Quantum sensing of axion dark matter with a phase resolved haloscope

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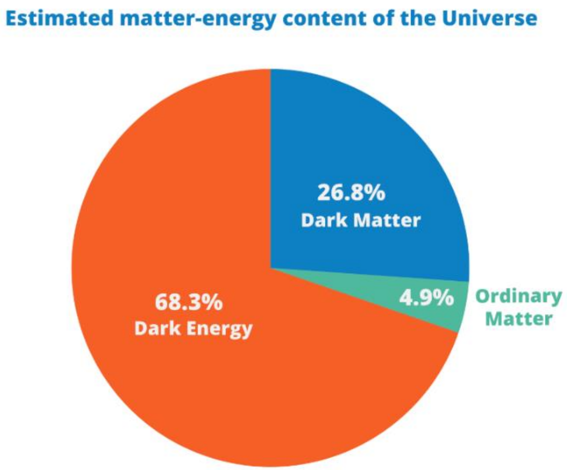
Theory : **A. Cottet**
DarkQuantum collab : I. Irastorza, W. Wernsdorfer, S. Paraoanu, B. Dobrich, A. Lindner

The dark universe



Planck satellite

The bullet cluster (ESA) : X-ray: NASA/CXC/CfA/M.Markevitch,
Optical and lensing map: NASA/STScI, Magellan/U.Arizona/D.Clowe,
Lensing map: ESO WFI

- Strong motivations for dark matter, extremely weakly coupled to light and ordinary matter.
- Many models: cold dark matter (axions) is favored.

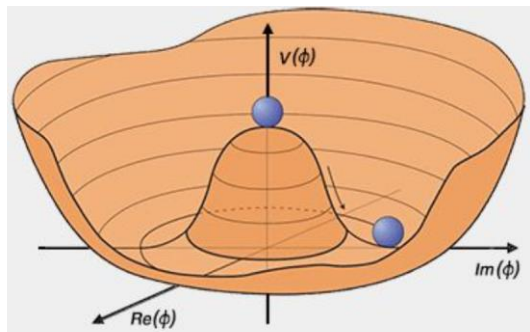
The axion paradigm

CP Conservation in the Presence of Pseudoparticles*

R. D. Peccei and Helen R. Quinn†
Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305
(Received 31 March 1977)

We give an explanation of the CP conservation of strong interactions which includes the effects of pseudoparticles. We find it is a natural result for any theory where at least one flavor of fermion acquires its mass through a Yukawa coupling to a scalar field which has nonvanishing vacuum expectation value.

R.D. Peccei and H.R. Quinn, PRL'77, Weinberg, PRL'78, Wilczek, PRL'78…



- Axion, new particle/field introduced to solve the strong CP problem (neutron EDM)
- Symetric potential: spontaneous breaking of symetry (pseudo Nambu-Goldstone boson)
- Mass range: μeV to meV

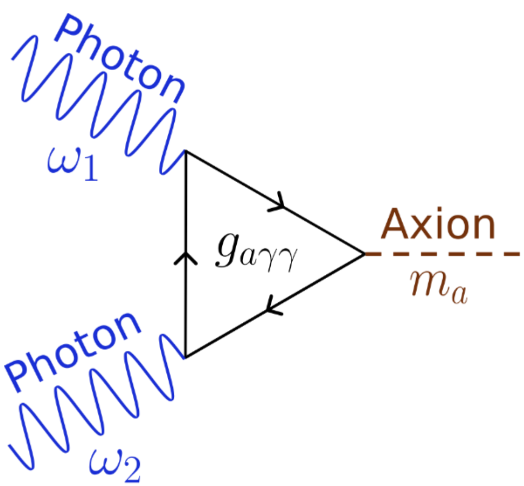
➡ Very light (μeV range for mass) and very weakly coupled field called axion good candidate for dark matter

The axion paradigm

Axion – two photons coupling:

$$g_{a\gamma\gamma}\phi_a \cos(\omega_a t)\vec{E}\cdot\vec{B}$$

$g_{a\gamma\gamma}$ coupling constant
ω_a axion angular frequency: $\omega_a = (c^2/\hbar)m_a$



$$|\omega_1 \pm \omega_2| = \sqrt{m_a^2 + p_a^2}$$

Modification of Lagrangian of electromagnetism (magneto-electric coupling).

Axion interactions are model dependant:

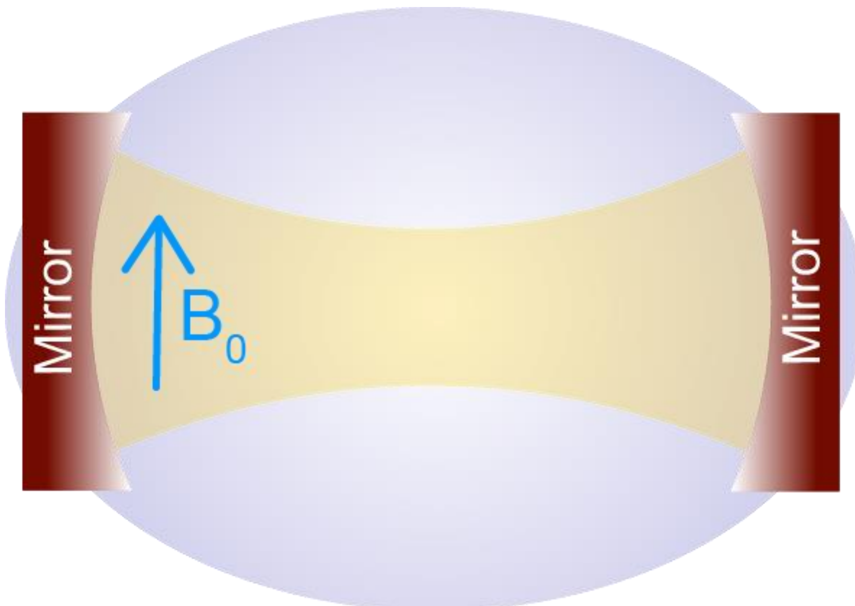
Kim-Shifman-Vainshtein-Zakharov (KSVZ) (-0.97)

Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) (0.36)

$P \sim 10^{-22}$ -10^{-24} W

How to detect such a small correction to Maxwell's equations?

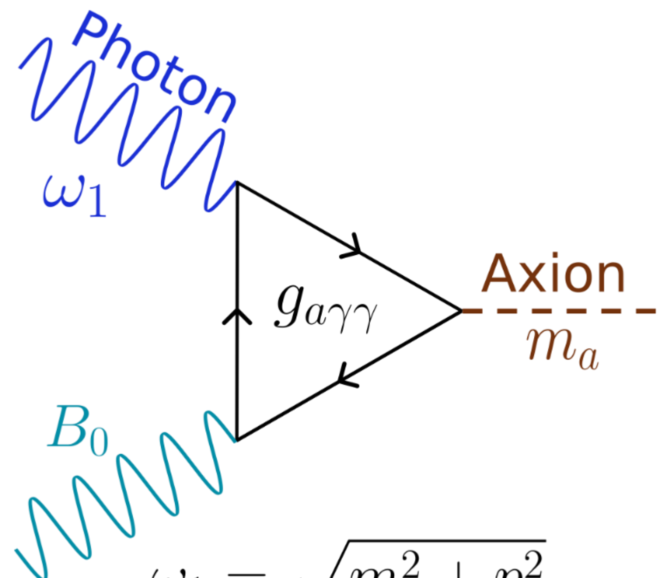
Sikivie's cavity haloscope



$$g_{a\gamma\gamma}\phi_a \cos(\omega_a t)\vec{E}.\vec{B}_0$$

P. Sikivie, PRL **51,** 1415 (1983)

Primakoff effect



$$\omega_1 = \sqrt{m_a^2 + p_a^2}$$

- Mixing term in the lagrangian revealed in coupled cavity/static magnetic field mode
- Dark matter axions «drive » a cavity at rest (fictitious port) and populate it with photons at the axion energy

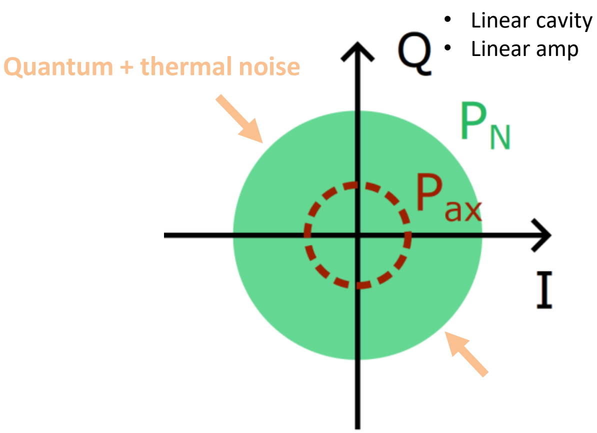
➡ « Needle in a haystack » problem (linewidth ~ kHz)) and very feeble signal (n~10^{-3} - 10^{-5})

Limitations of current haloscopes

P. Sikivie, PRL **51,** 1415 (1983)

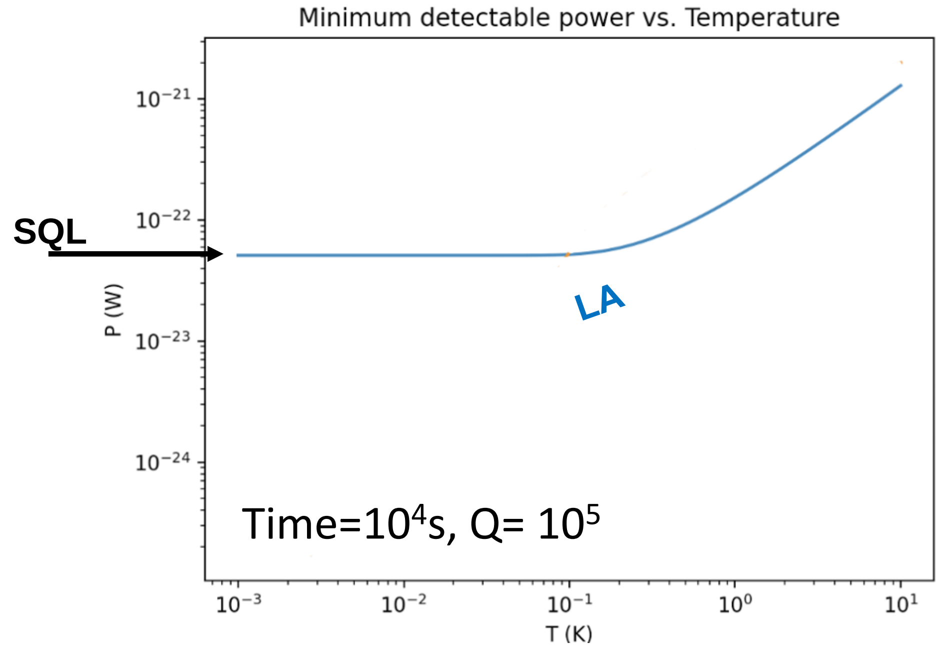
- From linear amplification (LA) to ***phase resolved haloscope***

