Detecting axions by way of their coupling to the spin of the nucleous or the electron

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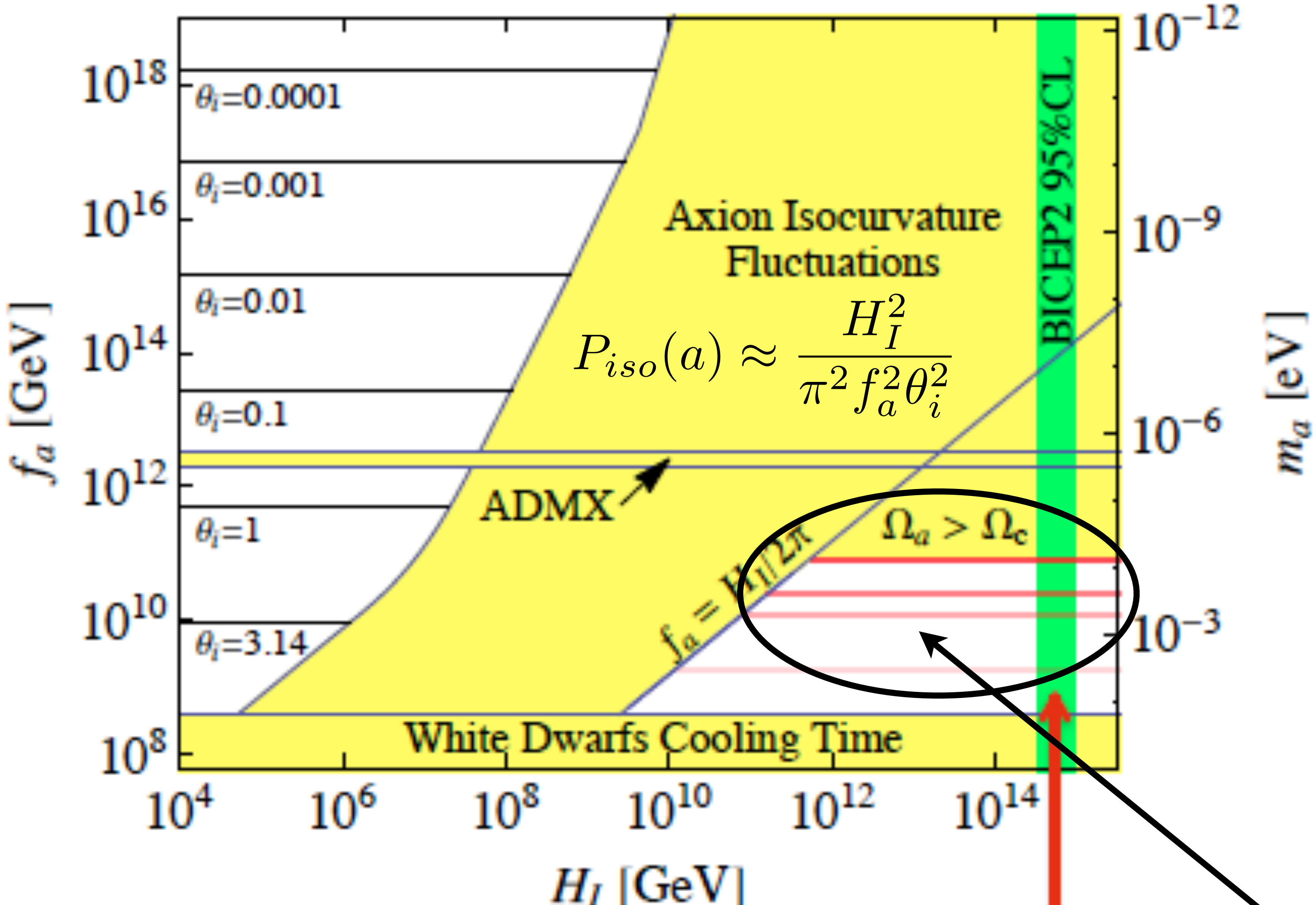
General motivation: (Try to) explore new directions in the search of new phenomena other than traditional ones (LHC, etc.)

Occasional motivation: A paper in 1989 ("unknown" by INSPIRE) + an INFN proposal under construction

Methodological example: Precise but limited knowledge of particle physics. More to know about other fields of physics

