Quantum Sensing for Particle Physics

QT4HEP-2025: International Conference on Quantum Technology for High-Energy Physics

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Deutsches Elektronen-Synchrotron (DESY) / Humboldt-Universität zu Berlin January 22, 2025

- Introduction: the "What" and "Why" of quantum sensing for Particle Physics
- Selected quantum sensing techniques
	- Cryogenic detectors
	- Superconducting devices
	- Spin-based, NV-diamonds
	- Metamaterials, 0/1/2-D materials
	- Ionic / Atomic / Molecular systems
	- Optical atomic clocks
	- Atom Interferometers
	- **Magnetometers**
- How to get started in Quantum Sensing: DRD5 / RDquantum

Outline

• Quantum Sensing: any sensing device enabled by the ability to manipulate and read out quantum states

-
- Requirements for a quantum sensor
	- Discrete quantum states (e.g. energy levels $|0\rangle$, $|1\rangle$)
	- Possibility to reset and readout
	- Coherent state manipulation possible (usually)
	- Sensitivity—something measurably changing (e.g. frequency ω_0 or transition rate $\Gamma)$
- Note that entanglement/squeezing not required, but can make even better sensors
- Close parallel to DiVencenzo Criteria for Quantum Computing, minus gate requirements
- (photons, matter), superconducting circuits, optomechanical systems, quantum materials

• *Many possible systems:* atoms (neutral, ions, Rydberg states), cavities, atomic clocks, interferometers

Quantum Sensing | Steven Worm | 22.1.25 **3 1.25** [Degen, Reinhard, Cappellaro, Rev. Mod. Phys. 89, 035002; DiVencenzo, https://arxiv.org/abs/cond-mat/9612126] 3

What is Quantum Sensing?

Why quantum sensing?

- Quantum Detectors: use quantum sensing to making extreme measurements possible
	- Enables (better) measurements, e.g. wavelengths
	- Extreme sensitivities (single-photon) or low noise

Quantum Detectors, Quantum Experiments

- A1: Potentially better sensitivity or noise performance
- A2: Because we have to (e.g. for ultra-light dark matter)!

- Quantum Experiments: sensing is used for fundamental physics measurements
	- Gravity, Lorentz Invariance, physical constants $(\alpha, \mu,$ dipole moments), etc
	- Techniques such as interferometry, magnetometry, clock-based systems, optomechanical devices

- Low energy and limits for ionisation
	- Limit for e/hole pairs in semiconductors is band gap energy (1.12 eV for Si)
	- Ionisation works above the band gap, below we detect the heat (phonons)
- Measuring small temperature differences
	- ΔT depends on energy and heat capacity ($C = c_p m$)
	- Heat capacity given by Debye equation, $C \propto (T/T_D)^3$, where T_D = Debye Temp
	- Silicon example: $\Delta T \approx 1\%$ requires mass of 1 µg and $T_0 = 0.1$ K
- Example1: Hitomi satellite, SXS (JAXA, CSA)
	- 36 pixels (814 µm) HgTe absorber at 50 mK
	- Energy between 0.3 and 12 keV, resolution \sim 7 eV
- Example2: Lynx X-ray Microcalorimeter (NASA)
	- ~50k pixels (25-50 µm) Au absorber at 50 mK
	- Energy between 0.2 and 15 keV, resolution <3 eV

Cryogenic Detectors

COEFFICIENT (cm-1)

ABSORPTION

5 [Hitomi; JATIS, Vol. 5, 021017 (2019)]

Transition Edge Sensors (TES)

- TES Operations: Measure ΔT with superconducting circuit
	- sharp transition between superconducting \rightarrow conducting
	- small temperature change, large resistance change
	- Detection limited by thermal noise; readout resistance << sensor resistance
- Readout: Superconducting Quantum Interference Devices (SQUIDs)
	- Two Josephson junctions in parallel: low temperature $(-0.5 K)$
	- Plus: Low temp, very low noise, moderate amplification
	- Minus: limited input, feedback (flux) loop required to lock at operating point
- Example: BICEP3
	- Used to study Cosmic Microwave Background (B-modes)
	- Monolithic arrays of 2400 antenna-array coupled TES detectors
- Arrays used from radio to X-ray with high spectral resolution (SPT, ATHENA, BICEP) \rightarrow now also particle physics (CDMS, ALPS...)

