“Superconducting devices as particle detectors”

(focusing only on quantum sensors)

M. Doser, CERN

30 minutes

PBC, Sept. 2024

(low energy) particle detectors:

quantum sensors register a change of quantum state caused by the interaction with an external system:

- transition between superconducting and normal-conducting
- transition of an atom from one state to another
- change of resonant frequency of a system (quantized)

} highly sensitive and highly specific sensors for minute perturbations of the environment in which they operate

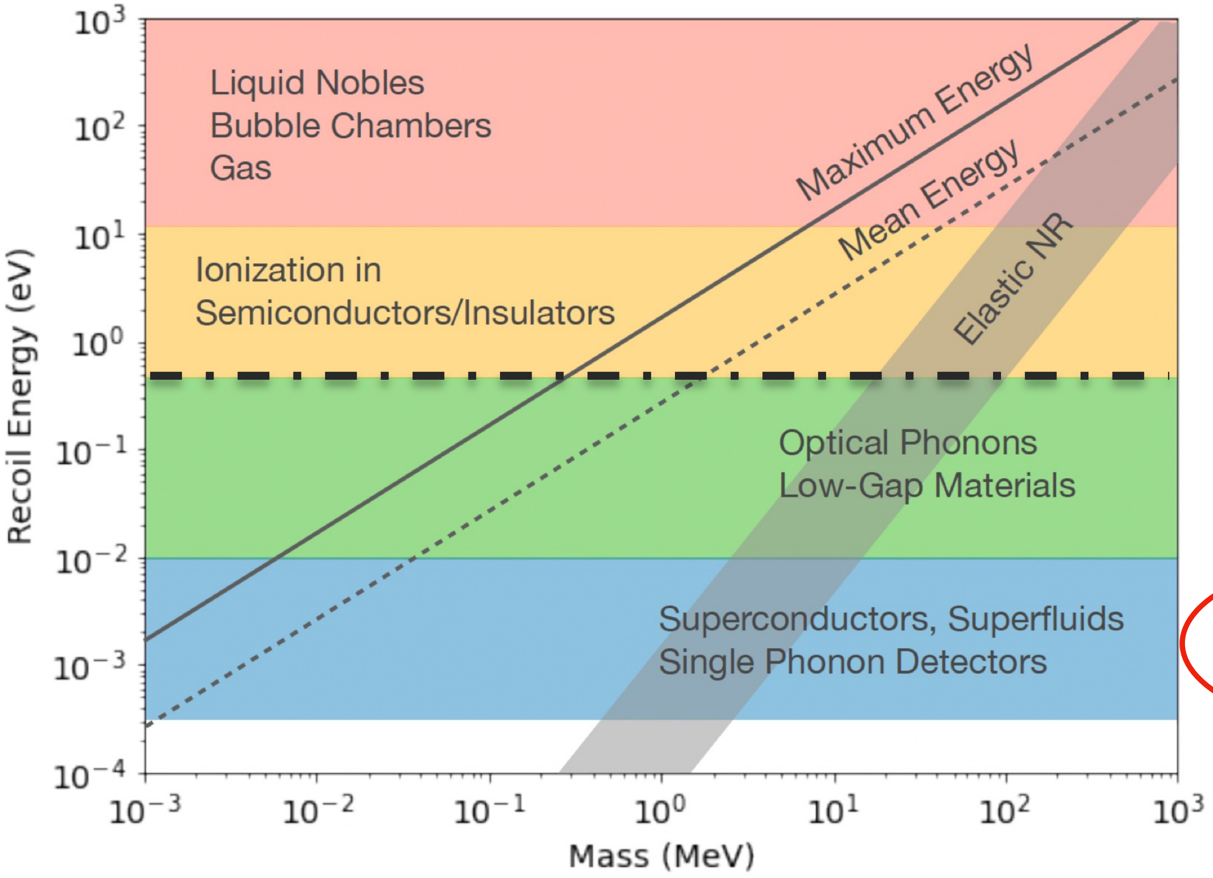
Then, a "quantum sensor" is a device, the measurement (sensing) capabilities of which are enabled by our ability to manipulate and/or read out its quantum states.

and because the commensurate energies are very low, unsurprisingly, quantum sensors are ideally matched to low energy (particle) physics; nevertheless, they can also form natural elements of HEP detectors

→ touch upon both

(I will *not* however be talking about entanglement and its potential applications)

Start with an example: Energy deposited in detectors by particles



Daniel Baxter I IDM 2024 Essig et al, Snowmass CF1 WP2 (2022) [arXiv:2203.08297]

$\Delta E \sim 1$ eV
e.g. Si, Ge, GaAs, diamond, Quantum Dots, organic scintillators…

$\Delta E \sim 10 - 100$ meV
e.g. GaAs, sapphire, Dirac materials, doped s/c, …

$\Delta E \sim 1$ meV
e.g. superfluids, superconductors

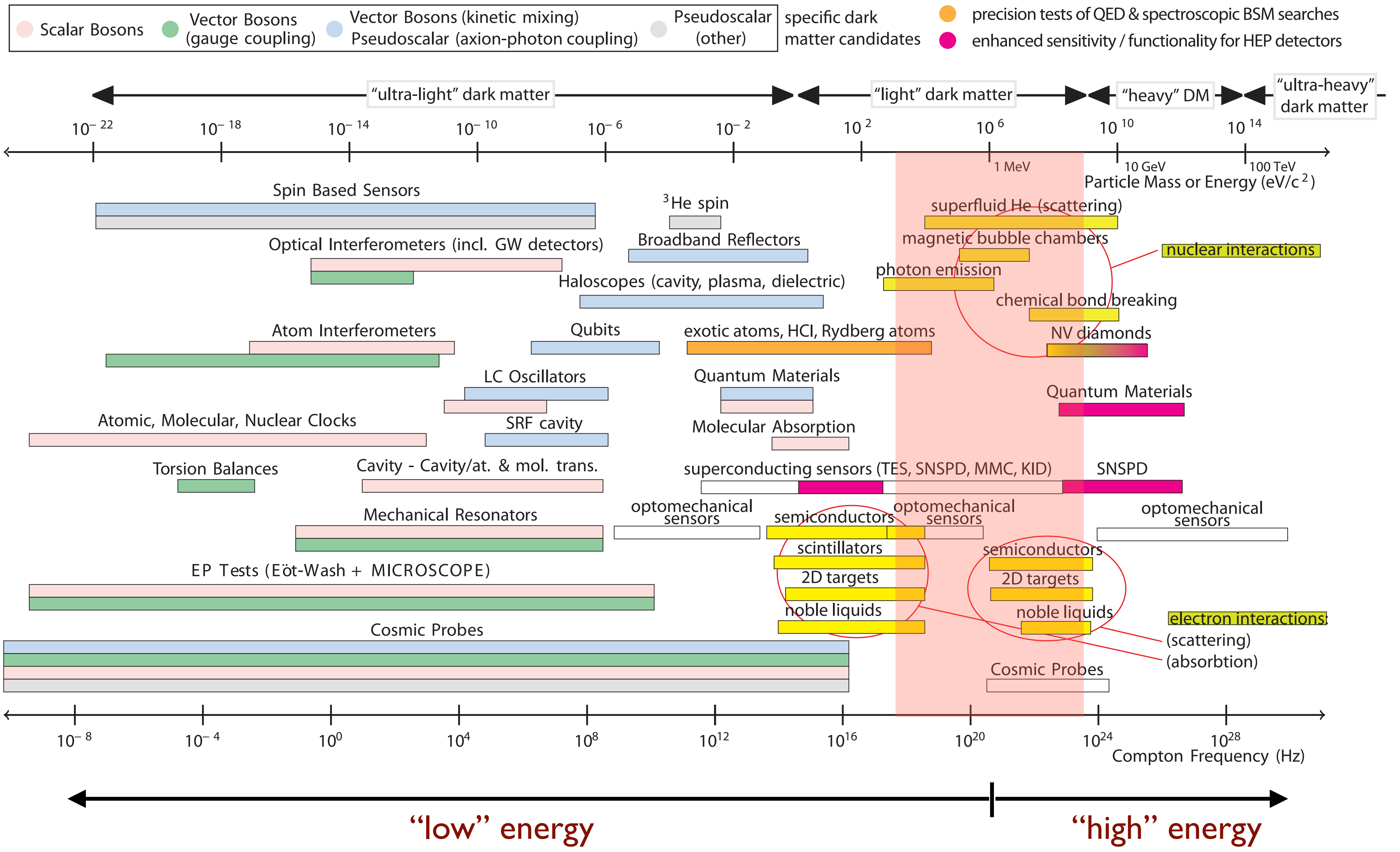
What's the goal? mip detection? or minute, sub-mip energy deposits?

Very low bandgap materials required to be sensitive to tiny energy deposits: milli-charged particles, nuclear recoil from very light DM, IR photons, precise photon #

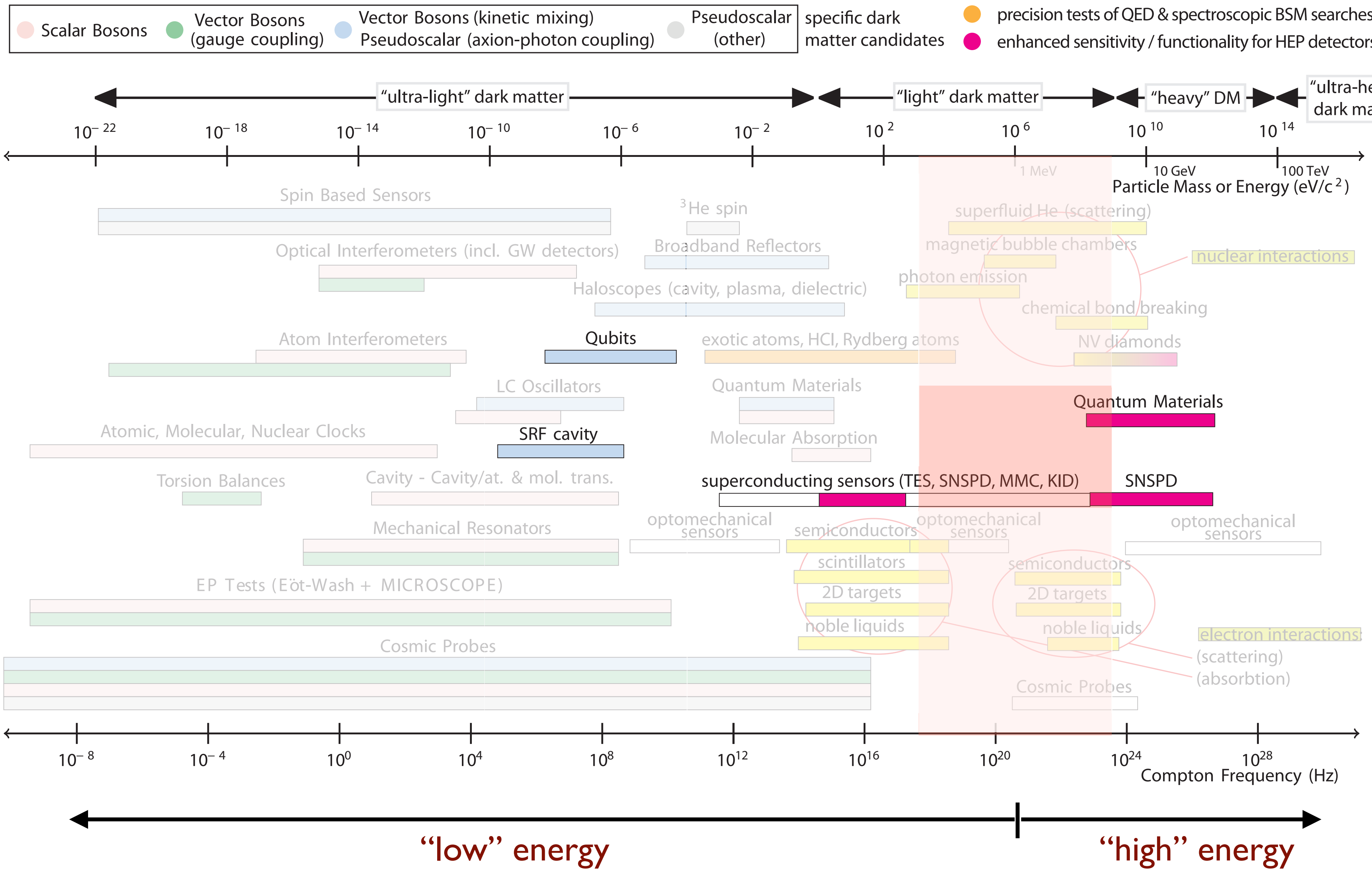
For much higher (or lower) particle masses (or better, very weak fields), other quantum sensing technologies are more appropriate:

quantum sensing & particle physics

Ranges of applicability of different quantum sensor techniques to searches for BSM physics



