Quantum Detectors for particle physics

(focus on applying quantum sensors to *both* "HEP" *and* low energy particle physics)

Clarification of terms

Quantum sensors for low energy particle physics

Quantum sensors for high energy particle physics

Some words on the landscape and the outlook

(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

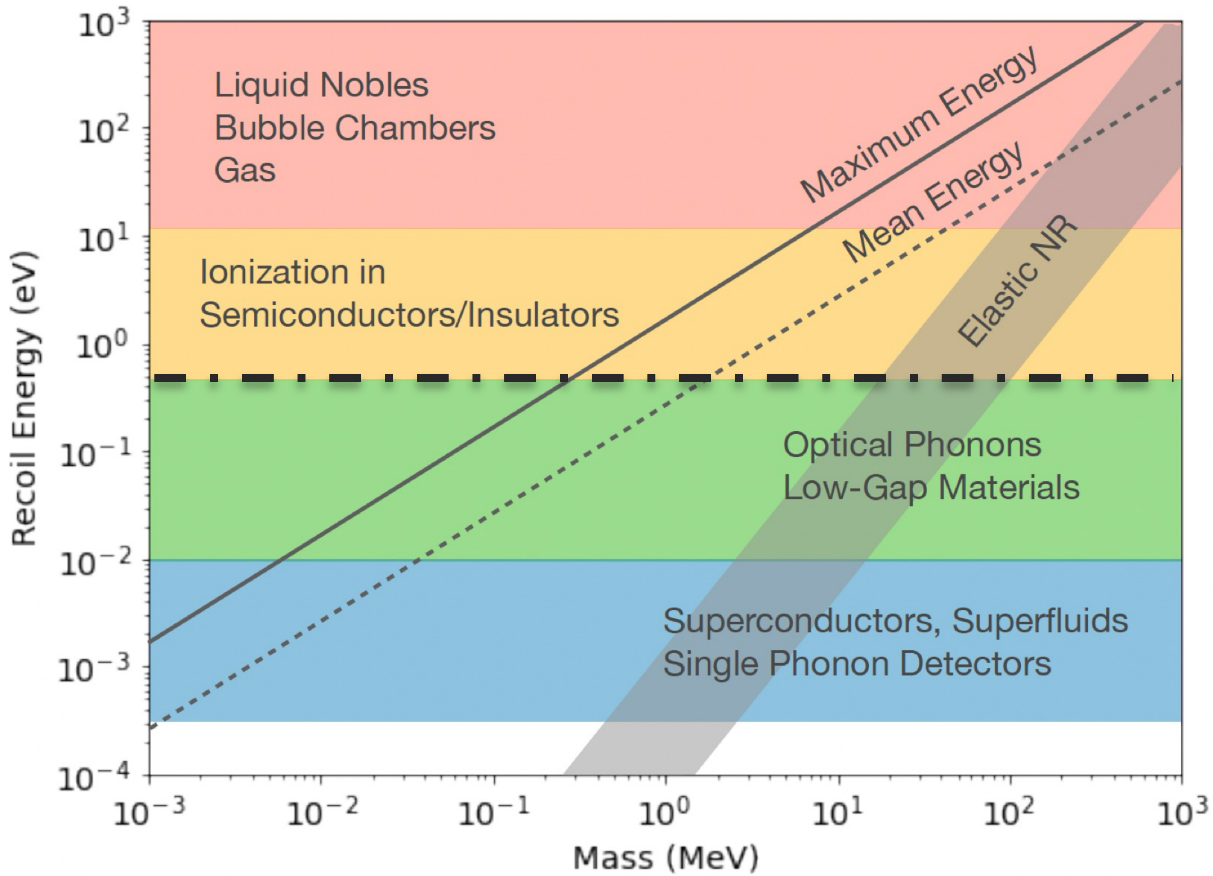
Then, a "quantum sensor" is a device, the measurement (sensing) capabilities of which are enabled by our ability to manipulate and/or read out its quantum states.

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



$\Delta E \sim 1$ 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

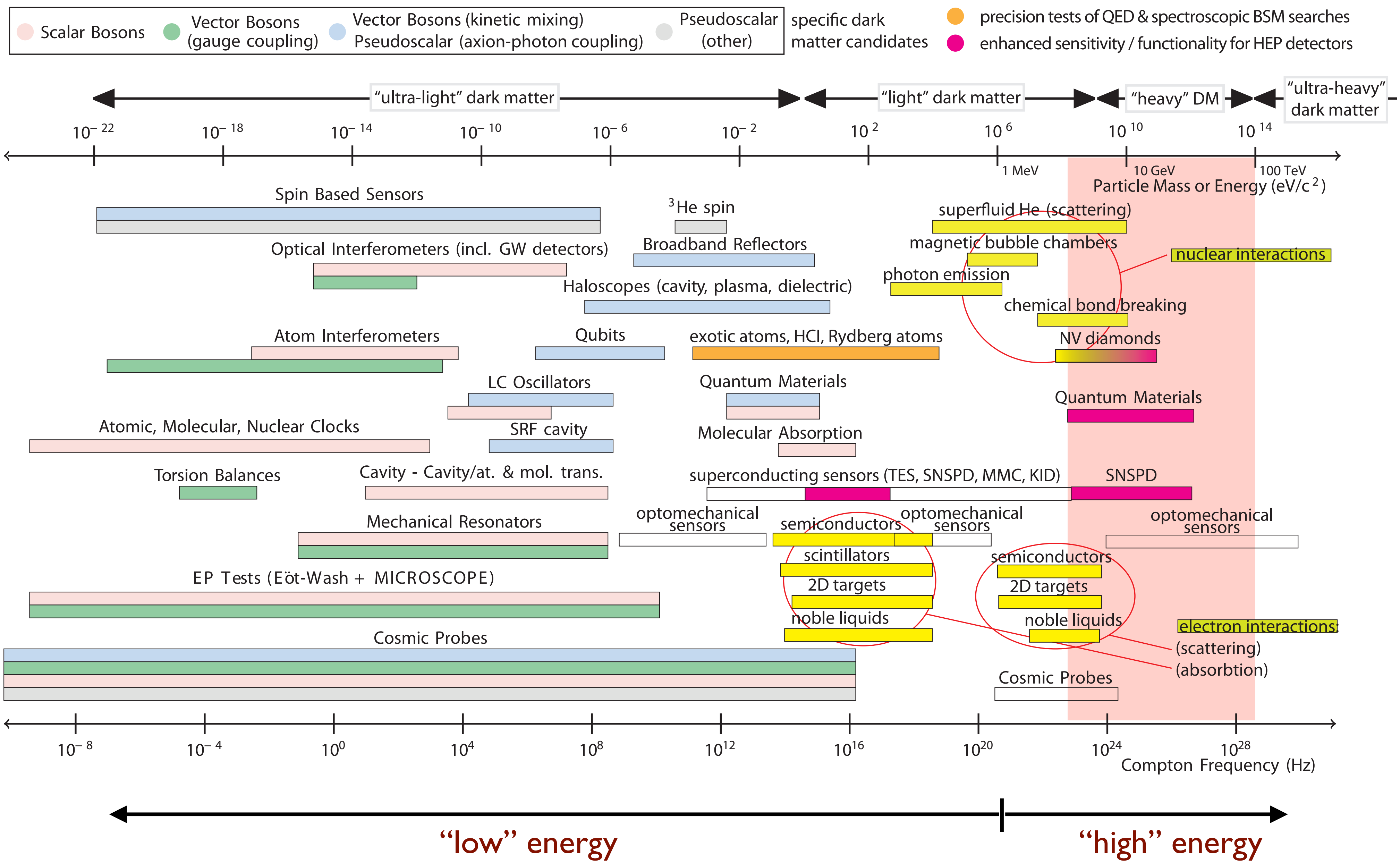
Daniel Baxter I IDM 2024 Essig et al, Snowmass CF1 WP2 (2022) [arXiv:2203.08297]

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, …

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

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 at low energy enabled by Quantum Sensors

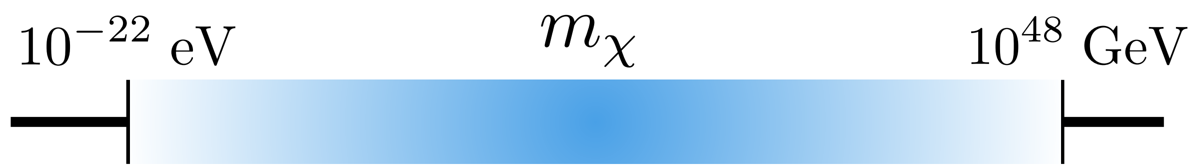
(focus on activities with CERN involvement, partly under the CERN QTI-2 program)

- RF cavities, cryodetectors (DM searches)
- atom interferometry, clocks, networks (DM, gravity)
- 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

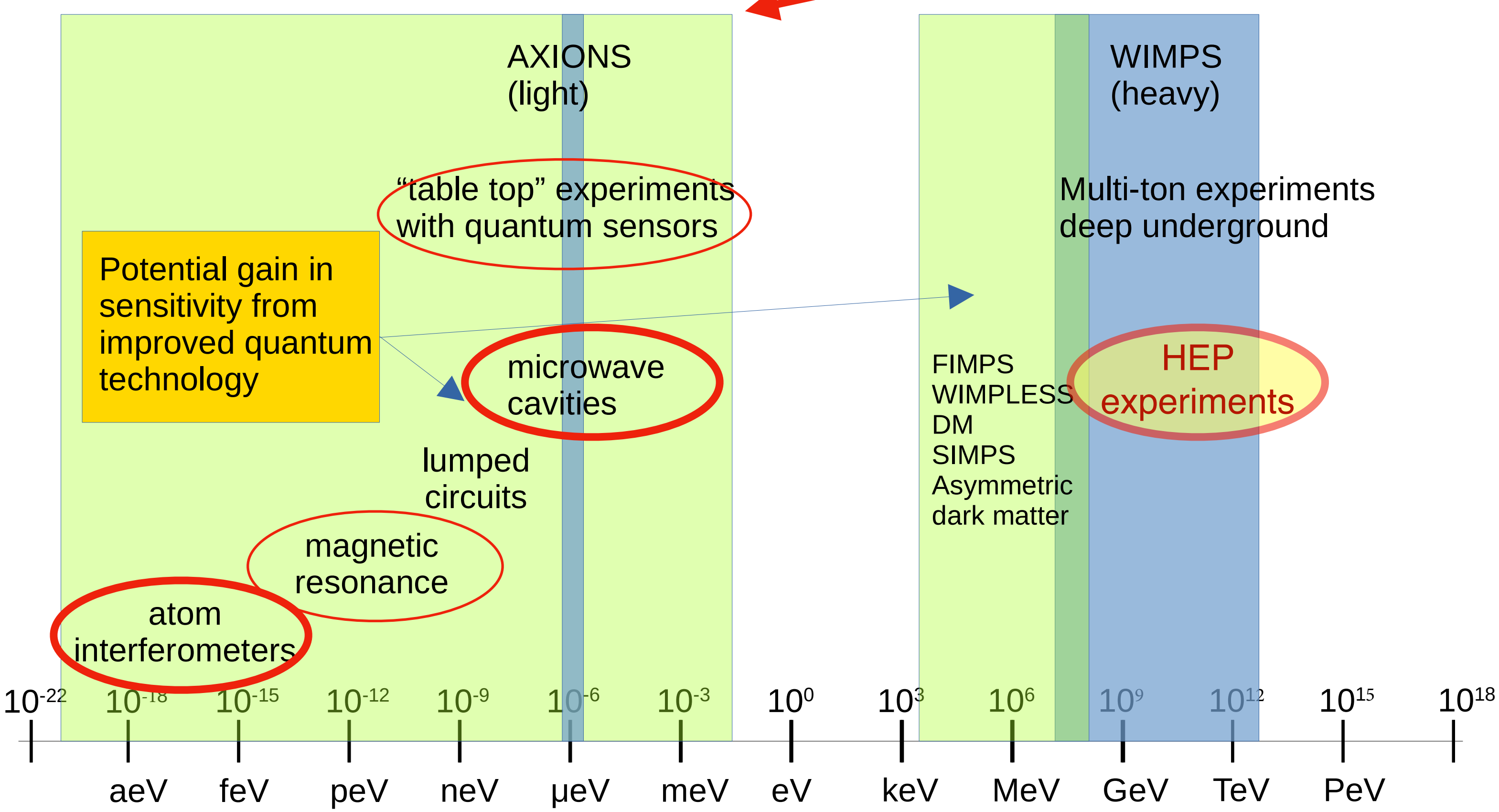
Axions, ALP's, DM & non-DM UL-particle searches

