Axions and Dark Matter

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Why it is expected that axion exists?

MOTIVATIONS

The Strong CP Problem

QCD vacuum is non trivial: non perturbative effects induce a term

$$\mathcal{L}^\star = \theta \frac{g^2}{32\pi^2} G_{\mu\nu} \cdot \tilde{G}^{\mu\nu}$$

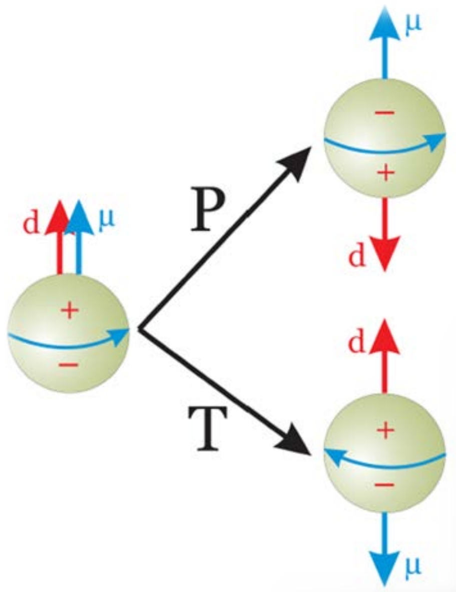
- Strong interactions violate P and CP. Physical effects proportional to

$$\overline{\theta} = \theta - \arg\det M_q$$

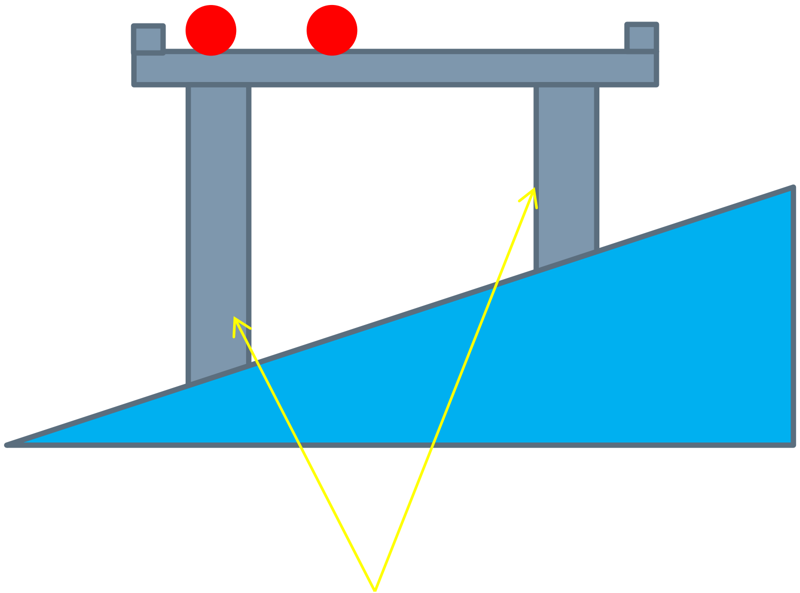
- Experimental limits on neutron electric dipole:

$$|\overline{\theta}| < 10^{-10}$$

Why it is so small?



The pooltable analogy[*]



No fine tuning

[*] P. Sikivie, Physics Today 49/12 (2008)

The Peccei-Quinn solution of the strong CP problem

A modified theory:

$$\mathcal{L}_A = \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{a}{f_a}\frac{g^2}{32\pi^2} G_{\mu\nu} \cdot \tilde{G}^{\mu\nu} + \cdots$$

- The role of $\overline{\theta}$ is played by

$$\frac{< a >}{f_a} - \arg\det M_q$$

and dynamically

$$< a >= f_a \arg\det M_q$$

- To get a consistent theory the axion field $a(x)$ must be the Goldstone boson of a spontaneously broken $U(1)_{PQ}$ symmetry at a scale f_a

PHENOMENOLOGY

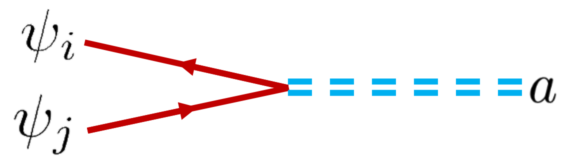
The axion is massive:

$$m_a = \frac{\sqrt{m_u m_d}}{m_u + m_d}\frac{f_\pi m_\pi}{f_a} = \left(\frac{10^{10}\,\mathrm{GeV}}{f_a}\right) 0.6\,\mathrm{meV}$$

For the purpose of our discussion its relevant interactions are:

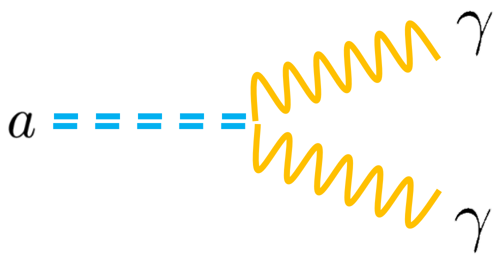
- Interactions with matter:

$$\mathcal{L}_{a,\mathrm{matter}} = \frac{g_{aij}}{f_a}\overline{\psi}_i \gamma^\mu \gamma^5 \psi_j \partial_\mu a$$



- Interaction with electromagnetic field:

$$\mathcal{L}_{a\gamma\gamma} = -\frac{\alpha}{2\pi}\frac{c_{a\gamma\gamma}}{f_a}\vec{E}\cdot\vec{B}\,a$$



$$c_{a\gamma\gamma} = \left(\frac{E}{N} - \frac{2}{3}\frac{4m_d + m_u}{m_d + m_u}\right)$$

$$\tau(a \to \gamma\gamma) \simeq \frac{0.8 \times 10^7}{c_{a\gamma\gamma}^2}\left(\frac{1\,\mathrm{eV}}{m_a}\right)^5 T_{\mathrm{univ}}$$

Axion-LIKE PARTICLES (ALP)

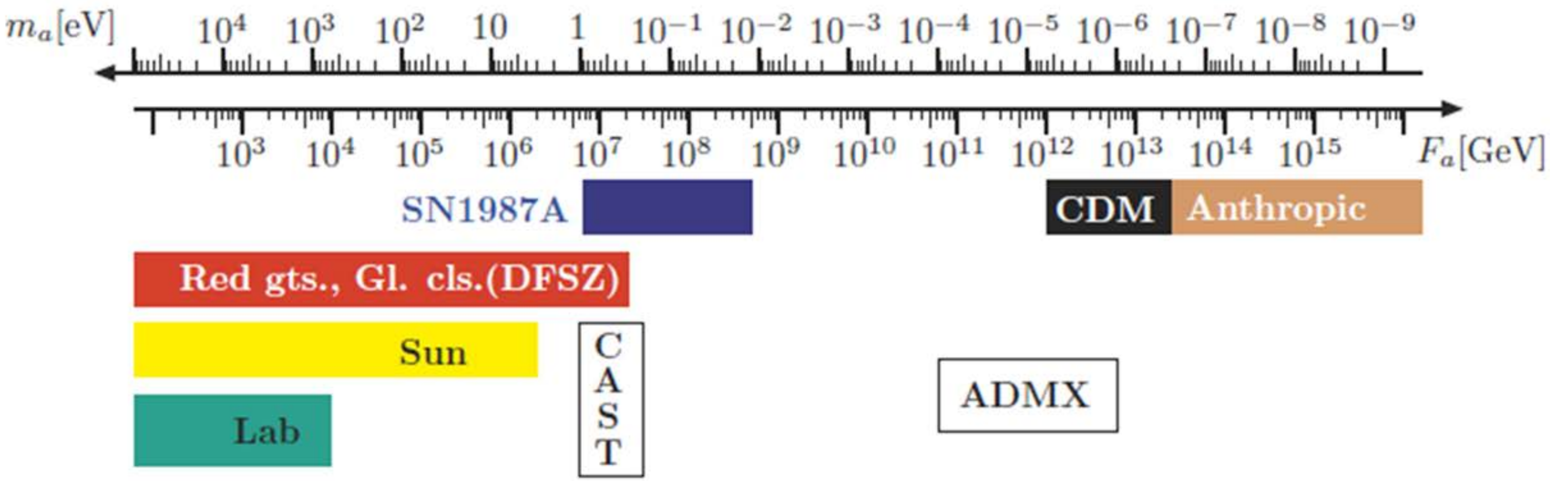
- Are present in several extension of the standard model
- Described by the interaction (pseudoscalar A)

$$\mathcal{L}_{A\gamma\gamma}^{\mathrm{ALP}} = -g_{A\gamma\gamma}^{\mathrm{ALP}}\, \vec{E} \cdot \vec{B}\, A$$

- Or by (scalar A')

$$\mathcal{L}_{A'\gamma\gamma}^{\mathrm{ALP}} = \frac{1}{2} g_{A'\gamma\gamma}^{\mathrm{ALP}}\, \left(E^2 - B^2\right)\, A'$$

- No coupling to the matter is assumed (to make them model-independent)



Where we can find an axion?

