STAX
An improved detection scheme for axion-like particles

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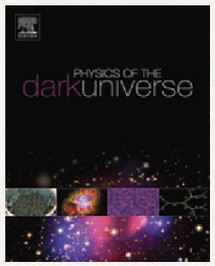

Axion-like particle searches with sub-THz photons

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ABSTRACT

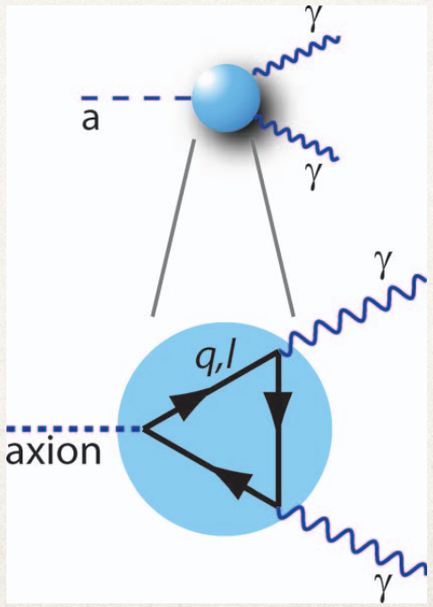
We propose a variation, based on very low energy and extremely intense photon sources, on the well established technique of Light-Shining-through-Wall (LSW) experiments for axion-like particle searches. With radiation sources at 30 GHz, we compute that present laboratory exclusion limits on axion-like 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.

Axion to photon conversion

- Light pseudo scalar $J^P = 0^-$ can solve both the dark matter problem and the CP symmetry puzzle in QCD

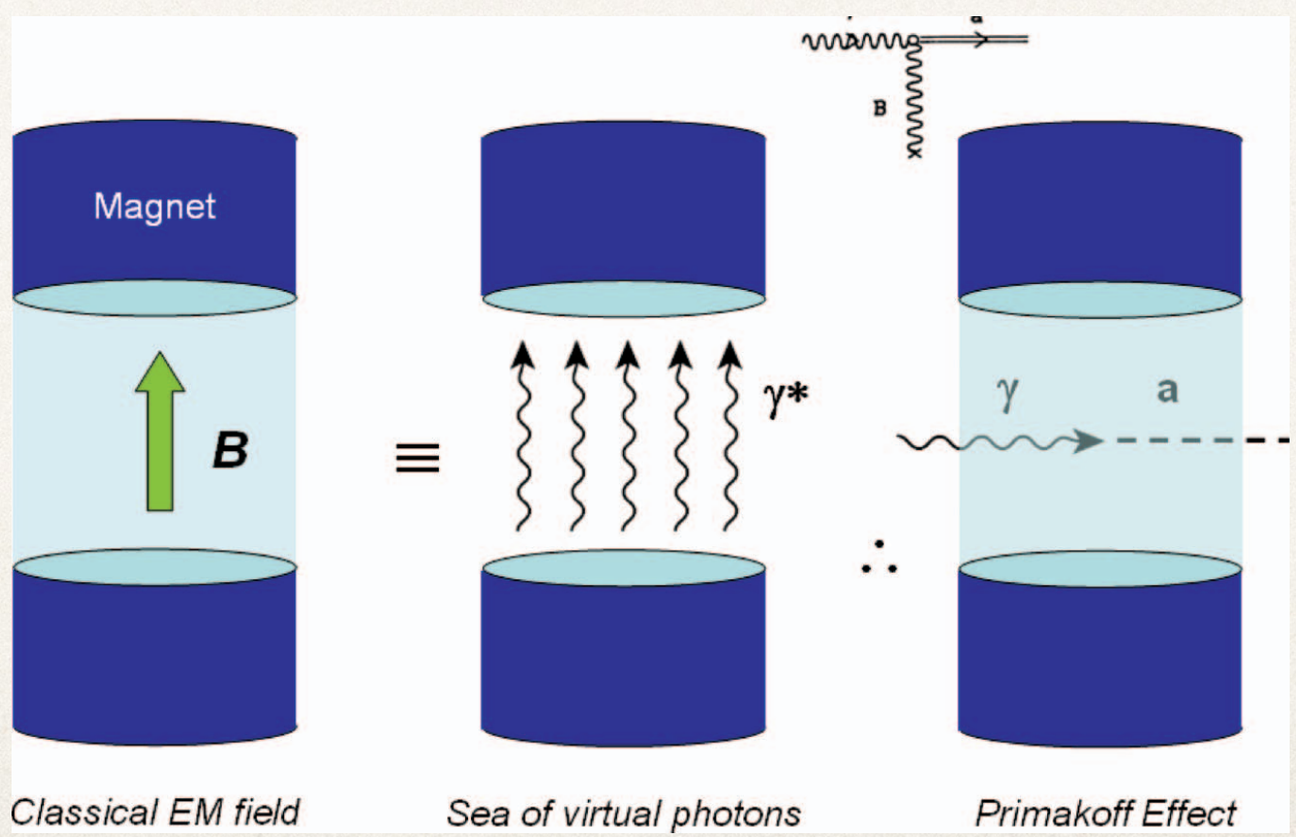
- $m_a < 3x10^{-3}$ eV from SN1987

- axion, like neutral pion couples to two photons via fermion loop (Primakoff effect)



Axion in magnetic field

Axion-B field interaction can be treat quasi-classically as an interaction of a photon with an external field with a photon-axion transition



Axion-Photon conversion probability

$$P_{\gamma\to a} = P_{a\to\gamma} = G^2 H^2 \frac{\sin^2(q_x L_x/2)}{q_x^2} \frac{\epsilon_\gamma}{\sqrt{\epsilon_\gamma^2 - m_a^2}}$$ with the transfered momentum $$q_x = \frac{m_a^2}{2\mathcal{E}_\gamma}$$

G is the axion-gamma coupling constant $< 10^{-10}$ GeV^{-1} from astrophysics

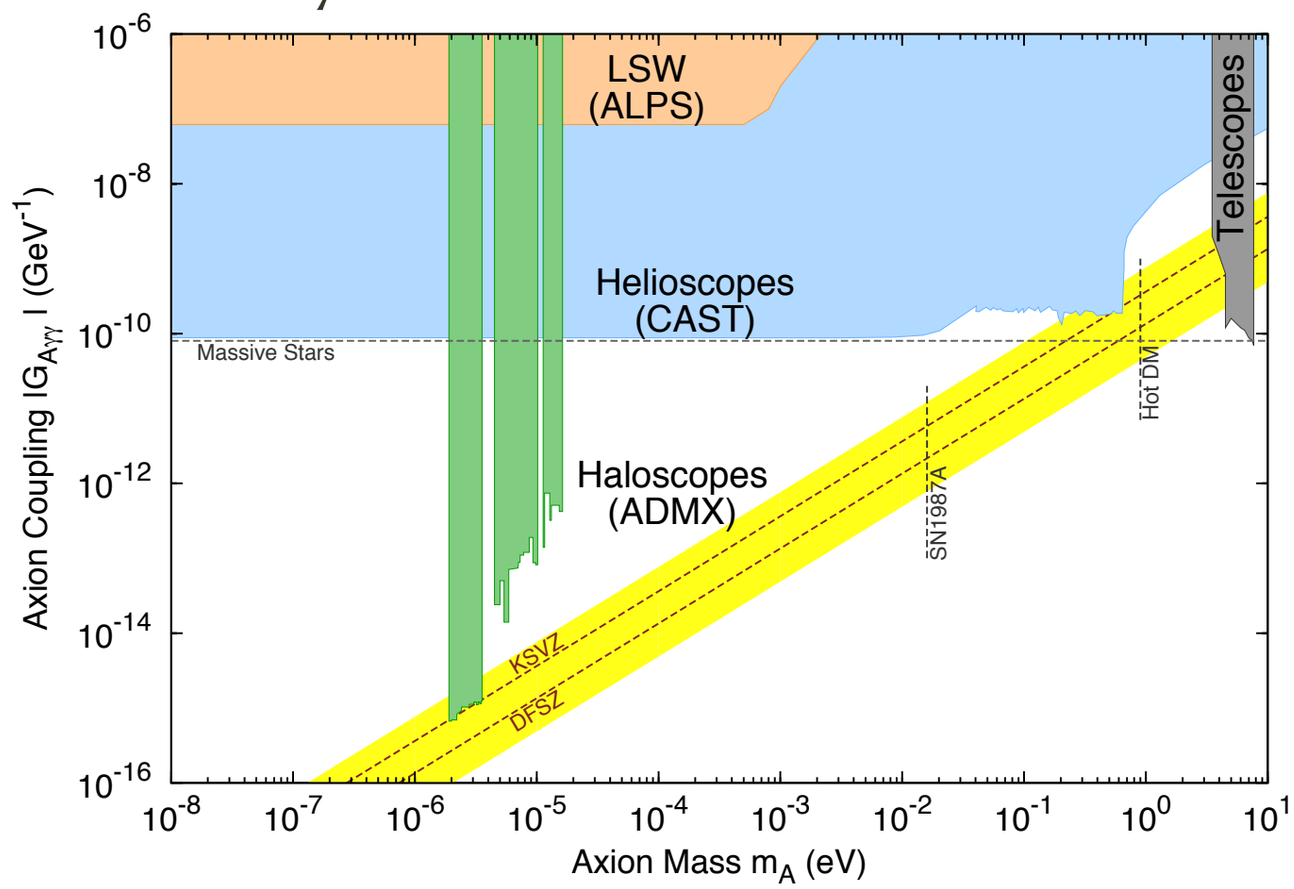
2 key points: very high H field
very intense source

