Axion-like particles with sub-THz photons

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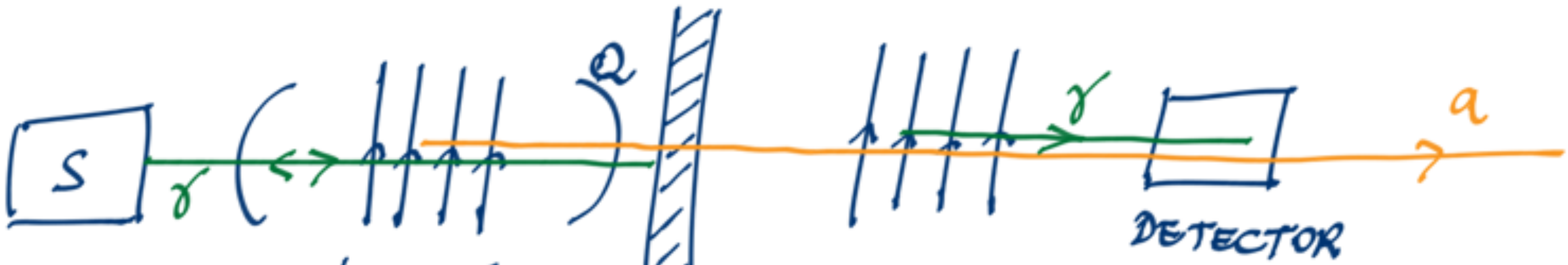
LIGHT-SHINING-THROUGH-WALL



$\mathcal{E}_D = \mathcal{E}_S$ & COLLINEAR

$$\dot{N}_e \propto \dot{N}_\gamma \, P_{\gamma \to a} \, P_{a \to \gamma}$$

$\propto \dot{N}_\gamma (G \cdot H \cdot L)^4$ where $G \sim 1/f$

with $G \lesssim 10^{-10}\,\mathrm{GeV}^{-1}$ (suggested by CAST)

$$(GHL)^4 \lesssim 10^{-35}$$

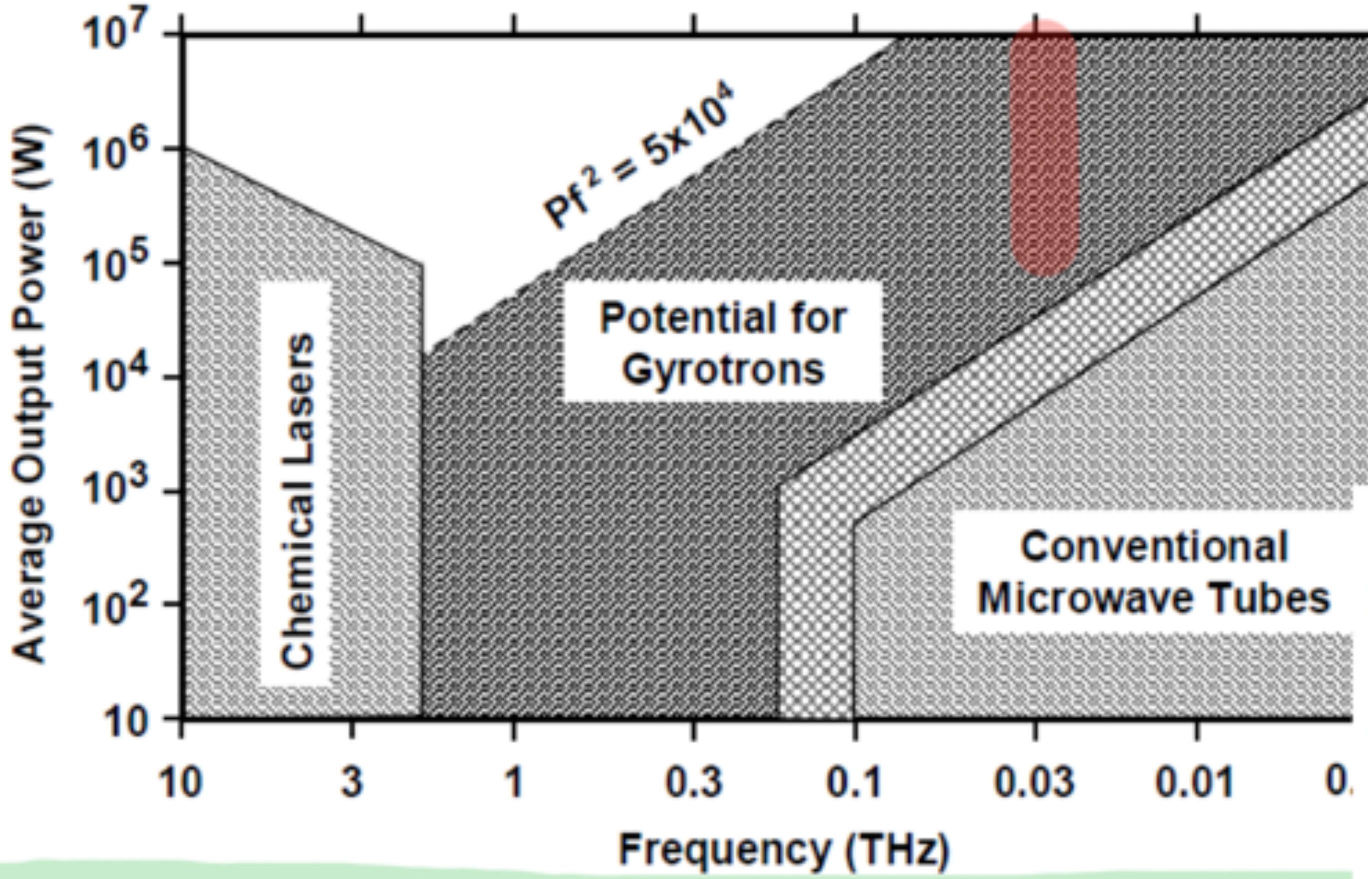
MEGAWATT GYROTRON SOURCES can produce (@30GHz)

