20. F. Hoogeveen and T. Ziegenhagen, *Nucl. Phys. B* **358**, 3 (1991); P. Sikivie, D.B. Tanner and K. van Bibber, *Phys. Rev. Lett.* **98**, 172002 (2007); G. Mueller et al., *Phys. Rev. D* **80**, 072004 (2009).
21. Pierre Sikivie, *Physics Today* **49**, 22 (1996).