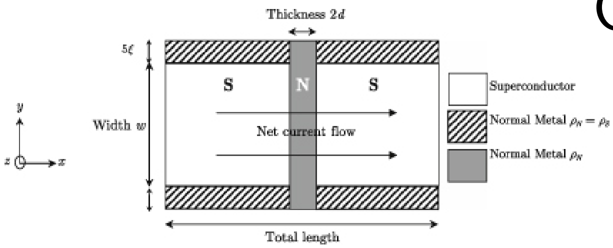
Axionic dark matter searches with Josephson junctions and SQUIDS



Christian Beck
Queen Mary, University of London

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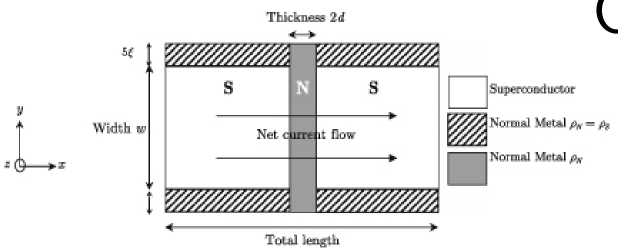

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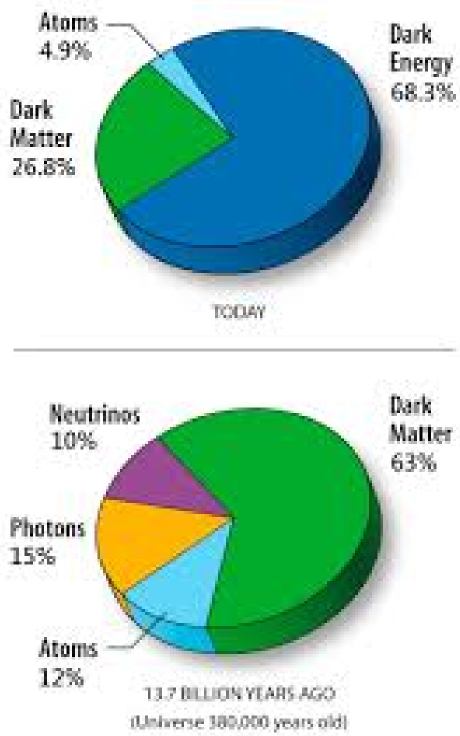
1 Introduction: Astrophysical evidence for dark matter



observational evidence for dark matter from galaxy rotation curves, gravitational lensing, CMB, structure formation, ...

2 Two main candidates for dark matter particles: WIMPS and 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)

2 Two main candidates for dark matter particles: WIMPS and axions

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

Strong CP problem...

- The QCD lagrangian contains a CP-violating term:

$$L_\Theta = \left(\theta_{QCD} + \arg\det M_q\right) \frac{\alpha_s}{8\pi} G_{\mu\nu a} \tilde{G}_a^{\mu\nu} = \Theta \frac{\alpha_s}{8\pi} G \tilde{G}$$

Gluon field strength

Phase from QCD vacuum

Quark mass matrix

$\boxed{-\pi \le \Theta \le \pi}$

- This induces a huge electric dipole moment for the neutron:

$$|d_n| \approx |\Theta|\, 10^{-16}\, e\,\mathrm{cm} \quad \text{vs} \quad |d_n| < 3 \times 10^{-26}\, e\,\mathrm{cm}$$

PDG 2010

Theory

Experiment

$$\rightarrow \quad \Theta < 10^{-9}$$

The strong CP problem
= Why is Θ so small??

Axion as a solution...

Peccei & Quinn 1977
Wilczek 1978
Weinberg 1978

- Introduce a new dynamical variable a(x) with coupling to GG:

$$L_\Theta \rightarrow L_a = \frac{1}{2}(\partial_\mu a)^2 - \frac{\alpha_s}{8\pi}\frac{a(x)}{f_a} G\tilde{G}$$

Axion = fundamentally massless pseudoscalar satisfying $a \rightarrow a + \text{const.}$

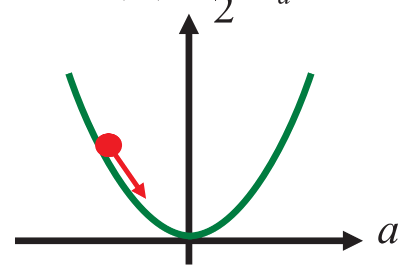
Axion decay constant; Peccei-Quinn scale

- aGG term induces axion mixing with π^0, η and η'.

→ Effective mass for the axion:

$$\boxed{m_a \approx \frac{\sqrt{m_u m_d}}{m_u + m_d}\frac{f_\pi}{f_a} m_\pi = \frac{6.0\,\text{eV}}{f_a/10^6\,\text{GeV}}}$$

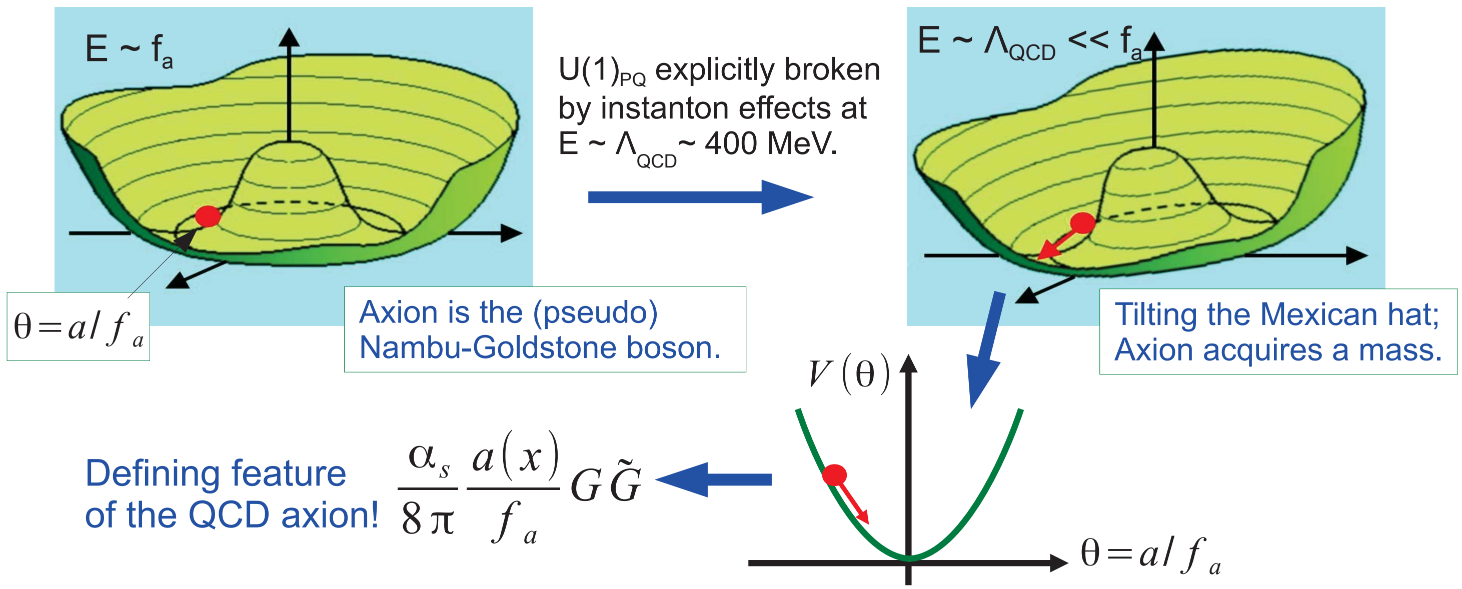
$$V(a) = \frac{1}{2} m_a^2 a^2 + \ldots$$



