INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION

INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
34100 TRIESTE (ITALY) - P.O.B. 586 - MIRAMARE - STRADA COSTIERA 11 - TELEPHONE: 2240-1
CABLE: CENTRATOM - TELEX 460392 - 1

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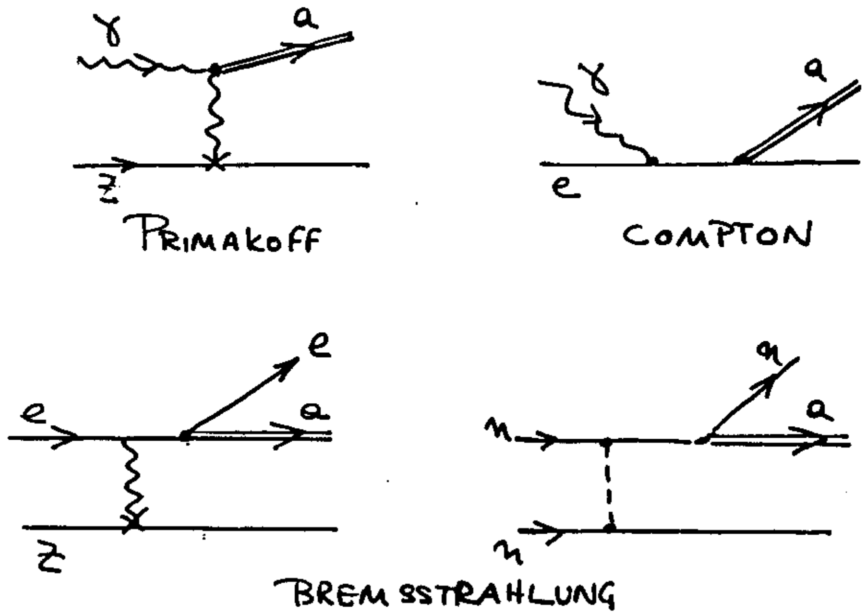
SCHOOL ON
NON-ACCELERATOR PHYSICS
25 April - 6 May 1988

DARK MATTER AND RELATED EXPERIMENTS (2)

by

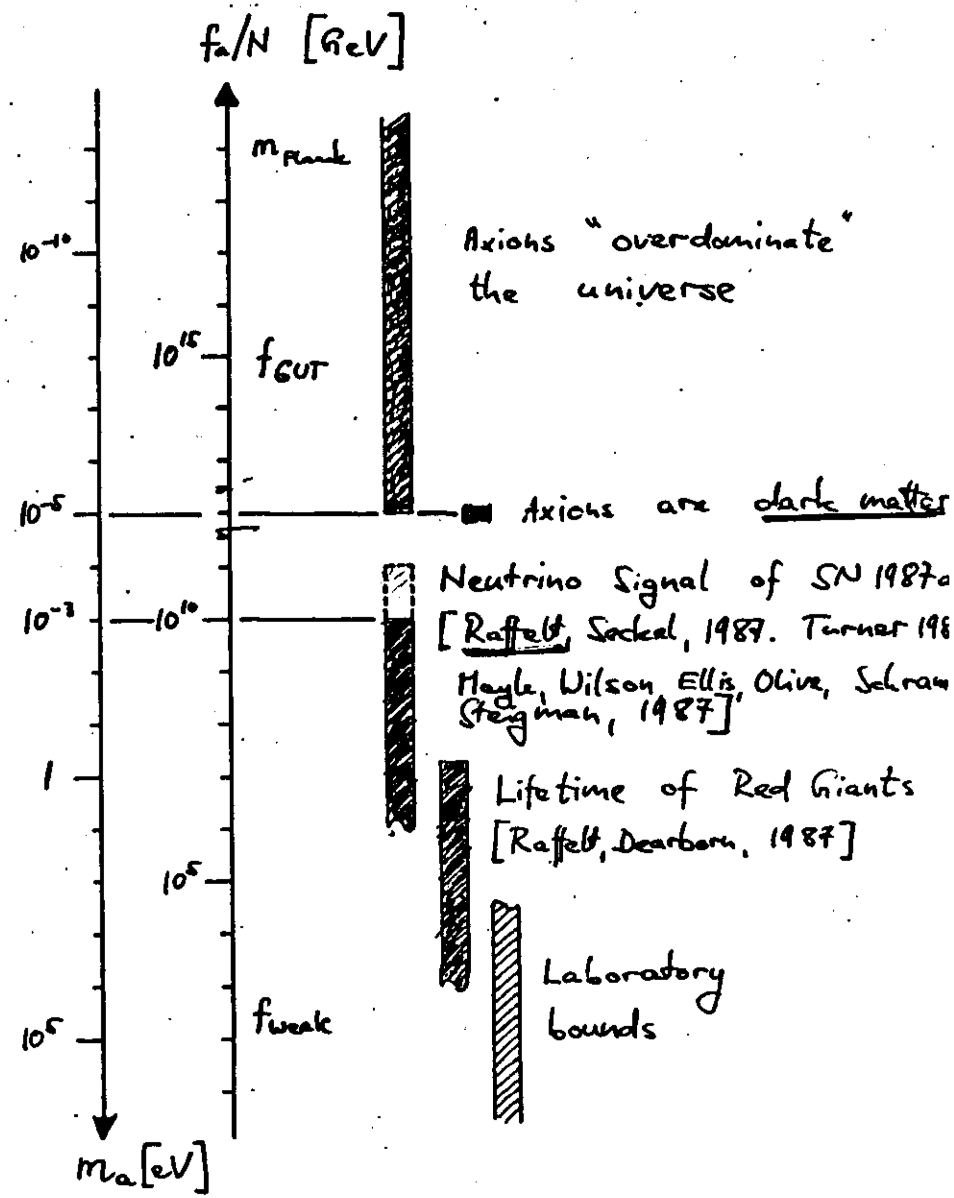
A. Melissinos
University of Rochester
U. S. A

CAN THE INVISIBLE AXION HAVE ESCAPED DETECTION?



- AXIONS PRODUCED IN THE INTERIOR OF STARS WILL ESCAPE — INCREASE COOLING RATE
- STRONG MAGNETIC FIELDS IN PULSARS
- INTERACTION OF AXIONS WITH BACKGROUND FIELD
  - COULD LEAD TO MONOCHROMATIC γ's
- LIFETIME $\tau \sim 10^{40}$ yrs

Summary of axion ...

