A glimpse at Quantum Sensing from a HEP perspective

Friederike Januschek, DESY
Physics At The Highest Energies With Colliders, Florence
30 August 2025

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

A glimpse at Quantum Sensing from a HEP perspective

… very biased

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What is Quantum Sensing?

A broad definition according to arXiv:2311.01930

"With a focus on **HEP applications**, we propose to adopt a **broad definition** of the term quantum sensor as any new quantum device or technique that has the potential to achieve **greater reach** towards beyond the-standard-model physics than that achievable through conventional techniques traditionally used in HEP." (arXiv:2311.01930, Quantum Sensors for HEP)

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Subclass:

*“**Quantum 2.0**”: a class of devices that actively create, manipulate and read out quantum states of matter, often using the quantum effects of superposition and entanglement.*

Why should we care?

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Quantum Sensing is already driving the program of precision measurements!

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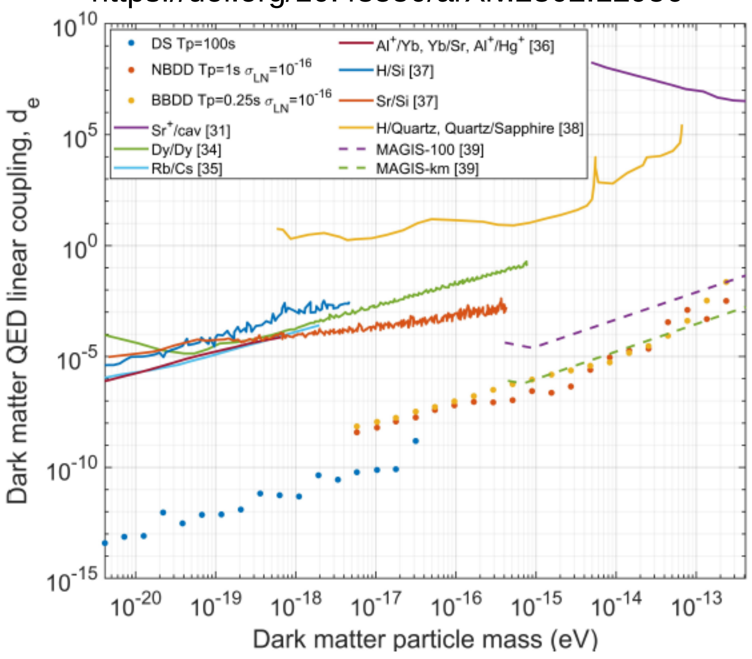
Quantum Sensing is already driving the program of precision measurements!

Quantum Sensing is potentially relevant for HEP (colliders) as well!

Why are Quantum Sensors relevant?

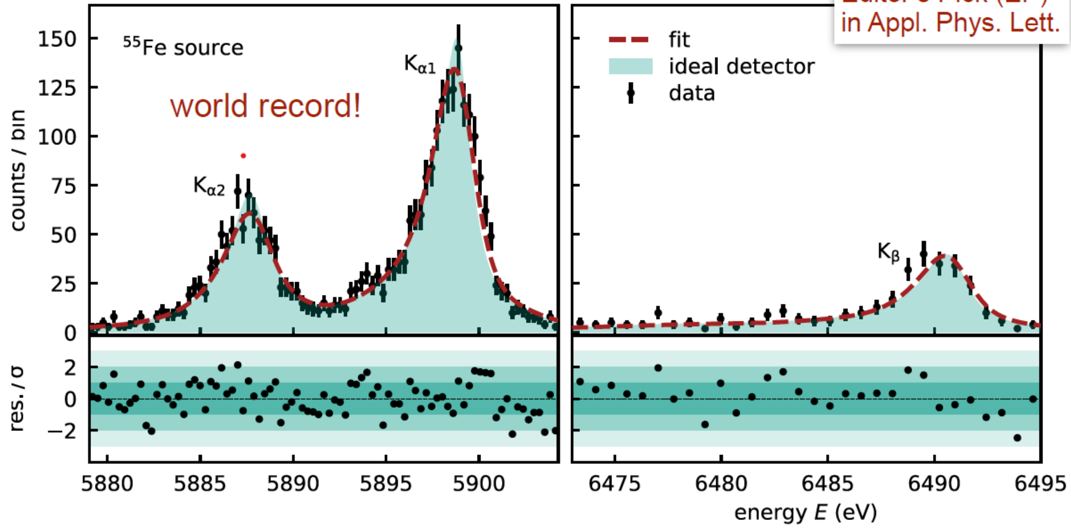
- Access to extremely small energies/ DM masses
- Ultra-low noise, extremely low dark counts
- Ultimate energy resolution
- New concepts ➔ new opportunities/possibilities

https://doi.org/10.48550/arXiv.2302.12956

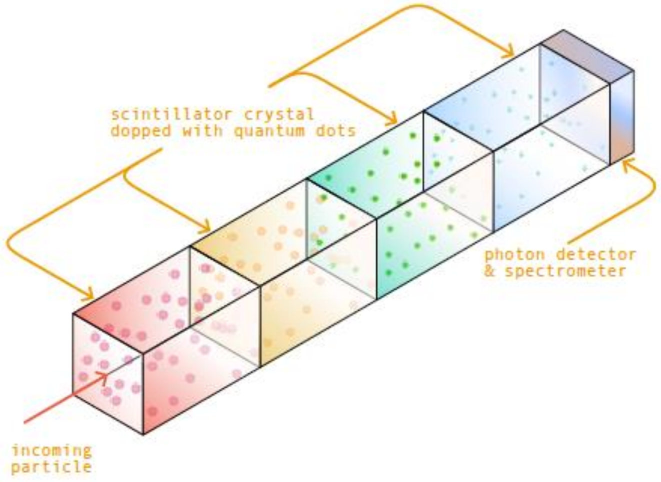


$\Delta E_{\mathrm{FWHM}} = 1.25(18)\,\mathrm{eV}$

Editor's Pick (EP) in Appl. Phys. Lett.

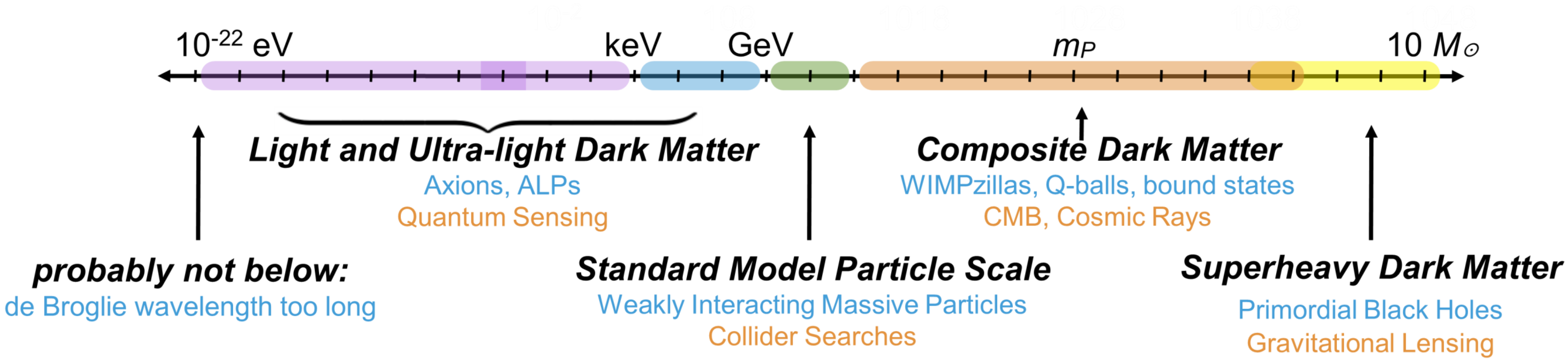


Appl. Phys. Lett.. 2024;124(3). doi:10.1063/5.0180903



Haddad et al. arXiv:2501.12738v1

(Ultra-)light dark matter is an obvious application



Courtesy of S. Worm, adapted from T. Lin, arXiv:1904.07915

… but it is not the only one

Dark sector and beyond

- **Dark Particles** e.g. axions
- Neutrinos
- Electric Dipole Moment
- Cosmology, dark energy, phase transitions
- Fine-structure constant
- Fundamental symmetries

… but it is not the only one

Dark sector and beyond

- **Dark Particles** e.g. axions
- Neutrinos
- Electric Dipole Moment
- Cosmology, dark energy, phase transitions
- Fine-structure constant
- Fundamental symmetries
- **Accelerators and colliders (?)**

What is out there?

Atom interferometry

Continous variables sensors

MMCs

Quantum materials

Quantum networks

KIDs

Spin sensors and NMR

SNSPDs

QCD

Optomechanical sensors

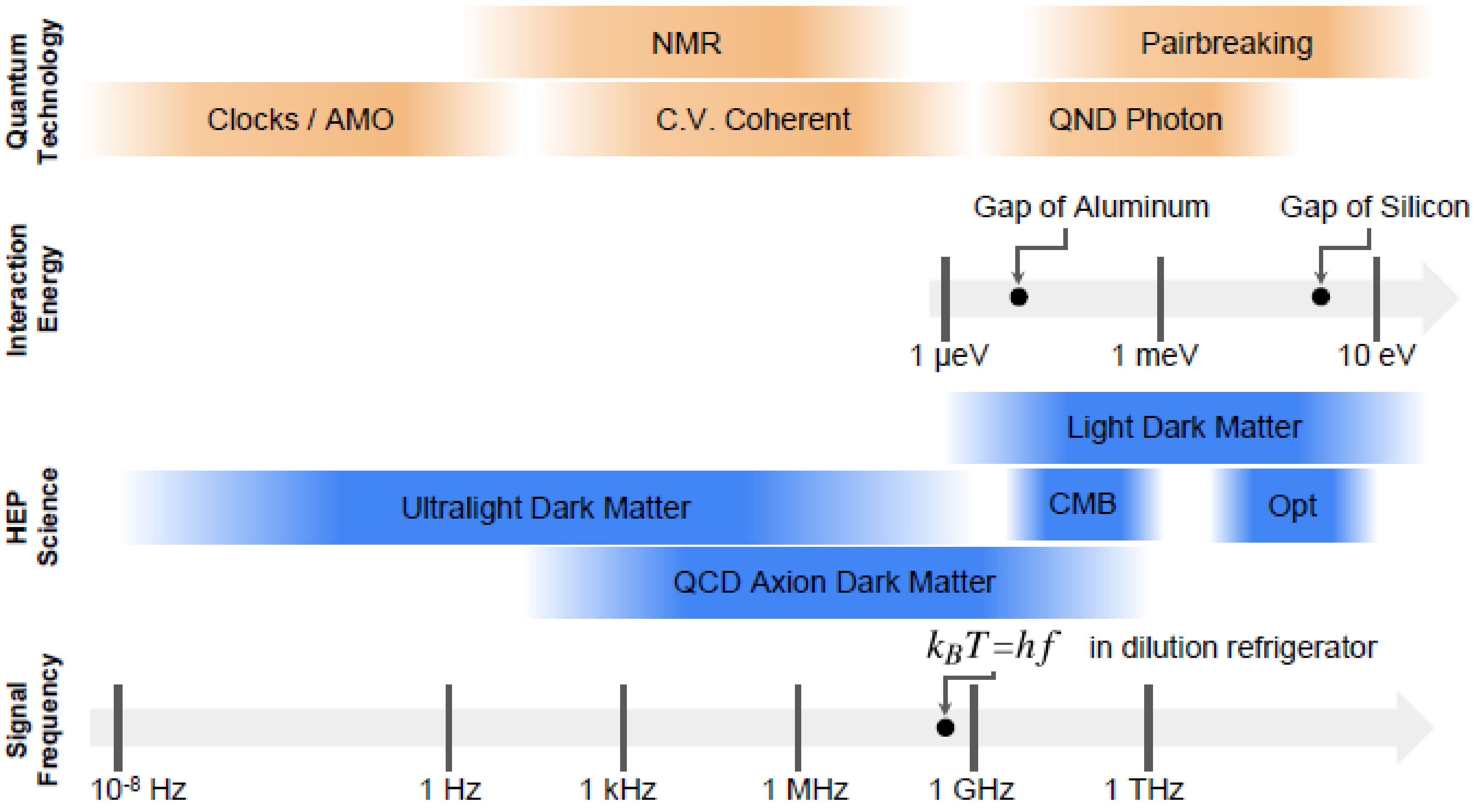
SC cavities

TESs

Clocks, Optical cavities

Energy matching science drivers and technologies

Dark sector and beyond



arXiv:2311.01930

One view on colliders

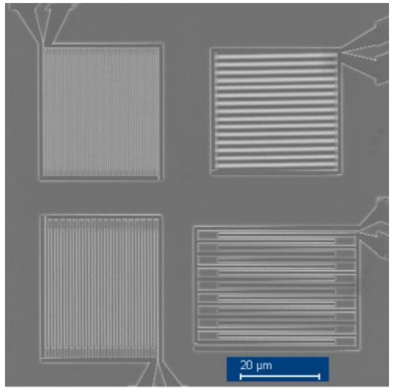
…but not the only one

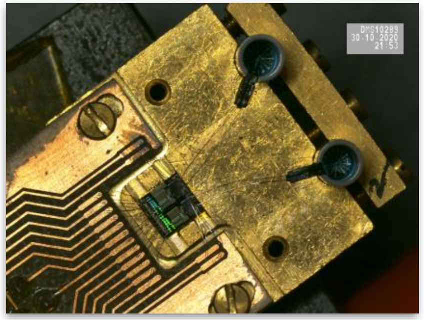
- Cryogenic sensors emerge as a possible topic of high relevance to colliders
- In addition:
  - Selected methods for light dark matter detection
  - Quantum systems

arXiv:2311.01930

	Dark waves	Dark particles	Cosmology, dark energy, phase transitions	Testing quantum mechanics	Quantum gravity	Telescopy	Collider, fixed target, high event rate	Symmetry violations
SC qubits. SC cavities, SC continuous variables (JPAs, RQUs, KI-TWPAs, etc), squeezing, bae,transduction	x	x		x				x
SC pairbreaking sensors (QCD, TES,MKID,SNSPD)	x	x	x		x	x	x	
Microcalorimetry, single phonon		x						
AMO, clocks, atom and photon interferometry	x	x	x	x	x	x		x
NMR	x	x	x					x
Optomechanics (squeezing, back-action evasion, etc)	x	x		x	x			
Quantum networks	x		x			x		
Sensor arrays, high channel count	x	x	x			x	x	
Quantum materials, metamaterials	x	x				x		
Foundry facilities	x	x	x	x			x	x

What to expect from this talk





https://doi.org/10.1016/j.nima.2024.169956

- **Cryogenic Sensors**, primarily, but not only for low energies
  - Superconducting Nanowire Single Photon Detectors
  - Transition Edge Sensors
  - (Microwave) Kinetic Inductance Detectors
  - Magnetic Microcalorimeters

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  - Superconducting Nanowire Single Photon Detectors
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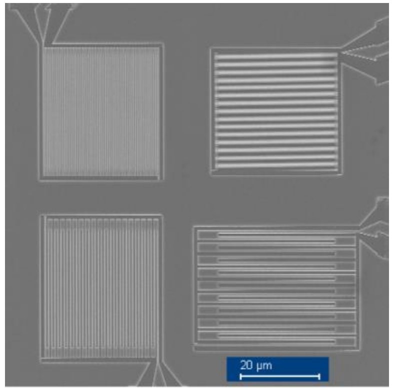
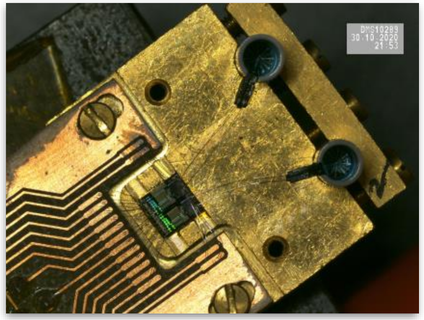
  - (Microwave) Kinetic Inductance Detectors
  - Magnetic Microcalorimeters
- **„Quantum 2.0“** for low energies
  - Atomic and Nuclear Clocks
  - Atom Interferometry





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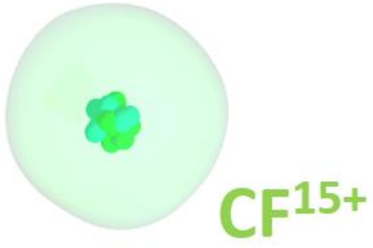
https://qsnet.org.uk/highly-charged-ion-cl



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  - Superconducting Nanowire Single Photon Detectors
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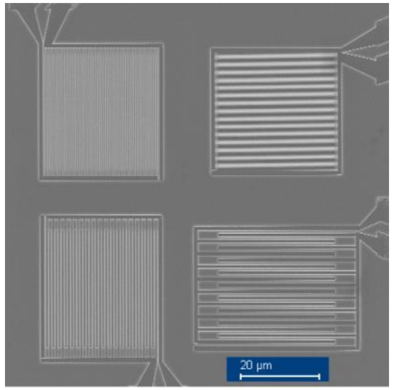
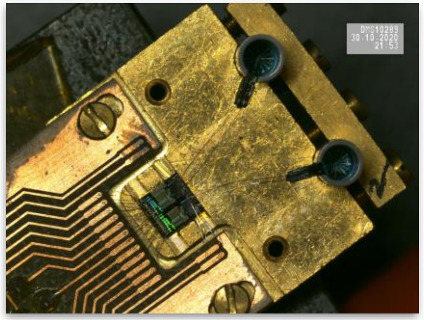
  - (Microwave) Kinetic Inductance Detectors
  - Magnetic Microcalorimeters
- **„Quantum 2.0“** for low energies
  - Atomic and Nuclear Clocks
  - Atom Interferometry
- **Quantum Systems** for higher energies
  - Quantum Dots
  - NV centers