$\dot{N}_\gamma \simeq 10^{28}$ /sec

w/ continuous emission.

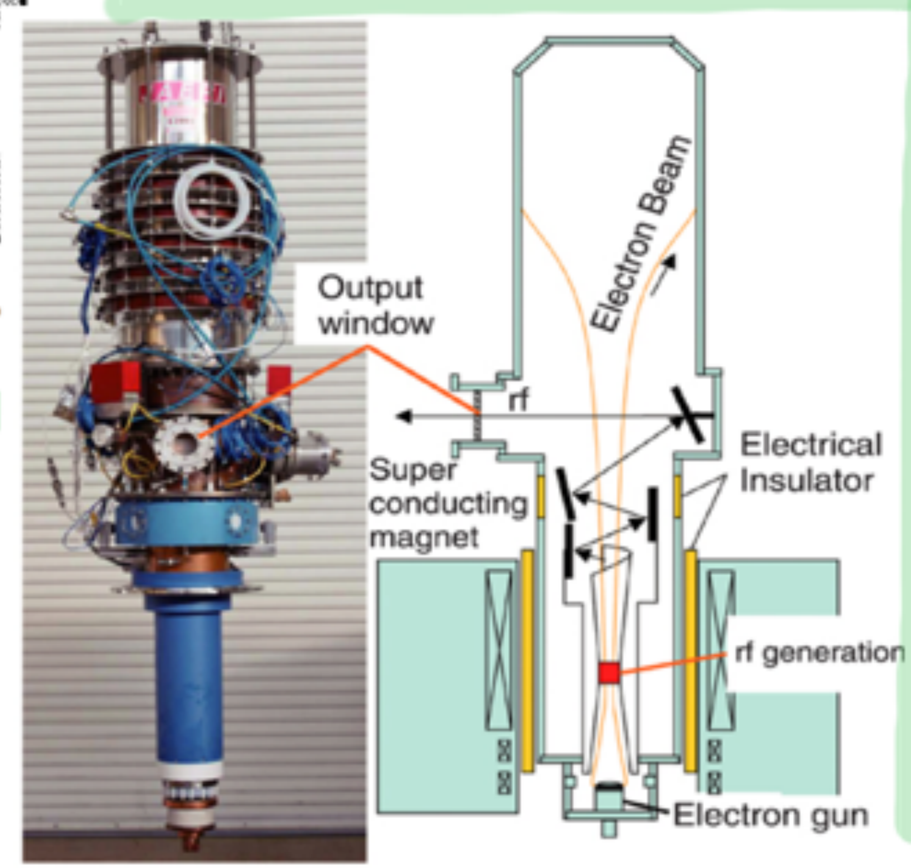
(10 LSW events/yr) × Q ($\simeq 10^4 \div 10^5$ for MW)