QCD Axions in cosmology

$$m_a f_a \approx 10^{-4}\ eV \cdot 10^{11} GeV$$

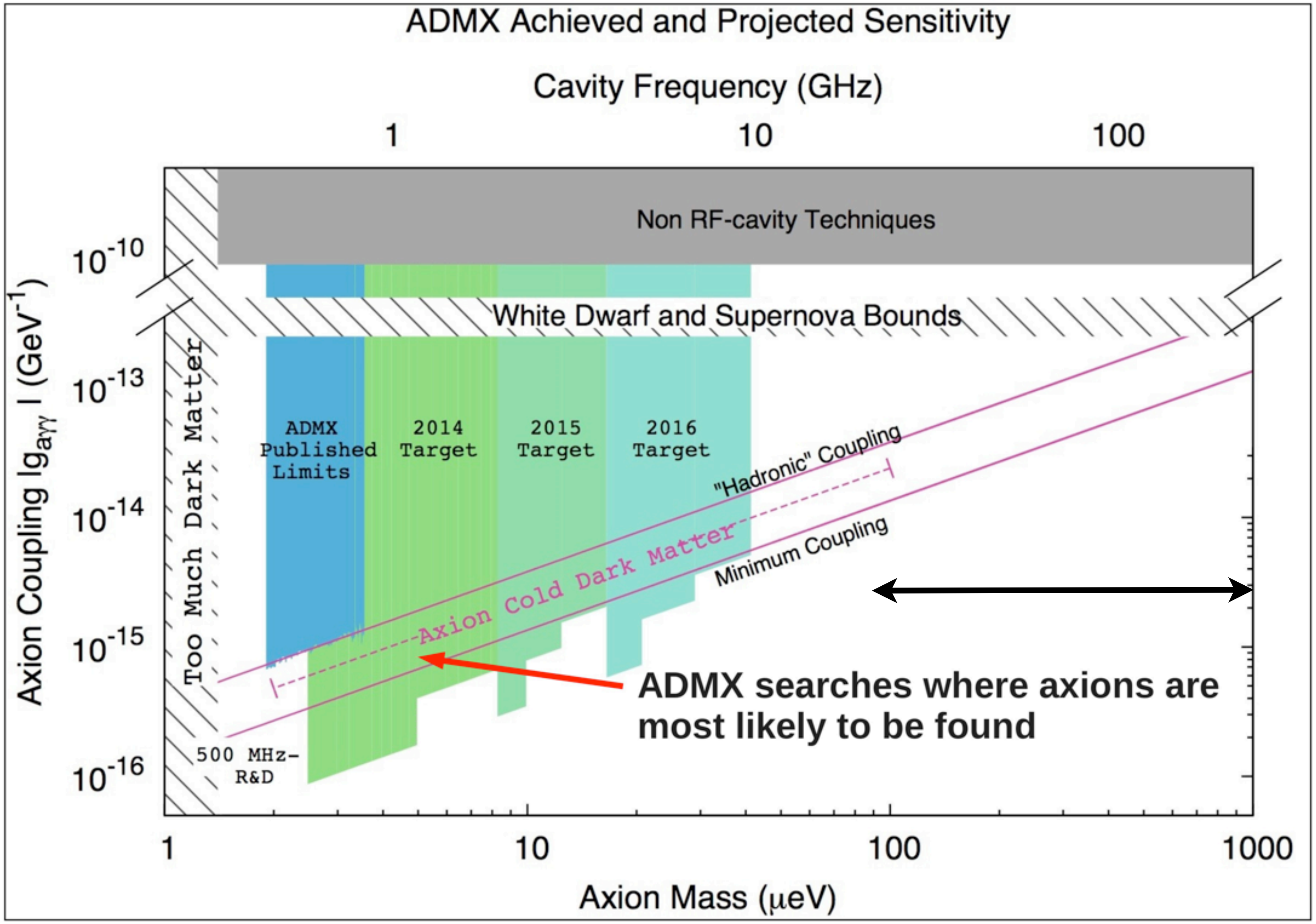


$$\Omega_a h^2 \approx 0.16\left(\frac{m_a}{10^{-5} eV}\right)^{-1.18} \theta_i^2 \qquad \theta_i = \frac{a_i}{f_a} \qquad \theta_i^2 = \frac{\pi^2}{3}$$

(Axion Like Particles: m and f unrelated)

The classic search

$$\mathcal{L}_{a\gamma\gamma} = -\left(\frac{\alpha}{\pi}\frac{g_\gamma}{f_a}\right) a\vec{E}\cdot\vec{B} = -g_{a\gamma\gamma} a\vec{E}\cdot\vec{B}$$



Not easy to explore the most relevant region

$$10^{-4} \lesssim m_a/eV \lesssim 10^{-3}$$

Rybka ADMX

The coupling to spin

$$L = \bar{\psi}(x)(i\hbar\partial\!\!\!/_x - mc)\psi(x) - a(x)\bar{\psi}(x)(g_s + ig_p\gamma_5)\psi(x)$$

$$g_p = A_\Psi \frac{m_\Psi}{f_a} \quad \left(g_s = 10^{-(12\div17)} g_p \frac{GeV}{m_\Psi}\right)$$

DFSZ $g_p(e) \approx 1$

KSVZ $g_p(e) \approx 10^{-3}$

NRL: $$i\hbar\frac{\partial\varphi}{c\partial t} = \left[-\frac{\hbar^2\nabla^2}{2m} + g_s c a - i\frac{g_p}{2m}\vec{\sigma}\cdot(-i\hbar\vec{\nabla}a)\right]\varphi$$

$$\gamma\vec{B}_{eff}\cdot\vec{\sigma}$$

$$\gamma = \frac{e}{2m_\Psi}$$

A coupling to the spin <u>and</u> to the Electric field

$$L \approx \frac{\alpha_S}{4\pi}\frac{a}{f_a}G_{\mu\nu}\tilde{G}^{\mu\nu} \quad \Rightarrow \quad d\,\vec{\sigma}\cdot\vec{E}$$

$$d \approx 10^{-16}\frac{a}{f_a}(e\cdot cm)$$

The axion as a source of an effective $\vec{B}$

1. By the Dark Matter wind

$$\vec{B}_{eff} = \frac{g_p}{e}\vec{\nabla}a = \frac{g_p}{e} m_a \vec{v}\; a_0 \cos m_a t$$

$$m_a \approx 10^{-4} eV \quad \text{(as reference)} \quad \omega = m_a \approx 100\; GHz$$

$$f_a \approx 10^{11} GeV$$

$$m_a\; a_0 \approx \sqrt{\rho_{DM}} \approx 0.3\; GeV/cm^3 \qquad v \approx 10^{-3}$$

coherence length $\lambda_a^C \approx \dfrac{1}{m_a v} \approx 3\; m$

coherence time $\tau_a \approx \dfrac{2\pi}{m_a v^2} \approx 10^{-4}\; sec$

$$B_{eff} \approx 10^{-22}\; Tesla \frac{m_a}{10^{-4} eV}$$

(on electrons)

(1000 bigger on nucleons)

Comparing numbers

(From the Dark Matter wind)

$$\gamma_e B_{eff}(e) \approx \gamma_N B_{eff}(N) \approx 10^{-26} eV \frac{m_a}{10^{-4} eV}$$

$$d\ E \approx 10^{-27} eV \frac{E}{10^8 V/cm}$$

(CASPEr)

versus, e.g.

