Quantum Particle Detectors

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

M. Doser, CERN

Tokyo, Aug. 2023

Clarification of terms

Some words on the landscape

Quantum sensors for low energy particle physics

Quantum sensors for high energy particle physics

(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)

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

and because the commensurate energies are very low, unsurprisingly, quantum sensors are ideally matched to low energy (particle) physics;

→focus on CERN activities both in low energy and high energy particle physics

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

bottom line: measure result of *a single* individual interaction

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

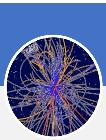
→ ECFA Detector R&D Roadmap Symposium of Task Force 5 Quantum and Emerging Technologies

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

CERN quantum initiative

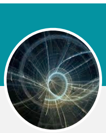
https://quantum.web.cern.ch/

CERN | IQ> QUANTUM TECHNOLOGY INITIATIVE



- Assess the **areas of potential quantum advantage** in HEP applications (QML, classification, anomaly detection, tracking)
- Develop **common libraries of algorithms, methods, tools**; benchmark as technology evolves
- Collaborate to the development of shared, **hybrid classic-quantum infrastructures**

Computing & Algorithms



- Identify and develop techniques for **quantum simulation** in collider physics, QCD, cosmology within and beyond the SM
- Co-develop quantum computing and sensing approaches by providing **theoretical foundations** to the identifications of the areas of interest

Simulation & Theory

⑥

- Develop and promote **expertise in quantum sensing** in low- and high-energy physics applications
- Develop quantum sensing approaches with emphasis on **low-energy particle physics measurements**
- Assess **novel technologies and materials** for HEP applications

Sensing, Metrology & Materials

currently: 3 PhD's

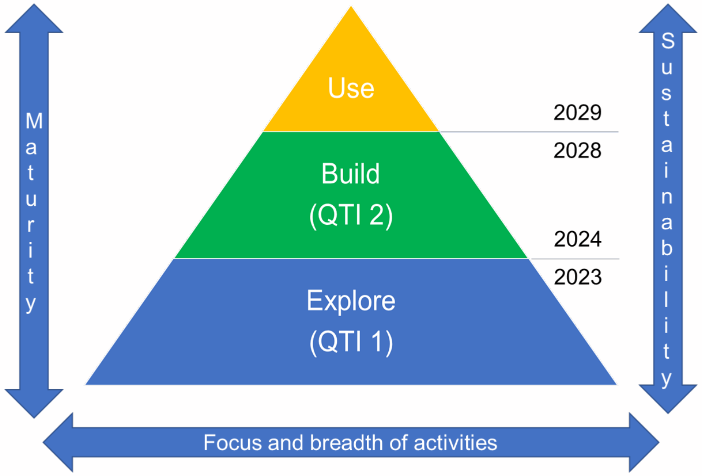
- **Co-develop CERN technologies relevant to quantum infrastructures** (time synch, frequency distribution, lasers)
- Contribute to the **deployment and validation of quantum infrastructures**
- Assess requirements and **impact of quantum communication on computing applications** (security, privacy)

Communications & Networks

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

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; quantum sensors for millicharged particles and Physics Beyond Colliders; quantum data acquisition.

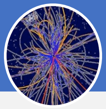
Specifically, the sensor-related goals of QTI 2 are intentionally aligned with the larger international framework of the ECFA roadmap and process (within which the technical developments focusing on quantum sensing R&D efforts for particle physics are integrated in the future international DRD5 collaboration),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

CERN quantum initiative (v2)

(1.2024-12.2028)

CERN | IQ⟩ QUANTUM TECHNOLOGY INITIATIVE

① ④ ⑤



- 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

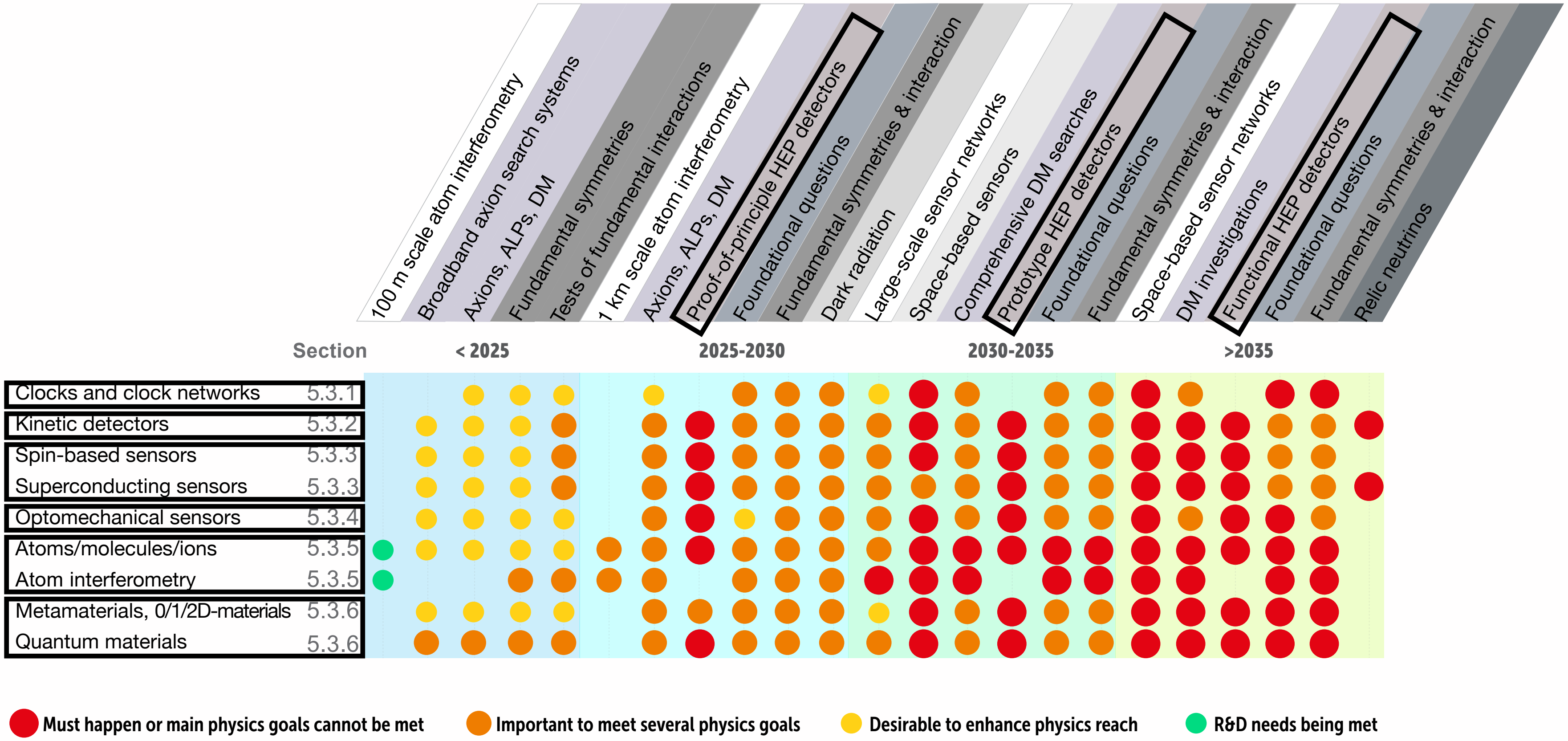
- Objective 2.1c: Benchmark and comparison of Rydberg states as qubits in prototype systems
- Objective 2.2b.3: Investigate scaling behavior of multiple qubits
- Objective 2.3c: Read-out-free detection & DAQ via entanglement between TES voxels and another system; machine-learning-based anomaly detection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

Long term objectives

RECFA Detector R&D roadmap 2021

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

Chapter 5: Quantum and Emerging Technologies Detectors



	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

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Chapter 4: Particle Identification and Photon Detectors

It is recommended that several "blue-sky" R&D activities be pursued. The development of solid state photon detectors from novel materials is an important future line of research, as is the development of cryogenic superconducting photosensors for accelerator- based experiments. Regarding advances in PID techniques, gaseous photon detectors for visible light should be advanced. Meta-materials such as photonic crystals should be developed, giving tune-able refractive indices for PID at high momentum. Finally, for TRD imaging detectors, the detection of transition radiation with silicon sensors is an important line of future research.

@ 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

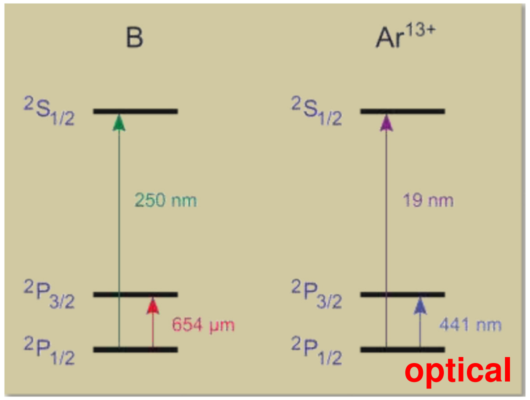
particles, atoms, ions, nuclei:

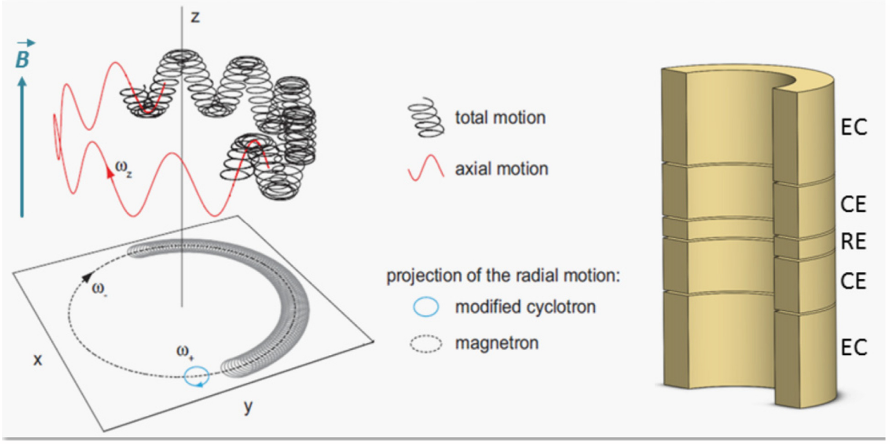
tests of QED, T-violation, P, Lorentz-violation, DM searches