Gyrotrons

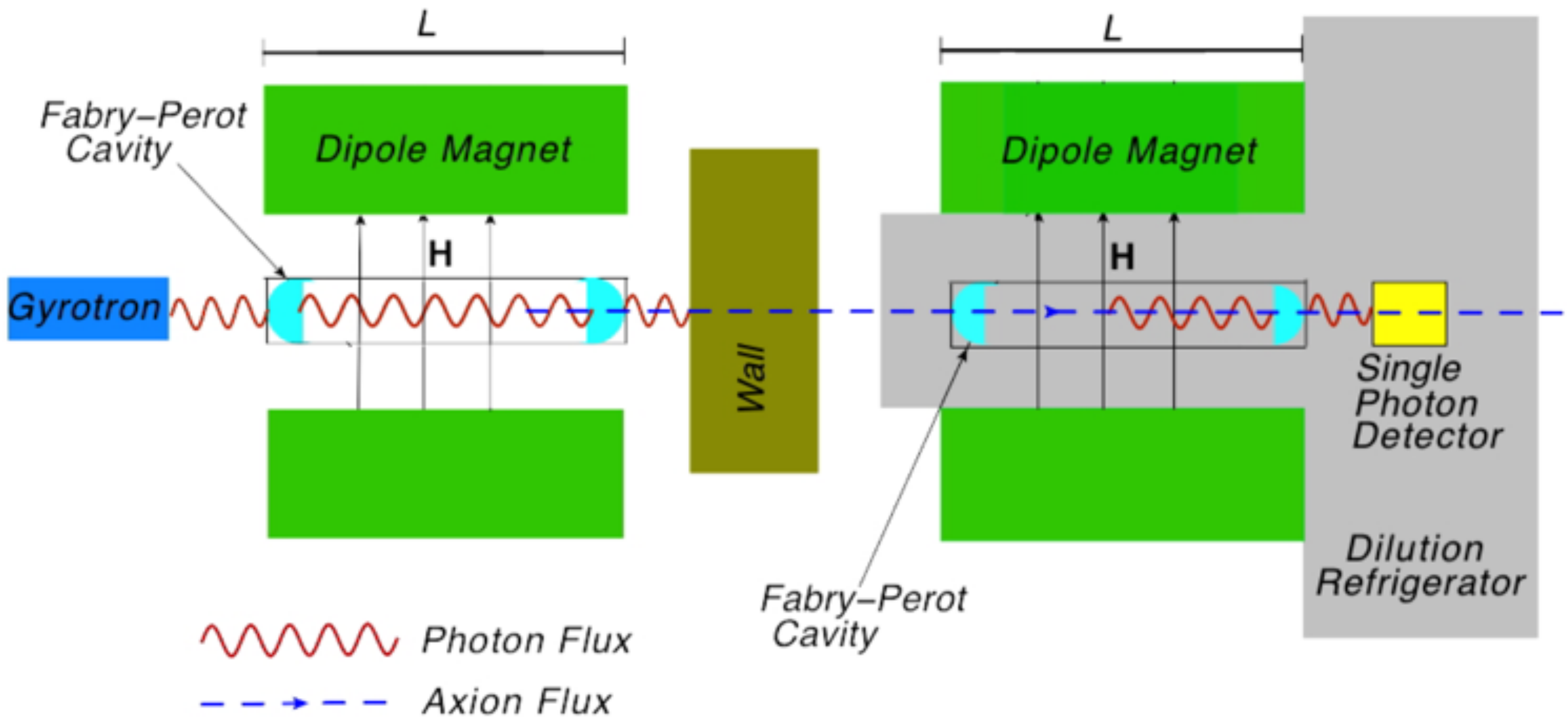


CW highly desired.

