QUAX and AXIOMA: new experimental methods in axion detection

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June 20, 2016

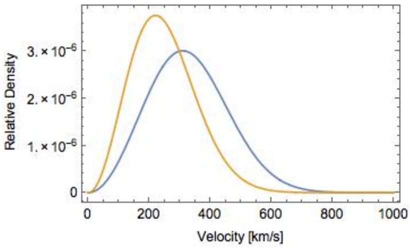
RELEVANT PROPERTIES OF THE AXION BACKGROUND

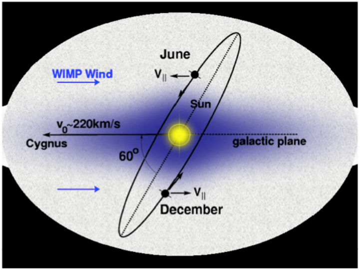
FROM Λ CDM COSMOLOGY

- hp: axionic DM
- cold DM $\longleftrightarrow$ coherent axion field filling the Universe
- cosmic axion density $\rho_{DM} \sim 300\,\text{MeV/cm}^3 \longrightarrow n_a \sim 3 \times 10^{12}\ (10^{-4}\ \text{eV}/m_a)$ axions/cm^3
- axion velocities are distributed according to a Maxwellian distribution $f(v) = 4\pi \left(\frac{\beta}{\pi}\right)^3 /2v^2 \exp(-\beta v^2)$, with $\beta = \frac{3}{2\sigma_v^2}$, σ_v velocity dispersion [Turner]
- + motion of E in the galaxy $\longrightarrow$ they can be seen as a wind with $v \sim 10^{-3}\,c$
- natural figure of merit of the axion linewidth $Q_a \approx 2 \cdot 10^6$
- De Broglie wavelength $\lambda \simeq \frac{\hbar}{m_a v_a} \simeq 13.8 \left(\frac{10^{-4}\text{eV}}{m_a}\right)$ m
  $\Longrightarrow \lambda \gg$ typical length of an experimental apparatus
- **DFSZ** – (Zhitnitskii 1980; Dine, Fischler, and Srednicki, 1981a, 1981b)

THE AXION WIND AS AN EFFECTIVE MAGNETIC FIELD

The axion velocities v are distributed according to a Maxwellian distribution with a velocity dispersion $\sim 270\,\text{km/sec}$ (in the rest frame of the Galaxy).





The Earth-based laboratory is moving through the local axion cloud with a time varying velocity $v_E = v_S + v_O + v_R$

v_S Sun velocity in the galactic rest frame (magnitude 230 km/sec)
v_O Earth's orbital velocity around the Sun (magnitude 29.8 km/sec)
v_R Earth's rotational velocity (magnitude 0.46 km/sec)
$\Longrightarrow v_a = v - v_E$

M. S. Turner, Phys. Rev. D, **42** 3572 (1990)

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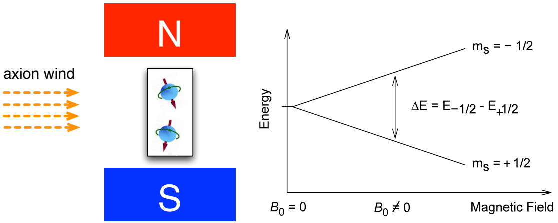
QUAX

INTERACTION OF THE AXION FIELD WITH A MAGNETIZED SAMPLE

- axion-electron coupling
- the axion DM acts as as **effective RF magnetic field** on the electron spin
- the magnetized sample behaves as an RF receiver tuned at the Larmor frequency
- the equivalent magnetic RF field excites a **transition** in the magnetized sample
  $\longrightarrow$ **variation in the magnetization**



L. M. Krauss, J. Moody, F. Wilczek, D.E. Morris, *Spin coupled axion detections* (1985)

R. Barbieri, M. Cerdonio, G. Fiorentini, S. Vitale, Phys. Lett. B **226**, 357 (1989)

A.I. Kakhizde, I.V. Kolokolov, Sov. Phys, JETP **72** 598 (1991)

THE AXION WIND AS AN EFFECTIVE MAGNETIC FIELD

The interaction of a spin 1/2 particle with the axion field $a(x)$ is described by the Lagrangian:

$$L = \bar{\psi}(x)(i\hbar\gamma^{\mu}\partial_{\mu} - mc)\psi(x) - ig_p a(x)\bar{\psi}(x)\gamma_5\psi(x)$$