→ Effective potential V(a) drives a(x) to zero.
CP symmetry is dynamically restored!

Implementing the PQ mechanism: generic recipe...

- Introduce a new complex scalar field with potential $V(|\varphi|)$, which couples (directly or indirectly) to (SM or exotic) quark(s).
- Impose a chiral $U(1)_{PQ}$ symmetry, spontaneously broken at $E \sim f_a$.



Pictures courtesy of Y. Wong, Aachen

All based on the same idea...

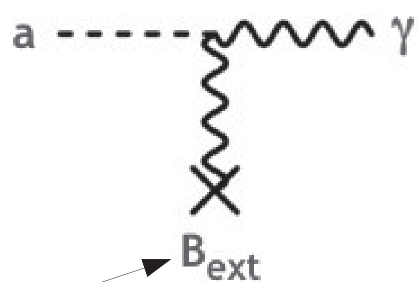
- Exploit axion coupling with electromagnetic field:

$$L_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma} \boldsymbol{E} \cdot \boldsymbol{B}\, a$$

- Make use of the inverse Primakoff effect to detect astrophysical and cosmological axions.

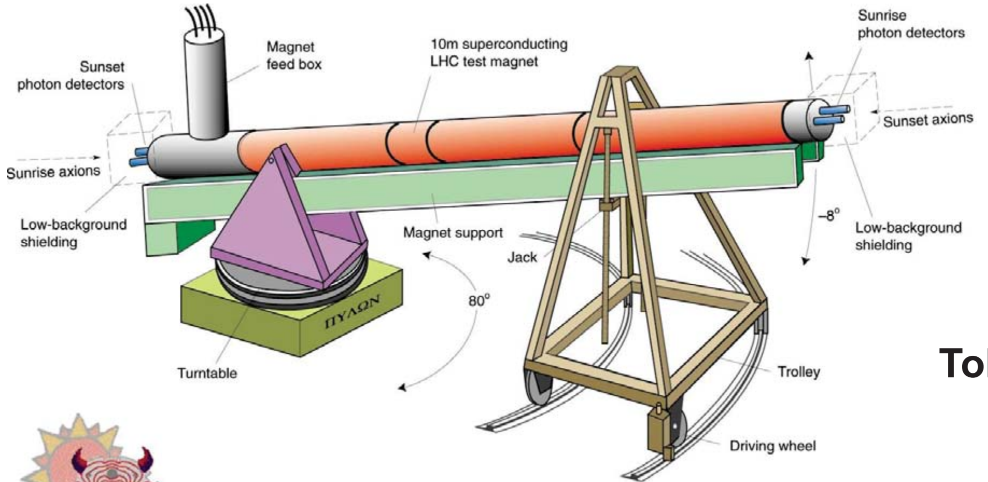
Sikivie 1983

Primakoff effect:
Production of neutral pseudoscalar mesons in an external E or B field from photons.



Magnet in your lab

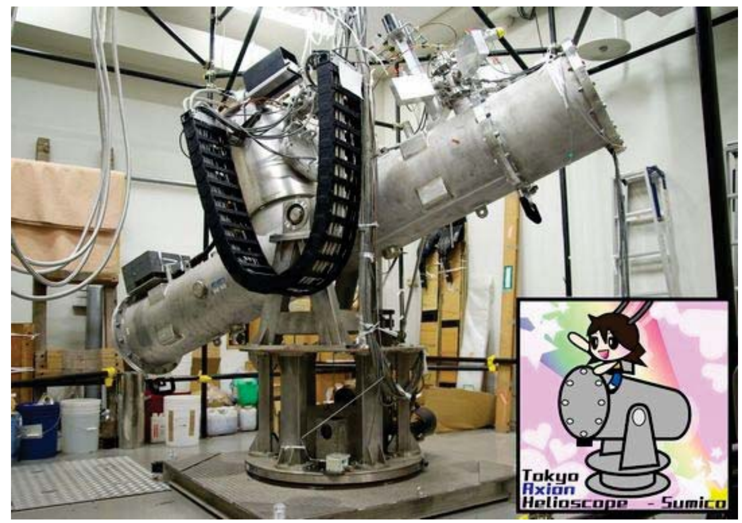
Axion to photon conversion



Cern Axion Solar Telescope

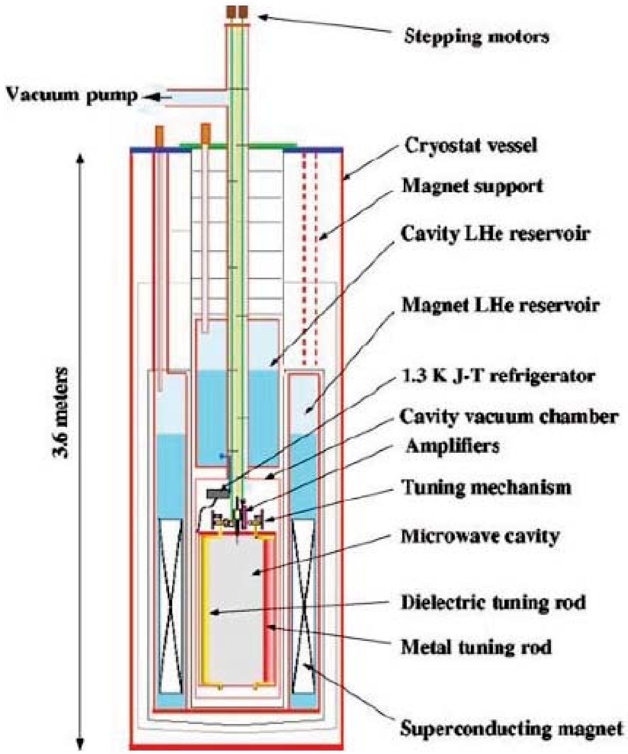
CERN Axion Solar Telescope (CAST)
L = 9.26 m
B = 9 T
(Decomissioned LHC test magnet)