HCI's in Penning traps

Scaling with a nuclear charge Z

Binding energy	~ Z^2
Hyperfine splitting	~ Z^3
QED effects	~ Z^4
Stark shifts	~ 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

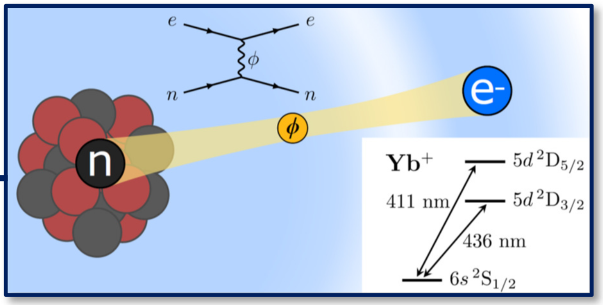
https://iopscience.iop.org/journal/2058-9565/page/Focus-on-Quantum-Sensors-for-New-Physics-Discoveries

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

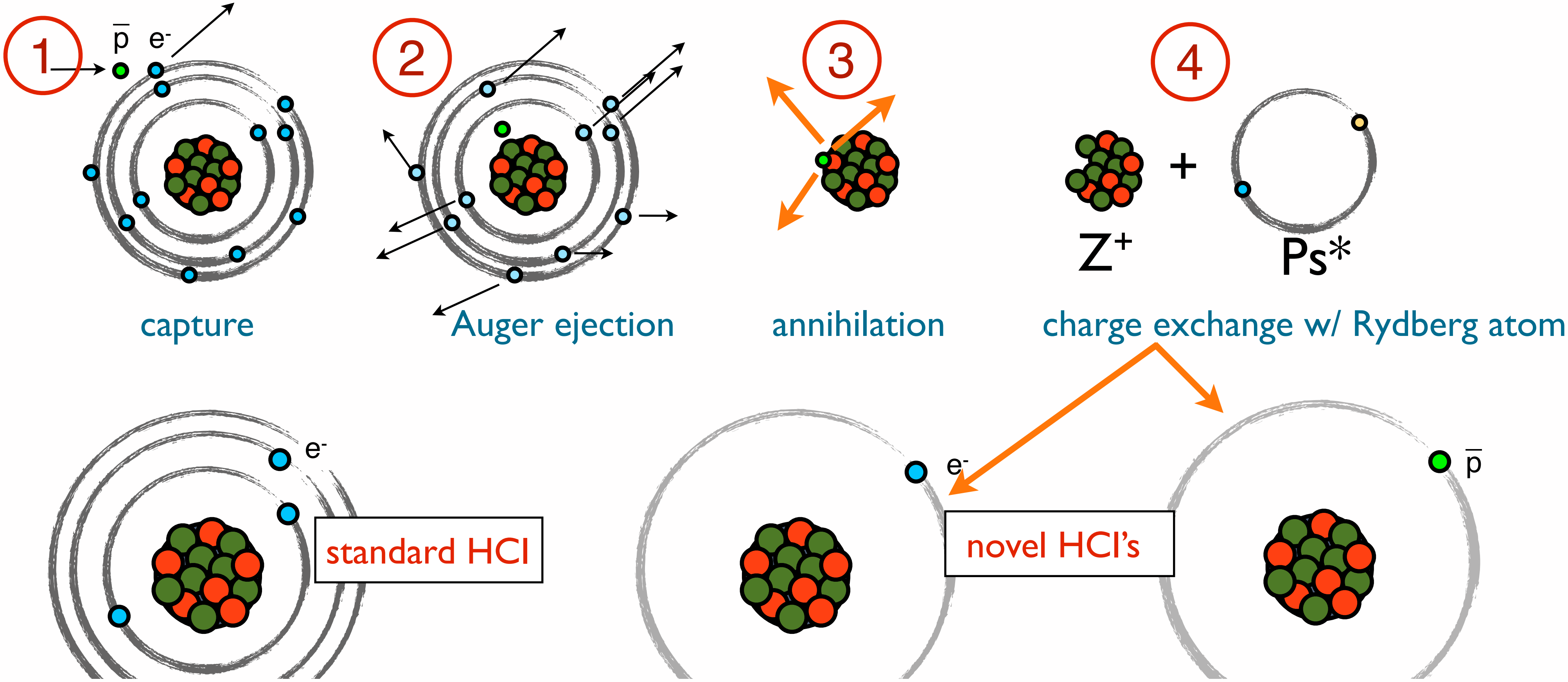
https://indico.cern.ch/event/999818/ Marianna Safronova (University of Delaware)

HCIs: **much larger** sensitivity to variation of α and dark matter searches then 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



Antiprotonic atoms → novel HCI systems



capture

Auger ejection

annihilation

charge exchange w/ Rydberg atom

standard HCI

novel HCI's

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

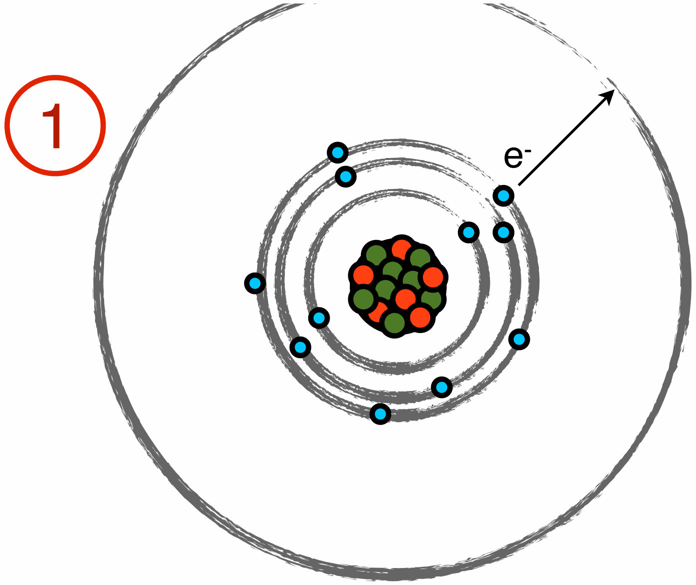
HCI*(stable or unstable), $(Z-1)^+$

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

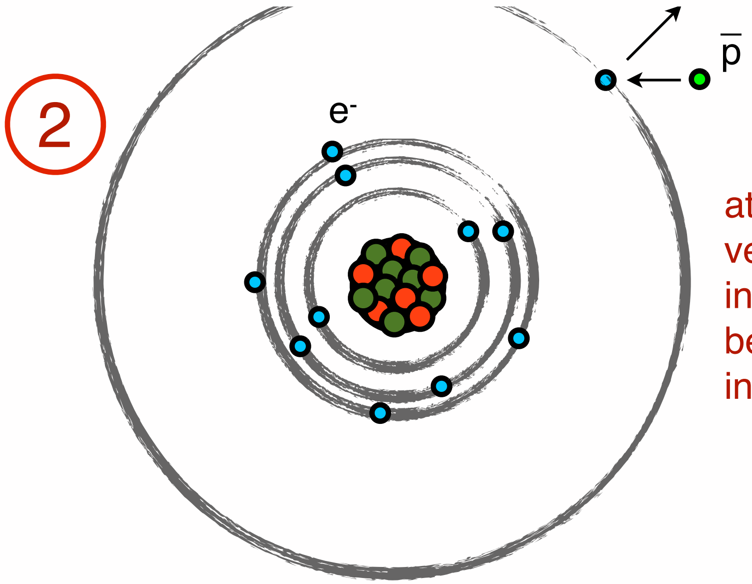
M. Doser, Prog. Part. Nucl. Phys, (2022), https://doi.org/10.1016/j.ppnp.2022.103964

Quantum sensors for new particle physics experiments: Penning traps

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



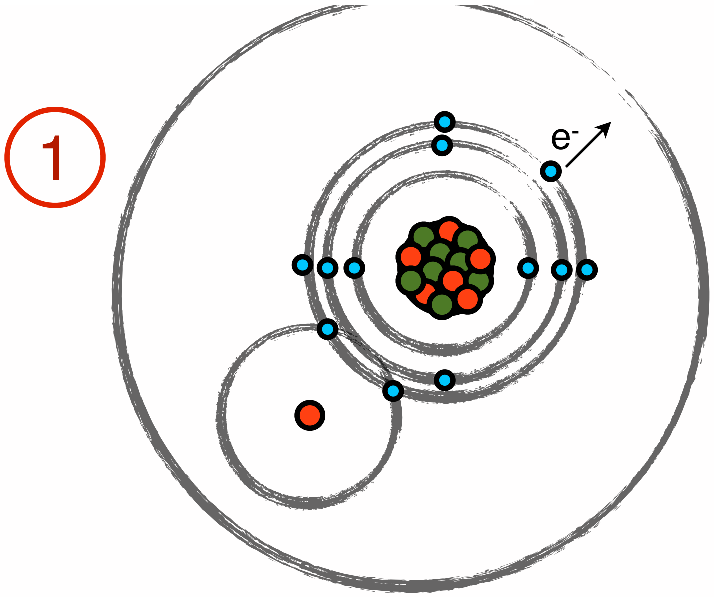
Rydberg excitation



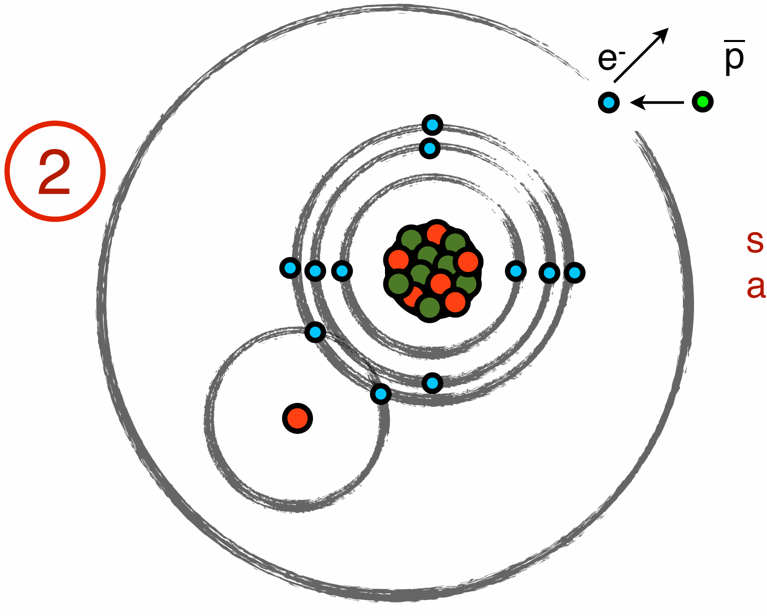
charge exchange

at end of cascade, $\bar{p}$ is very close to nucleus… investigate long-range behavior of strong interaction?

