STAX

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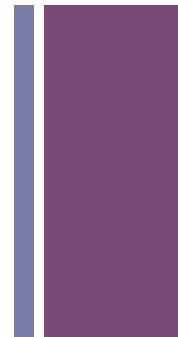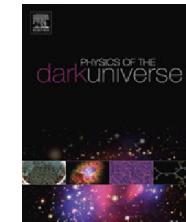
Axion-like particle searches with sub-THz photons

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ARTICLE INFO

ABSTRACT

We propose a variation, based on very low energy and extremely intense photon sources, on the well established technique of Light-Shining-through-Wall (LSW) experiments for axion-like particle searches. With radiation sources at 30 GHz, we compute that present laboratory exclusion limits on axion-like particles might be improved by at least four orders of magnitude, for masses $m_a \lesssim 0.01$ meV. This could motivate research and development programs on dedicated single-photon sub-THz detectors.

Presented at ICHEP16

Axions Experiments

3 classes of experiments: Haloscopic, Helioscopic, LSW

Axion, like neutral pion couples to two photons via Primakoff effect) Detected in a magnetic field H


$m_a < 3 \times 10^{-3}$ eV from SN1987
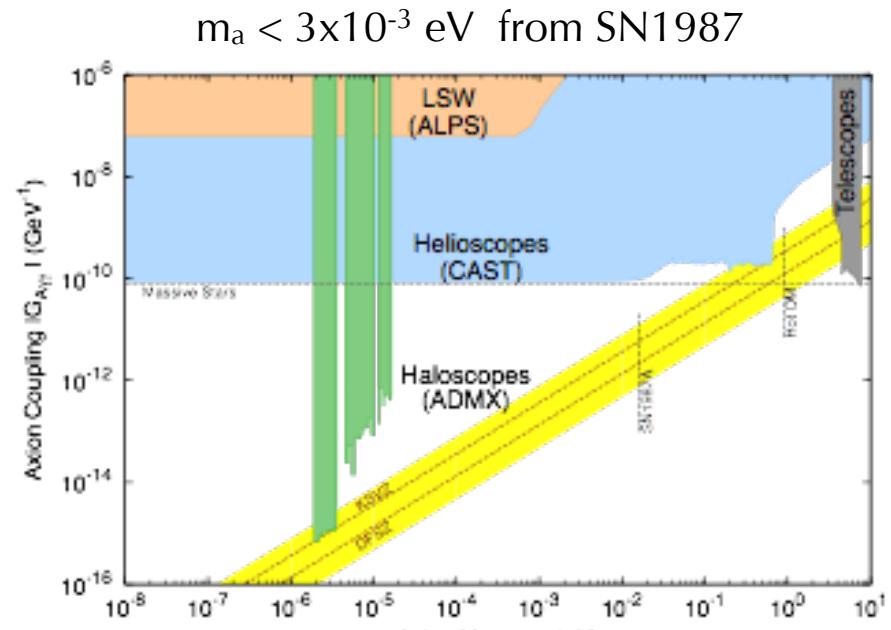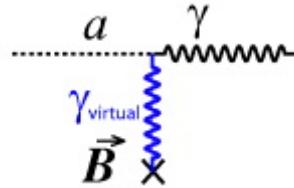
Yellow band represent theoretical predictions from DFSZ and KSVZ axion models

Haloscopic: cavity
Helioscopic depend on stellar models
CAST (best limit at the moment) and
IAXO (next CERN exp.) use LHC dipoles
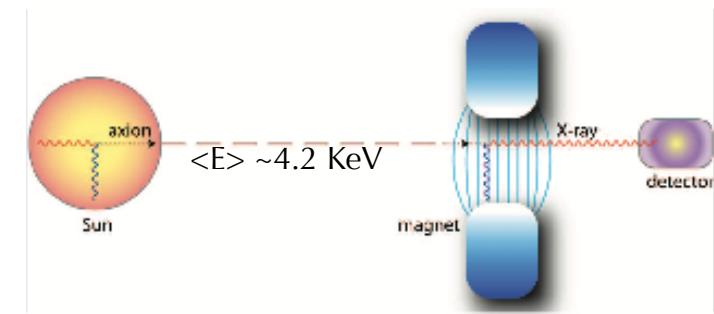
Light Shining through a Wall Experiments
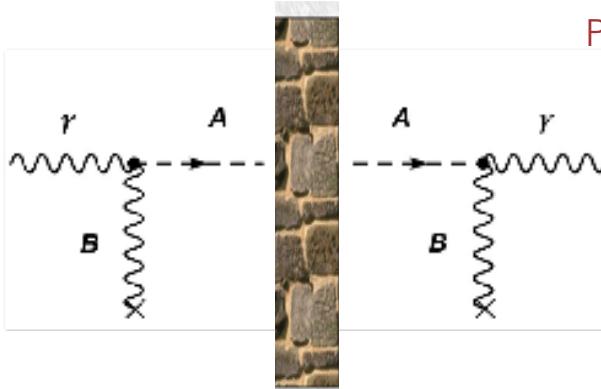
LAB experiment
Laser Source
Higher Luminosity

Double process
Rate ~ G^4

$$\dot{N}_{\text{evts}} \propto \dot{N}_\gamma \, P_{\gamma \to a} \times P_{a \to \gamma} \sim \dot{N}_\gamma \, G^4 H^4 L^4$$

Sensitivity on G linear with L and H, quartic root of luminosity (not depending on E_γ)

The STAX key points are:
- High Luminosity (gyrotrons in the SubTHz region)
- intense H ~ 15 Tesla with L ~ 50 cm dipole
- Sub-THz single photon detector using TES