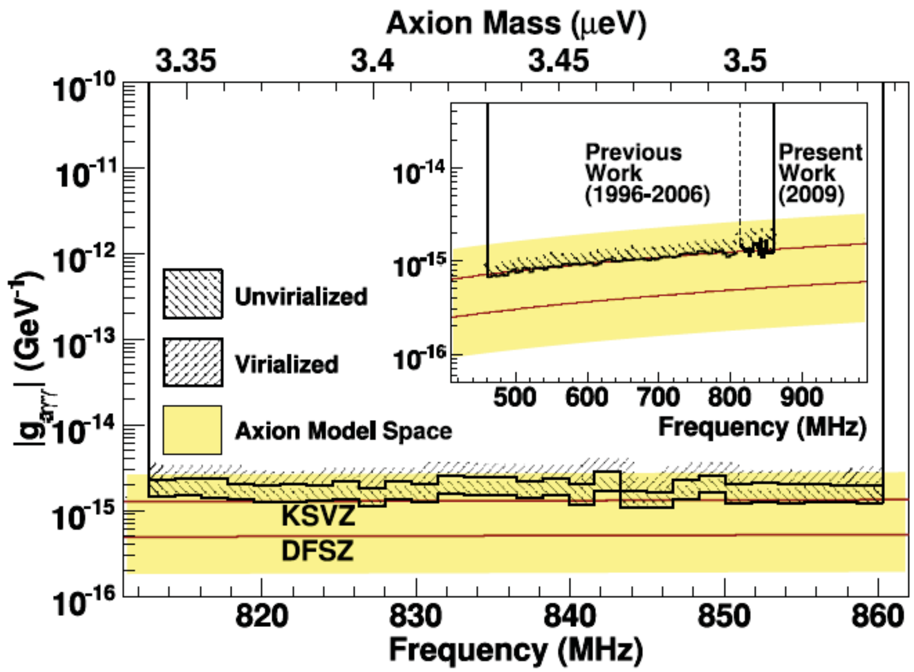
Tokyo Axion Helioscope "Sumico"
L = 2.3 m
B = 4 T



Axion Dark Matter EXperiment (ADMX)

Asztalos et al. PRL 2010





B = 8.5 T; h = 1 m
Q ~ 10^5; d = 0.6 m

Between 1996 and 2009, already excluded KSVZ (hadronic) axions in the mass range:

$$1.9 < m_a / \mu\,\mathrm{eV} < 3.53 \qquad (f_a \sim 10^{12}\,\mathrm{GeV})$$

Where we stand...

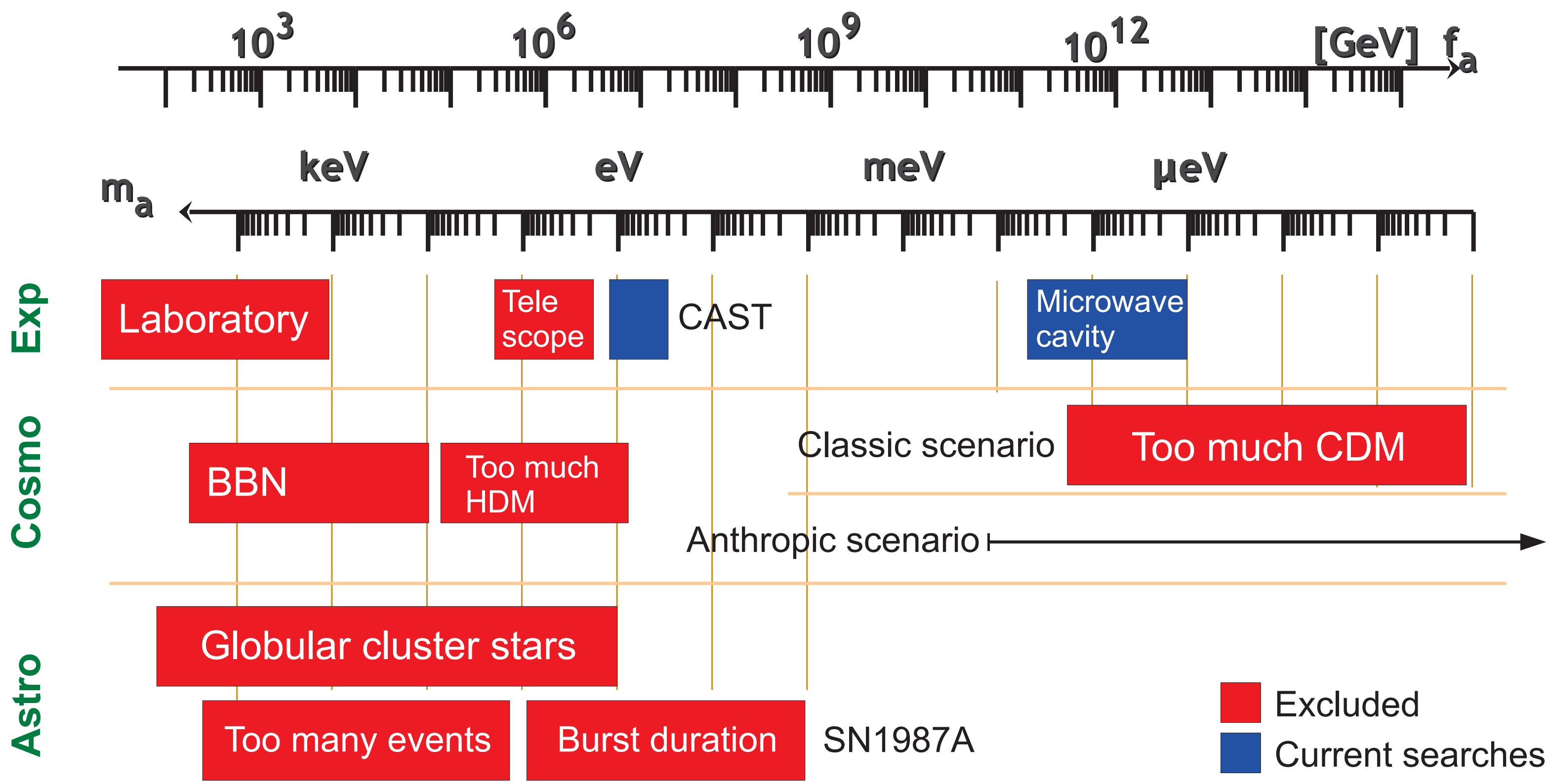
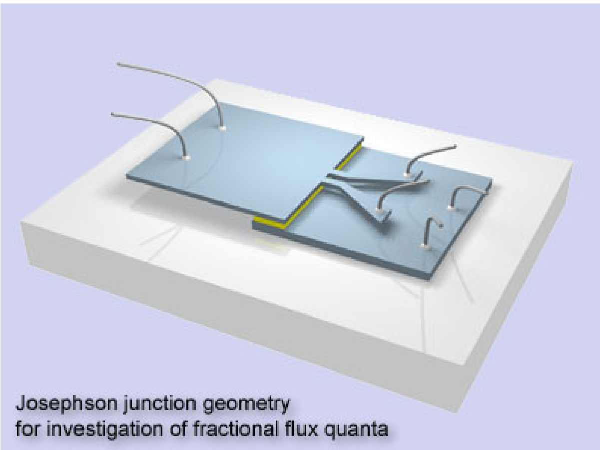


