STAX
An improved detection scheme for axion-like particles

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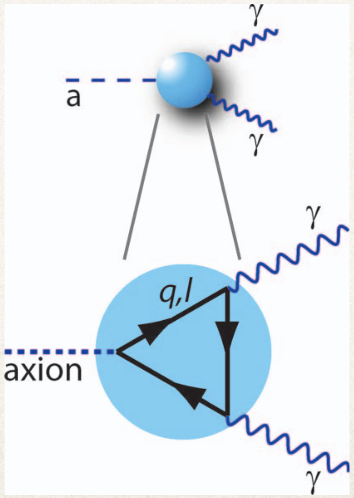
OUTLINE

- Axions Search: motivation and theory
- How to detect Axions
- STAX
- Detector R&D

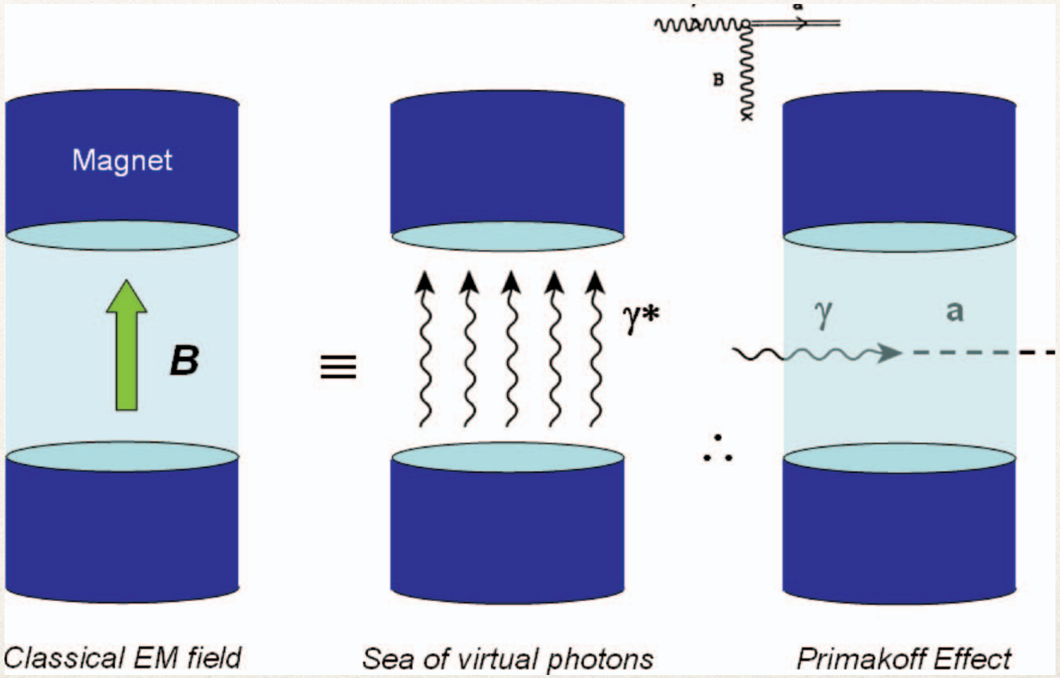
Axion to photon conversion

- 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



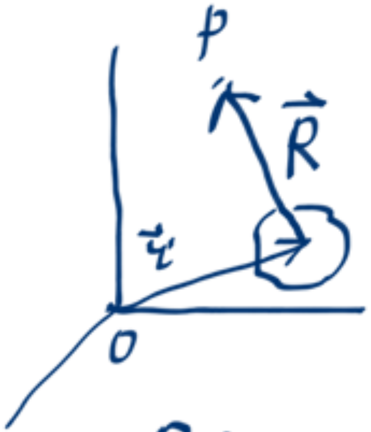
Axion-Like particles

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

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

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

Cfr. Poisson eq. in electricity:

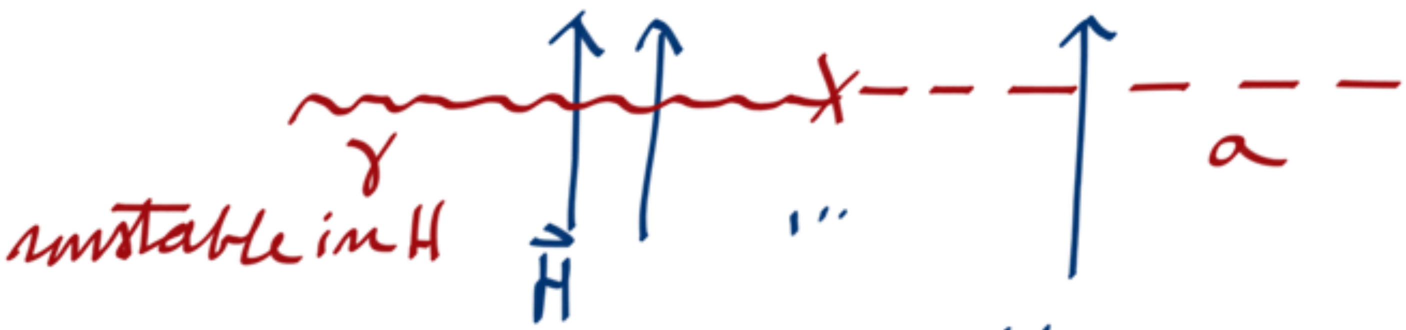


$$\Delta \phi + k^2 \phi = -4\pi \rho$$

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

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

Photon - Axion Conversion



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

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

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 $L_x \lesssim 1/q_x$.

