The Aharonov-Bohm effect and hidden photons

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9th PATRAS workshop on axions, WIMPs and WISPs 23-28 June, 2013

The A-B effect in a nutshell

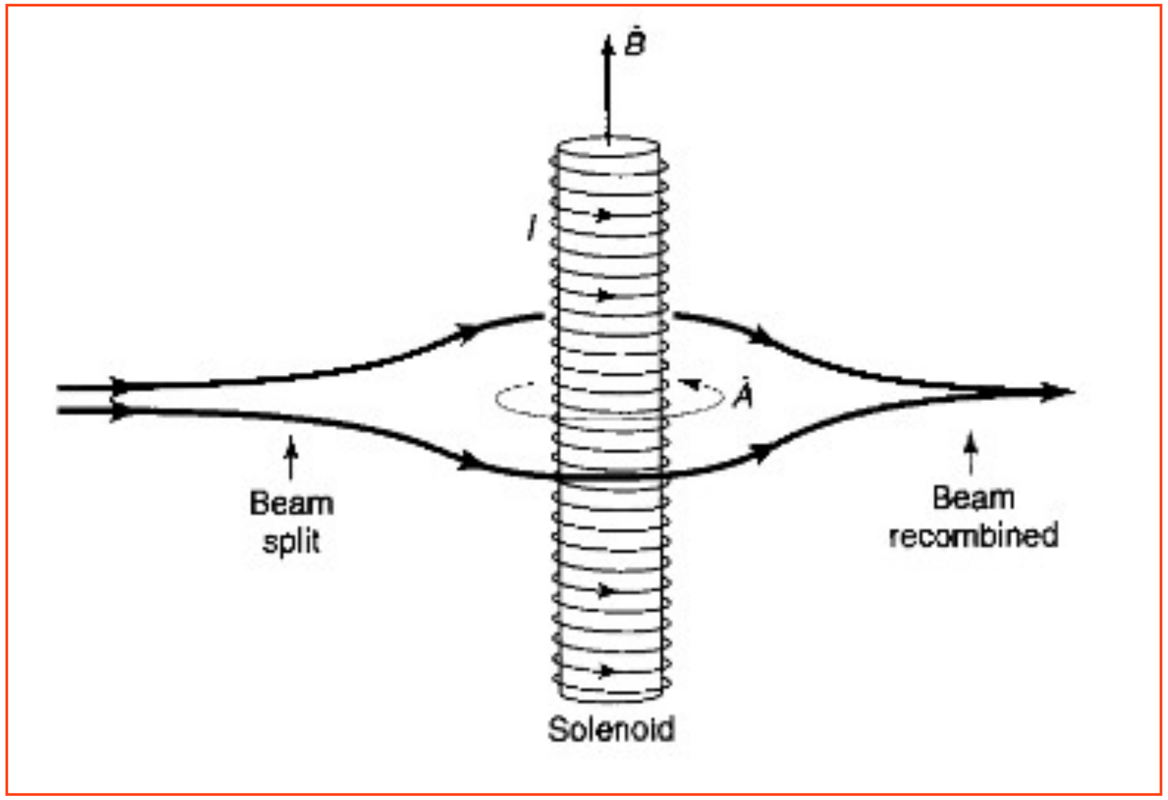
The effect proofs that the vector potential of electrodynamics is physical after all, or interaction between particles and fields is non local.

Simplest experiment:

