共鳴管と量子ホール状態の温度上昇；
マイクロ波の吸収で、2次元電子系の温度上昇を観測し共鳴点（アクシオン質量）を探る

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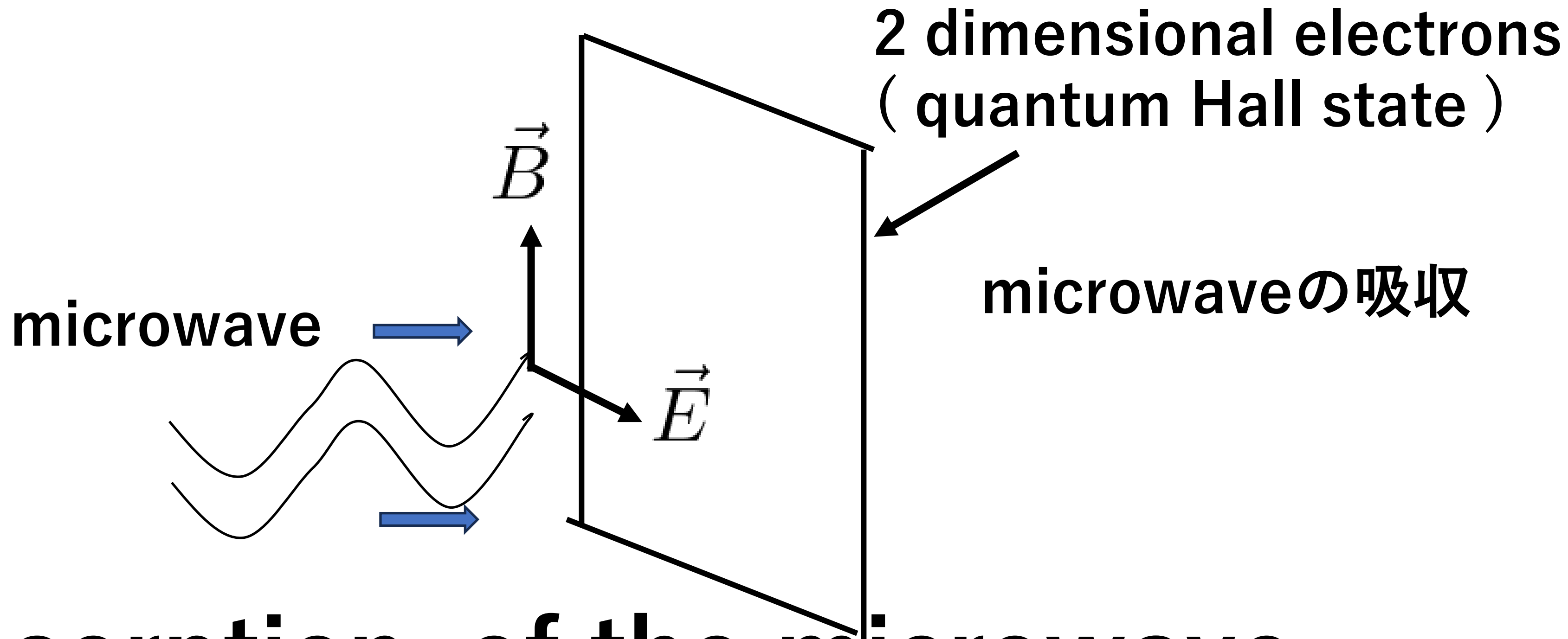
1) Absorption of axion induced microwave by quantum Hall state inside axion Haloscope

