0.5 eV QCD Axion Dark Matter

“To see a World in a Grain of Sand. . . ”— William Blake

Noah Bray-Ali

Science Synergy and AlphaXiv
https://science-synergy.com
https://alphaxiv.org

arXiv.org:2108.12243 [hep-ph], *submitted* to JCAP

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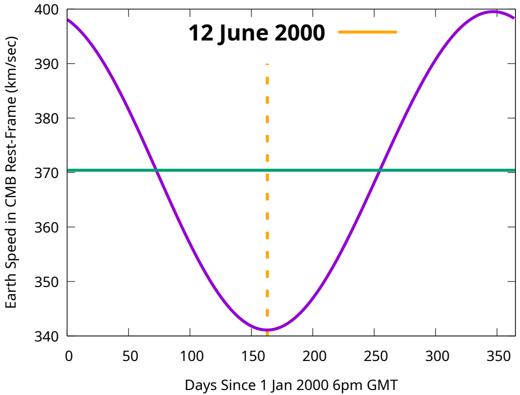
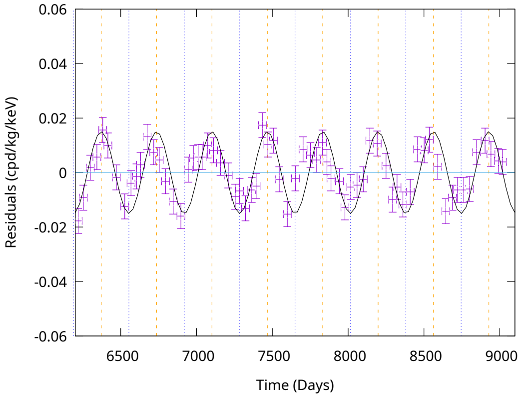
CMB Rest-Frame Earth Speed Annual Modulation



- Solar System Barycenter (SSB) rest-frame Earth velocity:
  C. McCabe, J. Cosmol. Astropart. Phys. 2014 (2014) 027.
- Cosmic Microwave Background (CMB) rest-frame Sun velocity:
  N. Aghanim+ (*Planck* Collaboration), Astron. and Astrophys. 641 (2020) A3.

DM model-independent Annual Modulation Result



- DAMA/LIBRA-Phase 2: 250 kg $\mathrm{NaI}:\mathrm{Tl}^+$ for 1.53 $\mathrm{ton} \times \mathrm{year}$, $1-6$ keV
- Period: 1.00 year, Phase: **Peak on June 12**, Amplitude: 0.0150 $\mathrm{cpd/kg/keV}$
- Fast dark counts: <150 ns, double-coincident photomultiplier noise
- Slow dark state scints: ~ 230 ns at 300 K, 3.2 keV $^{40}\mathrm{Ar}$ Auger and soft x-ray.

