The Standard Model and (some of) its extensions

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GGI, Florence, January 9-27, 2017

V. Axion searches by way of their coupling to the spin

Thanks to the QUAX collaboration, B, Braggio et al 2016

2. Why $\theta \lesssim 10^{-10}$? $\theta G_{\mu\nu}\tilde{G}^{\mu\nu}$

How do we know that $\theta \lesssim 10^{-10}$?

$\theta G_{\mu\nu}\tilde{G}^{\mu\nu}$ is T-odd and (almost) the only source of T-violation in the SM

	$\vec{\mu}\cdot\vec{B}$	$\vec{d}\cdot\vec{E}$
T	$+$	$-$

$$|\vec{\mu_N}| = 2\cdot 10^{-14} e\cdot cm$$
$$|\vec{d_N}| \approx \theta\cdot 10^{-15} e\cdot cm$$
$$|\vec{d_N}|_{exp} < 3\cdot 10^{-26} e\cdot cm$$

⇒ Make θ a dynamical field forced in its cosmological history to relax to 0 (almost) and (possibly) appear as DM

A quick introduction to axions

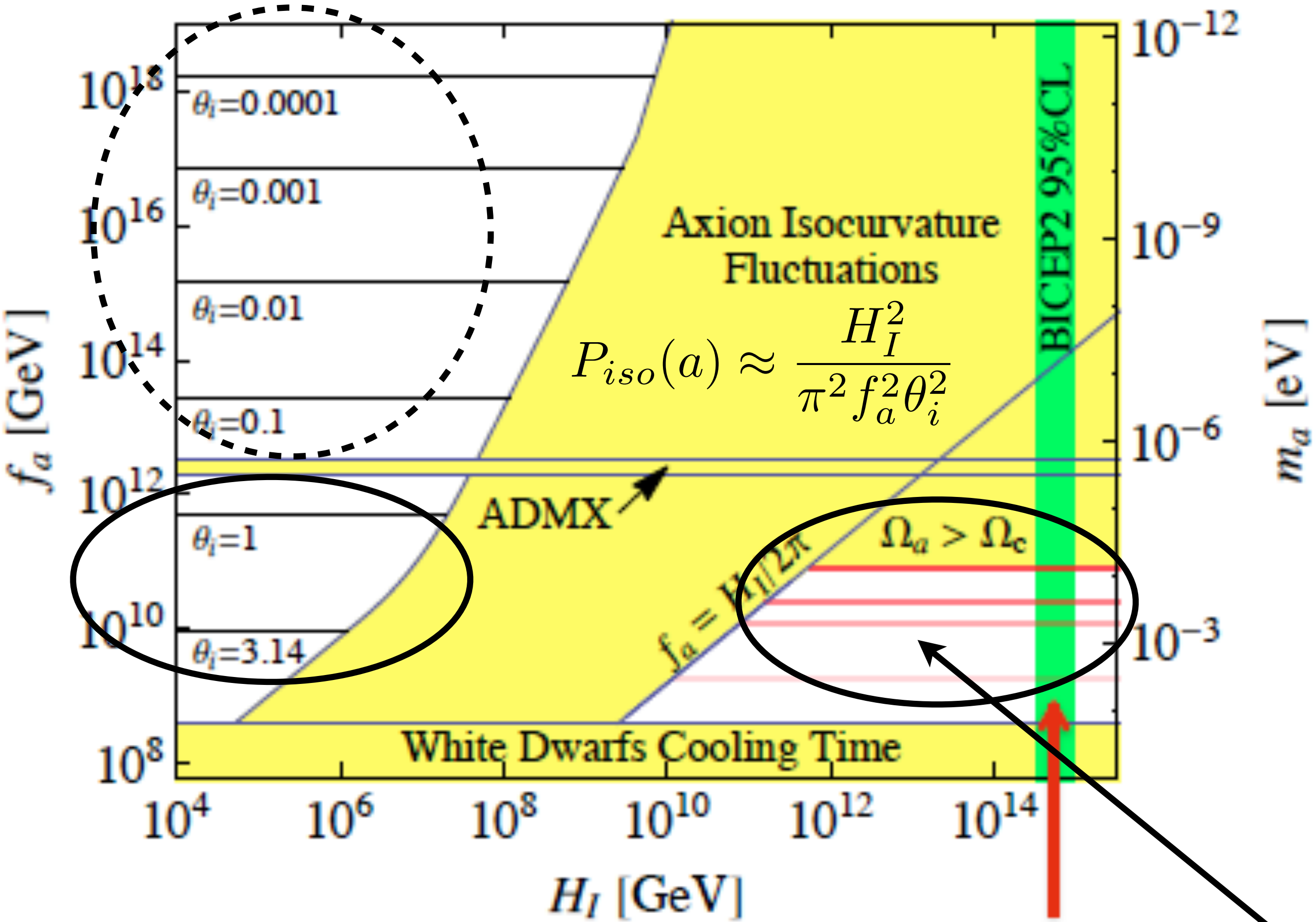
See lecture II

$$\mathcal{L}_a = -\frac{1}{2}|\partial_\mu a|^2 + \frac{\partial_\mu a}{f_a} J_\mu^{PQ} + \frac{a}{f_a}\frac{\alpha_S}{8\pi} G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{a}{f_a}\frac{\alpha}{8\pi} C_\gamma F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$J_\mu^{PQ} = \sum_\Psi Q_\Psi^{PQ} \bar{\Psi}\gamma_\mu\gamma_5\Psi$$

