The Standard Model and (some of) its extensions

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Zuoz, August 14-20, 2016

I. The SM and its status, as of 2016

II. Problems of (questions for) the SM

III. Mirror Twin Higgs World

IV. Anomalies in B-decays

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

Axion searches by way of their coupling to the electron spin

Thanks to the QUAX collaboration

A quick introduction

1. Due to the triangle anomaly

$$\partial_\mu J_{\mu 5} = \alpha_S c_S G_{\mu\nu}\tilde{G}^{\mu\nu} + \alpha c_{EM} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

2. In spite of being a 4-divergence $\mathcal{L}_\theta = \theta G_{\mu\nu}\tilde{G}^{\mu\nu}$ is physical

3. Actually

$$\int d^4x \mathcal{L} \to \epsilon \int d^4x \partial_\mu J_{\mu 5}$$

$$\Rightarrow \theta_{eff} = \theta + argdet M_q$$

4. To solve the strong CP problem

Embed the chiral symmetry into an exact classical U(1)-symmetry (PQ) spontaneously broken at a scale f_a

DFSZ $$\mathcal{L} = \lambda S H_u H_d + Y_u \bar{Q} H_u u + Y_d \bar{Q} H_d d + Y_e \bar{Q} H_d e$$

KSVZ $$\mathcal{L} = \lambda S \bar{T} T + \bar{T}\gamma_\mu D_\mu T + M \bar{T} T$$

The axion a(x) is the corresponding (pseudoGB)

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$$\mathcal{L}_a = \frac{\partial_\mu a}{f_a} J^{PQ}_\mu + \frac{a}{f_a}\frac{\alpha_S}{8\pi} G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{a}{f_a}\frac{\alpha}{8\pi} c^0_{em} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$q \longrightarrow e^{i\gamma_5 \frac{a}{f_a} Q_a} q \qquad TrQ_a = 1$$

$$\mathcal{L}_a \rightarrow \frac{\partial_\mu a}{f_a}(J^{PQ}_\mu - \bar{q}\gamma_\mu\gamma_5 Q_a q) + \frac{a}{f_a}\frac{\alpha}{8\pi} c_{em} F_{\mu\nu}\tilde{F}^{\mu\nu} - \bar{q}_L \tilde{M}_q(a) q_R$$

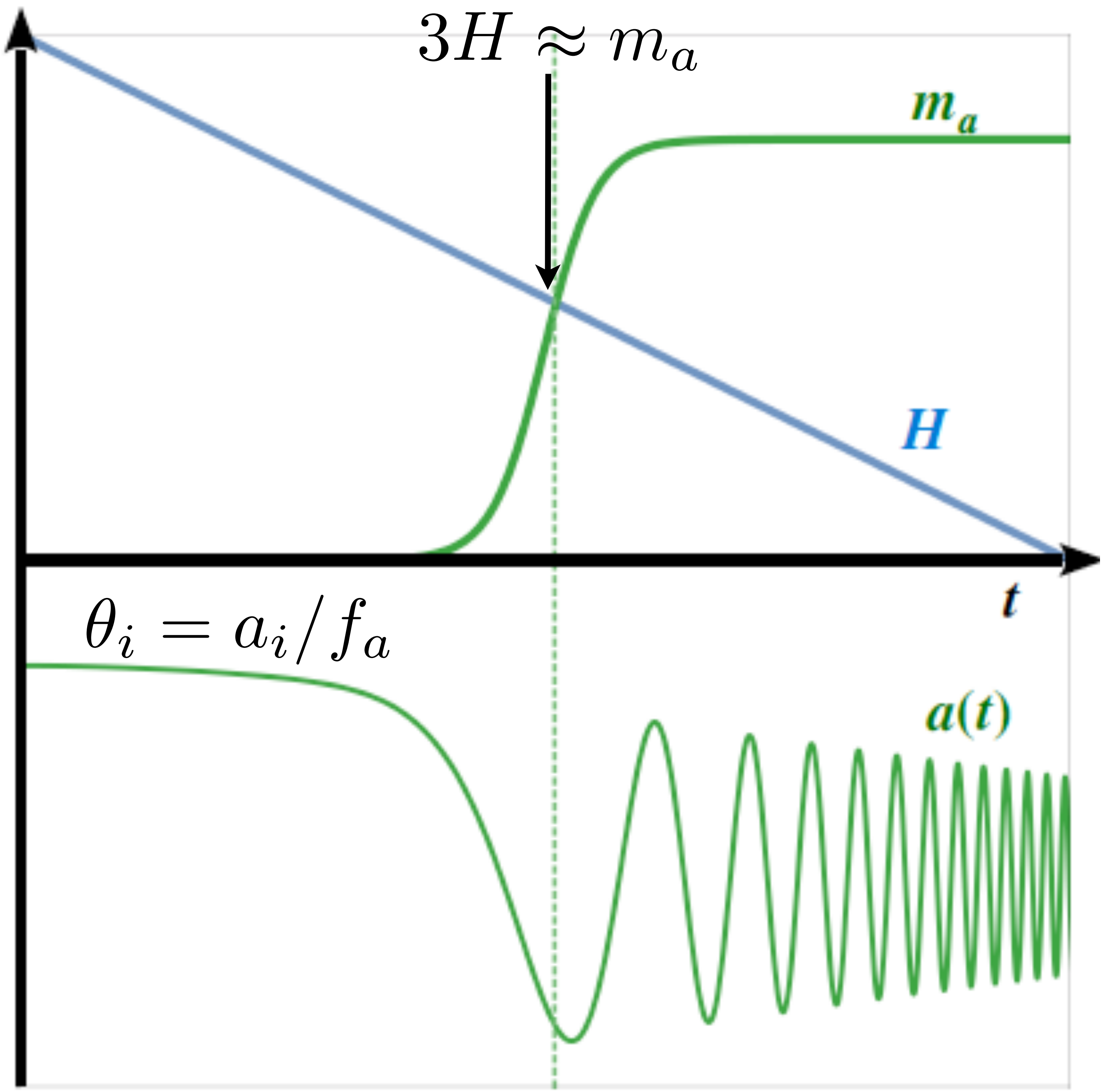
$$\tilde{M}_q(a) = e^{i\frac{a}{f_a}Q_a} M_q e^{i\frac{a}{f_a}Q_a}$$

