Quantum Particle Detectors

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

M. Doser, CERN

ICHEP, Prague, July 2024

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

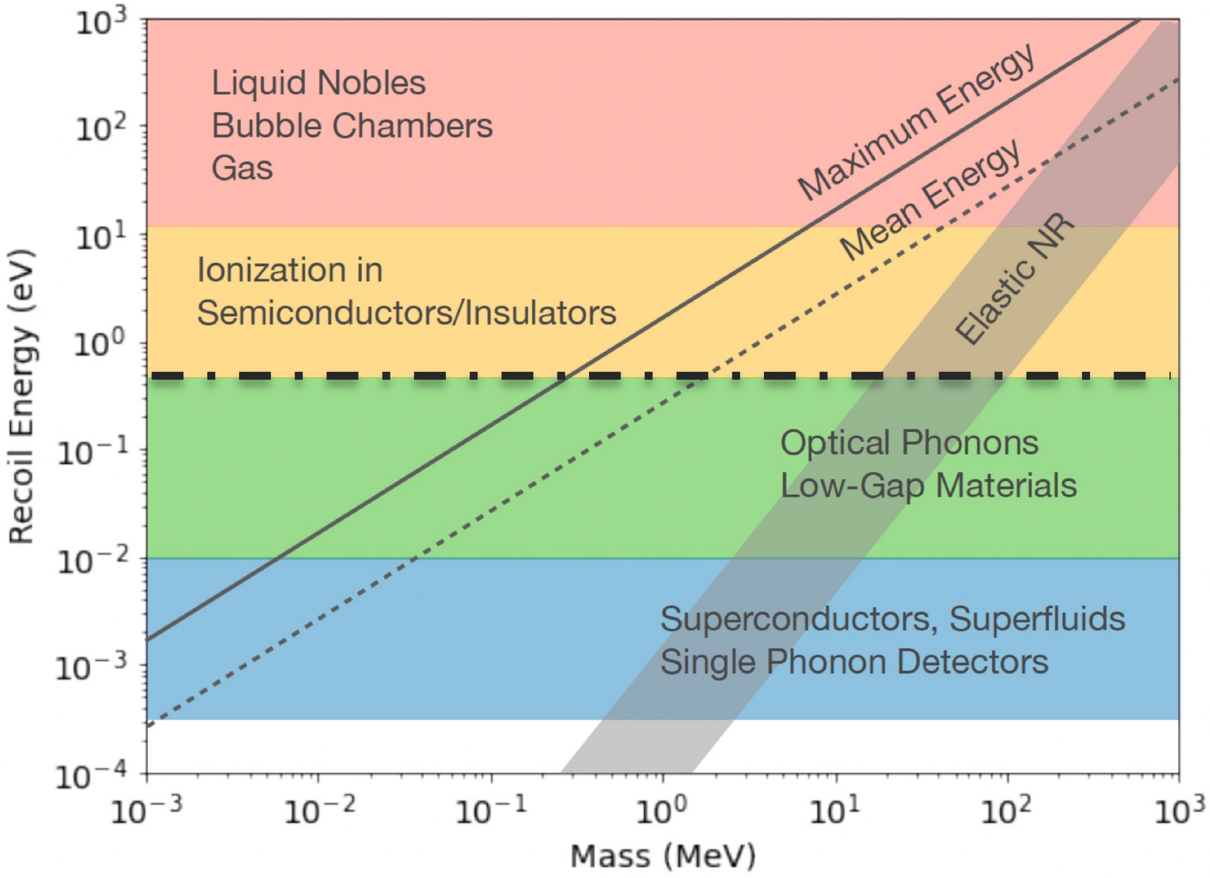
Then, a "quantum sensor" is a device, the measurement (sensing) capabilities of which are enabled by our ability to manipulate and/or read out its quantum states.

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]

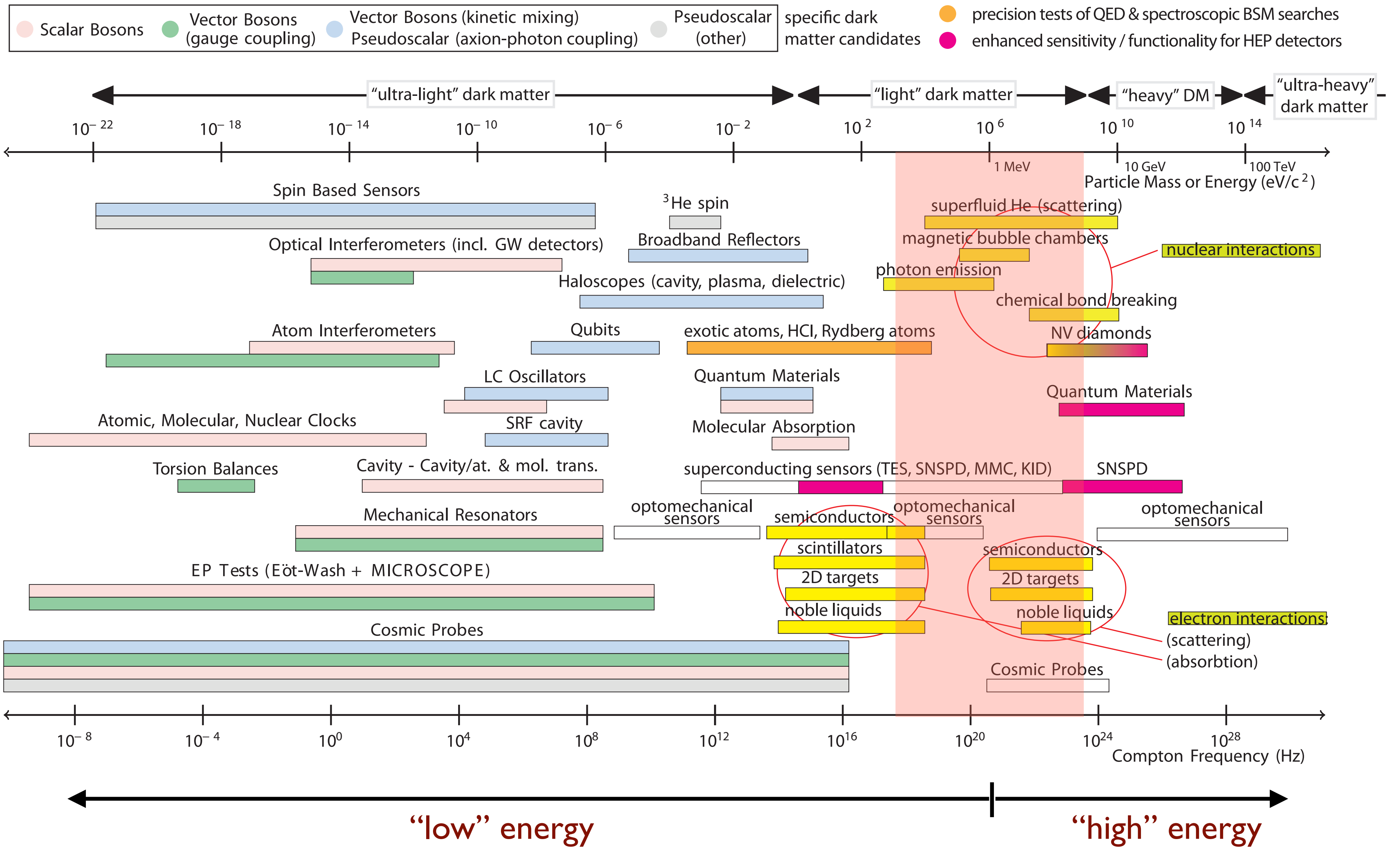
What's the goal? mip detection? or minute, sub-mip energy deposits?

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:

quantum sensing & particle 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/

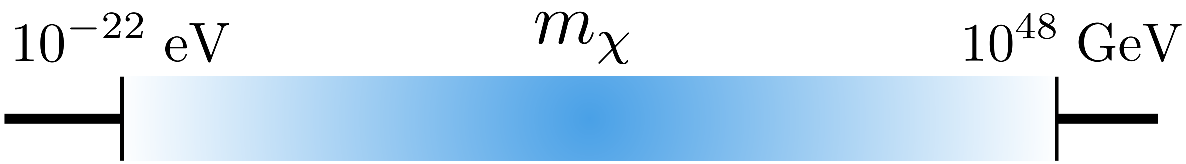
A *ridiculously* rapid overview of a selection of particle physics at low energy enabled by Quantum Sensors

- RF cavities, cryodetectors (DM searches)
- field sensors (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

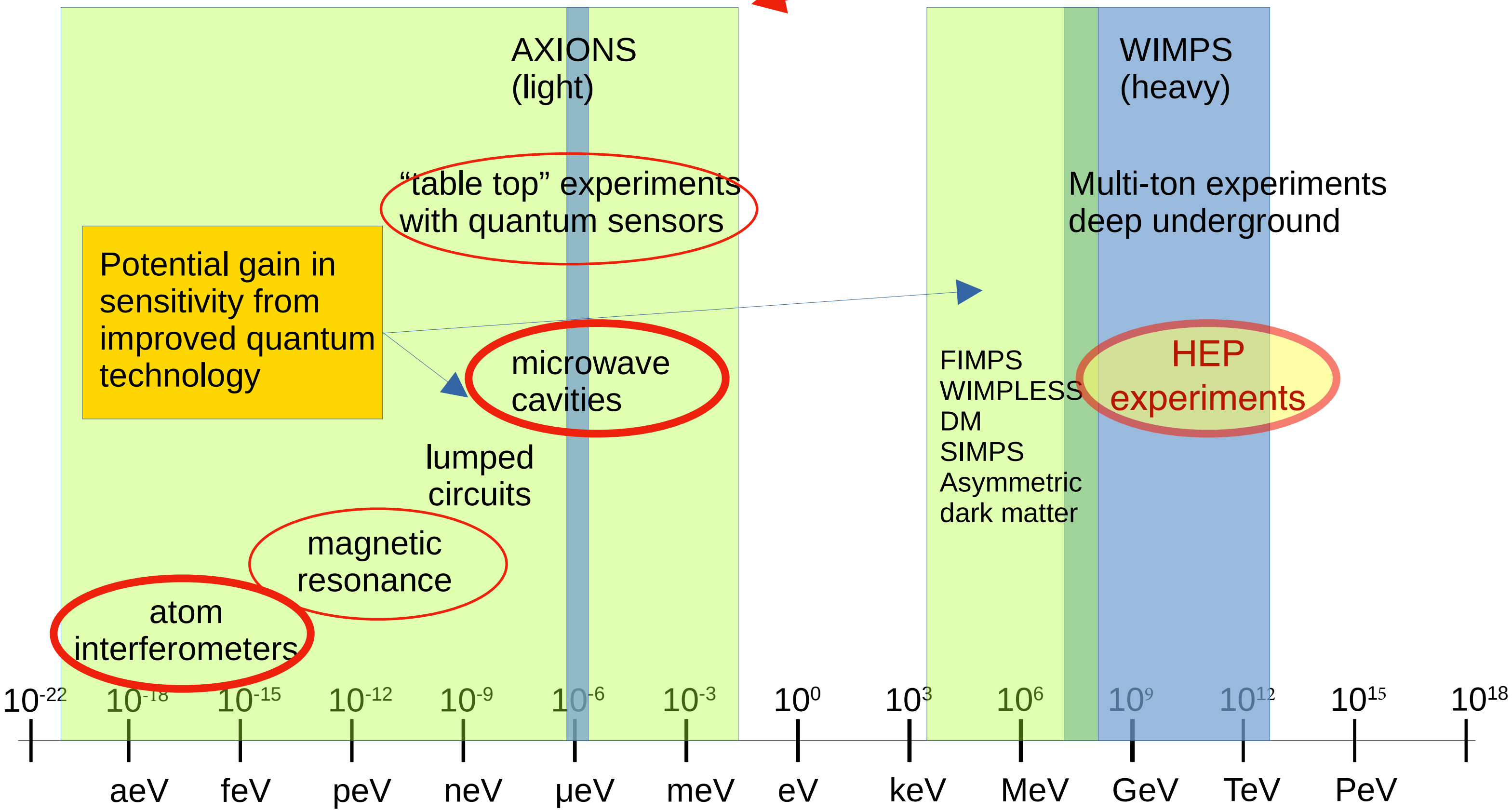


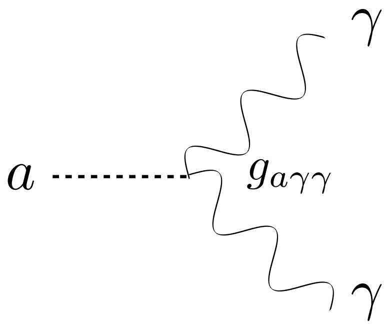
cavity size = axion size

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



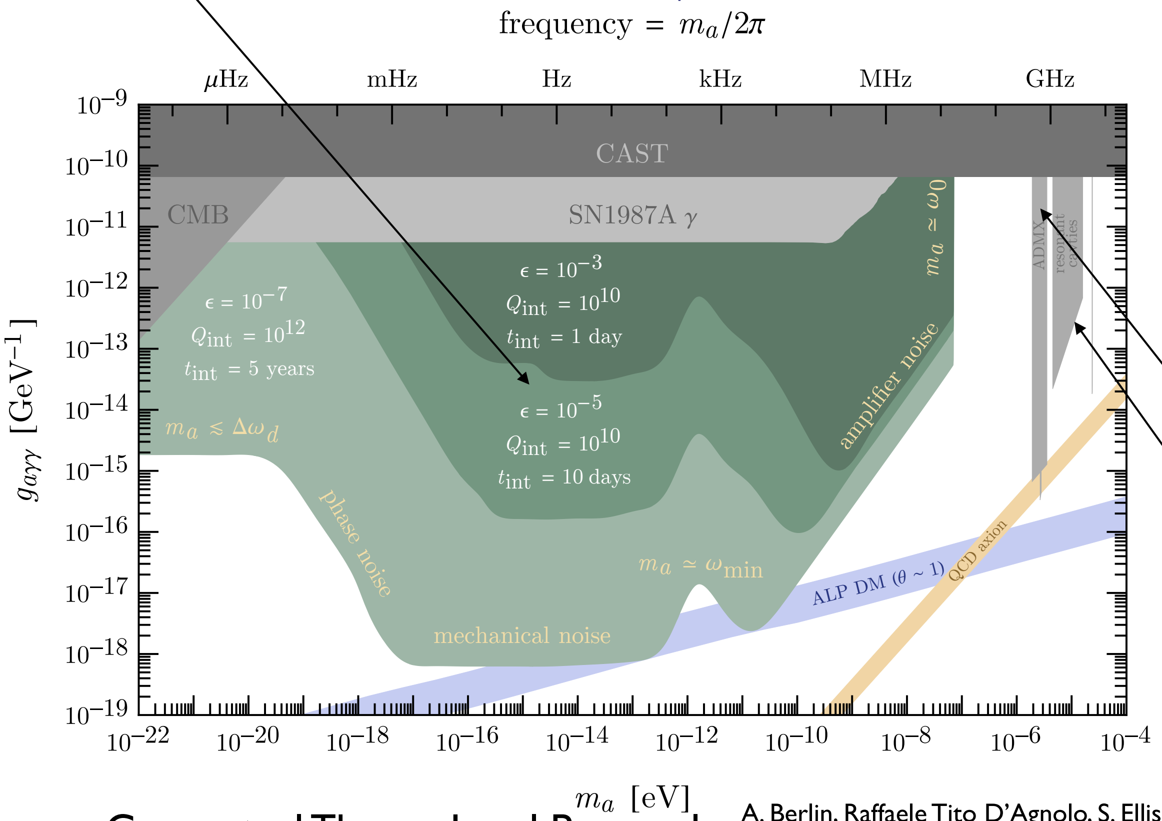


(but not only…)

Axion heterodyne detection

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

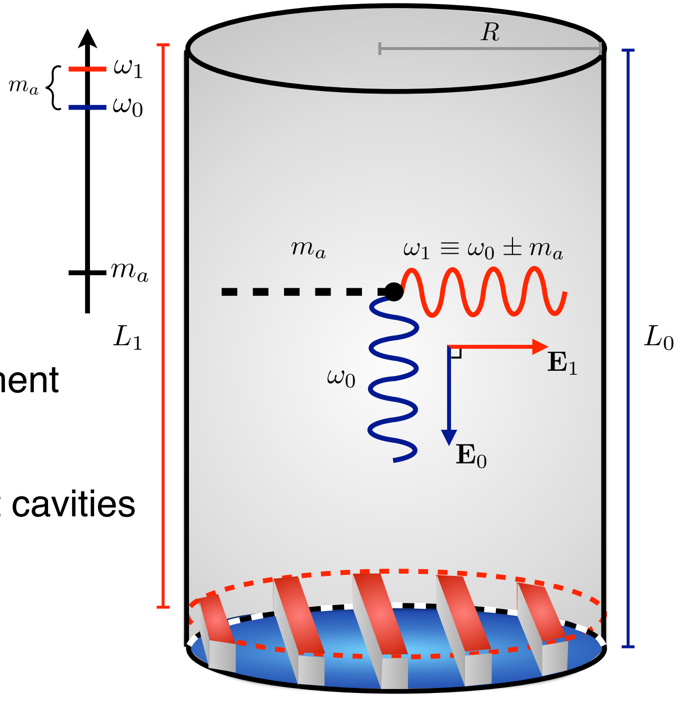
resonant cavities

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

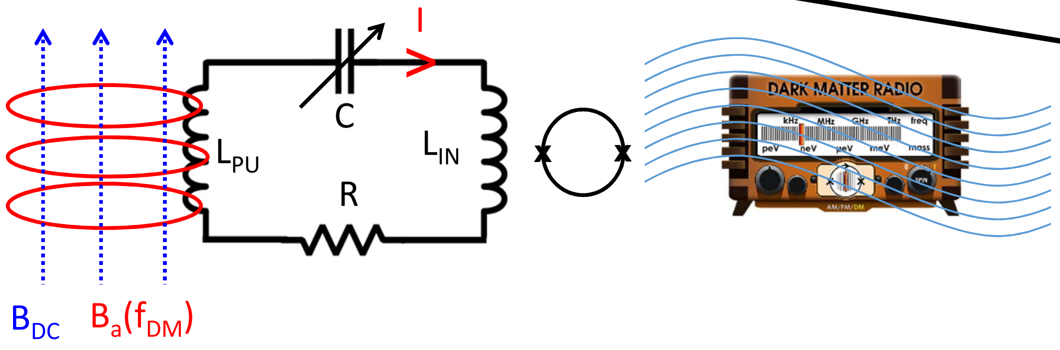
Asher Berlin, Raffaele Tito D'Agnolo, Sebastian A. R. Ellis, Christopher Nantista, Jeffrey Neilson, Philip Schuster, Sami Tantawi, Natalia Toro, Kevin Zhou, https://arxiv.org/abs/1912.11048

"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."

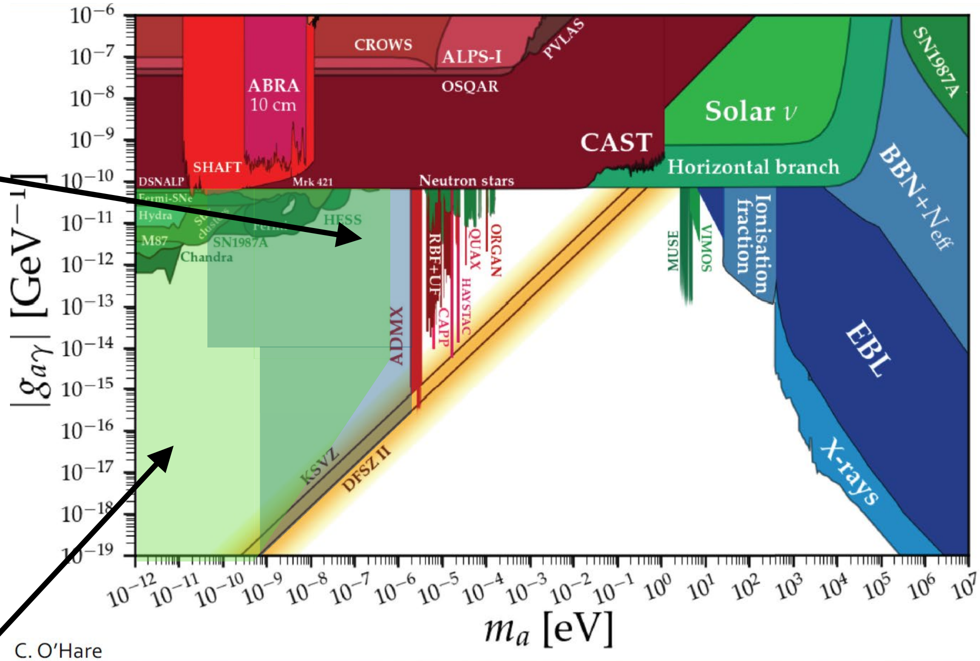
Focus on detecting not a particle (a photon), but a field

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:

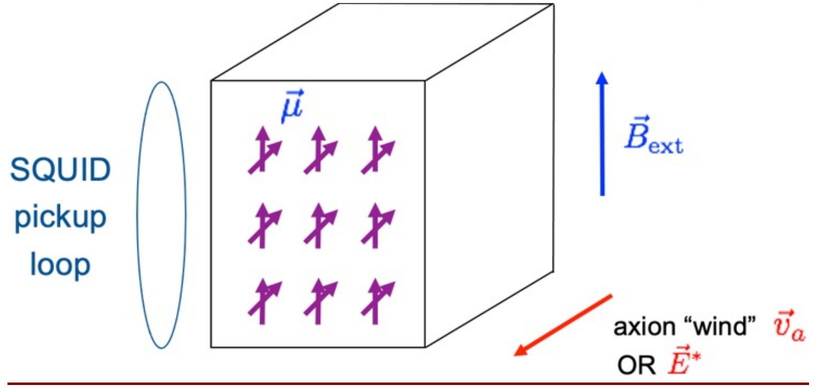
$$\boxed{H_e \propto a\boldsymbol{\sigma}\cdot\boldsymbol{E}^*}$$

CASPEr-electric

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

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

CASPEr-gradient

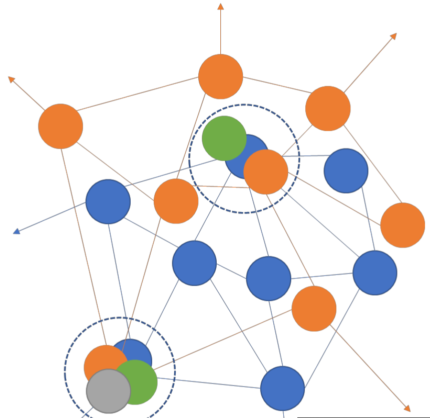


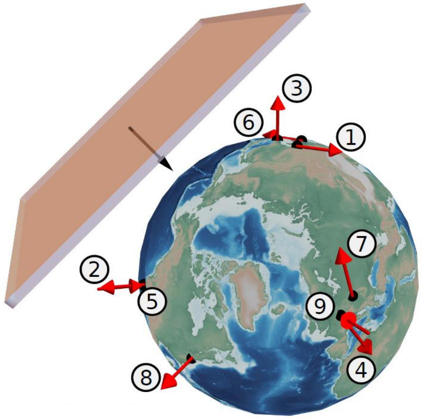
ECFA Detector R&D Roadmap Symposium of Task Force 5 Quantum and Emerging Technologies

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

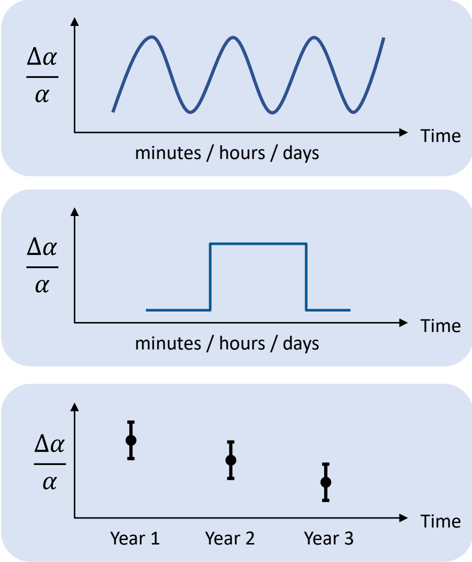
search for NP / BSM

networks of sensors





- Oscillations
- Fast transients
- Slow drifts



→ Very light DM

→ DM- topological defects

→ 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)

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): 2024-2025

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

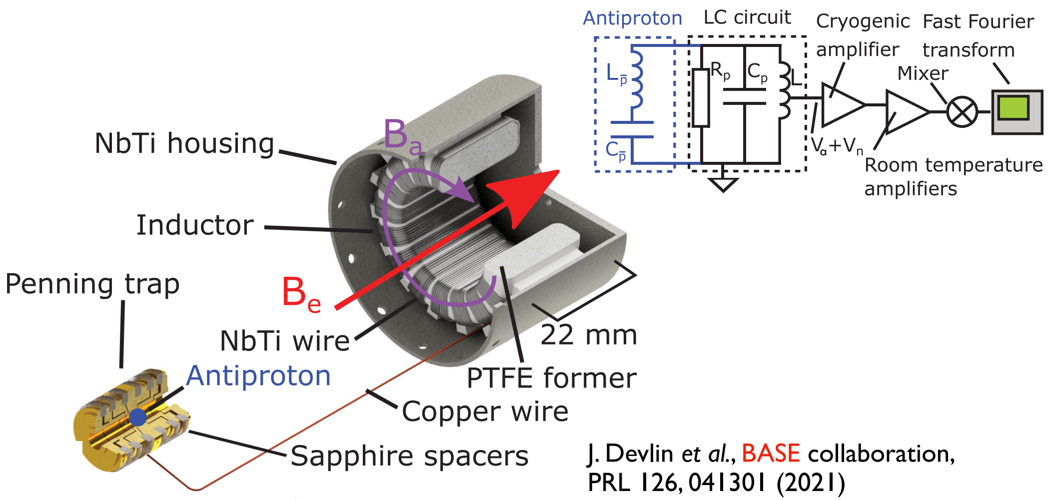
AION: ~2045 satellite mission

AEDGE: ~2045 satellite mission

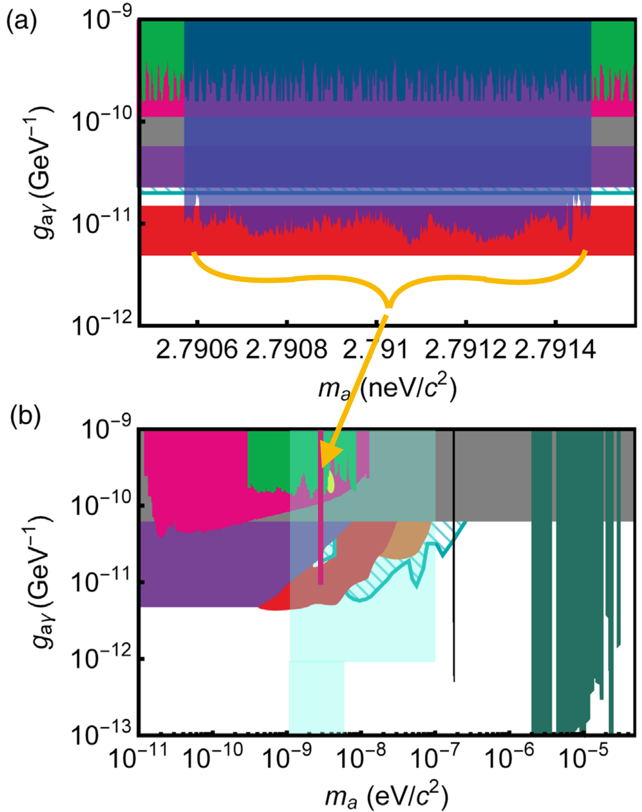
El-Neaj, Y.A., Alpigiani, C., Amairi-Pyka, S. *et al*. AEDGE: Atomic Experiment for Dark Matter and Gravity Exploration in Space. *EPJ Quantum Technol*. **7,** 6 (2020). https://doi.org/10.1140/epjqt/s40507-020-0080-0

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)

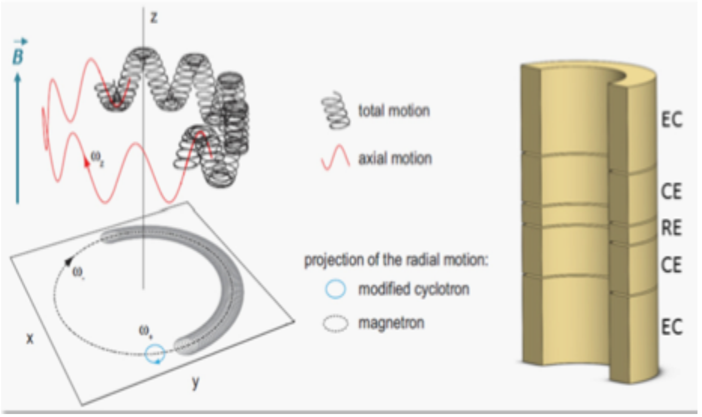


Trapped ions: tests of QED, symmetry tests, DM searches

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

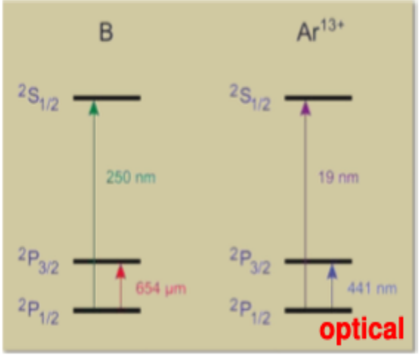
- Searches for the variation of fundamental constants
- Tests of QED: precision spectroscopy
- Fifth force searches: precision measurements of isotope shifts with HCIs to study non-linearity of the King plot

