Principles

$$\boxed{\mathcal{L}_{A\gamma\gamma} = -g_{\gamma} \frac{\alpha}{\pi} \frac{A(x)}{f_A} \vec{E}\cdot\vec{B}}$$

axion → photon mixing in B-field

⇒ conversion of axion to photon in magnetic field (or vice versa)

Primakoff effect:

DM {
- Microwave cavity experiments
- ~~Helioscopes~~
- NEW: open ~~resonator~~ quasiresonator approach

{
- Photon regeneration: light shining through the wall
- Helioscopes

[• Polarization effects]

Dark Matter axions
Resonant conversion (cavities)
Axions at rest?

②

The axion acts like a classical field leading to oscillations of $\vec{E}$

⇒ modifies Maxwell equations!

For the interesting mass/frequency range (DM):

1 GHz ≃ 100 GHz

with $v \simeq 10^{-3} c$: "quasi non-propagating:"

extension of experiment $l \simeq 1\,m$, 1 GHz

⇒ takes ≃ $\Delta t = \frac{\Delta l}{v} \simeq \frac{1\,m}{10^{-3}c} = 10^4 \frac{m}{c} \simeq \frac{10^3}{3 \cdot 10^8}\,s \approx 3 \cdot 10^{-6}\,s$

for axion to pass experiment

Period of axion induced ~~ph~~ photon $\frac{1}{100\,GHz} - \frac{1}{GHz} = 10^{-11}\,s - 10^{-9}\,s$

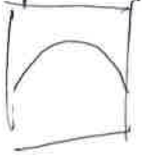
⇒ While axion is passing through experiment 1 GHz - 100 GHz:

~ 10^3 to 10^5 ~~periods~~ phases, respectively

⇒ Photon part of wave function does ~~resonantly~~ coherently couple to experimental infrastructure

⇒ ~~[illegible]~~ In resonance: constructive Superposition of > 10^3 periods of photon part of wave function

⇒ axion field "pumps" cavity with E field power if in resonance



Resonance increases expected output power (pumping of cavity):

$$P_{sig} = g_{A\gamma\gamma}^2 \left(\frac{\rho_a}{m_a}\right) B^2 \cdot V \cdot Q_{L,A} \; C$$

$$Q = \frac{\text{Energy in cavity}}{\text{Energy dissipated in walls per rad}}$$

$$Q_{L} = \frac{\text{center frequency}}{\text{frequency bandwidth}}$$

↑ including loss through coupling

ρ_a = DM density

m_a = Axion mass

V = Volume of cavity

$Q_{L,A}$ = loaded quality factor of cavity or of axion signal, whichever is lower

C = overlap integral of external B field with oscillating E-field of the mode

$$= \frac{\left|\int_V d^3x \, \vec{E}_\omega \cdot \vec{B}_0\right|^2}{\vec{B}_0^2 \, V \int_V d^3x \, \varepsilon \, |E_\omega|^2}$$

ε ← dielectric const.

$$\Rightarrow P_{sig} \simeq \underline{0{,}5 \cdot 10^{-26}\,W} \left(\frac{V}{500\,l}\right) \left(\frac{B_0}{7T}\right)^2 C \left(\frac{g_{A\gamma\gamma}}{0{,}36}\right)^2 \cdot \left(\frac{\rho_a}{0{,}5 \cdot 10^{-24}\,\frac{g}{cm^3}}\right)$$

$$\cdot \left(\frac{m_a}{2\pi [GHz]}\right) \cdot Q_{L,A}$$

Can calculate sensitivity of experiment using Dicke's radiometer formula:

(how long does it take to detect signal P_{sig} with $\frac{S}{N}$)

$$\frac{S}{N} = \frac{P_{sig}}{k_B T_{sys}} \sqrt{\frac{t_{scan}}{\Delta\nu}}$$

with $\Delta\nu \simeq 10^{-6} \cdot \nu_a$

with $\frac{S}{N} \simeq 5$ (standard assumptions)