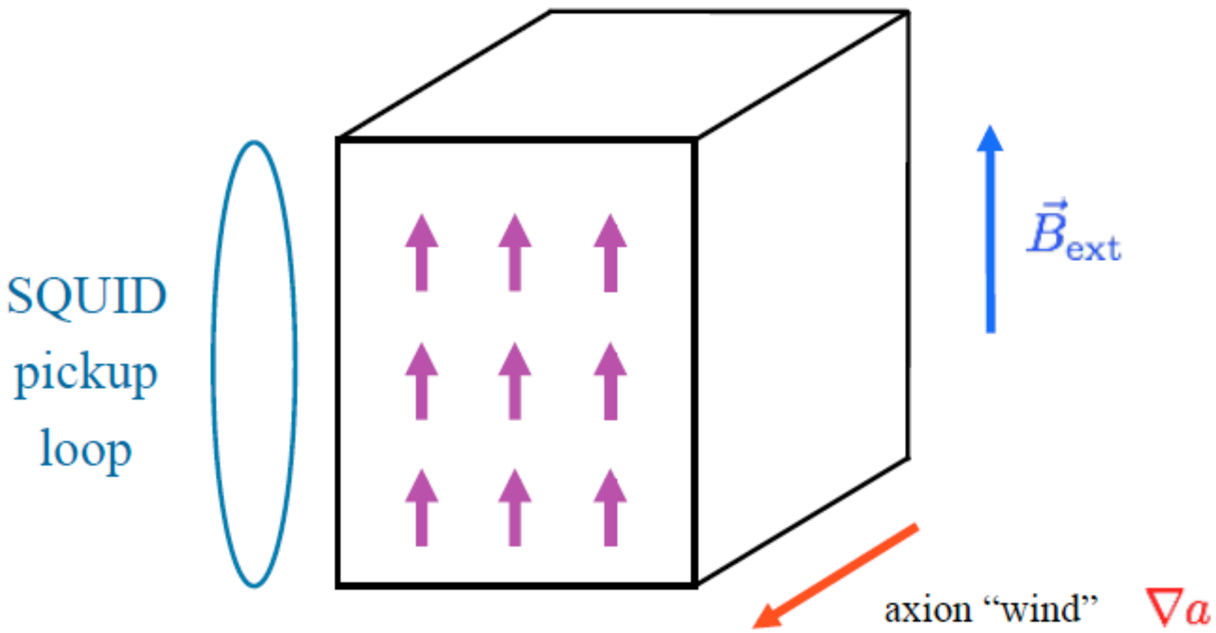
(Gabrielse et al)

$$\Delta(g-2)_e < 10^{-13} \ \Rightarrow \ \gamma_e B \lesssim 10^{-17} eV \frac{B}{5\ Tesla}$$

$$d_e < 10^{-28} e \cdot cm \ \Rightarrow \ d_e E \lesssim 10^{-17} eV \frac{E}{10^{11} V/cm}$$

Need to work on some resonant phenomenon

Proposal 1 (axion DM wind)



on electron spins
B, Cerdonio, Fiorentini, Vitale 1989

on nucleon spins
Graham, Rajendram 2010
CASPEr 2014

Solving Block eq.s, at resonance

$$\frac{d\mathbf{M}}{dt} = \gamma \mathbf{M} \times \mathbf{B} - \frac{1}{T_1, T_2} \mathbf{M}$$

$$m_a = \begin{cases} \xrightarrow{e} \; 2\gamma_e B^{ext} \approx 10^{-4}\ eV \dfrac{B^{ext}}{T} \\ \xrightarrow{N} \; 2\gamma_N B^{ext} \approx 10^{-7}\ eV \dfrac{B^{ext}}{T} \end{cases}$$

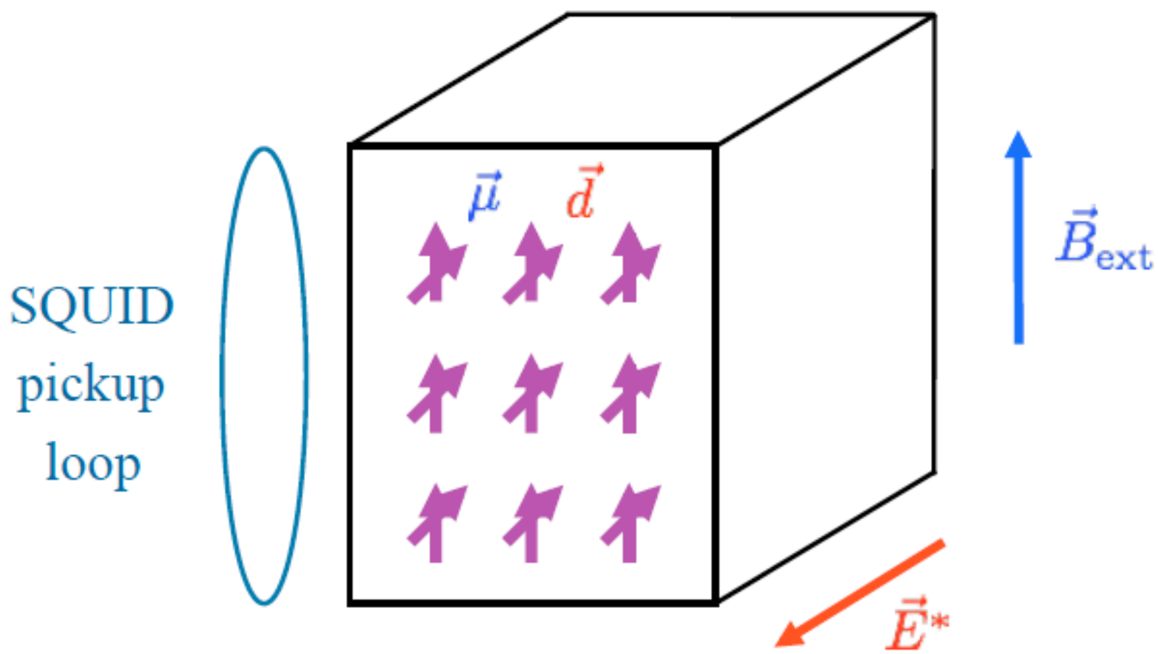
$$M_T = \gamma_{e,N}^2 B_{e,N}^{eff} n_S \tau \cos(m_a t) \begin{cases} \xrightarrow{N} \; 10^{-19} T\ (m_a = 10^{-7}\ eV,\ \tau = 0.1\ sec) \\ \xrightarrow{e} \; 10^{-21} T\ (m_a = 10^{-4}\ eV,\ \tau = 10^{-6}\ sec) \end{cases}$$