$\psi(x)$ is the spinor field of the fermion with mass m

γ^{μ} are the 4 Dirac matrices, $\gamma^5 = i\gamma^0\gamma^1\gamma^2\gamma^3$

g_p dimensionless pseudo-scalar coupling constant

Non-relativistic limit of the Euler-Lagrange equation:

$$i\hbar\frac{\partial\varphi}{\partial t} = \left[-\frac{\hbar^2}{2m}\nabla^2 - \frac{g_p\hbar}{2m}\boldsymbol{\sigma}\cdot\boldsymbol{\nabla}a\right]\varphi\,,$$

$$-\frac{g_p\hbar}{2m}\boldsymbol{\sigma}\cdot\boldsymbol{\nabla}a \equiv -2\frac{e\hbar}{2m}\boldsymbol{\sigma}\cdot\left(\frac{g_p}{2e}\right)\boldsymbol{\nabla}a$$

$-2\mu_B\boldsymbol{\sigma}$,

μ_B the Bohr magneton

$$B_a \equiv \frac{g_p}{2e}\boldsymbol{\nabla}a$$

effective magnetic field

THE AXION WIND AS AN EFFECTIVE MAGNETIC FIELD

In the E lab the effective axion microwave field has a mean amplitude

$$B_a = 9.2 \cdot 10^{-23} \left(\frac{m_a}{10^{-4}\text{eV}} \right) \text{ T}$$

and central frequency

$$\frac{\omega_a}{2\pi} = 24 \left(\frac{m_a}{10^{-4}\text{eV}} \right) \text{ GHz},$$

The value of the static B_0 field determines the Larmor frequency and therefore the axion mass probed

R. Barbieri *et al*,
“Searching for galactic axions through magnetized media: the QUAX proposal”
http://arxiv.org/abs/1606.02201

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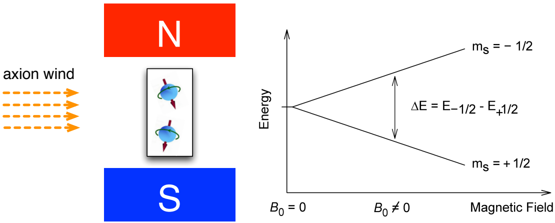

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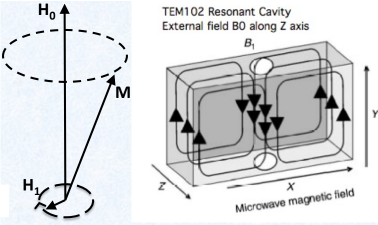
THE EXPERIMENTAL TECHNIQUE: EPR/ESR – FMR

Magnetic resonance arises when energy levels of a quantized system of electronic moments are **Zeeman split** ($\Longleftrightarrow$ the magnetic system is placed in a uniform magnetic field B_0) and the system absorbs EM radiation in the microwave range.

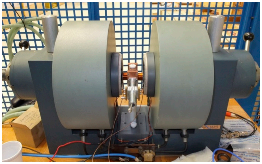
An experimental geometry with **crossed magnetic fields** is needed:

- B_0 along z
- a microwave field is applied to the xy plane sum of two counter-rotating fields $2A\cos\omega t = A(e^{i\omega t} + e^{-i\omega t})$
- resonance occurs when the Larmor precession of the magnetic moment is synchronized with the clockwise or anticlockwise component
- no resonance occurs when the AC field is parallel to B_0

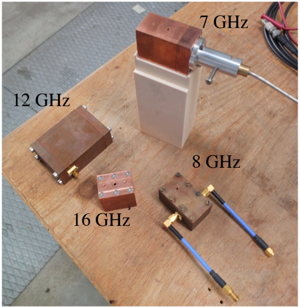


THE EXPERIMENTAL TECHNIQUE: EPR/ESR – FMR

The Larmor precession frequency for electron spin is $f_L = \omega_L/2\pi = \frac{ge}{4\pi m_e}B$, where $\gamma = \frac{ge}{4\pi m_e}$=28 GHz/T $\rightarrow$ X-band microwaves (~ 9 GHz, $\lambda = 3$ cm) determine a resonance at about 300 mT).



free field



cavity

In a **ferromagnet** the magnetization is largely due to the spin moments of the electrons, thus resonant frequencies for FMR are similar to those for EPR.