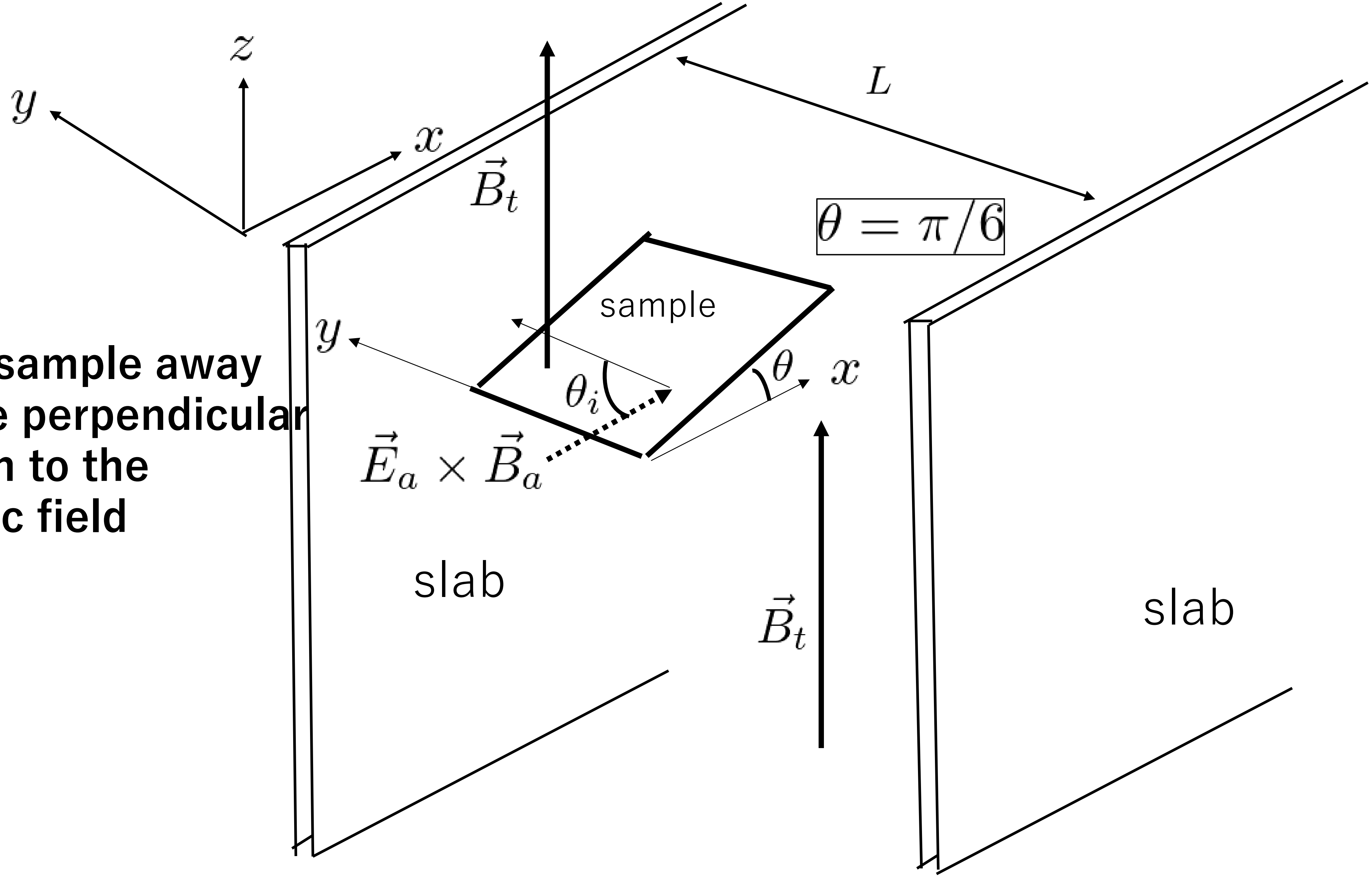


The absorption of the microwave

Increase of temperature $\Delta T \sim 1\mathrm{mK}$ from $T_{in} = 1\mathrm{mK}$