30 GHz
= 20 μeV



STAX scheme



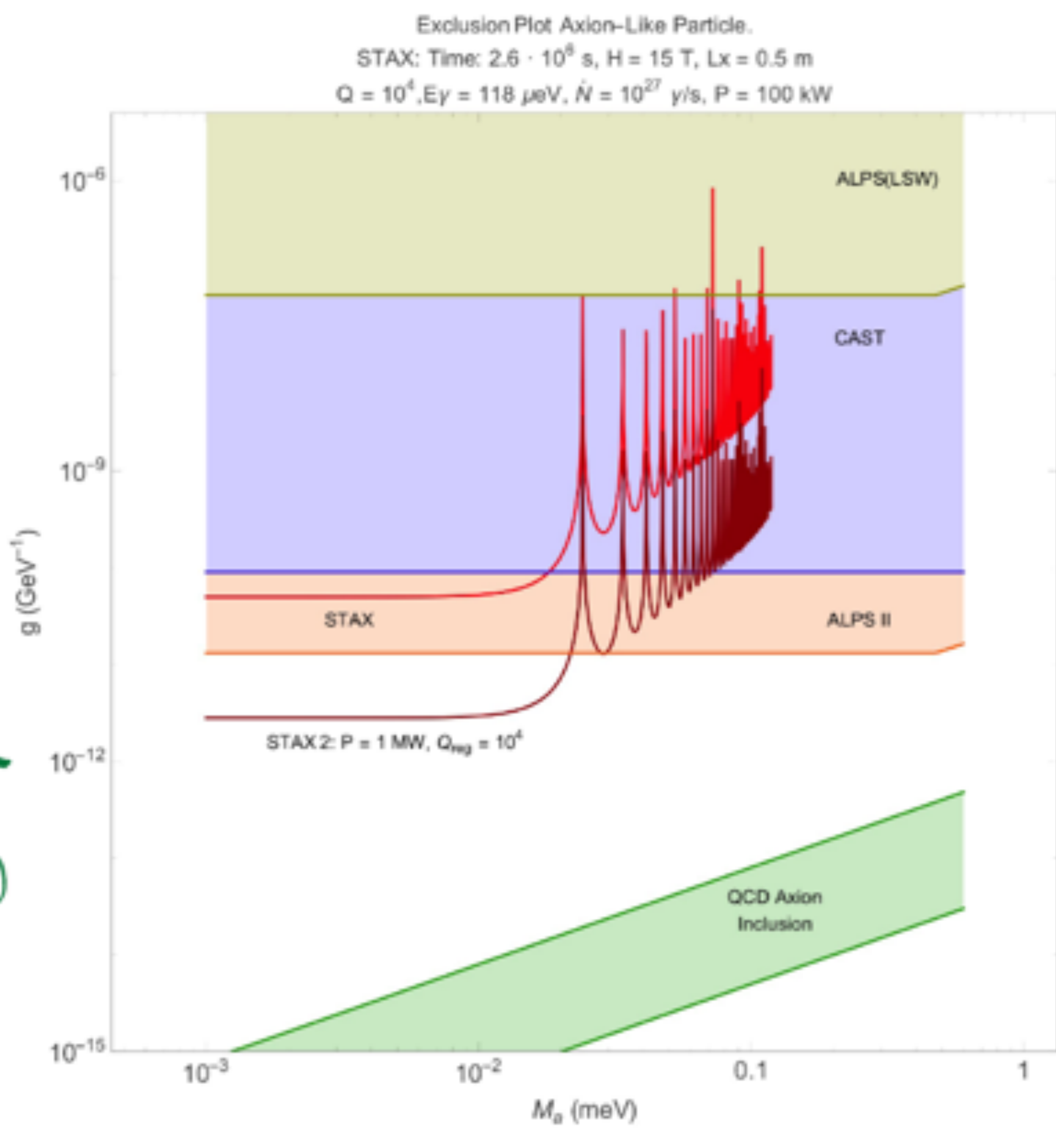
10 mK

100 kW STAX I ($\dot{N}_\gamma = 10^{27}\ \gamma/s$)
1 MW STAX II

POTENTIAL REACH

$$P = G^2 H^2 \frac{\sin^2(qL/2)}{q^2} \frac{E_\gamma}{1/L + \sqrt{E_\gamma^2 - m_a^2}}$$

$$q = E_\gamma - \sqrt{E_\gamma^2 - m_a^2} - 1/2L$$



IAXO ($m_a \lesssim 0.02$ meV)

↑ 20 μeV

EXCLUSION @ 90% CL

IN CASE OF A NULL RESULT FOR AXIONS $m_a \lesssim 0.02$ meV

ONE MONTH EXPOSURE AND ZERO DARK COUNTS

STAX @ 100 kW

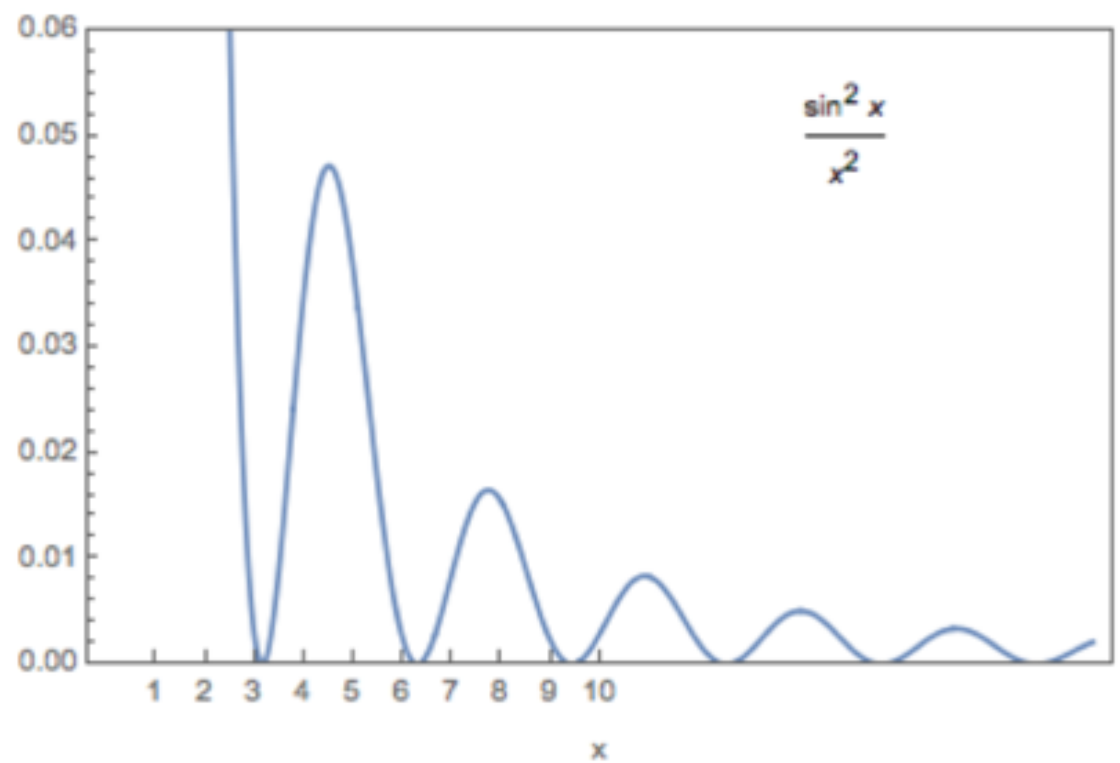
STAX2 @ 1 MW + REG. Q.

L. CAPPARELLI et al. PHYS. DARK. UNIV. 12 (2016) 37

OSCILLATIONS

$$\frac{\sin^2 qL/2}{q^2} = \frac{L^2}{4}\,\frac{\sin^2 x}{x^2}\,, \quad L = 50\,\mathrm{cm}$$

SEARCH: $m_a = 0.01\,\mathrm{meV}$



$\mathcal{E}_\gamma$	q	x
$20\,\mu\mathrm{eV}$	$2.5\,\mu\mathrm{eV}$	3
$1\,\mathrm{eV}$	$5\times10^{-5}\,\mu\mathrm{eV}$	10^{-4}

OSCILLATIONS

Occur when $qL \ll 1$ fails.

$(E_\gamma \gg m_a)$ $$q \simeq \frac{m_a^2}{2E_\gamma} \longrightarrow \frac{(m_a - m_\gamma^*)^2}{2E_\gamma}$$

Shifts the onset of oscillations to higher m_a values.

Example (CAST)

Introduce He gas in the cavity, γ will have an effective velocity $c/n(\omega) = |\vec{k}|/E_\gamma$

$\Rightarrow m^* > 0$. N.B. CAST uses X-rays.