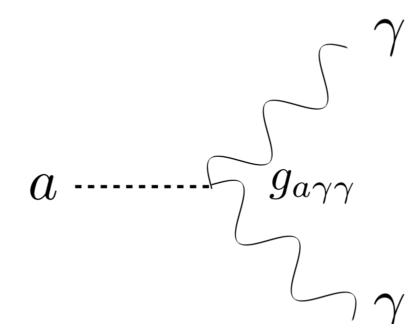


cavity size = axion size
axion mass = unknown

$$F \sim g^2_{a\gamma} m^2_A B^4 V^2 T^{-2}_{sys} G^4 Q,$$

system noise temperature
cryo-amplifiers JJPA





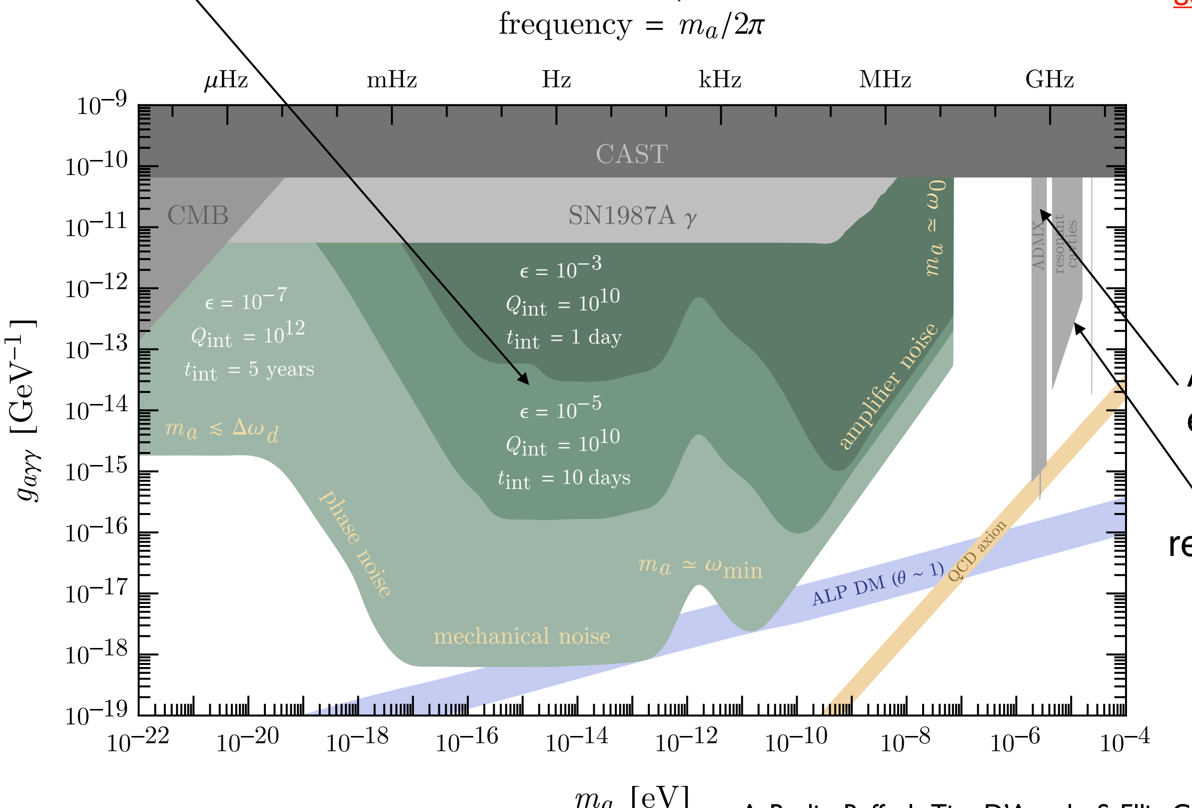
(but not only…)

Axion heterodyne detection

novel qubit (?)

$Q_{int} \gtrsim 10^{10}$ 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

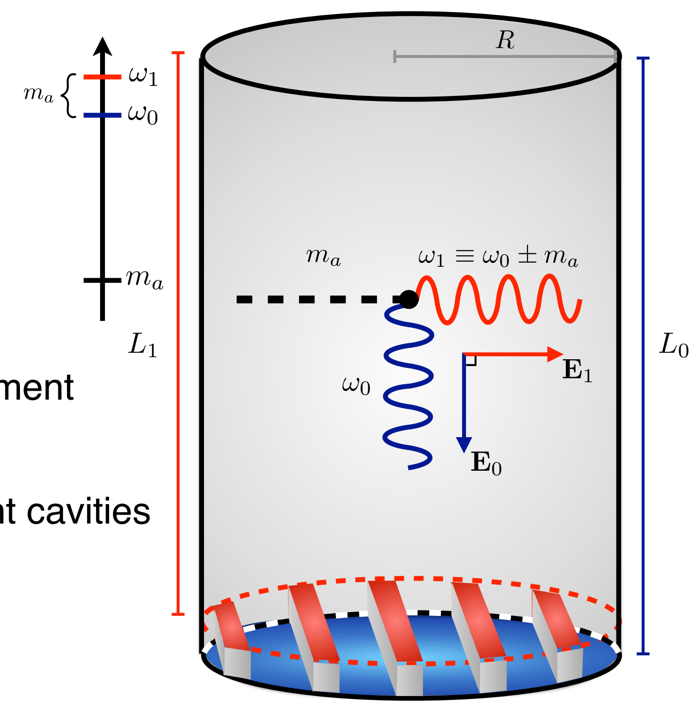


problem: cavity resonance generally fixed

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.

<u>Conceptual Theory Level Proposal:</u>

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."

AION: atom interferometer (start small, ultimately → space)

L. Badurina et al., AION: An Atom Interferometer Observatory and Network, JCAP 05 (2020) 011, [arXiv:1911.11755].

Where does this fit in? Go after 10^{-20} eV < m_a < 10^{-12} eV,

but also topological DM, ultralight DM, gravitational waves, Lorentz invariance, ...

atom interferometry at macroscopic scales: arXiv:2201.07789v1 [astro-ph.IM] 19 Jan 2022

MIGA (France) AION (UK) ZAIGA (China)

CERN? shafts (100~500 m ideal testing ground), cryogenics, vacuum, complexity…

MAGIS (Fermilab)

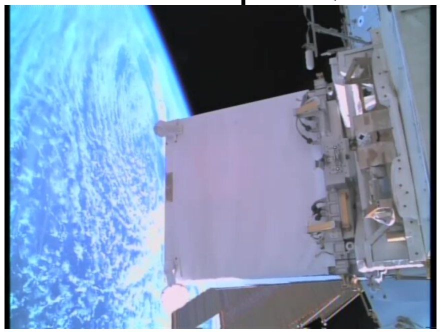
M. Abe, P. Adamson, M. Borcean, D. Bortoletto, K. Bridges, S. P. Carman et al., Matter-wave Atomic Gradiometer Interferometric Sensor (MAGIS-100), arXiv:2104.02835v1.

MAGIS collaboration, Graham PW, Hogan JM, Kasevich MA, Rajendran S, Romani RW. Mid-band gravitational wave detection with precision atomic sensors. arXiv:1711.02225

satellite missions:

ACES (Atomic Clock Ensemble in Space): launched Apr. 21, 2025, switched on Apr. 28, 2025

- ESA mission for ISS
- two on-board clocks rely on atomic transitions in the microwave domain
- probe time variations of fundamental constants, and to perform tests of the Lorentz-Violating Standard Model Extension (SME). Possibly topological dark matter



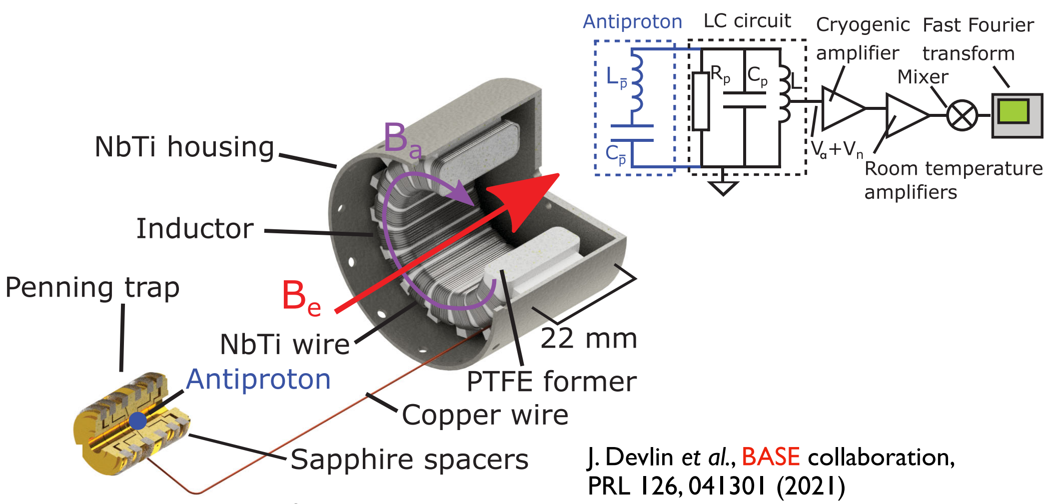
pathfinder / technology development missions: ~2030

- I-SOC: key optical clock technology (laser cooling, trapping, optical resonators) for space; Sr optical lattice clock / Sr ion clock; microwave and optical link technology;
- FOCOS (Fundamental physics with an Optical Clock Orbiting in Space): Yb optical lattice clock with 1 × 10^{-18} stability

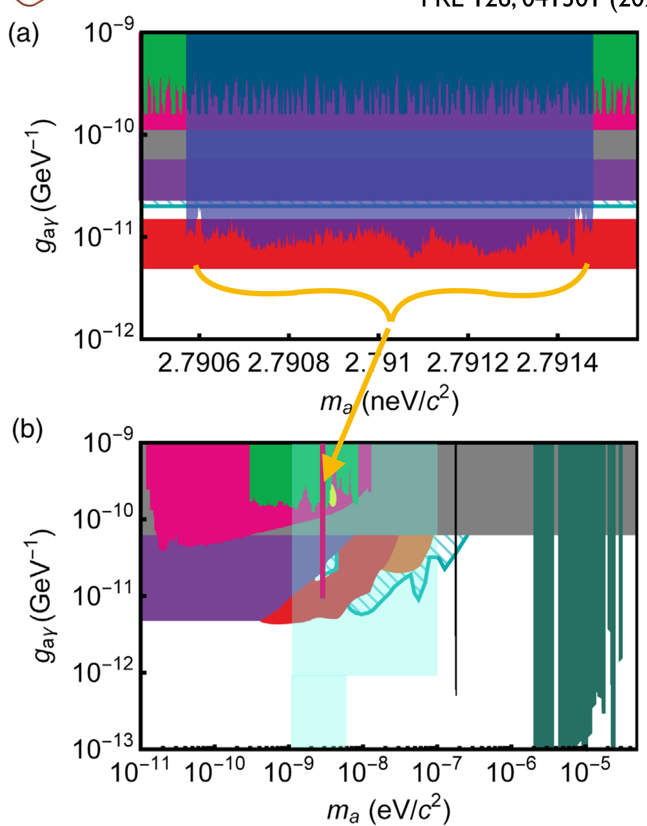
AION: ~2045 satellite mission
AEDGE: ~2045 satellite mission