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

$$\boxed{q_x = \frac{m_a^2}{2E_\gamma}}$$

$$|\vec{k}_a| = E_a^2 - m_a^2 = E_\gamma^2 - m_a^2 \sim E_\gamma \text{ as } E_\gamma \gg m_a$$

Axion-Photon conversion probability

$$P_{\gamma \leftrightarrows a} = g^2 H^2 \frac{\sin^2\left(\frac{q_x L_x}{2}\right)}{q_x^2}$$ with the transfered momentum $$q_x = \frac{m_a^2}{2\mathcal{E}_\gamma}$$

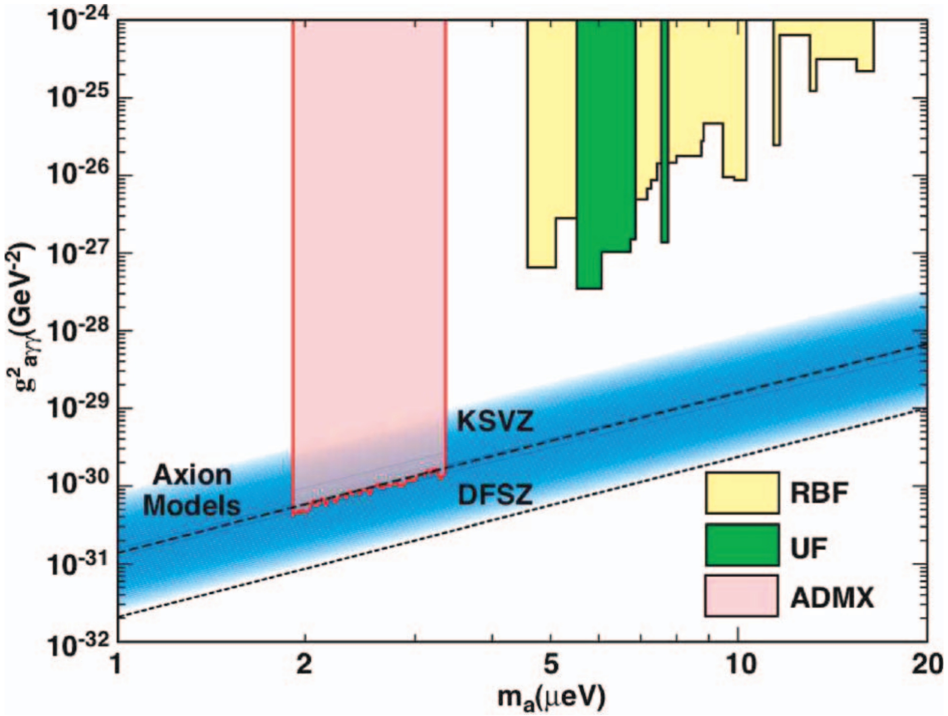
g is the axion-gamma coupling constant $< 10^{-10}$ GeV^{-1} from astrophysics

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

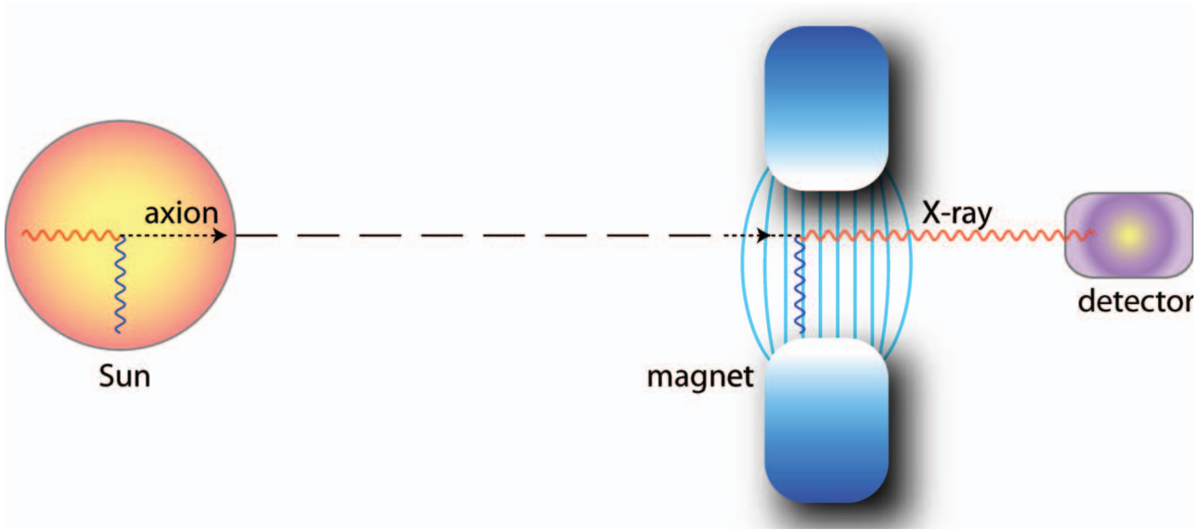
Only experiments hitting Peccei-Quin region



Ex: ADMX Livermore

Axions Experiments

- Three types: Haloscopic, Helioscopic, LSW
- First two suffer by low intensity source or depends on stellar/galactic models