FABRY-PEROT CAVITIES

$$P \sim (GH)^4 \cdot L^2 \cdot L^2$$

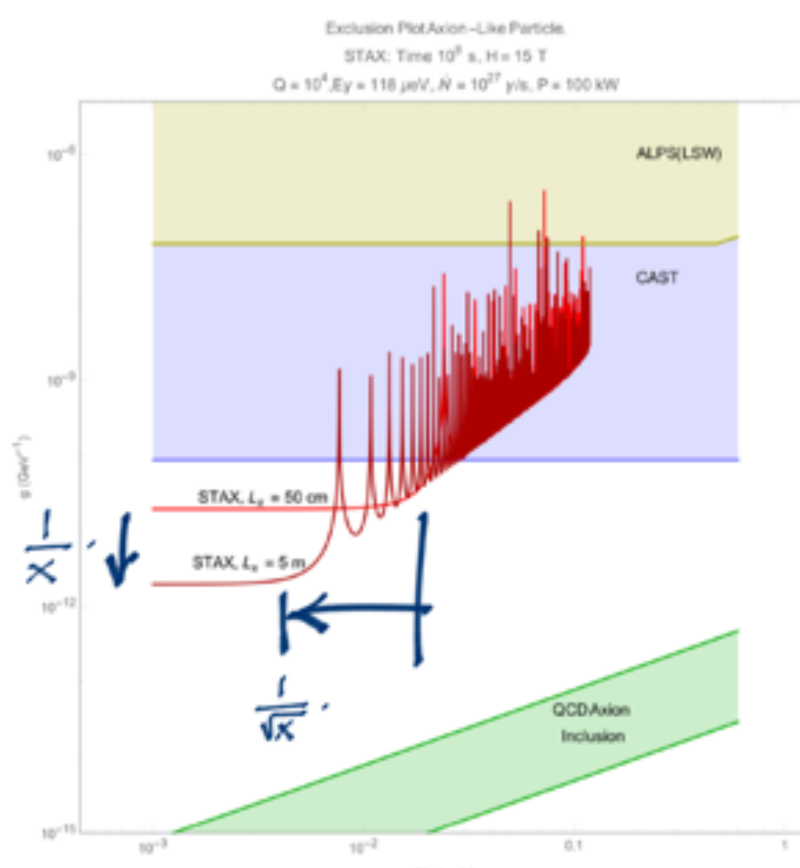
$$\downarrow$$

$$QL^2 \quad (Q \sim 10^5 \text{ in MW})$$

THIS ALLOWS TO EXPLORE G-VALUES SMALLER BY $Q^{-1/4}$

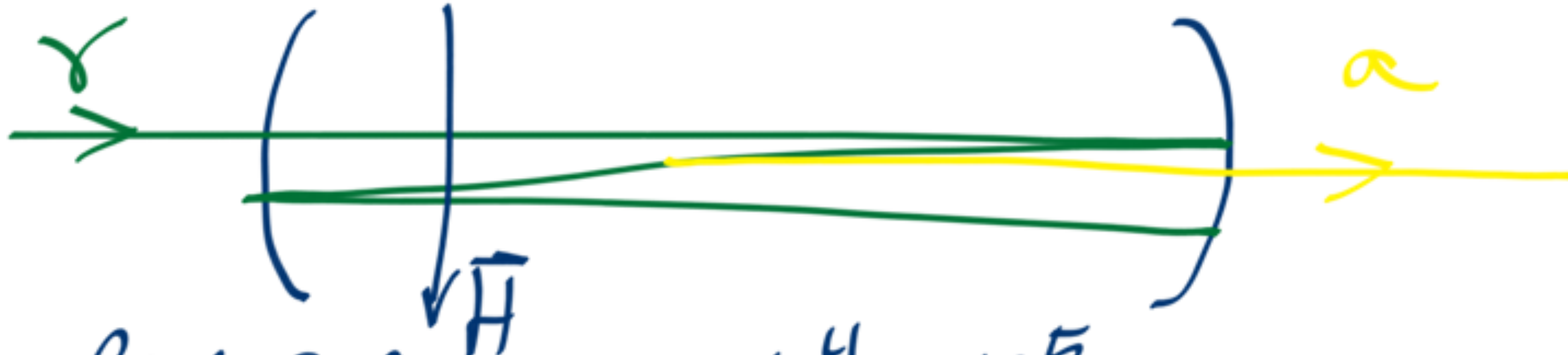
Someone suggests $Q^{-1/2}$ by setting a 'regeneration' cavity.