Figure adapted from G. Raffelt

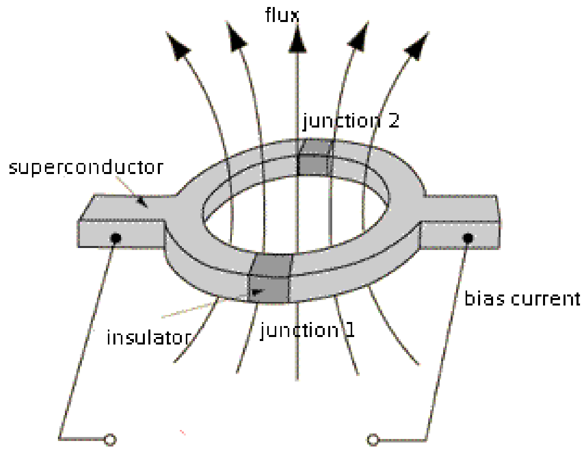
Very recently (2013-14), four completely new ideas to detect dark matter axions in the lab have been suggested. All have in common that they search for coherent axion oscillations, i.e. a small electric signal that oscillates with the axion mass $\hbar\omega = m_a c^2$ (this frequency is in the GHz region).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

- P.W. Graham, S.Rajendran, Phys. Rev. D 88, 035023 (2013): Use NMR (nuclear magnetic resonance) setup
- C. Beck, Phys. Rev. Lett. 111, 231801 (2013): Use S/N/S Josephson junctions
- P. Sikivie, N. Sullivan, D.B. Tanner, Phys. Rev. Lett. 112, 131301 (2014): Use LC circuit cooled down to mK temperatures
- B.M. Roberts et al., Phys. Rev. Lett. 113, 081601 (2014): Use parity non-conserving transitions in heavy atoms

4 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)
- 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 $a = f_a\theta$. Classical eq. of motion of the axion misalignement angle θ:

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

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

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

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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

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

I_c: critical current of the junction, R: normal resistance, C: capacity of the junction.

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Equations of motion are basically the same.

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).

Hence it is natural to think about possible interactions between JJs and axions.

Field equations of axions in a Josephson junction environment:

$$\ddot{\boldsymbol{\theta}} + \Gamma\dot{\boldsymbol{\theta}} - \boldsymbol{c}^2\nabla^2\boldsymbol{\theta} + \frac{\boldsymbol{m}_a^2\boldsymbol{c}^4}{\boldsymbol{\hbar}^2}\sin\boldsymbol{\theta} = -\frac{\boldsymbol{g}_\gamma}{4\boldsymbol{\pi}^2}\frac{1}{\boldsymbol{f}_a^2}\boldsymbol{c}^3\boldsymbol{e}^2\vec{\boldsymbol{E}}\vec{\boldsymbol{B}} \tag{3}$$

$$\nabla \times \vec{\boldsymbol{B}} - \frac{1}{\boldsymbol{c}^2}\frac{\partial\vec{\boldsymbol{E}}}{\partial \boldsymbol{t}} = \boldsymbol{\mu}_0\vec{\boldsymbol{j}} + \frac{\boldsymbol{g}_\gamma}{\boldsymbol{\pi}}\boldsymbol{\alpha}\frac{1}{\boldsymbol{c}}\vec{\boldsymbol{E}} \times \nabla\boldsymbol{\theta} - \frac{\boldsymbol{g}_\gamma}{\boldsymbol{\pi}}\boldsymbol{\alpha}\frac{1}{\boldsymbol{c}}\vec{\boldsymbol{B}}\dot{\boldsymbol{\theta}} \tag{4}$$

$$\nabla\vec{\boldsymbol{E}} = \frac{\boldsymbol{\rho}}{\boldsymbol{\epsilon}_0} + \frac{\boldsymbol{g}_\gamma}{\boldsymbol{\pi}}\boldsymbol{\alpha}\boldsymbol{c}\vec{\boldsymbol{B}}\nabla\boldsymbol{\theta} \tag{5}$$

$$\ddot{\boldsymbol{\delta}} + \frac{1}{\boldsymbol{RC}}\dot{\boldsymbol{\delta}} + \frac{2\boldsymbol{eI}_c}{\boldsymbol{\hbar C}}\sin\boldsymbol{\delta} = \frac{2\boldsymbol{e}}{\boldsymbol{\hbar C}}\boldsymbol{I} \tag{6}$$

$$\boldsymbol{P}_{a\to\gamma} = \frac{1}{16\boldsymbol{\beta}_a}(\boldsymbol{g}_\gamma\ \boldsymbol{Bec}\ \boldsymbol{L})^2\frac{1}{\boldsymbol{\pi}^3\boldsymbol{f}_a^2}\frac{1}{\boldsymbol{\alpha}}\left(\frac{\sin\frac{qL}{2\hbar}}{\frac{qL}{2\hbar}}\right)^2 \tag{7}$$