$$\tau = min(\tau_a, \tau_{rel}, \tau_R)$$

$$n_S = 10^{22}/cm^3$$

On the same line (axion DM wind in NMR)

Graham, Rajendram 2010
CASPEr 2014



$$d\,\vec{\sigma}\cdot\vec{E}$$

$$d \approx 10^{-16}\frac{a}{f_a}(e\cdot cm)$$

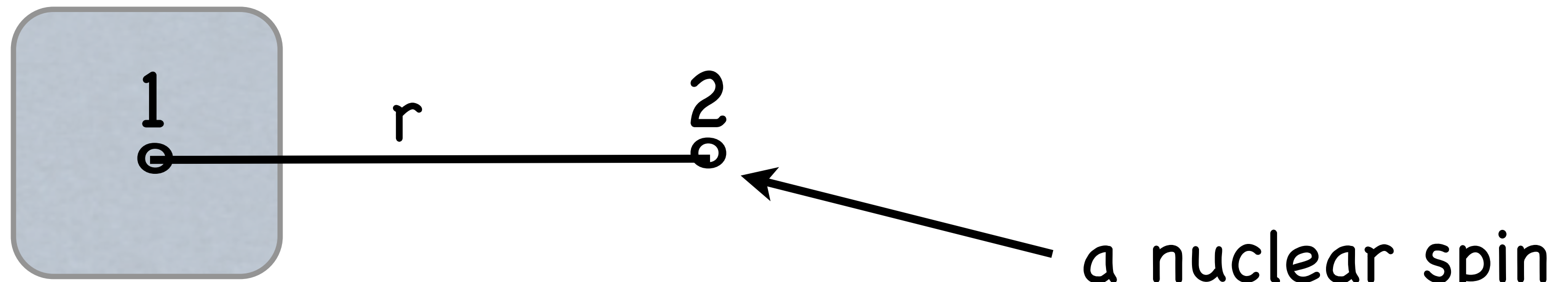
$$M_T = \gamma_N\ d\cdot E\ n_S\tau\cos(m_a t) = 10^{-17}T\ (m_a = 10^{-7}\ eV,\ \tau = 0.1\ sec)$$

since $$\frac{dE}{\gamma_N B_N^{eff}} \approx 10^2\frac{m_a}{10^{-7}\ eV}$$

The axion as a source of an effective $\vec{B}$

2. From a static source

Moody, Wilczek 1984



$$U_{DD} \approx \frac{g_p^1 g_p^2}{m_1 m_2} \frac{e^{-r/\lambda_a}}{r^3} \vec{\sigma}_1 \cdot \vec{\sigma}_2 \qquad \Rightarrow E_1(2) \approx \gamma_2 \vec{B}_{eff}^{DD} \cdot \vec{\sigma}_2$$