$$V(a, \pi_0) \quad \Rightarrow$$

$$< a >= 0$$

$$m_a^2 = \frac{m_u m_d}{m_u + m_d}\frac{m_\pi^2 f_\pi^2}{f_a^2}$$

Relic abundance of the QCD axion



$$H = T^2/M_{Pl}$$

$$m_a$$

$T > \Lambda_{QCD}$: $\frac{m_\pi}{f_a}\left(\frac{\Lambda_{QCD}}{T}\right)^4$

$T < \Lambda_{QCD}$: $\frac{m_\pi}{f_a}$

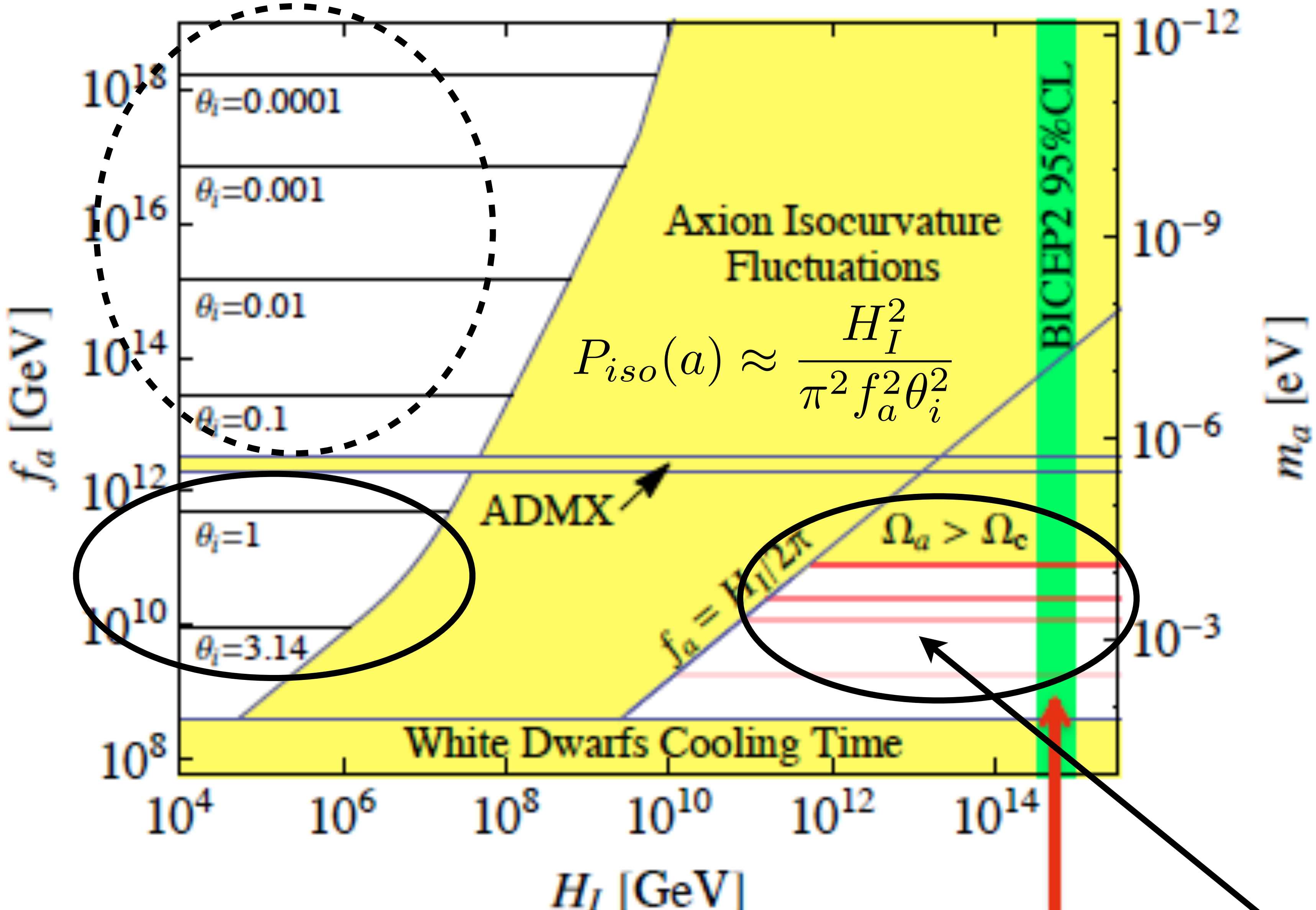
$$\rho_a = m_a^2 a^2 \propto T^3 \propto 1/R^3$$

i.e. cold Dark Matter

$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$

QCD Axions in cosmology

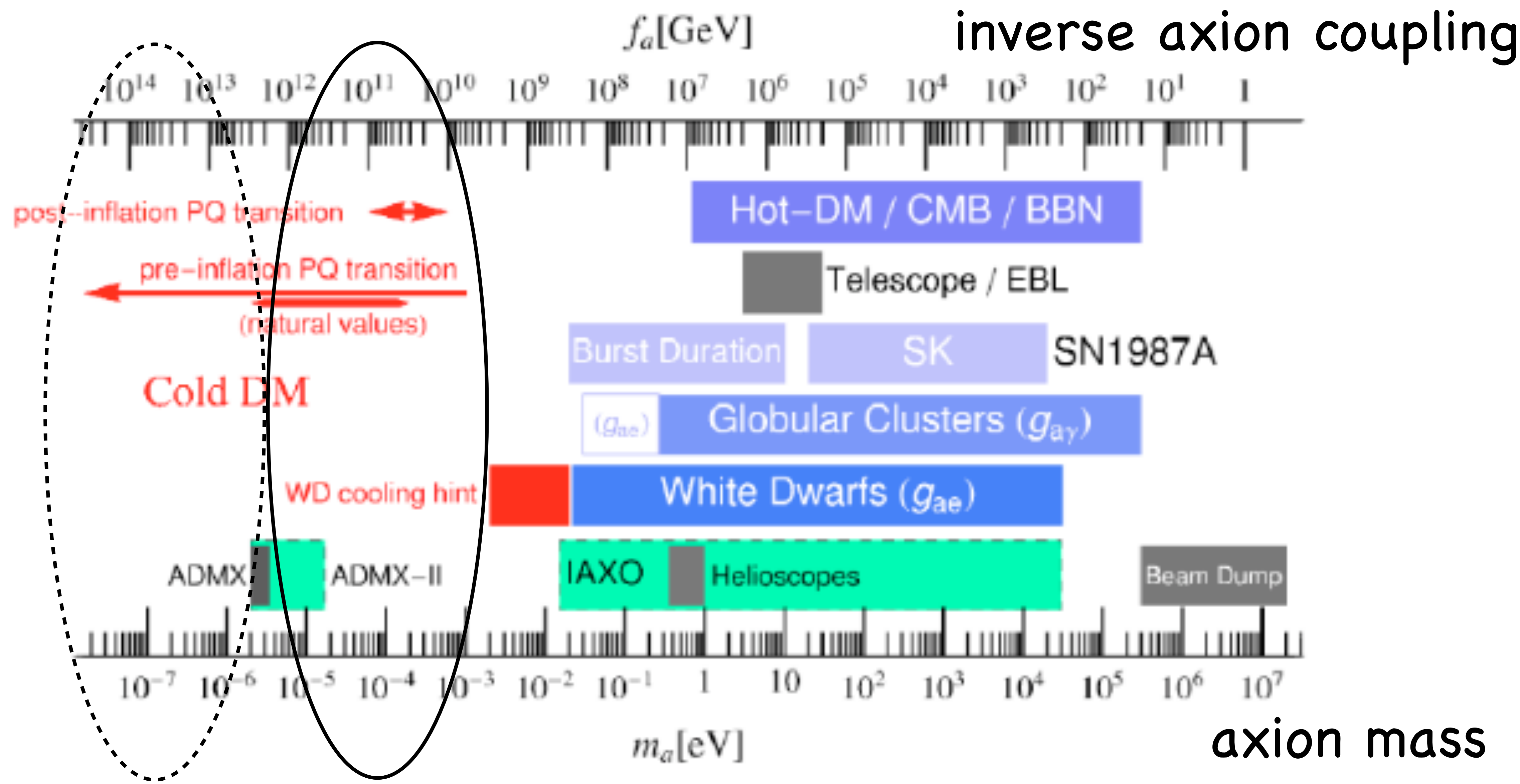
$$m_a f_a \approx 10^{-4}\ eV \cdot 10^{11} GeV$$



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

(Axion Like Particles: m and f unrelated)

The dynamical field, a, is the "axion"



Olive et al, 2104

and is very intensively searched for

(with the most interesting region still unaccessible)

The coupling to spin 1

$$L = \bar{\psi}(x)(i\hbar\not{\partial}_x - mc)\psi(x) - a(x)\bar{\psi}(x)(g_s + ig_p\gamma_5)\psi(x)$$

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

DFSZ $g_p(e) \approx 1$

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

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

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

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

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

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

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

1. By the DM axion wind

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

$m_a \approx 10^{-4} eV$ (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 $\lambda_a^C \approx \dfrac{1}{m_a v} \approx 10\ m$