$\boldsymbol{m}_a$ axion mass, $\boldsymbol{f}_a$ axion coupling constant, $\boldsymbol{\beta}_a = \boldsymbol{v}_a/\boldsymbol{c}$ axion velocity, $\vec{\boldsymbol{E}}$ electric field, $\vec{\boldsymbol{B}}$ magnetic field, $\boldsymbol{g}_\gamma = -0.97$) for KSVZ axions, $\boldsymbol{g}_\gamma = 0.36$ for DFSZ axions, $\boldsymbol{q}$ momentum transfer, $\boldsymbol{P}_{a\to\gamma}$ probability of axion decay, $\boldsymbol{I}_c$ critical current of junction.

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

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

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

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

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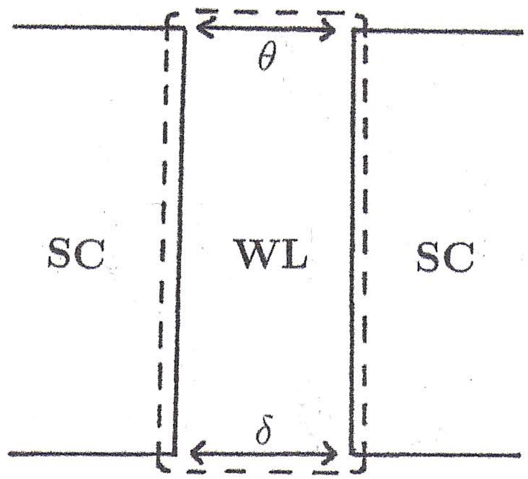
Equations allow for an axion-induced supercurrent with linearly increasing phase difference. A linearly increasing axion phase induces a large B-field, vertically entering axions decay.

If axion decays, its effect is similar to a second Josephson junction with phase difference $\boldsymbol{\theta}$ in addition to the measuring one with phase difference $\boldsymbol{\delta}$.



Joint axion Josephson wave function $\boldsymbol{\Psi} = |\boldsymbol{\Psi}| e^{i\varphi}$ must be single-valued. This means that for a given closed integration curve (dashed line above) one has

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

$\Longrightarrow$ $\boldsymbol{\delta}, \boldsymbol{\theta}$ 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

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

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

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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, $\hat{\gamma}_1 := -\gamma_1$.

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

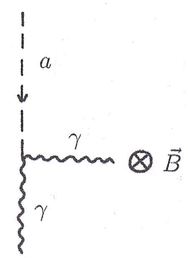
$$\gamma_2 = \hat{\gamma}_1 \tag{12}$$

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

Can calculate the formal magnetic field that would be there if axion were still present in the weak link:

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

This formal $\boldsymbol{B}$-field is huge, but it's only formal: $\boldsymbol{B \sim 10^{20} T}$. It means the axion immediately decays into 2 microwave photons when entering the weak-link region.



Primakoff effect:

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

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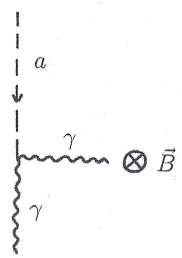

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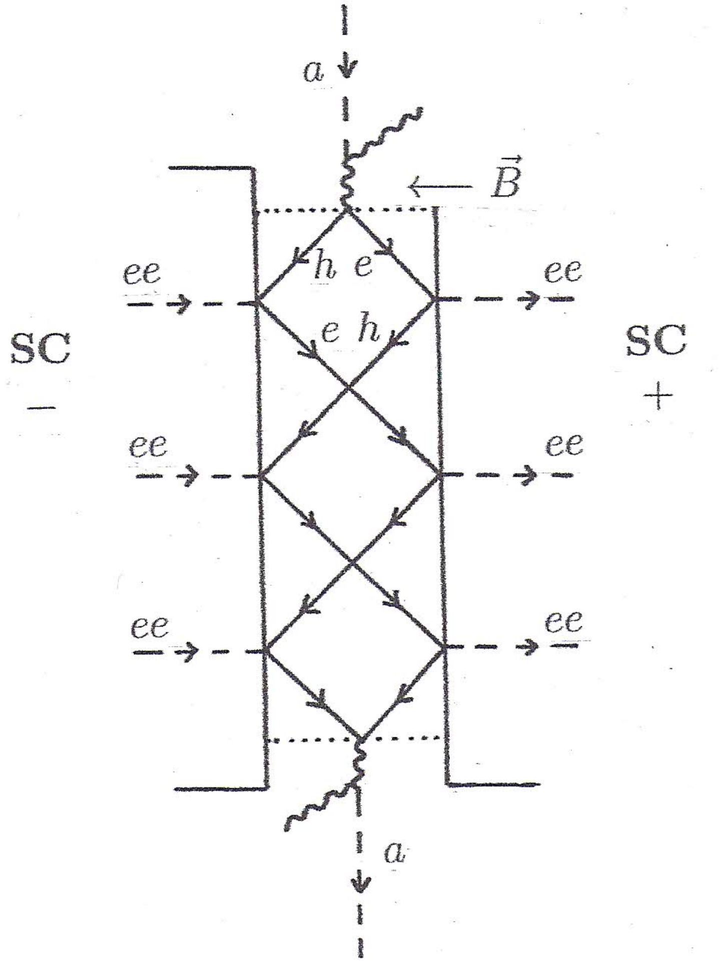
The very large formal $\boldsymbol{B}$-field can always be expressed by the flux through a tiny area — the flux $\boldsymbol{\Phi = B\cdot}$ tiny area is just of ordinary size...



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)):

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

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

$2eV_s = m_ac^2$ (V_s: signal voltage)

Expected signal power from axions:

$$P_s = \rho_a v A. \tag{16}$$

ρ_a: axionic dark matter density near the earth, $v = 2.3\cdot 10^5\frac{m}{s}$, A: Area of weak-link region of JJ.