MAKING L LONGER MEANS THAT THE ONSET OF OSCILLATIONS SHIFTS TO SMALLER VALUES BY $1/\sqrt{x}$ IF $L \to xL$



Some Numbers

Improvements are possible w/ FP cavities



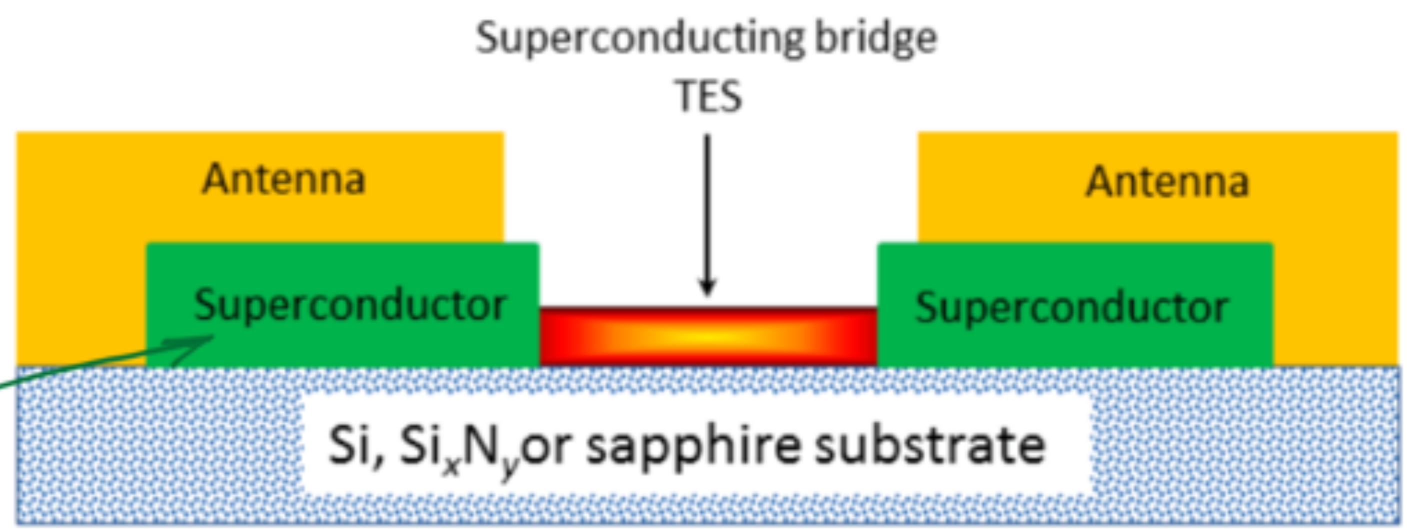
very high Q for mw. ~ $10^4 \div 10^5$

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			~ 10^4		~ $8x10^5$

30 GHz γ-DETECTION

1. SINGLE-γ detection ← CRYOGENIC (10 mK)
2. MW screening
3. ...

⋮



- $T_c < 20$ mK
- α-W, Ti-Au, Ti-Cu
- $V \sim 10^{-3} \div 10^{-4}\ \mu m^3$
- low noise SQUID readout.

TES

TES work @ T slightly below T_c.