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



Rydberg excitation



charge exchange

similar approach as eEDM in molecules

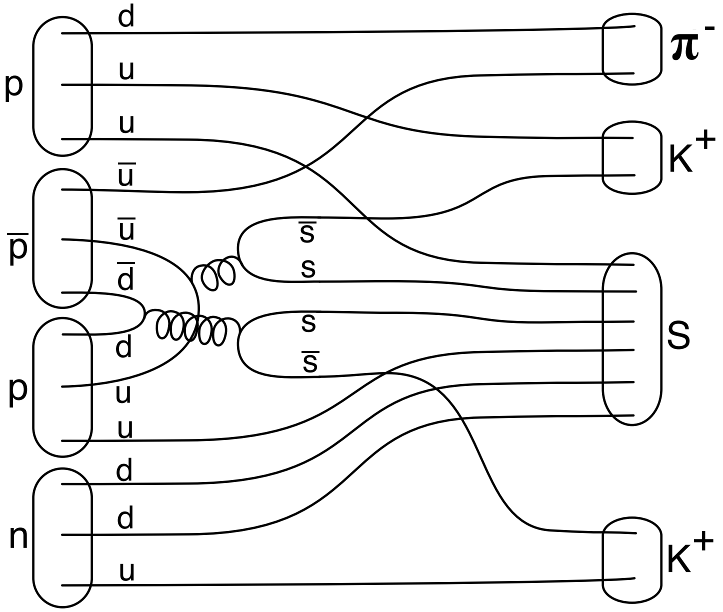
AEḡIS : a novel dark matter search

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

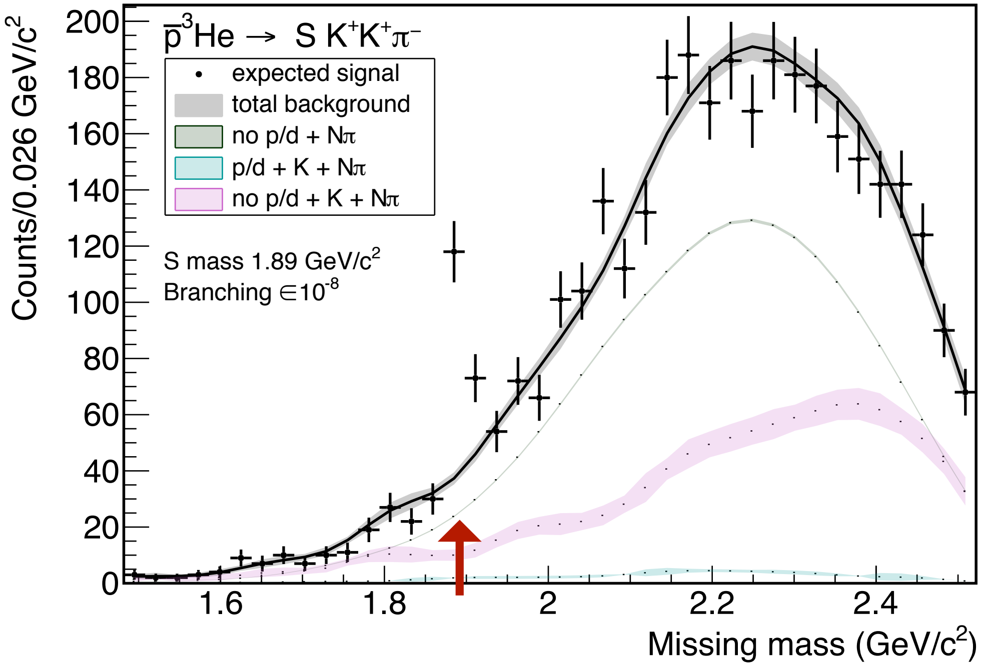
not excluded by prior searches for similar states (among them, the H dibaryon) in the GeV region
astrophysical bounds can be evaded
standard model compatible (uuddss bound state)

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

S= +2, Q= +1



Geant-4 simulation

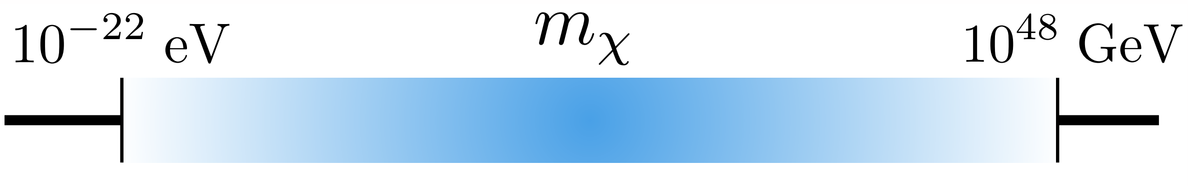


→ ***in-trap formation of antiprotonic atoms***
charged particle tracking, PID
detection of spectator p, d

→ ***sensitivity down to 10^{-9}***

RF cavities:

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

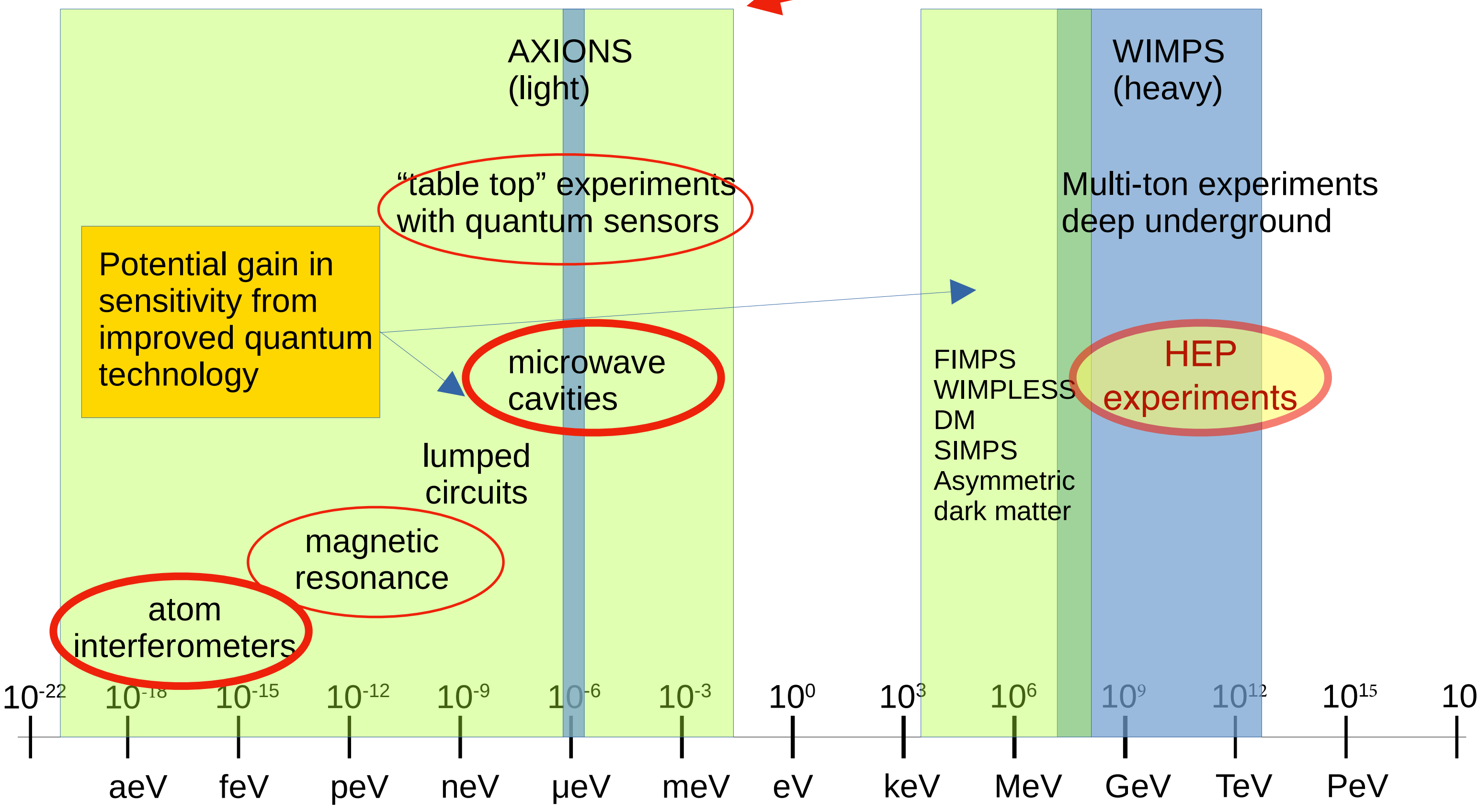


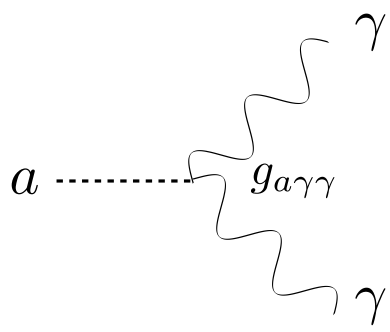
cavity size = axion size

axion mass = unknown

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

system noise temperature
cryo-amplifiers JJPA





(but not only…)