CONSTRAINTS

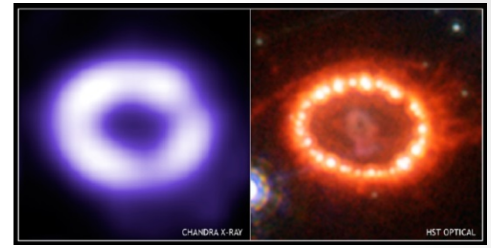
Particle physics experiments

$$m_a \lesssim 0.6\,\mathrm{keV} \qquad f_a \gtrsim 10^4\,\mathrm{GeV}$$

In the original proposal $f_a \simeq G_F^{-1/2}$ (Peccei-Quinn-Weinberg-Wilczek axions)

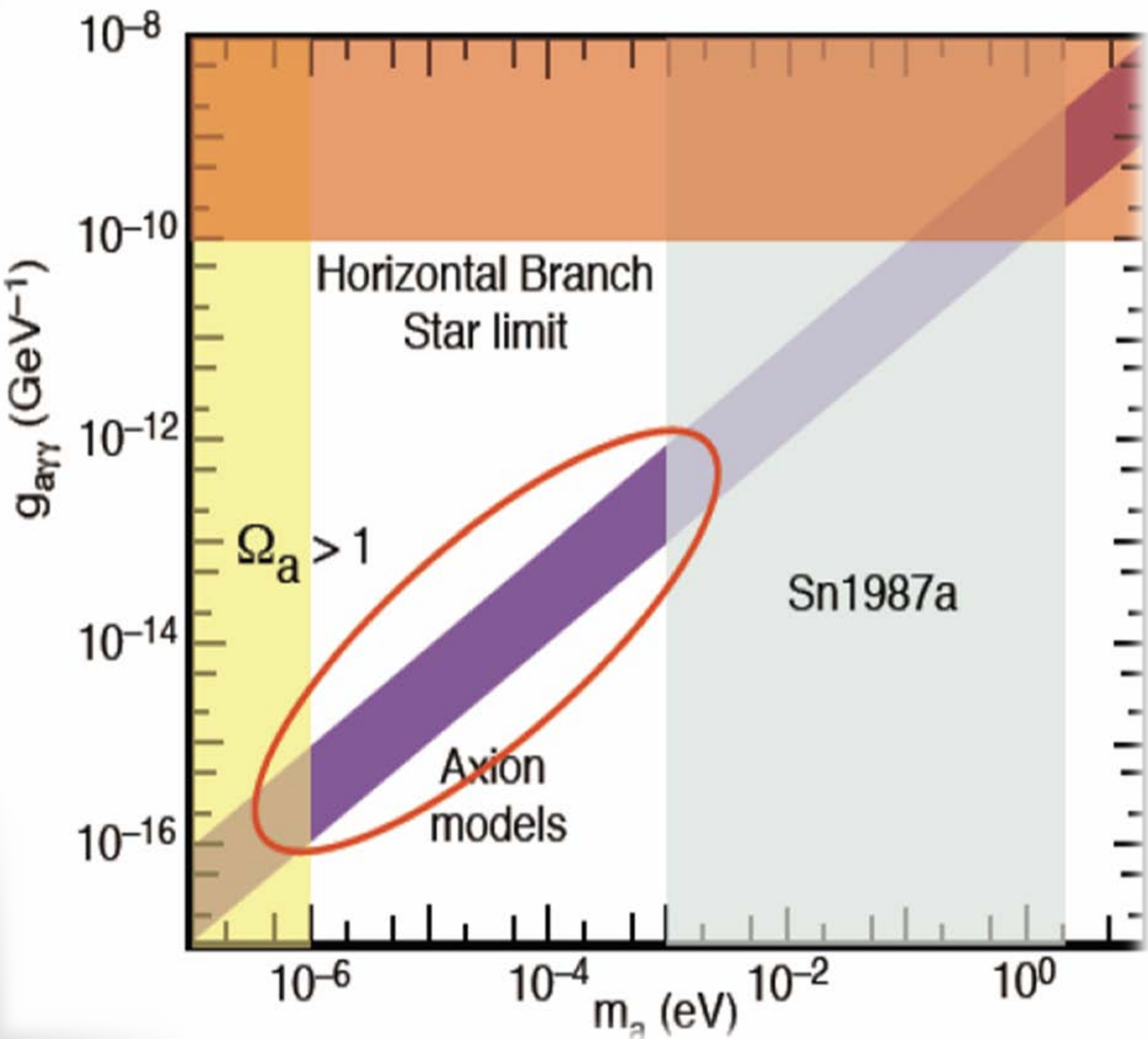
- This means $m_a \simeq 24$ keV and strong coupling to matter
- No axion production detected. Some examples:
  - K-meson decay: $\mathrm{BR}\left(K^+ \to \pi^+ a\right) < 3.0 \times 10^{-18}$
  - Heavy quarkonium decay: $\mathrm{BR}\left(\Upsilon \to \gamma a\right) < 9.1 \times 10^{-4}$
    $\mathrm{BR}\left(J/\psi \to \gamma a\right) < 1.4 \times 10^{-5}$
  - Nuclear transitions: $\mathrm{BR}\left({}^{12}C^* \to {}^{12}C\gamma\right) < 1.5 \times 10^{-4}$