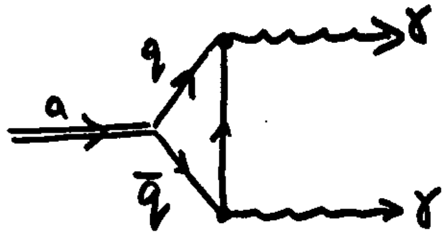


INVISIBLE AXION [D.F.S & others]

HIGGS DOUBLET $f_a \to 10^{12}$

$$m_a = 0.6 \times 10^{-5}\,\mathrm{eV}\left[\frac{10^{12}\,\mathrm{GeV}}{f_a}\right]$$

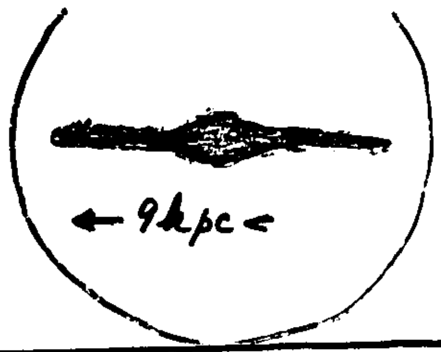
$$g_{a\gamma\gamma} \sim \frac{3}{10^{16}\,\mathrm{GeV}}\left[\frac{10^{12}\,\mathrm{GeV}}{f_a}\right]$$



$$g_{a\gamma\gamma} \sim \frac{\alpha}{4\pi}\frac{1}{f_a}$$

PROPRETIES OF COSMIC AXIONS

Axions Condense into galactic halos



$$\boxed{m_a = 10^{-5}\,\mathrm{eV}\left[\frac{10^{12}}{f_a(\mathrm{GeV})}\right] \qquad \nu = 2.4\ \mathrm{GHz}}$$

$\rho_a \sim 5\times 10^{-25}\ \mathrm{g/cm^3} = 300\ \mathrm{MeV/cm^3}$

$v = \beta c \qquad \beta \sim 10^{-3}$ Galactic virial velocity

$$E_a = m_a\left(1 + \tfrac{1}{2}\beta^2\right)$$

$\Delta E/E \sim \frac{1}{2}\beta^2 \to 10^{-7}$ Narrow line

$$\lambda_{DB} = 2\pi\frac{\hbar}{p} = \frac{\lambda_c}{\beta}$$

for $m_a = 10^{-5}\,\mathrm{eV}$ $\quad \lambda_c \sim 10\ \mathrm{cm}$

$\lambda_{DB} \sim 10^4\ \mathrm{cm}$ Coherence length

SEARCH FOR COSMIC AXIONS

S. DePANFILIS
A. MELISSINOS
B. MOSKOWITZ
J. ROGERS
Y. SEMERTZIDIS
W. WUENSCH

UNIVERSITY OF ROCHESTER

H. HALAMA
A. PRODELL

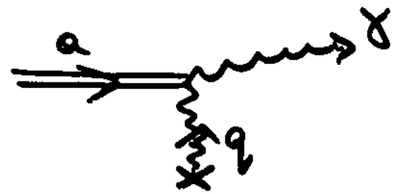
BROOKHAVEN

W. FOWLER
F. NEZRICK

FERMILAB

AXION DETECTION

PRIMAKOFF EFFECT [E. WITTEN, P. SIKIVIE]



$\Delta p \sim m_a$

$E_\gamma = E_a \approx m_a$

— VIRTUAL PHOTONS — FROM STATIC MAGNE[TIC] FIELD B_0

— INTERACTION TERM $(\vec{E}_\gamma \cdot \vec{B}_0)\,\phi_a$

— CAVITY TUNED TO E_γ ENHANCES TRANSI[TION]

— TRANSITION RATE

$$R = g_{a\gamma\gamma}^2\, \hbar c^3 \langle B_0^2 \rangle \frac{Q}{\omega} G_j^2$$

$$P = (\hbar\omega) R\, V \rho_a'$$

G_j^2 = filling factor
ρ_a' = number densit[y]

$$\boxed{P = \frac{g_{a\gamma\gamma}^2}{m_a^2} (\hbar c)^3 \langle B_0^2 \rangle V Q \omega \langle \rho_a \rangle G_j^2}$$

Note: $[g_{a\gamma\gamma}^2/m_a^2]$ [illegible]

INTERACTION RATE (I)

$$\mathcal{L} = \frac{1}{8\pi}(E^2 - B^2) - \frac{g_{a\gamma\gamma}}{4\pi}\vec{E}\cdot\vec{B}\,\phi_a$$

$$\nabla^2\vec{E} - \frac{1}{c^2}\frac{\partial^2\vec{E}}{\partial t^2} = g_{a\gamma\gamma}\,B_0\,\frac{\partial^2\phi_a}{\partial t^2}$$

Solve in terms of eigenmodes $\vec{e}_j$ of the cavity.

$$U_j = \frac{g_{a\gamma\gamma}^2}{4\pi\epsilon}\,G_j^2\langle B^2\rangle V\int\frac{|\phi_a|^2\omega^4}{(\omega^2-\omega_j^2)^2+\omega^4/Q^2}\,\frac{d\omega}{2\pi}$$

G_j^2 = Dimensionless filling factor

When ϕ_a is narrower than cavity width

$Q_a > Q$ $\qquad\qquad$ $\omega_j = \omega_0$

$$U_j = \frac{g_{a\gamma\gamma}^2}{4\pi m_a^2}\,G_j^2\langle B^2\rangle V Q^2\langle\rho\rangle$$

$$\langle\rho\rangle = m_a^2\langle\phi_a^2\rangle = 5\times10^{-25}\ g/cm^3$$

$$\boxed{P = \frac{U\omega}{Q} = \frac{g_{a\gamma\gamma}^2}{4\pi m_a^2}\,G_j^2\langle B^2\rangle V Q\omega\langle\rho_a\rangle}$$

independent of f_a !

