Axion overview

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with help from the
ADMX collaboration
and the
REAPR collaboration

Topics

- Detection: $a \rightarrow \gamma$; measure photon spectrum
- Signal ← Axion properties and statistics

- Properties
  - Strong CP; Peccei-Quinn; axion
  - Invisible axon; mass range bounded
  - Making it visible

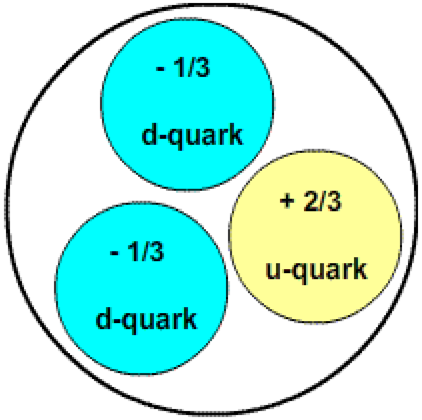
- Where to look?
  - For the Galactic halo
  - At the Sun
  - In your lab
  - To the sky

The strong CP problem

- QCD contains a P and CP violating term

$$L_\theta = \frac{\theta g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\,\mu\nu}$$

  for nonzero θ.
- The neutron would have an electric dipole moment of, say, $d_n = 10^{-15}$ e-cm.
- Instead it has $d_n < 2.9 \times 10^{-26}$ e-cm.
- Suppression of θ by a factor of ~10^{11}
- Seems unnatural.



Peccei and Quinn

- Replaced θ by a/f_a, where a is a dynamical field.
- Non perturbative effects produce an effective potential that forces θ to zero.
- The strong CP problem is solved.
- Here, f_a, with units of energy, is the axion decay constant.
- The quantum of a is the axion

- 2013 J.J. Sakurai Prize for Theoretical Particle Physics is awarded to Roberto Peccei and Helen Quinn for solving the strong CP problem, which, in turn, led to the invention of axions.

The axion

- Weinberg and Wilczek: PQ mechanism means a new particle, the axion
- The axion mass is

$$m_a = 6\mu\mathrm{eV}\,\frac{10^{12}\mathrm{GeV}}{f_a}$$

- All interactions scale as $1/f_a$
- Decays by two-photon emission $a \to \gamma\gamma$
- If f_a is at the electroweak scale (250 GeV), m_a ~ 20 keV and interactions are relatively strong
- Quickly ruled by experiments at beam dumps and reactors

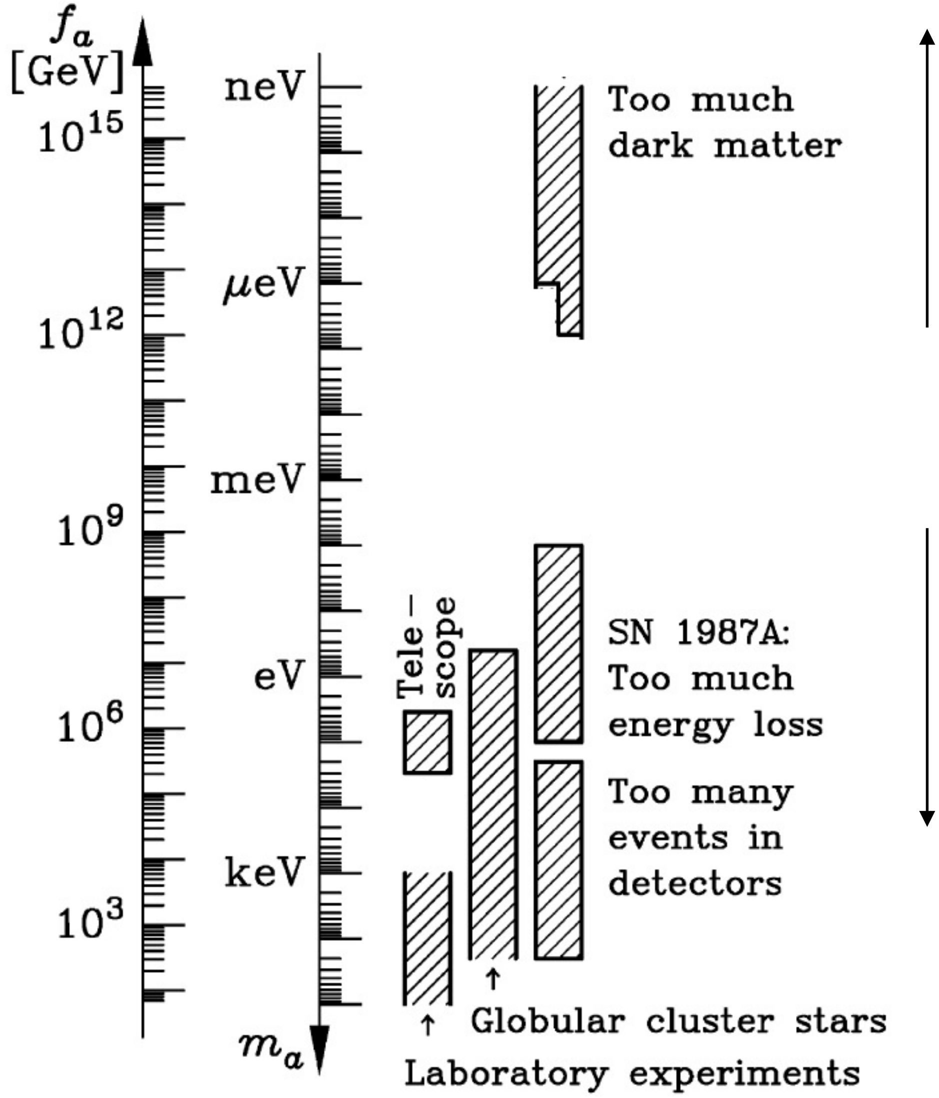
The invisible axion

- Make f_a larger and larger, so that interactions become weaker and weaker.
- Various constraints rule out ranges of f_a (and mass)
- Axions lighter than ~ 20-40 eV have half-lives longer than the age of the universe.
- Relic axions would be cold dark matter.
- *Very* cold if in axion BEC
- Abundance roughly *inverse* in mass: $\Omega_a \sim (m_a)^{-7/6}$
- Gives lower limit on mass to avoid overclosing the universe.
- Galactic halos may consist of axions; at the Earth,

$$\rho_{\mathrm{halo}} = 0.45 \text{ GeV/cm}^3$$

- Or $n_a \sim 2 \times 10^{13}$ /cm^3 if $m_a = 20$ μeV (gives $\Omega_a = 0.23$)