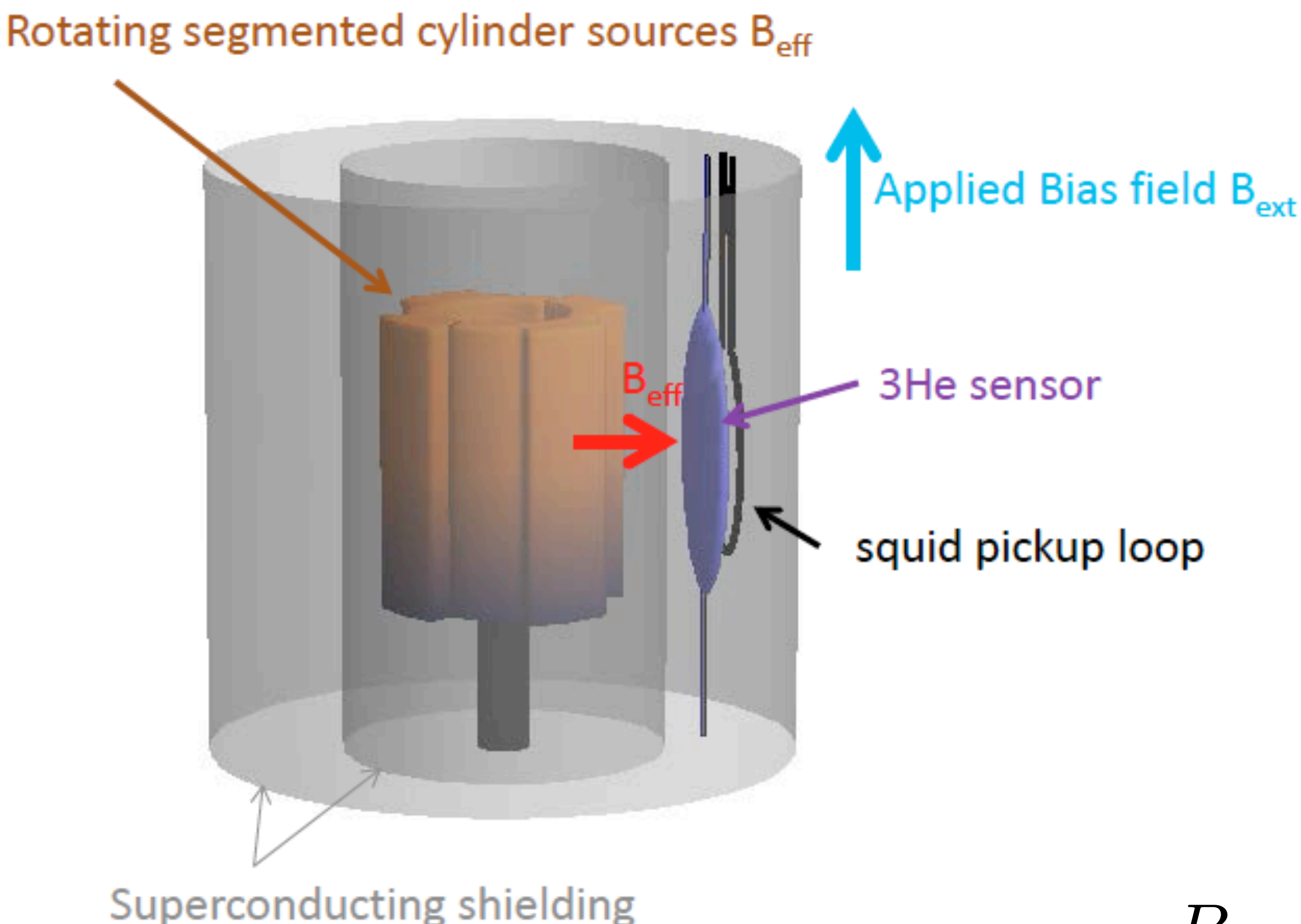
$$B_{eff}^{DD} \approx \frac{1}{\gamma_2} \frac{g_p^1 g_p^2}{m_1 m_2} n_s^1 e^{-r/\lambda_a} \approx 10^{-25} T \left(\frac{m_a}{10^{-4} eV}\right)^2 \frac{n_s^1}{10^{22}/cm^3} e^{-r/\lambda_a}$$

$$U_{MD} \approx \frac{g_s^1 g_p^2}{m_2} \frac{e^{-r/\lambda_a}}{r^2} \hat{r} \cdot \vec{\sigma}_2 \qquad \Rightarrow E_1(2) \approx \gamma_2 \vec{B}_{eff}^{MD} \cdot \vec{\sigma}_2$$

$$B_{eff}^{MD} \approx \frac{1}{\gamma_2} \frac{g_s^1 g_p^2}{m_2} n^1 \lambda_a e^{-r/\lambda_a} \lesssim 10^{-23} T \frac{m_a}{10^{-4} eV} \frac{n^1}{10^{24}/cm^3} e^{-r/\lambda_a}$$

Proposal 2 (a static force from a rotating source)

Arvanitaki, Geraci 2014



!! $w = 200\ Hz$!!

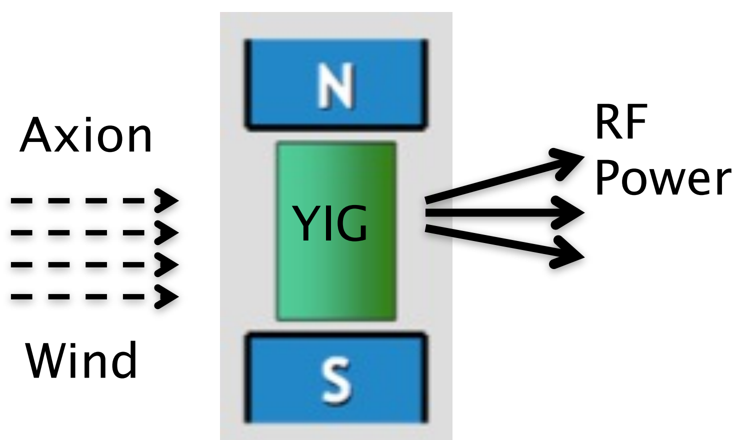
but B^{eff} smaller than in the axion wind case

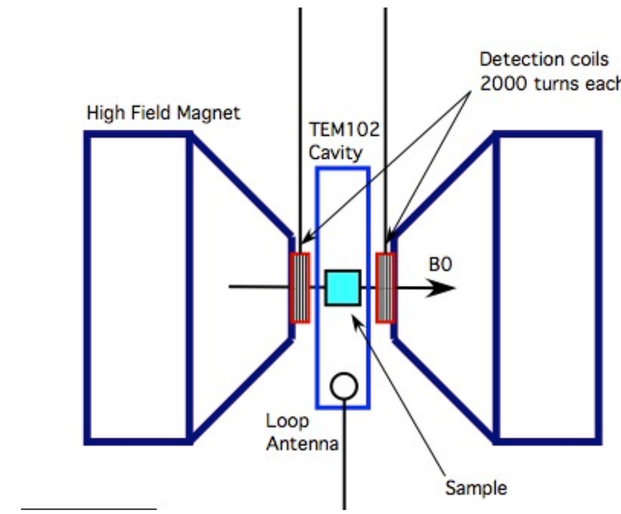
$$B_{eff}/T \lesssim 10^{-23} \qquad M_T/T \lesssim 10^{-20}$$

Proposal 3 (axion DM wind)

QUaerere AXions (under construction)

