Research group

Lab @INFN-LNL, HE building

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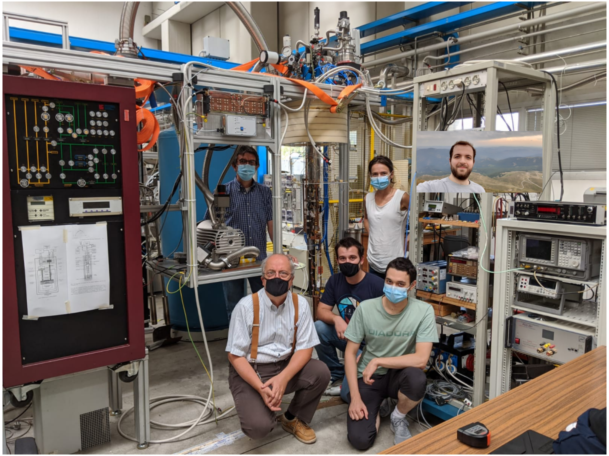
FUNDING ID:

QUAX	INFN-CSN2	2021-2025
SQMS	DOE, USA	2020-2024
TERAPOL	INFN-CSN5	2021-2022
ATTRACT	EU	2019-2020
SUPERGALAXY	FET-EU	2020-2024
DEMIURGOS	INFN-CSN5	2019-2021



PHYSICS IN THE DARK: SEARCHING FOR THE UNIVERSE'S MISSING MATTER

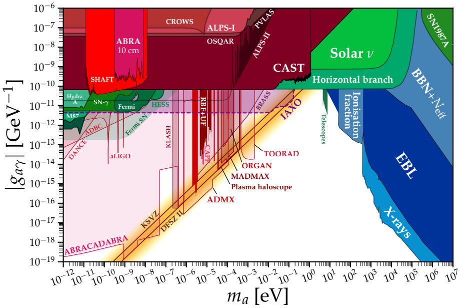
Our research in the framework: *"Physics of the Universe"*

→ search for axion DM in the Galactic halo

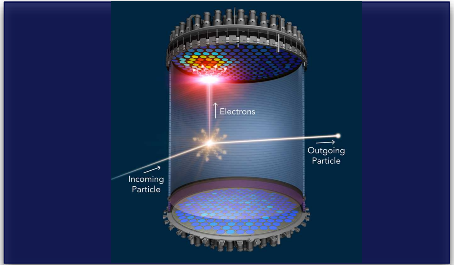
Physics in the Dark: searching for the Universe's missing matter

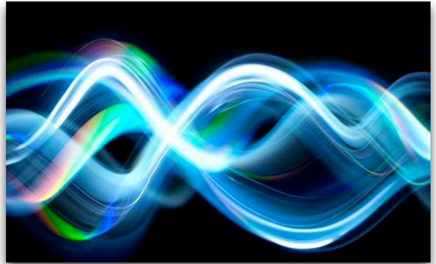
Our research in the framework: *"Physics of the Universe"*

→ search for axion DM in the Galactic halo
→ the axion: weakly interacting, light particle
→ it manifests as an AC effective field



AXION VS WIMP DETECTION





WIMP [1-100 GeV]
– number density is small
– tiny wavelength
– no detector-scale coherence

$\Longrightarrow$ observable: **scattering** of individual particles

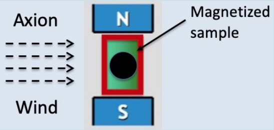
AXION [$m_A \ll$ eV]
– number density is large (bosons)
– long wavelength
– coherence within detector

$\Longrightarrow$ observable: classical, oscillating, **background field**

QUAX - QUAERERE AXIONS

Detection of cosmological axions through their **coupling to electrons** or **photons**

