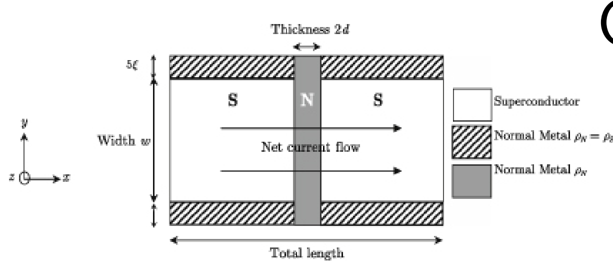
AXION MASS ESTIMATES FROM RESONANT JOSEPHSON JUNCTIONS



Christian Beck
Queen Mary, University of London

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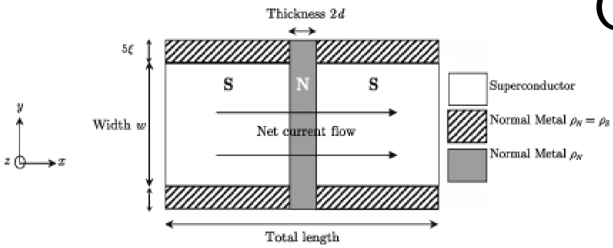

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Contents

1 Candidates for dark matter particles: WIMPS, axions, ...

- WIMPS (weakly interacting particles): mass $\sim \mathbf{100}\boldsymbol{GeV}$
  motivated by supersymmetry (lightest supersymmetric particle should be stable)
- axions: mass $\sim \mathbf{100}\boldsymbol{\mu eV}$
  motivated by Standard Model of Particle Physics, no supersymmetry needed (solution of strong CP problem)
- Both are cold dark dark matter (CDM) but with subtle differences for halo physics. Axions most likely to form a very cold quantum liquid, a Bose-Einstein condensate (Sikivie et al 2009)

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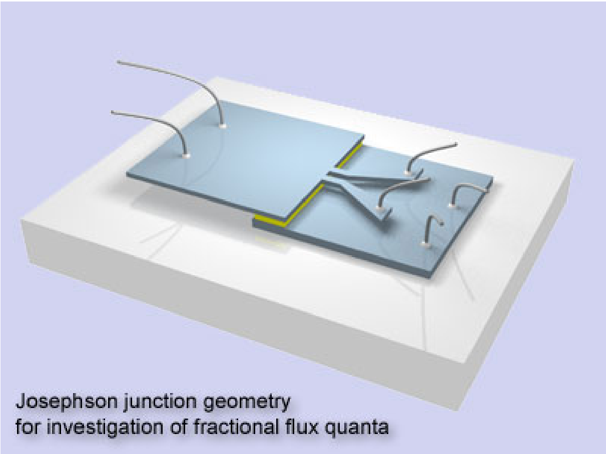
Original motivation for axions: QCD (Peccei Quinn 1977).

2 Recent proposals for new direct detection methods for axions

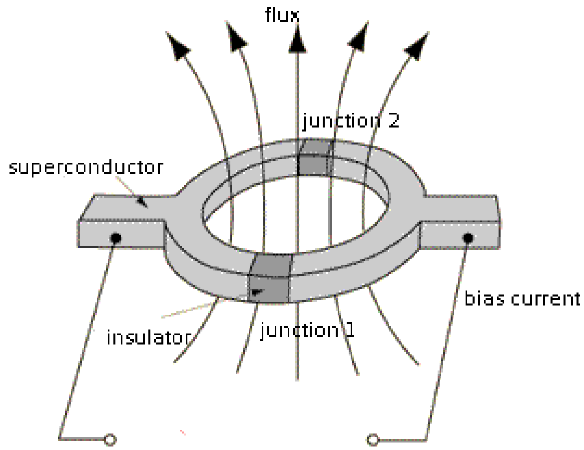
Very recently (2013-14), three completely new ideas to detect dark matter axions in the lab have been suggested. All have in common that they search for coherent axion oscillations, i.e. a small electric signal that oscillates with the axion mass $\hbar\omega = m_a c^2$ (this frequency is in the GHz region). Still the details of these proposals, of course, are very different.

