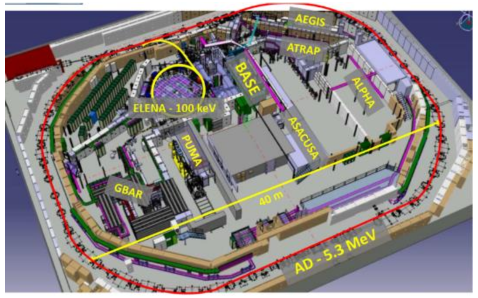
15th Terascale Detector Workshop 2023

Search for Dark Matter with Quantum-Inspired Technologies



Present some recent ideas and developments that emerged from precision experiments taylored to measuring fundamental constants at the low energy frontier

Stefan Ulmer

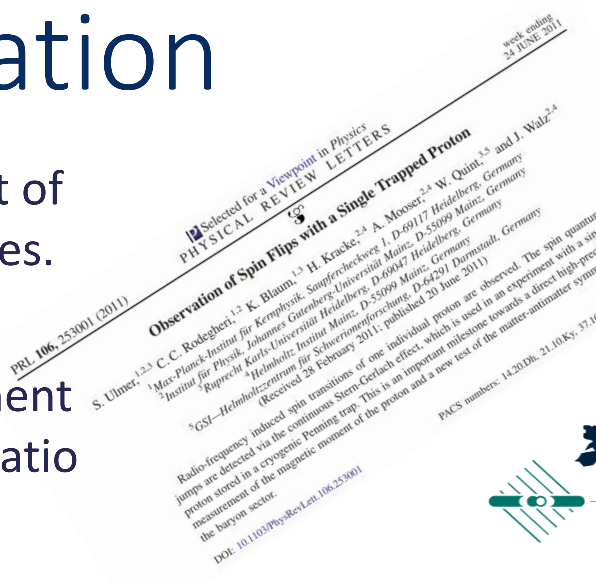
HHU Düsseldorf / RIKEN

2023 / 03 / 01

BASE – Collaboration

- **Mainz:** Measurement of the magnetic moment of the proton, implementation of new technologies.

- **CERN-AD:** Measurement of the magnetic moment of the antiproton and proton/antiproton q/m ratio
- **BASE-STEP:** Development of transportable antiproton traps
- **Hannover/PTB:** QLEDS-laser cooling project, new technologies



Selected for a Viewpoint in *Physics*

PRL **106,** 253001 (2011) PHYSICAL REVIEW LETTERS week ending 24 JUNE 2011

Observation of Spin Flips with a Single Trapped Proton

S. Ulmer,[1,2,3] C. C. Rodegheri,[1,2] K. Blaum,[1,3] H. Kracke,[2,4] A. Mooser,[2,4] W. Quint,[3,5] and J. Walz[2,4]

[1]*Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-69117 Heidelberg, Germany*
[2]*Institut für Physik, Johannes Gutenberg-Universität Mainz, D-55099 Mainz, Germany*
[3]*Ruprecht Karls-Universität Heidelberg, D-69047 Heidelberg, Germany*
[4]*Helmholtz Institut Mainz, D-55099 Mainz, Germany*
[5]*GSI—Helmholtzzentrum für Schwerionenforschung, D-64291 Darmstadt, Germany*
(Received 28 February 2011; published 20 June 2011)

Radio-frequency induced spin transitions of one individual proton are observed. The spin quantum jumps are detected via the continuous Stern-Gerlach effect, which is used in an experiment with a single proton stored in a cryogenic Penning trap. This is an important milestone towards a direct high-precision measurement of the magnetic moment of the proton and a new test of the matter-antimatter symmetry in the baryon sector.

DOI: 10.1103/PhysRevLett.106.253001 PACS numbers: 14.20.Dh, 21.10.Ky, 37.10.Rs, 37.10.Ty

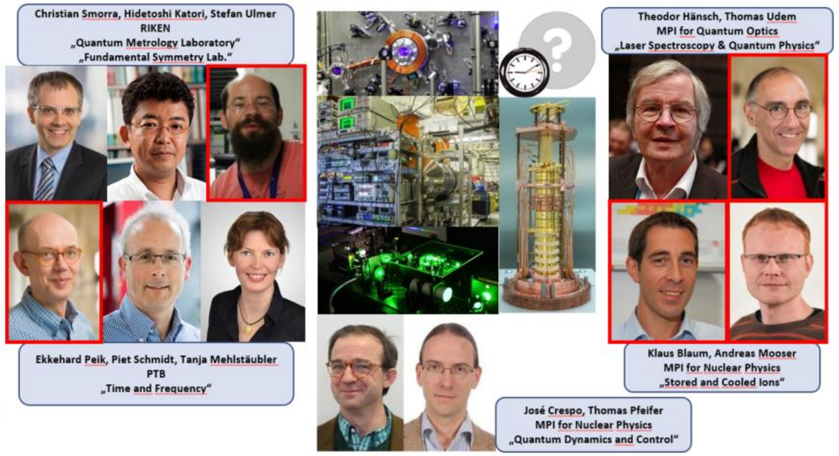
Institutes: RIKEN, MPIK, CERN, University of Mainz, Tokyo University, GSI Darmstadt, University of Hannover, PTB Braunschweig, ETH Zuerich

Team at CERN, running 24/7 since 2013

Three experiments, 9 institutes, about 30 collaborators, 10 at CERN

C. Smorra et al., EPJ-Special Topics, The BASE Experiment, (2015)

Some Groups Active



Christian Smorra, Hidetoshi Katori, Stefan Ulmer
RIKEN
„Quantum Metrology Laboratory“
„Fundamental Symmetry Lab.“

Ekkehard Peik, Piet Schmidt, Tanja Mehlstäubler
PTB
„Time and Frequency“

José Crespo, Thomas Pfeifer
MPI for Nuclear Physics
„Quantum Dynamics and Control“

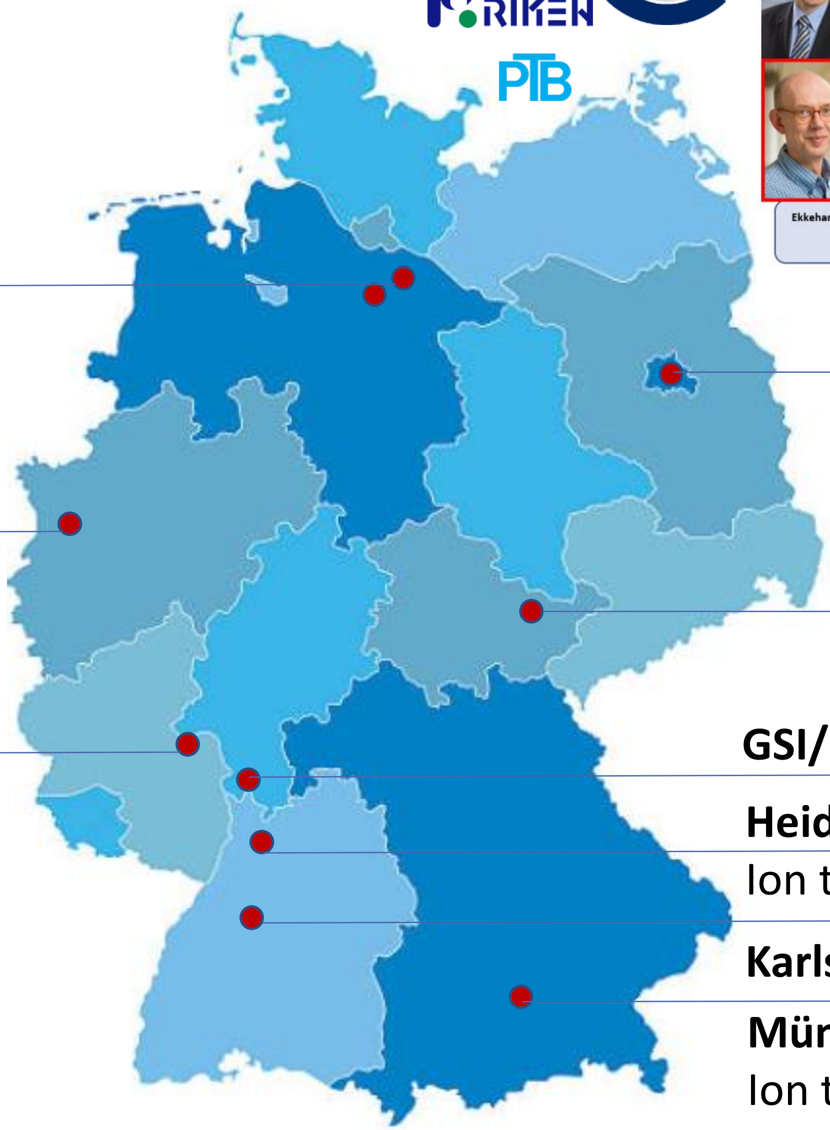
Theodor Hänsch, Thomas Udem
MPI for Quantum Optics
„Laser Spectroscopy & Quantum Physics“

Klaus Blaum, Andreas Mooser
MPI for Nuclear Physics
„Stored and Cooled Ions“

Hannover / Braunschweig
Ion and atom traps / clocks / QI

Düsseldorf
Ion traps / antimatter / molecules / clocks

Mainz
Ion traps / Magnetometers / QI



Berlin
SQUIDS, References

Jena
X-ray detectors

GSI/FAIR: MMC’s / HCI’s

Heidelberg
Ion traps / SQUIDS / MMC’s etc.

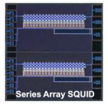
Karlsruhe: SQUIDS / etc.

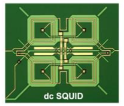
München
Ion traps / precision laser-spectroscopy

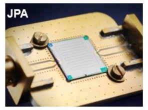
Blaum
Budker
Crespo
Enss
Galatyuk
Latacz
Mooser
Noertershaeuser
Obertelli
Ospelkaus
Ospelkaus-Schwarzer
Peik
Schiller
Schmidt
Schmidt-Kaler
Smorra
Stoehlker
Sturm
Ulmer
…

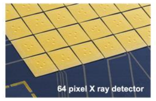
Consortium for Cryogenic Detectors and Superconducting Electronics
(founded 2020)

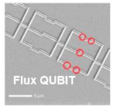
- SQUIDs
- Microwave SQUID multiplexer
- Qubits
- Quantum limited Amplifiers
- Cryogenic detectors MMCs, TES, KIDs, …