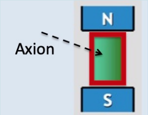
ELECTRON COUPLING – **QUAX**



the axion DM cloud acts as an **effective RF magnetic field** on the electron spin exciting **magnetic transitions** in a magnetized sample (YIG) $\rightarrow$ **RF photons**

$$P_{\mathrm{ax}} = 3.3 \cdot 10^{-24}\,\mathrm{W} \left(\frac{V_{\mathrm{eff}}^{\mathrm{Sa}}}{2.3 \cdot 10^{-5}\,\mathrm{m}^3}\right) \left(\frac{B}{8\,\mathrm{T}}\right)^2 \times \left(\frac{g_\gamma}{-0.97}\right)^2 \left(\frac{\rho_a}{0.45\,\mathrm{GeV\,cm}^{-3}}\right) \left(\frac{f}{13.5\,\mathrm{GHz}}\right) \left(\frac{Q_L}{145\,000}\right)$$

PHOTON COUPLING – **QUAX** aγ



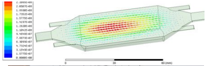
DM axions are converted into **RF photons** inside a **resonant cavity** immersed in a **strong magnetic field**

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

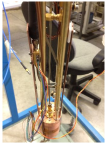
QUANTUM SENSING

To get to **cosmologically relevant sensitivity**:

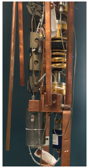
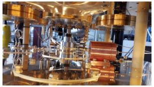
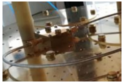
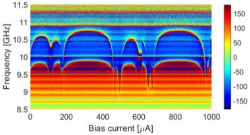
- we develop **high Q** ($\gtrsim 10^6$) microwave cavities, compatible with **strong magnetic fields** ($B \gtrsim 8\,\mathrm{T}$)

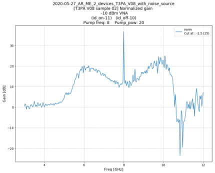






- **we use the best preamplifiers (research, not commercially available)** $\rightarrow$ JPA (Josephson Parametric Amplifier) key element in **qbit** readout, TW (Travelling Wave) JPA (thanks to collaboration with N. Roche, Grenoble)

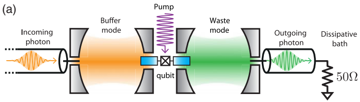








QUANTUM SENSING (CONTINUED)

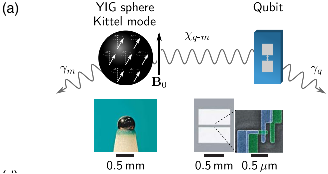
To get to **cosmologically relevant sensitivity**:

- (next step in sensitivity*) we need to be able to **count photons**
  $\Longleftrightarrow$ develop the **microwave SPD** = enabling technology quantum computing
  NOTE: photon detection at optical frequencies relies on ionization, microwave photons are 5 orders of magnitude lower!



PHYSICAL REVIEW X **10,** 021038 (2020)

Quantronics Group, FR (E. Flurin)



PHYSICAL REVIEW LETTERS **125,** 117701 (2020)

Nakamura-Usami Group, JP

linear amplifier σ^{LA}, and quantum counter σ^{LA} power sensitivity
$T_N^{LA} = 1$ K, QC noise rate $R_n = 100$ Hz, $f = 10$ GHz, $Q_a = 10^6$
$\rightarrow$ sensitivity improved by a factor 14 $\Longleftrightarrow$ 200 in measurement time!

$$\frac{\sigma^{\mathrm{QC}}}{\sigma^{\mathrm{LA}}} = \frac{h}{k_B T_n^{\mathrm{LA}}} \sqrt{f Q_a R_n}$$