$$\psi_1(x) = Ae^{ikx_1}$$

$$\psi_2(x) = Ae^{ikx_2}$$

for $\mathbf{B} = 0$

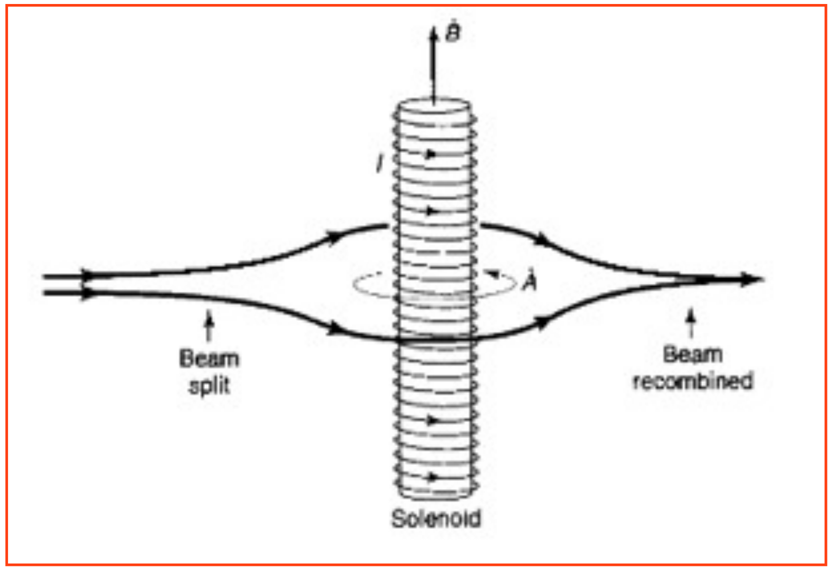


when recombined:

$$\psi(x) = Ae^{ik(x_1 - x_2)}$$

Interference pattern

But when the magnetic field in the solenoid is on......



$B \neq 0$

$$\psi_1(x) \propto e^{ie \int_{C_1} \vec{A}\cdot d\vec{\ell}}$$

$$\psi_2(x) \propto e^{ie \int_{C_2} \vec{A}\cdot d\vec{\ell}}$$

(assuming the wave function is expelled from the solenoid).

So when recombined the wave function picks up another phase, shifting the interference pattern:

$$\Delta\varphi = e\int_{C_1} \vec{A}\cdot d\vec{\ell} - e\int_{C_2} \vec{A}\cdot d\vec{\ell} = e\oint_C \vec{A}\cdot d\vec{\ell}$$

And

$$e\oint_C \vec{A}\cdot d\vec{\ell} = e\Phi_0$$

Magnetic flux enclosed by C

AB effect not necessarily because A is gauge field....

PHYSICAL REVIEW
LETTERS

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Aharonov-Bohm Effect and the Mass of the Photon

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Physics Department, Brandeis University, Waltham, Massachusetts 02254
(Received 16 May 1989; revised manuscript received 25 July 1989)

We show that the Aharonov-Bohm effect requires that the vector potential couple minimally to matter, not that it be a gauge field: The effect is present in massive (finite-range) electrodynamics, reducing smoothly to the original result in the limit of infinite range. Indeed, it may be used to provide an experimental bound on the range which is much larger than the "table-top" apparatus, namely a lower limit of order 10^2 km.