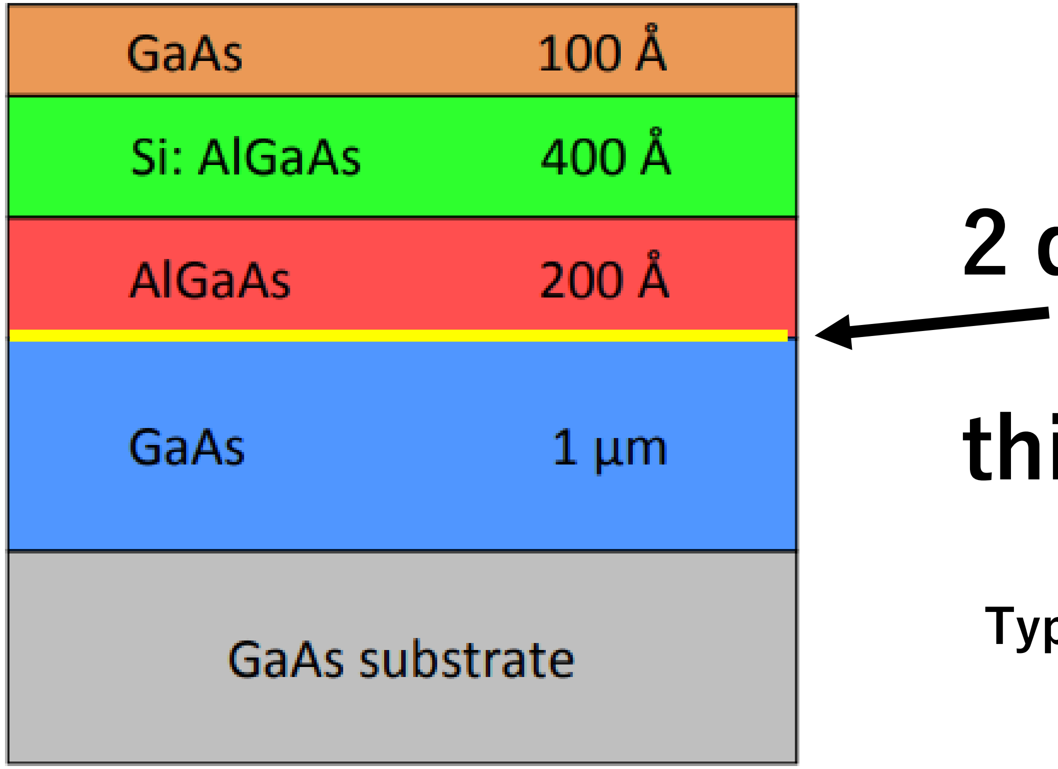
2)

Tilt the sample away from the perpendicular direction to the magnetic field



3)

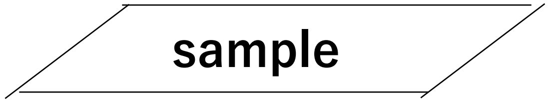
A sample exhibiting quantum Hall effect



2 dimensional electrons

thickness $< 0.01\mu\mathrm{m} = 100\text{Å}$

Typical scale $100\mu\mathrm{m} \times 400\mu\mathrm{m}$



electric permittivity of GaAs $\epsilon \simeq 13$

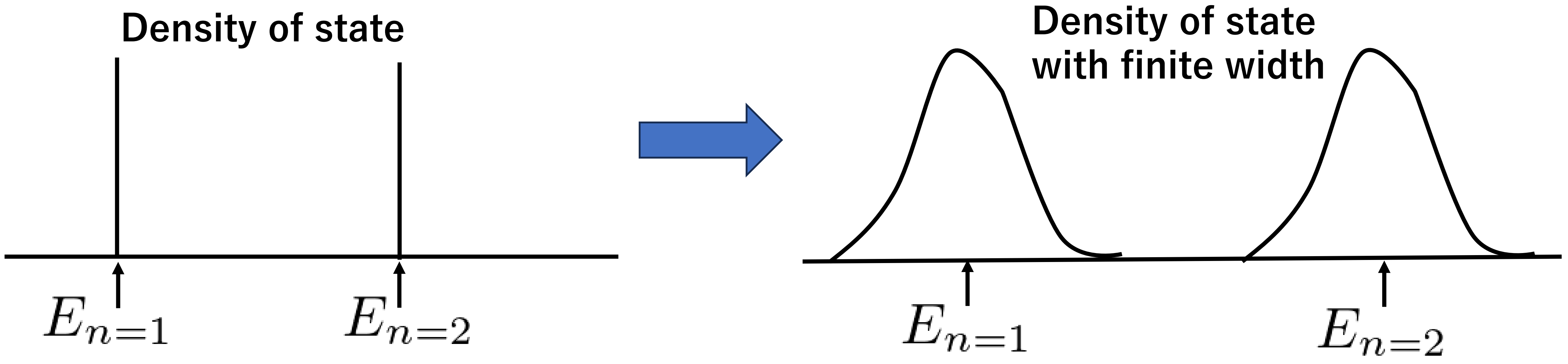
We take into account refraction of microwave in the sample of GaAs