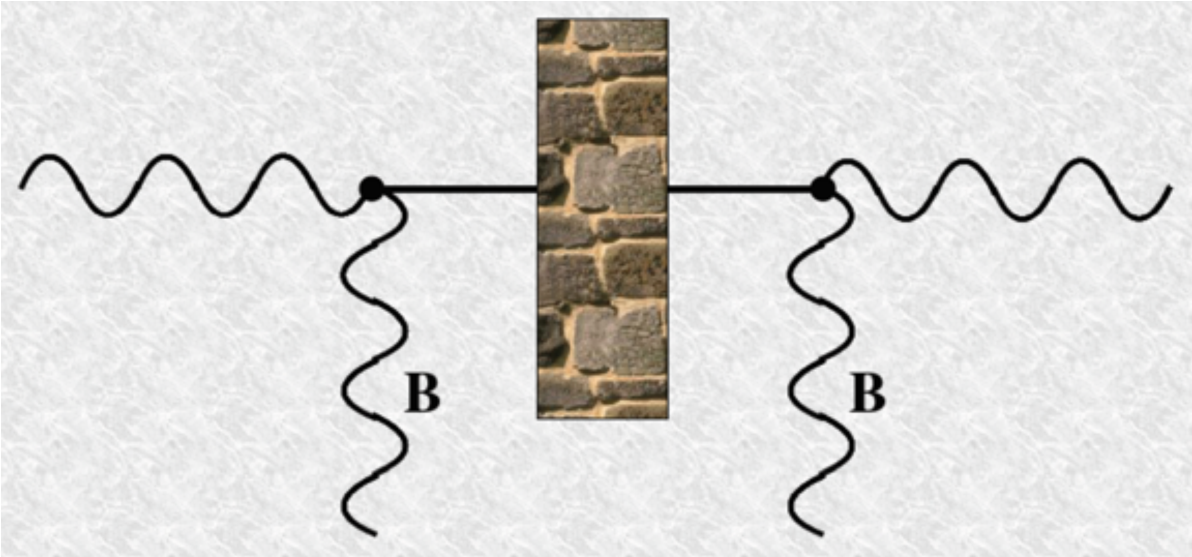


<E> ~4.2 KeV

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

Ex: CAST and IAXO (CERN) use LHC dipoles

LSW: Light Shining through the Wall



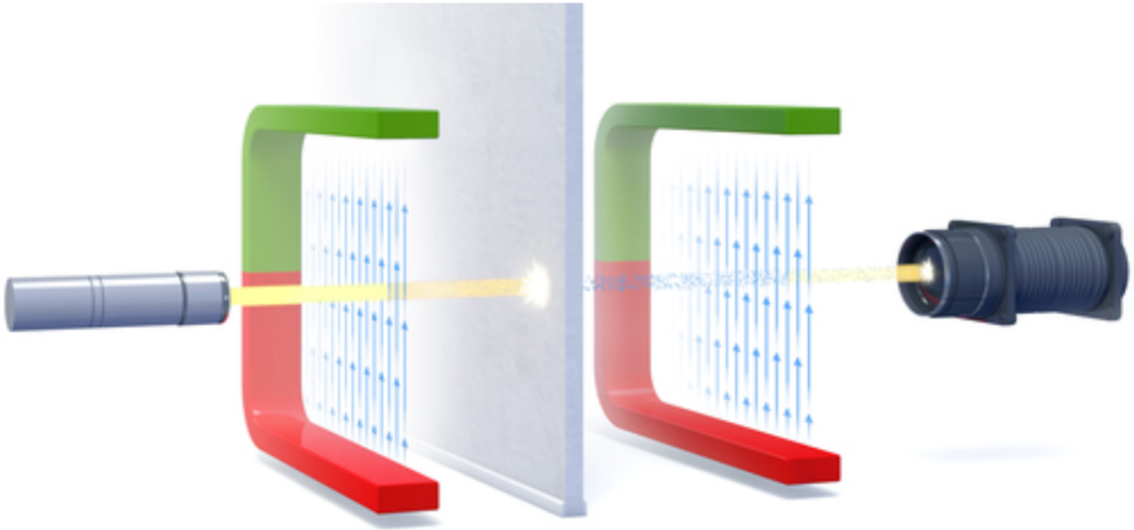
Laser Source

Higher Luminosity

Double process

~ g^4

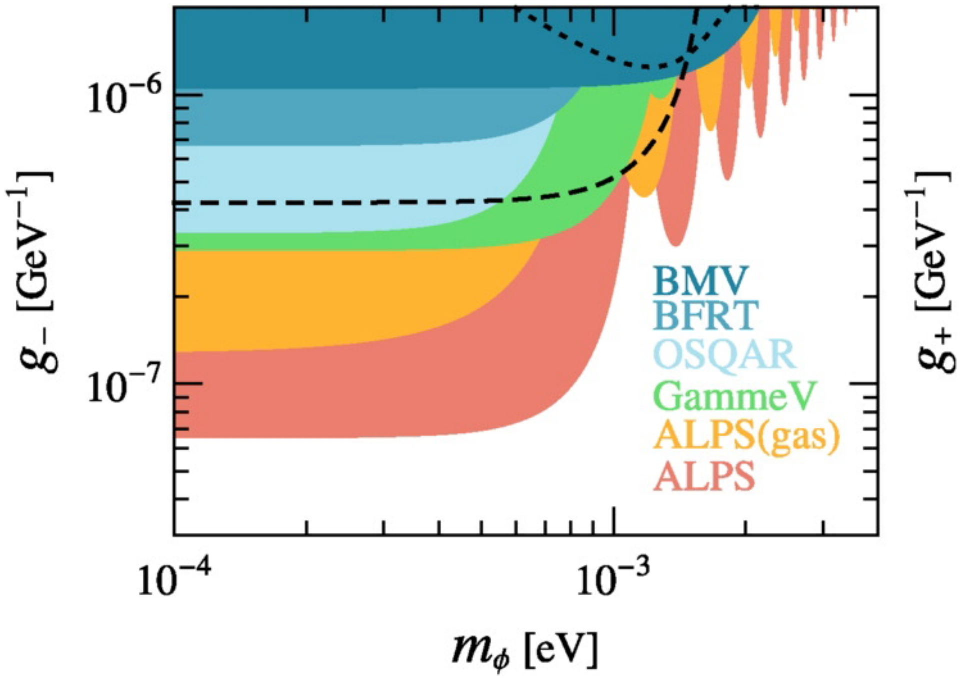
$N_a \sim 6\text{x}10^{16}$ / s

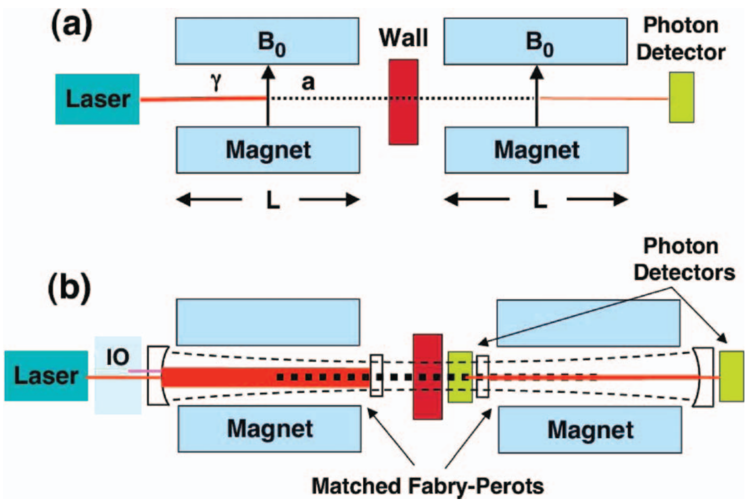


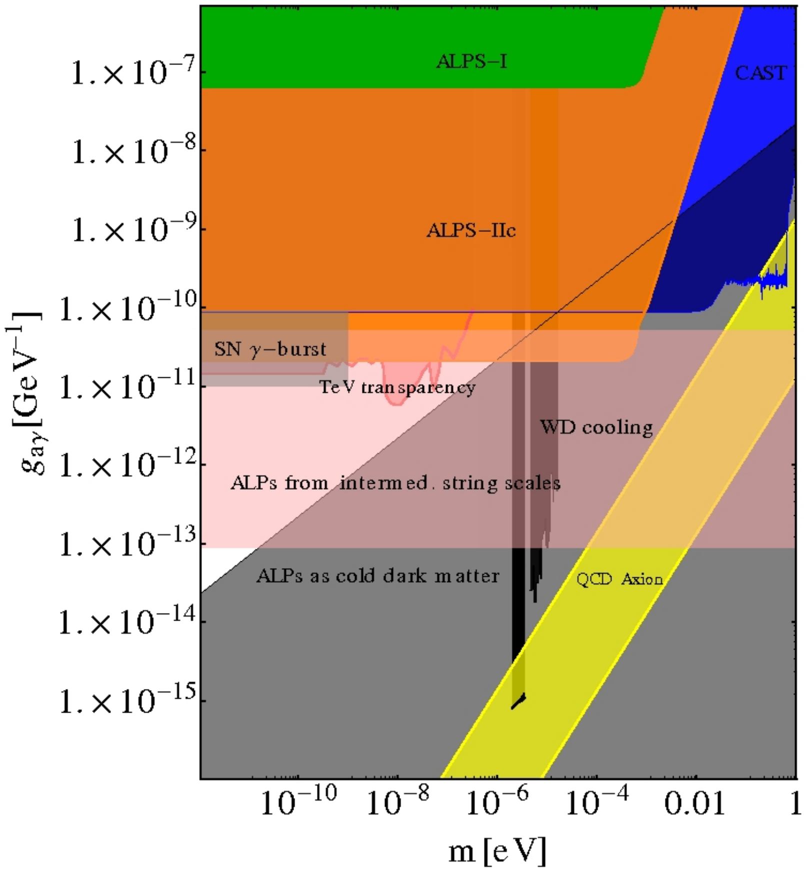
$$\dot{N} \propto \dot{N}_{\text{source}} \times P_{\gamma\to a}\, P_{a\to\gamma} \simeq \dot{N}_{\text{source}} \times g^4 H^4 L_x^4$$

