# 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

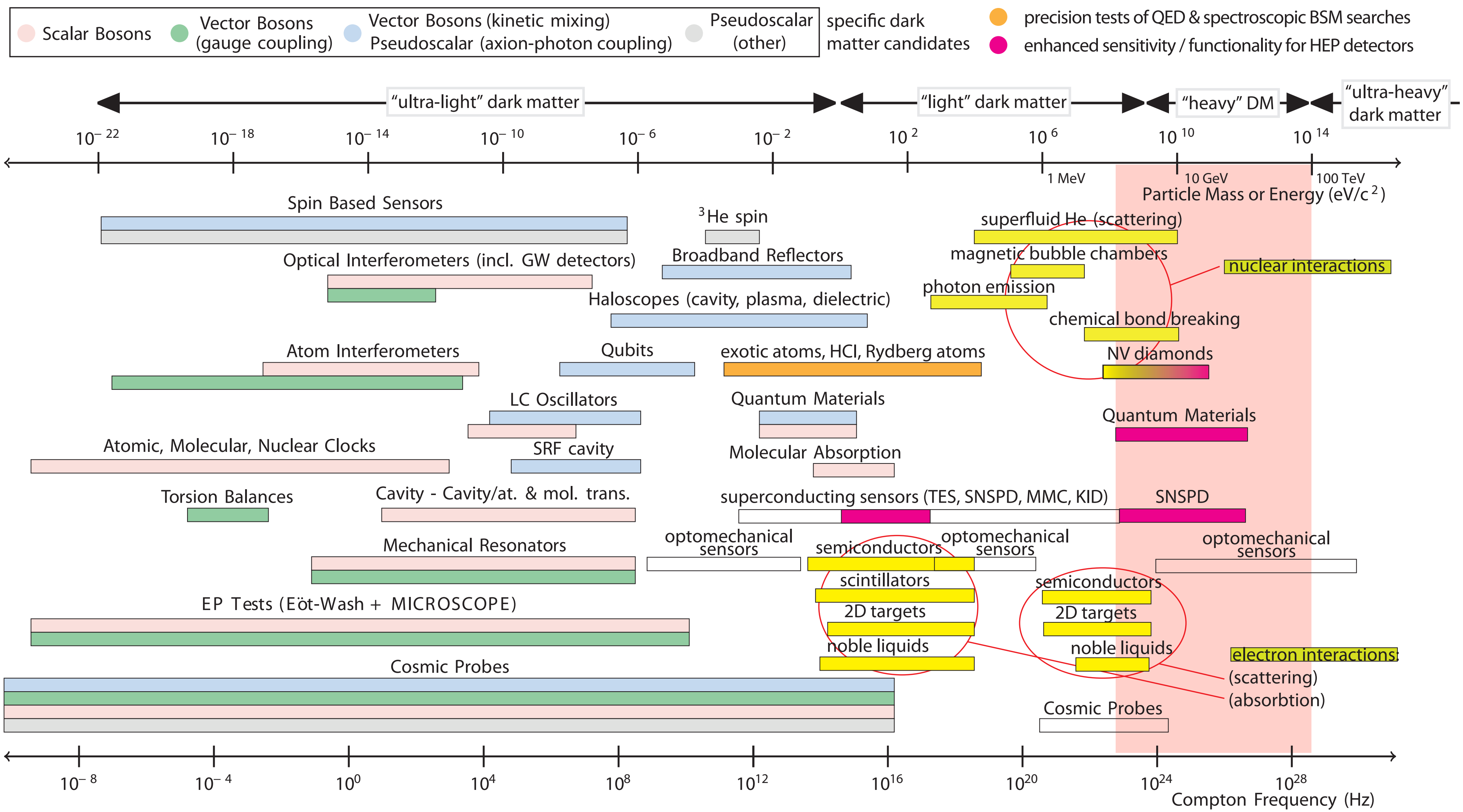
***Then, a "quantum sensor" is a device, the measurement (sensing) capabilities of which are enabled by our ability to manipulate and/or read out its quantum states.***

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)

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




"low" energy

"high" energy

# 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

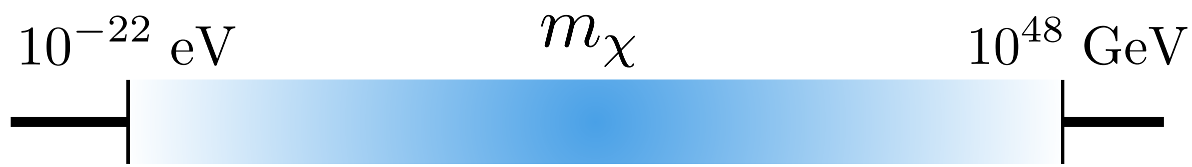
(focus on activities with CERN involvement, partly under the CERN QTI-2 program)

- 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

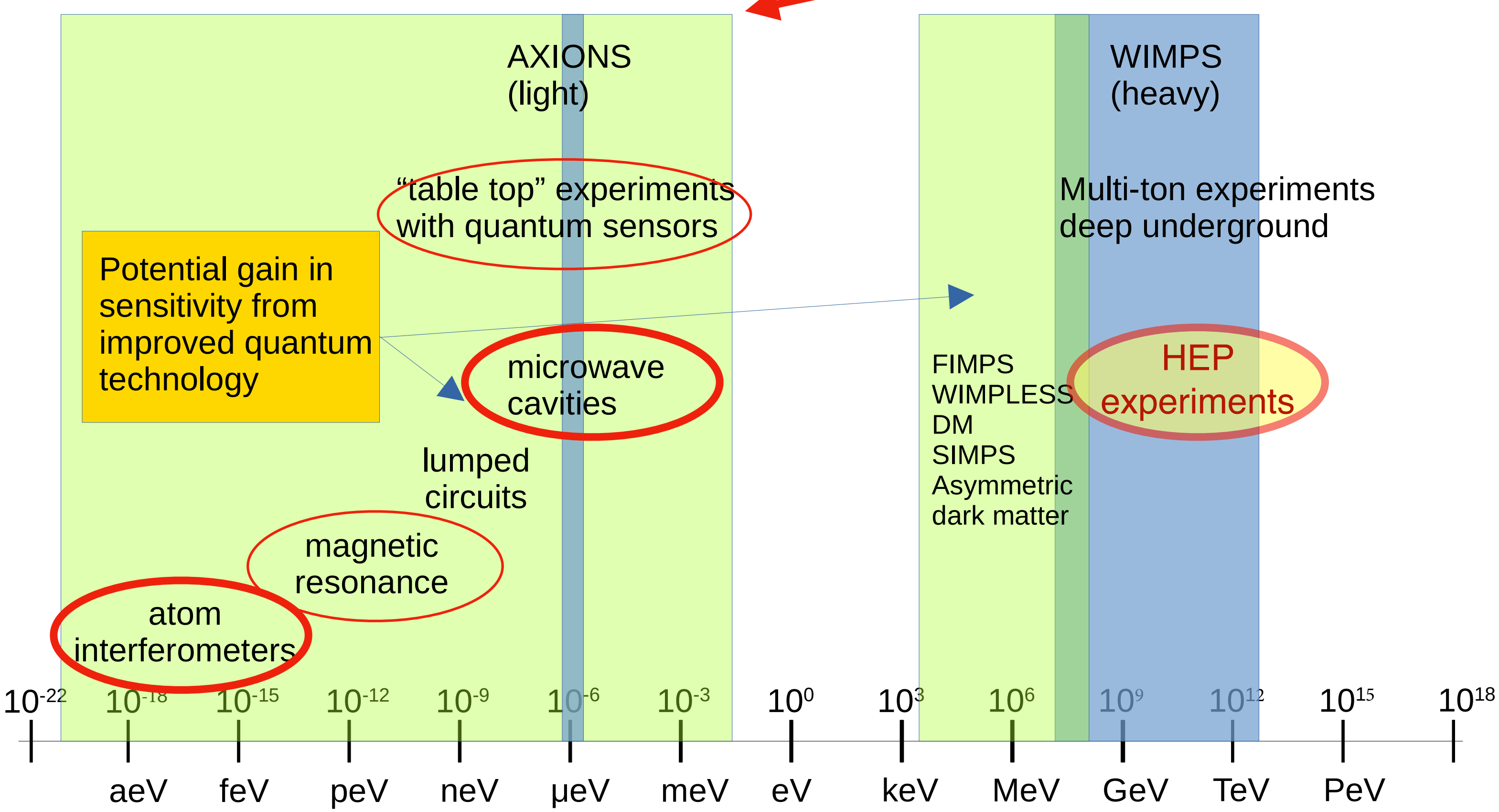
**Axions, ALP's, DM & non-DM UL-particle searches**