4) Quantum Hall States (2 dimensional electrons)

Electrons form Landau level

Energy $E_n = \omega_c(n + 1/2) : \quad \omega_c = \dfrac{eB}{m_e}$

Effect of disorder potential



$\text{Number of states} \sim 10^{11}/\text{cm}^2 \quad \text{for} \quad \text{B} = 10\text{T}$

5)

Transition by microwave absorption

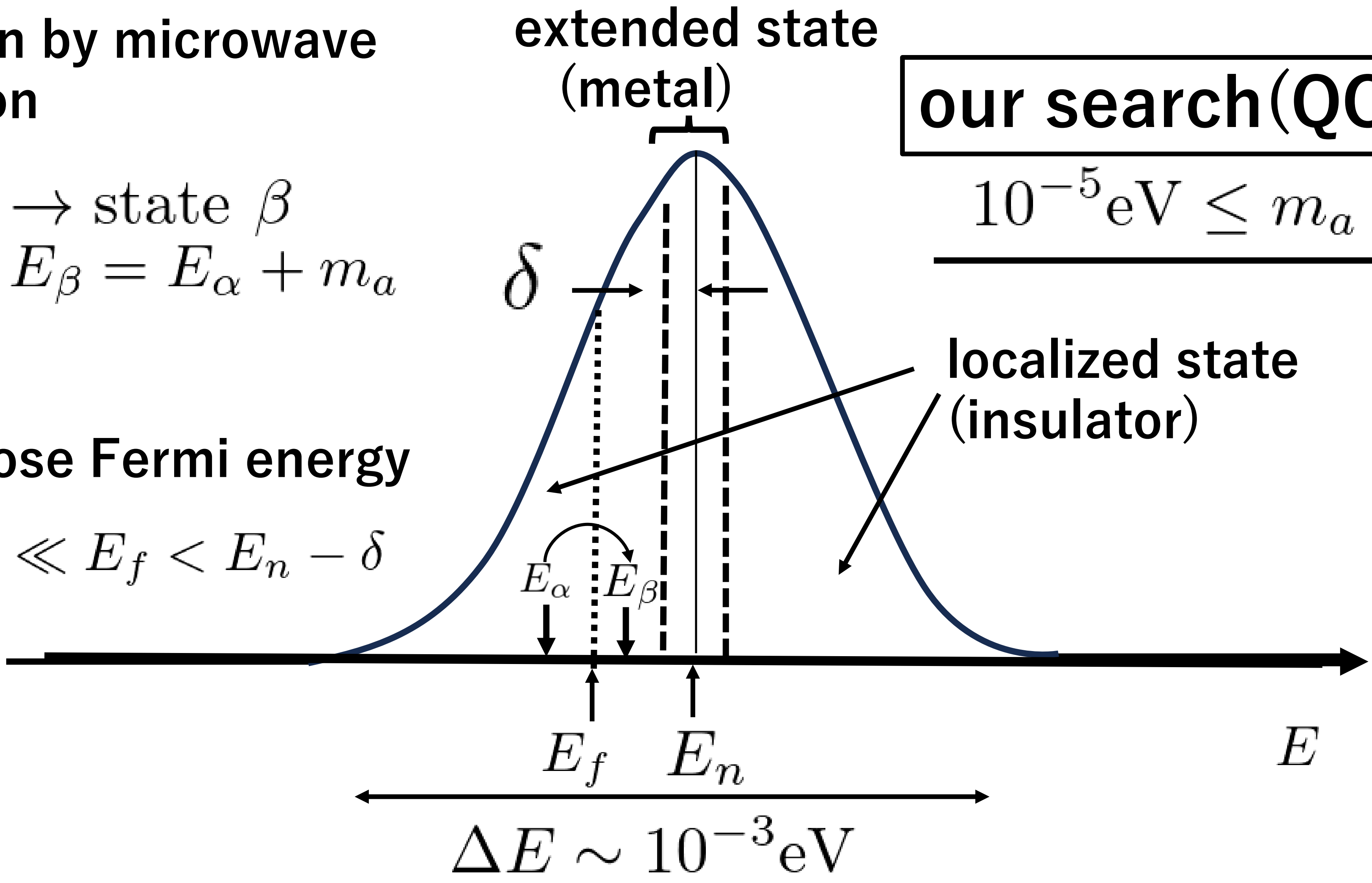
$$\text{state } \alpha \rightarrow \text{state } \beta$$
$$E_\alpha \rightarrow E_\beta = E_\alpha + m_a$$