Optimal Working Point ~ 30 GHz

Light Shining through a Wall Experiments: ALPS
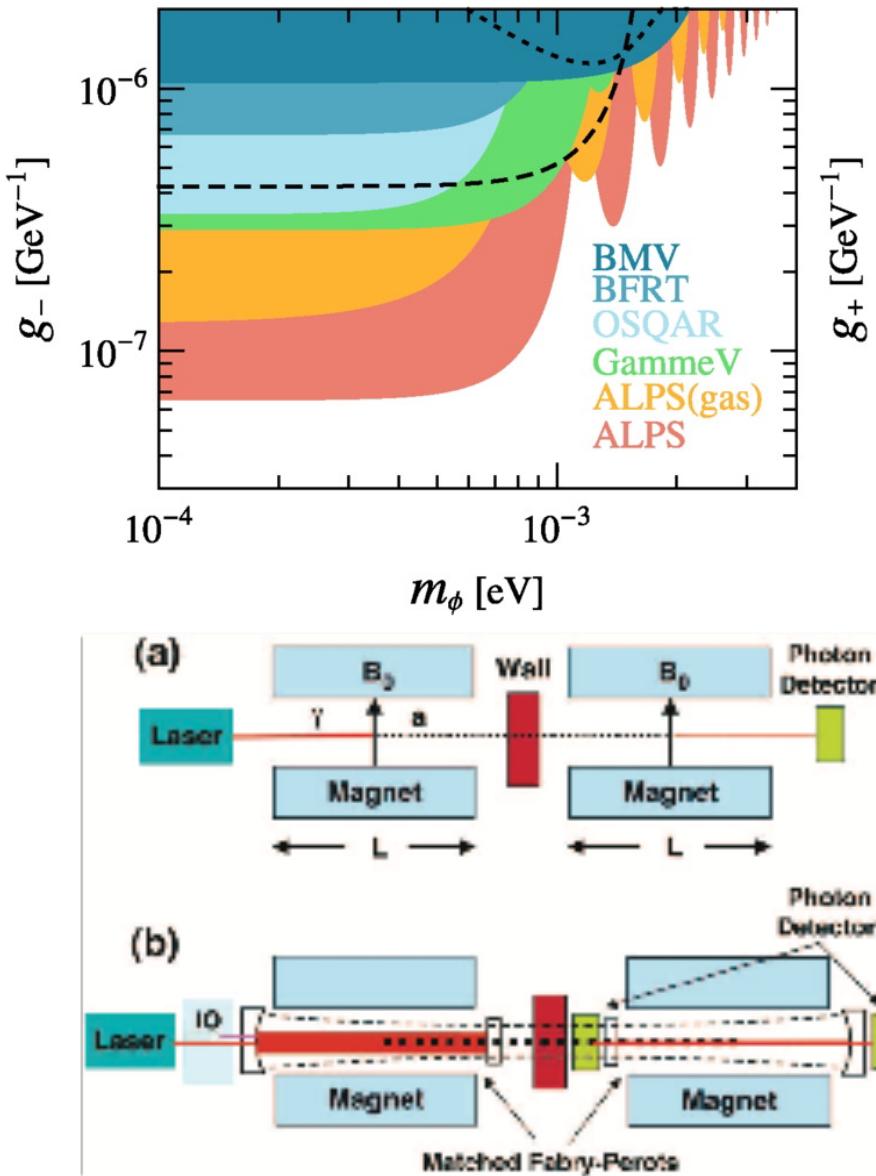
Ex: ALPS Desy use the Hera dipoles
N~ 10^{19} photons/s
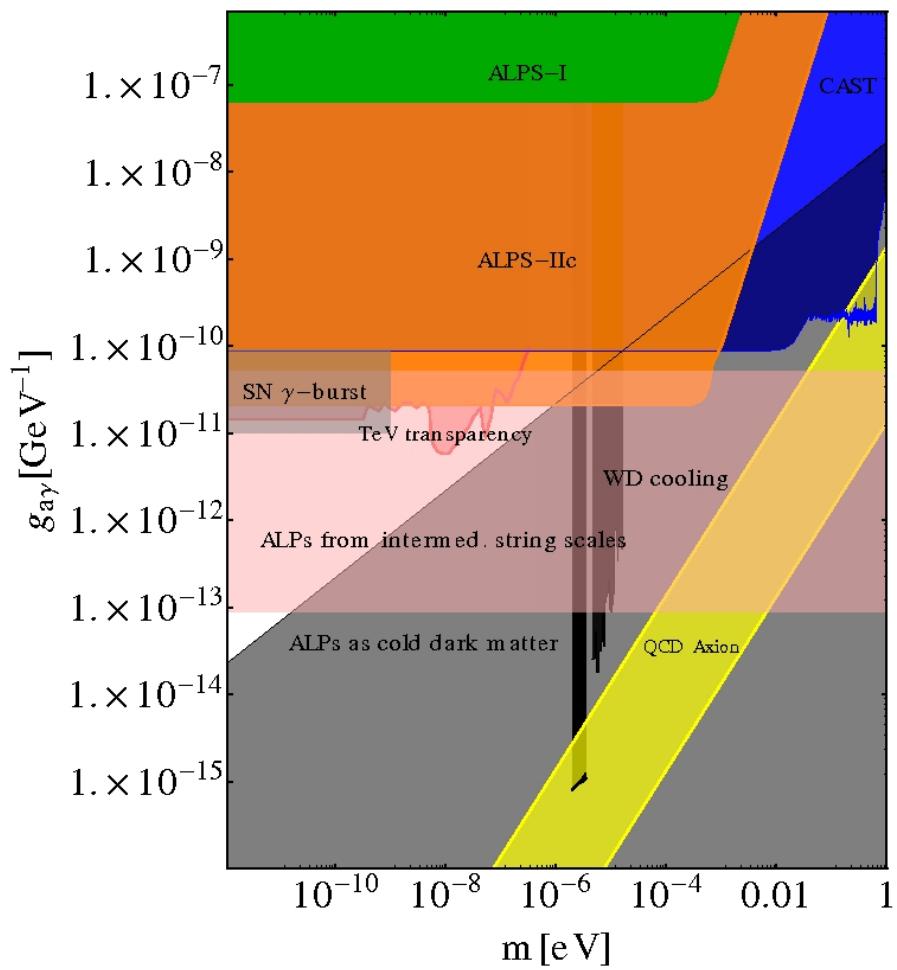
High Luminosity Photon Sources
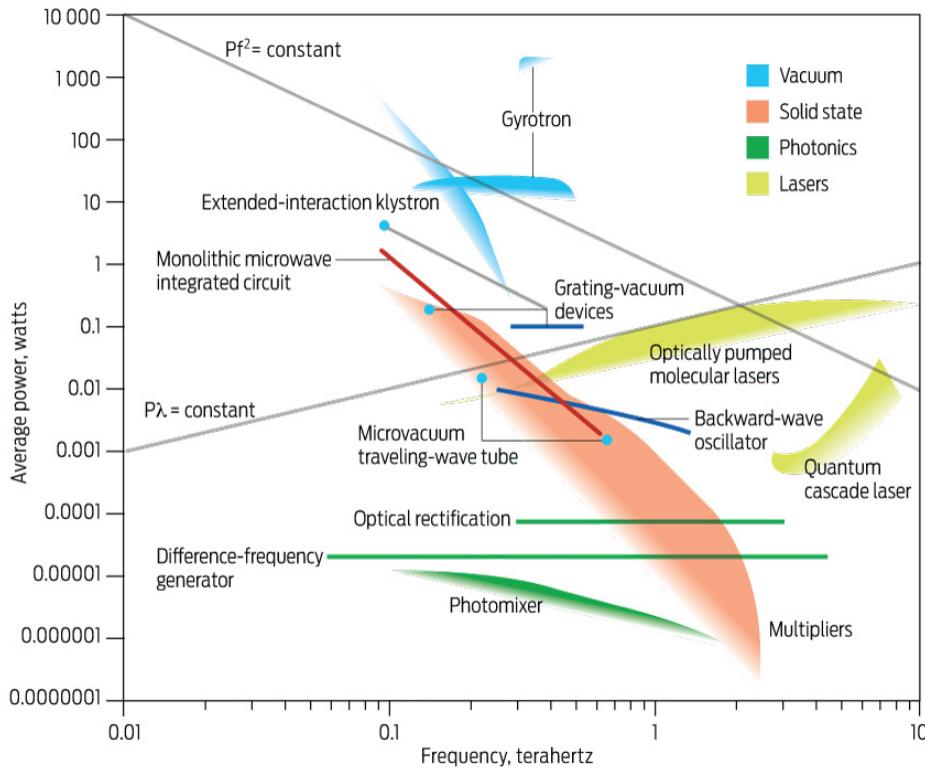
photon-axion conversion probability depends on luminosity, not energy
$\Rightarrow$ sub-THz

Reference:
30 GHz ~ 120 µeV ~ 1 cm

- Klystrons and gyrotrons sources in the 30-100 GHz range.