Present (soft) limits on the axion mass



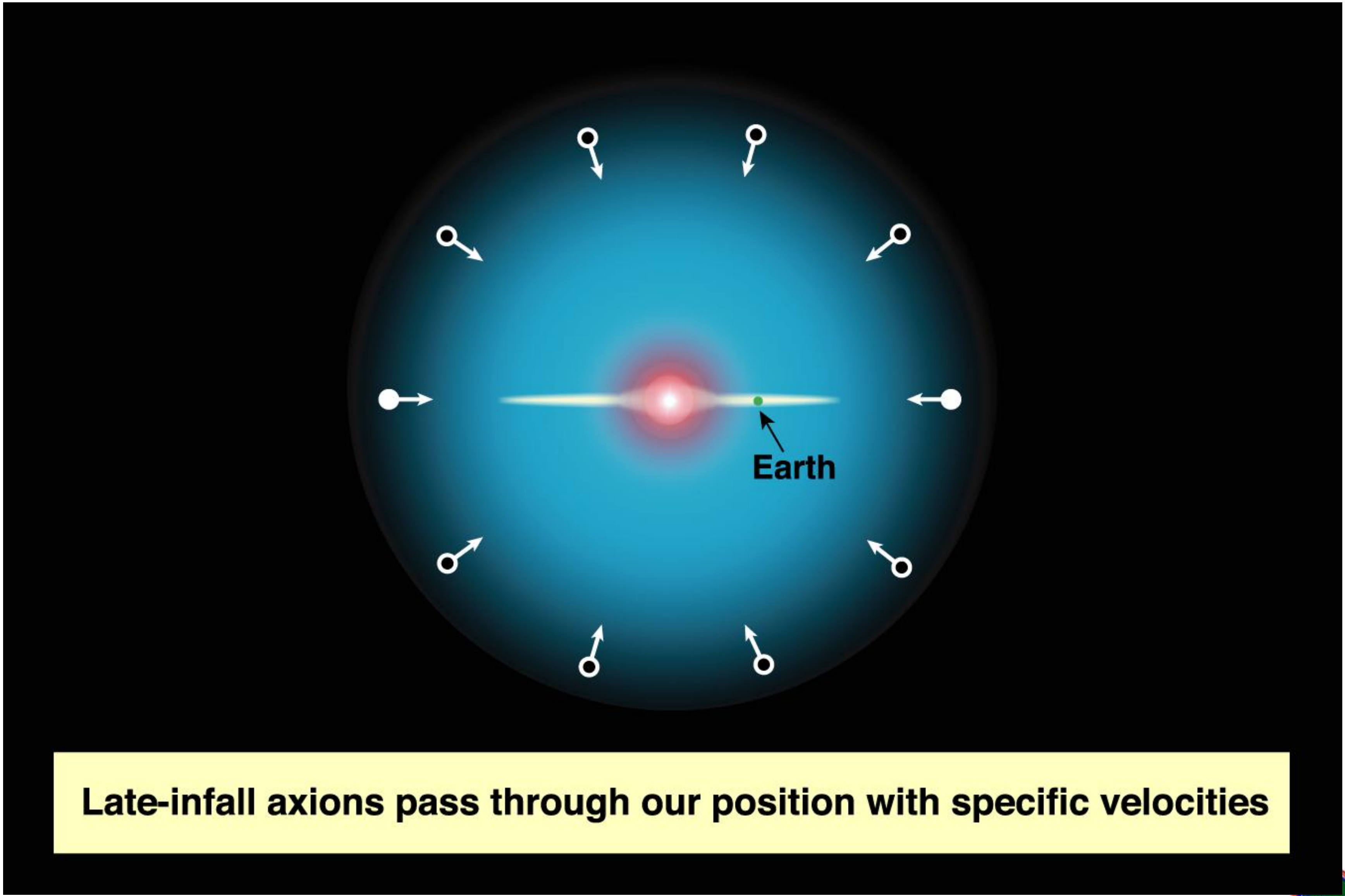
Very light axions forbidden; else too much dark matter

⇐ Dark matter range: very hard to detect, "invisible axions"

m_a > 20–40 eV, τ_{half} < t_{universe}

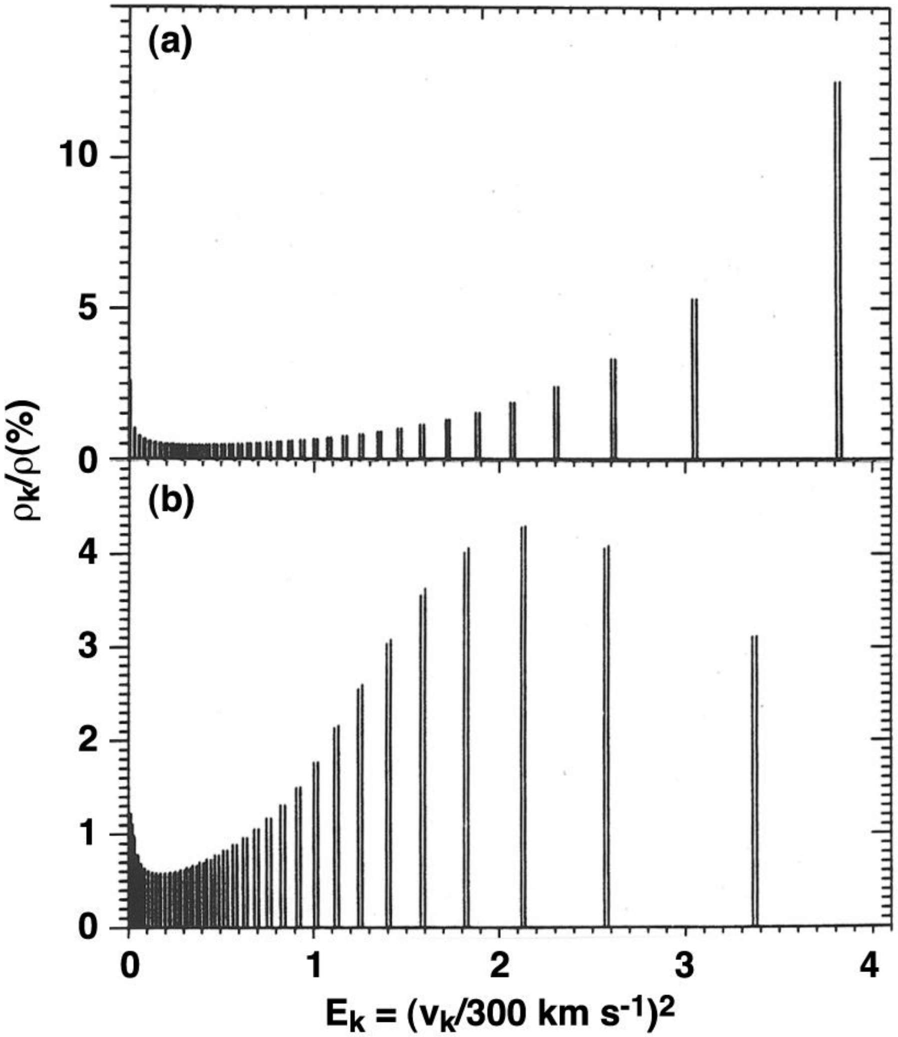
Heavy axions forbidden; else new pion-like particle

Possible sharp features in the axion spectrum



Late-infall axions pass through our position with specific velocities

Velocity spectrum of axions at our detector



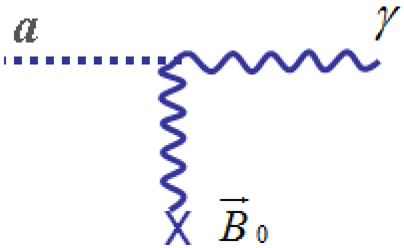
(a) No angular momentum

(b) Finite angular momentum

For more, see Aravind Natarajan, 9:45

The Sikivie detection mechanism

- 1983. Used by essentially every experiment.
- Stimulate the decay of relic axions by placing them in a strong, static, magnetic or electric field.