[Nagler et al, JATIS, 7(1), 011005 (2021); BICEP3]

• Extremely low energy threshold, extremely fast potentially improve the minimum achievable jitter. If no other funda**biguerionsula** Pho very narrow (1 Δ heorntion of the superconduction ps anning resord of Currently he mental limitation for the time is discovered, the time is discovered, the time of the time \sim counter for Comparation counter for Connected that cal excitation density.87 applicable for **Explaining the leading to explain the leading to explain the leading to explain the leading to e** operation mechanism and provide the state theorem \blacksquare But very small volume neands

Figure 2. This calculated to be of the original provides similarly significant to be of the original provides similar to be of the original provides similar to be of the original provides similar to be of the original prov \mathcal{F} absorbed photos can be defined by \mathcal{F} • Applications for quantum pixels, ultra-sensitive tracking, milli-charged particles $\frac{1}{2}$ er available - quantum communications are the history and development of SNSPDs over the SNSP meander biased conduction on ps timing resolution Currently hair Very low dark count rheached detected potential functions are discussed in Sec. III. Finally, we provide the second in Sec. III. wantum Sensing for Particle Physics State of Absorption of ph \sim 3. Register \sim 1 and technical review of SNSPD's working principle, interior working principle, interior working principle, interior working and the state of the tions, and design solutions, we refer the ref. 88. \Box Absorption of ph \Box \Box \Box \Box \Box \Box Very narrow (Non-dest meander biased close to transition of the close to transition of the close to transition of the close to transition Absorption of photon drives normal Absorption of Provides simi \overline{a} Very low dark count rate demonstrated, Very narrow (~100 nm) Non-destructive Since SNSPDs typically cover areas of hundreds of square micrometrical de considerer.⁸² in 2017, 83 the influence of Fano fluctuations on the influence of Fano fluctuations on the international continuously and the international continuously and the international continuously and t distributed electronic and geometric induced electronic induced electronic inhomogeneity of a superconbased on the two-temperature model coupled with the modified timewas shown to depend on the critical temperature of the superconducted on the superconducted \mathcal{L}_{max} \mathbf{V}_{c} with a critical temperature of 100 kg \mathbf{V}_{c} cal excitation density.87 \blacksquare Currently being applications of DM searches, and also, volume induced just an induced just an induced just a co Currently heing annlied for DM $\overline{}$ ps times the contract of the resolution \mathbb{R} demonstrated with \mathbb{R} based oncent onned noise of the model coupled timeinfluence on the minimum \sim the minimum jitter. The minimum jitter. The minimum jitter. The minimum jit temperature is not the minimum jitter. The minimum jitter. The minimum jitter. The minimum jitter. The minimum jitt films with a critical temperature of \mathbf{r} $\mathcal{L}_{\mathcal{D}}$ which depends on material, temperature, and the optimization, temperature, and the optimization, Thrachold detector for s A bsorption of ph A and A $\forall x \in \mathbb{R}$ potential funture applications are discussed in Sec. II. Finally, we provide the second in Sec. II. Pow-light-level as tion on the photon of But very small volume multi-pixel56 and multi-element structures80 were proposed and demmance and even offering photon number resolution prospects.81 \mathbf{b} Δ hsorption of $ph \Delta$ 3 Δ n $\sum_{i=1}^n$ $\sum_{n=1}^{\infty}$ fining recolution $\sum_{n=1}^{\infty}$ Absorption of $ph \beta \rightarrow \mathbb{R}$ all ps timing resolutio