El-Neaj, Y.A., Alpigiani, C., Amairi-Pyka, S. *et al*. AEDGE: Atomic Experiment for Dark Matter and Gravity Exploration in Space. *EPJ Quantum Technol*. **7**, 6 (2020). https://doi.org/10.1140/epjqt/s40507-020-0080-0

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

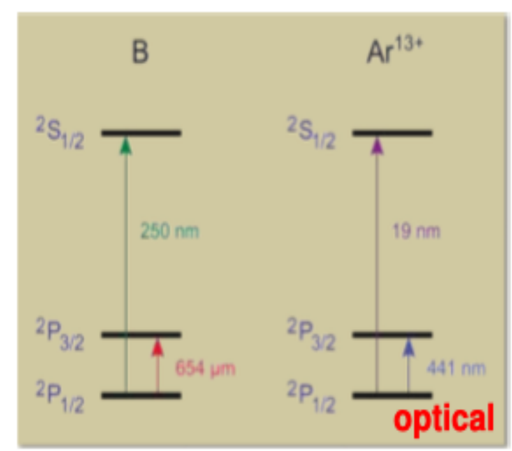
HCIs: much larger sensitivity to variation of α and for dark matter searches than current clocks

- 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

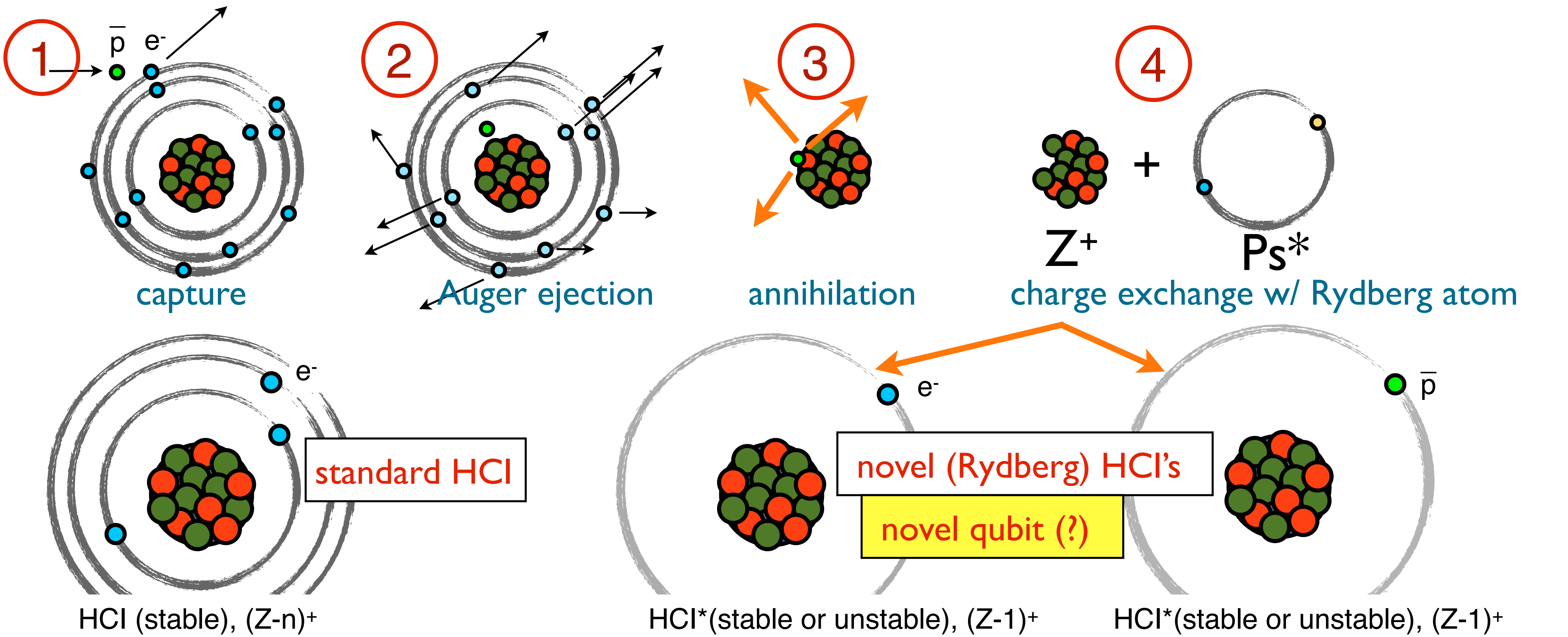
Binding energy	~ Z^2
Hyperfine splitting	~ Z^3
QED effects	~ Z^4
Stark shifts	~ Z^{-6}



Exotic systems for tests of QED, searches for BSM, probes of fundamental symmetries

Antiprotonic atoms ⟶ novel HCI systems

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



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

Antiprotonic Rydberg molecules: $\bar{p}$EDM? precision spectroscopy?

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

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

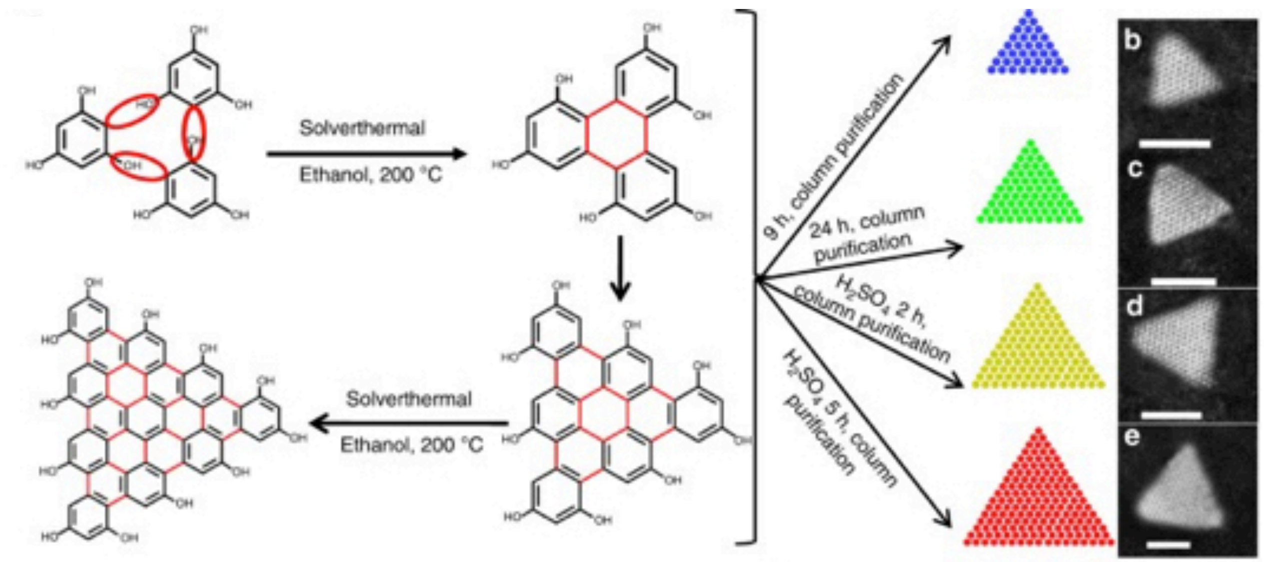
Spin-based sensors

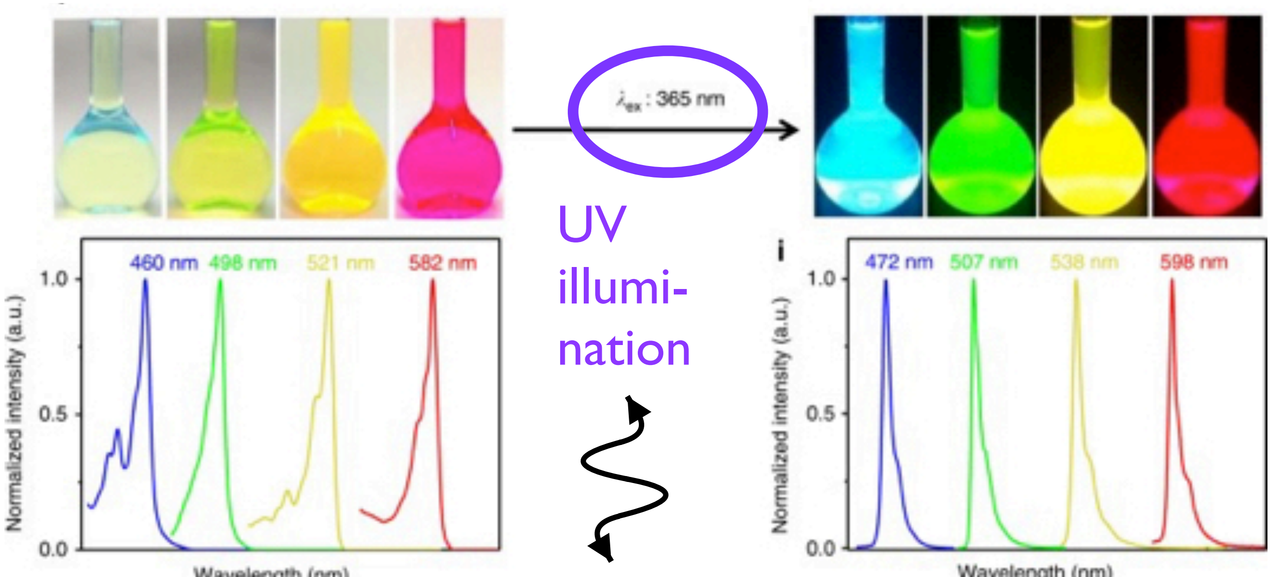
quantum-polarized helicity detection — helicity detectors

Superconducting sensors

quantum pixel ultra-sensitive tracking — milli-charge trackers

Quantum dots: chromatic calorimetry





absorption e.m. shower emission

F. Yuan, S. Yang, et al., Nature Communications 9 (2018) 2249

idea: seed different parts of a "crystal" with nanodots emitting at different wavelengths, such that the wavelength of a stimulated fluorescence photon is uniquely assignable to a specific nanodot position