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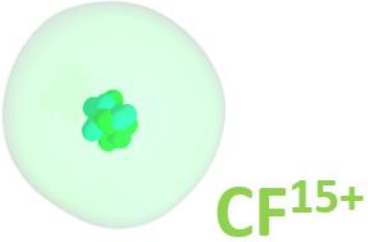
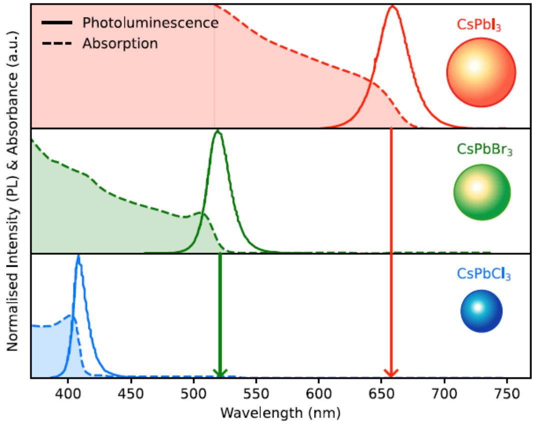
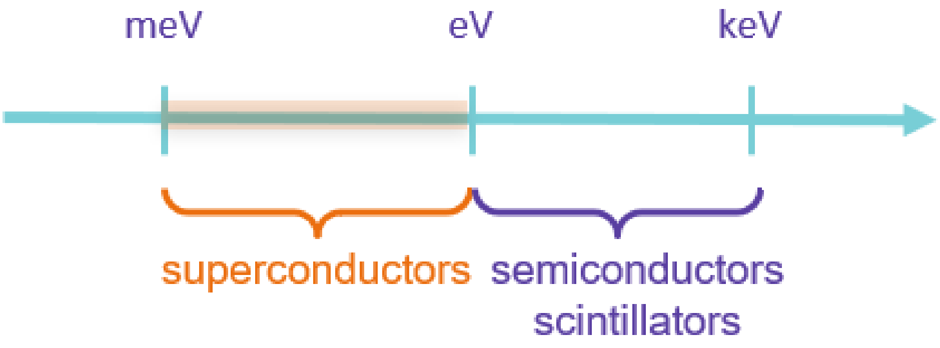




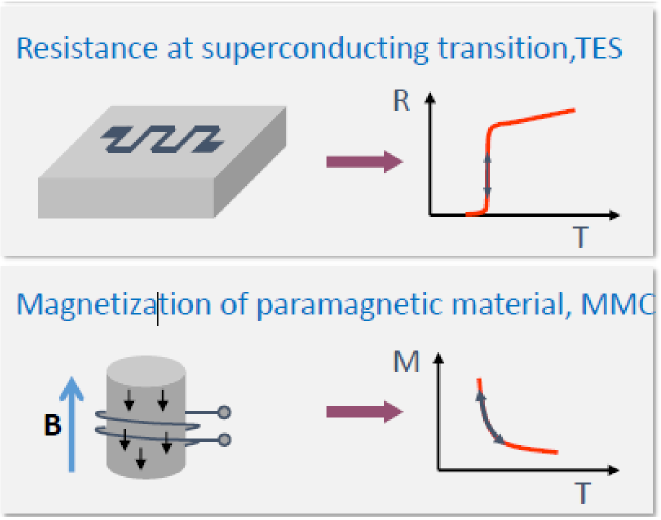
Haddad et al. arXiv:2501.12738v1

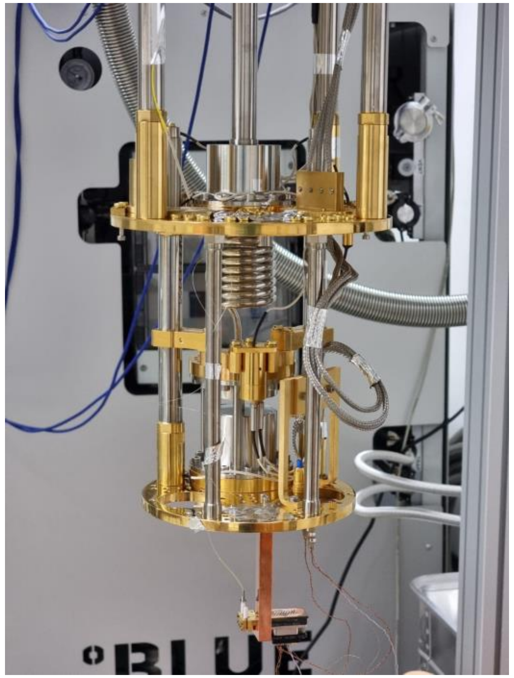
Taking advantage of superconductivity for particle detection

Cryogenic Detectors



- Materials at cryogenic temperatures, have interesting (and highly sensitive!) physical properties ➔ superconductivity
- **Nanowires** (SNSPDs)
- „**Thermometers**“: using steep temperature dependance of
  - Resistance (TES)
  - Magnetization (MMC)
  - Kinetic Inductance (KID)
- Features of a a “typical” cryogenic detector:
  - Small volume
  - Working temperature below 1 K
    - Small specific heat
    - Small thermal noise
  - Read out by SQUIDs



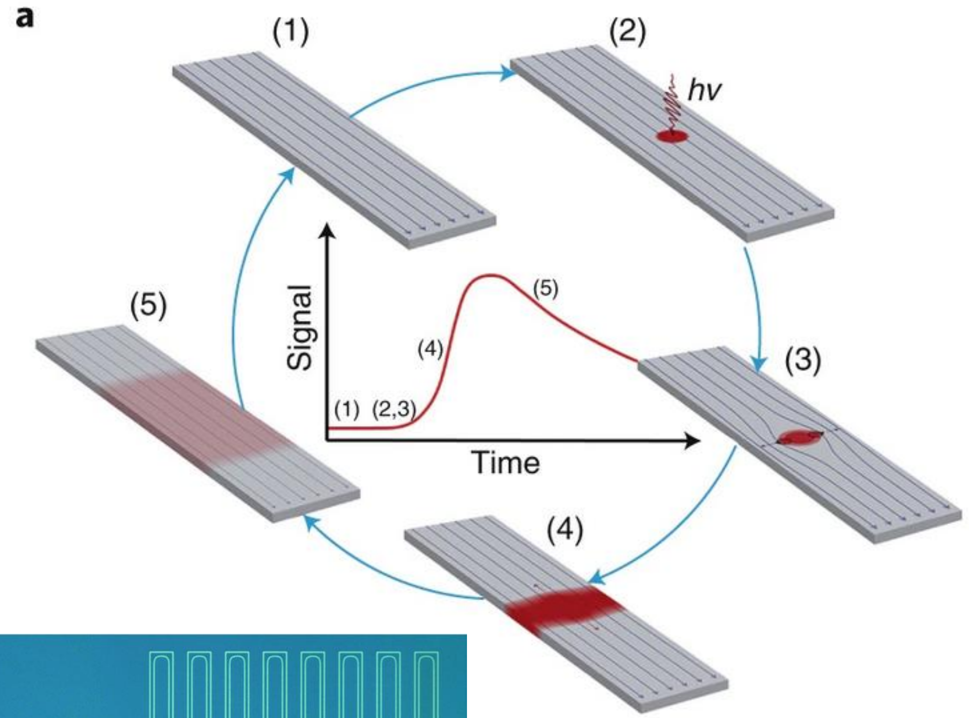


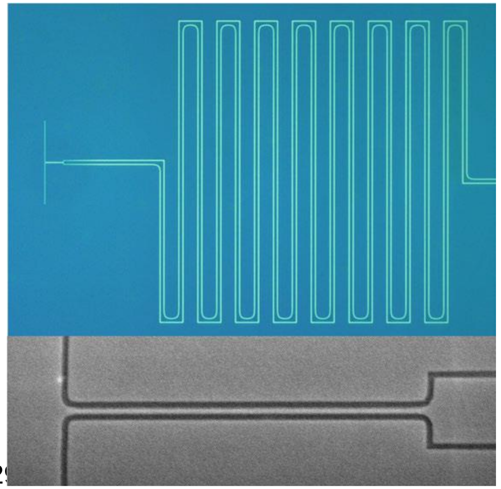
Adapted from Loredana Gastaldo

Superconducting nanowires can count photons

Superconducting nanowire single photon detectors (SNSPDs)

- Concept:
  - A superconducting wire is cooled below the superconducting transition temperature.
  - Biased to be just below the superconducting critical current.
  - Single photon ➔ change from superconducting to resistive state.
  - Pulse can be read out.
- SNSPDs are:
  - High speed
  - Low noise
  - High-efficiency (depending on the setup)
  - Single-photon detection possible from UV to mid-infrared wavelengths
  - Counting devices (no energy resolution)





Nature Photonics **volume 14**, pages 201–202 (2020)

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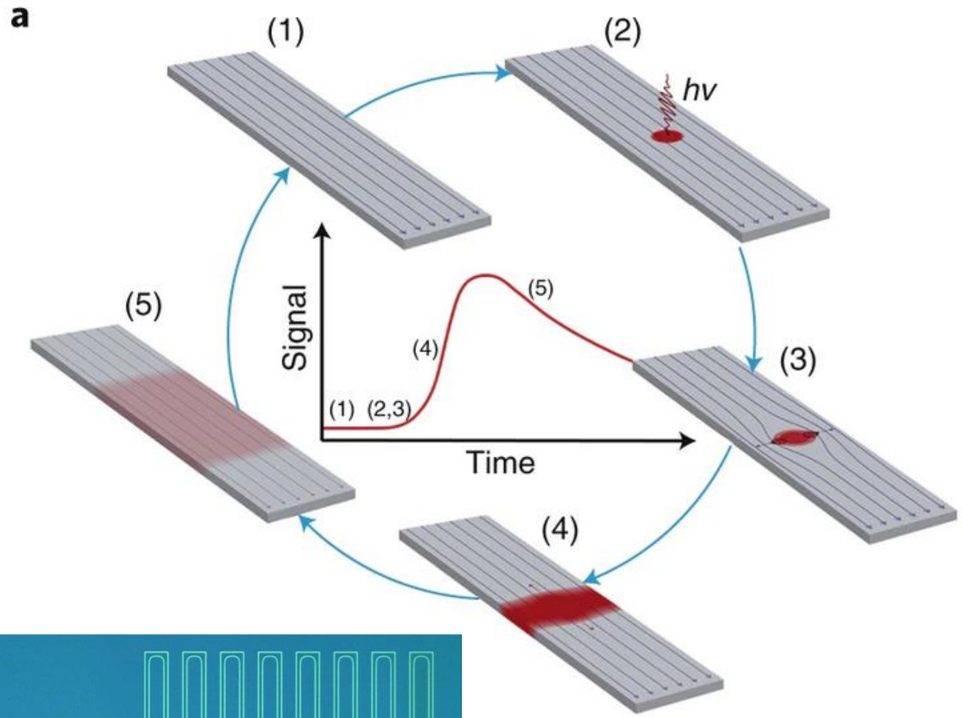
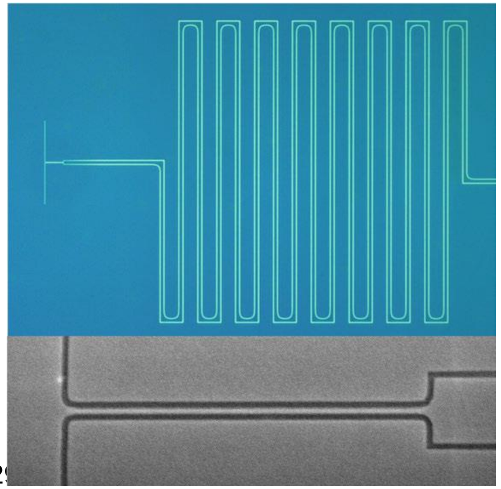
- SNSPDs are:
  - **High speed ➔ picoseconds ➔ could we use this?**
  - Low noise
  - High-efficiency (depending on the setup)
  - Single-photon detection possible from UV to mid-infrared wavelengths
  - Counting devices (no energy resolution)





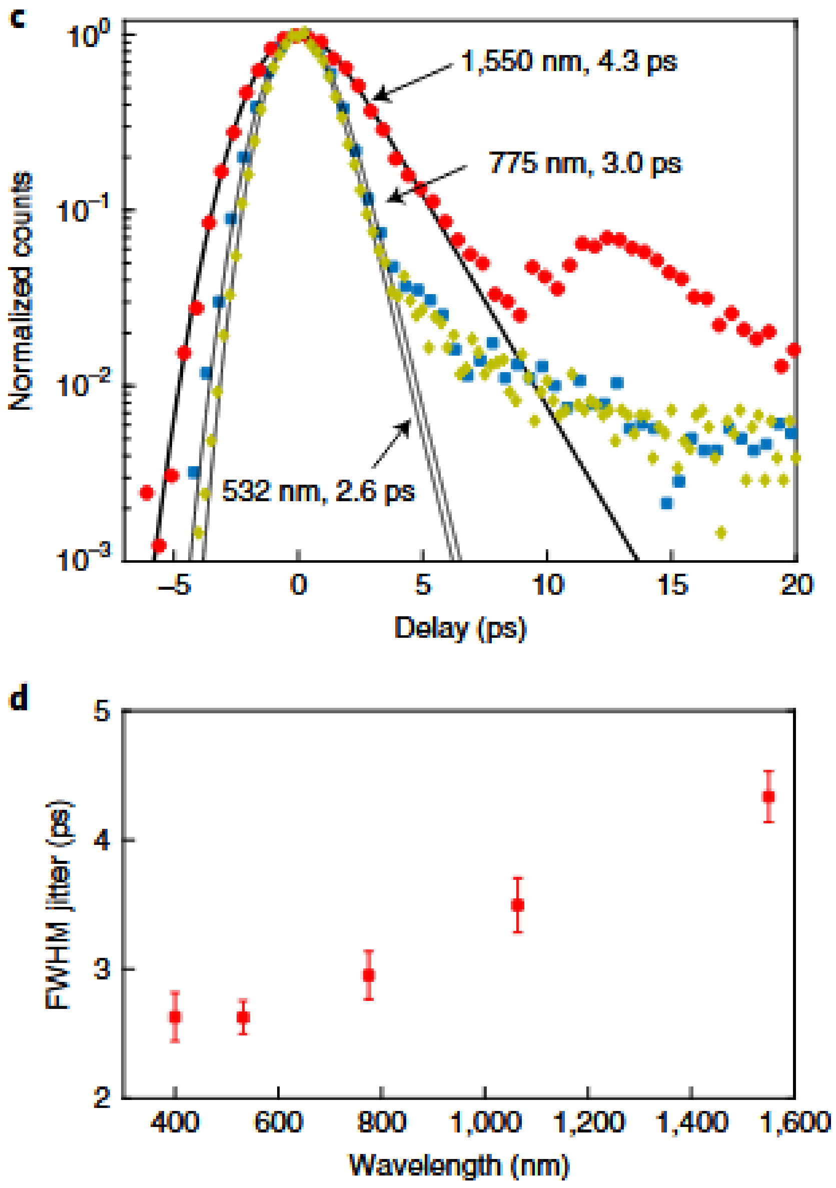
Nature Photonics **volume 14**, pages 201–202 (2020)

SNSPDs have picosecond timing jitter!

Currently **2.6 ps** demonstrated for photons in a SNSPD

➔ For the Muon Collider or FCC timing jitter might be key!

➔ Is there potential for a multilayered charged particle tracking detector???

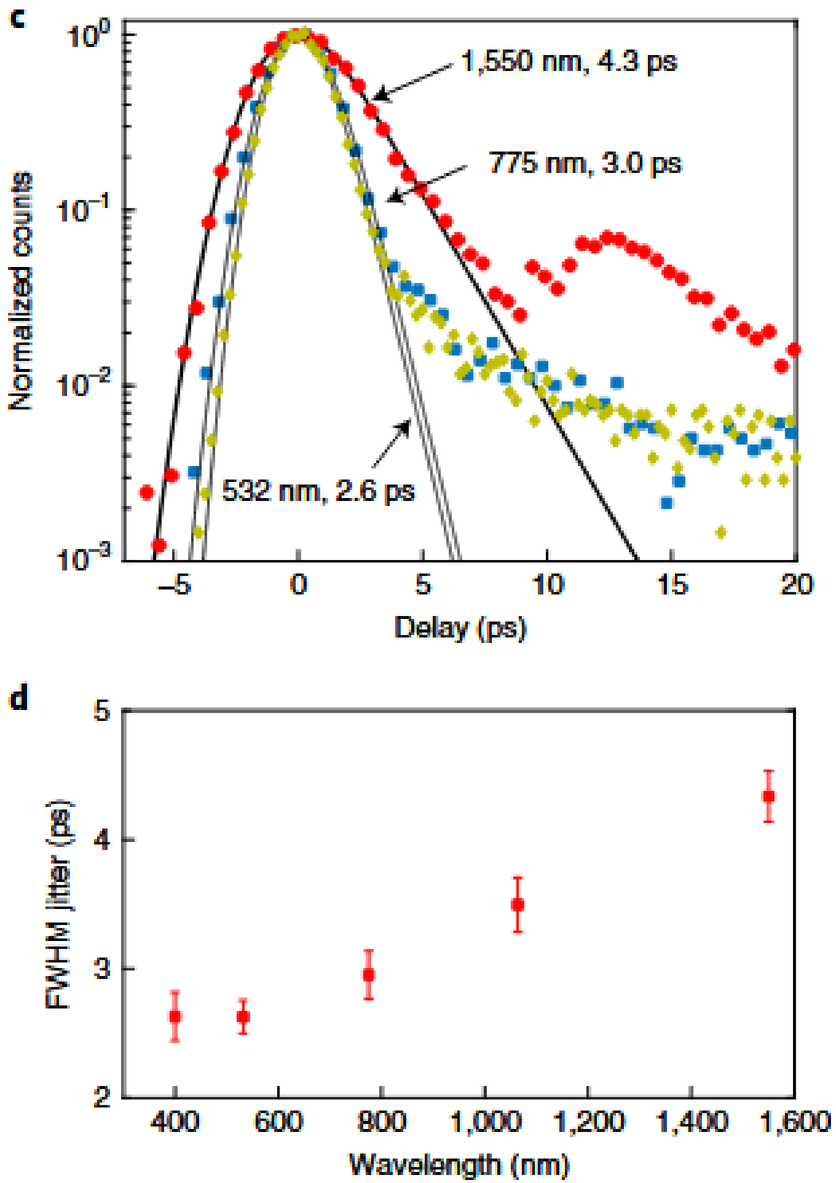


Nature Photonics **volume 14**, pages 250–255 (2020)

Can we use SNSPDs in HEP Tracking?