We suppose Fermi energy

$$E_n - \Delta E \ll E_f < E_n - \delta$$

our search(QCD axion)

$$10^{-5}\text{eV} \leq m_a < 10^{-4}\text{eV}$$



6)

Axion induced microwave in resonant cavity

Microwave produced at non resonance

$$E_a = g_{a\gamma\gamma} a(t) B$$

amplified at resonance

$$\frac{E_a}{m_a \delta_e},$$

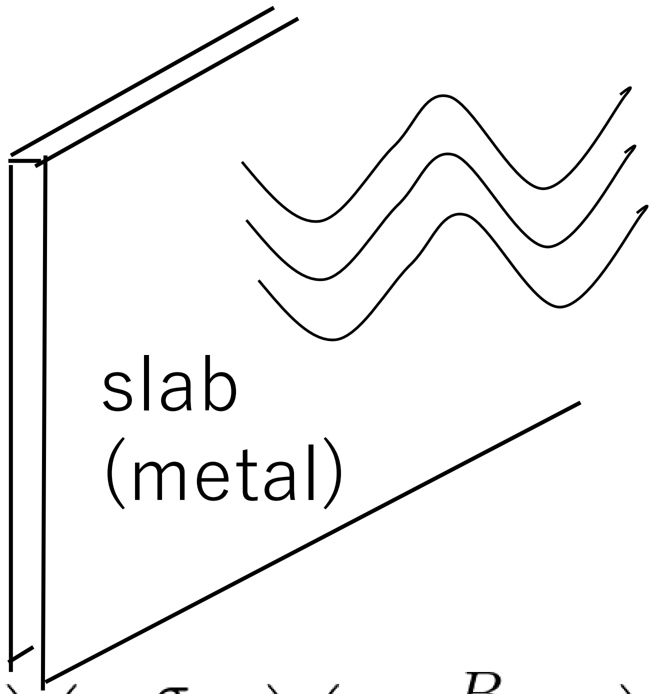
penetration depth

$$\delta_e = \sqrt{\frac{2}{m_a \sigma}}$$

$$\frac{1}{m_a\sigma} \simeq 1.3\times 10^6 \sqrt{\Big(\frac{\sigma}{3.3\times10^7\mathrm{eV}}\Big)\Big(\frac{10^{-5}eV}{m_a}\Big)}$$

$$\sigma \simeq 3.3\times 10^7\mathrm{eV} \quad (1/\sigma = 0.1\times 10^{-11}\Omega\mathrm{m})$$

electric conductivity of slab (6N cupper)



Real absorbed flux of the microwave

$$P_{ra} \sim 0.46\times\Big(\frac{E_a}{m_a\delta_e}\Big)^2 S \sim 1.8\times10^{-18} W g_\gamma^2 \frac{S}{\mathrm{cm}^2}\Big(\frac{10^{-5}\mathrm{eV}}{m_a}\Big)\Big(\frac{\sigma}{10^7\mathrm{eV}}\Big)\Big(\frac{B}{10^5\mathrm{Gauss}}\Big)^2$$

7)

Transition amplitude $\text{state } \alpha \to \text{state } \beta$

$$\tau^{-1}(\alpha \to \beta) = 2\pi S \int dE_\beta \rho(E_\beta) | < \beta | H_a | \alpha > |^2 \delta(E_\alpha + m_a - E_\beta)$$

$$= 2\pi S \rho(E_\alpha + m_a) m_a^2 \left(e\vec{A}'_a \cdot \vec{L}_{\alpha\beta} \right)^2$$

$$\simeq 2\pi S m_a^2 \left(\frac{eB}{2\pi} \frac{2}{\pi \Delta E} \right) e^2 A_0'^2 A^2 l_B^2$$