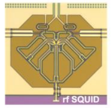


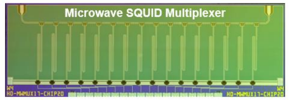








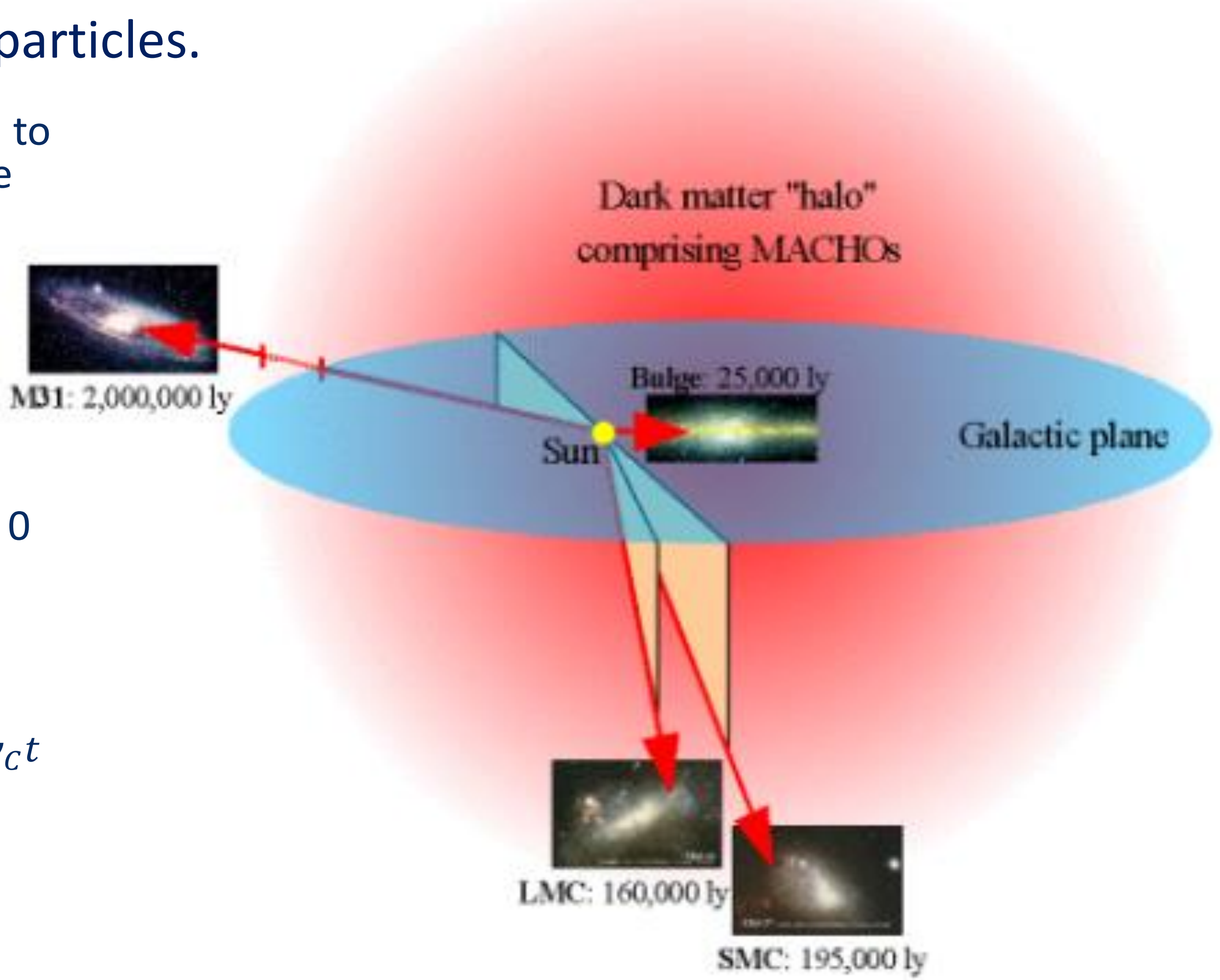




Properties of Cold Dark Matter

Some precision measurements and their signatures are hypothetically sensitive to signatures produced by axion like particles.

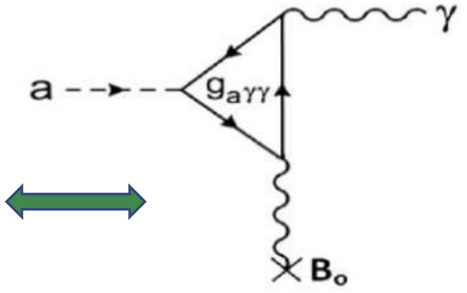
- Dark matter density has been estimated to be at a level of $\rho_{DM} \approx 0.4\mathrm{GeV/cm}^3$, one H-atom in 2 cm^3
- Dark matter RMS velocity is at $v_{DM} \approx 300\mathrm{km/s}$.
- Non-relativistic form of matter, e.g. spin 0 bosons oscillating at their Compton frequencies
  - $\nu_c = \frac{m_a c^2}{h}$ with $\Phi(t) = \frac{\sqrt{2\rho_{DM}}}{m_\Phi} \cos 2\pi\nu_C t$
- Mass range $10^{-21}eV < m_a < 1eV$



Axion Electrodynamics

- Lagrange density in presence of axion like particles modifies to

$$\mathcal{L}_{em,a} = \frac{1}{2}(\boldsymbol{E}\cdot\boldsymbol{E} - \boldsymbol{B}\cdot\boldsymbol{B}) - \rho_{el}\Phi + \boldsymbol{j}_{el}\cdot\boldsymbol{A} + \frac{1}{2}\left((\partial_t a)^2 - (\nabla a)^2\right) - \frac{1}{2}m_a^2 a^2 - g\,a\,\boldsymbol{E}\cdot\boldsymbol{B}$$



- Leads to modified **Maxwell equations**

$$\nabla\cdot(\boldsymbol{E} - g\,a\,\boldsymbol{B}) = \rho_{el}$$

$$\nabla\times(\boldsymbol{B} + g\,a\,\boldsymbol{E}) - \partial_t(\boldsymbol{E} - g\,a\,\boldsymbol{B}) = \boldsymbol{j_{el}}$$

$$\nabla\times\boldsymbol{E} + \partial_t\boldsymbol{B} = 0$$

$$\nabla\cdot\boldsymbol{B} = 0$$

- In vacuum, at constant magnetic field, and **low mass**, the modified ampere law becomes:

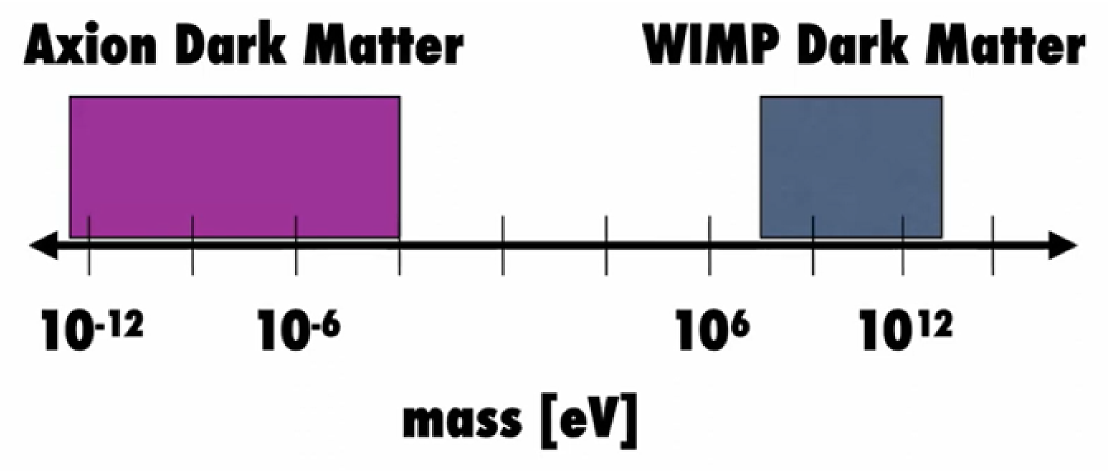
$$\nabla\times(\boldsymbol{B} + g\,a\,\boldsymbol{E}) - \partial_t(\boldsymbol{E} - g\,a\,\boldsymbol{B}) = \boldsymbol{j_{el}}$$

$$\rightarrow \nabla\times\boldsymbol{B} = -(g\,\boldsymbol{B}\partial_t a)$$

- In a constant, strong magnetic field $\boldsymbol{B}$ the axions are sourcing an azimuthal magnetic field that can be picked up with toroidal detectors.

P. Sikivie, https://arxiv.org/pdf/2003.02206.pdf
P. Sikivie, https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.51.1415

In particular



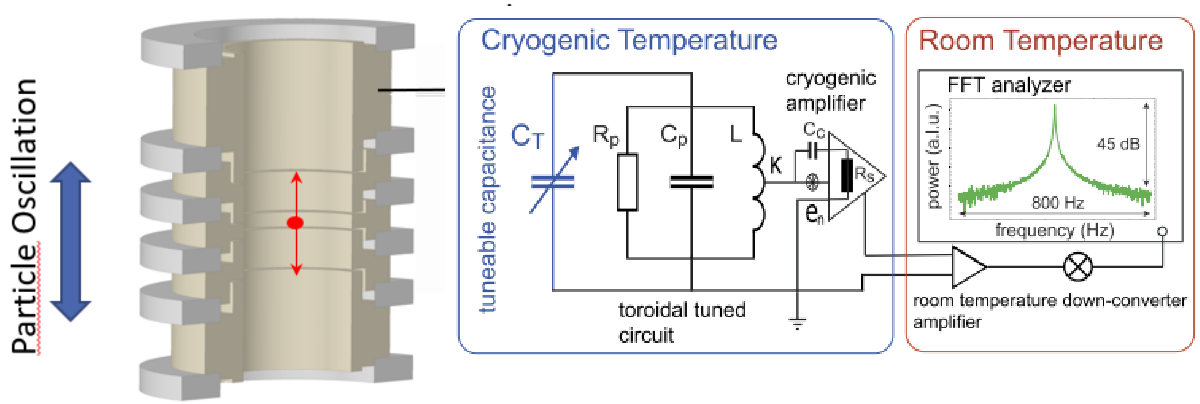
$\rho_{DM} \approx 0.4 \mathrm{GeV/cm^3}$

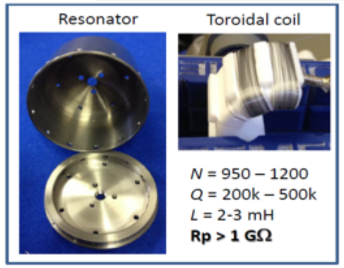
	Axion (wave)	WIMP (particle)
Mass	$m_a = 10^{-9} eV$	$m_{WMP} = 100\ GeV$
De Broglie WL	$\lambda_{dB} = 10^4\ km$	$\lambda_{dB} = 10^{-16}\ km$
Occupancy	$N = 10^{44}$	$N = 10^{-36}$

- Scenarios:
  - Quasi-static regime for $\lambda_{dB} \gg R_{ex}$
    - $\nabla \times \boldsymbol{B} = \left(-g_{a\gamma\gamma}\boldsymbol{B}\frac{\partial a}{\partial t}\right)$
  - Cavity regime for $\lambda_{dB} \approx R_{ex}$
    - $\nabla \times \boldsymbol{B} = \frac{\partial \boldsymbol{E}_r}{\partial t} + \left(-g_{a\gamma\gamma}\boldsymbol{B}\frac{\partial a}{\partial t}\right)$
  - Radiation regime for $\lambda_{dB} \ll R_{ex}$
    - $0 = \frac{\partial \boldsymbol{E}_r}{\partial t} + \left(-g_{a\gamma\gamma}\boldsymbol{B}\frac{\partial a}{\partial t}\right)$

Single Particle Penning Trap Detectors

- In high-precision Penning trap experiments, sensitive superconducting detectors to record coherent oscillations of **SINGLE PARTICLES** are used as interfaces between particles and experimentalists.
- Usually used to measure frequencies to derive fundamental constants, such as mass ratios and magnetic moments

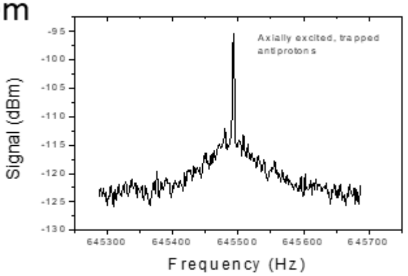




Inductor compensates system capacitance

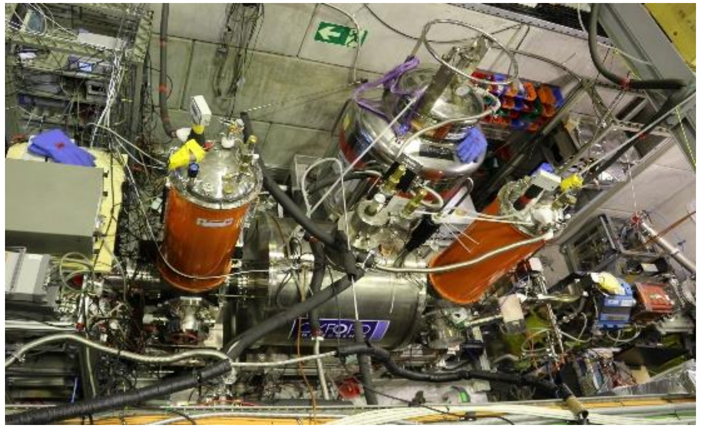
$$I_{p,x} \sim \frac{q}{D_{eff}} (2\pi\nu_x)x$$

$$I_{p,x} \sim 0.1\ fA\,/(MHz\ \mu m)$$



- Devices have a very **high sensitivity,** are operated in **strong magnetic fields**, have geometry that is sensitive to **pickup of magnetic fields sourced by axions**.