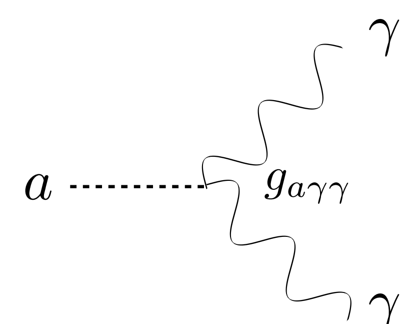



cavity size = axion size
axion mass = unknown

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

system noise temperature
cryo-amplifiers JJPA



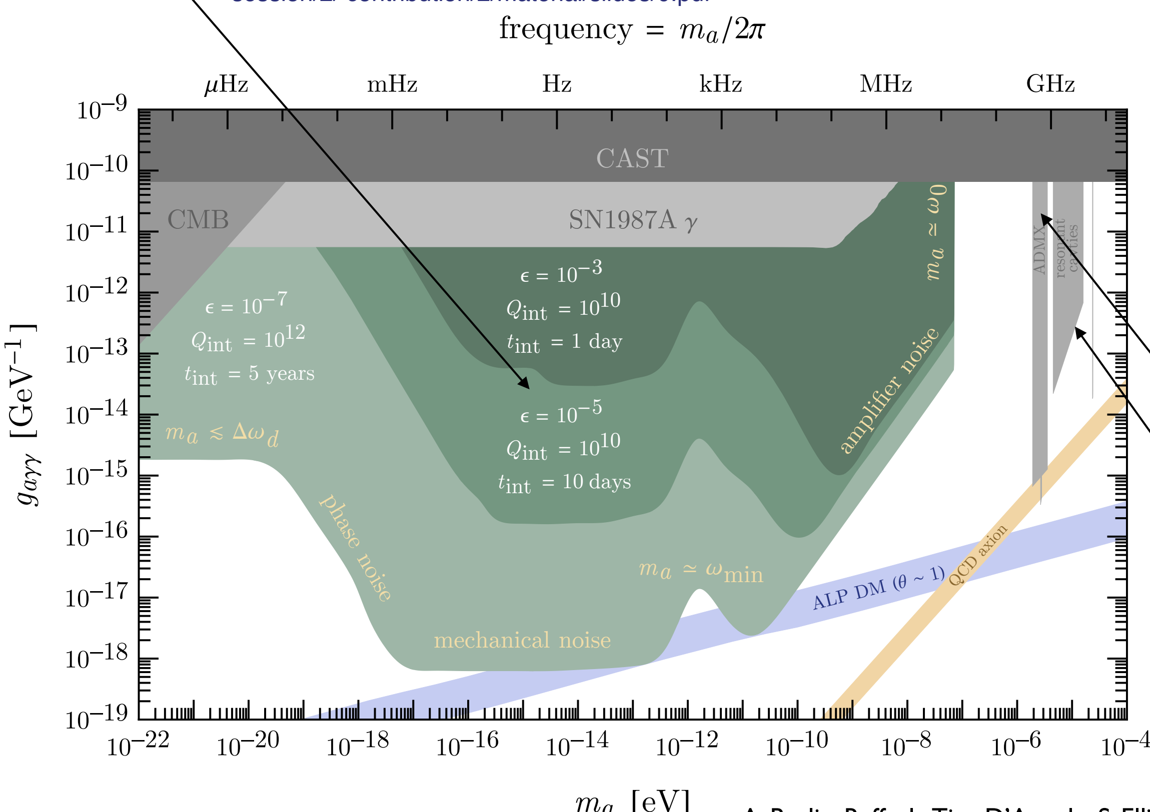

(but not only…)

# 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




ADMX experiment

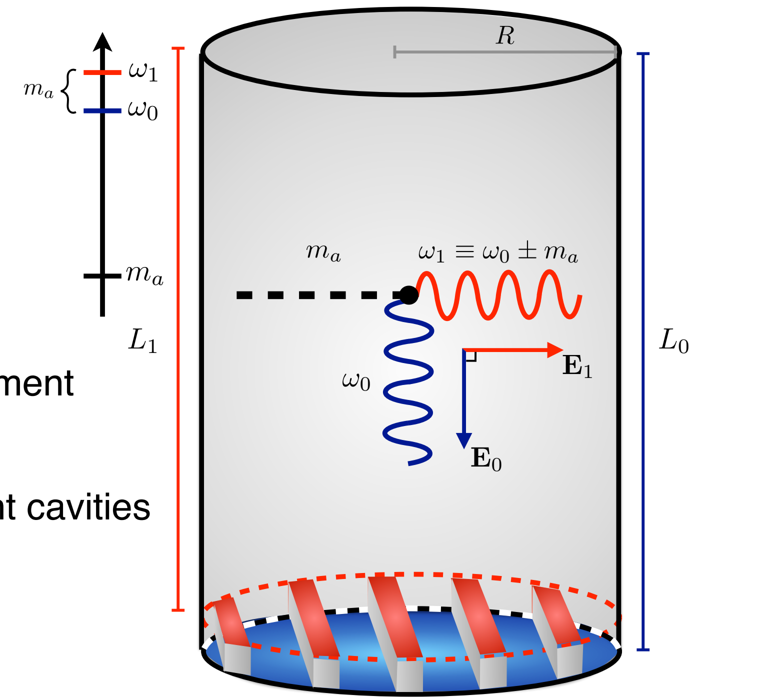
resonant cavities

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 $\omega_0$ 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 $\omega_0$ and $\omega_1$ 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

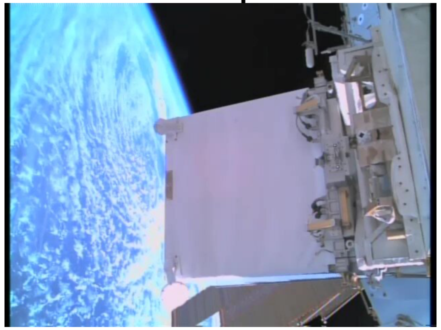
satellite missions:

## 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 $1 \times 10^{-18}$ stability

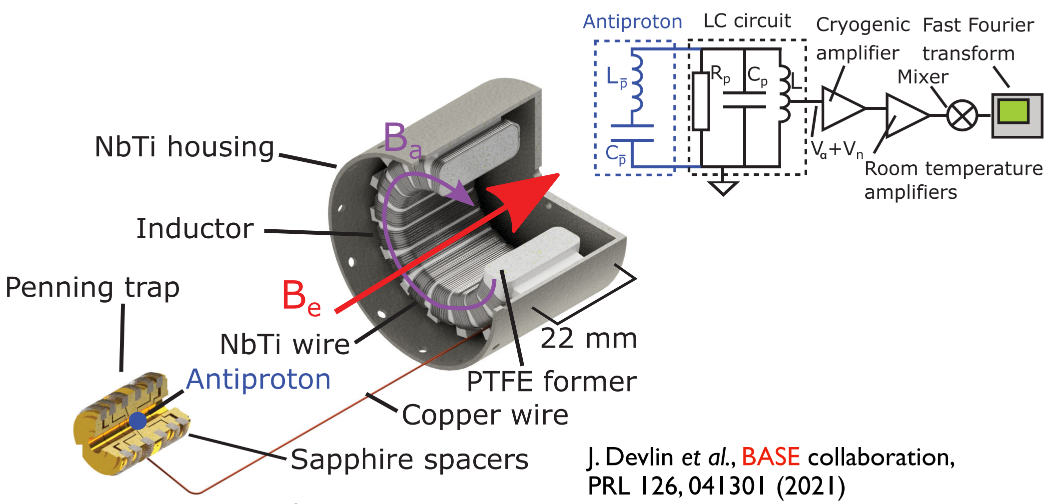
## AION: ~2045 satellite mission

## AEDGE: ~2045 satellite mission

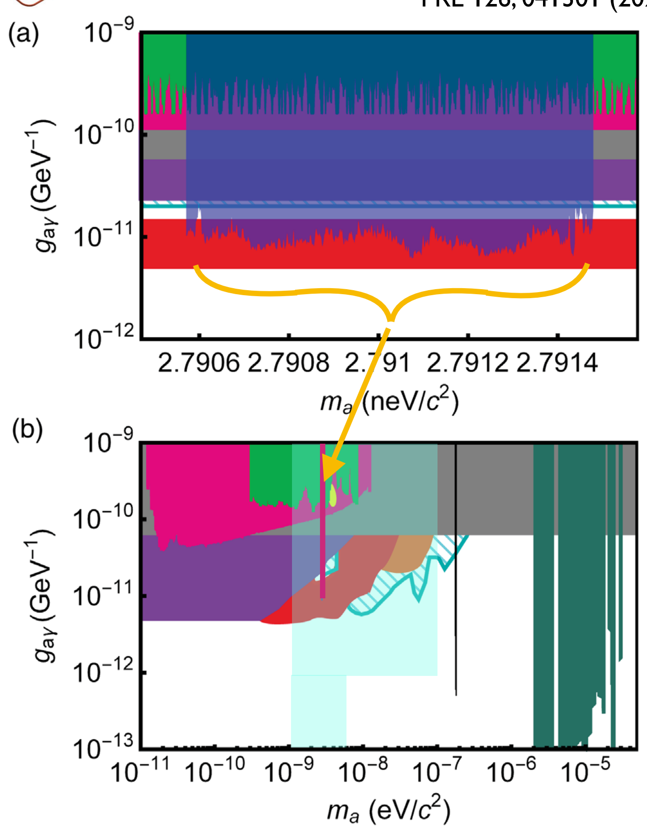
El-Neaj, Y.A., Alpigiani, C., Amairi-Pyka, S. *et al*. AEDGE: Atomic Experiment for Dark Matter and Gravity Exploration in Space. *EPJ Quantum Technol*. **7**, 6 (2020). https://doi.org/10.1140/epjqt/s40507-020-0080-0

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

**Trapped p̄: symmetry tests, DM searches**




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




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

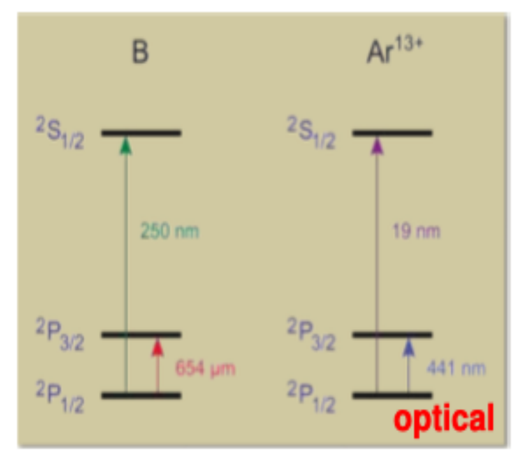
**HCIs: much larger sensitivity to variation of α and for dark matter searches than current clocks**