- P.W. Graham, S.Rajendran, PRD 88, 035023 (2013): Use NMR (nuclear magnetic resonance) setup
- C. Beck, PRL 111, 231801 (2013): Use S/N/S Josephson junction
- P. Sikivie, N. Sullivan, D.B. Tanner, PRL 112, 131301 (2014): Use LC circuit cooled down to mK temperatures

3 Josephson junctions as axion detectors



- Josephson junction (JJ) consists of two superconductors separated by a weak-link region (yellow)
- weak link-region is an insulator for tunnel junctions and a normal metal for S/N/S junctions
- distance between superconducting plates: $d \sim 1nm$ for tunnel junctions, $d \sim 1\mu m$ for S/N/S junctions
- If voltage V is applied then JJ emits Josephson radiation of frequency $\hbar\omega_J = 2eV$



- Important technical device: Two Josephson junctions can form a ‘bounded state’, a SQUID (Superconducting Quantum Interference Device) $\boldsymbol{\delta_1 - \delta_2 = 2\pi \frac{\Phi}{\Phi_0}}$
- Used e.g. for high-precision magnetic flux measurements
- See any textbook on superconductivity (e.g. ‘Introduction to Superconductivity’ by M. Tinkham) how this works

Axion field $\boldsymbol{a = f_a \theta}$. Classical eq. of motion of the axion misalignement angle $\boldsymbol{\theta}$:

$$\ddot{\theta} + \Gamma\dot{\theta} + \frac{m_a^2 c^4}{\hbar^2}\sin\theta = \frac{g_\gamma}{\pi}\frac{1}{f_a^2}c^3 e^2 \vec{E}\vec{B} \tag{1}$$

$\boldsymbol{f_a}$ axion coupling, $\boldsymbol{m_a}$ axion mass, $\boldsymbol{g_\gamma = -0.97}$ for KSVZ axions, or $\boldsymbol{g_\gamma = 0.36}$ for DFSZ axions. In the early universe, $\boldsymbol{\Gamma = 3H}$, where $\boldsymbol{H}$ is the Hubble parameter. $\vec{E}$, $\vec{B}$: external electric and magnetic field.

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Compare this with the eq. of motion of a Josephson junction (JJ). The phase difference δ of a JJ driven by a bias current I satisfies

$$\ddot{\delta} + \frac{1}{RC}\dot{\delta} + \frac{2eI_c}{\hbar C}\sin\delta = \frac{2e}{\hbar C}I \tag{2}$$

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The numerical values of the coefficients for typical QCD axion physics and typical JJ physics are also quite similar (see C. Beck, Mod. Phys. Lett. 26, 2841 (2011) for examples).

Natural to think about possible interactions between JJs and axions.

Field equations of axions in a Josephson junction environment:

$$\ddot{\theta} + \Gamma\dot{\theta} - c^2\nabla^2\theta + \frac{m_a^2 c^4}{\hbar^2}\sin\theta = -\frac{g_\gamma}{4\pi^2}\frac{1}{f_a^2}c^3 e^2 \vec{E}\vec{B} \quad (3)$$

$$\nabla \times \vec{B} - \frac{1}{c^2}\frac{\partial \vec{E}}{\partial t} = \mu_0 \vec{j} + \frac{g_\gamma}{\pi}\alpha\frac{1}{c}\vec{E} \times \nabla\theta - \frac{g_\gamma}{\pi}\alpha\frac{1}{c}\vec{B}\dot{\theta} \quad (4)$$

$$\nabla \vec{E} = \frac{\rho}{\epsilon_0} + \frac{g_\gamma}{\pi}\alpha c \vec{B}\nabla\theta \quad (5)$$