Overlapping of α and β

$$\vec{L}_{\alpha\beta} \equiv < \beta | \vec{x} | \alpha > \sim A(\alpha\beta) l_B$$

$$\vec{A}'_a \cdot \vec{L}_{\alpha\beta} = A'_0 A(\alpha\beta) l_B$$

assumption $A(\alpha\beta) \sim A$ independent of α, β $\quad A \gg 1$

$$\tau \sim 1\,\mathrm{s} \left(\frac{m_a}{10^{-5}\mathrm{eV}} \right)$$ **at resonance**

cyclotron radius $l_B = 0.8 \times 10^{-6}\mathrm{cm} \sqrt{\frac{10\mathrm{T}}{\mathrm{B}}}$

S; surface area, typically $\sim 10^{-3}\mathrm{cm}^2$

Density of state

$$\rho(E) = \rho_0 \sqrt{1 - \left(\frac{E - E_c}{\Delta E} \right)^2}; \quad \rho_0 \equiv \frac{eB}{2\pi} \times \frac{2}{\pi \Delta E}$$

$$H_a = \frac{-ie\vec{A}'_a \cdot \vec{P}}{m^*}$$

$$|\vec{A}'_0| = E'_p / m_a \simeq 0.35 g_{a\gamma\gamma} a_0 B_t / m_a$$

Energy density of axion $m_a^2 a_0^2 / 2 \simeq 0.3\mathrm{GeV/cm}^3$

8) flux of absorbed microwave at resonance

$$P_a=\int_{E_f-m_a}^{E_f} m_a dE_\alpha S\rho(E_\alpha)\tau^{-1}(\alpha\beta)\sim N m_a\tau^{-1};\quad N=\frac{SeB}{2\pi}\times\frac{2m_a}{\pi\Delta E}$$

$$g_\gamma(KSVZ)\simeq -0.96,\quad g_\gamma(DFSZ)\simeq 0.37$$

$$P_a\sim 1.3\times10^{-18}\mathrm{W}g_\gamma^2\left(\frac{A}{1}\right)^2\left(\frac{S}{10^{-3}\mathrm{cm}^2}\right)^2\left(\frac{10^{-3}\mathrm{eV}}{\Delta E}\right)^2\left(\frac{\rho_d}{0.3\,\mathrm{GeVcm}^{-3}}\right)\left(\frac{B}{10^5\mathrm{Gauss}}\right)^3\left(\frac{m_a}{10^{-5}\mathrm{eV}}\right)^2$$

$$\gg \underline{SE'_aB'_a\sim10^{-21}\mathrm{W}}$$

Microwave flux irradiated to 2 dimensional electrons

It is overestimation. The estimation does not involve microwave irradiated to 2 dimensional electrons, it simply involves the presence of oscillating electric field in the sample

Real absorbed flux of the microwave

No. of axions per unit time passing the sample

$$SE'_aB'_a\sim10^{-21}\mathrm{W}\left(\frac{m_a}{10^{-5}\mathrm{eV}}\right)^2 \qquad \sim10^3\mathrm{s}^{-1}\left(\frac{m_a}{10^{-5}\mathrm{eV}}\right)$$

$S=10^{-3}\mathrm{cm}^2$ **Energy density of axion** $\simeq 0.3\mathrm{GeV}/\mathrm{cm}^3$

9)

All of axion induced microwaves at resonance are absorbed

No. of axion induced microwave per unit time passing the sample with $S=10^{-3}\mathrm{cm}^2$

$$\sim 10^3\mathrm{s}^{-1}\left(\frac{m_a}{10^{-5}\mathrm{eV}}\right)^{-2}\left(\frac{S}{10^{-3}\mathrm{cm}^2}\right)$$

Absorption rate of an electron per unit time

$$\tau^{-1}\sim 1\,\mathrm{s}^{-1}\left(\frac{m_a}{10^{-5}\mathrm{eV}}\right)^{-1}\left(\frac{S}{10^{-3}\mathrm{cm}^2}\right)$$

No. of electrons able to absorb microwave In the sample with $S=10^{-3}\mathrm{cm}^2$

$$\sim 10^9\left(\frac{m_a}{10^{-5}\mathrm{eV}}\right)\left(\frac{S}{10^{-3}\mathrm{cm}^2}\right)$$