- Power exceeding 1 MW in this frequency range

- Luminosity up to 10^{28}-10^{29} γ/s in CW

- Lasers commonly used in LSW experiments ~ 10^{19} γ/s
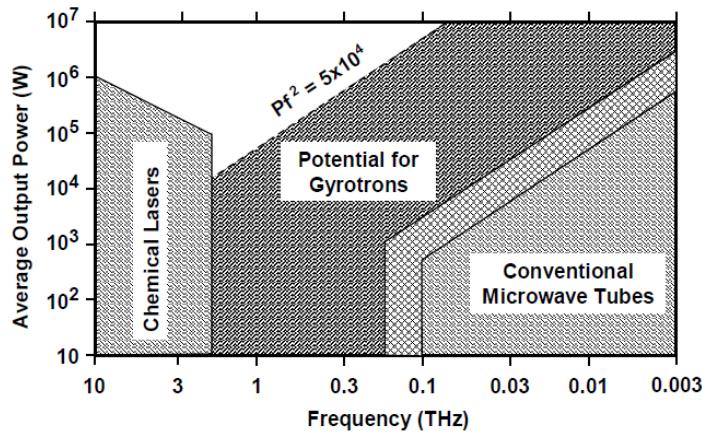
Gyrotrons

The operating region of gyrotrons
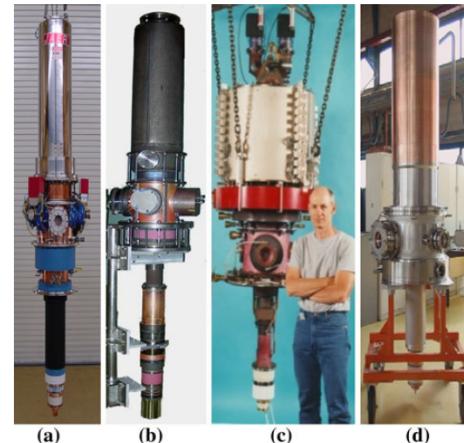
Fig. 2 Typical high power gyrotrons **a** JAERI/TOSHIBA 0.82 MW, 170 GHz, **b** GYCOM 1 MW, 170 GHz, **c** CPI 0.9 MW, 140 GHz, **d** TED 0.9 MW, 140 GHz
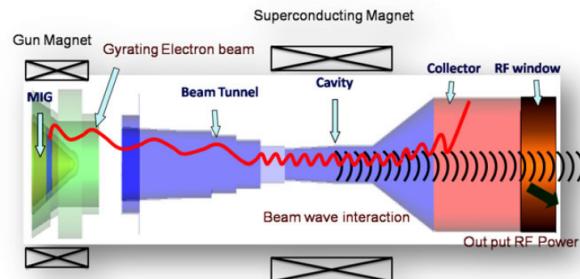
Now beyond 1 MW power

STAX Experiment
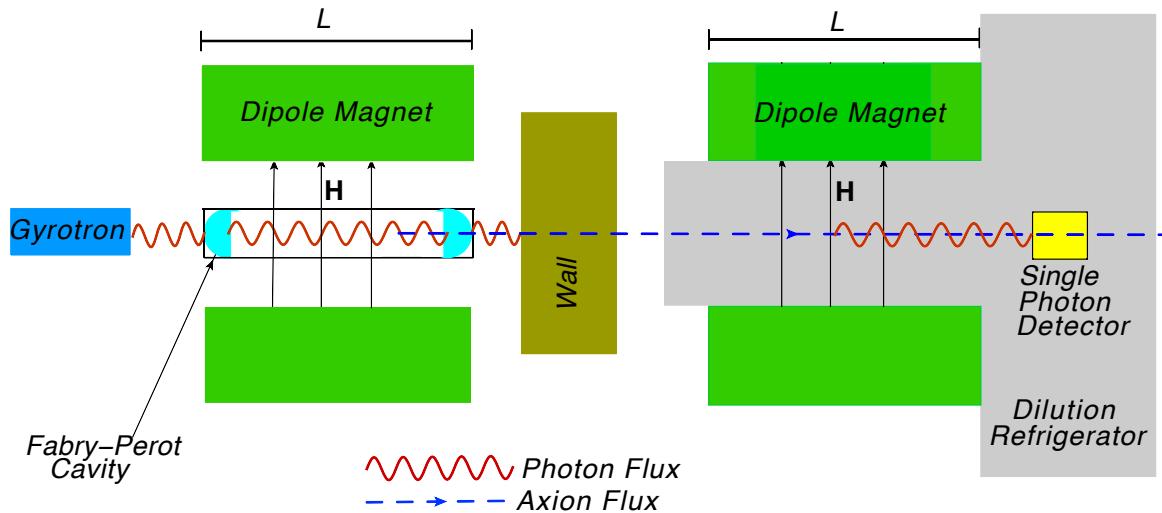
- Magnetic field: $H = 15$ T, $L = 0.5$ m
- Source: gyrotron; $P \approx 100$ kW, $\Phi_\gamma = 10^{27}$ s^{-1}, $\varepsilon_\gamma = 120$ µeV ($\nu \approx 30$ GHz)
- Fabry-Perot cavity: $Q \approx 10^4$

- Sub-THz single-photon detection based on TES technology, $\eta \approx 1$
- Possible second FP cavity behind the wall to enhance axion-photon conversion rate

P. Sikivie, D.B. Tanner and K. Van Bibber, Phys. Rev. Lett. 98, 172002 (2007)

STAX detector

Superconducting bridge TES

Antenna | Antenna

Superconductor | Superconductor

Si, Si$_x$N$_y$or sapphire substrate
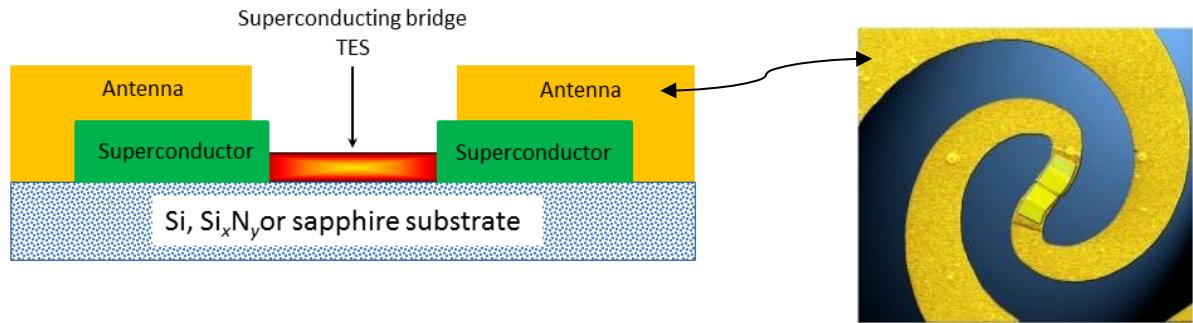
- Sub-THz single photon detector

- Transition Edge Sensor TES: ultra-low critical temperature superconductor bridge between two superconducting electrodes. TES coupled to a log periodic antenna.