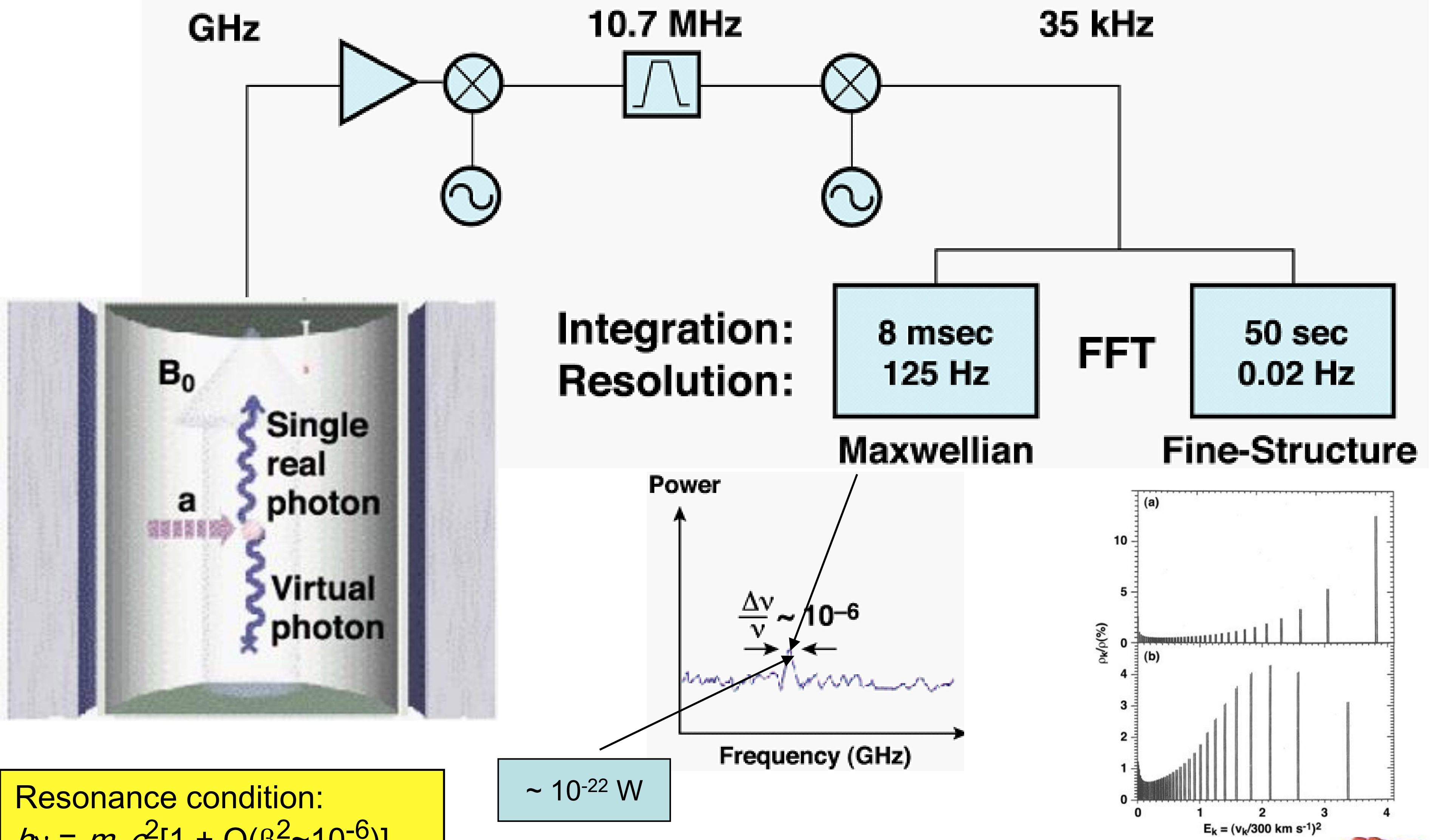


- Primakoff mechanism
- Axion-photon interaction is

$$\mathcal{L}_{a\gamma\gamma} = g_\gamma a \vec{E} \cdot \vec{B}_0$$

- Conserve energy: $m_a c^2 + \frac{1}{2} m_a v^2 = h\nu$ with $v/c \sim 10^{-3}$
- Conserve momentum: (1) use cavity (standing wave), (2) have axions highly relativistic, (3) have space variation in B_0

Cavity haloscope



~ 10^{-22} W

Resonance condition:
$h\nu = m_a c^2[1 + O(\beta^2 \sim 10^{-6})]$

Signal strength

- Power from the cavity is

$$P = 4\cdot 10^{-22}\ \mathrm{W}\left(\frac{V}{200\ \ell}\right)\left(\frac{B_0}{8\ \mathrm{Tesla}}\right)^2\left(\frac{g_\gamma}{0.97}\right)^2 \cdot \left(\frac{\rho_\mathrm{a}}{0.5\cdot 10^{-24}\ \mathrm{g/cm}^3}\right) C_{nl}\left(\frac{m_\mathrm{a}}{1\ \mathrm{GHz}}\right)\left(\frac{\min(Q_\mathrm{L}, Q_\mathrm{a})}{1\times 10^5}\right)$$

- Q_L ~ 10^5 and Q_a ~10^6

- For KSVZ axions, g_γ ~ 0.97,[1] whereas for DFSZ axions g_γ ~ 0.36.[2]

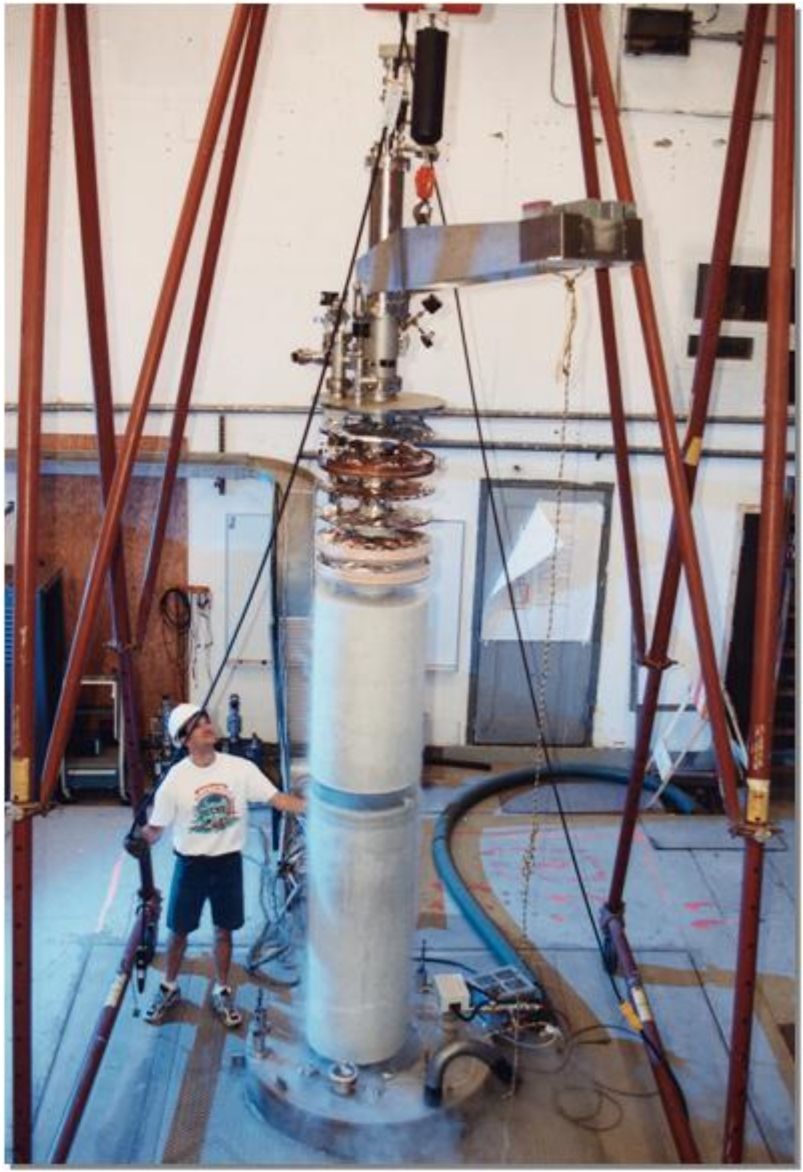
[1] The KSVZ model is one implementation of the ‘hadronic axion,’ J.E. Kim, Phys. Rev. Lett. **43**, 103 (1979); M.A. Shifman, A.I. Vainshtein and V.I. Zakharov, Nucl. Phys. **B166**, 493 (1980).

[2] The DFSZ model is based on a simple GUT scenario M. Dine, W. Fischler, and M. Srednicki, Phys. Lett. **B104**, 199 (1981); A.R. Zhitnitsky, Yad. Fiz. **31**, 497 (1980) [Sov. J. Nucl. Phys. **31**, 260 (1980)].

Microwave Cavity Searches for Axions

- 1980s: RBF and UF, few liters at 8 T.
- Carrack, using Rydberg atoms for readout (Kyoto)
- Potential new experiment in Korea
- ADMX (LLNL → UW)

Talk by Gianpaolo Carosi, 8:25



Higher frequencies?

- Single cylinder:

$$f = \frac{c}{2.61r}$$

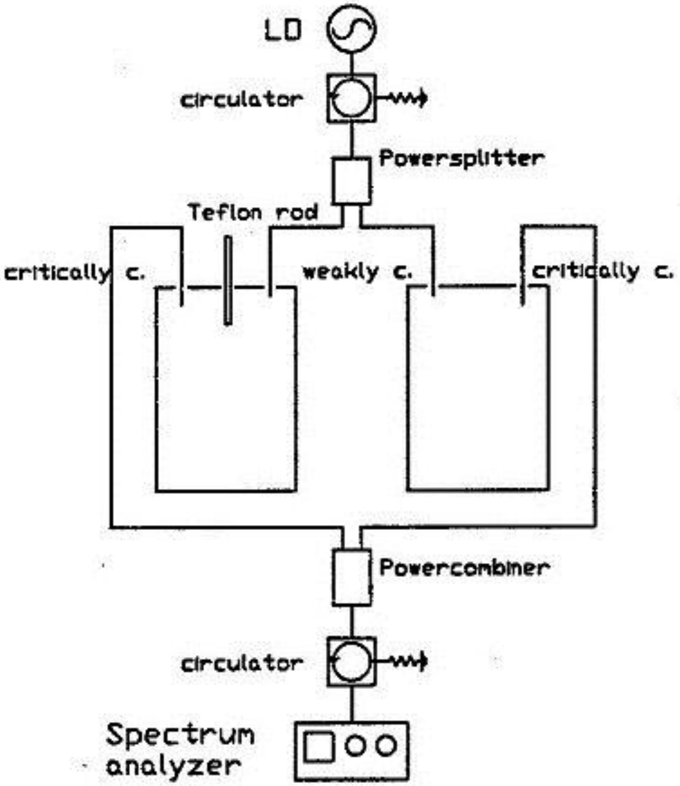
$$P = 2 \times 10^{-22}\ \mathrm{Watt} \left(\frac{\mathrm{GHz}}{f}\right)^{2.67}$$