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



Scaling with a nuclear charge Z

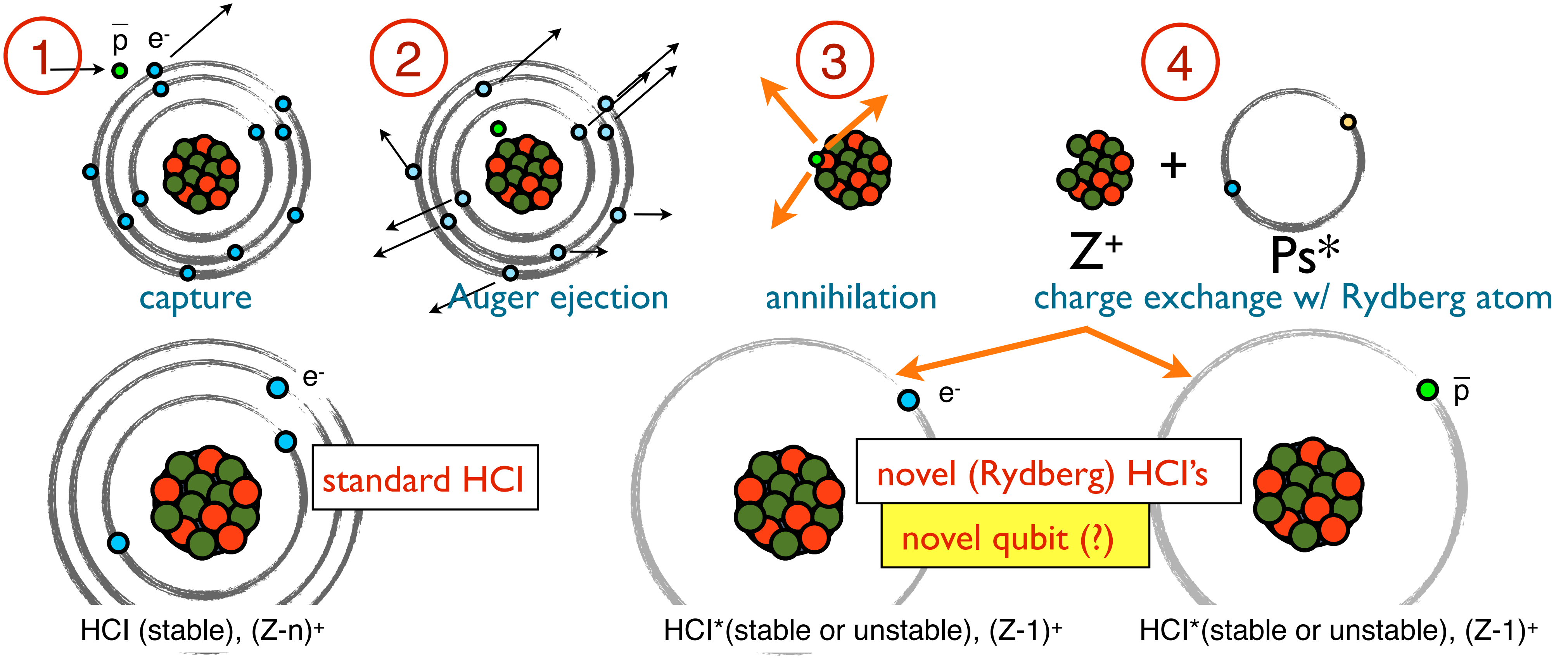
Binding energy	~ Z^2
Hyperfine splitting	~ Z^3
QED effects	~ Z^4
Stark shifts	~ Z^{-6}



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

DM formation within Penning traps; starting from trapped $\bar{p}$ and trapped $^3He^+$

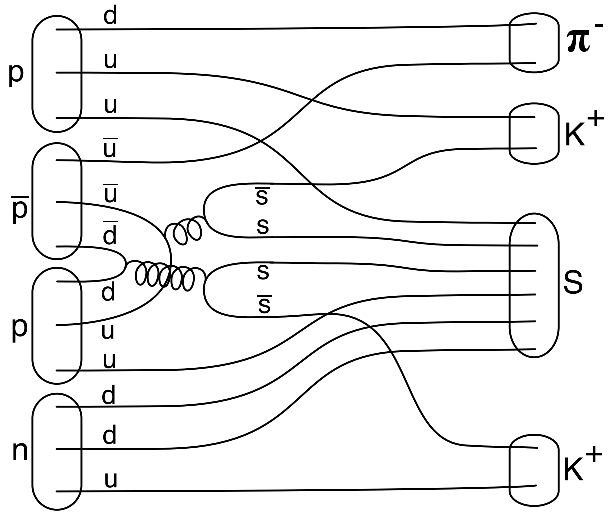
G. Farrar, G. Kornakov, M. Doser, EPJC 83, 1149 (2023)

sexaquark: $(u\uparrow u\downarrow d\uparrow d\downarrow s\uparrow s\downarrow)$ scalar QCD bound state

$(m \sim 2m_n, < 2m_\Lambda)$ Glennys Farrar, arxiv:1808.08951v2 (2017)

not excluded by prior searches
compatible with astrophysical bounds
standard model compatible

formation reaction:
$(\bar{p}\ ^3He)^* \rightarrow S(uuddss) + K^+K^+\pi^-$

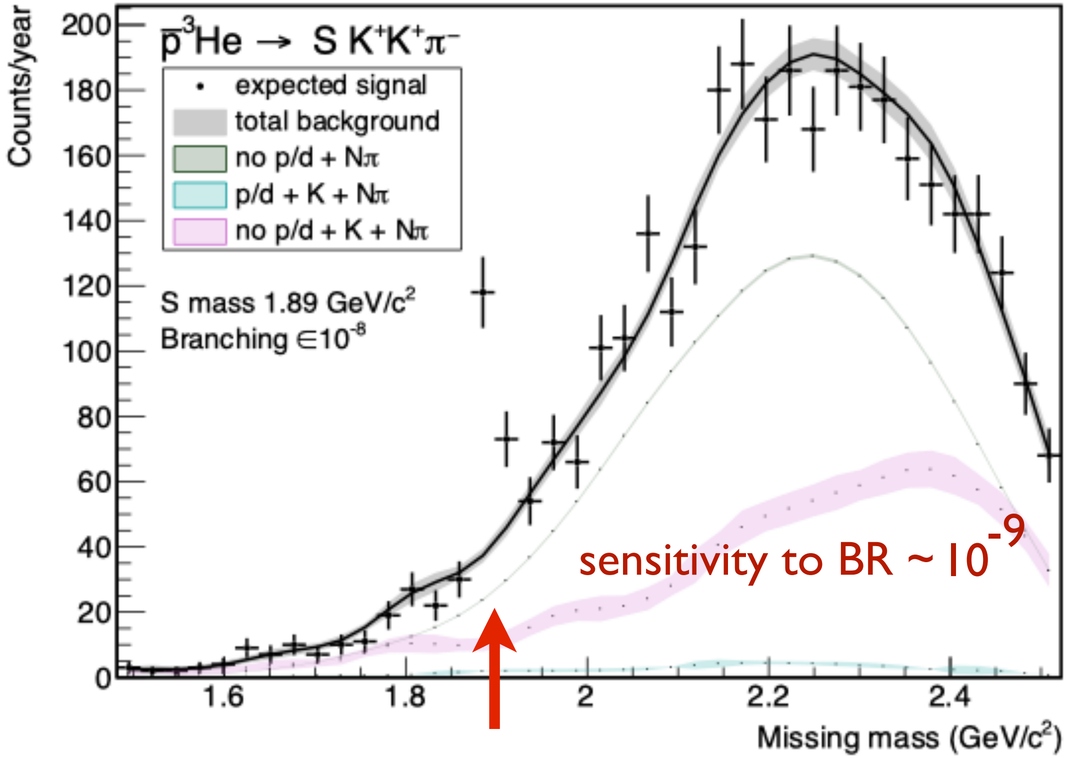


S= +2, Q= +1

Tracking detector with good particle ID

Assume: mis-identification p' ~1% ; detection cut-off ~50 MeV/c

signal: mm^2 recoiling against $\pi^- K^+K^+$



sensitivity to BR ~ 10^{-9}

background: $\pi^-\ \pi^+K^+K_L$ with π^+ misidentified as K^+, recoiling against (undetected) p+n or d

10^{-3} 10^{-5} 10^{-7}

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

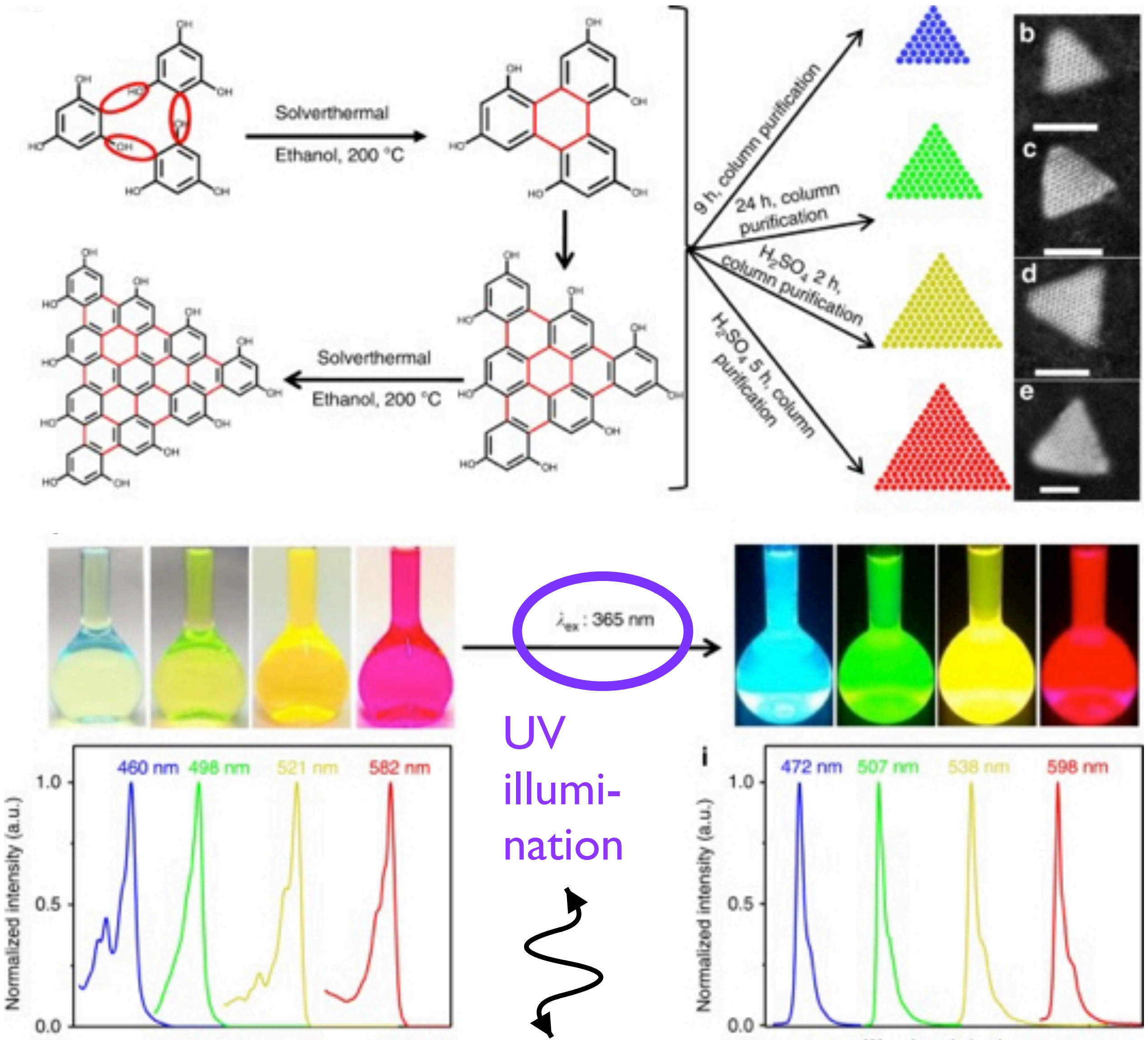
Spin-based sensors

quantum-polarized helicity detection	helicity detectors

Superconducting sensors

quantum pixel ultra-sensitive tracking	milli-charge trackers

Quantum dots: chromatic calorimetry



UV illumi- nation

e.m. shower

absorption

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

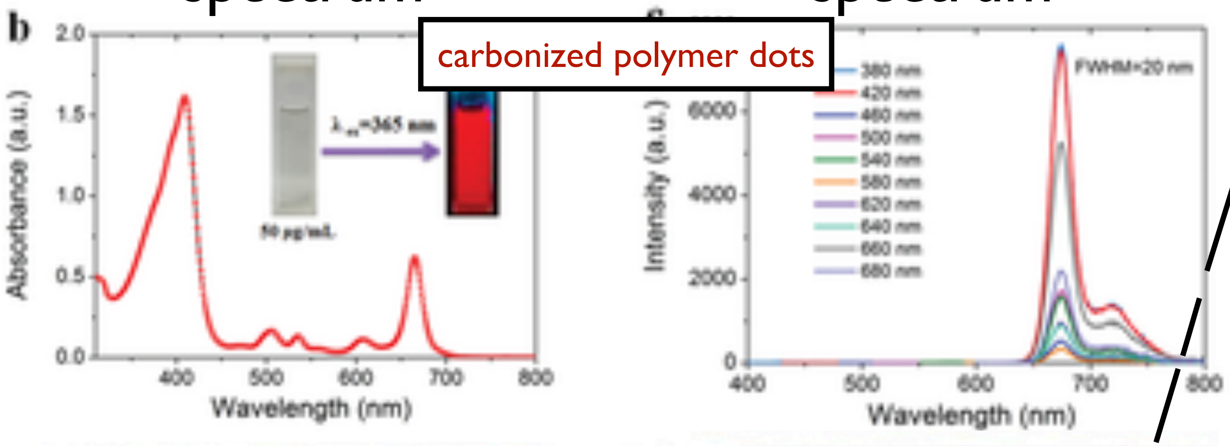
requires:
- narrowband emission (~20nm)
- only absorption at longer wavelengths
- short rise / decay times

select appropriate nanodots

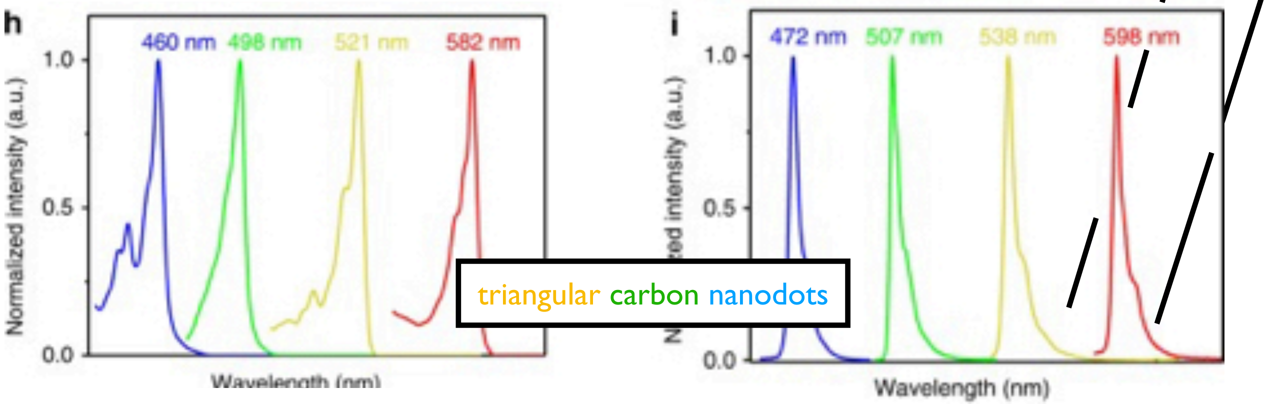
e.g. triangular carbon nanodots

absorption spectrum

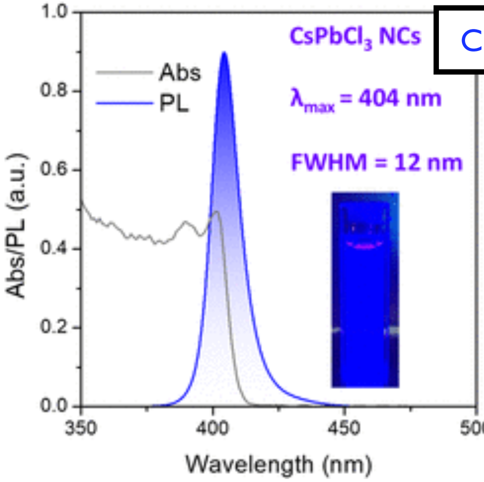
emission spectrum



carbonized polymer dots



triangular carbon nanodots



CsPbCl3 nanocrystals

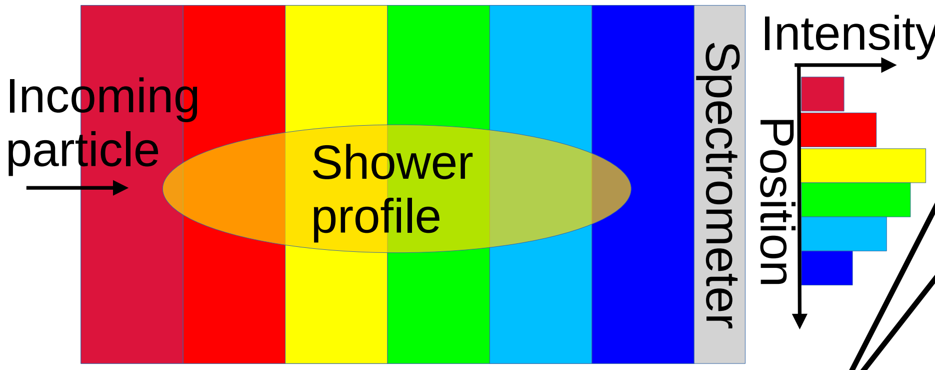
leftmost nanodots:
absorb wavelengths < 650 nm
emit at > 680 nm

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)

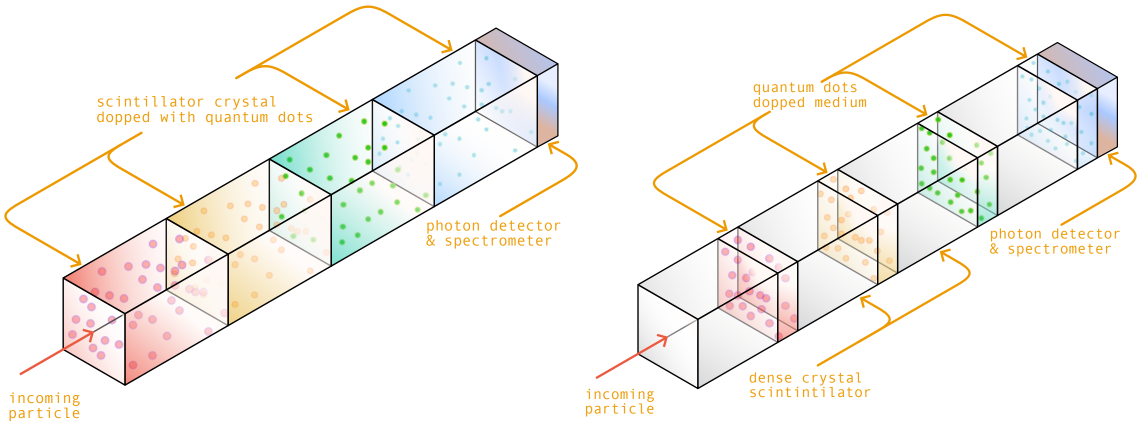
Metalenses?

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

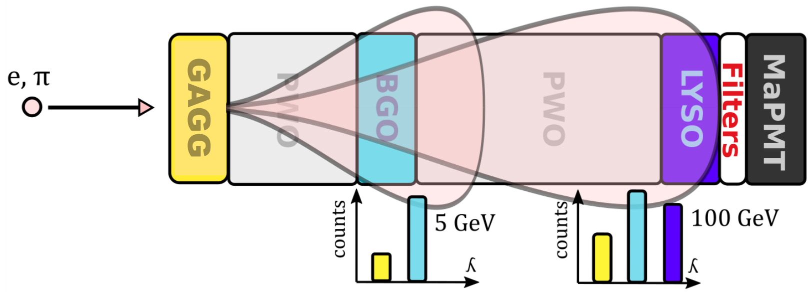
(shower profile via ***spectrometry***)

This slide courtesy Devanshi Arora, CALOR'24

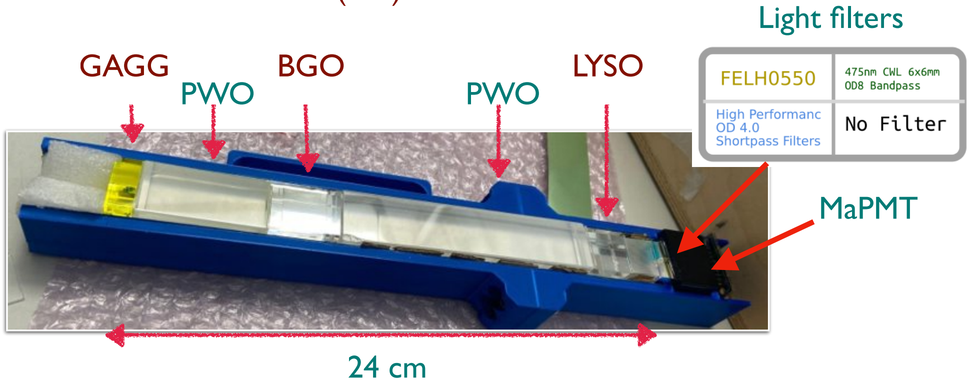
quantum dots for calorimetry

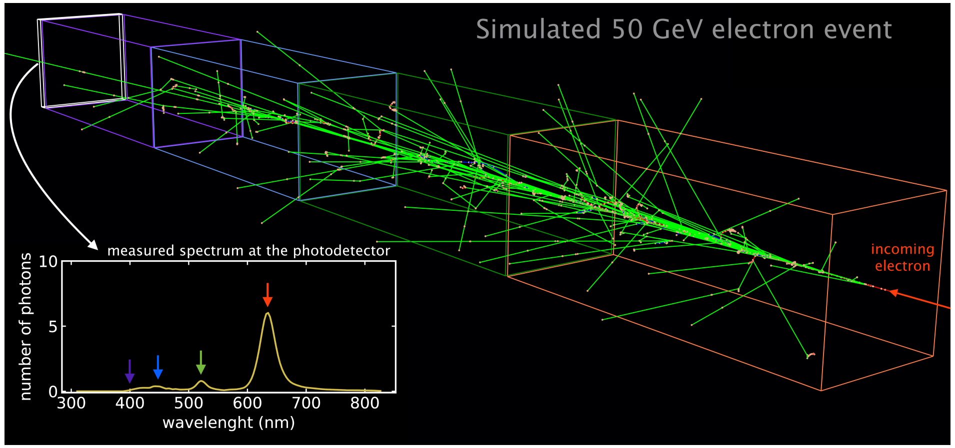


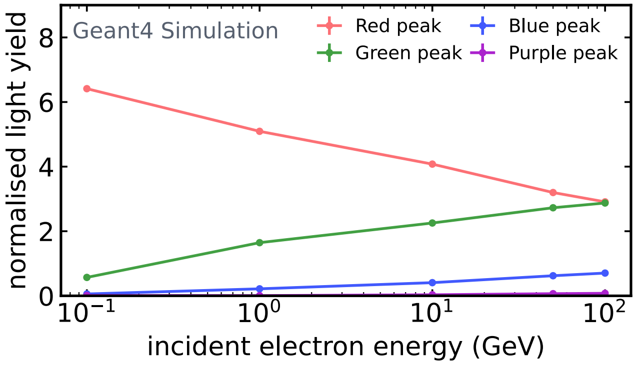
courtsey Y. Haddad, N U, Boston, USA



Beam test results (SPS) 2023

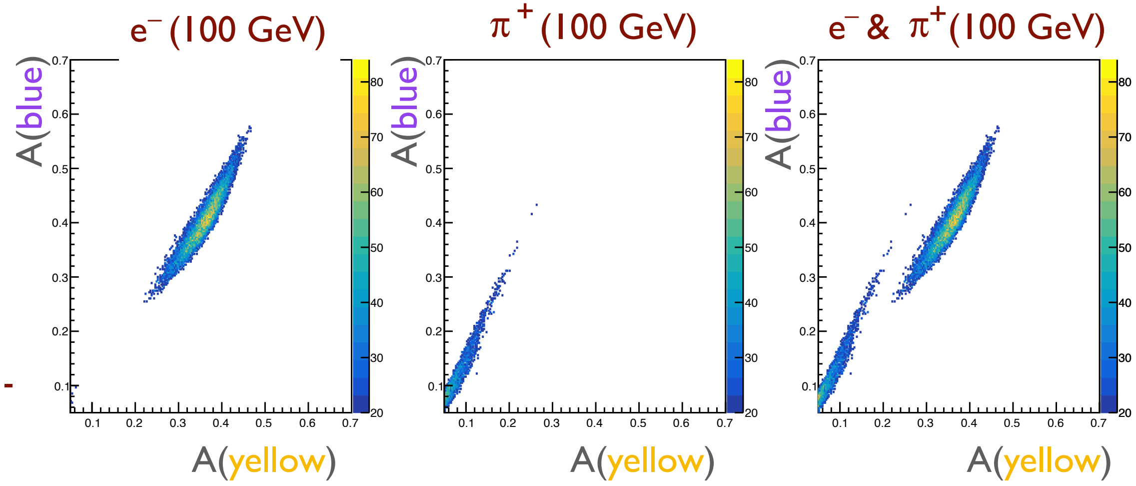






"Chromatic" energy measurement

"Chromatic" electron - pion discrimination



86% "chromatic" electron - pion discrimination

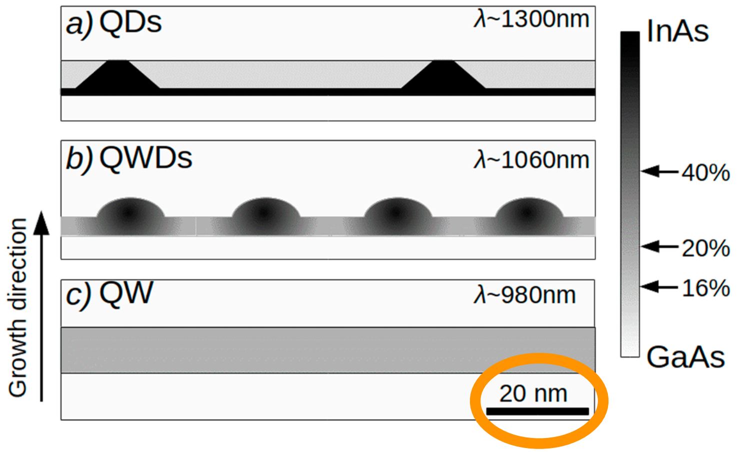
Active scintillators (QWs, QDs, QWDs, QCLs)

standard scintillating materials are passive

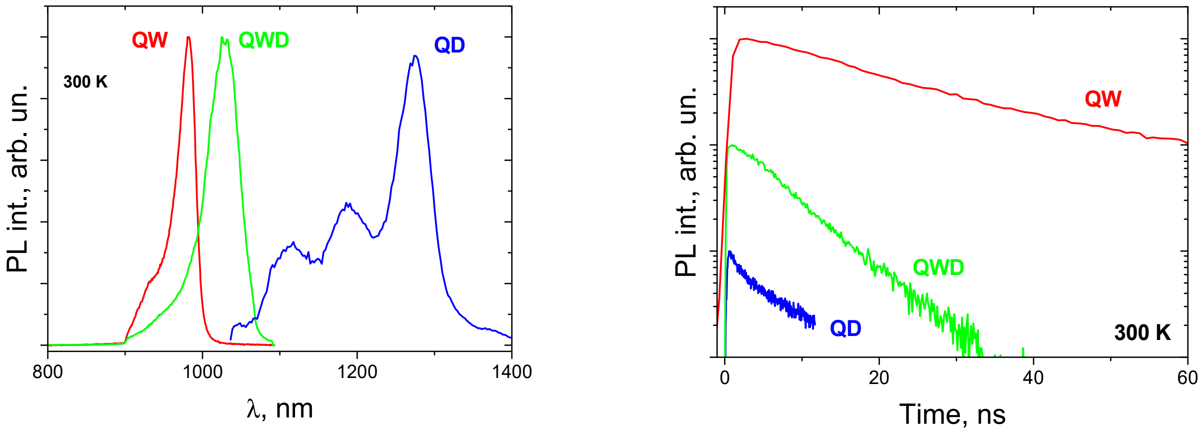
- can not be amplified
- can not be turned on/off
- can not be modified once they are in place

is it possible to produce active scintillating materials?