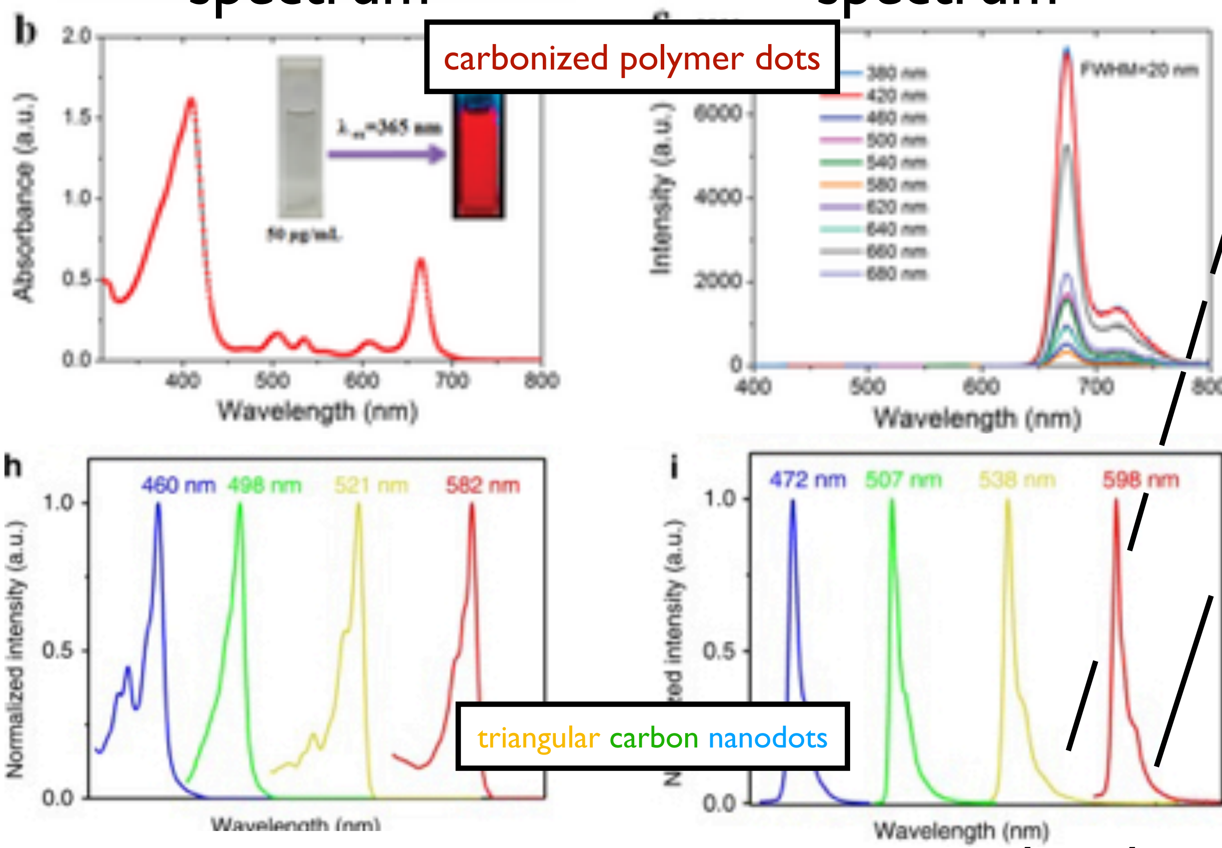
requires:
- narrowband emission (~20nm)
- only absorption at longer wavelengths
- short rise / decay times

select appropriate nanodots

e.g. triangular carbon nanodots

absorption spectrum

emission spectrum



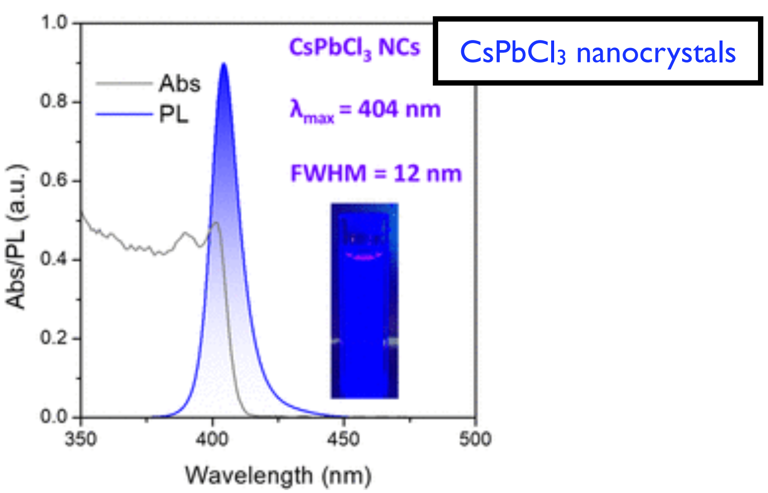
leftmost nanodots:
absorb wavelengths < 650 nm
emit at > 680 nm

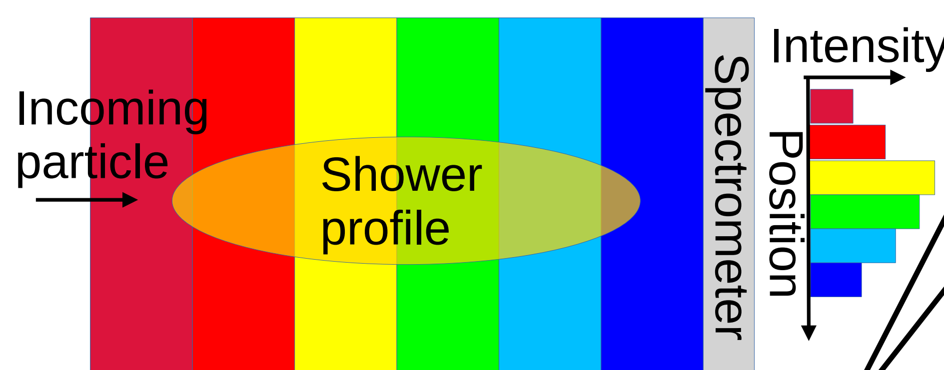
next band:
absorb wavelengths < 590 nm
emit at > 590 nm

…

rightmost nanodots:
absorb wavelengths < 410 nm
emit at > 420 nm

if high-Z substrate transparent in 400-700 nm, then no re-absorption of emitted light





Monochromators + PD?

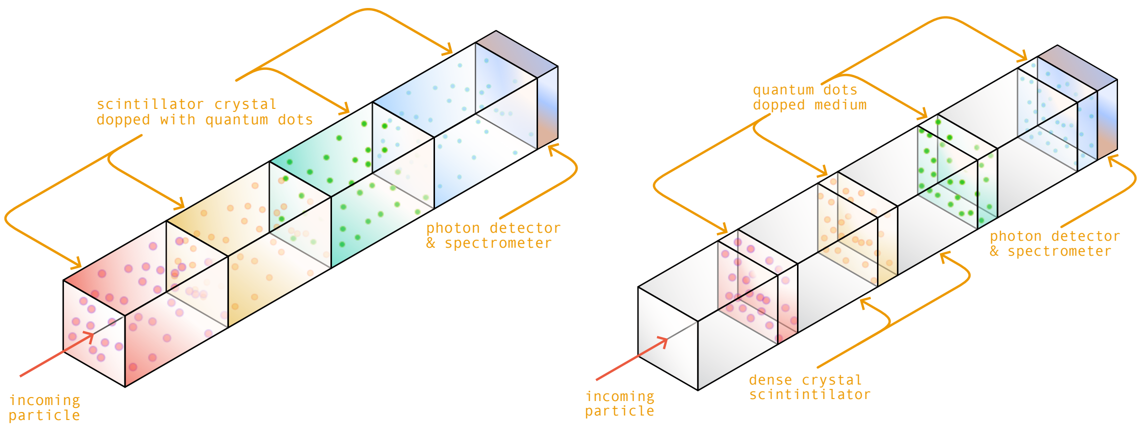
Y.T. Lin & G. Finlayson, Sensors 23, 4155 (2023)

Metalenses?

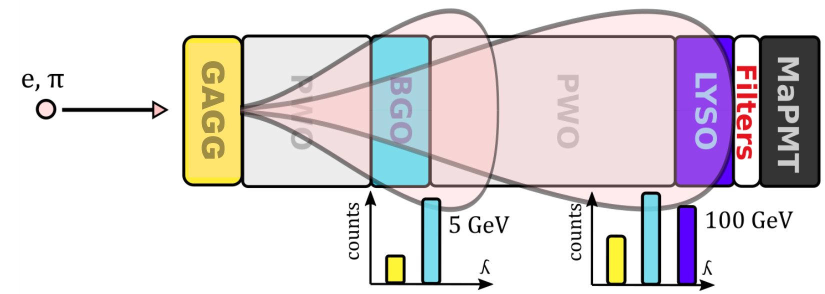
M. Khorasaninejad & F. Capasso, Science 358, 6367 (2017)

(shower profile via ***spectrometry***)

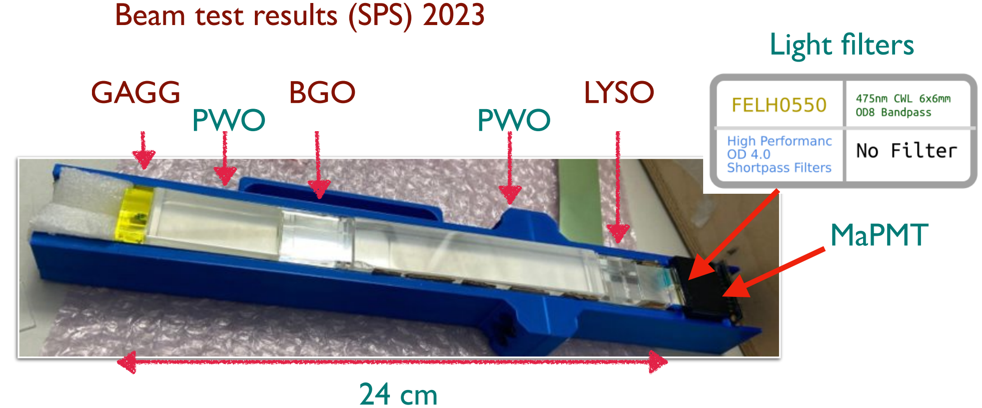
This slide courtesy Devanshi Arora, CALOR'24