[I,Q]=i



Conventional haloscope

In-phase(I) and Out of phase (Q) conjugates limited by SQL



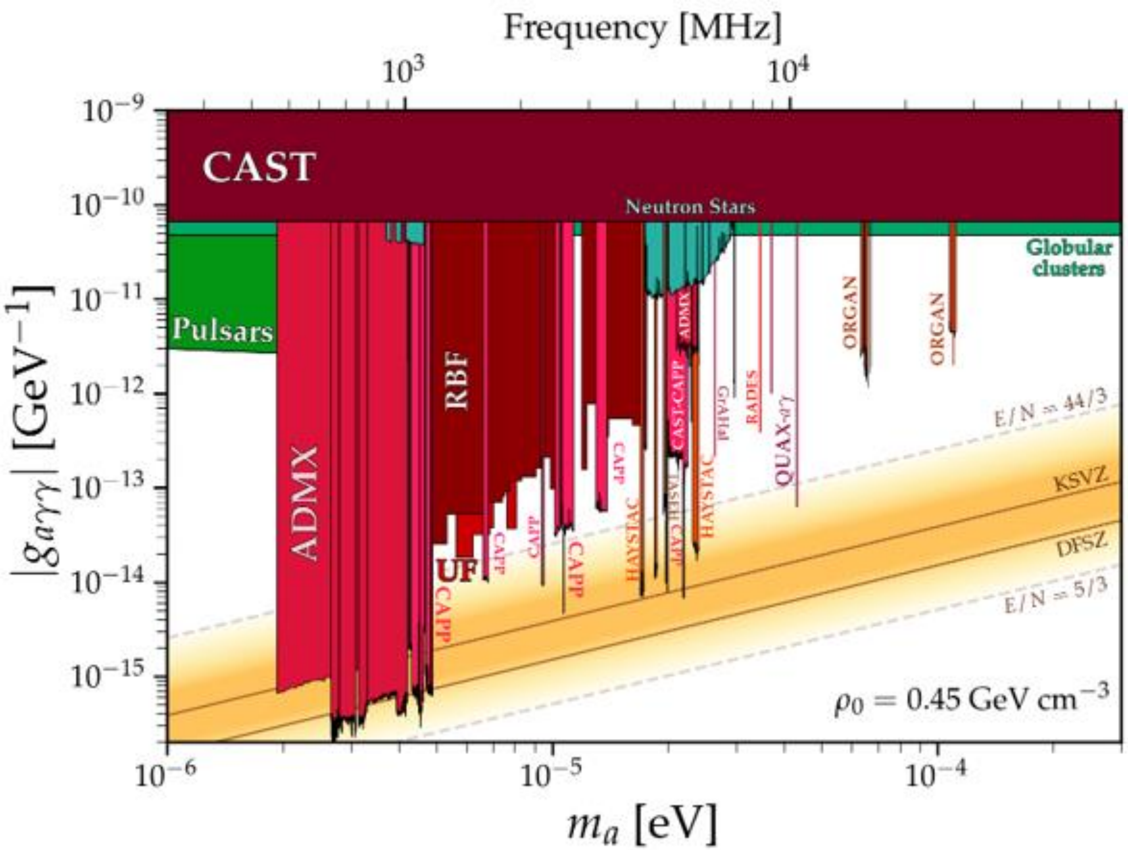
Limitation of Linear Amplifier (LA)

- Detection SNR limited by standard quantum limit (**SQL**)
- Very narrow range can be probed in a single experiment

➡ Substantially slow down the Axion Dark Matter search

Experimental overview

https://cajohare.github.io/AxionLimits/



ADMX : T. Braine et al. PRL **124** 101303 (2020) Mass range 2-3 μeV

HAYSTAC : B.M. Brubaker et al. PRL **118** 061302 (2017) Mass range 23.55-24 μeV

QUAX : N. Crescini et al. PRL 124, 171801 (2020) Mass range 42-43 μeV

HAYSTAC alike : M. Malnou et al., PRX **9**, 021023 (2019), K.M. Backes, Nature **590** 238 (2021)

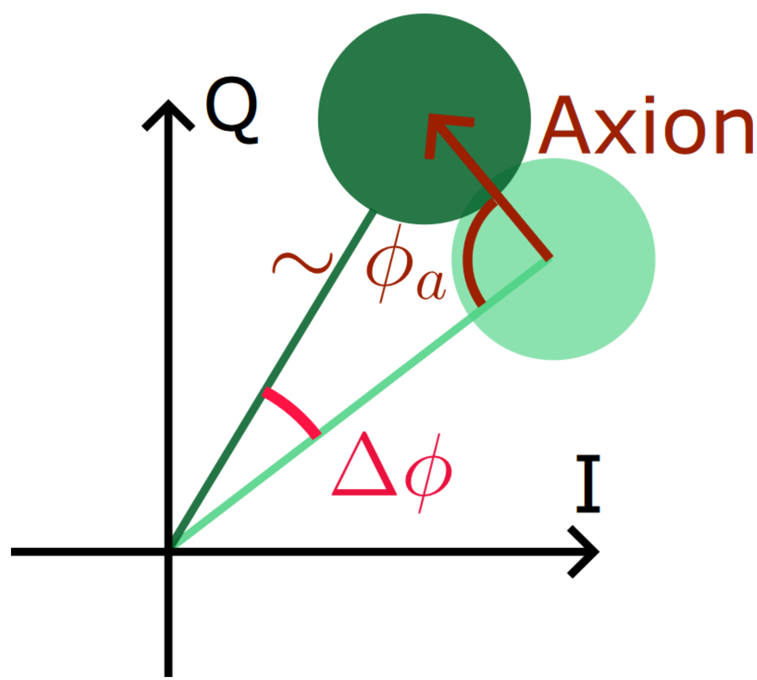
A lot of pioneer experiments : ADMX, HAYSTAC, QUAX…

- Use of quantum limited microwave amplifiers : Josephson Parametric Amplifiers (JPA) or alike

➡ Very difficult to reach the cosmogically relevant level for coupling strengths

Principle of a phase resolved haloscope

[N,ϕ]=i



DETOX haloscope

- Non-linear cavity
- Linear amp

- $F_{halo} = \left(\frac{P_{out}\sqrt{\kappa}}{T_{sys}}\right)^2 \propto \rho_a^2 g_{a\gamma}^4 \omega_a^2 B_0^4 V^2 T_{sys}^{-2} |\mathcal{G}|^4 Q$ limited by SQL-> two quadratures measured
- Phase resolved detections evade the SQL-> information in one quadrature only

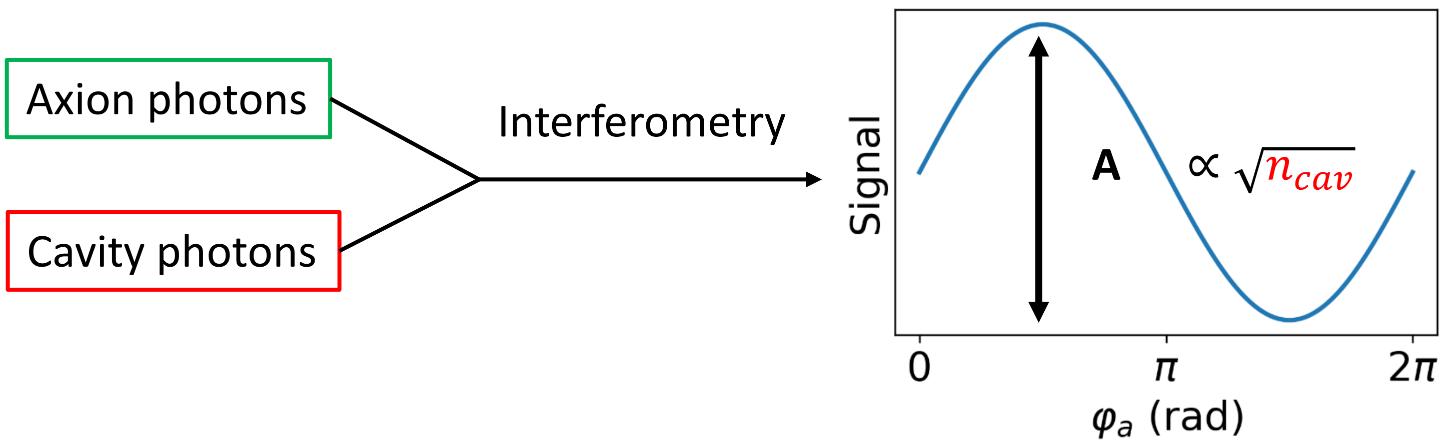
  $F_{phase} \propto \rho_a g_{a\gamma}^2 B_0^2 V T_{sys}^{-1} |\mathcal{G}|^2 \cos^2(\varphi_a - \varphi_{cav})$ A. Cottet and T.K. in preparation'24

➡ Expect 4 to 5 orders of magnitude increase of figure of merit using phase haloscope