QCD Axions in cosmology

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

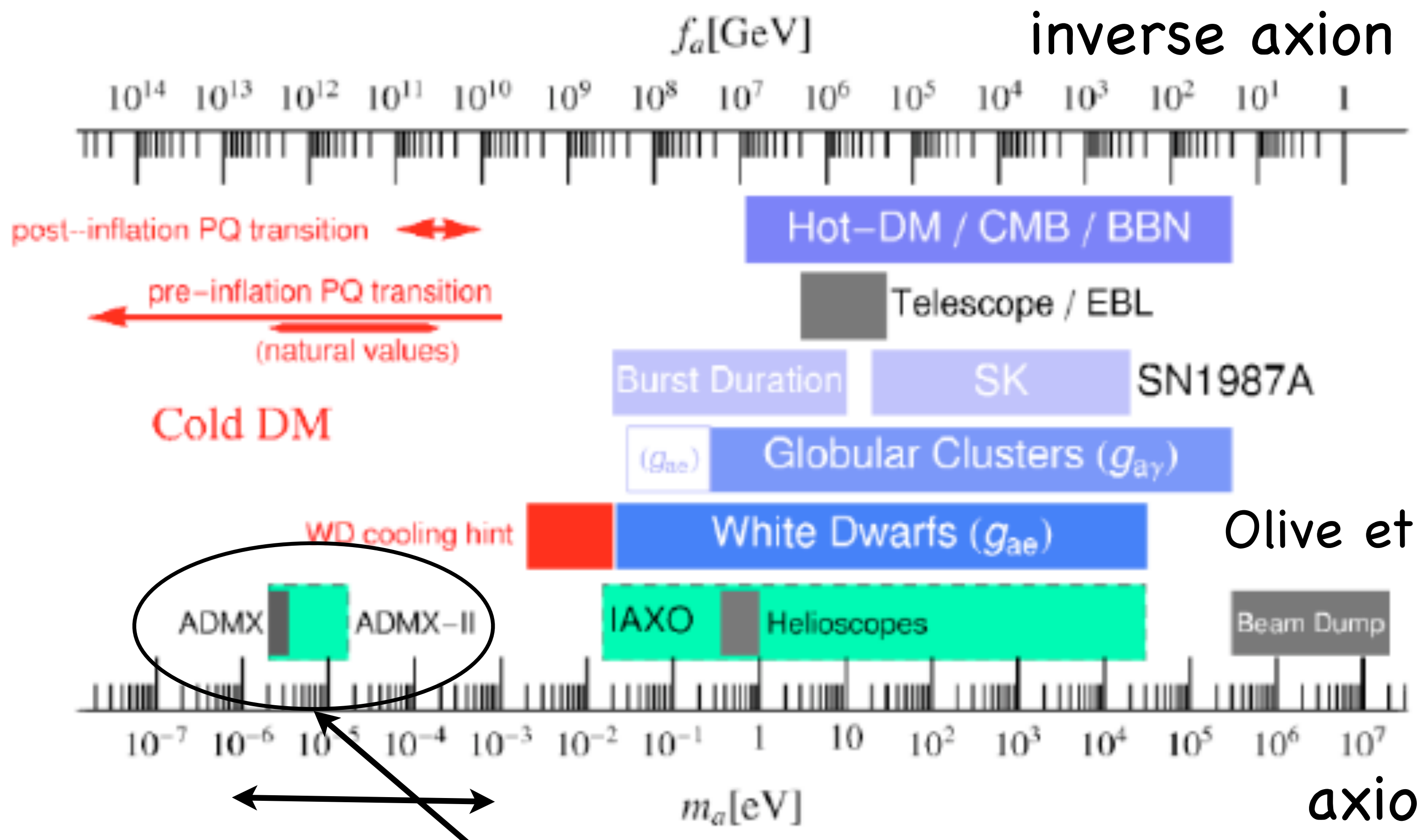


$$\Omega_a h^2 \approx 0.16 \left(\frac{m_a}{10^{-5} eV}\right)^{-1.18} \theta_i^2 \qquad \theta_i = \frac{a_i}{f_a} \qquad \theta_i^2 = \frac{\pi^2}{3}$$

For θ_i of order unity $m_a \sim 10^{-(3\div 5)}\ eV$ is mostly interesting

The dynamical field, a, is the "axion"

inverse axion coupling



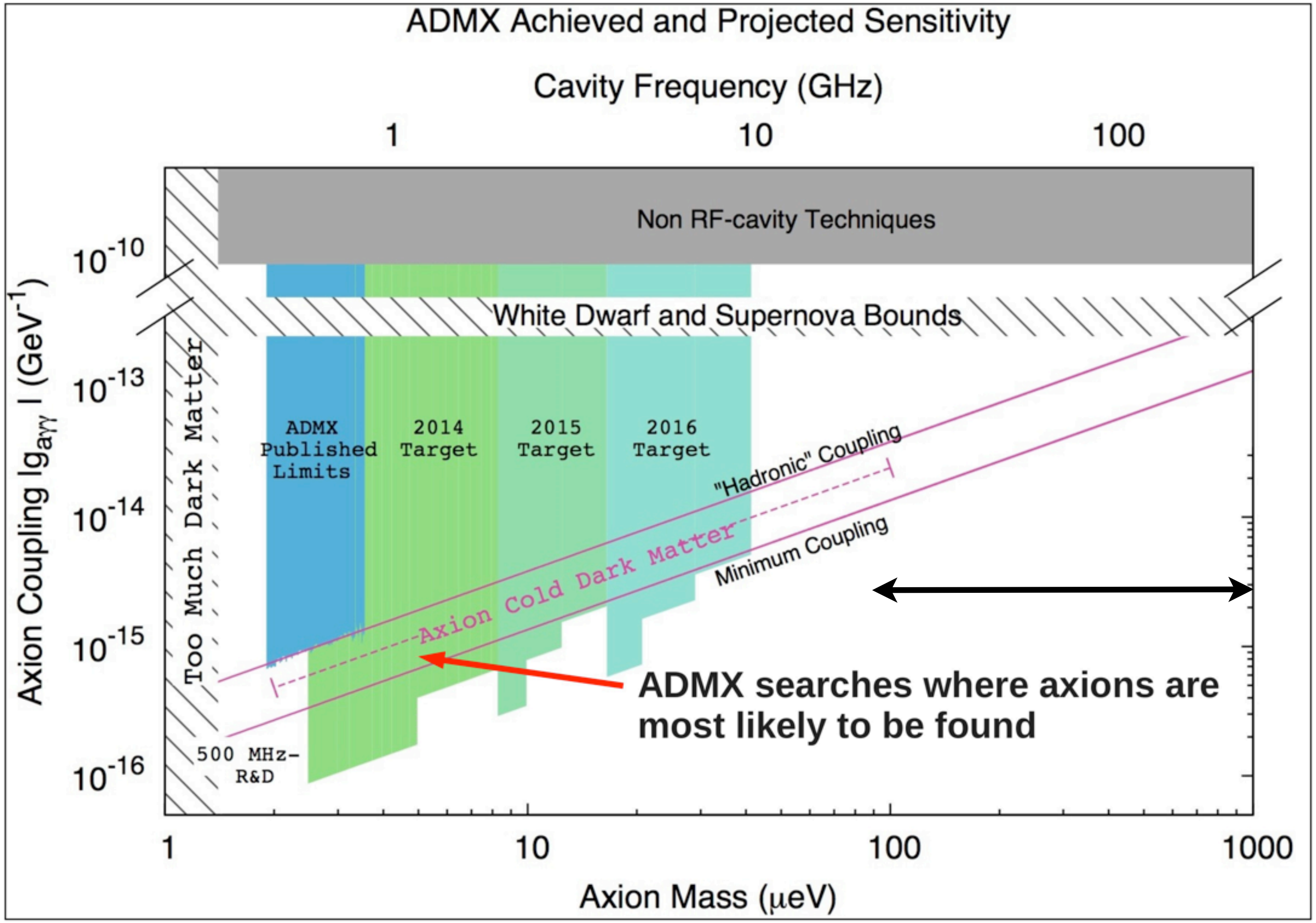
Olive et al, 2104

axion mass

$$\frac{a}{f_a}\frac{\alpha}{8\pi}C_\gamma F_{\mu\nu}\tilde{F}^{\mu\nu} \quad \Rightarrow \quad a \xrightarrow{\vec{B}} \gamma$$