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

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

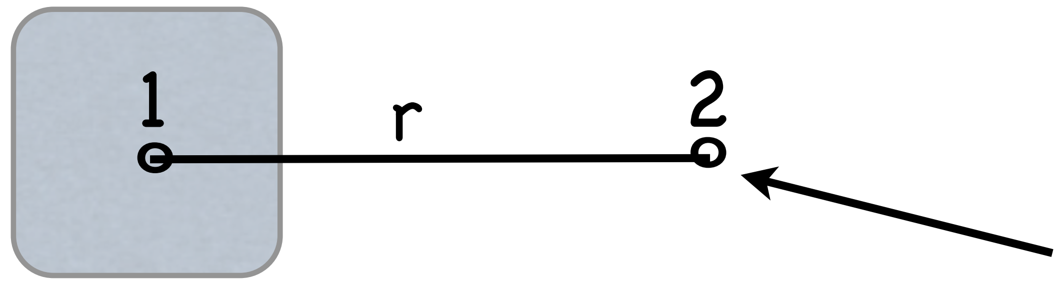
(on electrons)

(1000 bigger on nucleons)

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

2. From a static source

Moody, Wilczek 1984



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

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

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

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

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)

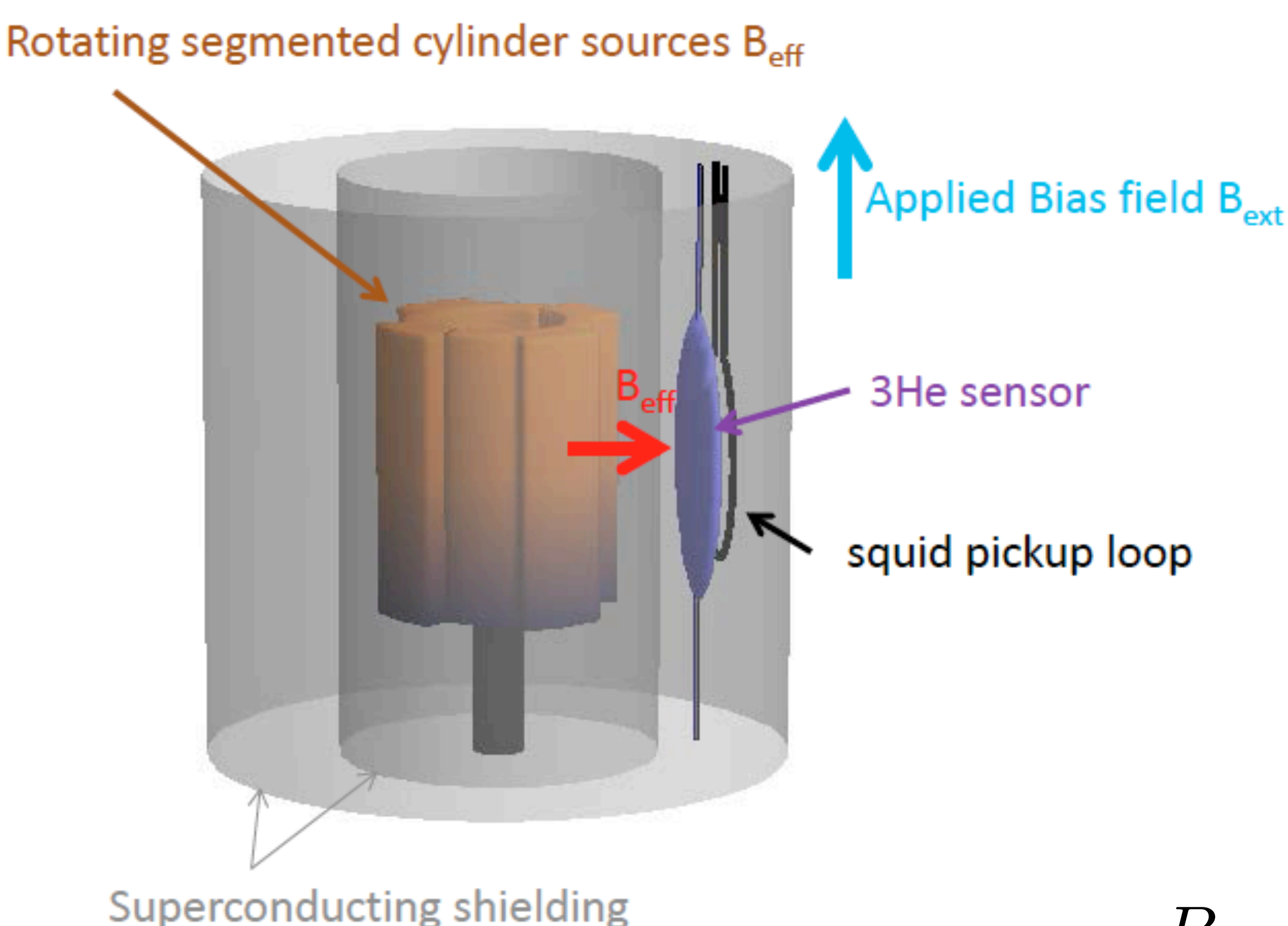
$$\Delta(g-2)_e < 10^{-13} \ \Rightarrow \ \gamma_e B \lesssim 10^{-17} eV \frac{B}{5\ Tesla}$$

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

Need to work on some resonant phenomenon

Proposal 1 (a static force from a rotating source)

Arvanitaki, Geraci 2014

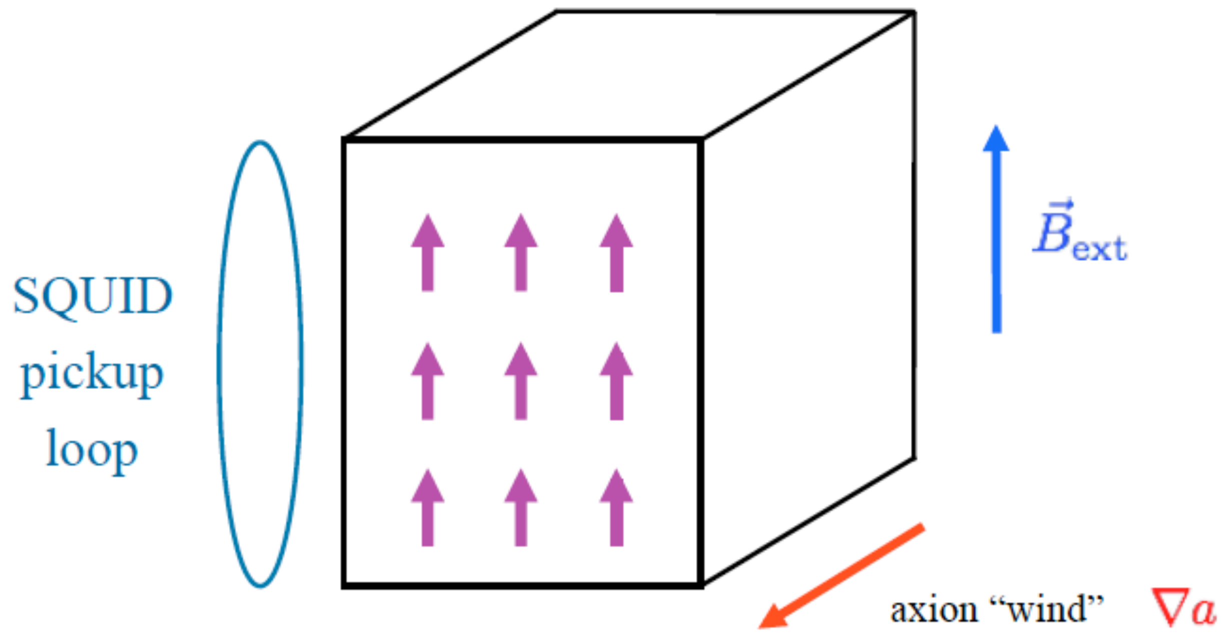


!! $w = 200\ Hz$!!