LSW: Light Shining through the Wall

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





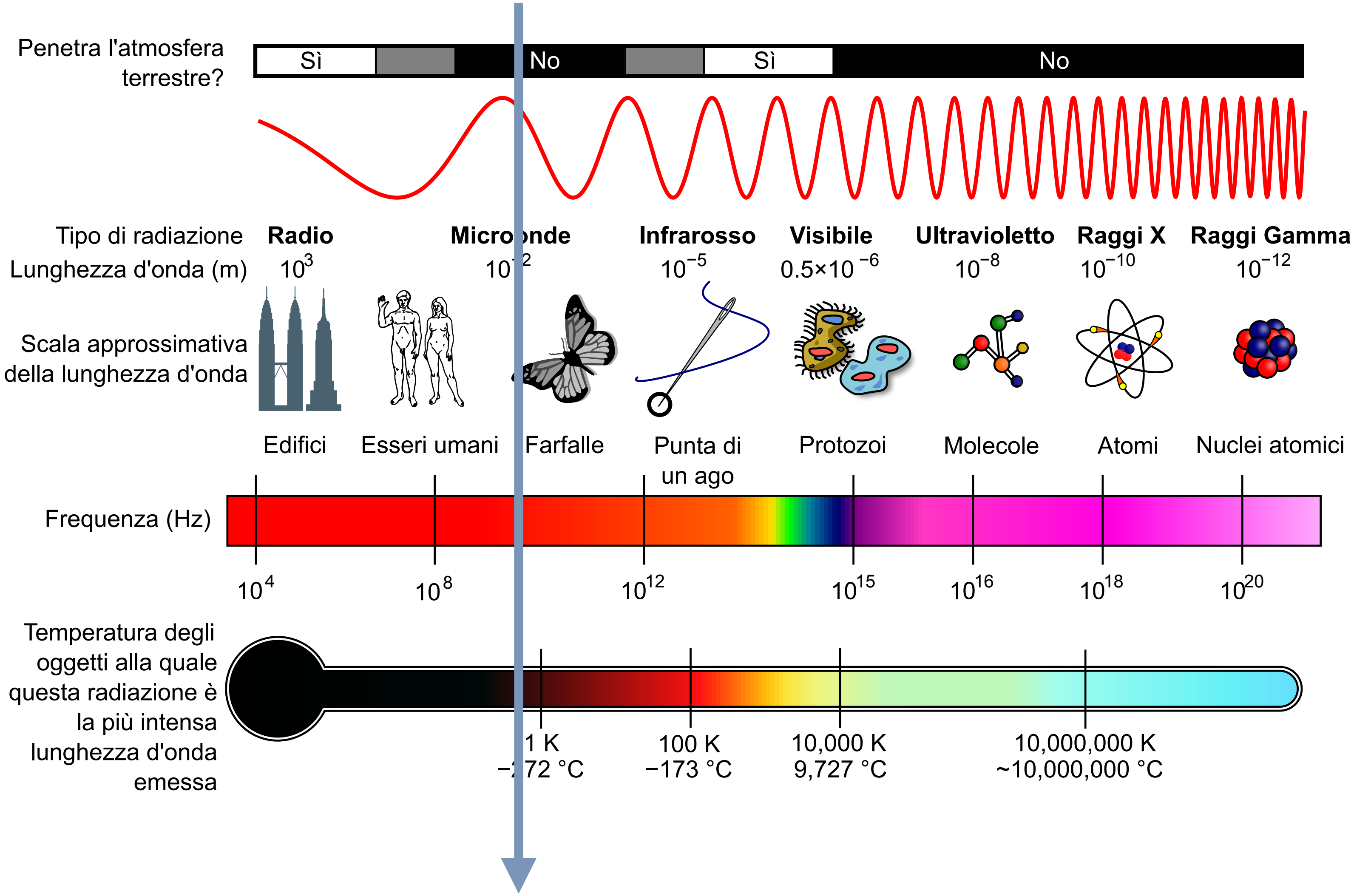


STAX: keypoints

- High dipole magnetic field soon available (dipoles of ~ 15 T)
- Very intense photon source gyrotrons up to 1 MW @ 30 GHz —> 10^{28} photons/s
- Energy range up to ~ 0.1 meV (30 GHz)
- Possibility to use Fabry-Perot Q~10^5 cavities to enhance the luminosity