Astrophysical bounds

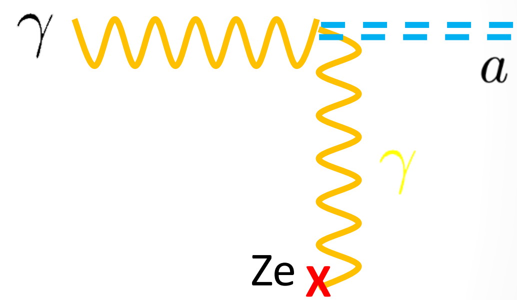


- SN1987A

Efficient axion production ⇒ too short ν burst if $m_a > 10^{-3}$ eV



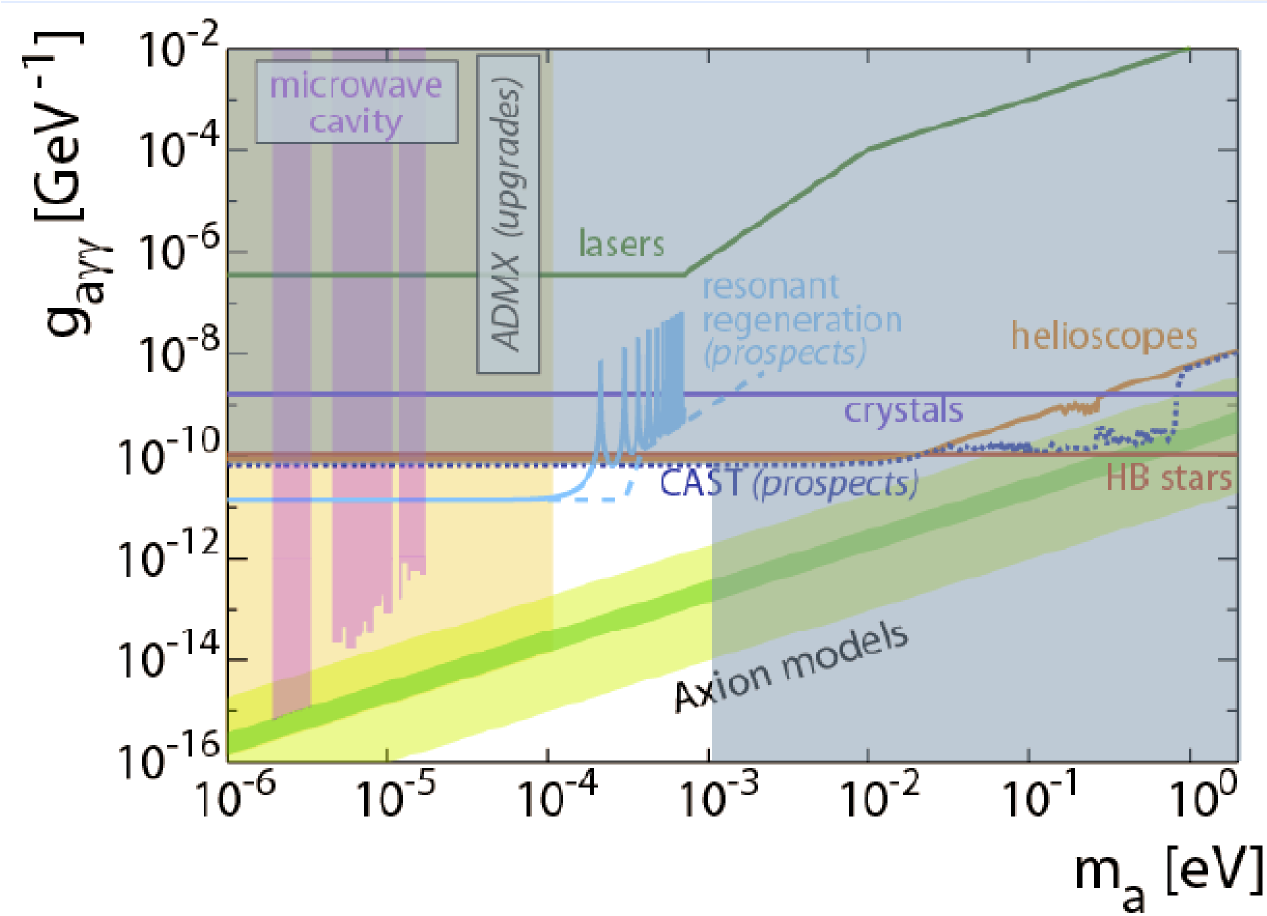
- Study of overall energy loss rate



$$L_a \propto g_{a\gamma\gamma}^2 L_\gamma$$

$$L_a < 10^{-1} L_\gamma$$

$$g_{a\gamma\gamma} < 7 \times 10^{-10}\,\mathrm{GeV}$$



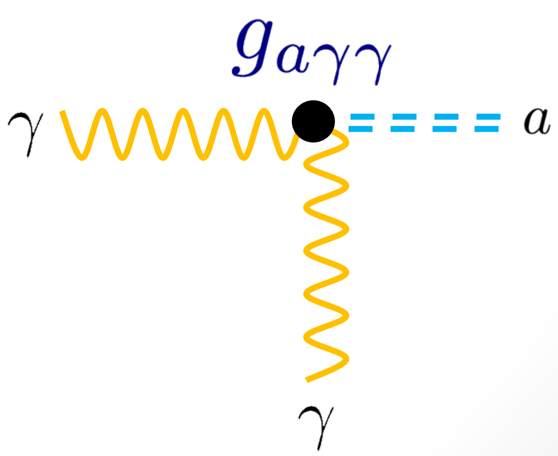
Proposed attempts for detection

LABORATORY EXPERIMENT

LABORATORY EXPERIMENTS

Several types of experiment have been performed:

- Based on astrophysical sources of axions
  - Microwave Cavity Experiment
  - Axion Helioscopes
- Direct production of axion in the laboratory
  - Polarization Effects
  - Photon Regeneration

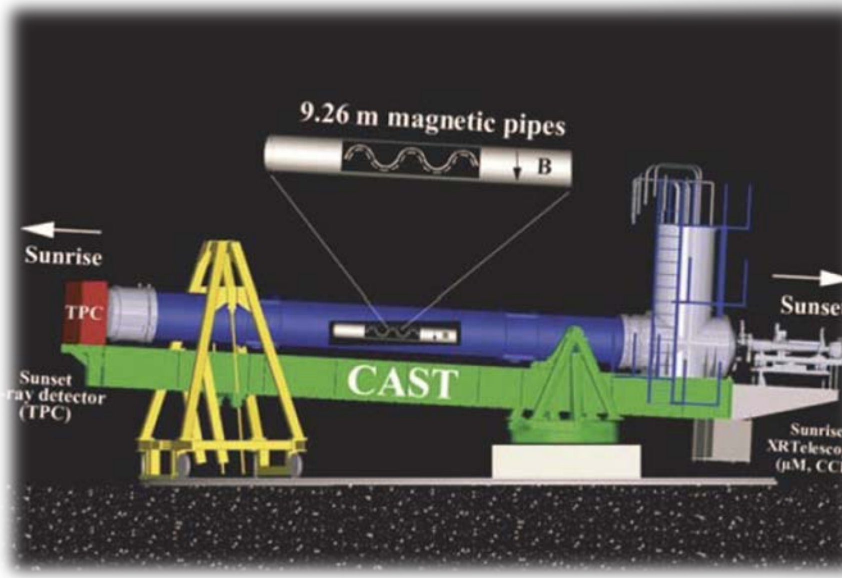


AXION HELIOSCOPES: CAST

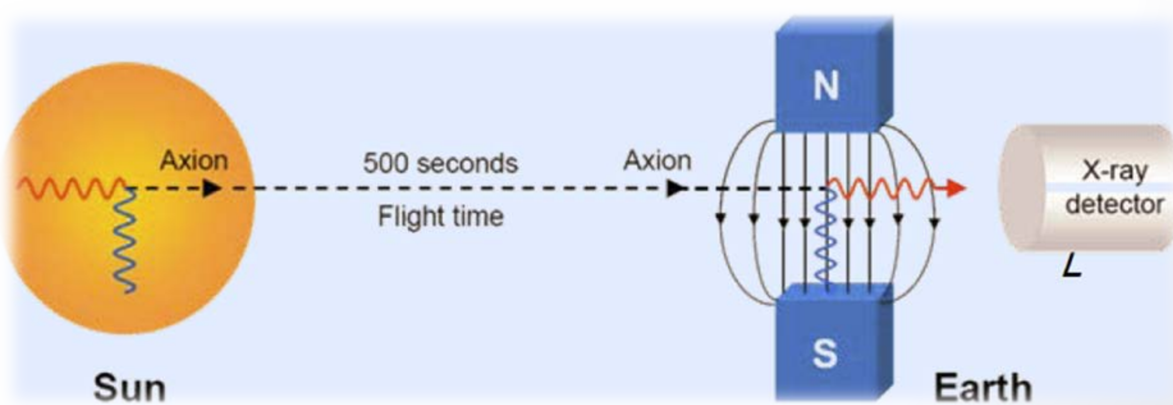
- Axions produced inside the sun
- Reversed Primakoff effect used for detection

$$P_{a\to\gamma} = \left(\frac{Bg_{a\gamma\gamma}}{2}\right)^2 2L^2 \frac{1-\cos qL}{(qL)^2}$$

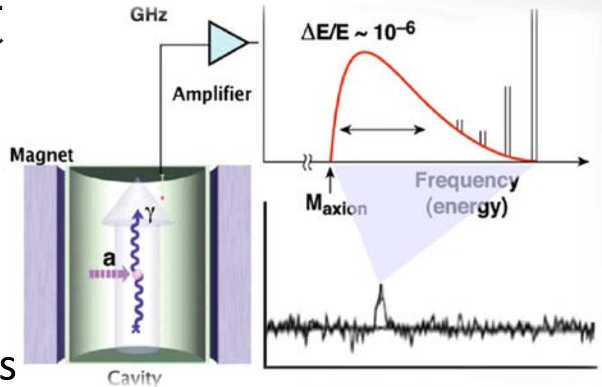
$$q = \frac{m_a^2}{2E_\gamma}$$



Loss of coherence for high m_a: buffer gas.