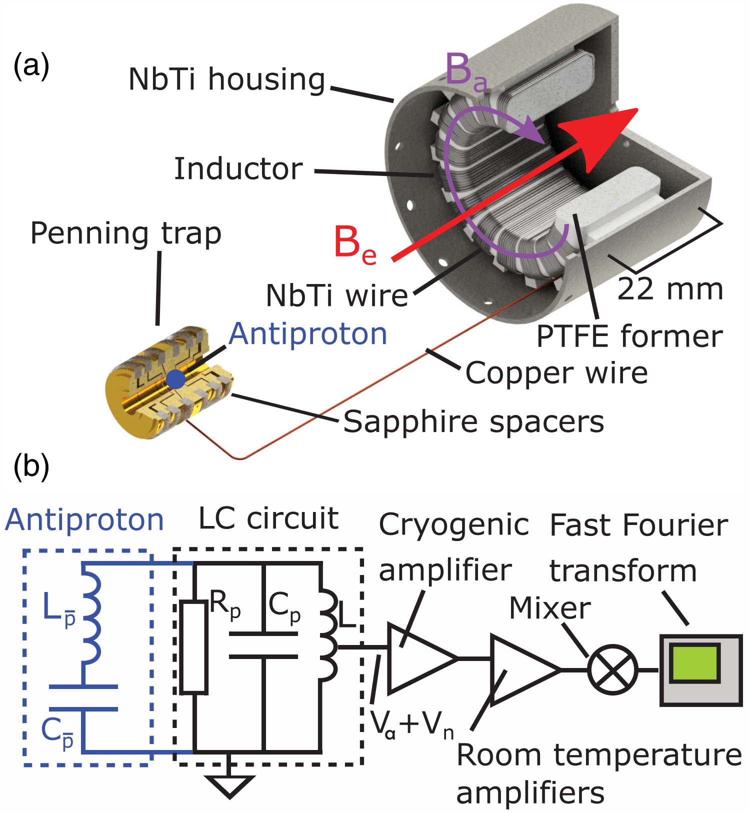
①

Quantum sensors for new particle physics experiments: Penning traps

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

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

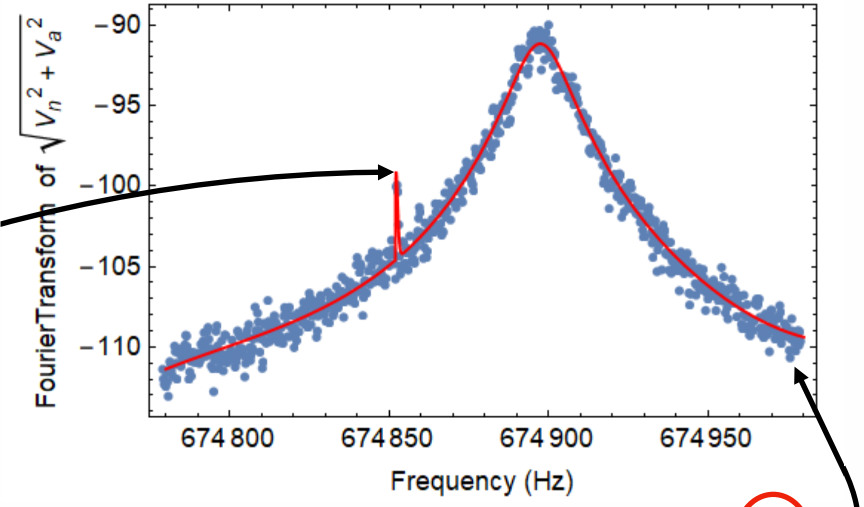
J. Devlin *et al.*, BASE collaboration, Physical Review Letters 126, 041301 (2021)



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

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

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



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

The axion signal

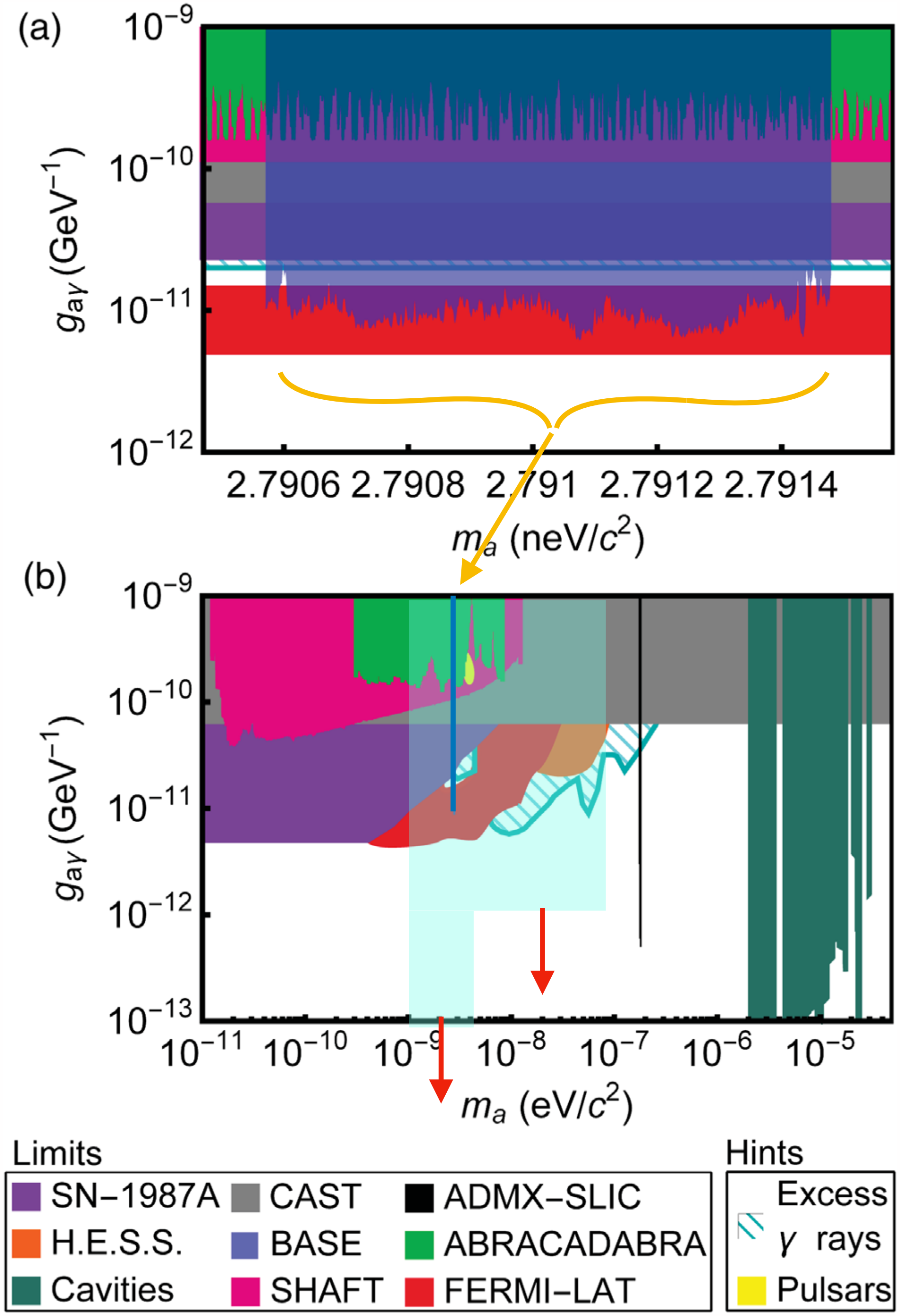
$$V_a = \frac{\pi}{2}\boxed{Q}\sqrt{f(\nu,Q,\mathbf{q})}\kappa\nu_a l N_{\mathrm{T}}(r_2^2-r_1^2)g_{a\gamma}\boxed{|\mathbf{B}_e|}\sqrt{\rho_a\hbar c}\,.$$

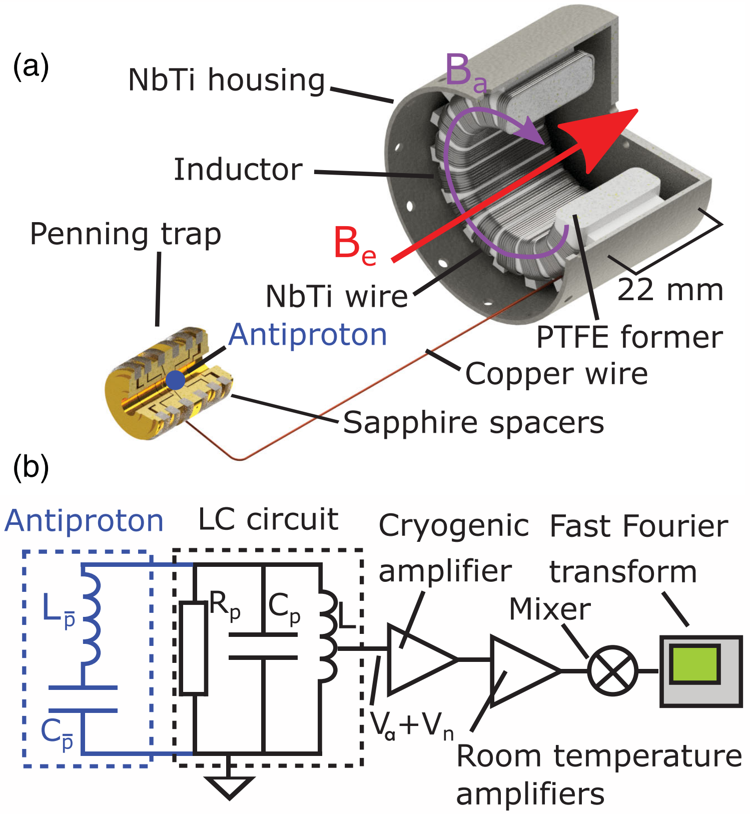
$f(\nu,Q,\mathbf{q})$ is a lorentzian line-shape function proportional to Re{Z}
e_n is the equivalent input noise of the amplifier
κ is the coupling constant
Q is the resonator Q-factor
N_T is the number of turns
l is the length of the toroid along the magnet B field

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!