$$\ddot{\delta} + \frac{1}{RC}\dot{\delta} + \frac{2eI_c}{\hbar C}\sin\delta = \frac{2e}{\hbar C}(I + I_a) \quad (6)$$

$$P_{a\to\gamma} = \frac{1}{16\beta_a}(g_\gamma\ Bec\ L)^2 \frac{1}{\pi^3 f_a^2}\frac{1}{\alpha}\left(\frac{\sin\frac{qL}{2\hbar}}{\frac{qL}{2\hbar}}\right)^2 \quad (7)$$

m_a axion mass, f_a axion coupling constant, $\beta_a = v_a/c$ axion velocity, $\vec{E}$ electric field, $\vec{B}$ magnetic field, $g_\gamma = -0.97)$ for KSVZ axions, $g_\gamma = 0.36$ for DFSZ axions, q momentum transfer, $P_{a\to\gamma}$ probability of axion decay, I_c critical current of junction.

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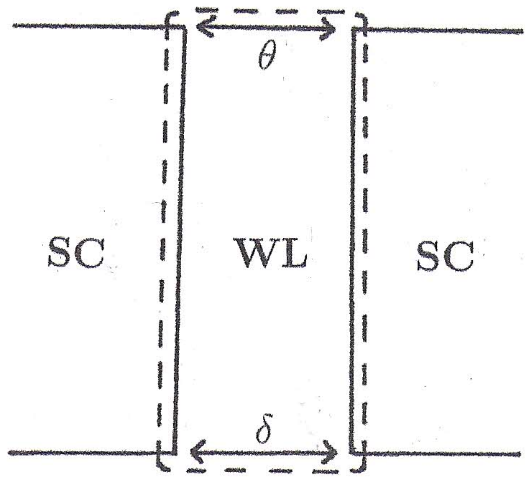
Inside WL equations allow for an axion-induced supercurrent with linearly increasing phase difference, a nontrivial solution.

- Field equations have a different solution $a(\vec{x},t) = f_a\theta(\vec{x},t)$ for $\vec{x}$ inside and outside the weak link (WL)
- $\vec{x} \notin$ WL: Ordinary dark matter physics
- $\vec{x} \in$ WL: SQUID-like physics, axion creates a phase difference
- Special care to be taken at the boundary region of WL.
- Formally (mathematically!), there is a huge magnetic field at the boundary of WL which makes axions decay via Josephson radiation
- Overall effect is that axions passing through WL tunnel the junction but triggers at the same time additional Cooper pairs to flow if the axion mass is at resonance with the Josephson frequyency, $m_a c^2 = \hbar\omega_J = 2eV$.
- In particular, for S/N/S junctions the axion triggers multiple Andreev reflections

For more details, see
C. Beck, PRL 111, 231801 (2013)
C. Beck, arXiv:1403.5676

Inside WL, effect of axion is similar to a second Josephson junction which produces an (ordinary electromagnetic) phase difference $\boldsymbol{\theta}$ in addition to the phase difference $\boldsymbol{\delta}$ of the measuring JJ.



Joint axion Josephson wave function $\boldsymbol{\Psi} = |\boldsymbol{\Psi}| \boldsymbol{e}^{i\varphi}$ must be single-valued. This means that for a given closed integration curve (dashed line above) one has including the interior region of the two superconductors (SC), the weak link region of the Josephson junction with phase difference $\boldsymbol{\delta}$ and the axion with phase difference $\boldsymbol{\theta}$, one has

$$\int_{SC} \nabla\varphi \cdot d\vec{s} + \delta + \theta = 0 \mod 2\pi \tag{8}$$

$\Longrightarrow \boldsymbol{\delta}, \boldsymbol{\theta}$ are no longer independent of each other but influence each other.