Axion Dark Matter eXperiment



- High Q cavity ($Q \simeq 10^5$) in a large magnetic field $B \simeq 8.5$ T
- Stimulated conversion of axions into cavity photons
- Modulated signal

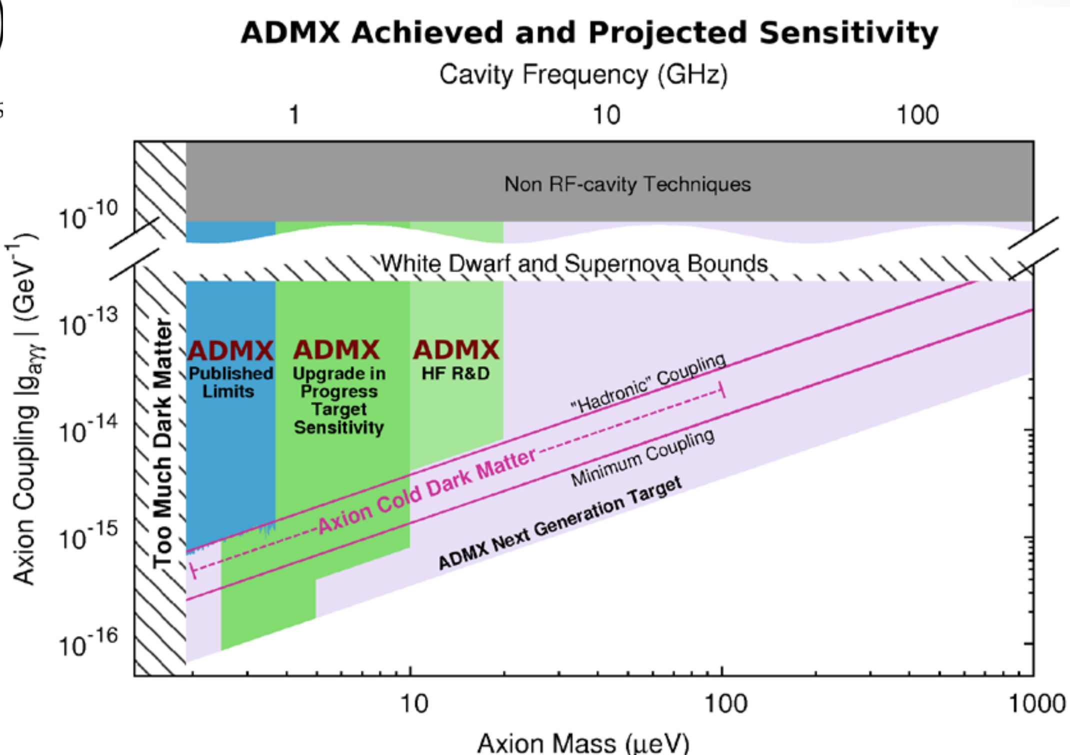
$$\beta_{rot} \simeq 10^{-6} \qquad f \simeq h^{-1}\left(1+\frac{\beta^2}{2}\right)$$

$$\beta_{rev} \simeq 10^{-4}$$

$$\beta_{Halo} \simeq 10^{-3} \qquad \left(\frac{\Delta f}{f}\right)_{Halo} \simeq 10^{-6}$$

- Late infalls[*] can give peaks with much higher SNR
- Cavity must be tuned
- Escluded region (1996-2004):

$$1.86\,\mu eV < m_a < 3.36\,\mu eV$$

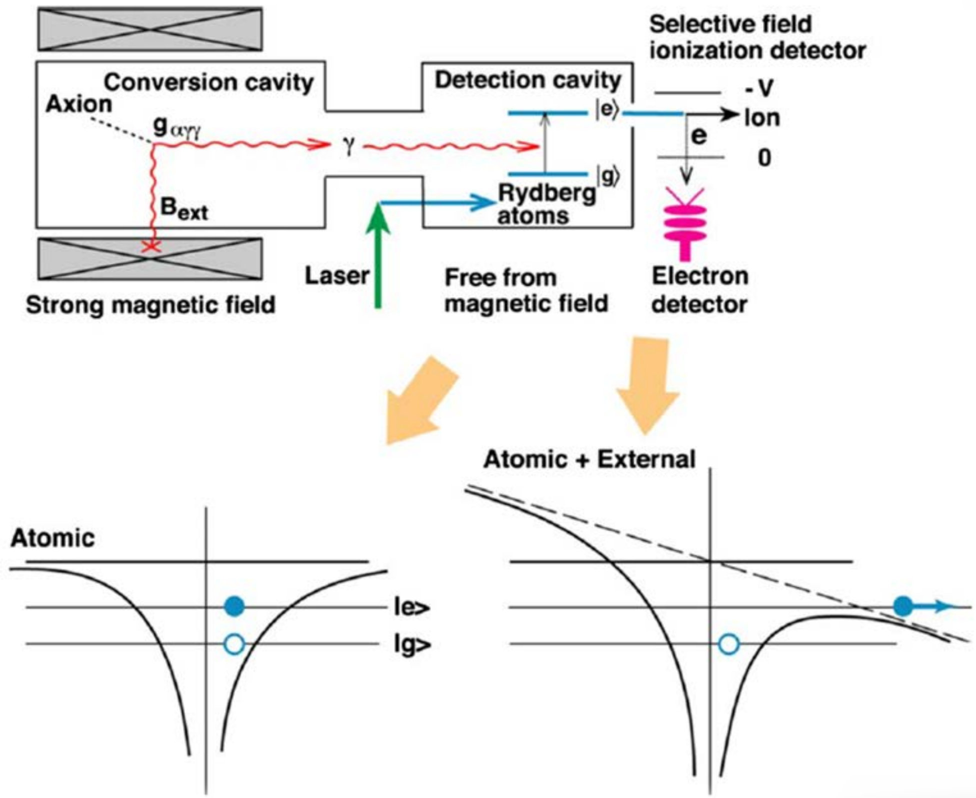


[*] *P. Sikivie, Phys. Lett. B 432 (1998) 139-144*

CaRRACK

- Same front end as ADMX
- Rydberg atoms (high n) used to detect photons
  - Transition in the microwave range
  - Long lifetime:
  - Use Stark effect to tune with
    the cavity
  - Selective ionization of excited atoms