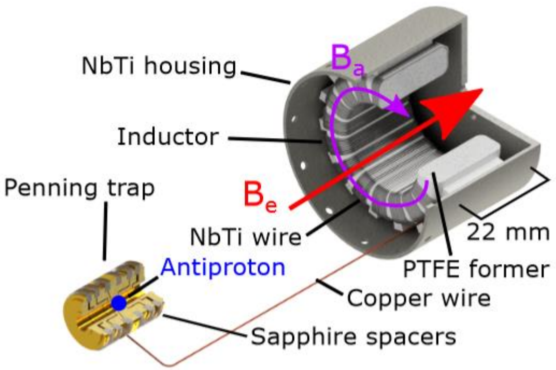
Parameter	Value
Frequency	500 kHz to 1 MHz
Q value	10.000 to 100.000
Rp	100 M to 1 G



Constraining Axion/Photon Coupling

J. Devlin et al., (BASE collaboration), Physical Review Letters. ***126,*** *041301 (2021).*

- Axions at the right Compton frequency would source a radio-frequency signal that could be picked up by our single particle detection systems

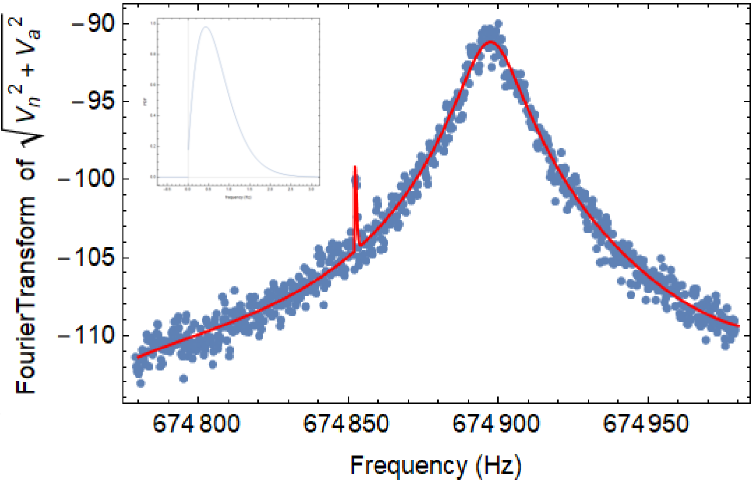


- Important feature: cold axions and axion like particles oscillate at their Compton frequencies

$$\nu_a = m_a c_0^2/h$$

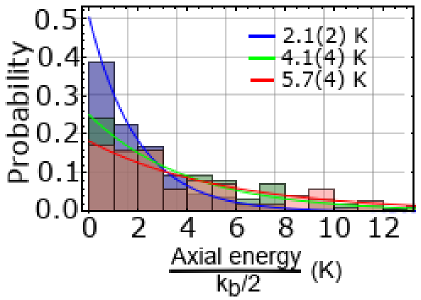
- In a strong external magnetic field **axions can convert into photons** via the inverse Primakoff effect.

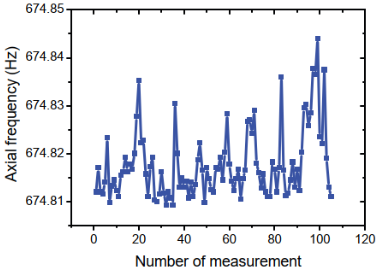
$$\rightarrow \nabla \times \boldsymbol{B} = -(g\, \boldsymbol{B} \partial_t a) \qquad \boldsymbol{B_a} = -\frac{1}{2} g_{a\gamma} r \sqrt{\rho_a c_0 \hbar} B_e \boldsymbol{e_\phi}$$

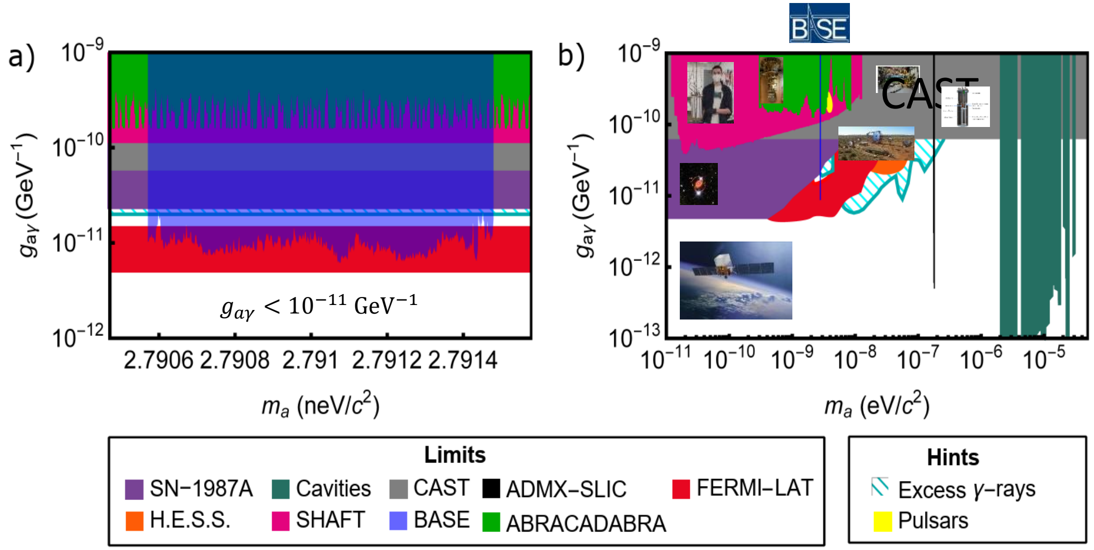


- Axion signal: $V_a = \frac{\pi}{2} g_{a\gamma} \nu_a \sqrt{\rho_a \hbar c_0} * Q\sqrt{\tau(\nu, Q, p)} \kappa N_T (r_2^2 - r_1^2) B_e$
- Noise-Floor: $V_n = \sqrt{e_n^2 \Delta\nu + 4 k_B T_z R_p \tau(\nu, Q, p) \kappa^2 \Delta\nu}$

The most important parameter to derive **appropriate limits** is the resonator temperature T_z