- **Superconducting Nanowire Single-Photon Detectors (SNSPD)** influence on the minimal achievable time jitter. The minimum jitter phonons94 or through a stochastic loss of excitation energy into the t_{N} multiple read cycles to the spatial process \blacksquare is modeled through deterministic kinetic equations for electrons and TECHNICAL DESCRIPTION ZHIL. is the size of the floating gate. Smaller floating gates have smaller capacitance and higher gain, but can be of the Skipper CCD are collected in Table I. To reduce the Skipper CCD are collected in Table I. To reduce the and queloc to tau cycles to sensor is operated at low temperatures. Here we operate t_{t} at A before charge-transfer eciency is significantly reduced. $\overline{}$ TECHNICAL DESCRIPTION OF PROPERTY OF P
The contract of the contract of **Mon-destructive multiple read cycle** f_{rad} pulses that reads the readout circuit at the real circuit at a geometrical times, leading the real circuit at \mathbf{p}_i detector area is well described by a classical electromagnetic theory. The classical electromagnetic theory. impact of 1/f amplitude in the 1/f amplitude in the 1/f amplitude in the 1/f amplitude in the 1/f amplitude in Non-destructive multiple read cycles to reduce electronics noise by √N won-destructive multiple read cycl and phonons. These processes are governed by electron-electron, suctive multiple read cycles to Photon Detectors (SNSPDs) $T_{\rm F}$ and $T_{\rm F}$ and $T_{\rm F}$ for single photons $T_{\rm F}$ Non-destructive multiple read cycles to Thurst detector indiciple read cycles to requce electronics hoise by $\bm{\mathtt{v}}$ in allow for quantitative modeling and design optimizations, the detec-Guantum Calorimeters Today Non-destructive multiple read cycles to reduce electronics noise by √N
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	- of the Skipper CCD are collected in Table I. To reduce $\frac{1}{2}$ number of $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ ting addited to sensor is operated at low temperatures. Here we operate the sensor at 140 K, but this could be lowered to include the lowered to lowered to lowered to lowered to which before charge-transfer eciency is significantly reduced. As we discuss further below, the dark current may be \bullet is the charge at the snapplications that \overline{f} FIG. 2002 LIG in a source follower configuration. Due to its floating gate, \mathbf{r} $\mathbf v$ a non-destructive measurement $\mathbf v$ Provides high-ef and low-light-level astronomy \blacksquare cated on \blacksquare ed for DIYI searches. sor is 200 *µ*m thick and composed of 15 *µ*m⇥15 *µ*m square $\overline{\mathbf{C}}$ the Skipper Collected in Table 1. The $\overline{\mathbf{C}}$ **Currently being applied for DM searches, Fig. 1996.** was systematically studied, and the theoretical limit of SNSPDs' intrin-terms intrin-terms intrin-terms in the
The theoretical limit of SNSPDs' intrin-terms in the theoretical limit of SNSPDs intrin-terms in the theoretic iow-light-level astronomy low-light-level astronomy Superconducting Nanowire Single evel astronomy \mathbf{F} 1. Single-electron charge resolution using a Skipper resolution using a Skipper resolution using a Skipper resolution using \mathbf{F} \blacksquare \cdots shown for pixels with low-light low level illumination (top) and stronger illumination (bottom). Integer electron peaks can be distinctly resolved in both regimes contemporaneously. The peak at 0 e has rms noise $\overline{}$ Iow-light-level astronomy **Currently being applied for DIM SE** WITH A WILLIAM A SUPERCONDUCTING FROM A THREE F Gonnliad for DM conrchas ps timing \mathbf{p} The detector studied here is a p-channel \sim cated on high resistivity ($\frac{1}{n}$ k $\frac{1}{n-1}$ was fully depleted at a substrate voltage of 40 V. The sensor is 200 *µ*m thick and composed of 15 *µ*m⇥15 *µ*m square p_{max} **Theory Deing applied for Drivinged** Currently being applied for DM se meters and the electrical signal propagates through the detector with finite speed, photons detected and at a different locations of a set α High-frequency differences of the reduced to reduced the reduced to reduced the reduced to reduced the reduced of the reduced to reduced the reduced to reduced the reduced to reduced the reduced to reduced the reduced to r Currently being applied for DM searches, λ of the nonlow-light-level astronomy
	- WSi demonstra behoton Detectors (SNSPDs) But very small volume https://singlequantum.com/technology/snspd/ \sum_{α} s $\sum_{i=1}^{\infty}$ \mathbf{S} As we discuss further below, the dark current may be Superconducting–Nanowire–Single $\begin{array}{ccc} \hline \end{array}$ influence on the minimum is minimal and minimal actions the minimum variable time \mathbf{F} Threshold detector for single photons **Personal Superconduction** $\sqrt{2}$ meand $\sqrt{2}$ Absorption drives not provided **Example 120 regions Conducting Nanowire Single** meand of the transition of the transition of the time is discovered to the time is discovered to the time of the time is discovered to the time is discovered to the time is discovered, under the time is discovered, under t Superconducting Nanowire Single Photon Detectors (SNSPDS) \blacksquare Perconducting indiriowing onlight with \sum_{left} ectors (SNSPDs) oton Detectors (SNSPDS Superconducting Nanowire Single ing jitter was also reported. In the same year, timing jitter caused by electronic distribution electronic inhomogeneity of a superconneity of a superconneity of a superconneity of a ducting nanowire84 was analyzed. Also, vortex-crossing-induced jitter Provides similar single-Comparished and Comparing for a search for a search for a search search for a search search search search search ctors-LSNSF Superconducting Nanowire Single Superconducting Nanowire Single Photon Detectors (SNSPDs)
		- ector for single photons and international $\overline{\mathcal{S}}$, and $\overline{\mathcal{S}}$, the superconduction state (see Fig.). In this current thin-film strip is current to the superconduction of $\overline{\mathcal{S}}$ the limiting factor for some applications that the limiting factor \mathbb{R} is a shipsey in the limiting \mathbb{R} Throchold dotoctor for single pho with conduction is not support the superconduction of the sup ps timing resolution Provides high-efficiency, high-fidelity photon **Inreshold detector for single photons** Thurshald detector for single she i hreshold detector for single pho etector for single photons The Integration Threshold detector for single photons **Party 1 2 2008**
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D. Scotting of this perspective count rate of the month of this perspective count rate of the month of the mon Very narrow (~100 nm) supercond $T_{\rm{max}}$ Very narrow (~100 nm) superconducting range. Very narrow (~100 nm) superconducting
		- Redirection of the current toward the readout electronics allows a recovery of the superconduction state $\frac{1}{2}$, which is a return of the current (V) to a return of the current (V) to its initial current (V) to its initia value to the third reset dynamics is limited by the kinetic inductance of the device. The device of the device. The device of the device of the device of the device. meander hiased close to transiti where the dynamics of superconductivity \mathbf{a} $\sqrt{2}$ f phi \sim \sim \approx As we discuss further below, the dark current may be Provides high-efficiency, high-fidelity photon Δ decaration of Δ meander blased close to transiti are $\frac{1}{2}$ tion maandar hissad close te trensiti influence on the minimum jitter. The minimum jitter. The minimum jitter. The minimum jitter. The minimum jit ased close to trans Absorption of photon drives normal meander biased close to transition