Quantum sensors for new particle physics experiments: Penning traps





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}

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

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

figure of merit axion mass cavity volume

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

→ frequency conversion: driving "pump mode" at ω_0 ~ 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

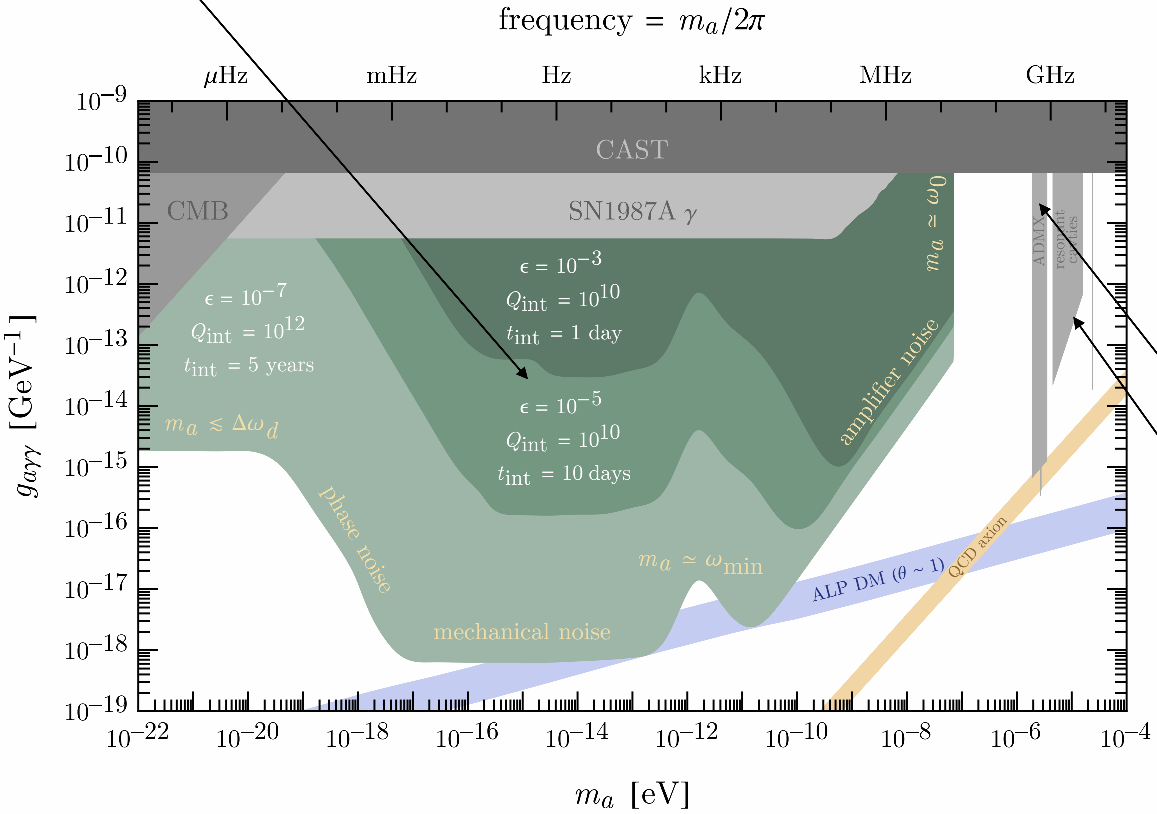
Tunability!

Axion heterodyne detection

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



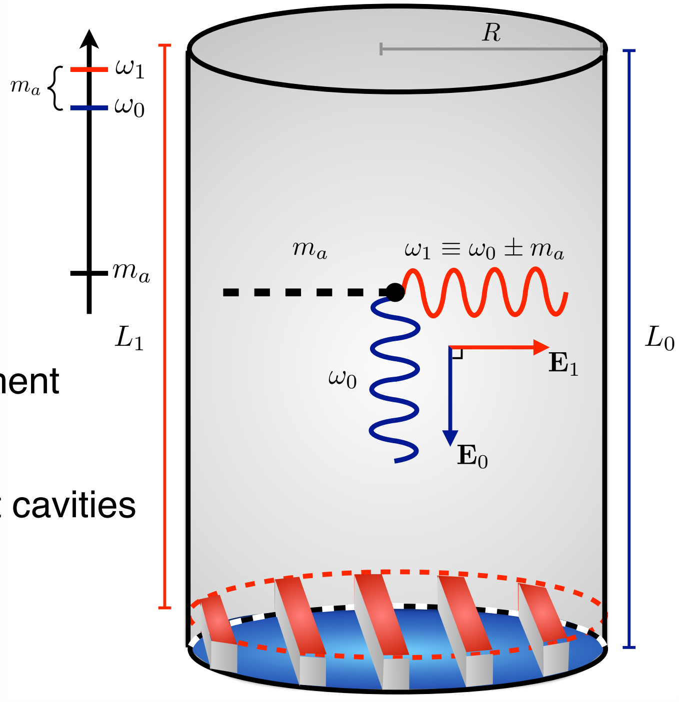
ADMX experiment

resonant cavities

<u>problem</u>: 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 $\omega_1 \sim \omega_0 \pm m_a$



(a) Cartoon of cavity setup.

<u>Conceptual Theory Level Proposal:</u> A. Berlin, Raffaele Tito D'Agnolo, S. Ellis, C. Nantista, J. Nielson, P. Schuster, S. Tantawi, N. Toro, K. Zhou, *JHEP* 07 (2020) 07, 088

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

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

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

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

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

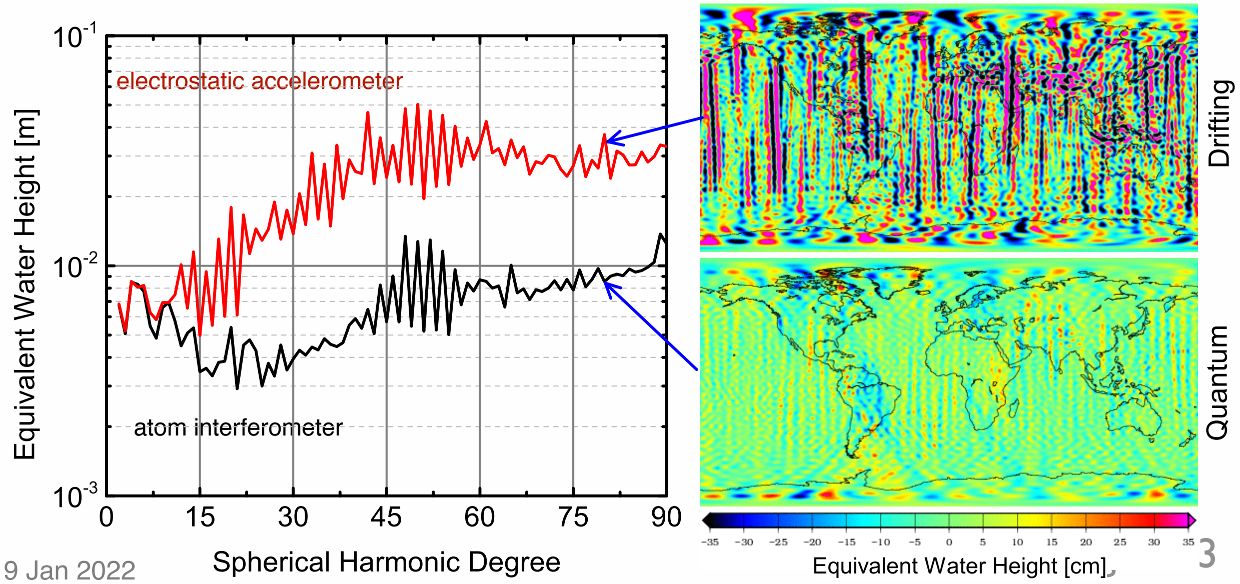
clocks act as narrowband detectors of the Doppler shift on the laser frequency due to the relative velocity between the satellites induced by the incoming gravitational wave

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



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

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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 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, nanolayers)

ultra-fast scintillators based on perovskytes

chromatic calorimetry (QDs)

active scintillators (QCL, QWs, QDs) 5.3.6 *

GEMs (graphene)