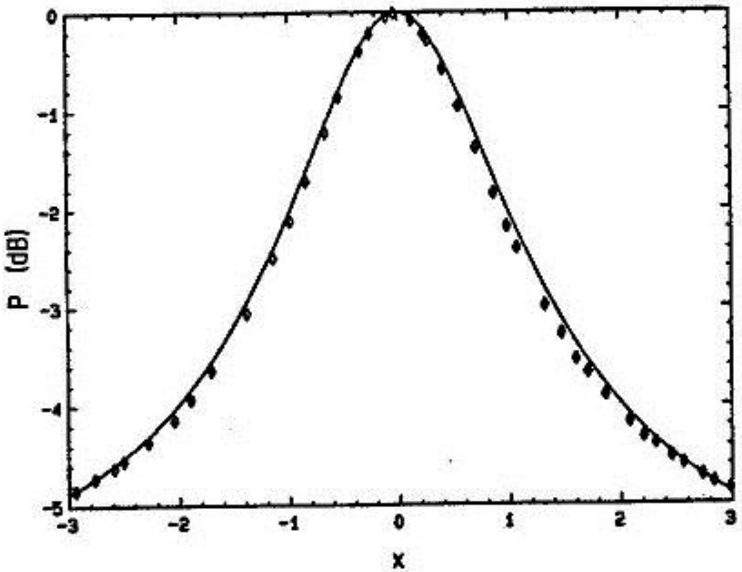
- Power decreases because the volume decreases as f^{-3}, the Q decreases as $f^{-2/3}$ while the mass increases as f.

$$P = 2.3 \cdot 10^{-26}\mathrm{Watt} \left(\frac{V}{200\ell}\right) \left(\frac{B_0}{8\mathrm{Tesla}}\right)^2 C_{nl} \left(\frac{g_\gamma}{0.97}\right)^2 \cdot \left(\frac{\rho_\mathrm{a}}{0.5 \cdot 10^{24}\mathrm{g/cm}^3}\right) \left(\frac{m_\mathrm{a}}{2\pi\mathrm{GHz}}\right) \min(Q_\mathrm{L}, Q_\mathrm{a})$$

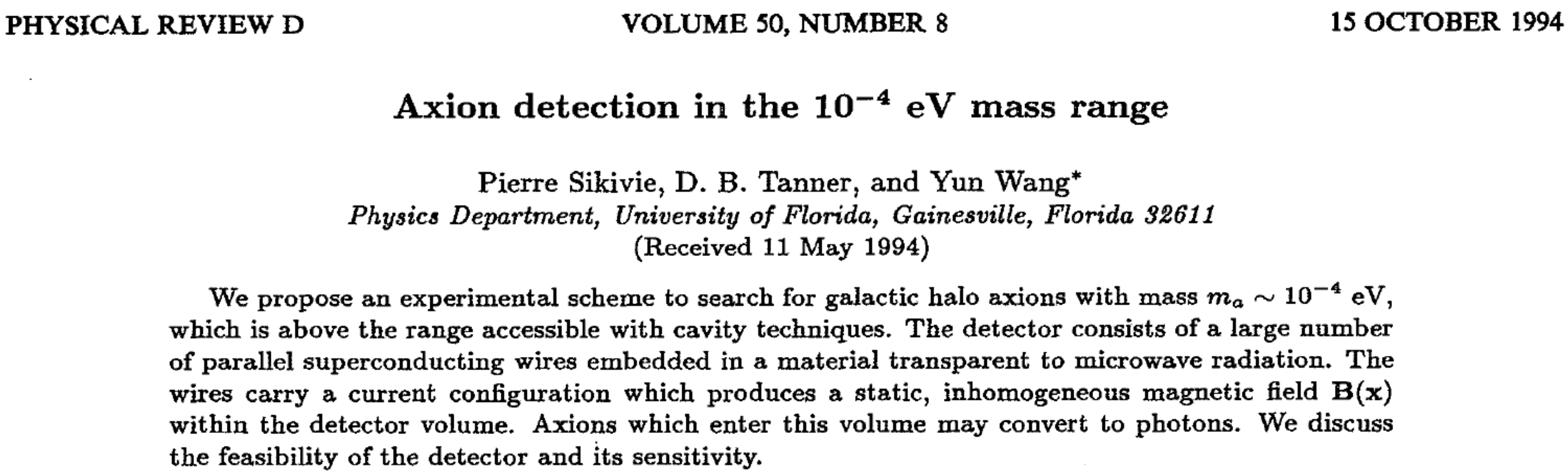
- Can use complex structure, must maintain $\vec{E} \cdot \vec{B}_0$
- Or multiple cavities, tuned together and added in phase

Cavities must operate at the same frequency





Search over 0.1 to 1 meV?



PHYSICAL REVIEW D VOLUME 50, NUMBER 8 15 OCTOBER 1994

Axion detection in the 10^{-4} eV mass range

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(Received 11 May 1994)

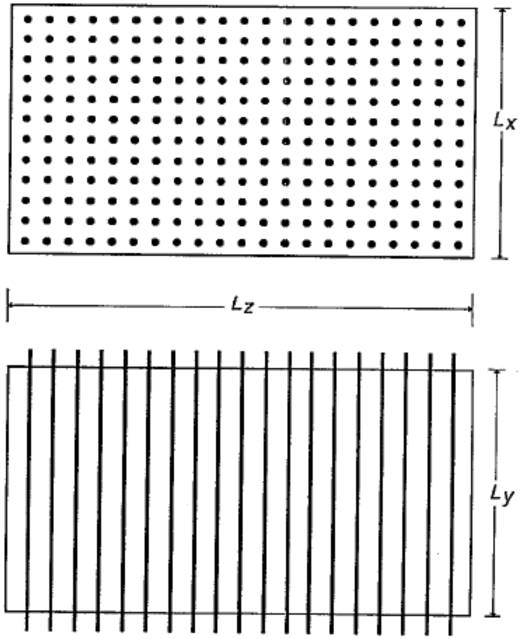
We propose an experimental scheme to search for galactic halo axions with mass $m_a \sim 10^{-4}$ eV, which is above the range accessible with cavity techniques. The detector consists of a large number of parallel superconducting wires embedded in a material transparent to microwave radiation. The wires carry a current configuration which produces a static, inhomogeneous magnetic field $\mathbf{B}(\mathbf{x})$ within the detector volume. Axions which enter this volume may convert to photons. We discuss the feasibility of the detector and its sensitivity.

- Synthesize static magnetic field with $q = q_\gamma$

$$\mathbf{B}(z) = -\hat{\mathbf{x}} B_0 \cos(qz)$$

- Current varies along z

$$I(n_z) = I_0 \sin(n_z d q)$$



Top and side views of the detector.