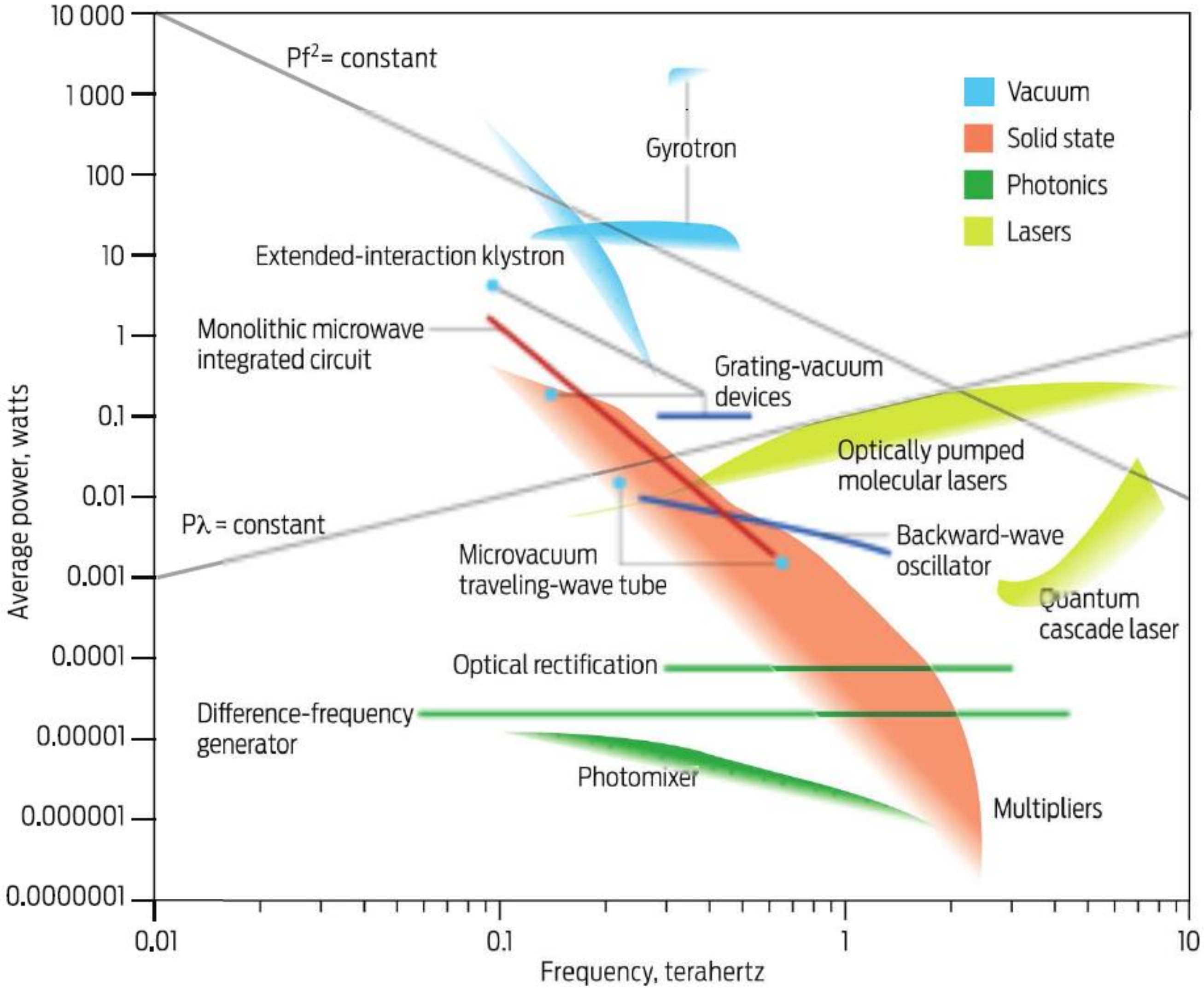
For reference 1 GHz = 4.1 μeV

STAX: gyrotrons



30-100 GHz is the optimal point

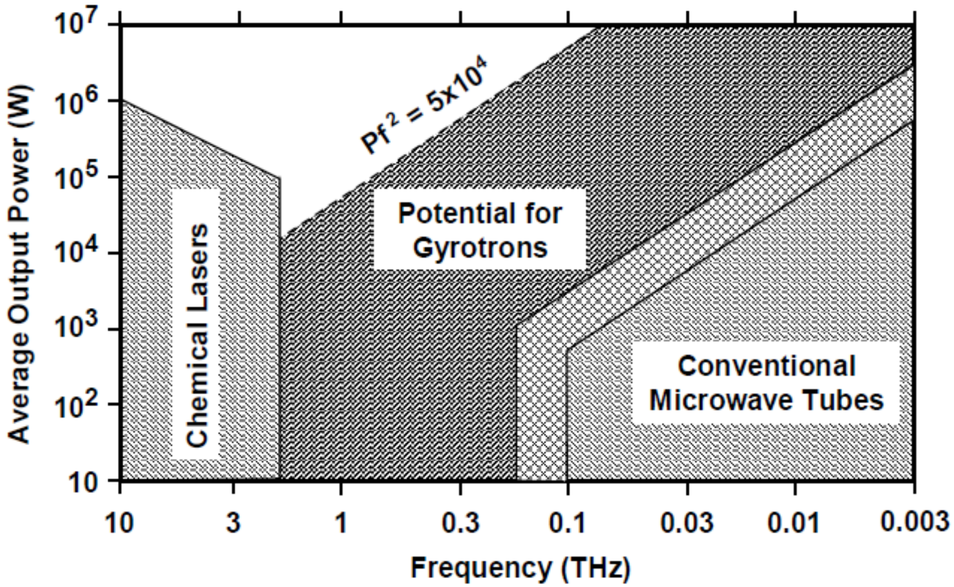
STAX: gyrotrons



30-100 GHz maximum laser power

STAX: gyrotrons