Atoms, molecules, ions

5.3.5 *

Rydberg TPC's

Spin-based sensors

5.3.3 *

helicity detectors

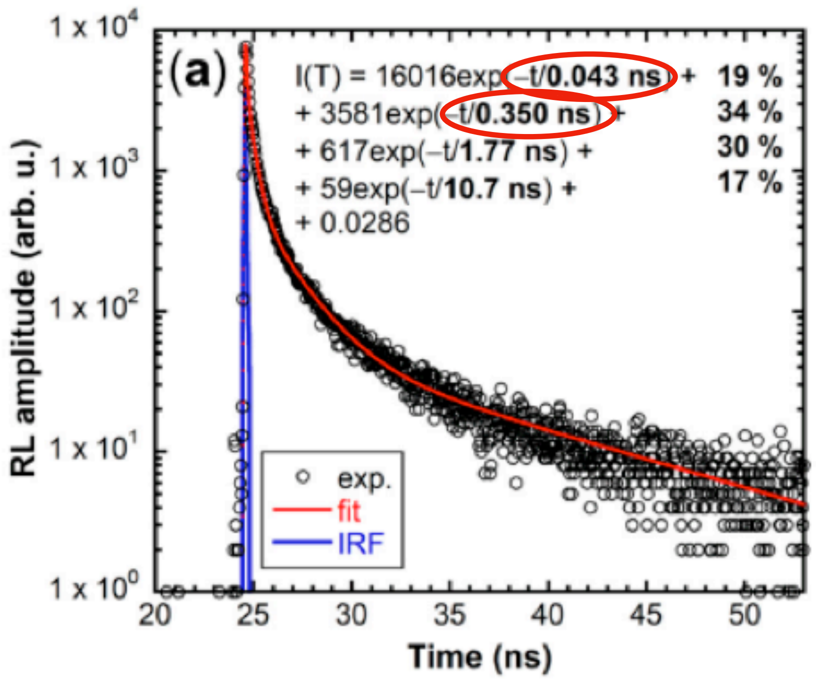
* https://cds.cern.ch/record/2784893

Superconducting sensors

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

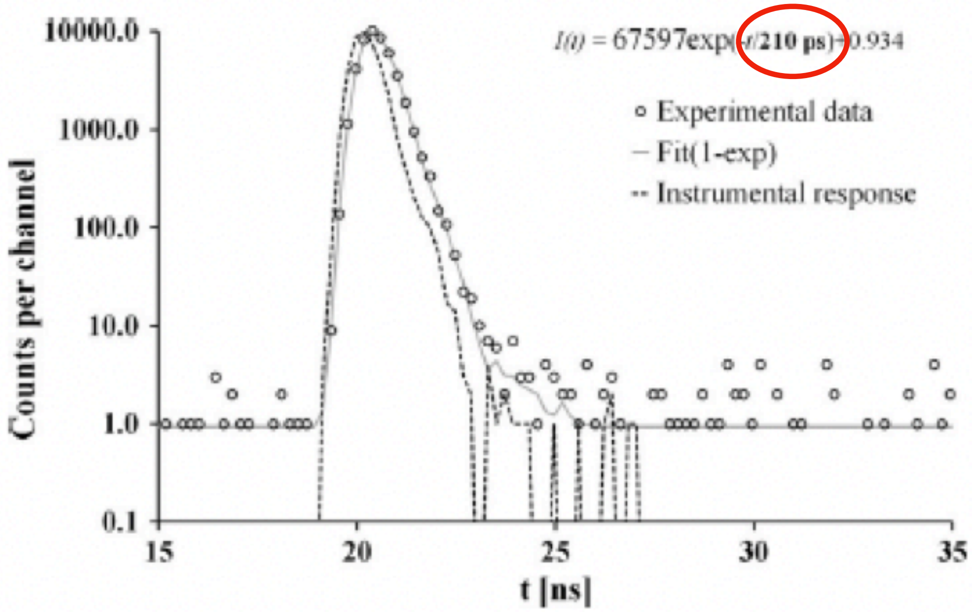


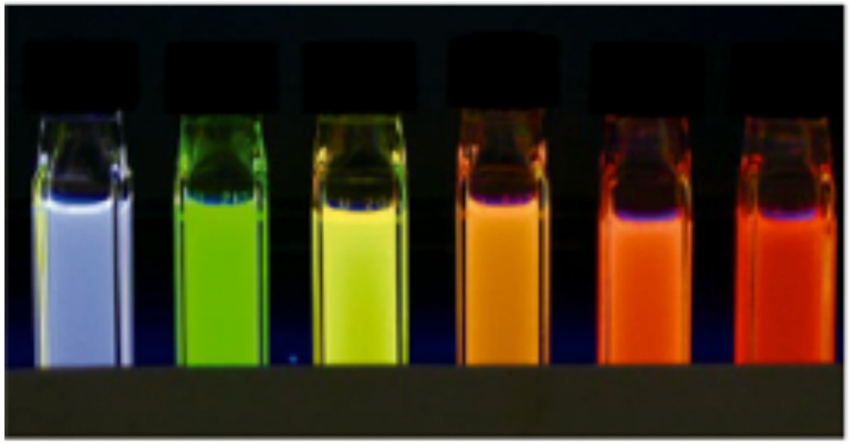
Fig. 9. Photoluminescence decay of ZnO:Ga sample at room temperature. Excitation nanoLED 339 nm, emission wavelength set at 390 nm. Decay curve is approximated by the convolution of instrumental response (also in figure) and single exponential function $I(t)$ provided in the figure.

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

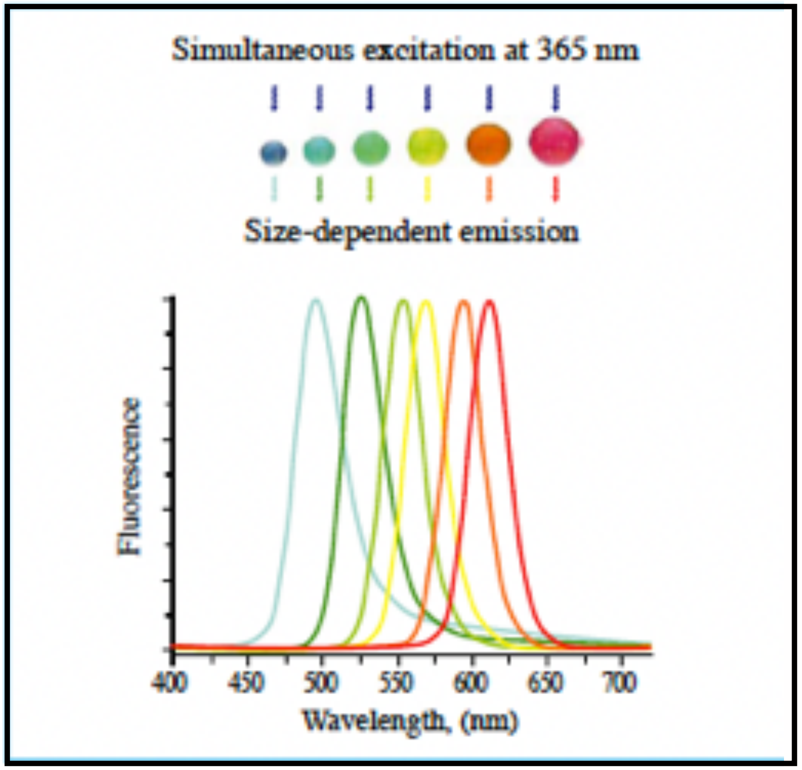
Concerns: integrated light yield (need many photons to benefit from rapid rise time)

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

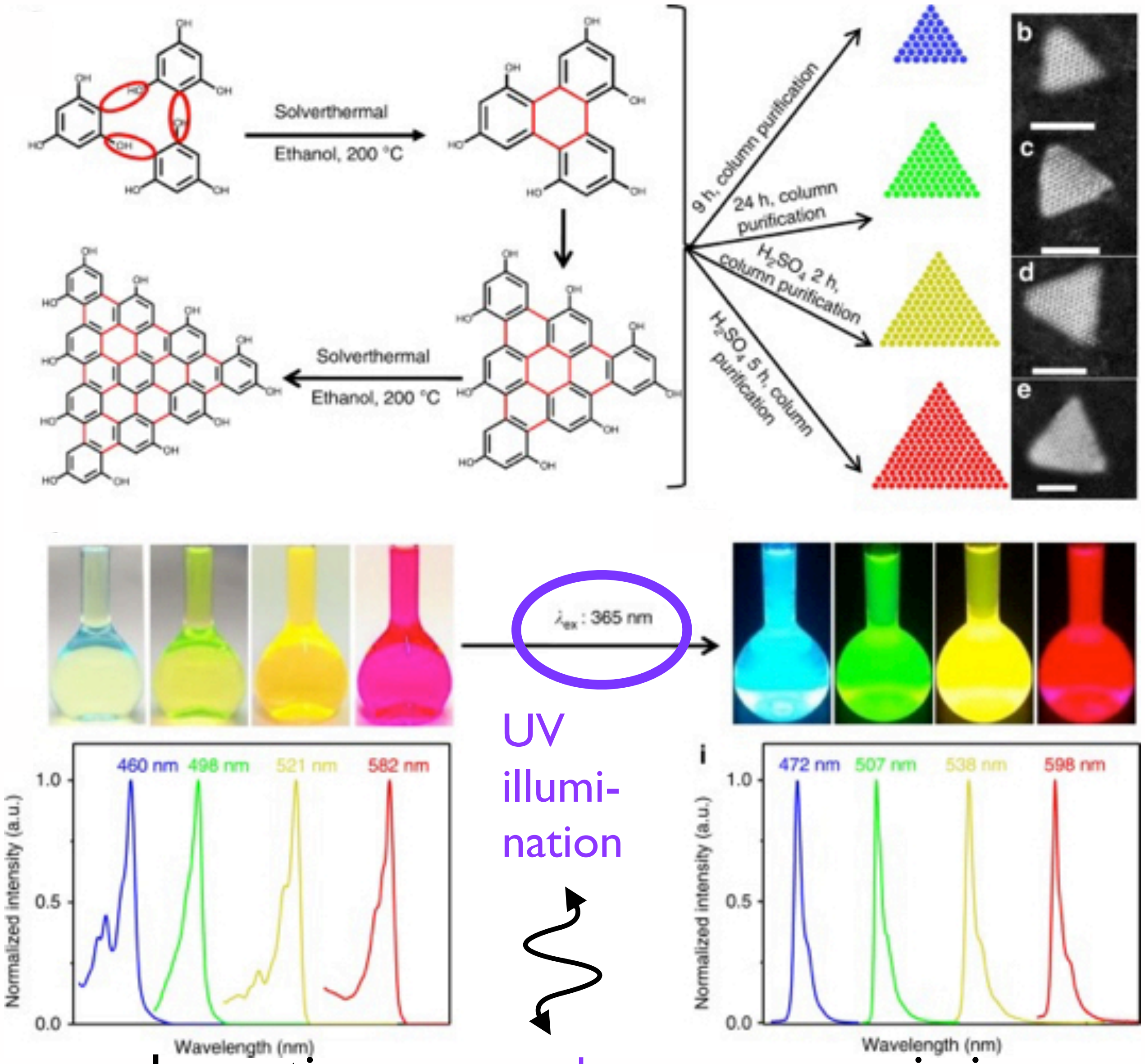


chromatic tunability → optimize for quantum efficiency of PD (fast, optimizable WLS)

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?)