Conceptual design

- Dimensions

  ~ 3 m x 3 m x 6 m
- Wire spacing

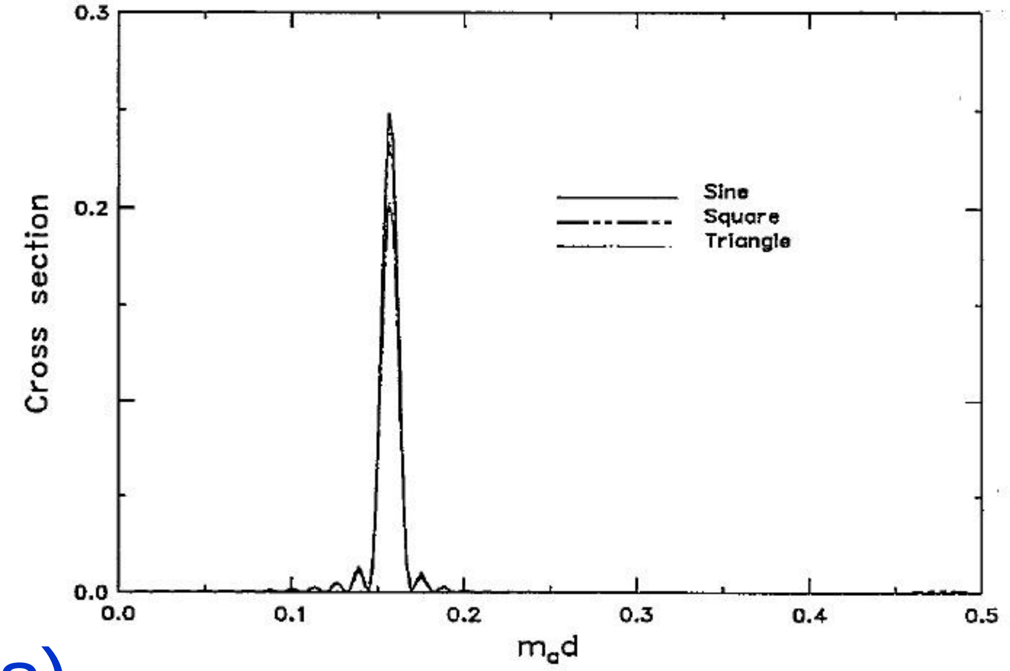
  ~ 2 mm
- Number of wires

  ~ 4 x 10^6

(but only ~3000 planes)

- Currents

  ~ 200 A



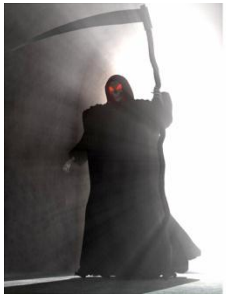
Conversion cross section of axions into photons

Axion Helioscope

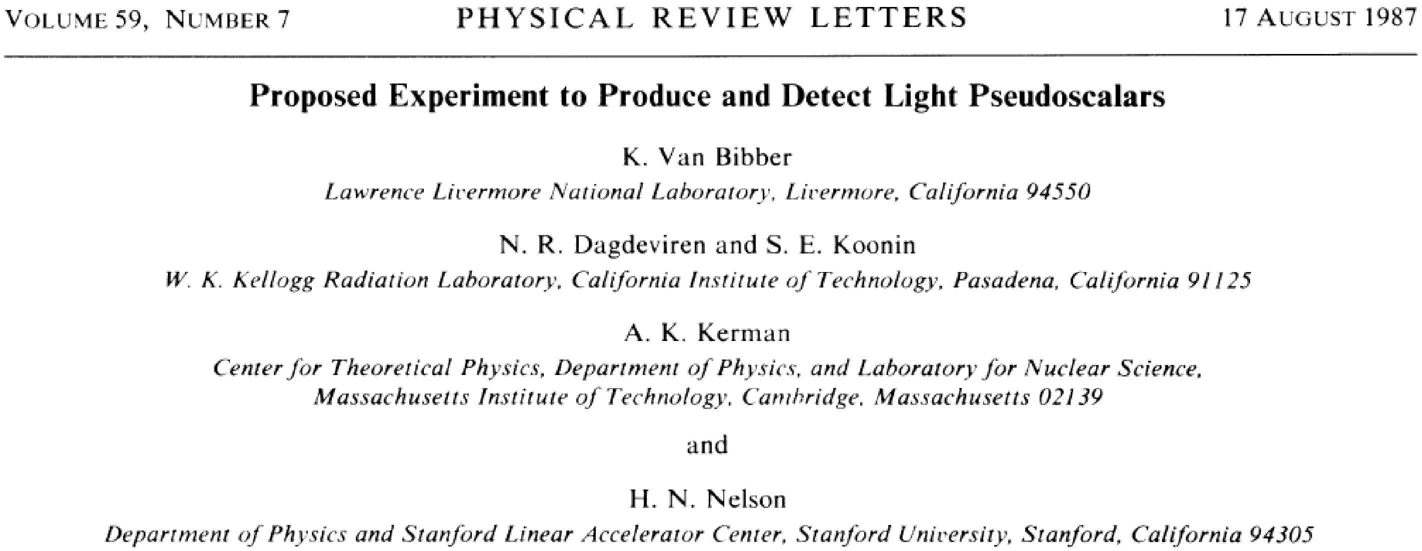
- Tokyo Axion Helioscope (Sumico) (Results since 1998)
- CERN Axion Solar Telescope (CAST) (Results since 2003)
- Talk by Jaime Ruz Armendáriz, 8:50

Resonantly enhanced axion photon regeneration

- Purely laboratory experiment
- Sensitive to all allowed axion masses
- Uses state-of-the-art (but available) technology
- Reaches $g_{a\gamma\gamma} \sim 2 \times 10^{-11}$ GeV^{-1}
- Alps 2, DESY (starting); Any Light Particle
- REAPR, UF + FNAL (planned/proposed)



Shining light through the wall



VOLUME 59, NUMBER 7 PHYSICAL REVIEW LETTERS 17 AUGUST 1987

Proposed Experiment to Produce and Detect Light Pseudoscalars

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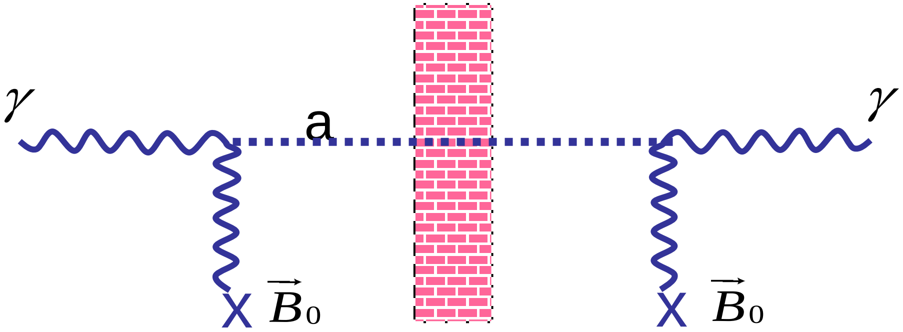
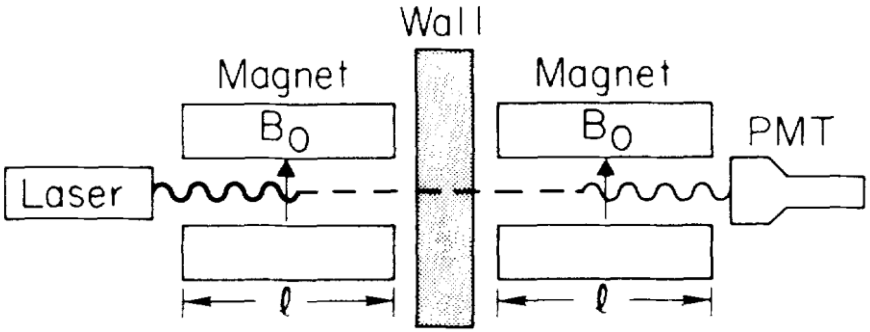
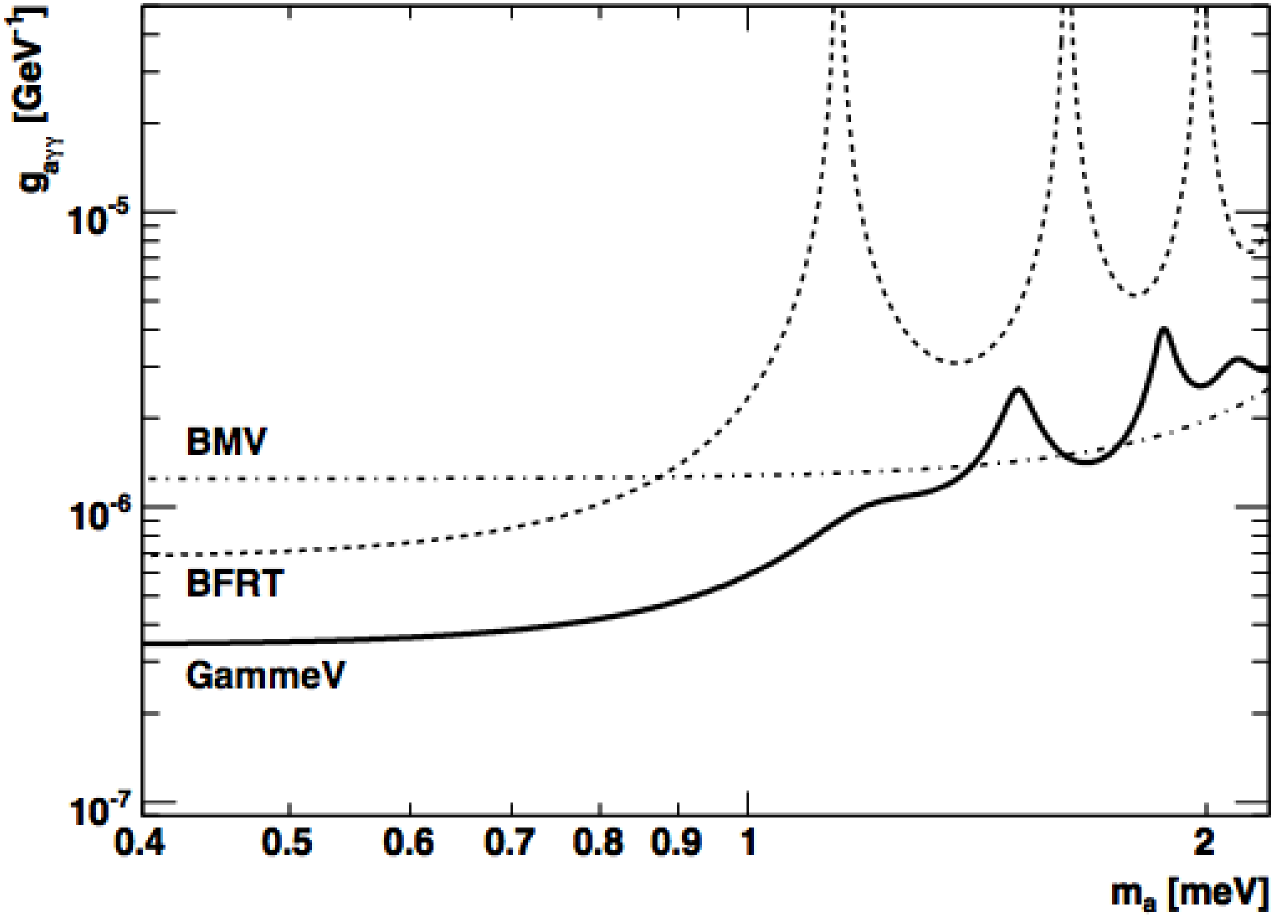
$$\text{rate} \propto \frac{1}{f_a^{\,4}}$$