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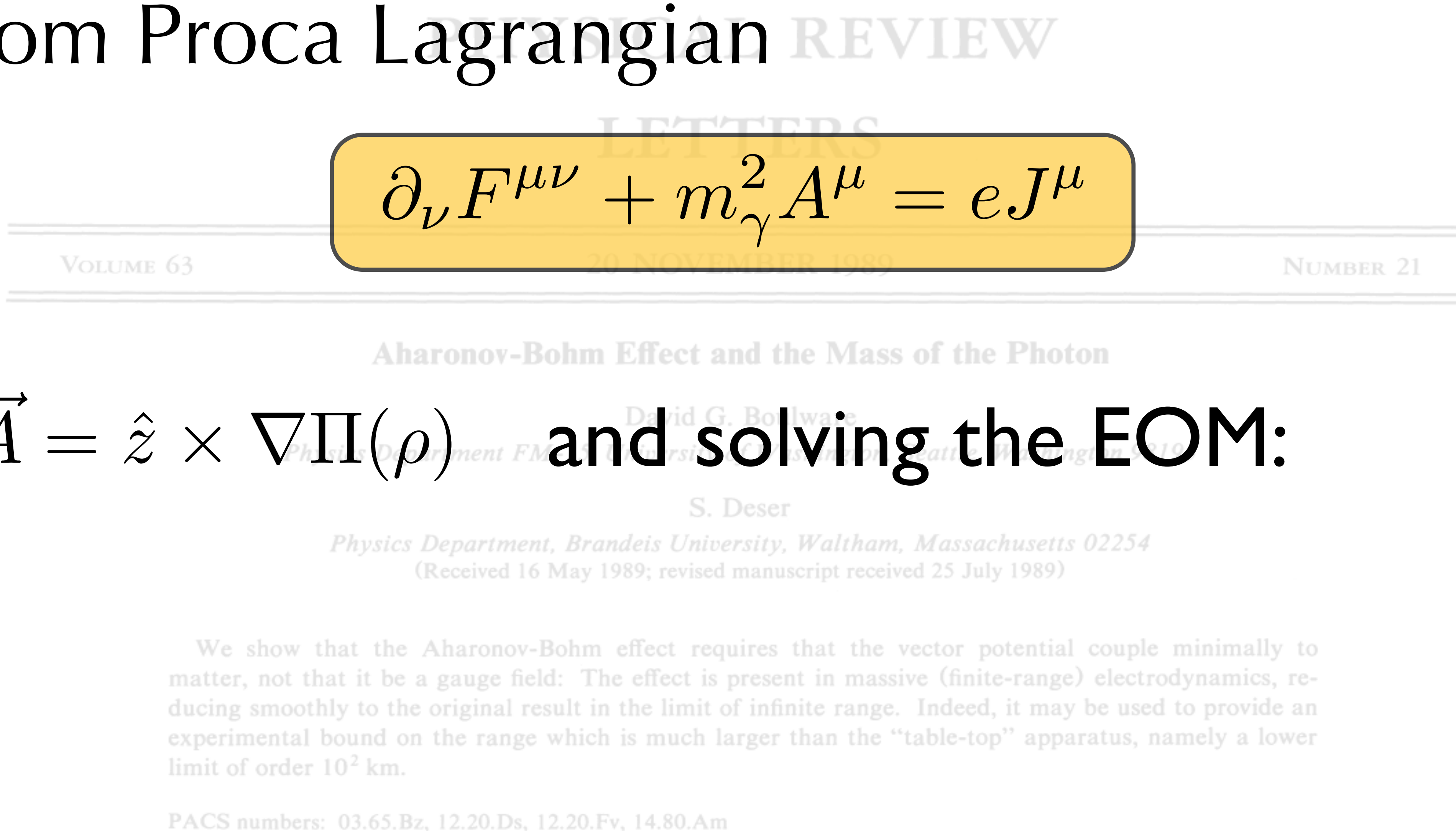
AB effect not necessarily because A is gauge field....

★ From Proca Lagrangian

$$\partial_\nu F^{\mu\nu} + m_\gamma^2 A^\mu = e J^\mu$$

$$\vec{A} = \hat{z} \times \nabla \Pi(\rho)$$ and solving the EOM:



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- From Proca Lagrangian

$$\partial_\nu F^{\mu\nu} + m_\gamma^2 A^\mu = eJ^\mu$$

$\vec{A} = \hat{z} \times \nabla \Pi(\rho)$ and solving the EOM:

Magnetic field gets an extra term

$$\vec{B} = \nabla \times \vec{A} = \hat{z}\, e\, j\, \Theta(a-\rho) + \hat{z}\, e\, j\, m_\gamma^2\, \Pi(\rho)$$

$$\Pi(r) = -\left[-\theta(r-a)K_0(mr)\int_0^a r'dr' I_0(mr') + \theta(a-r)\left(K_0(mr)\int_0^r r'dr' I_0(mr') + I_0(mr)\int_r^a r'dr' K_0(mr')\right)\right]$$

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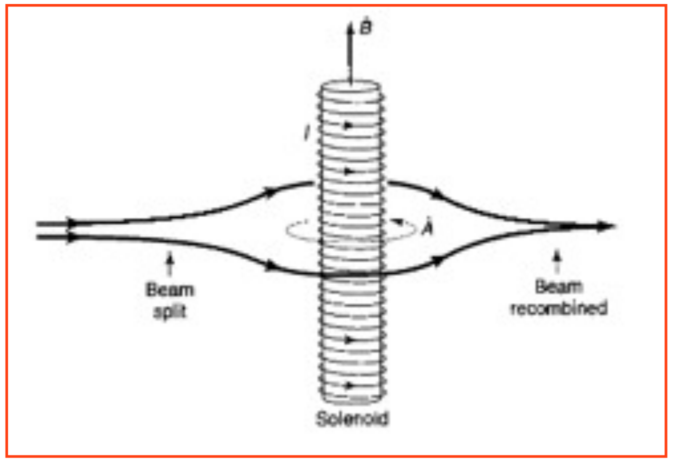
Boulware & Deser (1989) proposed a slightly modified AB experiment, of bigger dimensions and high magnetic field



$$a \sim 0.1\,\mathrm{cm}$$

$$B \sim 10\,\mathrm{T}$$

to get a lower bound for the mass of the photon

$$m \leq 10^{-12}\,\mathrm{eV}$$

AB + Hidden photons

Our Lagrangian at low energies:

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}G_{\mu\nu}G^{\mu\nu} - \frac{\sin\chi}{2}F_{\mu\nu}G^{\mu\nu} + \cos^2\chi\frac{m^2_{\gamma'}}{2}X^\mu X_\mu + J_\mu A^\mu$$

for $m_{\gamma'}$, χ small.

Note in this basis A_μ couples to matter (minimal coupling), thus

$$\mathbf{B} = \nabla \times \mathbf{A}$$

Kinetic mixing can be removed by a change of basis:

$$\tilde{A}_\mu \to A_\mu + \sin\chi X_\mu \qquad \tilde{X}_\mu \to \cos\chi X_\mu$$

Leading to

$$\mathcal{L} = -\frac{1}{4}\tilde{F}_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{4}\tilde{G}_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{m^2_{\gamma'}}{2}\tilde{X}^{\mu}\tilde{X}_{\mu} + J_{\mu}\left(\tilde{A}^{\mu} - \chi\tilde{X}^{\mu}\right)$$

The EOM in this basis are:

$$\partial_\nu \tilde{F}^{\mu\nu} = e\, J^{\mu}$$

- Normal eq. for massless gauge field

$$\partial_\nu \tilde{G}^{\mu\nu} + m^2_{\gamma'}\tilde{X}^{\mu} = -e\,\chi\, J^{\mu}$$

- Proca equation, same as BD

Magnetic field for $\tilde{X}$ picks up an extra contribution

$$\vec{B}_{\tilde{X}} = -\hat{z}\,\chi\, e\, j\,\Theta\,(a-\rho) - \hat{z}\, e\,\chi\, j\, m^2_{\gamma'}\Pi(\rho)$$

Meanwhile

$$\vec{B}_{\tilde{A}} = \hat{z}\, e\, j\, \Theta\,(a-\rho)$$

But recall the real magnetic field, associated with $\vec{A}$

$$A = \tilde{A} - \chi\tilde{X}$$

$$\vec{B}_A = \hat{z}\, e\, j\, \Theta\,(a-\rho)\left(1+\chi^2\right) + \hat{z}\, e\; j\, \chi^2\, m_{\gamma'}^2 \Pi(\rho)$$

$$\Pi(r) = -\left[-\theta(r-a)K_0(mr)\int_0^a r'dr' I_0(mr') + \theta(a-r)\left(K_0(mr)\int_0^r r'dr' I_0(mr') + I_0(mr)\int_r^a r'dr' K_0(mr')\right)\right]$$

And the phase of the electron

$$\Delta\varphi = e^2\, j\, A\, \left(1+\chi^2\right) + e^2\; j\, A\, \chi^2\, m^2_{\gamma'} \int \Pi(r) dS$$

Get's modified by the hidden photon!

Detection?

How sensitive can be the AB effect to constrain χ ?

$$\Delta\varphi = e^2\, j\, A\, (1+\chi^2) + e^2\, j\, A\, \chi^2\, m_{\gamma'}^2 \int \Pi(r) dS$$

- electric charge redefinition
- independent measurement (e.g. electron g-2)

(Phys.Rev. D86 (2012) 095029)

- precision for $\Delta\varphi$ and B measurements

In order to get a bound we follow the procedure outlined by Jaeckel and Roy at Phys. Rev. D **82**, 125020 (2010)

$$\chi \leq \sqrt{\frac{\frac{|\delta\varphi|}{\Delta\varphi} + \frac{|\delta\alpha|}{\alpha_0} + \frac{|\delta B|}{B_0}}{|f(m_{\gamma'})|}}$$