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- After summarizing the history and development of SNSPDs over solution \Box Provides high-efficiency high-fidelity phot applicable for DM searchest and DM search
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- Appl. Phys. Lett. 118, 190502 (2021); doi: 10.1063/5.0045990 118, 190502-3 the past two decades, we highlight the leading theories to explain the leading theories to ex where \mathbf{e} is the dynamics of superconductivity of superconductivity \mathbf{e} Very low dark count rate demonstrated, \overline{a} and \overline{a} applications \overline{a} and \overline{a}

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have smaller capacitance and higher gain, but can be

^a The upper limit on dark current comes from measurements on

of the Skipper CCD $\begin{array}{ccc} \hline \text{F} & \text{F} &$ \bigcirc noto pixels arranged in a 4 Γ he detector stud be lowered to Γ was fully depleted at ϵ sor is 200 $\mu \mathrm{m}$ thick an Γ he dotogtor stud $\frac{1}{10}$ decreads to duction. vas fully depleted at was runy depieted at $\sec 200 \mu \text{m}$ thick an \sum nato Bixels arranged in a 4 of the The detector studied **The detector** of the Skipper Cated on Table I. was fully depleted at $\mathbf{t} = \mathbf{t} \cdot \mathbf{t}$ \vee DIROLORES arran \overline{A} we define the data function of the data current may be defined as \overline{A} cated on high resistiv the number of electrons promoted to the silicon conduc-

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SNSPD: Advances & Expected Performance advances in superconduction in superconduction $\frac{1}{2}$

[1] Korzh, Zhao et al, *Nature Photonics 1*4, 250 (2020)

[2] Reddy et al, *Optica* 7, 1649 (2020)

[3] Oripov, Rampini, Allmaras, Shaw, Nam, Korzh, and McCaughan, *Nature* 622, 730 (2023)

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[4] Craiciu, Korzh et al, *Optica* 10, 183 (2023) [5] Resta et al, *Nano Letters* (2023) [6] Chiles, *PRL* 128, 231802 (2022) [7] Taylor, Walter, Korzh et al, *Optica,* (2023)

- Superconducting Tunnel Junctions (STJ)
	- Exploit quantum tunnelling in a junction of two superconductors
	- Direct tunnel current measurement (non-Heterodyne): simultaneous fast photon counting and spectroscopy in IR, Vis, UV bands
- Microwave Kinetic Inductance Detectors (MKIDs)
	- Exploits change in phase of an inductor capacitor (LC) oscillator in thin superconductor
	- Read-noise free, easier multiplexing: arrays of \sim 10k under test
- Superconductor-Insulator-Superconductor (SIS) receivers
	- Enabling technology for sub-mm Astronomy
	- Superconducting circuits allow phase coherent downconversion THz \rightarrow GHz