Axion interferometry

Coupling | **Axion photons**

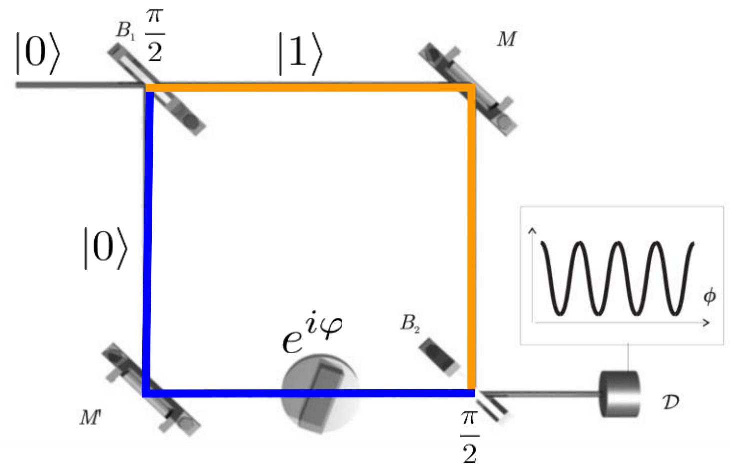
$$\cos(\omega_a t + \varphi_a)\vec{E} \cdot \overrightarrow{B_0} \longrightarrow \cos(\omega_a t + \varphi_a)$$



$$\frac{\Delta f}{\kappa} \sim -\frac{2K}{\kappa}\frac{g^2}{\Delta^2}\left|\sqrt{n_{cav}} + \sqrt{n_{ax}}e^{i\varphi_a}\right|^2$$

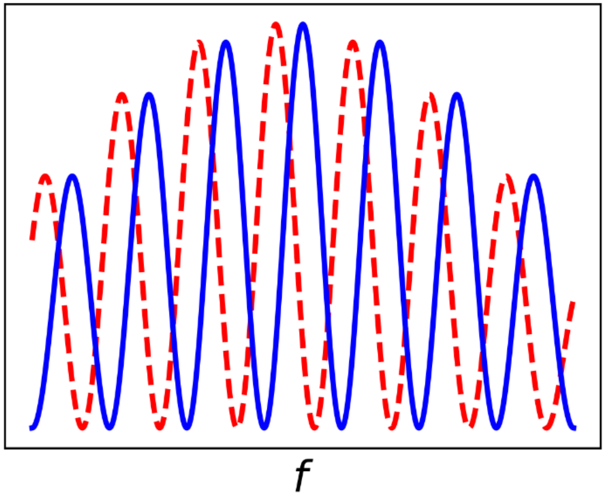
Nonlinear amplification of axion signal using cavity photons.

Measuring phase shifts with Ramsey interferometry



Mach Zehnder interferometer picture

$$\varphi = \Delta f \times t$$



- Ramsey interferometry used to measure phase shift (atomic clocks)

→ Superconducting circuit to carry out Ramsey measurement

Recapitulation of our detector goals

Haloscopes: measurement of photons from axion decay in a microwave cavity

Non-linear amplification

↓

Reducing the measurement time by going below the Standard Quantum Limit

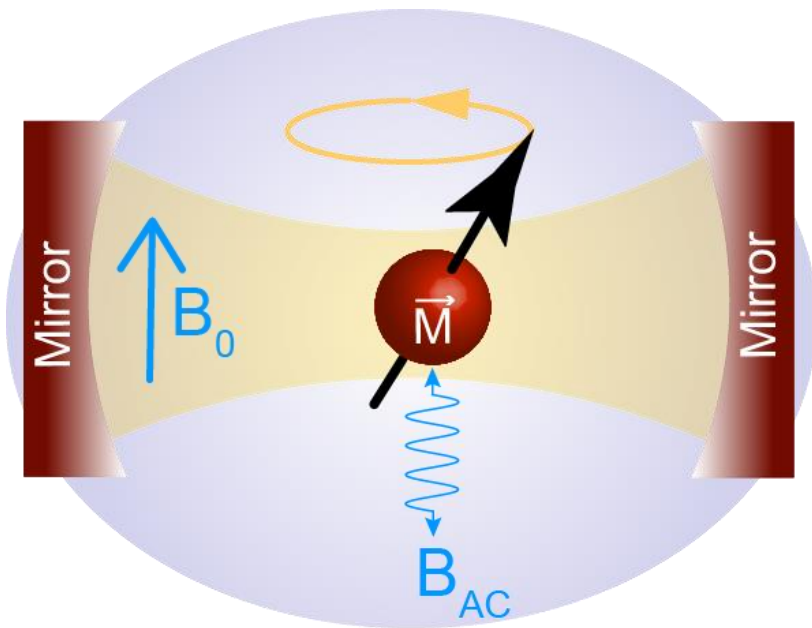
Frequency tunability

↓

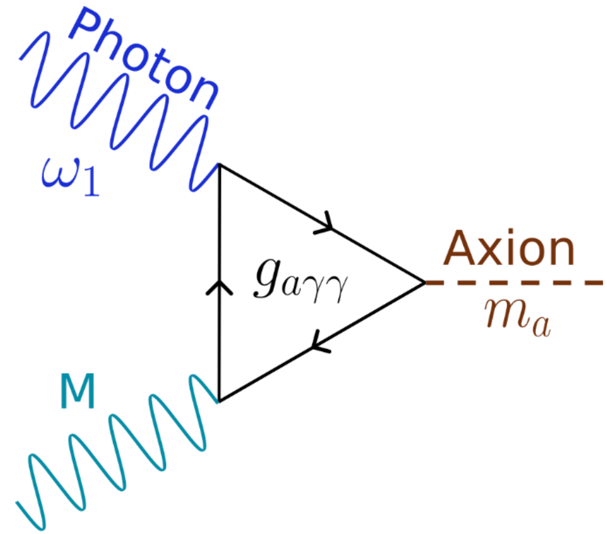
Excluding a large mass range in a single run

➡ How can we implement such features?

The DETOX hybrid cavity-magnon haloscope



$g_{a\gamma\gamma}\phi_a \cos(\omega_a t)\vec{E}.\vec{M}$



B_0~28 GHz/T

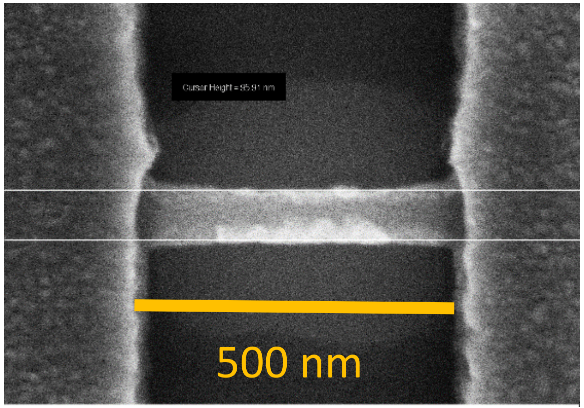
See also QUAX collaboration : N. Crescini et al. PRL **124**, 171801 (2020)

Landau-Lifschitz-Gilbert

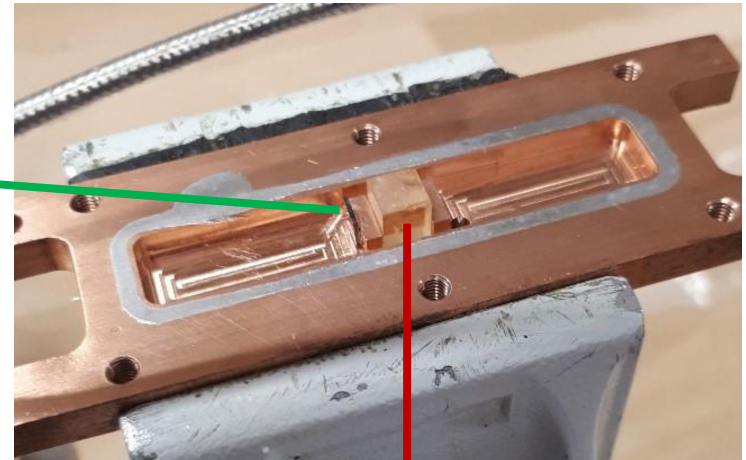
$$\partial_t \mathbf{M} = -\gamma\mu_0 \mathbf{M} \times \mathbf{H}_{\text{eff}} + \frac{\alpha}{M_S}\mathbf{M} \times \partial_t \mathbf{M}$$

- Mixing term in the lagrangian revealed in coupled cavity/magnon (Kittel mode) dynamics
- Dispersion of the magnon mode allows a tunability of the cavity on a large frequency range.

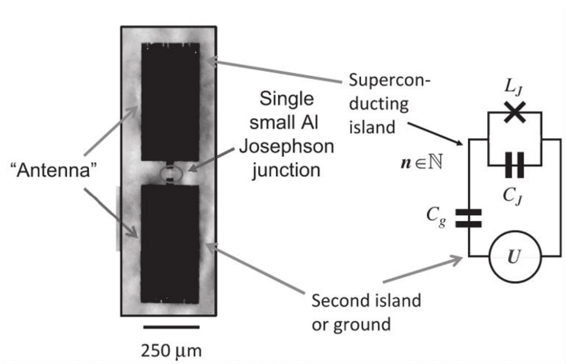
DETOX haloscope: implementation



Granular aluminium transmon like superconducting circuit



GdVO$_4$ antiferromagnetic crystal



Girvin, S. M.et al., Lecture Notes of the Les Houches Summer School: Volume 96, July 2011

P. Winkel et al. PRX 10, 031032 (2020)

- Magnetic resonance provides tunability with B-field
- Anharmonicity of GrAl Qcircuit gives a resource for photon to frequency conversion