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Thanks Joerg!! ☺

should be fine

$\sim 10^{-10}$

- Ideal: High and stabilized

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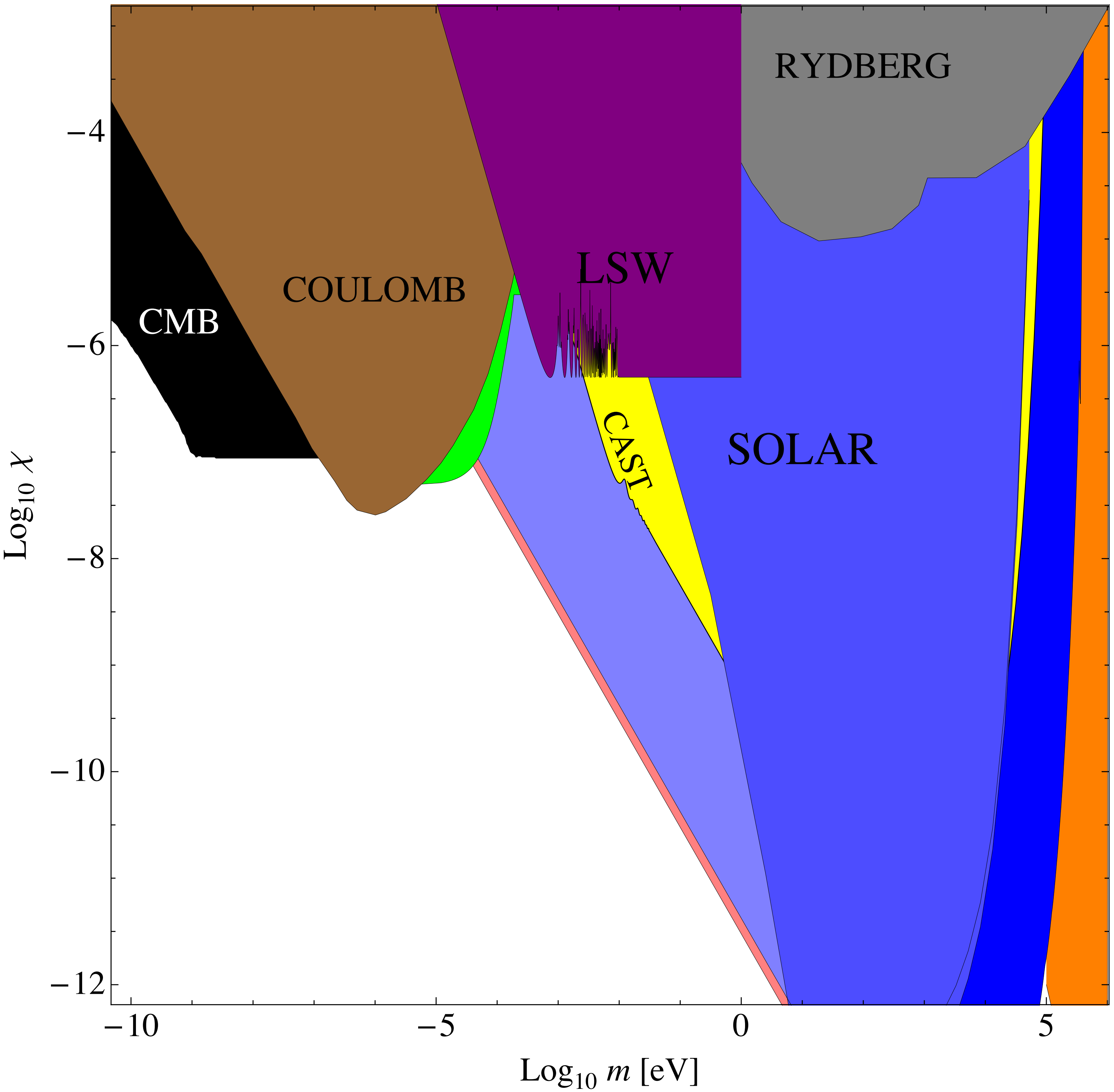
should be fine $\quad \sim 10^{-10} \quad$ • Ideal: High and stabilized