In the presence of a vector potential $\vec{A}$ define gauge-invariant phase differences γ_i by

$$\gamma_1 := \delta - \frac{2\pi}{\Phi_0}\int_{weak\ link\ 1} \vec{A}\cdot d\vec{s} \tag{9}$$

$$\gamma_2 := \theta - \frac{2\pi}{\Phi_0}\int_{weak\ link\ 2} \vec{A}\cdot d\vec{s}. \tag{10}$$

Standard formalism exploiting uniqueness of axion-Josephson wave function then yields

$$\hat{\gamma}_1 - \gamma_2 = 2\pi\frac{\Phi}{\Phi_0} \mod 2\pi, \tag{11}$$

Φ: magnetic flux through the area enclosed by the chosen closed line of integration, $\Phi_0 = \frac{h}{2e}$: flux quantum, $\hat{\gamma}_1 := -\gamma_1$.

If $\Phi << \Phi_0$ or if Φ is an integer multiple of Φ_0 then

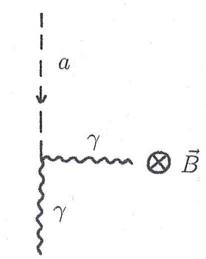
$$\gamma_2 = \hat{\gamma}_1 \tag{12}$$

meaning the phase difference θ created by the axion synchronizes with the Josephson phase difference δ.

In the boundary, a formal magnetic field occurs in the calculations

$$\boldsymbol{B = \frac{2\pi\Gamma f_a^2 d}{g_\gamma \hbar c^3 e}}. \tag{13}$$

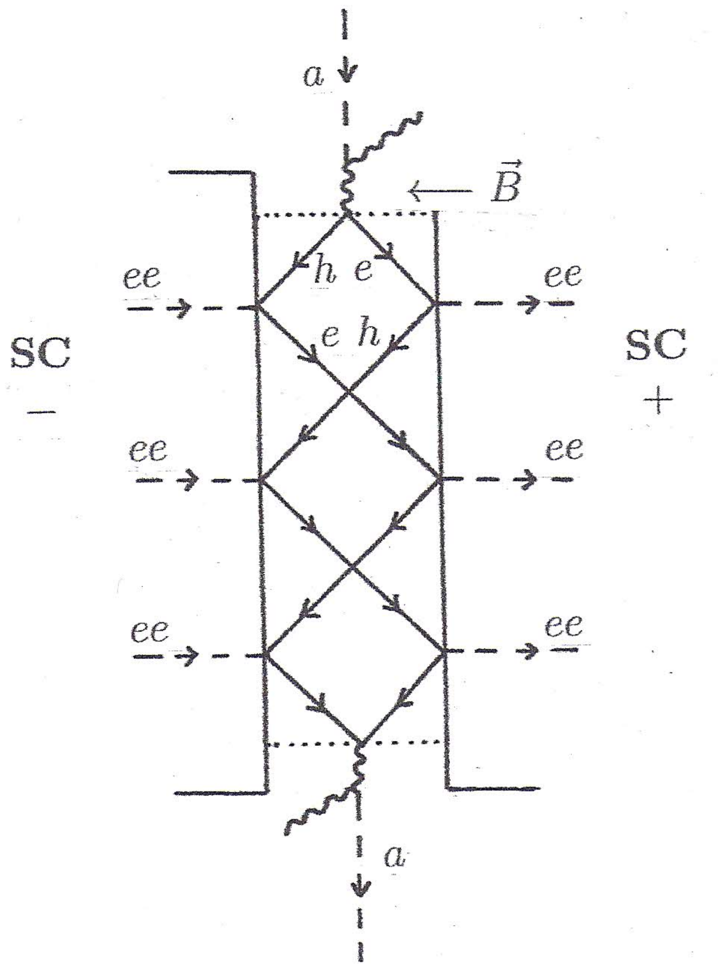
This formal $\boldsymbol{B}$-field is huge! $\boldsymbol{B \sim 10^{20} T}$. Axion decays but triggers Cooper pair flow at the same time.