Ranges of applicability of different quantum sensor techniques to searches for BSM physics



quantum sensors & particle physics: what are we talking about?

quantum technologies

① superconducting devices (TES, SNSPD, …) / cryo-electronics

② spin-based, NV-diamonds

③ optical clocks

④ ionic / atomic / molecular

⑤ optomechanical sensors

⑥ metamaterials, 0/1/2-D materials

domains of physics

search for NP / BSM

Axions, ALP's, DM & non-DM UL-particle searches

tests of QM wavefunction collapse, decoherence

EDM searches & tests of fundamental symmetries

Development of new detectors

→ ECFA Detector R&D Roadmap Symposium of Task Force 5 Quantum and Emerging Technologies
https://indico.cern.ch/event/999818/

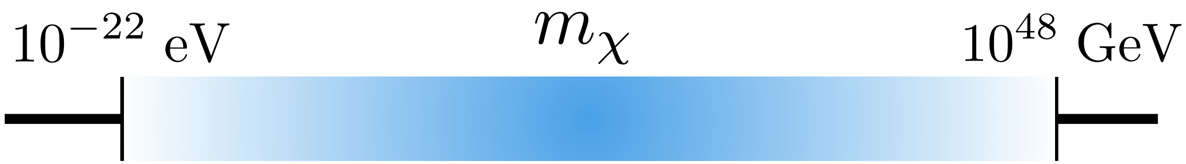
A *ridiculously* rapid overview of a selection of particle physics enabled by SC Quantum Sensors

- RF cavities, cryodetectors (DM searches)
- field sensors (DM searches)
- exotic systems (QED, BSM, gravity, symmetries, DM)

These and many others are covered here → Marianna S Safronova and Dmitry Budker 2021 *Quantum Sci. Technol.* **6** 040401

Superconducting sensors: RF cavities

Axions, ALP's, DM & non-DM UL-particle searches

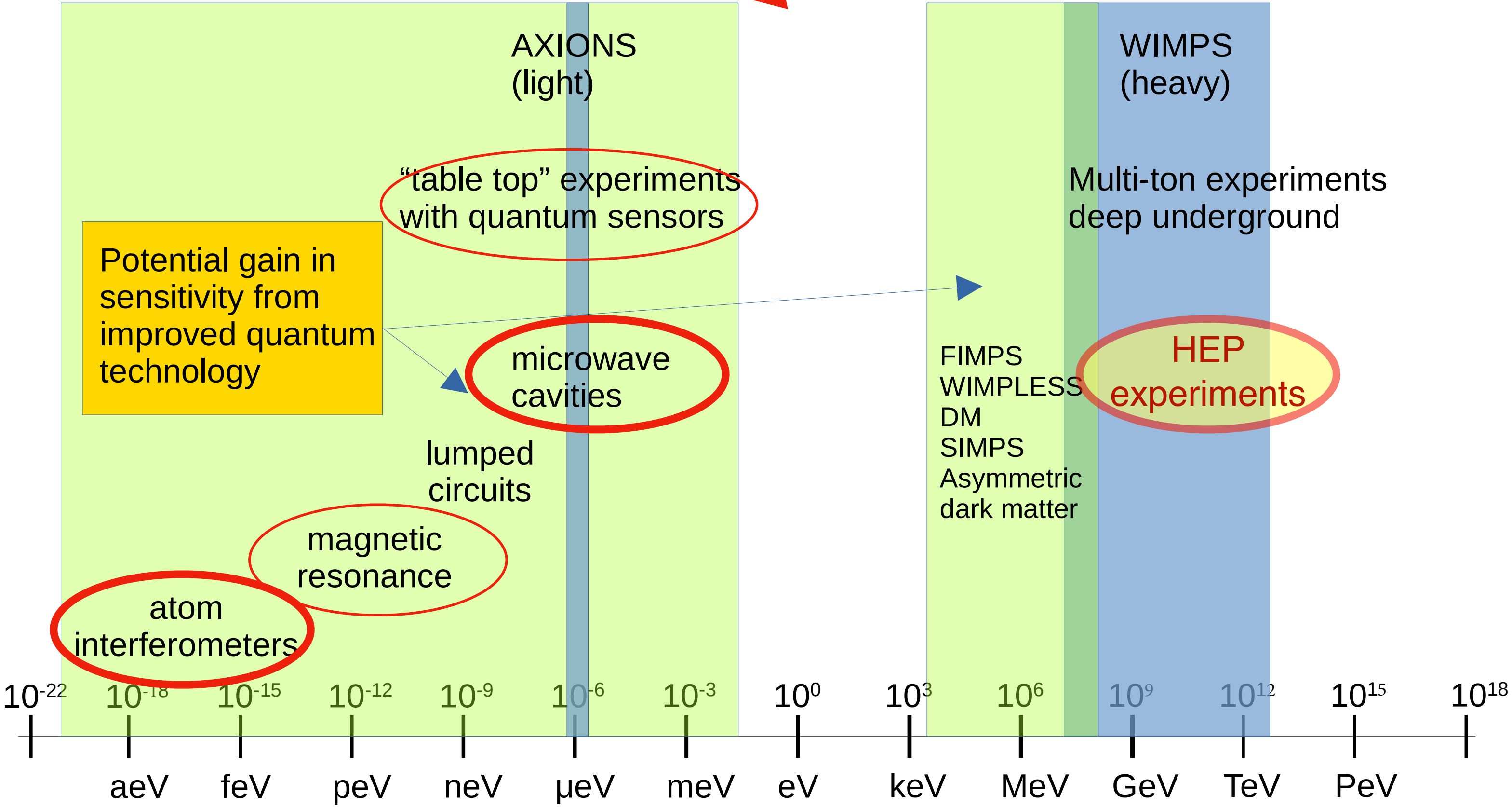


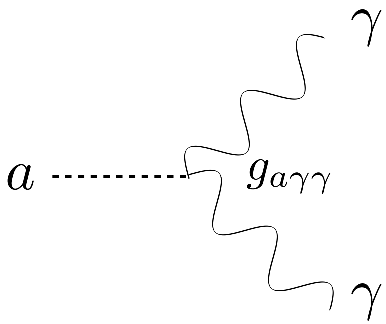
cavity size = axion size

axion mass = unknown

$$F \sim g_{a\gamma}^2 m_A^2 \boxed{B^4}\,\boxed{V^2}\,\boxed{T_{sys}^{-2}}\,G^4 \boxed{Q},$$

system noise temperature
cryo-amplifiers JJPA



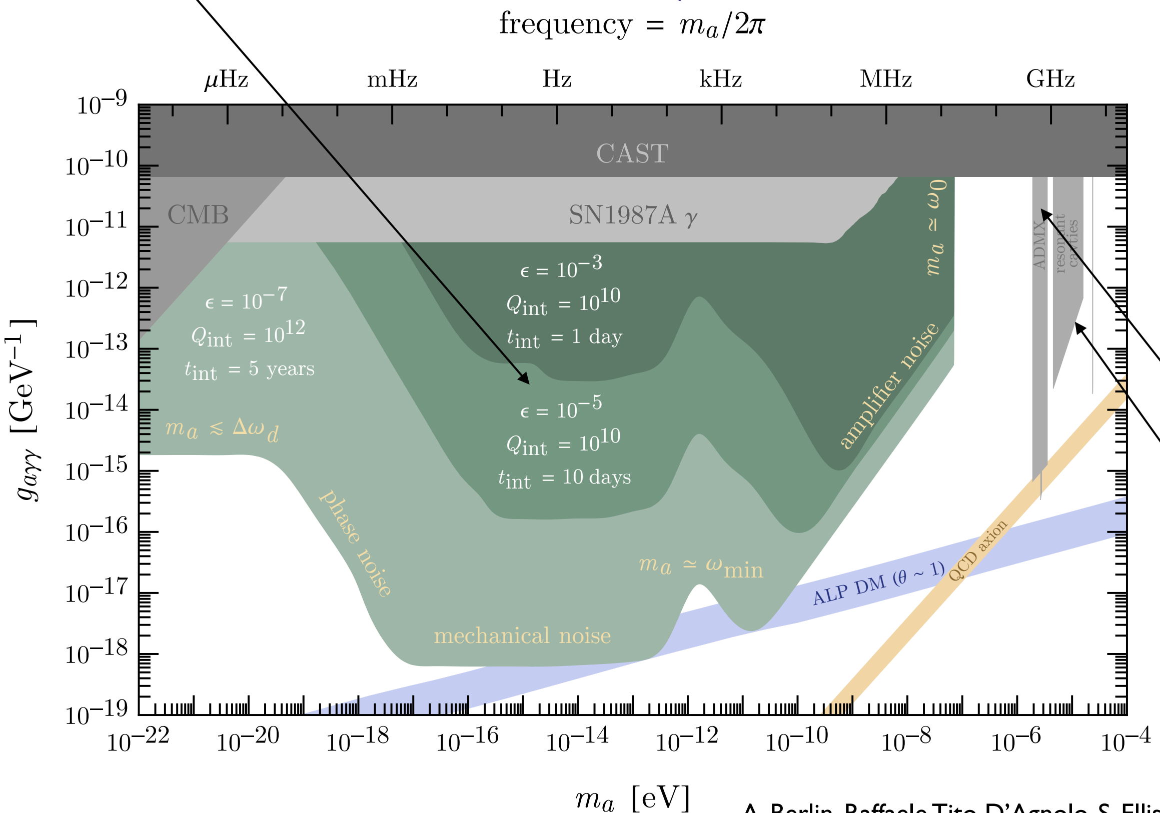


(but not only…)

Axion heterodyne detection

$Q_{int} \gtrsim 10^{10}$ achieved by DarkSRF collaboration
(sub-nm cavity wall displacements)

A. Grassellino, "SRF-based dark matter search: Experiment," 2019. https://indico.fnal.gov/event/19433/session/2/ contribution/2/material/slides/0.pdf