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

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

Proposal 2 (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

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

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

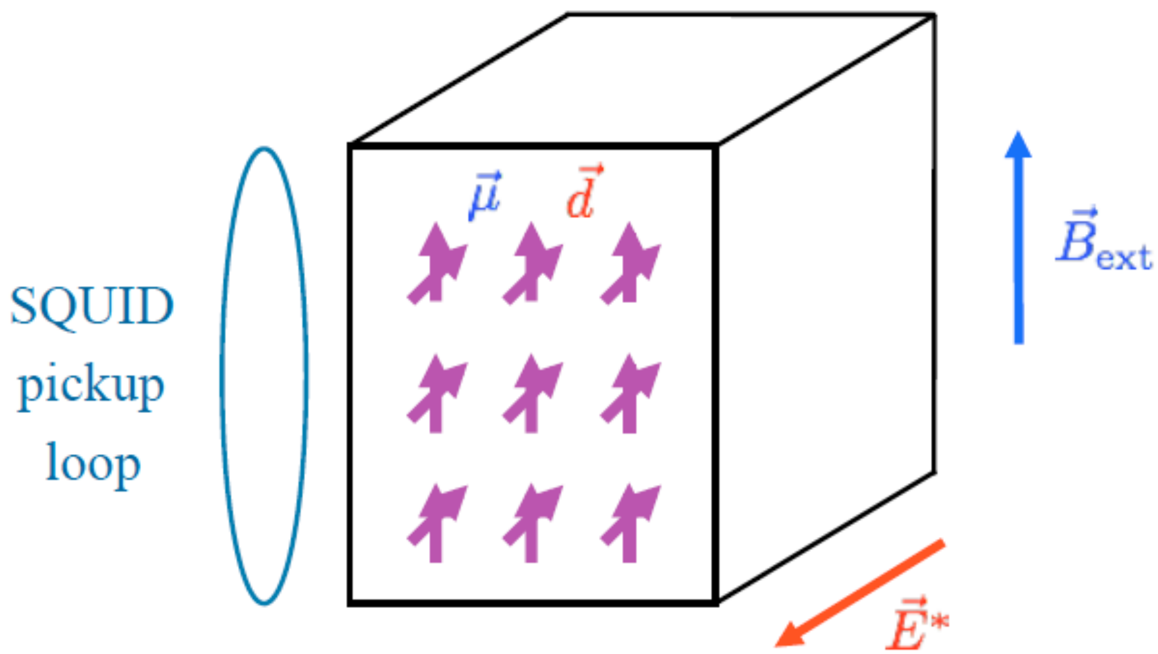
$$M_T = \gamma_{e,N}^2 B_{e,N}^{eff} n_S \tau \cos(m_a t) \begin{cases} \xrightarrow{N} \; 10^{-19} T \ (m_a = 10^{-7}\ eV,\ \tau = 0.1\ sec) \\ \xrightarrow{e} \; 10^{-21} T \ (m_a = 10^{-4}\ eV,\ \tau = 10^{-6}\ sec) \end{cases}$$

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

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

On the same line (axion DM wind in NMR)

Graham, Rajendram 2010
CASPEr 2014



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

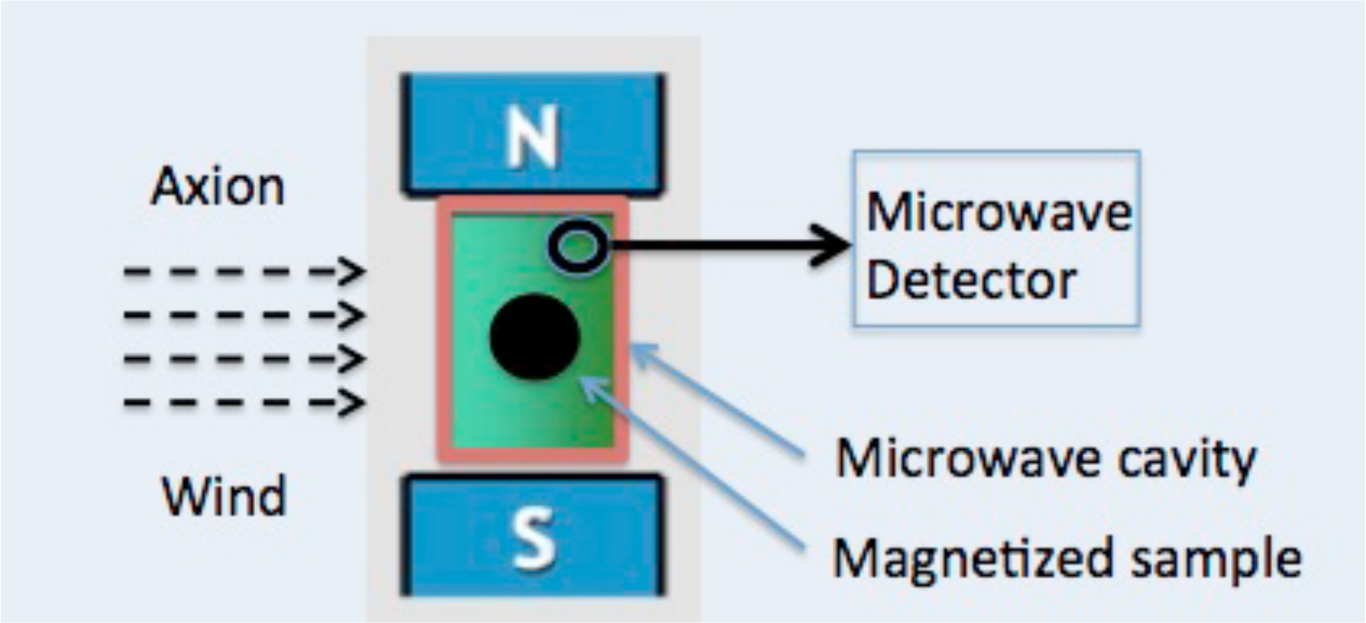
$$d \approx 10^{-16}\frac{a}{f_a}(e\cdot cm)$$

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

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

QUaerere AXions

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 $w = m_a$

About "radiation dumping"

Bloom 1957

Back to the transverse magnetization

(for axion wind only)

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

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

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

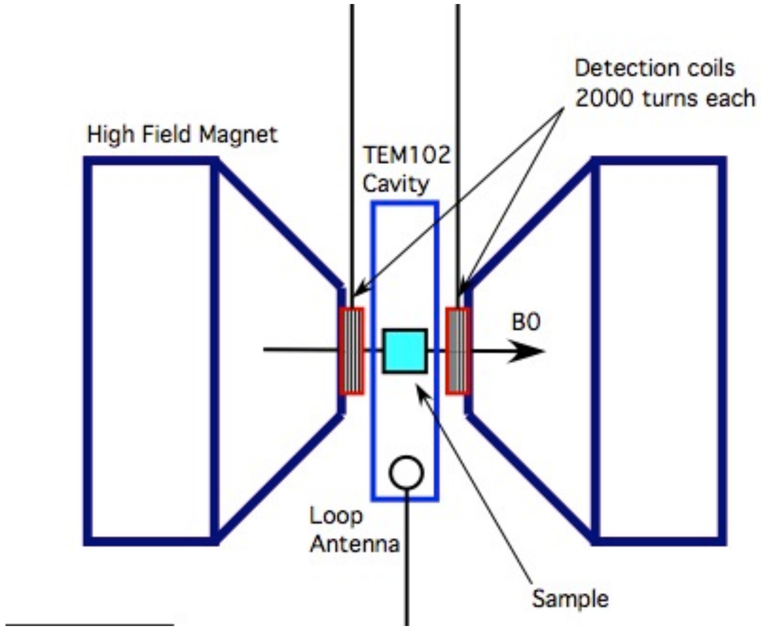
$$\tau_R = \frac{1}{\gamma^2 n_S w^3 V} \approx (\frac{10^{-4} eV}{w})^3 \frac{mm^3}{V} \frac{10^{22}/cm^3}{n_S} \times \begin{cases} 10^{-9} \; sec \; for \; EMR \\ 10^{-3} \; sec \; for \; NMR \end{cases}$$