- SQUID: $\delta B \sim 10^{-4}\,\mathrm{nT}$ but $B_0 \leq 10^{-4}\,\mathrm{T}$

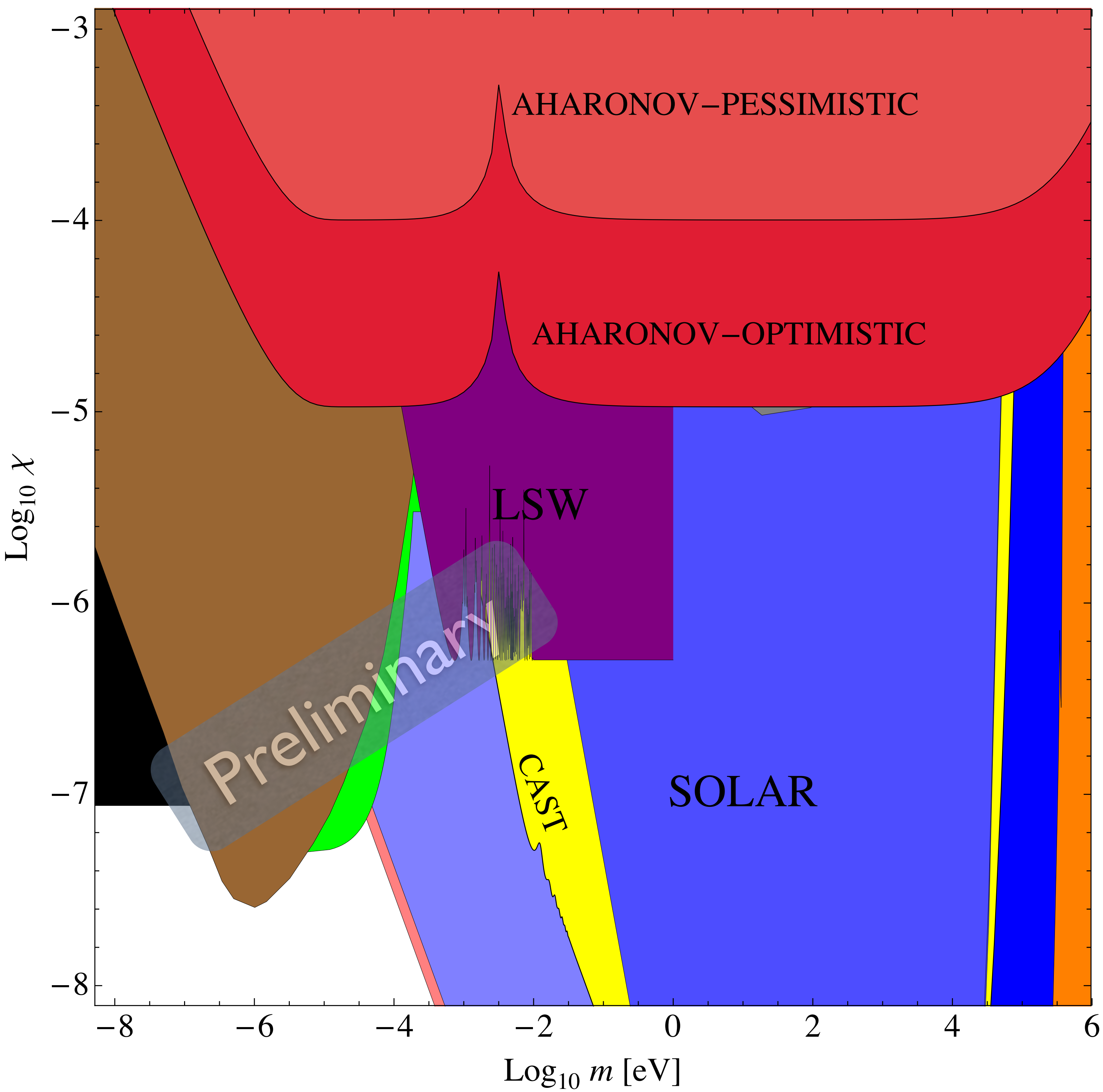
Relative uncertainty $\frac{|\delta B|}{B_0} \sim 10^{-8} - 10^{-9}$