Primakoff effect:

$$\boldsymbol{P_{a\to\gamma} = \frac{1}{4\beta_a}(g\ Bec\ L)^2 \left(\frac{sin\frac{qL}{2\hbar}}{\frac{qL}{2\hbar}}\right)^2 = P_{\gamma\to a}} \tag{14}$$

"Renormalization": The very large formal $\boldsymbol{B}$-field can always be expressed by the flux through a tiny area — the flux $\boldsymbol{\Phi = B\cdot}$ tiny area is just of ordinary size. Also, the final result for the critical current produced by axions does not depend on the huge formal $\boldsymbol{B}$-field, it drops out of the equations.



Microscopic model of what happens in an S/N/S junction.
Axion tunnels through junction (ATJ) and triggers (by multiple Andreev reflection) the transport of n Cooper pairs ($n = 3$ in the example plotted)

Some relevant formulas (C. Beck, PRL 111, 231801 (2013), C. Beck, arXiv:1403.5676):

Signal shape in RSJ approximation (Shapiro step without externally applied microwave radiation)

$$I_s(V) = \frac{P_s}{4}(RI_c)^2 \frac{1}{V^2}\left[\frac{V+V_s}{(V+V_s)^2+(\frac{\delta V}{2})^2} + \frac{V-V_s}{(V-V_s)^2+(\frac{\delta V}{2})^2}\right]. \tag{15}$$

$2eV_s = m_a c^2$ (V_s: signal voltage)

Total signal current produced by axions in S/N/S junction:

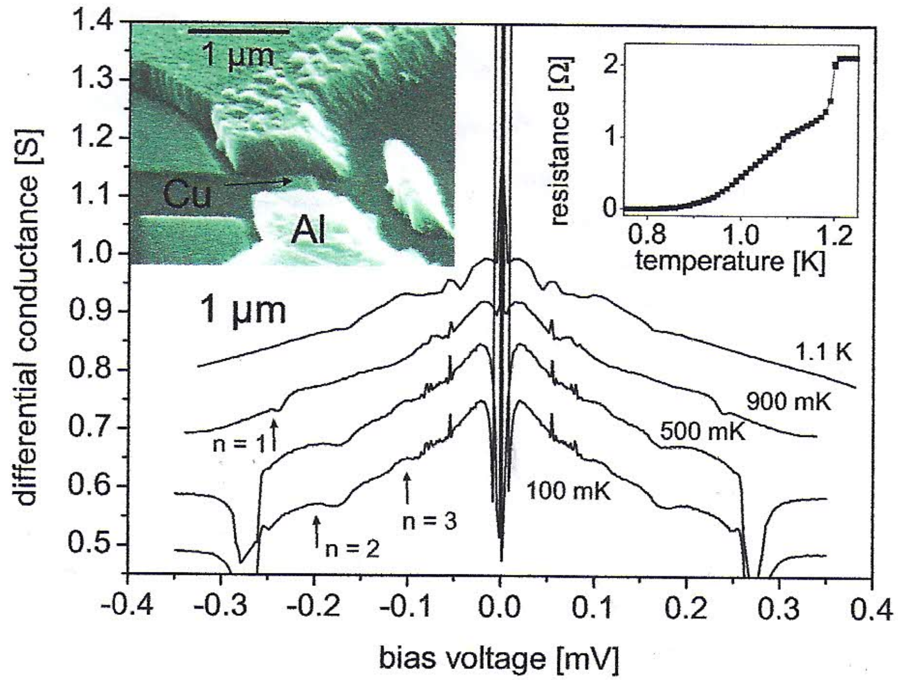
$$I_s = \int G_s dV = \frac{N_a}{\tau} \cdot n \cdot 2e = \frac{\rho_a}{m_a c^2} vA \cdot n \cdot 2e \tag{16}$$

where N_a/τ is the number of axions hitting the normal metal region per time unit τ. ρ_a: axionic dark matter density near the earth, $v \approx 2.3 \cdot 10^5 \frac{m}{s}$, A: Area of weak-link region of JJ.