ADMX experiment

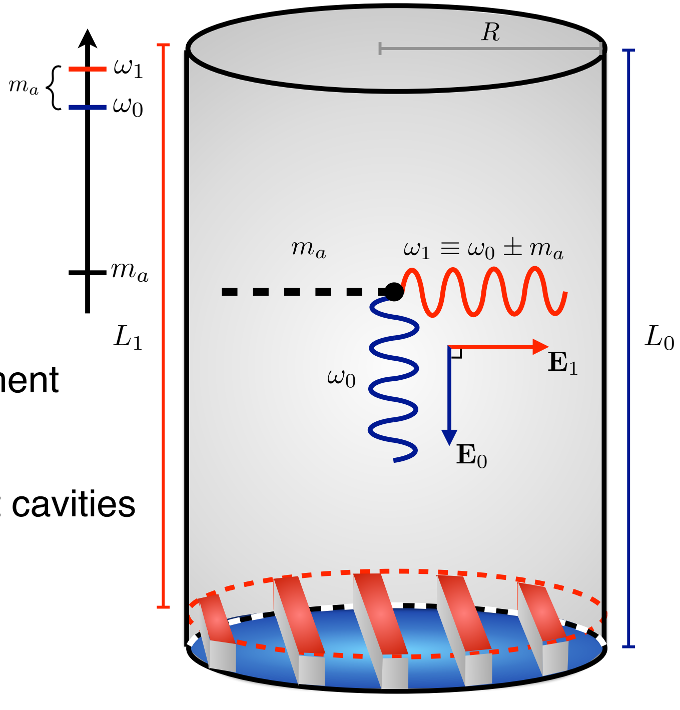
resonant cavities

problem: cavity resonance generally fixed

Resonant cavities possible down to μeV;
below that, need huge volume

driving "pump mode" at $\omega_0 \sim$ GHz allows axion to resonantly drive power into "signal mode" at $\omega_1 \sim \omega_0 \pm m_a$

solution for tuning: mechanical deformation; field tuning (SRF)



(a) Cartoon of cavity setup.

Conceptual Theory Level Proposal:

A. Berlin, Raffaele Tito D'Agnolo, S. Ellis, C. Nantista, J. Nielson, P. Schuster, S. Tantawi, N. Toro, K. Zhou, *JHEP* 07 (2020) 07, 088

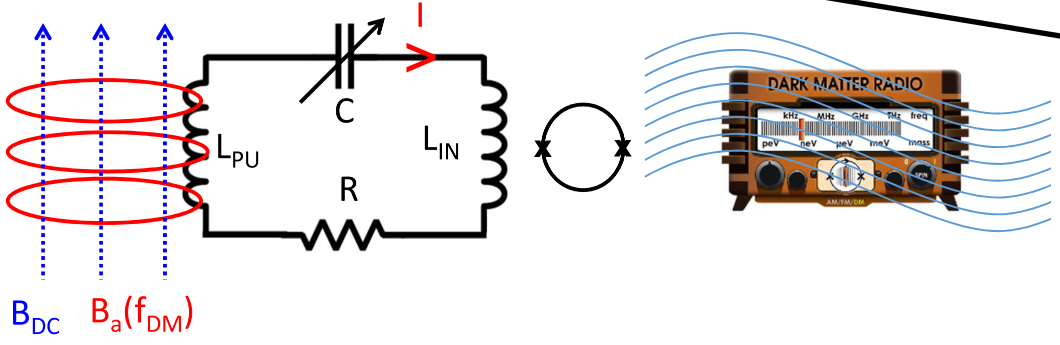
Asher Berlin, Raffaele Tito D'Agnolo, Sebastian A. R. Ellis, Christopher Nantista, Jeffrey Neilson, Philip Schuster, Sami Tantawi, Natalia Toro, Kevin Zhou, https://arxiv.org/abs/1912.11048

"The cavity is designed to have two nearly degenerate resonant modes at ω_0 and $\omega_1 = \omega_0 + m_a$. One possibility is to split the frequencies of the two polarizations of a hybrid HE_{11p} mode in a corrugated cylindrical cavity. These two polarizations effectively see distinct cavity lengths, L_0 and L_1, allowing ω_0 and ω_1 to be tuned independently."

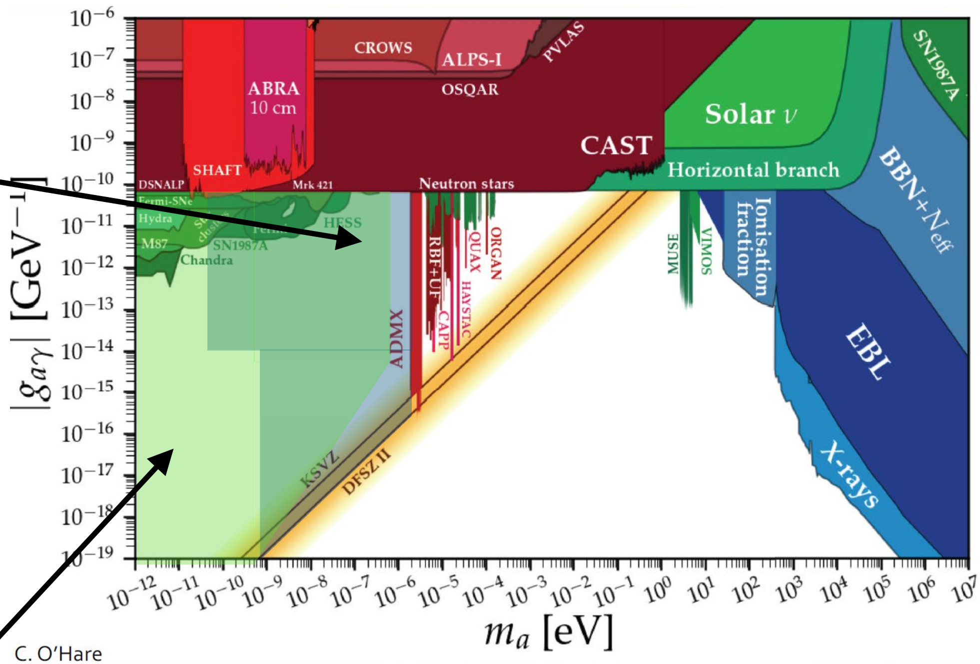
Focus on detecting not a particle (a photon), but a field

Quantum sensors for DM searches: field-sensitive devices

DMRadio



- Axion field converts to oscillating EM signal in background DC magnetic field
- Detect using tunable resonator
- Signal enhancement when resonance frequency matches rest-mass frequency $\nu_{DM}=mc^2/h$
- SQUID's, RF Quantum upconverters, cryoamplifiers



C. O'Hare

CASPEr electric NMR (Gen. 3)

Axion-like dark matter can exert an oscillating torque on ^{207}Pb nuclear spins via the electric dipole moment coupling g_d or via the gradient coupling g_{aNN}.

Cosmic Axion Spin Precession Experiment is based on a precision measurement of ^{207}Pb solid-state nuclear magnetic resonance in a polarized ferroelectric crystal.

→ spin $\boldsymbol{\sigma}$ to axion coupling:

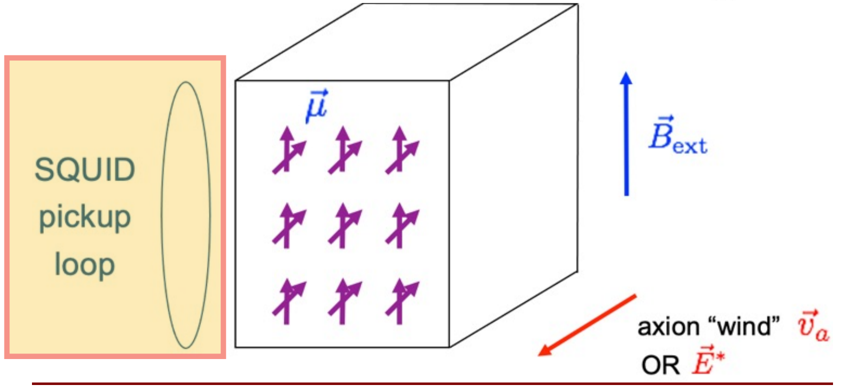
$$\boxed{H_e \propto a\boldsymbol{\sigma}\cdot\boldsymbol{E}^*}$$

CASPEr-electric

→ spin $\boldsymbol{\sigma}$ to axion gradient coupling:

$$\boxed{H_g \propto \boldsymbol{\sigma}\cdot\boldsymbol{\nabla}a}$$

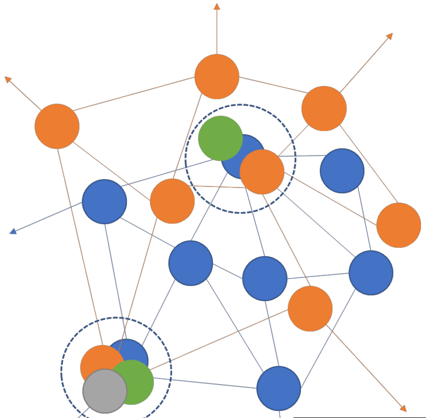
CASPEr-gradient

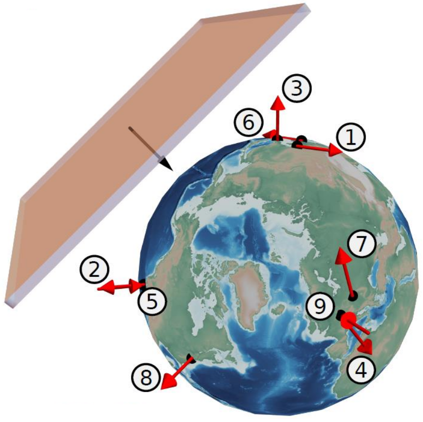


ECFA Detector R&D Roadmap Symposium of Task Force 5 Quantum and Emerging Technologies

https://indico.cern.ch/event/999818/ Kent Irwin (Stanford University), Dima Budker (Mainz University)

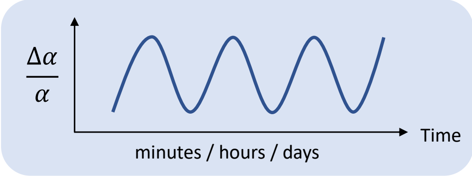
search for NP / BSM





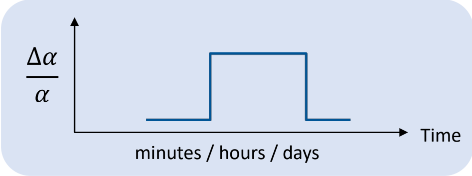
networks of sensors

- Oscillations



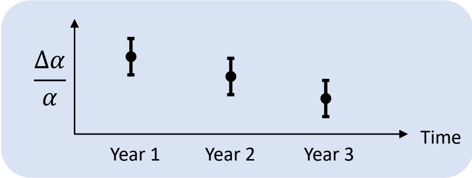
→ Very light DM

- Fast transients



→ DM- topological defects

- Slow drifts



→ New physics

magnetometers

Afach et al, arXiv:2102.13379v2

atomic clocks nuclear, HCI, molecules

Wcislo et al, Sci. Adv. 4, 4869 (2018)

optical fiber networks

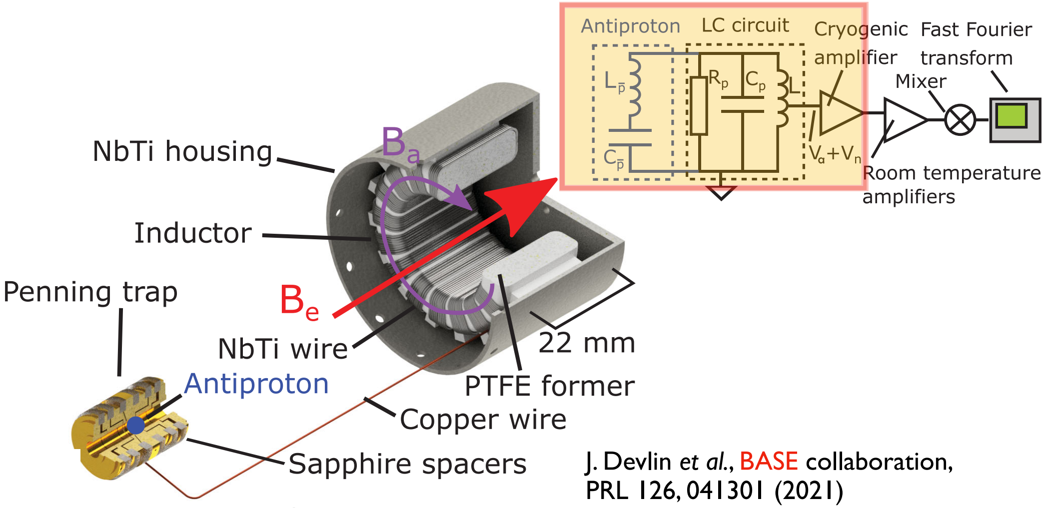
Roberts et al, New J. Phys. 22, 093010 (2020)