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 (1)

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

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

DFS $g_p(e) \approx 1$

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

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

!?!?!?!!!!

$$\gamma \vec{B}_{eff} \cdot \vec{\sigma} \qquad \gamma = \frac{e}{2m_\Psi}$$

(Also: a coupling to the spin and to the Electric field)

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

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

The axion as a source of an effective $\vec{B}$ (1)

1. By the DM axion wind seen on earth moving in the galaxy $a \sim a_0 \sin(m_a t - m_a \vec{v} \cdot \vec{x})$

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

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

$f_a \approx 10^{11} GeV$

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

coherence length $\lambda_a^C \approx \frac{1}{m_a v} \approx 10\ m$

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

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

(on electrons)

(1000 bigger on nucleons)

Comparing numbers

(From the DM axion 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)

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

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

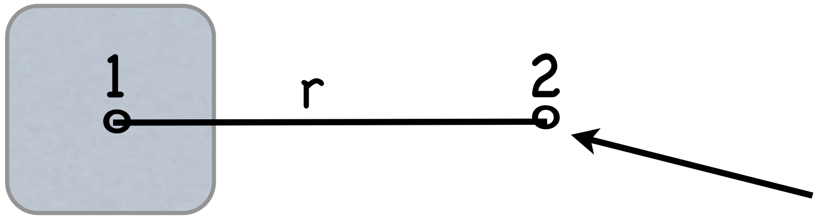
Need to work on some resonant phenomenon

The axion as a source of an effective $\vec{B}$ (2)

2. From a static source

Moody, Wilczek 1984

D = dipole
M = monopole



$\lambda_a = 1/m_a$

?

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

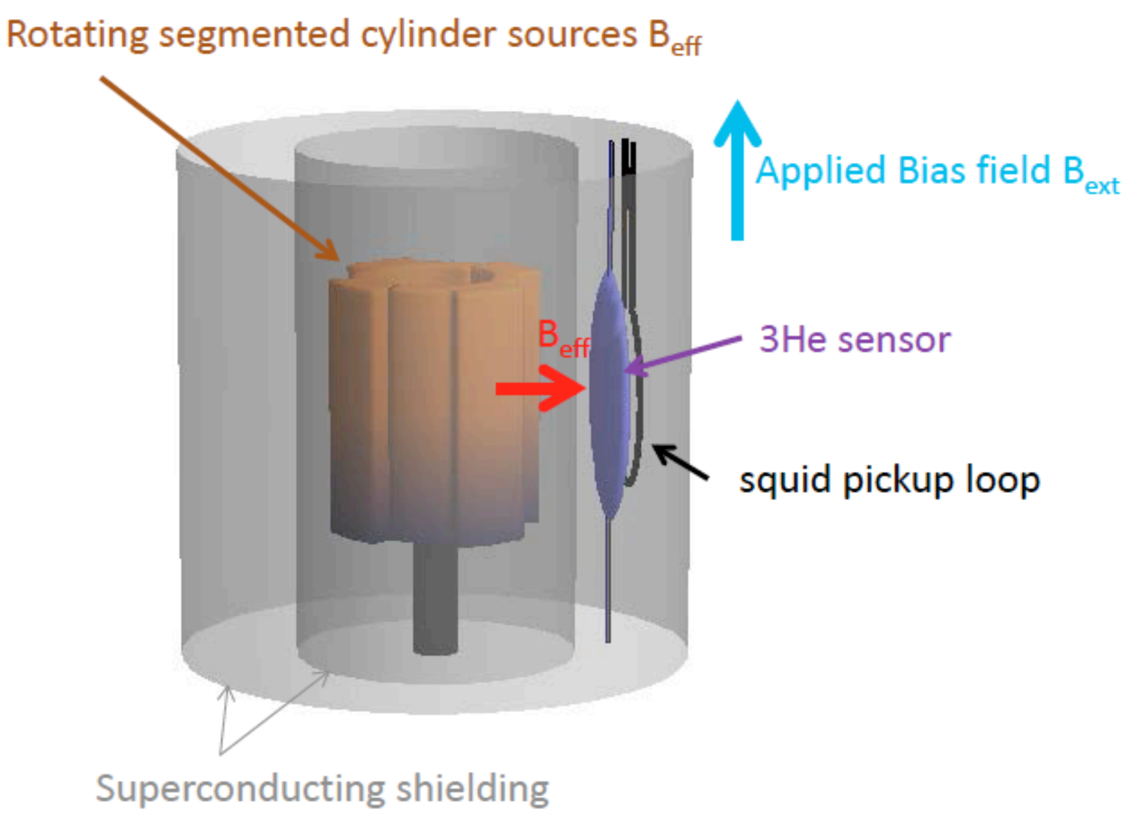
$$B_{eff}^{DD} \approx \frac{1}{\gamma_2} \frac{g_p^1 g_p^2}{m_1 m_2} n_s^1 e^{-r/\lambda_a} \approx 10^{-25} T (\frac{m_a}{10^{-4} eV})^2 \frac{n_s^1}{10^{22}/cm^3} e^{-r/\lambda_a}$$

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

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

Proposal 2 (a static force from a rotating source)