- TES operates within its superconducting transition. DC bias voltage applied. When TES absorbs an incoming photon, it heats up above critical temperature Tc. Change of resistance and current flowing in the circuit, measured by a SQUID

- Material: choice of a Superconductor with low critical temperature (Tc ≈ 20 mK) to have a good energy resolution α-W or bilayer Ti-Au or Ti-Cu

- TES bridge Ti-Cu (gap ~20 μeV), superconducting electrodes Nb (gap ~ 1 meV)

- Very high efficiency

- Ultra low background/dark count

$I \sim V_{out}$

$\tau_\uparrow$ $\tau_\downarrow$

time t
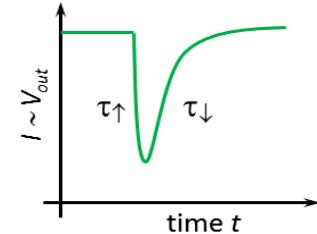
STAX detector

- Tailoring TES active volume to reduce thermal capacitance **(10^{-3}-10^{-4} μm^3)**

$$\sigma_E \approx 0.3\sqrt{k_B T_c^2 C_e}$$

C = γ V T   V ~ 300x40x20 nm ^{3}

- low-noise SQUID readout electronics optimization (operating at 80 mK)

- Sensitivity $\delta T = \delta E / C_e$ thermalization $T(t) = \exp(-t/\tau)$ $\tau = C_e/G$
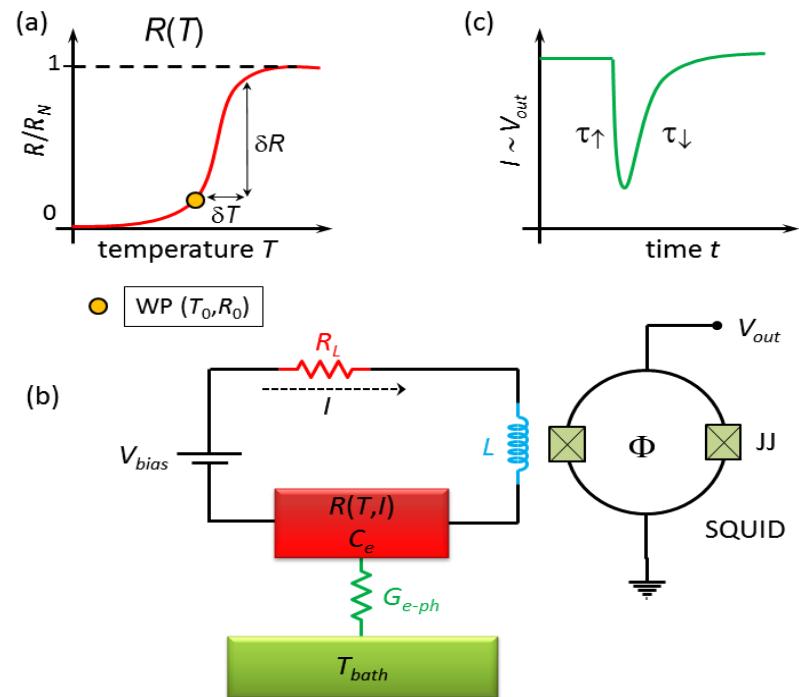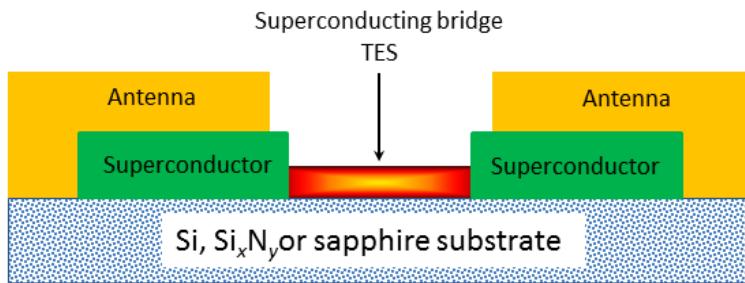
Noise

- Dark count rate (phonon noise) $< 6 \times 10^{-10}$ s^{-1}

- Black Body: at 10mK peaked around 0.6 GHz with a negligible rate of 10^{-30} m^{-2} s^{-1} photons irradiated

- Cosmic bkg: 1μ/cm^{-2}/min with 10 eV released in 10nm of material saturates the TES, bkg. under control translated in a negligible dead time of the TES ~ 0.1%

$$N_d = \frac{\beta_{eff}}{\sqrt{2\pi}} \int_{E_T/\sigma_E}^{\infty} exp(-x^2/2)\, \mathrm{d}x.$$

where $\beta_{eff} = 1/\tau_{eff}$ is the effective detection bandwidth, and E_T is the discrimination threshold energy.

$$\eta = \frac{1}{\sqrt{2\pi}} \int_{(E_T-h\nu)/\sigma_E}^{\infty} exp(-x^2/2)\, \mathrm{d}x.$$

Scheme of the temperatures in the experimental dilution cryostat set-up
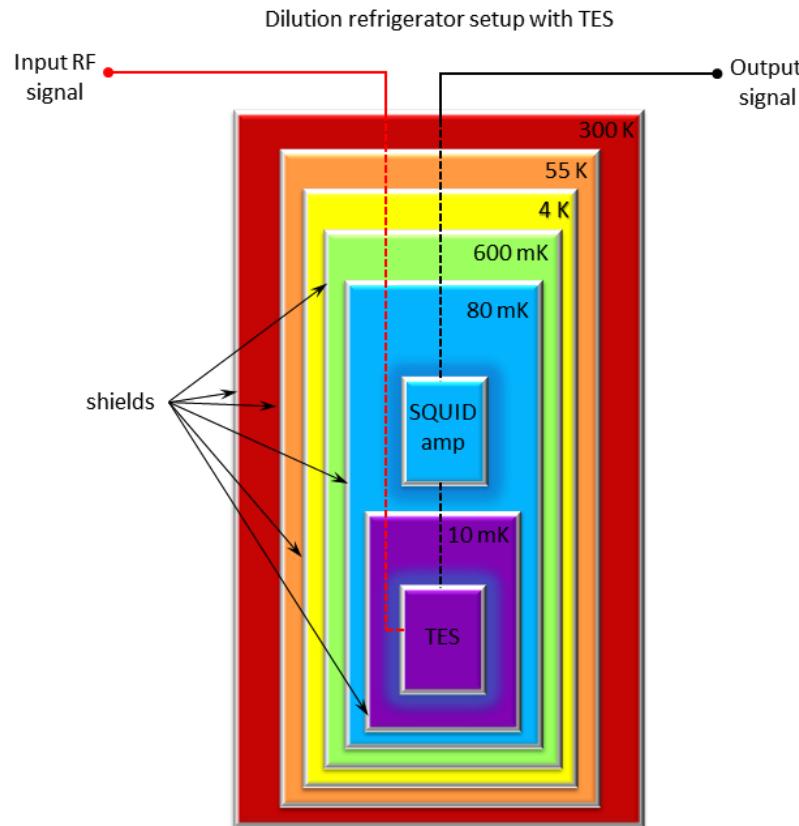
Figure 8 *Scheme of the experimental setup of the TES based on a dilution refrigerator. The cryostat metallic shields reside at different temperatures from 300 K to below ~ 10 mK. The enclosure containing the TES element is at the fridge base temperature whereas the readout SQUID amplifier is kept at 80 mK to improve its noise performance. Input microwave radiation is fed into the fridge, and thereby into the TES detector, via coaxial cables while the low-frequency output signal coming from the SQUID is read via conventional DC lines.*

Alternative choices to boost the experiment

- Work with a new concept Fabry Perot to enhance the Q factor

- An upgrade in Q translates into the need of a lower power of the source P/Q^2

$$\dot{N}_{\text{evts}} \propto \dot{N}_\gamma \, P_{\gamma \to a} \times P_{a \to \gamma} \times Q^2$$

- Fabry Perot with Q exceeding 10^{10} have been recently develoved with superconducting cavities

- Material choice need to be shaped to work in this particular environment
  - Low temp
  - High B field

- High Q and lower P can drive the use of other (more refined and easier to handle) photon sources than gyrotrons (klystrons?)