$$\tau_{100} = 1\,\text{msec}$$



Light shining through a wall

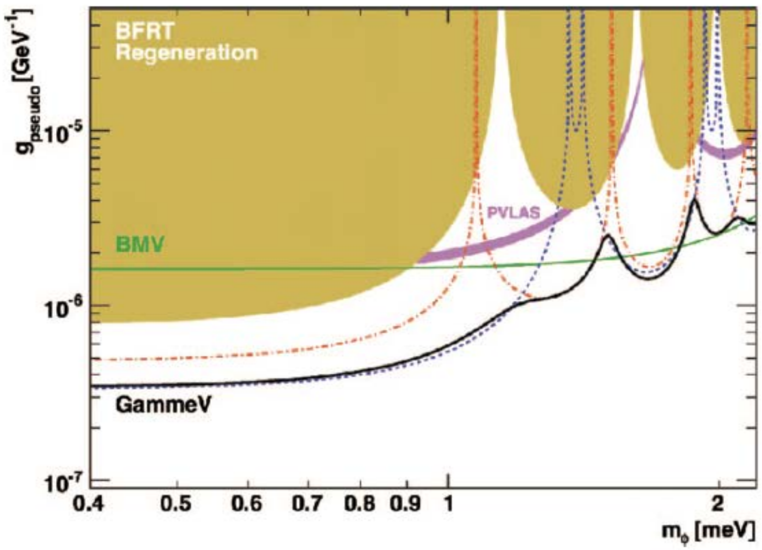
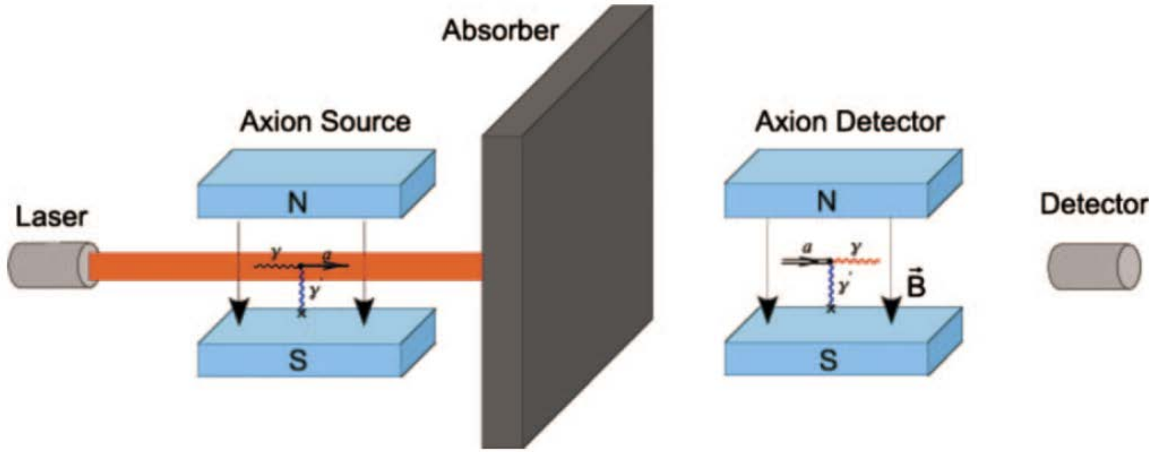
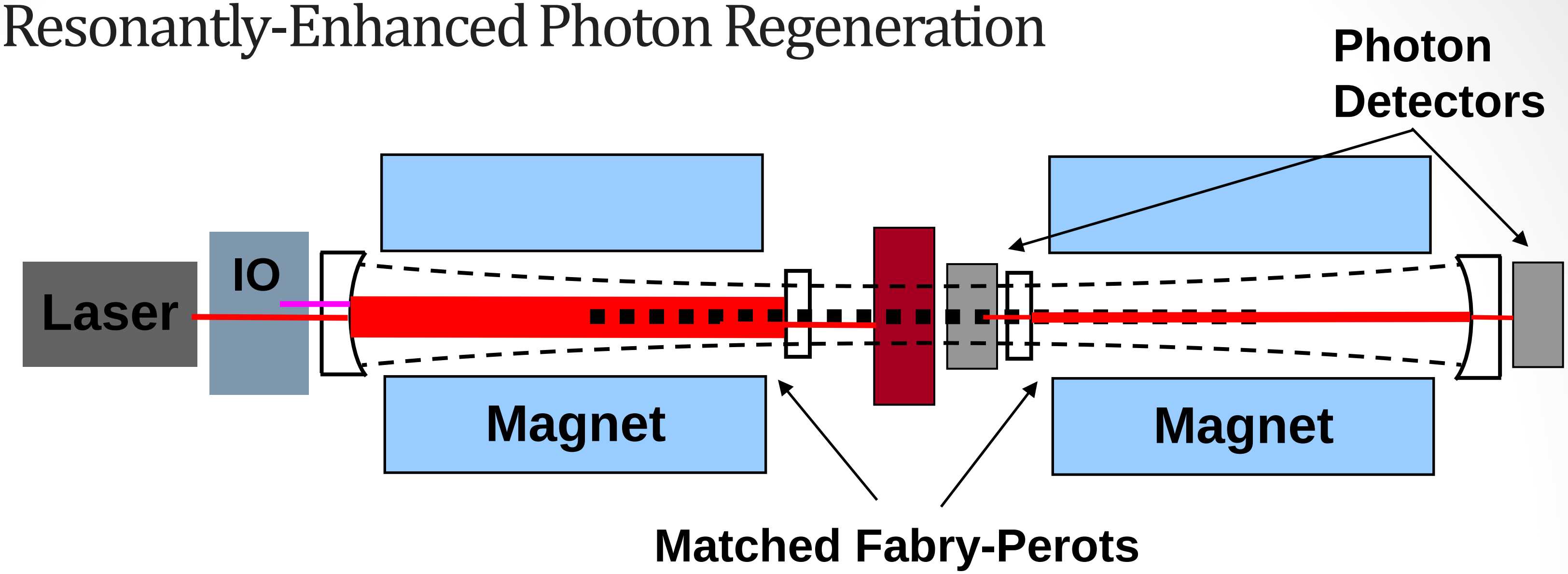


FIG. 24. (Color) Current limits on axion coupling from the GammeV Collaboration (Chou *et al.*, 2008; Yoo, 2008).



Resonantly-Enhanced Photon Regeneration



Basic concept – use Fabry-Perot optical cavities in production and regeneration magnet.

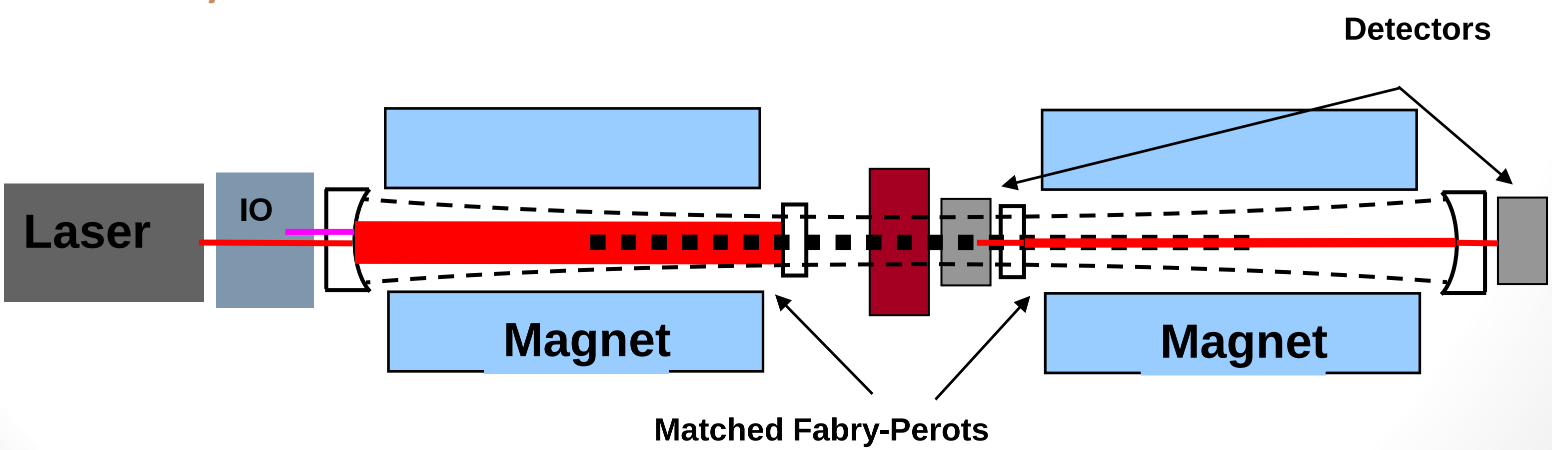
$$P^{\star}(\gamma \to a \to \gamma) = \frac{2}{\pi^2} \mathcal{F} \mathcal{F}' P(\gamma \to a \to \gamma)$$

where $\mathcal{F}$, $\mathcal{F}'$ are the finesses of the cavities

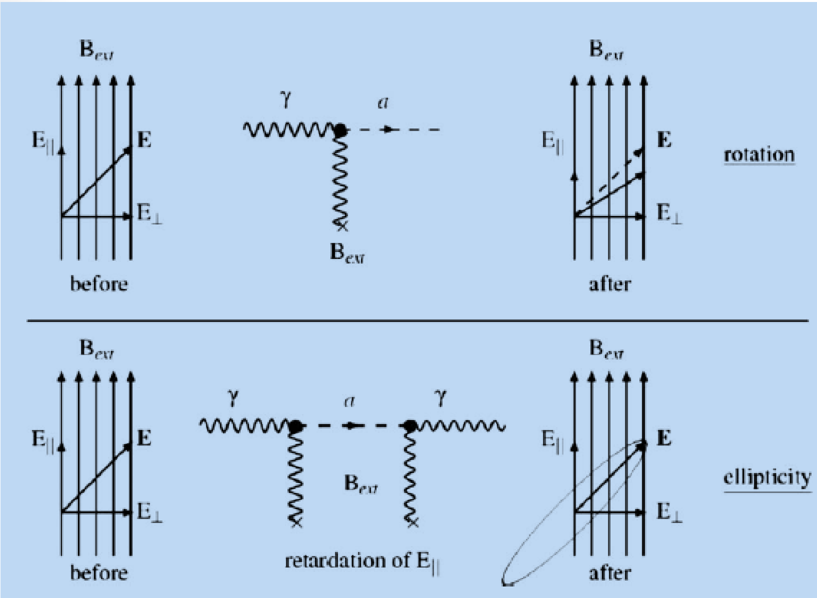
Hoogeveen and Ziegenhagen (1991); Sikivie, DT, and van Bibber (2007); Mueller et al (2009)

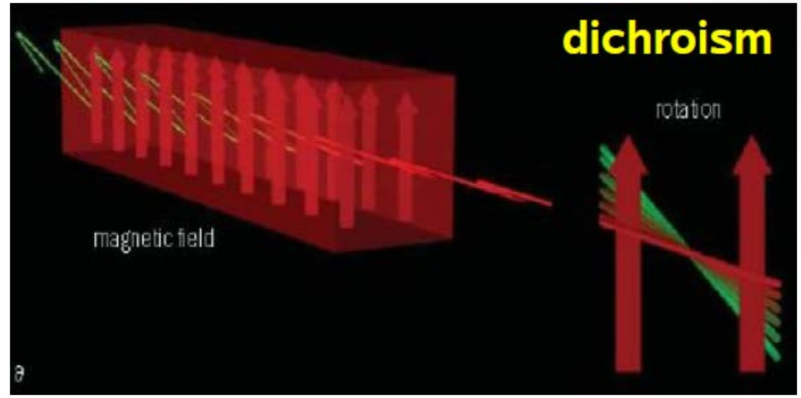
Requirements

- 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.