$V_{TES} \approx 2 \times 10^{-22}\, m^3$ @ 10 mK

$1\gamma\,(30\,\mathrm{GHz}) \rightarrow \Delta T_e \approx 40\,\mathrm{mK}$

Estimate & engineer ΔI –

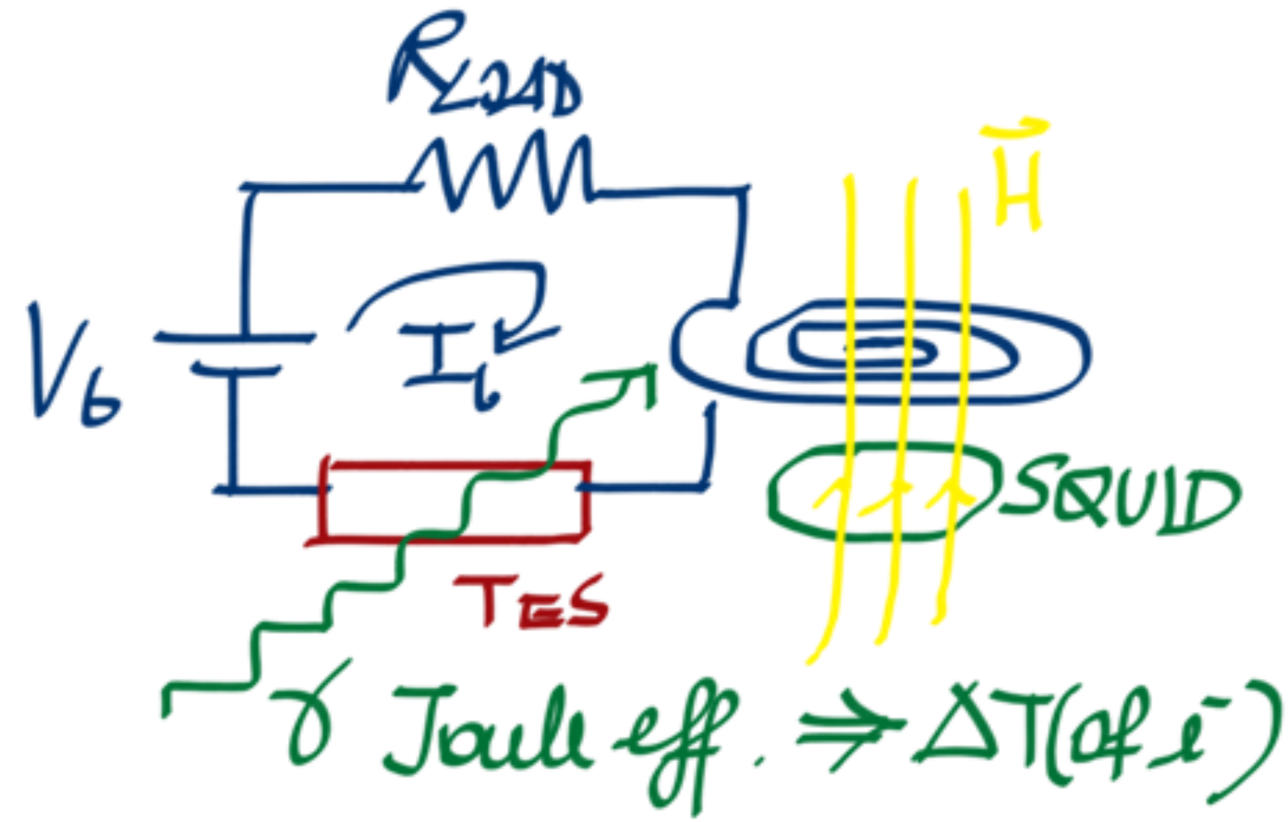
– SQUID SPECTRAL NOISE DENSITY

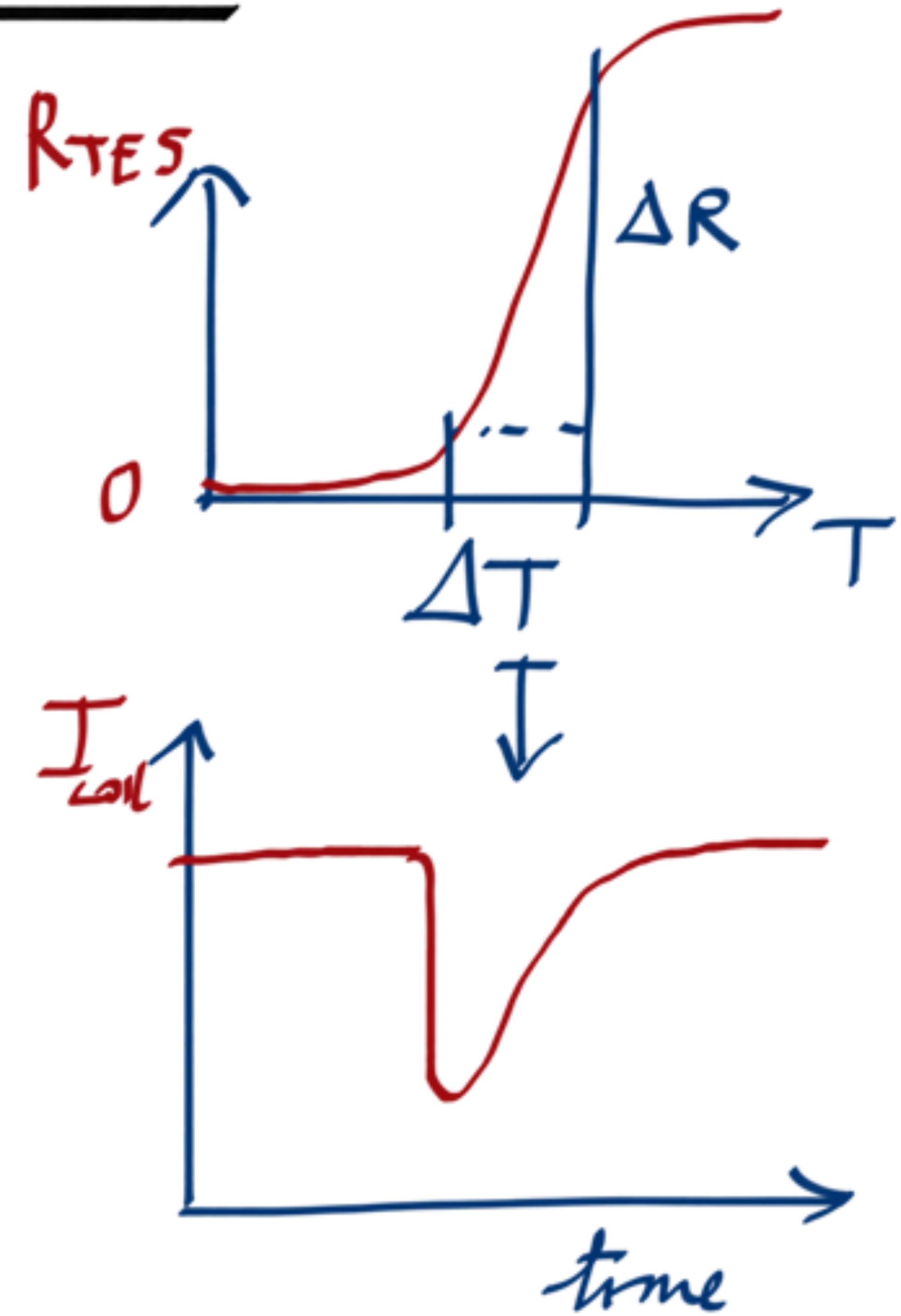
$$\frac{1\,\mathrm{pA}}{\sqrt{\mathrm{Hz}}}$$

– to be multiplied by the det. passband$^{1/2}$

$$\approx \sqrt{100\,\mathrm{Hz}}$$

EYE SCHEME





$\tau(e^- - \phi \ @ \ 10\,mK) \gtrsim 0.1\,sec$

Read a voltage on SQUID

R&D on $\Delta T, \Delta R, \Delta V_{SQUID}$ @ 30 GHz & 10 mK.