- or also to a lighter B fiels (split coil vs solenoid?)

Exclusion Plot Axion–Like Particle.
STAX: Time: $2.6 \cdot 10^6$ s, H = 15 T, Lx = 0.5 m
Q = 10^4, Eγ = 118 μeV, $\dot{N}$ = 10^{27} γ/s, P = 100 kW

$$P_{\gamma \leftrightarrows a} = g^2 H^2 \frac{\sin^2\left(\frac{q_x L_x}{2}\right)}{q_x^2}$$

$$q_x = \frac{m_a^2}{2\mathcal{E}_\gamma}$$

ALPS(LSW)

CAST

STAX

ALPS II

STAX 2: P = 1 MW, Q_{reg} = 10^4

QCD Axion
Inclusion

$2\text{x}10^{-11}$

$1.2\text{x}10^{-12}$

g (GeV^{-1})

M_a (meV)
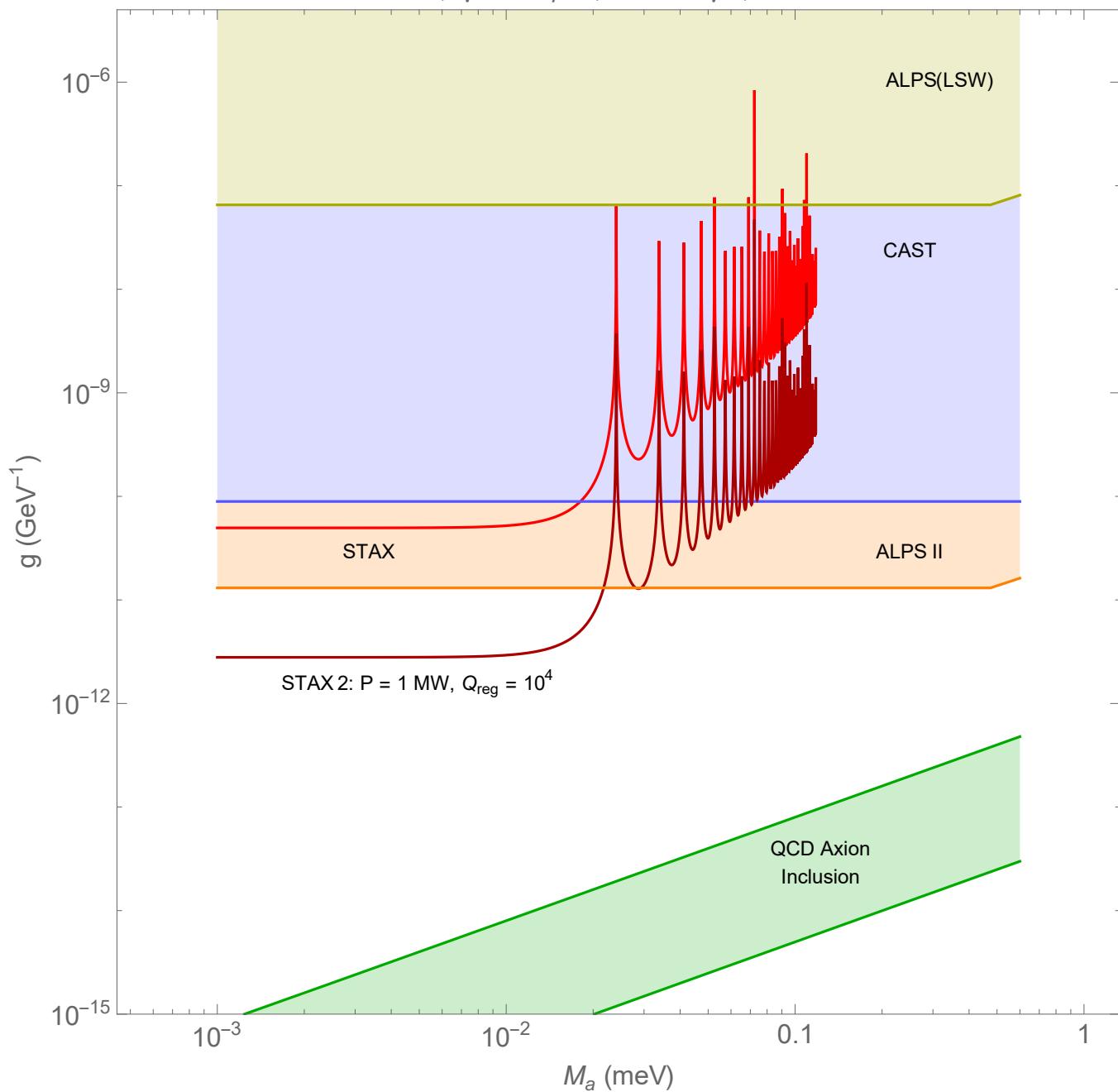
Parameter	ALPS	STAX	g_{ALPS} / g_{STAX}	STAX II	g_{ALPS} / g_{STAXII}
Laser Power	0.8 W	100 kW	18.8	1 MW	188
Photon Energy	2.327 eV	124 µeV	11.7	124 µeV	11.7
Cavity Q-factor	55.0	10^4	3.7	10^8	37
H * L$_x$	22 T m	7.5 T m	0.3	7.5 T m	0.3
Detection Efficiency	0.9	1.0	1.0	1.0	1.0
Detector Noise	$1.8 \ 10^{-3} \ sec^{-1}$	$10^{-9} \ sec^{-1}$	34.0	$10^{-9} \ sec^{-1}$	34
Combined Improvement			$\sim 10^4$		$\sim 8x10^5$

- **Cu/Al** and **Cu/Ti** bilayers designed as **5 μm X 200 nm strip** of different total thickness and thickness ratio