Recapitulation

Non-linear amplification

↓

Reducing the measurement time by going below the Standard Quantum Limit

↓

Quantum circuit (qubit) resilient to magnetic field

Frequency tunability

↓

Excluding a large mass range in a single run

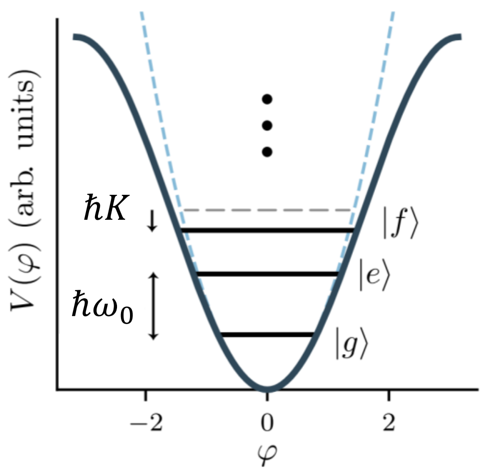
↓

Magnetic resonance (magnons) tunable with magnetic field

➡ We need to calibrate each element of our detector

Detecting dark matter with quantum circuits

Anharmonic circuit:



Cavity – circuit – magnons hamiltonian:

$$\frac{\hat{H}}{\hbar} = \omega_c \hat{a}^\dagger \hat{a} + \omega_0 \hat{b}^\dagger \hat{b} + \underbrace{\frac{K}{2}\hat{b}^\dagger \hat{b}^\dagger \hat{b}\hat{b}}_{\text{Kerr nonlinearity}} + g\left(\hat{a}^\dagger \hat{b} + \hat{b}^\dagger \hat{a}\right) + \omega_m \hat{m}^\dagger \hat{m} + g_m\left(\hat{a}^\dagger \hat{m} + \hat{m}^\dagger \hat{a}\right)$$

Circuit-cavity dispersive regime:

$$\frac{\hat{H}}{\hbar} = \tilde{\omega}_c \hat{a}^\dagger \hat{a} + \tilde{\omega}_0 \hat{b}^\dagger \hat{b} + \underbrace{\frac{K_a}{2}\hat{a}^\dagger \hat{a}^\dagger \hat{a}\hat{a}}_{\text{Induced nonlinearity}} + \frac{K}{2}\hat{b}^\dagger \hat{b}^\dagger \hat{b}\hat{b} + \underbrace{\chi_{ab}\hat{a}^\dagger \hat{a}\hat{b}^\dagger \hat{b}}_{\text{Cross kerr}}$$

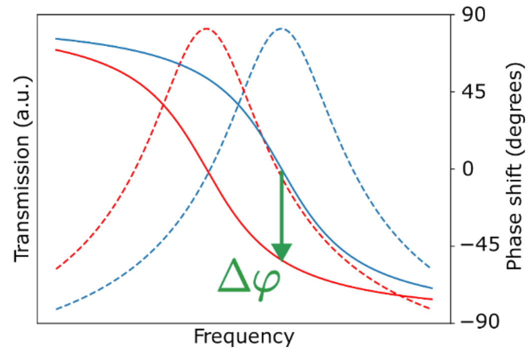
$$K_a = K\left(\frac{g}{\Delta}\right)^4 \qquad \chi = 2\chi_{ab} = \frac{g^2 K}{\Delta(\Delta - K)} \qquad \Delta = \omega_c - \omega_0$$

Blais et al. RMP 93, 025005 (2021)

Detecting dark matter with quantum circuits

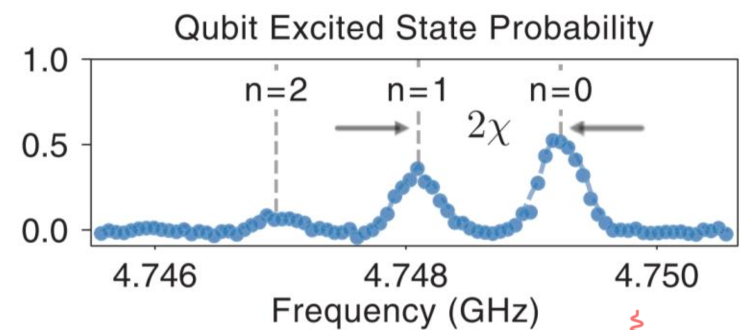
Cavity induced nonlinearity:

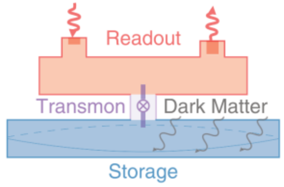
$$\hat{H} \approx \hbar\left(\omega_c + K_a\langle\hat{a}^\dagger\hat{a}\rangle\right)\hat{a}^\dagger\hat{a} + \cdots$$



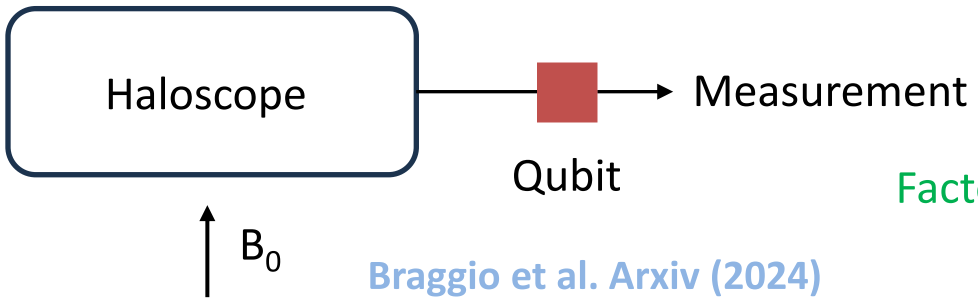
AC Stark-shift (cross-Kerr):

$$\hat{H} \approx \hbar\left(\omega_q + \chi_{ab}\langle\hat{a}^\dagger\hat{a}\rangle\right)\hat{b}^\dagger\hat{b} + \cdots$$





Dixit et al. PRL 126, 141302 (2021)

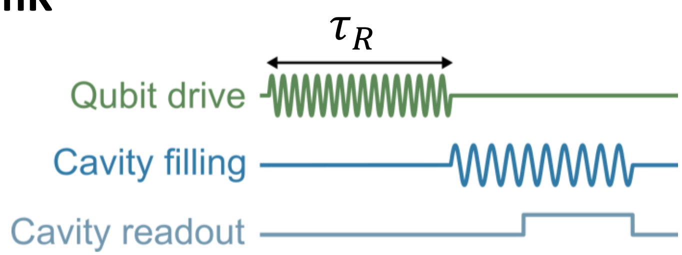


Factor 20 on the measurement speed

Braggio et al. Arxiv (2024)

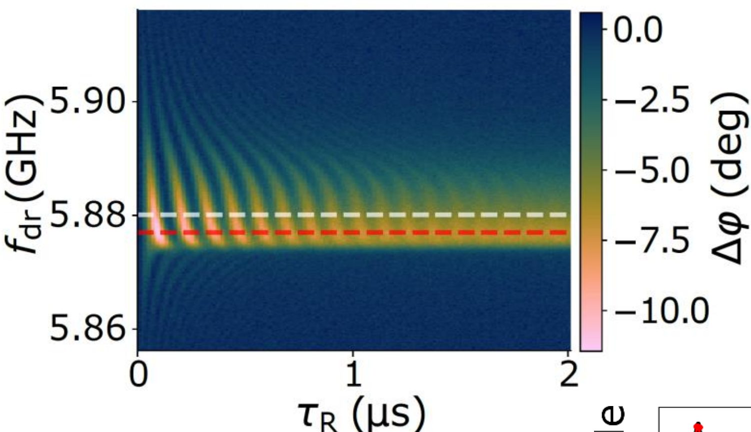
Time domain qubit like manipulation

T=20mK

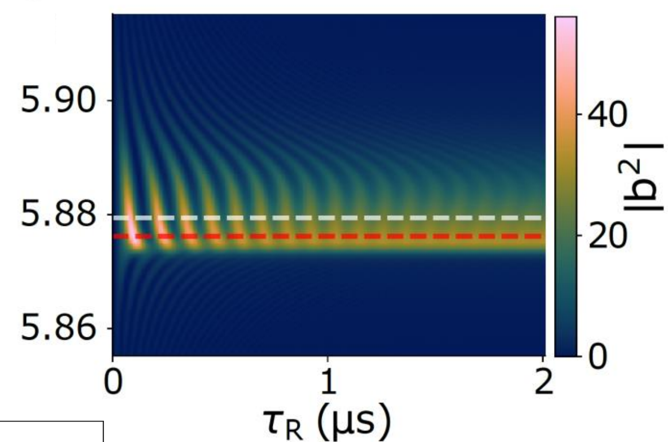


$$\hat{H} = \hbar\Delta_{dr}\hat{b}^\dagger\hat{b} + \hbar K\hat{b}^\dagger\hat{b}^\dagger\hat{b}\hat{b} + A * (\hat{b} + \hat{b}^\dagger)$$

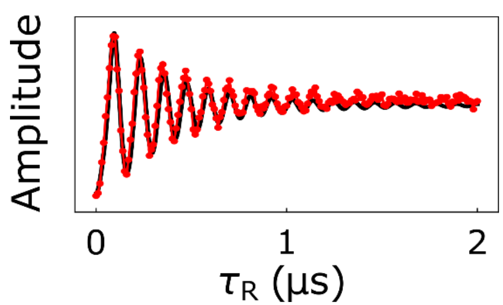
$$K = -2\pi \times 200\ \text{kHz},\ \Gamma = 2\pi \times 954\ \text{kHz}$$



Experiment



Model (qutip)



A. Théry et al. PRB'24

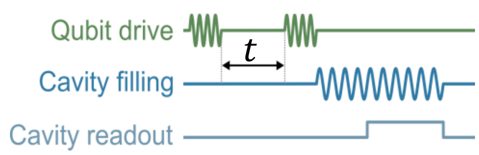
Weak anharmonicity ➡ Asymmetric Rabi chevron