Dark State Scintillation Thermal Activation

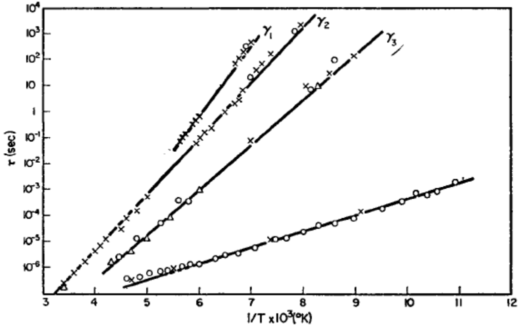


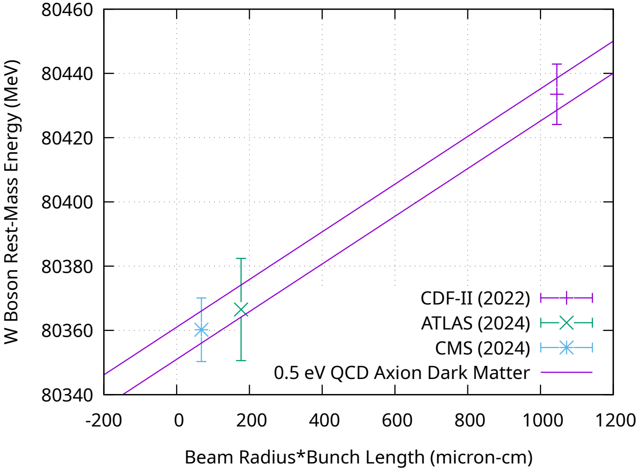
FIG. 11.19. NaI(Tl) crystals. Log $\tau = f(1/T)$ (Bonanomi and Rossel, 1952). ○ "Pure" NaI, grown; × NaI(Tl), grown; △ NaI(Tl), precipitated.

- J. B. Birks, *The Theory and Practice of Scintillation Counting*, pgs. 453–455 (1964).
- Longest-lived low-temperature channel (γ_1) activates with energy $W(\gamma_1) = \mathbf{0.53\ eV}$.

$$\begin{aligned}\Delta M_W &= M_W \log\left(\frac{M_Z}{M_W}\right)\frac{\alpha_s(M_W)}{8\pi}\frac{p_W c}{f_A}\sqrt{\frac{\rho_A V T}{\hbar}} \\ &= 0.074\ (4)\frac{\mathrm{MeV}}{\mu\mathrm{m}\cdot cm}\sigma_x\sigma_z\end{aligned}$$

- $\rho_A (= \rho_{DM})$: A.-C. Eilers+, ApJ 871 (2019) 120.
- $m_A c^2 f_A (= \sqrt{\chi_{\mathrm{QCD}}})$: Gorghetto+, JHEP 2019 (2019) 33.
- p_W: CDF Collaboration, Phys. Rev. D 52 (1995) 4784.

Catching 0.5 eV QCD Axion Dark Matter with Hadronic Haloscopes



- $M_W(SM)$: Global Electroweak Fit, Particle Data Group (2024).

0.5 eV QCD Axion Dark Matter Rest-Mass Energy

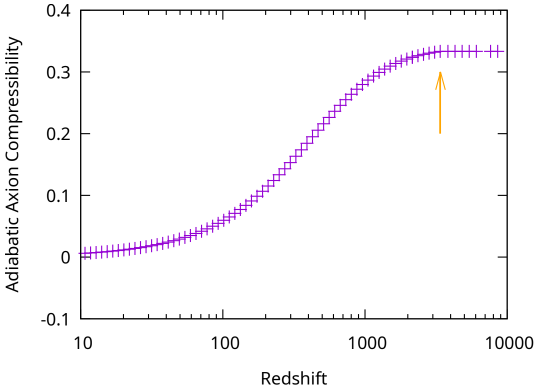
Six axions per photon:

$$\begin{aligned} m_A c^2 &= \frac{u_A}{n_A} \\ &= kT_\gamma \, \frac{n_\gamma}{n_A} \, \frac{\Omega_A h^2}{\Omega_\gamma h^2} \, \frac{u_\gamma}{n_\gamma k T_\gamma} \\ &= k \, (2.7255 \ \mathrm{K}) \, \frac{1}{\mathbf{6}} \, \frac{0.11882 \ (86)}{2.473 \times 10^{-5}} \, \frac{3! \zeta(4)}{2! \zeta(3)} \\ &= hc \times 4097 \ (30) \ \mathrm{cm}^{-1} \\ &= 0.508 \ (4) \ \mathrm{eV} \end{aligned}$$

- T_γ: D. J. Fixsen, ApJ 707 (2009) 916.
- $\Omega_A h^2 (= \Omega_c h^2)$: *Planck*, A&A 641 (2020) A6, 68% σ, analysis 2.40.
- Blackbody: Peebles, *Principles of Physical Cosmology* (1993), pgs. 134–138, 158.