Cryogenic Quantum Sensors

Superconducting Tunnel Junction

MKID operating principle

Cryogenic Quantum Sensors vs. Wavelength

-
- Quantum dots: nanometer-sized semiconductor structures, e.g. in carbon, perovskites, etc. • Tuneable, with properties between single atoms and bulk material

- Seed different parts of a detector with nanodots emitting at different wavelengths
- Wavelength of fluorescence photon indicates specific nanodot position: shower profile from spectrometry Chromatic community of the Chromatic Chromatic Chromatic Chromatic Chromatic Chromatic Chromatic Chromatic Chr CHROMATIC CHROMATIC
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Quantum Dots and Chromatic Calorimetry

• Two Design Approaches: Exploring direct embedding of quantum dots in high-Z materials and a hybrid design • Two Design Approaches: Exploring direct embedding of quantum dots in high-Z materials and a hybrid design

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- Quantum Dots, Quantum Wires, Quantum Wells… many structures possible
- Quantum Well-dots: aiming for active scintillators
	- electronic amplification / modulation
	- pulsed / primed operation
	- gain adapted in-situ
- Quantum Dots in CMOS pixels: DoTPiX
	- n-channel MOS transistor + buried quantum well gate
	- gate collects holes, modulates current
- Tracking with Quantum Dots: Scintillating (Chromatic) Tracking
	- GaAs bulk to generate e/h pairs, InAs quantum dots to trap charge
	- Dots emit photons from photoluminescence, collected by photodiode

 $\frac{1}{200}$ κ $\frac{1}{20}$ $\frac{1}{2}$ to take a lattice during the MOCVD deposition of a lattice-mismatched mismatches $\frac{1}{2}$ InGaAs thin film on the GaAs substrate. Structures have been grown on exact oriented (100) and $\overline{\varpi}$ and $\overline{\varpi}$ and $\overline{\varpi}$ and $\overline{\varpi}$ installation with a low pressure (100 mbar) installation with a low pressure (100 mbar) installation with a low pressure (100 mbar) installation with a low pressure (100 horizontal reactor. Metal alkyls (trimethylgallium, trimethylaluminum, trimethylindium) and arsine $m = 1$ as precursors. Galaxyers were deposited at 700 \pm 100 \pm 100 \pm molar flows were deposited at 700 \pm $\overline{\text{a}}$ is about 30, and $\sqrt{11}$ and $\sqrt{20}$ lowered and the ratio of molar flows of molar flows of \mathcal{A} to \mathcal{A} to III group precursors is \mathcal{A} about 30 and 0.2 nm/s growth rate. Composition rate. Composition \mathcal{A} migration of Indian fields. In atoms in the lateral strain fields. In other words, the appearance of In-rich is
In the appearance of In-rich is lateral strain fields. In other words, the appearance of In-rich is lateral st energetical in the partial strain relation. On the one hand, elastic strain relation. On the one hand, elastic λ . nm organized $\mathcal{O}_\mathcal{S}$ the strain energy depends both on the thickness and composition of the lattice-lattice- $\overline{Q}DPL$ i.e., $\overline{P}DArray$ i.e., the most direct method be optimized. The most optimized method optimized. The most optimized optimized method to \overline{P} most direct method to structural properties of \mathbf{I} and \mathbf{I} and \mathbf{I} \mathbf{F} microscopy (TEM). The combination of combination of combination and plan-view TEM images allows one combination and plan-view TEM images allows one combination and plan-view TEM images allows one combination and $t = \frac{1}{2}$ Let us constitutions of the growth of the growth of InxGa₁ substrate. Deposition of In0.2Ga \sim 2Ga \sim concentration exceeds 60%, the growth occurs in Stranski–Krastanow mode via the formation of the wetting layer on the top of which large-sized pyramid-shaped islands are formed. In both cases of which largelow and high In contents, QWDs are not observed in TEM images. The window of In composition to **2. Growth and Structural Properties** \mathbf{S} to take a lattice during the MOCVD deposition of a lattice-mismatched mismatches \mathbf{A} \mathcal{S} substrate. Structures have been grown on exact oriented (100) and vicinal vi $\frac{1}{\sqrt{2}}$ and $\frac{1}{\sqrt{2}}$ and $\frac{1}{\sqrt{2}}$ installation with a low pressure (100 mbar) horizontal horizontal reactor. Metal alkyls (trimethylgallium, trimethylaluminum, trimethylindium) and arsine were used as precursors. Galaxyers were deposited at 700 \uparrow 100 \uparrow 100 \uparrow $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ nm/s $\frac{1}{2}$ nm/s are formed at lowered at lowere growth temperatures 500–550 C, the ratio of molar flows of V to III group precursors is about 30 and $\overline{1}$ and this growth rate. Composition of surface migrations appear due to surface migrations appear due to surface migrations $\overline{1}$ In atoms in the lateral strain fields. In other words, the appearance of In-rich islands is energetically favorable because of partial strain relation. One hand, elastic strain should be strain show the one hand, ela λ not be the other hand, it should not be the other hand, it should not be too high in order to avoid the other to avoid the should not be to transition to the Stranski–Krastanow growth mode and formation of conventional self-organized QDs. study the structural properties of InGaAs nanostructures is transmission electron microscopy (TEM). $T_{\rm eff}$ combination and plan-view TEM images allows one to determine the size, shape, s $\frac{1}{2}$ in AS QD/GaAS $\frac{1}{2}$ and $\frac{1}{2}$ $\sum_{i=1}^n a_i$ exceeds 60%, the growth occurs in Stranski–Krastanow mode via the formation of the wetting layer on the wetting layer on the top of which large-sized pyramid-shaped islands are formed. In both cases of low and high In both cases of contents, QWDs are not observed in TEM images. The window of In composition to grow QWDs is Figure 2 illustrates the impact of indium composition on structural properties of InGaAs layers 800 1000 1200 1200 1400 **4:' 4'** PL int., arb. un. λ , nm **QW . Figure 9.** Normalized PL spectra (**a**) and temporal evolution of PL signal at its spectral maximum (**b**) \mathcal{L}_max plus the fitted by a mono-exponential exponential exponential exponential exponential expression, which is a is as critical to the absence of discrete high energy levels involved in carrier relaxation processed to the a
The absence of discrete high energy levels in carrier relaxation processed to the absence of the absence of th the ground-state. The PL decay time at 1/2 ns. The PL decay time at 1/2 ns. The PL decay time at 1/2 ns. The P The QW structure shows the slowest PL decay with a characteristic time of 20 ns. This value is value is value **Figure 9.** Normalized PL spectra (**a**) and temporal evolution of PL signal at its spectral maximum (**b**) **QD/GaAs** $\rightarrow M$ Figure 9b compares the temporal evolution of PL signal for the QD, QWD, and QW structures [53]. In case of $\mathbb T$ intensity temporal evolution can be well fitted by bi-exponential exponential expon PL(*t*) = A1exp(⌧*1*/*t*) + A2exp(⌧*2*/*t*). The decay of PL signal is characterized by the fast component \blacksquare \blacksquare