$T_{sys} = 1\,K$ (LHe cooled cryostat + noise temp of devices)

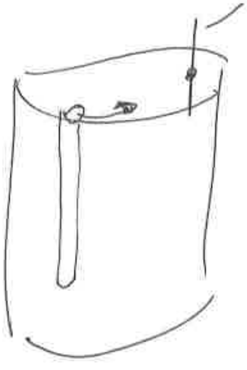
$t_{scan} \simeq 100\,s$ (High Q_L ⇒ @once: scan small range ⇒ many measurements, ie $t_{scan} \lesssim 100\,s$)

$$\Rightarrow P_{sens} = 5 \cdot k_B \cdot T_{sys} \sqrt{\frac{\Delta\nu}{t_{scan}}} \simeq 10^{-23}\,W$$

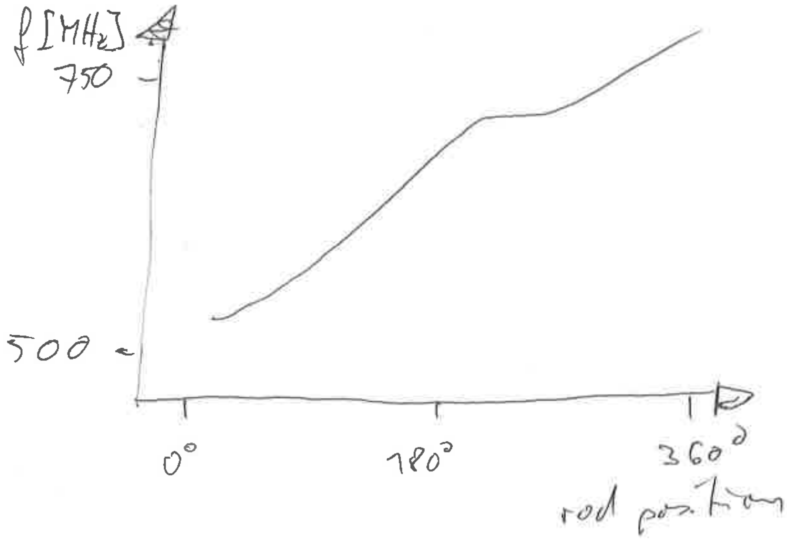
ADMX

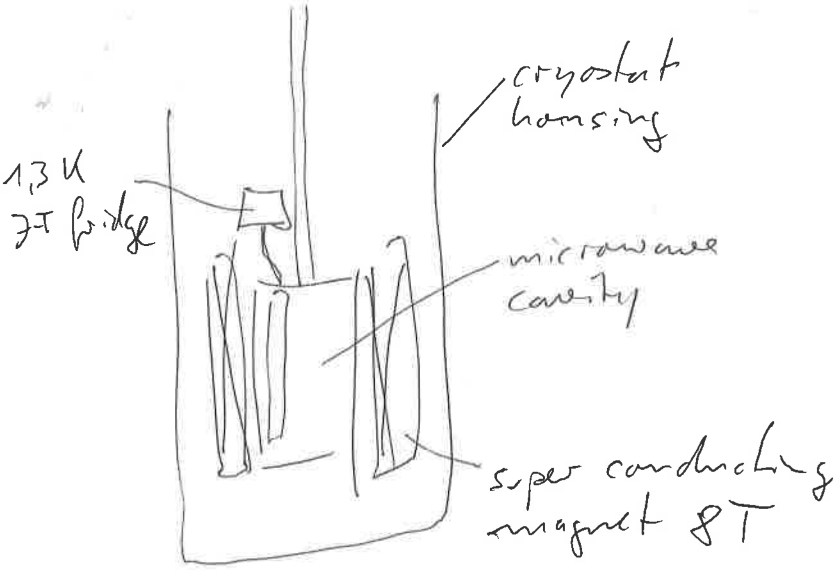
Use resonant cavity with dielectric tunable rods

antenna to couple to resonant frequency



by turning rod within cavity: change resonance frequency of cavity:





$T_{phys} \sim 1{,}5\,K$

$\Rightarrow$

$T_{sys} \sim 3\,K$

$Q_L \sim 10^5$

$V \sim 100\,l$

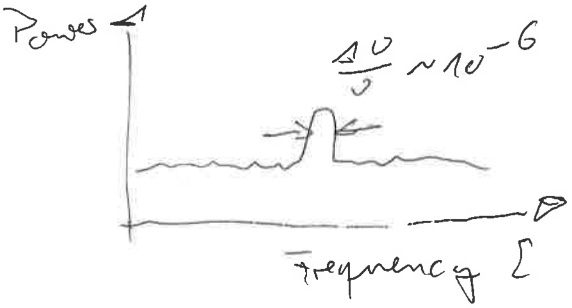
$B_0 = 8\,T$

$C \sim 0{,}5$

⇒ expected power for DM axion signal:

$P_{sig, DM} \simeq 10^{-23}$ Watt ✓

Look for (gaussian) peak over backround



in GHz regime

⇒ Sensitivity for DM axions in ~GHz to 10 GHz
(~µeV to 20µeV Axion mass)
using SQUID amplification and heterodyne mixing

Higher frequencies: sensitivity getting worse due to

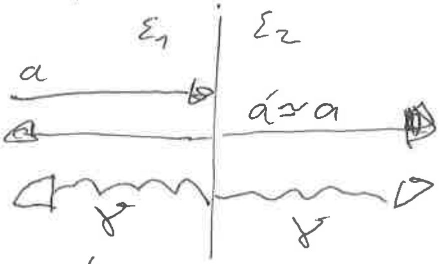
- smaller volumes (higher frequencies large wavelength)
- Q_L decreasing for smaller volumes

Madmax

During passage of axions through B. field: axion - photon mixing (Primakoff effect)

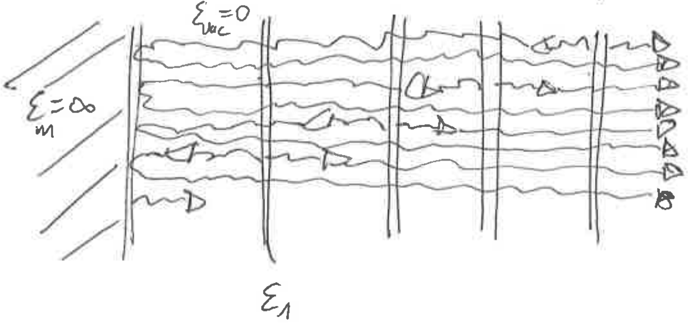
⇒ photon part of wave fct. "feels" transitions btw. different media, i.e. difference in refractive index, di-electric constant

⇒ Conservation of momentum:
Emission of two photons perpendicular to surfaces in both directions



$$\left(\frac{P}{A}\right)_{\text{Mirror}} = 2 \cdot 10^{-27} \frac{W}{m^2} \left(\frac{B_{||}}{10T}\right)^2 (g_{a\gamma\gamma} m_a)^2$$

Due to coherence (same as for microwave cavities): constructive interference possible of γs emitted at different surfaces



⇒ 2 effects:

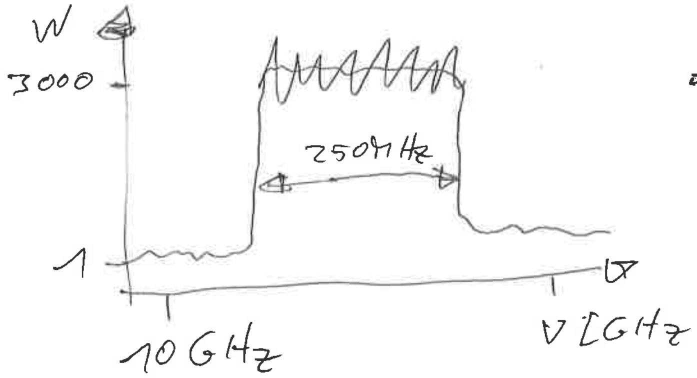
1. ~~Resonant~~ Constructive interference
2. Additional radiation by extra surfaces