INTERACTION RATE (II)

$$S_{fi} = \langle f|\int 4g\,\phi_a\,\frac{\partial\vec{A}}{\partial t}\cdot\vec{B}(x)\,d^3x\,dt\,|i\rangle$$

Replace $\vec{B}(x)$ by $\vec{B}_0$

$\phi_a(\vec{x},t)$ Classical field

$\vec{A}(\vec{x},t)$ Quantized field

$$S_{fi} \rightarrow \sum_n 2\pi\,\delta(\omega_k-\omega_n)\int d^3x\,\vec{\epsilon}^{\,*}(\vec{k},\lambda)\cdot\vec{B}(\vec{x})\,\phi_n(\vec{x})\,e^{-i\vec{k}\cdot\vec{x}}$$

$$R = \frac{d}{dt}\int dE\,|S_{fi}|^2\,\frac{dN}{dE}$$

In cavity $\quad \dfrac{dN}{dE} = \dfrac{1}{\Delta E} = \dfrac{1}{\hbar\omega/Q} = \dfrac{Q}{\hbar\omega}$

$$R = g^2\hbar c^3\langle B^2\rangle G^2\frac{Q}{\omega}$$

$$P = (\hbar\omega)R(\rho_a' V) \qquad \rho_a' = \text{number density}$$

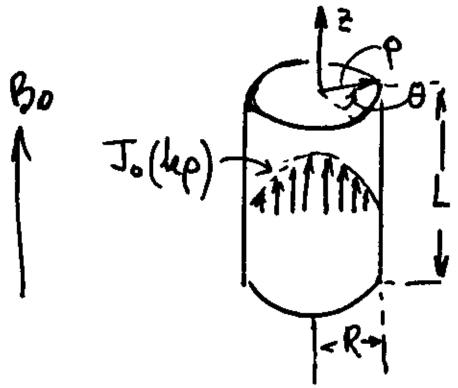
$$\boxed{P = \frac{g^2}{m_a^2}(\hbar c)^3 G^2\langle B^2\rangle V Q\omega\langle\rho_a\rangle}$$

as before

BECAUSE

$$\mathcal{L}_{int} = \vec{E}\cdot\vec{B}\,\phi_a$$

$\vec{E}$ [OF CONVERTED PHOTON INSIDE CAVITY] <u>MUST BE</u> // TO B_0



$\downarrow$

CAVITY MODES

TM_{0n0} ← No θ-depend.

No z-dependence

ρ-dependence $n=1$ $kR = x_{01}$

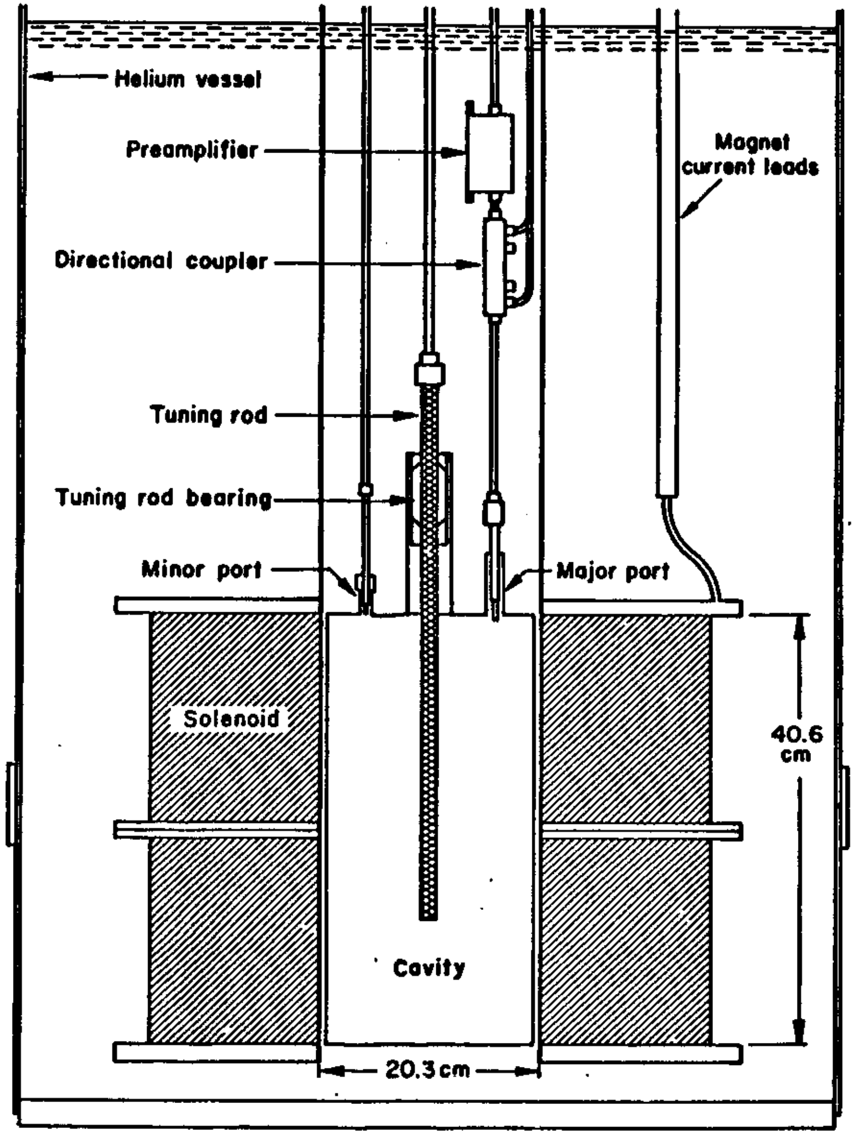
HOW TO TUNE CAVITY?

VARY "RADIUS" BY INSERTING <u>DIELECTRIC</u>

FOR
$B = 5\,T$
$V = 10^4\,cm^3$ $\rho = 300\ MeV/cm^3$
$Q_0 = 10^5$ TM_{010}
$m_a = 1\ GHz$

$$P = 2.2\times10^{-24}\ W$$ VERY SMALL!!