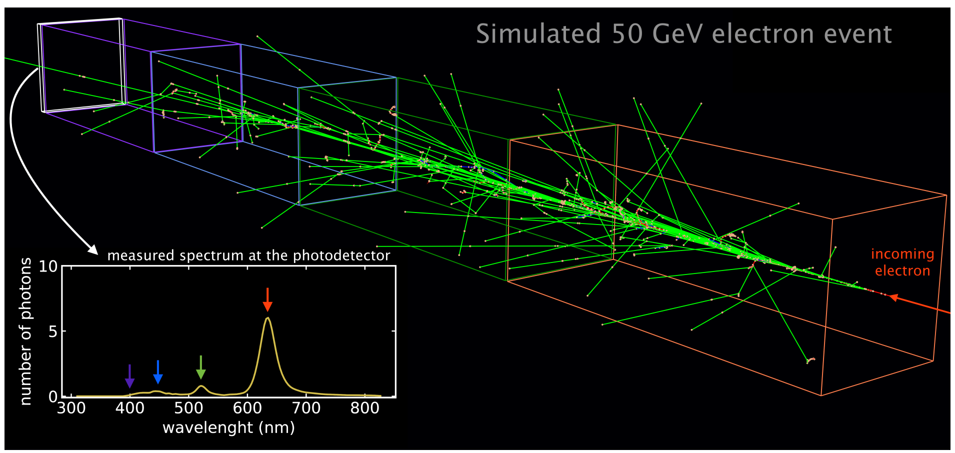


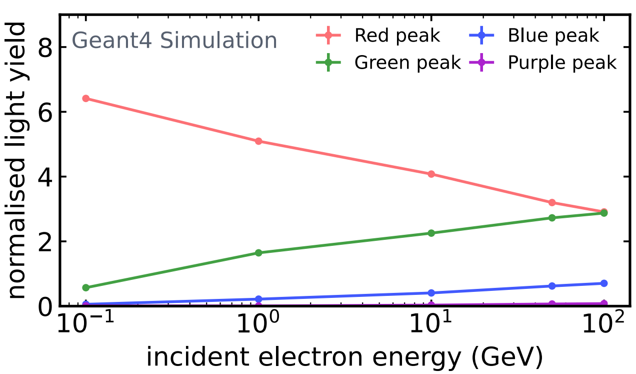
courtesy Y. Haddad, N U, Boston, USA



Beam test results (SPS) 2023

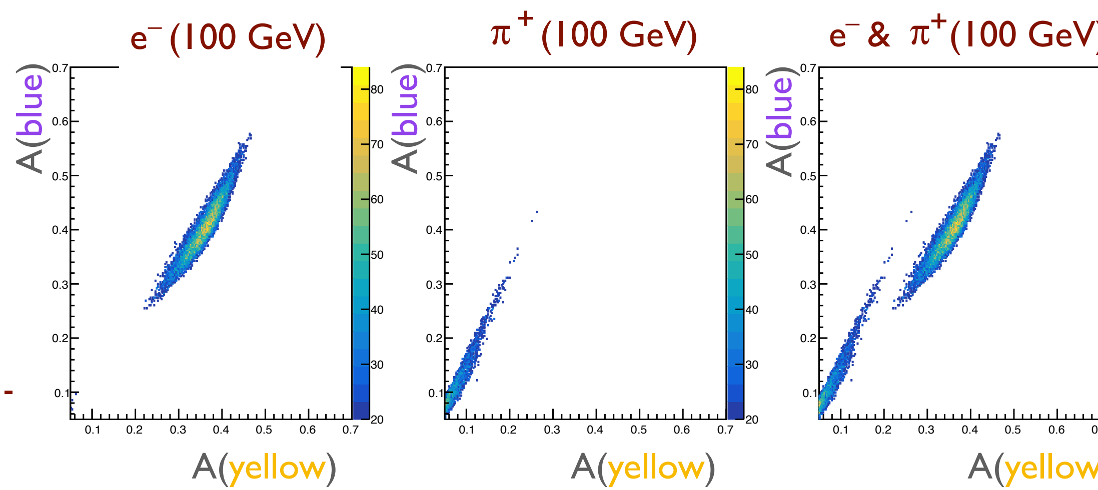






"Chromatic" energy measurement

"Chromatic" electron - pion discrimination



86% "chromatic" electron - pion discrimination

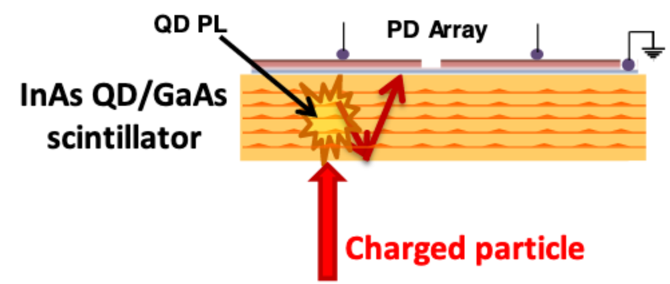
Quantum dots and wells: DoTPiX

standard scintillating materials are passive
- can not be amplified
- can not be turned on/off
- can not be modified once they are in place

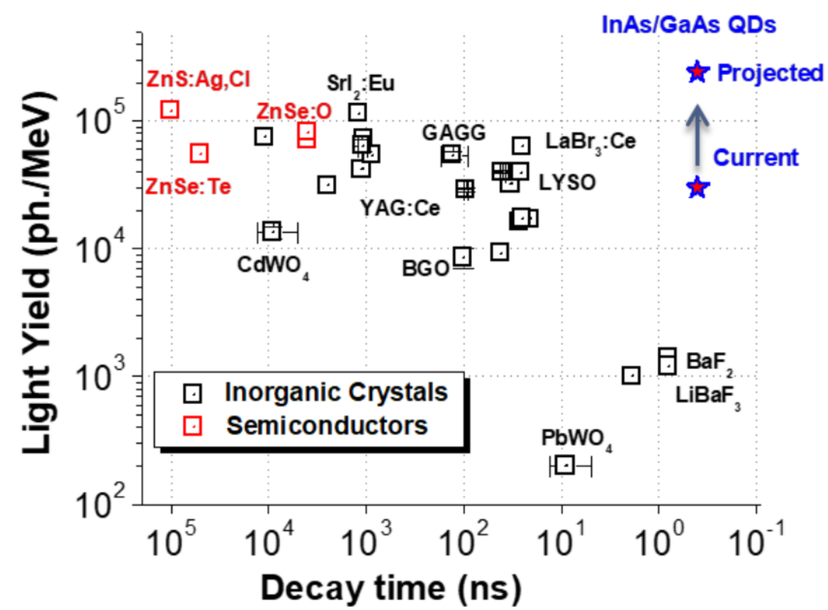
is it possible to produce active scintillating materials?
- electronically amplified / modulable
- pulsed / primed
- gain adapted in situ

scintillating (chromatic) tracker

https://link.springer.com/article/10.1557/s43580-021-00019-y



IR emission from InAs QD's integrated PD's (1-2 μm thick)



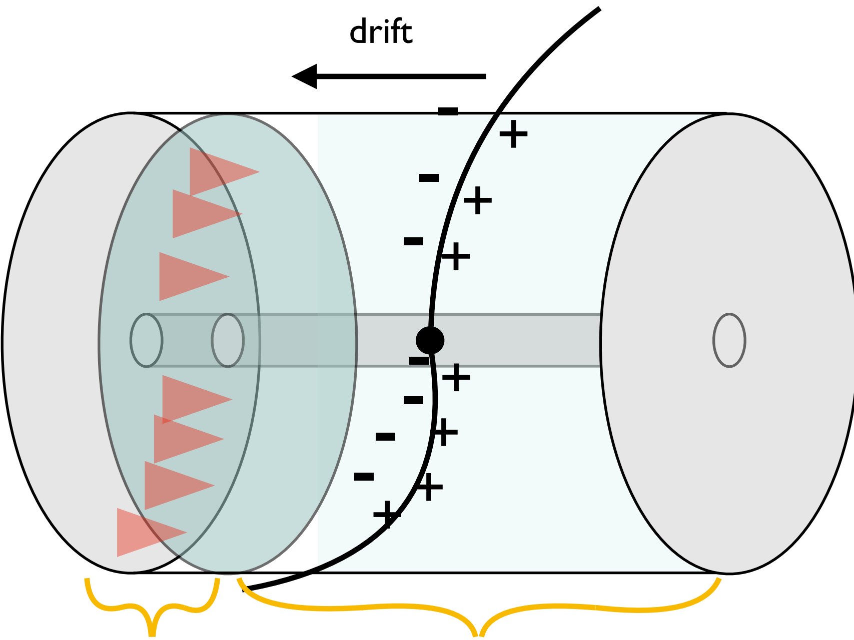
A charged particle enters the GaAs bulk, producing electron-hole pairs. The electrons are then quickly trapped by the positively charged InAs quantum dots (QDs). The QDs undergo photoluminescence (PL) and emit photons that travel through the medium (GaAs absorption edge at 250 nm). The emitted photons are collected by a immediately adjoining photodiode (PD) array.

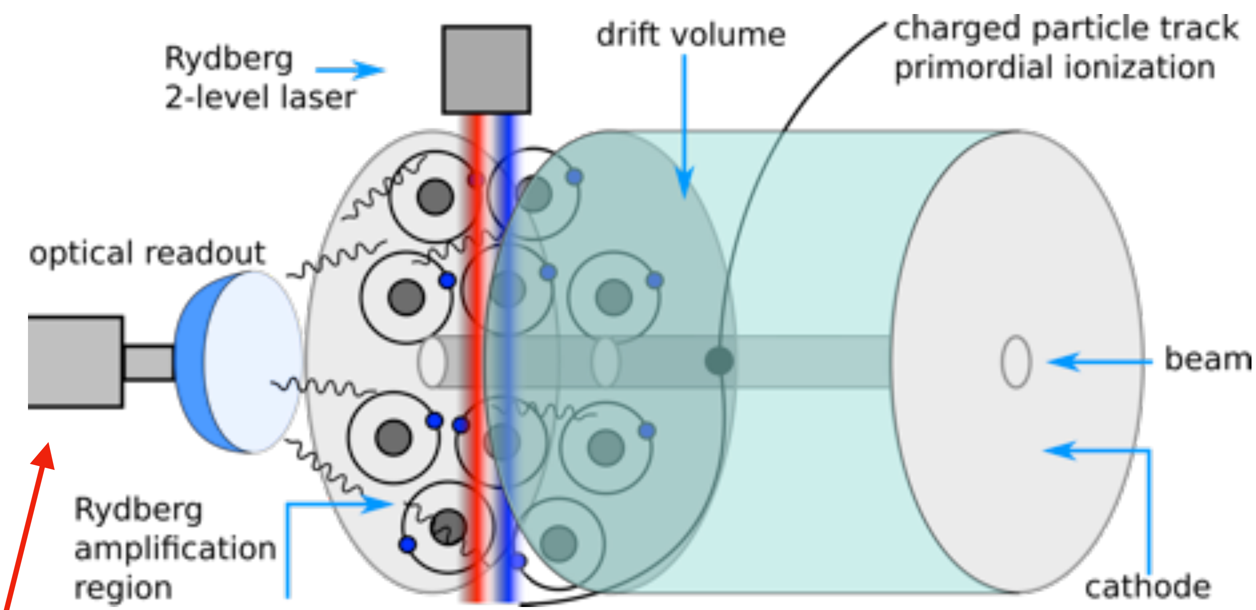
Novel Sensors for Particle Tracking: a Contribution to the Snowmass Community Planning Exercise of 2021, M.R. Hoeferkamp et al., arXiv:2202.11828

Rydberg atom TPC's

Georgy Kornakov / WUT

Act on the amplification region





enhanced electron signal through "priming" of gas in amplification region: ⟶ effective reduction of ionization threshold of gas in amplification region ⟶ higher electron yield

Rydberg atoms can serve to up-convert THz / GHz radiation into the optical regime ⟶ optical R/O of avalanche intensities

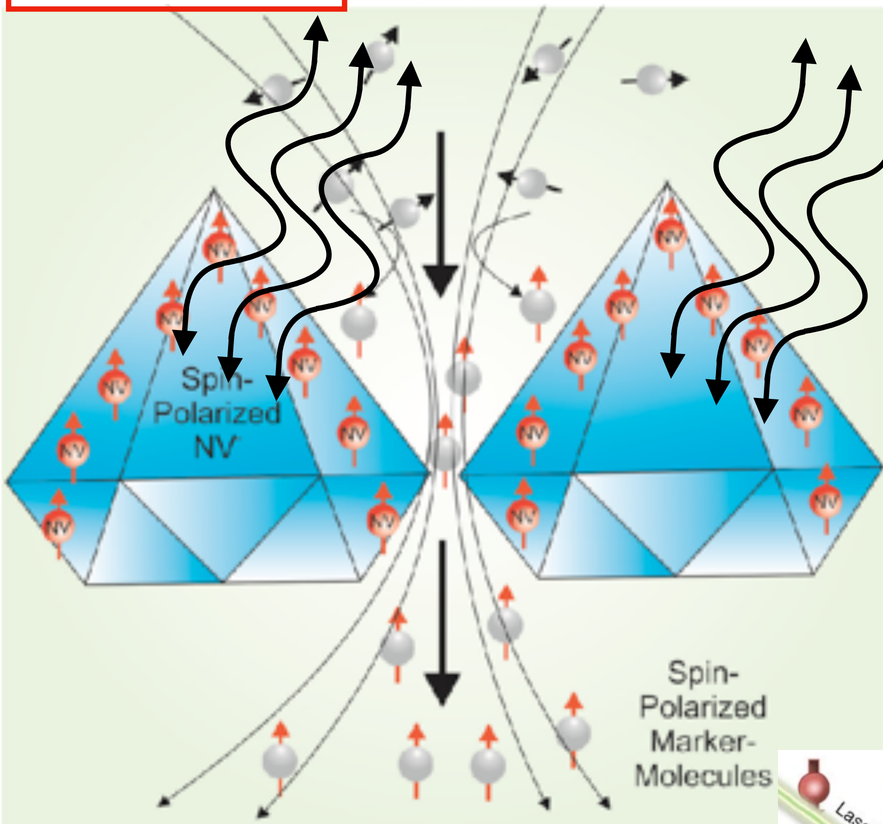
optically polarizable elements: Nitrogen-vacancy diamonds (NVD)

Georgy Kornakov / WUT

spin-spin scattering for helicity determination:
usually with polarized beams and/or polarized targets

introduce polarized scattering planes to extract track-by-track particle helicity