- 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

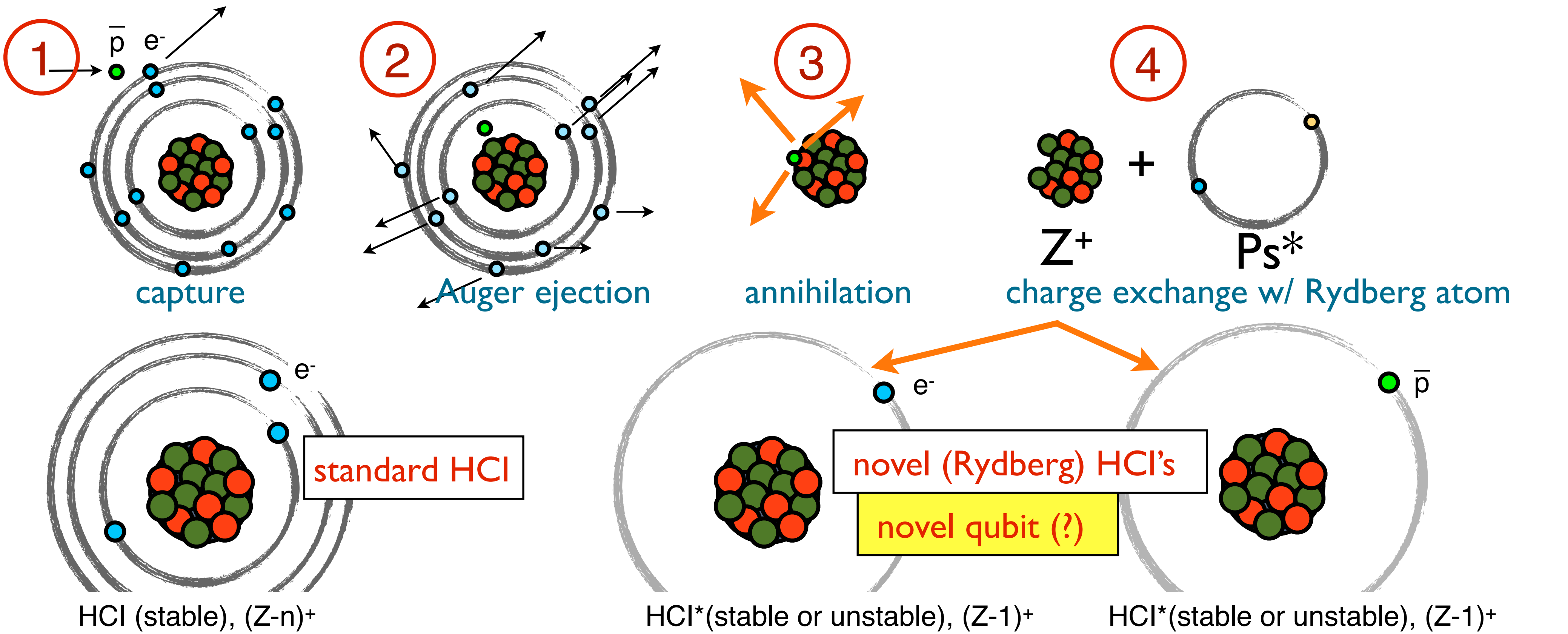
| | |
|---|---|
| Binding energy | ~ $Z^2$ |
| Hyperfine splitting | ~ $Z^3$ |
| QED effects | ~ $Z^4$ |
| Stark shifts | ~ $Z^{-6}$ |



# 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: p̄EDM? 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 |

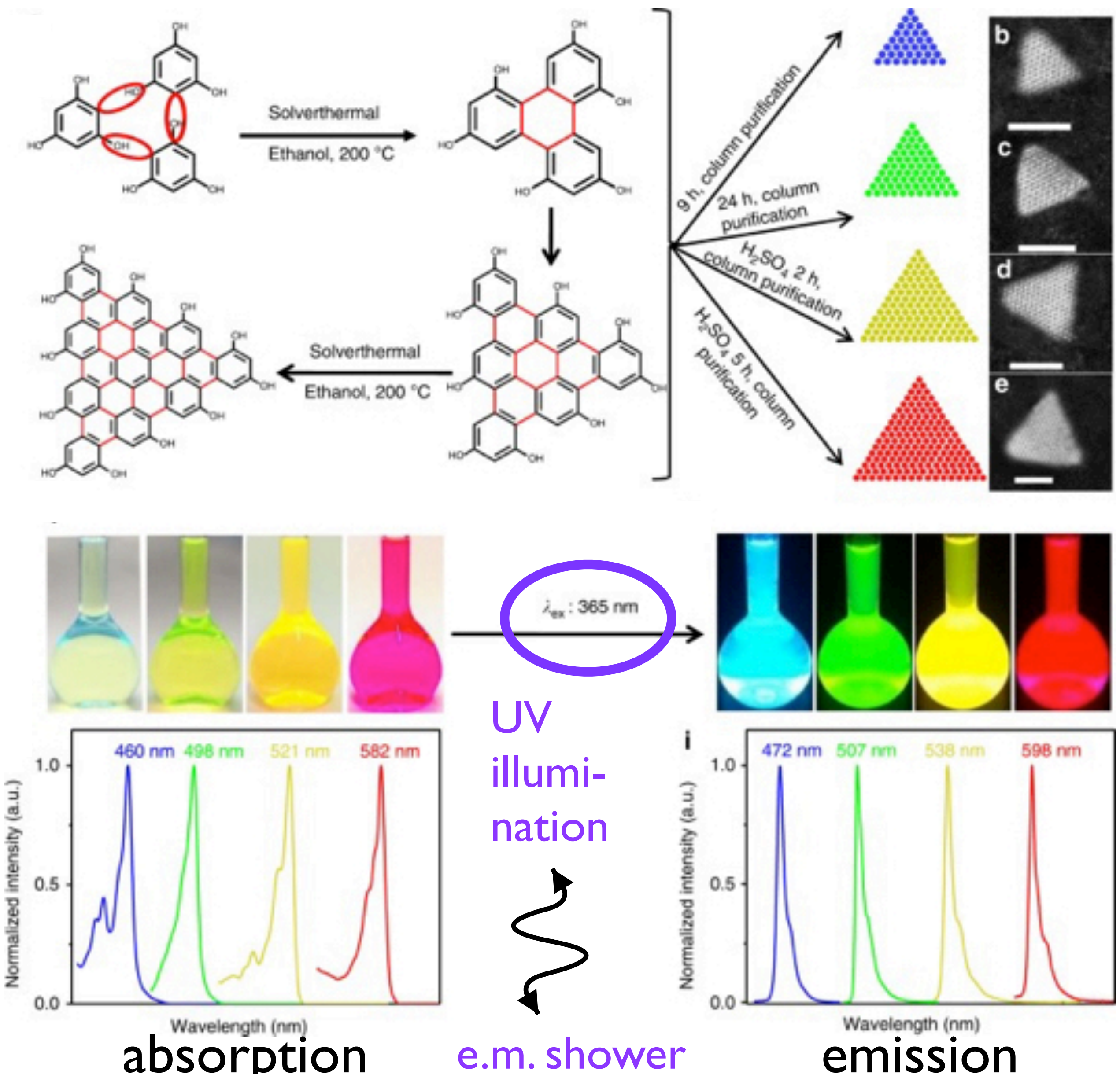
## Spin-based sensors

| | |
|---|---|
| quantum-polarized helicity detection | helicity detectors |

## Superconducting sensors

| | |
|---|---|
| quantum pixel ultra-sensitive tracking | milli-charge trackers |

# Quantum dots: chromatic calorimetry




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

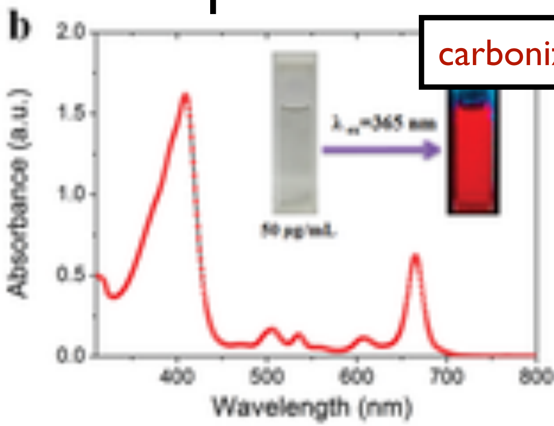
requires:

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

select appropriate nanodots

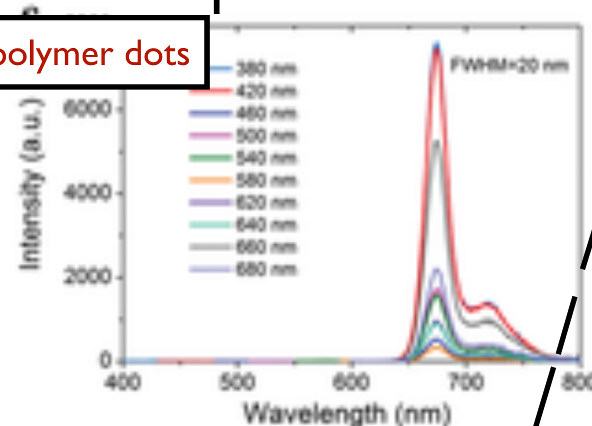
e.g. triangular carbon nanodots

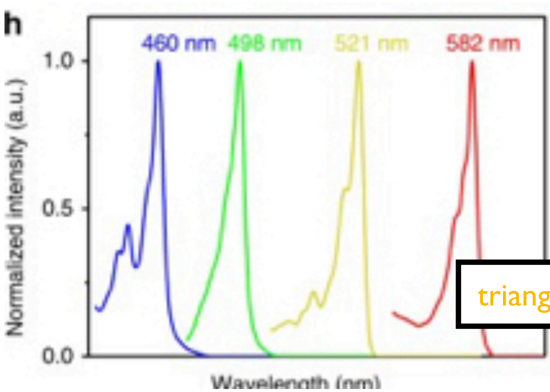
absorption spectrum



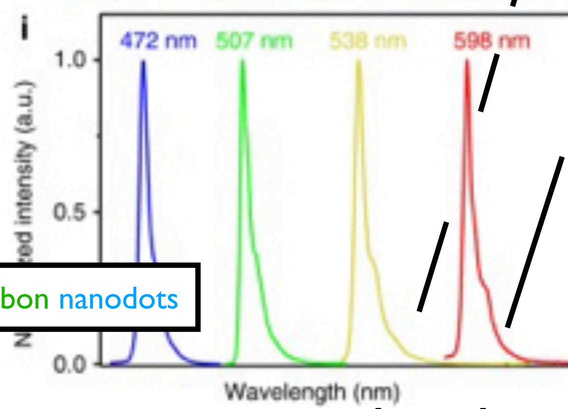

carbonized polymer dots

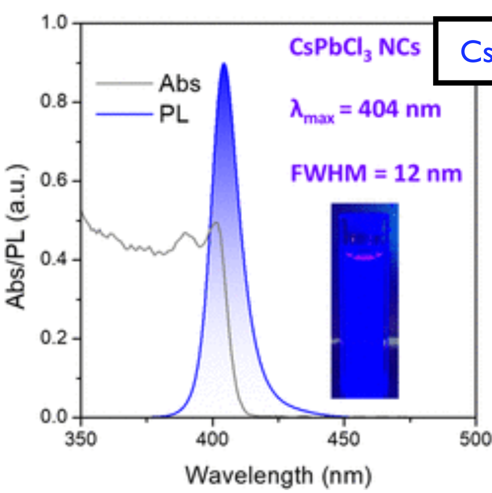
emission spectrum




triangular carbon nanodots




CsPbCl3 nanocrystals

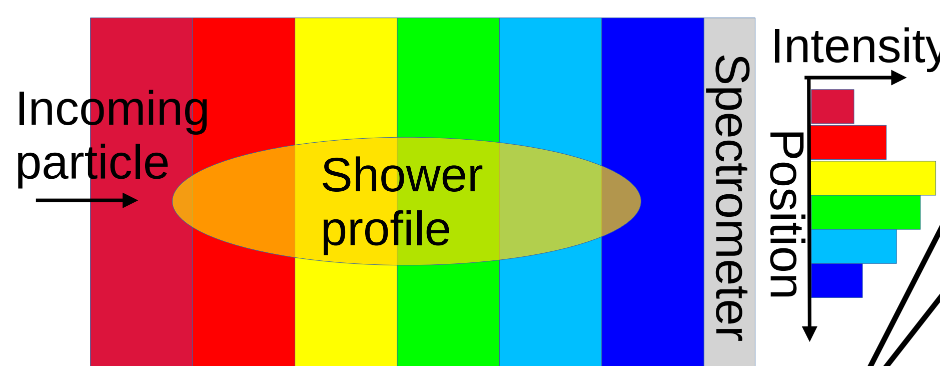
leftmost nanodots:
absorb wavelengths < 650 nm
emit at > 680 nm

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?