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

$$I_s = \int G_s dV = \frac{N_a}{\tau}\cdot n\cdot 2e = \frac{\rho_a}{m_ac^2}vA\cdot n\cdot 2e \tag{17}$$

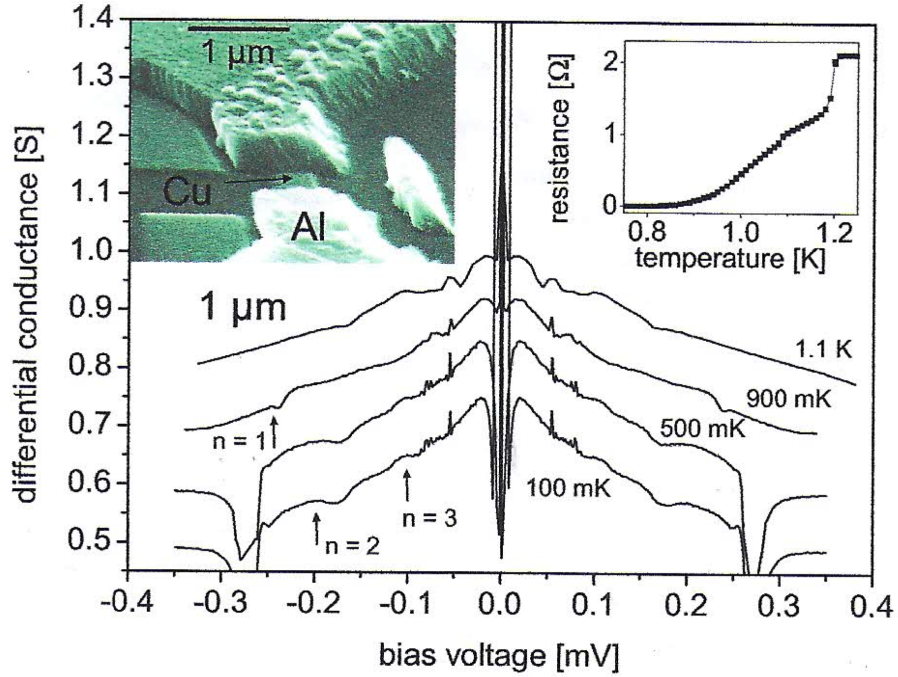
where N_a/τ is the number of axions hitting the normal metal region per time unit τ.

Axion density from

$$\rho_a = \frac{I_sV_s}{vAn}. \tag{18}$$

This can be used to experimentally estimate the axion mass m_a and dark matter density ρ_a from an experimental measurement of V_s and I_s.

5 An observed candidate signal in S/N/S Josephson junctions



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

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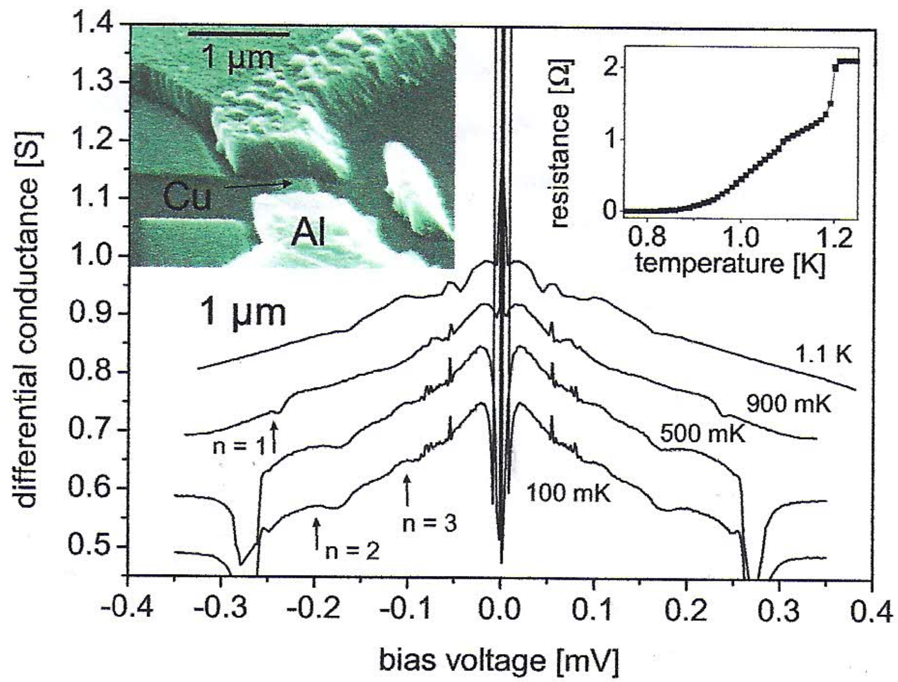


C. Hoffmann, F. Lefloch, M. Sanquer, B. Pannetier, Phys. Rev. B 70, 180503(R) (2004)
They measured differential conductivity $\boldsymbol{G(V) = dI/dV}$ and observed signal peak 'of unknown origin' at $\boldsymbol{V_s = \pm 0.055mV}$.

- Hoffmann et al. (2004) observe a signal of unknown origin that is consistent with our theoretical expectations. Independent of the temperature (which is varied from 0.1K to 0.9K) they consistently observe a small peak in their measured differential conductivity $G(V)$ at the voltage $V_s = \pm 0.055mV$
- Their measurements provide evidence for a signal current feature of size $I_s = (8.1 \pm 1.0) \cdot 10^{-8} A$ obtained by integrating the area under the observed signal peak of the differential conductivity.
- Their noise measurements also indicate that every quasi-particle performs $n = 7$ Andreev reflections.
- Area A of the metal plate of their junction is $A = 0.85\mu m \times 0.4\mu m = 3.4 \cdot 10^{-13} m^2$.
- From $2eV_s = ma_c^2$ we thus obtain an axion mass prediction of $m_a c^2 = 110\mu eV$ (equivalent to $f_a \sim 5.5 \cdot 10^{10} GeV$), and $\rho_a = \frac{I_s V_s}{vAn}$ yields the prediction $\rho_a = (0.051 \pm 0.006) GeV/cm^3$.

Is this value of axionic dark matter density ($\boldsymbol{\rho_a = (0.051 \pm 0.006) GeV/cm^3}$) as predicted by our theory based on Hoffmann et al.'s measurements reasonable?

Is this value of axionic dark matter density ($\rho_a = (0.051 \pm 0.006) GeV/cm^3$) as predicted by our theory based on Hoffmann et al.'s measurements reasonable?