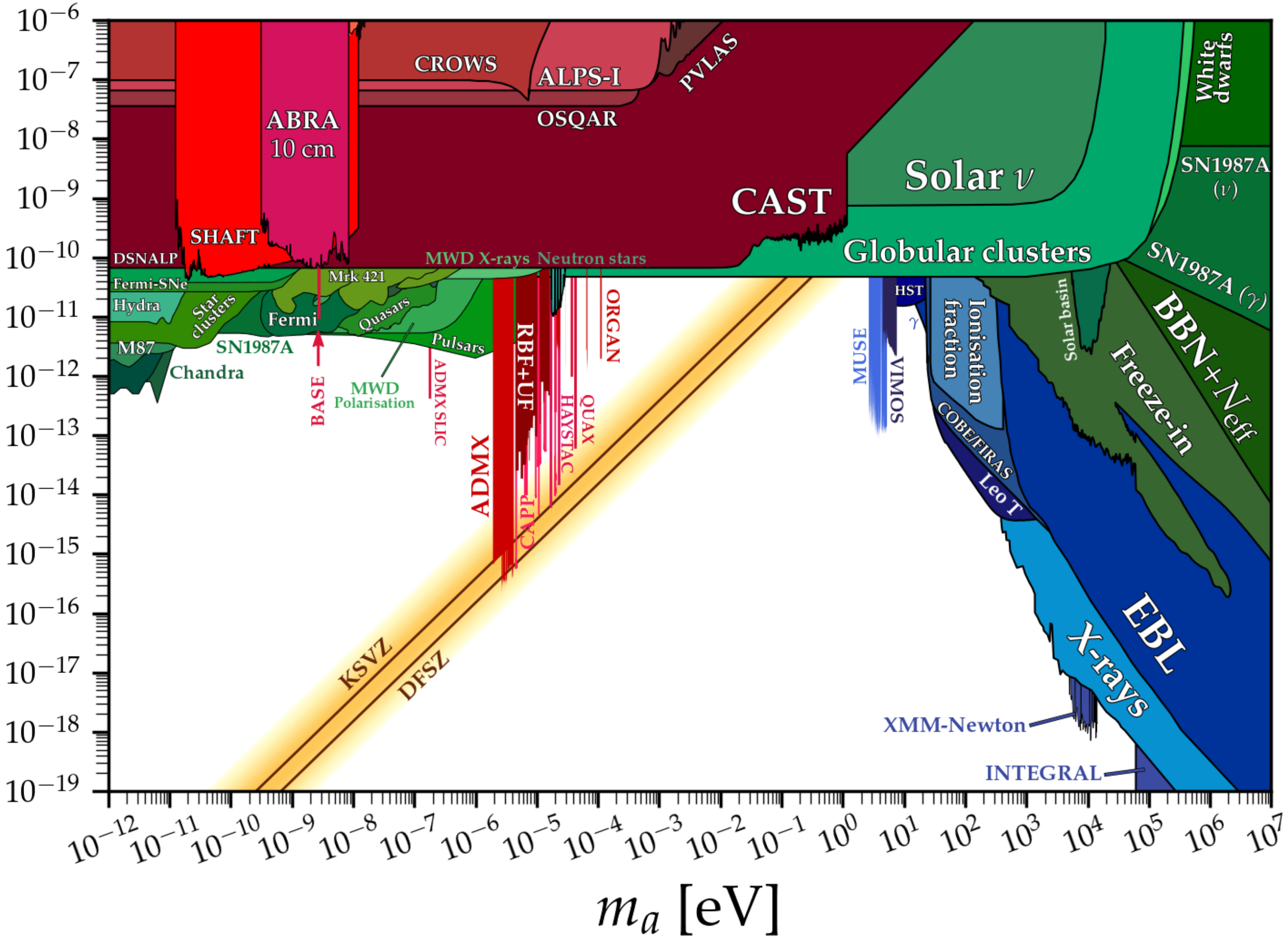






Penning trap: calibrated by **single particle quantum jump thermometry**

Axion Searches

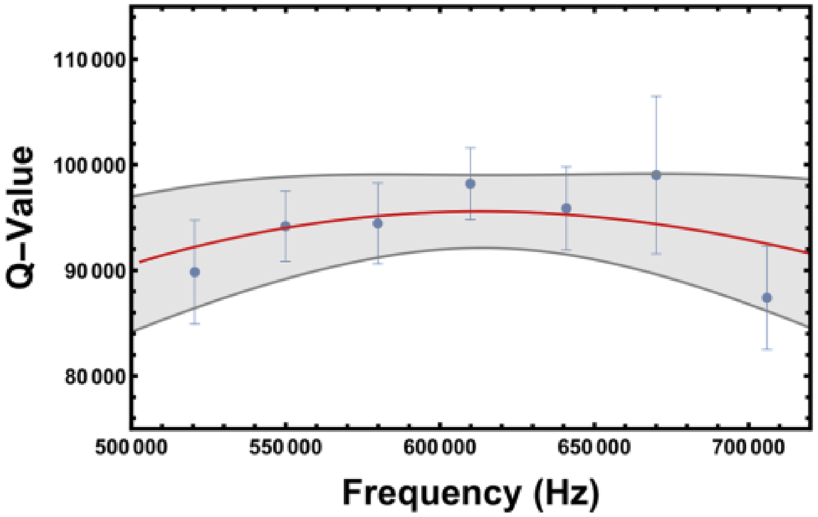


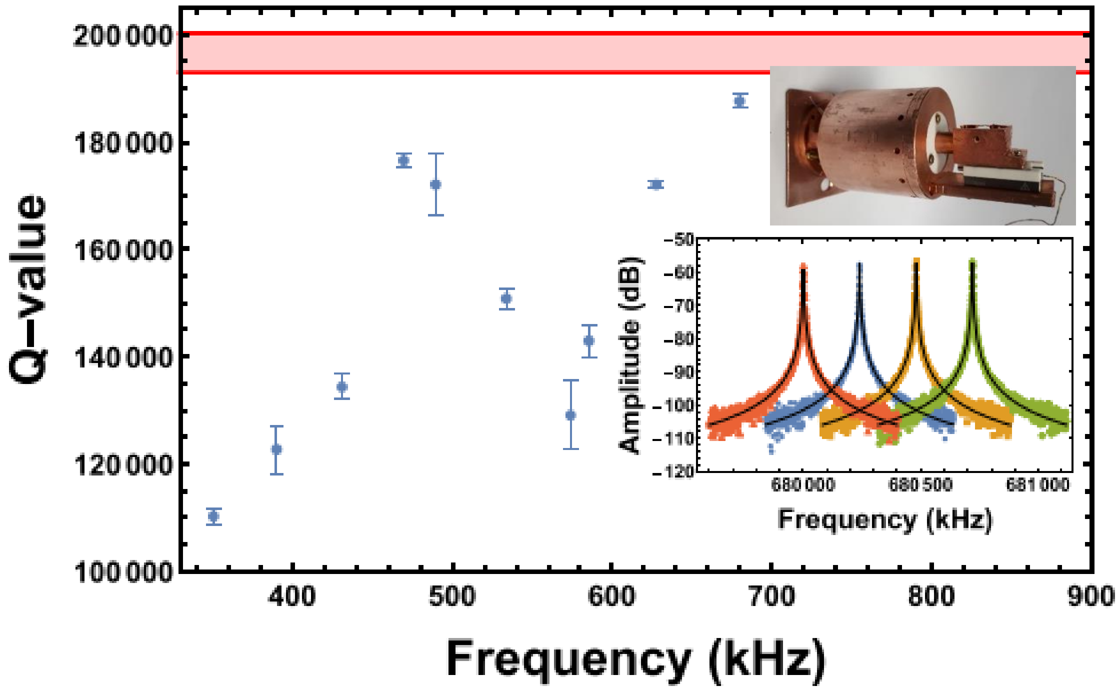
- Our tiny contribution:
  - Parasitic experiment
  - Not optimized for axion detection
  - Volume limited
  - Magnetic field limited
  - Background limited
  - Bandwidth limited
- Still a lab-device at a cost of a superconducting magnet and some adds that make not more than 100.000,- and competes with satellites!

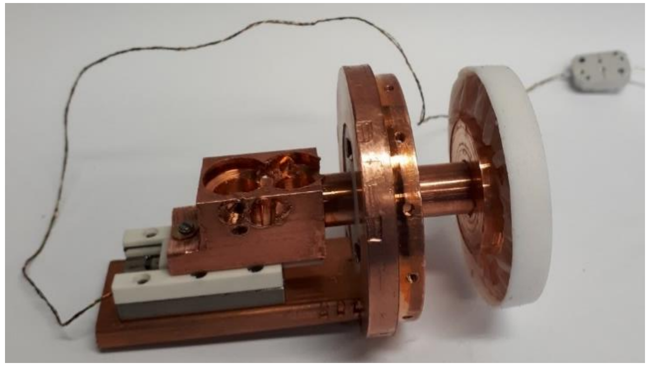
https://github.com/cajohare/AxionLimits/blob/master/AxionPhoton.ipynb

Frequency Tuning

Cryogenic adjustable capacitance with no loss of Q developed, at 5 times higher detection sensitivity.







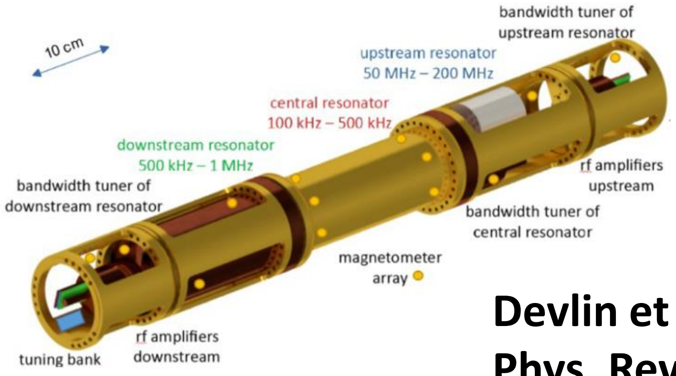
Already could cover one frequency octave

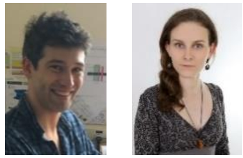
Future Projection

- With a purpose-built experiment we should be able to improve the sensitivity considerably

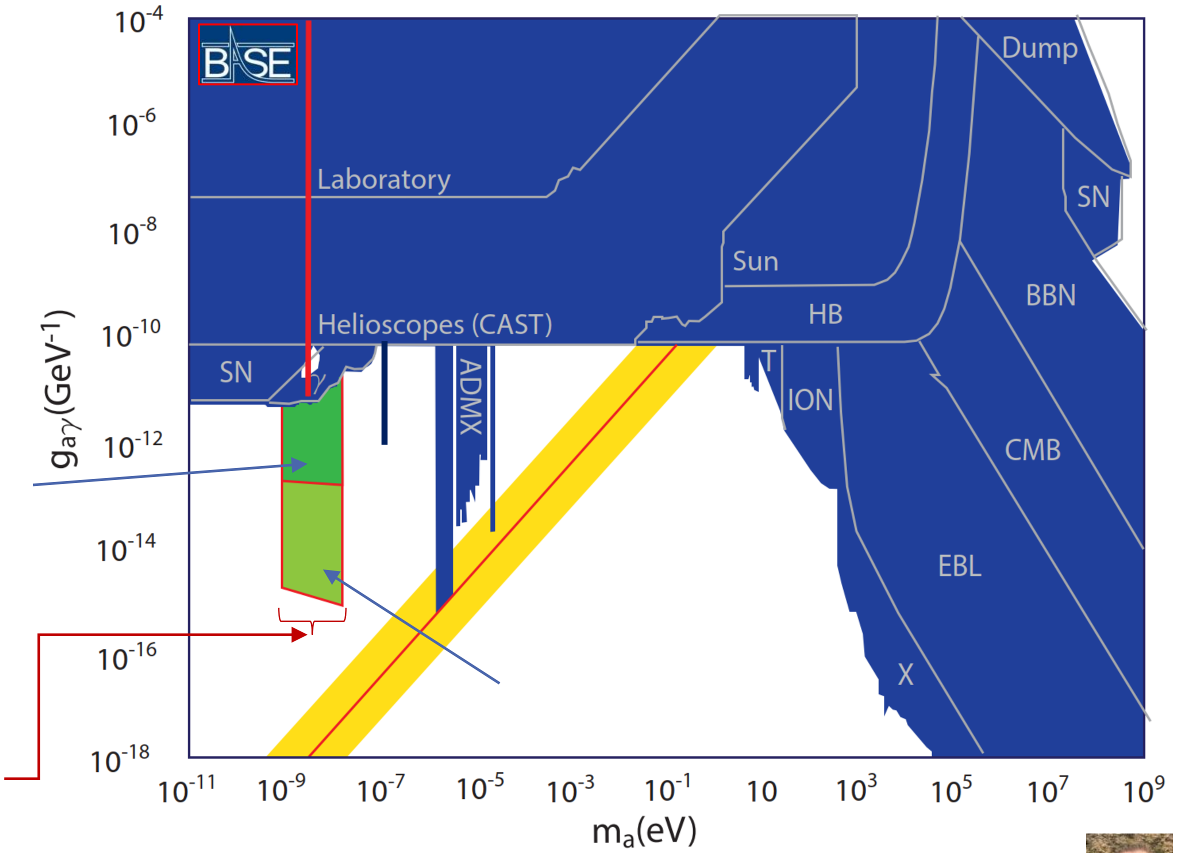
$$\frac{V_a}{V_n} \propto \frac{\pi}{2} g_{a\gamma}\sqrt{\nu_a \rho_a \hbar c_0} * \sqrt{\frac{f(Q)}{4k_B g(T_z)}}\sqrt{(r_2-r_1)}(r_2+r_1)^{3/2}B_e$$

Parameter	Current	New	Factor
Temperature	$5.5\,K$	$0.05K-0.1K$	>3
Q	$40\,k$	$160\,k$	>1.4
e_n	$1\,nV/\sqrt{Hz}$	$0.1\,nV/\sqrt{Hz}$	>3
B_0	$1.8\,T$	$7.0\,T$	3.9
Geometry	1	16	16
Peak Sens.	1		>260

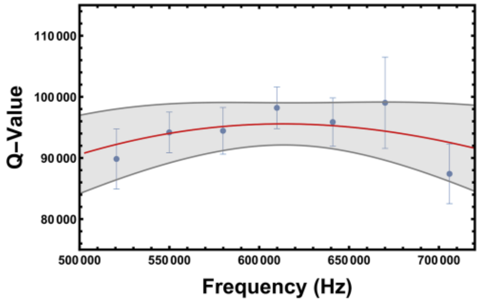




Devlin et al., BASE, Phys. Rev. Lett. 126, 041301



Bandwidth-gain: > 1000



Technologies available to build such an experiment / discussion with IAXO started

Josephon-Junction-based Quantum Technology

- Planned to connect these efforts with already existing consortium for cryogenic detectors and superconducting electronics.

CDS

Consortium for Cryogenic Detectors and Superconducting Electronics
(founded 2020)

- SQUIDs
- Microwave SQUID multiplexer
- Qubits
- Quantum limited Amplifiers
- Cryogenic detectors MMCs, TES, KIDs, …

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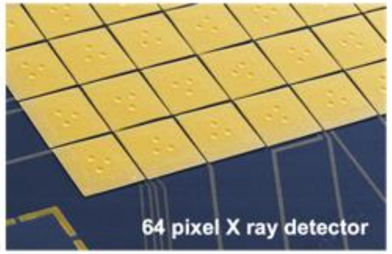
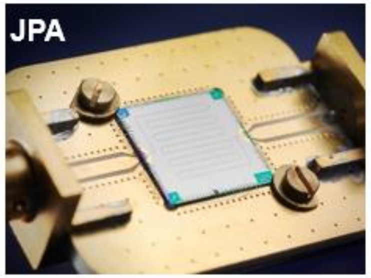
HELMHOLTZ
Helmholtz-Institut Jena

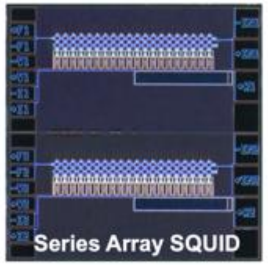
PTB

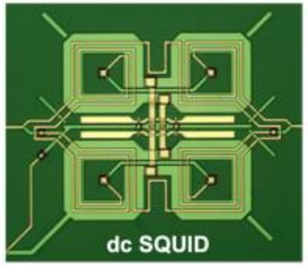
ENTROPY

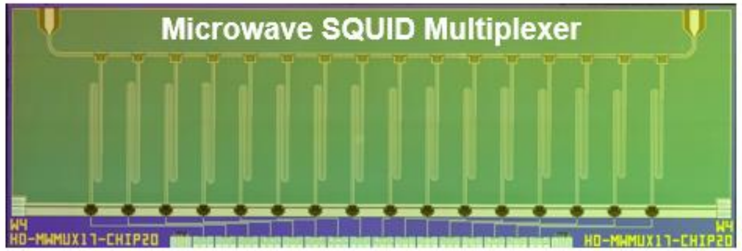
MAGNICON

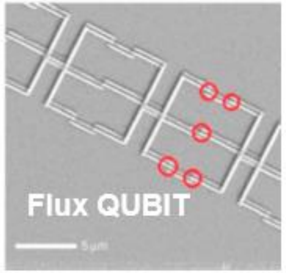


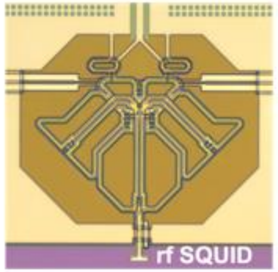












Dark-Matter/Antimatter Interaction

Measure the coupling $\mathcal{L}_{\text{int}} = -\frac{\partial a}{f_a}\bar{\psi}\gamma^{\mu}\gamma^{5}\,\psi$ between ultralight, pseudoscalar ALP relic dark matter and $\bar{p}$