  - Fabrication via e-beam lithography + e-beam evaporation

  - 4-wires measurements of the resistance using a lock-in circuit

LNA

LOCK-IN

i

1 MΩ

200nm

TRANSITION CURVE
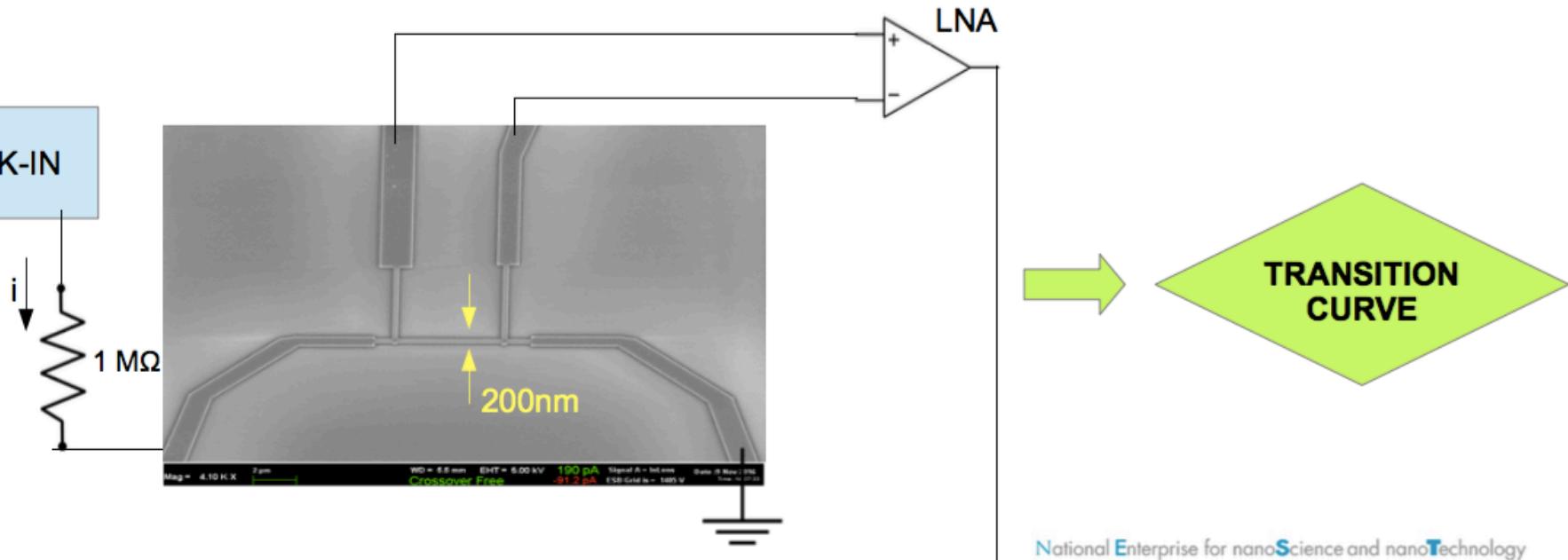
Yuri Venturini

National Enterprise for nanoScience and nanoTechnology

NEST

Tc of Cu/Al bilayers

Legend:
- Cu 10nm / Al 20nm
- Cu 10nm / Al 15nm
- Cu 10nm / Al 10nm
- Cu 15nm / Al 10nm
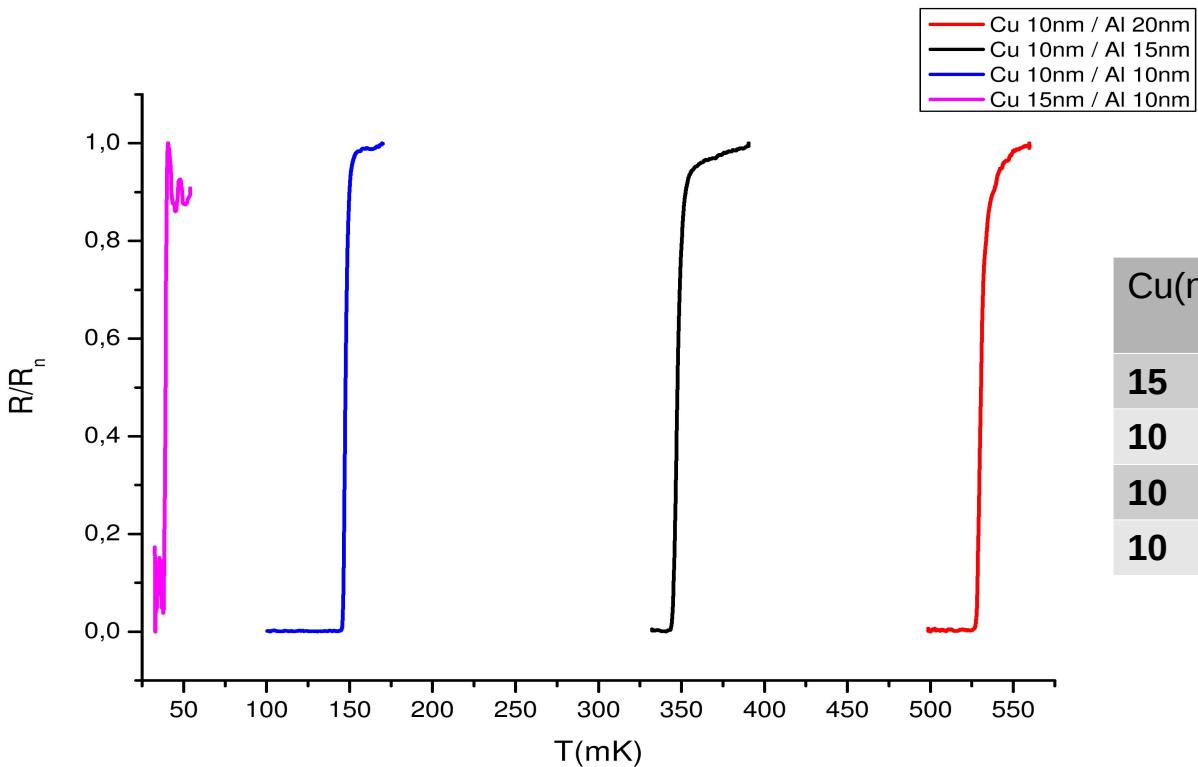
alpha=MAX(T/R dR/dT)

Cu(nm)	Al(nm)	Tc (mK)	Rn (ohm)	alpha
15	**10**	40	70	100
10	**10**	147	165	420
10	**15**	347	115	500
10	**20**	530	75	900

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NEST

Tc of Cu/Al bilayers (1)

all transitions are measured with a lock-in circuit with input current i = 6nA, except for Cu15Al10 (i=0.1nA)
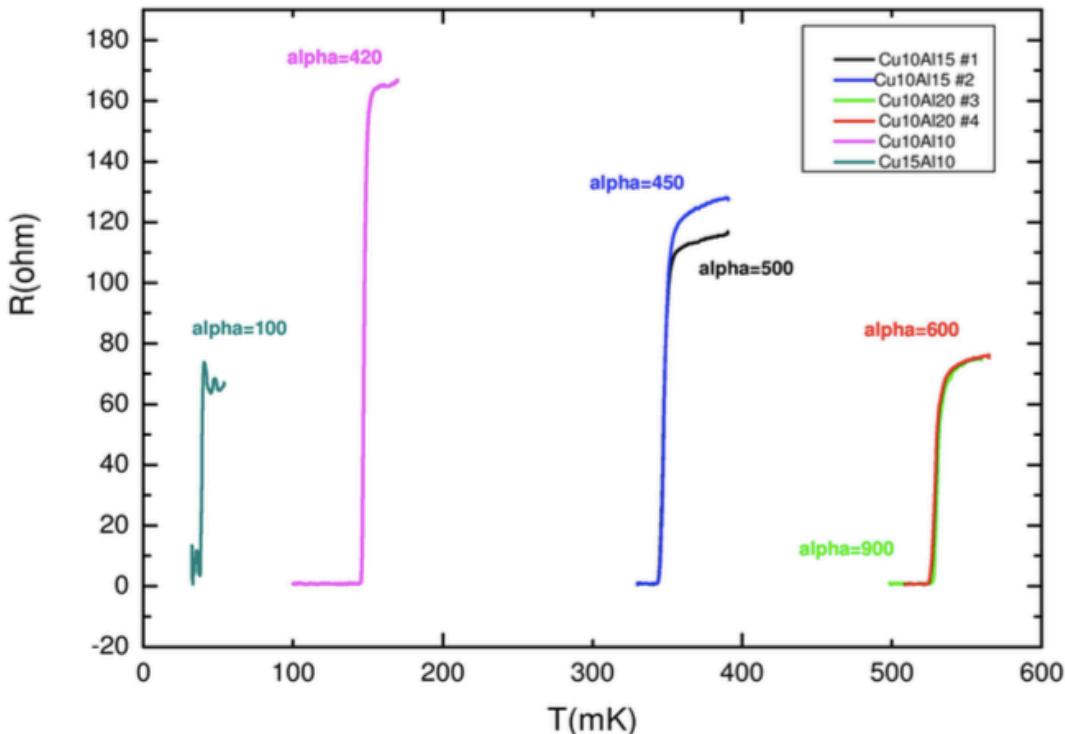
Data analysis: extraction of alpha=T/R * dR/dT
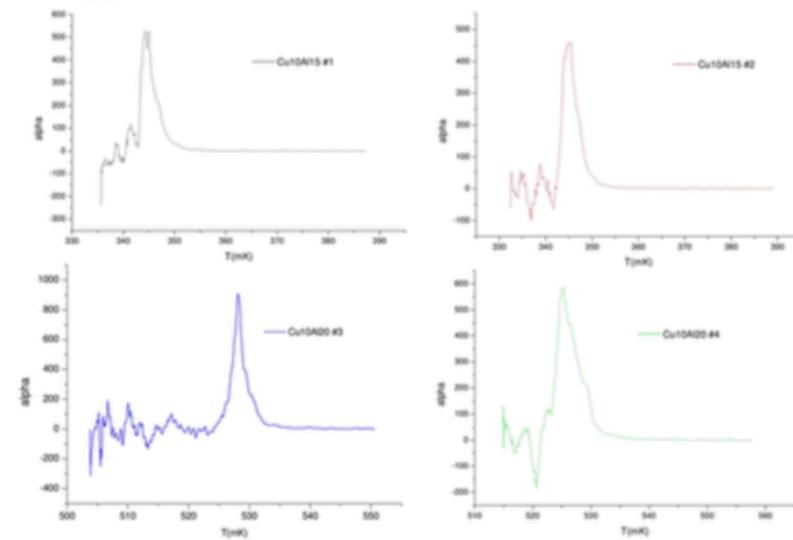
In the plot are reported the thicknesses and the max value of alpha