Optimum Josephson axion detector should satisfy $dn \approx \frac{m_a c^2}{\sqrt{\alpha h \rho_a v_a}}$

$n \approx \frac{2\Delta}{eV} + 1$ (Δ: gap energy, n: number of Andreev reflections)

4 An observed candidate signal



C. Hoffmann, F. Lefloch, M. Sanquer, B. Pannetier, Phys. Rev. B 70, 180503(R) (2004)

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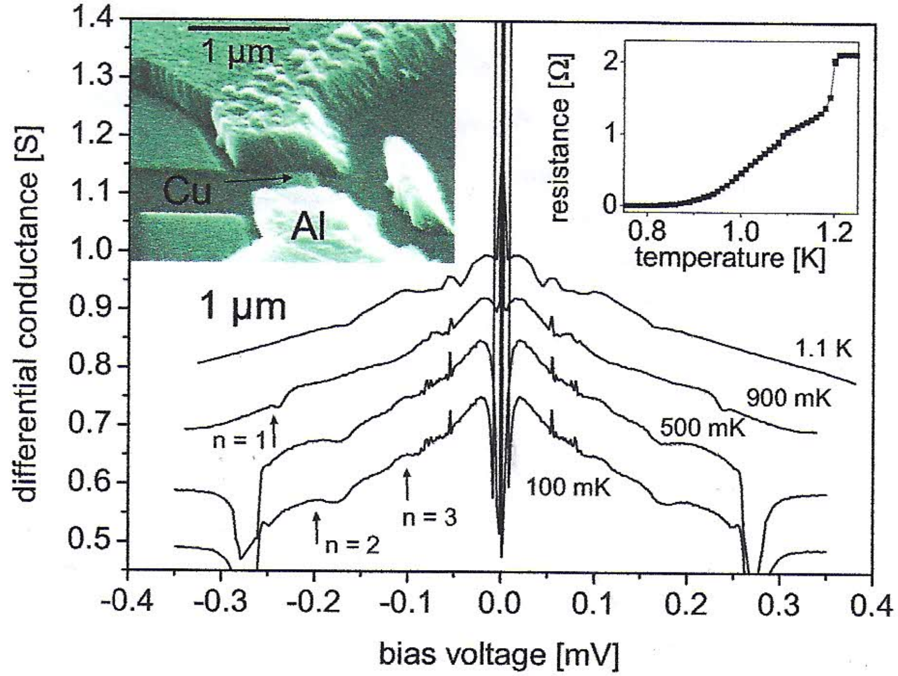

C. Hoffmann, F. Lefloch, M. Sanquer, B. Pannetier, Phys. Rev. B 70, 180503(R) (2004)
They measured differential conductivity $G(V) = dI/dV$ and observed signal peak 'of unknown origin' at $V_s = \pm 0.055 mV$.

Observed signal position V_s can be used to estimate the axion mass: $m_a c^2 = 2eV_s$.

Result: $m_a c^2 = (110 \pm 2)\mu$eV

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Result: $\boldsymbol{\rho_a \sim 0.05}GeV/\boldsymbol{cm^3}$

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Astrophysical models suggest that the galactic dark matter density ρ_d near the earth is about $\rho_d = (0.3 \pm 0.1) GeV/cm^3$ (Weber, de Boer 2010). This includes all kinds of dark matter particles. The above estimated value for ρ_a would suggest that axions account only for about 17% of dark matter in halo. Rest could be e.g. WIMPS.