⇒ Power boost $W = \frac{P_{cavity}}{P_{mirror}} \propto$ Number of discs $\cdot \varepsilon_1$

⇒ To get reasonable power for detection ($\sim 10^{-23}$ W):
Need $\varepsilon \simeq 25$ $N \approx 80$ $T \simeq 10T$ $A \simeq 1m^2$

Simulations (EM - 1D):

For $\varepsilon \simeq 25$ $N=20$ $\Delta\nu = 250\,\mathrm{MHz}$

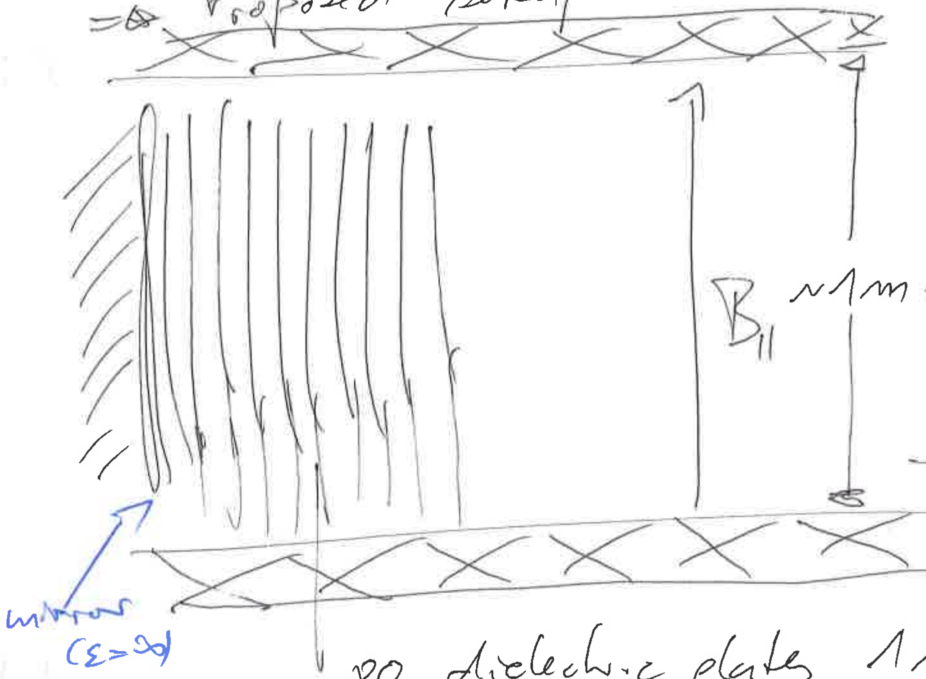


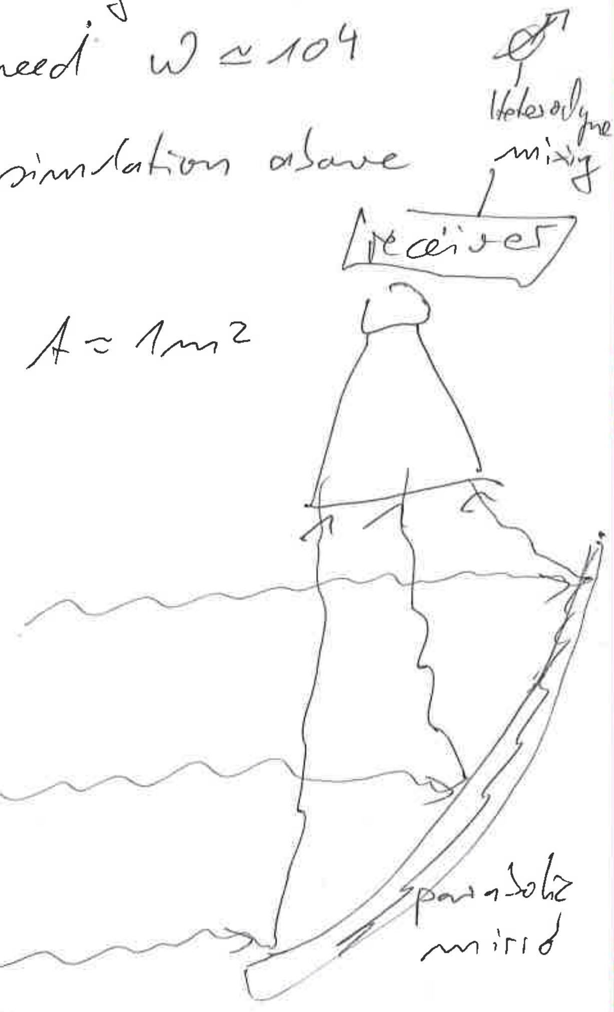
⇒ For $P_{sig} \simeq 10^{-23}\,W$ need $\omega \simeq 10^4$

take simulation above

⇒ $N=80$ $B_{\parallel}=10T$ $\varepsilon=25$ $A \simeq 1m^2$

⇒ Proposed setup