Investigate very light scalar and pseudo-scalar DM candidates over ~10 orders of magnitude in mass and different couplings

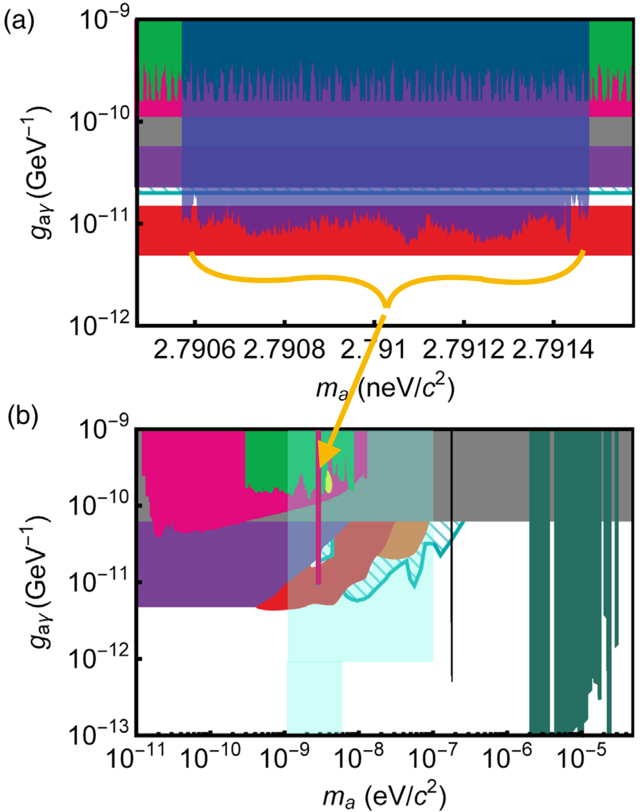
→ ECFA Detector R&D Roadmap Symposium of Task Force 5 Quantum and Emerging Technologies
https://indico.cern.ch/event/999818/ Giovanni Barontini (Birmingham)

Tests of QED, searches for BSM, probes of fundamental symmetries with trapped ions

Trapped $\bar{p}$: symmetry tests, DM searches



J. Devlin *et al.*, BASE collaboration, PRL 126, 041301 (2021)

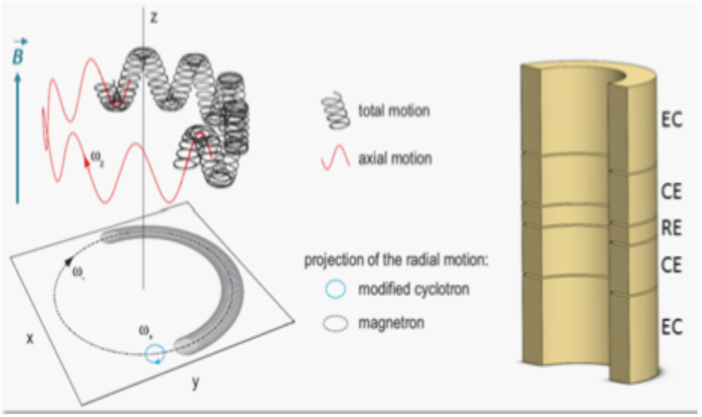


Trapped ions: tests of QED, symmetry tests, DM searches

HCIs: much larger sensitivity to variation of α and for dark matter searches than current clocks

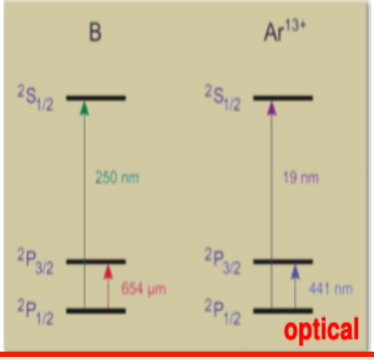
- Searches for the variation of fundamental constants
- Tests of QED: precision spectroscopy
- Fifth force searches: precision measurements of isotope shifts with HCIs to study non-linearity of the King plot

Review on HCIs for optical clocks: Kozlov *et al.*, Rev. Mod. Phy. **90**, 045005 (2018)



Scaling with a nuclear charge Z

Binding energy ~ Z^2
Hyperfine splitting ~ Z^3
QED effects ~ Z^4
Stark shifts ~ Z^{-6}



Fluorescence spectroscopy in exotic atoms (incl. HCI's)

Metamaterials, 0 / 1 / 2-dimensional materials

quantum dots for calorimetry	chromatic calorimetry
quantum dots for tracking	chromatic tracking

Atoms, molecules, ions

quantum-boosted dE/dx	Rydberg TPC's

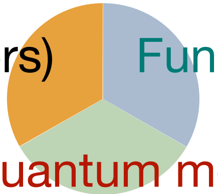
Spin-based sensors

quantum-polarized helicity detection	helicity detectors

Superconducting sensors

microcalorimeters	X-ray spectroscopy
quantum pixel ultra-sensitive tracking	milli-charge trackers

Potential HEP impact



Applied (detectors)

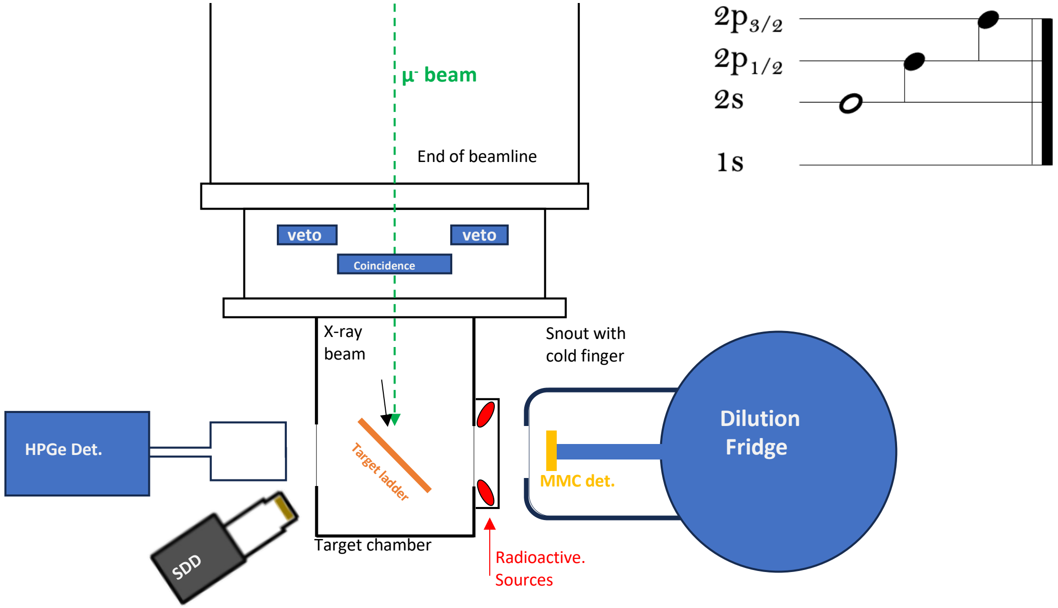
Fundamental physics

Improved quantum measurements

HEP function Work package	Tracking	Calorimetry	Timing	PID	Helicity
WP 1 (Quantum systems in traps and beam)	Rydberg TPC	BEC WIMP scattering (recoil)	O(fs) reference clock for time-sensitive synchronization (photon TOF)	Rydberg dE/dx amplifiers	
WP2 (Quantum materials: 0-, 1- and 2-D)	"DotPix"; improved GEM's; chromatic tracking (sub-pixel); active scintillators	Chromatic calorimetry	Suspended / embedded quantum dot scintillators	Photonic dE/dx through suspended quantum dots in TPC	
WP 3 (Superconducting quantum devices)	O(ps) SNSPD trackers for diffractive scattering (Roman pot)	FIR, UV & x-ray calorimetry	O(ps) high Tc SNSPD	Milli- & microcharged particle trackers in beam dumps	
WP 4 (scaled-up bulk systems for mip's)	Multi-mode trackers (electrons, photons)	Multi-mode calorimeters (electrons, photons, phonons)	Wavefront detection (e.g. O(ps) embedded devices)		Helicity detector via ultra-thin NV optically polarized scattering / tracking stack
WP 5 (Quantum techniques)				Many-to-one entanglement detection of interaction	
WP 6 (capacity building)	Technical expertise of future workforce (detector construction); broadened career prospects and thus enhanced attractiveness; cross-departmental networking and collaboration; broadened user base for infrastructure (beam tests, dilution refrigerators, processing technologies)				

(under way; in preparation; under discussion or imaginable applications; long-range potential)

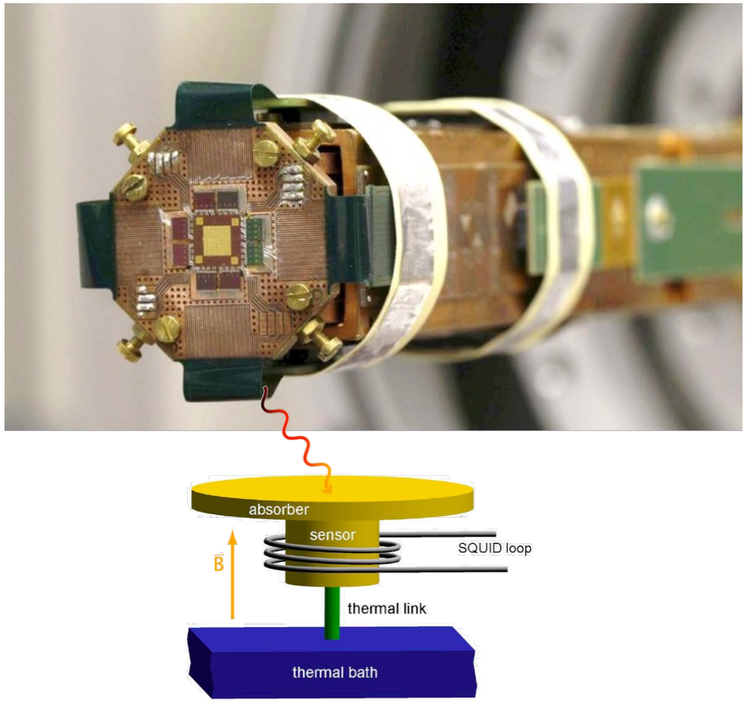
Fluorescence spectroscopy in muonic atoms