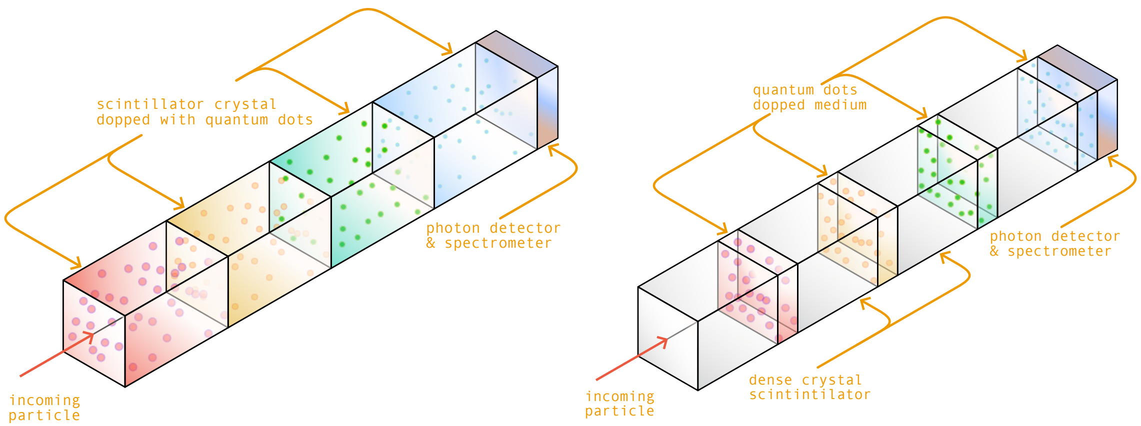
Y.T. Lin & G. Finlayson, Sensors 23, 4155 (2023)

Metalenses?

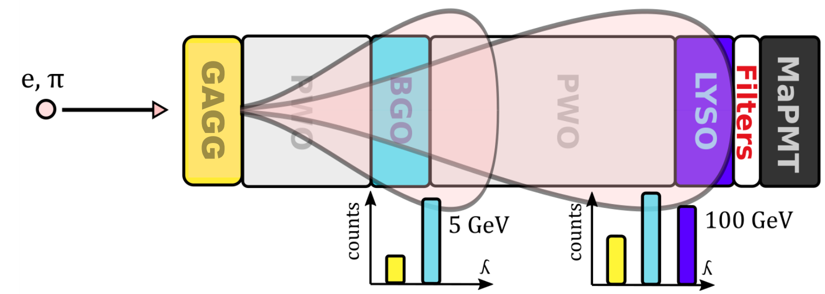
M. Khorasaninejad & F. Capasso, Science 358, 6367 (2017)

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

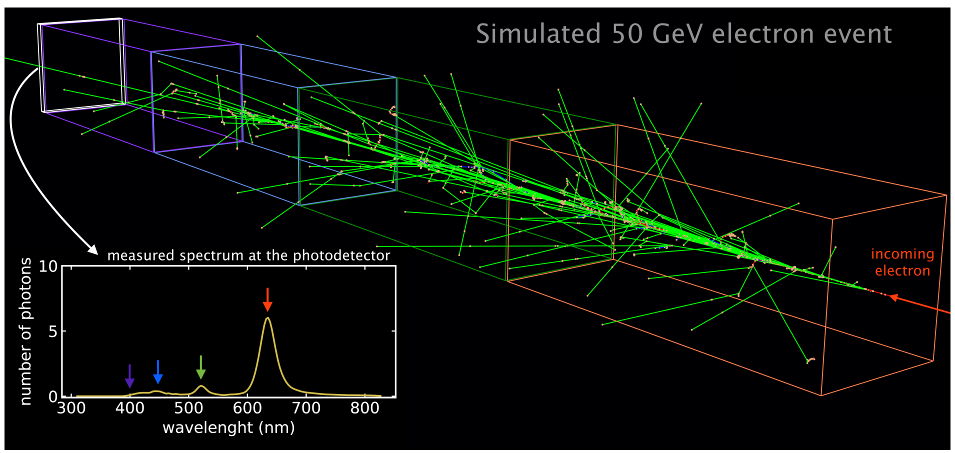
This slide courtesy Devanshi Arora, CALOR'24

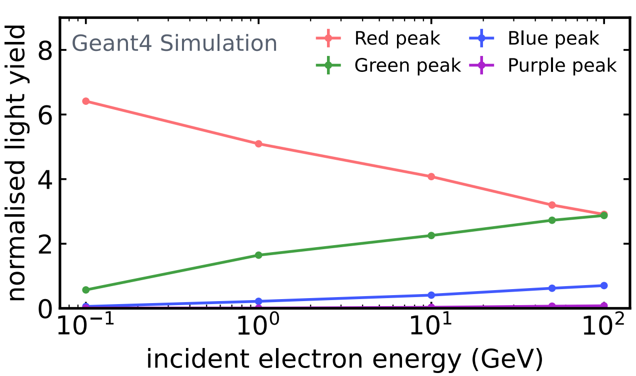



courtesy Y. Haddad, N U, Boston, USA



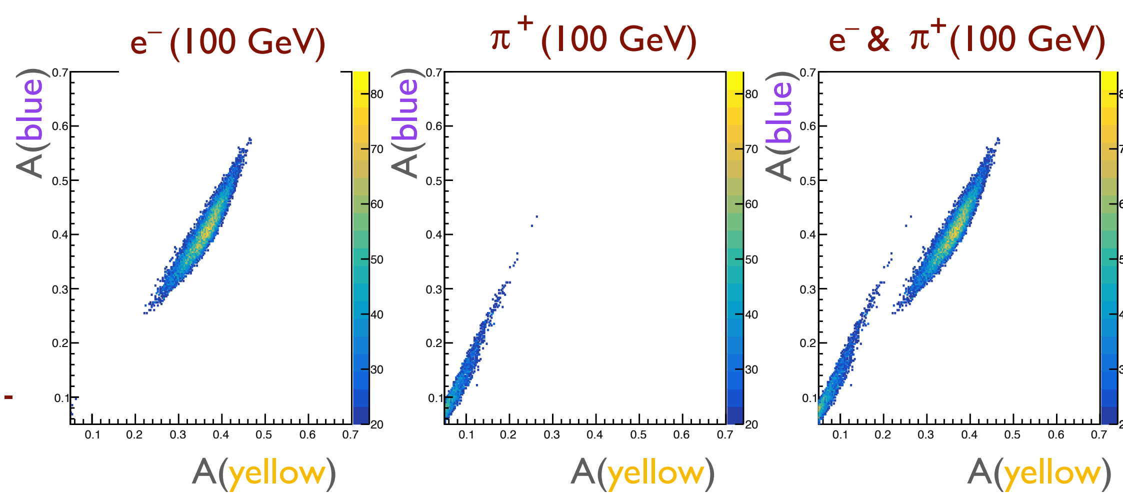

Beam test results (SPS) 2023


"Chromatic" energy measurement

"Chromatic" electron - pion discrimination




86% "chromatic" electron - pion discrimination

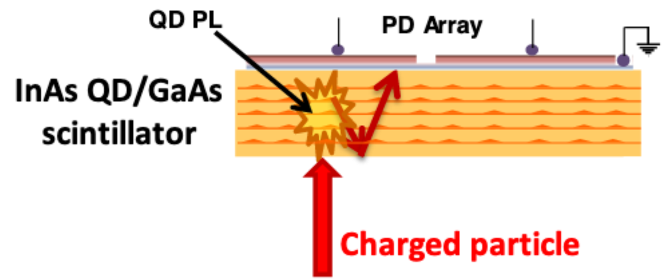
# Quantum dots and wells: DoTPiX

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

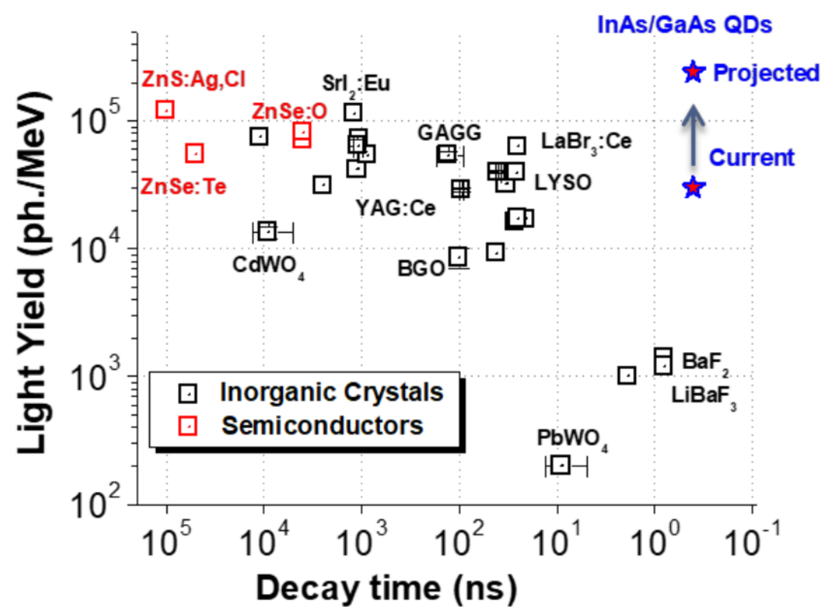
https://link.springer.com/article/10.1557/s43580-021-00019-y