Axions Experiments

- Three types: Haloscopic, Helioscopic, LSW
- Halo often use cavities: High sensitivity but limited mass window

Only experiments hitting Peccei-Quin region

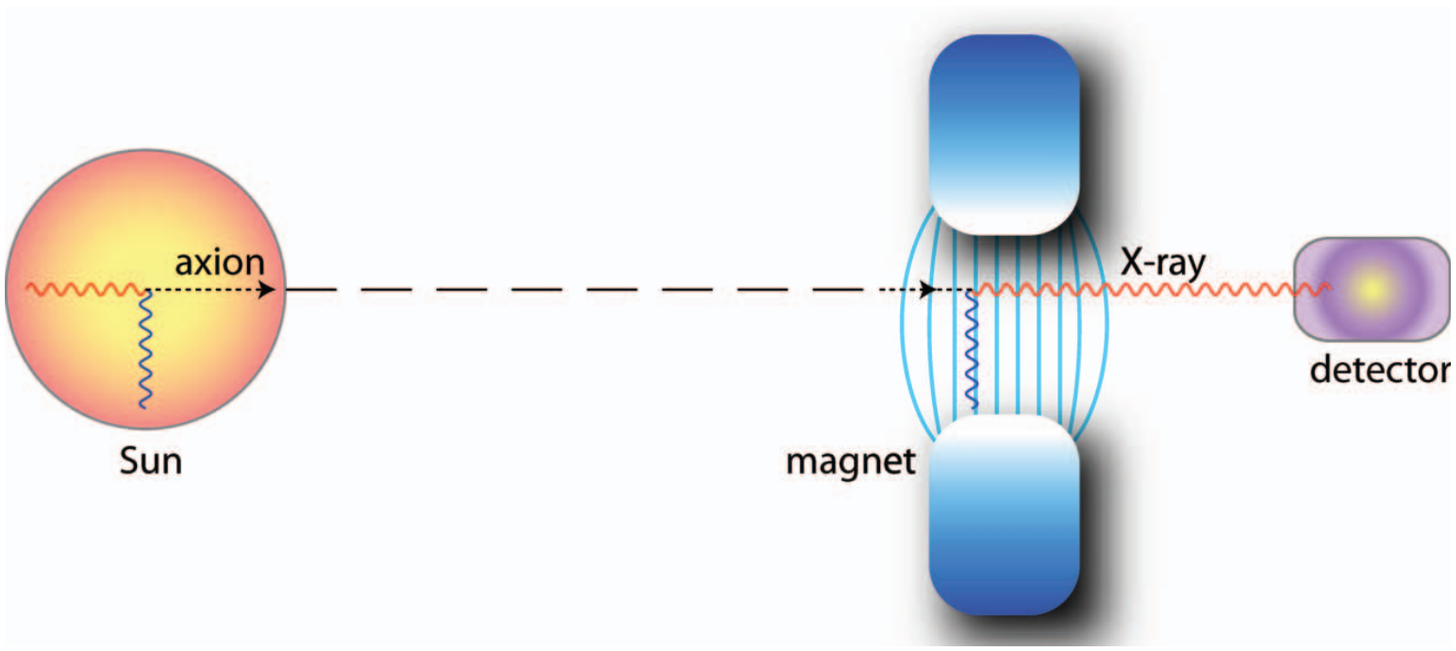
Ex: ADMX Livermore



Yellow band represent theoretical predictions from DFSZ and KSVZ axion models

Axions Experiments

- Three types: Haloscopic, Helioscopic, LSW
- Helioscopic depend on stellar/galactic models



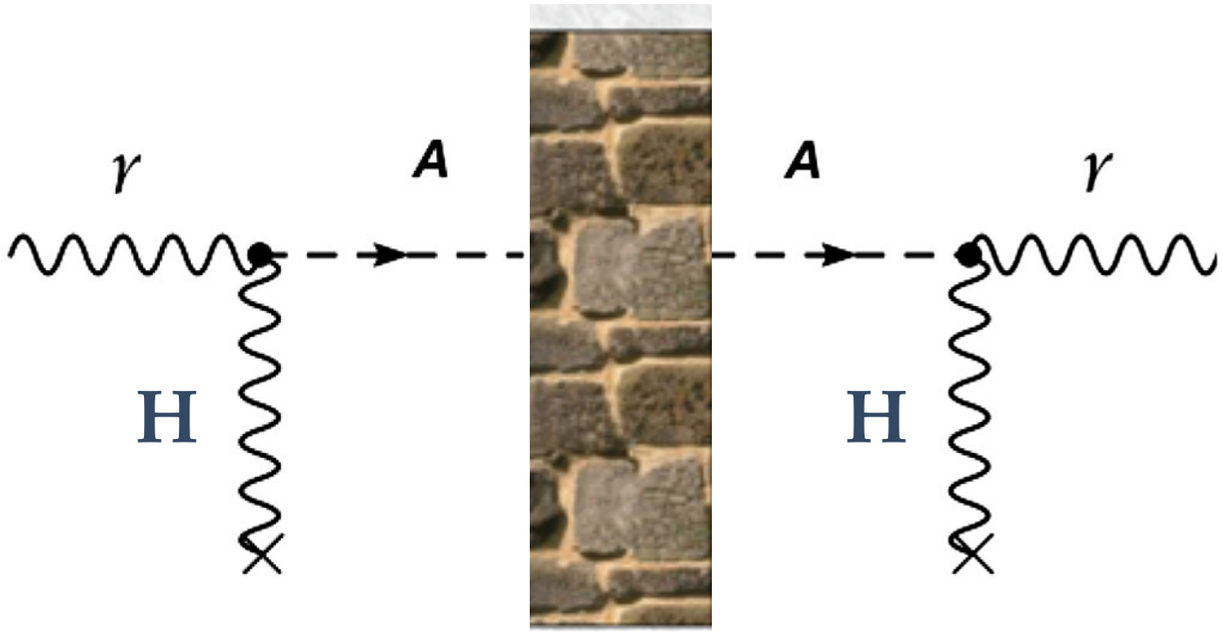
<E> ~4.2 KeV

$$\Phi_a \sim 4 \times 10^{11} \cdot g_{10}^2 \, \mathrm{cm}^{-2} \, \mathrm{s}^{-1}, \quad g_{10} \equiv g_{a\gamma\gamma}/10^{-10} \ \mathrm{GeV}^{-1}$$