A CRUCIAL ISSUE: THE RADIATION DAMPING MECHANISM

The dynamics of the magnetic sample is well described by its magnetization **M**, whose evolution is given by the Bloch equations with dissipations and radiation damping:

$$\begin{aligned} \frac{dM_x}{dt} &= \gamma(\mathbf{M}\times\mathbf{B})_x - \frac{M_x}{\tau_2} - \frac{M_x M_z}{M_0\tau_r} \\ \frac{dM_y}{dt} &= \gamma(\mathbf{M}\times\mathbf{B})_y - \frac{M_y}{\tau_2} - \frac{M_y M_z}{M_0\tau_r} \\ \frac{dM_z}{dt} &= \gamma(\mathbf{M}\times\mathbf{B})_z - \frac{M_0 - M_z}{\tau_1} - \frac{M_x^2 + M_y^2}{M_0\tau_r}, \end{aligned} \tag{1}$$

τ_r = radiation damping time

τ_1 = longitudinal (or spin-lattice) relaxation time

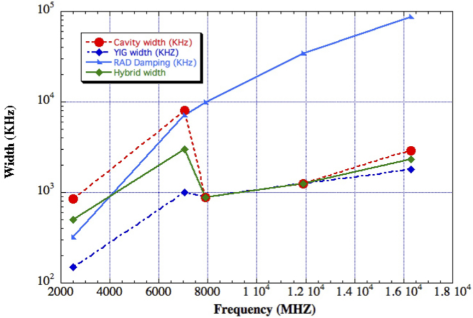
τ_2 = transverse (or spin-spin) relaxation time

The damping term related to τ_r affects the *maximum allowed coherence* hence the integration time of the magnetic system with respect to the axion driving input

SOLUTION TO THE RADIATION DAMPING LIMITATION

In a free field environment and for $f \gtrsim$ GHz, radiation damping is dominated by the magnetic dipole emission from the magnetized sample of volume V_s

$$\tau_r = 4\pi \frac{c^3}{\omega_L^3} \frac{1}{\gamma \mu_0 M_0 V_s}$$



SOLUTION: the magnetic detecting material is embedded inside a microwave cavity in the **strong coupling regime**

$\Longrightarrow$ the limited phase space of the resonator inhibits the damping mechanism $\tau_{\min} = \min(\tau_a, \tau_2, \tau_c)$, where τ_c is the cavity decay time

RADIATION DAMPING IN CAVITIES

A fourth equation is added to the Bloch equations to account for the cavity dynamics.
N. Bloembergen and R. V. Pound, Phys. Rev. **95**, 8 (1954)

$$\begin{aligned} \frac{dM_x}{dt} &= \gamma M_y B_0 - \frac{M_x}{\tau_2} \\ \frac{dM_y}{dt} &= \gamma(M_z K I - M_x B_0) - \frac{M_y}{\tau_2} \\ \frac{dM_z}{dt} &= -\gamma K' I M_y - \frac{M_0 - M_z}{\tau_1} \\ L\frac{dI}{dt} &= K\frac{dM_x}{dt} - RI - \frac{1}{C}\int^t I dt + V_{\mathrm{rf}} \end{aligned}$$

RLC cavity parameters

mode of frequency $\omega_c = (LC)^{-1/2}$

$I = B_1/K'$ is the equivalent current generating B_1 field

K is the coupling between the magnetization and the equivalent current

K and K' are geometrical factors

The radiation damping term is present in the solution of the transverse field as it contributes to the frequency separation of the cavity and kittel modes $\Delta\omega$.

RADIATION DAMPING IN CAVITIES

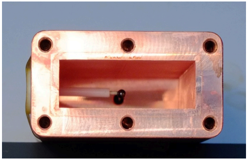
In the solutions we find the dynamics of two coupled oscillators with the complex frequency of the two modes described by

$$\omega_L \pm \frac{1}{2}\left[\frac{4}{\tau_c}\left(\frac{1}{\tau_2}+\frac{1}{\tau_r}\right)-\left(\frac{1}{\tau_c}+\frac{1}{\tau_2}\right)^2\right]^{1/2}+\frac{i}{2}\left(\frac{1}{\tau_c}+\frac{1}{\tau_2}\right)=\omega_\pm+\frac{i}{2\tau_\pm}$$

In contrast with the free space case, the radiation damping characteristic time is given by $\tau_r = (2\pi\mu_0 M_0 Q\gamma\zeta)^{-1}$, with ζ filling factor