INFN (PD, Legnaro, TO), Birmingham, Moscow



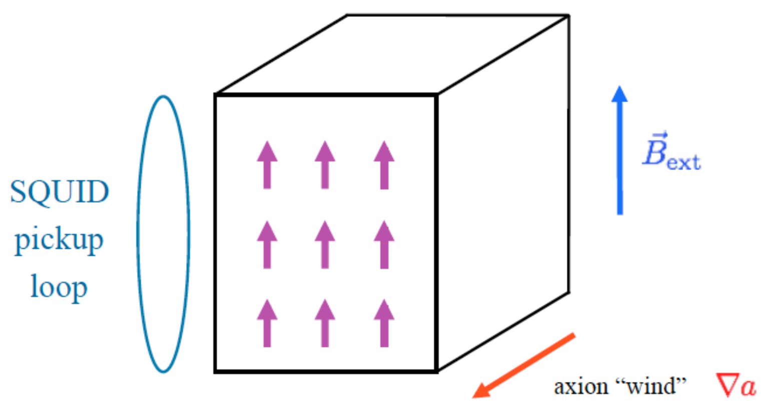


Use the coupling to the electron spin (to avoid the frequency cutoff)

and (try to) detect the RF power emitted by the coherent magnetic dipole oscillating at $w = m_a$

Difficult to see M_T by a magnetometer (squid) as in the other exp.s because of the frequency range

Summary on proposed exp.s using NMR/EMR

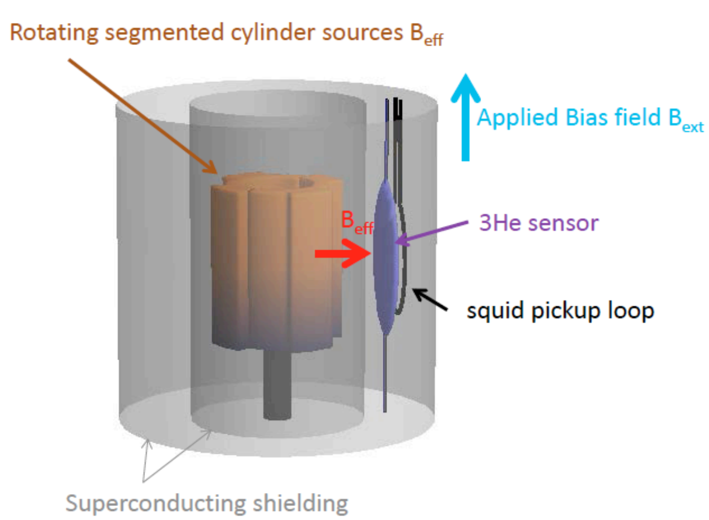


CASPEr axion wind/NMR

limited in frequency (mass)
but size of the effect OK

$$(m_a/eV = 10^{-7},\ \tau = 0.1 sec)$$

$$B_{eff}/T \approx 10^{-22} \qquad M_T/T \approx 10^{-19}$$

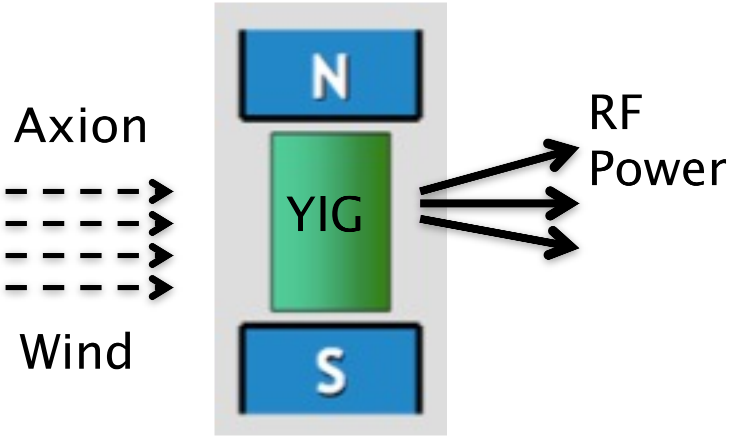


static source NMR

not limited in frequency
but size of the effect smaller

$$(m_a/eV = 10^{-4},\ \tau = 0.1 sec)$$

$$B_{eff}/T \lesssim 10^{-23} \qquad M_T/T \lesssim 10^{-20}$$



QUAX axion wind/EMR

frequency OK
detection method still under scrutiny

$$(m_a/eV = 10^{-4},\ \tau = 10^{-6} sec)$$

$$B_{eff}/T \approx 10^{-22} \qquad M_T/T \approx 10^{-21}$$

About "radiation dumping"

Back to the transverse magnetization

(for axion wind only)

$$M_T = \gamma_{e,N}^2 B_{e,N}^{eff} n_S \tau \cos(m_a t) \qquad \tau = min(\tau_a, \tau_{rel}, \tau_R)$$

$$\tau_a \approx \frac{2\pi}{m_a v^2} \approx 10^{-4}\ sec \frac{10^{-4}\ eV}{m_a}$$

$$\tau_{rel} \approx \begin{cases} 0.1\ sec\ for\ NMR \\ 10^{-6}\ sec\ for\ EMR \end{cases}$$

$$P = wN^2 \frac{dW}{dt} = -\frac{Nw}{\tau_R} \qquad \frac{dW}{dt} \approx \gamma^2 w^3 \qquad N = \frac{M_0 V}{\gamma} = n_S V$$

$$\tau_R = \frac{1}{\gamma^2 n_S w^3 V} \approx \left(\frac{10^{-4} eV}{w}\right)^3 \frac{mm^3}{V} \frac{10^{22}/cm^3}{n_S} \times \begin{cases} 10^{-9}\ sec\ for\ EMR \\ 10^{-3}\ sec\ for\ NMR \end{cases}$$

$\Rightarrow \tau_R$ large, hence negligible, for NMR exp.s (CASPEr, static force)