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Next Steps…

- Cu/Ti up down to Tc ~ 20mK

- Coupling with a SQUID read-out

- Test with a 30 GHz photon source

- R&D of the Fabry Perot

- Design of the log periodic antenna

- R&D of the Fabry Perot

- Magnet design

BACK UP SLIDES

- Wavelength associated to virtual axion $\lambda = 1/p_x \approx L_x$

  Uncertainty principle: $\Delta x \approx L_x \rightarrow \Delta p \geq 1/L_x$

  In more details, if $\lambda/2 < L_x$ the entire process takes place in the $H \neq 0$ region

- Consider $\varepsilon_\gamma \neq m_a$, so that $q_1 \geq m_a + 1/2L$, $q_2 \leq m_a - 1/2L$

  Poles coincide when $\varepsilon_\gamma = m_a$ ($p^* = 0$)

  Minimum distance between poles must satisfy: $\min(q_1 - q_2) = 1/L$

- We argue the formula

$$P_{\gamma \rightarrow a} \approx G^2 H^2 \frac{\sin^2(q_x L_x/2)}{q_x^2} \frac{\epsilon_\gamma}{\frac{1}{L_x} + \sqrt{\epsilon_\gamma^2 - m_a^2}}$$

to be used when $\varepsilon_\gamma \approx m_a$ to avoid unphysical divergences

Axion-Like particles

$$\mathcal{L}_I = \frac{1}{M} a \, F_{\mu\nu} \, \tilde{F}^{\mu\nu}$$

$$\tilde{F}^{\mu\nu} = \frac{1}{2} \epsilon^{\mu\nu\rho\sigma} F_{\rho\sigma}$$

$$\Box a = \frac{1}{M} \vec{H}^{ext} \cdot \frac{\partial}{\partial t} \vec{A} - m^2 a$$

Cfr. Poisson eq. in electricity:
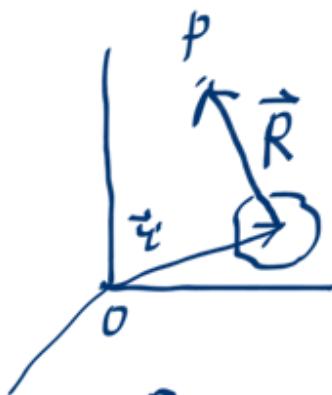
$$\Delta \phi + k^2 \phi = - 4\pi \rho$$

$$\phi = \int \rho\left(\vec{r}', t - \frac{R}{c}\right) \frac{e^{iKR}}{R} \, dV'$$

$$R \simeq r - \vec{r} \cdot \vec{n}' \qquad \vec{k}' = k \vec{n}' \qquad r \gg r'$$

Photon - Axion Conversion

γ

unstable in H

$\vec{H}$

a
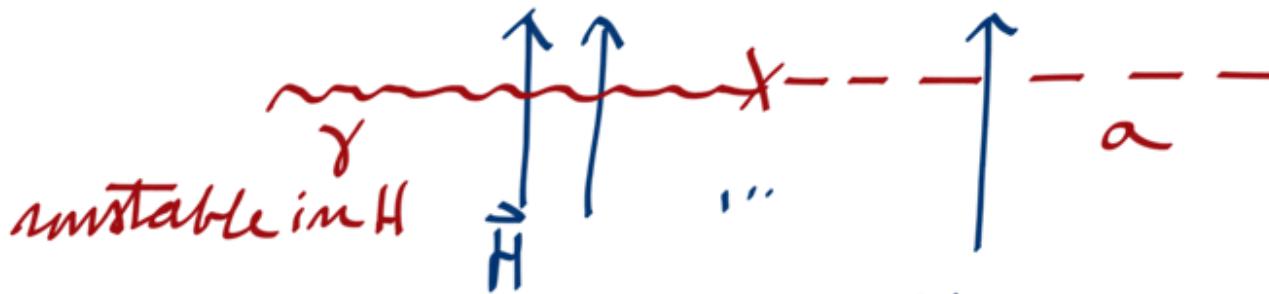
$a = f \dfrac{e^{ikr}}{r}$

$$\left| M_{\gamma \rightleftarrows a} \right|^2 = \frac{1}{4H^2} \left| \int e^{i\vec{q}\cdot\vec{n}} \, \vec{H}(\vec{n}) \cdot \vec{E}(\vec{k}_\gamma, \chi) \, dV \right|^2$$

Max when $\vec{k}_\gamma \perp \vec{H}$

Formula holds for $\boxed{\mathcal{E}_\gamma = \mathcal{E}_a}$

Notice $|\vec{k}_\gamma| \neq |\vec{k}_a|$ and $\vec{q} = \vec{k}_\gamma - \vec{k}_a$

Conversion Probability

In the $\perp$ plane H extends over long dist. wrt $1/q_y$ & $1/q_z$ - In the $\parallel$ direction we assume $\underline{L_x \lesssim 1/q_x}$.

$$P_{\gamma \rightleftarrows a} = \frac{H^2}{M^2} \frac{\sin^2\left(\frac{q_x L_x}{2}\right)}{q_x^2} \left(\frac{\mathcal{E}_\gamma}{|\vec{k}_a|}\right)$$

$$q_x = \frac{m_a^2}{2\mathcal{E}_\gamma}$$

$$|\vec{k}_a) = \mathcal{E}_a^2 - m_a^2 = \mathcal{E}_\gamma^2 - m_a^2 \sim \mathcal{E}_\gamma \text{ as } \mathcal{E}_\gamma \gg m_a$$