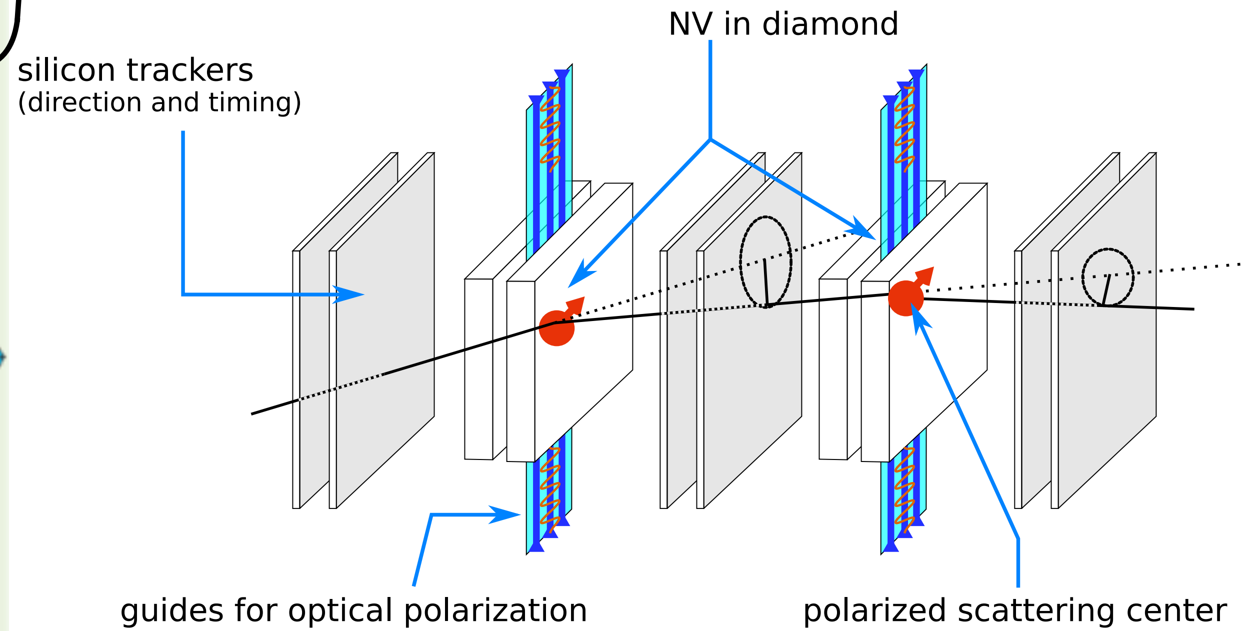
$10^{16} \sim 10^{18}$ / cm^3

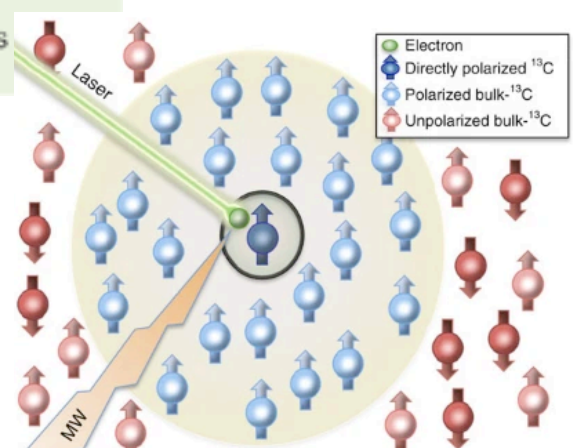


© Dr. Christoph Nebel, Fraunhofer IAF

https://www.metaboliqs.eu/en/news-events/MetaboliQs_PM_first_year.html

Diamond plates of up to 8 × 8 mm^2 in size, fabricated by Element Six



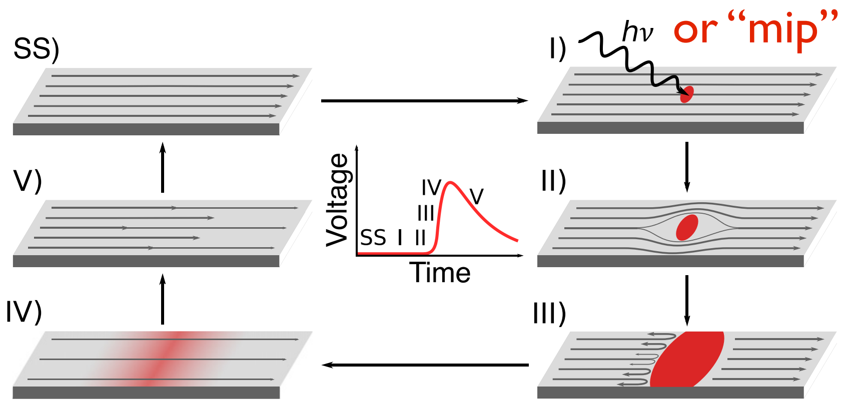


Local and bulk ^{13}C hyperpolarization in nitrogen-vacancy centred diamonds at variable fields and orientations, G. Alvarez et al., *Nature Communications* **6**, 8456 (2015)

https://www.nature.com/articles/ncomms9456

x 10^2

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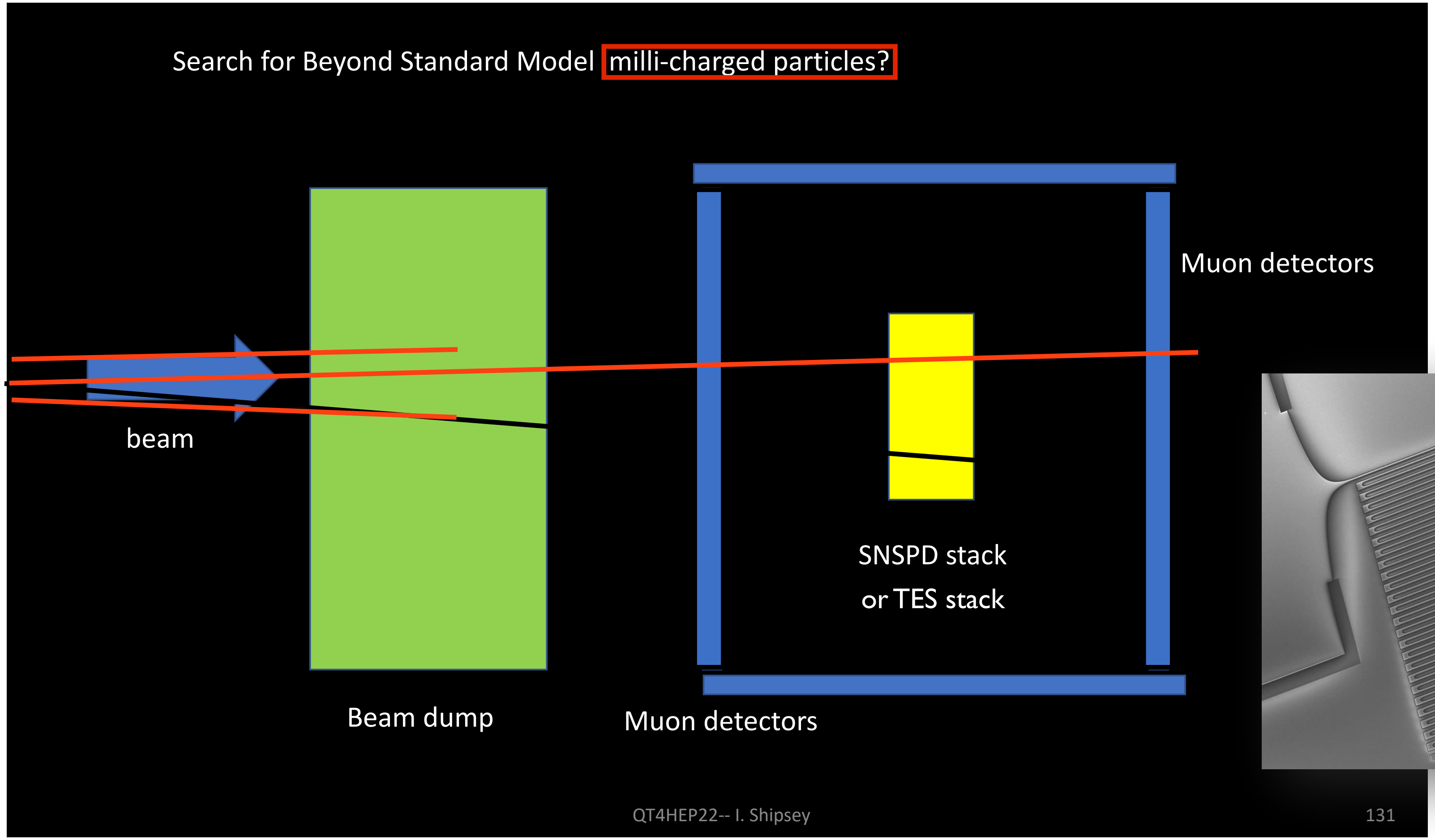
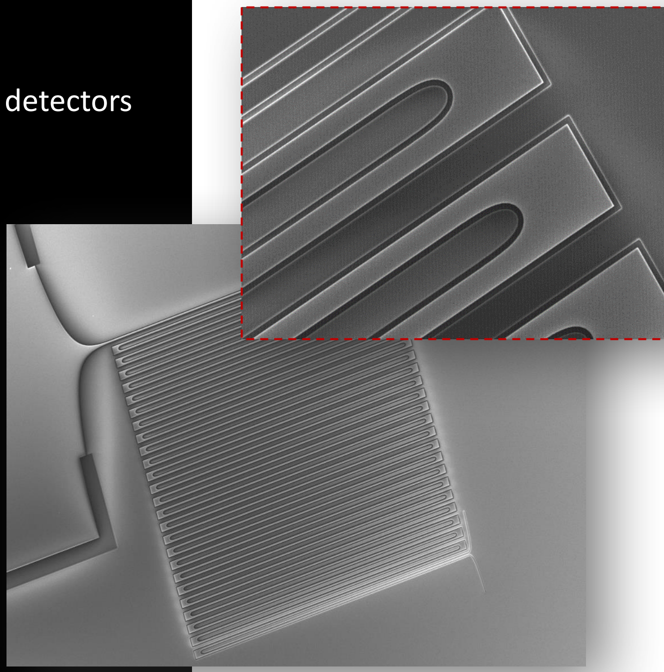
Moving to SC strips conventional lithography → scale up
Development towards SC SSPM

QT4HEP22-- I. Shipsey 125

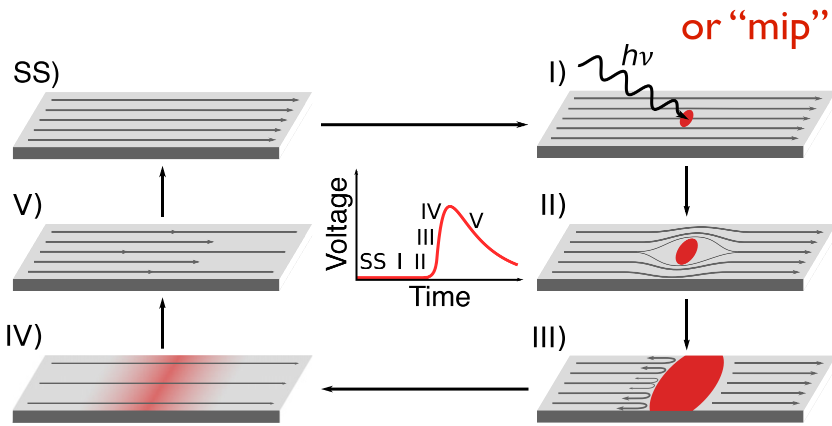


mip: ~20 keV/100 μm

x 10^6 sensitivity



Extremely fast detectors: SNSPD



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Snowmass2021 - Letter of Interest