Arvanitaki, Geraci 2014



Solving Block eq.s, at resonance

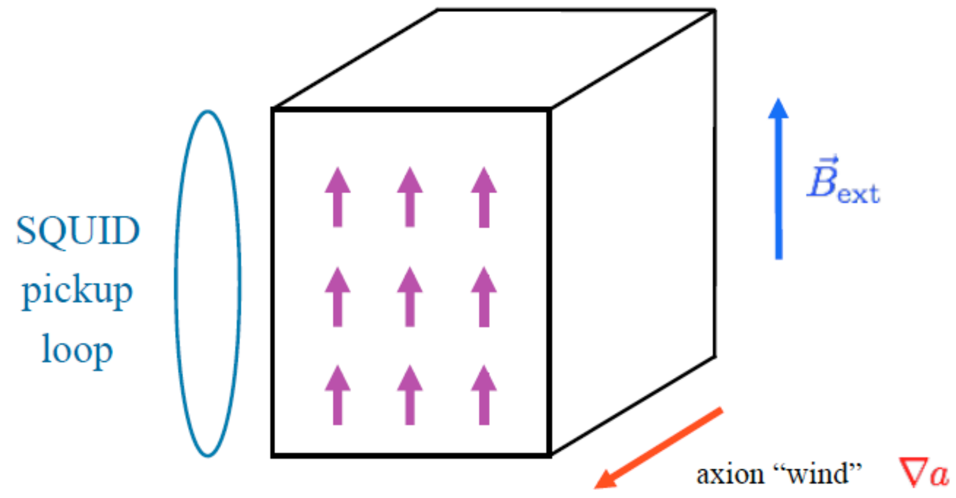
$$\frac{d\mathbf{M}}{dt} = \gamma \mathbf{M} \times \mathbf{B} - \frac{1}{T_1, T_2}\mathbf{M}$$

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

!! $w = 200\ Hz$!!

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

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

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

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

$$M_T = \gamma_{e,N}^2 B_{e,N}^{eff} n_S \tau \cos(m_a t)$$

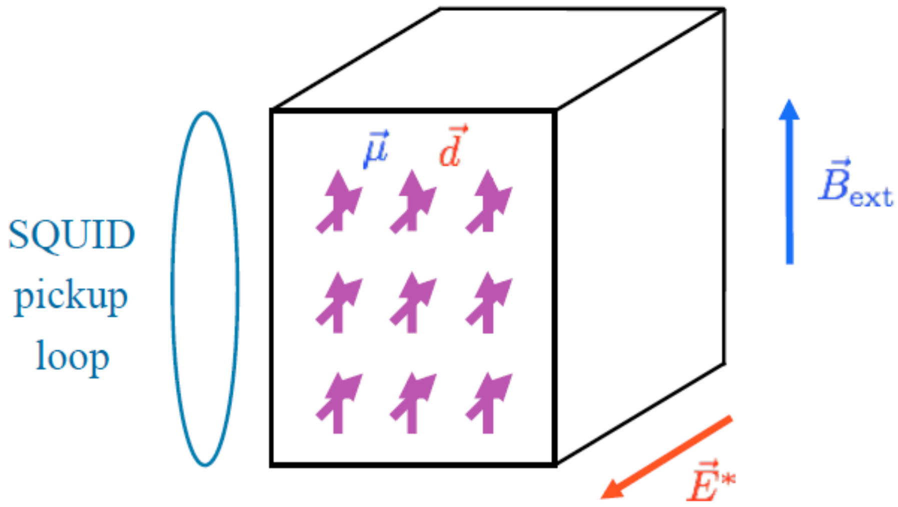
$$\begin{cases} \text{N:} & 10^{-19} T\ (m_a = 10^{-7}\ eV,\ \tau = 0.1\ sec) \\ \text{e:} & 10^{-21} T\ (m_a = 10^{-4}\ eV,\ \tau = 10^{-6}\ sec) \end{cases}$$

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

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

On the same line (axion DM wind in NMR)

Graham, Rajendram 2010
CASPEr 2014



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

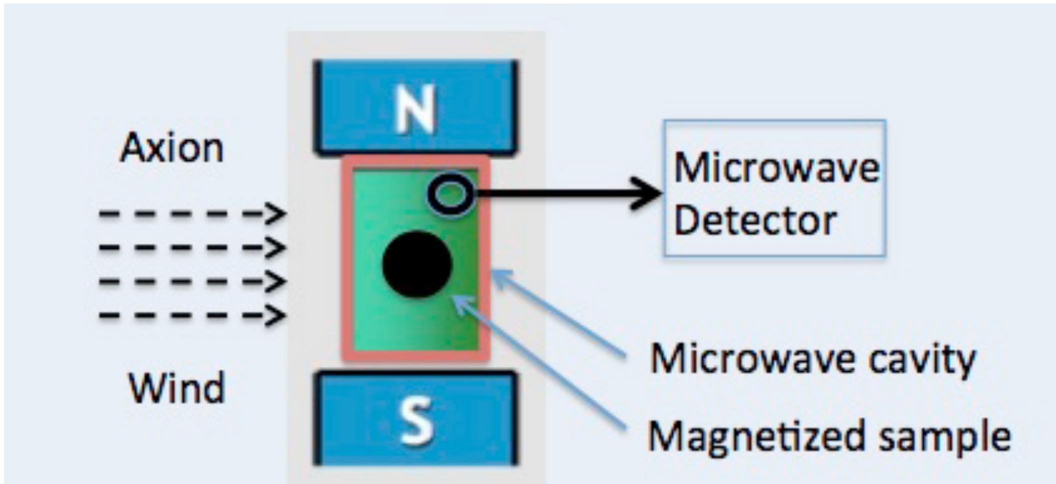
$$d \approx 10^{-16}\frac{a}{f_a}(e\cdot cm)$$

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

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

QUaerere AXions

QUAX collaboration



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 $w = m_a$

A simpler way to understand τ_R

Bloom 1957

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

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

About "radiation dumping"

Bloom 1957

Back to the transverse magnetization

(for axion wind only)

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

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

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

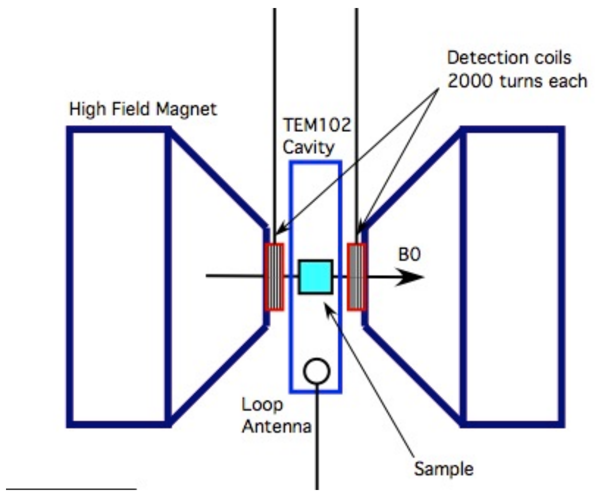
$$\tau_R = \frac{1}{\gamma^2 n_S w^3 V} \approx (\frac{10^{-4} eV}{w})^3 \frac{mm^3}{V} \frac{10^{22}/cm^3}{n_S} \times \begin{cases} 10^{-9}\ sec\ for\ EMR \\ 10^{-3}\ sec\ for\ NMR \end{cases}$$