From Light-Like to Matter-Like at "Matter-Radiation Equality"

Six axions per photon **at Big Bang**:



- Axion temperature $(1 + z)T_\gamma$ at redshift z
- $z_{\rm eq}$: *Planck*, A&A 641 (2020) A6, 68% σ, baseline analysis 2.40.

Why Six Axions Per Photon

One flavor of axion A_M for each quark and for each lepton M

$$A_M = M_L^- \overline{M}_L^- - M_R^+ \overline{M}_R^+ + M_L^+ \overline{M}_L^+ - M_R^- \overline{M}_R^-$$

- Each A_M made in equal amounts in Big Bang as each polarization of light.
- Twelve flavors of quarks and of leptons in Standard Model.
- Two polarizations of photons.

- Neutrinos: Same $\mathcal{C}$, $\mathcal{P}$, $\mathcal{T}$ as charged leptons, quarks

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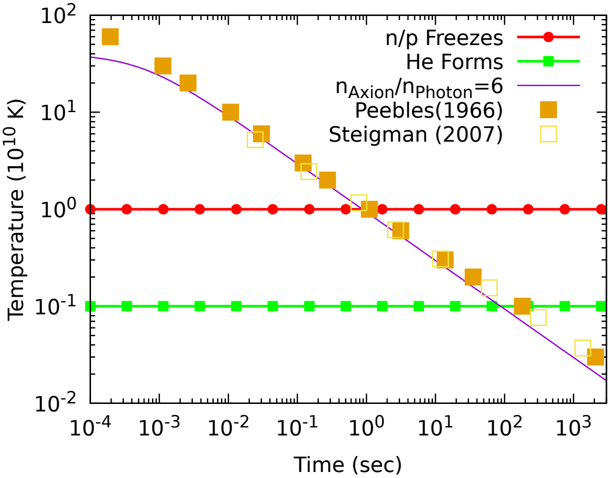
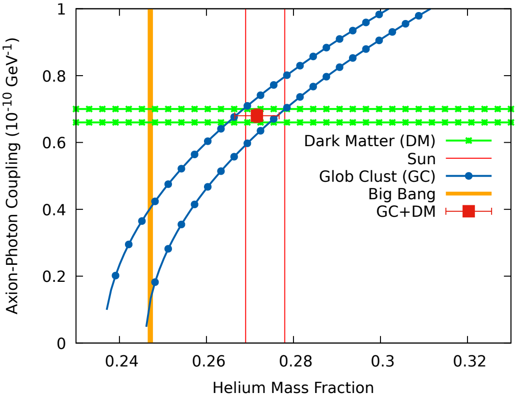
- Helicity H: R (L) spin along (against) momentum. $\mathcal{P}, \mathcal{T}$ flip H.
- Chirality P: $+$ ($-$) does not feel (does feel) weak nuclear force. $\mathcal{C}, \mathcal{P}$ flip P.
- Axion Symmetry: $\mathcal{C}A_M = +A_M, \mathcal{P}A_M = -A_M, \mathcal{T}A_M = -A_M$

Big Bang Nucleosynthesis with Six Axions per Photon



5σ More Core Helium When Globular Clusters Form



- Globular Clusters: Ayala+, PRL 113 (2014) 191302.
- Axion-Photon Coupling: Bray-Ali, arXiv:2108.12243 [hep-ph]
- Big Bang Nucleosynthesis: Pitrou+, Phys. Rep. 754 (2018) 1.

0.5 eV QCD Axion Dark Matter JWST NIRSPEC Blank-Sky Observations

- "Cold" 0.5 eV QCD axion dark matter ruled out: E. Pinetti, arXiv:2503.11753.