➡ Quantitative understanding of the GrAl circuit using numerical model

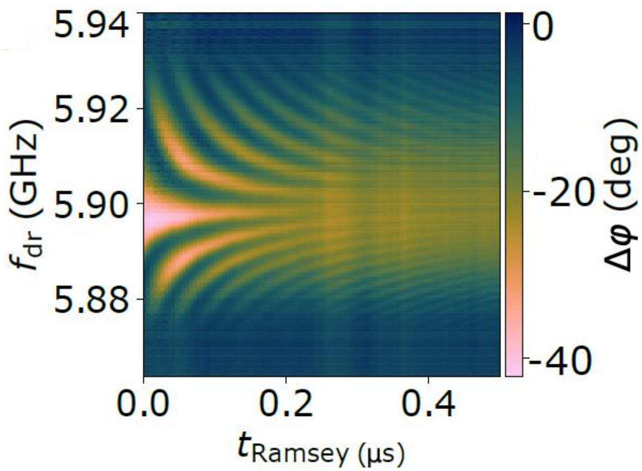
‘Ramsey interferometry’ with our GrAl quantum circuit

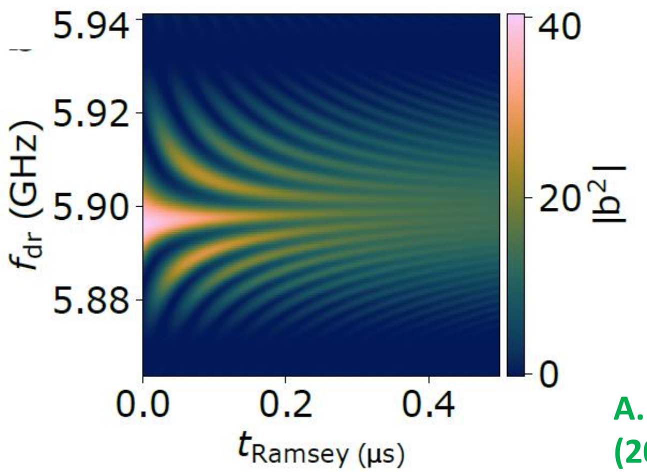
$\Delta = 2\pi \times 80$ MHz
$\kappa = 2\pi \times 2.2$ MHz
$g = 17$ MHz
$K = -2\pi \times 200$ kHz

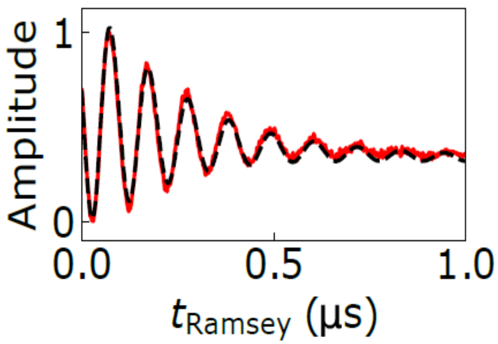
Ramsey sequence



T=20mK







Experiment **Model**

A. Théry et al. PRB 109, 06450524 (2024)

- Ramsey fringes implemented
- Consistent with squeezing dynamics
- Ramsey fringes qualitatively similar to qubit case. Quantitative understanding.

Recapitulation

Non-linear amplification

↓

✓ **Quantum circuit** (qubit)
resilient to magnetic field

↓

- Quantitative understanding
- $K = -2\pi \times 200$ kHz
- Ramsey fringes

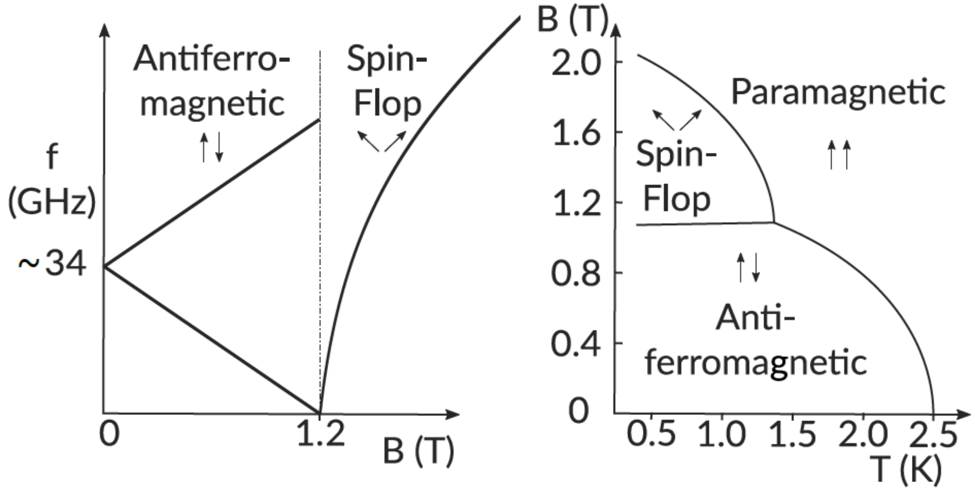
Frequency tunability

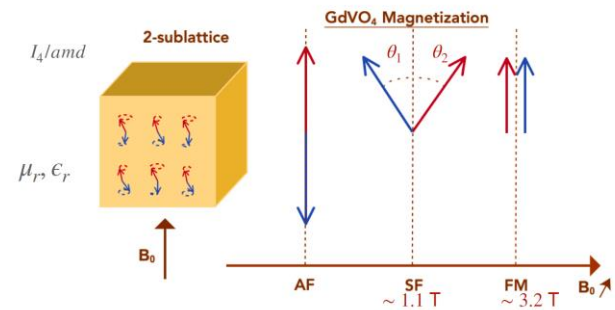
↓

Magnetic resonance (magnons)
tunable with magnetic field

Tuning the mass range with an antiferromagnet

$$U = -J\overrightarrow{M_1} \cdot \vec{M}_2 - \vec{H} \cdot \left(\overrightarrow{M_1} + \vec{M}_2\right) - K(\cos^2\theta_1 + \cos^2\theta_2)$$





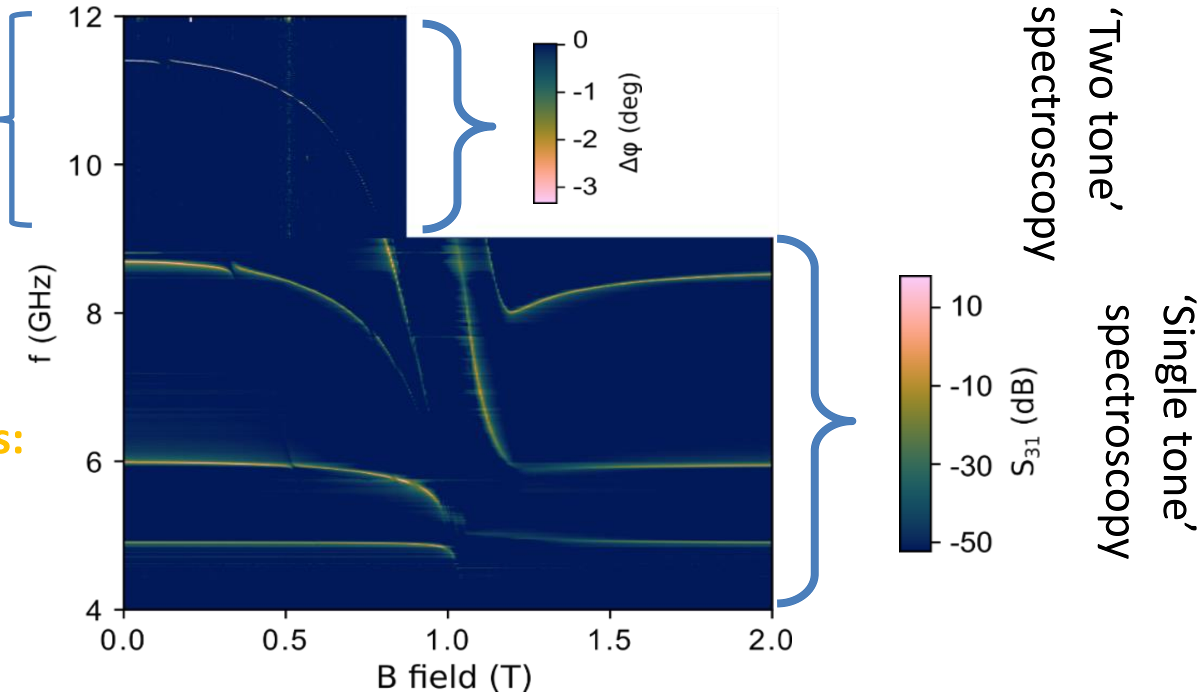
J. Everts et al. PRB 101, 214414 (2020)

A.G. Gurevich an G.A. Melkov, (1996)

- Antiferromagnet (TNéel~2.5K)
- Two counter rotating modes for the two sublattices
- Span of 68 GHz if we address the upper transition (good for large detector scanning range)

Magnetic field tuning of cavity modes in the full setup

$\chi_{ac}\hat{a}^\dagger\hat{a}\hat{m}^\dagger\hat{m}$



T=20mK

Haloscope parameters:
5.9075 GHz
0.7 T

$g_{mc}{\sim}1.5\ GHz$

A. Théry, C. Fruy et al. in preparation '24

- System with B-resilient grAl circuit, magnetic material (GdVO4), copper cavity.
- 'Dispersive read-out' of modes on a large frequency span -> anharmonicity magnetic field resilient

➡ Tunability over 4GHz more than 2 orders of magnitude larger than previous haloscopes