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

$w \doteq 200\ Hz$

$\Rightarrow \tau_R$ seriously relevant for EMR

Working in a cavity



a = axion mode
c = cavity mode
m = magnon mode

(Sum over modes left understood)

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

$$g_{am}(ma^+ + m^+a) + g_{mc}(mc^+ + m^+c)$$

$$\gamma_c = 1/\tau_c$$
$$\gamma_a = 1/\tau_a$$
$$\gamma_m = 1/\tau_{rel}$$

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

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

$$i\dot{M} = [M, H] \qquad M = \begin{pmatrix} m \\ c \end{pmatrix}$$

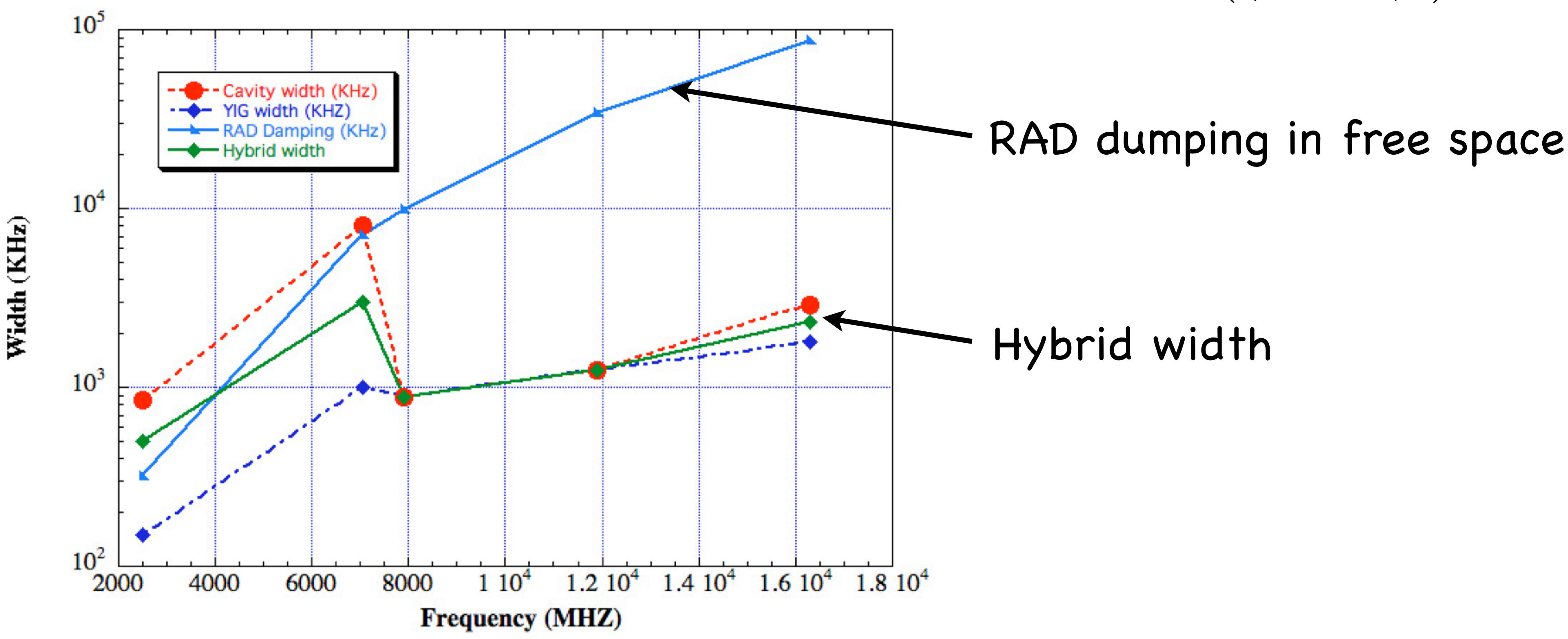
RF power exiting from the cavity

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

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

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

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



RF power and counting rate

Using realistic numbers for n_S and V

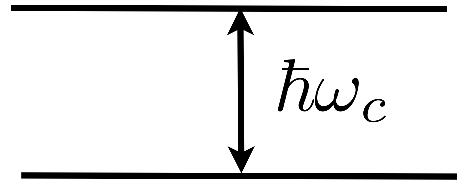
$$P_{out} \approx 10^{-25} Watt (\frac{n_s}{10^{22}/cm^3})(\frac{V}{10^3 cm^3})(\frac{\tau}{10^{-6} sec})(\frac{m_a}{2 \cdot 10^{-4} eV})^3$$

$$R_a = \frac{P_{\text{out}}}{\hbar\omega_a} = 2.6 \times 10^{-3} \left(\frac{m_a}{2 \cdot 10^{-4}\,\text{eV}}\right)^2 \left(\frac{V_s}{1\ \text{liter}}\right) \left(\frac{n_S}{10^{28}/\text{m}^3}\right) \left(\frac{\tau_{\text{min}}}{10^{-6}\,\text{s}}\right) \text{Hz}$$

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

Maximal expected sensitivity

Ultimate noise from the thermal bath



$$\bar{n} = \frac{1}{e^{\frac{\hbar\omega_c}{k_B T_c}} - 1} \qquad R_t = \bar{n}/\tau_c$$

Number of counts in a time t_m $\qquad N = \eta(R_a + R_t)t_m$

$$\mathrm{SNR} = \frac{\eta R_a t_m}{\sqrt{\eta(R_a + R_t)t_m}} = \frac{R_a}{\sqrt{R_a + R_t}}\sqrt{\eta t_m}$$

Given R_a above, for SNR > 3

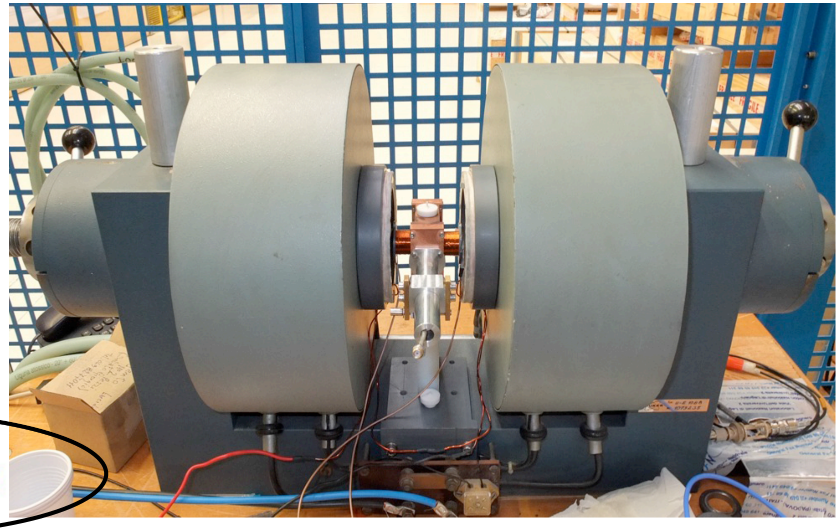
$$R_t < R_a\left(\frac{R_a \eta t_m}{\mathrm{SNR}^2} - 1\right) = 1.6\,R_a \sim 4 \times 10^{-3}\,\mathrm{Hz}$$