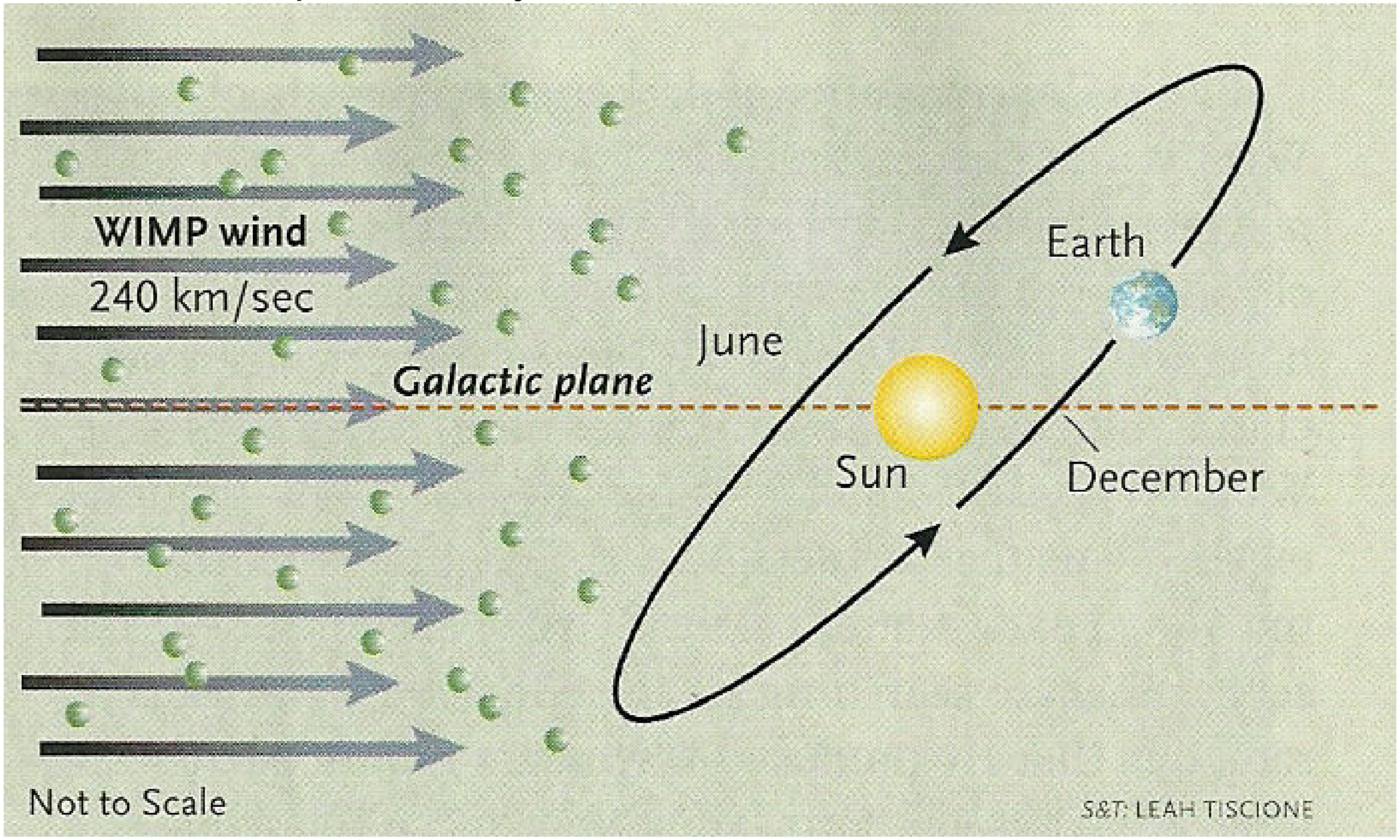
Yes, it is.

- Astrophysical observations 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). But this includes all kinds of dark matter particles, including WIMPS.
- Generally, axions of high mass will make up only a fraction of the total dark matter density of the universe: $\rho_a/\rho_d \approx (24\mu eV/m_a c^2)^{7/6}$ (Duffy, van Bibber (2009))
- For $m_a c^2 = 110\mu eV$ we thus expect an axionic dark matter density that is a fraction $(24/110)^{7/6} \approx 0.17$ of the total dark matter density, giving $\rho_a \approx 0.17 \cdot \rho_d = (0.051 \pm 0.017) GeV/cm^3$. The intensity of the JJ signal is thus in perfect agreement with what is expected from astrophysical observations.
- A very recent analysis of rotation curves of galaxies is consistent with these values (M-H Li and Z-B Li, Phys. Rev. D 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 BEC (Sikivie et al. 2009) of the galactic halo exhibits a yearly modulation of about 10%, with a maximum in June and a minimum in December. Hence JJ signal intensity should exhibit the same yearly modulation.
- Independent experiments (such as upgraded versions of ADMX) would need to confirm the suggested value of $m_a c^2 = 110 \mu eV$.

Experimental check: Search for annual modulation of the intensity of a Shapiro step-like feature —if it is produced by axions



Maximum expected in June, minimum in December.