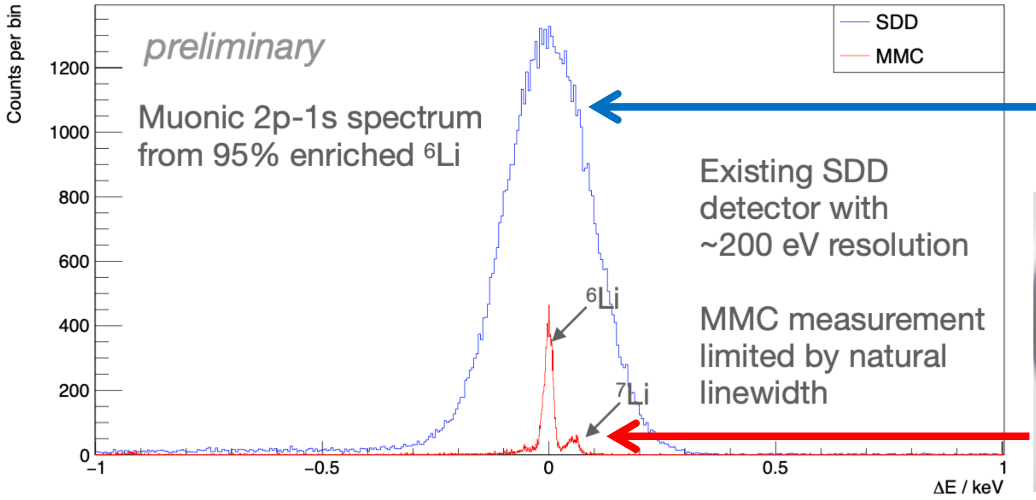


QUARTET

The Heidelberg Metallic Magnetic Calorimeter (MMC)

maXs-30 mounted on coldfinger of a dry dilution fridge

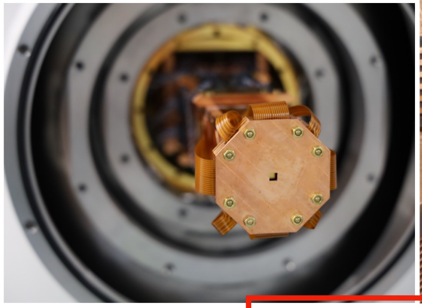


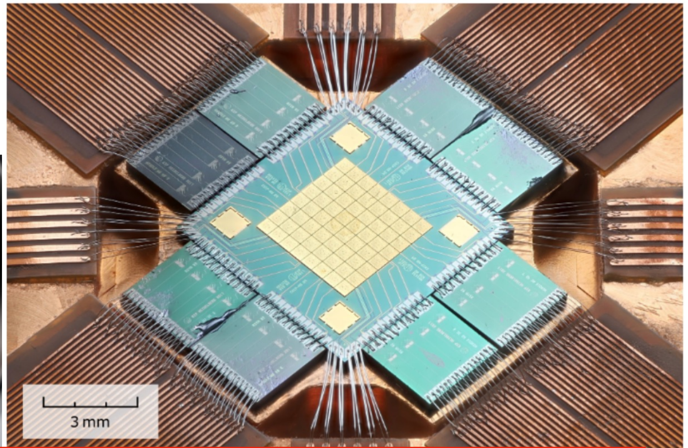


Muonic 2p-1s spectrum from 95% enriched ^{6}Li

Existing SDD detector with ~200 eV resolution

MMC measurement limited by natural linewidth





Slide elements from Nancy Paul, EXA/LEAP’24 Vienna

Fluorescence spectroscopy in antiprotonic atoms

ANTIPROTONIC ATOM X-RAY SPECTROSCOPY

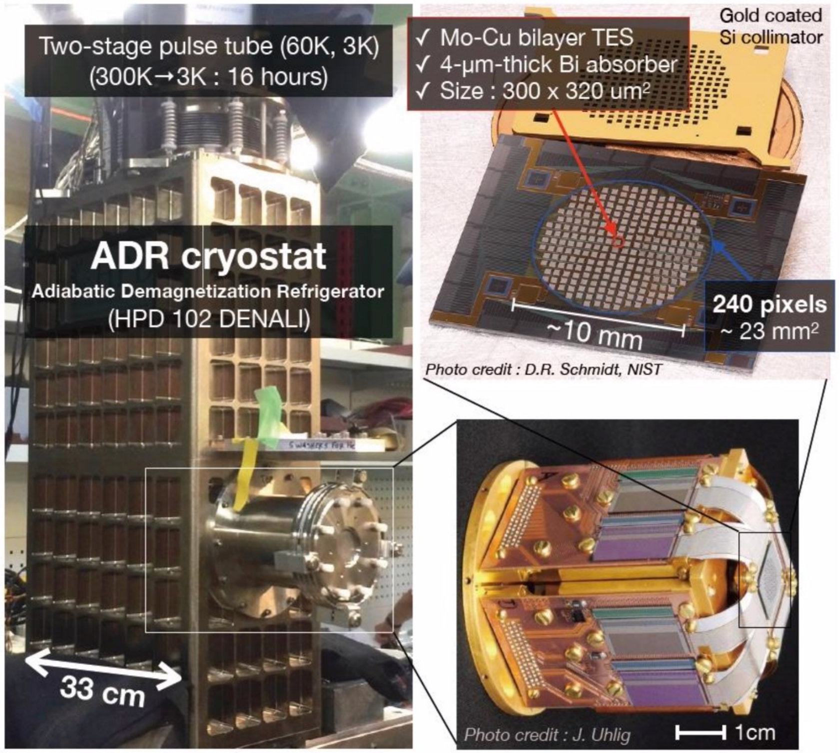
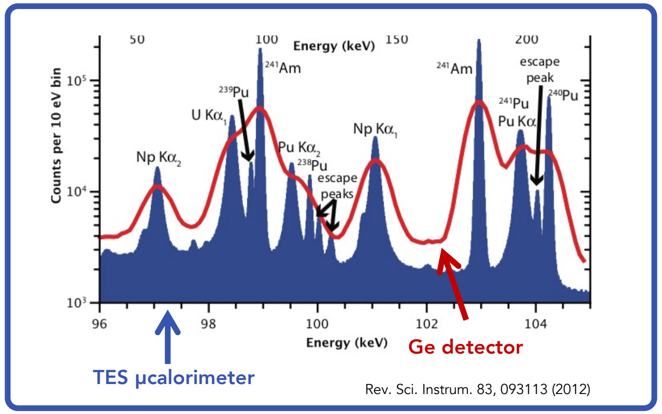


Photo credit : D.R. Schmidt, NIST

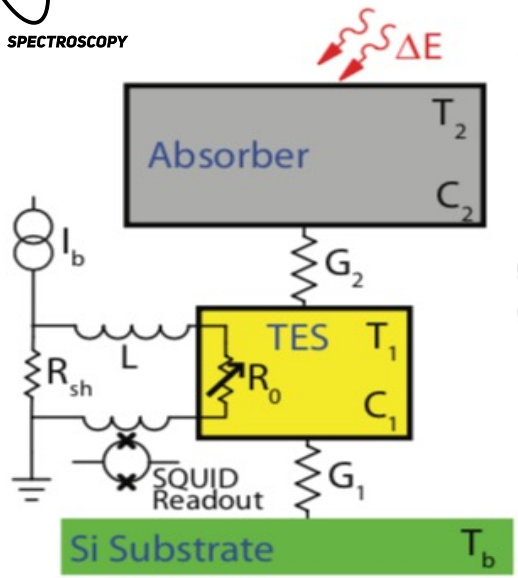
Photo credit : J. Uhlig

Key technology

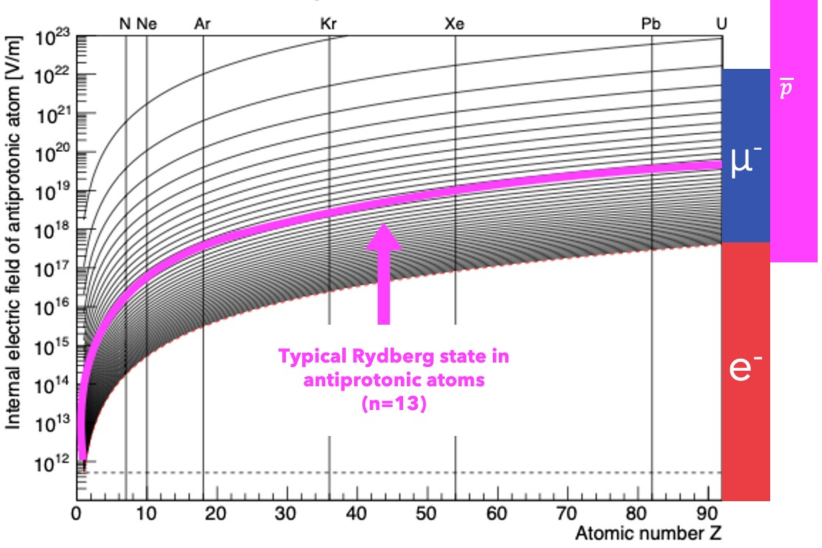
- High energy resolution ($\Delta E/E \sim 10^{-4}$)
- High quantum efficiency (~0.8)



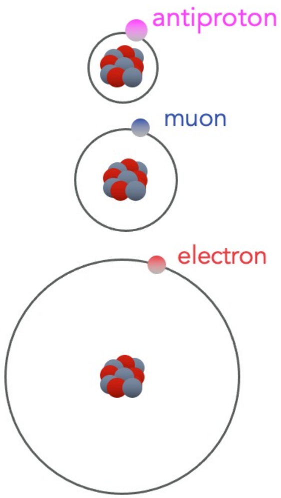
Rev. Sci. Instrum. 83, 093113 (2012)