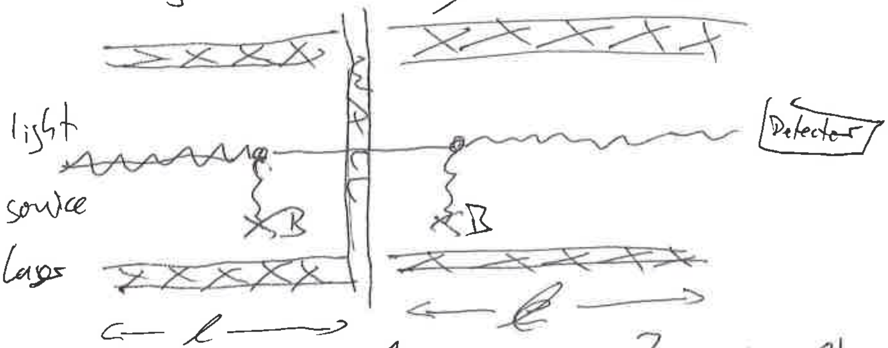
80 dielectric plates $1m^2$ made of $LaAlO_3$ $\varepsilon \simeq 24$
positioning tunable ⇒ scan different
frequency ranges ⇒ $P_{sig} \sim 10^{-23}\,W$ ✓

~~DM~~ axion
⇒ scan range 10GHz - 100GHz (~40μeV - 400μeV)

Photon regeneration in lab:

Light shining through the wall:

axions with momentum



$$P_{\gamma\to a} = \frac{1}{4}\left(g_{a\gamma\gamma} B\ell\right)^2 F(q\ell)$$

$$\boxed{(p_\gamma - p_a)}$$

$$= \frac{1}{4}\left(g_{a\gamma\gamma} B\ell\right)^2 \frac{\sin\left(\frac{1}{2}q\ell\right)}{\frac{1}{2}q\ell}$$

4th power!