Status



RYDBERG
LSW
COULOMB
CMB
CAST
SOLAR
−4
−6
−8
−10
−12
$\mathrm{Log}_{10}\,\chi$
−10
−5
0
5
$\mathrm{Log}_{10}\,m$ [eV]

Bounds



- Pessimistic

$$\frac{|\delta B|}{B_0} \sim 10^{-8}$$

- Optimistic

$$\frac{|\delta B|}{B_0} \sim 10^{-10}$$

Conclusions

- We used the AB effect as a probe of hidden photons
- A dedicated A-B experiment will not improve existing bounds, with current available detectors.
- The experiment might be worth (if improved, somehow) because provides a pure laboratory probe in the showed parameter space
- ..... work in progress!!

THANKS!

The experiment

The AB effect was accepted as a physical effect thanks to the experiment of Tonomura et al in 1986.

Their set up is not suitable for our purposes to get a nice bound.....

Small toroidal magnet, low magnetic field.

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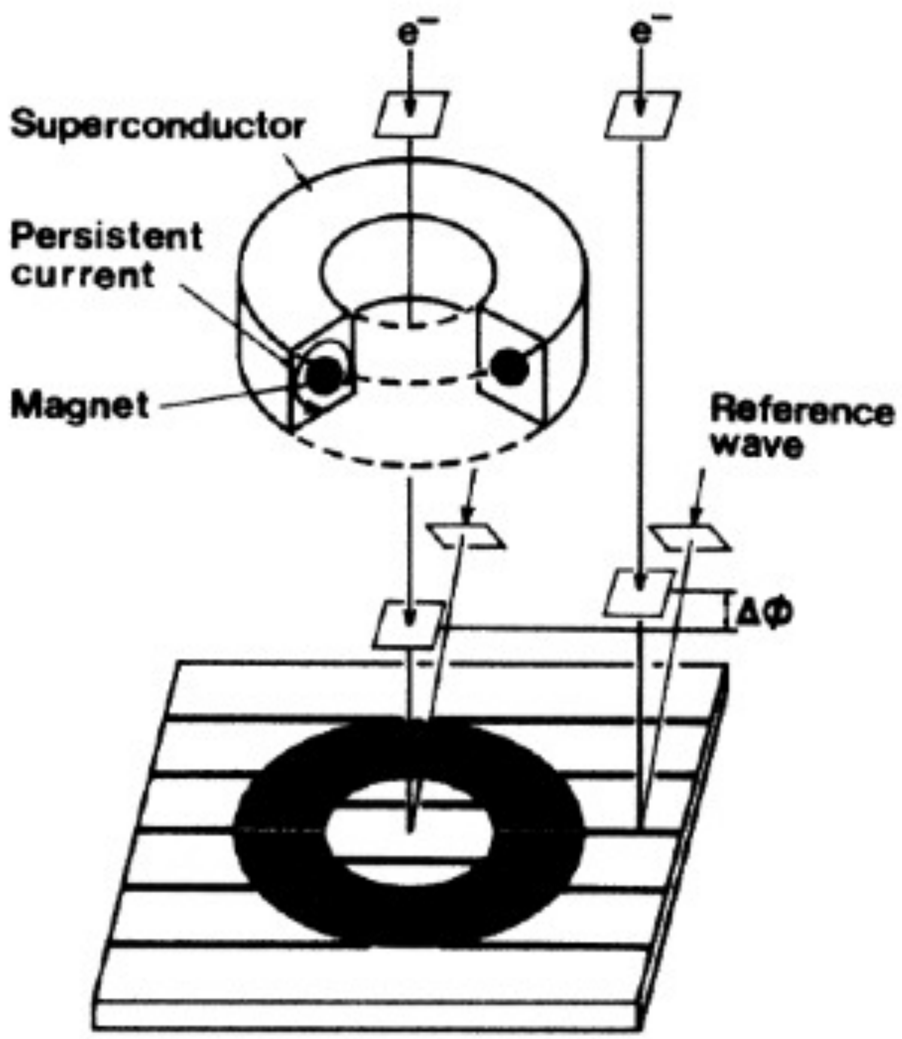

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B&D suggest an experiment using a solenoid (as the old experiment of C... in 60's) and use a strong magnetic field.

This proposal would fit also our requirements!!