$w = 200\ Hz$

$\Rightarrow \tau_R$ seriously relevant for EMR

Another way to understand τ_R

Bloembergen, Pound 1954

Incoming power

$$P_{in} = w(M_T V)B_T$$

RF power emitted by the oscillating macroscopic dipole

$$P_R = w^4(M_T V)^2$$

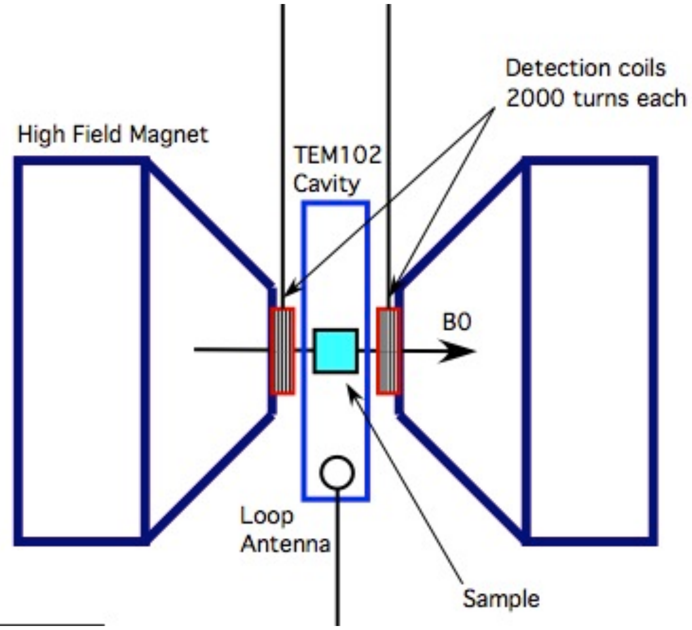
Transverse oscillating magnetization

$$M_T = \gamma^2 B_T n_S \tau$$

Energy conservation

$$P_{in} = P_R \Rightarrow \tau = \frac{1}{\gamma^2 w^3 V n_S} = \tau_R$$

Can a cavity help?



$$H = (w_m - i\frac{\gamma_m}{2})m^+m + (w_a - i\frac{\gamma_a}{2})a^+a + (w_c - i\frac{\gamma_c}{2})c^+c+$$
$$g_{am}(ma^+ + m^+a) + g_{mc}(mc^+ + m^+c)$$

axion-magnon coupling $\qquad g_{am} = \frac{v_a}{f}(n_S w_a)^{1/2}$

magnon-cavity mode coupling $\qquad g_{mc} = \frac{e}{m_e}(n_S w_c V/V_c)^{1/2}$

RF power exiting from the cavity

$$z = \frac{1}{(2w_c)^{1/2}}(c + c^+)$$

$$P_c = \frac{\gamma_c}{2} < \dot{z}^2 >= \gamma_m \frac{w_a^2}{w_c} \frac{g_{am}^2 g_{mc}^2 N_a}{|(w_a - w_m + i\frac{\gamma_m}{2})(w_a - w_c + i\frac{\gamma_c}{2}) - g_{mc}^2|^2}$$

$$= P^{vac}(\tau_R >> \tau_a, \tau_m) f$$

Looks OK, since no τ_R and $f(w_a = w_{m/c} \pm g_{mc}) = \frac{4\gamma_m \gamma_c}{(\gamma_m + \gamma_c)^2}$

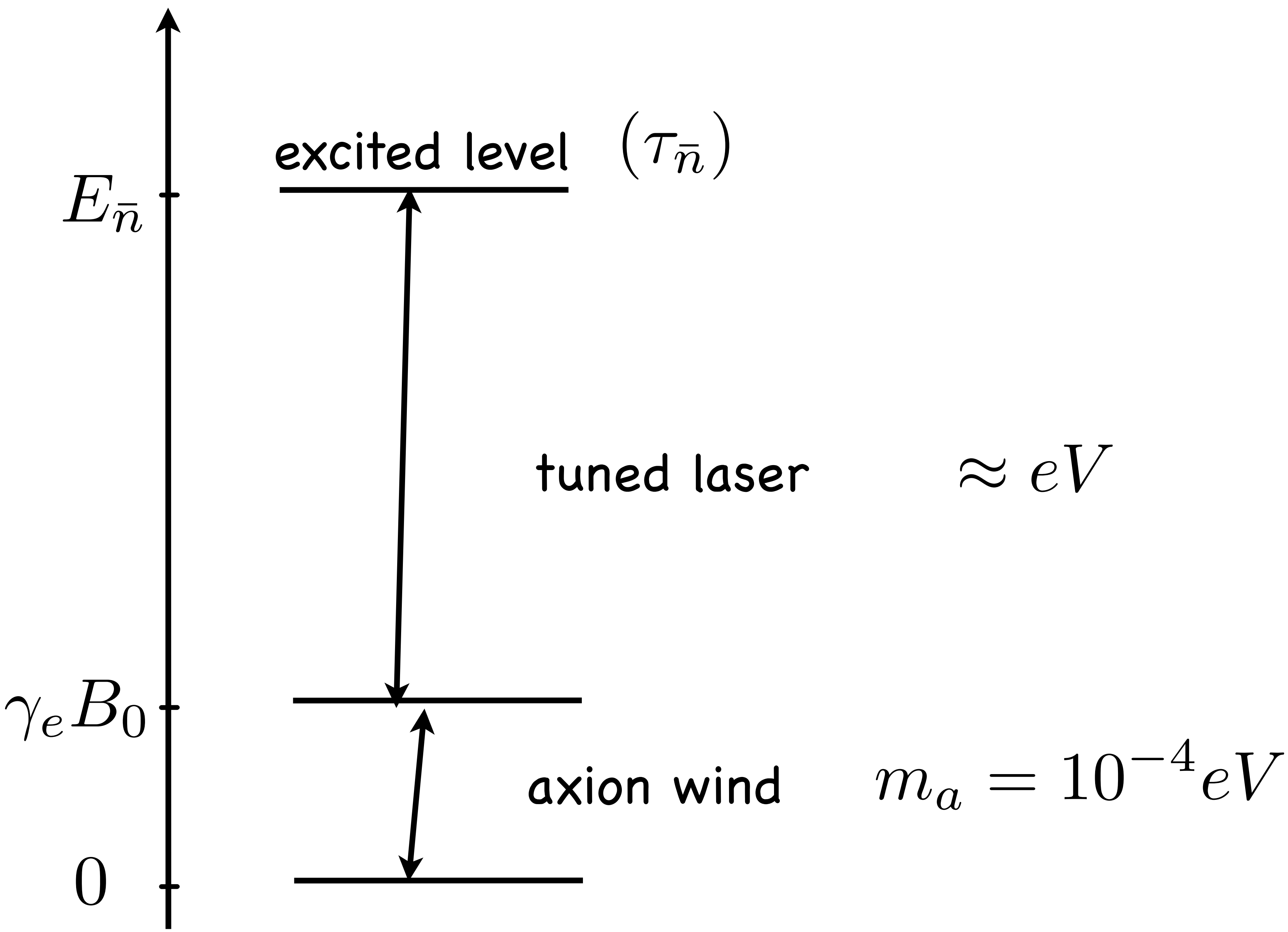
for $w_m = w_c$ and $g_{mc} >> \gamma_m, \gamma_c$ (strong coupling)