## 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

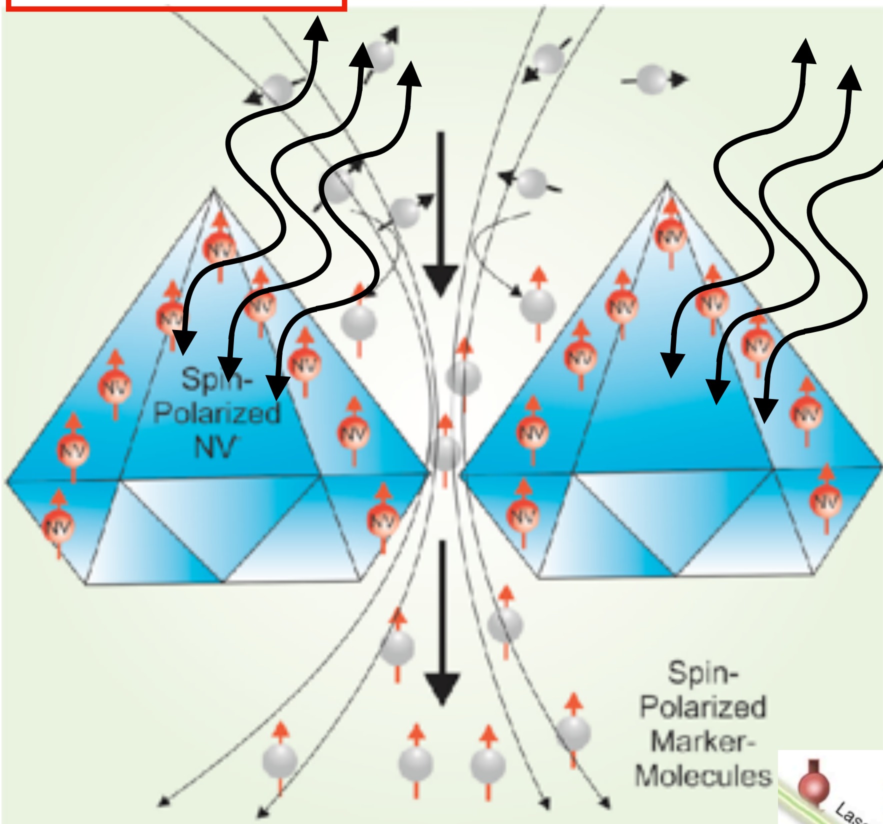
# optically polarizable elements: Nitrogen-vacancy diamonds (NVD)

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

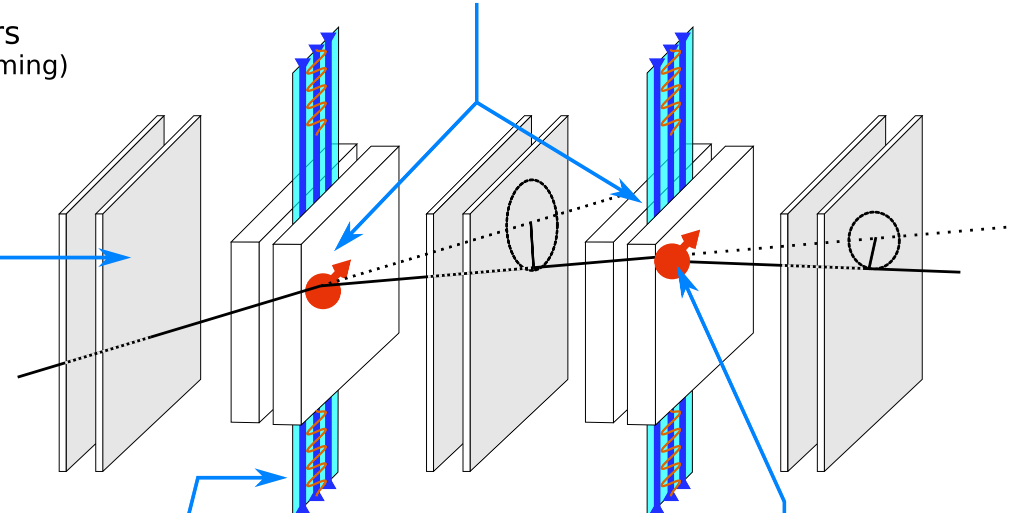
$10^{16} \sim 10^{18}$ / cm$^3$

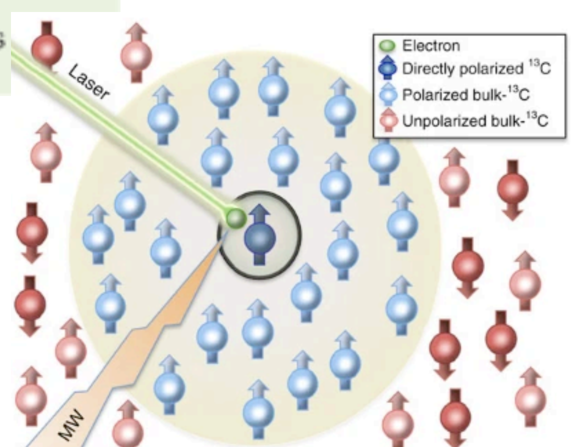



© Dr. Christoph Nebel, Fraunhofer IAF

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



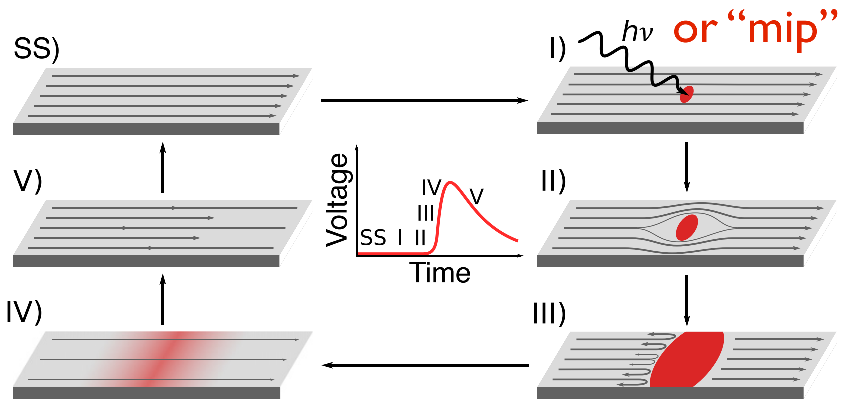




Local and bulk $^{13}C$ hyperpolarization in nitrogen-vacancy centred diamonds at variable fields and orientations, G. Alvarez et al., *Nature Communications* **6**, 8456 (2015)

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 % @10$\mu$m |
| Energy Threshold | 0.125 eV (10 $\mu$m) | 12.5 meV (100 $\mu$m) |
| 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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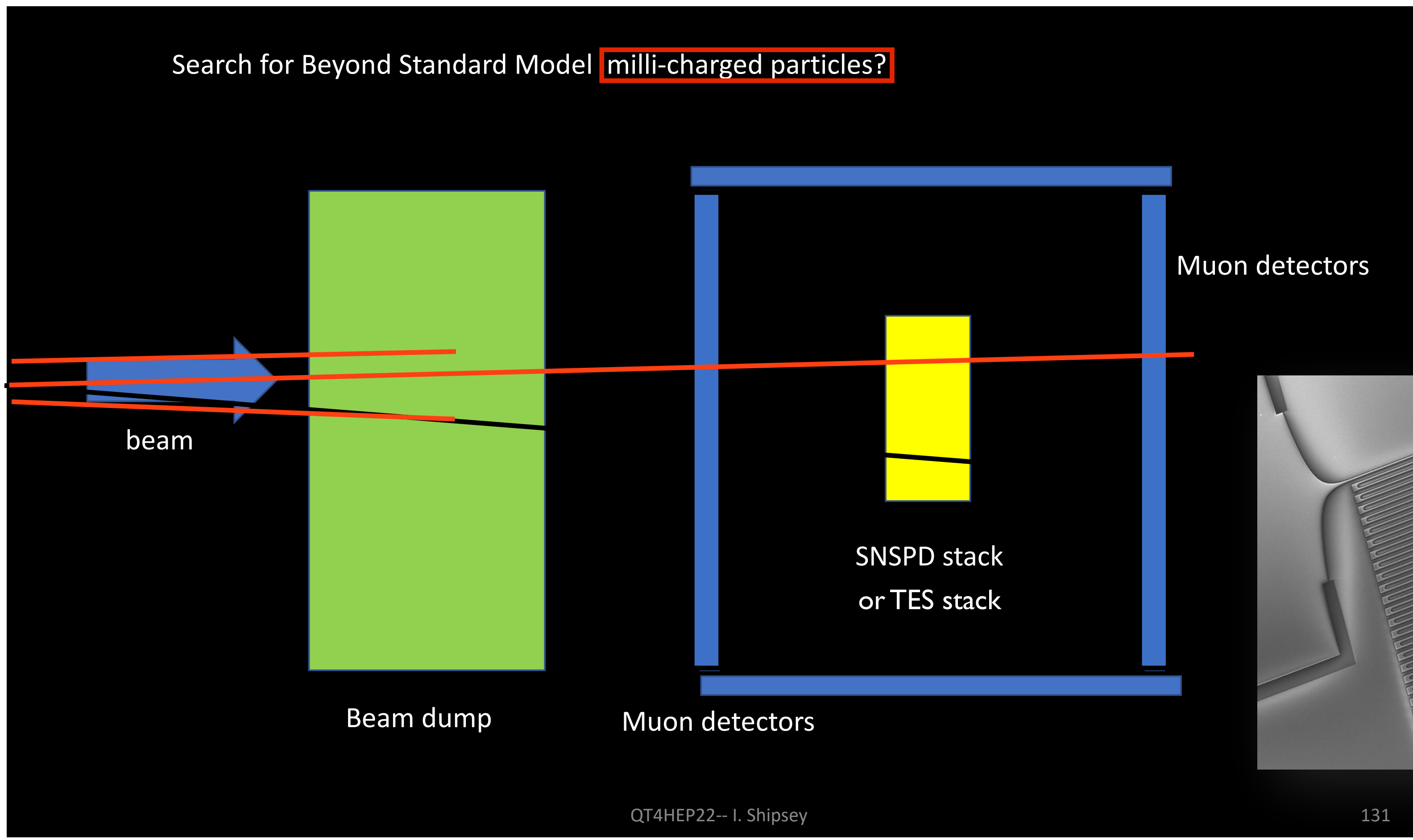
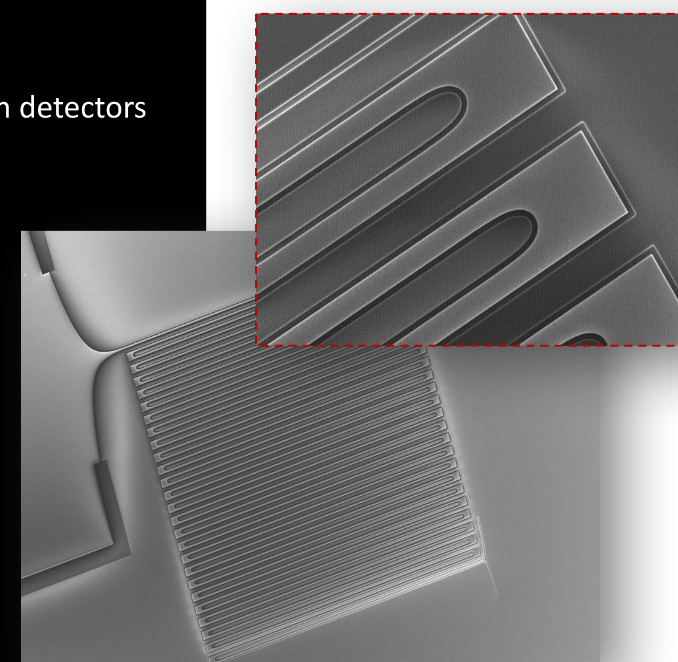
Moving to SC strips conventional lithography → scale up
Development towards SC SSPM