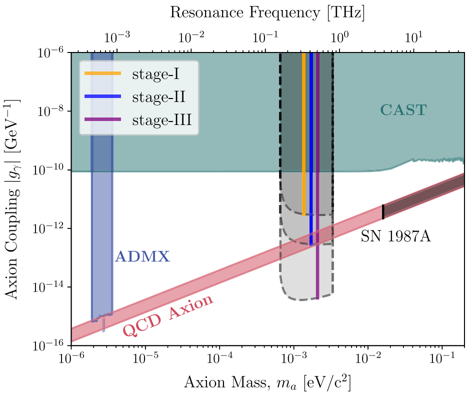
TERAPOL

We investigate AntiFerromagnetic Topological Insulators (AF-TIs) (e.g. $Mn_xBi_yTe_z$) for the development of **axion detectors** by means of a terahertz time domain spectroscopy apparatus (THz-TDS)

AF-TIs materials can host quasiparticles which are **resonantly driven** in the presence of axions and emit THz photons which can be detected using a single photon detector

- $0.7 < m_a < 3.5\,\mathrm{meV}$, axion mass interval currently **inaccessible** to other DM experiments or proposals
- $V_s \lesssim 1\,\mathrm{cm}^3$ (stage I); x100 (stage II)
- tunability of the resonance with applied magnetic field

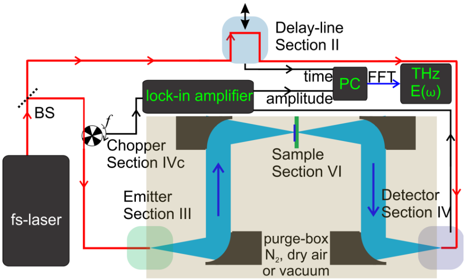
proposal by D. Marsh *et al* PRL 123, 121601 (2019)



Terahertz time domain spectroscopy (1)

Spectral range 0.1 – 1 THz
→ region of interest for vibrational spectroscopy of liquids, low frequency modes of molecular crystals, drugs, explosives…
→ suited to measure the dynamics of mobile charge carriers since they reflect and absorb terahertz radiation
MIR experiment (gr2) in 2012 to test high speed semiconductors

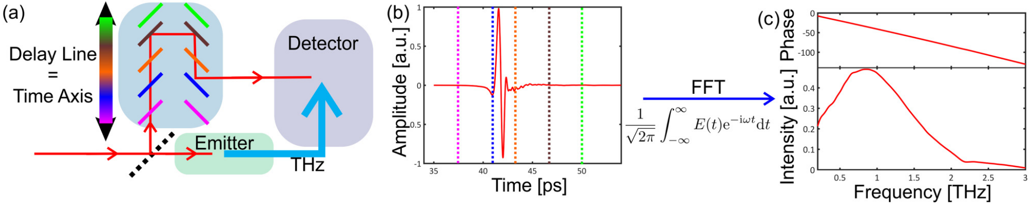
- femtosecond laser (mode-locked Ti:Sa)
- two beam paths:
  1. **detector** line with delay
  2. THz pulse generation line → **emitter**
- convolution between the THz pulse (ps-duration) and the optical pulse (fs-duration)
- photoconductive antennas
- lock-in techniques



TERAHERTZ TIME DOMAIN SPECTROSCOPY (2)

In the transmission spectrum we search for a resonance whose frequency and width coincide with the relevant polariton parameters necessary to use AF-TIs as axion dark matter detectors.

How **time domain** measurements can provide **spectral information**:



1. different colours → different delay-line positions, corresponding to different time points in (b)
2. measured THz time-domain signal (amplitude of the THz field at the detector antenna)
3. the FFT of the signal in (b) is used to infer system dynamic range

SF emission by an ensemble of $N = 10^{13}$ correlated atoms

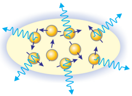
the smallest of interaction rates (axion, neutrino) might be

intrinsically amplified by a mechanism of macrocoherence

independent atoms

correlated atoms

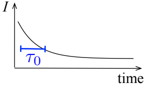
FLUORESCENCE



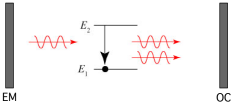
— spontaneous emission
(O) incoherent emission