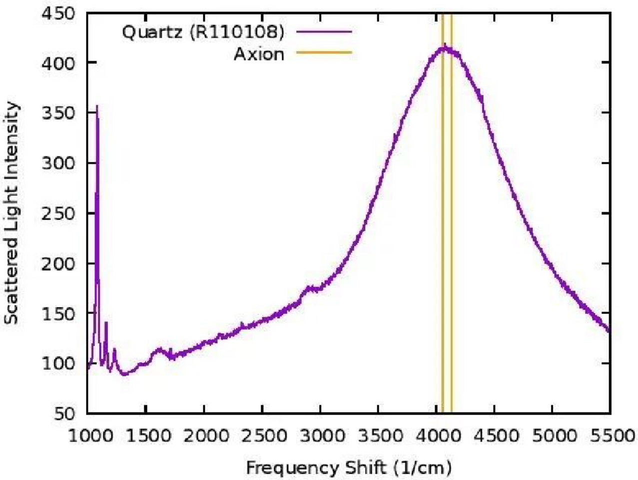
- "Cold" dark matter is in *gravitational* equilibrium: 220 $\mathrm{km/sec}$ velocity dispersion.
- This is 50 times *sharper* than 0.5 eV QCD axion dark matter.

- 0.5 eV QCD axion dark matter is in *thermal* equilibrium with CMB at T_γ.
- Velocity dispersion is $c \times \sqrt{3kT_\gamma/m_A c^2} = 11,000\ \mathrm{km/sec}$.
- The two-photon decay "line" blends into the "smooth background."

Synthetic Quartz Crystal, RRUFF Project

https://rruff.info/quartz/R110108

Making 0.5 eV QCD Axion Dark Matter with Raman Spectroscopy



Details: 532 nm, 150 mW, 4 cm^{-1}, 293 K, 1 atm, 0 T, 0 $\mathrm{V/cm}$

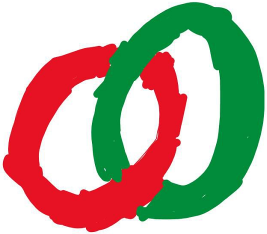
Making 0.5 eV QCD Axion Dark Matter with Tunable Infrared Laser

$$\begin{aligned}\Delta P_{\mathrm{IR}}(\nu) &= P_{\mathrm{IR}}\frac{1}{2}(m_A c^2 g_{A\gamma\gamma})^2 \frac{B_{\mathrm{DC}}^2 \pi(\phi/2)^2 L}{\mu_0 h \Delta\nu} \frac{(\Delta\nu)^2}{(\nu-\nu_A)^2+(\Delta\nu)^2} \\ &= 8\ \mathrm{pW}\left(\frac{B_{\mathrm{DC}}}{8\ \mathrm{T}}\right)^2 \left(\frac{L}{8\ \mathrm{m}}\right) \frac{(\Delta\nu)^2}{(\nu-\nu_A)^2+(\Delta\nu)^2}\end{aligned}$$

- Dipole Magnet: strength B_{DC}, length L
- Diode Laser (Sacher): power $P_{\mathrm{IR}} = 3\ \mathrm{mW}$, line-width $\Delta\nu = 1\ \mathrm{MHz}$, frequency ν
- Photodiode (Hamamatsu): $\phi = 3\ \mathrm{mm}$ diameter, $0.6\ \mathrm{pW}/\sqrt{\mathrm{Hz}}$ NEP at $2.45\ \mu\mathrm{m}$
- $\nu_A = m_A c^2/h = 122\,302.4\ (5.4)\ \mathrm{GHz}$ [44 ppm] (Bray-Ali, arXiv:2108.12243)
- Modulate ν through $\nu_A \pm 5.4\ \mathrm{GHz}$ window with diode laser controller piezo voltage
- Lock-in amplify, notch-filtered, pre-amplified photodiode current: 90 dB CMMR

0.5 eV QCD Axion Dark Matter

To see a World in a Grain of Sand
And a Heaven in a Wild Flower,
Hold Infinity in the palm of your hand
And Eternity in an hour.



Noah Bray-Ali, 0.5 eV QCD Axion Dark Matter, arxiv.org:2108.12243 [hep-ph]