Ex: CAST (best limit at the moment) and IAXO (CERN) use LHC dipoles

LSW: Light Shining through the Wall

P. Sikivie, Phys. Rev. Lett. **51**, 1415 (1983)



LAB experiment
Laser Source
Higher Luminosity

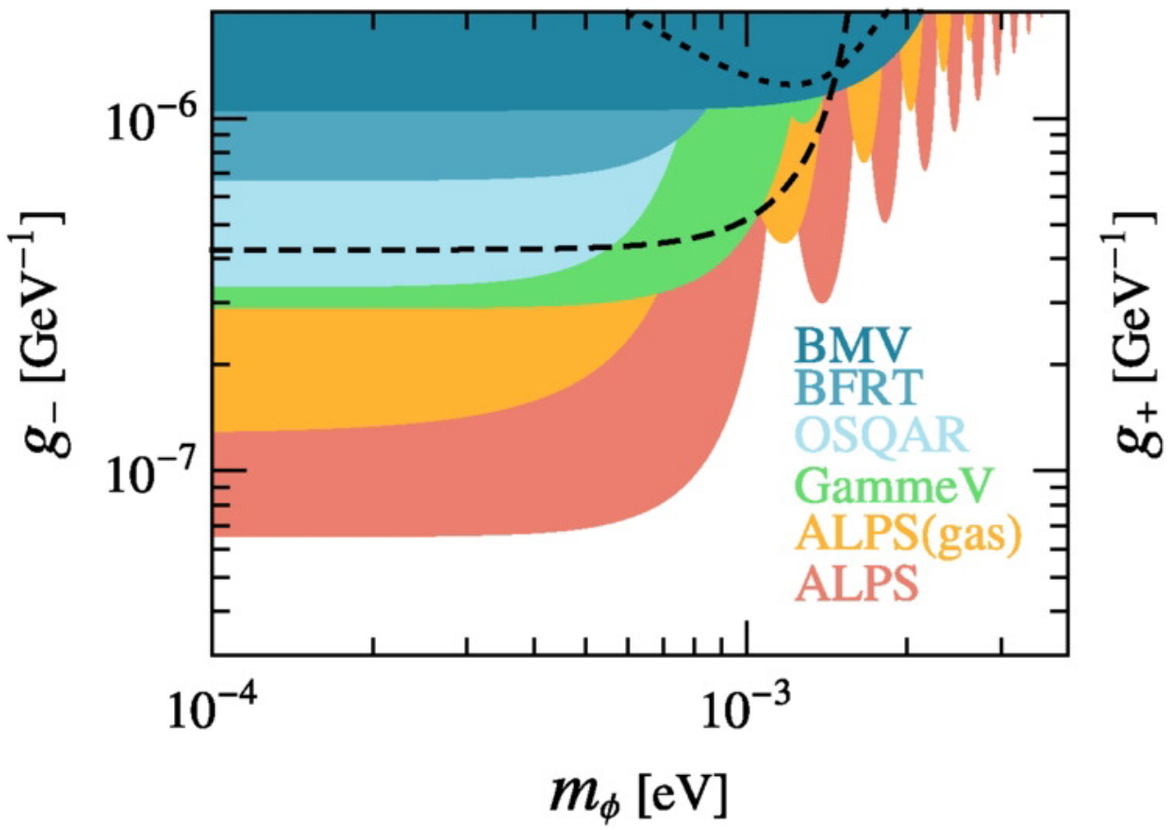
Double process
Rate dumped by ~ g^4

$$\dot{N} \propto \dot{N}_{\text{source}} \times P_{\gamma\to a}\, P_{a\to\gamma} \simeq \dot{N}_{\text{source}} \times g^4 H^4 L_x^4$$

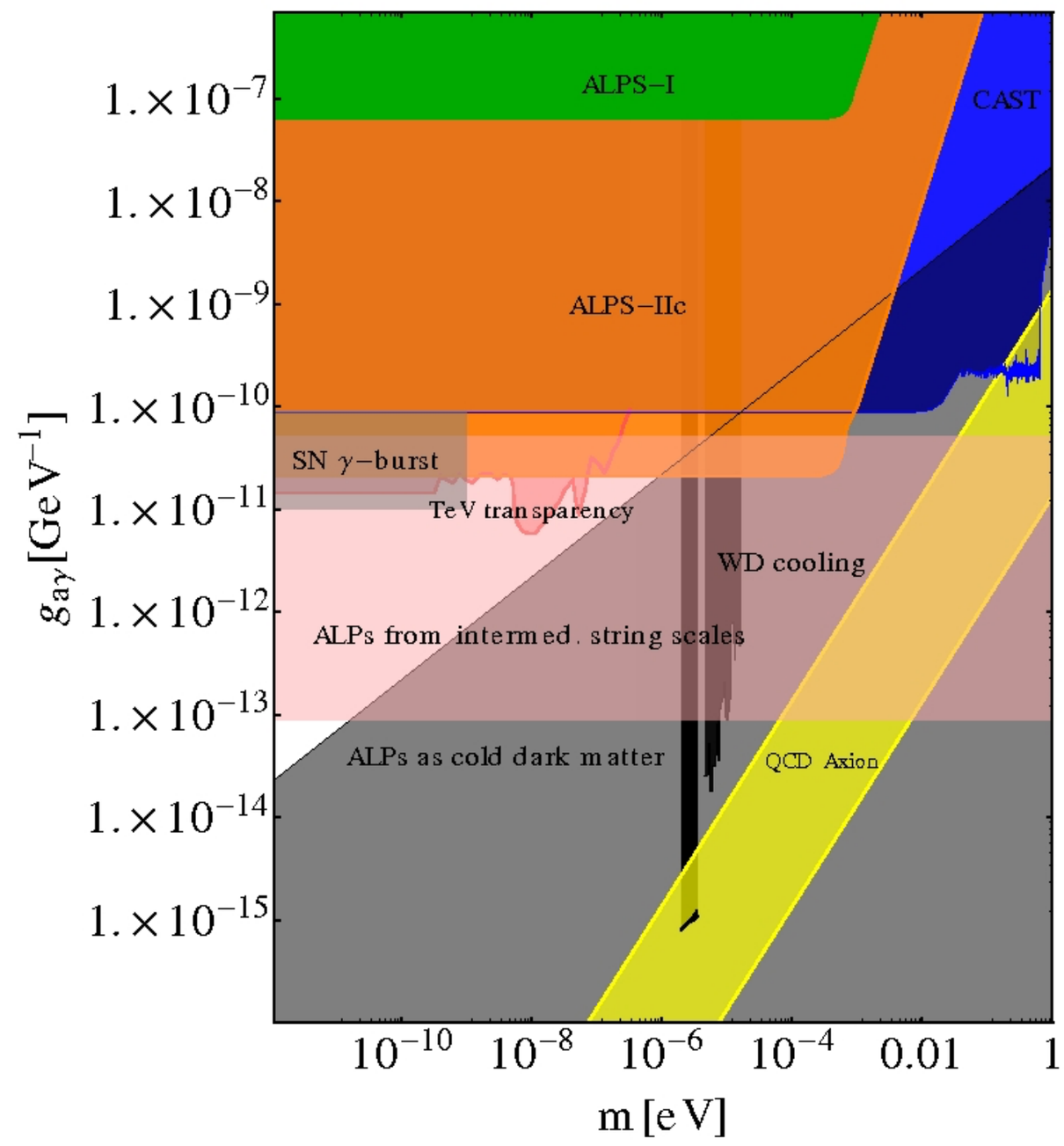
Sensitivity on g turns out to be:

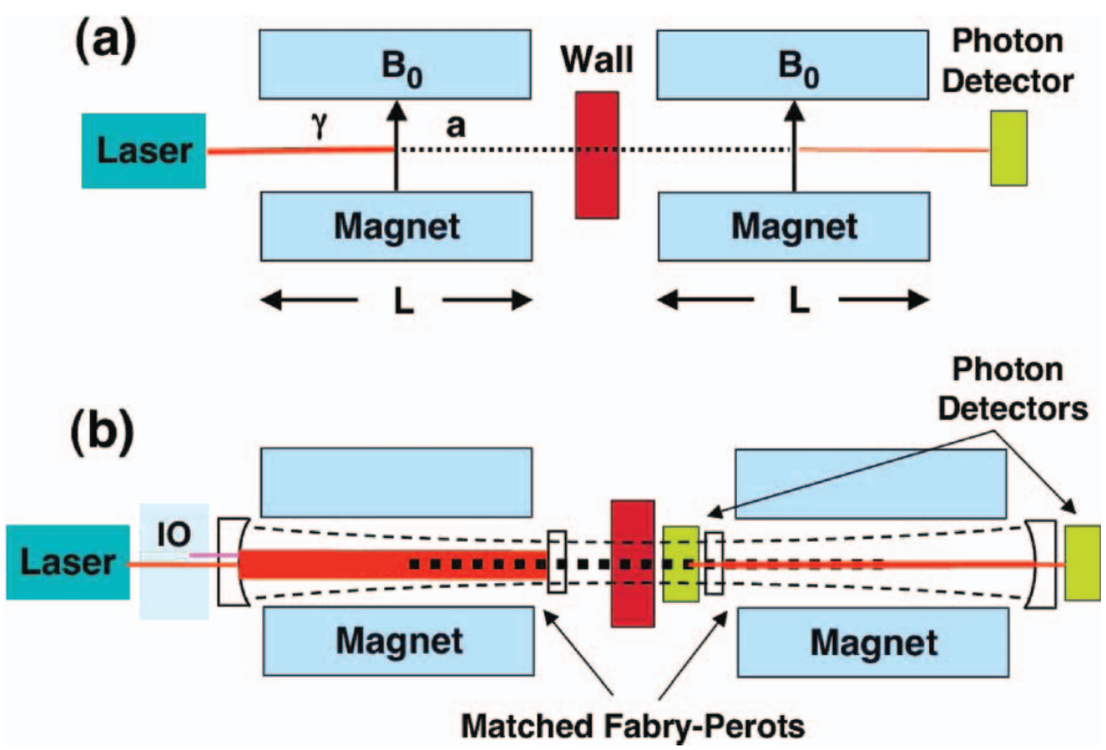
- Linear with magnetic field H and path
- quartic root of time and flux