See also : D. Lachance-Quirion et al. Science'20

Recapitulation

Non-linear amplification

↓

✓ **Quantum circuit** (qubit)
resilient to magnetic field

↓

- Quantitative understanding
- $K = -2\pi \times 200$ kHz
- Ramsey fringes

Frequency tunability

↓

✓ **Magnetic resonance** (magnons)
tunable with magnetic field

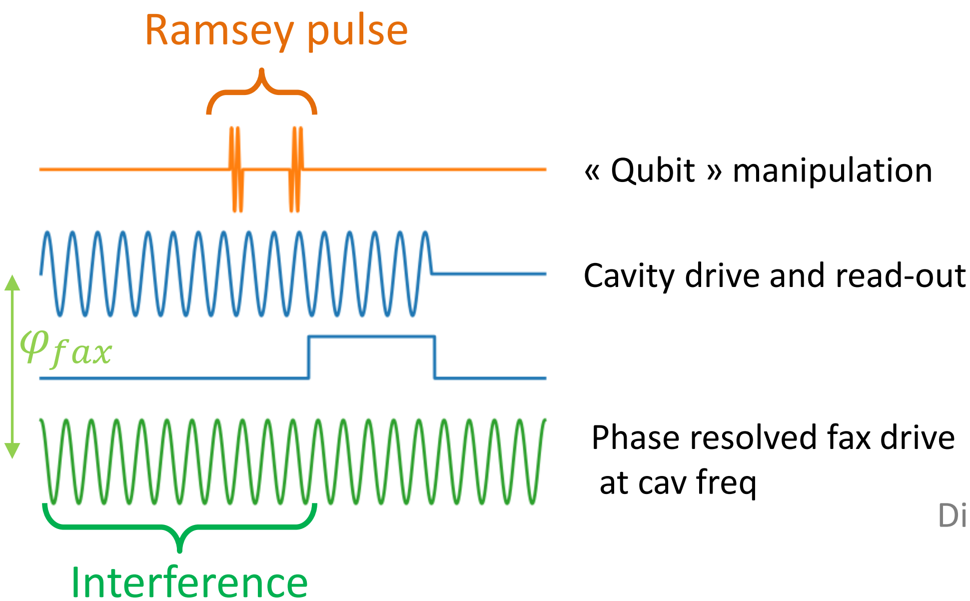
↓

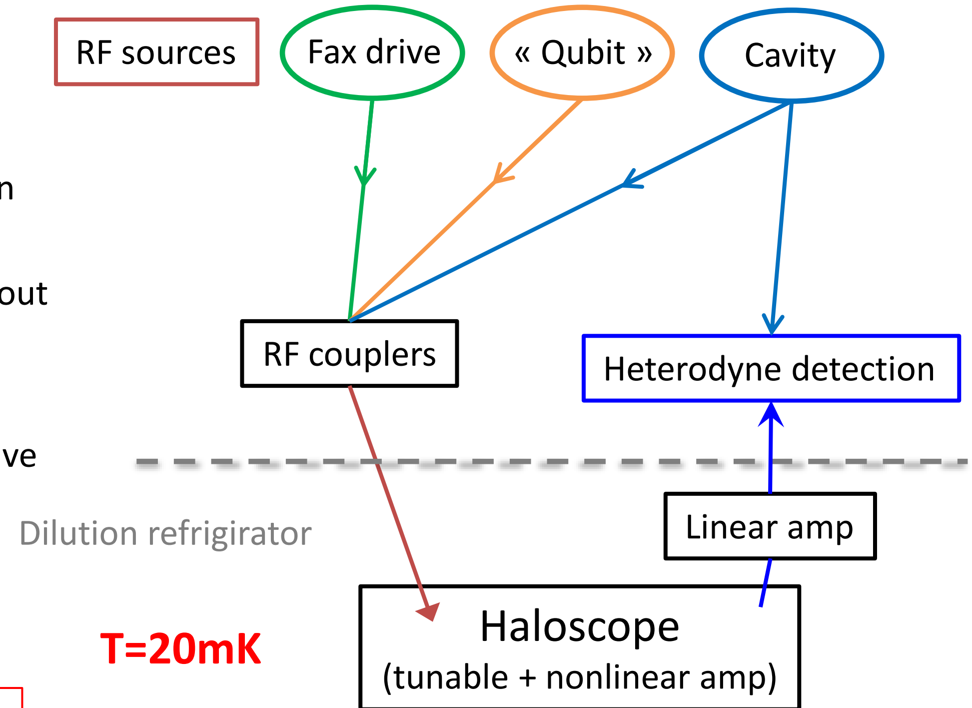
- Ultrastrong coupling cavity-magnons
- Up to 4 GHz tunability

➡ How can we perform dark matter measurements with this detector?

Ramsey interferometry of fake axions

Measurement sequence

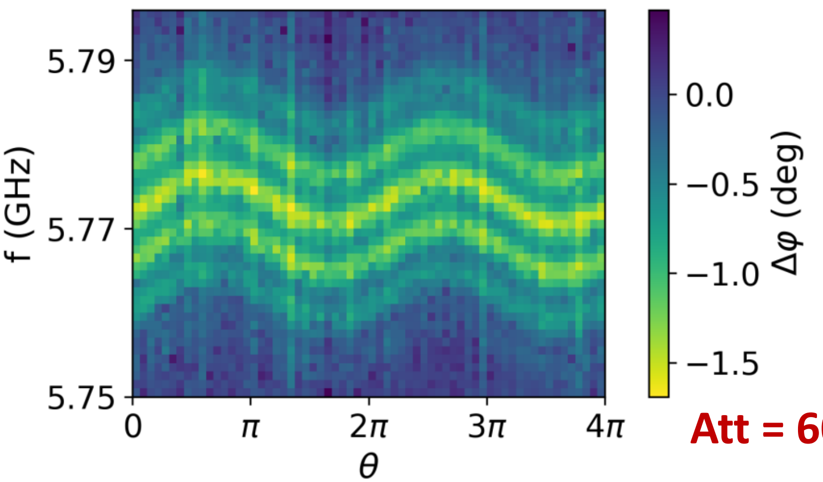




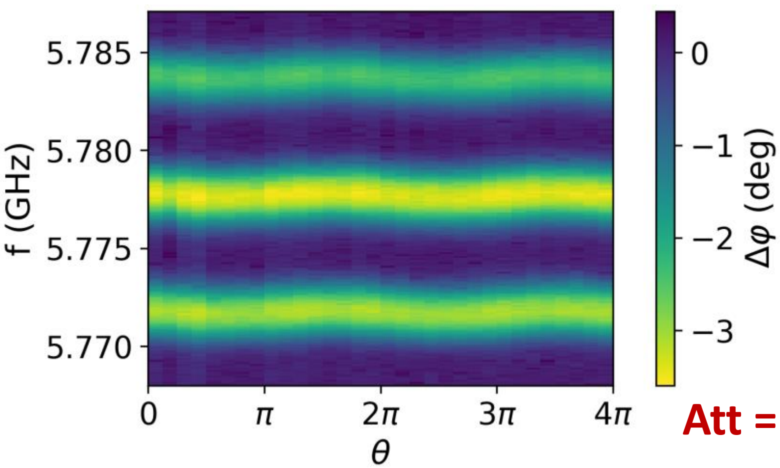
$$\Delta\varphi \sim -\frac{2K}{\kappa}\frac{g^2}{\Delta^2}\left|\sqrt{n_{cav}}+\sqrt{n_{fax}}\,e^{i\varphi_{fax}}\right|^2$$

- Simulate an axion signal with additionnal (weak) power which interferes with cavity photons
- Transforms power into a phase signal via change of frequency of GrAl Qcircuit

Ramsey measurements at 0 field



Att = 60 dB

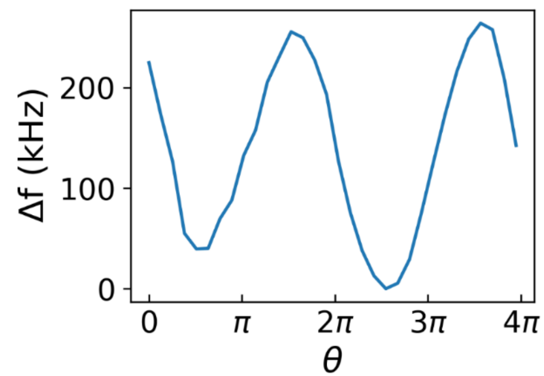


Att = 80 dB

T=20mK, B=0.0T

$n_{cav} \approx 500{,}000$

$\Delta = 2\pi \times 80$ MHz
$\kappa = 2\pi \times 2.2$ MHz
$g = 17$ MHz
$K = -2\pi \times 200$ kHz



$$\Delta\varphi \sim -\frac{2K}{\kappa}\frac{g^2}{\Delta^2}\left|\sqrt{n_{cav}} + \sqrt{n_{ax}}e^{i\varphi_a}\right|^2$$

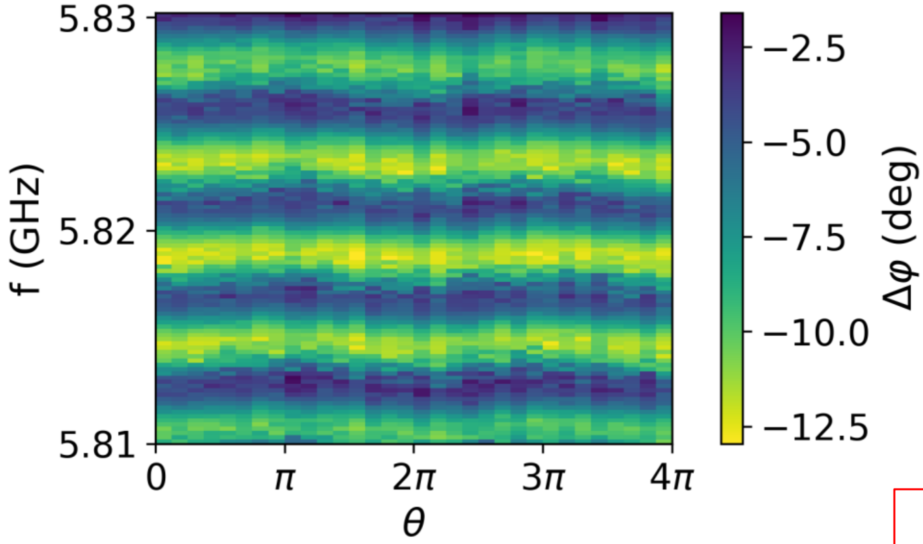
- Observation of Ramsey fringes
- Strongly modulated by interfering faxion. Measurement time = 0.8s /point

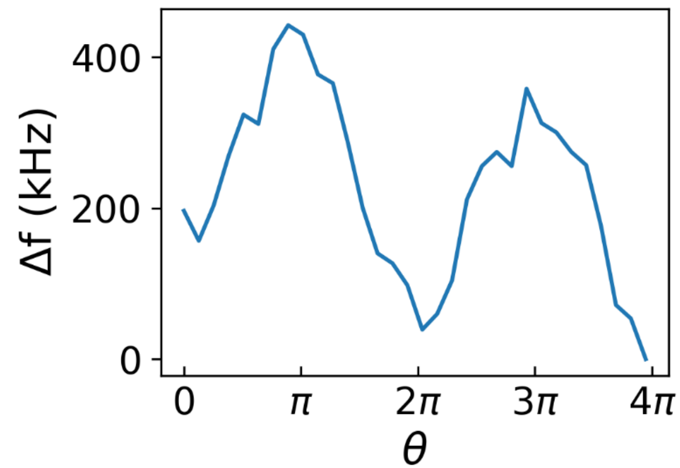
➡ What is the minimum amplitude of faxion which can be detected ?