Dark photons

- Massive vectors of hidden $U(1)_h$

- Visible and hidden-sector photons Lagrangian:

$$\mathcal{L} = -\tfrac{1}{4}F^{\mu\nu}F_{\mu\nu} - \tfrac{1}{4}B^{\mu\nu}B_{\mu\nu} + eJ^{\mu}_{\text{em}}A_{\mu}$$
$$+ e_{\text{h}}J^{\mu}_{\text{h}}B_{\mu} - \tfrac{1}{2}\mu^2 B^{\mu}B_{\mu}$$

$F^{\mu\nu}$ = field strength tensor for A^{μ}; $B^{\mu\nu}$ = field strength tensor for B^{μ} (paraphoton)

- **A** and **B** rotated into $\mathbf{B}_1$ and $\mathbf{B}_2$; mixing angle $\chi < 10^{-2}$
  $\mathbf{B}_1$ and $\mathbf{B}_2$ acquire masses $m_1 = \mu\chi$, $m_2 = \mu$

- Photon field evolve as:

$$A(r) = \tfrac{1}{\chi^2+1}e^{-i(\epsilon_\gamma t - k_1 r)}\left[A(1+\chi^2 e^{-iqr})\right.$$
$$\left. + \chi B(e^{-iqr}-1)\right]$$

$$k_1 \approx \epsilon_\gamma$$
$$k_2 \approx \sqrt{\epsilon_\gamma^2 - \mu^2}$$
$$q = k_1 - k_2$$

Dark photons
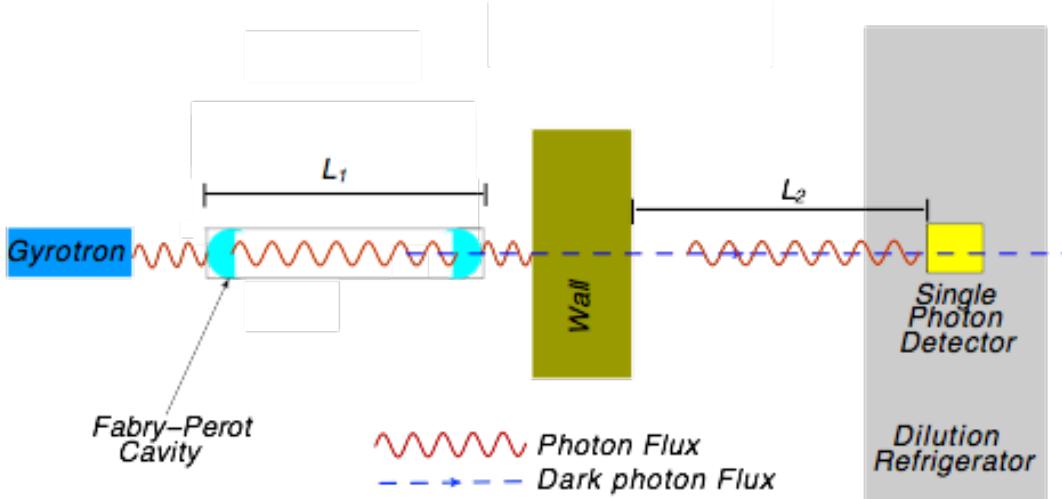
- Conversion probability: $P_{\gamma \to \gamma'}(r) = 4\chi^2 \sin^2\left(\frac{qr}{2}\right)$

$$P_{\gamma \to \gamma' \to \gamma} = P_{\gamma \to \gamma'}(L_1) P_{\gamma' \to \gamma}(L_2)$$

$$= 16\chi^4 \left[\sin\left(\frac{q L_1}{2}\right) \sin\left(\frac{q L_2}{2}\right)\right]^2$$

- Rate: $\dfrac{\mathrm{d}N_\gamma}{\mathrm{d}t} = \eta\, \Phi_\gamma \left[\dfrac{N_{\text{pass}} + 1}{2}\right] P_{\gamma \to \gamma' \to \gamma}$

Φ_γ = photon flux (s^{-1}), η = detector efficiency

Search for dark photons at STAX

L.M. Capparelli *et al.*, Phys. Dark Univ. **12**, 37 (2016)

- Exclusion limits STAX may achieve in case of null result

- **STAX** limits compared to
  - **ALPS LSW** results
    Lett. B **689**, 149 (2010)
  - **CROWS** results
    Rev. D **88**, 075014 (2013)
  - **Spring-8** results
    Lett. B **722**, 301 (2013)
  - **XENON10** results
    Lett. B **689**, 149 (2010)
  - Constraints on dark photons from measurements of the **CMB**
    Astrophys. J. **473**, 576 (1996)
  - Searches for modifications of **Coulomb's Law**
    Phys. Rev. Lett. **61**, 2285 (1988)

Exclusion Plot for Paraphotons
STAX (90% CL): time=1 month, Q=10^4, L=1 m
E_γ=118 μeV $\dot{N} = 10^{27}$ γ/s

Legend: ALPS, CMB, Coulomb, CROWS, SPring-8, STAX, XENON10

Axes: χ vs μ [ev]

3 years R&D project

Activities	201	2016				2017				2018				20
	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q
▼ **STAX-RD**														
▼ **Sensor**														
Cryostat setup														
TES SC layer														
TES optimization (geometry, thermal capacitance)														
TES sensor ready														
▼ **Antenna**														
design and nanofabrication														
SQUID electronics														
Integration														
Measurement														
Single 30-100 GHz photon detector ready														

Facilities located between INFN-Pisa and NEST-Pisa
possibility to use INFN S.Piero Labs

Financial Plan and Requests

Description	Quantity	Unit Price	Cost
cryogen-free dilution refrigerator	1	€200.000	€200.000
SQUID amplifiers	2	€ 20.000	€ 40.000
mw Gunn oscillator radiation sources	3	€ 30.000	€ 90.000
vector network analyser	1	€100.000	€100.000
mw NbTi superconducting coaxial cables	6	€ 2.000	€ 12.000
10 Tb disk storage	1	€ 3.000	€ 3.000
CPU (HS06 units)	500	€ 12	€ 6.000
Consumables per year	3	€ 15.000	€ 45.000
travel cost per year	3	€ 15.000	€ 45.000
publication cost per year	3	€ 4.000	€ 12.000
personnel per year	6	€ 30.000	€180.000
Total			**€733.000**

Financial Plan and Requests

Description	2016	2017	2018	Total
cryogen-free dilution refrigerator	€200.000			€200.000
SQUID amplifiers		€ 20.000	€ 20.000	€ 40.000
radiation sources		€90.000		€ 90.000
vector analyser			€100.000	€100.000
superconducting coaxial cables	€ 12.000			€ 12.000
Storage		€ 3.000		€ 3.000
CPU		€ 6.000		€ 6.000
Consumables	€ 15.000	€ 15.000	€ 15.000	€ 45.000
travel cost	€ 15.000	€ 15.000	€ 15.000	€ 45.000
publication cost		€ 6.000	€ 6.000	€ 12.000
personnel	€ 60.000	€ 60.000	€ 60.000	€180.000
Total	**302.000 €**	**215.000 €**	**216.000 €**	**733.000 €**