LSW: Light Shining through the Wall



Ex: ALPs Desy use the Hera dipoles
N~ 10^{19} photons/s





STAX: keypoints

- Up to $m_a \approx 0.1\ \varepsilon_\gamma$, photon-axion conversion probability depends on luminosity, not on photon energy ==> **sub-THz photons** sources have the largest luminosity

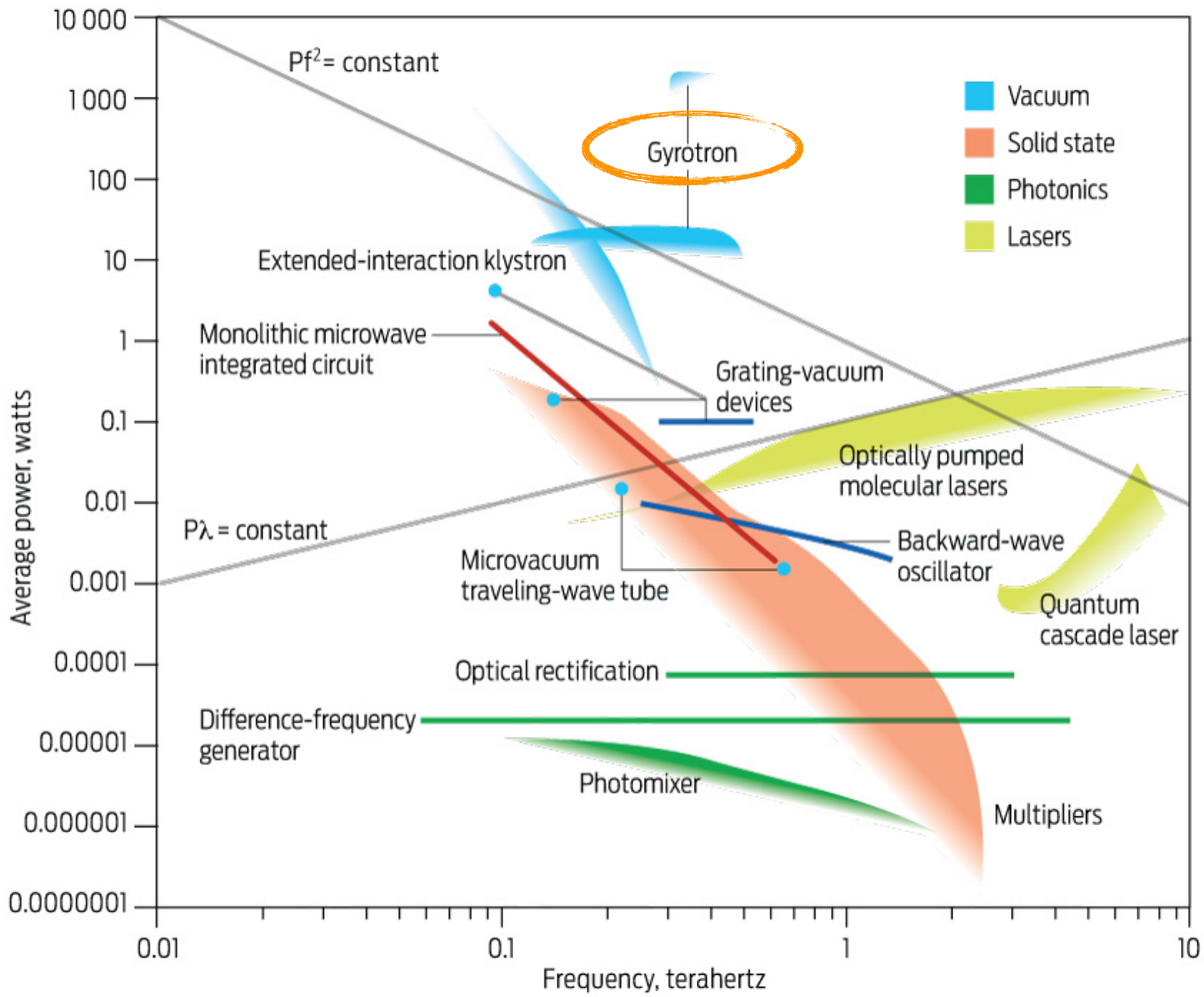
- **Very intense photon source**: gyrotrons up to 1 MW @ 30 GHz —> 10^{28} photons/s for the first lab set up $P \approx 100$ kW, $\Phi_\gamma = 10^{27}\ s^{-1}$, $\varepsilon_\gamma = 120\ \mu eV$ ($\nu \approx 30$ GHz)

- **High dipole magnetic field** of ~ 15 T and Lx = 50 cm

- **Sub-THz single-photon detector**: based on TES technology, $\eta \approx 1$, dark count negligible

30-100 GHz is the optimal point
For reference 1 GHz = 4.1 μeV

STAX: gyrotrons

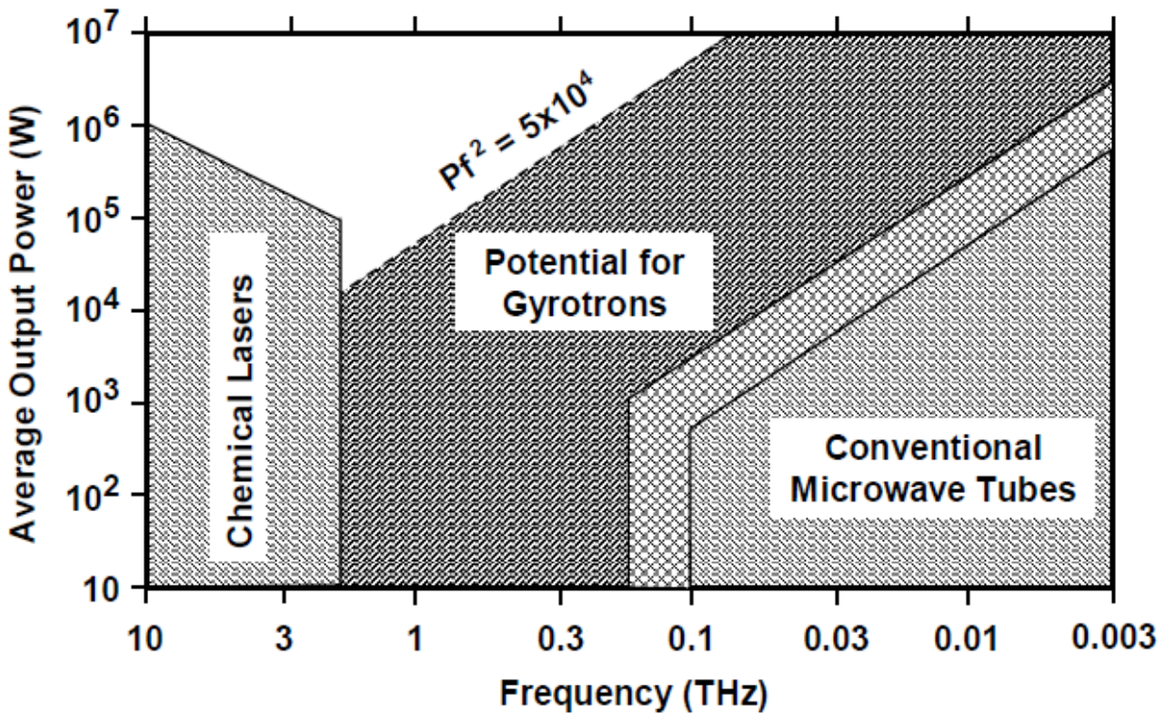


30-100 GHz is the optimal point

For reference 1 GHz = 4.1 μeV

STAX: gyrotrons

P(MW) x ν^2(GHz^2) = const.