Some related questions

- Timing resolution ➔ OK
- Can they be small enough?
- Can they be radiation hard?
- How difficult are they to fabricate?
- How can they be read out?
- How do they respond to charged particles?
- Can they operate in a magnetic field?
- …

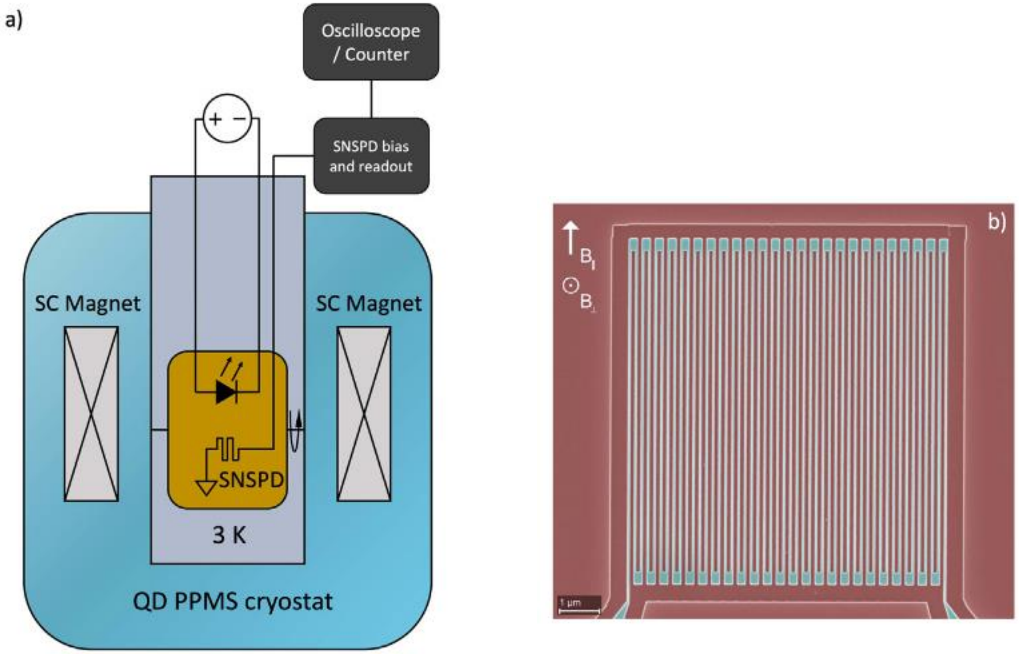


Nature Photonics **volume 14**, pages 250–255 (2020)

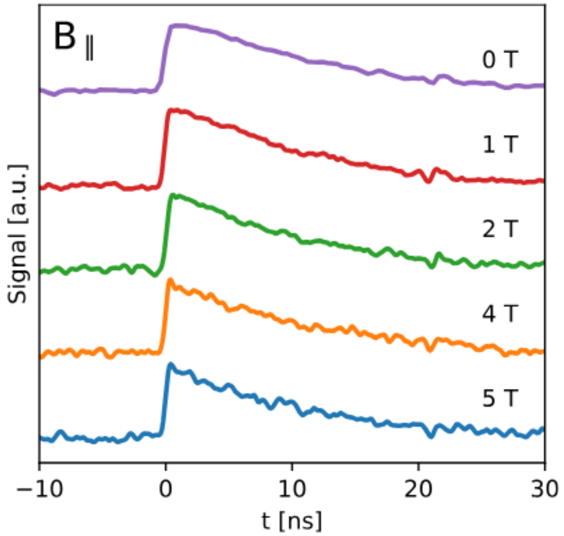
SNSPDs can operate within a magnetic field

- Successful test of operation in a magnetic field up to 5 T (parallel) and 0.5 T (perpendicular) has been shown
- NbN SNSPDs
- High rate detection possible (here: 10^8 count/s at 100 μm^2 pixel size)
- Low dark counts 1/s

➔ Potential for high-rate measurements in strong field environments like tracking



Nuclear Inst. and Methods in Physics Research, A 959 (2020) 163543



SNSPDs can measure GeV protons

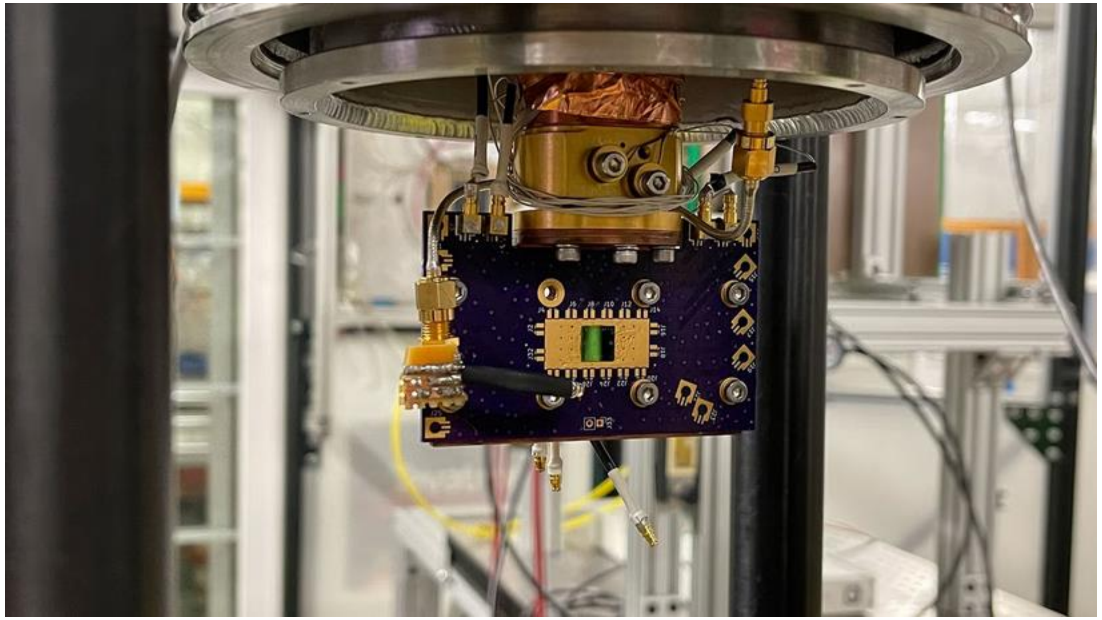
Cryogenic Detectors at a Beamline

- Successful test of SNSPDs as a proton detector at a beamline at FERMILAB
- Direct detection of 120 GeV proton beam
- Testing with different wire widths at a temperature of 2.82 K ➔ Ideal wire width around 250 nm for this application

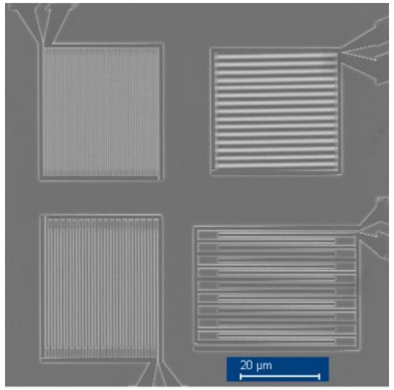
➔ Viability of SNSPDs as particle detectors at accelerator-based experiments might be possible

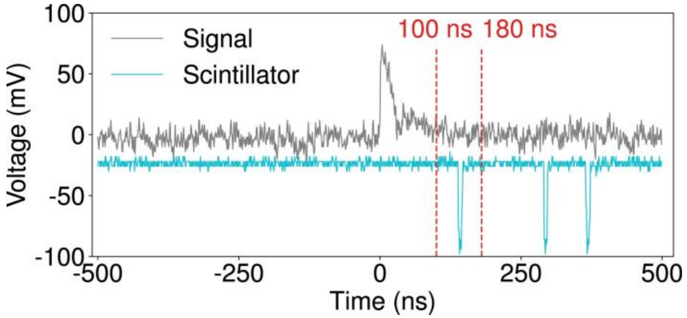
➔ Still many things to show (simultaneously!) though, but: certainly interesting

➔ One key problem: cryogenic environment



CREDIT: Sangbaek Lee/Argonne National Laboratory https://www.thebrighterside.news/post/scientists-make-major-breakthrough-in-high-energy-particle-detection/



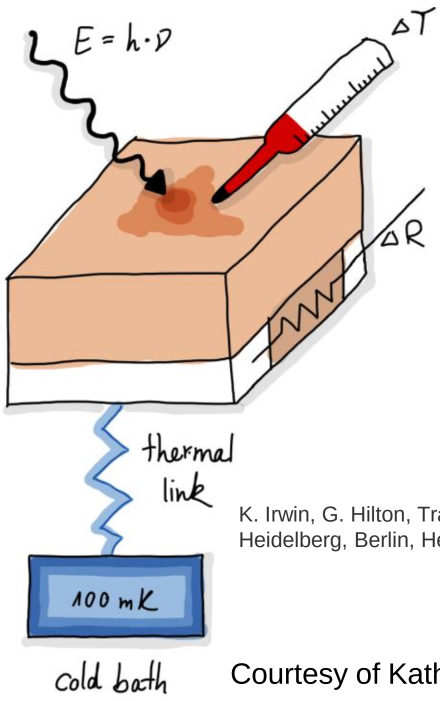


https://doi.org/10.1016/j.nima.2024.169956

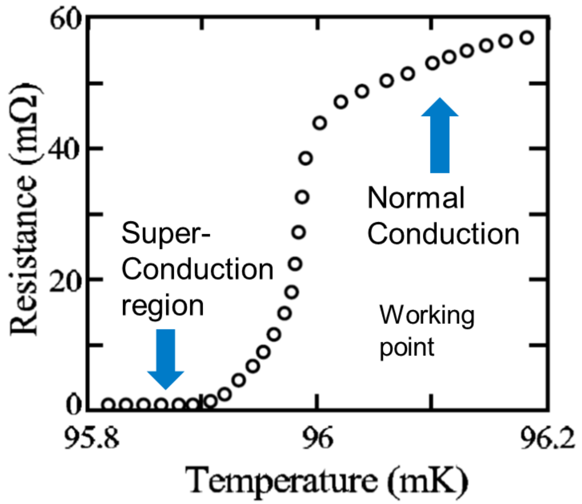
Using the edge of the transition

Transition Edge Sensors (TESs)

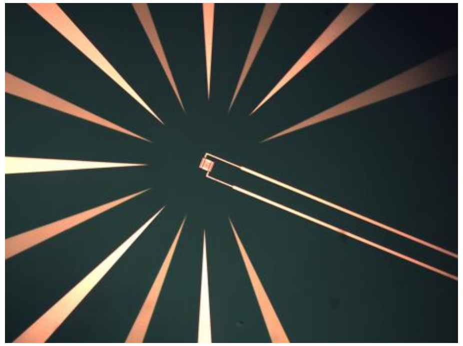
- Concept:
  - A superconductor is cooled below the superconducting transition temperature
  - It is biased to be on the superconducting transition, where there is extreme (and linear) temperature dependence of R
  - Single photon ➔ change of current
  - Pulse can be read out (usually by SQUIDs)
- TESs are:
  - Low noise
  - High-efficiency (close to 1 at optical/infrared)
  - Single-photon detection possible from THz to Xrays
  - Good energy resolution

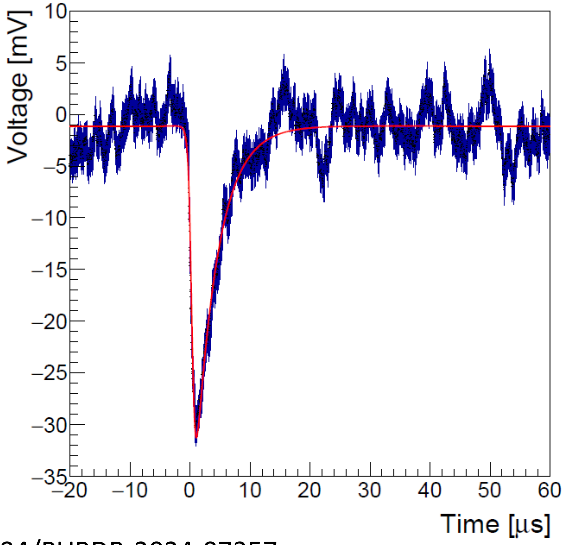


Courtesy of Katharina-Sophie Isleif



K. Irwin, G. Hilton, Transition-edge sensors, in: Cryogenic Particle Detection, Springer Berlin Heidelberg, Berlin, Heidelberg, 2005, pp. 63–150, http://dx.doi.org/10.1007/10933596_3.



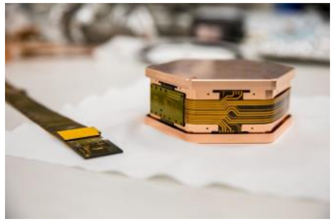


doi:10.3204/PUBDB-2024-07357

TES can be the sensor for Dark Matter particles

TESs are the detector of choice for a whole range of Dark Matter search experiments

- Due to their high sensitivity and low noise, TES are employed in a full range of Dark Matter Searches
- Dark matter interacts with the nucleons of a target
- TES detects the phonons and/or photons of the target
- Sensitivity to sub-GeV to GeV scale Dark Matter (mainly WIMPs)
- Examples:
  - SuperCDMS
  - EDELWEISS
  - COSINUS
  - CRESST



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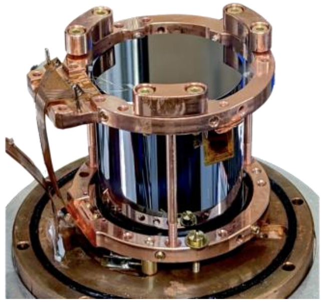

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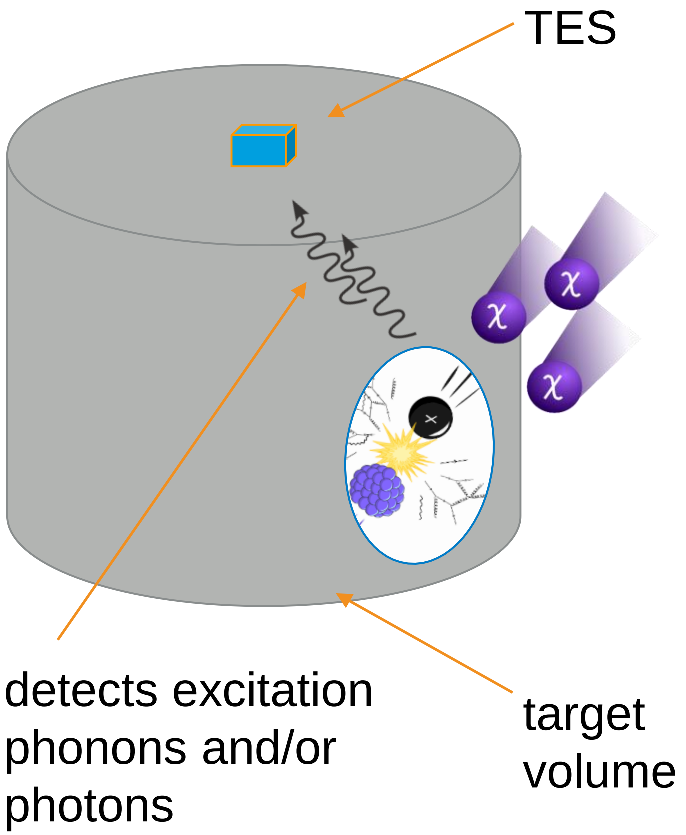
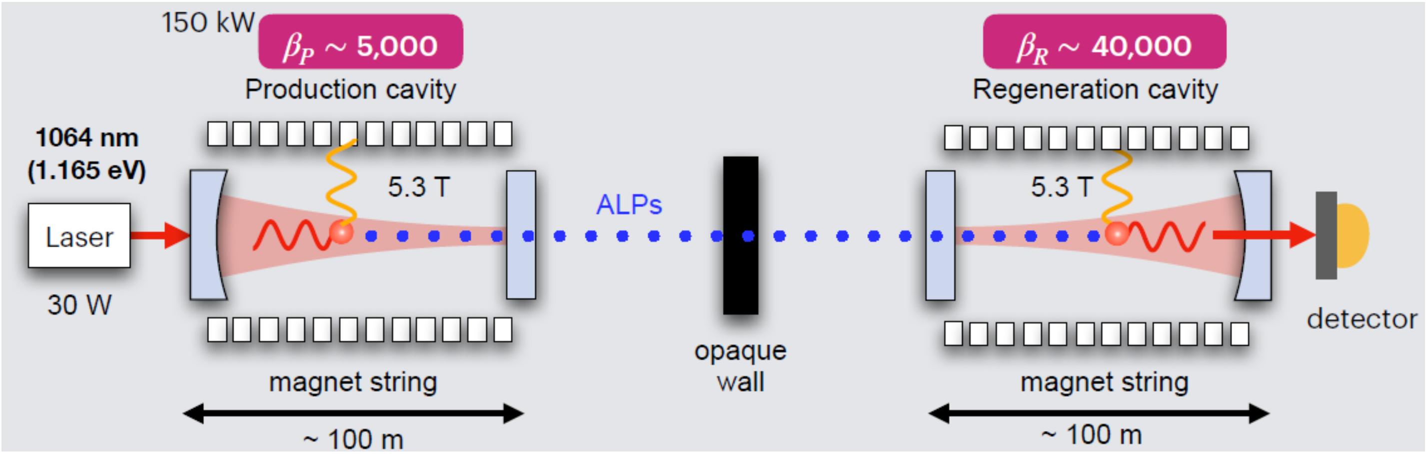


Courtesy of Christina Schwemmbauer

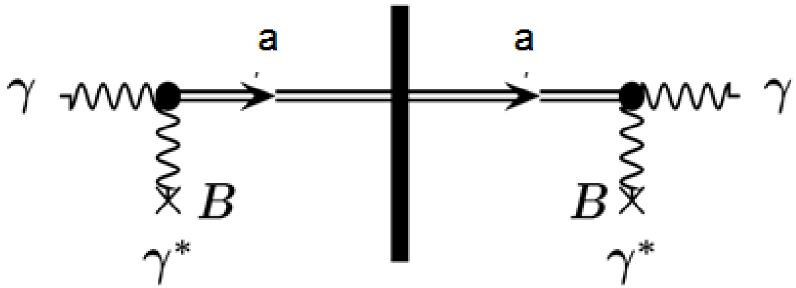
Detecting single low-rate infrared photons is a challenge