However, using realistic numbers for n_S and V

$$P^{vac}(\tau_R >> \tau_a, \tau_m) \approx 10^{-27} Watt (\frac{n_s}{10^{22}/cm^3})(\frac{V}{10^2 cm^3})(\frac{\tau}{10^{-6} sec})(\frac{m_a}{10^{-4} eV})^3$$

Atomic transitions from DM wind

Sikivie 2014



Requires:

$$N_A e^{-m_a/kT} < 0.1$$

$$T \lesssim 10\ mK(\frac{m_a}{10^{-4}eV})$$

to depopulate the higher spin state in absence of axion wind

Photon rate from de-excited atoms:

$$\frac{dN}{dt} \approx n_M 10^{-3}\ Hz \frac{min(t, t_a, \tau_{\bar{n}})}{10^{-6} sec}$$

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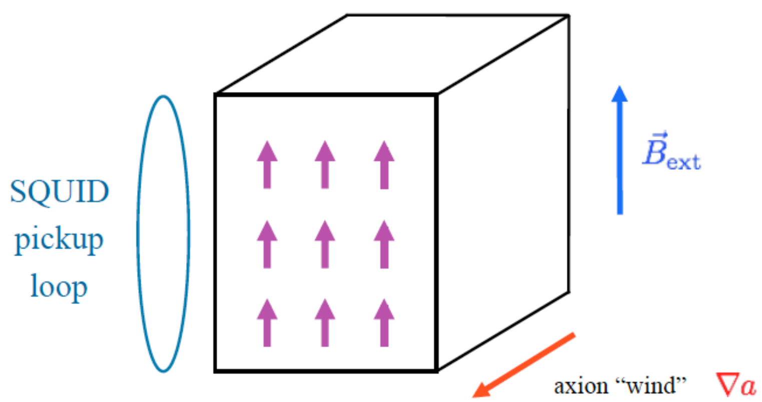

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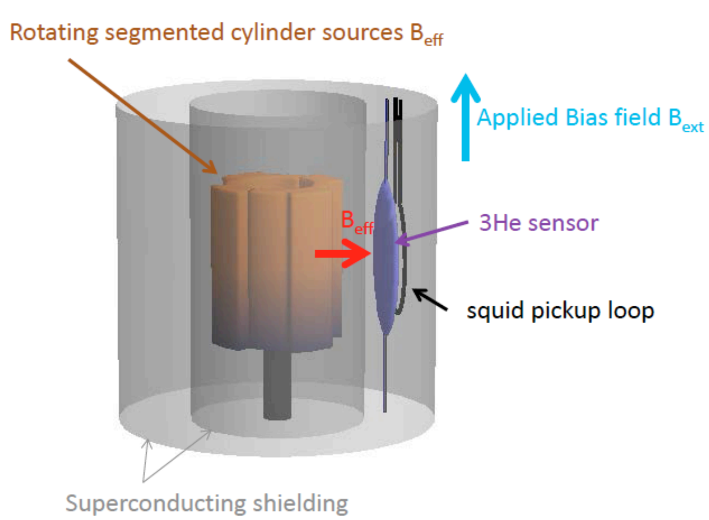

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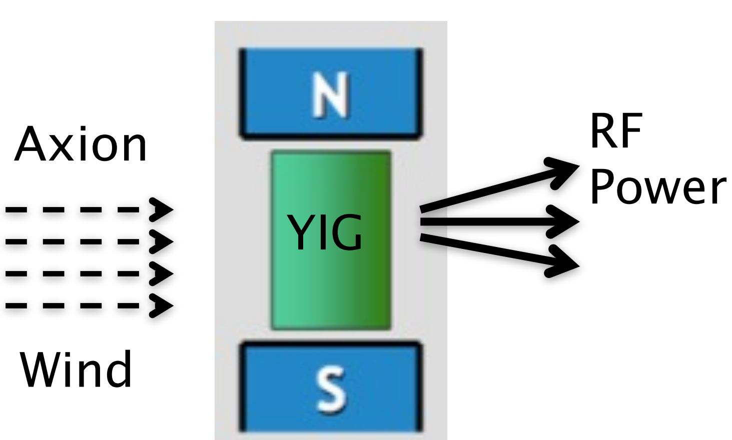

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