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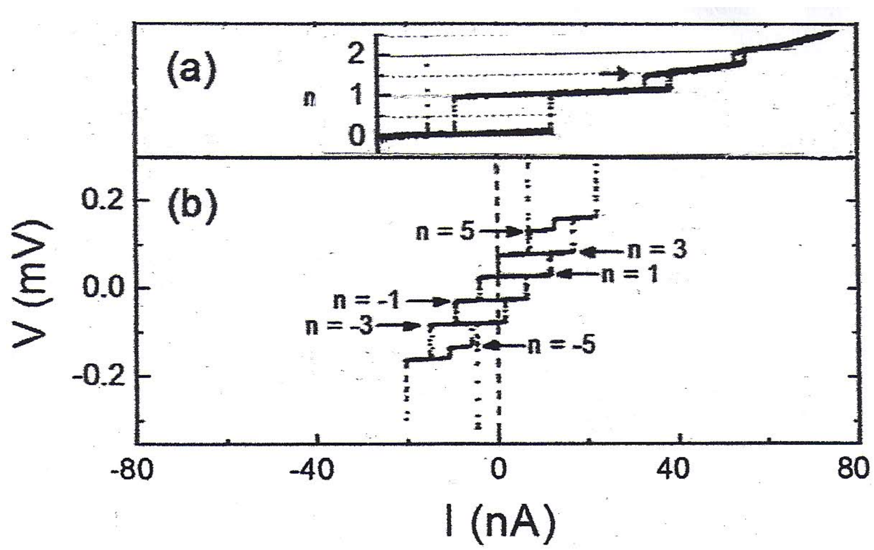
Recent analysis of galactic rotation curves based on axionic Bose Einstein condensate consistent with the above axion density: M.-H. Li, Z.-B. Li, PRD 89, 103512 (2014)

Need further measurements to confirm (or refute) dark matter nature of the observed candidate signal:

- Does the signal survive careful shielding of the junction from any external microwave radiation? A signal produced by axions cannot be shielded.
- Should look for a possible small dependence of the measured signal intensity on the spatial orientation of the metal plate relative to the galactic axion flow (a precise directional measurement would be extremely helpful).
- The velocity v by which the earth moves through the axionic Bose Einstein condensate of the galactic halo exhibits a yearly modulation of about 10%, with a maximum in June and a minimum in December. JJ signal peak intensity predicted to exhibit a similar modulation as seen in the DAMA/LIBRA experiment in WIMP searches.
- Independent experiments (such as upgraded versions of ADMX, see e.g. G. Rybka, A. Wagner, arXiv:1403.3121) would need to confirm the suggested value of $m_a c^2 = 110 \mu eV$.

Three other Josephson experiments (performed by different experimental groups with different types junctions) also contain some measured anomalies which seem consistent with an axion mass of about 110μeV, see C. Beck, arXiv:1403.5676 for more details.