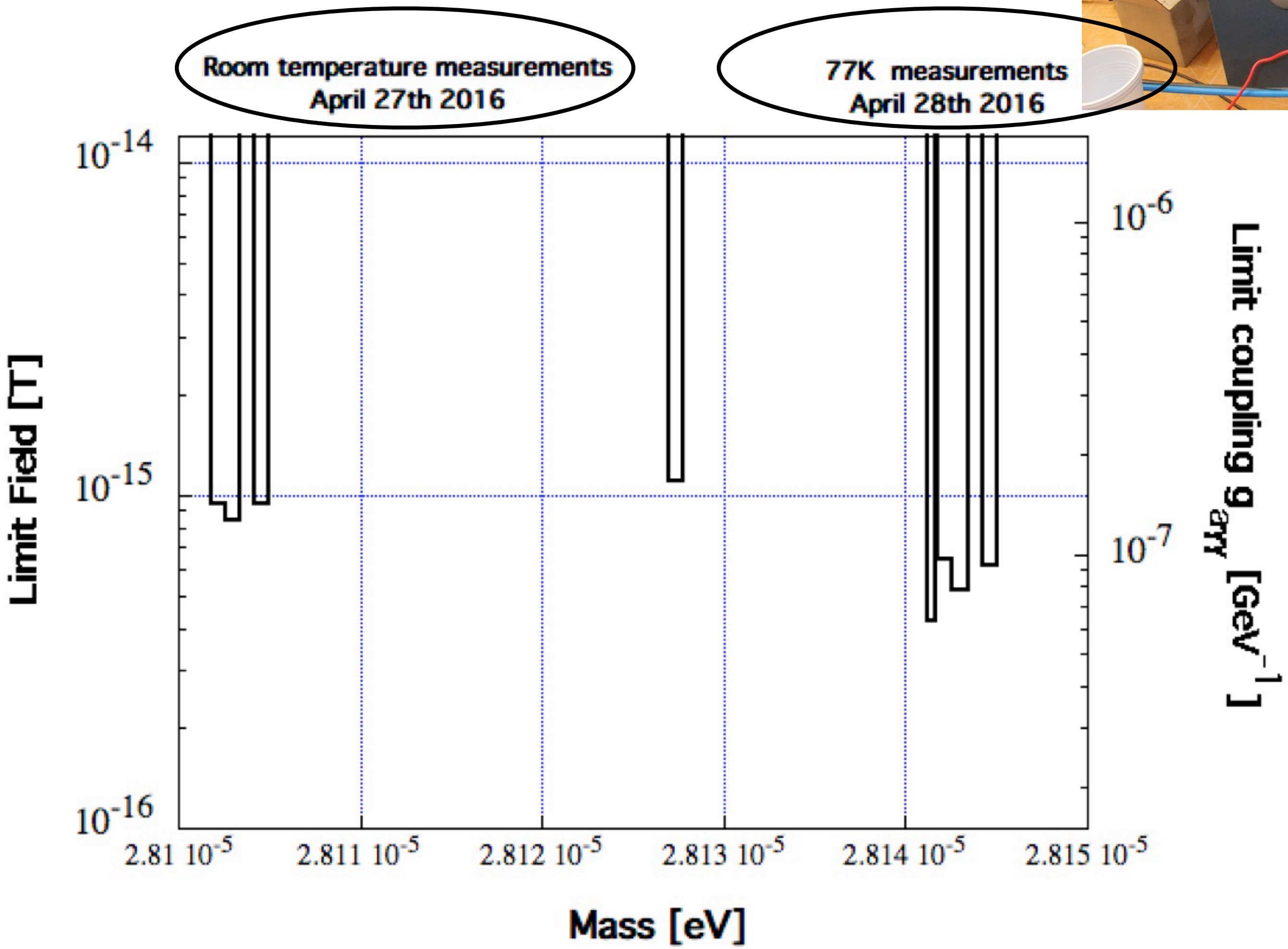
⇒ Working at $w = 48\ GHz$ and $\tau_c = 1\ \mu s$