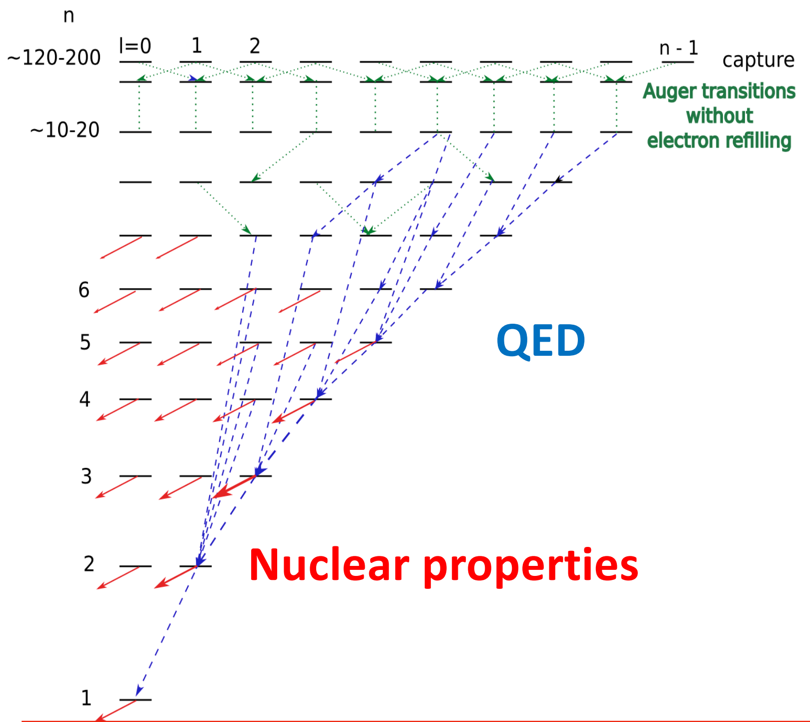


Pionic, muonic, Antiprotonic atoms



Strongest field QED



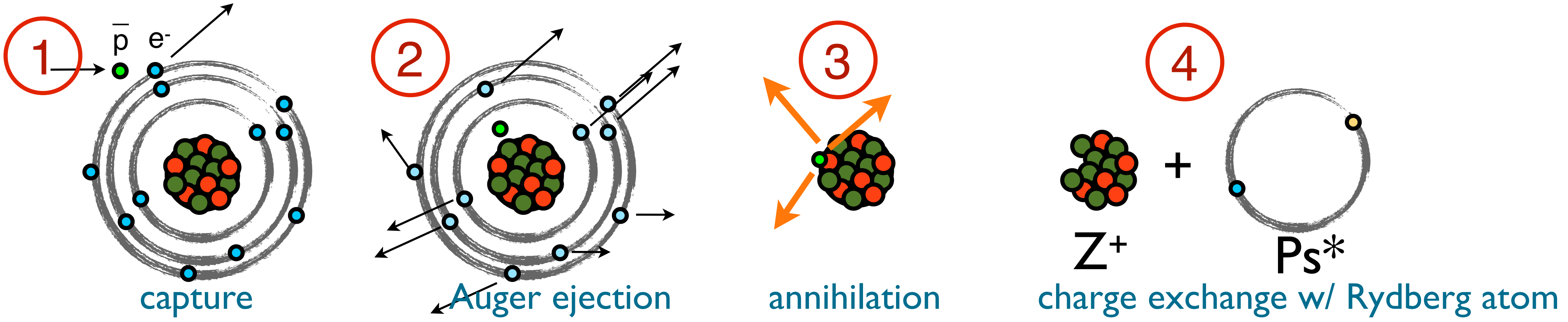


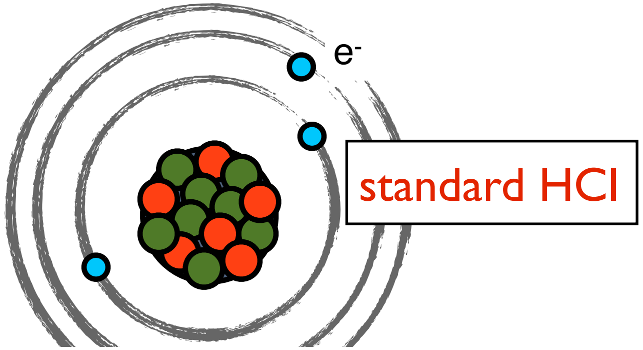
Slide elements from Nancy Paul, EXA/LEAP'24 Vienna

Fluorescence spectroscopy in H-like HCI's atoms (incl. antiprotonic, antideuteronic* HCI's)

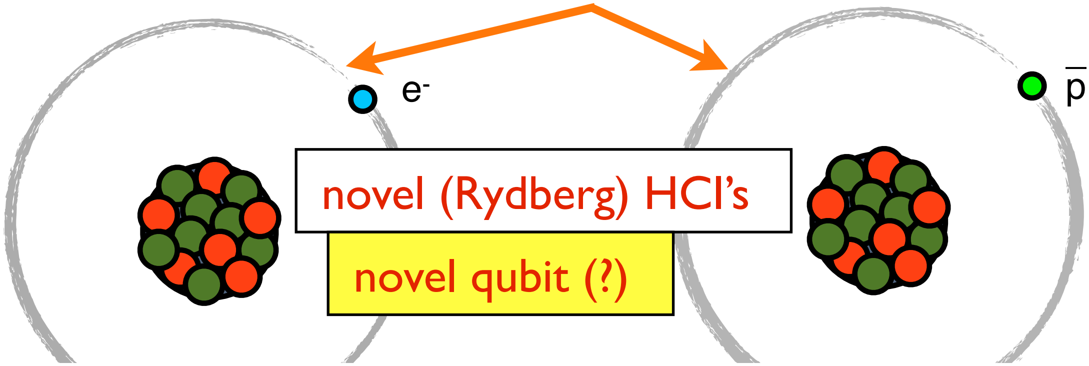
Antiprotonic atoms → novel HCI systems

M. Doser, Prog. Part. Nucl. Phys, (2022), https://doi.org/10.1016/j.ppnp.2022.103964





HCI (stable), $(Z-n)^+$



HCI*(stable or unstable), $(Z-1)^+$

HCI*(stable or unstable), $(Z-1)^+$

Antiprotonic Rydberg atoms: exotic couplings, similar approach as spectroscopy of muonic atoms, CPT tests

Antiprotonic Rydberg molecules: pEDM? precision spectroscopy?

Antiprotonic ^{3}He: novel search for QCD 6-quark DM: G. Farrar, G. Kornakov, M. Doser, EPJC 83, 1149 (2023)

*Antideuteronic atoms: Fredrik Gustafsson, Tomasz Sowiński typically not obvious, given that most detectors rely on detecting the product of many interactions between a particle and the detector (ionization, scintillation, Čerenkov photons, …)

handful of ideas that rely on quantum devices, or are inspired by them. not necessarily used as quantum detectors per se, but rather their properties to enhance / permit measurements that are more difficult to achieve otherwise

main focus on tracking / calorimetry / timing / novel observables / PU ...

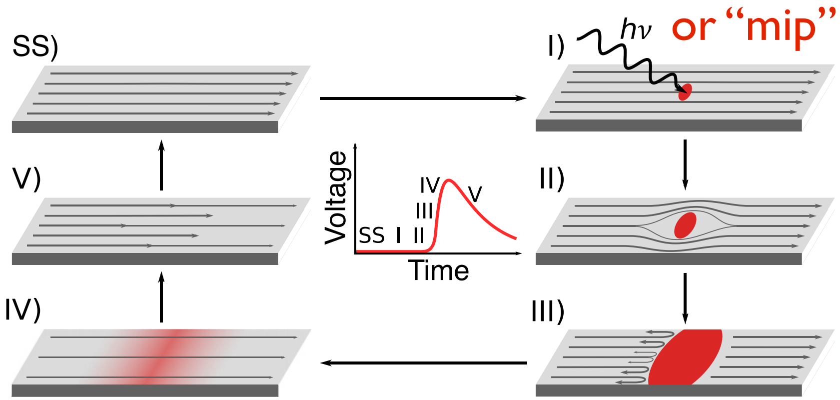
closely related: nanostructured materials

→ Frontiers of Physics, M. Doser et al., 2022
doi: 10.3389/fphy.2022.887738

these are not fully developed concepts, but rather the kind of approaches one might contemplate working towards

very speculative!

Extremely low energy threshold detectors: SNSPD



quantum pixel ultra-sensitive tracking

Parameter	SOA 2020	Goal by 2025
Efficiency	98% @ 1550nm	>80 % @10μm
Energy Threshold	0.125 eV (10 μm)	12.5 meV (100 μm)
Timing Jitter	2.7 ps	< 1ps
Active Area	1 mm^2	100 cm^2
Max Count Rate	1.2 Gcps	100 Gcps
Pixel Count	1 kilopixel	16 megapixel
Operating Temperature	4.3K	25 K

Snowmass2021 - Letter of Interest

Superconducting Nanowire Single-Photon Detectors

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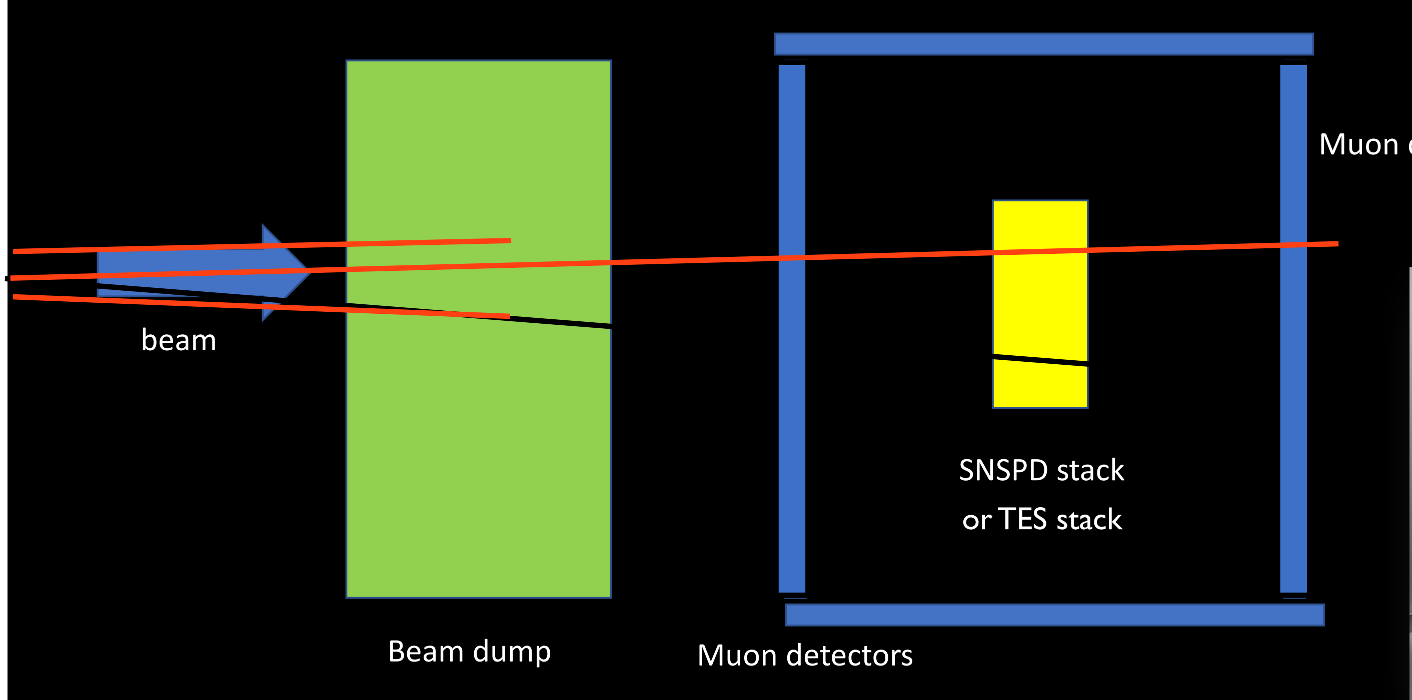
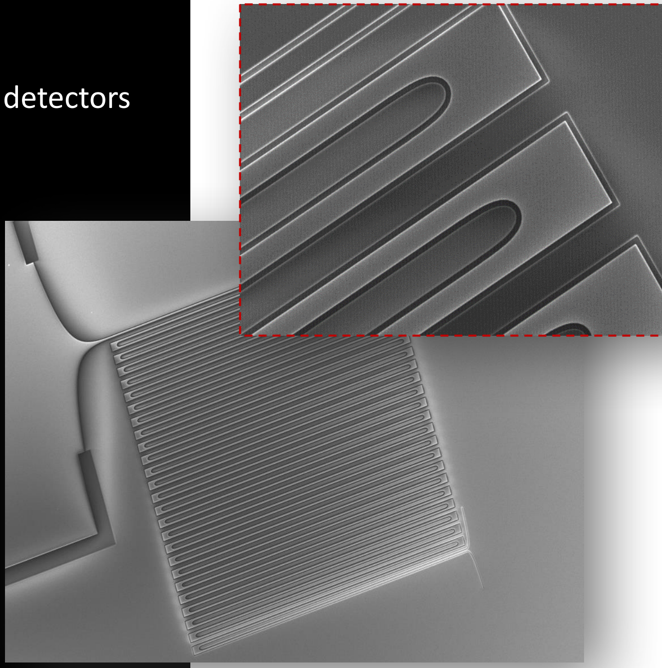
Moving to SC strips conventional lithography → scale up
Development towards SC SSPM

Search for Beyond Standard Model milli-charged particles?