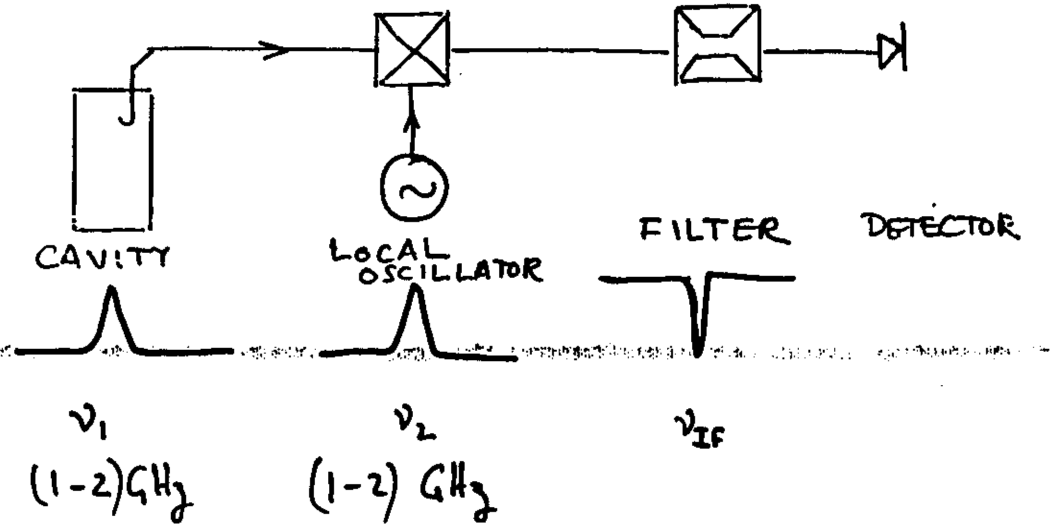
$R = 10^{-17}/sec$



DETECTION PRINCIPLE

HETERODYNE — AS IN RADIO

BUT ANTENNA IS VERY NARROW TUNED



WE MUST SATISFY

$$\nu_1 - \nu_2 = \nu_{IF} \pm \Delta\nu_{IF}$$

50 ± 0.25 kHz

L.O MUST "TRACK" CAVITY
TO 1 PART/10^7

RECALL ν_1, ν_2 are $f(t)$

CAVITY & L.O. MUST BE IN TUNE
AND SWEPT

L.O →

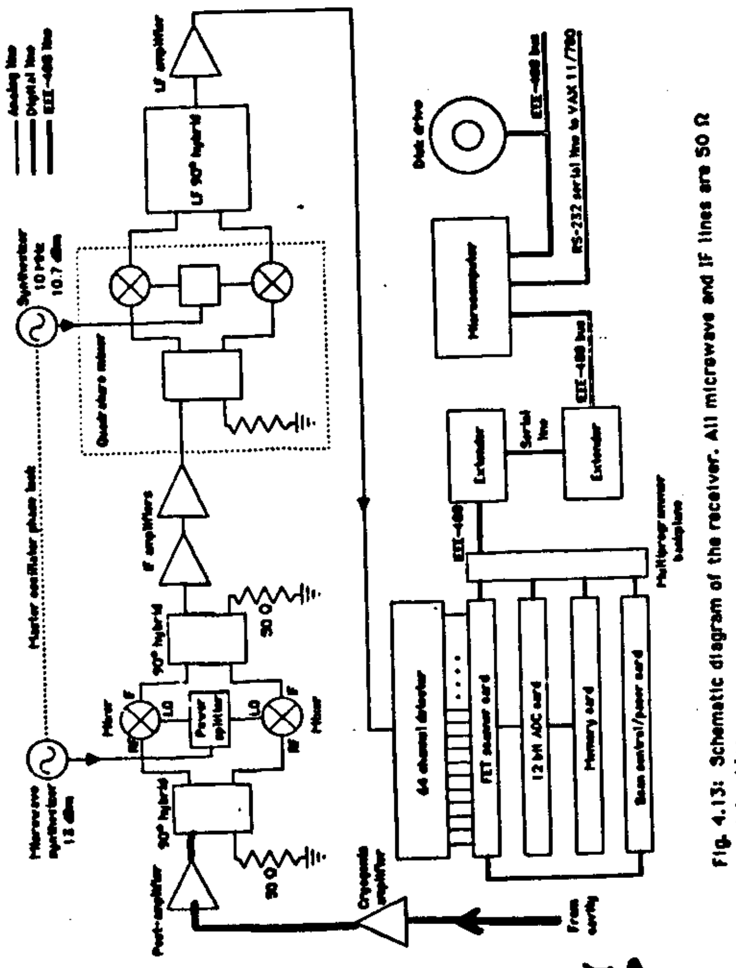
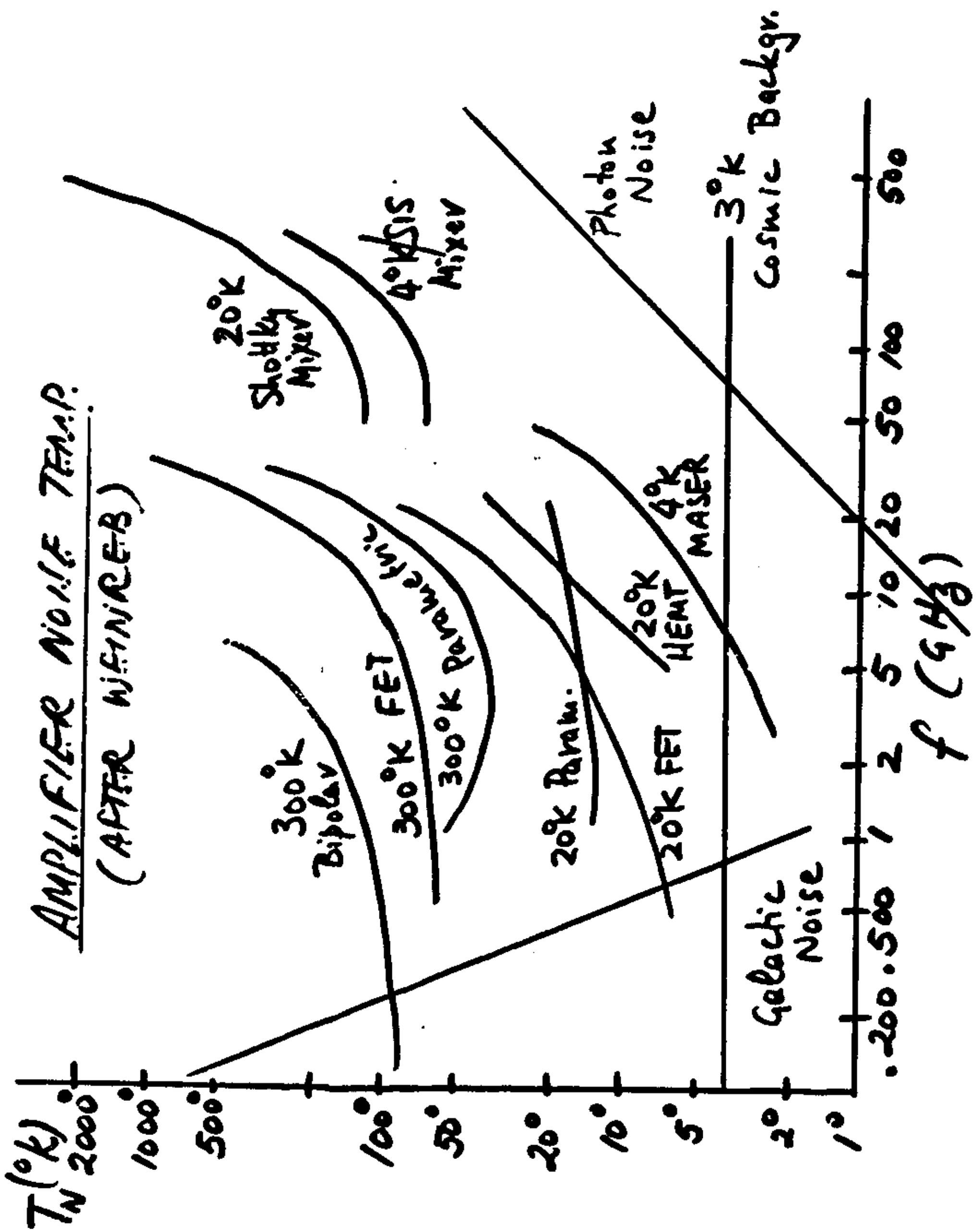