The operating region of gyrotrons

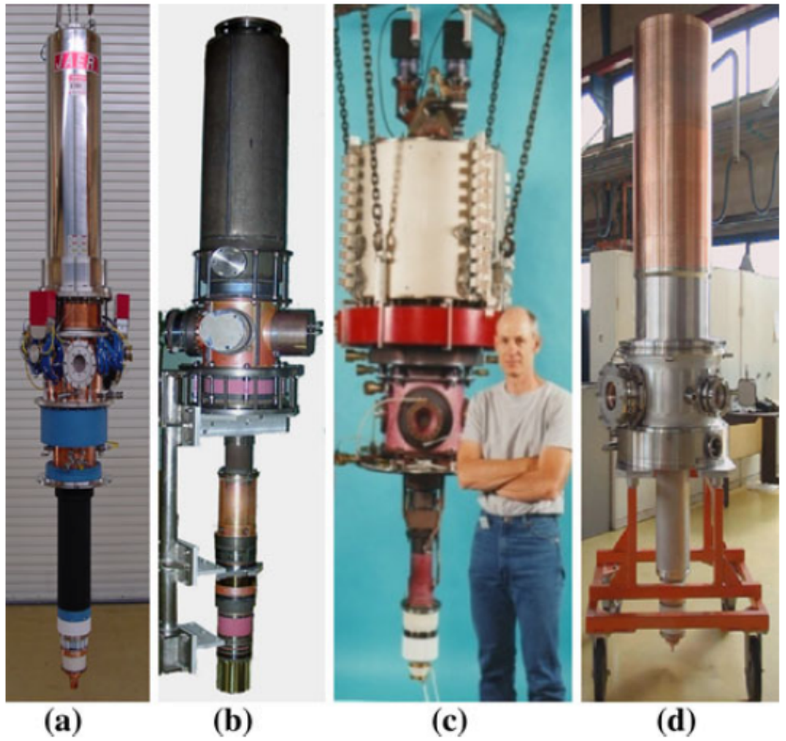
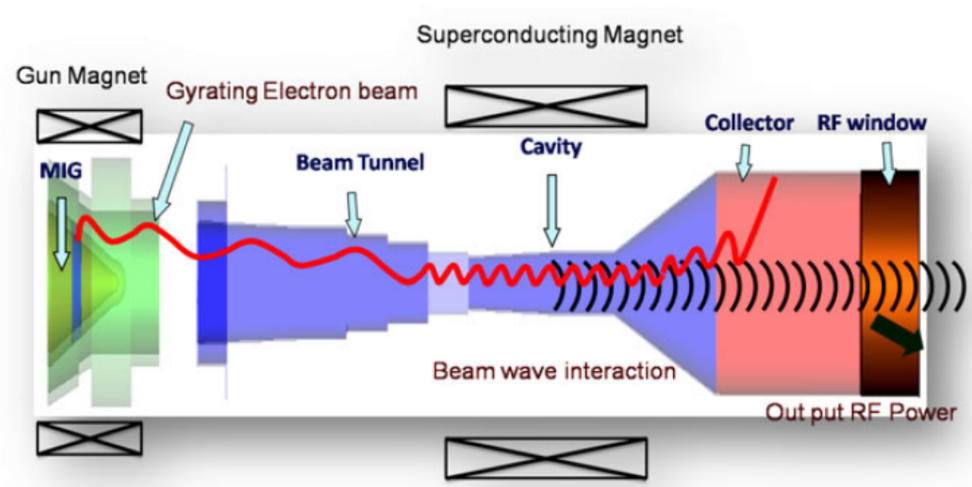


Fig. 2 Typical high power gyrotrons **a** JAERI/TOSHIBA 0.82 MW, 170 GHz, **b** GYCOM 1 MW, 170 GHz, **c** CPI 0.9 MW, 140 GHz, **d** TED 0.9 MW, 140 GHz



Now beyond 1 MW power

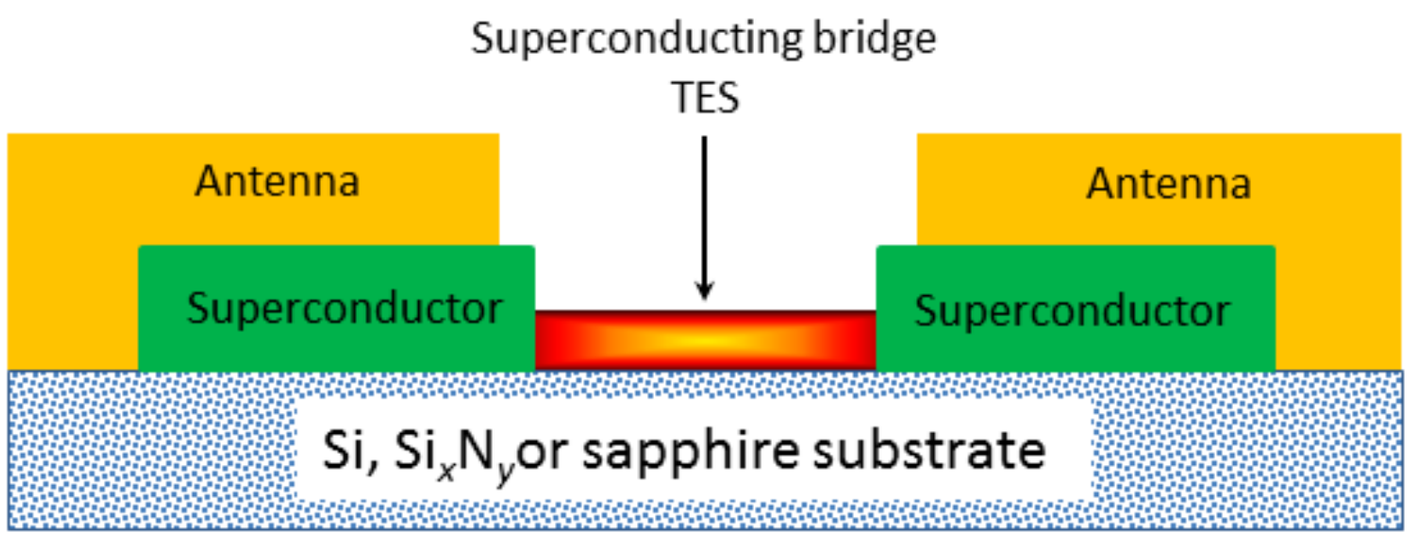
STAX: TES detectors

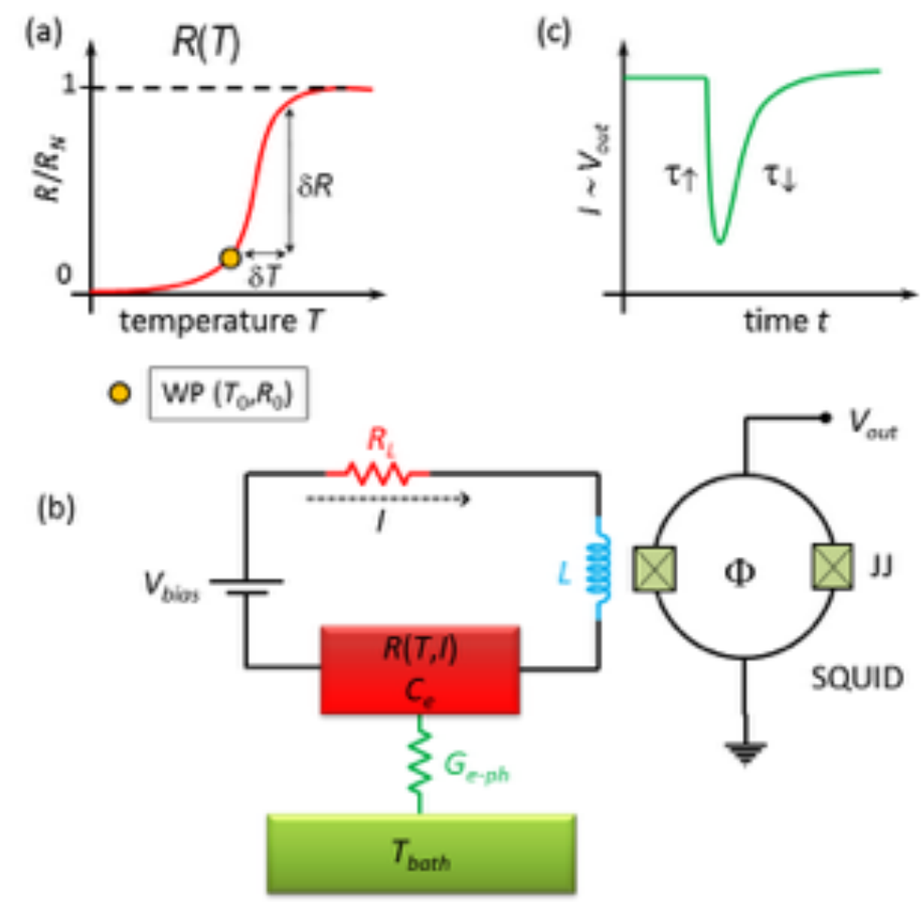
- Transition Edge Sensor (TES): **ultra-low** critical temperature superconductor between two superconducting electrodes. TES coupled to antenna.

- TES operated 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.