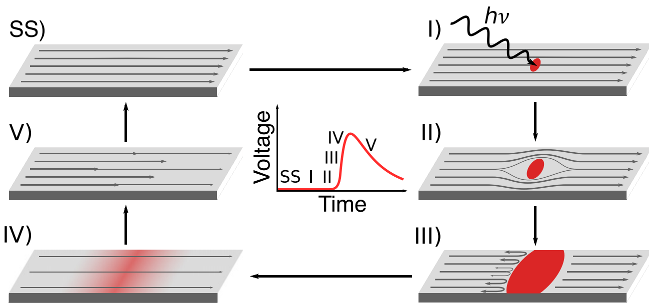


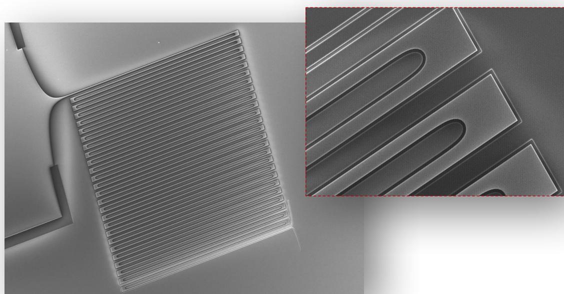

mip: ~20 keV/100 μm

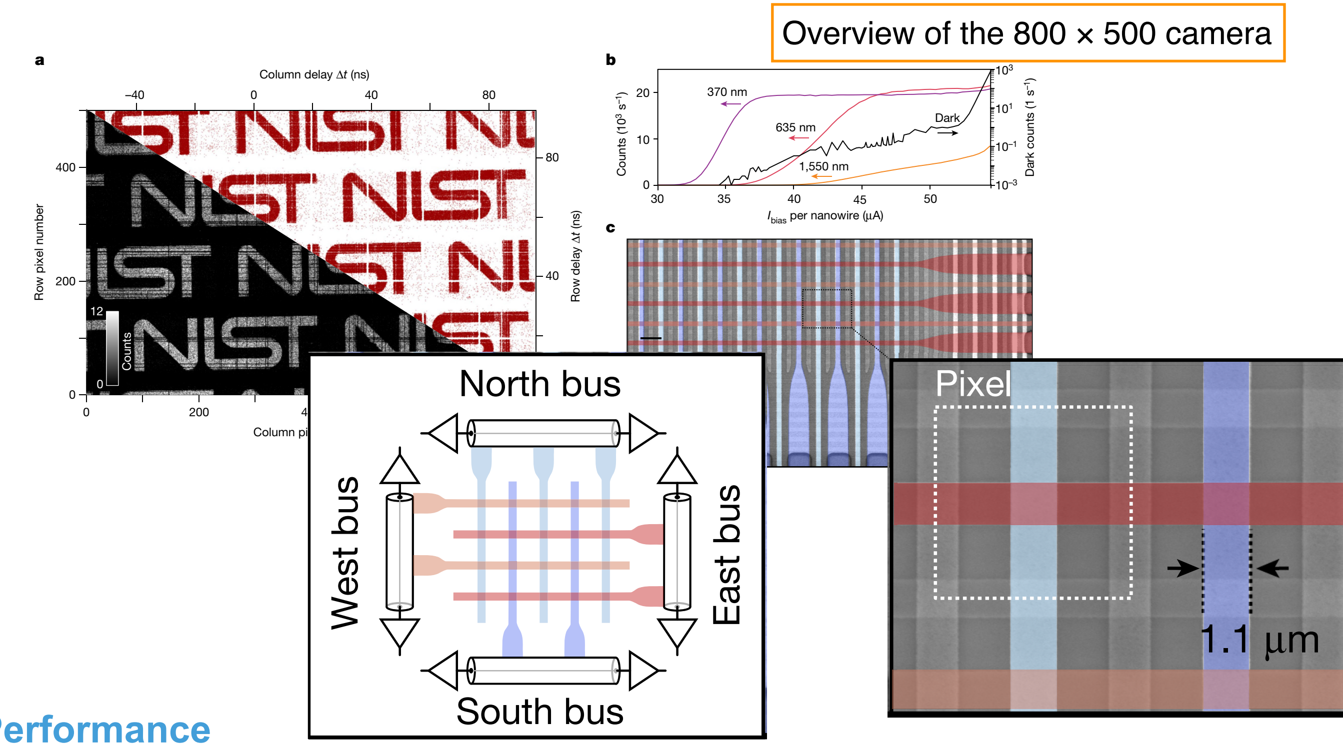
x $10^6$ sensitivity



# Specific examples for potential particle physics impact: WP-3






## SNSPD: Advances & Expected Performance

| Operating Temperature | Timing jitter | Intrinsic photon number resolution | Efficiency | Array size | Maximum count rate | Dark count rate | Active area | Cut-off wavelength | |
|---|---|---|---|---|---|---|---|---|---|
| 4.3 K | 18 ps | None | 93% | 64 | 1 Gcps | 4 /s/mm$^2$ | 0.001 cm$^2$ | 5 µm | Records in 2016 |
| | 2.6 ps [1] | 3-5 photons | 98% [2] | 4x10$^5$ [3] | 1.5 Gcps [4,5] | 4x10$^{-5}$ /s/mm$^2$ [6] | 0.1 cm$^2$ [3] | 29 µm [7] | **Current records for isolated devices** |
| 25 K | 1 ps | 10 | 99 % | 10$^7$ | 10 Gcps | 1x10$^{-6}$ /s/mm$^2$ | 1 cm$^2$ | 100 µm | Expected performance by 2030 |

## Multi-layer stacked dets

- millicharged particles
- diffractive scattering
- luminosity monitors

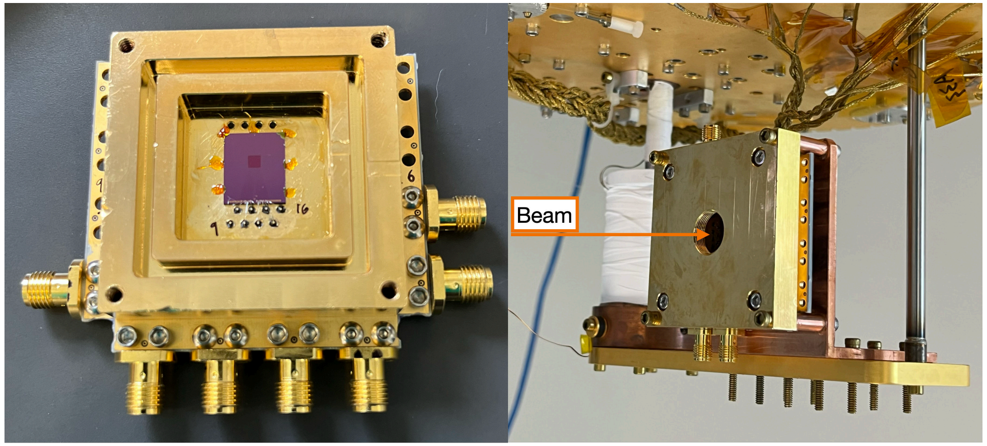
(https://indico.cern.ch/event/1439855/contributions/6461493/)
(https://indico.cern.ch/event/1439855/contributions/6461614/)


[1] Korzh, Zhao et al, ***Nature Photonics*** 14, 250 (2020)
[2] Reddy et al, ***Optica*** 7, 1649 (2020)
[3] Oripov, Rampini, Allmaras, Shaw, Nam, Korzh, and McCaughan, ***Nature*** 622, 730 (2023)
[4] Craiciu, Korzh et al, ***Optica*** 10, 183 (2023)
[5] Resta et al, ***Nano Letters*** (2023)
[6] Chiles, ***PRL*** 128, 231802 (2022)
[7] Taylor, Walter, Korzh et al, ***Optica***, (2023)

# Extremely fast detectors: SNSPD

## quantum pixel ultra-sensitive tracking

Beam tests with 120 GeV/c protons & 8 GeV/c pions & electrons @ FNAL




Cristián Peña et al 2025 JINST 20 P03001

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Snowmass2021 - Letter of Interest