Fig. 4.13: Schematic diagram of the receiver. All microwave and IF lines are 50 Ω coaxial cables.

CAVITY ↑



SIGNAL POWER

CAVITY: $R = 9.5$ cm $\quad L = 50$ cm

$\nu = 1.2$ GHz $\quad$ Mode TM_{010}

$Q_0 = 3 \times 10^5 \leftarrow$

FIELD: $\langle B_0 \rangle = 5$ T

AXION DENSITY: $\rho_a = 5 \times 10^{-25}$ g/cm^3 $[10^{13}$ axions/cm$^3]$

$$\boxed{P_a = 0.2 \times 10^{-23} \left[\frac{\nu_0}{1\ \text{GHz}} \right] \text{Watts}}$$

NOISE POWER $\quad P_N = k T_N (BW)$

k = Boltzmann constant

T_N = Noise temperature $= 8°$ K

BW = Bandwidth $= \nu_0 \left(\frac{\Delta E}{E} \right) \simeq 100$ Hz

$$\boxed{P_N \sim 10^{-20} \text{ Watts}}$$

SIGNAL TO NOISE & SWEEP RATE

SIGNAL TO NOISE (SNR)

$$r = \frac{P_a}{\Delta P_N} \qquad \left(\text{Not: } \frac{P_a}{P_N}\right)$$

$$\Delta P_N = \frac{P_N}{\sqrt{N}} \qquad P_N = kT_N \Delta f$$

Δf = channel width (Hz)

$$N = \frac{\Delta t}{\tau} m$$

Δt = time on channel $= \dfrac{\Delta f}{d\nu/dt}$

$d\nu/dt$ = sweep rate

τ = time for 1 measurement $\quad \tau = 1/\Delta\omega \rightarrow 1/\Delta f$

m = multiplexer channels

$$\therefore \quad \Delta P_N = \frac{kT_N \Delta f}{\sqrt{(\Delta f)^2 m/(d\nu/dt)}} = kT_N \sqrt{\frac{d\nu/dt}{m}}$$

$$r = \left(\frac{P_a}{kT_N}\right) \sqrt{\frac{m}{(d\nu/dt)}}$$

Solve for $(d\nu/dt)$

$$\boxed{\frac{d\nu}{dt} = \frac{m}{r^2} \left[\frac{P_a}{kT_N}\right]^2}$$

SENSITIVITY

Choose $\quad d\nu/dt = 400$ Hz/sec

Efficiency $\quad \epsilon = 0.5$

Make sweep twice

IN 2 YEARS

$$\Delta\nu = (6\times10^7 s) \times \frac{1}{2} \times 0.5 \times 400 \frac{Hz}{s} = 6\ GHz$$

— FIND P_a LEVEL

$m = 64$

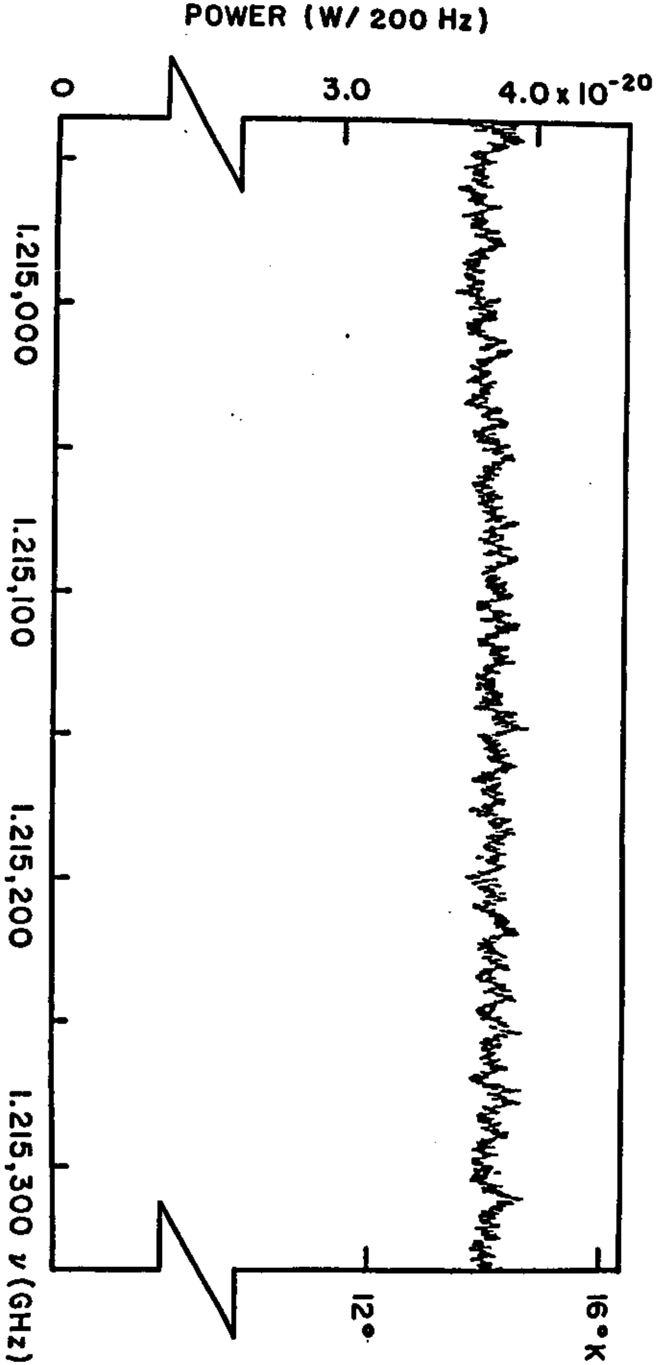
$r = 4$ $\quad [k = 1.4\times10^{-23}\ J/°K]$