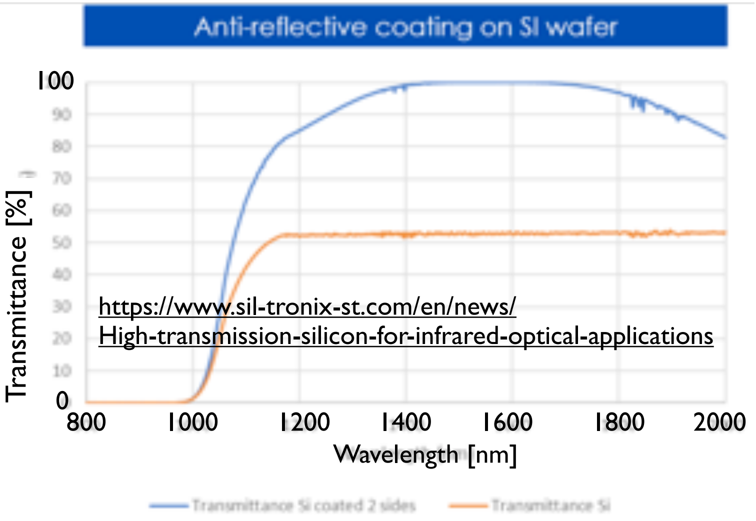
- electronically amplified / modulable
- pulsed / primed
- gain adapted in situ



existing QD's, QWD's are elements of optoelectronic devices, typically running at 10 GHz, quite insensitive to temperature



Light Emitting Devices Based on Quantum Well-Dots, Appl. Sci. 2020, 10, 1038; doi:10.3390/app10031038



https://www.sil-tronix-st.com/en/news/High-transmission-silicon-for-infrared-optical-applications

Emission in IR! Silicon is ~transparent at these wavelengths…
Can this IR light be transported *through* a tracker to outside PDs?

QD's are radiation resistant (10^{12} p/cm^2)

R. Leon et al., "Effects of proton irradiation on luminescence emission and carrier dynamics of self-assembled III-V quantum dots," in IEEE Transactions on Nuclear Science, 49, 6, 2844-2851 (2002), doi: 10.1109/TNS.2002.806018.

N. Sobolev, https://doi.org/10.1016/B978-0-08-046325-4.00013-X : "The QD heterostructures and QD lasers are generically more resistant to radiation damage than their bulk and two-dimensional (2D) counterparts, which is caused not only by the localization of the wavefunction of the confined carriers but also by the expulsion of the mobile defect components to the surface/interface of the nanocrystals."

Quantum dots and wells:

https://arxiv.org/abs/2202.11828

submicron pixels

DoTPiX

= single n-channel MOS transistor, in which a buried quantum well gate performs two functions:

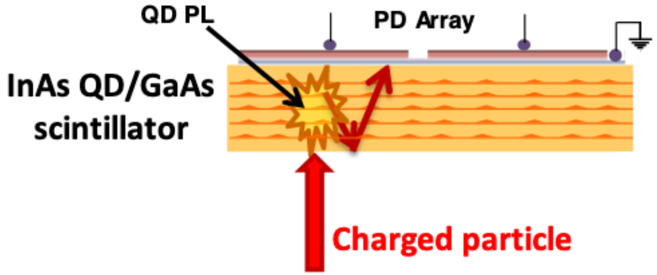
- as a hole-collecting electrode and
- as a channel current modulation gate

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.

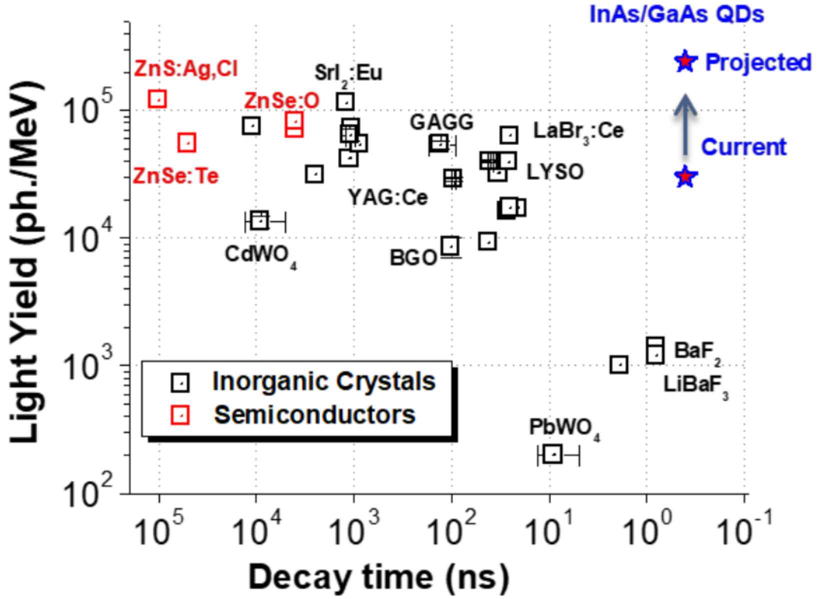
Novel Sensors for Particle Tracking: a Contribution to the Snowmass Community Planning Exercise of 2021, M.R. Hoeferkamp et al., arXiv:2202.11828

scintillating (chromatic) tracker

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



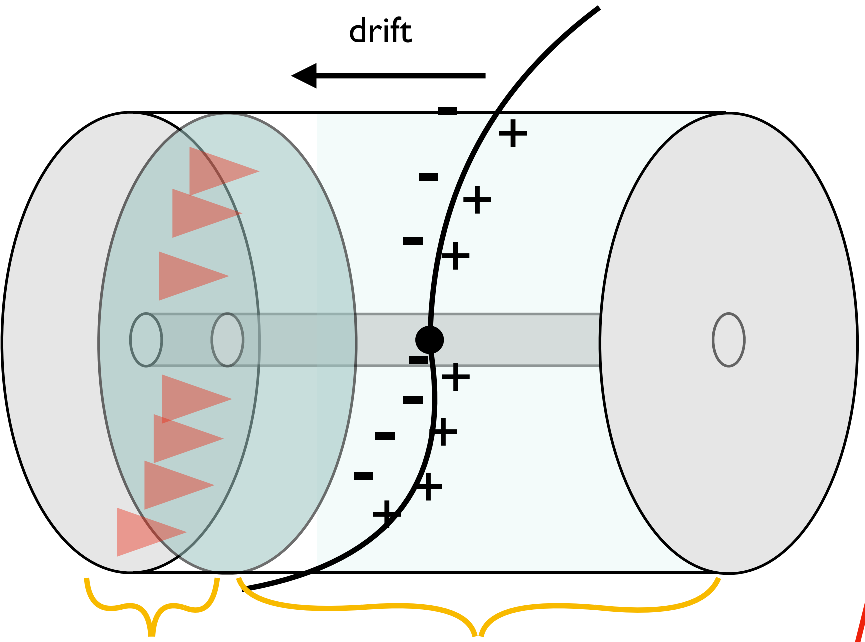
IR emission from InAs QD's integrated PD's (1-2 μm thick)



Rydberg atom TPC's

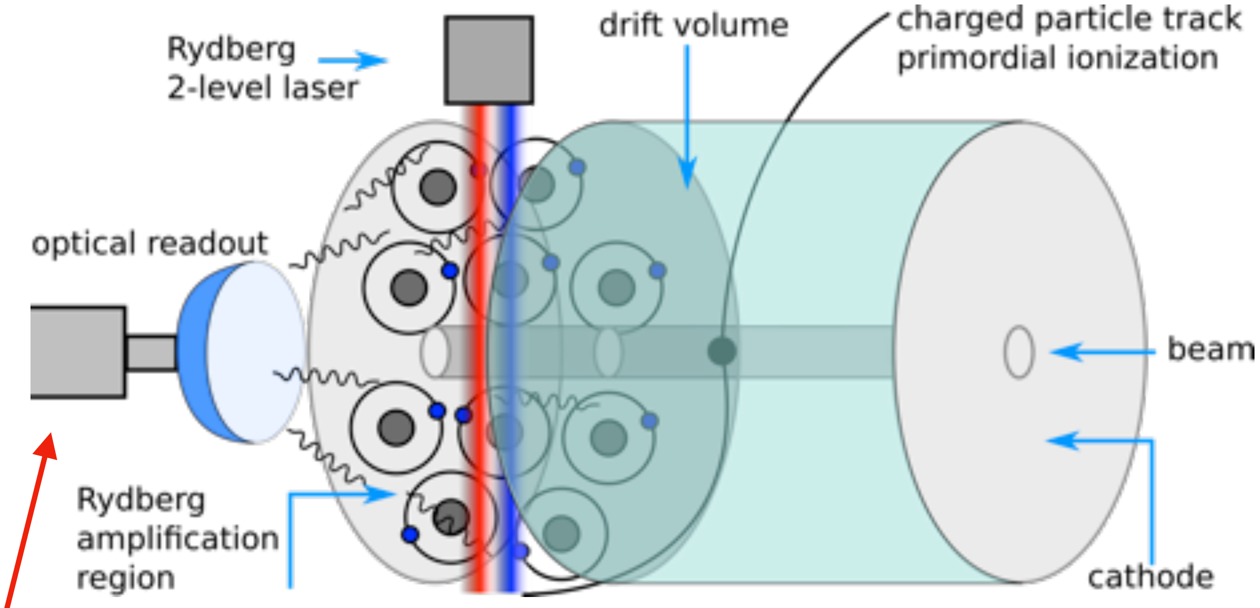
Georgy Kornakov / WUT

Act on the amplification region



amplification region

drift region



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

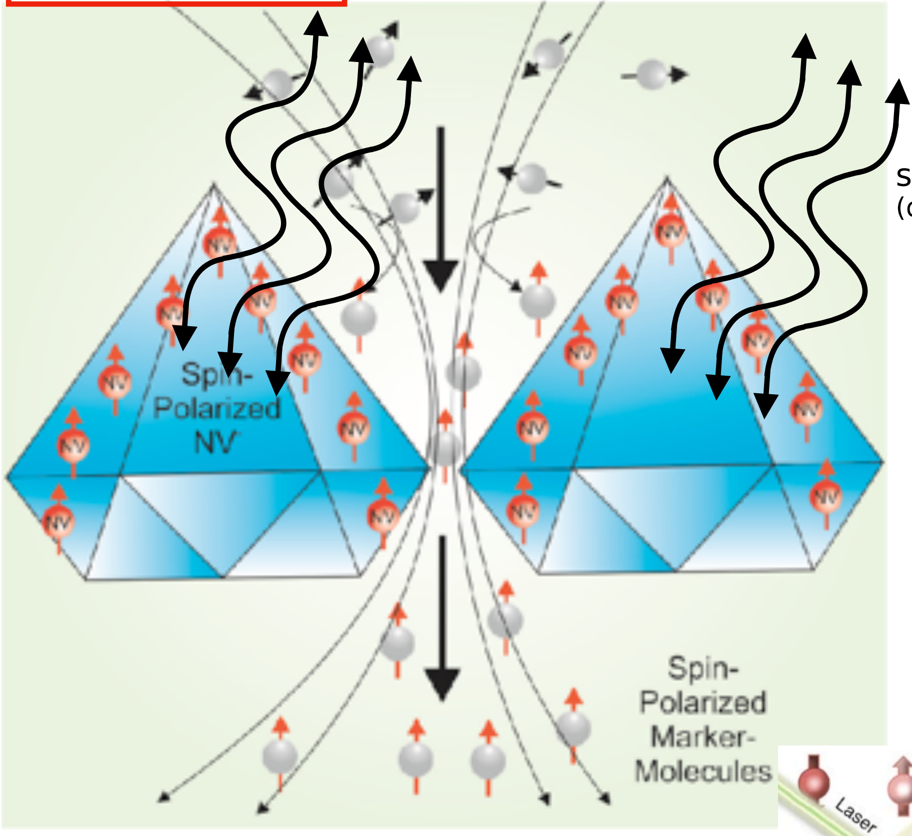
Rydberg atoms can serve to up-convert THz / GHz radiation into the optical regime ⟶ optical R/O of avalanche intensities

optically polarizable elements: Nitrogen-vacancy diamonds (NVD)

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

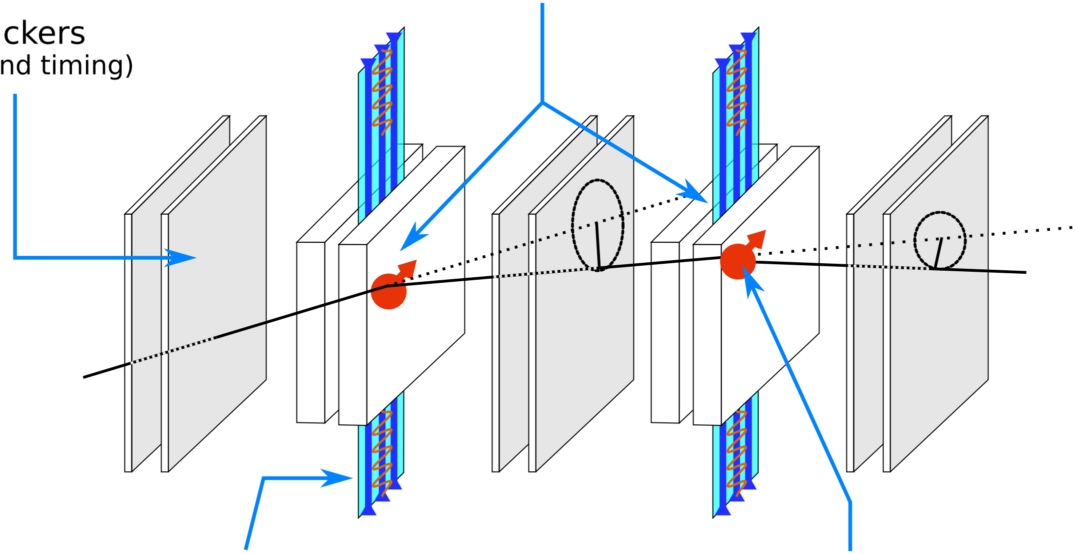
$10^{16} \sim 10^{18}$ / cm^3



© 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

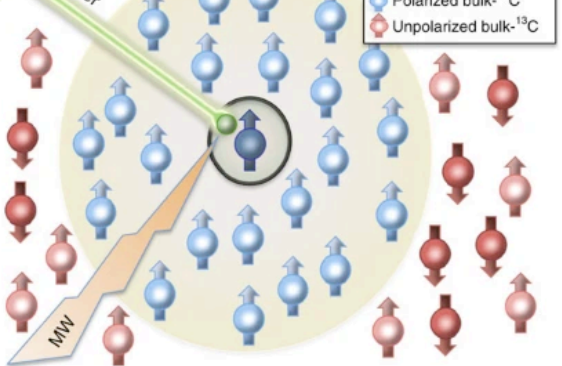


NV in diamond

silicon trackers
(direction and timing)

guides for optical polarization

polarized scattering center

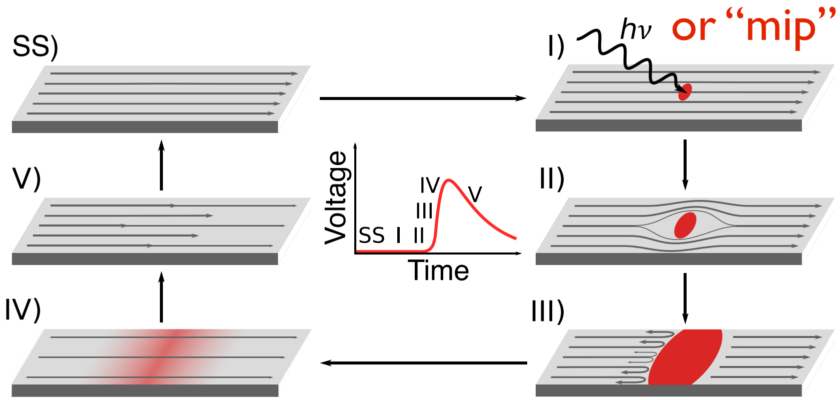


Local and bulk ^{13}C hyperpolarization in nitrogen-vacancy centred diamonds at variable fields and orientations, G. Alvarez et al., *Nature Communications* **6**, 8456 (2015)

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

Contact Information:
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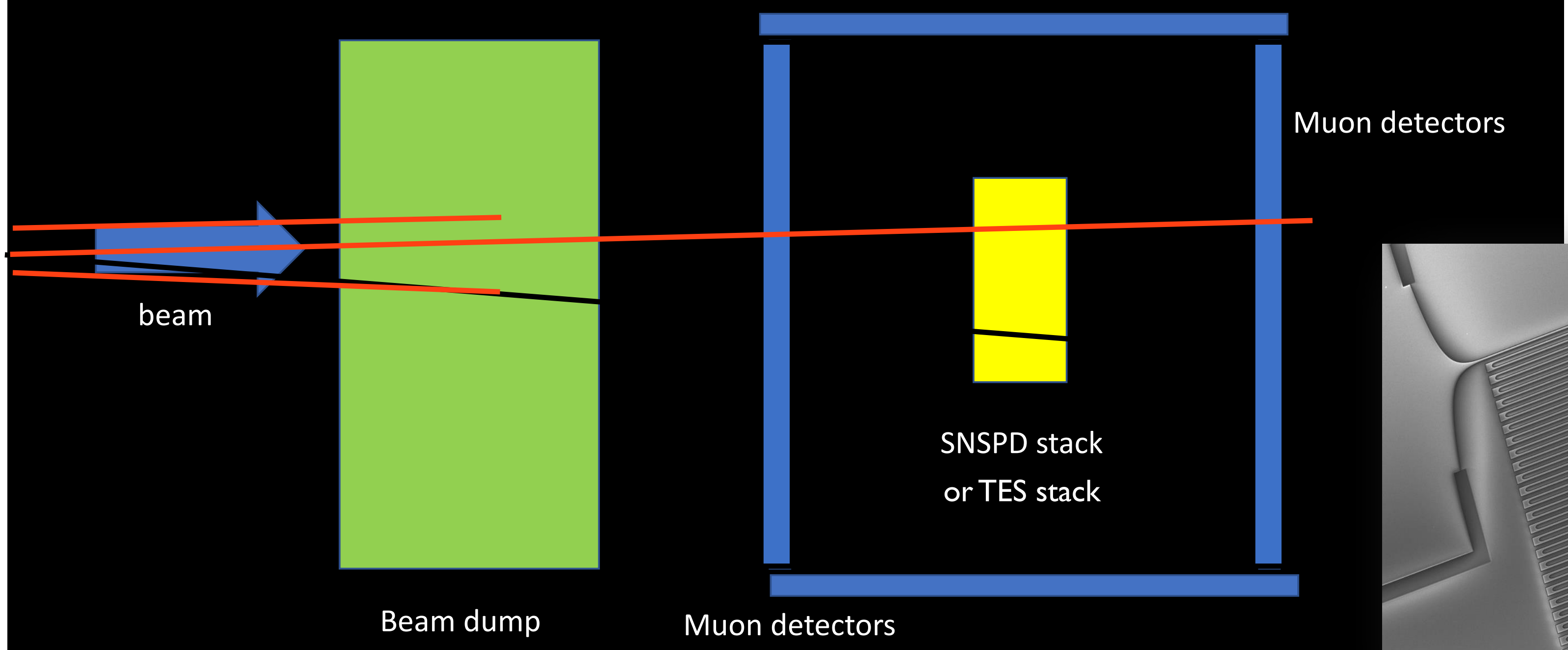
Matt Shaw, mattshaw@jpl.nasa.gov

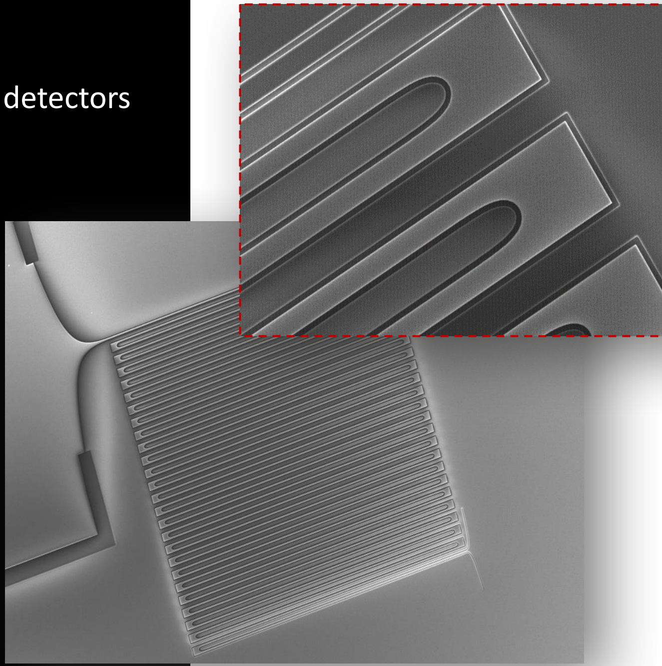
Moving to SC strips conventional lithography → scale up
Development towards SC SSPM

Search for Beyond Standard Model milli-charged particles?



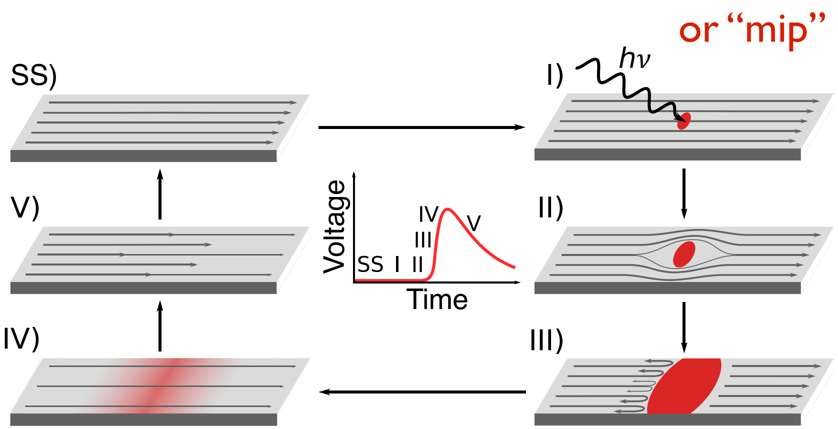
mip: ~20 keV/100 μm

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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Superconducting Nanowire Single-Photon Detectors

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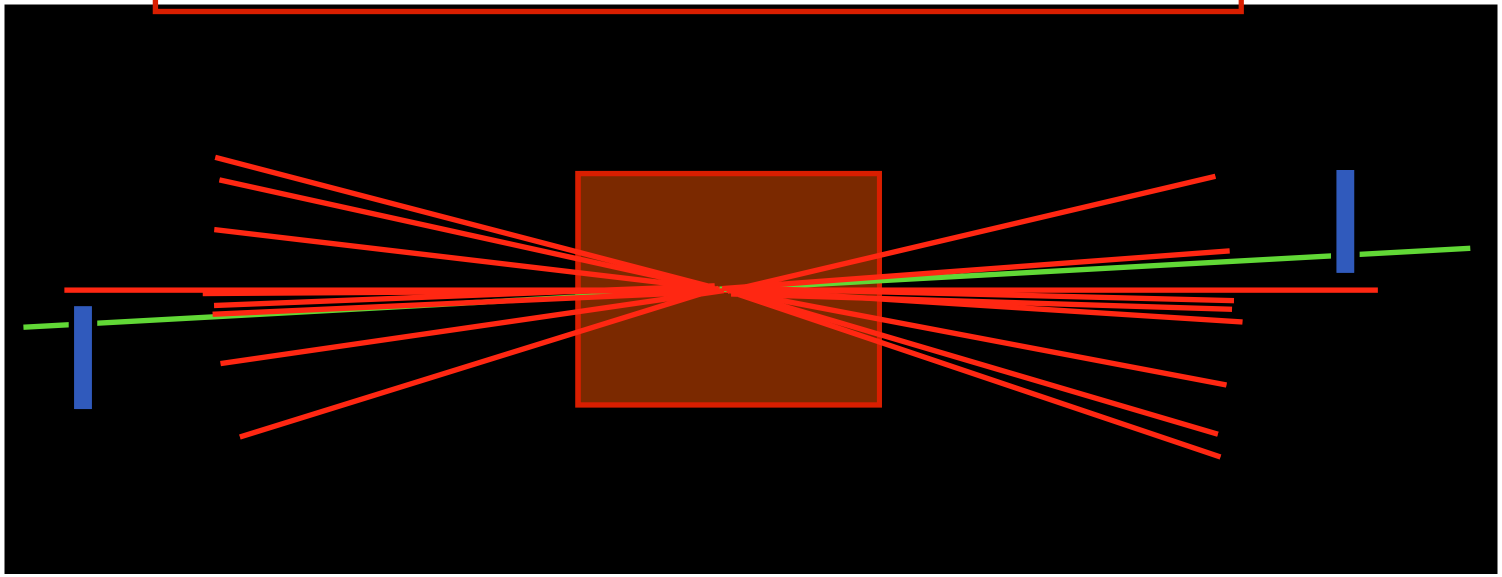
diffractive scattering via ps-resolution tracking in Roman pots



@ 2.8 K

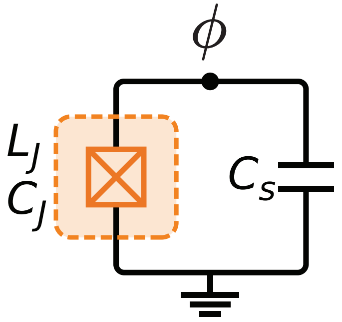
S. Lee et al., (2024)
arXiv:2312.13405v2
SNSPD w/ p@120 GeV
for use e.g. at EIC

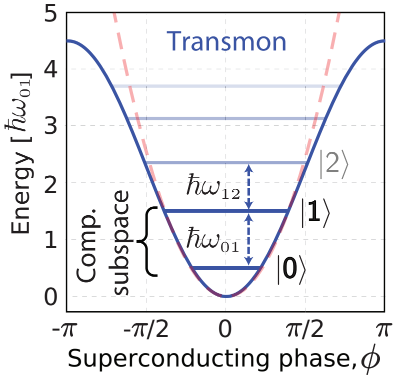
low energy particle physics: dark count rate is critical !
high energy particle physics: dark count rate is not a problem: high Tc is imaginable

Beyond existing sensors: using (superconducting) qubits

commonly used qubits: transmons

Josephson junction qubit





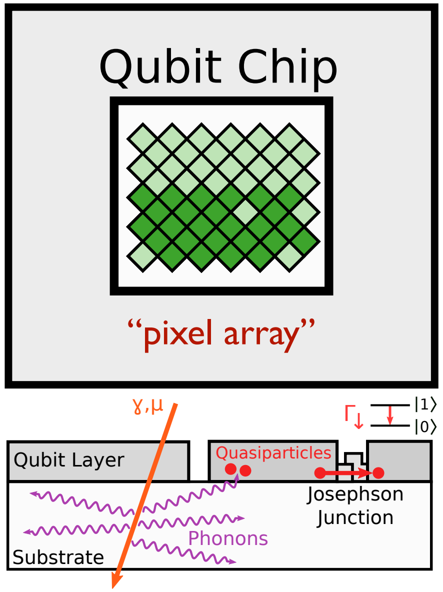
variant of a harmonic oscillator (with numerous equally-spaced energy levels):