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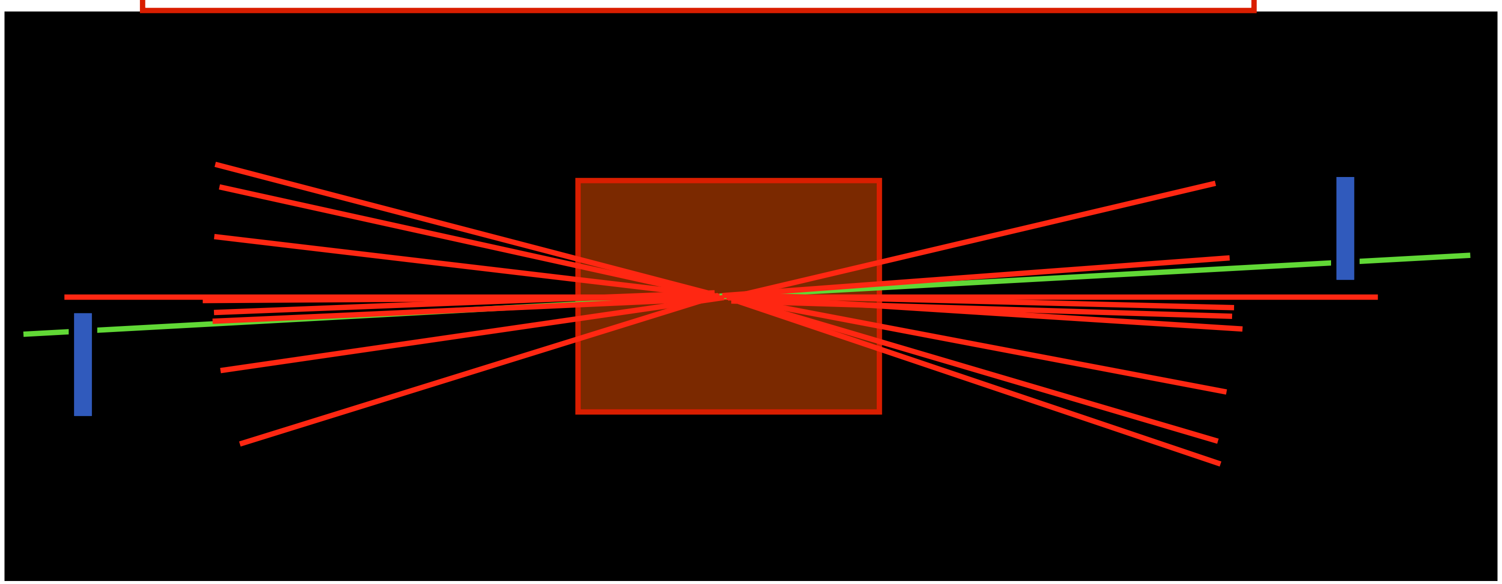
Matt Shaw, mattshaw@jpl.nasa.gov


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

QT4HEP22-- I. Shipsey

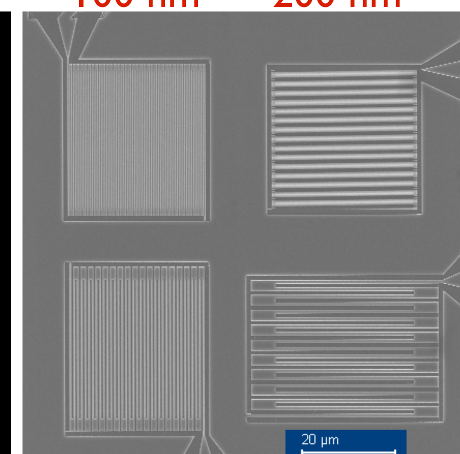
125

- diffractive scattering via ps-resolution tracking in Roman pots
- luminosity monitoring



@ 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

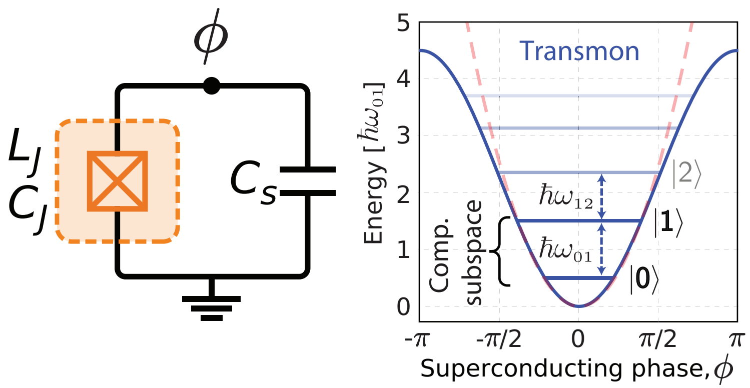
C. Peña et al., JINST (2025)
https://iopscience.iop.org/article/10.1088/1748-0221/20/03/P03001/pdf

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



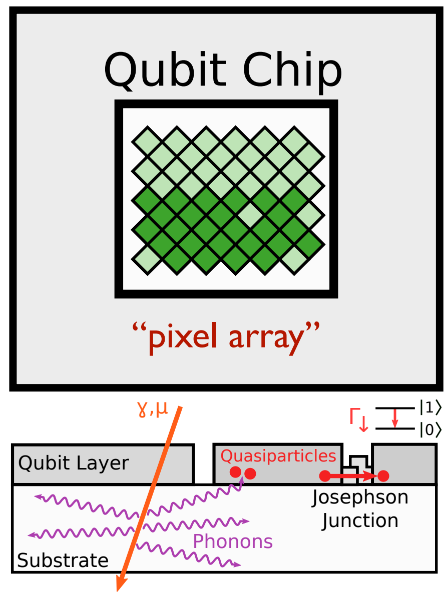

variant of a harmonic oscillator (with numerous equally-spaced energy levels):

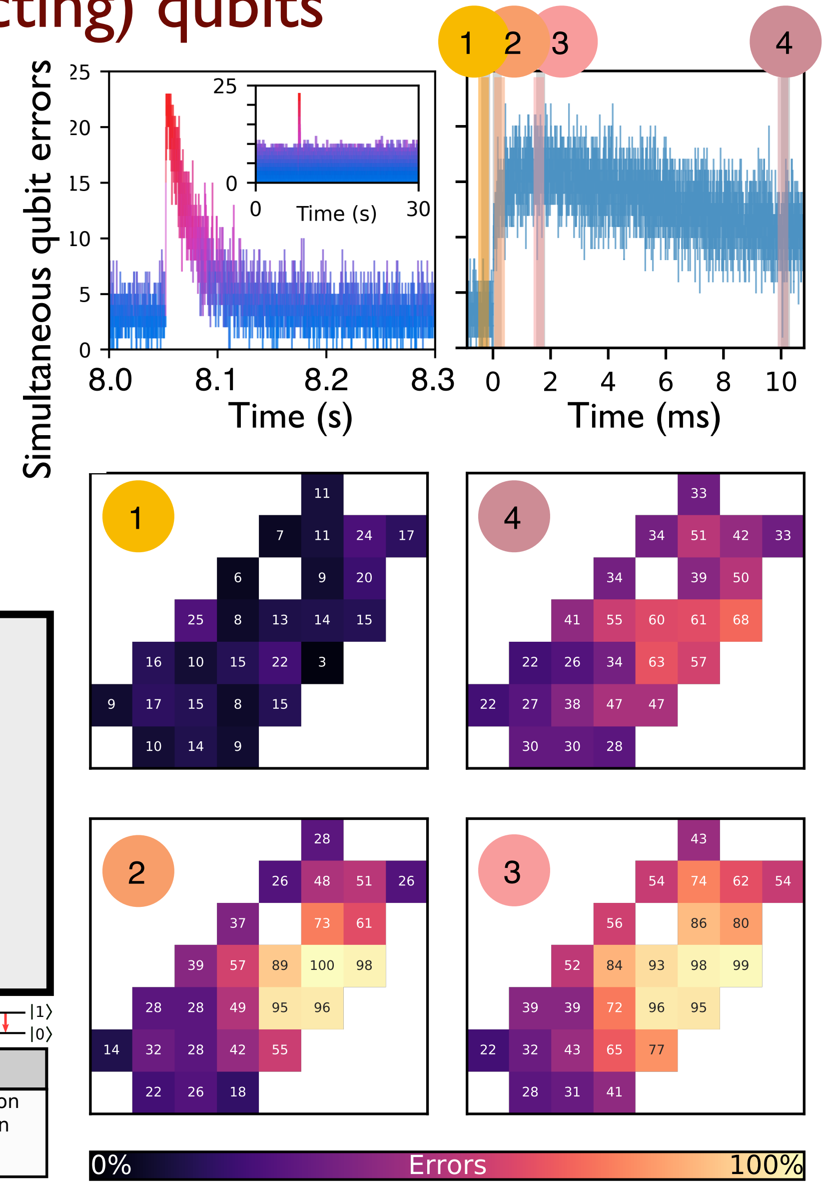
need to be able to define a computational subspace consisting of only two energy states (usually the two-lowest energy eigenstates) in between which transitions can be driven without also exciting other levels in the system: |0⟩ and |1⟩

Energy scale: 25$\mu$eV (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

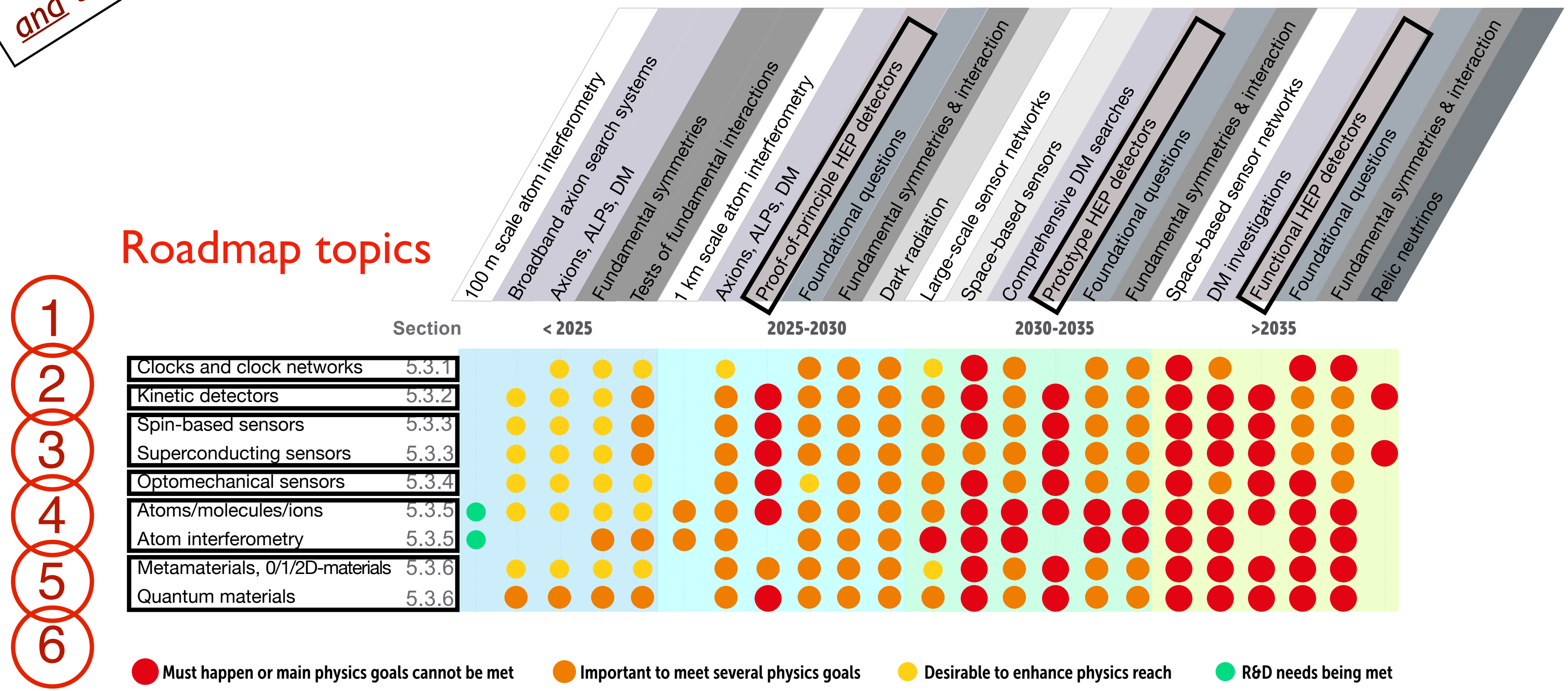
This slide stolen from Daniel Baxter, IDM, L'Aquila, 2024