- efficiency ~ 1

- Negligible background / dark count





Sub -THz TES for STAX

R&D goal: implement TES sensors in the working region between 30-100 GHz through 4 drivers

- Material: choice of a Superconductor with low critical temperature (Tc ≈ 15 mK) to have a good energy resolution (~$T^{3/2}$) use α-tungsten (or Ti based bi-layers) for implementation of TES with Tc ≈ 15 mK.
  - α-W, bilayer Ti-Au or Ti-Cu

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

- Tailoring TES active volume to reduce thermal capacitance
  - **(10^{-3}-10^{-4} μm^3)**
- low-noise SQUID readout electronics optimization (operating at 100 mK)
- Efficient New log-periodic spiral antenna with planar design to enhance the efficiency

STAX potential exclusion reach

cit. Phys. Dark Univ. **12**, 37 (2016)

- Exclusion limits STAX may achieve in case of null result
- **STAX** limits compared to
  - **ALPS LSW** results
    Phys. Lett. B **689**, 149 (2010)
  - **CAST** results
    Phys. Rev. D **92**, 021101 (2015)
  - Calculated limits of **ALPS II**
    JINST **8**, T09001 (2013)
    arXiv:1309.3965
  - **QCD Axion models** predictions
    (Inclusion limits)

STAX: 1 month exposure time P= 100KW

STAX2: P=1MW and Fabry-Perot Q~10^4 cavities to enhance the luminosity

STAX2 option B: new concept Q ~$10^6 \div 10^8$ cavities with lower source power of P = 100W ÷ 1KW and highest purity

STAX vs ALPS

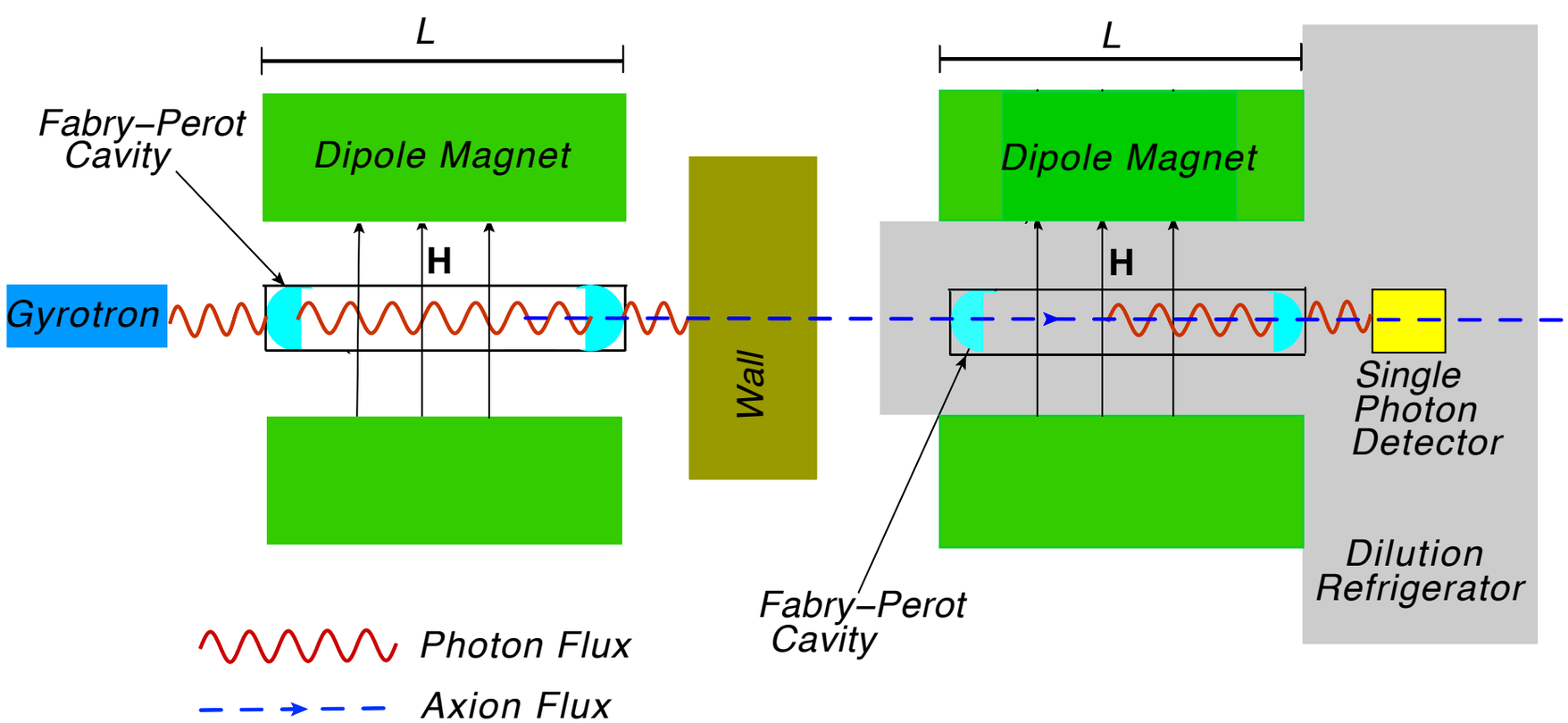
Parameter	ALPS	STAX	G_{ALPS}/G_{STAX}
Laser Power	0.8 W	100 kW	18.8
Photon Energy	2.327 eV	124 μeV	11.7
Q-Factor	55.0	104	3.7
$H \cdot L_x$	22 T·m	7.5 T·m	0.3
Detection Efficiency	0.9	1.0	1.0
Detector Noise	$1.8 \cdot 10^{-3}\ s^{-1}$	$10^{-9}\ s^{-1}$	34.0
Combined Improvement			$\sim 10^4$

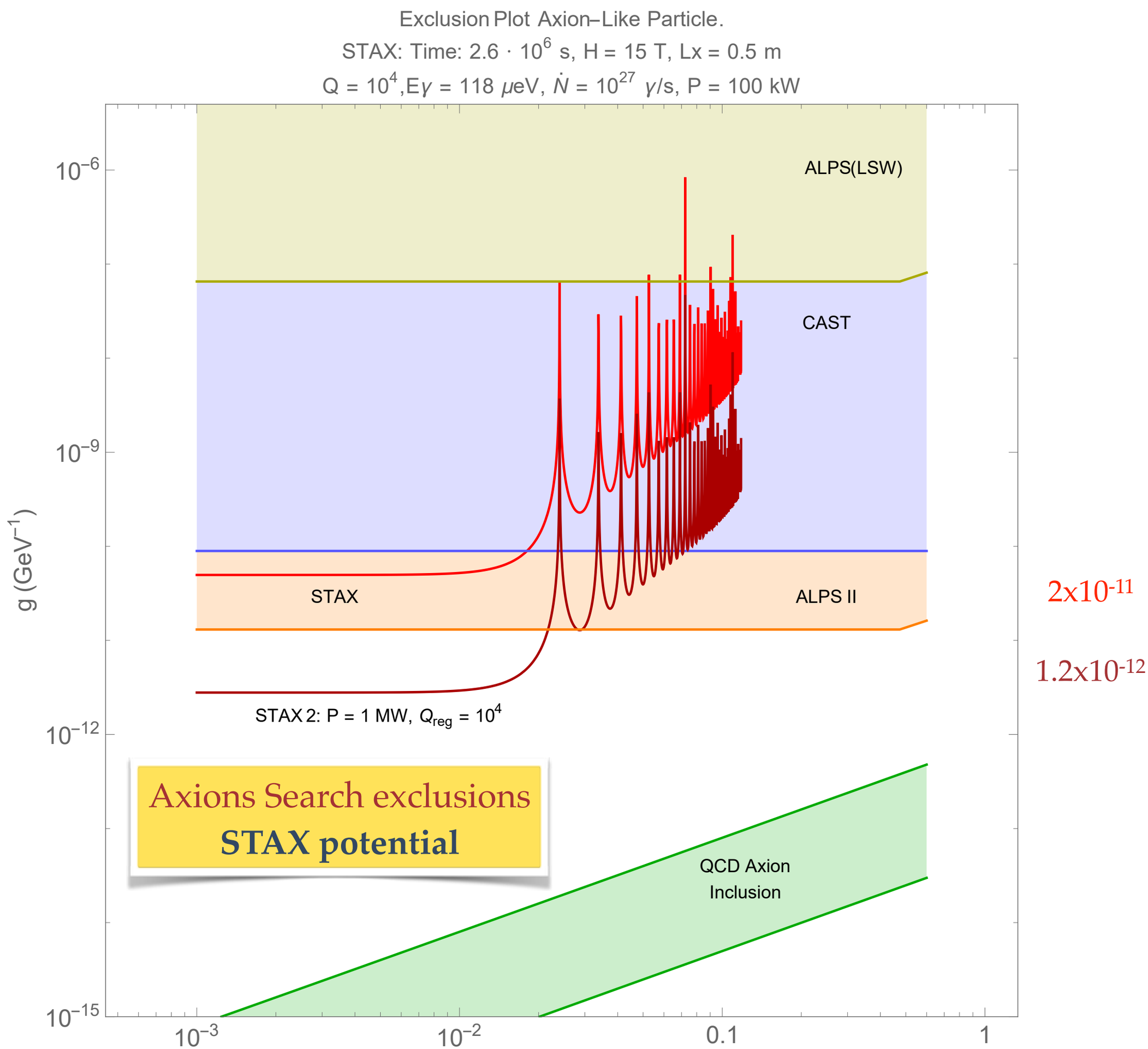
STAX2 layout

cit. Phys. Dark Univ. **12**, 37 (2016)