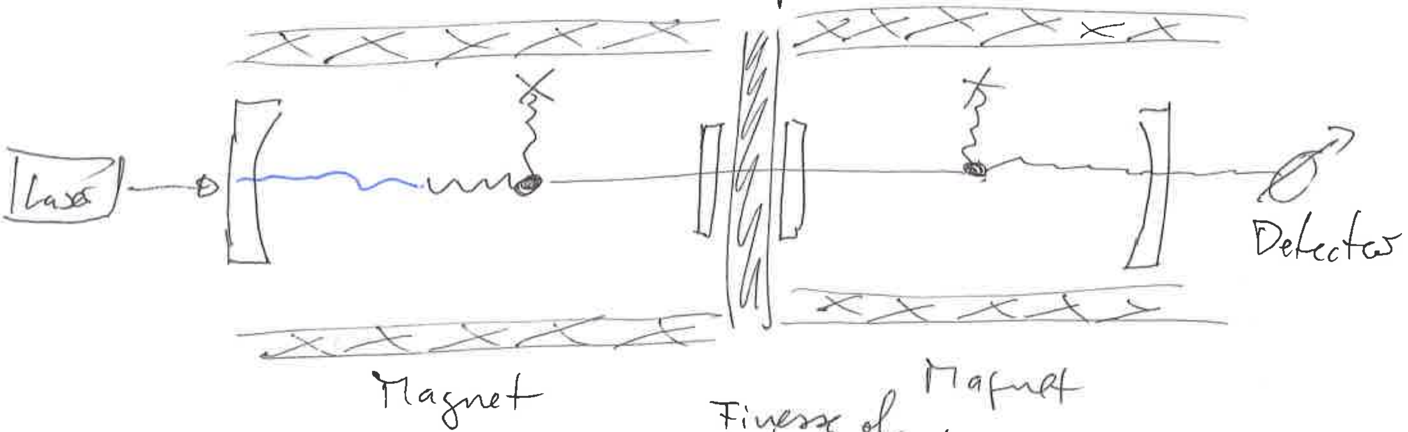
$$\Rightarrow P_{a\to\gamma\to a} = \frac{1}{16}\left(g_{a\gamma\gamma} B\ell\right)^{\boxed{4}} F^2(q\ell)$$

$$= \underline{\underline{6\cdot 10^{\boxed{-38}}}} \left(\frac{g_{a\gamma}}{10^{-10}\,\mathrm{GeV}^{-1}}\right)^4 \left(\frac{B}{1T}\right)^4 \left(\frac{\ell}{10m}\right)^4$$

!

⇒ Long strings of dipole magnets

⇒ Implement Optical resonators to recycle light & to boost re-conversion to photons behind wall



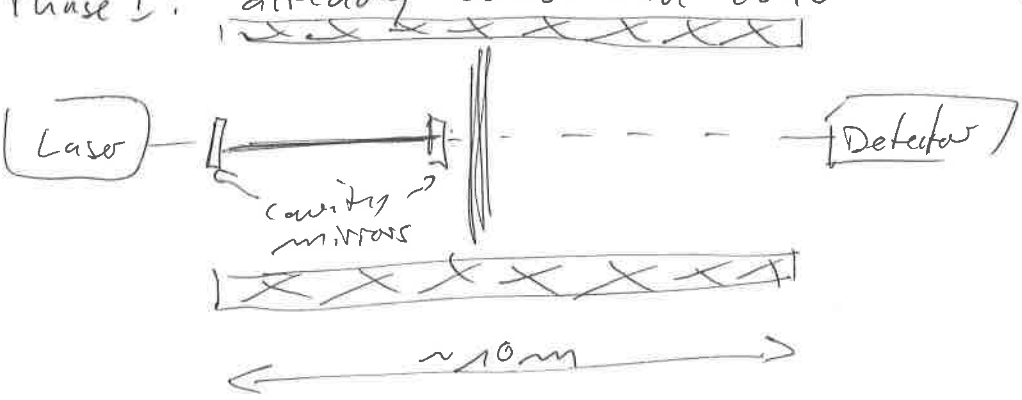
Finesse of interferometers

$$\Rightarrow \text{~~Power~~}\ P_{a\to\gamma\to a} = 6\cdot 10^{-38}\, F_{PC}\, F_{RC} \left(\frac{g_{a\gamma}}{10^{-10}\,\mathrm{GeV}^{-1}}\right)^4 \left(\frac{B}{1T}\right)^4 \left(\frac{\ell}{10m}\right)^4$$