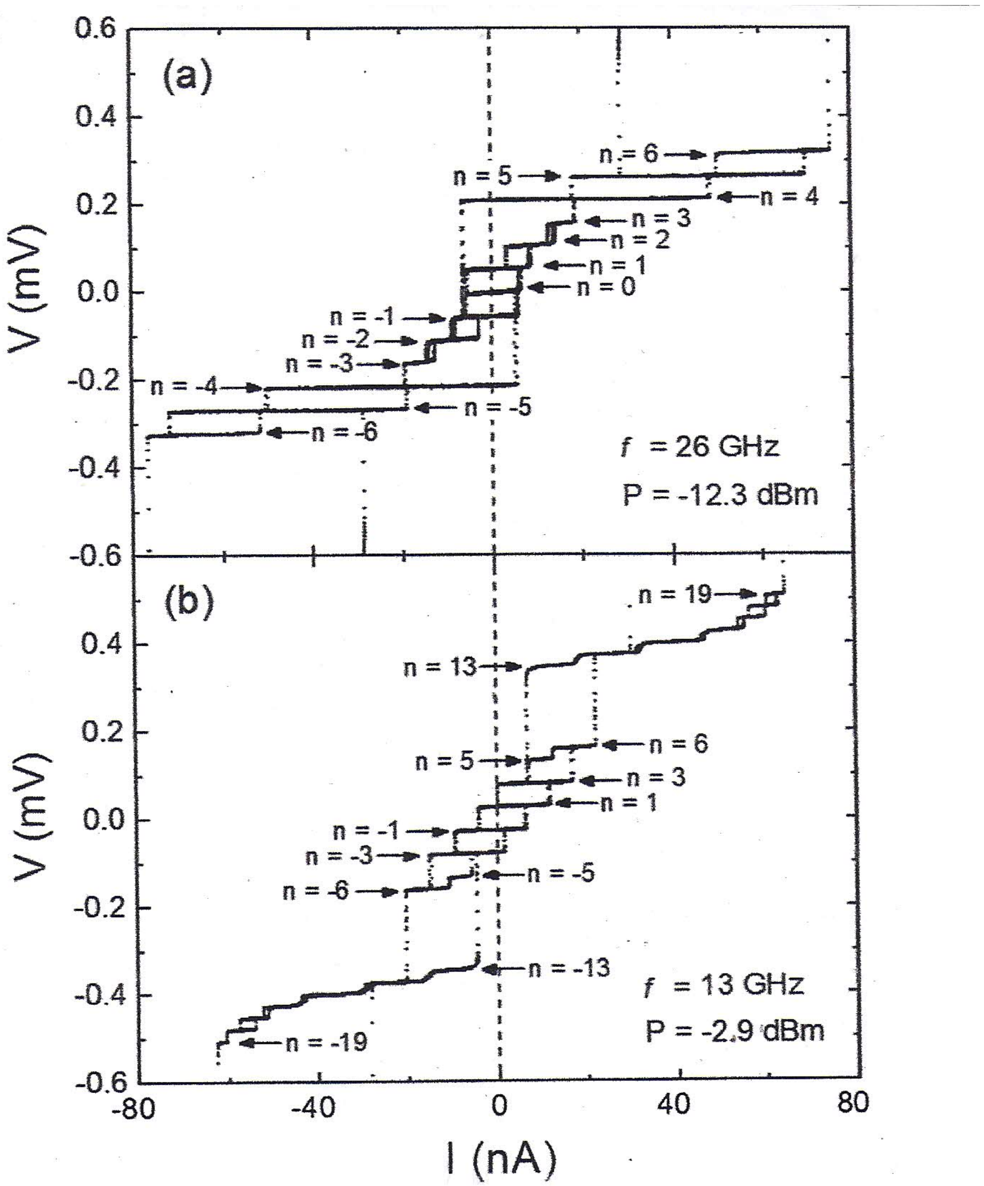
Latest developments

- The latest BICEP2 results (PRL 112, 241101 (2014)), if taken at face value, would single out the inflationary scale as $H_I \sim 1.1 \cdot 10^{14}$GeV.
- From this Visinelli et al. (PRL 113, 011802 (2014)) derive a lower bound on the axion mass: $m_a c^2 \geq 72\mu$eV.
- This lower bound is bigger than most people expected for the axion, but in line with our suggested value 110μeV. It implies that the Peccei-Quinn phase transition took place after inflation.
- Further experiments that seem to see peculiarities at $V_a = 55\mu$V are discussed in C. Beck, arXiv:1403.5676:

  Golikova et al. PRB 86, 064416 (2012) — based on Al-(Cu/Fe)-Al junctions

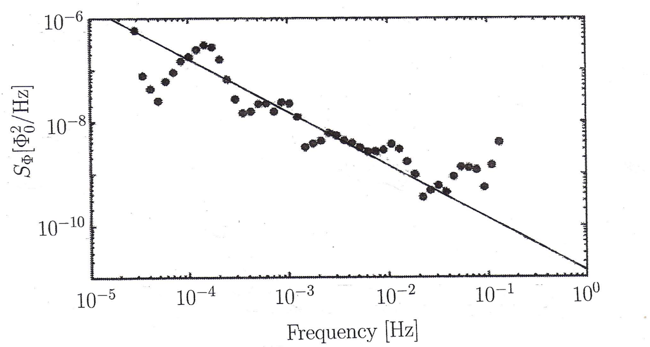
  L. He et al. arXiv:1107.0061 — based on W-Au-W junctions

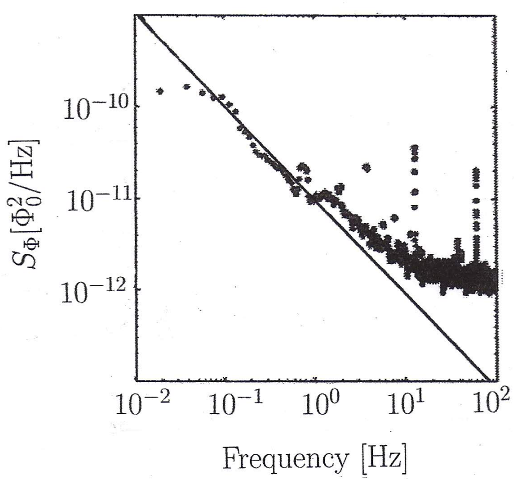
  Bae et al. PRB 77, 144501 (2008) — based on high T_c (BI-2212) junctions
- There could also be broad-band noise effects of axions (C. Beck, arXiv:1409.4759)



Shapiro steps at voltages nhf as measured by Bae et al. for external frequency (a) $f = 26$ GHz and (b) $f = 13$ GHz.

Flux noise in SQUIDS and q-bits as measured by Bialczak et al. (PRL 2007) and Sendelbach et al. (PRL 2008)





Low-frequency part could be due to axionic density fluctuations. Predicted power spectrum (C. Beck, arXiv:1409.4759): $\boldsymbol{S_\phi(f) = \frac{\theta_1^2 \Phi_0^2 A_s}{16\pi^2} \left(\frac{f}{vk^*}\right)^{n_s-1} \frac{1}{f}}$

6 Summary

- Nobody really knows what dark matter is...
- Recent experimental suggestions to search for dark matter axions are based on small devices, not big machines!
- Axions hitting the weak-link region of S/N/S junctions may 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 0.05 GeV/cm^3. C. Beck, Phys. Rev. Lett. 111, 231801 (2013)
- Interesting interdisciplinary problem at the interface between astrophysics, condensed matter physics, nanotechnology, and particle physics.