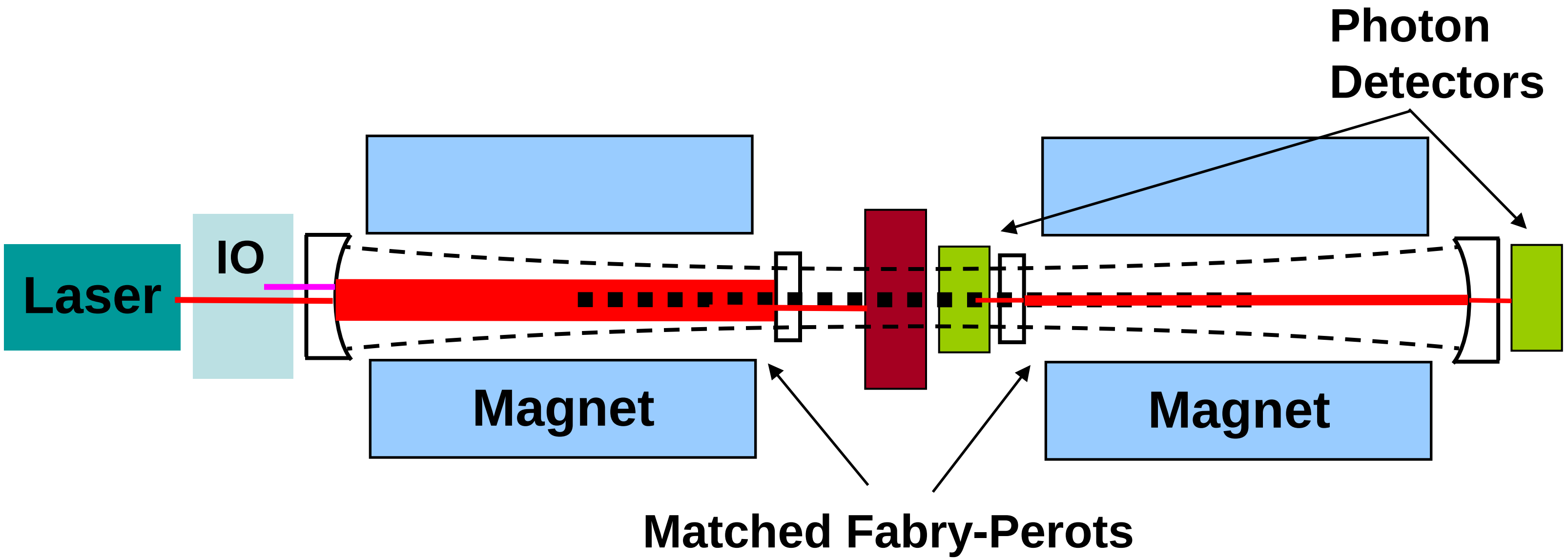


GammeV, BFT, BMV, limits.

ALPS, LIPPS, OSQAR similar



Resonantly-Enhanced Photon Regeneration



Basic concept – use Fabry-Perot optical cavities in both the production and the regeneration magnets.

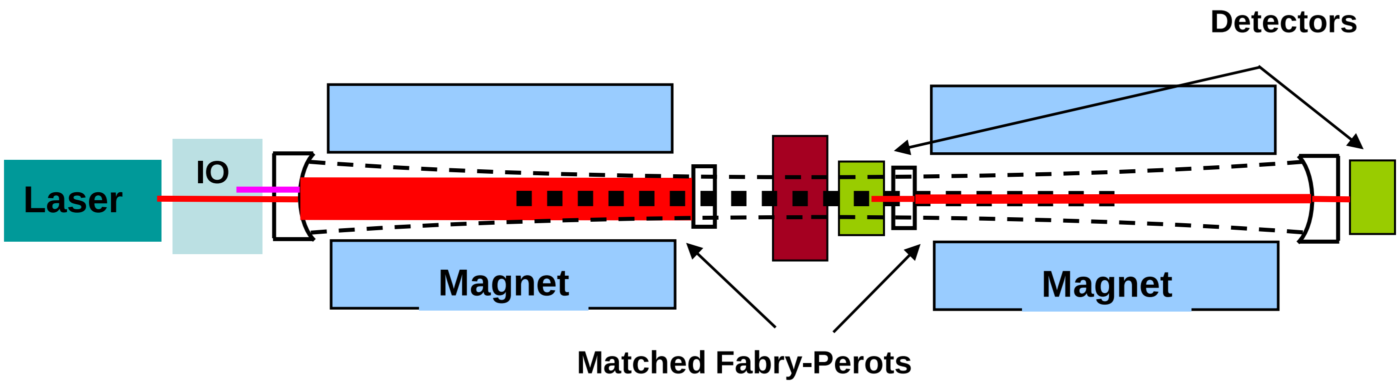
$$P^{\mathrm{Resonant}}(\gamma \rightarrow a \rightarrow \gamma) = \frac{2}{\pi^2} F F' \cdot P^{\mathrm{Simple}}(\gamma \rightarrow a \rightarrow \gamma)$$