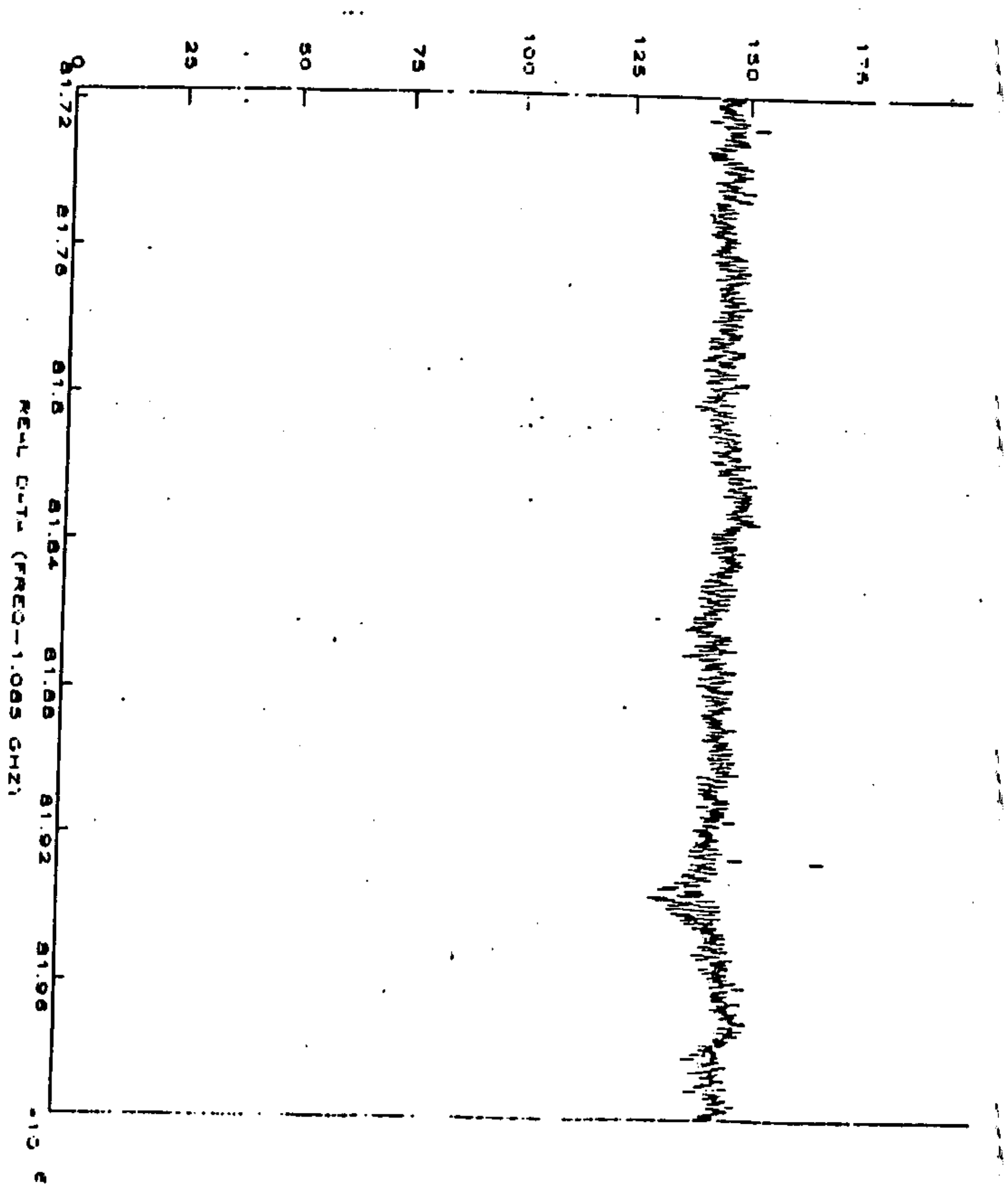
$T_N = 20°K$

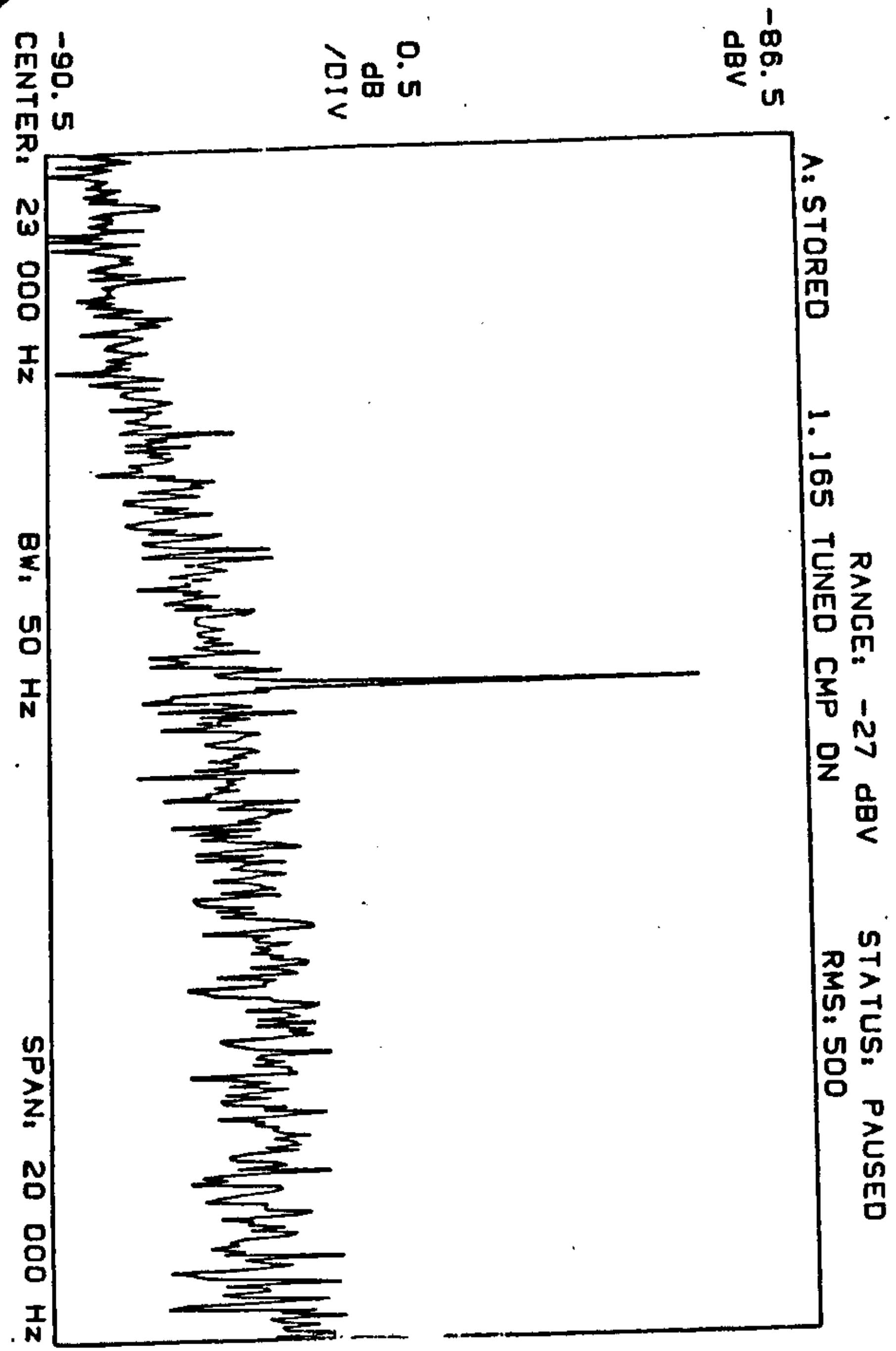
$$\frac{P_a}{kT_N} = \frac{r}{\sqrt{m}} \sqrt{\frac{d\nu}{dt}} = \frac{4}{8} 