- Enhanced gyrotron power up to 1 MW

- A second cavity installed in the magnetic field region behind the wall
- A coherent axion beam excite the cavity electromagnetic modes enhanced axion-photon conversion P. Sikivie, D.B. Tanner and K. Van Bibber, Phys. Rev. Lett. 98, 172002 (2007)



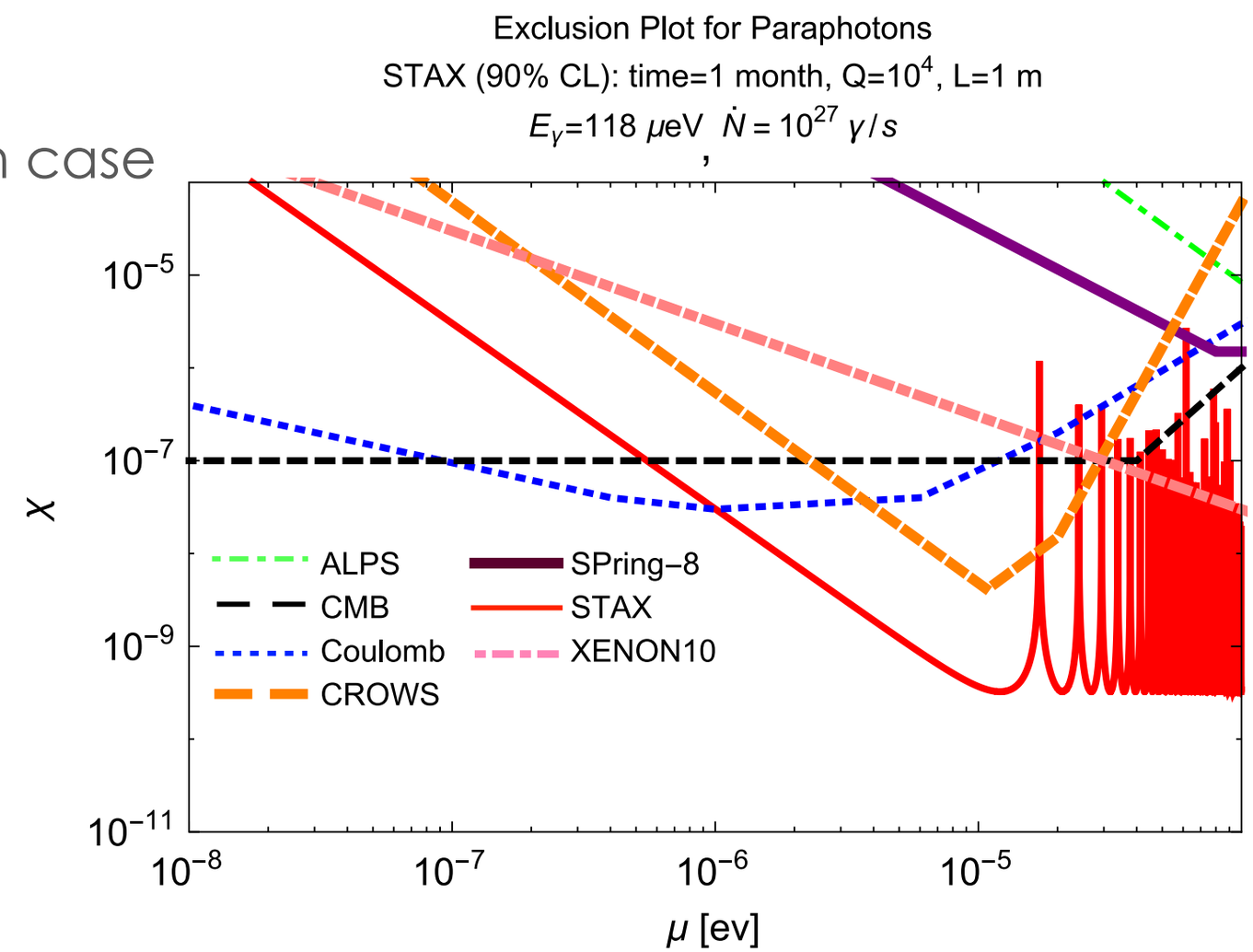


Axions Search exclusions
STAX potential

Dark Photons

cit. Phys. Dark Univ. **12**, 37 (2016)

- Exclusion limits STAX may achieve in case of null result
- **STAX** limits compared to
  - **ALPS LSW** results
    Phys. Lett. B **689**, 149 (2010)
  - **CROWS** results
    Phys. Rev. D **88**, 075014 (2013)
  - **Spring-8** results
    Phys. Lett. B **722**, 301 (2013)
  - **XENON10** results
    Phys. 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)



Conclusions

- We propose an improved detection scheme for axion-like particles searches based on a Light-Shining-Through-Wall (LSW) experiment in a photon frequency domain never explored before and a relative low cost (~ 5Meu)
- The aim is that of setting the most stringent exclusion limits on axion-like particles ever reached in this kind of experiments.
- To pursue the final objective we need to undergo an intermediate phase of R&D on the basic unit of the apparatus we have in mind to build: a TES detector for sub-THz photons.
- The antenna and the cavities implementation will be other important milestone

BACK-UP

- 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

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

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

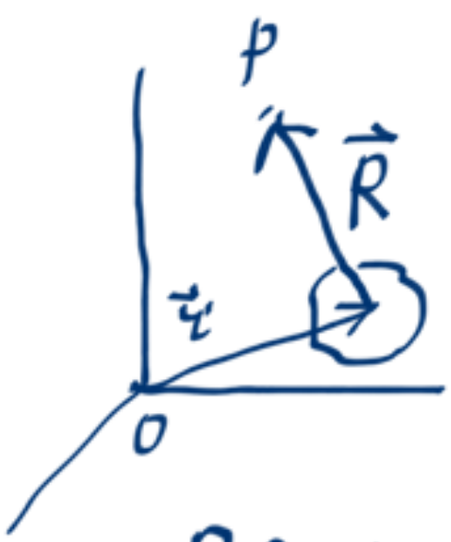
Axion-like particles

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

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

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

Cfr. Poisson eq. in electricity:

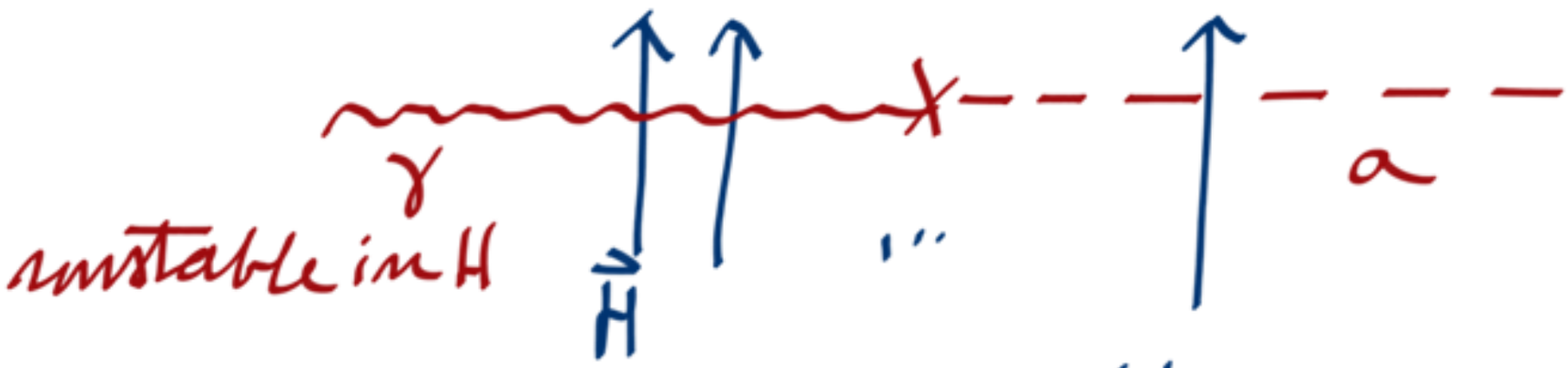


$$\Delta \phi + k^2 \phi = -4\pi \rho$$

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

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

Photon - Axion Conversion



$$a = f\,\frac{e^{ikr}}{r}$$

$$\boxed{\left|\mathcal{M}_{\gamma \rightleftarrows a}\right|^2 = \frac{1}{4H^2}\left|\int e^{i\vec{q}\cdot\vec{r}}\,\vec{H}(\vec{r})\cdot\vec{\epsilon}(\vec{k}_\gamma,\lambda)\,dV\right|^2}$$

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 $\underline{L_x \lesssim 1/q_x}$.