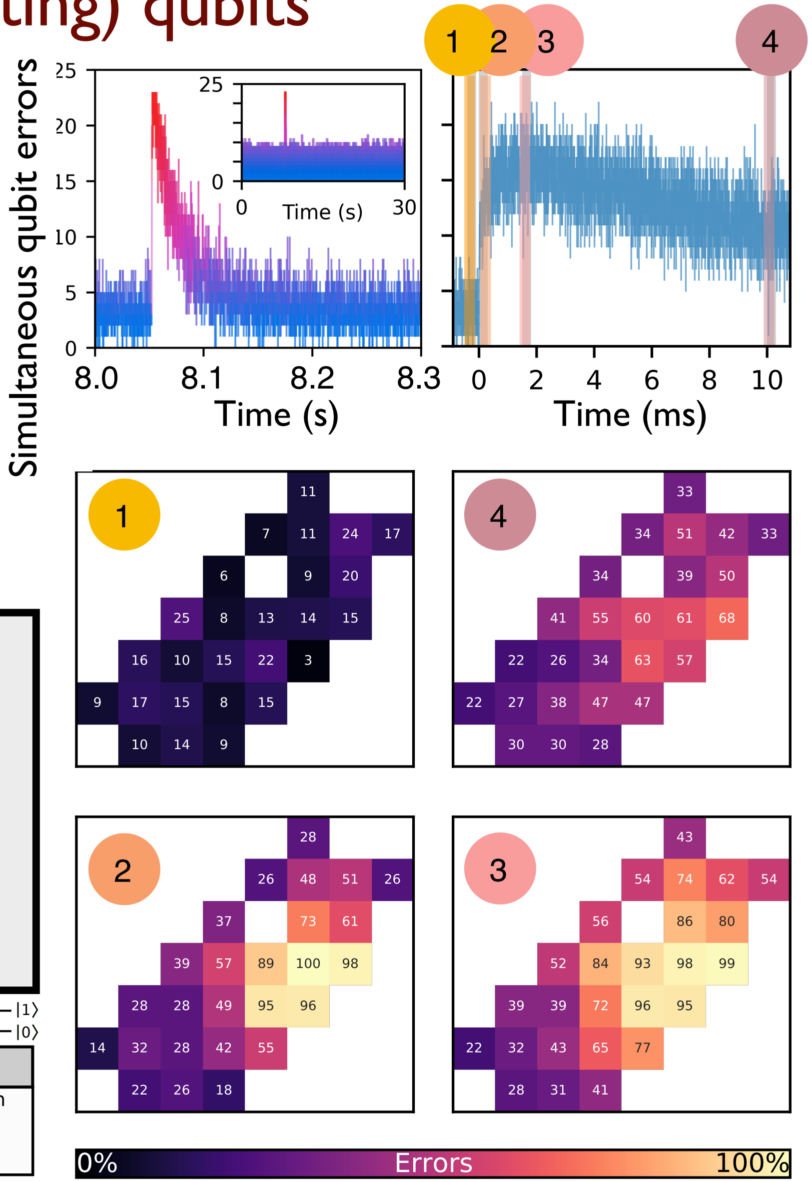
need to be able to define a computational subspace consisting of only two energy states (usually the two-lowest energy eigenstates) in between which transitions can be driven without also exciting other levels in the system: $|0\rangle$ and $|1\rangle$

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

Quantum sensor R&D: outlook

RECFA Detector R&D roadmap 2021

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

Chapter 5: Quantum and Emerging Technologies Detectors

focus on physics
and technology

1

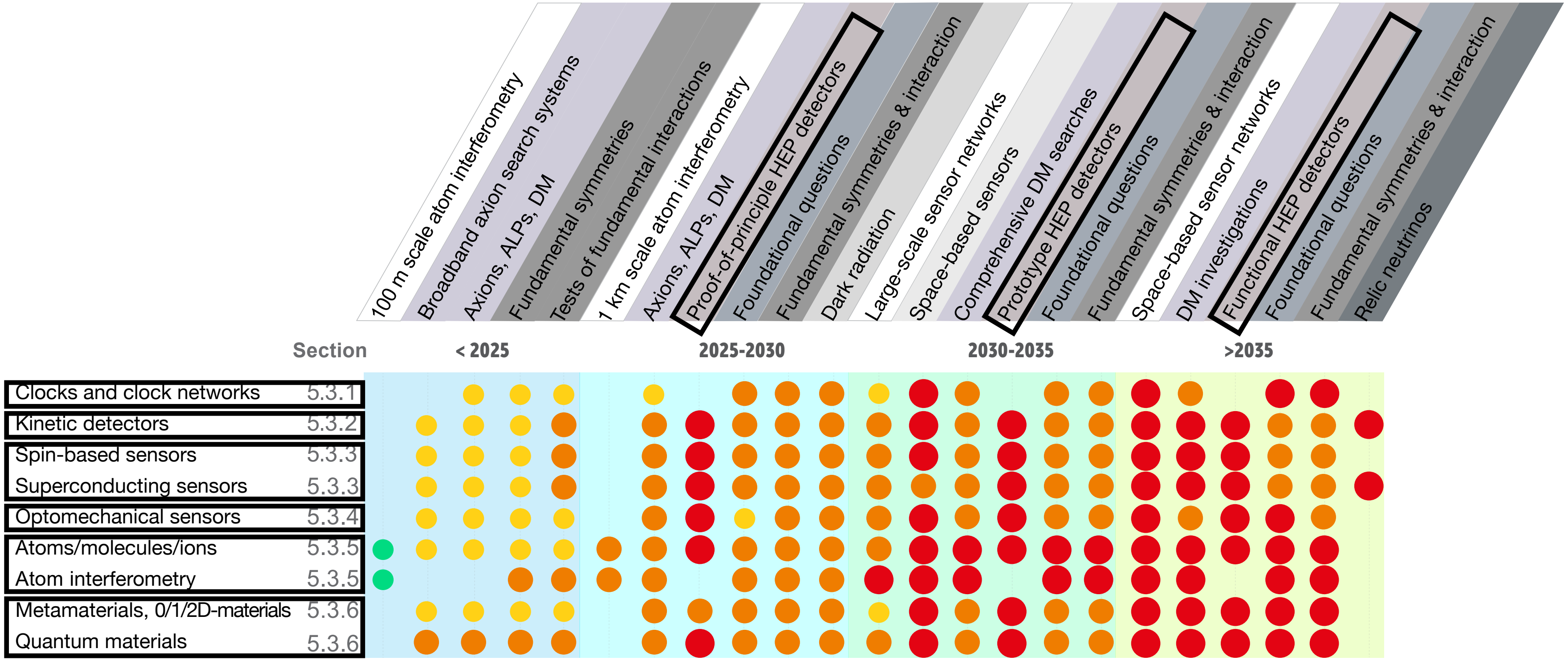
2

3

4

5

6



	Section	< 2025					2025-2030						2030-2035						>2035					
		100 m scale atom interferometry	Broadband axion search systems	Axions, ALPs, DM	Fundamental symmetries	Tests of fundamental interactions	1 km scale atom interferometry	Axions, ALPs, DM	Proof-of-principle HEP detectors	Foundational questions	Fundamental symmetries & interaction	Dark radiation	Large-scale sensor networks	Space-based sensors	Comprehensive DM searches	Prototype HEP detectors	Foundational questions	Fundamental symmetries & interaction	Space-based sensor networks	DM investigations	Functional HEP detectors	Foundational questions	Fundamental symmetries & interaction	Relic neutrinos
Clocks and clock networks	5.3.1			🟡	🟡	🟡		🟡		🟠	🟠	🟠	🟡	🔴	🟠		🟠	🟠	🔴	🟠		🔴	🔴	
Kinetic detectors	5.3.2		🟡	🟡	🟡	🟠		🟠	🔴	🟠	🟠	🟠	🟠	🔴	🟠	🔴	🟠	🟠	🔴	🔴	🔴	🟠	🟠	🔴
Spin-based sensors	5.3.3		🟡	🟡	🟡	🟠		🟠	🔴	🟠	🟠	🟠	🟠	🔴	🟠	🔴	🟠	🟠	🔴	🔴	🔴	🟠	🟠	
Superconducting sensors	5.3.3		🟡	🟡	🟡	🟠		🟠	🔴	🟠	🟠	🟠	🟠	🔴	🟠	🔴	🟠	🟠	🔴	🔴	🔴	🟠	🟠	🔴
Optomechanical sensors	5.3.4		🟡	🟡	🟡	🟡		🟠	🔴	🟡	🟠	🟠	🟠	🔴	🟠	🔴	🟠	🟠	🔴	🟠	🔴	🔴	🟠	
Atoms/molecules/ions	5.3.5	🟢	🟡	🟡	🟡	🟡	🟠	🟠	🔴	🟠	🟠	🟠	🟠	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	
Atom interferometry	5.3.5	🟢			🟠	🟠	🟠	🟠		🟠	🟠	🟠	🔴	🔴	🔴		🔴	🔴	🔴	🔴		🔴	🔴	
Metamaterials, 0/1/2D-materials	5.3.6		🟡	🟡	🟡	🟡		🟠	🟠	🟠	🟠	🟠	🟡	🔴	🟠	🔴	🟠	🟠	🔴	🔴	🔴	🔴	🔴	
Quantum materials	5.3.6		🟠	🟠	🟠	🟠		🟠	🔴	🟠	🟠	🟠	🟠	🔴	🟠	🔴	🟠	🟠	🔴	🔴	🔴	🔴	🔴	

🔴 **Must happen or main physics goals cannot be met** 🟠 **Important to meet several physics goals** 🟡 **Desirable to enhance physics reach** 🟢 **R&D needs being met**

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

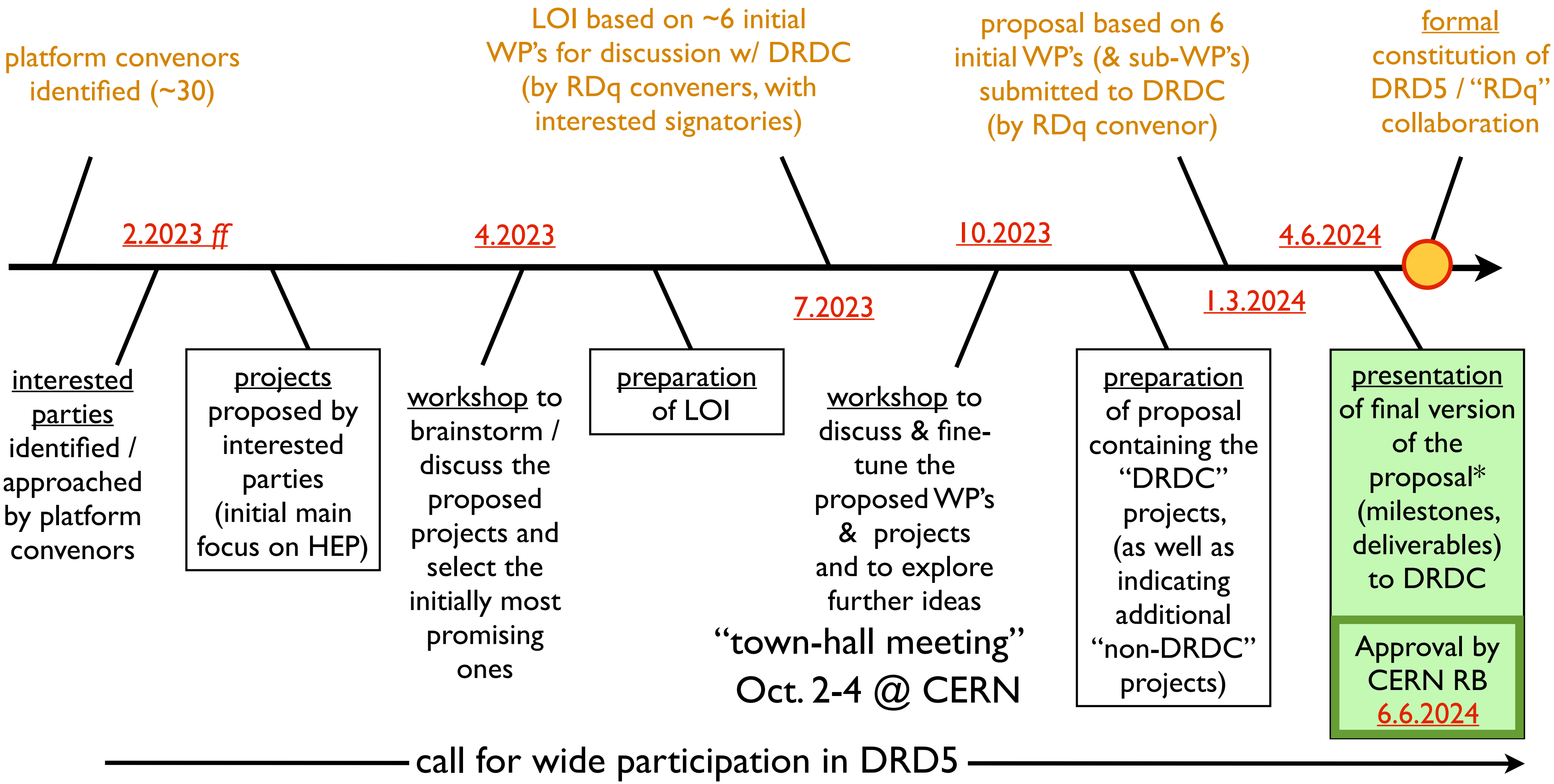
Ensure that all sensor families that were identified in the roadmap as relevant to future advances in particle physics are included

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

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

Approval by CERN RB 6.6.2024

formal constitution of DRD5 / "RDq" collaboration

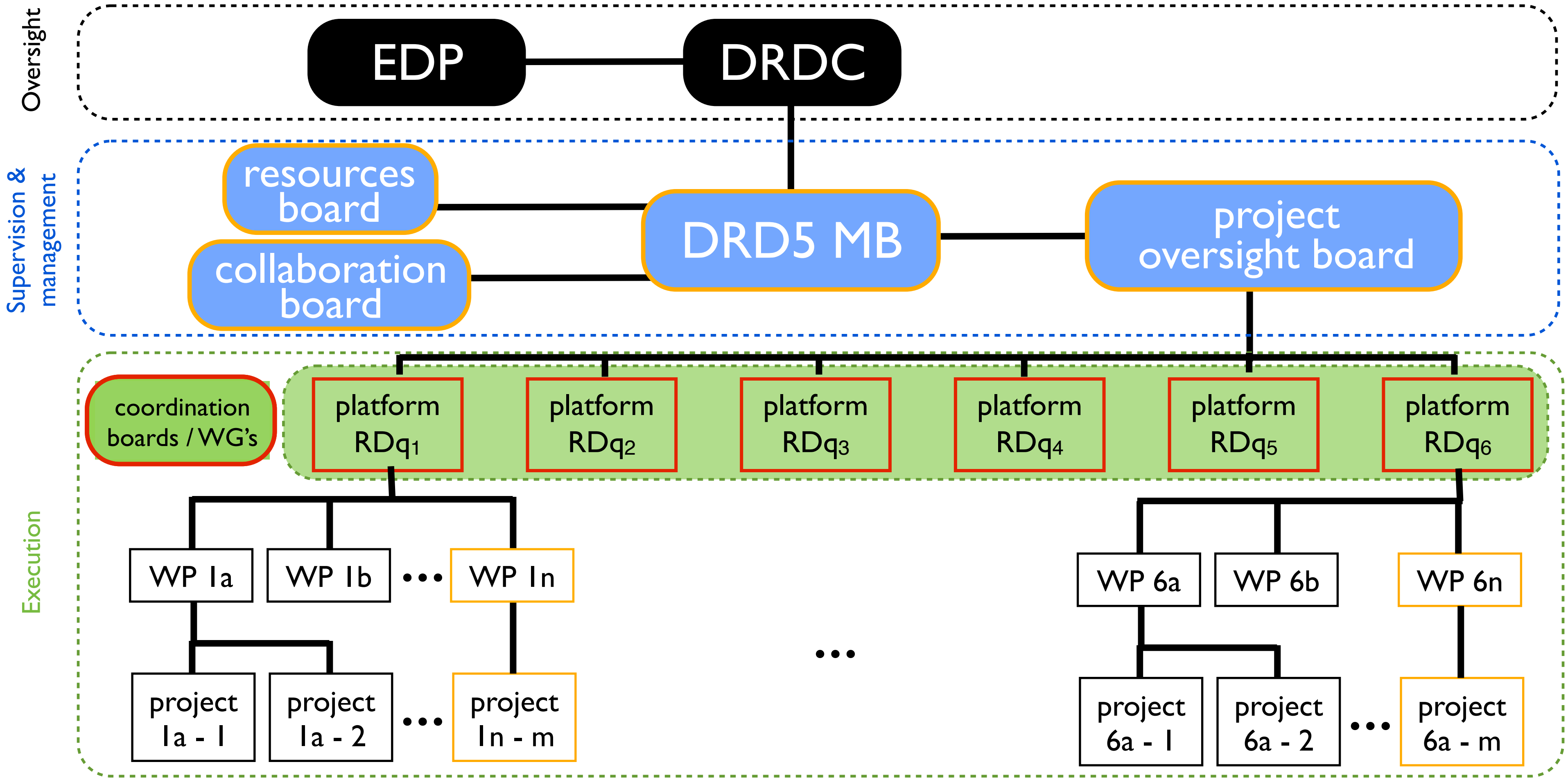
call for wide participation in DRD5

---

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

DRD5: WP's and structure

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)



Oversight

EDP

DRDC

Supervision & management

resources board

collaboration board

DRD5 MB

project oversight board

Execution

coordination boards / WG's

platform RDq1

platform RDq2

platform RDq3

platform RDq4

platform RDq5

platform RDq6

WP 1a

WP 1b

…

WP 1n

project 1a - 1

project 1a - 2

…

project 1n - m

…

WP 6a

WP 6b

WP 6n

project 6a - 1

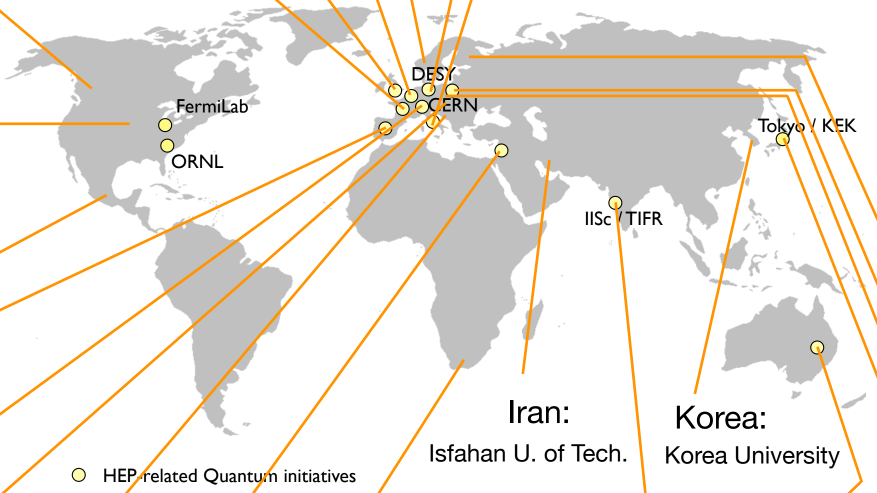
project 6a - 2

…

project 6a - m

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

DRD5: 96 involved groups (as of 3.6.2024)



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 Queensland
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

Japan:
QUP / KEK
Kyoto University
Tokyo University / ICEPP

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U. de Valencia
U. de Lleida

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

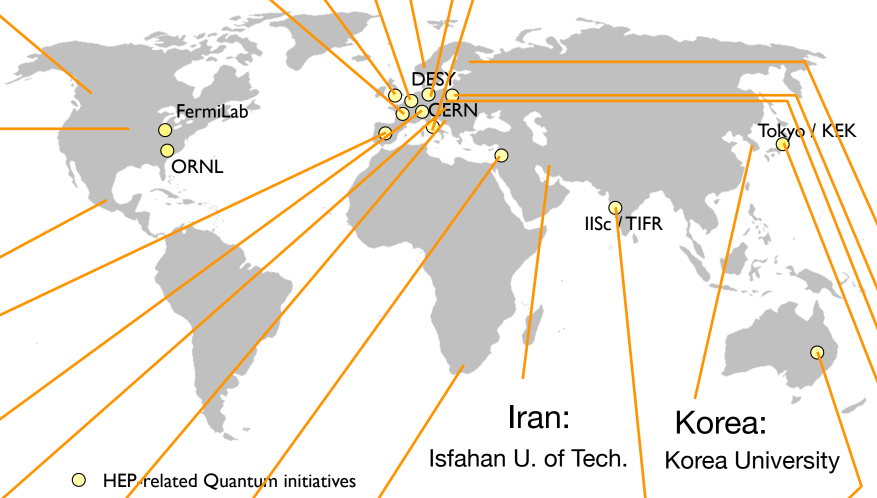
Netherlands: U. of Groningen

Norway: Oslo University

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!)



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TIFR, Mumbai
University SOA Bhuvaneswar

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Czech Republic:
Czech Tech. University

Japan:
QUP / KEK
Kyoto University
Tokyo University / ICEPP

thank you!

particle physics: what are we talking about?

Background

- Light DM candidate have large mode volume occupation number -> can be treated as classical fields

- QCD Axions and ALPs $\mathcal{L}_{axion} \supset \sum_f \frac{c_f}{\Lambda} \partial_\mu a \, \bar{f} \gamma^\mu \gamma^5 f \rightarrow \mathrm{H} \propto \sum_f \boldsymbol{\nabla} a \cdot \boldsymbol{S}_f$
  - $\boldsymbol{\nabla} a$ acts as a pseudo magnetic field → can be detected by atomic magnetometers

- Scalar fields $\mathcal{L}_{scalar} \supset \frac{\phi^n}{\Lambda_\gamma^n} F_{\mu\upsilon} F^{\mu\upsilon} - \sum_f \frac{\phi^n}{\Lambda_f^n} m_f \bar{f} f$
  - Λ_γ^n alter the fine structure constant α, Λ_f^n the fermionic masses -> manifest as variations of fundamental constants

- symmetry violations probed via precision measurements ($\not{C}$P, C$\not{P}$T, Lo$\not{r}$enz, W$\not{E}$P, …) → SME

D. Colladay, V.A. Kostelecký, "CPT violation and the standard model". Physical Review D. 55 (11) (1997) 6760–6774. arXiv:hep-ph/9703464

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

https://indico.cern.ch/event/999818/

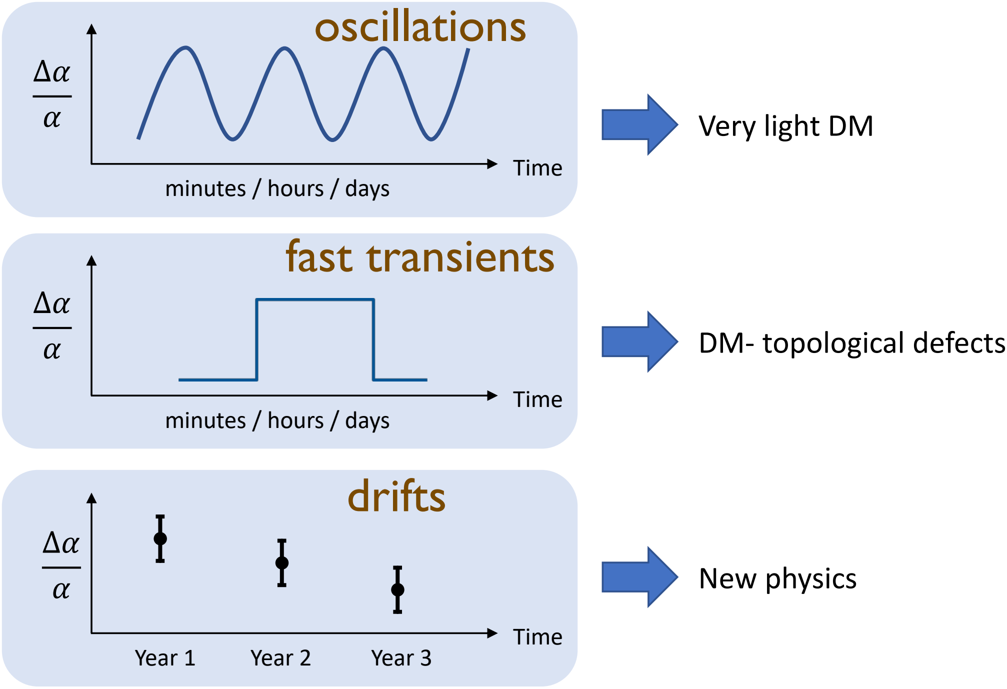
Giovanni Barontini (Birmingham)

particle physics: what are we talking about?

search for NP / BSM

networks of sensors

- The only possibility of detecting transient events such as topological defects, solitons, Q balls and dark stars
- Oscillations of dark matter fields at different locations as long as the distance is below the coherence length (100 km: mass ~10^{-9} eV)
- Sensors with similar sensitivities and different systematics are necessary to confirm any measurements and reject false positives
- Using multiple sensors increases the detection confidence and sensitivity
- Multimessenger detection, discriminating between different couplings

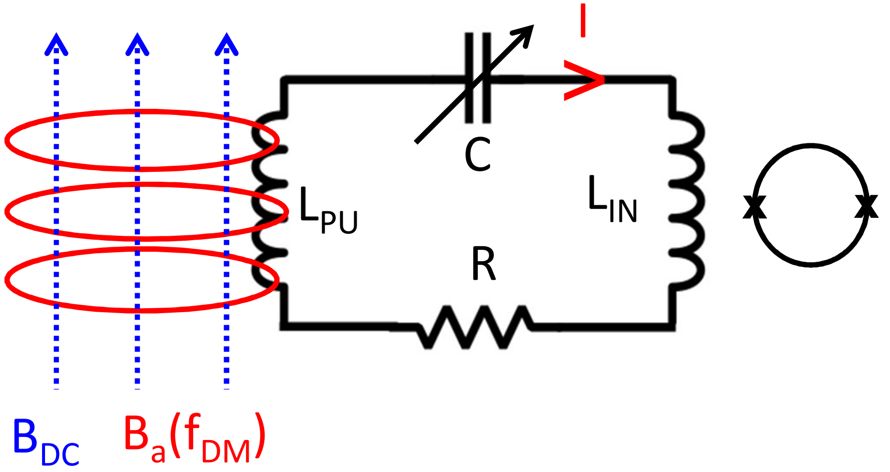


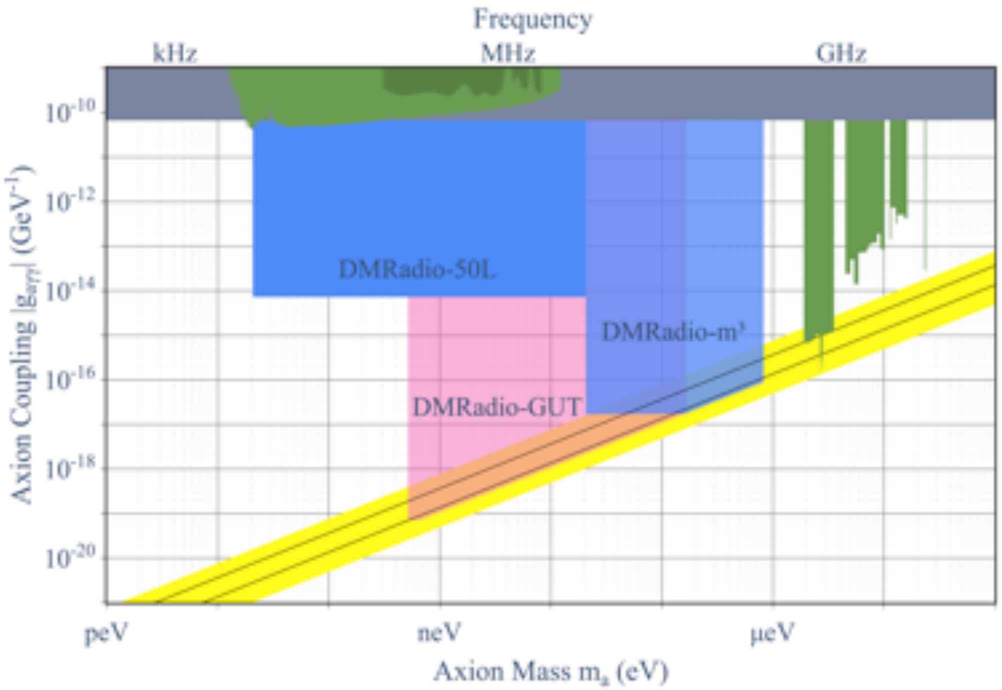
→ ECFA Detector R&D Roadmap Symposium of Task Force 5 Quantum and Emerging Technologies
https://indico.cern.ch/event/999818/

DMRadio

Focus on electromagnetic interaction: axions and photons mix in the presence of a strong magnetic field

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





- 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 (e.g. JJPA)

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

https://indico.cern.ch/event/999818/

Kent Irwin (Stanford University)

CASPEr electric NMR

Focus on different interactions: the electric dipole moment (EDM) interaction and the gradient interaction with nuclear spin I. The EDM interaction arises from the coupling of the axion to the gluon field.