Ramsey measurements at 0.7 T

T=20mK, B= 0.7T, f=5.9075 GHz

Att = 80 dB





$$\Delta\varphi \sim -\frac{2K}{\kappa}\frac{g^2}{\Delta^2}\left|\sqrt{n_{cav}} + \sqrt{n_{ax}}e^{i\varphi_a}\right|^2$$

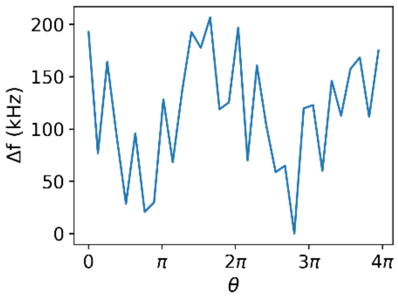
$n_{cav} \approx 500{,}000$

- Simulate an axion signal with additionnal (weak) power which interferes with cavity photons
- Transforms power into a phase signal via change of frequency of GrAl Qcircuit

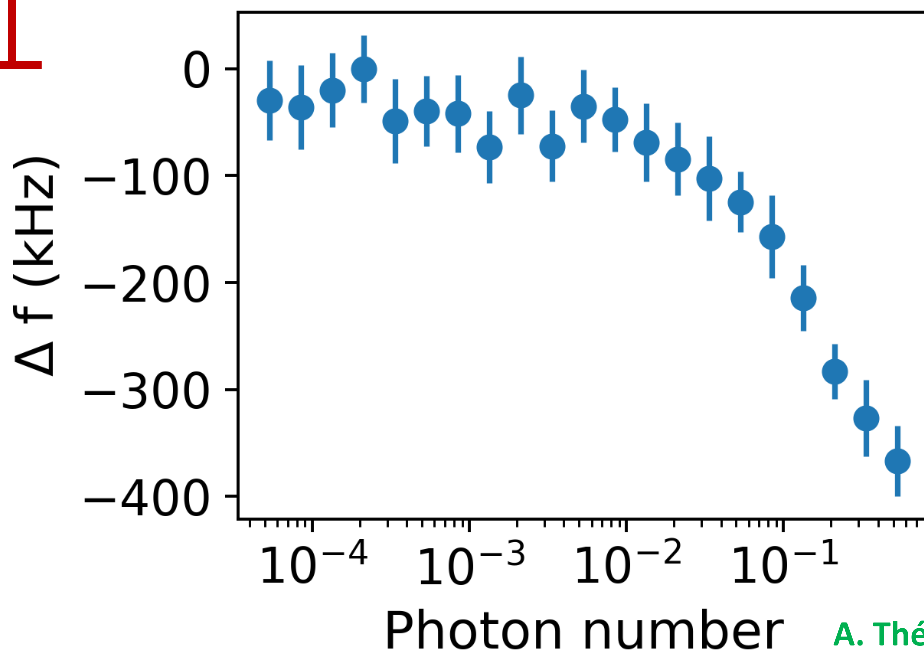
Ramsey measurements at 0.7 T

Haloscope parameters

T=20mK, B= 0.7T, f=5.9075 GHz, V≈1 cm^3?



4.10^{-3} photon

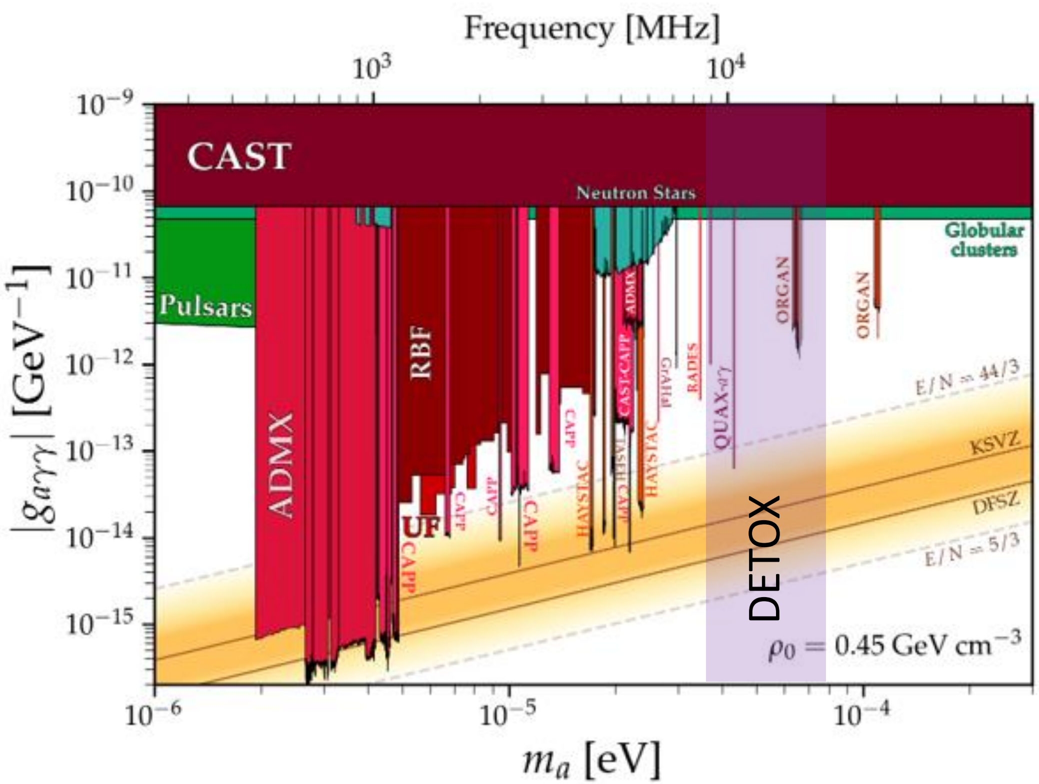


A. Théry, C. Fruy et al. in preparation '24

- Fit of the Ramsey interferometer signal : down to 10^{-3} photon, 80 points in frequency, effective meas 50 ms/points, 28 phase points.
- Transforms power into a phase signal via change of frequency of GrAl Qcircuit

Prospects for mass scan range and sensitivity

https://cajohare.github.io/AxionLimits/



ADMX : T. Braine et al. PRL **124** 101303 (2020) Mass range 2-3 μeV

HAYSTAC : B.M. Brubaker et al. PRL **118** 061302 (2017) Mass range 23.55-24 μeV

QUAX : N. Crescini et al. PRL 124, 171801 (2020) Mass range 42-43 μeV

HAYSTAC alike : M. Malnou et al., PRX **9**, 021023 (2019), K.M. Backes, Nature **590** 238 (2021)

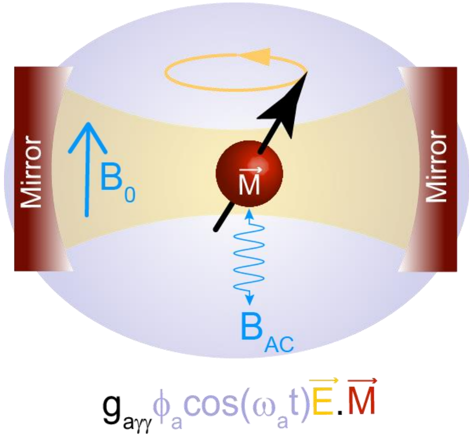
- Prospects sensitivity using the previous Ramsey measurements -> evaluation of the mode volume
- Scanning haloscope using magnetic tuning

➡ First « detection » run on the way (mode volume, B-field, Ramsey sequence can still be optimized…)

Conclusion

✓**Hybrid cavity-superconducting circuit-antiferromagnet system -> can be used to tune strongly cavity modes at large field (∼several T)**