Figure 2 illustrates the impact of indium composition on structural properties of InGaAs layers

 $\overline{}$ 20 $\overline{}$ mm

Quantum Dots: Active Scintillators & Tracking *Apple. 2020***, 2020, 2020, 2020, 2020, 2020, 2020, 2020, 2020, 2020** *Appl. Sci.* **2019**, *9*, x 5 of 28 in low dimensional structures. In this section, we compared results of time-resolved PL studies for 0D

Quantum Sensing | Steven Worm | 22.1.25 [Maximov et al., Appl. Sci. 2020, 10, 1038; M.Hoeferkamp et al., arXiv:2202.11828; A. Minns et al., MRS Advances 6, 297–302 (2021)] 12 comparable with career radiative measured for QUS in the temperature measured for $\frac{1}{200}$ $\frac{1}{2}$. Those, $\frac{1}{2}$ is limited by and is decay to reading both $\frac{1}{2}$ is defined and is defined and is defined as $\frac{1}{2}$ l1828; A. Minns et al., MRS Advances 6, 297–302 (2021)] 12 π ilip et di., dixiv.2202. Hozo, π . Iviliho et di., Ivitto π uvalices 0, 297–002 (2021)] T2 [Maximov et al., Appl. Sci. 2020, 10, 1038; M.Hoeferkamp et al., arXiv:2202.11828; A. Minns et al., MRS Advances 6, 297–302 (2021)]

Quantum-Polarized Helicity Detection in NV Centres

- Photoluminescent point defect in diamond nitrogen-vacancy centres (NV-)
	- Spin-dependent photoluminescence to measure electronic spin state
	- Relatively long (millisecond) spin coherence at room temperature
- Spin-spin scattering for helicity determination
	- Usually requires polarized beams and/or polarized targets
	- Polarized scattering planes possible to measure track-by-track particle helicity