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

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

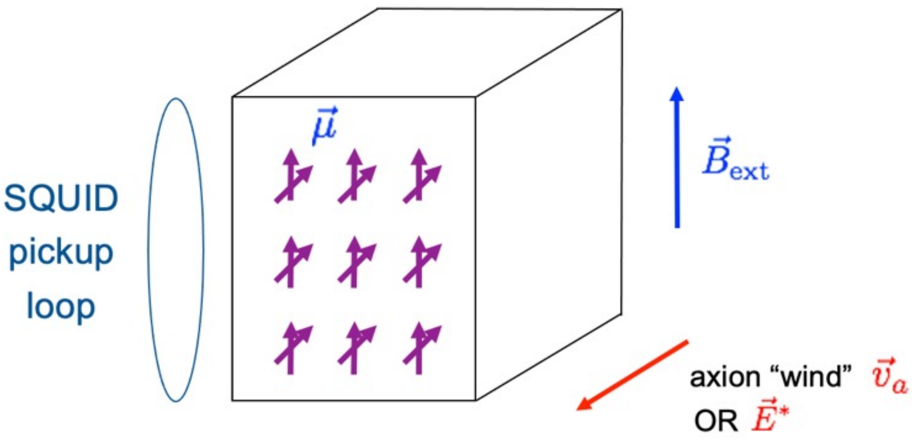
$$\boxed{H_e \propto a\boldsymbol{\sigma}\cdot\boldsymbol{E}^*}$$

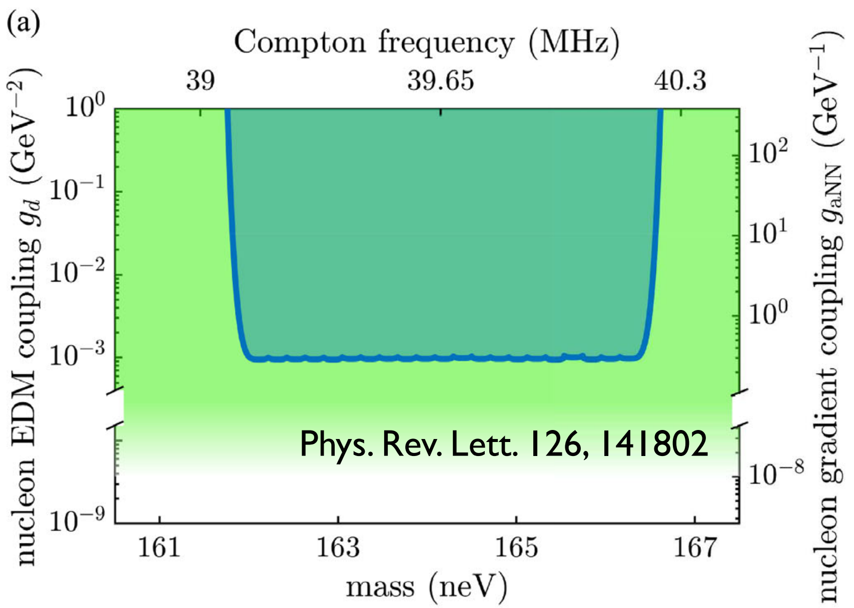
CASPEr-electric

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

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

CASPEr-gradient





Phys. Rev. Lett. 126, 141802

numerous improvements possible ➔ many orders of magnitude in mass and sensitivity range

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

https://indico.cern.ch/event/999818/

Dima Budker (Mainz University)

Axion heterodyne detection

problem: cavity resonance generally fixed

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

A. Berlin, Raffaele Tito D'Agnolo, S. Ellis, K. Zhou, arXiv:2007.15656

$$\underset{\text{figure of merit}}{F} \sim g_{a\gamma}^2 \underset{\text{axion mass}}{\boxed{m_A^2}} B^4 \underset{\text{cavity volume}}{\boxed{V^2}} T_{sys}^{-2} G^4 Q,$$

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

Quantum sensors for new particle physics experiments: tunable RF cavities

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

→ scan over axion masses m_a = slight perturbation of cavity geometry, which modulates the frequency splitting $\omega_0 - \omega_1$

→ superconducting RF cavities

①

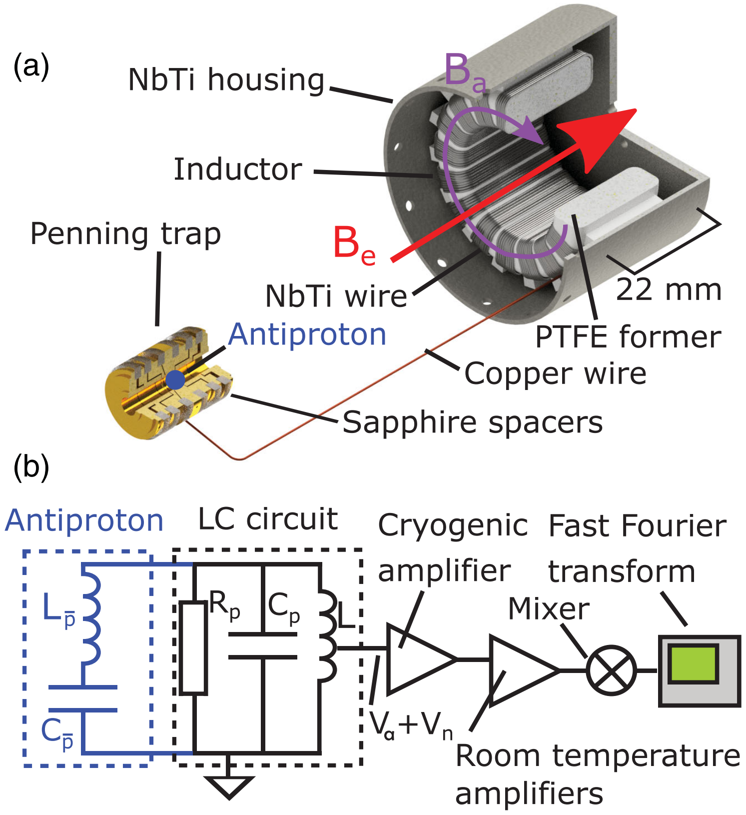
Tests of QED, searches for BSM, probes of fundamental symmetries

search the noise spectrum of fixed-frequency resonant circuit for peaks caused by dark matter ALPs converting into photons in the strong magnetic field of the Penning-trap magnet

Resolving single antiproton spin flips requires the highest Q and lowest temperature LC resonant detectors ever built: BASE-CERN is the state of the art

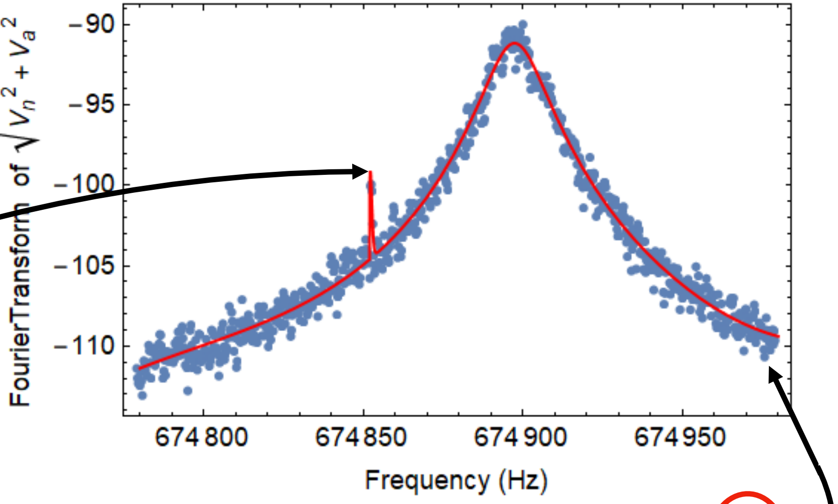
Constraints on the Coupling between Axion-like Dark Matter and Photons Using an Antiproton Superconducting Tuned Detection Circuit in a Cryogenic Penning Trap

J. Devlin *et al.*, BASE collaboration, Physical Review Letters 126, 041301 (2021)



H. Nagahama et al., Rev. Sci. Instrum. 87, 113305 (2016)

https://indico.cern.ch/event/1002356/



resonator background ∝ $\sqrt{T_z}$
from antiproton spin-flip

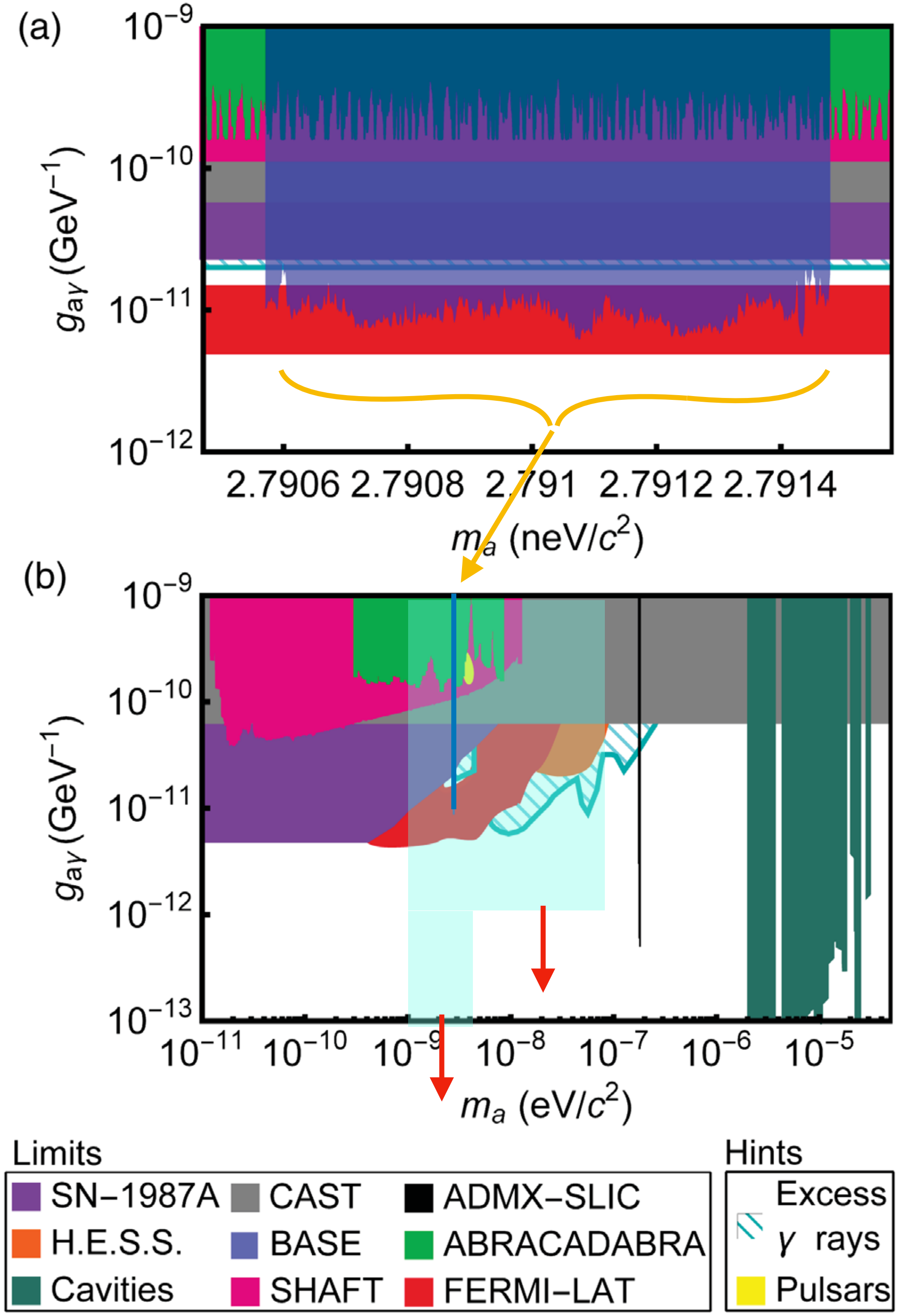
The axion signal

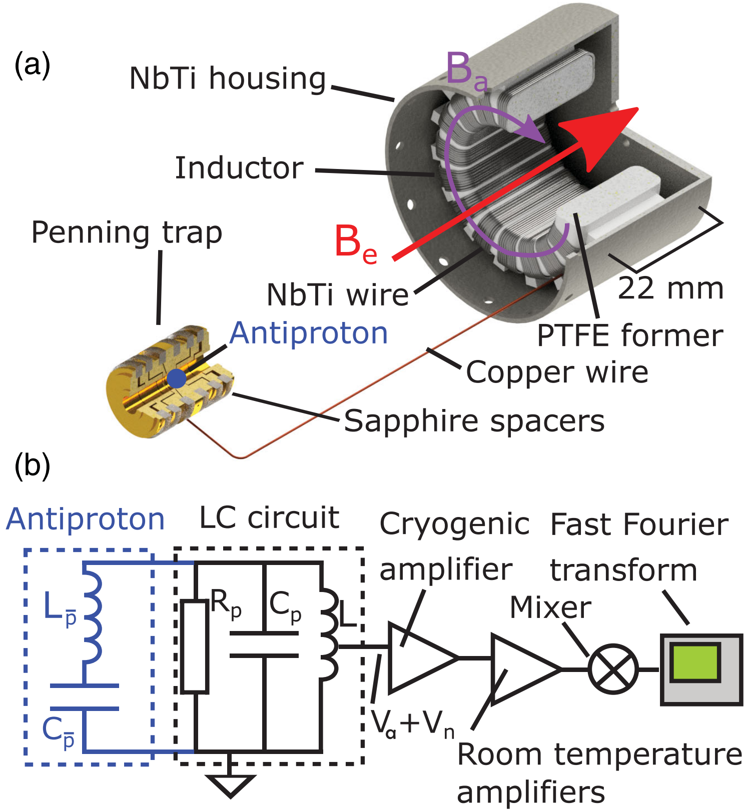
$$V_a = \frac{\pi}{2} Q \sqrt{f(\nu, Q, \mathbf{q})} \kappa \nu_a l N_\mathrm{T} (r_2^2 - r_1^2) g_{a\gamma} |\mathbf{B}_e| \sqrt{\rho_a \hbar c}\,.$$

$f(\nu,Q,\mathbf{q})$ is a lorentzian line-shape function proportional to Re{Z}
e_n is the equivalent input noise of the amplifier
κ is the coupling constant
Q is the resonator Q-factor
N_T is the number of turns
l is the length of the toroid along the magnet B field

r_1 is the inner radius of the toroid
r_2 is the outer radius
$g_{a\gamma}$ is the coupling constant
B is the static magnetic field
ρ_a is the dark matter density

Tunability!





currently developing superconducting tunable capacitors & laser-cooled resonators

7 T magnet + broader FFT span: one month ⟶
2 and 5 neV to an upper limit of 1.5 × 10^{-11} GeV^{-1}

High Q in high B!

Quantum sensors for new particle physics experiments: thin film SRF cavities

Axion searches with resonant haloscopes: resonant cavity immersed in a high and static magnetic field

Relic Axion Detector Exploratory Setup (RADES) searches for axion dark matter with $m_a > 30\ \mu\text{eV}$

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

figure of merit magnetic field quality factor

Cavity coatings: type II superconductor with a critical magnetic field B_c well above 11 T at 4.2 K

Thin Film (High Temperature) Superconducting Radiofrequency Cavities for the Search of Axion Dark Matter

S. Golm, …, Sergio Calatroni, … *et al.* https://ieeexplore.ieee.org/document/9699394 DOI: 10.1109/TASC.2022.3147741

→ developments of HTS for coatings is essential in improving the sensitivity of resonant haloscopes

Multiple cavities: optimal coupling with external B field, very selective (high Q), centered on resonant ν

Universe **2022**, *8*(1), 5; https://doi.org/10.3390/universe8010005

other frequencies: e.g. solenoidal magnet in dilution cryostat at 10 mK (Canfranc Underground Lab.)

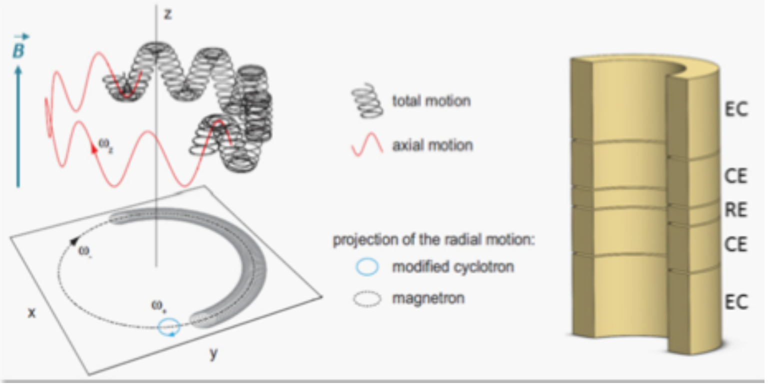
→ to exploit the ultra-low temperatures and go beyond the standard quantum limit:
Josephson parametric amplifiers (JPA), superconducting qubit-based single photon counters,
(or for higher frequencies, kinetic inductor devices (KID))

Universe **2022**, *8*(1), 5; https://doi.org/10.3390/universe8010005

particles, atoms, ions, nuclei:

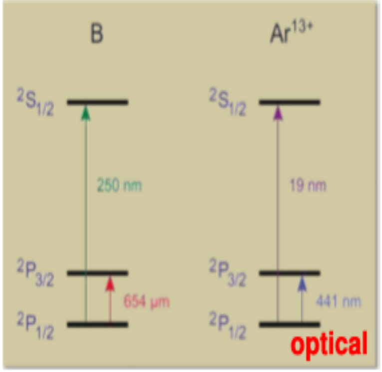
tests of QED, T-violation, P, Lorentz-violation, DM searches

HCI's in Penning traps



Scaling with a nuclear charge Z

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



K. Blaum et al., Quantum Sci. Technol. 6 014002 (2021)

eEDM's in molecules

nuclear clock (^{229}Th)

molecular / ion clocks

Quantum Sensors for New-Physics Discoveries

https://iopscience.iop.org/journal/2058-9565/page/Focus-on-Quantum-Sensors-for-New-Physics-Discoveries

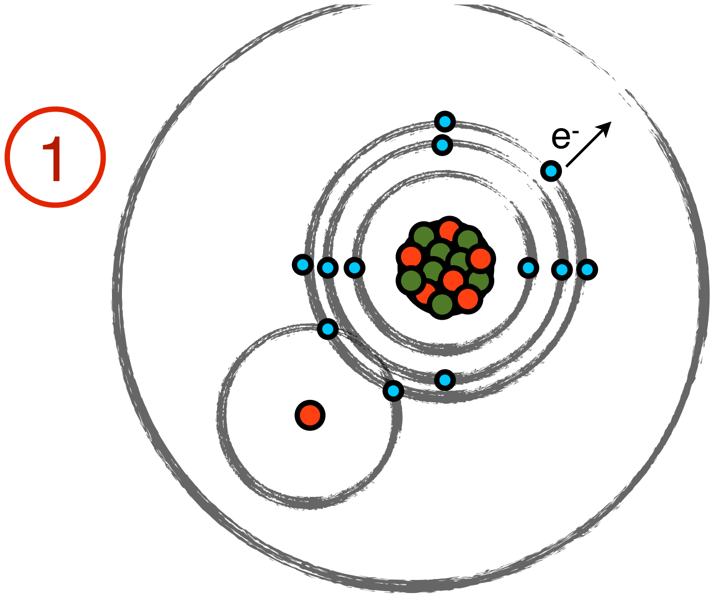
→ ECFA Detector R&D Roadmap Symposium of Task Force 5 Quantum and Emerging Technologies

https://indico.cern.ch/event/999818/ Marianna Safronova (University of Delaware)

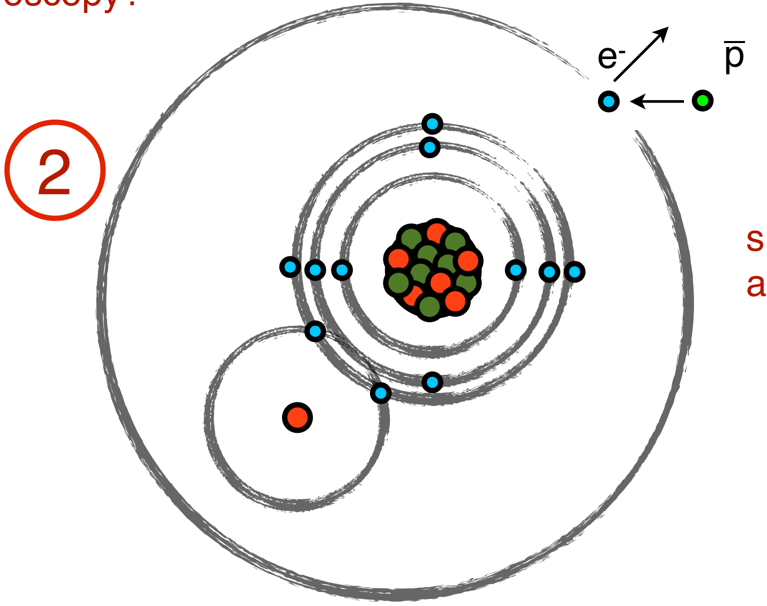
Exotic systems for tests of QED, searches for BSM, probes of fundamental symmetries

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

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



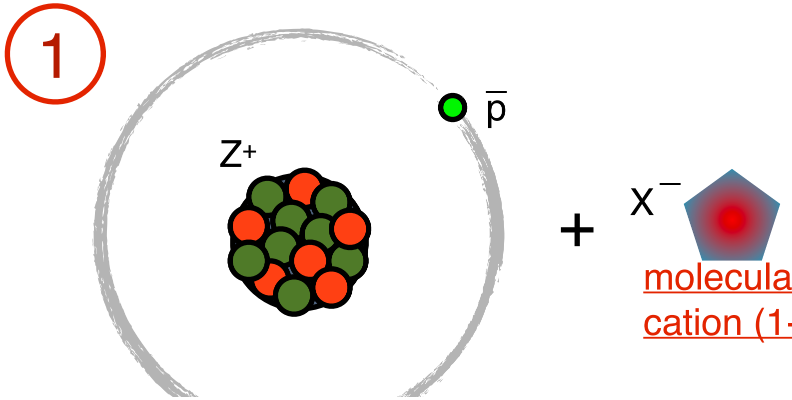
Rydberg excitation



charge exchange

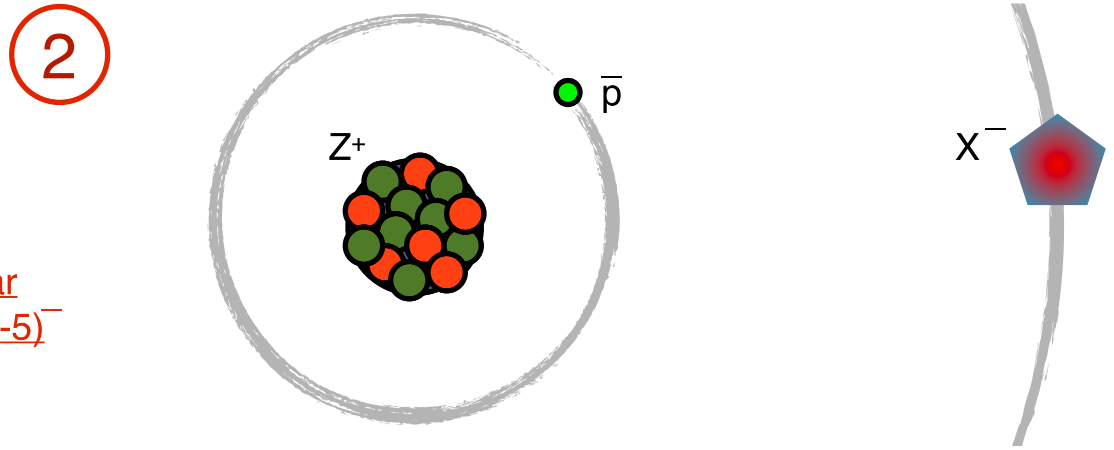
similar approach
as eEDM in molecules

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



molecular
cation (1-5)$^-$

$\bar{p}$ H-like HCI, $(Z-1)^+$



Antiprotonic atoms → novel DM search

Focus on a recently proposed category of dark matter candidates: sexaquarks

G. Farrar , https://arxiv.org/abs/2201.01334 (2022)

not excluded by prior searches for similar states (among them, the H dibaryon) in the GeV region

astrophysical bounds can be evaded

standard model compatible (uuddss bound state)

mass window ~ 1.5 GeV - 2.1 GeV (stable or quasi-stable against decay)

formation requires dense volume of u, d and s

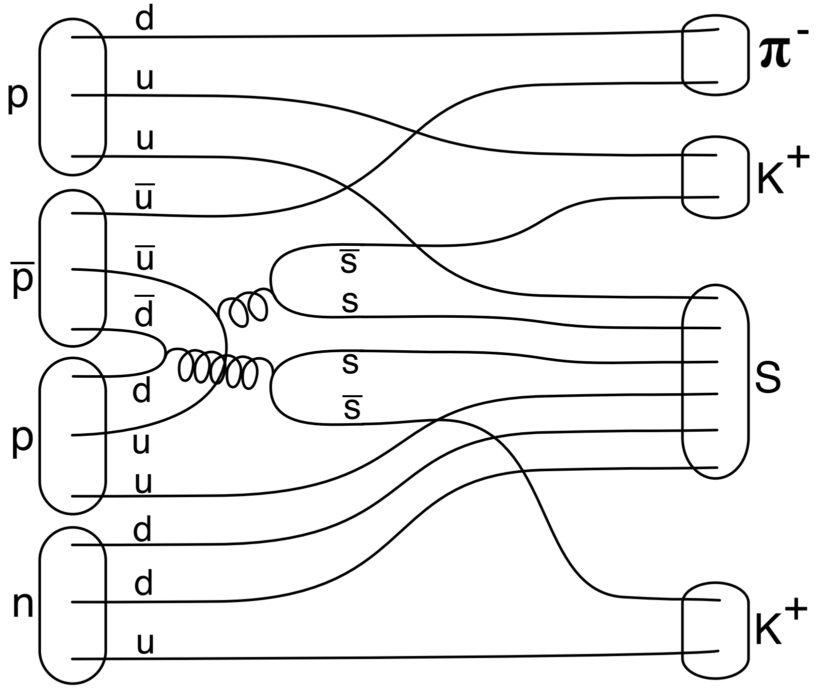
- p-p or Pb-Pb at LHC

  R. Bruce et al. , https://arxiv.org/abs/1812.07688 (2018)

- multi-nucleon annihilation ($\bar{p}$ ^{3}He)

  G. Farrar, G. Kornakov, M. Doser, EPJC 83, 1149 (2023)

- multi-nucleon annihilation ($\bar{p}$ d) observed @ 10^{-5}



Antiprotonic atoms → novel DM search

G. Farrar, G. Kornakov, M. Doser, EPJC 83, 1149 (2023)

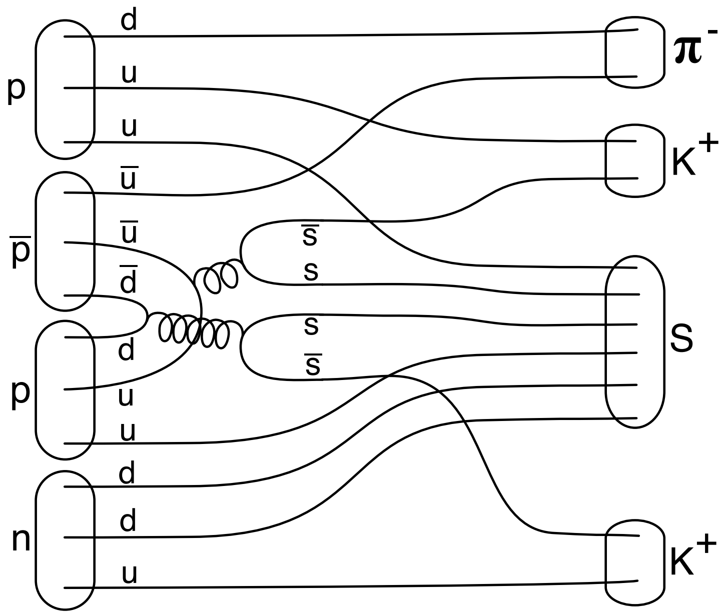
***sexaquark: uuddss bound state** (m ~ 2m_p) [Glennys Farrar* https://arxiv.org/abs/1708.08951*]*

not excluded by prior searches for similar states (among them, the H dibaryon) in the GeV region
astrophysical bounds can be evaded
standard model compatible (uuddss bound state)

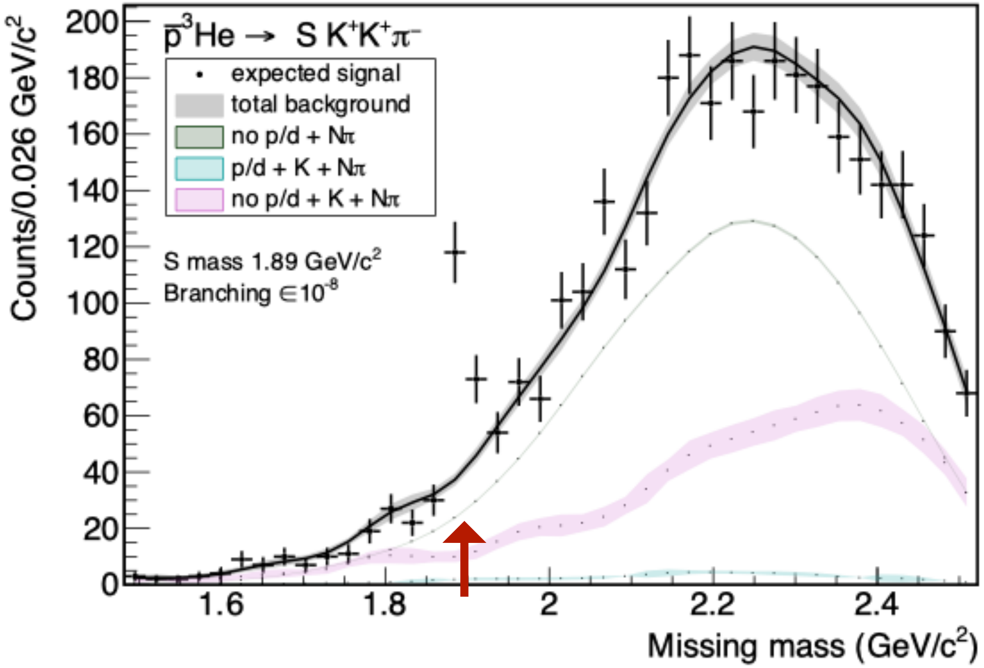
AE$\bar{g}$IS experiment
(gravitational interactions of antimatter systems)

formation reaction:
$(\bar{p}\ {}^3\mathrm{He})^* \rightarrow S(uuddss) + K^+K^+\pi^-$

$S = +2, Q = +1$



Geant-4 simulation



→ ***in-trap formation of antiprotonic atoms***
charged particle tracking, PID
detection of spectator p, d

→ ***sensitivity down to 10^{-9} prod. rate***

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].