Courtesy of Katharina-Sophie Isleif

The ALPS Experiment



- ALPS II @ DESY aims to produce and detect axion-like particles in a light-shining-through-walls setup
- Currently running with heterodyne detection scheme
- Need to detect single 1064 nm photons at extremely low rates
  - Low energy photon detection (1064 nm, i.e. 1.16 eV)
  - Sensitivity to very low rates (1-2 photons a day)
  - Long term stability (~20 days)
  - High system detection efficiency
  - Low background rate: <7.7·10^{-6} cps, good energy resolution

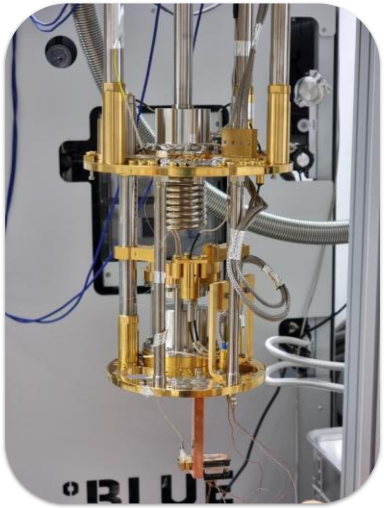


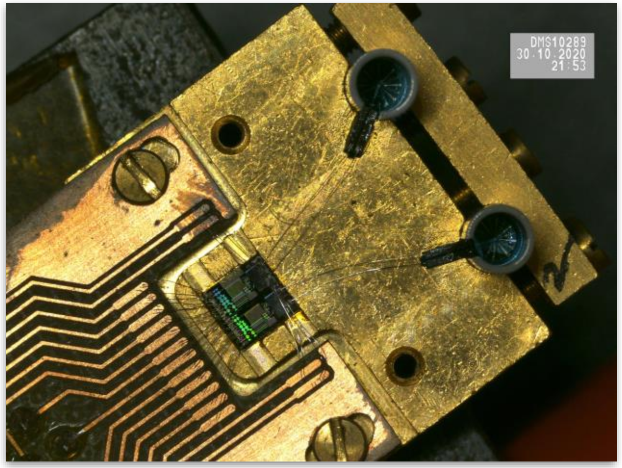
TESs can meet this challenge

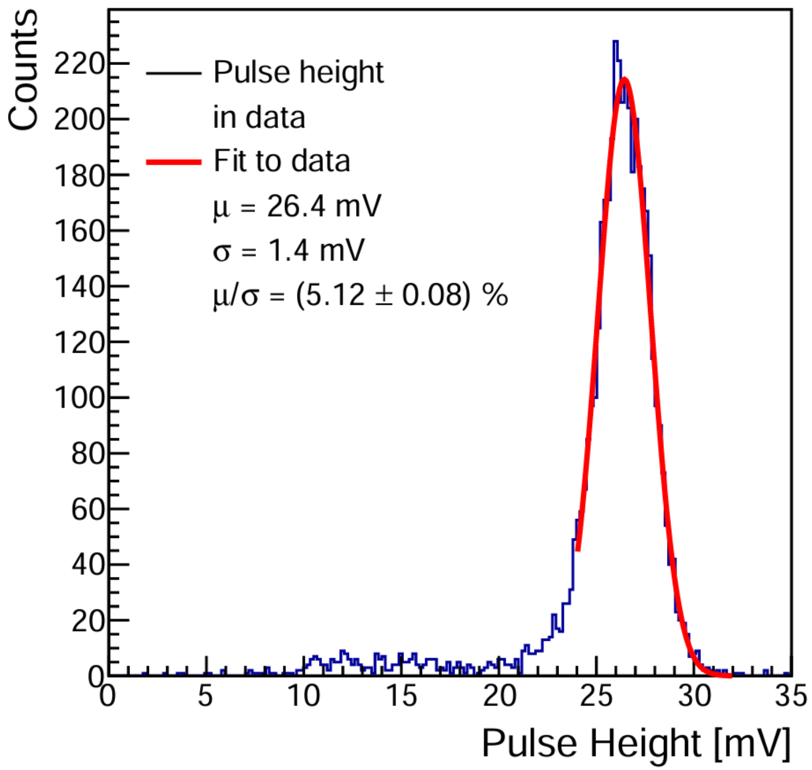
TES would be a viable option

- Low energy (1064 nm) single photon detection
- Sensitivity to very low rates (1-2 photons a day)
- Long term stability (~20 days)
- 90% efficiency measured
- Energy resolution of about 5 % @ 1064 nm (0.12eV) *PoS(EPS-HEP2023)567*
- Extremely low intrinsic dark count rate $<6.9 \cdot 10^{-6}$ Hz for 1064 nm photons shown *J Low Temp Phys* (2022). https://doi.org/10.1007/s10909-022-02720-0

See later: Direct dark matter searches with cryogenic detectors.



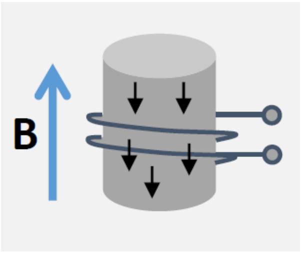


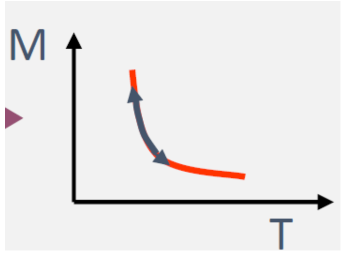


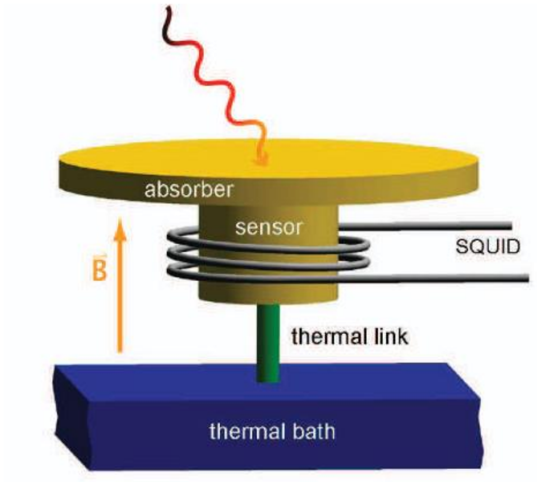
Detecting Xrays with magnetization

Magnetic Microcalorimeters (MMCs)

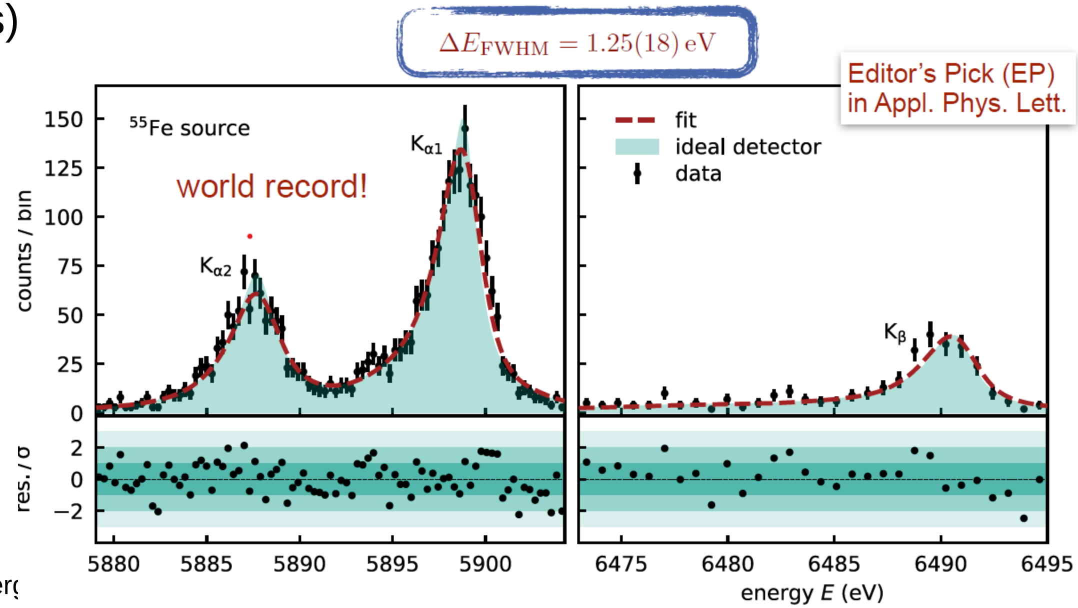
- Concept:
  - Magnetic microcalorimeters employ the temperature dependence of magnetization of a paramagnetic sensor.
  - Xray photon ➔ increase of temperature➔ decrease of magnetization➔SQUID read out
- MMCs are:
  - Low noise
  - Single-photon detection possible (mostly Xrays)
  - Fast rise time
  - World-record energy resolution
  - Often used in arrays







Adapted from Loredana Gastaldo

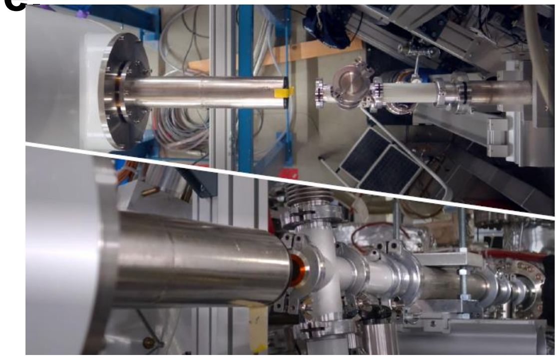


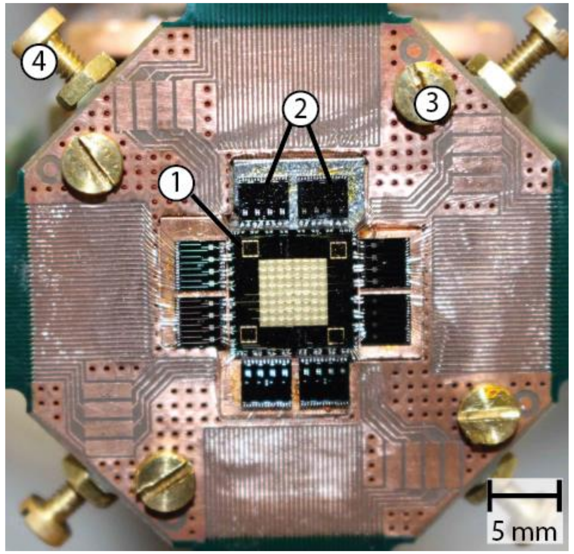
Appl. Phys. Lett.. 2024;124(3). doi:10.1063/5.0180903

MMCs do measure at beamlines

Heavy Ion measurements

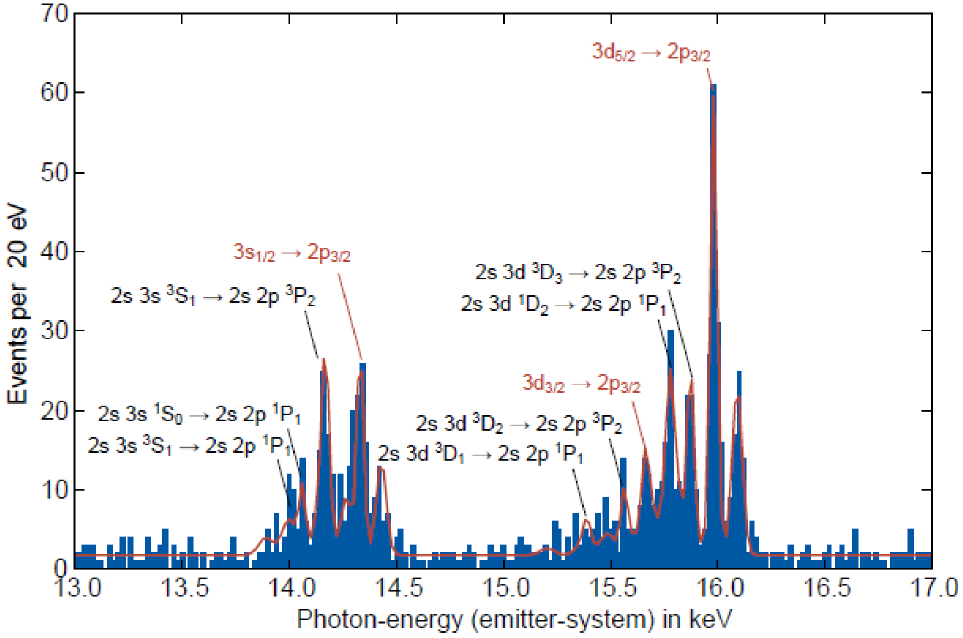
- Pilot experiment at the ESR storage ring at GSI, Germany with a MMC array
- maXs-30 type MMC-spectrometer (MMC array optimized for 30 keV)
- X-rays emitted in collisions of lithium-like uranium ions with a molecular nitrogen gas jet
- Sample spectra show many X-ray transitions.
- **“Excellent tool for precision X-ray spectroscopy in the hard X-ray range.”**





D.Hengstler 10.11588/heidok.00023815

maXs-30 type MMC-spectrometer

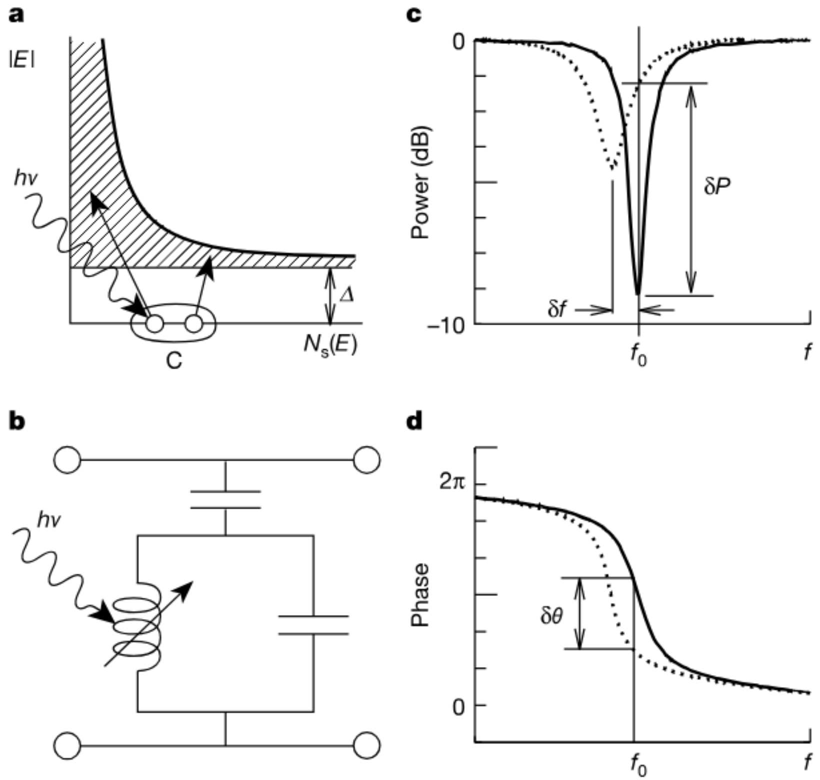


Atoms **2023**, 11, 13. https://doi.org/10.3390/atoms11010013

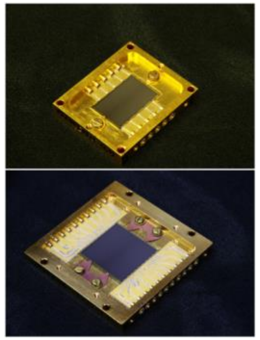
Kinetic Inductance can also be employed – with advantages

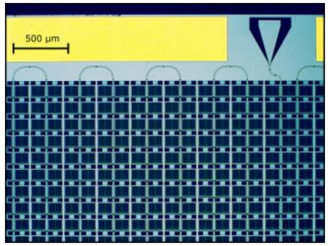
(Microwave) Kinetic Inductance Detectors ((M)KIDs)

- Concept:
  - A superconducting thin film is cooled well below the superconducting transition temperature
  - The film is used as an active part of a resonant circuit
  - Single photon ➔ change of kinetic inductance of the superconductor ➔ change of microwave signal through the circuit
- KIDs are:
  - Low noise
  - Single-photon detection possible from THz (mainly) to optical
  - Good time/energy resolution
  - Simple to manufacture
  - Possible to use with frequency domain-multiplexing by using high-quality factor circuits ➔ see later



Nature **volume 425**, pages 817–821 (2003)