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

$w = 200 \; Hz$

$\Rightarrow \tau_R$ seriously relevant for EMR

Working in a cavity



a = axion mode

c = cavity mode

m = magnon mode

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

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

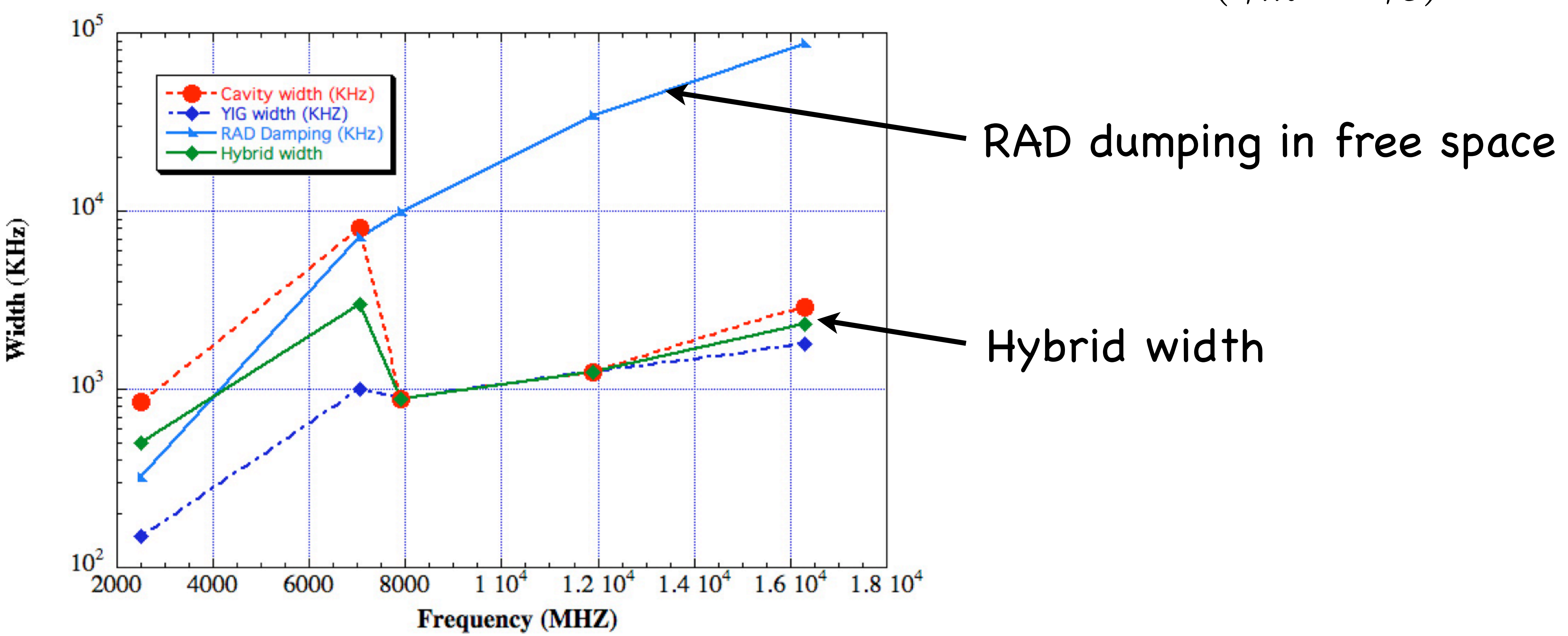
magnon-cavity mode coupling $\quad g_{mc} = \frac{e}{m_e}(n_S w_c V/V_c)^{1/2}$

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 $f(w_a = w_{m/c} \pm g_{mc}) = \frac{4\gamma_m \gamma_c}{(\gamma_m + \gamma_c)^2}$



RF power and counting rate

Using realistic numbers for n_S and V

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

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

Maximal expected sensitivity

Ultimate noise from the termal 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

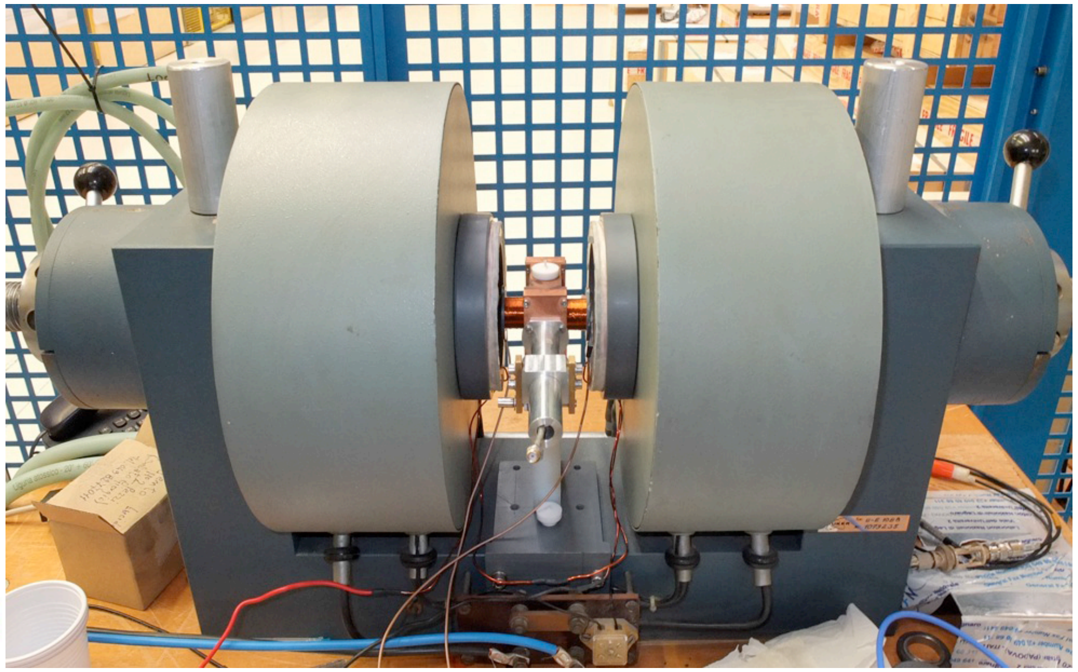
$$R_t < R_a \left(\frac{R_a \eta t_m}{\mathrm{SNR}^2} - 1 \right) = 1.6\, R_a \sim 4 \times 10^{-3}\,\mathrm{Hz}$$