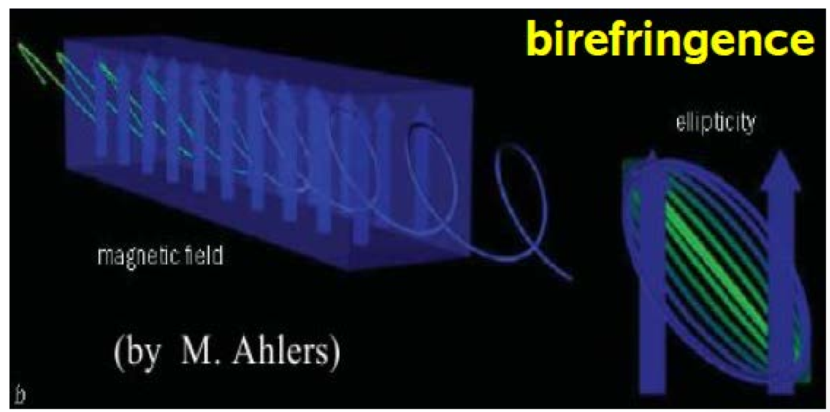


Magneto-optical vacuum effects





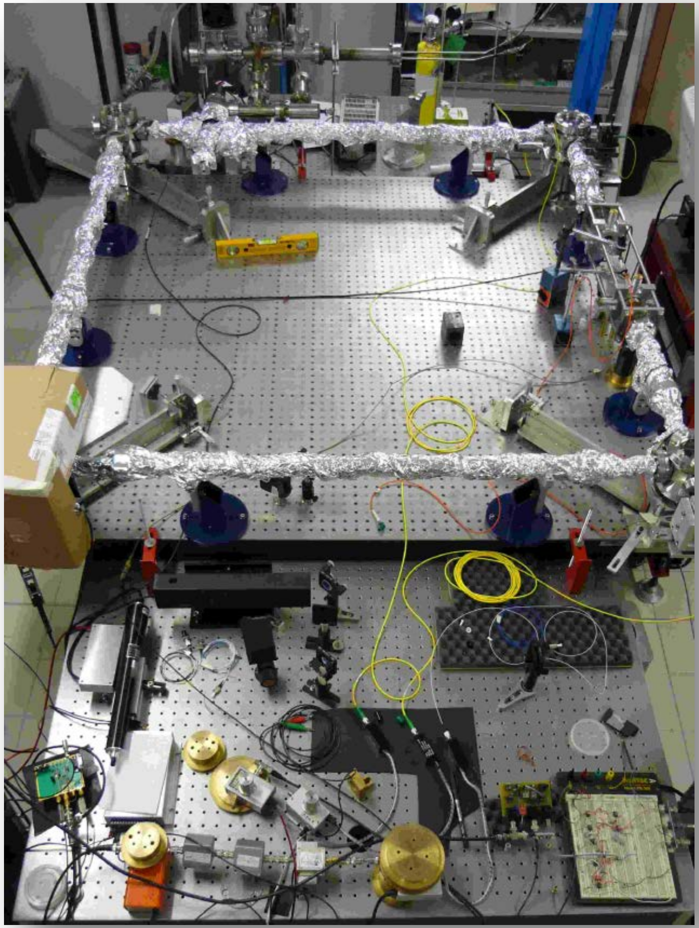
- **dichroism:** $E_{||}$ but not $E_{\perp}$ is depleted by axion production
  → rotation of polarized light



- **birefringence:** mixing of virtual axions in $E_{||}$ state (not for $E_{\perp}$)
  → linearly polarized light develops elliptical polarization

1. An external magnetic field produces photon conversion (real axion)
2. An external magnetic field produces photon retardation (virtual axion)

Only $\vec{E}_{\perp}$ is involved

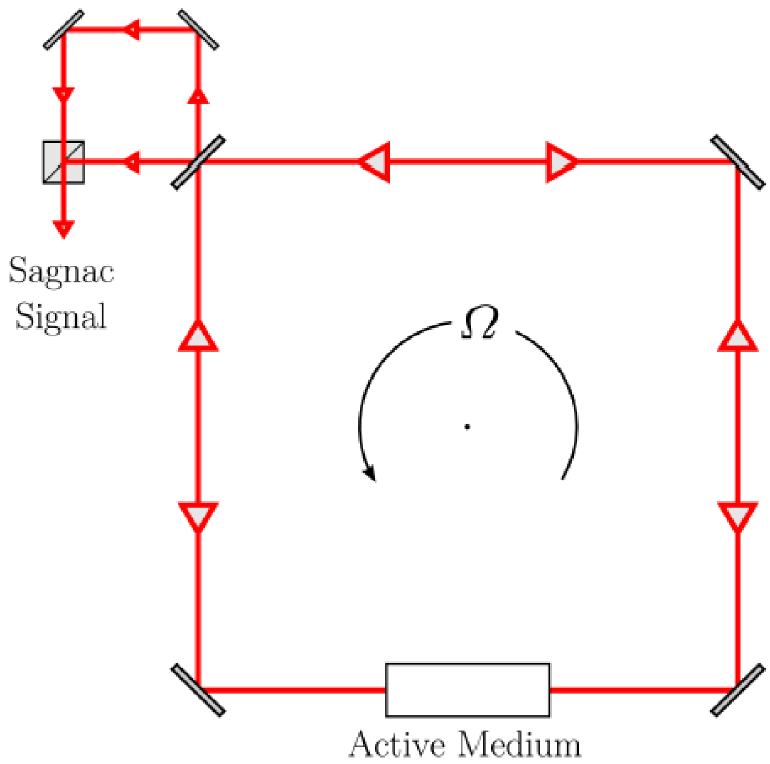


The Stedman proposal

GYROLASERS?

Sagnac effect

- Measures the difference between optical paths of two counter-propagating beams
- Sensitive to time reversal symmetry violations

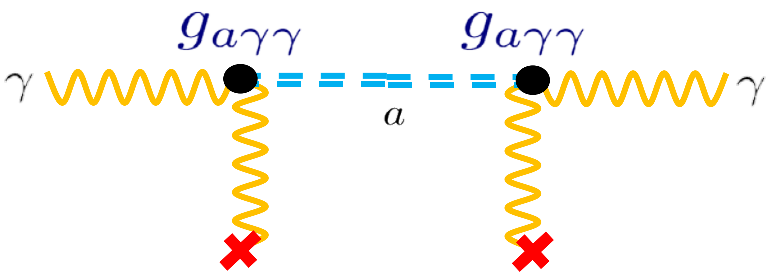


Rotations......

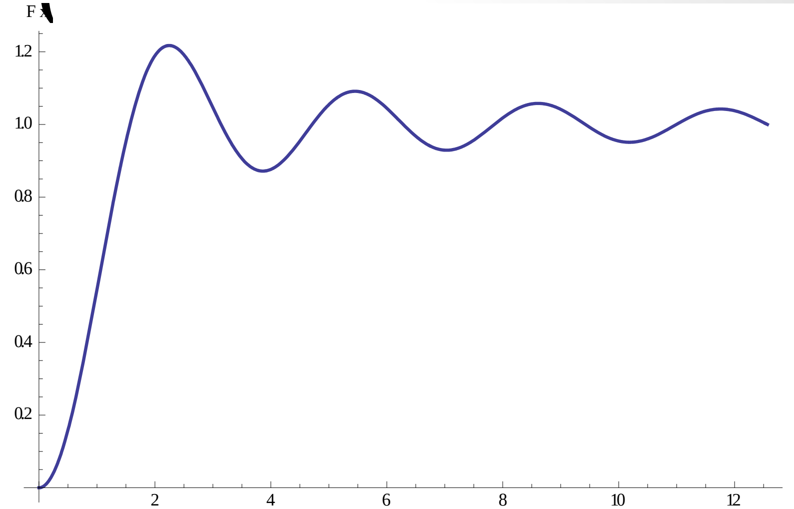
$$\Delta f = \frac{4\vec{S}\cdot\vec{\Omega}}{\lambda \ell}$$

...but not only.