Topological Dark Matter (TDM)

TDM can be expressed as a scalar field that couples to fundamental constants, thus producing variations in the transition frequencies of atomic clocks at its passage.

Ultralight Dark Matter

spatial variation of the fundamental constants associated with a change in the gravitational potential

Local Lorentz Invariance (LLI)

independence of any local test experiment from the velocity of the freely-falling apparatus.

searching for daily variations of the relative frequency difference of e.g. Sr optical lattice clocks or Yb^+ clocks confined in two traps with quantization axis aligned along non-parallel directions

Local Position Invariance (LPI)

independence of any local test experiment from when and where it is performed in the Universe

comparing atomic clocks based on different transitions can be used to constrain the time variation of fundamental constants and their couplings, comparison of two $^{171}Yb^+$ clocks and two Cs clocks -> limits on the time variation of the fine structure constant and of the electron-to-proton mass ratio

Gravitational wave detector

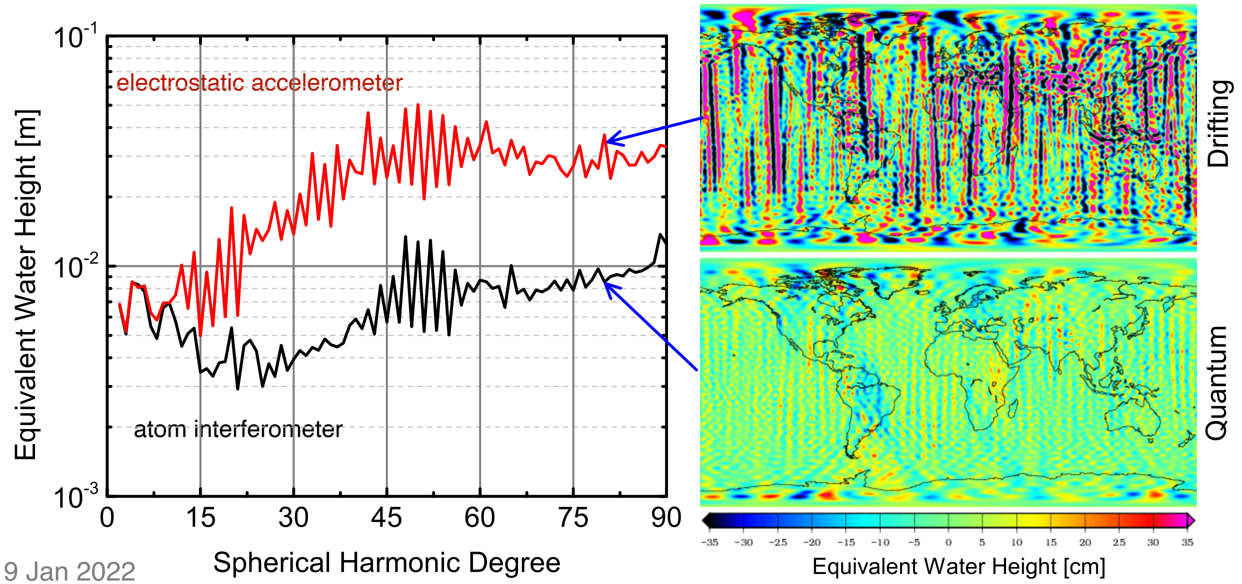
clocks act as narrowband detectors of the Doppler shift on the laser frequency due to the relative velocity between the satellites induced by the incoming gravitational wave

R & D needed:

Optical lattice clocks at up to 1×10^{-18} relative accuracy

& expanded optical fibre network (operated between a number of European metrology institutes)

& develop cold atom technology for robust, long-term operation



Ultralight Dark Matter

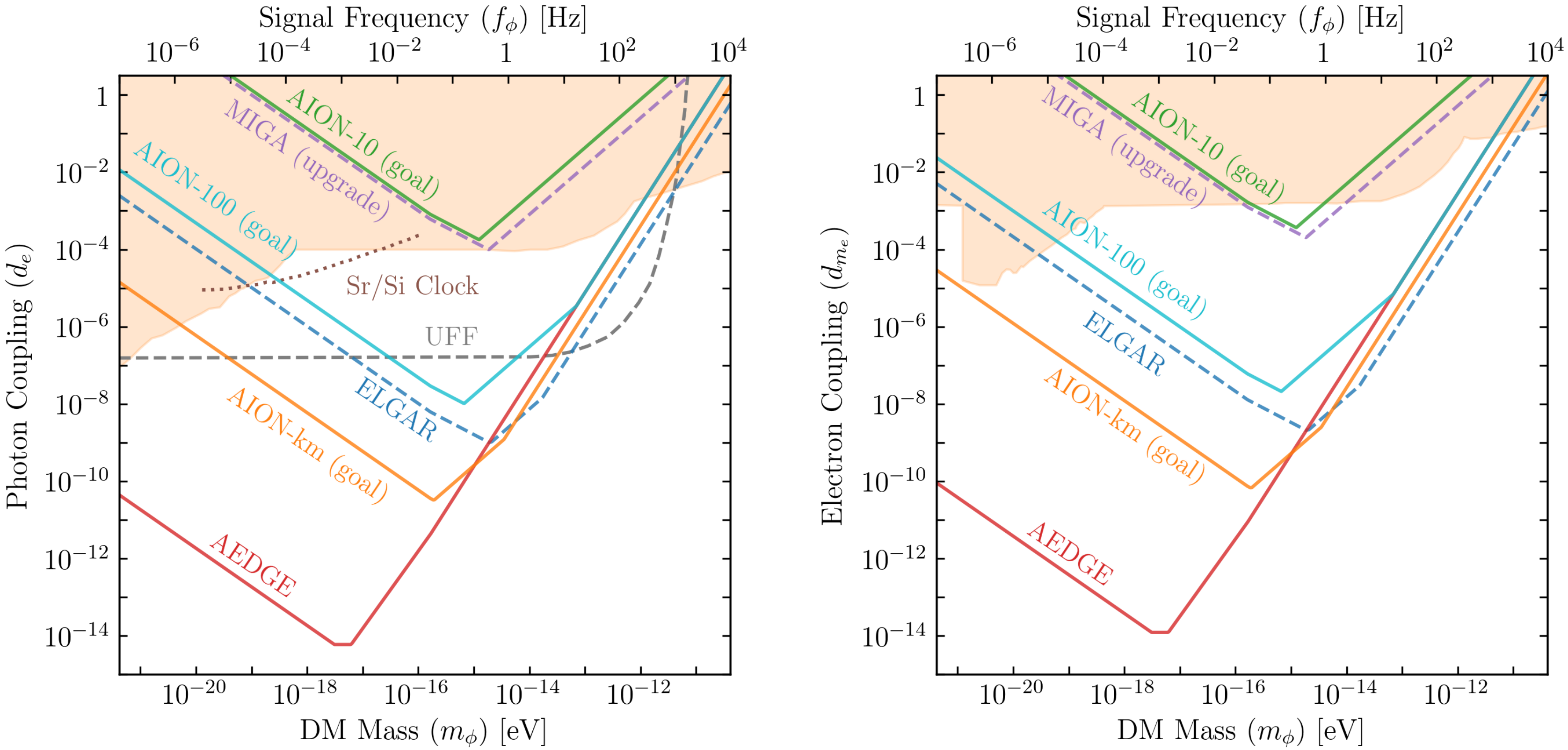
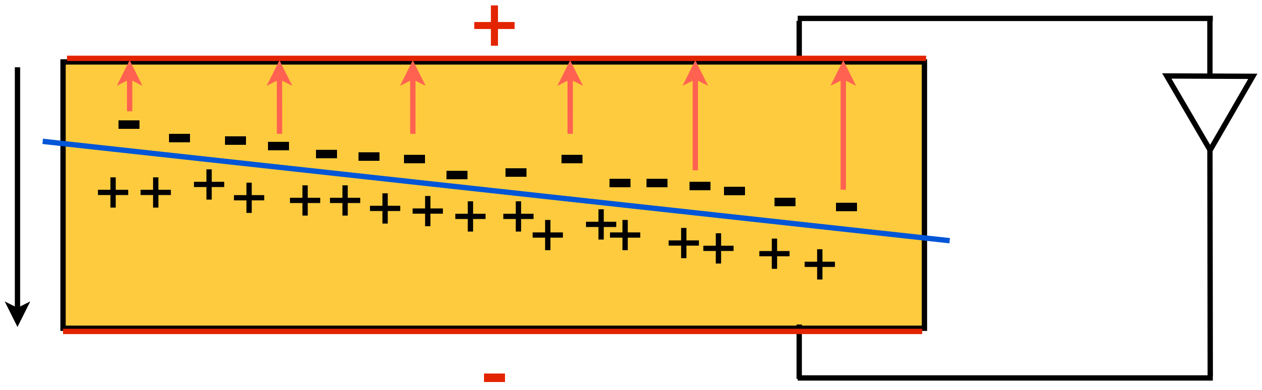


Figure 10. *Sensitivities to the possible couplings of scalar ULDM to photons (left panel) and to electrons (right panel) of the terrestrial AION [181], MIGA [182] and ELGAR [180] experiments, and of the AEDGE space-borne concept [5]. Also shown is a combination of the current constraints from MICROSCOPE [189] and terrestrial torsion balance and atomic clock experiments and (in the left panel) the sensitivity of a prospective measurement of the universality of free fall (UFF) with a precision of* 10^{-17} *[6].*

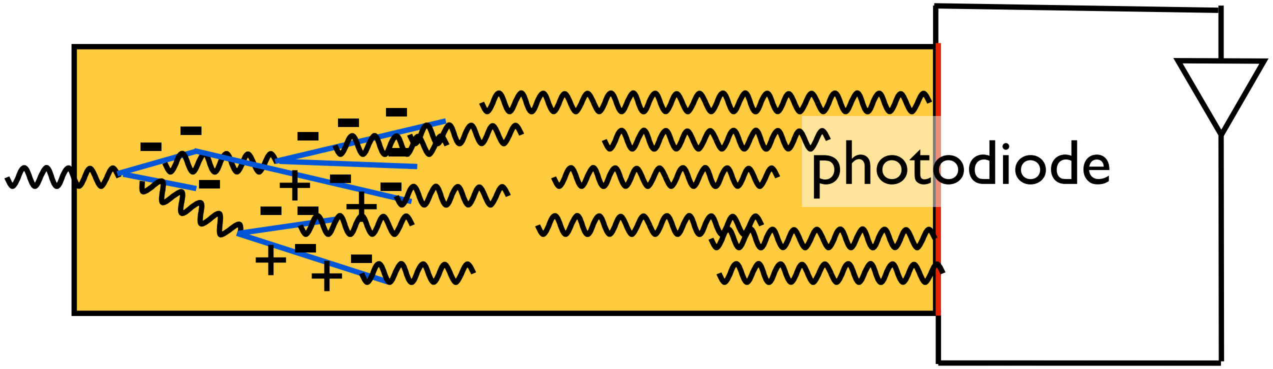
arXiv:2201.07789v1 [astro-ph.IM] 19 Jan 2022

(High energy) particle detectors:

ionization of atoms through a charged particle



ionization of atoms through a photon

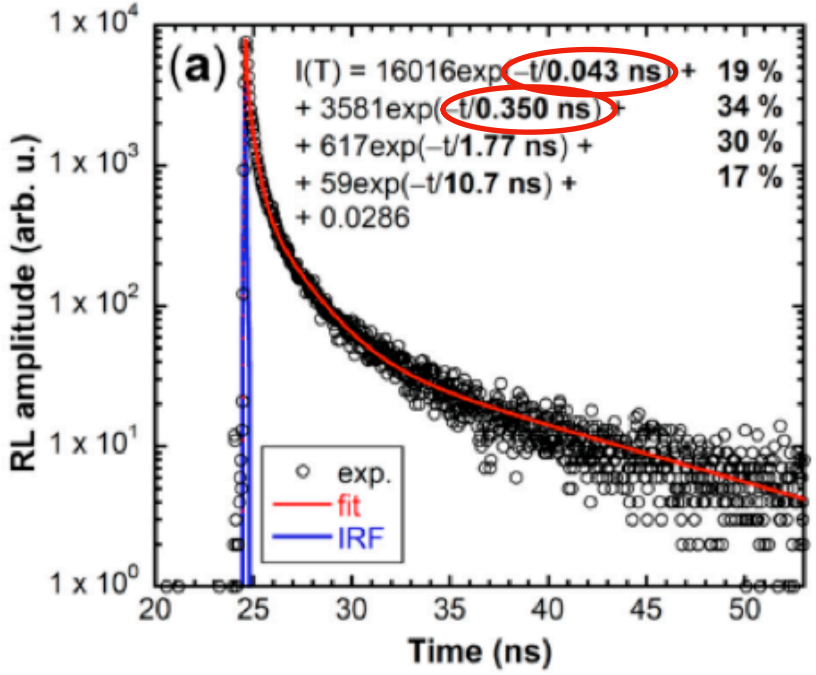


bottom line: measure result of *many* individual interactions

Quantum dots: timing

Etiennette Auffray-Hillemans / CERN

Scintillation decay time spectra from $CsPbBr_3$ nanocrystal deposited on glass



K. Decka et al., Scintillation Response Enhancement in Nanocrystalline Lead Halide Perovskite Thin Films on Scintillating Wafers. Nanomaterials 2022, 12, 14. https://doi.org/ 10.3390/nano12010014

ZnO:Ga embedded in SiO_2 or polystyrene

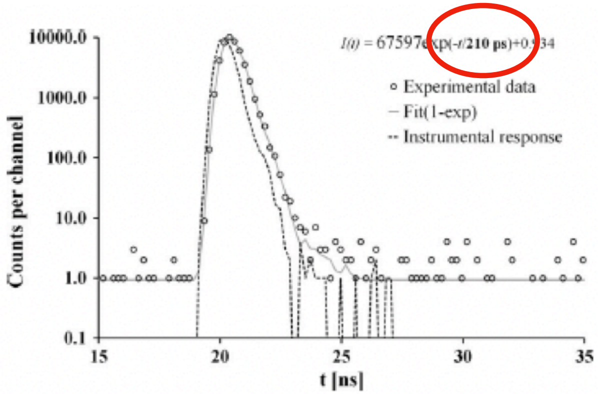
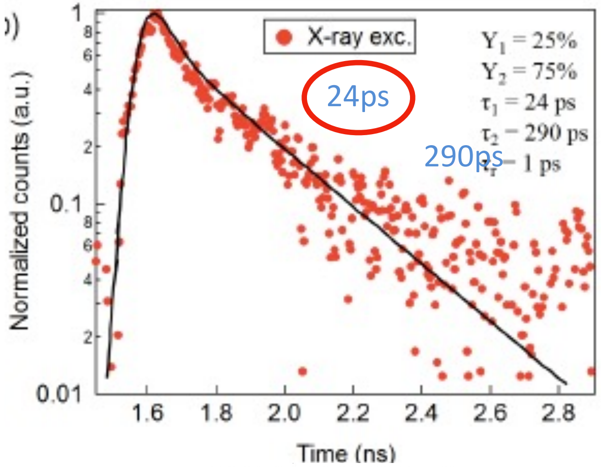


Fig. 9. Photoluminescence decay of ZnO:Ga sample at room temperature. Excitation nanoLED 339 nm, emission wavelength set at 390 nm. Decay curve is approximated by the convolution of instrumental response (also in figure) and single exponential function $I(t)$ provided in the figure.

Lenka Prochazkova et al., Optical Materials 47 (2015) 67–71

CdSe nanoplatelet,

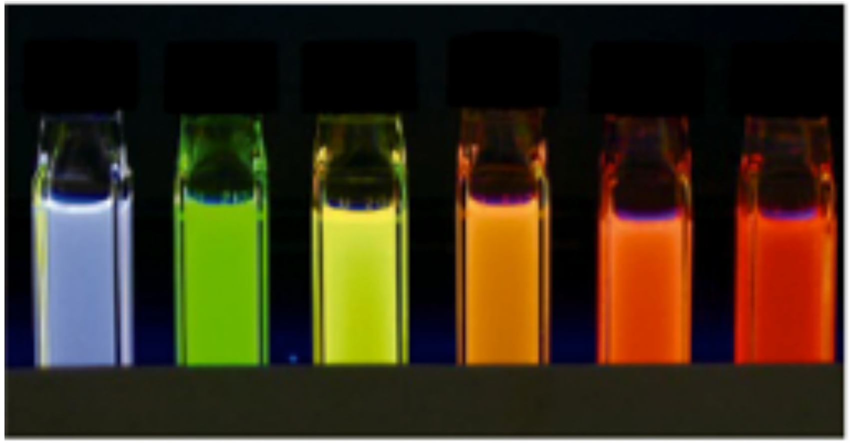


J. Grim et al., *Nature Nanotechnology,* **9**,2014, 891–895
R. Martinez Turtos et al., 2016 JINST_11 (10) P10015

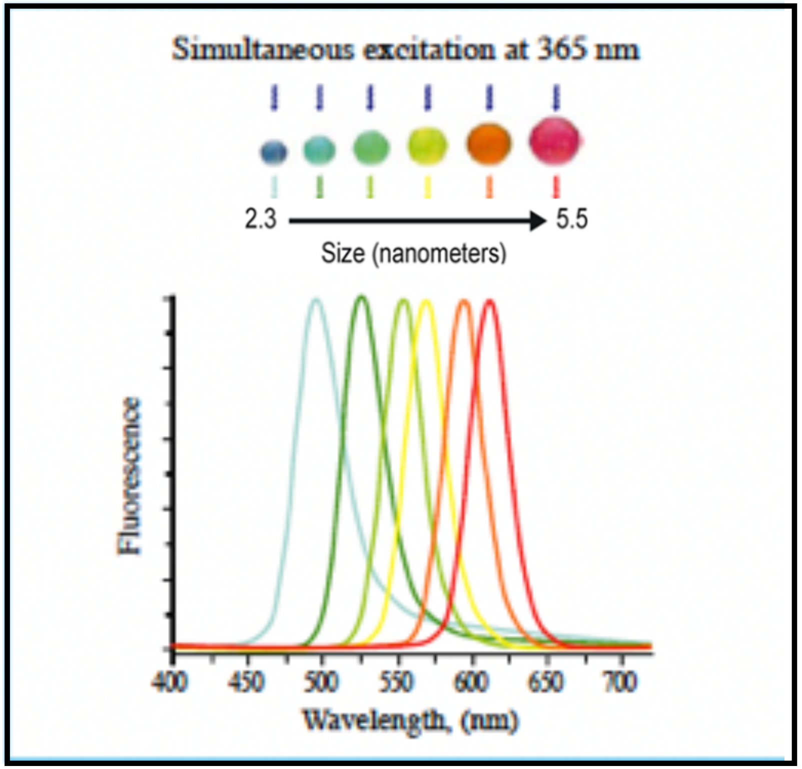
Concerns: integrated light yield (need many photons to benefit from rapid rise time)

Quantum dots: chromatic tunability

Etiennette Auffray-Hillemans / CERN



Hideki Ooba, "Synthesis of Unique High Quality Fluorescence Quantum Dots for the Biochemical Measurements," AIST TODAY Vol.6 , No.6 (2006) p.26- 27



chromatic tunability → optimize for quantum efficiency of PD (fast, optimizable WLS)

deposit on surface of high-Z material → thin layers of UV → VIS WLS

embed in high-Z material ? two-species (nanodots + microcrystals) embedded in polymer matrix?
→ quasi continuous VIS-light emitter (but what about re-absorbtion?)

2-D materials for MPGDs

Florian Brunbauer / CERN

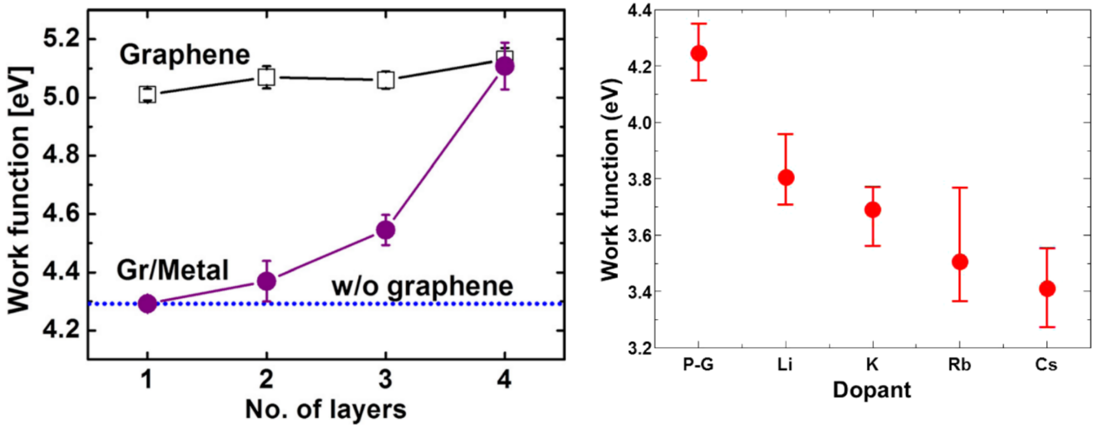
State-of-the-art MPGDs:
- high spatial resolution
- good energy resolution
- timing resolution <25ps (PICOSEC Micromegas)

use of 2-D materials to improve:
- tailor the primary charge production process,
- protect sensitive photocathodes in harsh environments
- improve the performance of the amplification stage

tunable work function

efficiency of the photocathode → timing resolution; QE
tune via resonant processes in low dimensional coating structures

(additionally, encapsulation of semiconductive as well as metallic (i.e. Cu) photocathodes increases operational lifetime)

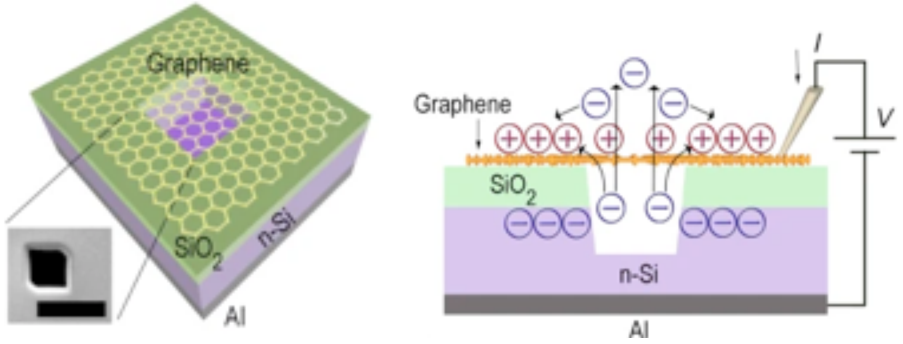


Tuning the work function of graphene toward application as anode and cathode, Samira Naghdi, Gonzalo Sanchez-Arriaga, Kyong Yop Rhee, https://arxiv.org/abs/1905.06594

amplification

back flow of positive ions created during charge amplification to the drift region can lead to significant distortions of electric fields

Graphene has been proposed as selective filter to suppress ion back flow while permitting electrons to pass:
Good transparency (up to ~99.9%) to very low energy (<3 eV) electrons (?)



Space charge neutralization by electron-transparent suspended graphene, Siwapon Srisonphan, Myungji Kim & Hong Koo Kim, Scientific Reports 4, 3764 (2014)

2-D materials for MPGDs

Gaseous detectors: timing

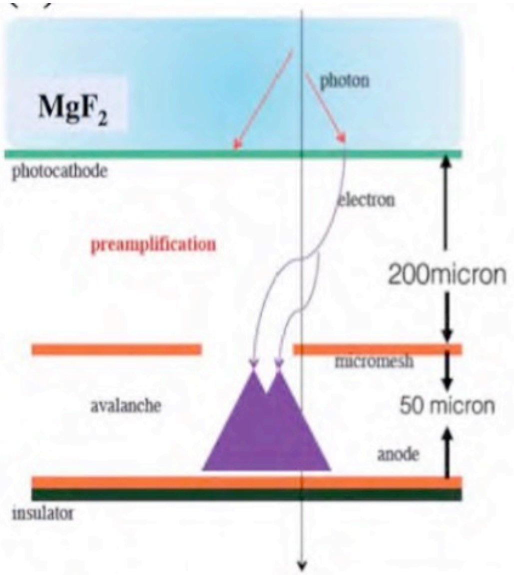
- **Gaseous detectors offer very competitive timing** through e.g.
  - **Multi-gap Resistive Plate Chambers** (down to 60 ps time resolution) (ALICE TOF Detector, Z.Liu, NIM A927 (2019) 396)

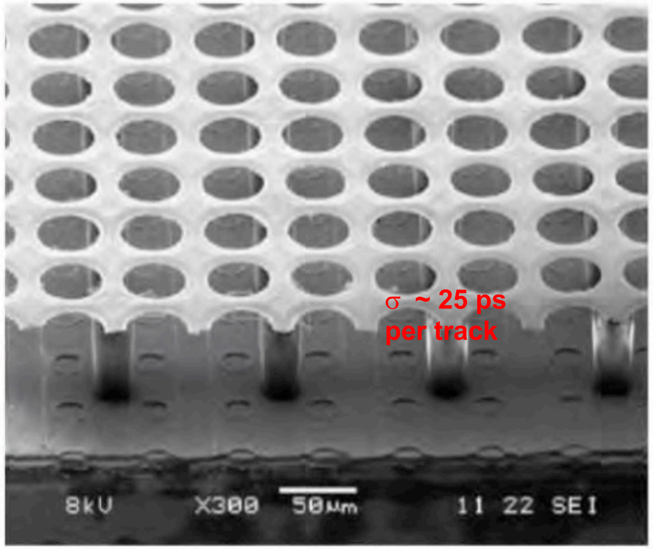
- An enabling emerging R&D: **Micromegas with timing** (PICOSEC concept)

→ Many developments emerged from the R&D studies within the RD51 Collaboration

Cherenkov radiator + Photocathode + MM

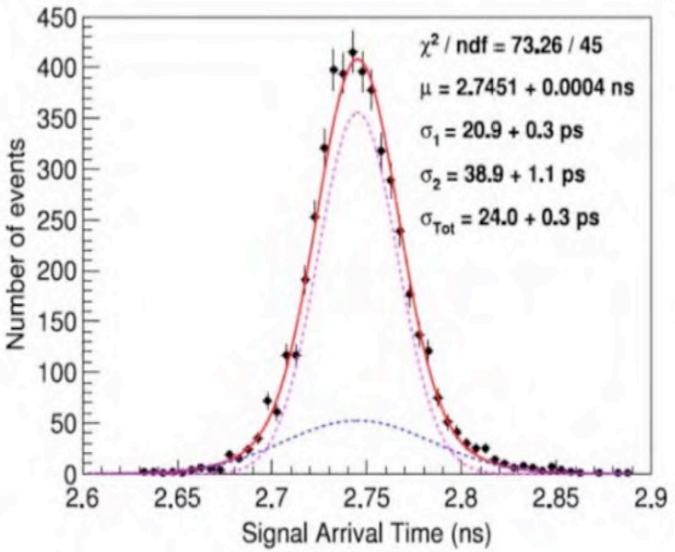
J. Bortfeldt, NIM A903 (2018) 317





σ ~ 25 ps per track

Timing (MIP test-beam):