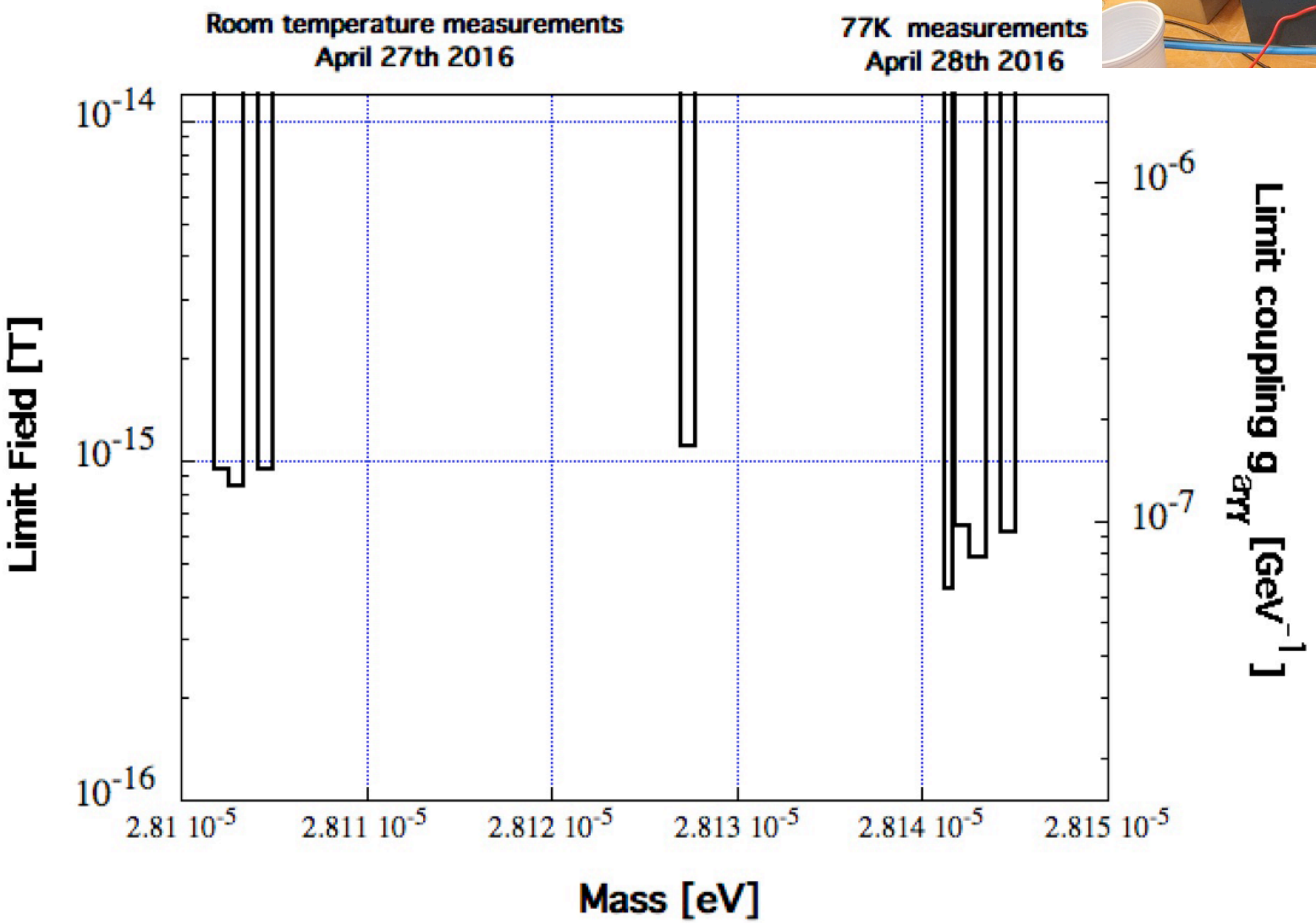
⇒ Working at $w = 48\ GHz$ and $\tau_c = 1\ \mu s$