$P(\mathrm{MW}) \times \nu^2(\mathrm{GHz}^2) = \mathrm{const.}$



The operating region of gyrotrons

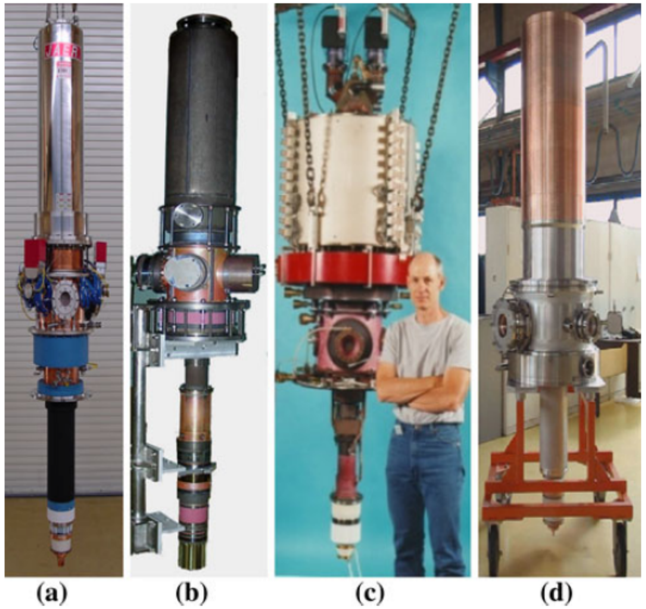
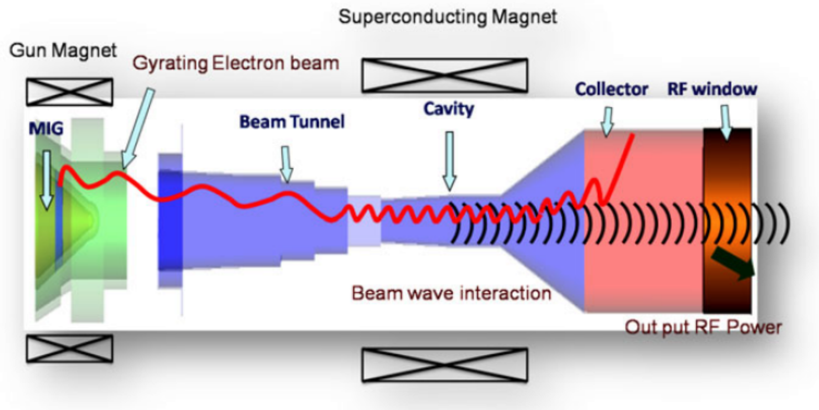
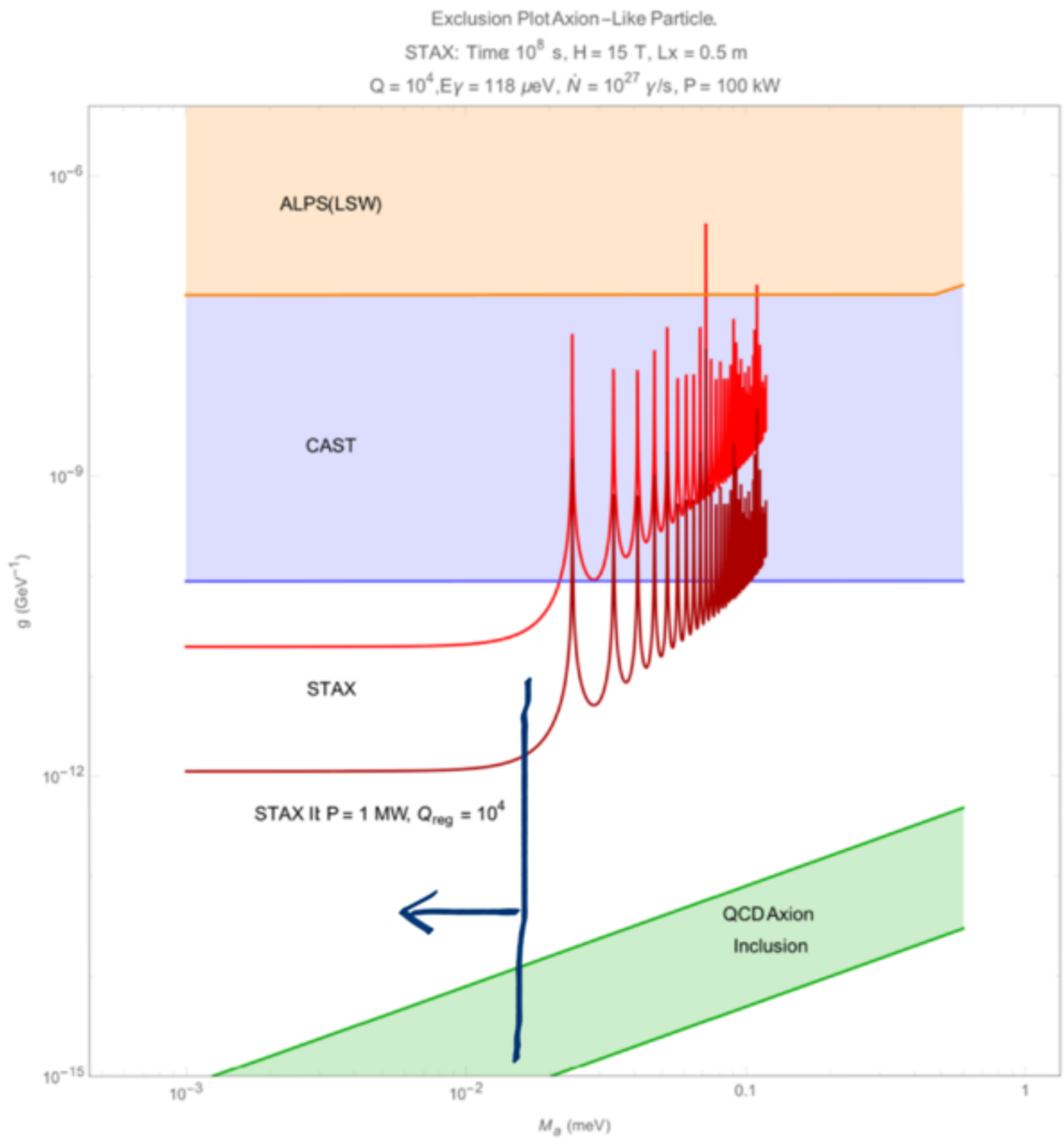