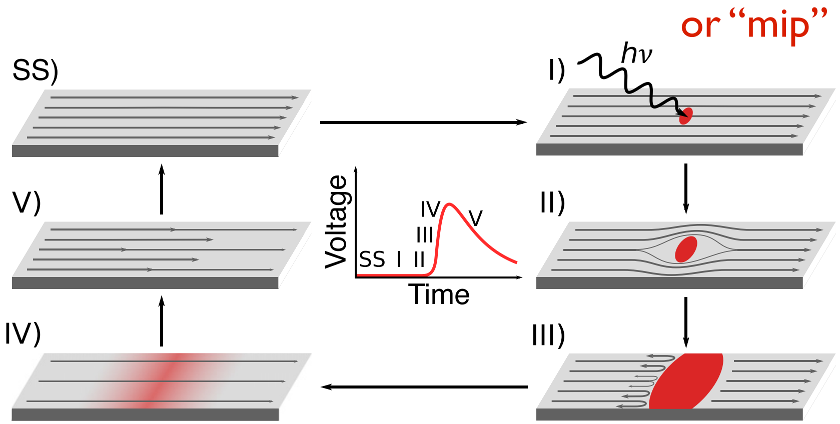
mip: ~20 keV/100 μm

x 10^6 sensitivity



Extremely fast detectors: SNSPD

quantum pixel ultra-sensitive tracking



or "mip"

Parameter	SOA 2020	Goal by 2025
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Snowmass2021 - Letter of Interest

Superconducting Nanowire Single-Photon Detectors

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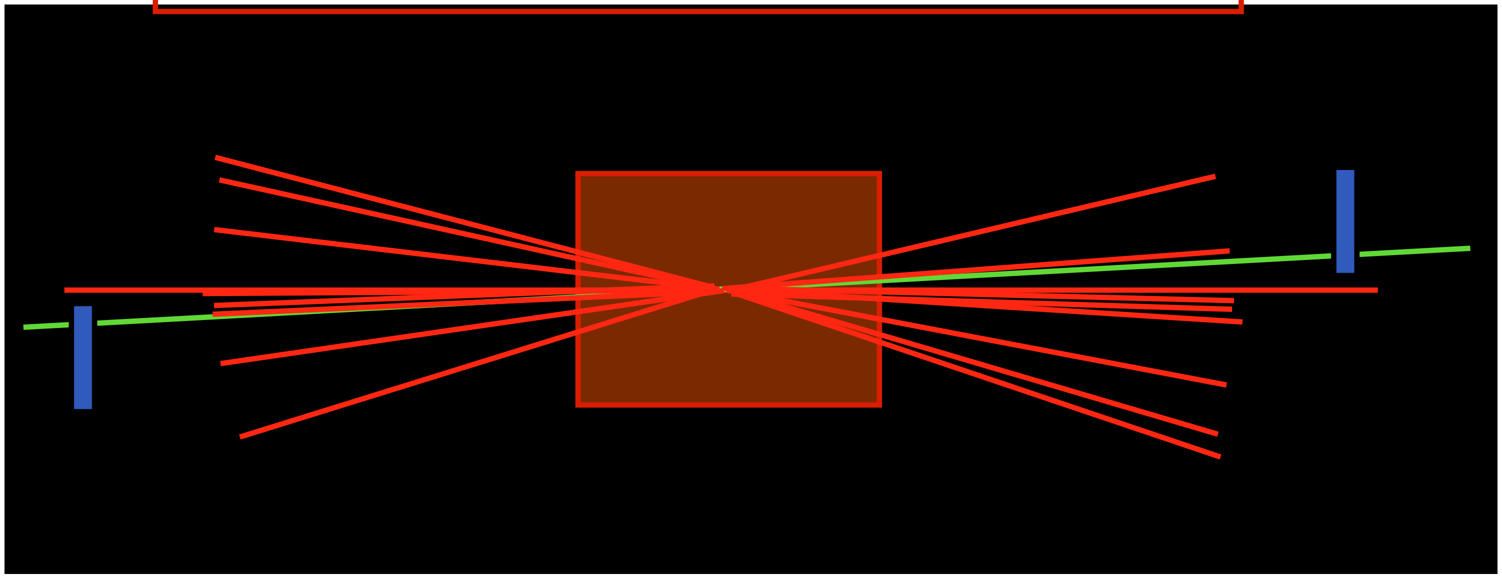
Matt Shaw, mattshaw@jpl.nasa.gov

Moving to SC strips conventional lithography → scale up
Development towards SC SSPM

QT4HEP22-- I. Shipsey

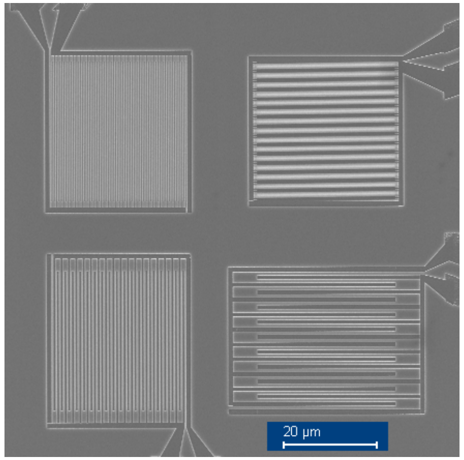
125

diffractive scattering via ps-resolution tracking in Roman pots



@ 2.8 K

100 nm 200 nm



400 nm 800 nm

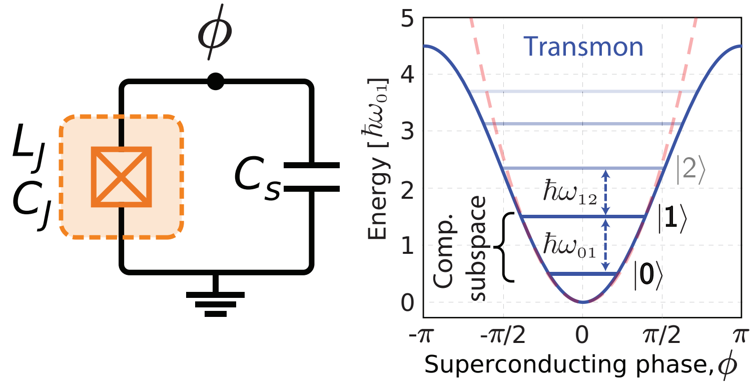
arXiv:2312.13405v2
[physics.ins-det]
5 Apr 2024

low energy particle physics: dark count rate is critical !
high energy particle physics: dark count rate is not a problem: high Tc is imaginable

Beyond existing sensors: using (superconducting) qubits

commonly used qubits: transmons

Josephson junction qubit



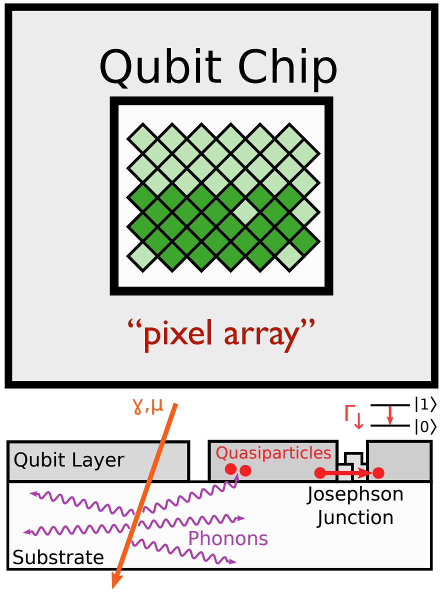
variant of a harmonic oscillator (with numerous equally-spaced energy levels):

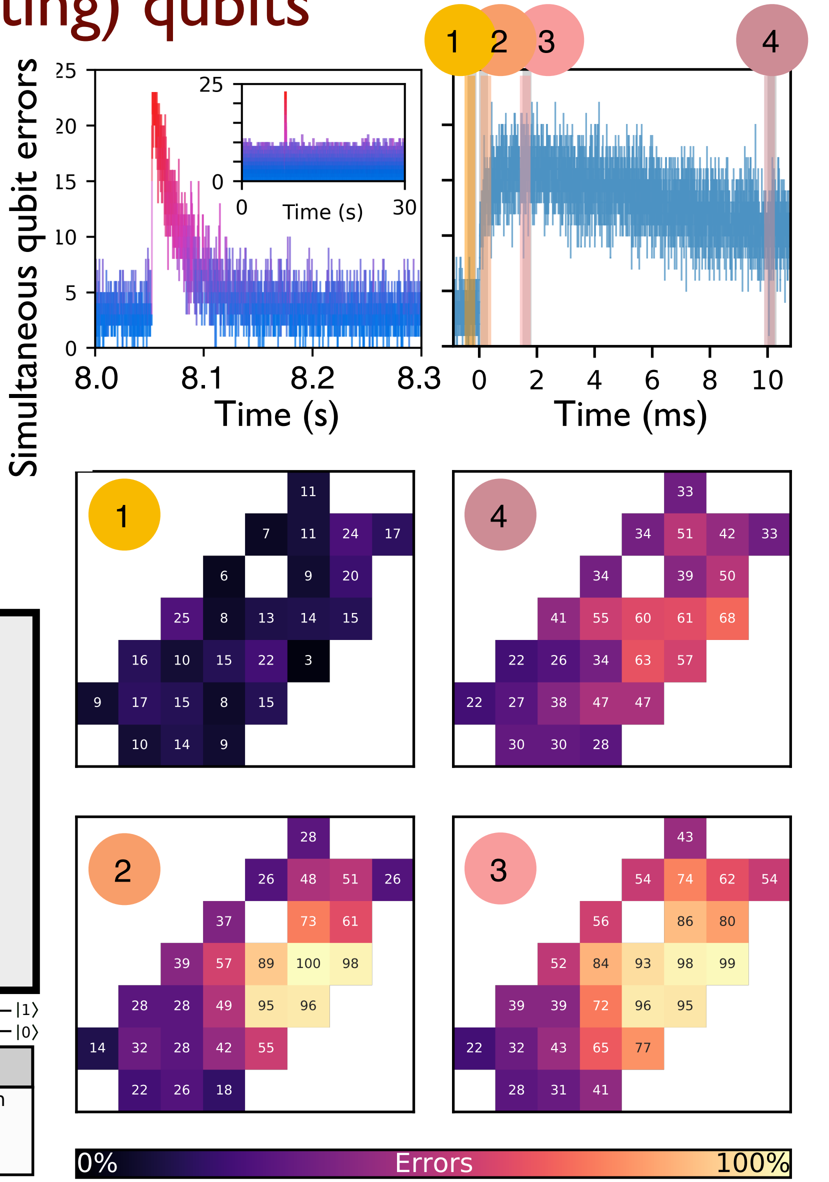
need to be able to define a computational subspace consisting of only two energy states (usually the two-lowest energy eigenstates) in between which transitions can be driven without also exciting other levels in the system: $|0\rangle$ and $|1\rangle$