Interaction

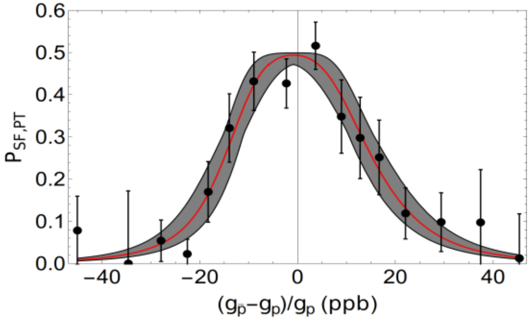
$$H_{\text{int}} = -\frac{C_{\bar{p}}a_0}{2f_a}\sin(\omega_a t)\,\vec{\sigma}_{\bar{p}}\cdot\vec{p}_a$$

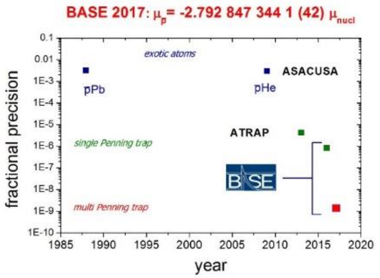
between the momentum of the axion field $\vec{p}_a$ and the antiproton spin vector $\vec{\sigma}_{\bar{p}}$ oscillating at the axion Compton frequency $\omega_a = m_a c^2/\hbar$

$$\boxed{\delta\omega_L^{\bar{p}}(t) \approx \frac{C_{\bar{p}} m_{\mathrm{a}} a_0 |\mathbf{v}_{\mathrm{a}}|}{f_{\mathrm{a}}}[A\cos(\Omega_{\mathrm{sid}}t+\alpha)+B]\sin(\omega_{\mathrm{a}}t)}$$

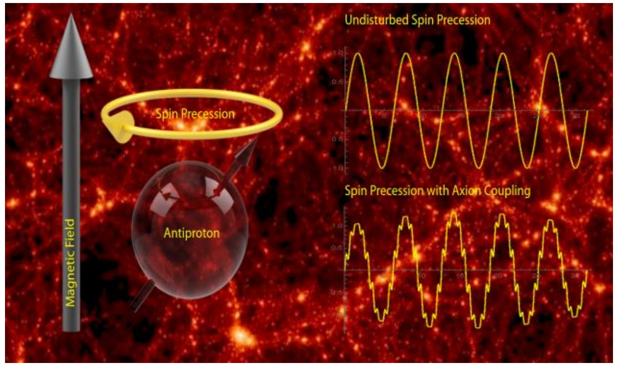
Should cause characteristic time dependent variation in ν_L, by constraining the size of this a-$\bar{p}$ coupling limits extracted

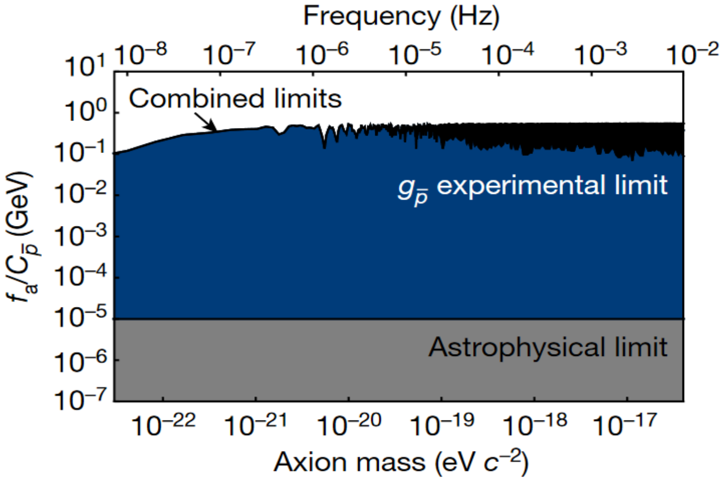
Do we detect sidebands in g-factor resonances?





First constraints on antimatter/dark matter coupling





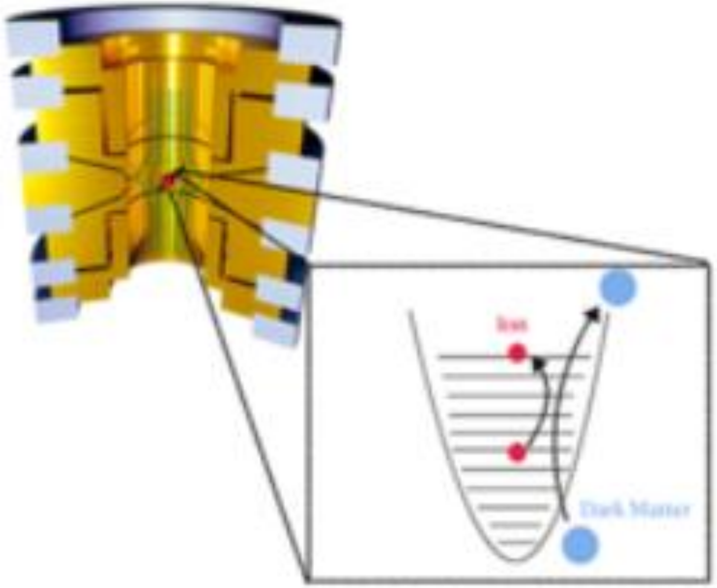
a- $\bar{p}$ coupling limits a natural bi-product of precision CPT tests

C. Smorra *et al.*, Nature **575**, 310 (2019).

Millicharged Dark Matter

- A real quantum experiment -> observe cyclotron quantum transition rates of a single trapped proton and set limits on the scattering of MCP’s.

- **Benefitial ion trap features:**
  - significant isolation of the ions from the environment
  - Trap vacuum is of order $< 10^{-18}$mbar (no background scattering)
  - low thresholds for the detection of energy deposition, down to nanoelectronvolt range.
  - ions are charged, and naturally have large cross sections for scattering with the millicharged particles



existing measurements put new constraints on millicharged dark matter that are many orders of magnitude beyond previous bounds.

Continuous Stern Gerlach Effect and Heating Rates

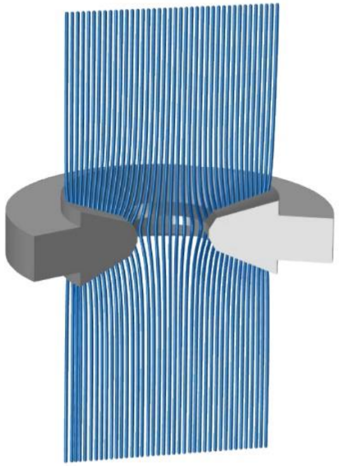
- Energy discrimination via strong magnetic bottles. Most sensitive experiments in this sector are proton/antiproton spin state detection experiments

Magnetostatic potential

$$\Phi_M = -(\overrightarrow{\mu_p} \cdot \vec{B})$$

Magnetic Bottle:

$$B_z = B_0 + B_2\left(z^2 - \frac{\rho^2}{2}\right)$$

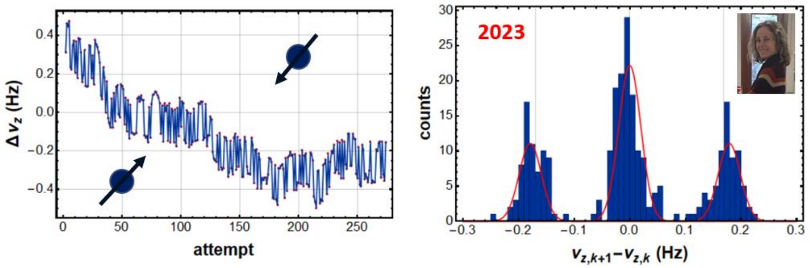


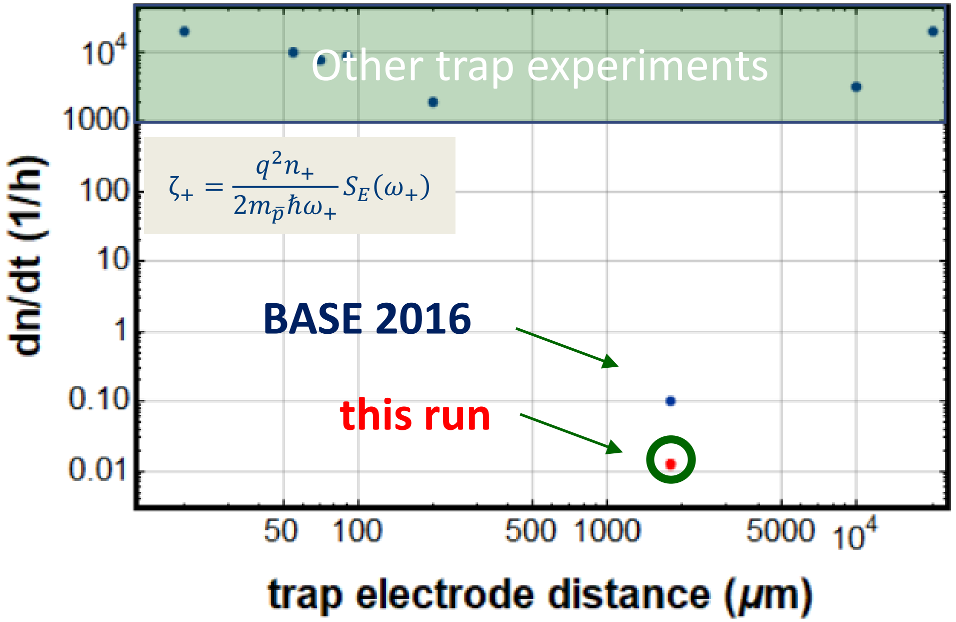
- Axial frequency becomes a function of the radial eigenstate:

$$\Delta\nu_z = \frac{h\nu_+}{4\pi^2 m_p \nu_z} \cdot \frac{B_2}{B_0} \cdot \left(\left(n_+ + \frac{1}{2}\right) + \frac{\nu_-}{\nu_+} \cdot \left(n_- + \frac{1}{2}\right) + \frac{g}{2} m_s\right)$$

- **Interesting here:** Magnetic bottle of $B_2 = 300000\ \mathrm{T/m^2}$ provides and energy resolution of $\approx 1\mathrm{Hz/\mu eV}$, can measure frequencies with 16 mHz resolution (**16 neV differential !!!**)

- Need this resolution to resolve nuclear magnetic moments in **quantum non-demolition spin state detection experiments**.





$$\zeta_+ = \frac{q^2 n_+}{2 m_{\bar{p}} \hbar \omega_+} S_E(\omega_+)$$

Quantum heating rates

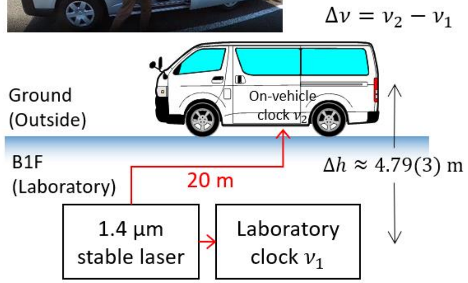
Analysis and Results

- **Basic idea:** Calculate the scattering cross-section for MCP and target particle, and derive the effective heating rate.