# RECFA Detector R&D roadmap 2021

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

## Chapter 5: Quantum and Emerging Technologies Detectors

focus on physics *and* technology




**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 → <br> 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 super-conducting 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

# DRD5 collaboration: approved in summer 2024



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

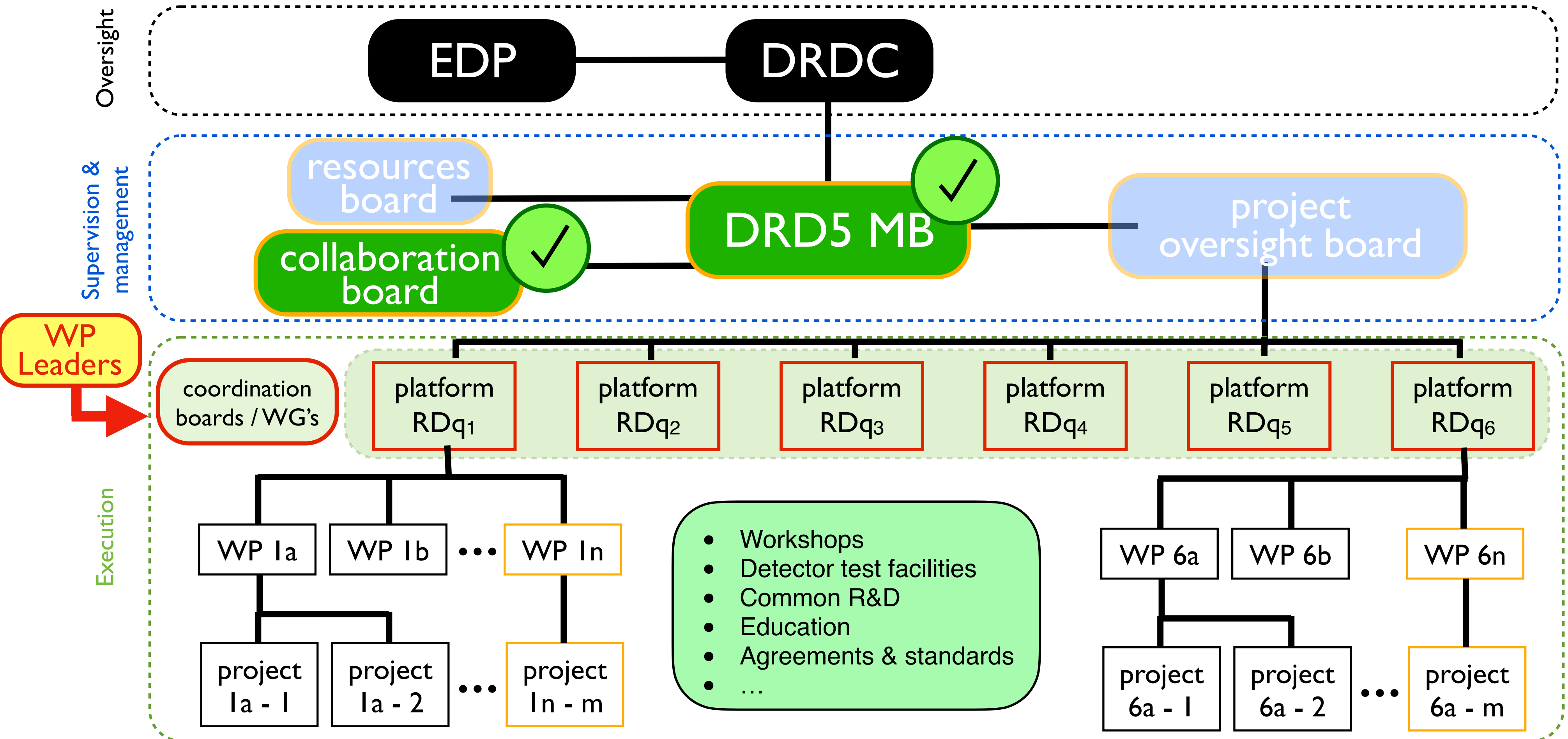
**WP2** — Quantum materials (0-, 1-, 2-D) (Engineering at the atomic scale)

**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,…)

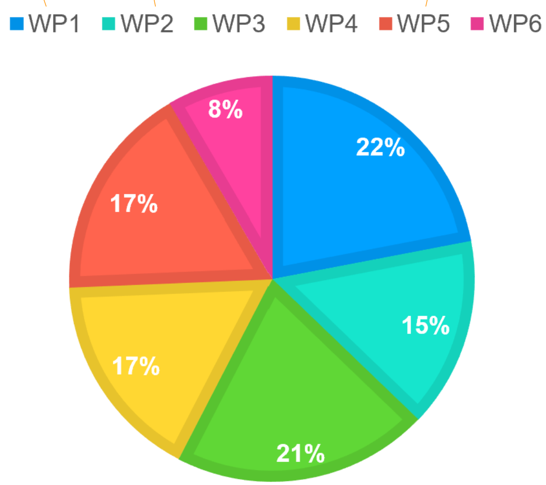
**WP5** — Quantum techniques for sensing (back action evasion, squeezing, entanglement, Heisenberg limit)

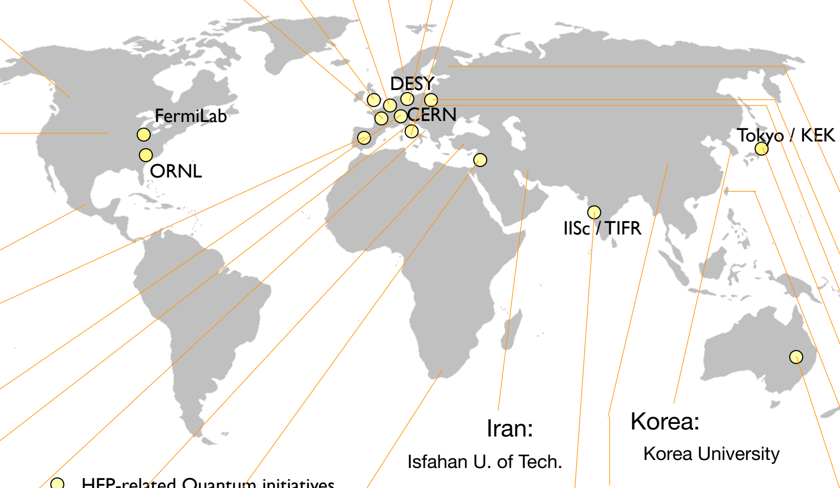
**WP6** — Capability expansion (cross-disciplinary exchanges; infrastructures; education)




(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

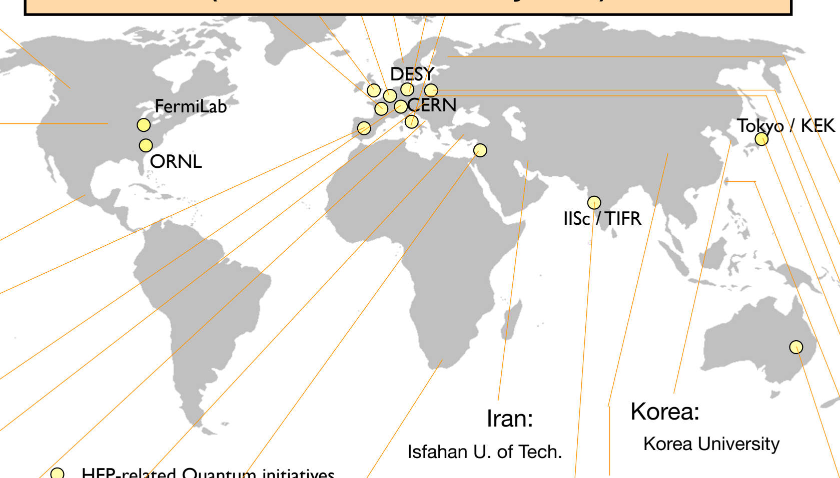
**Japan:** QUP / KEK; Kyoto University; Tokyo University / ICEPP; University of Shizuoka

# 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!)




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
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U. de Valencia
U. de Lleida
IEM, CSIC

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

Austria:
IQOQI Vienna
TU Wien

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Inst. of Physics, Zagreb

Türkiye:
Ankara Univ.
Duzce Univ.
Sabanci Univ.

Israel:
Technion, Haifa

South Africa:
U. of Cape Town

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

Iran:
Isfahan U. of Tech.

Korea:
Korea University

China:
IHEP, Beijing

Australia:
University of Western Australia
Swinburne University of Technology

Taiwan:
Academia Sinica & NTU

Netherlands:
U. of Groningen

Norway:
Oslo University

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

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University West Bohemia
Charles Univ., Prague

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

thank you!