Superconducting Nanowire Single-Photon Detectors

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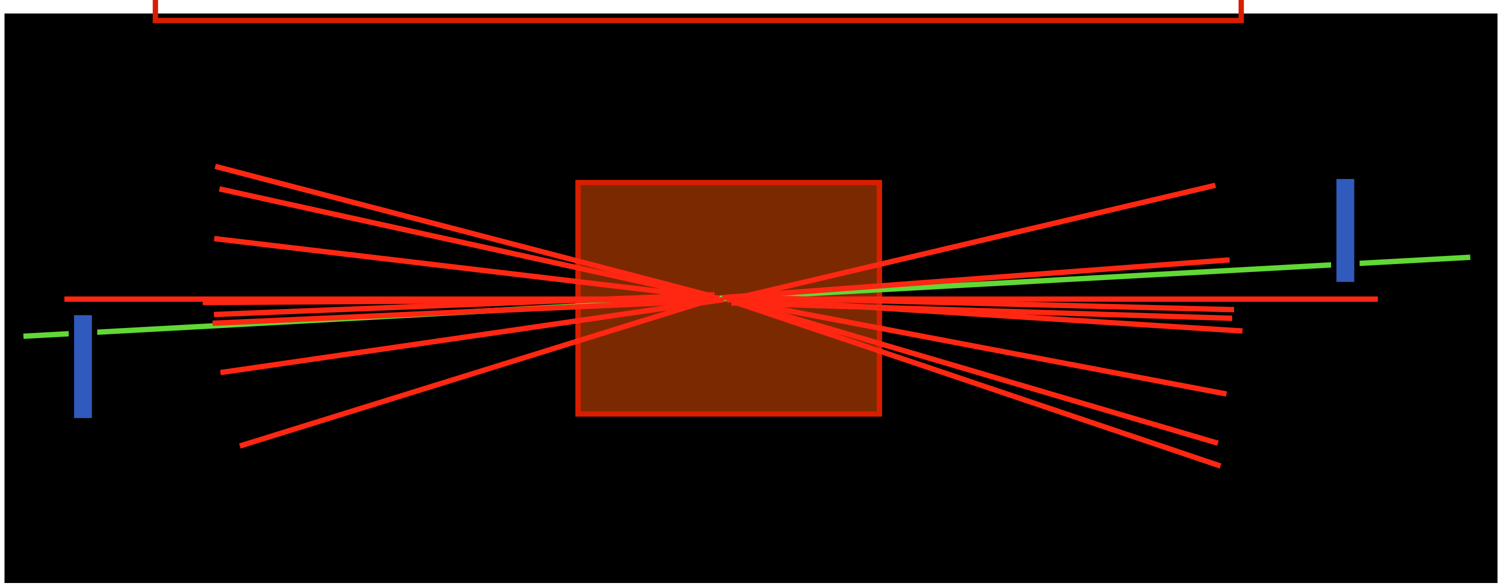
Moving to SC strips conventional lithography → scale up
Development towards SC SSPM

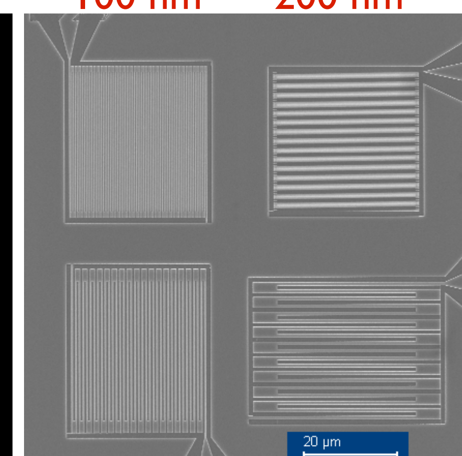
QT4HEP22-- I. Shipsey 125

diffractive scattering via ps-resolution tracking in Roman pots



@ 2.8 K

100 nm 200 nm



400 nm 800 nm

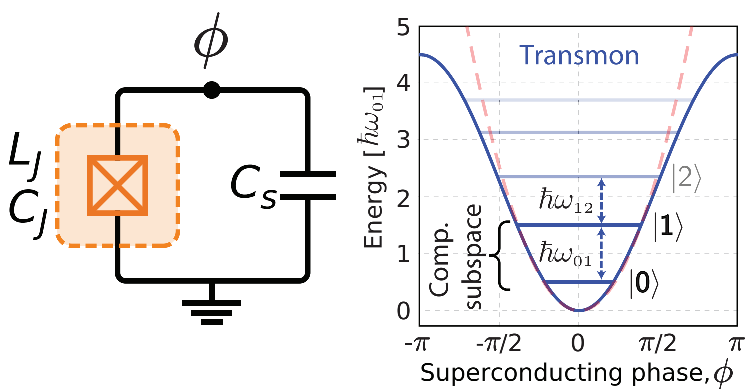
S. Lee et al., (2024)
arXiv:2312.13405v2
SNSPD w/ p@120 GeV
for use e.g. at EIC

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



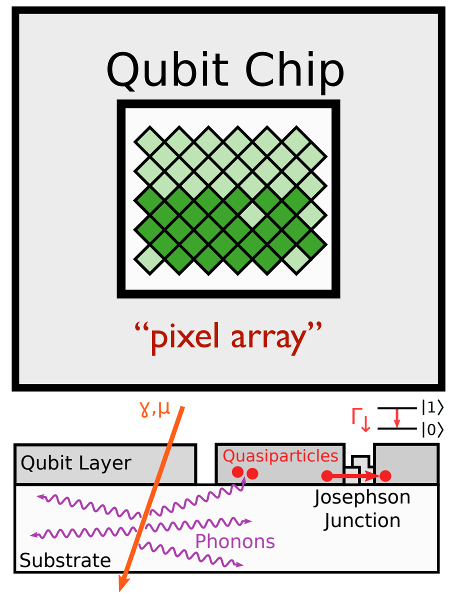
variant of a harmonic oscillator (with numerous equally-spaced energy levels):

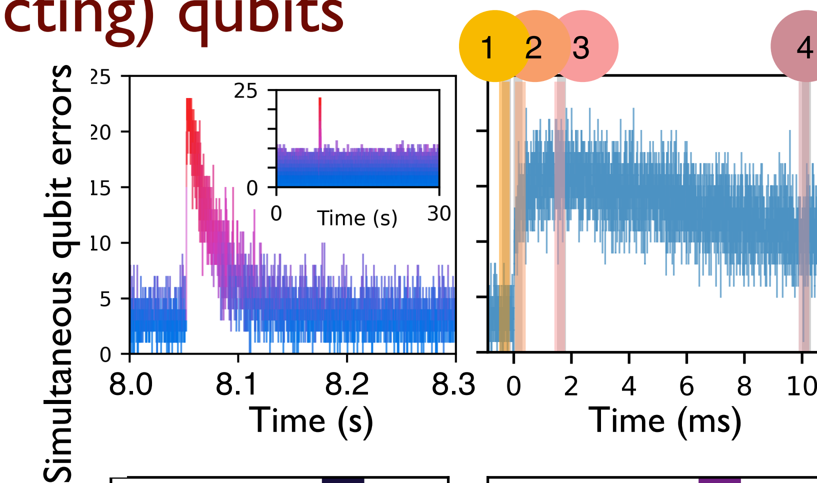
need to be able to define a computational subspace consisting of only two energy states (usually the two-lowest energy eigenstates) in between which transitions can be driven without also exciting other levels in the system: $|0\rangle$ and $|1\rangle$

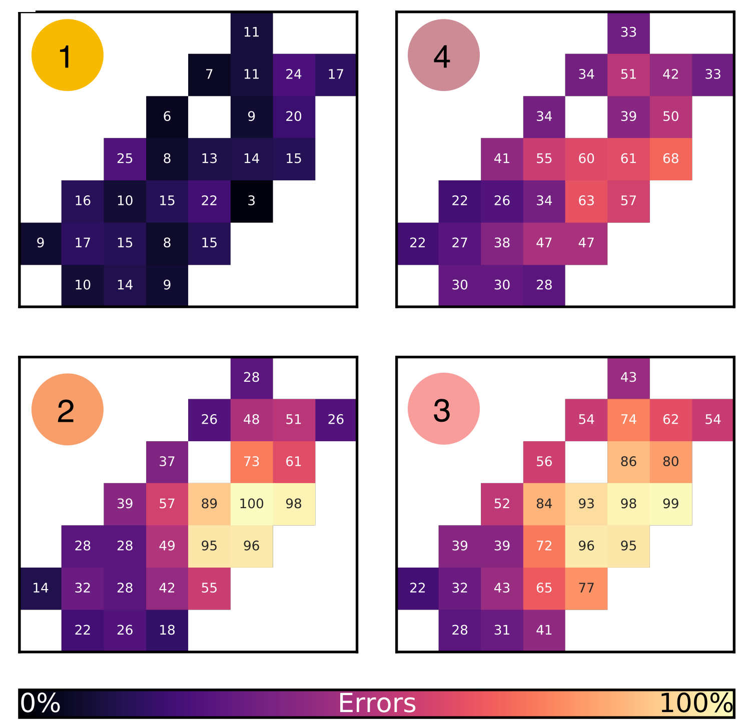
Energy scale: 25μeV (cosmic: 0.1~1 MeV)

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

RECFA Detector R&D roadmap 2021

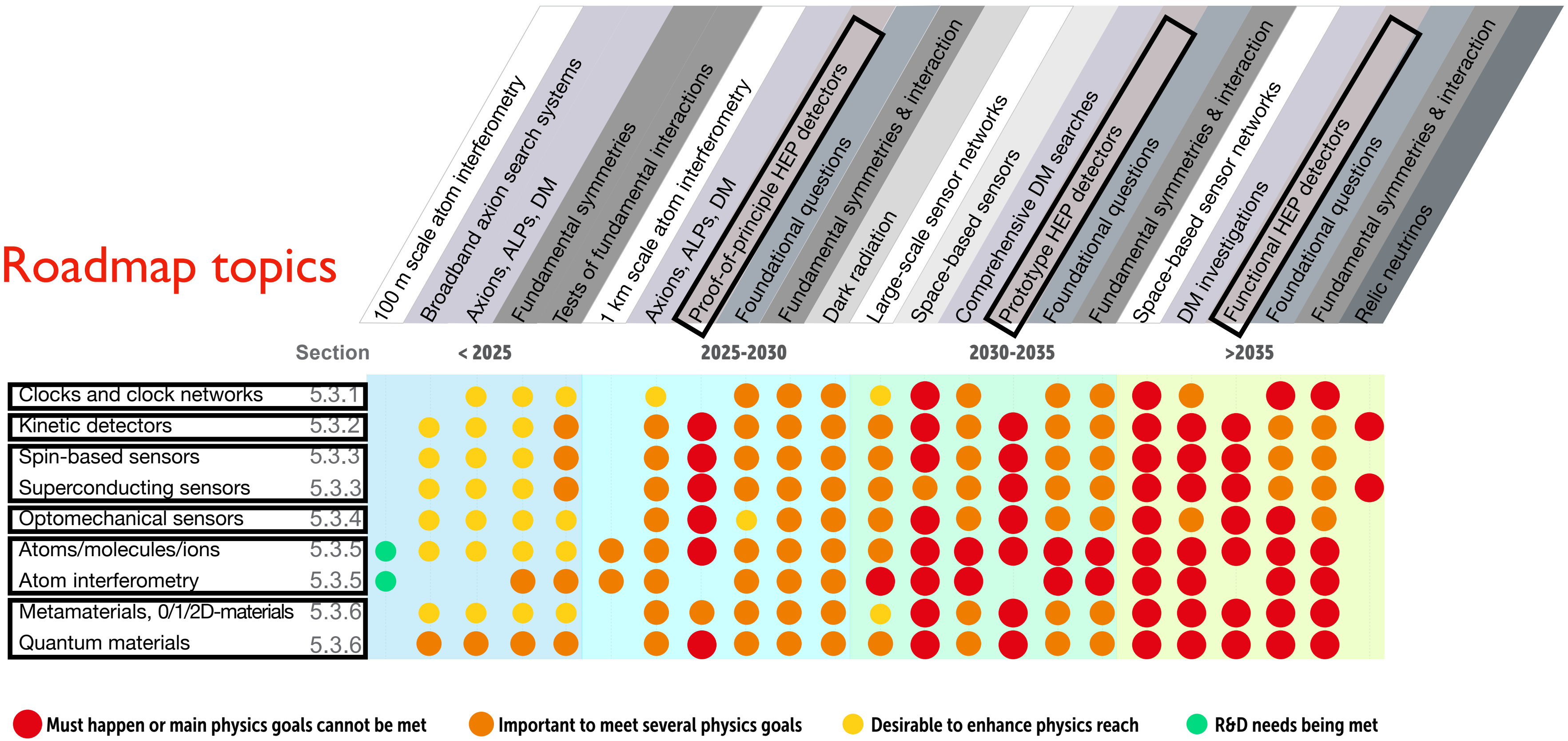
https://cds.cern.ch/record/2784893

Chapter 5: Quantum and Emerging Technologies Detectors

focus on physics *and* technology

Roadmap topics

1
2
3
4
5
6



Requires: R&D on quantum sensors

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)