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- Rydberg readout of a Time Projection Chamber
	-
	-
	-
- Antiprotonic atoms and novel HCI systems
	-
	- isotope shift (King plot), EDM measurements

amplification

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Quantum-enabled Experiments & Ultra-light Dark Matter

Primordial Black Holes Gravitational Lensing

[T. Lin, arXiv:1904.07915] 15

 Quantum Sensing needed for Light/Ultralight Dark Matter

 $\phi(t) \approx \phi_0 \cos(m_\phi c^2 t/\hbar)$

Ultra-Light Dark Matter: Phenomenology

- Adding new DM interaction (field) to Standard Model Lagrangian
	- Bosonic: Ultra-light DM must be bosonic in nature
	-
	- Non-relativistic (\sim 10⁻³c): so it neither leaves the galaxy or clumps near the center • Oscillating classical field: coherent, practically monochromatic \rightarrow wave-like

$$
\mathcal{L}_{DM} = \frac{\phi}{\Lambda_{\gamma}} \frac{F_{\mu\nu}F^{\mu\nu}}{4} - \frac{\phi}{\Lambda_{e}} m_{e}\bar{\psi}\psi
$$

• At the effective new physics energy scales Λ_{α} and Λ_{e} , α and m_{e} appear to oscillate

$$
\frac{d\alpha}{\alpha} \approx \frac{\phi_0 \cos(m_\phi t)}{\Lambda_\gamma},
$$

$$
\frac{dm_e}{m_e} \approx \frac{\phi_0 \cos(m_\phi t)}{\Lambda_e}
$$

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$$
\mathcal{L}_{int} = \frac{4\pi\phi}{M_{pl}} \left(\frac{d_e}{4e^2} F_{\mu\nu} F^{\mu\nu} - d_{m_e} m_e \bar{e}e - \frac{d_g \beta_3}{2g_3} G^A_{\mu\nu} G^{A\mu\nu} - \sum_{i=u,d} (d_{m_i} + \gamma_{m_i} d_g) m_i \bar{\psi}_i \psi_i \right)
$$

• Coupling to Lagrangian is linear (in ϕ) for lowest order interaction w/ scalar field

Quantum Sensing Methods for Testing Δα/α

Atomic spectroscopy (clocks)

 $\delta(v_1/v_2) \propto \cos(m_\varphi t)$ 10⁻²³ eV < m_φ < 10⁻¹⁶ eV

Laser interferometry (cavities)

 $\delta\Phi \propto \delta(vL) \propto \cos(m_\varphi t)$ 10⁻²⁰ eV < m_φ < 10⁻¹⁵ eV

Atom interferometry

 $\boldsymbol{F}(t) \propto \boldsymbol{p}_{\varphi} \sin(m_{\varphi} t)$ 10⁻²³ eV < m_{φ} < 10⁻¹⁶ eV

Quantum Sensing Methods for Testing Δµ/µ

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-
-

 Hyperfine transitions: Optical transitions: Vibrational transitions: $\nu_{\text{vib}} = C \cdot \mu^{1/2} \cdot R_{\infty}$ $\nu_{\text{hf}} = A \cdot \mu \alpha^2 F_{\text{hf}}(\alpha) \cdot R_{\infty}$ $\nu_{\text{opt}} = B \cdot F_{\text{opt}}(\alpha) \cdot R_{\infty}$

- Calculate sensitivities to variations in α or μ given by K_{α} and K_{μ}
- Search for variation in α : ultra-light Dark Matter
	- Measure ratios of frequencies $(R = \nu_1/\nu_2)$ for two clocks, look for oscillations
	- Highly charged ions give excellent sensitivity
	- Th-229 nuclear clock \rightarrow extreme sensitivity

Quantum Sensing with Optical Atomic Clocks feedback

- Optical Atomic Clock
	- Laser for oscillator, usually a narrow frequency around atomic transition
	- Ultra-stable laser locked to atomic transition, "counted" with frequency comb
- Atomic clock transition scale and sensitivity is "selectable"
	- For $R_{\infty} = \alpha^2 m_e c / 4 \pi \hbar$, fine structure const. α , and $\mu \equiv m_p / m_e$

Clocks proposed for QSNET

- NPL-SYRTE-PTB demonstrated an optical clock network with dark fibres
- Comparing optical clocks with different sensitivities to variations of *α*
- Results for $T = 0.9, 12, 45$ hours
- Results for previously unconstrained parameter space (topological defect DM)

Quantum Sensing | Steven Worm | 22.1.25 **2000** [Roberts et al, New J. Phys. 22, 093010 (2020); P. Delva et al., Phys. Rev. Lett., 118 221102 (2017)] 20

Quantum Sensing: Networks of Optical Clocks

- Superimpose waves to look for interference \rightarrow precise measure of (e.g.) distance
- Source is split and sent on two (or more) different paths, then recombined
- Interference (eg from changes in arm length) analysed by Fourier analysis, fringes, etc.