Fig. 2 Typical high power gyrotrons **a** JAERI/TOSHIBA 0.82 MW, 170 GHz, **b** GYCOM 1 MW, 170 GHz, **c** CPI 0.9 MW, 140 GHz, **d** TED 0.9 MW, 140 GHz



Exclusion Plot



Some Numbers

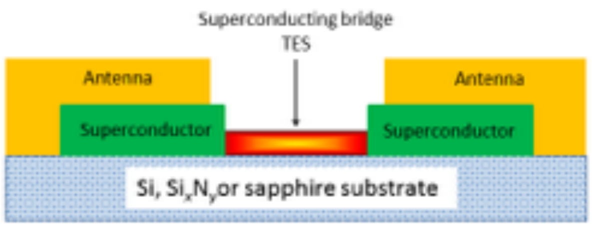
(VERY) PRELIMINARY

Parameter	ALPS	STAX	g_{ALPS} / g_{STAX}
Laser Power	0.8 W	100 kW	18.8
Photon Energy	2.327 eV	118 μeV	11.8
Cavity Q-factor	55.0	10^4	3.7
H * L_x	22 T m	7.5 T m	0.3
Detection Efficiency	0.9	1.0	1.0
Detector Noise	1.8 10^{-3} sec^{-1}	10^{-9} sec^{-1}	34.0
Combined Improvement			~ 10^4

STAX: detector

Sub THz Single Photon Detector REQUIREMENTS

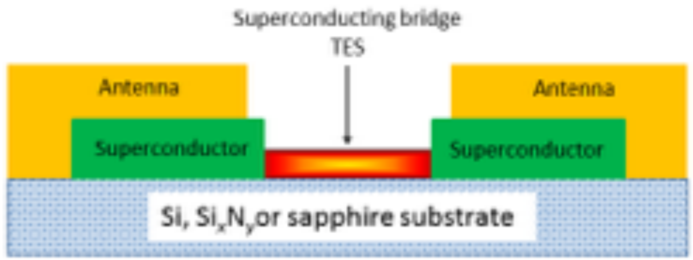
- Able to detect a single photon < THz
- efficiency ~ 1
- Negligible background / dark count
- ……