$I_t \propto N$

$I = I_0 \exp(-t/\tau_0)$

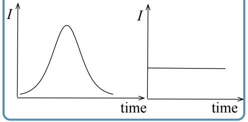


LASER/ASE (OSCILLATION AND AMPLIFICATION)



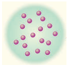
— stimulated emission
(O) coherent emission

$I_t \propto N$



SUPERRADIANCE R. Dicke (1954)

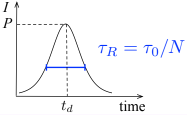
$V \ll \lambda^3$



— initial moment
(O) pulsed coherent emission

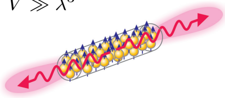
$I_t \propto N^2$

$I(t) = 4P\,\mathrm{sech}^2\left(\frac{t - t_d}{2\tau_R}\right)$



MACROCOHERENCE/ SUPERFLUORESCENCE

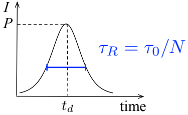
$V \gg \lambda^3$



— macro-dipole formation
(O) pulsed coherent emission

$I_t \propto N^2$

$I(t) = 4P\,\mathrm{sech}^2\left(\frac{t - t_d}{2\tau_R}\right)$



as the coherent region is limited by the emission wavelength (~1 μm) → $N < 10^8$ (for 10^{20} cm^{-3})

N can reach the Avogadro number

WRAP UP

- We BUILD table-top experiments in the lab, **at the low energy frontier of particle physics**
- **Quantum Information Science $\Longleftrightarrow$ Particle Physics**

https://arxiv.org/abs/1803.11306
Quantum Sensing for High Energy Physics (2018), signed by more than a hundred leading scientists in United States

https://cds.cern.ch/record/2729937
QUANTUM SENSORS of the DARK and EARLY UNIVERSE: Exploiting Quantum Entanglement in the Laboratory for Detection of Particles and Fields Beyond the Standard Model (BSM) and signals from Very Early Universe

We are part of this NQI center led by FNAL, A. Grassellino

- We are open to collaboration within this Excellence Project

PostDoc Positions are open!

LAB EXPERTISE

QUANTUM SENSING	JPA (Josephson Parametric Amplifiers) amplifiers, SQUID, TW JPA, microwave SPD (single photon detector)
Microwave resonators	photonic cavities, hybrid (magnon-photon) systems, NC and SC cavities (Nb and type II SC)
LASER systems LAB (former ALICE clean room)	Femtosecond and picosecond mode-locked lasers, CW tunable narrow linewidth Ti:Sa lasers, MOPA lasers
CRYO TESTBEDS	dilution refrigerators (mK), superfluid He vessel, liquid helium cryosystems, pulse tubes (> 4K)
MATERIALS SCIENCE	RE (rare-earth) doped materials, YIG (Yttrium Iron Garnet), AF-TI (Antiferromagnetic Topologic Insulators), SC
Magnetic fields	2T, 8 T SC magnets — 14T to come!

MORE DETAILS on:

HALOSCOPE	PRL 124, 171801 (2020) Rev. Sci. Instrum. 91,094701(2020) PRD 99, 101101(R) (2019) EPJC 78:703 (2018) Phys. Dark Univ. 15 (2017) 135–141 Sci. Rep. 7: 15168 (2017)
OPTOMAGNONICS	Commun. Physics 3:164 (2020) PRL 118, 107205 (2017)
MACROCOHERENCE	arXiV:2009.06016 (2020) PRR 118, 107205 (2017)
OTHER TOPICS	[...]

INTERNATIONAL COLLABORATIONS:

CNRS, Grenoble INP, Institut Neel
(N. Roche group) TW-JPA

Quantronics Group, SPEC, CEA, CNRS, Gif-sur-Yvette, France
(E. Flurin group) SPD

Quantum Information Physics and Engineering
(Nakamura-Usami group) SPD

M. Yoshimura and N. Sasao group
Okayama University, JP