requires $T_c < 130\ mK$

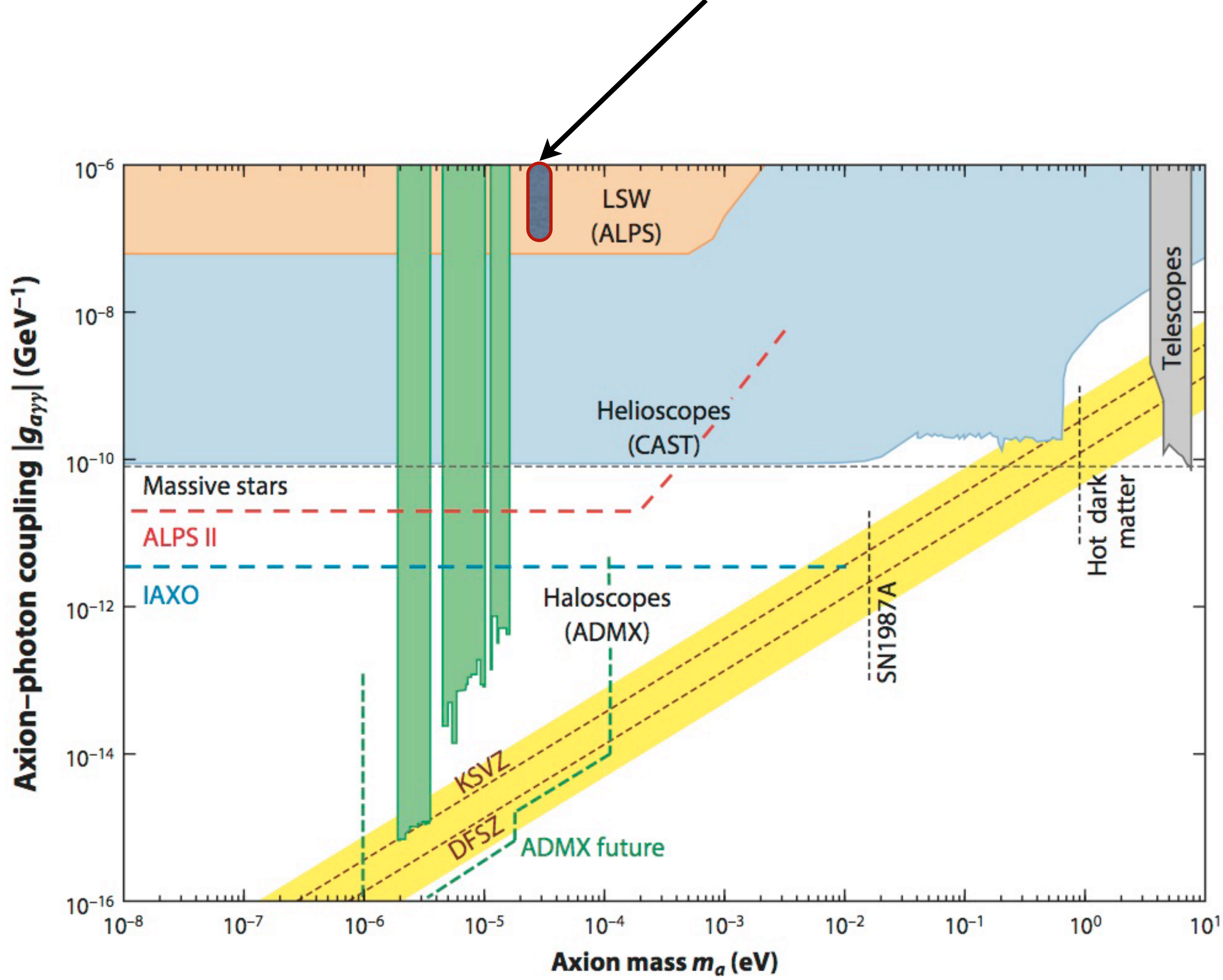
Some very preliminary measurements

Using a sphere of YIG of about $20\ mm^3$





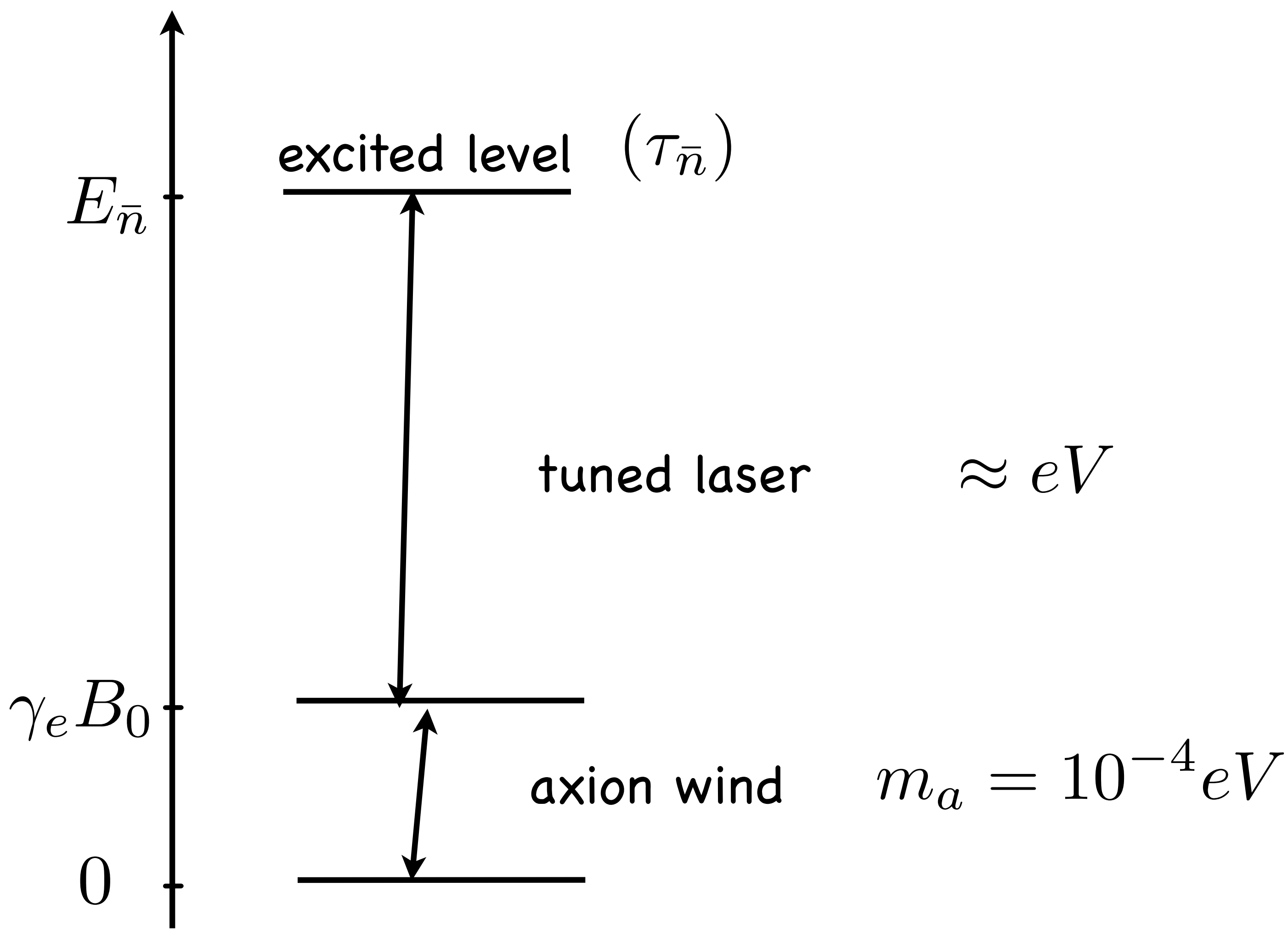
still a bit far from the desired sensitivity



Graham et al, 2106

Atomic transitions from DM wind

Sikivie 2014



Requires:

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

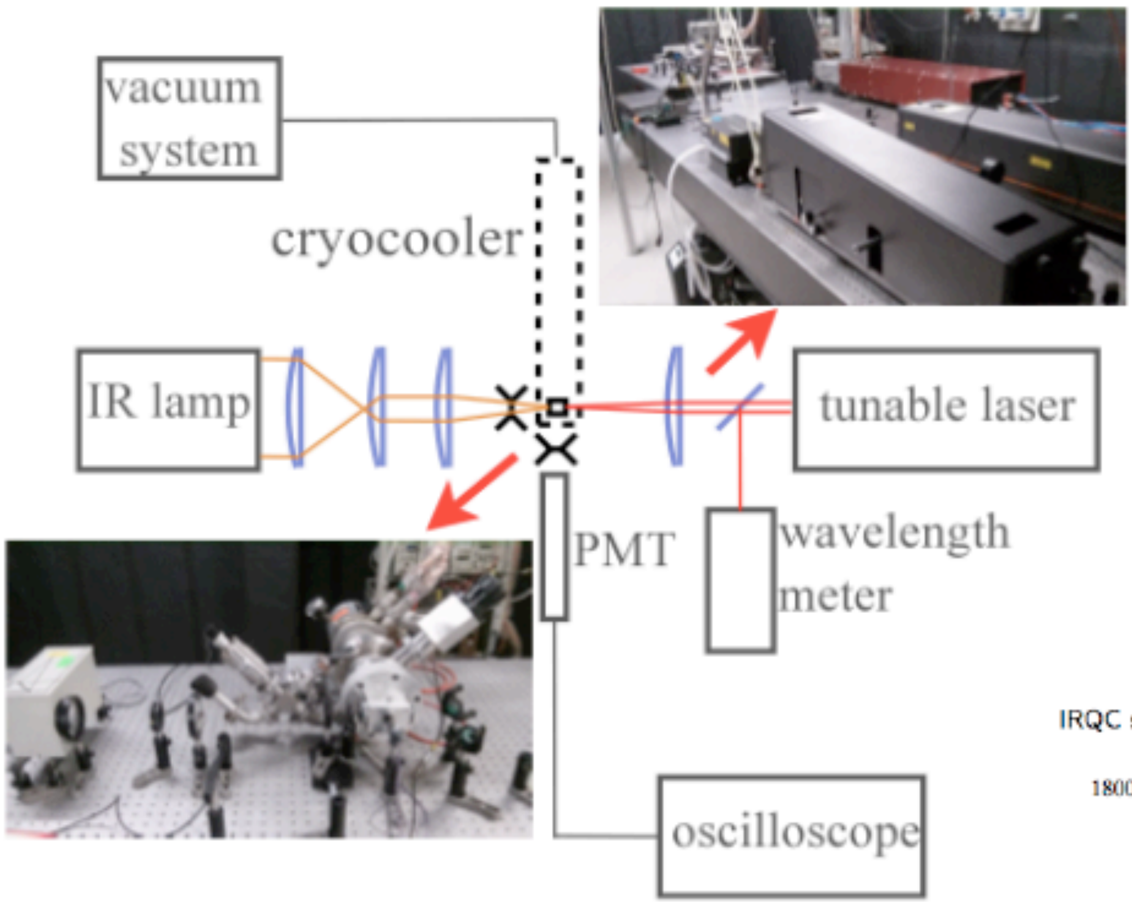
$$T \lesssim 10\ mK (\frac{m_a}{10^{-4} eV})$$

to depopulate the higher spin state in absence of axion wind

Photon rate from de-excited atoms:

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

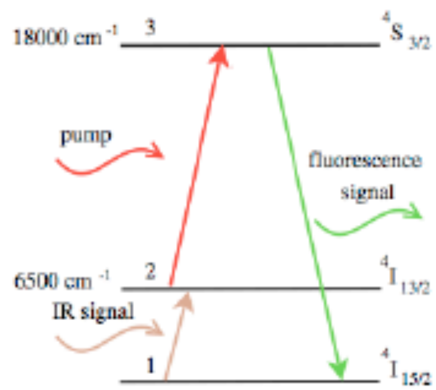
AXIOMA LAB @ LNL: FIRST RESULTS



features

- 10 K cryocooler;
- IR source (power~ 1 mW/nm);
- Ti:Sa laser → wavelength range 780-880 nm;

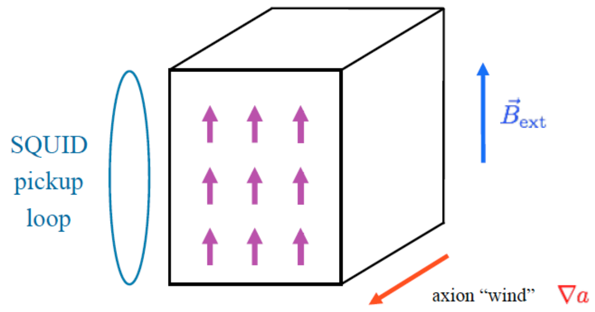
IRQC scheme in Er^{3+}



properties in YAG

- GSA absorption in 1450 ± 50 nm band;
- ~10 ms lifetime of $^4I_{13/2}$;
- pump wavelength ~839 nm;

(Some) proposed experiments using NMR/EMR

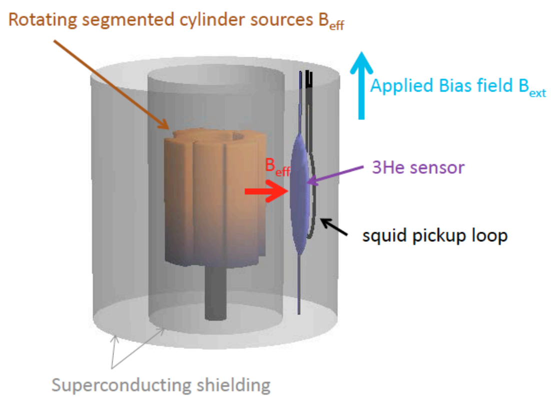


CASPEr axion wind/NMR

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

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

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

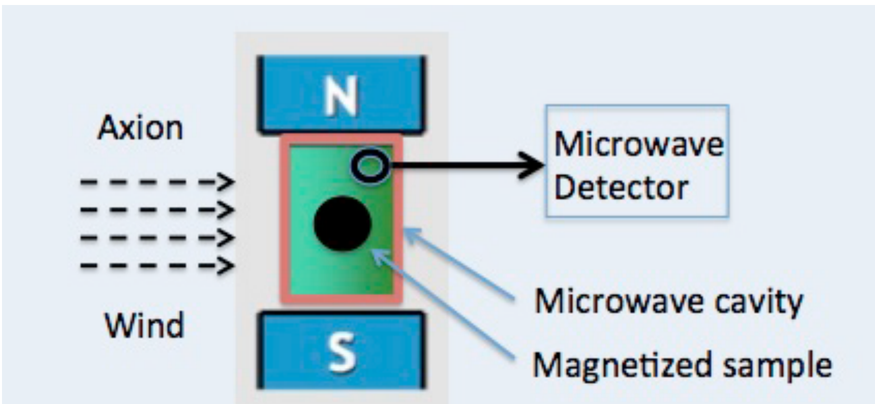


ARIADNE static source/NMR

frequency OK but effect smaller

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

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



QUAX axion wind/EMR

frequency OK

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

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

for question time