✓**Scanning phase haloscope (DETOX)**

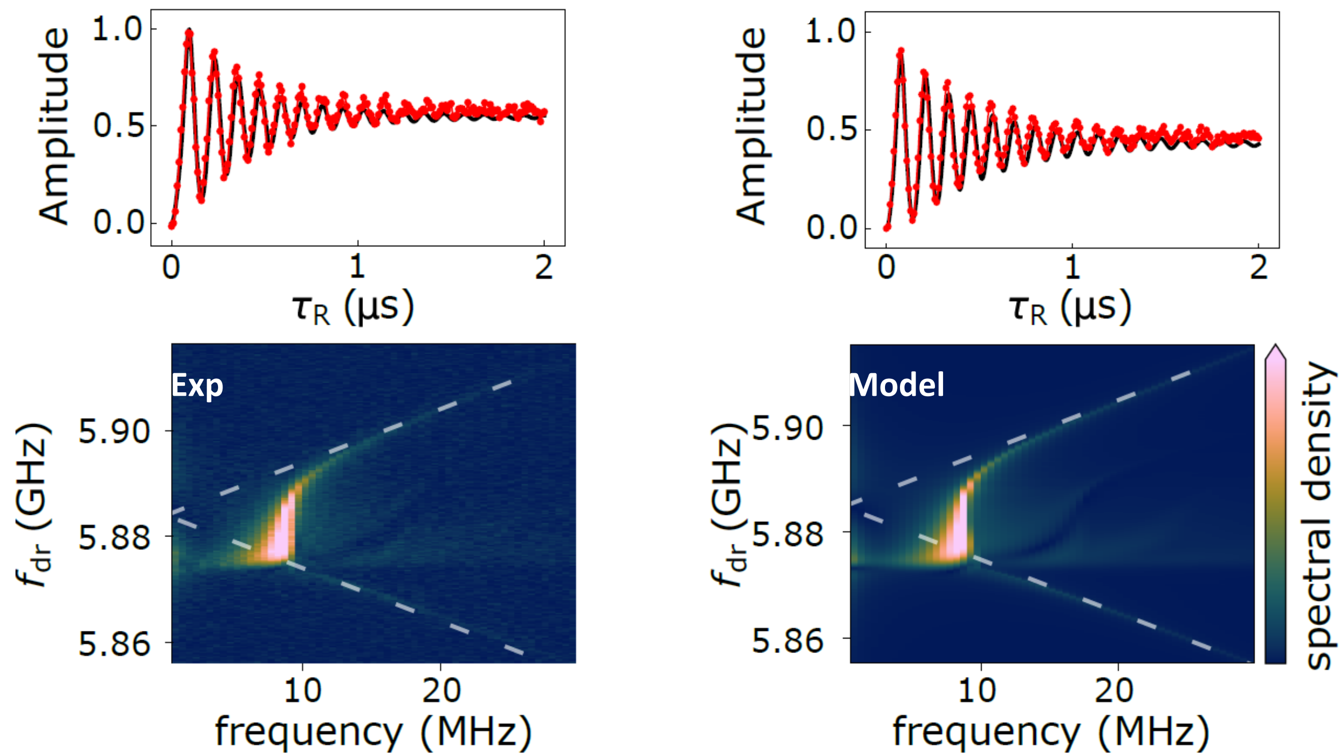


✓**10^{-3} photon in ∼100 s.**

✓**DETOX data taking for different masses on the way**

✓**Example of Qtech for cosmological signal measurements**

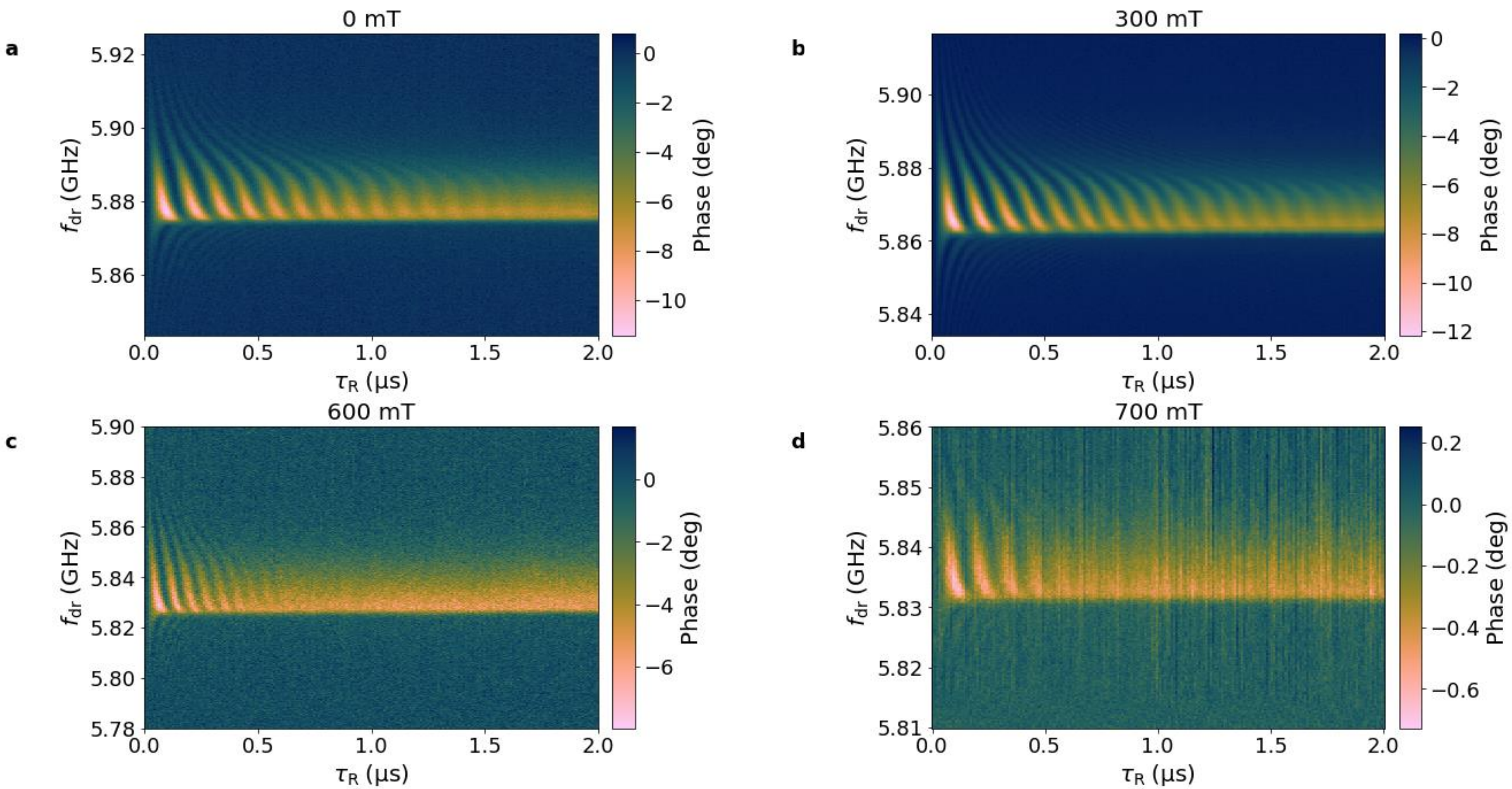
Time domain qubit like manipulation



- Model (Qutip) with K=-2πx200kHz, Γ=2πx477 kHz, ω_0=2πx5.89GHz and 70 levels.
- Fourier transform of the oscillations and time domain are in good agreement

A. Théry et al. PRB'24

Rabi-like drive at finite B-field



T=20mK

- Magnetic field resilience up to 700 mT for in-plane B-field
- Magnetic field resilience up to 200 mT for out-of-plane B-field

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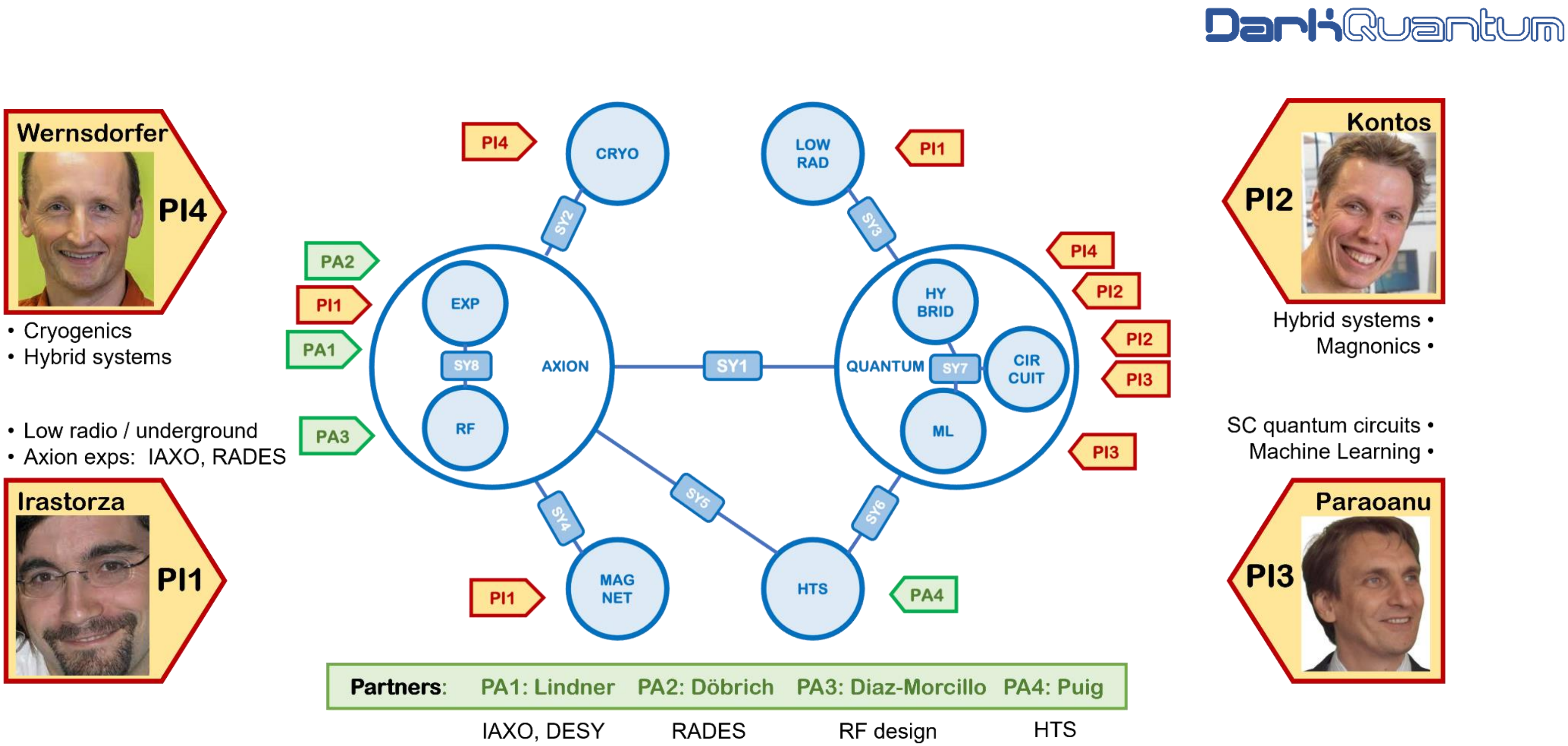
The Dark Quantum project



- Implementation of Quantum Sensing methods for full test of axion paradigm
- Both low mass (BabyIAXO at DESY !) and high mass range will be covered

→ Substantial speed-up of the Axion Dark Matter search

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