Modified Gyrolaser[*]

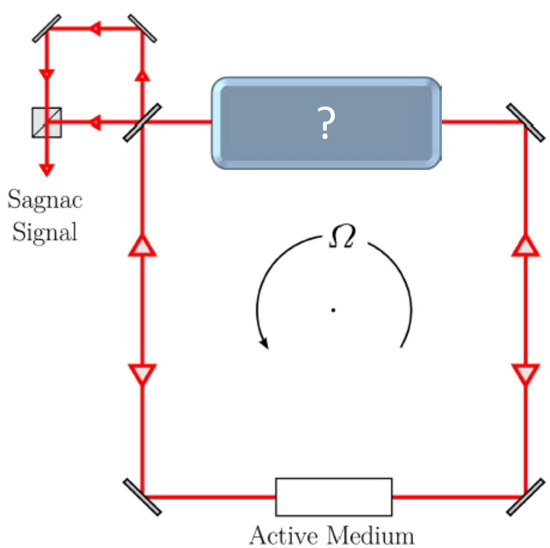


1. Refraction index correction
2. Attenuation



$$\Delta n = \frac{\alpha^2}{4\pi^2}\left(\frac{g_{a\gamma\gamma}}{f_a}\right)^2 \frac{B_{ext}^2}{2m_a^2} F\left(\frac{Lm_a^2}{2\omega}\right)$$

$$\delta = 2\left(\frac{\omega B_{ext} g_{a\gamma\gamma}}{m_a^2}\right)^2 \sin^2\left(\frac{m_a^2 \ell}{4\omega}\right)$$



- Only the $\vec{E}_\perp$ is affected
- Phase modulation
- Amplitude modulation

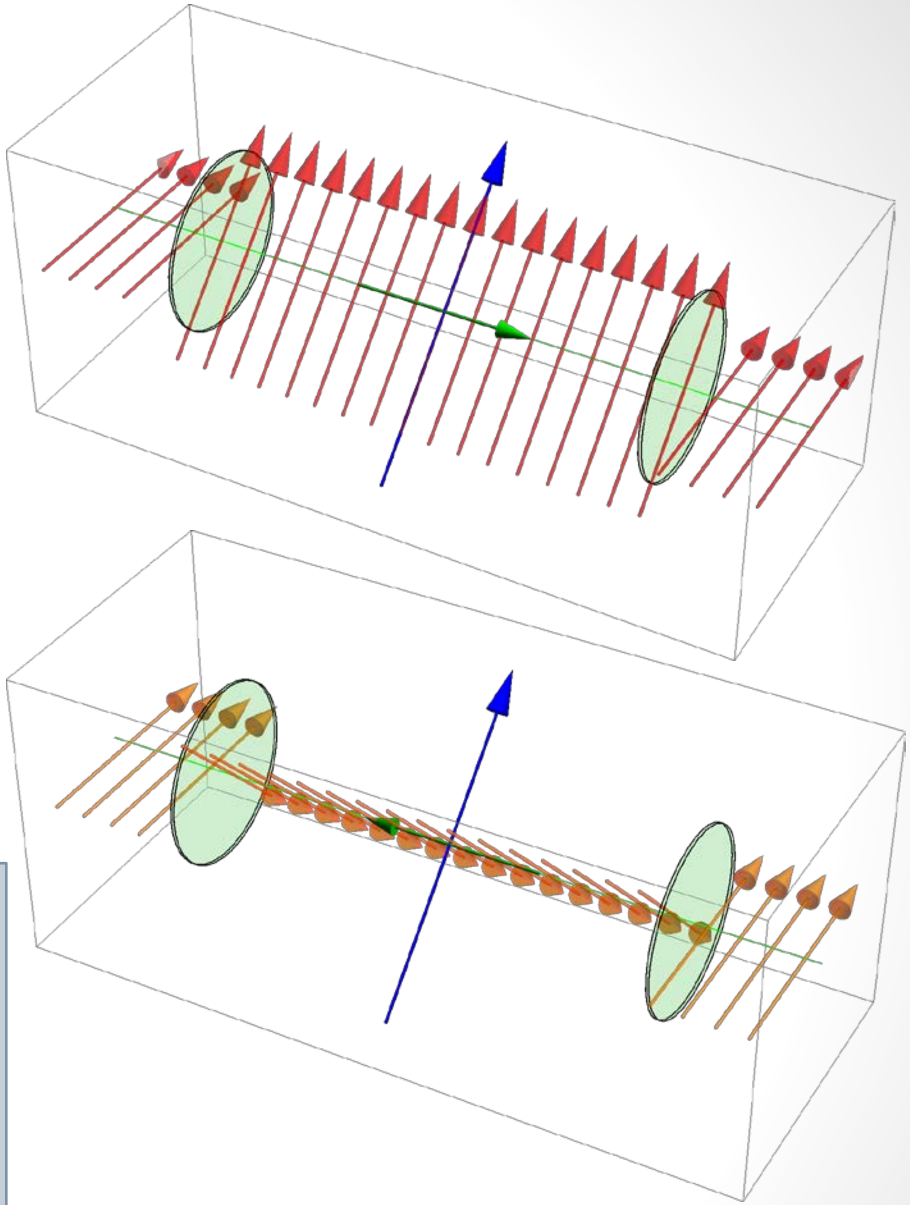
[*] L. Cooper, GE. Stedman/ Physics Letters B 357 (1995) 464-468

Modified Gyrolaser

- Simplest scheme (sensitivity below QN)
- Losses introduced by Faraday rotators

$$\frac{\Delta f}{f} = \frac{\ell}{L}\Delta n$$

- Improvements:
  - Better rotators
  - Multipass geometry
  - Modulation spectroscopy
  - Magnetic field modulation