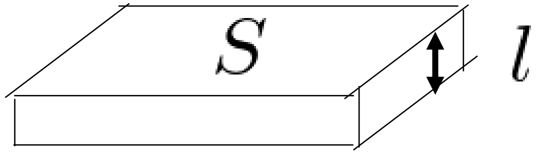
10) Increase of temperature of GaAs sample

$$\Delta\dot{T} = \frac{P_{ra}}{C(T)} \simeq \frac{1.1\mathrm{mK}}{\mathrm{ms}} g_\gamma^2 \Big(\frac{1\mathrm{mK}}{T}\Big)^3 \Big(\frac{10^{-5}\mathrm{eV}}{m_a}\Big)\Big(\frac{2\mu\mathrm{m}}{l}\Big)\Big(\frac{B_t}{5\times 10^4\mathrm{Gauss}}\Big)^2$$

Heat capacity of <u>GaAs sample</u>

$$C(T, \mathrm{density} = 5.3g/cm^3) \simeq 1.94\times 10^3 \Big(\mathrm{J/g\,K}\Big)\Big(\frac{T}{T_d}\Big)^3 \times (\frac{\mathrm{density}}{M}) \times Sl$$

T_d Deby temperature=360K, M molecule weight=144 l thickness of sample



Heat dissipation into thermal bath

$$C\frac{d\Delta T}{dt} = -G\Delta T + P_{ra}$$

G thermal conductivity

$$\Delta T(t=\infty) \simeq \frac{1.1\mathrm{mK}\tau}{\mathrm{ms}} g_\gamma^2 \Big(\frac{1\mathrm{mK}}{\Delta T(t=\infty)+1\mathrm{mK}}\Big)^3 \Big(\frac{10^{-5}\mathrm{eV}}{m_a}\Big)\Big(\frac{2\mu\mathrm{m}}{l}\Big)\Big(\frac{B_t}{5\times 10^4\mathrm{Gauss}}\Big)^2$$

$\tau \equiv C/G$ Time constant independent of temperature $\Delta T \propto \exp(-t/\tau)$ when no heat source $P_{ra}=0$

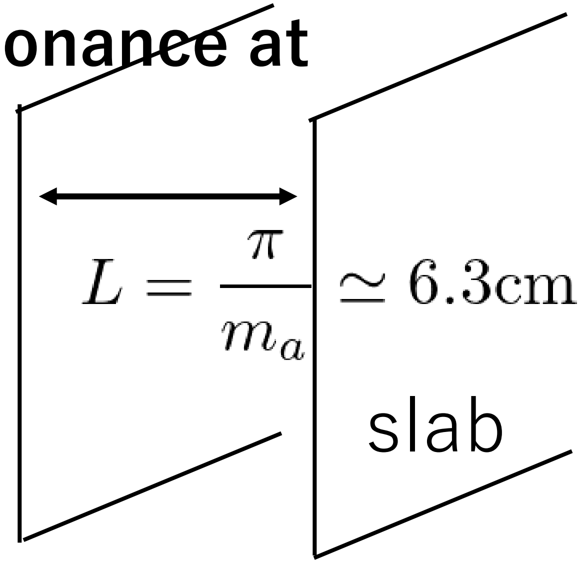
11) Temperature increase at initial $T_{in} = 1\mathrm{mK}$

$$\Delta T(t=\infty) \simeq 1.3\mathrm{mK} \quad \text{with} \quad \tau = 10\mathrm{ms}, \quad (\, g_\gamma = 1\,)$$

$$\Delta T(t=\infty) \sim 5\mathrm{mK}\Big\{\Big(\frac{\tau}{1\mathrm{s}}\Big)\Big(\frac{10^{-5}\mathrm{eV}}{m_a}\Big)\Big(\frac{2\mu\mathrm{m}}{l}\Big)\Big(\frac{B_t}{5\times 10^4\mathrm{Gauss}}\Big)^2 g_\gamma^2\Big\}^{1/4} \ \text{for} \ \tau \gg 1\mathrm{ms}$$

Resonance at

Axion energy= $m_a + \dfrac{m_a v^2}{2}$; $v \sim 10^{-3}$



$$L = \frac{\pi}{m_a} \simeq 6.3\mathrm{cm}\Big(\frac{10^{-5}\mathrm{eV}}{m_a}\Big)$$

$$\delta L \sim 10^{-6} \times 6.3\mathrm{cm}\Big(\frac{10^{-5}\mathrm{eV}}{m_a}\Big)$$