Any Light Particle Search (ALPS):

@ DESY use old HERA magnets ~ 5,3T
~ 10m length
~ 50mm aperture

Phase I: already concluded 2010



Limits $g_{a\gamma\gamma}$ to few · 10^{-8} GeV^{-1} for $m_a \lesssim 1$ meV

Phase II:

- use 10 + 10 magnets ⇒ total length ~2·100m
- Regeneration cavity to increase back-conversion probability
- Single photon counter using superconducting transition edge sensor (TES)

⇒ Increase of sensitivity by

$$\mathcal{F}_{PC} \cdot \tilde{\mathcal{F}}_{RC} \cdot N^4 \simeq 5000 \cdot 40.000 \cdot 10^4$$
$$= 2 \cdot 10^8$$

Challenges:

- magnets from HERA are bent ⟶ straighten (possible!)
- Optics: operate two ~100m long optical resonators with high finesse that are mode matched (→ alignment precision!)
  ⇒ Experience from GW...
- Detectors: Single photon count @ 1064 nm (laser frequency)

Helioscopes:

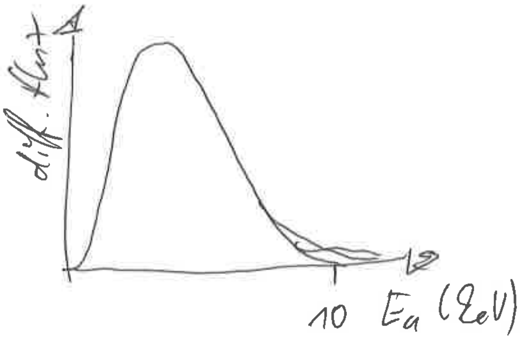
- Look for axions produced in the sun:

Robust prediction: if axions exist, they are emitted by the sun

$\Rightarrow$ No model dependence (like DM)!

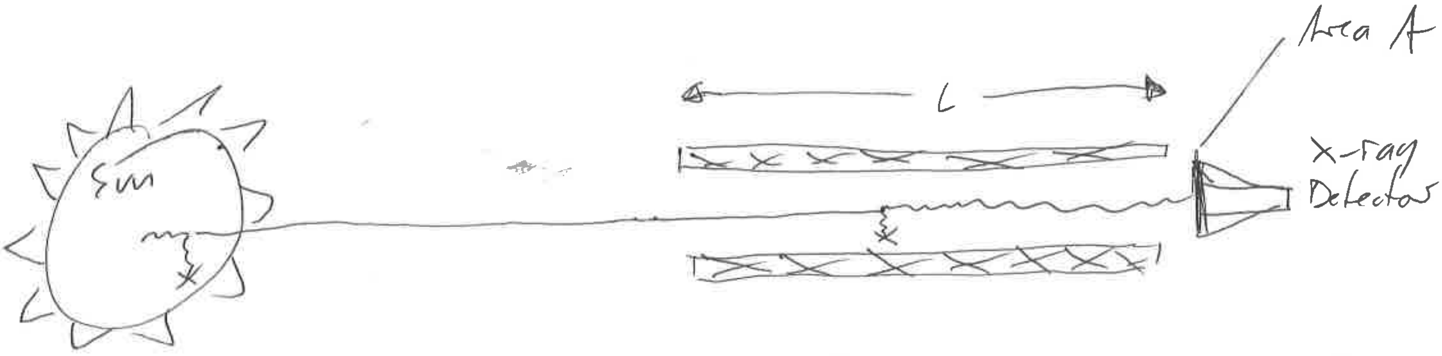
Production mechanism in sun:

Again: Primakoff effect



Detection mechanism:

Again: Primakoff effect



$$P_{a\gamma} = 2.6 \cdot 10^{-17} \left(\frac{B}{10T}\right)^2 \left(\frac{L}{10m}\right)^2 \left(g_{a\gamma} \cdot 10^{10}\,GeV\right)^2 \mathcal{F}$$