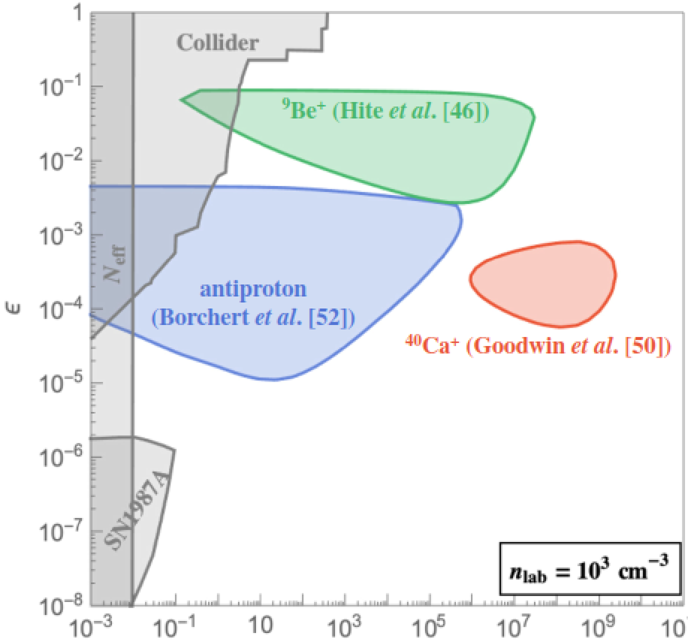
$$\frac{d\sigma}{d\Omega} = \frac{2\pi\alpha^2\epsilon^2}{\mu^2 v_{\mathrm{rel}}^4 (1-\cos\theta)^2},$$

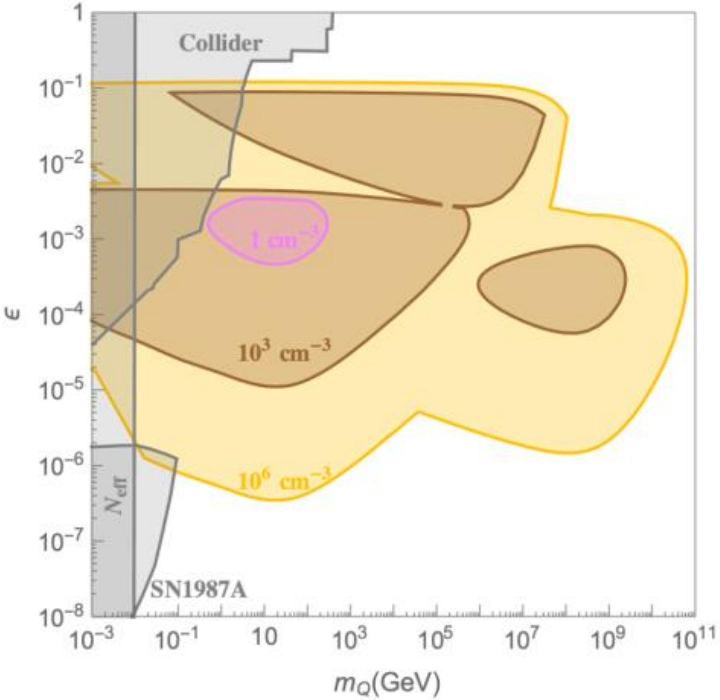
$$\dot{H} = \sqrt{\frac{2}{\pi}}\,\frac{n_Q m_Q m_{\mathrm{ion}}(T_Q - T_{\mathrm{ion}})}{(m_{\mathrm{ion}}+m_Q)^2}\,\frac{\sigma_0}{u_{\mathrm{th}}^3}$$

- Ion traps are moveable devices, profile the height distribution of MCP experiments

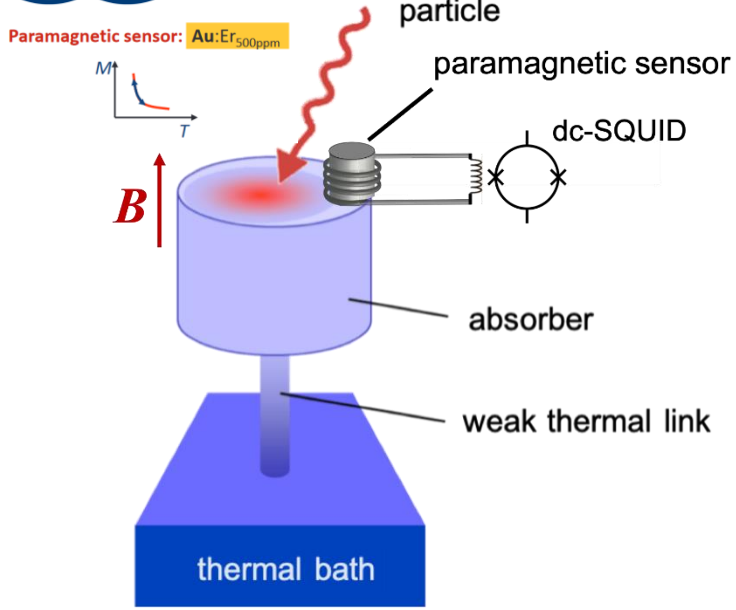


- Collaboration of HHU-D, RIKEN, Max Planck Society and PTB, to develop transportable proton and antiproton traps.





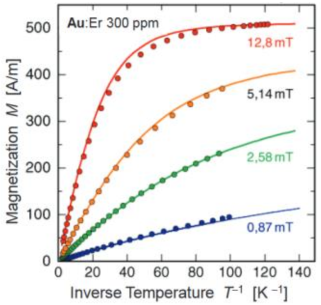
Metallic Micro Calorimeters (MMC)

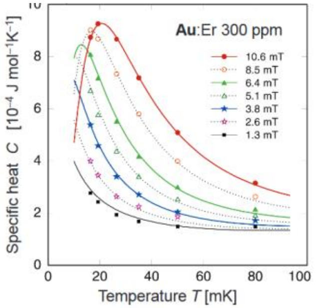


Principle:

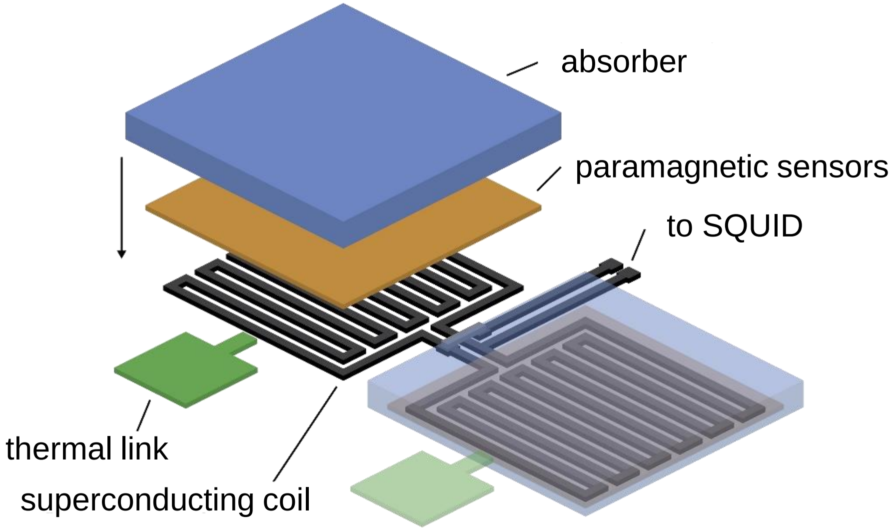
- Use dM/dT in polarized paramagnetic medium

$$\delta M = \frac{\partial M}{\partial T}\delta T = \frac{\partial M}{\partial T}\frac{E_\gamma}{C_{\mathrm{tot}}}$$



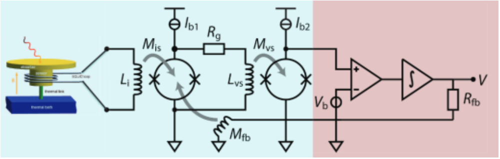


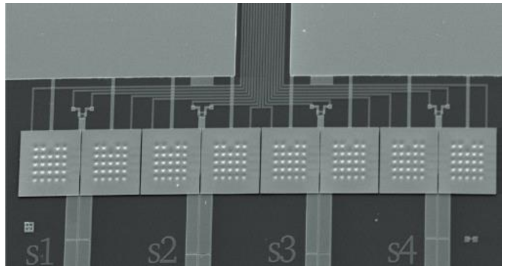
Planar realization



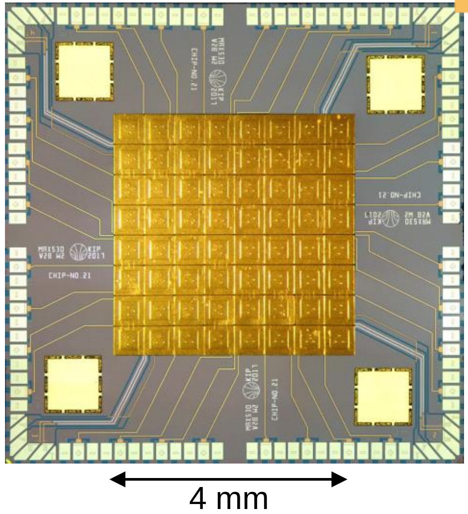
$$\Delta T \propto \Delta M \propto \Delta\phi \propto \Delta U$$

- Current applications

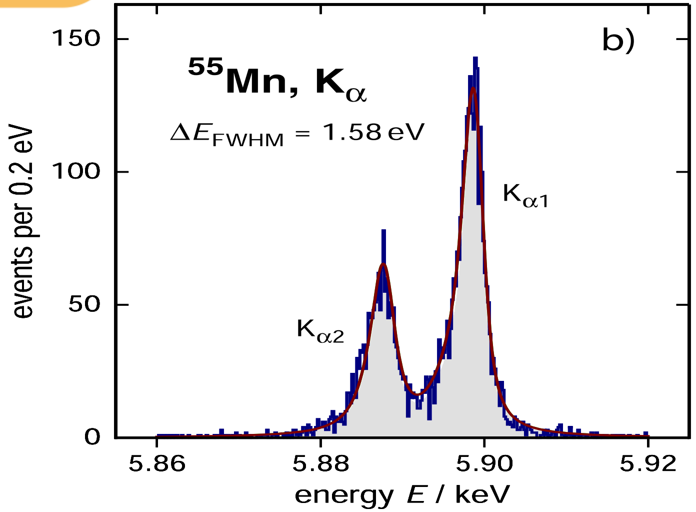




- X-ray and γ-ray spectroscopy (LYNX)
- nuclear and atomic physics (APPA)
- neutrino physics (AMoRE, ECHo)
- light dark matter (DELight)
- axions (IAXO)



Performance at 6 keV

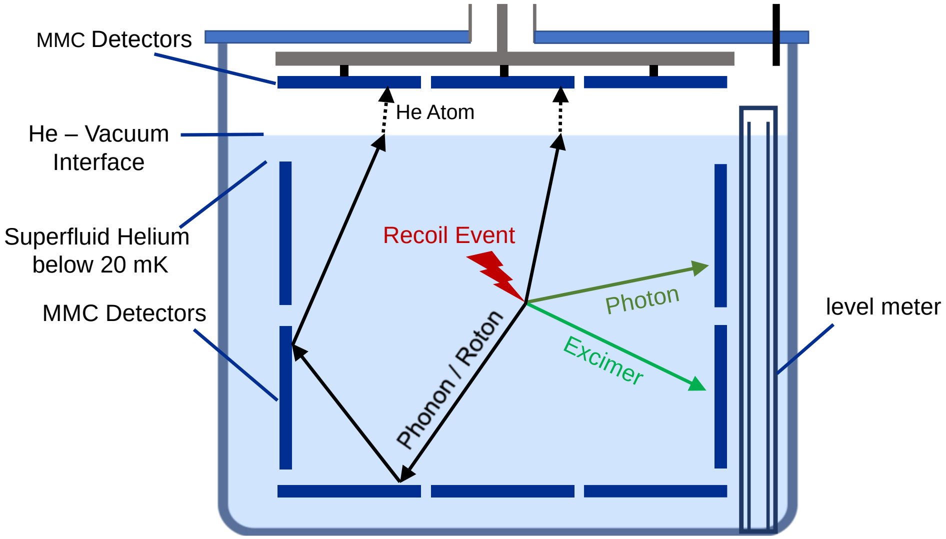


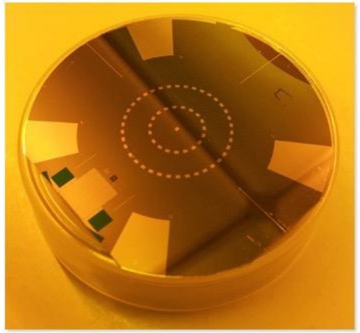
Direct Search Experiment for Light Dark Matter with superfluid Helium as Target