Quantum dots: chromatic calorimetry



UV illumination

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

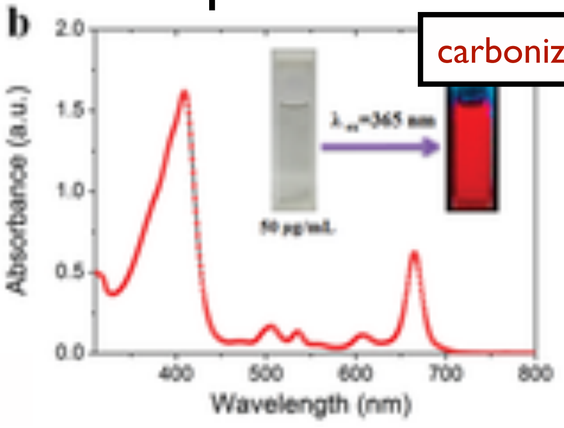
select appropriate nanodots

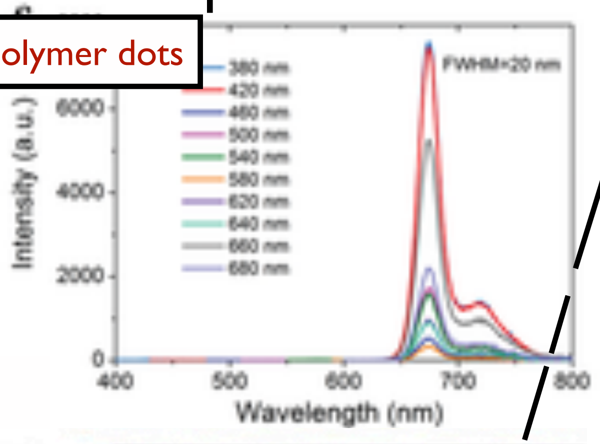
e.g. triangular carbon nanodots

absorption spectrum

emission spectrum

carbonized polymer dots





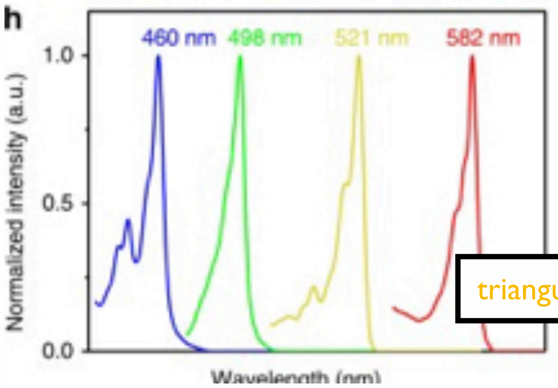
leftmost nanodots:
absorb wavelengths < 650 nm
emit at > 680 nm

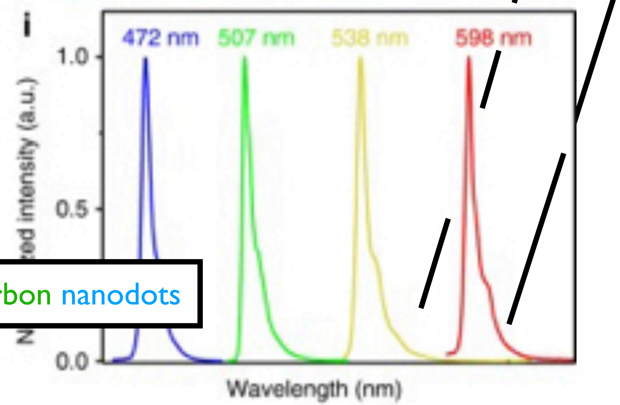
next band:
absorb wavelengths < 590 nm
emit at > 590 nm

…

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

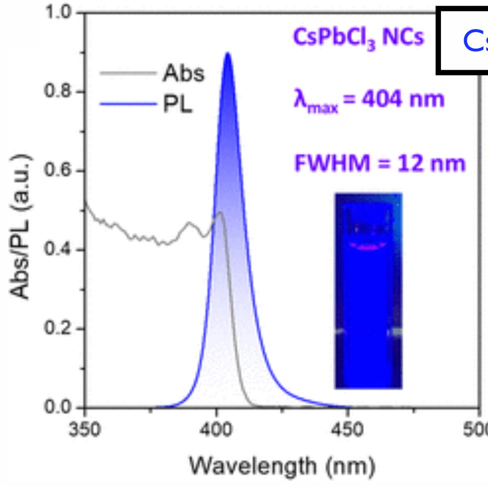
triangular carbon nanodots

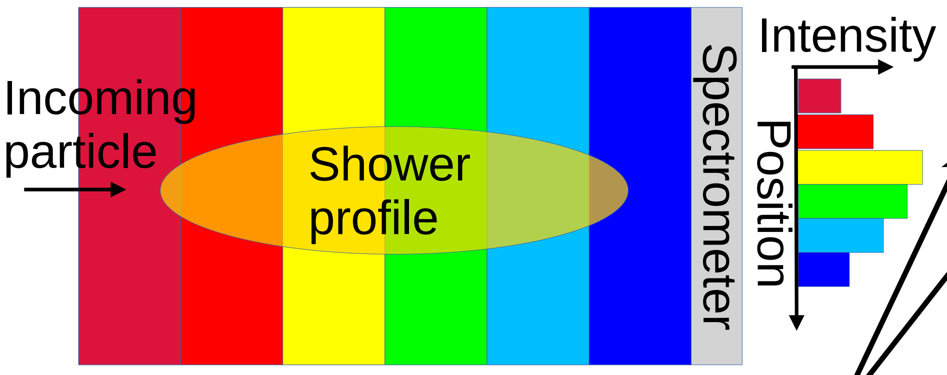




if high-Z substrate transparent in 400-700 nm, then no re-absorption of emitted light

CsPbCl₃ nanocrystals





Monochromators + PD?

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

Metalenses?

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

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

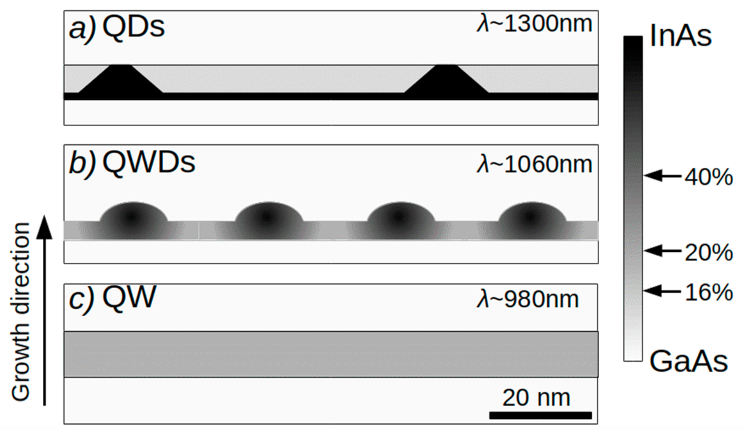
Active scintillators (QWs, QDs, QWDs, QCLs)

standard scintillating materials are passive

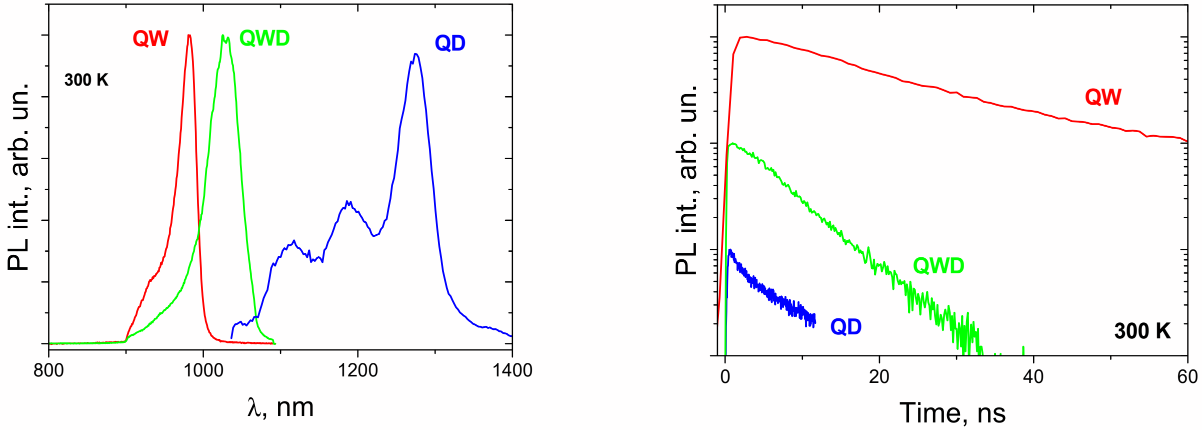
- can not be amplified
- can not be turned on/off
- can not be modified once they are in place

is it possible to produce active scintillating materials?