where F, F' are the finesses of the cavities. Each could be 10^5

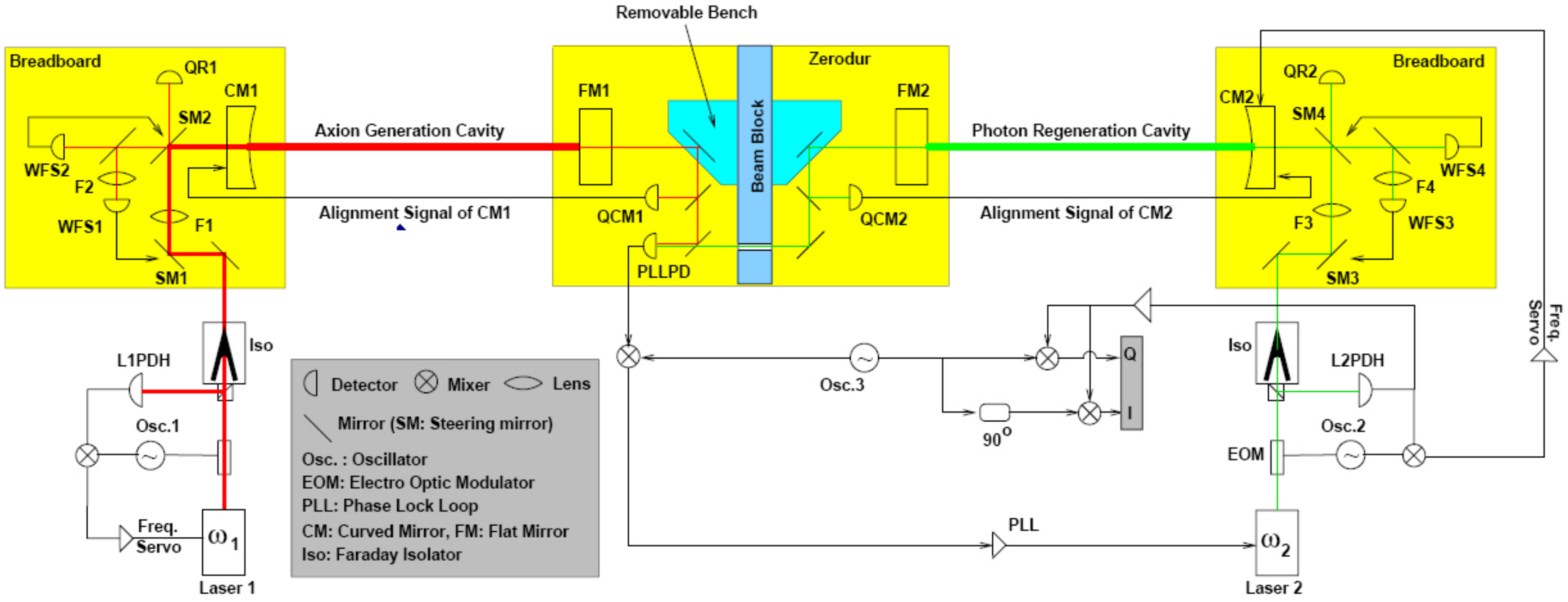
Hoogeveen and Ziegenhagen (1991); Sikivie, DT, and van Bibber (2007), Mueller et al (2009)

Requirements

- Laser must be “locked” to axion generation cavity.
- Photon regeneration cavity must be locked to resonance of production cavity *without filling it with light at the laser wavelength.*
- Cavities must be aligned on mirror image modes (as if inner mirrors and wall were not present).
- Need sensitive readout of weak emission from regeneration cavity.

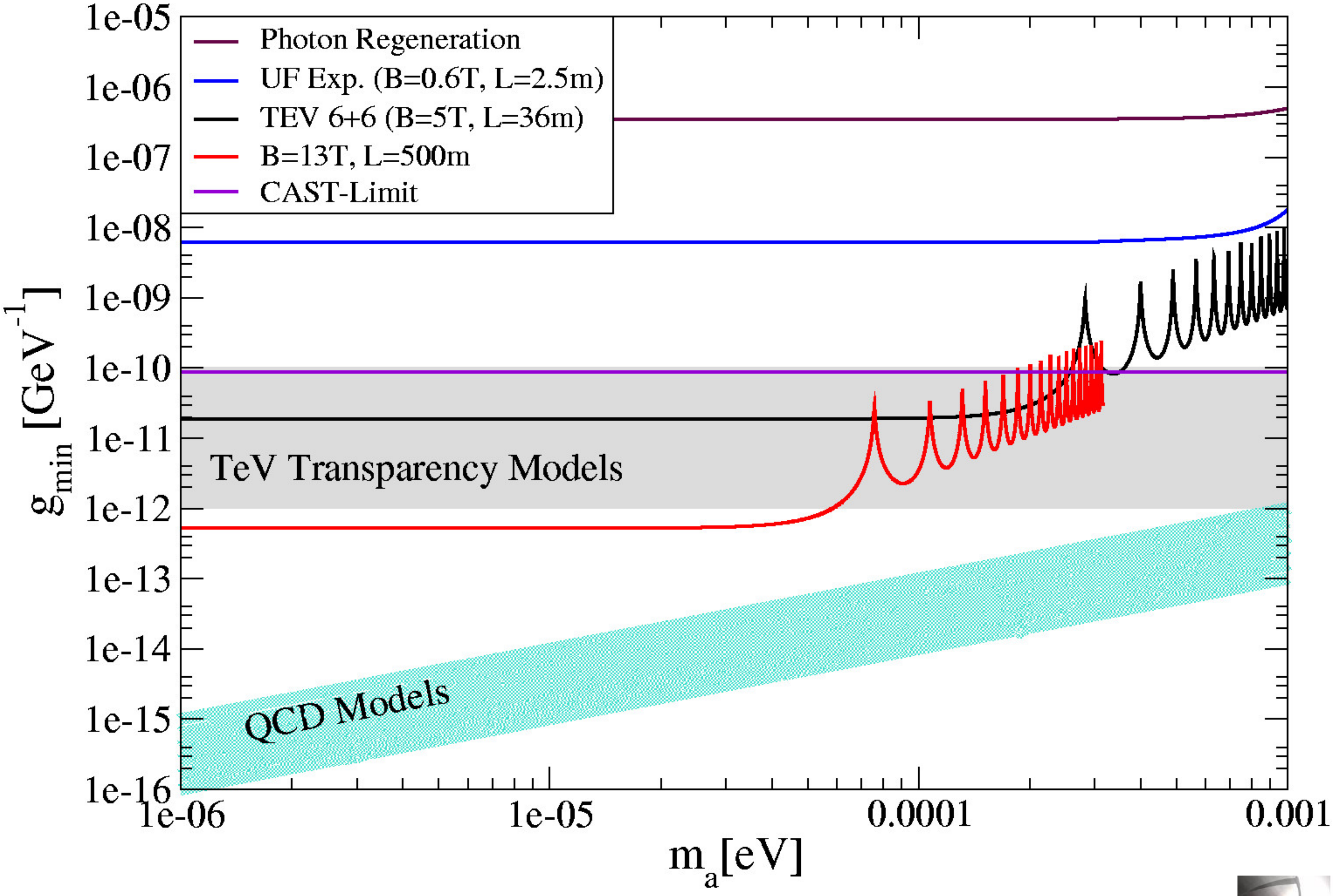


Preliminary design



- Use two lasers.
- Laser 1 injects power into generation cavity
- Laser 2 is offset locked to Laser 1
- Offset frequency Ω = integer * FSR of the cavities
- Regeneration cavity is PDH locked to Laser 2
- Laser 2 used as LO for heterodyne readout of signal in regeneration cavity
- Can detect single photon in regeneration cavity (with SNR of 1)