Quantum Sensing with Interferometry

- Demonstrated at ~meter scale, proposing 100m and ultimately km (space)
	- AION: Atom Interferometer Observatory and Network
	- ELGAR: European Laboratory for Gravitation and Atom-interferometric Research
	- MIGA: Matter wave-laser based Interferometer Gravitation Antenna
	- MAGIS: Matter-wave Atomic Gradiometer Interferometric Sensor
	- ZAIGA: Zhaoshan Long-baseline Atom Interferometer Gravitation Antenna
	- AEDGE: Atomic Experiment for Dark Matter and Gravity Exploration in Space
- Matches lab infrastructure; underground shafts (CERN, Fermilab, etc)
- Ultralight DM, but also topological DM, gravitational waves, Lorentz invariance

MINOS

Detector

Long-Baseline Atom Interferometry

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- Resonant cavities possible down to μ eV; below that, need huge volume
- Tunable superconducting RF cavity:
	- Frequency conversion: drive $\omega_0 \approx \textsf{GHz} \rightarrow$ axion gives $\omega_1 \approx \omega_0 \pm m_a$
	- Corrugated cavity with two polarizations (and lengths)
	- Separate scales allows separate tuning of ω_0 and ω_1
- Scan over axion masses:
	- Change of cavity geometry modulates the frequency splitting $\omega_0 \omega_1$
	- Huge parameter space to explore, but technical (cryo) challenges

Quantum Sensing | Steven Worm | 22.1.25 23 axions, experiments have to form proposed using the resonance resonance resonance in the not direct $\frac{1}{2}$ μ , siter b/ (2020) or, 000, dinivizoor.19090] \sim FIG. 1. Berlin et al., JHEP 07 (2020) 07, 088; arXiv:2007.15656] 23

(a) Cartoon of cavity setup.

Cavities: Axion Heterodyne Detection

- DarkSRF Collaboration aiming for tunable cavities
	- Figure of merit (F) proportional to square of DM mass (m_a) and cavity volume (V)

$$
F \sim g_{a\gamma}^2 m_d^2 B^4 \overline{V}^2 T_{\rm sys}^{-2} G^4
$$

Q

m^a

Quantum Sensing with Magnetometry: CASPEr

- Cosmic Axion Spin Precession Experiment (CASPEr)
	- Measure two interactions: electric dipole moment (EDM) and the gradient interaction with nuclear spin • Solid-state NMR of ²⁰⁷Pb in a polarized ferroelectric crystal
	-
	- Axion-like DM exerts an oscillating torque
- Limits for neV DM masses vs EDM coupling g_d and gradient coupling g_{aNN} ; many ideas for improvements

Quantum Sensing | Steven Worm | 22.1.25 24 [D. Aybas et al., Phys. Rev. Leh. 126, 141802]

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-
-
- Other light DM detection (annihilating, decaying, fifth-force coupling, phonon scattering)

Quantum Sensing | Steven Worm | 22.1.25 25 [S. Bass, M. Doser, Nat Rev Phys 6, 329–339 (2024)]

• Collaboration recently launched, preliminary WP structure now set

• Focus on exploring new technologies, connecting to HEP needs, and *community-building*

 1st Collaboration Meeting: 17-19 February @ CERN (https://indico.cern.ch/event/1503433/)

Scaling up to macroscopic ensembles (spins; nano-structured materials; hybrid devices, opto-mechanical sensors,…)

RDquantum / DRD5: Get started with Quantum Sensing

Exotic systems in traps & beams (HCI's, molecules, Rydberg systems, clocks, interferometery, …)

> Quantum techniques for sensing (back action evasion, squeezing, entanglement, Heisenberg limit)

Capability expansion (cross-disciplinary exchanges; infrastructures; education) WP6

Quantum superconducting systems (4K electronics; MMC's,TES, SNSPD, MKID's… integration challenges)

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