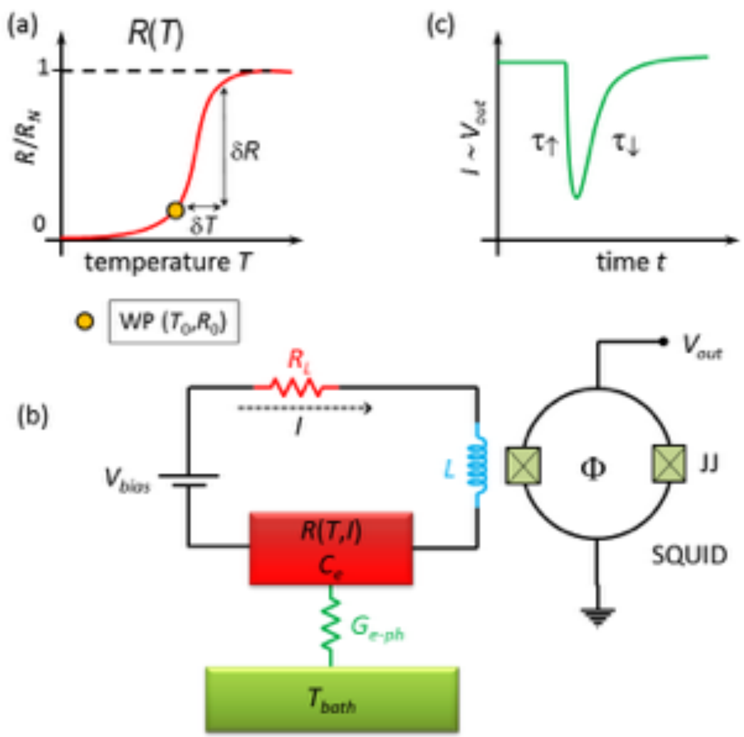


OUTCOME of these requirements: TES (Transition Edge Sensor)

TES detectors

- Electronic bolometer made by a low critical temperature superconductor
- efficiency ~ 1
- Negligible background / dark count
- ultralow T





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 T (< 20 mK) to have a good energy resolution (~$T^{3/2}$)
  - alfa-W, bilayer Ti-Au or Ti-Cu
- Tailoring TES active volume to reduce thermal capacitance
  - **(10^{-3}-10^{-4} μm^3)**
- New antenna planar design to enhance the efficiency
- low-noise SQUID readout electronics optimization (operating at 100 mK)

Dark count and other bkg sources

- Dark count rate (phonon noise) ~ 6x10 $^{-13}$ s^{-1}

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

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

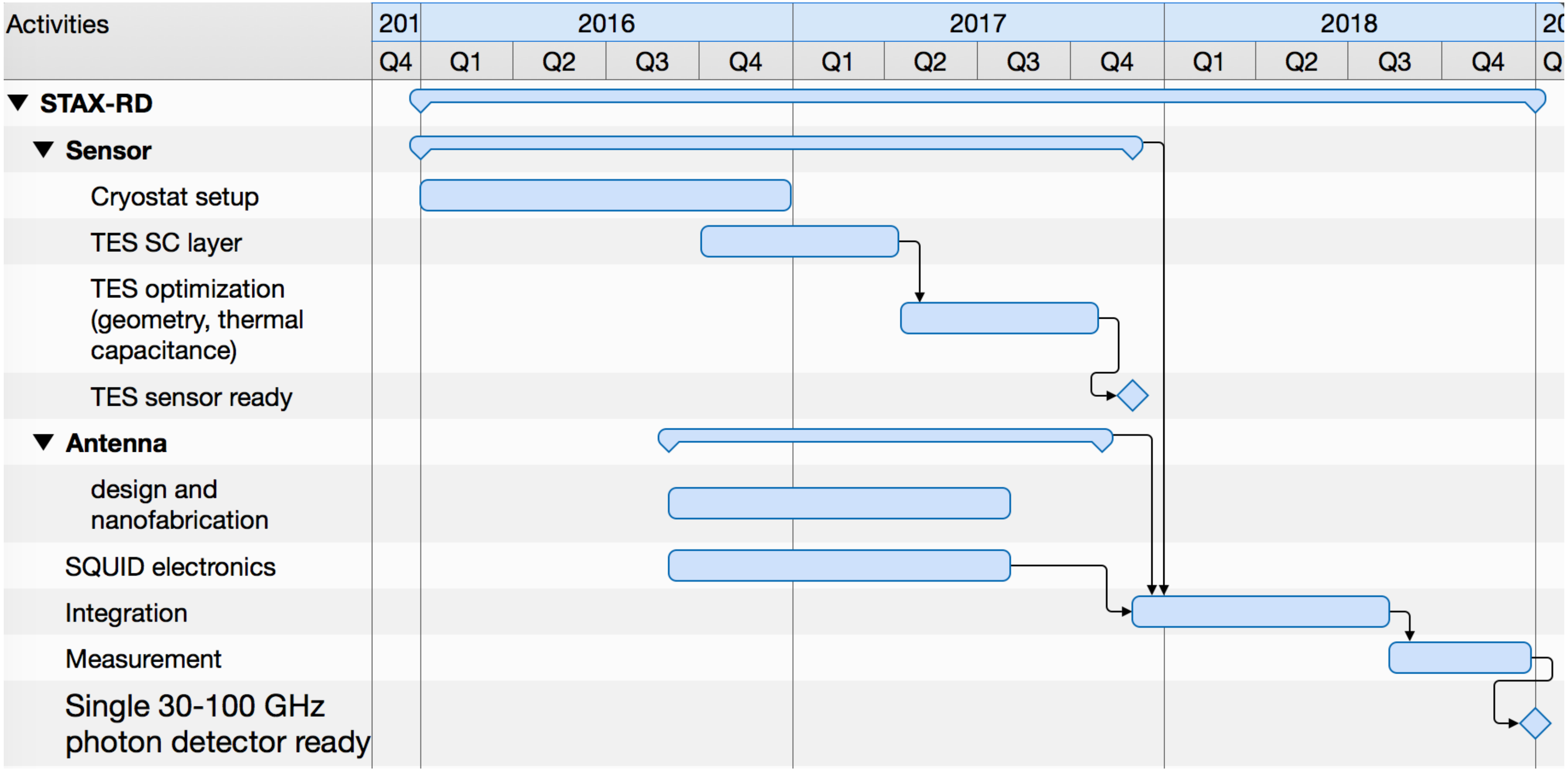
- Black Body: at 10mK peaked around 0.6 GHz with a negligible rate of 10 $^{-30}$ m^{-2} s^{-1} photons irradiated

- 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 €**

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
- 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 research and development on the basic unit of the apparatus we have in mind to build: a detector of sub-THz photons.
- This R&D is the goal of this CSN5 call submission