For $\tau_r \ll \tau_c$ we have two modes (mode hybridization) at frequencies

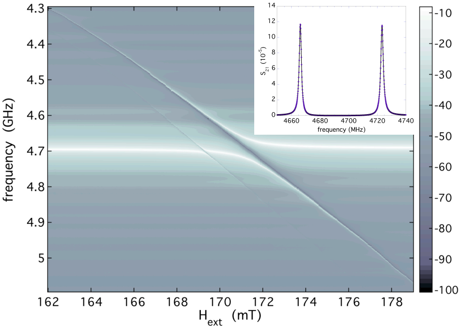
$$\omega_\pm = \omega_L \pm \frac{1}{2}\left[\frac{4}{\tau_c}\left(\frac{1}{\tau_2}+\frac{1}{\tau_r}\right)-\left(\frac{1}{\tau_c}+\frac{1}{\tau_2}\right)^2\right]^{1/2}$$

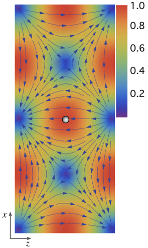


and with the same decay time, independent of the size and filling factor:

$$\tau_\pm = \bar{\tau} = \left(\frac{1}{\tau_c}+\frac{1}{\tau_2}\right)^{-1}$$

THE STRONG COUPLING REGIME: HYBRIDIZATION





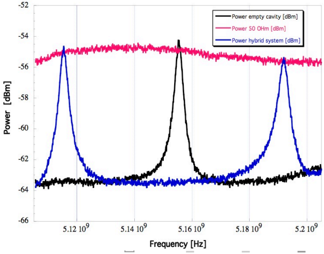
$$S_{21}(\omega) \simeq \frac{1}{i(\omega-\omega_c) - \frac{k_c}{2} + \frac{|g_m|^2}{i(\omega-\omega_m)-k_m/2}},$$

$k_c = 1/\tau_c$ = cavity linewidth

$k_m = 1/\tau_2$ = linewidth of the ferromagnetic resonance

$k_h = \frac{1}{2}(k_c + k_m)$ linewidth of a single hybridized mode

$\longrightarrow$ no excess noise with YIG!



THE PHOTON COUNTER

In the presence of the axion wind the average amount of power absorbed by the magnetized material is:

$$P_{\text{in}} = \mu_0 \mathbf{H} \cdot \frac{d\mathbf{M}}{dt} = B_a \frac{dM_a}{dt} V_s = \gamma \mu_B n_S \omega_a B_a^2 \tau_{\text{min}} V_s$$

$$P_{\text{out}} = \frac{P_{\text{in}}}{2} = 8 \times 10^{-26} \left(\frac{m_a}{2 \cdot 10^{-4}\ \text{eV}} \right)^3 \left(\frac{V_s}{1\ \text{liter}} \right) \left(\frac{n_S}{10^{28}/\text{m}^3} \right) \left(\frac{\tau_{\text{min}}}{10^{-6}\ \text{s}} \right) \text{W}$$

In terms of *fundamental detection limits* (no technical noise) the best detector for such an exceedingly small signal is a *single-photon detector*.
Lamoreaux S. K. *et al* Phys. Rev. D **88** 035020 (2013)

$$\Longrightarrow R_a = \frac{P_{\text{out}}}{\hbar\omega_a} = \text{expected rate of emitted photons in a photon counter} =$$
$$= 2.6 \times 10^{-3} \left(\frac{m_a}{2 \cdot 10^{-4}\ \text{eV}} \right)^2 \left(\frac{V_s}{1\ \text{liter}} \right) \left(\frac{n_S}{10^{28}/\text{m}^3} \right) \left(\frac{\tau_{\text{min}}}{10^{-6}\ \text{s}} \right) \text{Hz}$$

SNR OF THE IDEAL PHOTON COUNTER

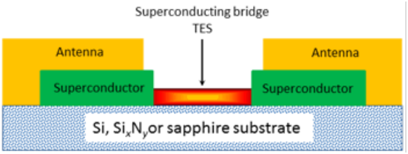
At $T \neq 0$ the single-photon detector is subject to noise from fluctuations in the number of detected *thermal photons*. Noise is determined by the thermal photon rate $R_{th} = \bar{n}\tau_c$

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

$\Longrightarrow$ SNR $= 3$ for $T = 13\,\text{mK}$ and $t_m = 10^4$ s

http://arxiv.org/abs/1606.02201

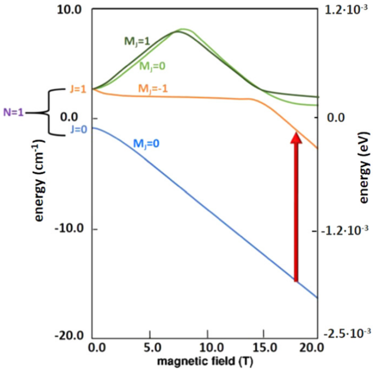
Single photon detector in the microwave range yet not developed.
Capparelli L.M. *et al* Phys. Dark Universe **12** 37 (2016)