20$$ [illegible]

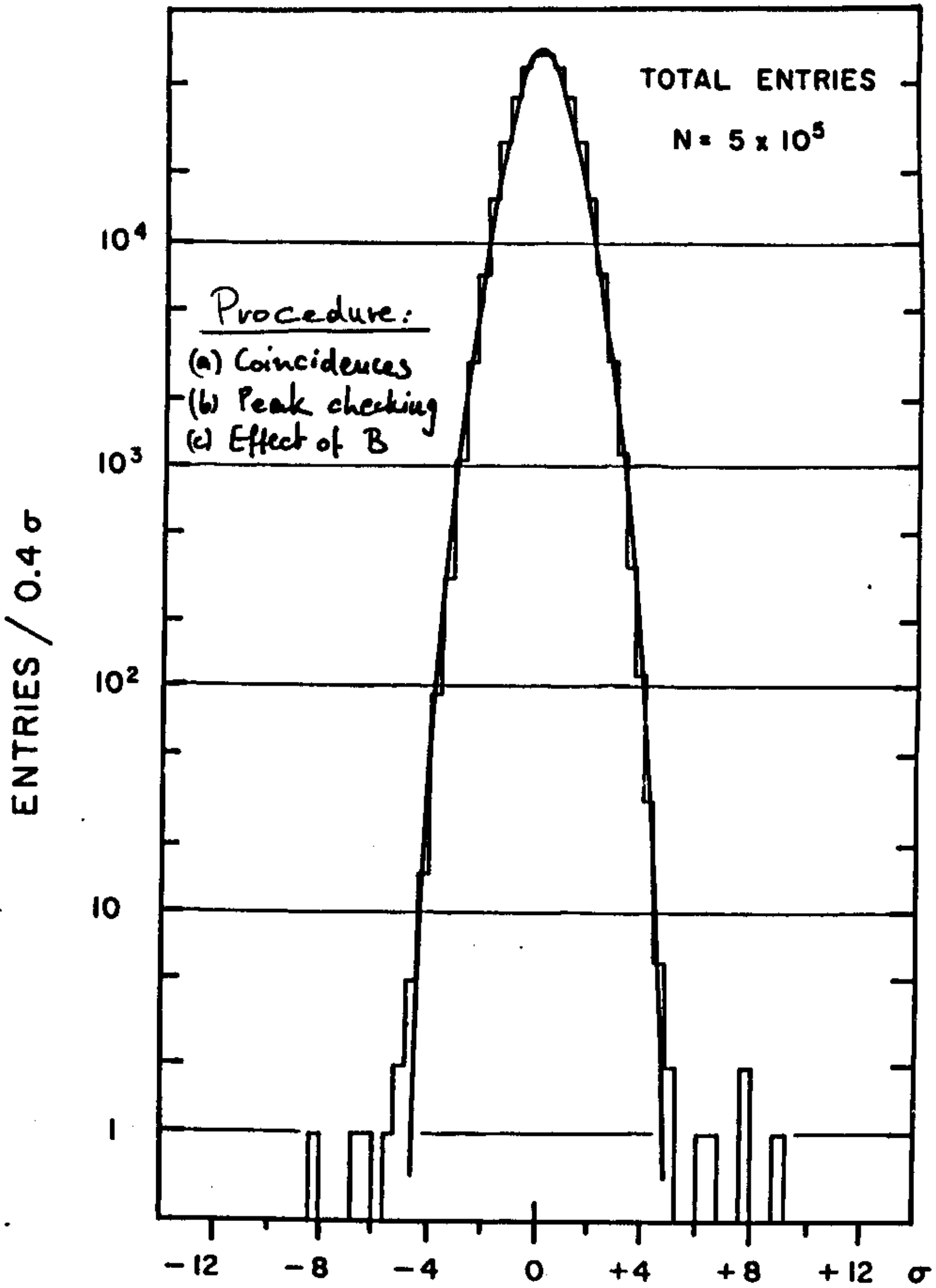
$$\therefore \quad P_a = 3\times10^{-22}\ W$$

But signal was $P_s = 2\times10^{-24}$ W !