2.2023 ff
- platform convenors identified (~30)
- 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

7.2023
- LOI based on ~6 initial WP's for discussion w/ DRDC (by RDq conveners, with interested signatories)

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)

1.3.2024
- proposal based on 6 initial WP's (& sub-WP's) submitted to DRDC (by RDq convenor)

4.6.2024
- presentation of final version of the proposal* (milestones, deliverables) to DRDC
- formal constitution of DRD5 / "RDq" collaboration

Approval by CERN RB 6.6.2024

call for wide participation in DRD5

* https://cds.cern.ch/record/2901426

DRD5: WP's and structure

Quantum sensor R&D: outlook

WP1 — Exotic systems in traps & beams (HCI's, molecules, Rydberg systems, clocks, interferometery, …)

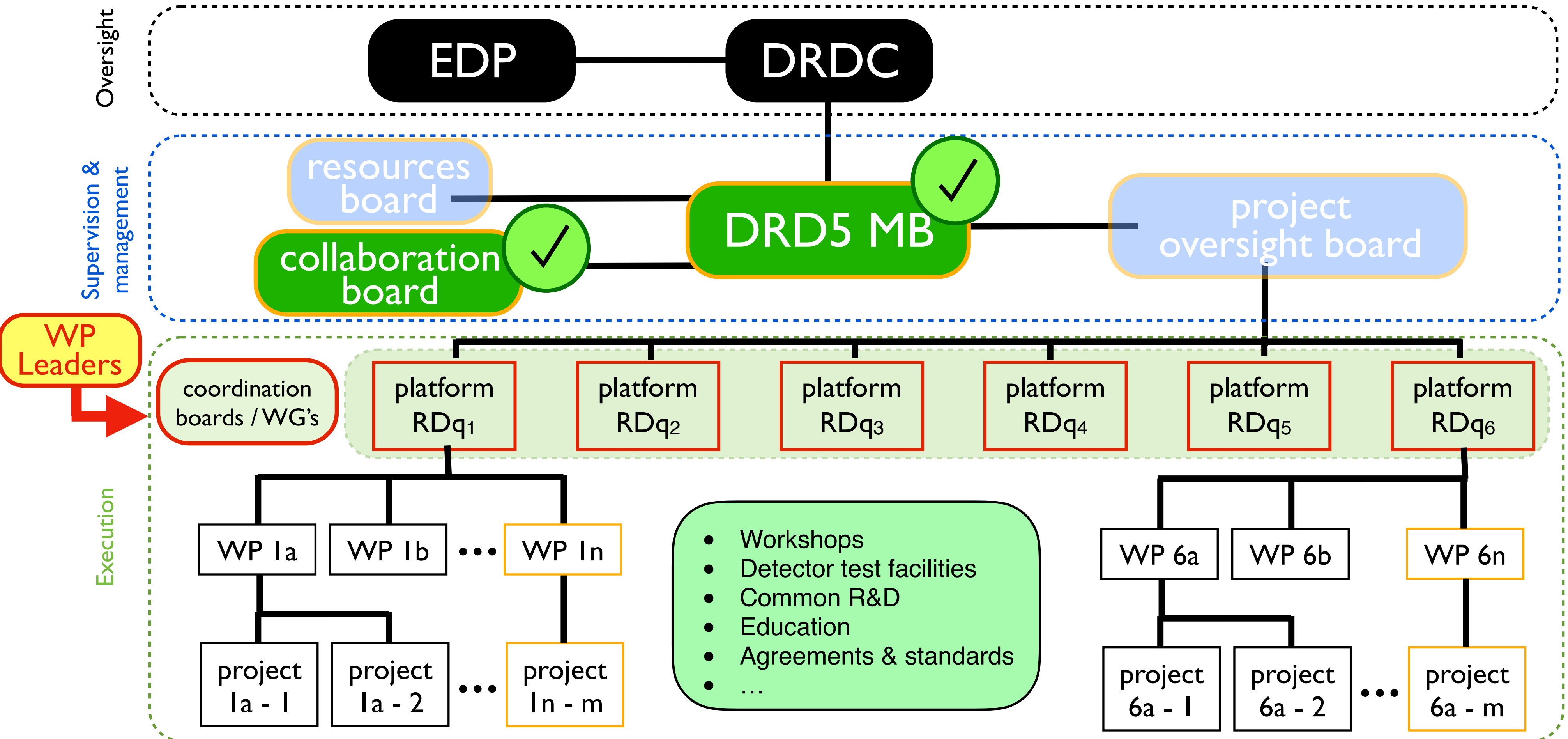
WP2 — Quantum materials (0-, 1-, 2-D) (Engineering at the atomic scale)

WP3 — Quantum superconducting systems (4K electronics; MMC's, TES, SNSPD, KID's/…; integration challenges)

WP4 — Scaling up to macroscopic ensembles (spins; nano-structured materials; hybrid devices, opto-mechanical sensors,…)

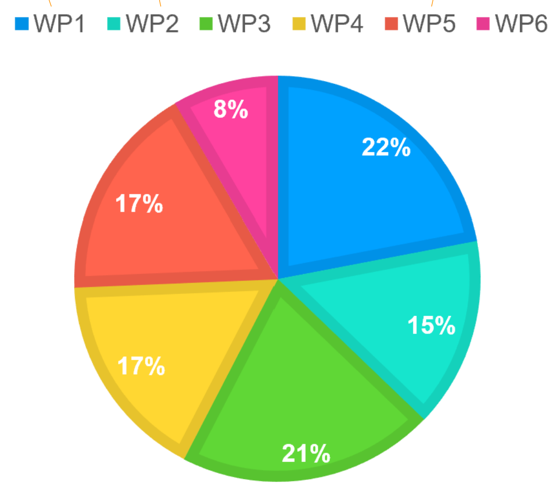
WP5 — Quantum techniques for sensing (back action evasion, squeezing, entanglement, Heisenberg limit)

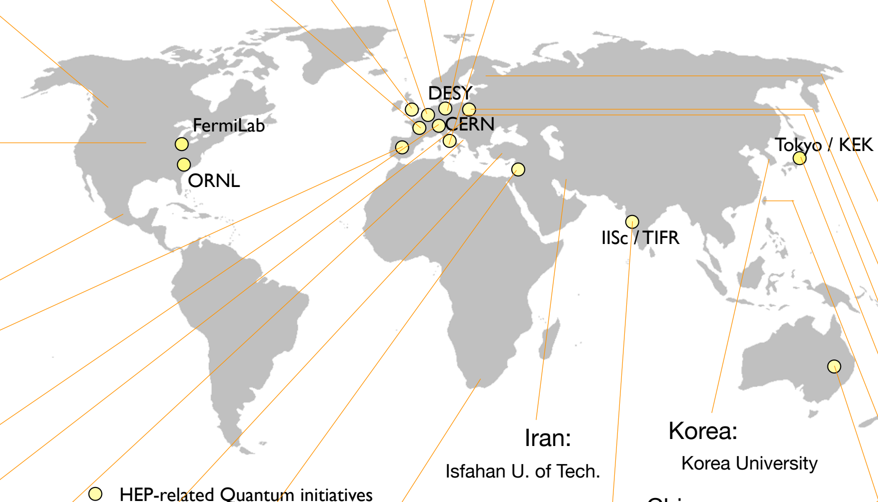
WP6 — Capability expansion (cross-disciplinary exchanges; infrastructures; education)



(WP's may be mono-site or multi-site but carry the responsibility to shepherd the spread-out activities related to their specific projects)

Creation of a global poly-disciplinary community: DRD5 (112 involved groups)





UK: Oxford University, Univ. of Warwick, Univ. of Birmingham, NPL, Imperial College, Univ. of Southhampton, Univ. of Sussex, Univ. of Manchester, Univ. of Liverpool

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

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, IEM, CSIC

Switzerland: U. of Geneva, U. of Zürich, CERN (QTI), ETHZ

Netherlands: U. of Groningen

Norway: Oslo University

Austria: IQOQI Vienna, TU Wien

Croatia: Inst. of Physics, Zagreb

Türkiye: Ankara Univ., Duzce Univ., Sabanci Univ.

Israel: Technion, Haifa

South Africa: U. of Cape Town

Iran: Isfahan U. of Tech.

India: IITTP, Tirupati, IEM, Kolkata, TIFR, Mumbai, LPU, Punjab, University SOA Bhuvaneswar, Institute of Engineering and Management, Kolkata

Korea: Korea University

China: IHEP, Beijing

Australia: University of Western Australia, Swinburne University of Technology

Taiwan: Academia Sinica & NTU

Germany: PTB, 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, Charles Univ., Prague

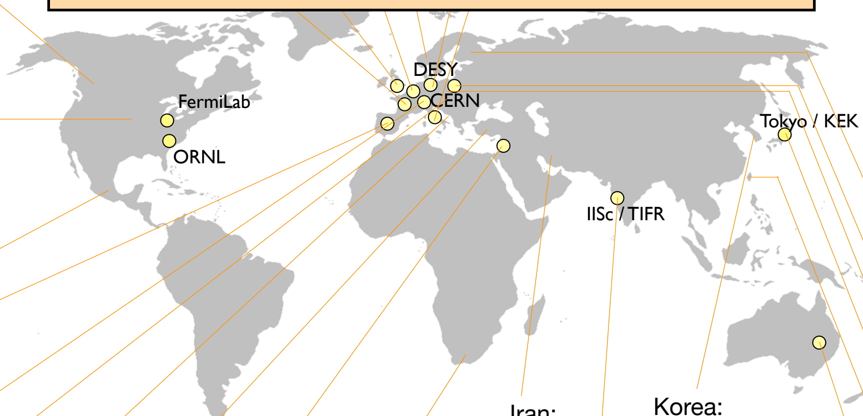
Japan: QUP / KEK, Kyoto University, Tokyo University / ICEPP, University of Shizuoka

Creation of a global poly-disciplinary community: DRD5 (112 involved groups)

Quantum sensor R&D collaboration currently being ramped up, 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!)



HEP-related Quantum initiatives

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

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

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
- IEM, CSIC

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

Netherlands:
- U. of Groningen

Norway:
- Oslo University

Austria:
- IQOQI Vienna
- TU Wien

Croatia:
- Inst. of Physics, Zagreb

Türkiye:
- Ankara Univ.
- Duzce Univ.
- Sabanci Univ.

Israel:
- Technion, Haifa

South Africa:
- U. of Cape Town

Iran:
- Isfahan U. of Tech.

India:
- IITTP, Tirupati
- IEM, Kolkata
- TIFR, Mumbai
- LPU, Punjab
- University SOA Bhuvaneswar
- Institute of Engineering and Management, Kolkata

Korea:
- Korea University

China:
- IHEP, Beijing

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

Taiwan:
- Academia Sinica & NTU

Germany:
- PTB
- 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
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- Nat. Lab. FAMO / Torun

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- University West Bohemia
- Charles Univ., Prague

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

thank you!