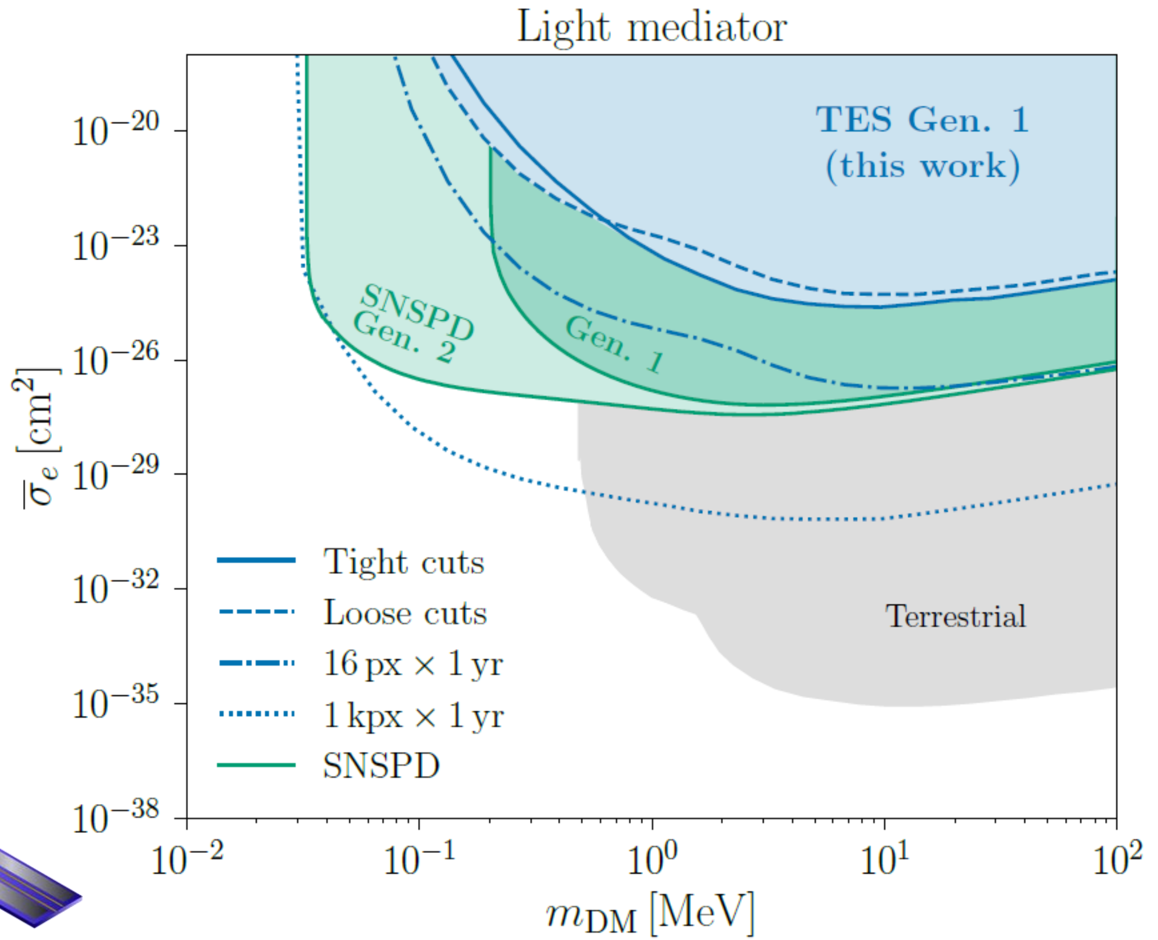


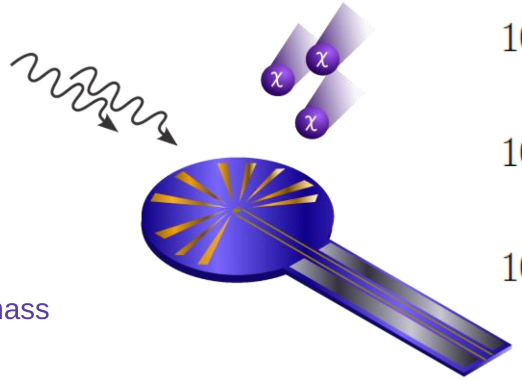
Opt Express. October 2017;25:25894–25909

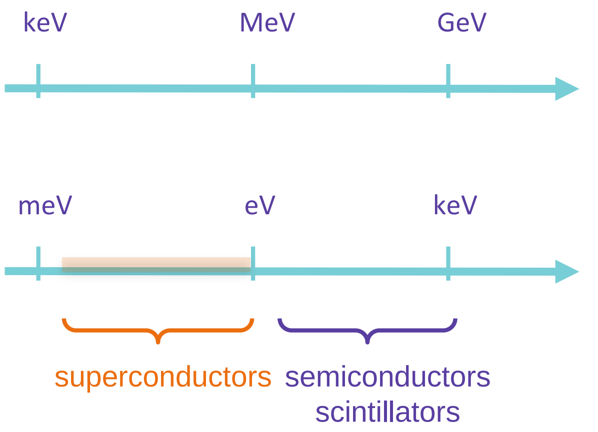
Using cryogenic detectors as direct dark matter detectors

Another way of applying TES, SNSPDs and KIDs

- Recently, cryogenic detectors have also been employed to look for dark matter particles, which directly scatter in the cryogenic detector.
- Sensitivity to energies as low as low as O(meV) ➔ DM particles as light as 1 keV could be detected.
- Challenge:
  - Dark counts (noise, background)
  - Small sensitive mass ➔ arrays?



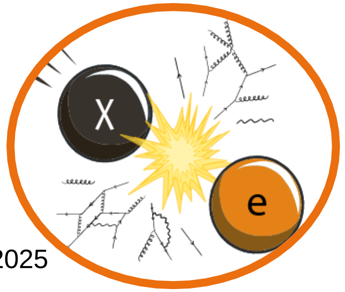




DM mass

Energy transferred in scattering process

Courtesy of Christina Schwemmbauer

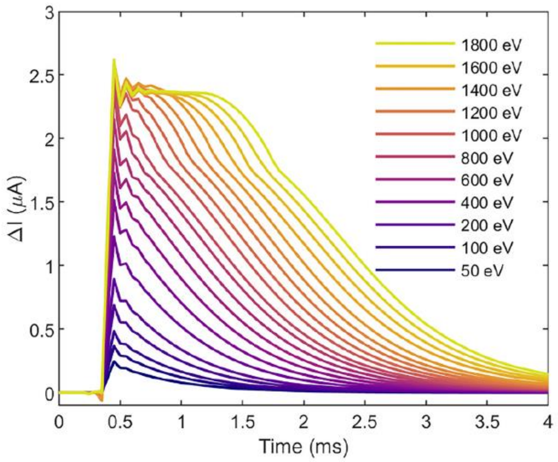


arXiv:2506.18982v1

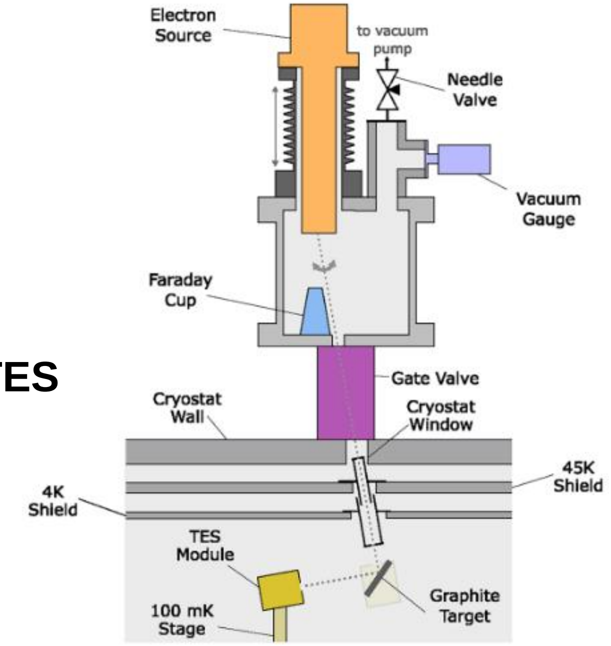
Cryogenic Detectors measuring electrons

On the road to high resolution electron spectroscopy e.g. for KATRIN++

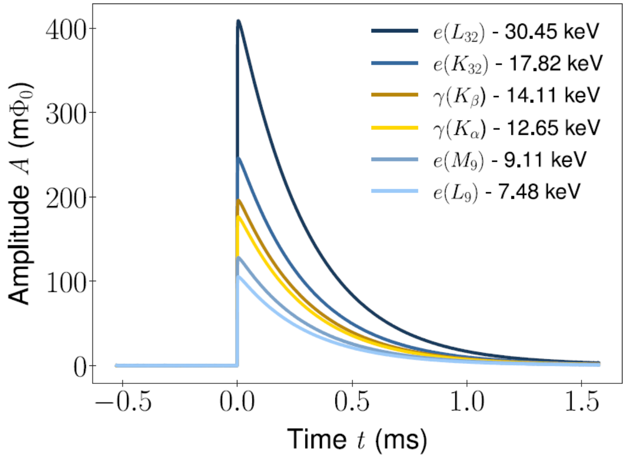
- Mostly cryogenic detectors are used for single photon detection ➔ extend to other particles, electrons
- Example application: KATRIN experiment measuring neutrino mass (limit), currently $m_{\nu e} \leq 0.45\ \mathrm{eV}/c^2$ at 90% CL ➔ become more precise
- TES: electron beam with energies between 750 and 2000 eV (scattered and direct)
- MMCs: ^{83}Rb/^{83m}Kr source for electrons and photons in parallel
- Response is very similar for electrons as for photons
- Cryogenic sensors can be used for high-resolution electron spectroscopy



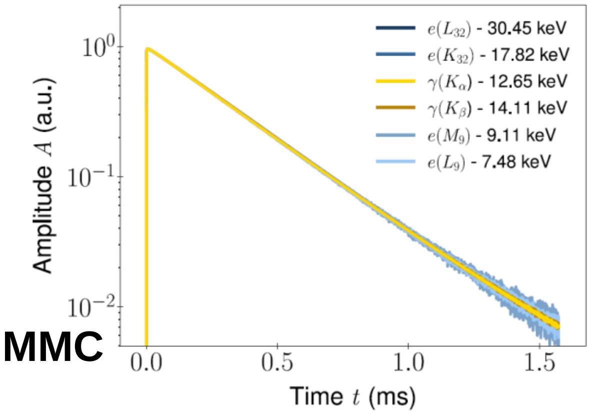
TES



J. Appl. Phys. 135, 224504 (2024)



MMC



NIM A 1080 (2025) 170662

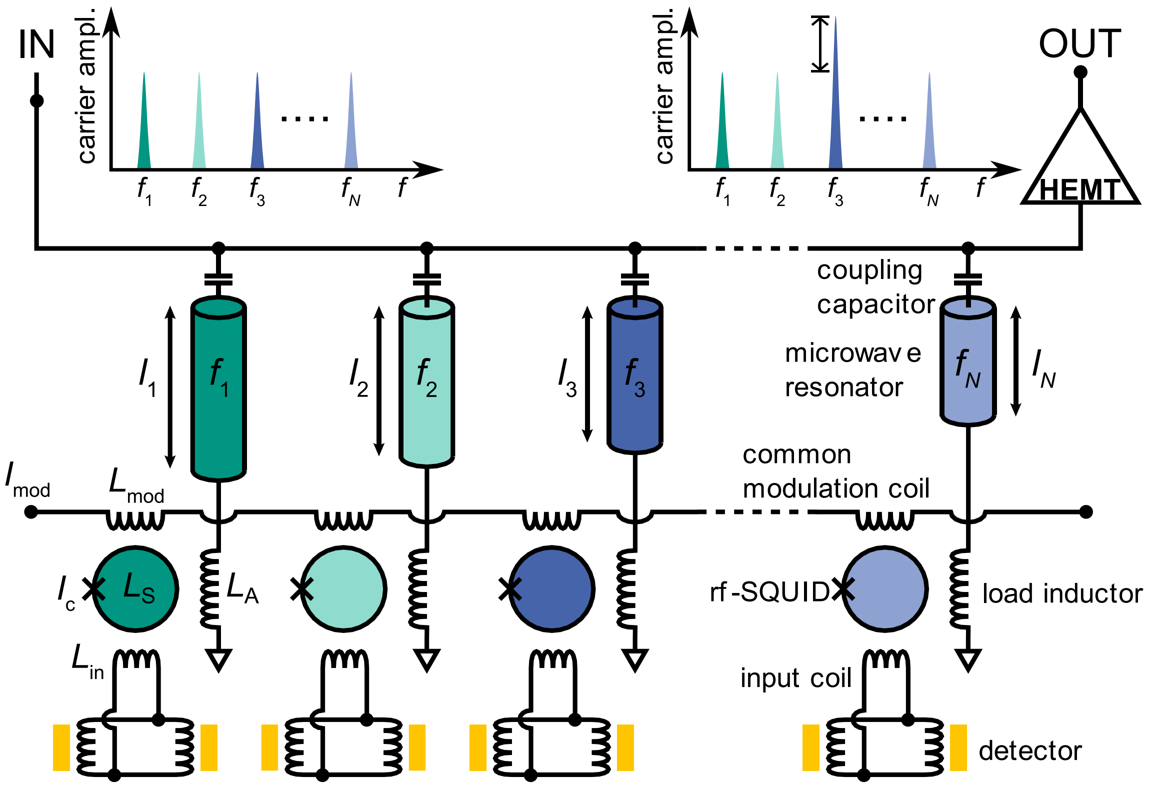
Cryogenic Detectors: How to read out an array

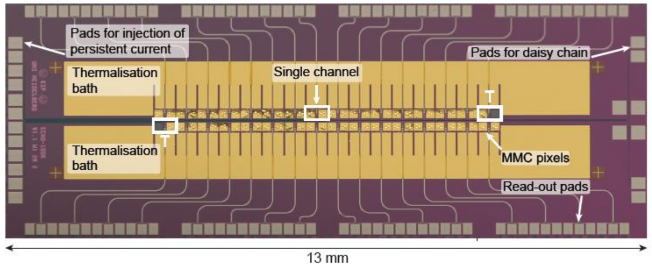
Multiplexing (here: frequency domain)

- High resolution cryogenic detectors ➔arrays ➔ difficult to read out due to heat and cabling
  - Multiplexing can be a solution (time, frequency)
- Microwave SQUID multiplexers (e.g. for the ECHo-100k experiment) enable readout of hundreds of sensors via a single RF line:
  - Each sensor inductively coupled to a SQUID
  - SQUID is inductively coupled to a microwave resonator

➔detector signal changes resonance frequency of the resonator

  - Capacitively coupling hundreds of such resonators with different resonant frequencies to a common transmission line.
  - Readout of detector signal.





https://www.ims.kit.edu/english/2553.php

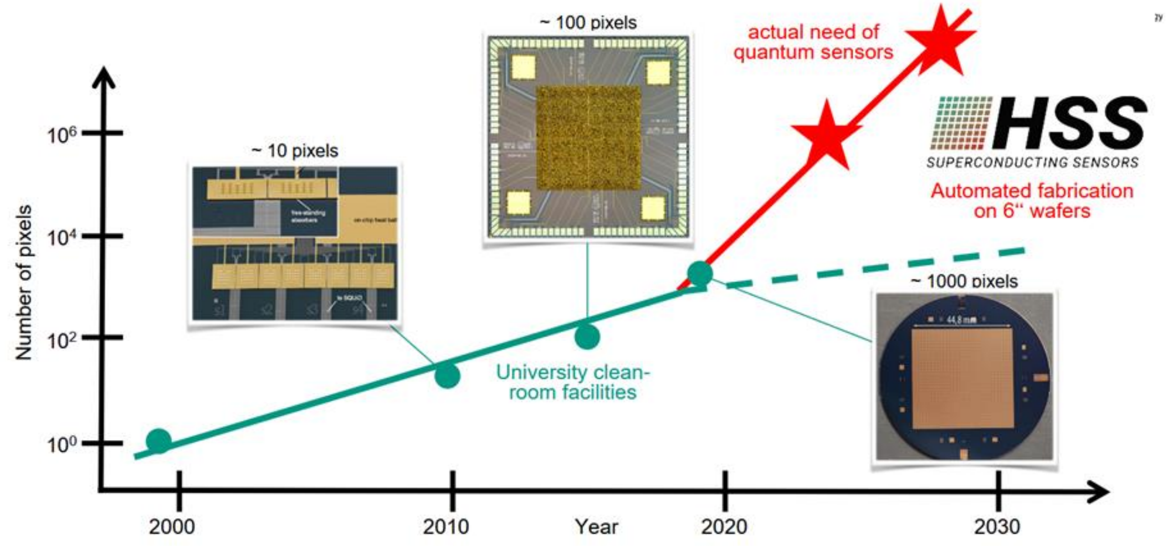
10.1016/j.nima.2023.168564

There are additional down-to-earth challenges

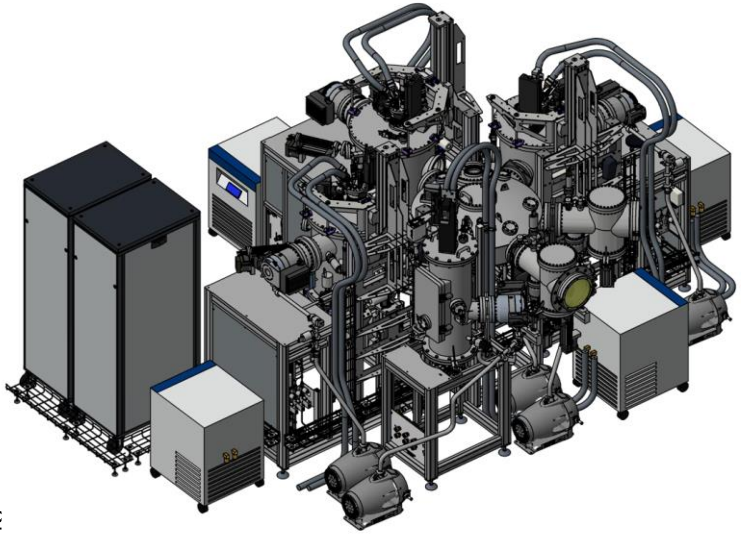
Infrastructure

- Number of pixels for typical experiments of cryogenic detectors is rising ➔ current small-scale university labs can no longer supply the sensors
- Several initiatives (example: HSS at KIT), but also at National Labs are happening, but sensor production currently still a bottleneck
- For supplying large HEP experiments, there needs to be the infrastructure for their production, testing, …

➔ major endeavour



Adapted from Mathias Wegner/Sebastian Kempf

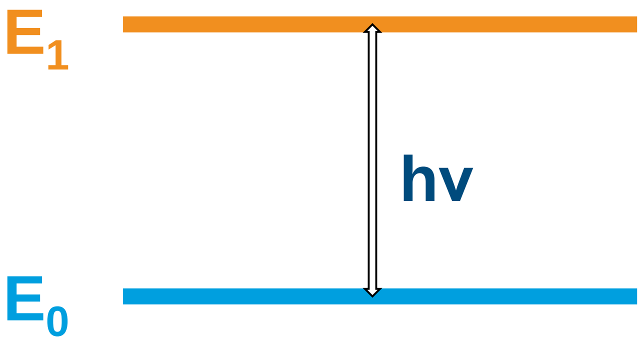


Moving on to Quantum states/systems

„Quantum 2.0“

Subclass:

*“**Quantum 2.0**”: a class of devices that actively create, manipulate and read out quantum states of matter, often using the quantum effects of superposition and entanglement.*