- Scope: Direct dark matter / nuleus scattering at the light WIMP scale (sub GeV particles)

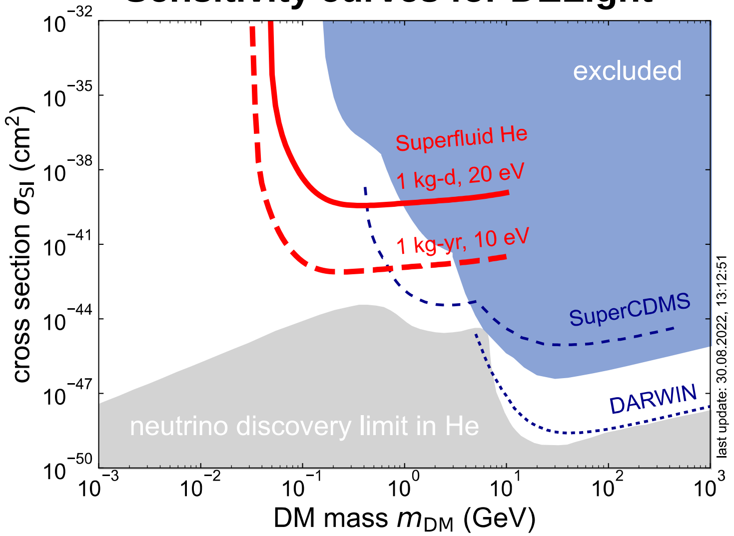
- Active Volume:
  - Superfluid He as active target
  - Light target / good kinematic matching to LDM / self cleaning / low background / high impedance to vibrational noise.
  - Radiopure and compact low background target with strong suppression of environmental effects.
  - 10l He volume for first phase / later upscaled to 100l.

- Detectors
  - Magnetic Micro Calorimeters





Sensitivity curves for DELight

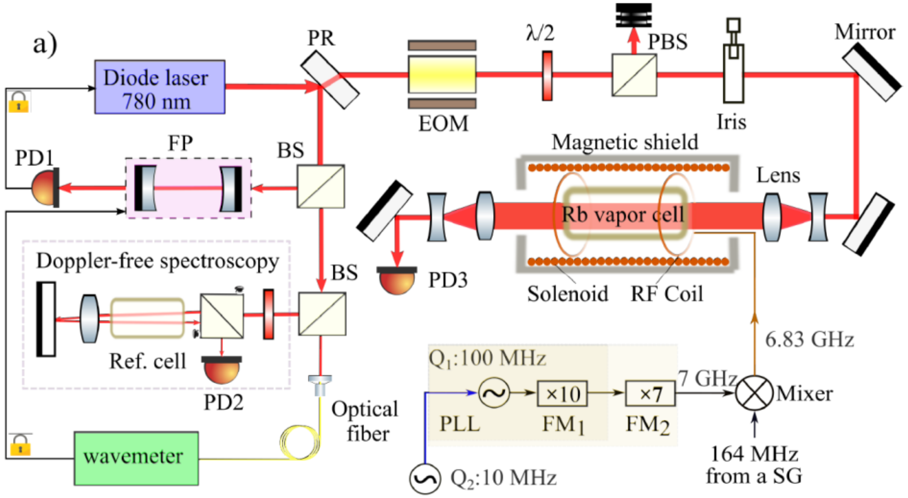


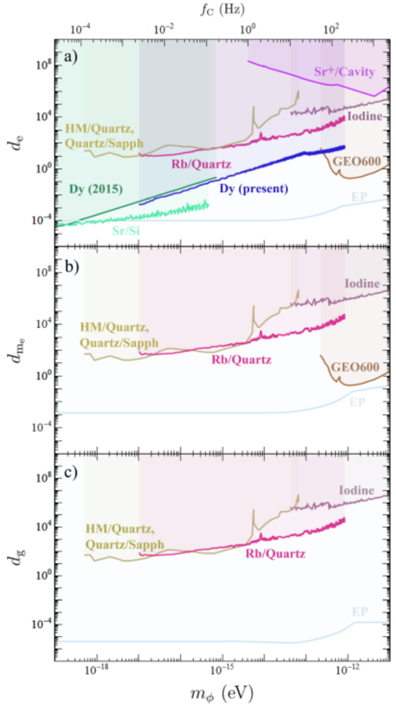
B. Krosigk, C. Enss et al., https://arxiv.org/abs/2209.10950

Clocks and other Spectroscopic Experiments

- Search for ultralight scalar dark matter (DM) with dilatonic interactions.
- Couplings can arise for the dilaton as well as for moduli and axion-like particles in the presence of CP violation.
- Ultralight dilaton DM acts as a background field that can cause tiny but coherent oscillations in Standard Model parameters such as the fine-structure constant and the proton-electron mass ratio.
- These minute variations can be detected through precise frequency comparisons of atomic clocks. Our experiment extends current searches for drifts in fundamental constants to the well-motivated high-frequency regime.

R. Oswald et al. PRL 129, 031302 (2022)
O. Tretiak et al. PRL 129, 031301 (2022)
X. Zhang et al. arXiv:2212.04413v1





Electronic atomic or molecular transition frequency	$f \propto m_e c^2 \alpha^2 \, H(\alpha)$
Hyperfine transition frequency	$f \propto m_e c^2 \alpha^4 F(\alpha) \left(\frac{m_e}{m_p}\right) \mu_{nuc}$
Molecular vibrational transition frequency	$f \propto m_e c^2 \alpha^2 \left(\frac{m_e}{M_{nuc}}\right)^{\frac{1}{2}} G\left(\frac{m_e}{M_{nuc}}\right)$
Electromagnetic cavity mode frequency (empty cavity)	$f \propto m_e c^2 \alpha$
Mechanical mode frequency	$f \propto m_e c^2 \alpha^2 \left(\frac{m_e}{M_{nuc}}\right)^{\frac{1}{2}}$

- Photodetectors for high light power and low noise
- Techniques for strong suppression of frequency noise of lasers
- Low-cost single-frequency fiber lasers
- Low-cost, high-sampling-rate DAQ systems
- New laser cooling procedures for non-standard atomic species (Dy)

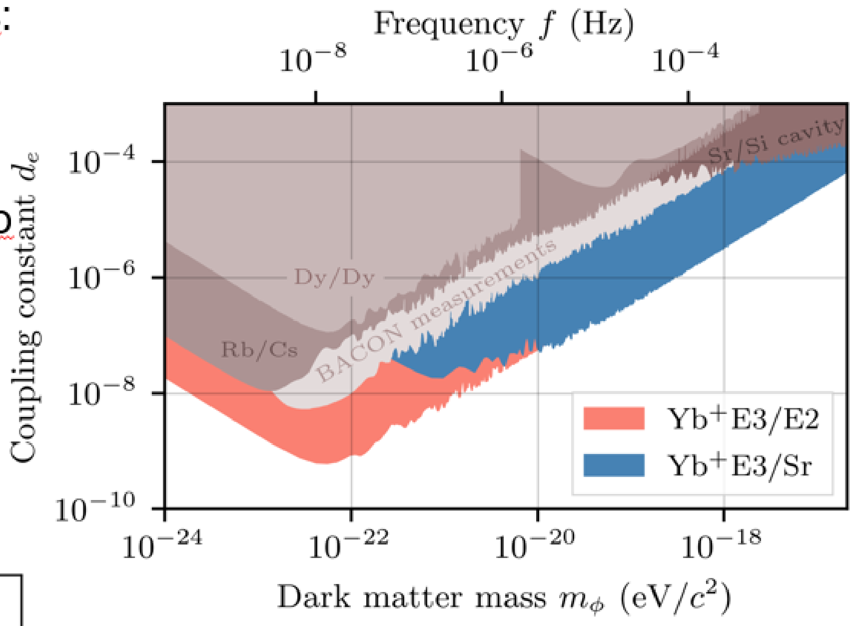
S. Schiller (HHU) and D. Budker (HIM)

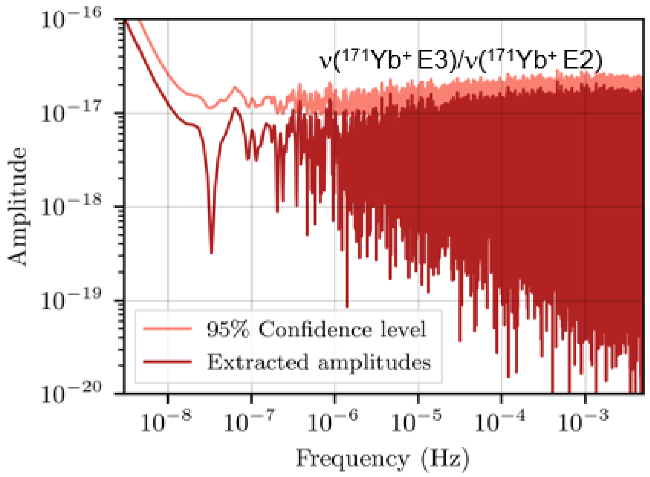
Search for light bosonic dark matter in atomic clock comparisons

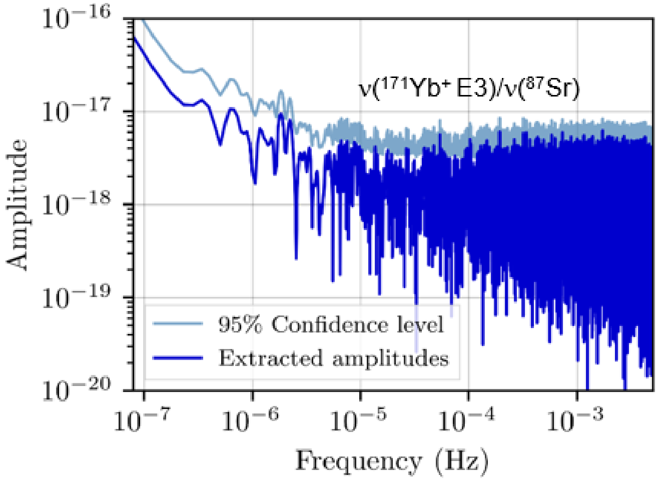
- Search for oscillations in measurements of optical frequency ratios: $\nu(^{171}\mathrm{Yb}^+\ \mathrm{E3})/\nu(^{171}\mathrm{Yb}^+\ \mathrm{E2})$ (best long term stability) and $\nu(^{171}\mathrm{Yb}^+\ \mathrm{E3})/\nu(^{87}\mathrm{Sr})$ (higher short term stability)
- Hypothetical coupling of ultralight dark matter with photons leads to an oscillation in the value of the fine structure constant [1]:

$$\alpha(t) \approx \alpha\,(1 + d_e\phi_0 \cos(\omega t + \delta))$$

- Improved limits on the coupling constant d_e





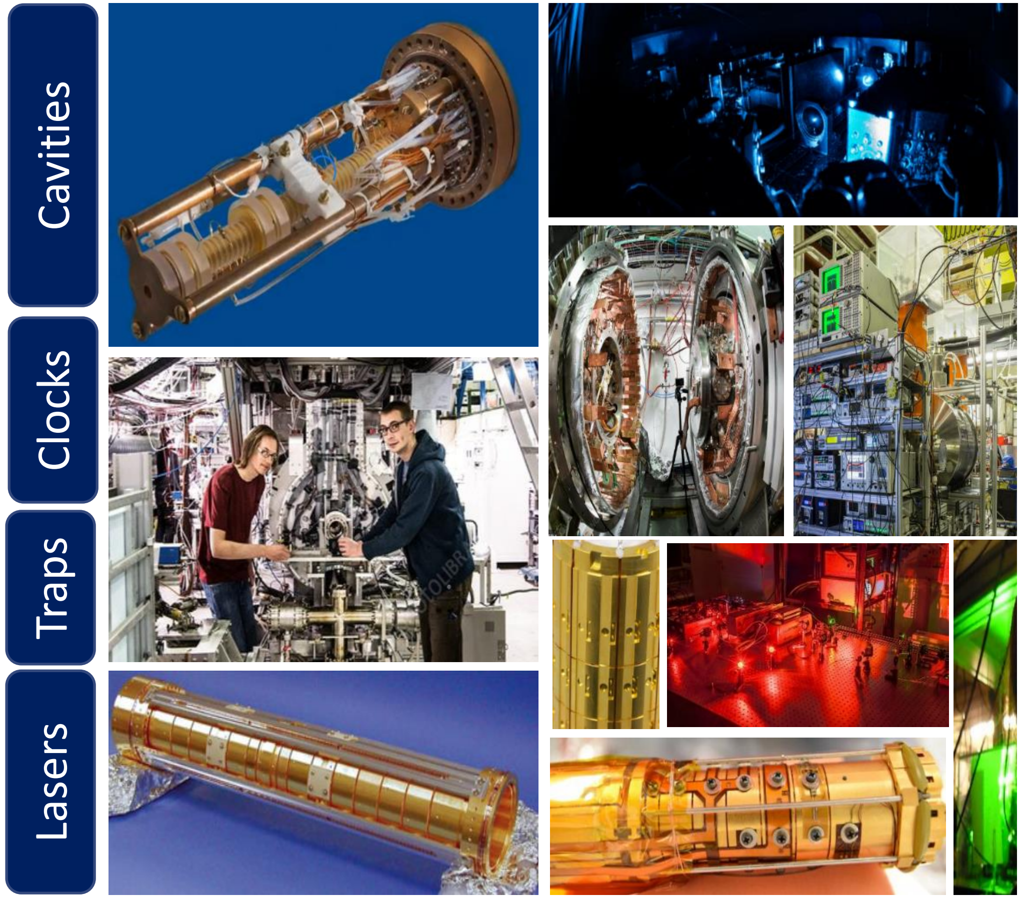


[1] A. Arvanitaki et al., PRD 91, 015015 (2015)
[Dy/Dy] K. Van Tilburg et al., PRL 115, 011802 (2015)
[Rb/Cs] A. Hees et al., PRL 117, 061301 (2016)
[Sr/Si cav] C. J. Kennedy et al., PRL 125, 201302 (2020)
[BACON] Nature 564, 564 (2021)
Boulder –Network of clocks at NIST-JILA

This work:
arXiv:2301.03433
arXiv:2301.10784

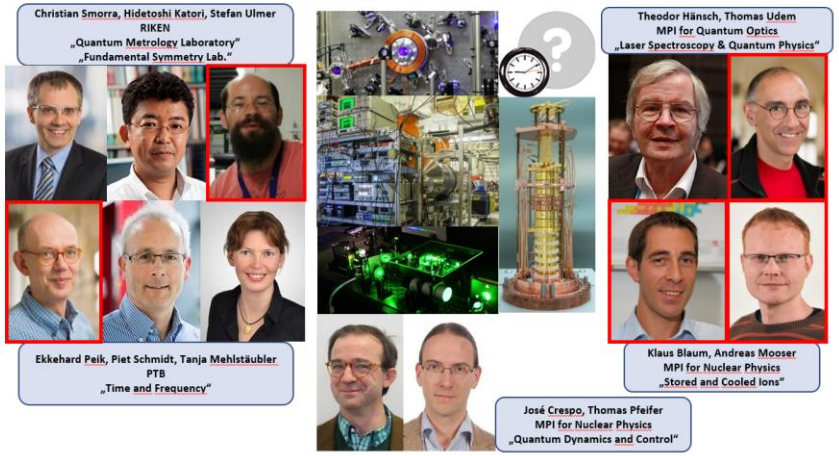
Summary

- Presented some recent ideas and developments that emerged from precision experiments taylored to measuring fundamental constants at the low energy frontier.



- Some methods interesting for detectors such as IAXO (MMC's and Superconducting resonators).
- Complementary methods to particle physics using very different detection approaches, such as ultra low-noise traps.
- Consortia partly organized within C-TCFS partly within CDS (ECHO experiment etc.)
- Perspective to form new consortia to produce productive synergies to set limits at even higher resolution.

Thanks for you attention



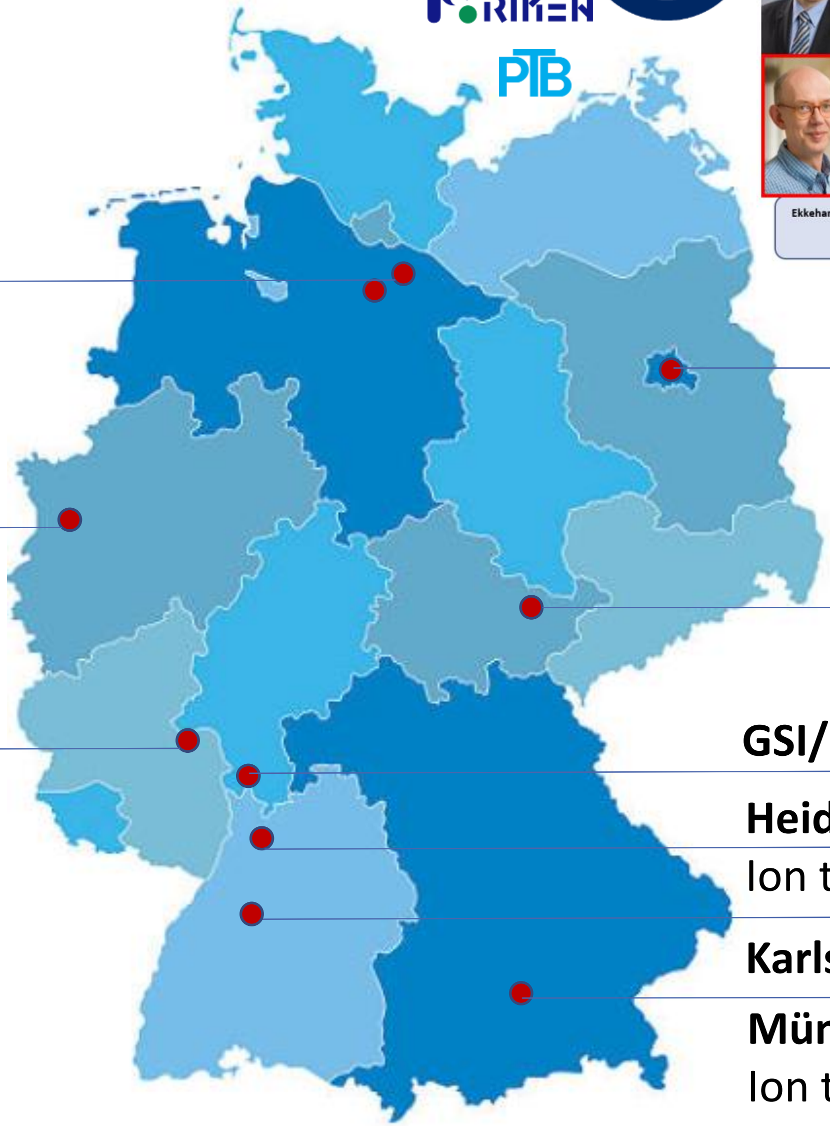
Christian Smorra, Hidetoshi Katori, Stefan Ulmer
RIKEN
„Quantum Metrology Laboratory“
„Fundamental Symmetry Lab.“

Ekkehard Peik, Piet Schmidt, Tanja Mehlstäubler
PTB
„Time and Frequency“

Theodor Hänsch, Thomas Udem
MPI for Quantum Optics
„Laser Spectroscopy & Quantum Physics“

Klaus Blaum, Andreas Mooser
MPI for Nuclear Physics
„Stored and Cooled Ions“

José Crespo, Thomas Pfeifer
MPI for Nuclear Physics
„Quantum Dynamics and Control“



Hannover / Braunschweig
Ion and atom traps / clocks / QI

Düsseldorf
Ion traps / antimatter / molecules / clocks

Mainz
Ion traps / Magnetometers / QI

Berlin
SQUIDS, References

Jena
X-ray detectors

GSI/FAIR: MMC's / HCI's

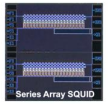
Heidelberg
Ion traps / SQUIDS / MMC's etc.

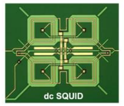
Karlsruhe: SQUIDS / etc.

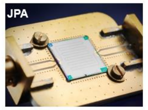
München
Ion traps / precision laser-spectroscopy

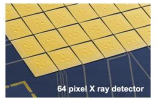
CDS Consortium for Cryogenic Detectors and Superconducting Electronics (founded 2020)

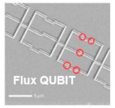
- SQUIDs
- Microwave SQUID multiplexer
- Qubits
- Quantum limited Amplifiers
- Cryogenic detectors MMCs, TES, KIDs, …

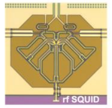


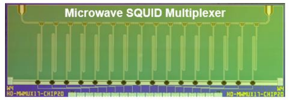












Blaum
Budker
Crespo
Enss
Galatyuk
Latacz
Mooser
Noertershaeuser
Obertelli
Ospelkaus
Ospelkaus-Schwarzer
Peik
Schiller
Schmidt
Schmidt-Kaler
Smorra
Stoehlker
Sturm
Ulmer
…

Coupling

- DM may consist of light bosons. These form a classical field Φ, which coherently oscillates at their Compton frequency

$$\boxed{f_C = m_\Phi\, c^2/h}$$

$$\boxed{\Phi(t) = \frac{\sqrt{2\rho_{DM}}}{m_\Phi}\cos 2\pi f_C t}$$

- Φ may have scalar interactions with the SM fields
- The fundamental constants (FC) may be expectation values of SM fields
- The coupling of Φ to SM fields may lead to oscillating fundamental constants

Mass of fermions

$$m_f(\phi) = m_f\left[1 + d_{m_f}\frac{\phi}{M_{\mathrm{Pl}}}\right],$$

Fine-structure constant

$$\alpha(\phi) \simeq \alpha\left[1 - d_\alpha \alpha\frac{\phi}{M_{\mathrm{Pl}}}\right],$$

Strong-coupling constant

$$\alpha_s(\phi) \simeq \alpha_s\left[1 - \frac{2d_g\beta(g_s)}{g_s}\frac{\phi}{M_{\mathrm{Pl}}}\right]$$

Mass of a nucleus

$$\frac{\delta m_N}{m_N} = 0.873\boxed{\frac{\Delta\Lambda_{\mathrm{QCD}}}{\Lambda_{\mathrm{QCD}}}} + 0.084\boxed{\frac{\Delta\hat{m}}{\hat{m}}} + 0.043\boxed{\frac{\Delta m_s}{m_s}} \qquad \hat{m}\ \hat{m} \equiv (m_u + m_d)/2$$

→ These FCs oscillate as $d_{\mathrm{X}}\ \frac{\phi(t)}{M_{\mathrm{Pl}}}$

How to look for oscillations in the ‘constants’?

- Compare the frequency of systems which have different sensitivities to the FCs:
- Measure $f_a(t)/f_b\,(t)$ over long time intervals and perform search for weak near-monofrequent signals.