Energy scale: 25μeV (cosmic: 0.1~1 MeV)

A quantum engineer's guide to superconducting qubits, P. Krantz et al., https://arxiv.org/pdf/1904.06560

Google Sycamore processor (Quantum Computer)





Correlated errors in neighboring qubits in a 26 qubit sub-array: cosmic ray "tracker"

McEwen et al., Nature 118, 107 (2022) arXiv:22014.05219

This slide stolen from Daniel Baxter, IDM, L'Aquila, 2024

Proposal for DRD5: R&D on quantum sensors

ECFA Roadmap topics → Proposal themes → Proposal WP's

ECFA Detector R&D Roadmap Symposium of Task Force 5 Quantum and Emerging Technologies

Roadmap topics

Proposal WP's

Sensor family → Work Package ↓	clocks & clock networks	superconducting & spin-based sensors	kinetic detectors	atoms / ions / molecules & atom interferometry	opto-mechanical sensors	nano-engineered / low-dimensional / materials
WP1 *Atomic, Nuclear and Molecular Systems in traps & beams*	X			X	(X)	
WP2 *Quantum Materials (0-, 1-, 2-D)*		(X)	(X)		X	X
WP3 *Quantum superconducting devices*		X				(X)
WP4 *Scaled-up massive ensembles* (spin-sensitive devices, hybrid devices, mechanical sensors)		X	(X)	X	(X)	X
WP5 *Quantum Techniques for Sensing*	X	X	X	X	X	
WP6 *Capacity expansion*	X	X	X	X	X	X

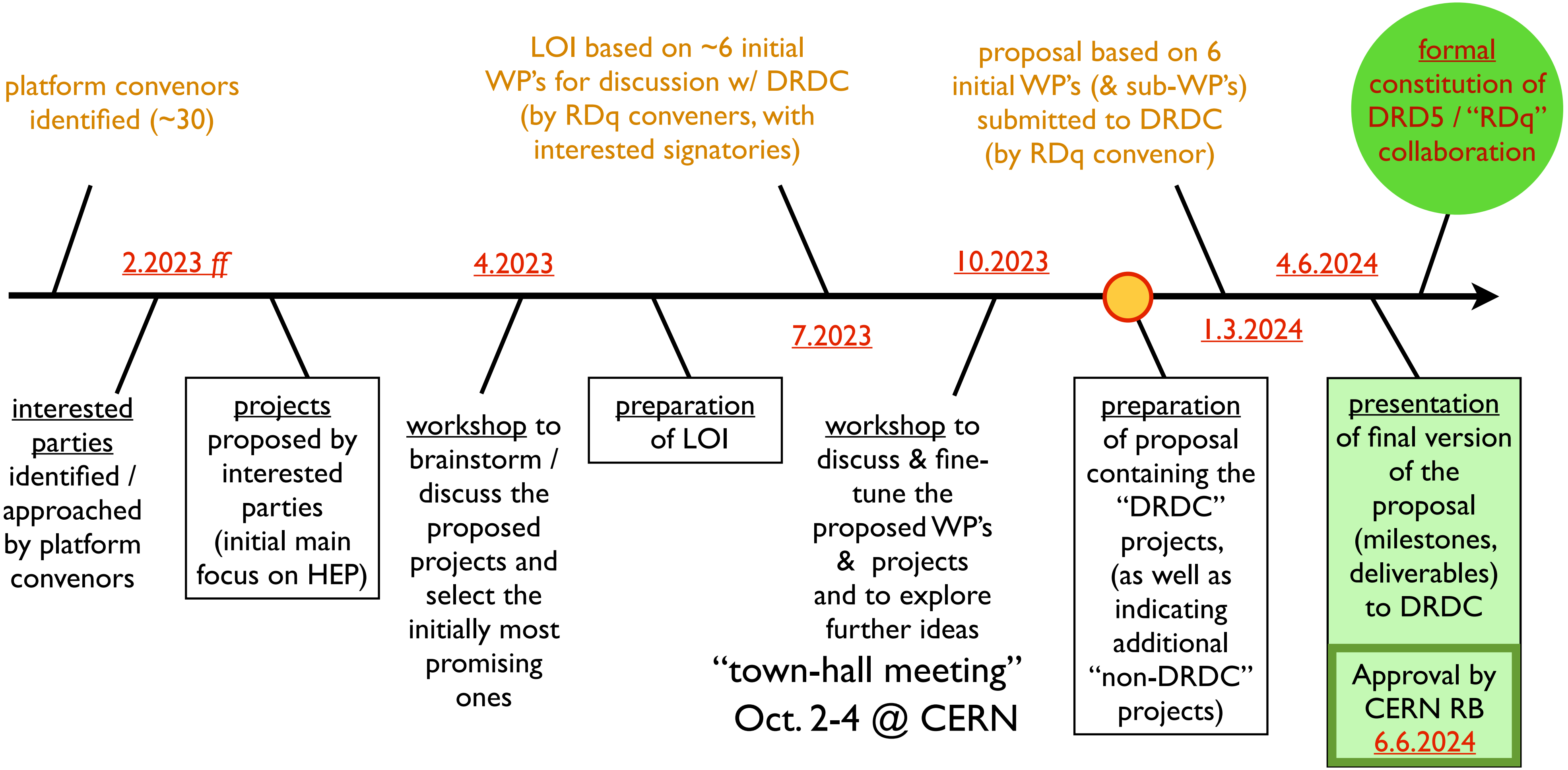
Ensure that all sensor families that were identified in the roadmap as relevant to future advances in particle physics are included

WP → sub-WP → sub-sub-WP

timeline

Two goals for DRD5 (Detector R&D on Quantum Sensors) in 2023/2024 :

- preparation of a proposal (LoI, White Paper) for detector R&D
- formation of a global collaboration (Europe, Americas, Asia)



platform convenors identified (~30)

2.2023 ff

interested parties identified / approached by platform convenors

projects proposed by interested parties (initial main focus on HEP)

4.2023

workshop to brainstorm / discuss the proposed projects and select the initially most promising ones

preparation of LOI

LOI based on ~6 initial WP's for discussion w/ DRDC (by RDq conveners, with interested signatories)

7.2023

10.2023

workshop to discuss & fine-tune the proposed WP's & projects and to explore further ideas

"town-hall meeting"
Oct. 2-4 @ CERN

preparation of proposal containing the "DRDC" projects, (as well as indicating additional "non-DRDC" projects)

proposal based on 6 initial WP's (& sub-WP's) submitted to DRDC (by RDq convenor)

1.3.2024

4.6.2024

presentation of final version of the proposal (milestones, deliverables) to DRDC

Approval by CERN RB 6.6.2024

formal constitution of DRD5 / "RDq" collaboration

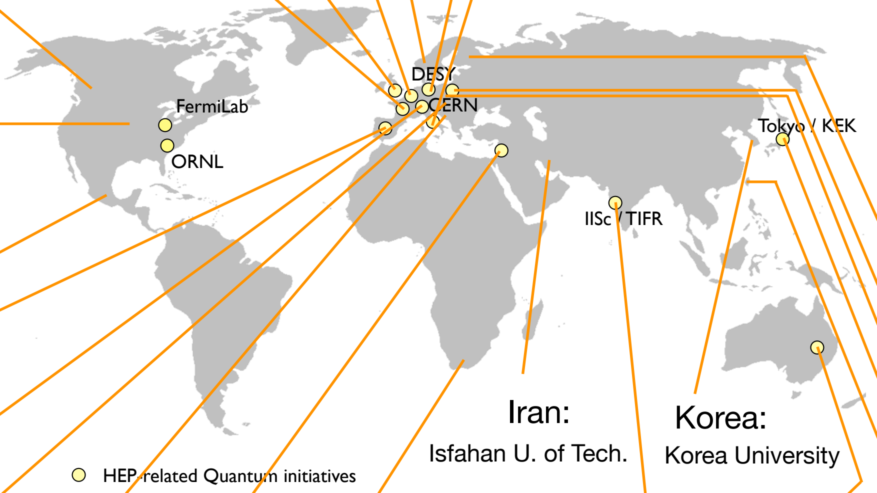
call for wide participation in DRD5 →

DRD5: 100 involved groups

Collaboration currently being put together, combines diverse communities, including HEP.

Many novel developments that benefit both quantum technologies and particle physics.

Open to all interested parties (and it's free to join!)



UK:
- Oxford University
- Univ. of Warwick
- Univ. of Birmingham
- NPL
- Imperial College
- Univ. of Southhampton
- Univ. of Sussex

France:
- SYRTE / OBSPM
- CNRS - U. Sorbonne Paris Nord
- LKB
- ILM - University Lyon 1

Canada:
- McGill Univ.
- TRIUMF

USA:
- UCLA
- ORNL
- Northwestern Univ.
- Caltech
- MIT
- Arizona State Univ.
- Yale
- Univ. of Arizona
- NIST
- LBNL
- Univ. of Delaware
- FNAL
- SLAC

Mexico:
- U. de Aguascalientes

Spain:
- U. de Zaragoza
- U. de Cartagena
- U. de Valencia
- U. de Lleida

Switzerland:
- U. of Geneva
- U. of Zürich
- CERN
- ETHZ

Netherlands:
- U. of Groningen

Norway:
- Oslo University

Austria:
- IQOQI Vienna

Croatia:
- Inst. of Physics, Zagreb

Israel:
- Technion, Haifa

South Africa:
- U. of Cape Town

Iran:
- Isfahan U. of Tech.

India:
- IITTP, Tirupati
- IISER, Kolkata
- TIFR, Mumbai
- University SOA Bhuvaneswar

Korea:
- Korea University

Australia:
- University of Western Australia
- Swinburne University of Technology

Germany:
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- Univ. Ulm
- Leibnitz Univ. Hannover
- KIT, Karlsruhe
- TU München
- DESY
- MPP Garching
- HU Berlin
- FBH Berlin
- Univ. Heidelberg
- Univ. Tübingen
- Univ. Düsseldorf
- Univ. Mainz
- Univ. Bremen / ZARM
- Semiconductor Lab HLL / MPG
- TU Darmstadt

Italy:
- U. of Pisa & INFN
- U. of Pavia
- U. of Firenze
- U. of Milano-Bicocca
- Fondazione Bruno Kessler, Trento
- IOM CNR, Elettra Sincrotrone, Trieste
- Univ. of Bari / INFN
- INFN Padova
- Univ. Roma 1 & 3
- Univ. Napoli
- INFN Roma Tor Vergata
- INFN LNF
- INFN Trento (TIFPA)
- INFN Torino
- INFN LNL
- INFN Lecce
- INFN Roma Tor Vergata
- U. of Camerino

Finland:
- Helsinki Inst. of Physics
- VTT

Poland:
- Warsaw TU
- Nat. Centre Nucl. Research / Warsaw
- Nat. Lab. FAMO / Torun

Czech Republic:
- Czech Tech. University
- University West Bohemia

Japan:
- QUP / KEK
- Kyoto University
- Tokyo University / ICEPP

Taiwan:
- Acadmia Sinica & NTU

thank you!