GAS SYSTEM – ULTRACOLD MOLECULAR OXYGEN $^{16}O_2$

DM axions may induce *dipolar transitions between Zeeman states in an atomic system, which differ by* m_a
(P. Sikivie, Phys. Rev. Lett. **113** 201301 (2014))

- axion transition $a \to b$
- Zeeman effect for $N = 1$ rotational levels in the GS of $^{16}O_2$
- mole-sized population of $^{16}O_2$molecules in a



ULTRACOLD MOLECULAR OXYGEN $^{16}O_2$

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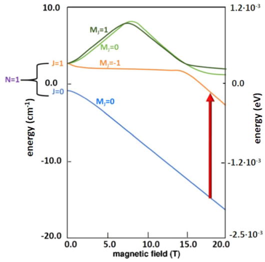
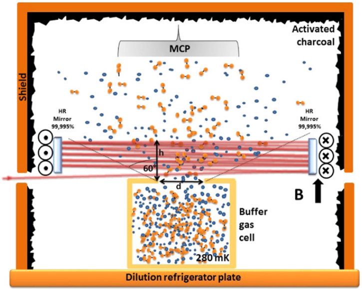
New J. Phys. **17** (2015) 113025



- BGC (buffer gas cooling). $^{16}O_2$ cooled by collisions with a helium-3 thermal bath at temperature $T_{He} \simeq 280\,\mathrm{mK} \Longrightarrow W_{ba}(B_{\min}) = 11\,\mathrm{cm}^{-1}$ (1.4 eV)
- magnetic field region:
  W_{ba} saturates for $B > B_{\max} = 18\,\mathrm{T}$
  $1.4\,\mathrm{eV} < m_a < 1.9\,\mathrm{eV}$
- detection: REMPI (resonance-enhanced multi-photon ionization spectroscopy)



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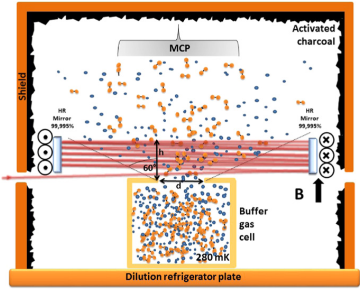
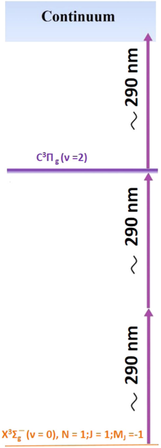
- detection: REMPI (resonance-enhanced multi-photon ionization spectroscopy)
- $N_{\text{refl}} = 13500$ to maximize the fraction of molecules that interacts with the laser beam
  $\mathcal{F} = (N_{\text{refl}}\,\pi\,w^2)/(h\,d + h^2\tan\theta)$



(2+1)REMPI
2 ph to intermediate state
+1 ph to ionize



GAS SYSTEM: ULTRACOLD MOLECULAR OXYGEN $^{16}O_2$

In 1 s, the number of oxygen molecules that have been exposed to the axion field is

$$N_{\text{molec}} = \frac{n_{\text{max}}}{4} \pi (d/2)^2 v_m ,$$

where $v_m = \sqrt{(8\, k_B\, T)/\pi\, m}$
and $n_{\text{max}} \simeq (1/30)\, n_{\text{He}} = 10^{15}\,\text{cm}^{-3}$ max molecular density that can be cooled to T_{He}

$\Longrightarrow$ the axion-induced absorption event number

$$N = N_{\text{molec}} \frac{\bar{h}}{v_m} \mathcal{R}_{ab} \mathcal{F} (n_{\text{days}} \cdot 24 \cdot 3600)$$

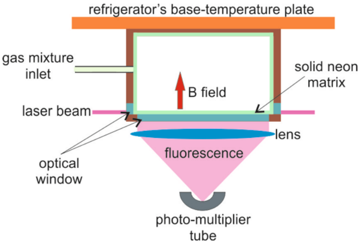
In the worst case $\mathcal{R}_{ab} = 1\,\text{Hz}/N_A \to N \simeq 1$ for an acquisition time of 10 days

. . . is it possible to increase the density?