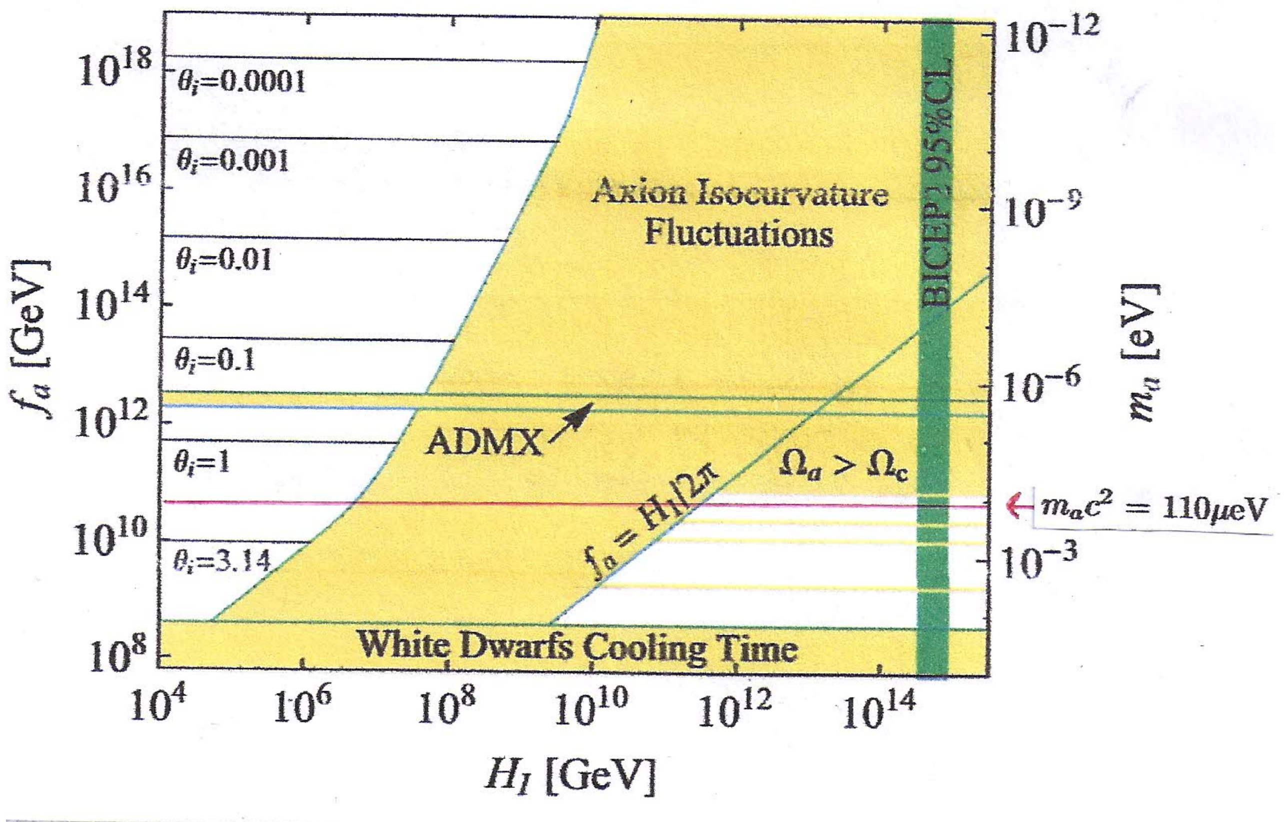
Anomalous Shapiro steps as measured by Bae et al., PRB 77, 144501 (2008)

5 Axion mass estimates in the light of BICEP2

Recent BICEP2 results [P.A.R. Ade et al., PRL 112, 241101 (2014)] exclude 'half' of the axion parameter space.

In particular, it now seems that the PQ symetry breaking phase transition must happen after inflation.

How does that fit with our mass prediction of the QCD axion mass of about 110μeV, assuming that the observed small resonance signals in JJs are due to axions?



(picture adopted from L. Visinelli and P. Gondolo, arXiv:1403.4594)

QCD axion coupling constant f_a versus Hubble parameter H_I at the end of inflation.
Yellow region: excluded.
Red line: Suggested axion mass from Josephson resonances [C.Beck, PRL 111, 231801 (2013)].
Green region: Inflationary energy scale H_I from BICEP2 measurements.

6 Summary

- We have discussed a macroscopic quantum effect in Josephson junctions, a kind of axionic Josephson effect.
- Does not change large-scale dark matter physics
- Axions hitting the weak-link region trigger the transport of additional Cooper pairs. Leads to a small measurable signal for the differential conductivity if axion mass resonates with Josephson frequency.
- Effect is particularly strong in S/N/S junctions which have a much larger weak-link region than tunnel junctions.
- Candidate signal of unknown origin has been observed in measurements of Hoffmann et al. Can be interpreted in terms of an axion mass of 0.11 meV and a local axionic dark matter density of about 0.05 GeV/cm^3. C. Beck, Phys. Rev. Lett. 111, 231801 (2013). Further systematic measurements needed.