Sensitivity: Only upper curve and CAST are achieved

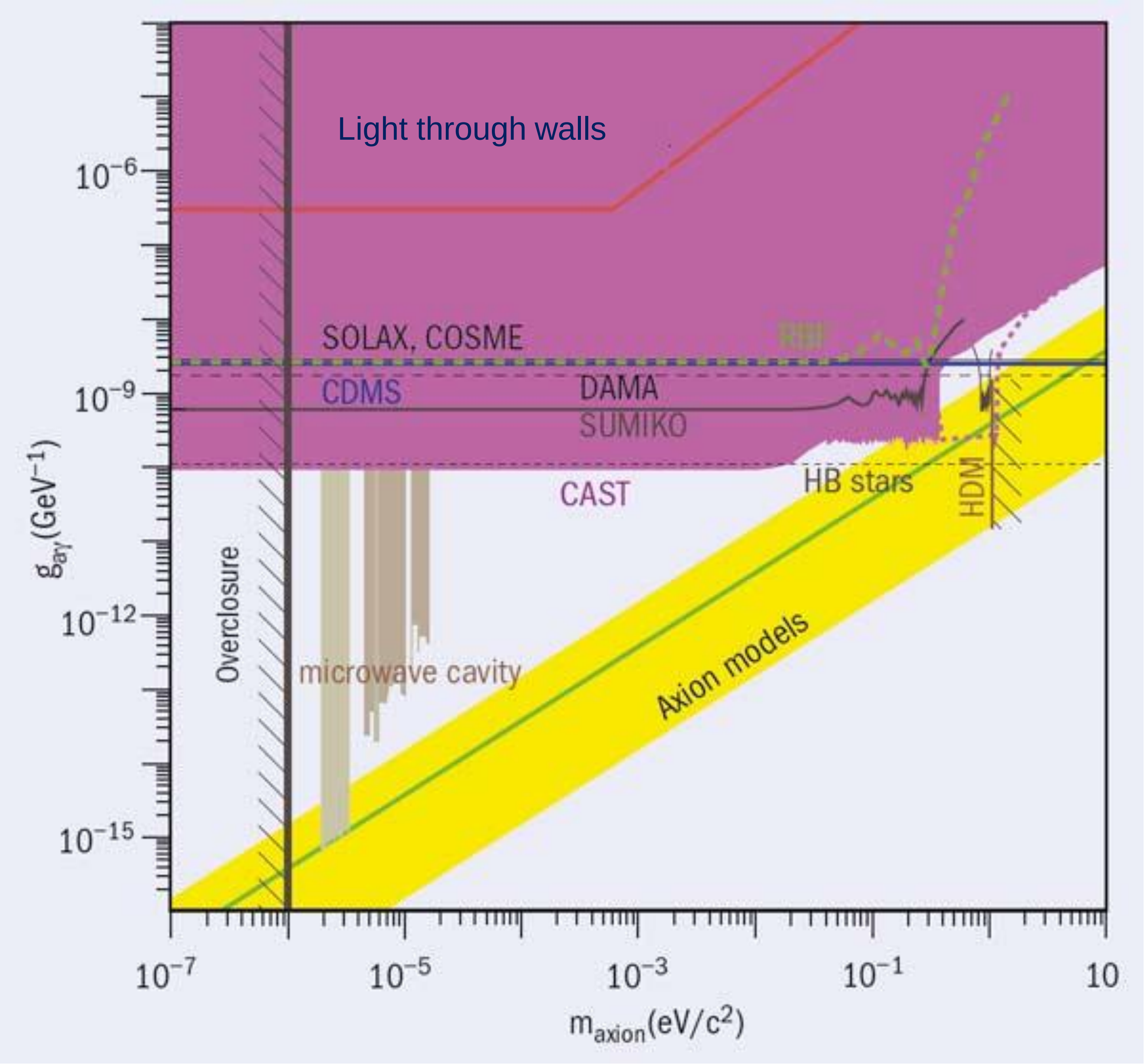


Telescope searches

- Look for emission from the sky (Galaxy or elsewhere)
- Axion decay via Primakoff process gives narrow line at the axion energy.
- Axion can just decay and emit.

- Caltech / INAF / Marseilles, ESO set a deep limit in the 4.7 to 7.5 eV range
- MIT obtained a null result over 35–45 GHz
- Proposal in Australia to look for a signal from the Milky way (starting at 200 MHz).

Present g_γ vs m_a exclusion plot



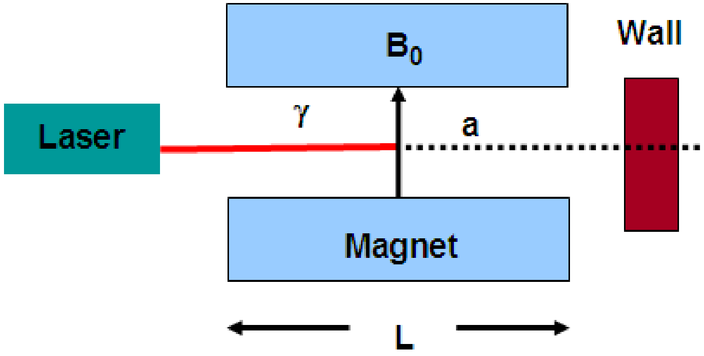
2011
plot
from
CAST

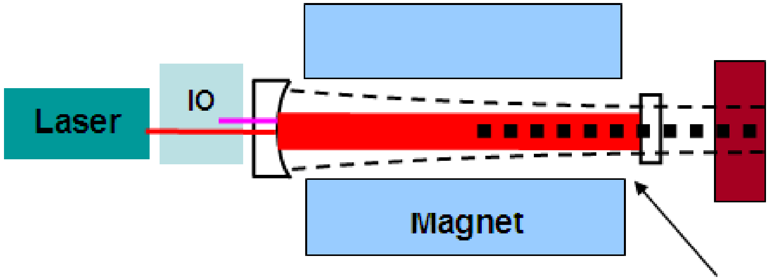
THE END

Karl van Bibber's "EE" argument

The gain on the production side is simple:

- The number of forward passes the light makes in the magnet is larger by a factor of F/π
- Or, the cavity gain in power is F/π
- The axion flux is larger by a factor of F/π





Karl van Bibber's "EE" argument

- On the regeneration side, 1 pass through the magnet produces:

$$P_1 = E_1^{\,2}$$

- In the cavity, the light approaching a mirror is

$$P_c = E_c^{\,2}$$

- After 1 round trip this partial ray has intensity

$$P_{rt} = R^2 * E_c^{\,2}$$

- This adds in phase to the regenerated wave E_1 (add amplitudes!)

$$E_c = R * E_c + E_1$$

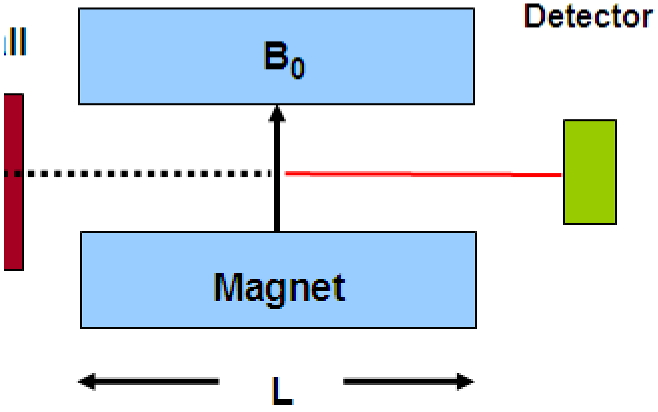
$$(1 - R) * E_c = E_1$$

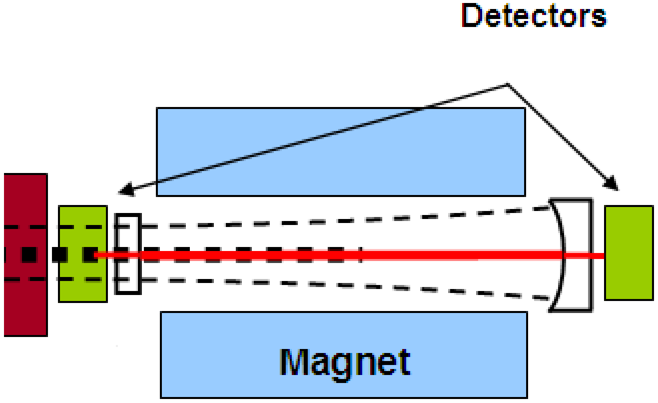
$$E_c = E_1/T$$

$$P_c = P_1/T^2$$

- This light is transmitted through the mirror to the detector

$$P_{det} = P_1/T \sim F * P_1/\pi$$





Take $R + T = 1$ for both mirrors

Readout scheme

- The axion field converts in the regeneration cavity to a signal field E_S at Laser 1 frequency ω_0.

$$E_S = E_{SO} e^{i\omega_0 t} e^{i\phi} \qquad \phi = k_a d$$

- Mix this with Laser 2 (the LO) at a photodiode; the signal is proportional to the intensity

$$S = \left|E_S\right|^2 = \left|E_{LO}\right|^2 + 2E_{LO}E_{SO}\cos\left(\Omega t + \phi\right)$$

- Write this in terms of the number of photons in each field

$$S = N_{LO} + S_I \cos\Omega t + S_Q \sin\Omega t$$

$$S_I = 2\sqrt{N_{LO}N_S}\cos\phi \qquad S_Q = 2\sqrt{N_{LO}N_S}\sin\phi$$

Readout scheme II

- Noise is shot noise:

$$\sigma_I = \sqrt{2\bar{N}} = \sqrt{2N_{LO}} = \sigma_Q$$

- Phase is arbitrary and unknown, so add I and Q in quadrature

$$S_\Sigma = \sqrt{S_I^2 + S_Q^2} = 2\sqrt{N_{LO}N_S}. \quad \sigma_\Sigma = \sqrt{\sigma_I^2 + \sigma_Q^2} = 2\sqrt{N_{LO}}$$

- Shot-noise limited SNR is

$$\frac{S_\Sigma}{\sigma_\Sigma} = \sqrt{N_S}$$

i.e, one photon at an SNR of 1.