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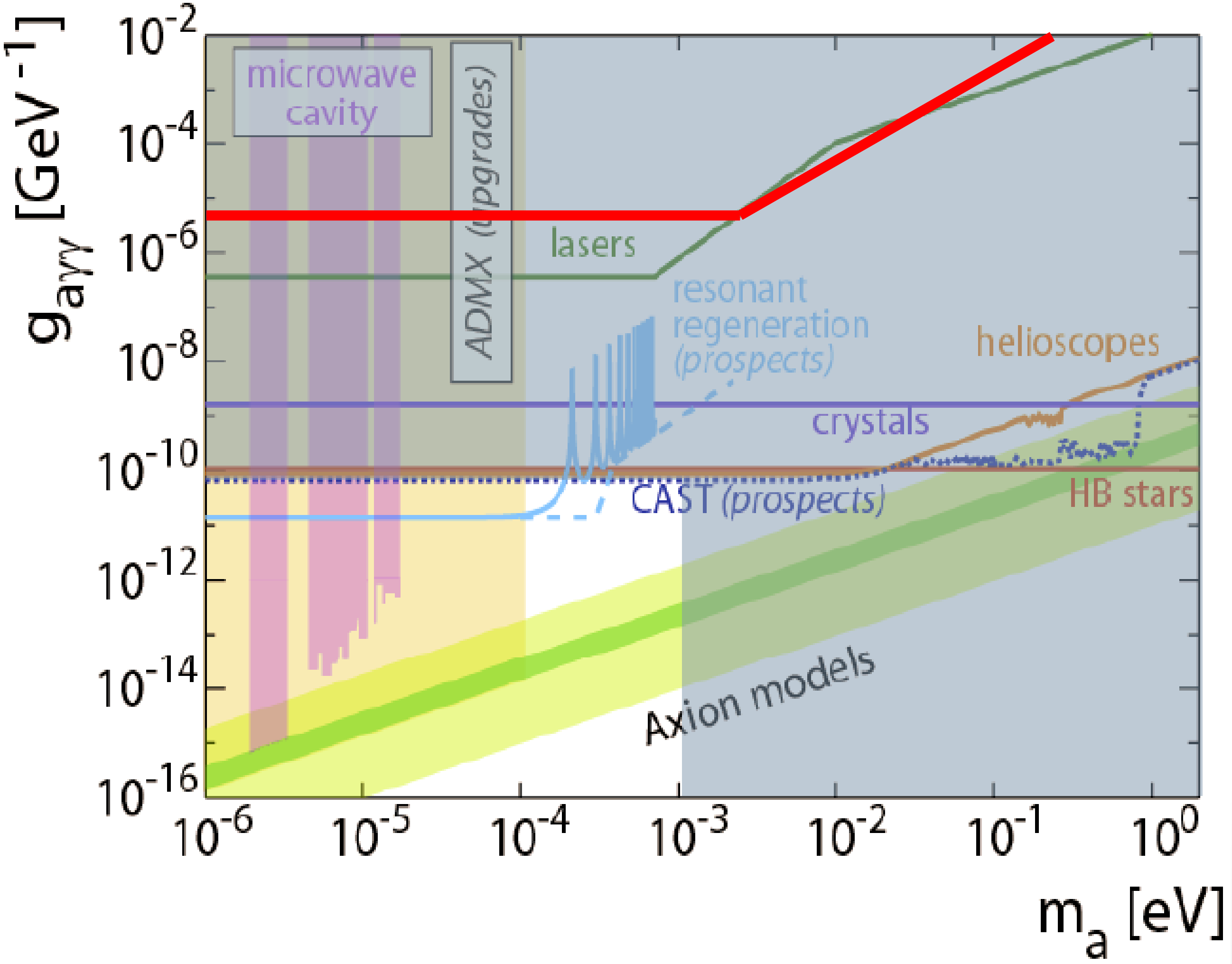
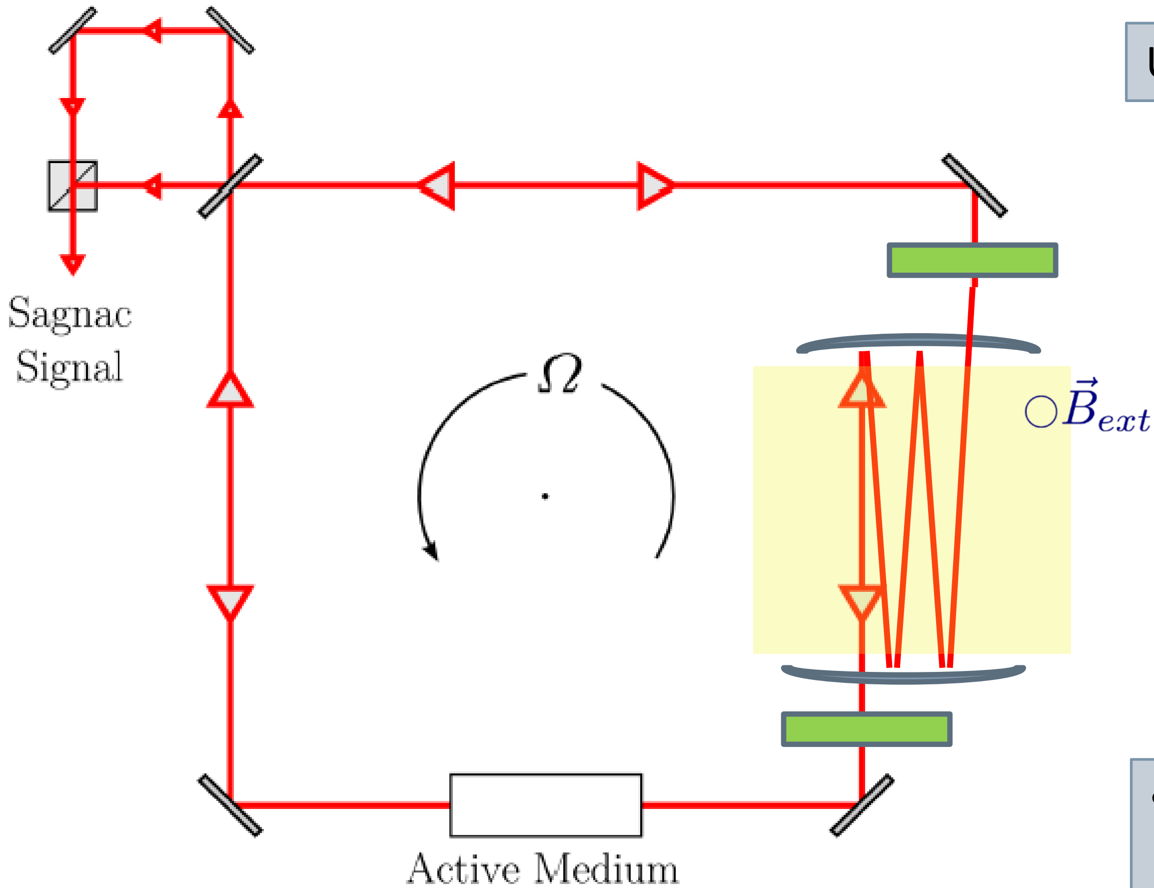
Modified Gyrolaser



Multipass Gyrolaser



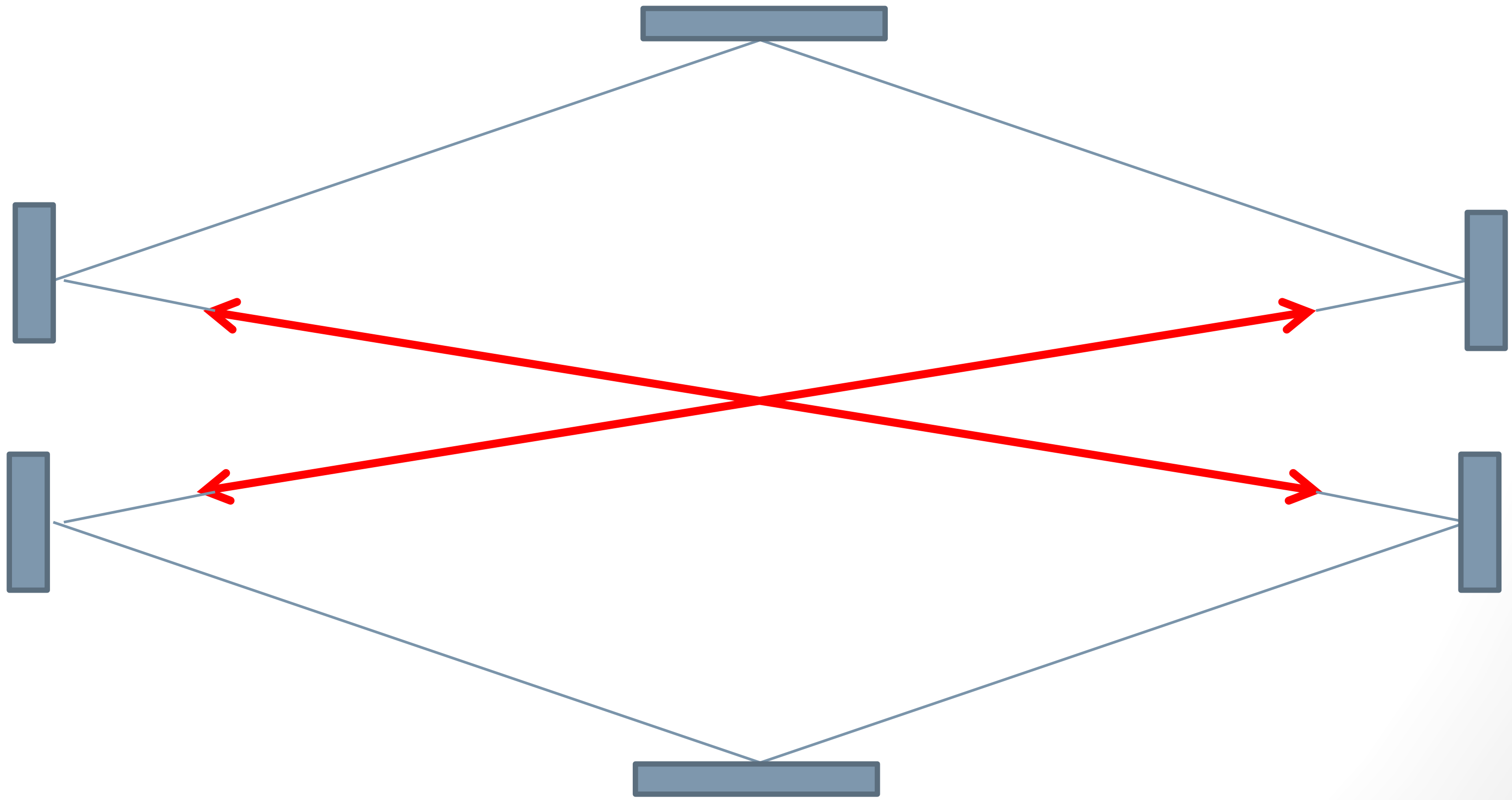
Use a delay line

$$\frac{\Delta f}{f} = \frac{\ell}{L} \Delta n$$

- Not a big improvement
- Losses are not reduced

Collider

- Much simpler with a resonant cavity
- Tricks with polarization modulation?



Loss reduction?