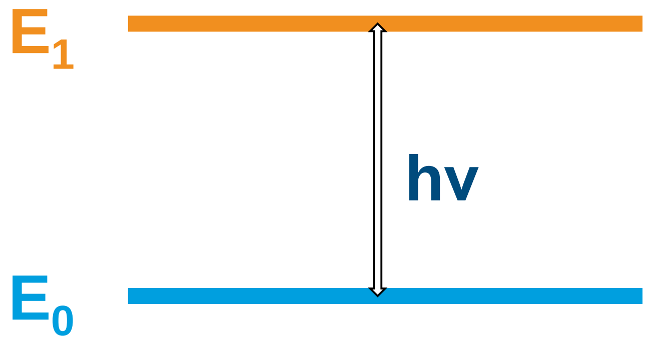


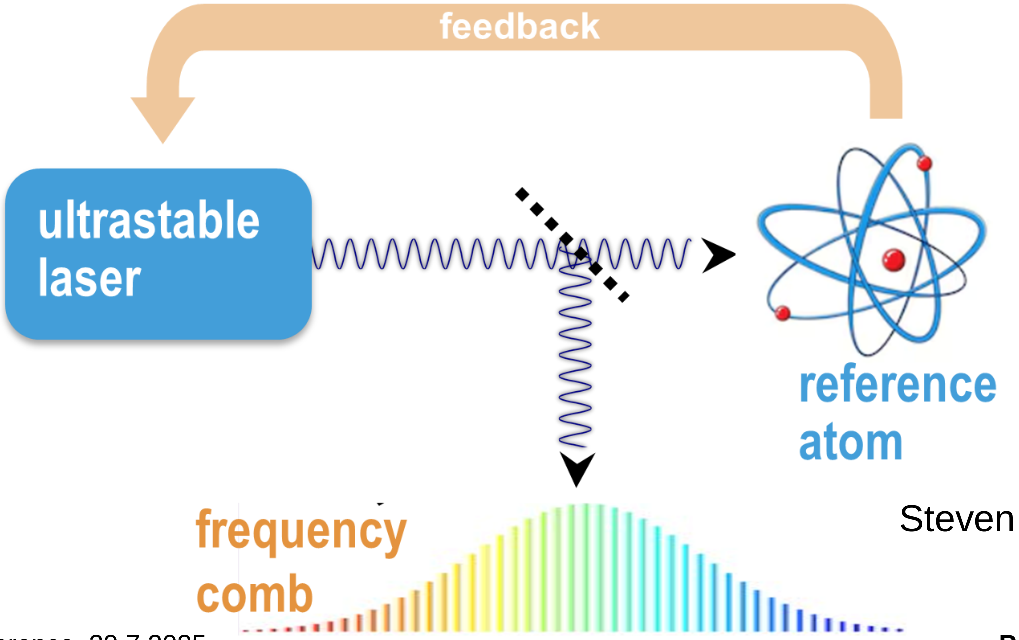
- Need discrete quantum states (e.g. energy levels $|\mathbf{0}\rangle$, $|\mathbf{1}\rangle$)
- Possibility to reset, manipulate and read out
- Sensitivity—something measurably changing
- Can often be enhanced by entanglement and squeezing
- Examples of possible systems:
  - Atomic/Nuclear clocks
  - Optomechanical systems
  - Quantum materials

We can get extremely precise with atomic transitions

Atomic clocks

- Atomic clocks are extremely precise
- Originally: microwaves (Cesium clock)
- Optical clocks are a first step to improve precision
  - Excitation of an atom with a laser ➔ looking for resonance frequency
  - Ultra-stable laser is then locked to atomic transition
  - The resonance frequency is then “counted” with a frequency comb
- Frequency measurement is extremely precise



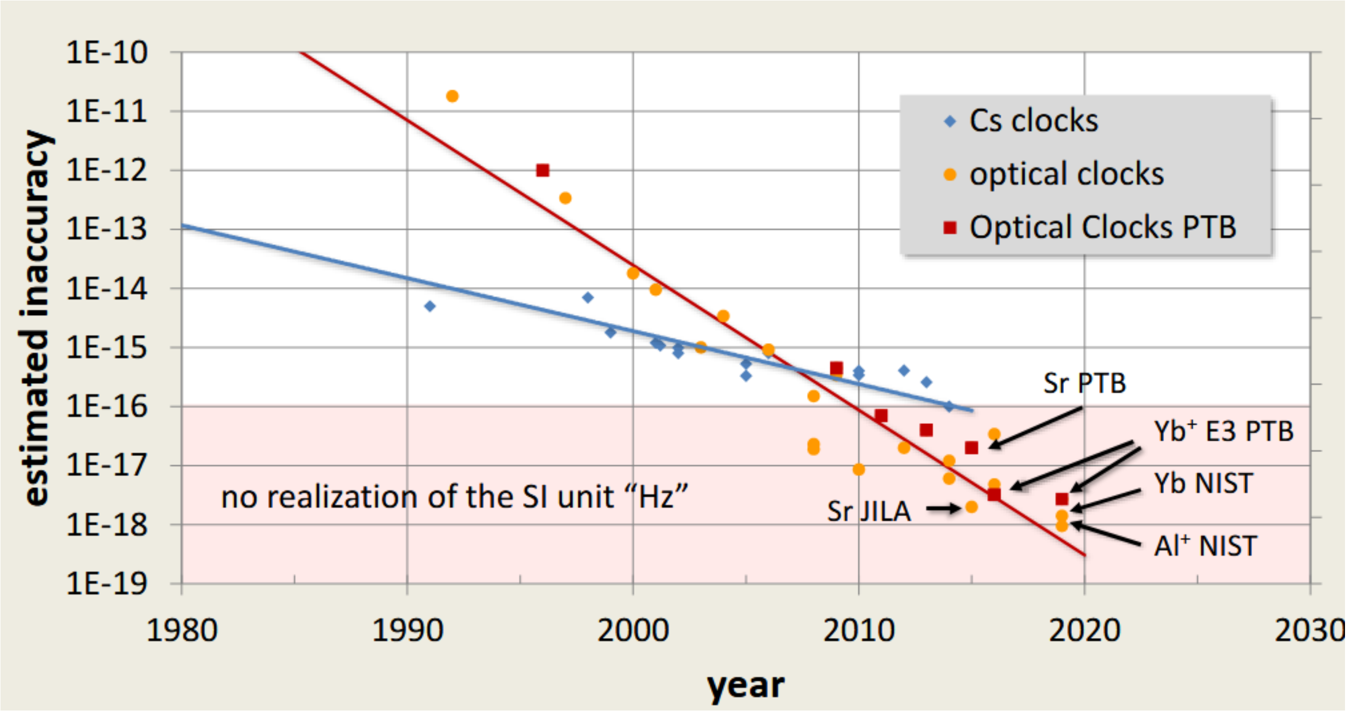


Steven Worm

We can use this high precision

The evolution of atomic clocks

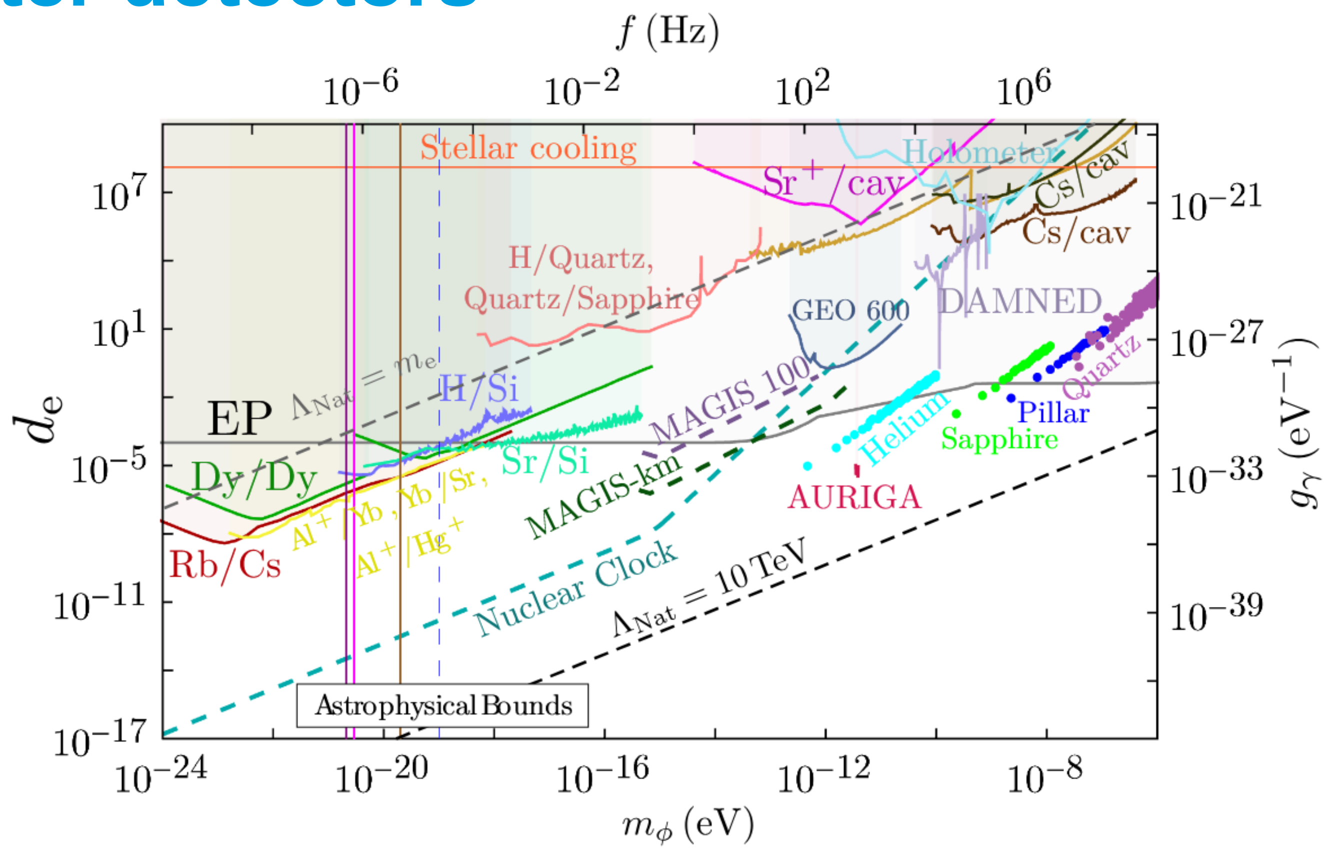
- The precision of optical clocks is continously improving (orders of magnitude)!
  - Present precision about 10^{-18}!
- We can take advantage of their precision as quantum sensors for our purpose
- Clocks are in particular sensitive to variations of fundamental constants and some light dark matter candidates



P.O. Schmidt

Clocks are fabulous dark matter detectors

- Ultralight scalars cause variation of fundamental constants leading to corresponding variation in atomic, molecular, and nuclear spectra ==> clock transition frequencies change!
- As a result, ultralight dark matter can be detected by measuring the time dependence of frequency ratios of two clocks
- Ultralight scalars for mass ranges under 10^{-15} eV can be uniquely probed by clocks.
- Further improcements:
  - Highly charged ions
  - Nuclear clocks



Snowmass 2021 White Paper
New Horizons: Scalar and Vector Ultralight Dark Matter
arXiv:2203.14915v1

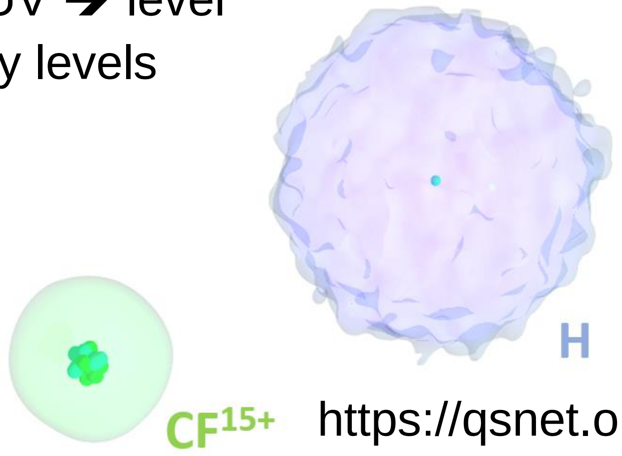
How can we get even more sensitive?

Highly charged ion clocks

- Highly charged ions can also be used for tests of ultralight dark matter
- Main advantage: strong binding energy of the remaining electrons to the nucleus ➔ low sensitivity to external electromagnetic fields
- Strong dependence on fine-structure constant
- Challenge: transitions often in XUV ➔ level crossings with degenerate energy levels

Clock	Kα	Kμ
Yb^{+} (467 nm)	-5.95	0
Sr (698 nm)	0.06	0
Cs (32.6 mm)	2.83	1
CaF (17 μm)	0	0.5
N_2^{+} (2.31 μm)	0	0.5
Cf^{15+} (618 nm)	47	0
Cf^{17+} (485 nm)	-43.5	0

Courtesy of Steven Worm

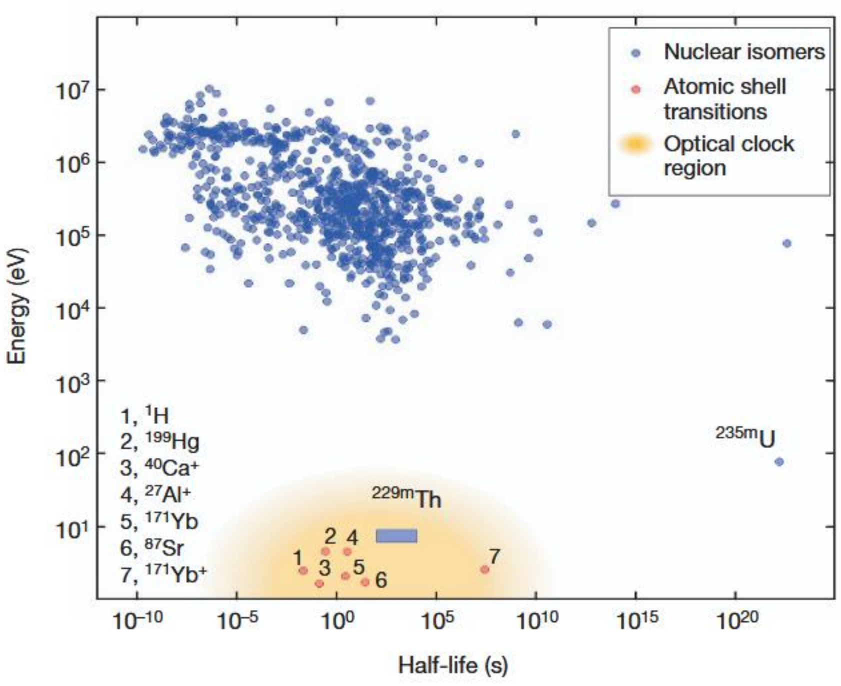


https://qsnet.org.uk/highly-charged-ion-clock/

… and even more sensitive?

The challenge and potential of nuclear clocks

- Nuclear clocks would be a nice (and possibly superior) alternative
- Much higher sensitivities to the variation of the fine structure constant (O(10^4))
- Nuclear clocks are also sensitive to the hadronic sector.
- Problem: Mostly transition in MeV region (not accessible with lasers easily)



v.d. Wende, Nature 533 (2016)

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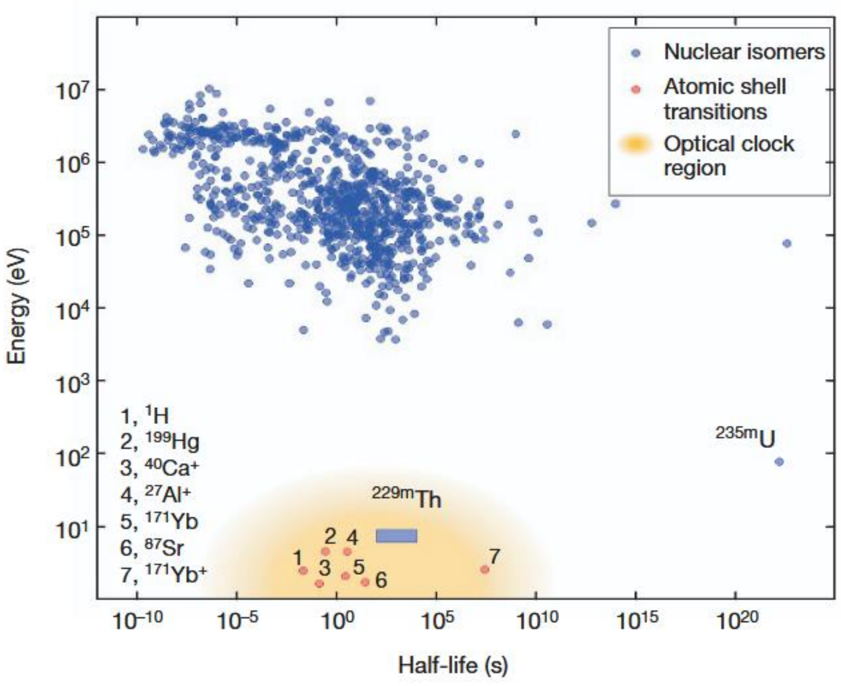
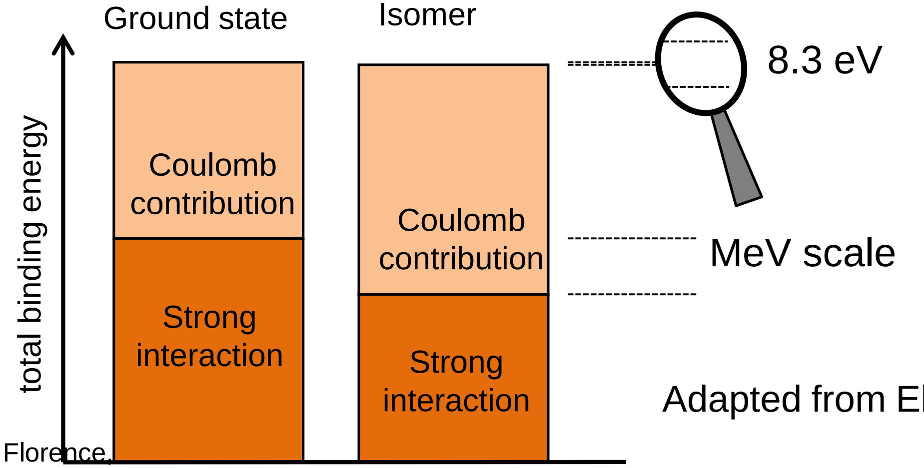
- Much higher sensitivities to the variation of the fine structure constant (O(10^4))
- Nuclear clocks are also sensitive to the hadronic sector.
- Problem: Mostly transition in MeV region (not accessible with lasers easily)
- **One candidate!** Thorium-229
- Laser excitation of Th-229 was recently obtained (*Nature* **volume 533**, pages 47–51 (2016)), first measurements done (*Nature* **volume 633**, pages 63–70 (2024)).