CAST @ CERN:

- Use decomissioned LHC test magnet $L = 10m$ $B = 9T$
- Moving platform: point towards sun
- x-ray detectors to detect ~keV x-rays from $a \to \gamma$ conversion

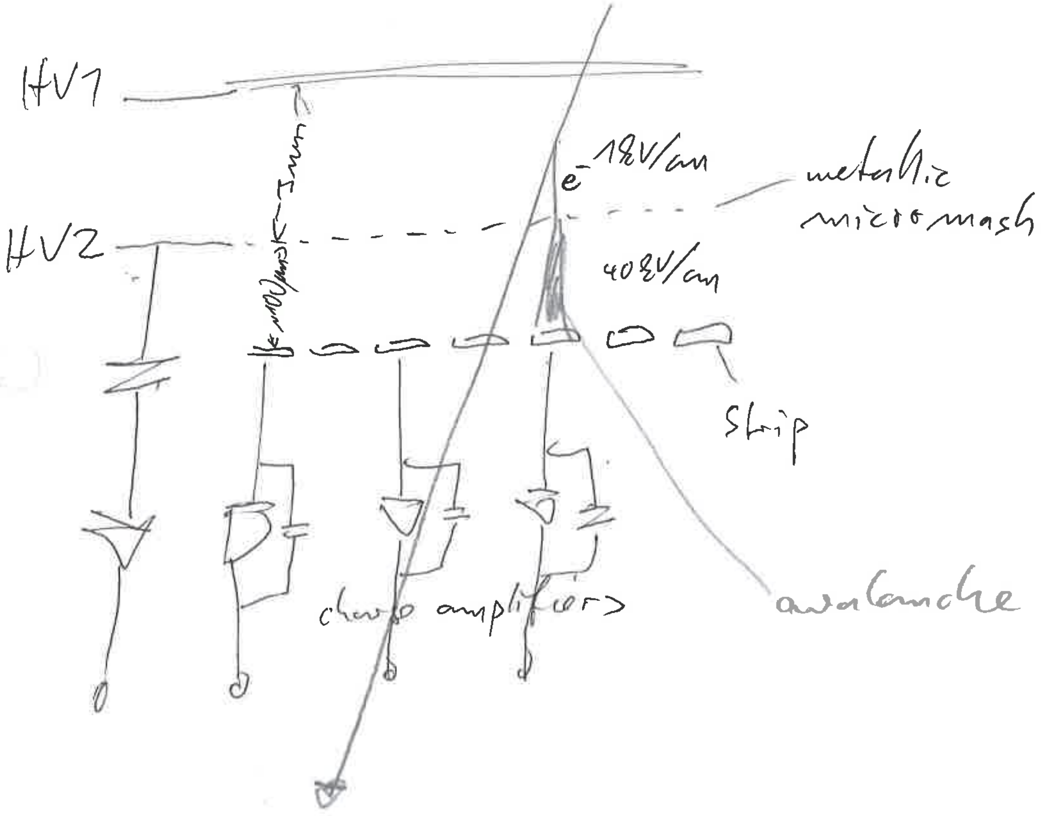
Future plan:

CAST limit
$g_{a\gamma} \leq 10^{-10}\,\mathrm{GeV}^{-1}$ for $m_a \lesssim 1\,\mathrm{eV}$

IAXO

Conceptual design:

- Use large toroidal 8-coil magnet $L \simeq 20\,\mathrm{m}$ Ø60cm
  Figure of merit: $B^2 \cdot L^2 \cdot A = 21\,T^2\,m^4$
  $$$
- Use x-ray optics to maximize A while reducing overall detector size, i.e. background
- Use "ultra-low background" x-ray detectors
  Micromegas from clean material



TES .....

⇒ projected sensitivity $g_{a\gamma} \sim$ ~~few~~ few $10^{-11}\,\mathrm{GeV}^{-1}$

Experimental situation & projections