SOLID NEON MATRIX

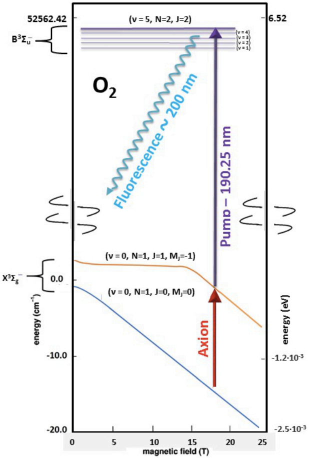
Alkali atom or molecular oxygen embedded in a condensed phase according to the matrix-isolation spectroscopy technique (MIS).

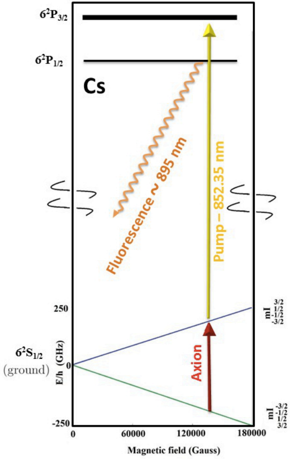
- 80 mK in **B** up to 18 T
- copper cell $1 \times 3 \times 3\,\mathrm{cm}^3$
- inject noble gas N and atomic/molecular species D (1:100 to 1:1000)



After a few hours of deposition, a 1-mm-thick noble gas matrix, incorporating species D is grown on each side of the walls.

SOLID NEON MATRIX: DOPANT SPECIES





Number of axion-induced absorption events:

$$N \cdot N_A = \mathcal{R}_{ab}\, n_{\text{Ne}}\, V_c\, d\, (3600\ \text{s}) n_h$$

some reasonable values:

$\mathcal{R}_{ab} = 1\,\text{Hz}$;

$n_{\text{Ne}} = 4.6 \cdot 10^{22}\,\text{cm}^{-3}$ neon density;

$V_c \sim 1\,\text{cm}^3$ crystal volume;

$d = 1\%$ doping ratio;

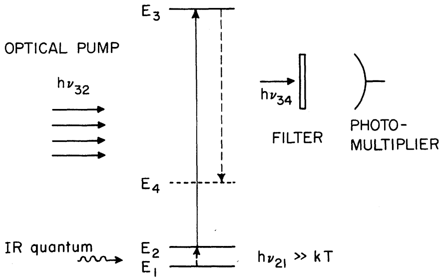
n_h acquisition time [hours]=4

$$\Longrightarrow N \cdot N_A = 10$$

RE-DOPED CRYSTALS

basic idea: **diminish** w**-value** in an **all-optical scheme** based on the IRQC concept

N. Bloembergen, *Phys. Rev. Lett.* **2**, 84 (1959)



- pump laser resonant with transition $2 \to 3$
- material transparent to the pump until an IR photon is absorbed $(1 \to 2)$
- level 3 is fluorescent $\Longrightarrow$ detection can be accomplished via conventional detectors (PMT or PD)
- such energy level scheme can be realized in wide bandgap materials doped with trivalent rare-earth ions

the whole field of **upconversion** can be traced back to this idea

(with applications in lasing, laser cooling, up-conversion based weak infrared photon detection, infrared imaging and so on)

CONCLUSIONS

QUAX

- preliminary R&D study results
- a hybrid system has been tested as an axion-matched detector
- in the hybrid system we found no excess noise (at 290 K and 77 K) http://arxiv.org/abs/1606.02201
- spin flips possibly to be detected by a microwave photon counter

AXIOMA

- results for a gas system New J. Phys. **17** (2015) 113025
- to increase the event rate we are investigating MIS and
- upconversion in RE-doped crystals Appl. Phys. Lett. **107** (2015) 93501

EXPERIMENTAL PARAMETERS

axion mass	$10^{-4}\,\text{eV} \leqslant m_a \leqslant 10^{-3}\,\text{eV}$
equivalent RF magnetic field	$10^{-22}\,\text{Tesla} \leqslant B \leqslant 10^{-21}\,\text{Tesla}$
frequency	$20\,\text{GHz} \leqslant f \leqslant 200\,\text{GHz}$
magnetizing field	$\nu_L = \gamma_e B_0$, with $\gamma_e = 28\,\text{GHz/Tesla}$ $\rightarrow 0.7\,\text{T} \leqslant B \leqslant 7\,\text{T}$
detector bandwidth	$\leqslant 100\,\text{kHz}$