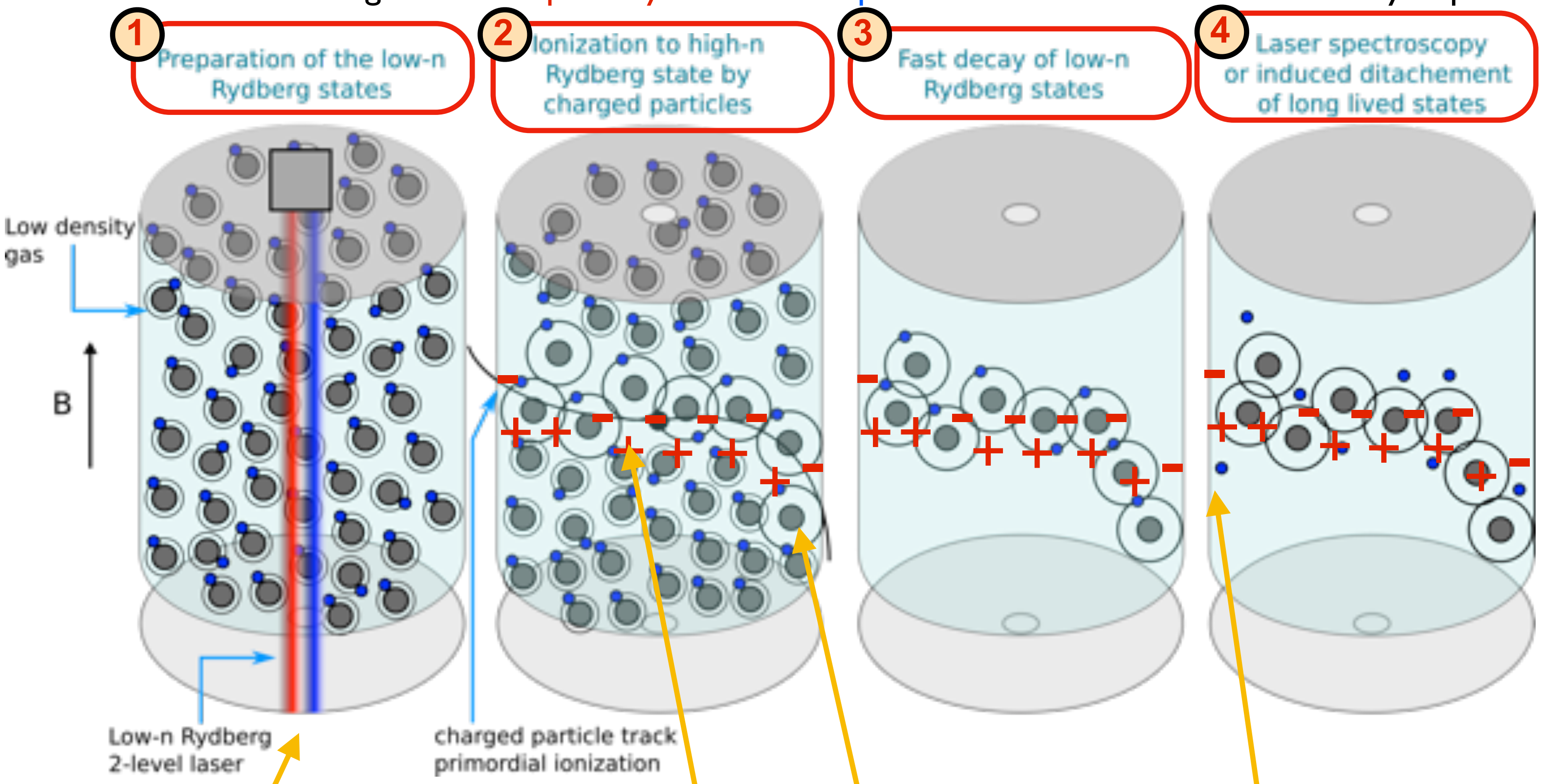


Rydberg atom TPC’s

Georgy Kornakov / WUT

Act on the drift region

principle carries over to drift region:
enhanced electron signal through “priming” of gas in drift region:
effective reduction of ionization threshold of gas in amplification region
increased dE/dx through standard primary ionization + photo-ionization of atoms excited by mip’s

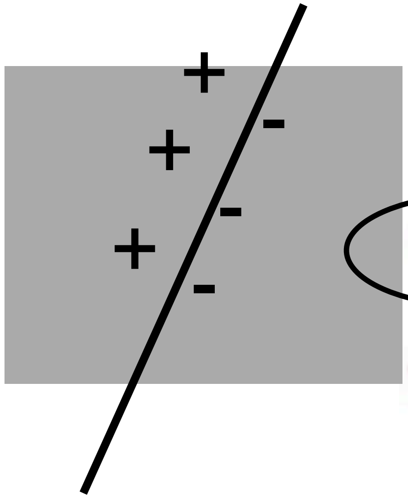


reduction of ionization and
atomic excitation threshold

ionization + excitation;
natural decay of unmodified atoms

photo-ionization of excited atoms

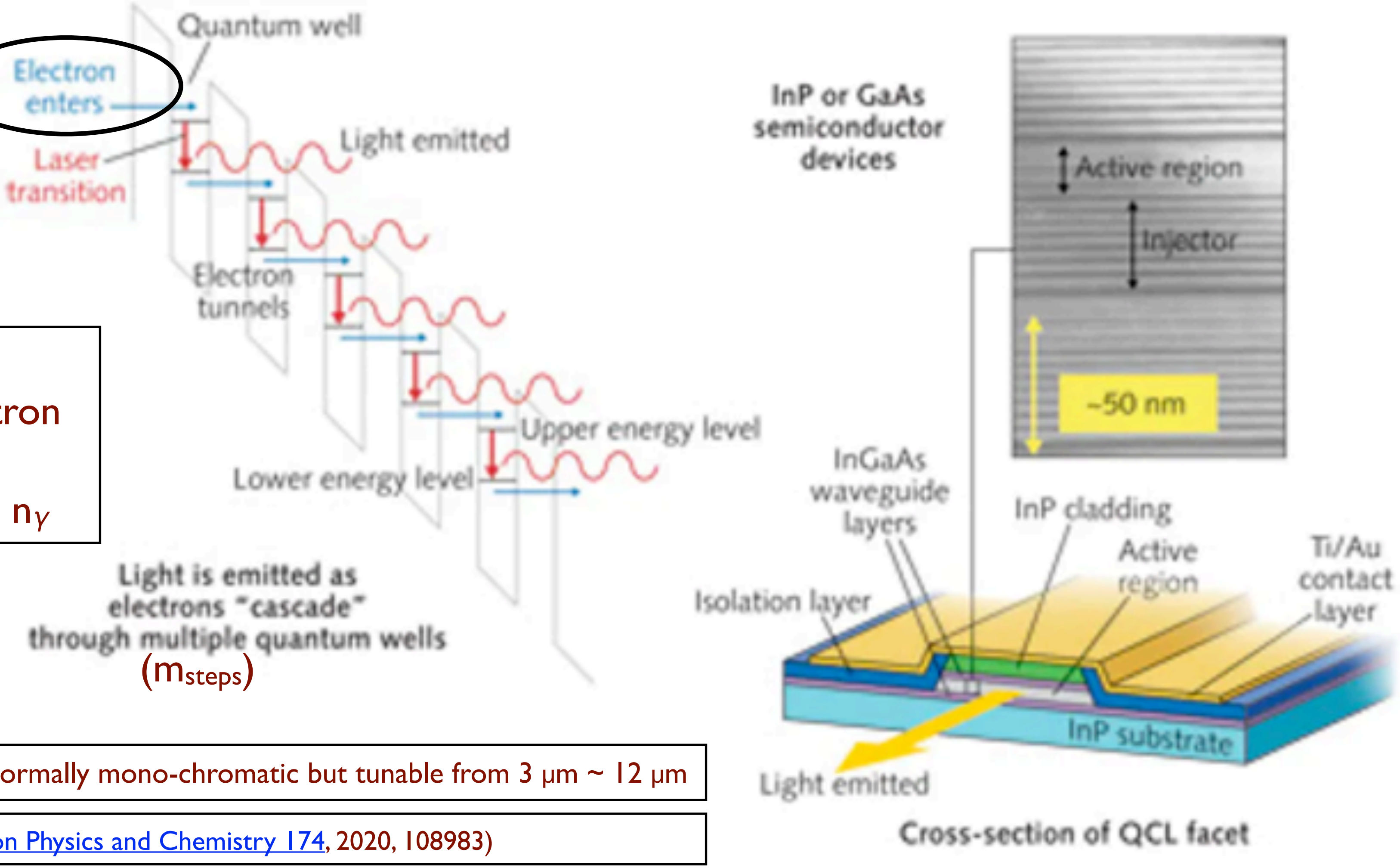
Active scintillators (QCLs, QWs, QDs, QWDs)



Couple bulk semi-conductor to electron injection layer:

$n_e \longrightarrow m_{steps} \times n_\gamma$

https://www.laserfocusworld.com/test-measurement/spectroscopy/article/16556856/quantumcascade-lasers-qcls-enable-applications-in-ir-spectroscopy



Light is emitted as electrons "cascade" through multiple quantum wells (m_{steps})

Cross-section of QCL facet

Emitted light is IR~THz, normally mono-chromatic but tunable from 3 μm ~ 12 μm

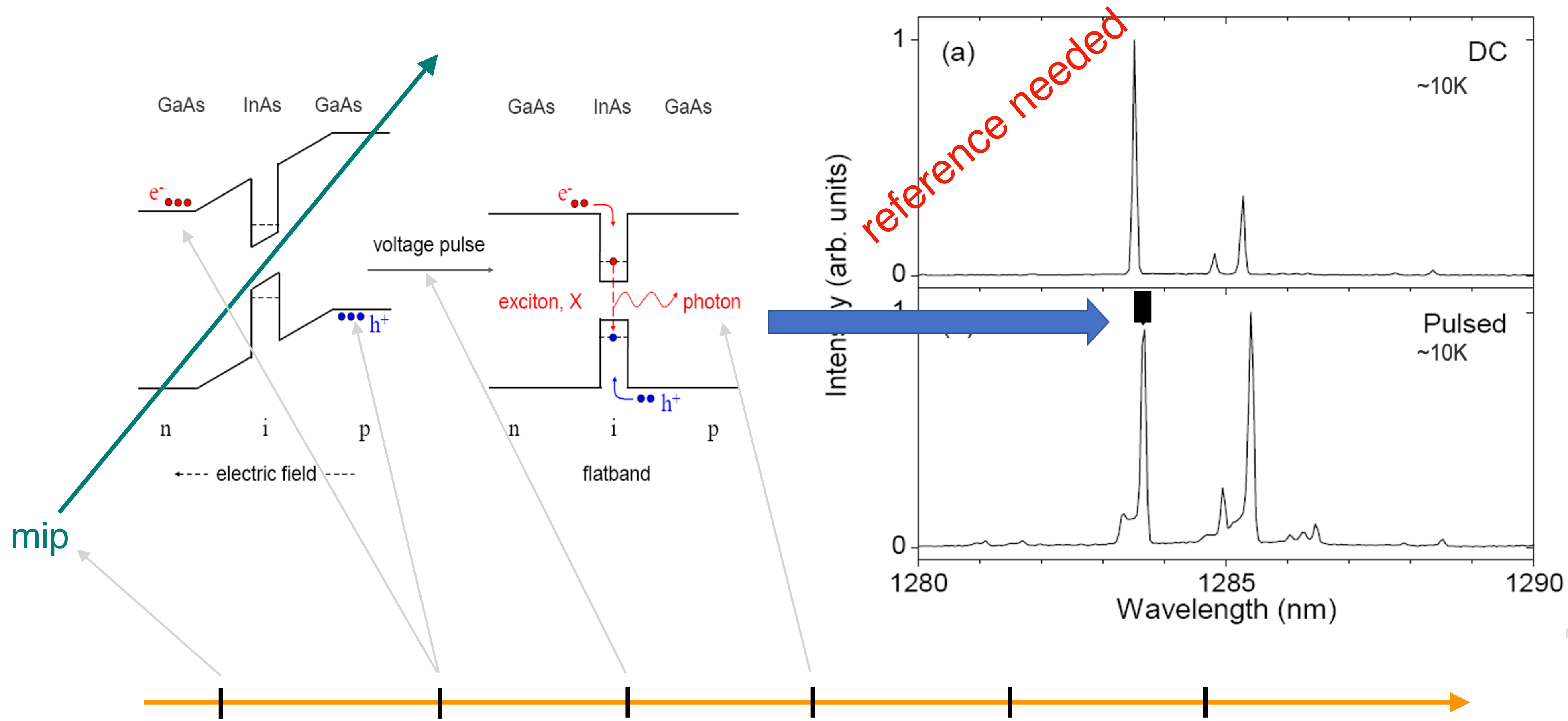
Radiation resistant (Radiation Physics and Chemistry 174, 2020, 108983)

Active scintillators (QWs, QDs, QWDs, QCLs)

QD's produce sharp atom-like emission peaks

generate photons by optical pumping or electrical injection
of electrons produced by mip's into the QD

Electroluminescence (DC and pulsed)

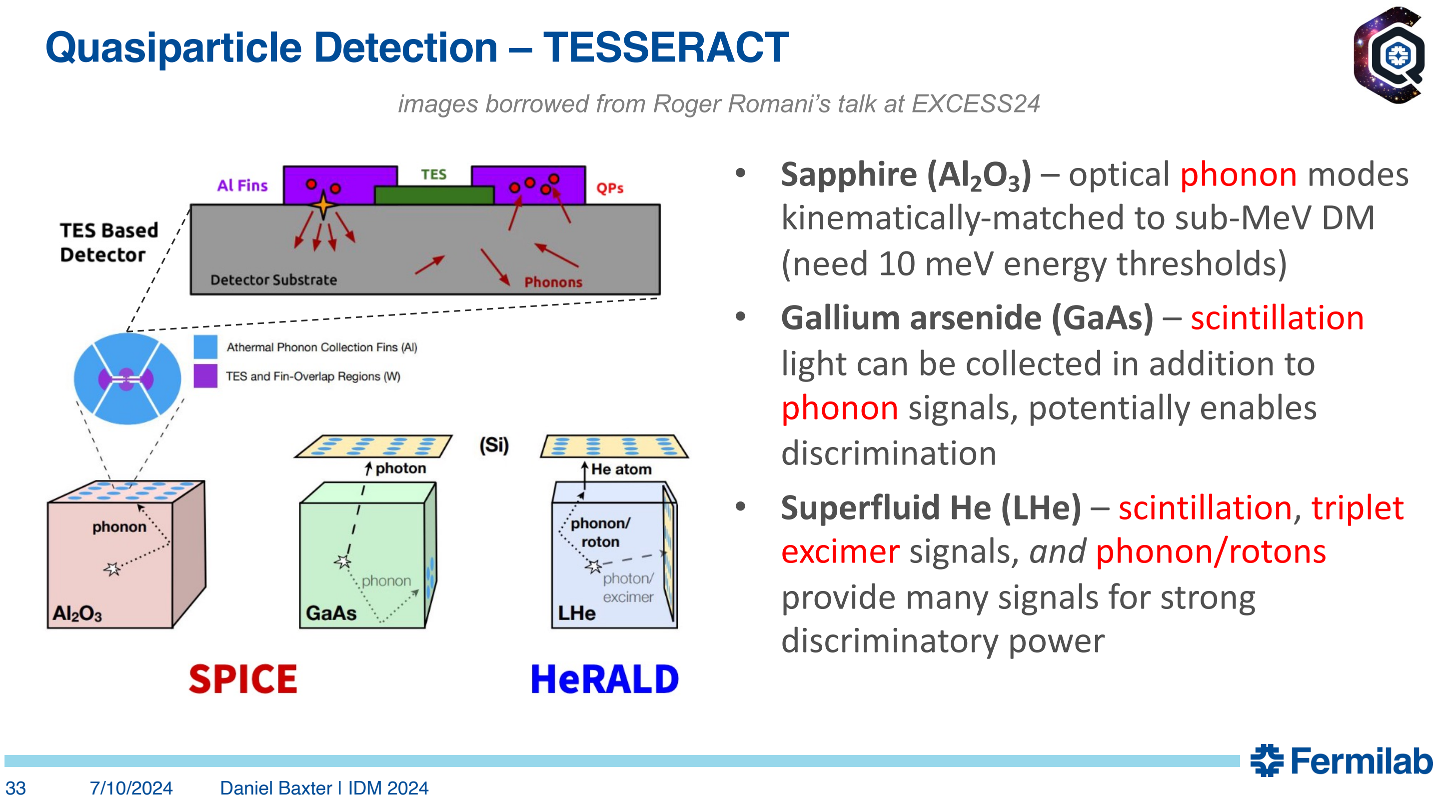


- mip passes through device
- e^-h^+ pairs produced
- switch off field
- e^-h^+ pairs produce photons
- switch on field
- system primed again
- time

1. **TES-based Crystal Detectors**
    - TESSERACT (SPICE)
2. **Superfluid Helium Detectors**
    - TESSERACT (HeRALD)
    - DELight
3. **MKID-based Detectors**
    - BULLKID
4. **Superconducting Qubit Sensors**
    - Cosmic Quantum (CosmiQ) at FNAL
    - SQUATs

MKID: Temples et al (2024) [arXiv:2402.04473]

MMC's: von Krosigk et al, SciPost Phys. Proc. 12, 016 (2023) [arXiv:2209.10950]



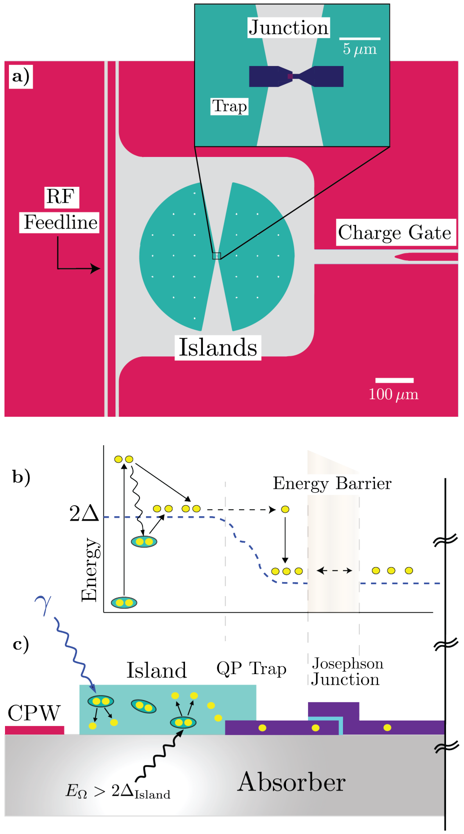
Quasiparticle Detection – TESSERACT

images borrowed from Roger Romani's talk at EXCESS24

- **Sapphire (Al_2O_3)** – optical phonon modes kinematically-matched to sub-MeV DM (need 10 meV energy thresholds)
- **Gallium arsenide (GaAs)** – scintillation light can be collected in addition to phonon signals, potentially enables discrimination
- **Superfluid He (LHe)** – scintillation, triplet excimer signals, *and* phonon/rotons provide many signals for strong discriminatory power

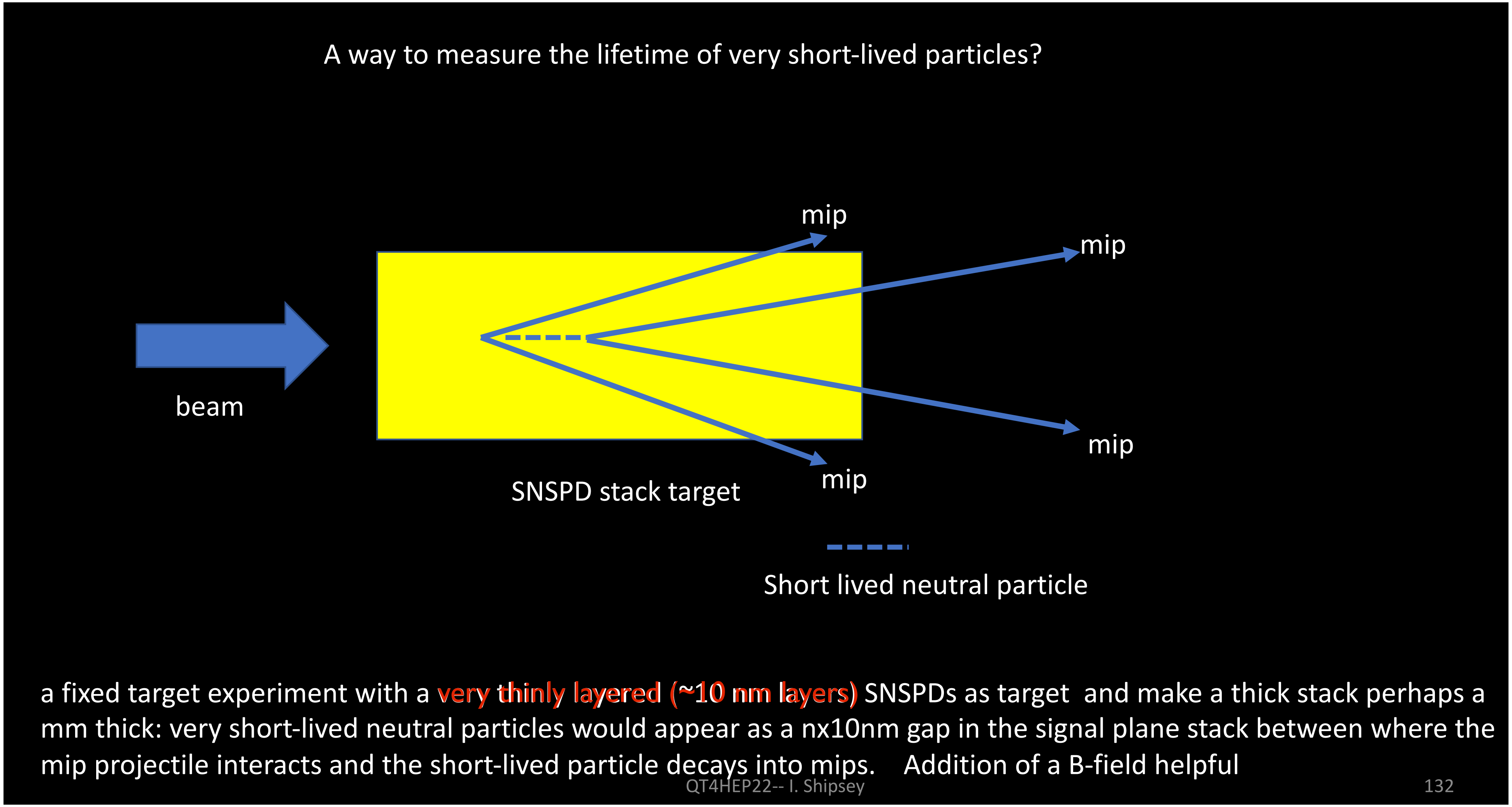
SQUATs (superconducting quasiparticle-amplifying transmon)

arXiv:2310.01345



While there already exists a large amount of competition in the space of superconducting sensors for low-energy rare-event measurement [60–66], the device we have proposed potentially offers multiple orders of magnitude of improvement in terms of absolute energy sensitivity beyond these currently existing detectors. Furthermore, because each qubit sensor is naturally read out individually, they inherently have a powerful background discrimination tool by determining the location in the detector in which the event occurred.

Extremely low energy threshold detectors: SNSPD

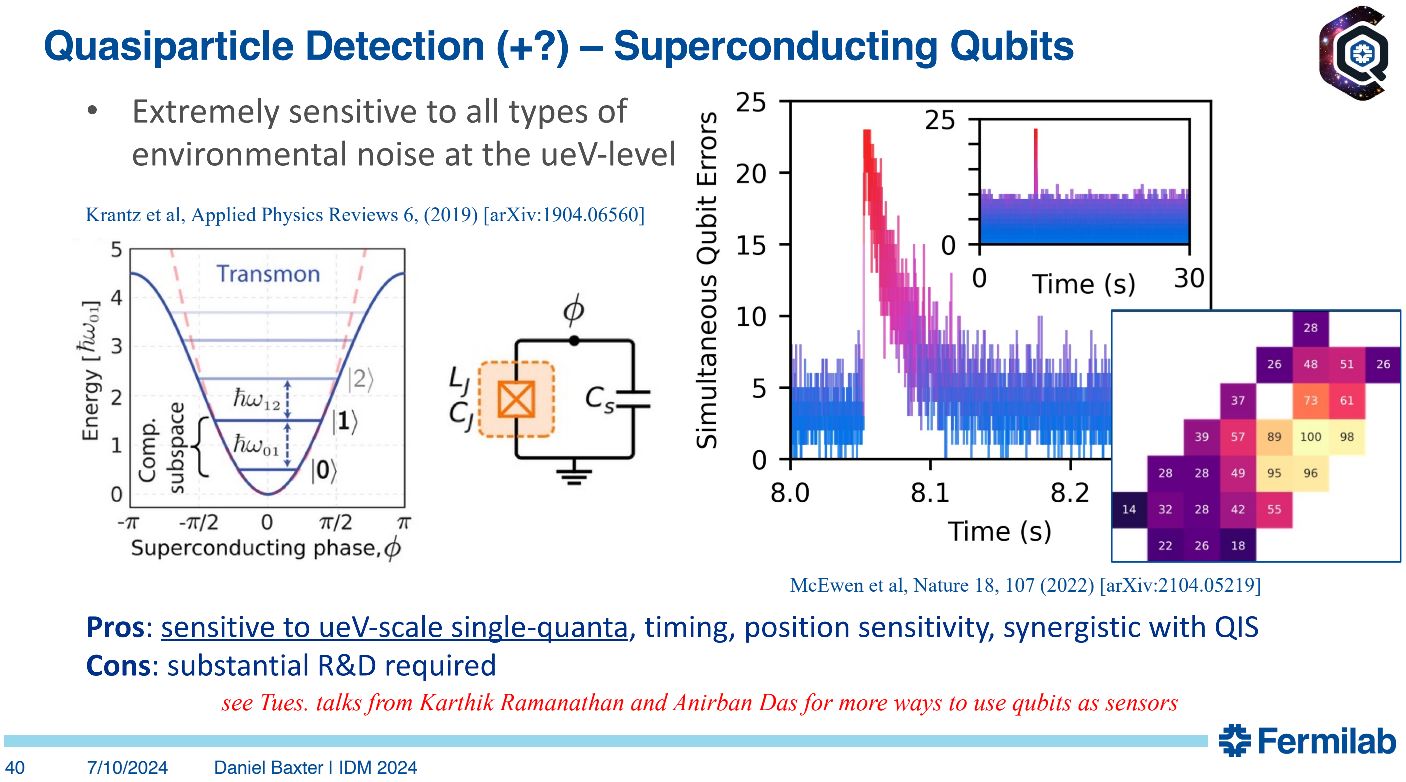


A way to measure the lifetime of very short-lived particles?

a fixed target experiment with a very thinly layered (~10 nm layers) SNSPDs as target and make a thick stack perhaps a mm thick: very short-lived neutral particles would appear as a nx10nm gap in the signal plane stack between where the mip projectile interacts and the short-lived particle decays into mips. Addition of a B-field helpful

QT4HEP22-- I. Shipsey 132

Beyond existing sensors: using (superconducting) qubits



Quasiparticle Detection (+?) – Superconducting Qubits

- Extremely sensitive to all types of environmental noise at the ueV-level

Krantz et al, Applied Physics Reviews 6, (2019) [arXiv:1904.06560]

McEwen et al, Nature 18, 107 (2022) [arXiv:2104.05219]

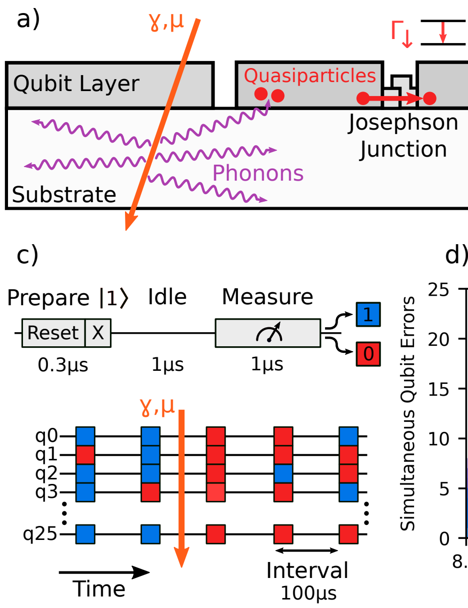
Pros: sensitive to ueV-scale single-quanta, timing, position sensitivity, synergistic with QIS

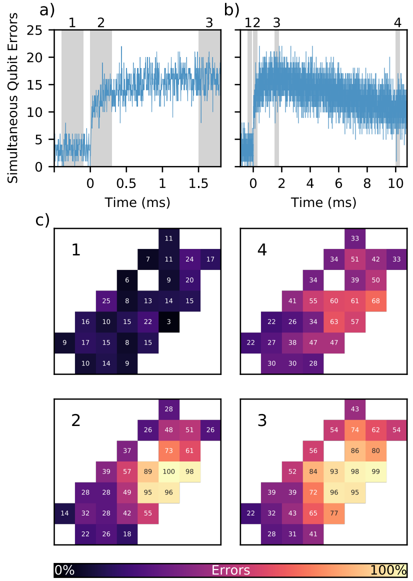
Cons: substantial R&D required

see Tues. talks from Karthik Ramanathan and Anirban Das for more ways to use qubits as sensors

Fermilab

40 7/10/2024 Daniel Baxter I IDM 2024

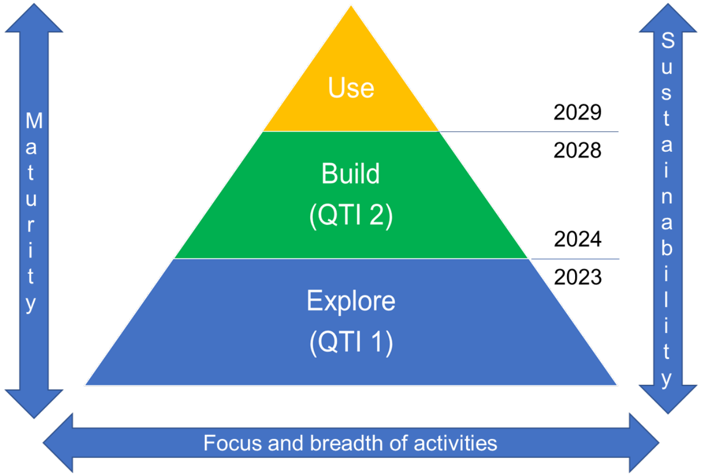




McEwen et al., Nature 118, 107 (2022) arXiv:22014.05219

CERN quantum initiative (v2)

https://quantum.web.cern.ch/



CC1: Hybrid Quantum Computing Infrastructures, Algorithms and Applications

CC2: CERN Technologies as Quantum Platforms Demonstrators

CC3: Quantum Networks and Communication Hub for Research

CC4: Collaboration for Impact

4 largely independent technology areas (or branches) → 4 interoperating thematic Centres of Competence

Exotic atoms and ions as qubits and Dark Matter sensors, atomic and nuclear clocks as sensors for new, feeble interactions; metrology and quantum states measurements; cryogenics and RF cavities design and characterisation for axion and Gravitational Wave searches; development and characterisation of multi-qubit systems with cavities, ion traps, and isotopes; superconducting quantum sensors for millicharged particles and Physics Beyond Colliders; quantum data acquisition.