requires $T_c < 13\ mK$

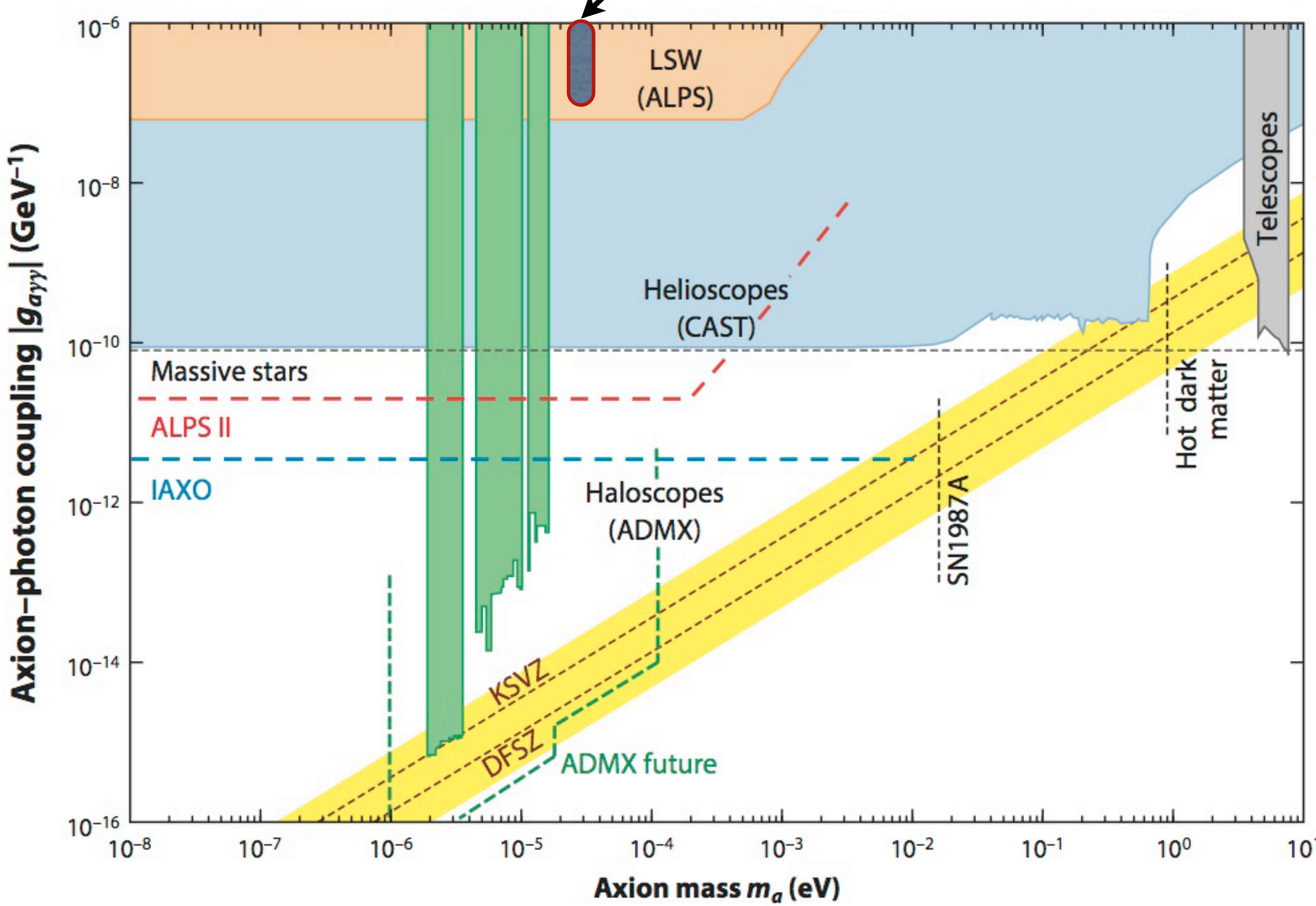
Some very preliminary measurements

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





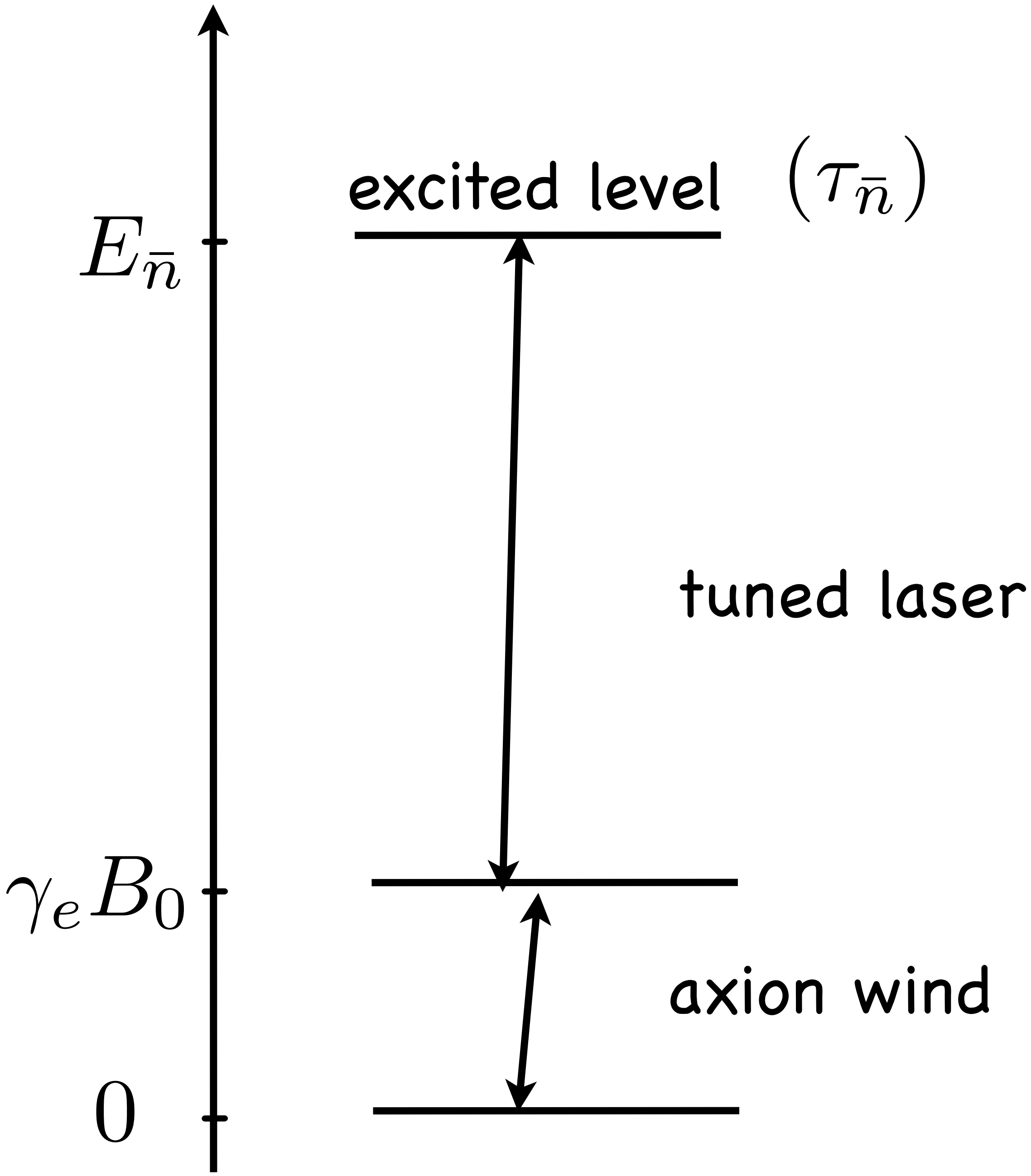
still a bit far from the desired sensitivity



Graham et al, 2106

Atomic transitions from DM wind

Sikivie 2014



$\approx eV$

$m_a = 10^{-4} eV$

Requires:

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

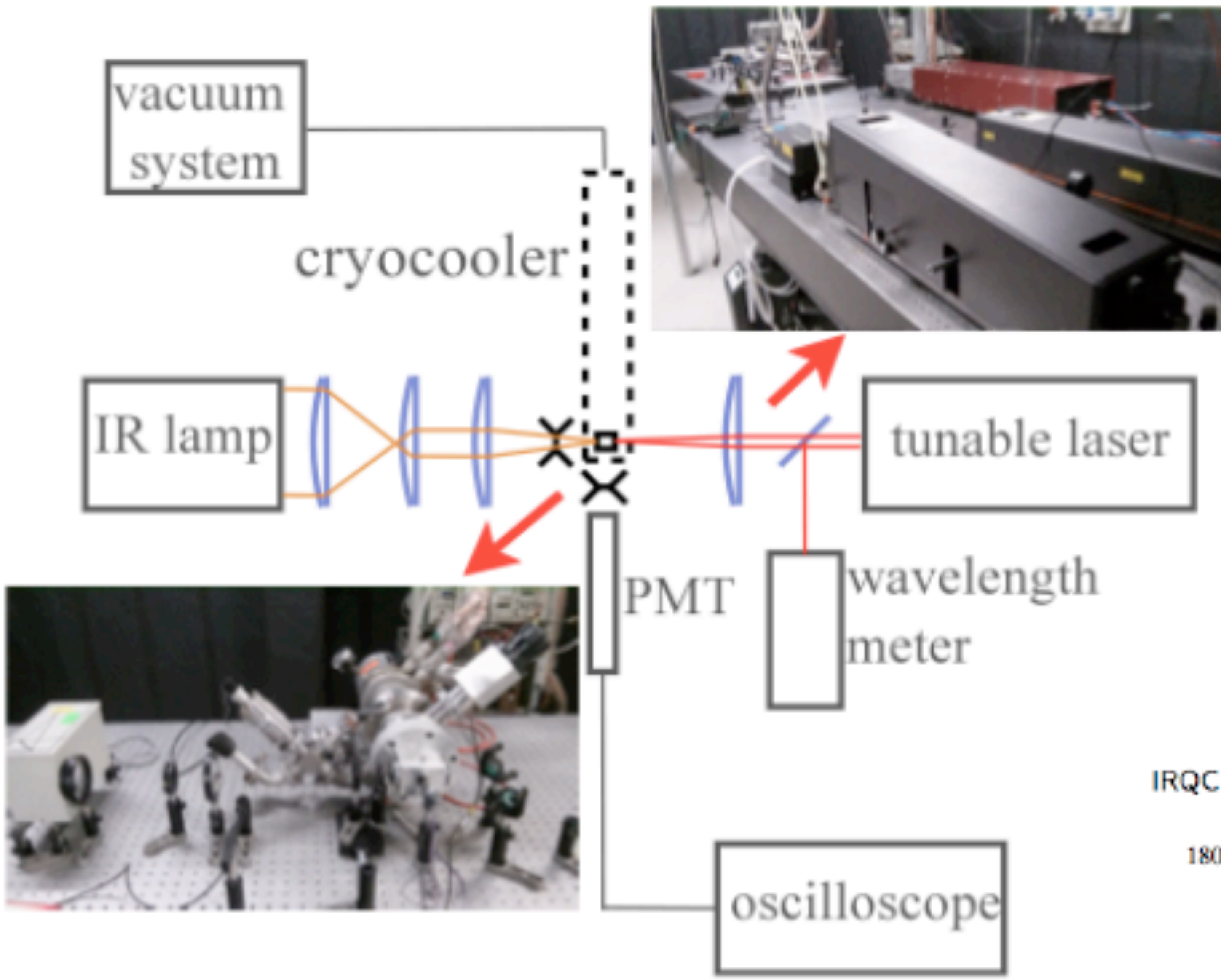
$$T \lesssim 10 \; mK (\frac{m_a}{10^{-4} eV})$$

to depopulate the higher spin state in absence of axion wind

Photon rate from de-excited atoms:

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

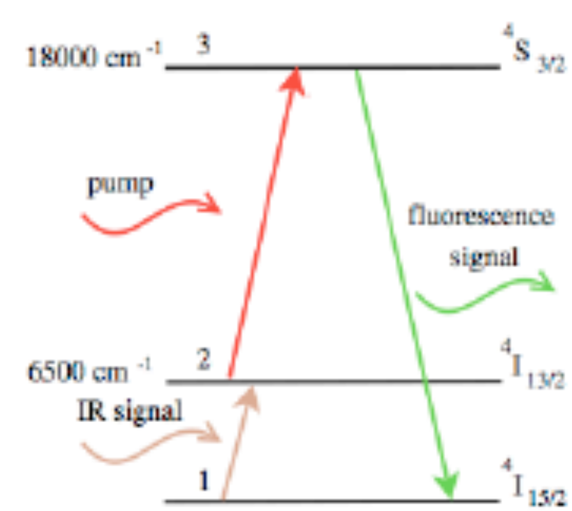
AXIOMA LAB @ LNL: FIRST RESULTS



features

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

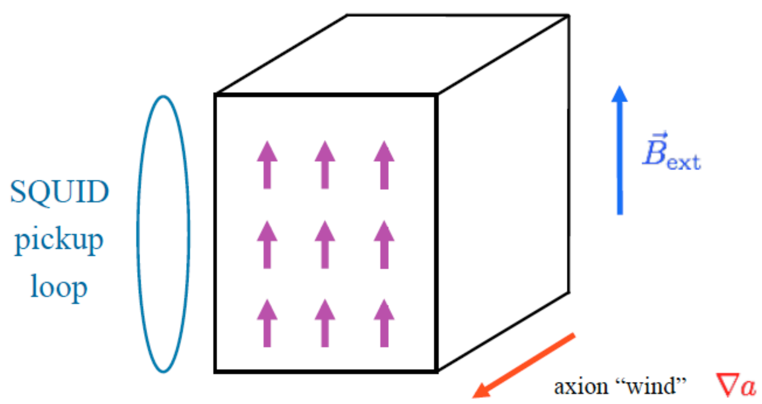
IRQC scheme in Er^{3+}



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

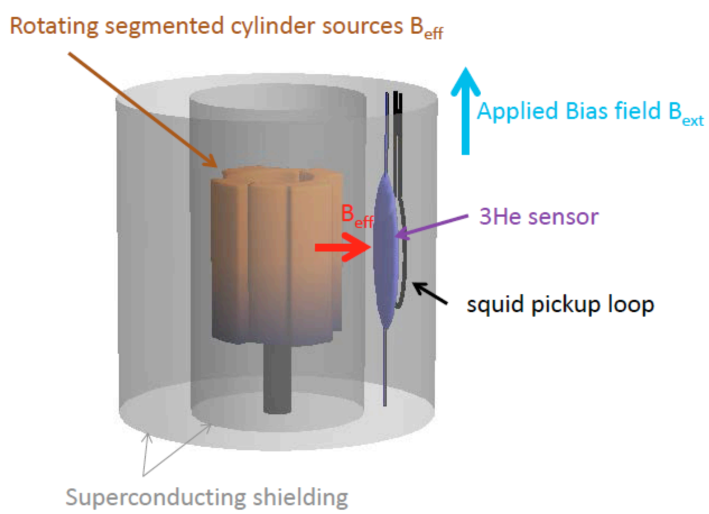


CASPEr axion wind/NMR

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

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

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

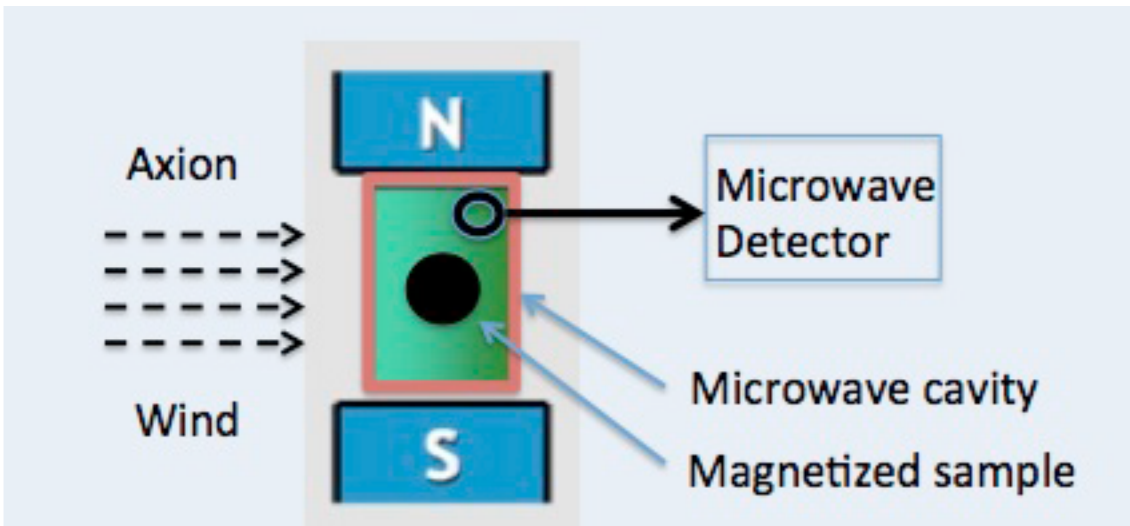


ARIADNE static source/NMR

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

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

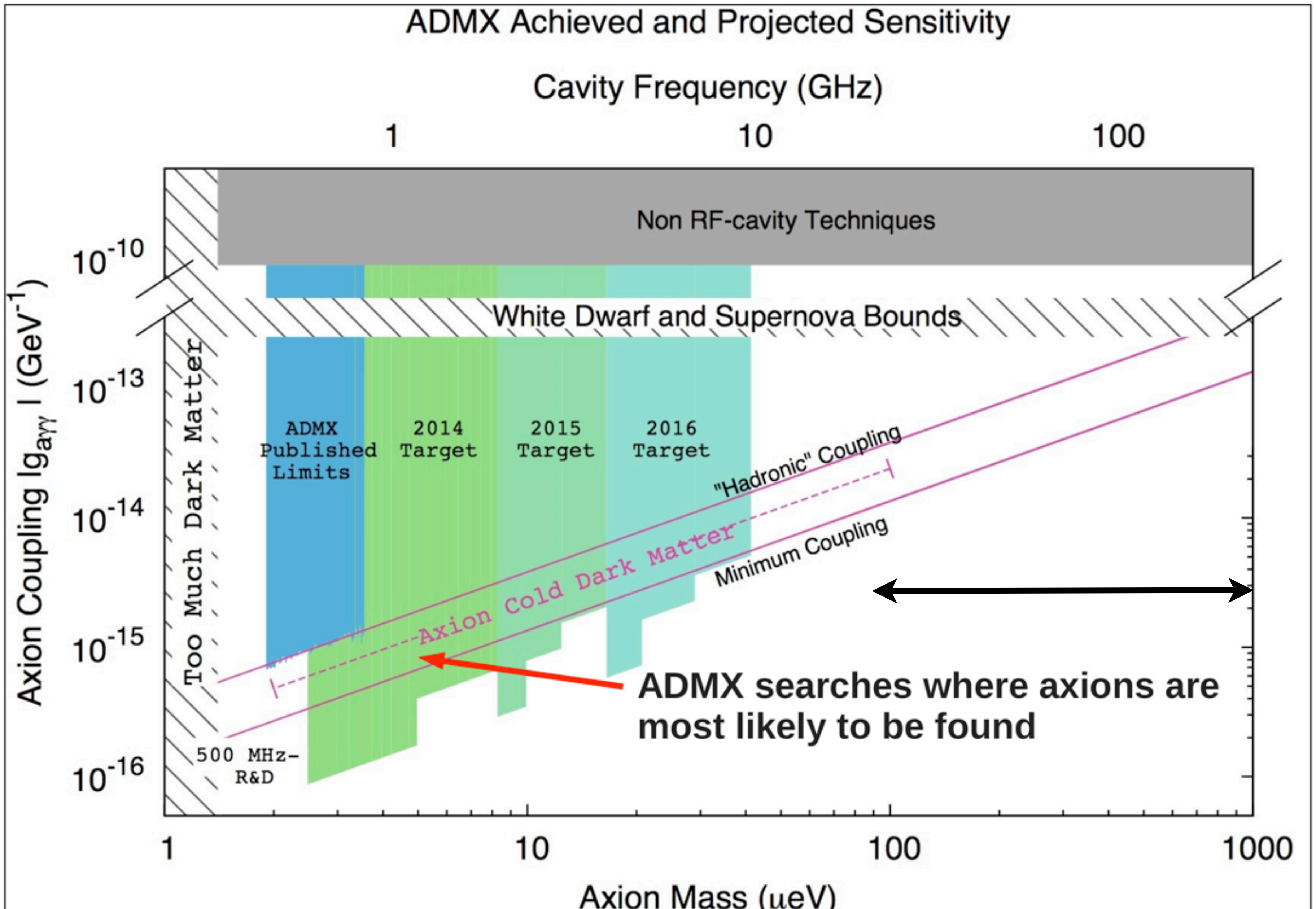
$$M_T = \gamma^2 B_T n_S \tau$$

Energy conservation

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

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