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

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

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

Dark photons

L.B. Okun, Sov. Phys.-JETP **56**, 502 (1982)
B. Holdom, Phys. Lett. B **166**, 196 (1986)

- Massive vectors of hidden $U(1)_h$
- Visible and hidden-sector photons Lagrangian:

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

$F^{\mu\nu}$ = 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:

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

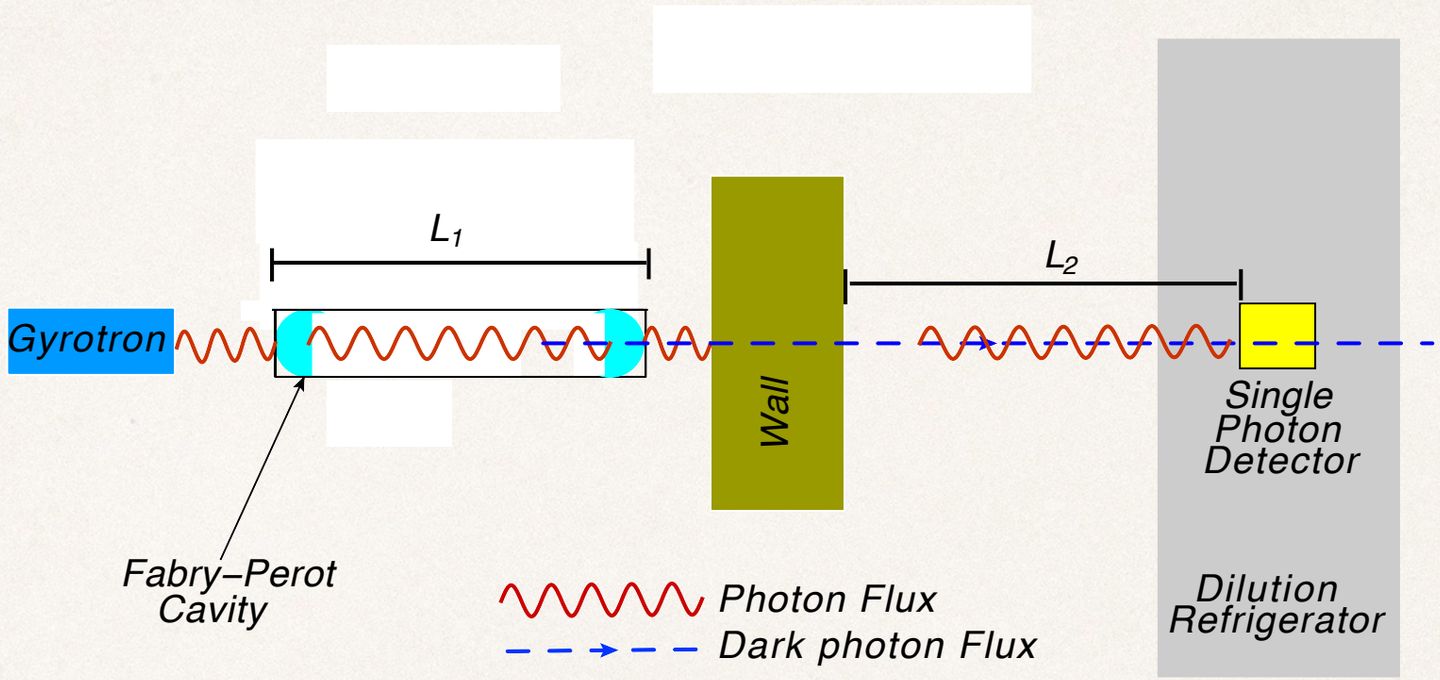
$$k_1 \approx \varepsilon_\gamma$$

$$k_2 \approx \sqrt{\varepsilon_\gamma^2 - \mu^2}$$

$$q = k_1 - k_2$$

Dark photons

L.B. Okun, Sov. Phys.-JETP **56**, 502 (1982)
B. Holdom, Phys. Lett. B **166**, 196 (1986)



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

$$\begin{aligned} P_{\gamma\to\gamma'\to\gamma} &= P_{\gamma\to\gamma'}(L_1)P_{\gamma'\to\gamma}(L_2) \\ &= 16\chi^4\left[\sin\left(\tfrac{q\,L_1}{2}\right)\sin\left(\tfrac{q\,L_2}{2}\right)\right]^2 \end{aligned}$$

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

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

Dark count and other bkg sources

- Dark count rate (phonon noise) ~ 6×10^{-13} s^{-1}

$$N_d = \frac{\beta_{\rm eff}}{\sqrt{2\pi}} \int_{E_T/\delta E}^{\infty} \exp(-x^2/2)\, dx$$

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

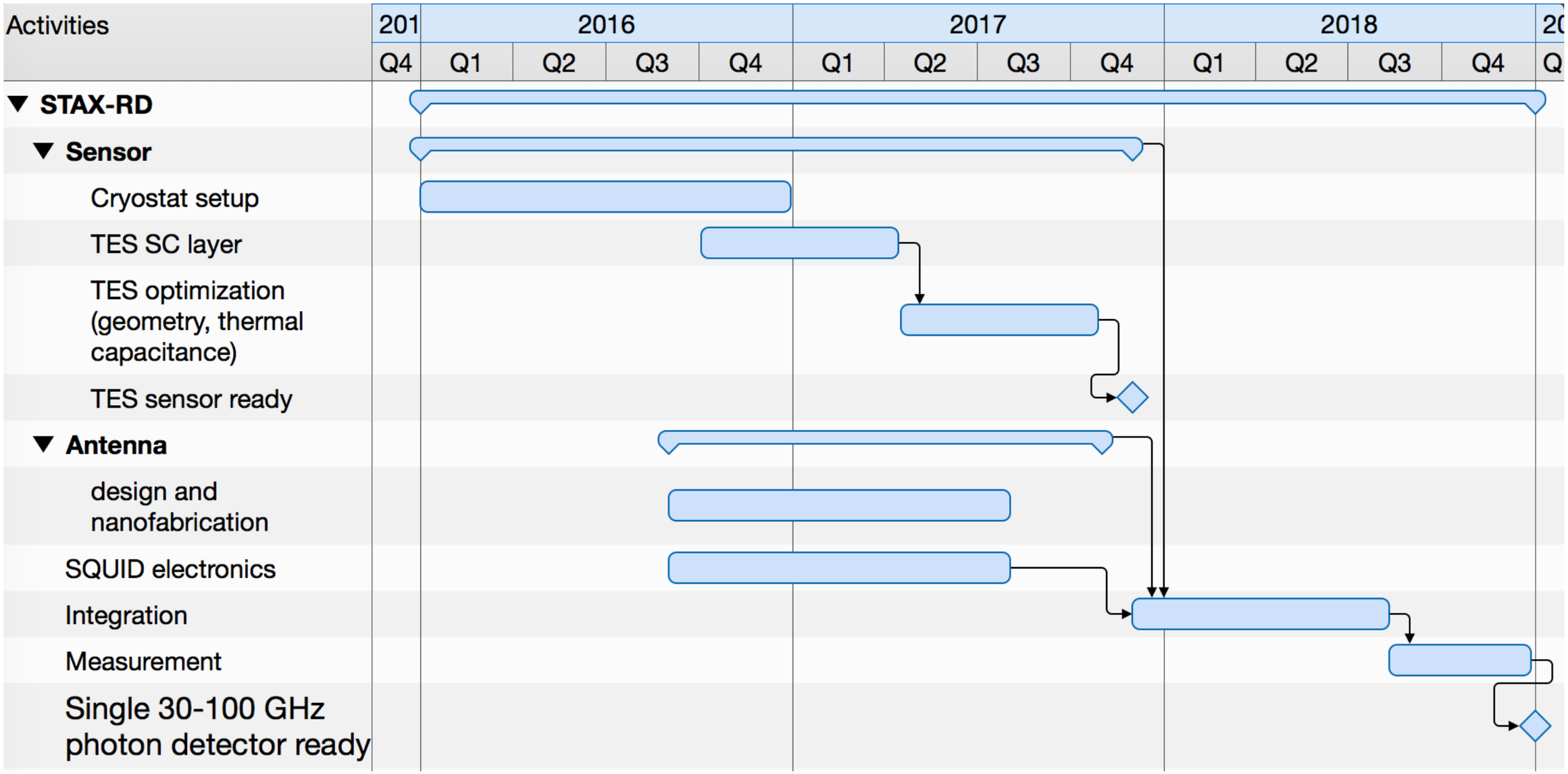
- Black Body: at 10mK peaked around 0.6 GHz with a negligible rate of 10^{-30} m^{-2} s^{-1} photons irradiated

- Cosmic bkg: 1mu/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%

- Environmental radioactivity: negligible with similar estimates

Dark count negligible at these sub THz frequencies

3 years R&D project



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 €**