Specifically, the sensor-related goals of QTI 2 are intentionally aligned with the larger international framework of the ECFA roadmap and process (within which the technical developments focusing on quantum sensing R&D efforts for particle physics are integrated in the future international DRD5 collaboration), while focusing on those areas that are uniquely suited to CERN's expertise, technologies and infrastructure.

CERN quantum initiative (v2)

(1.2024-12.2028)

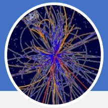
focus on technology

quantum sensing & particle physics

CERN | QUANTUM TECHNOLOGY INITIATIVE

DRD5 WP's

① ③ ⑥



- Objective 2.1a: Exotic atoms as qubits and Dark Matter sensors (Rydberg states characterisation, spectroscopy; atom interferometry; entangled Rydberg states as quantum demonstrators for qubits)
- Objective 2.2a: RF cavities and coating for axion searches; designing, building and operating a tuneable RF cavity for axion and GW searches
- Objective 2.2b.1: Development of a multi-qubit demonstrator platform (cryogenic infrastructure and RF cavity technology; design intermediate control software layer)
- Objective 2.3a: Quantum Sensors and Quantum Data Acquisition (TES as quantum sensors for millicharged DM searches in beam dumps, test bed for Quantum DAQ)

Core goals

- Objective 2.1b: Evaluation of the interplay between interferometric inertial sensors and cosmology to improve understanding of properties of Dark Matter and sources of GWs
- Objective 2.2b.2: Develop device-aware algorithms for qubits with SRF cavities
- Objective 2.3b: Cryogenic veto system, tuneable low-energy deposit calibration set-up; Monte Carlo simulation for tracks of backgrounds and signals, pushing the modeling towards low-energy deposits

Extended objectives

- Objective 2.1c: Benchmark and comparison of Rydberg states as qubits in prototype systems
- Objective 2.2b.3: Investigate scaling behavior of multiple qubits
- Objective 2.3c: Read-out-free detection & DAQ via entanglement between TES voxels and another system; machine-learning-based anomaly detection of millicharged DM particles in TES

Long term objectives

focus on physics

@ CERN: PBC, large low energy physics community…

https://indico.cern.ch/event/1002356/ PBC technology annual workshop 2021 (focus on quantum sensing)
https://indico.cern.ch/event/1057715/ PBC technology mini workshop: superconducting RF (Sep. 2021)

Initial experiments with quantum sensors world-wide
→ rapid investigation of new phase space

→ scaling up to larger systems, improved devices
  → expanding explored phase space

→ particles, atoms, ions, nuclei:	tests of QED, symmetries
→ RF cavities:	axion searches
→ atom interferometers:	DM searches

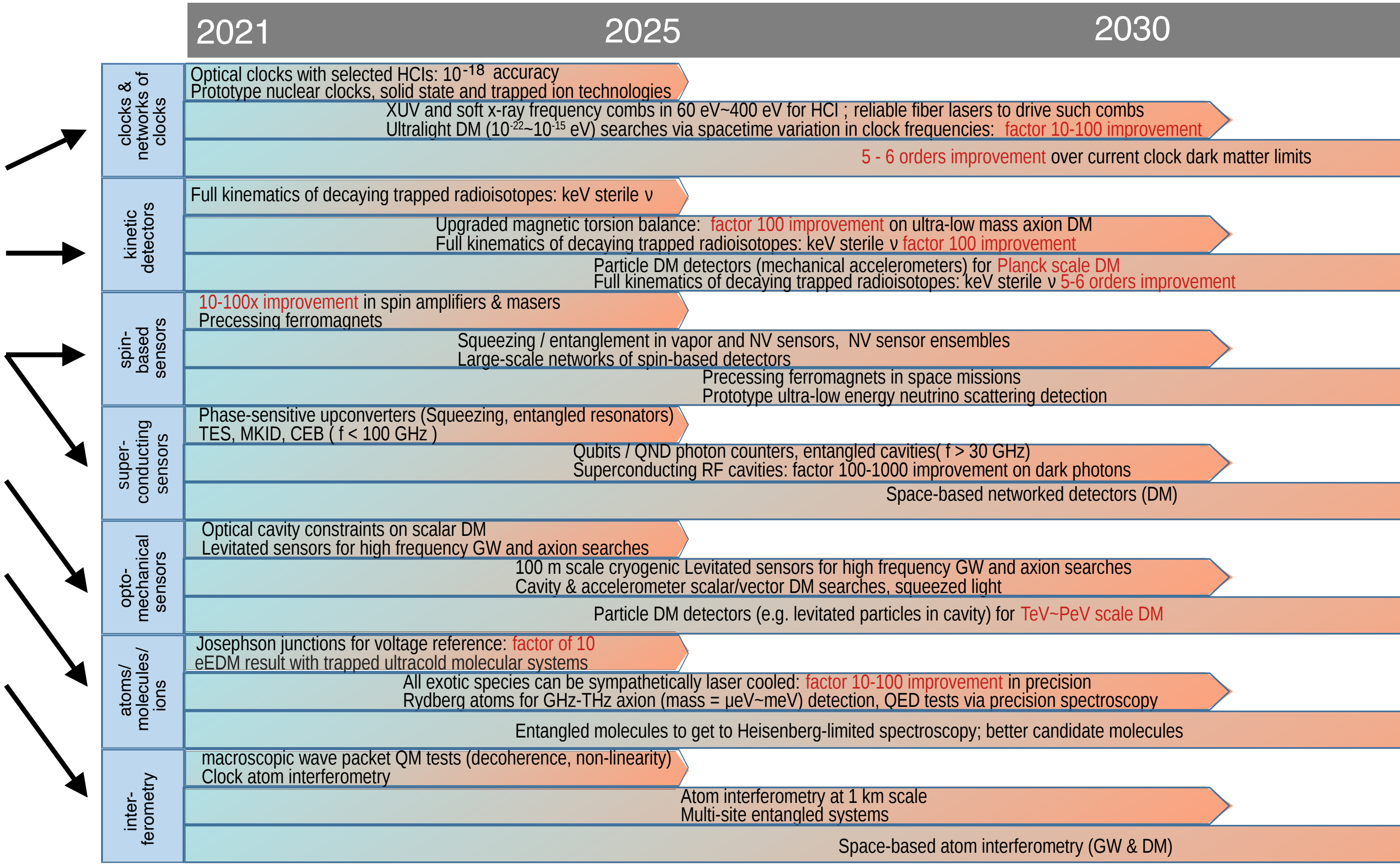
What's next?

These potential applications of quantum sensors also in HEP require dedicated R&D to evaluate their potential and feasibility.

In line with the RECFA R&D roadmap, it makes sense to consider a quantum-sensing R&D program that brings together the following strands:

- Clocks and clock networks 5.3.1
- Kinetic detectors 5.3.2
- Spin-based sensors 5.3.3
  Superconducting sensors 5.3.3
- Optomechanical sensors 5.3.4
- Atoms/molecules/ions 5.3.5
  Atom interferometry 5.3.5
- Metamaterials, 0/1/2D-materials
  Quantum materials 5.3.6

also for HEP!



clocks & networks of clocks

Optical clocks with selected HCIs: 10^{-18} accuracy
Prototype nuclear clocks, solid state and trapped ion technologies

XUV and soft x-ray frequency combs in 60 eV~400 eV for HCI ; reliable fiber lasers to drive such combs
Ultralight DM (10^{-22}~10^{-15} eV) searches via spacetime variation in clock frequencies: factor 10-100 improvement

5 - 6 orders improvement over current clock dark matter limits

kinetic detectors

Full kinematics of decaying trapped radioisotopes: keV sterile ν

Upgraded magnetic torsion balance: factor 100 improvement on ultra-low mass axion DM
Full kinematics of decaying trapped radioisotopes: keV sterile ν factor 100 improvement

Particle DM detectors (mechanical accelerometers) for Planck scale DM
Full kinematics of decaying trapped radioisotopes: keV sterile ν 5-6 orders improvement

spin-based sensors

10-100x improvement in spin amplifiers & masers
Precessing ferromagnets

Squeezing / entanglement in vapor and NV sensors, NV sensor ensembles
Large-scale networks of spin-based detectors

Precessing ferromagnets in space missions
Prototype ultra-low energy neutrino scattering detection

super-conducting sensors

Phase-sensitive upconverters (Squeezing, entangled resonators)
TES, MKID, CEB (f < 100 GHz)

Qubits / QND photon counters, entangled cavities(f > 30 GHz)
Superconducting RF cavities: factor 100-1000 improvement on dark photons

Space-based networked detectors (DM)

opto-mechanical sensors

Optical cavity constraints on scalar DM
Levitated sensors for high frequency GW and axion searches

100 m scale cryogenic Levitated sensors for high frequency GW and axion searches
Cavity & accelerometer scalar/vector DM searches, squeezed light

Particle DM detectors (e.g. levitated particles in cavity) for TeV~PeV scale DM

atoms/ molecules/ ions

Josephson junctions for voltage reference: factor of 10
eEDM result with trapped ultracold molecular systems

All exotic species can be sympathetically laser cooled: factor 10-100 improvement in precision
Rydberg atoms for GHz-THz axion (mass = μeV~meV) detection, QED tests via precision spectroscopy

Entangled molecules to get to Heisenberg-limited spectroscopy; better candidate molecules

inter-ferometry

macroscopic wave packet QM tests (decoherence, non-linearity)
Clock atom interferometry

Atom interferometry at 1 km scale
Multi-site entangled systems

Space-based atom interferometry (GW & DM)

What’s next?

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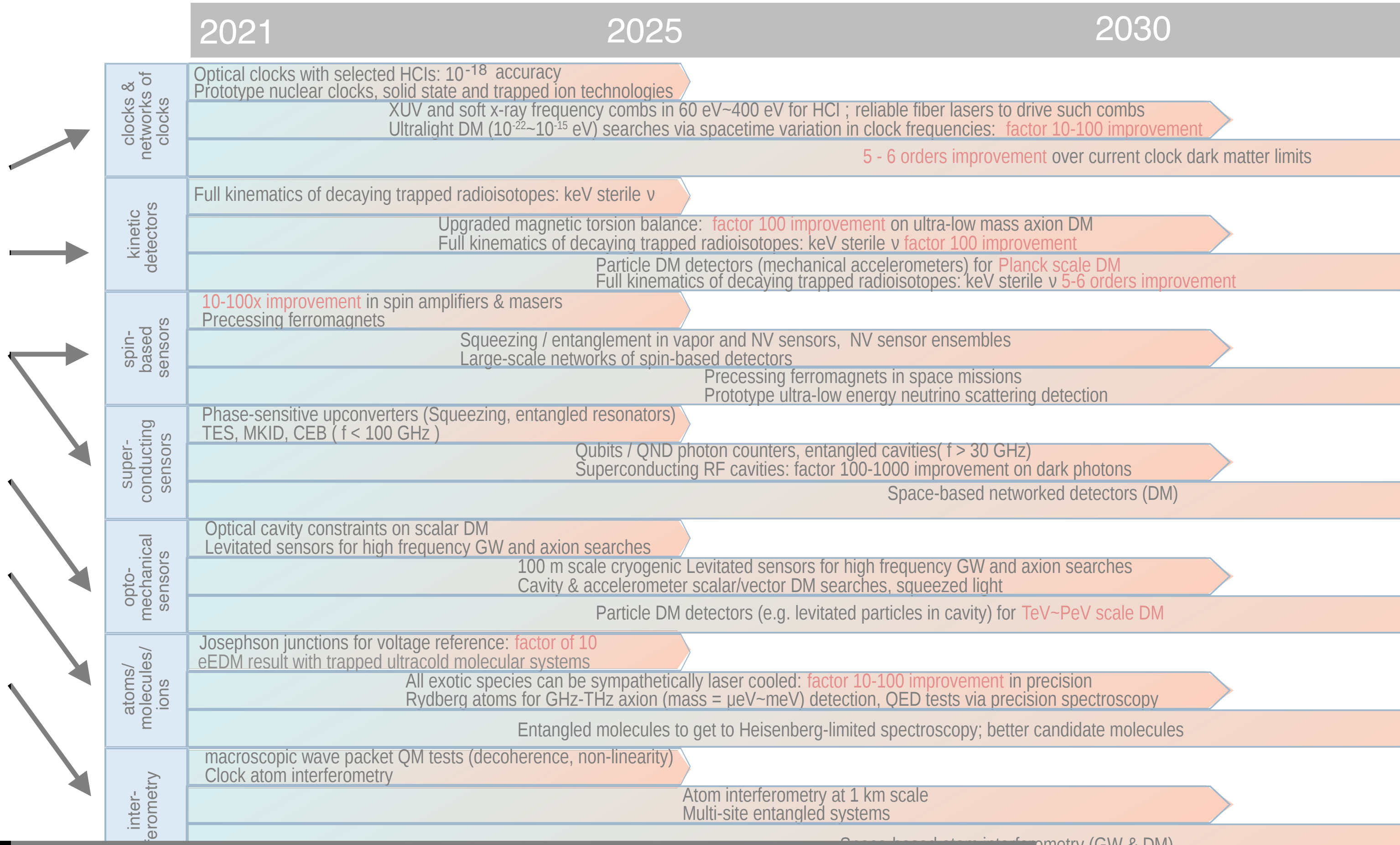
Atom interferometry 5.3.5

Metamaterials, 0/1/2D-materials
Quantum materials 5.3.6



2021 2025 2030

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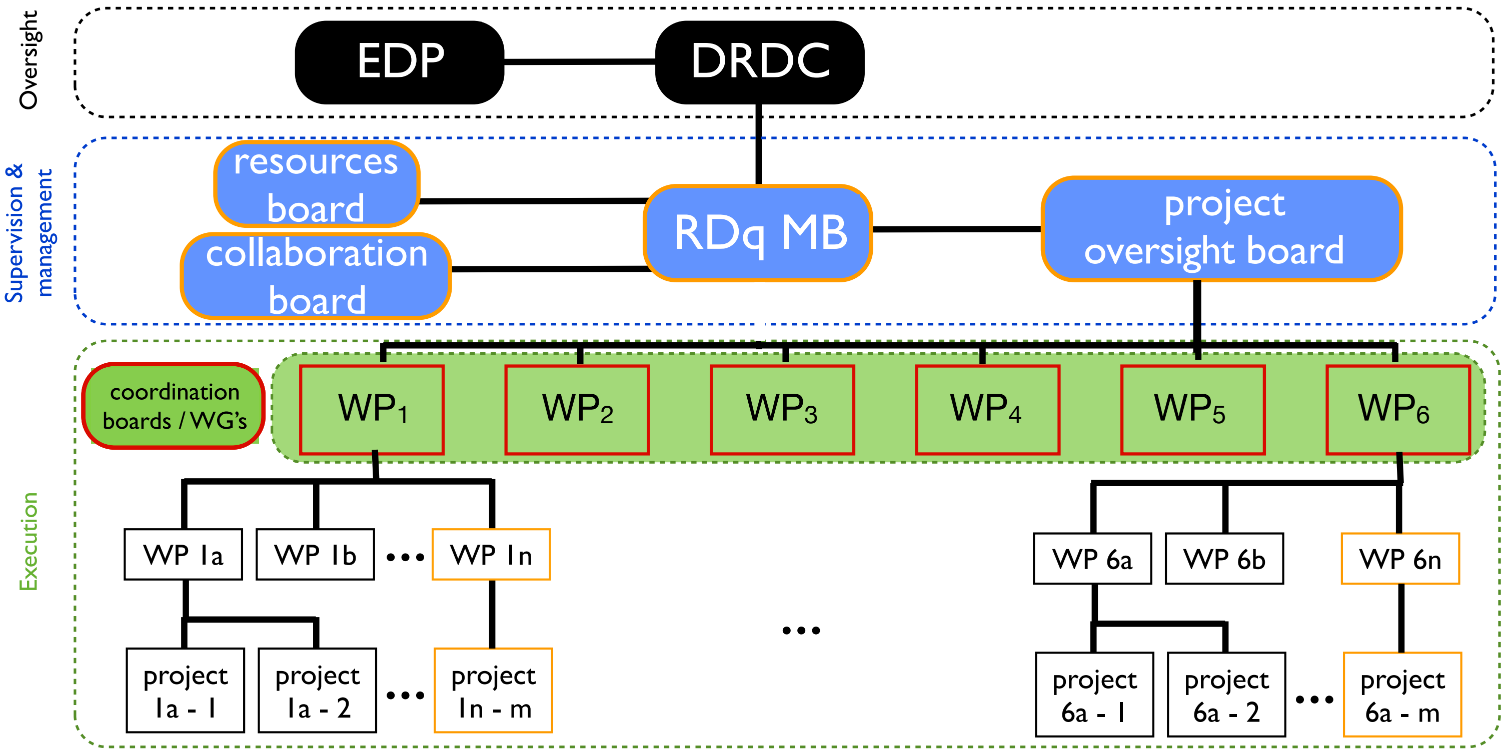
  Clock atom interferometry
- Atom interferometry at 1 km scale
  Multi-site entangled systems
- ometry (GW & DM)

also for HEP!

next step: implementation of ECFA detector R&D pgm

Structure of DRD5:



Membership is free (no common fund contributions)! (Only for academics! industry?)

Simple membership access (via request to CB) / leave (inform CB) processes;

WP's are coordinated as WG's

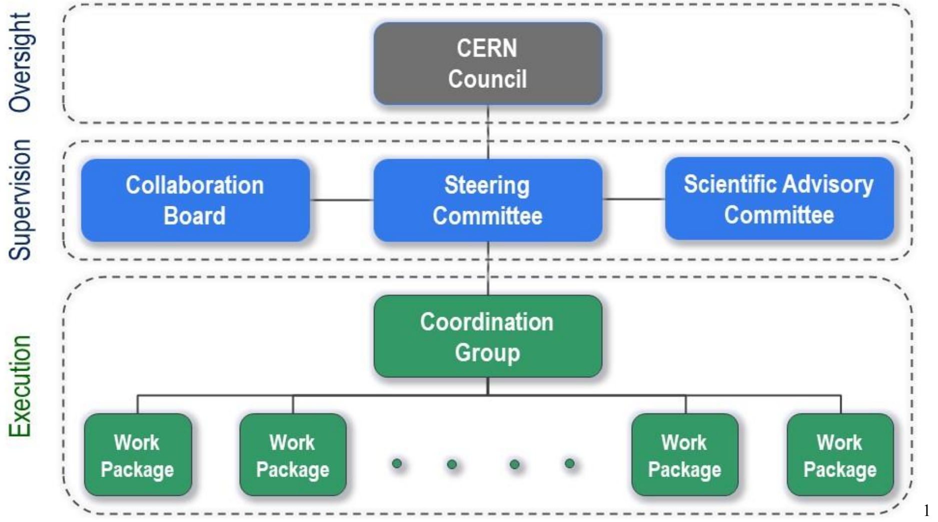
MB, POB, WG coordinators: by election through CB (1 institute = 1 vote) (Attention to balance!)
(sub-WP coordinators are appointed by WP coordinator)

MB = spokesperson, deputy, CB, RB and POB chairs

* CB: collaboration board; MB: management board; POB: project oversight board; RB: resources board; WG: working group for a specific Work Package

structure of RDq

example from FCC



Oversight

CERN Council

Supervision

Collaboration Board

Steering Committee

Scientific Advisory Committee

Execution

Coordination Group

Work Package

Work Package

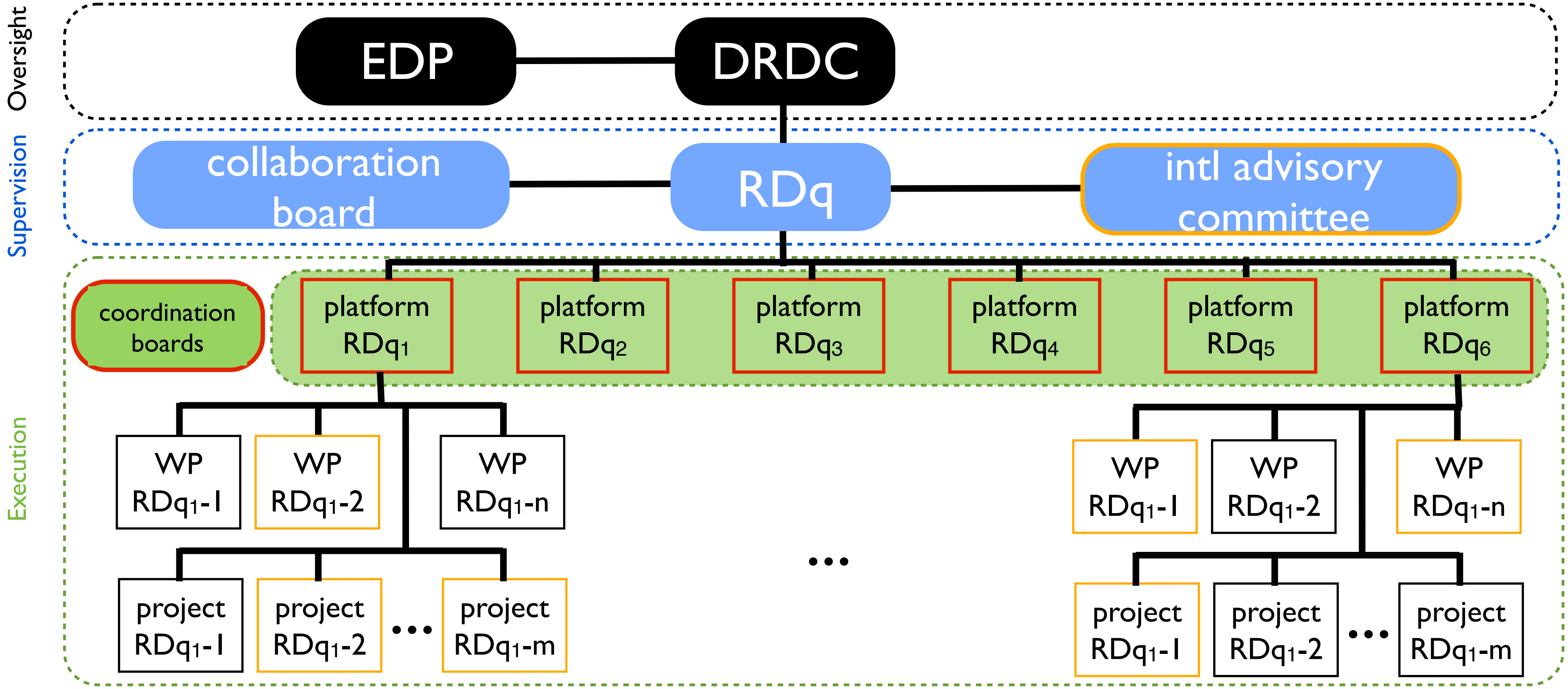
. . . .

Work Package

Work Package

1

https://fcc.web.cern.ch/Documents/Organisation/FCC-1409051000-JGU_GovernanceStructure_V0200.pdf



Oversight

EDP

DRDC

Supervision

collaboration board

RDq

intl advisory committee

Execution

coordination boards

platform RDq1

platform RDq2

platform RDq3

platform RDq4

platform RDq5

platform RDq6

WP RDq1-1

WP RDq1-2

WP RDq1-n

project RDq1-1

project RDq1-2

...

project RDq1-m

...

WP RDq1-1

WP RDq1-2

WP RDq1-n

project RDq1-1

project RDq1-2

...

project RDq1-m

draft 25/10/22 M. Doser

Open symposium organized by TF5

Anna Grassellino, Marcel Demarteau, Michael Doser, Caterina Braggio, Stafford Withington, Peter Graham, John March-Russel, Andrew Geraci

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

Symposium: April 12, 2021 https://indico.cern.ch/event/999818/

14 presentations

first block covering physics landscape

following blocks focusing on technologies

discussion of three important points

ECFA Detector R&D Roadmap Symposium of Task Force 5: Quantum and emerging technologies

Monday 12 Apr 2021, 09:00 → 18:30 Europe/Zurich

09:00 → 09:15 Introduction

09:15 → 11:00 science targets – Overview and Landscape

9:15 EDM searches & tests of fundamental symmetries Peter Fierlinger / TU Munich

9:45 Tests of QM [wavefunction collapse, size effects, temporal separation, decoherence]

10:15 Multimessenger detection [including atom interferometer or magnetometer networks] Giovanni Barontoni / Birmingham

10:45 Axion and other DM (as well as non-DM Ultra-light) particle searches Mina Arvanitaki / Perimeter Institute

11:15 → 11:30 Coffee break

11:30 → 12:30 Experimental methods and techniques - Overview and Landscape

11:30 Precision spectroscopy and clocks, networks of sensors and of entangled systems [optical atomic clocks] David Hume / NIST

12:00 Novel ionic, atomic and molecular systems [RaF, multiatomic molecules, exotic atoms] Marianna Safranova / U. Delaware

12:30 → 13:30 Lunch break

13:30 → 16:00 Experimental and technological challenges, New Developments

13:30 Superconducting platforms [detectors: TES, SNSPD, Haloscopes, including single photon detection]

14:00 High sensitivity superconducting cryogenic electronics, low noise amplifiers Stafford Withington / Cambridge

14:30 Broadband axion detection Kent Irwin / Stanford

15:00 Mechanical / optomechanical detectors Andrew Geraci / Northwestern

15:30 Spin-based techniques, NV-diamonds, Magnetometry Dima Budker / Mainz

16:00 → 16:15 Coffee break

16:15 → 18:30 Experimental and technological challenges, New Developments

16:15 Calorimetric techniques for neutrinos and axions potential speaker identified

16:35 Quantum techniques for scintillators potential speaker identified

16:55 Atom interferometry at large scales (ground based, space based) Jason Hogan / Stanford

17:25 → 18:15 Discussion session : discussion points
- Scaling up from table-top systems
- Networking – identifying commonalities with neighboring communities
- Applying quantum technologies to high energy detectors

18:15 → 18:30 Wrap-up

Quantum Technologies for High Energy Physics (QT4HEP) (Nov. 1-4, 2022)

https://indico.cern.ch/event/1190278/timetable/

	topics chosen to overlap with CERN focus and expertise
Applications of superconducting technologies to particle detection Caterina Braggio (Univ. Padova (IT))	DM searches via RF, superconducting electronics, coatings, cavities
Scaling up of atomic interferometers for the detection of dark matter Oliver Buchmuller (Imperial College (GB))	AION, MAGIS, ... DM searches via atom interferometers in vertical shaf
Applying traps and clocks to the search for new physics Piet Schmidt (Univ. Hannover / PTB (DE))	AD, ISOLDE: symmetry & BMS tests via precision spectroscopy
Applications of quantum devices to HEP detectors Ian Shipsey (University of Oxford (GB))	Quantum systems for HEP (novel or enhanced detectors)
Molecular systems for tests of fundamental physics Steven Hoekstra (Univ. Groeningen (NL))	AD, ISOLDE: symmetry & BMS tests via precision spectroscopy
Development of detectors for ultra-low energy neutrinos Gianluca Cavoto (Sapienza Universita e INFN, Roma I (IT))	neutrino physics at the low energy frontier (CNB)

quantum sensors (an electromagnetic perspective)

	Microwave	Submillimetre	Far infrared	Optical	High energy
	10 – 100 GHz 3 cm- 3 mm	100 GHz – 1 THz 3 mm – 300 µm	1 – 10 THz 300 – 30 µm	2 µm – 300 nm	UV, ϒray and Xray
SIS mixers		🟢			
HEB			🟢		
CEB		🟢			
TES	🔴	🟢	🟢	🟢	🟢
KID	🔴	🟢	🟢	🟢	
SNSPD			🔴	🟢	
SQUID	🟢				
JJPA	🟢				
TWPA	🟢	🔴			

Stafford Withington (Cambridge)