SOME NUMBERS

1. $\text{Resolution} = \sigma_E \approx \sqrt{k_B T_c^2 C_e}$

$$C_e \approx \gamma V T_e$$

$$\gamma \simeq 136 \ J/{}^\circ K/m^3$$

V = sensor volume
T_e = electron temp. } to be decreased to decrease σ_E

$V = 300 \times 40 \times 20 \ nm^3$ & $\alpha - W$ $\rightarrow \sigma_E \approx 560 \ MHz$

2. At 10mK, blackbody peaks at 0.6 GHz

$$P \sim 10^{-52} \ W/m^2$$

3. Cosmic $\mu^\pm$ release about 10 eV in 10 nm

$\Rightarrow$ drastically increase detector temp. which takes τ_d to go back to 10 mK. We estimate

$$\tau_d \ll \tau_{\mu-\mu}$$

STAX PROPOSAL

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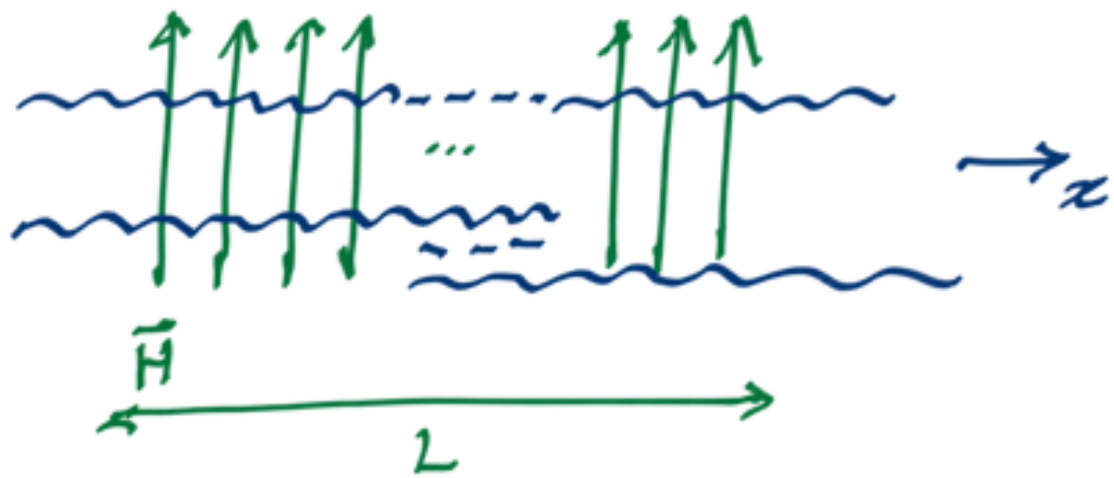
APPENDIX



$$\Sigma \sim G^2 H^2 \mathcal{E}_\gamma^2 \int dq \; \frac{\sin^2(qL/2)}{q^2(p^2 - m_a^2 + i\epsilon)}$$

$$(p^2 - m_a^2 + i\epsilon) = -(q-(q_1+i\epsilon))(q-(q_2-i\epsilon))$$

$$q_1 = \mathcal{E}_\gamma + p^* \qquad i\epsilon \leftarrow i\epsilon p^* - \epsilon^2$$

$$q_2 = \mathcal{E}_\gamma - p^*$$

$$p^* = \sqrt{\mathcal{E}_\gamma^2 - m_a^2} > 0$$

Do integral in the complex plane, take it's 'Im' part and get the standard formule

APPENDIX

$$P = G^2 H^2 \frac{\mathcal{E}_\gamma}{\sqrt{\mathcal{E}_\gamma^2 - m_a^2}} \left(\frac{\sin^2(q_2 L/2)}{q_2^2} + (2 \to 1) \right)$$

$$\frac{\lambda_a}{2} < L \Rightarrow |p| > \frac{1}{2L}$$

FWD a's $\quad q < \mathcal{E}_\gamma - \frac{1}{2L}$

from $p = k - q$

BKWD a's $\quad q > \mathcal{E}_\gamma + \frac{1}{2L}$

Since $q_1 > q_2$

$$q_2 \lesssim m_a - \frac{1}{2L}$$

$$q_1 \gtrsim m_a + \frac{1}{2L}$$

$$\min(q_1 - q_2) = \frac{1}{L}$$

Going back to the contour integral evaluation we find that this condition translates into an upper bound for the P

$$P_{max} = G^2 H^2 \frac{\sin^2(qL/2)}{q^2} \frac{m_a}{1/L}$$

APPENDIX

$$\frac{\partial}{\partial L}\int dq\, \frac{\sin^2(qL/2)}{q^2(p^2-m_a^2+i\epsilon)} = \frac{1}{2}\int dq\, \frac{\sin qL}{q(p^2-m_a^2+i\epsilon)}$$

$$= -\frac{1}{2}\int dq\, \frac{\sin qL}{q(q-(q_1+i\epsilon))(q-(q_2-i\epsilon))}$$

$$= -\frac{1}{2}\left(\frac{\pi}{q_1 q_2} + \frac{\pi}{q_1-q_2}\left(\frac{e^{iLq_1}}{q_1} - \frac{e^{-iLq_2}}{q_2}\right)\right)$$