v.d. Wende, Nature 533 (2016)

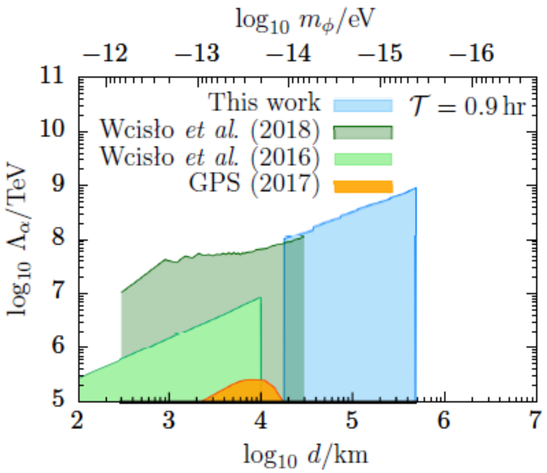


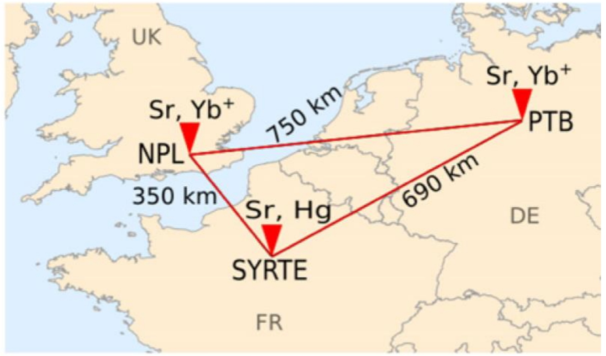
Adapted from Ekkehard Peik

Profiting from cooperation

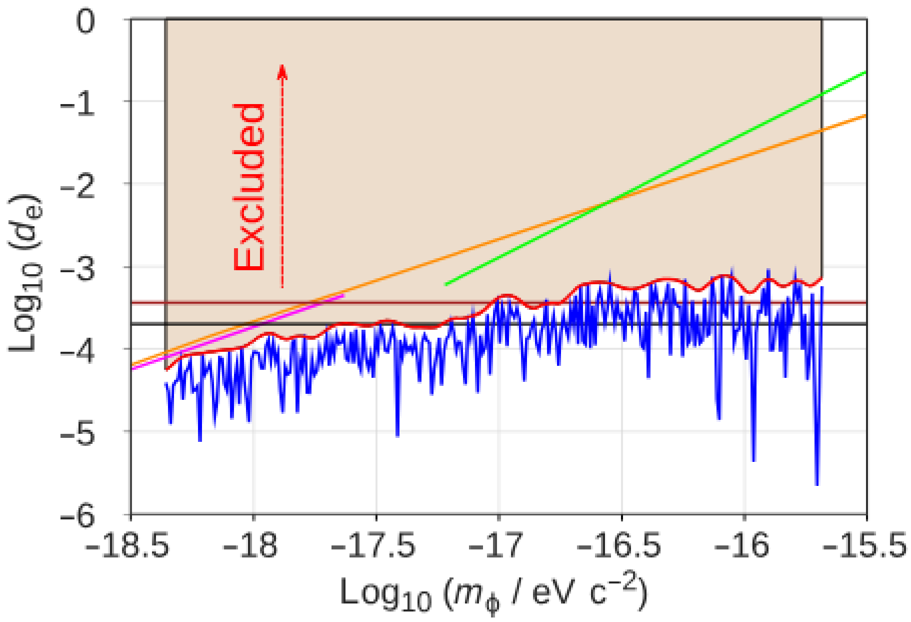
Clock networks

- There is a push for quantum clock networks, which could enhance sensitivity by combining clocks of different types and at different locations
- First activities have started and results published on comparing optical clocks with different sensitivities to variations of α e.g. for DM





B M Roberts et al 2020 New J. Phys. 22 093010

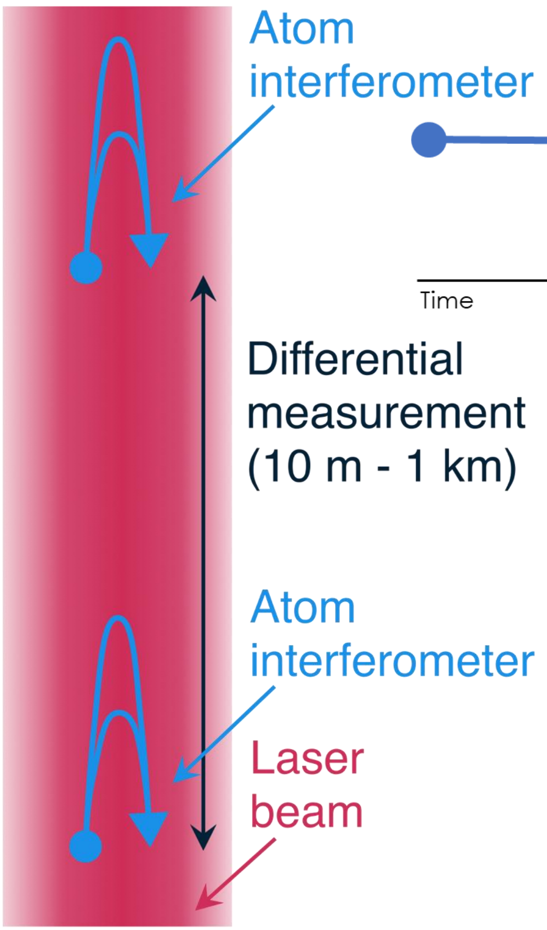


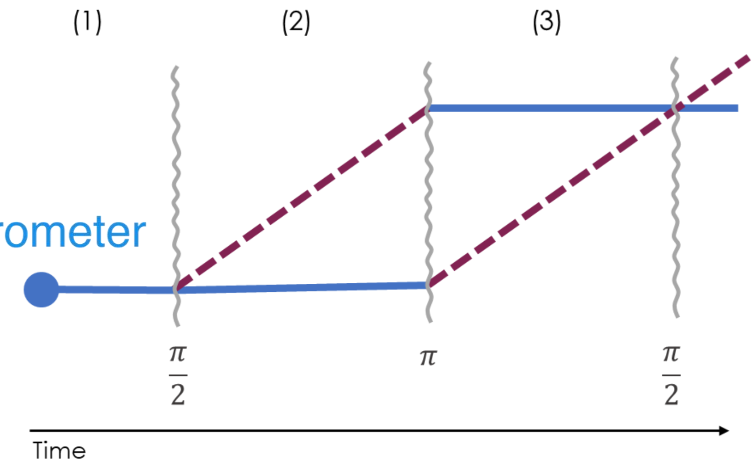
Sci.Adv. 2018 Dec 7;4(12):eaau4869. doi: 10.1126/sciadv.aau4869

Can we interfere matter?

Atom Interferometry

- Laser interferometry is a great tool e.g. for gravitational wave and axion searches
- Atoms have a shorter wavelength ➔ better precision ➔ try to interfere them
- Ultracold atoms are controlled and manipulated using systems of lasers. Differences of atoms with different paths is measured
- Sensitive e.g. to light dark matter, the fine-structure-constant depending on the setup
- **Long-baseline atom interferometry**: atom interferometers separated by baseline (horizontal or vertical), addressed by common laser



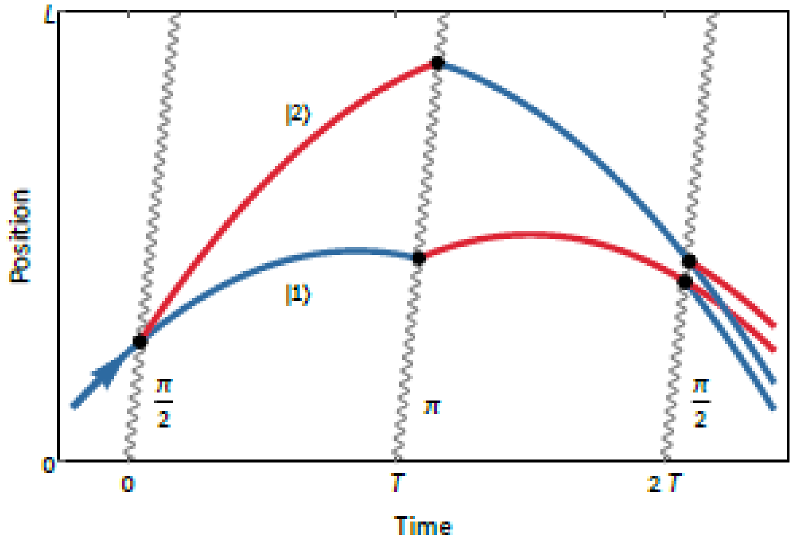


Pictures from Tiffany Harte 22/01/2025, QT4HEP

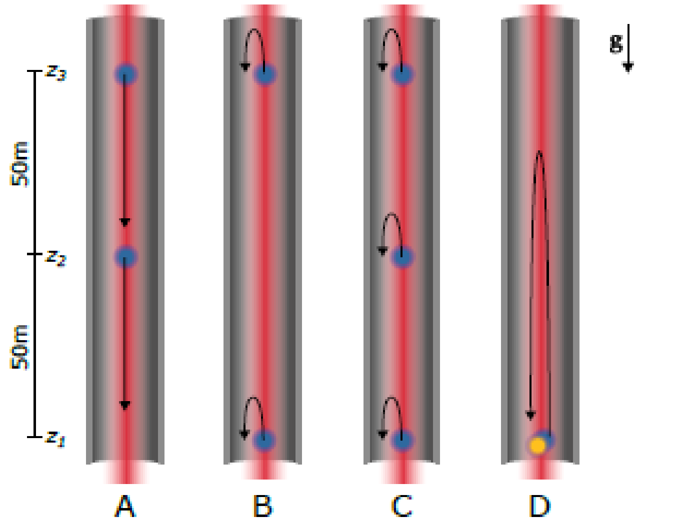
We can look at many questions with a hybrid…

MAGIS 100: Matter wave Atomic Gradiometer Interferometric Sensor

- MAGIS-100 is a hybrid of atom interferometer and atomic clock under construction at Fermilab
- 100-meter baseline
- Several different operation modi
- Ultralight dark matter, gravitational waves, gravity, …
- Smaller prototype for 1 km experiment
- Similar other experiments (AION in UK, MIGA in France, ELGAR in EU, ZAIGA in China …)



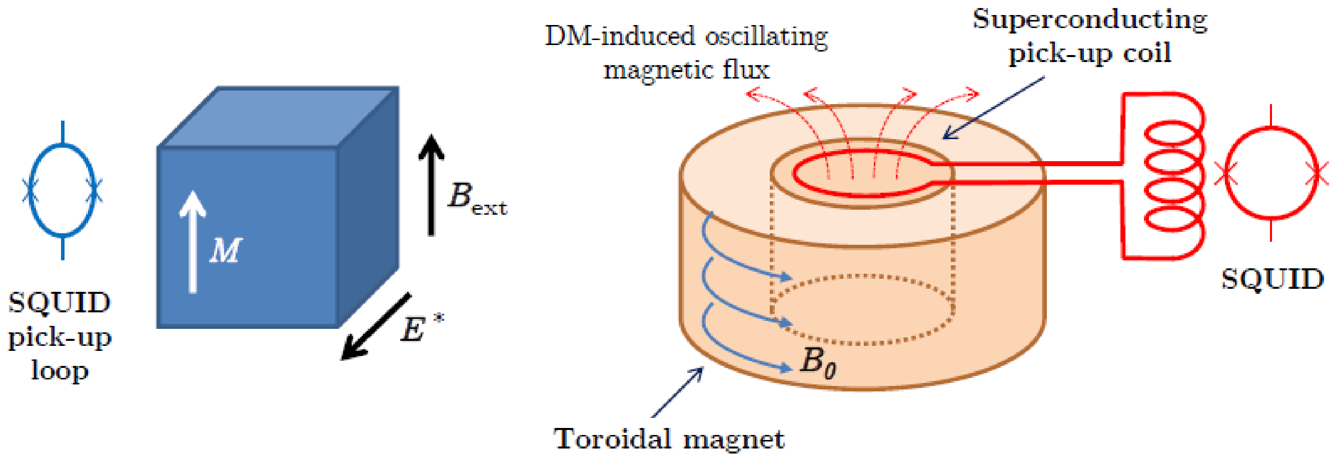
arXiv:2104.02835v1



We can also use quantum to search for EDMs

Nuclear Magnetic Resonance

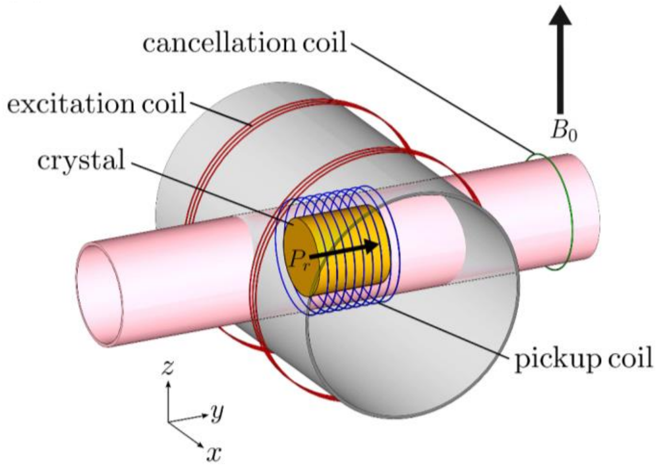
- Axion searches like ALPS, but also other methods (helioscopes and haloscopes) mostly concentrate on the axion/ALP-photon coupling
- The signature coupling of the axion is its axion-nucleon coupling though ➔ CP violation
- Nuclear magnetic resonance (NMR) can be used to search for the electric dipole moment (EDM) interaction of the QCD axion
- The axion field excites an oscillating E field along the field lines of a static toroidal field B. The oscillating E induces an oscillating B field along the symmetric axis read by a pickup coil connected to a SQUID.

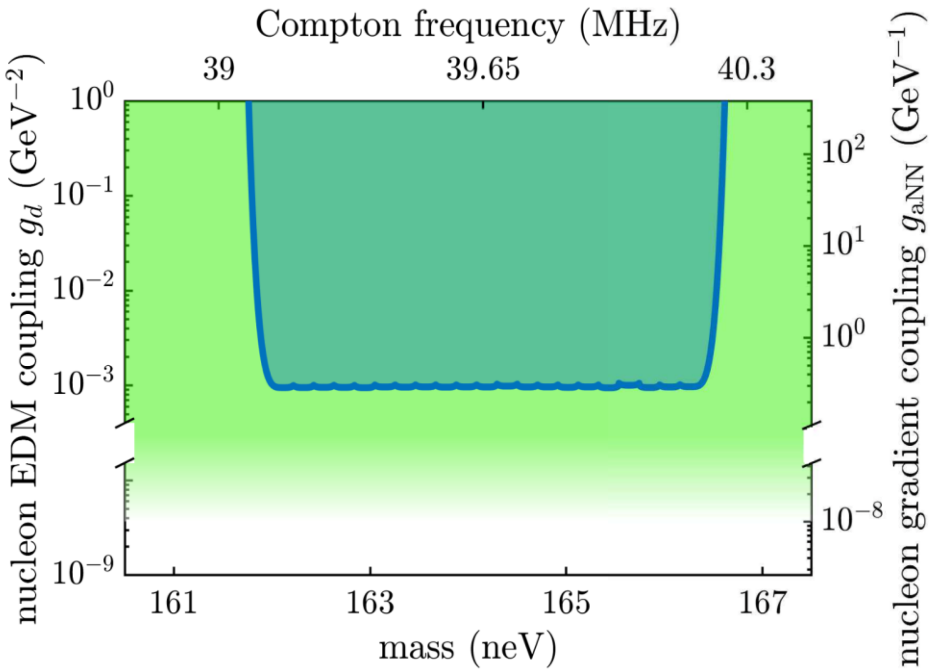


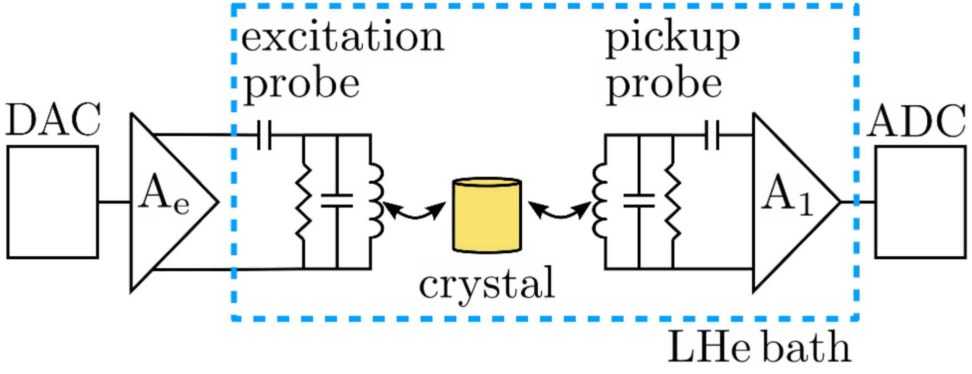
arXiv:1801.08127v2

Cosmic Axion Spin Precession Experiment (CASPEr-e)

- CASPEr-electric is a direct, model-independent search for the EDM interactions of axion-like dark matter➔ QCD axion
- Precision NMR measurement of ^{207}Pb in a polarized ferroelectric crystal
- Proof of feasibility
- Limits for neV DM masses vs EDM coupling
- Limited by the magnet to ≤µeV, need to scan