POWER (W/ 200 Hz)
0
3.0
4.0 x 10^-20
1.215,000
1.215,100
1.215,200
1.215,300 ν (GHz)
12°
16°K


0
25
50
75
100
125
150
175
81.72
81.76
81.8
81.84
81.88
81.92
81.96


-86.5
dBV
0.5
dB
/DIV
-90.5
CENTER: 23 000 Hz
BW: 50 Hz
SPAN: 20 000 Hz
A: STORED
1.165 TUNED CMP ON
RANGE: -27 dBV
STATUS: PAUSED
RMS: 500

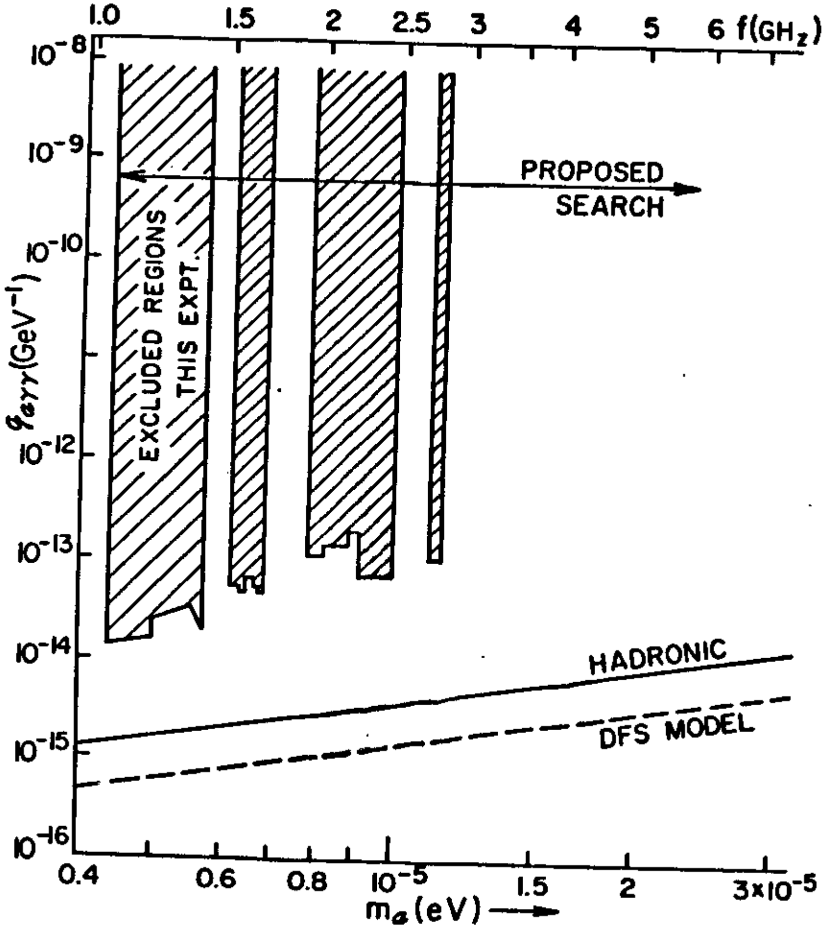

TOTAL ENTRIES
N = 5 x 10^5
Procedure:
(a) Coincidences
(b) Peak checking
(c) Effect of B
ENTRIES / 0.4 σ
10^4
10^3
10^2
10
1
-12
-8
-4
0
+4
+8
+12
σ

COSMIC AXION SEARCH

ROCHESTER-BNL-FERMILAB

COUPLING LIMITS ASSUMING TURNER DENSITY

UPDATED 4/88



CONTINUOUS AXION SPECTRUM

Assume $\frac{d\rho}{d\nu}$ where $\int \frac{d\rho}{d\nu}\, d\nu = \rho_a = 300 \frac{\text{keV}}{\text{cm}^3}$

Questions: (1) Where is $\frac{d\rho}{d\nu}$ centered?

(2) How wide in ν is $\frac{d\rho}{d\nu}$?

Example: $I(\nu)d\nu = \frac{8\pi h \nu^3}{c^3}\frac{1}{e^{h\nu/kT}-1}\, d\nu$

$h\nu_{max} = kT$ $\quad\Delta\nu \sim \nu$

∴ Assume: $\nu_{max} \sim 1$ GHz

$\Delta\nu \sim \nu \sim 1$ GHz

OBSERVE $\frac{\Delta P \text{ (Magnet on-off)}}{P} \lesssim 10^{-2}$

$\rightarrow \Delta P < 6\times10^{-22}$ W/200 Hz

$\frac{d\rho}{d\nu} \sim 6\times10^{-5}$ MeV/200 Hz-cm^3

$$g_{a\gamma\gamma} \lesssim 10^{-8} \text{ GeV}^{-1}$$

Notes: (1) Axions are now relativistic (∴ No condensation)

(2) Effect of magnetic field on electronics

PRODUCE AXIONS IN CAVITY

PRINCIPLE: FEED R.F. IN CAVITY
OBSERVE INCREASED DISSIPATION
WHEN B ON / B OFF

[SIMILAR TO "MAGNETORESISTANCE"]

MEASURE POWER DISSIPATION BY CHANGE IN Q

$$\frac{\Delta Q}{Q} \sim 10^{-3} \rightarrow \frac{\Delta P}{P} \sim 10^{-3}$$

$$\frac{dN_a}{dt} \left(\frac{\text{axions produced}}{\text{sec}}\right) = N_\gamma \,(\text{photons in cavity}) \cdot R_{\gamma\to a}$$

But $R_{\gamma\to a} = R_{a\to\gamma} = 10^{-17}/\text{sec.}$ ← predicted

$$P_a = \hbar\omega \frac{dN_a}{dt} = \hbar\omega N_\gamma R = U\,[\text{Energy stored}] \cdot R = \Delta P$$

$$P_{lost} = \frac{U\omega}{Q} = P$$

$$10^{-3} > \frac{\Delta P}{P} = \frac{Q}{\omega} R = \frac{6\times10^{4}}{2\pi\times10^{9}} R$$

$$\rightarrow R < 10^{2}/\cancel{\text{sec}} = 10^{19} R_{theory}$$

$$\therefore \quad \boxed{g_{a\gamma\gamma} < 3\times10^{9}\, g_{a\gamma\gamma\ theory} \sim 10^{-6}\ \text{GeV}^{-1}}$$