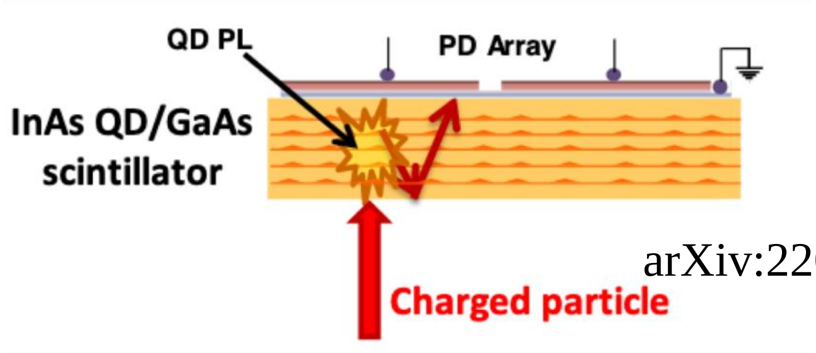


D. Aybas et al., Phys. Rev. Lett. 126, 141802

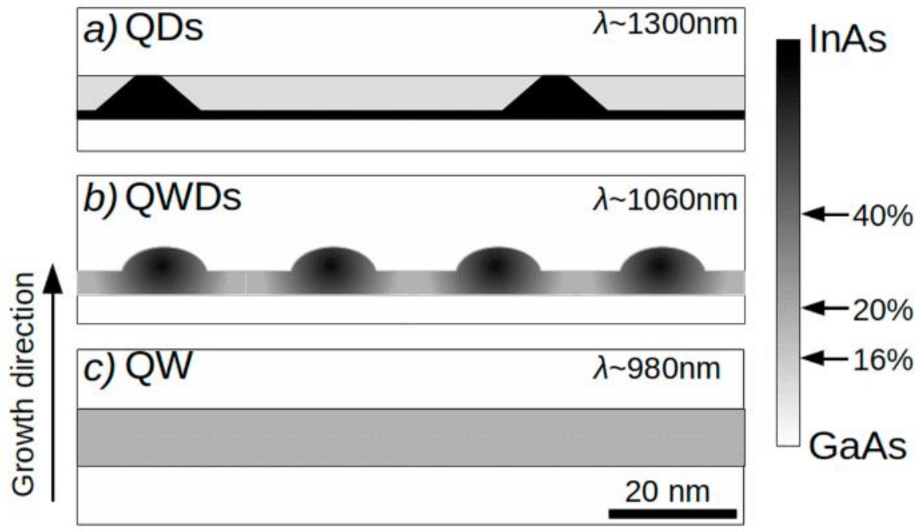
Quantum Systems are interesting

Can we use them in HEP?

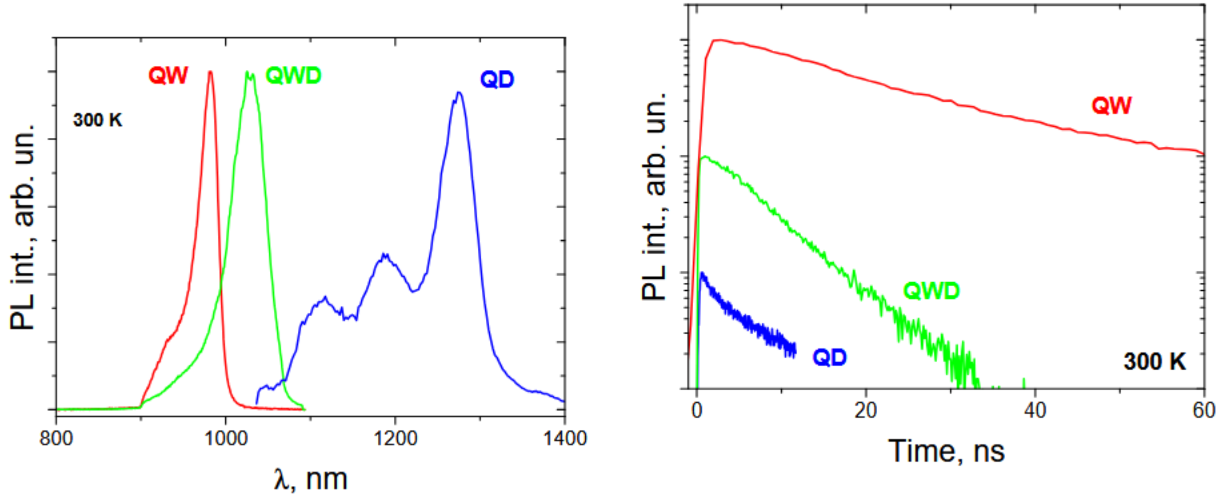
- Quantum confinement leads to size-dependent optical and electrical properties
- With low-dimensional systems like quantum dots, quantum wells etc we can configure different light emission properties
- There could be a multitude of applications in tracking or timing and in calorimetry
- Example: Scintillating Quantum Dots in GaAs for Charged Particle Detection ➔ tracking?



arXiv:2202.11828v1



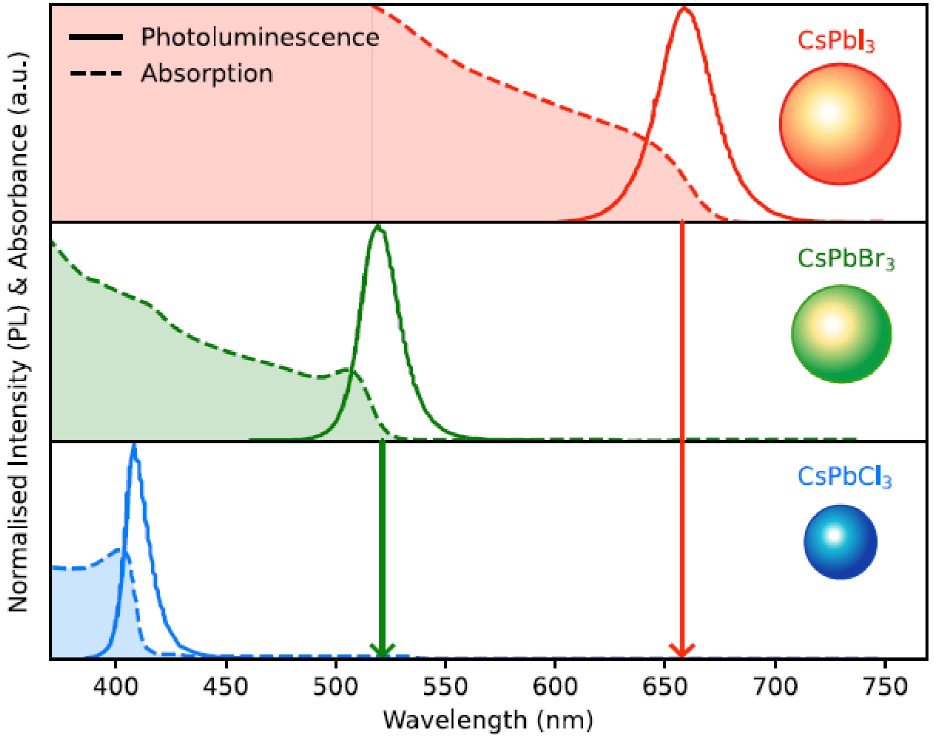
Appl. Sci. 2020, 10, 1038

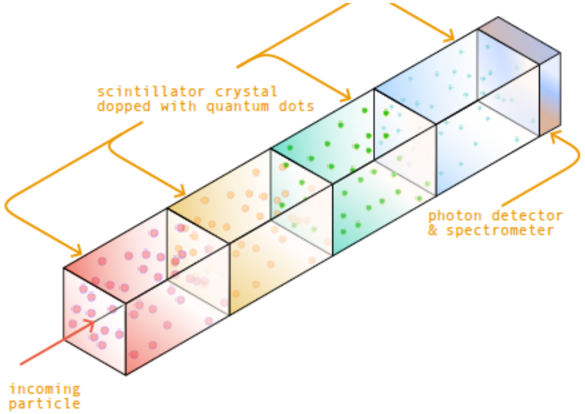


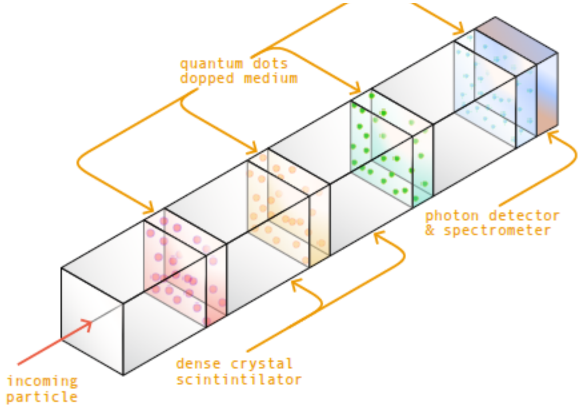
Quantum Dots enable Chromatic Calorimetry

Quantum Dot Calorimeter Concept

- Fully absorbing crystal calorimetry could be enhanced by quantum engineering of materials
- Emission spectra of Quantum Dots are tunable and narrow ➔ Integrating Quantum Dots into traditional homogenous calorimetry?
- Idea: “**Chromatic Calorimetry**”: put quantum dots at different places within the scintillating crystal ➔ Improvement in longitudinal resolution (longer wavelengths in the front, shorter wavelength at the back)
- 20 nm emission bandwidth ➔ up to 20 layers







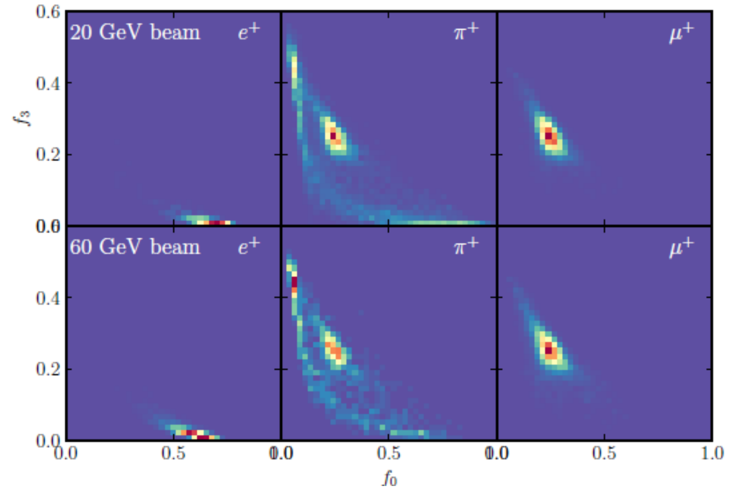
Haddad et al. arXiv:2501.12738v1

Can we simulate and test this concept?

Simulations and particle discrimination for chromatic calorimetry

Haddad et al. arXiv:2501.12738v1

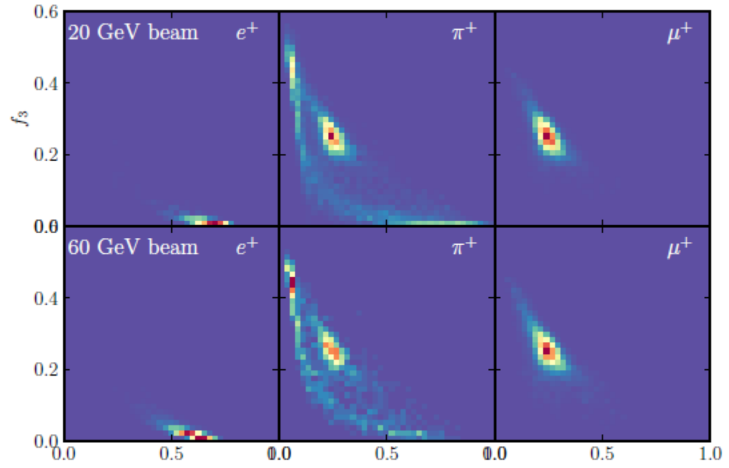
- Simulations with GEANT 4 show promises of using Quantum Dot Calorimeters for enhanced particle identification.



Can we simulate and test this concept?

Simulations and particle discrimination for chromatic calorimetry

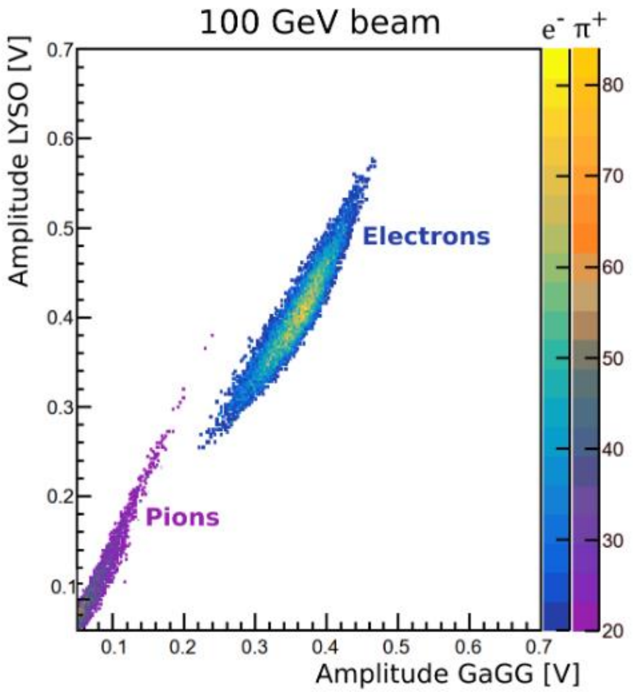
Haddad et al. arXiv:2501.12738v1



- Simulations with GEANT 4 show promises of using Quantum Dot Calorimeters for enhanced particle identification.

- Experimental proof-of-concept for chromatic calorimetry (100 GeV beam, 86% electron/pion discrimination).

- Many experimental challenges remaining as well as experimental validation of a quantum dot calorimeter.

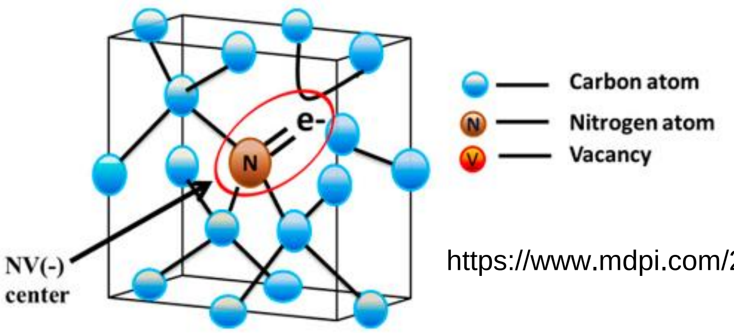


Arora et al. arXiv:2501.08483v1

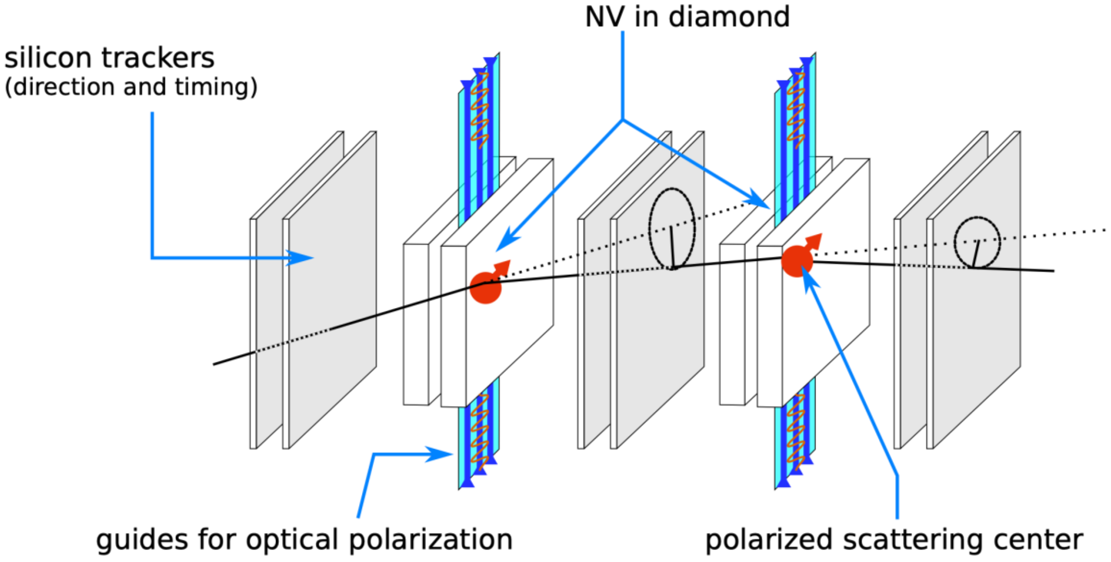
We could use quantum for polarimetry in tracking

NV Centers in Diamond Arrays

- Nitrogen-Vacancy (NV) defect in diamond: spin state can be optically prepared and be read out using the photoluminescence properties of the crystal.



https://www.mdpi.com/2504-4494/1/1/6



Front. Phys. 10:887738

- Idea: Include thin polarized layers within trackers
  - Charged particles undergoing elastic scattering with the polarized centers will have a small anisotropy in the left-right scattering direction.
- Aim: access to determining single particle spin orientations

Summary

Focusing on light dark matter etc

- There is an abundance of definitions of „Quantum Sensing“
- Within particle physics most obvious applications for quantum sensing are dark matter, axions, neutrinos
- Quantum sensing technologies are already applied in dark matter searches etc where they open up new possibilities
  - Going to much lower energies
  - Low noise, dark counts
  - Superior energy resolution
- Examples for important technologies are
  - Cryogenic detectors
  - Clocks
  - Atom interferometry
- Many results out there already, more to come!

Outlook for next generation colliders

- Quantum Sensing is interesting for „classical“ HEP as well
  - Possible applications in tracking and calorimetry
- Cryogenic detectors, in particular SNSPDs could be interesting for future tracking due to ps time resolution
- Quantum systems, in particular Quantum dots have been investigated as part of calorimeters and show promise
- Much potential still for R&D and addressing challenges
- Combination of HEP and quantum technologies can be very fruitful
- All in all: Exciting possibilities are on the horizon