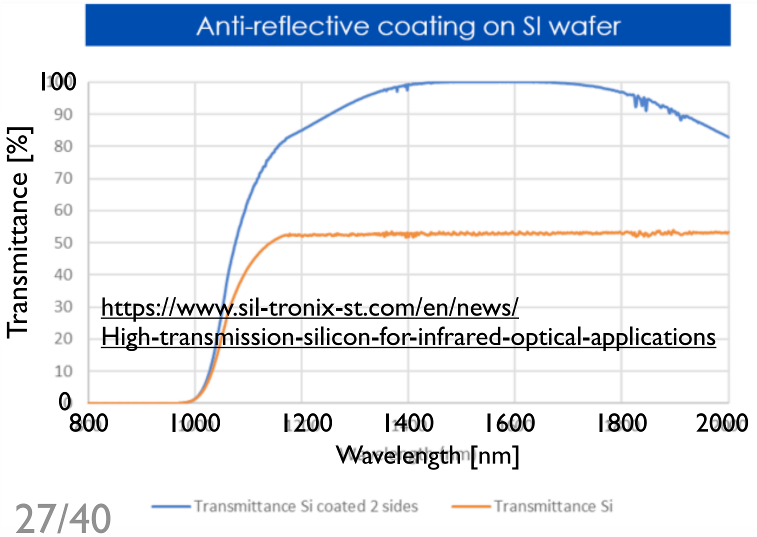
- electronically amplified / modulable
- pulsed / primed
- gain adapted in situ



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

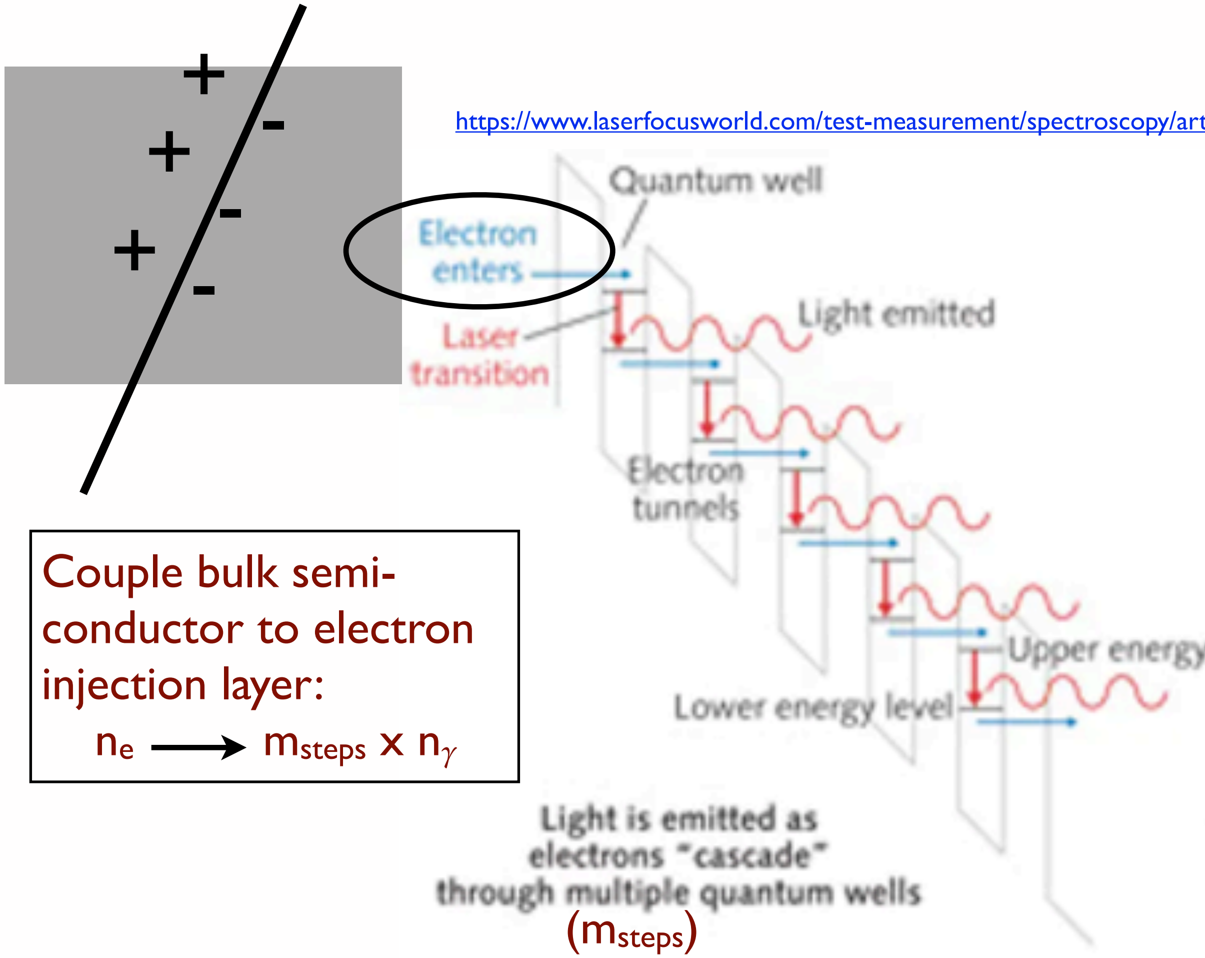
Emission in IR! Silicon is ~transparent at these wavelengths… Can this IR light be transported *through* a tracker to outside PDs?

QD's are radiation resistant

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.

Active scintillators (QCLs, QWs, QDs, QWDs)

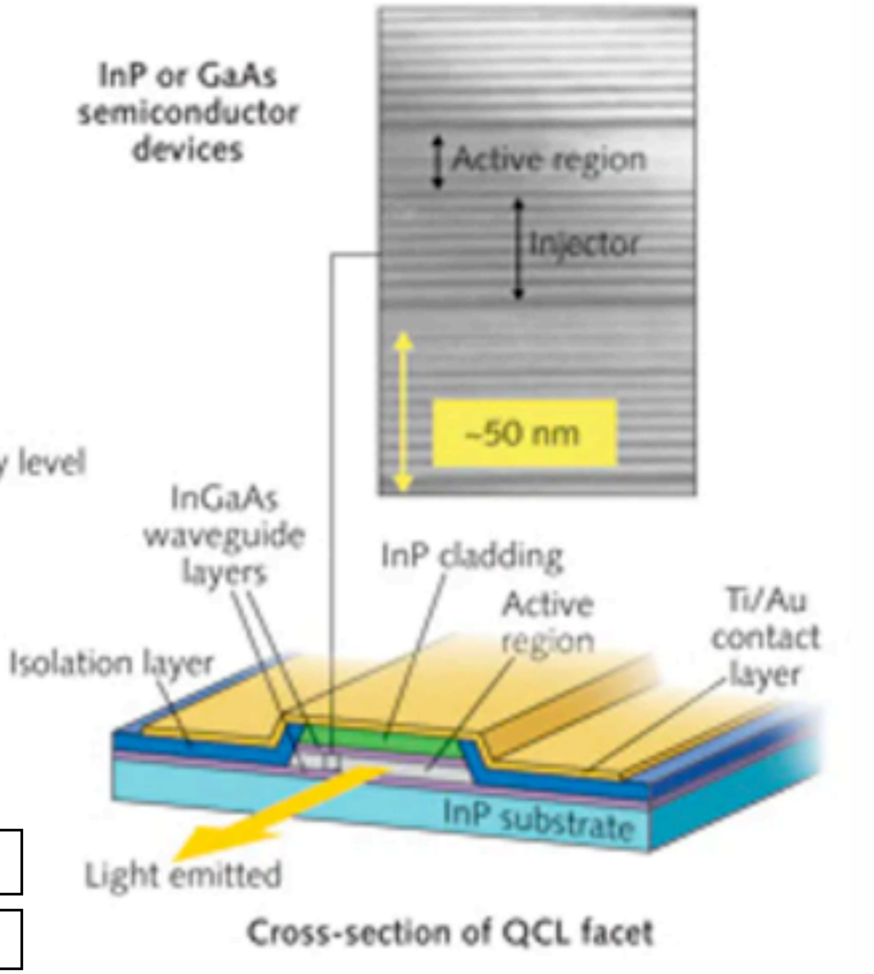
https://www.laserfocusworld.com/test-measurement/spectroscopy/article/16556856/quantumcascade-lasers-qcls-enable-applications-in-ir-spectroscopy



(m_{steps})

Couple bulk semi-conductor to electron injection layer:

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



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)

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

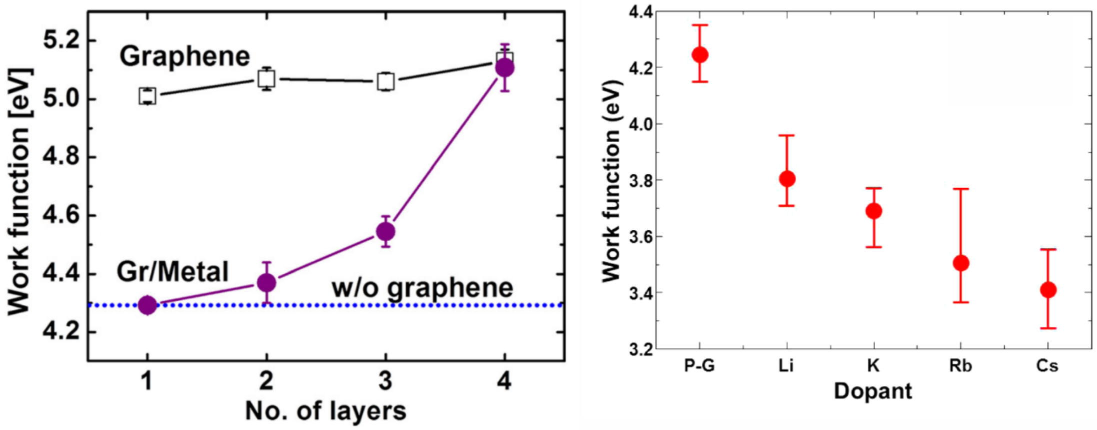
efficiency of the photocathode → timing resolution; QE
tune via resonant processes in low dimensional coating structures

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

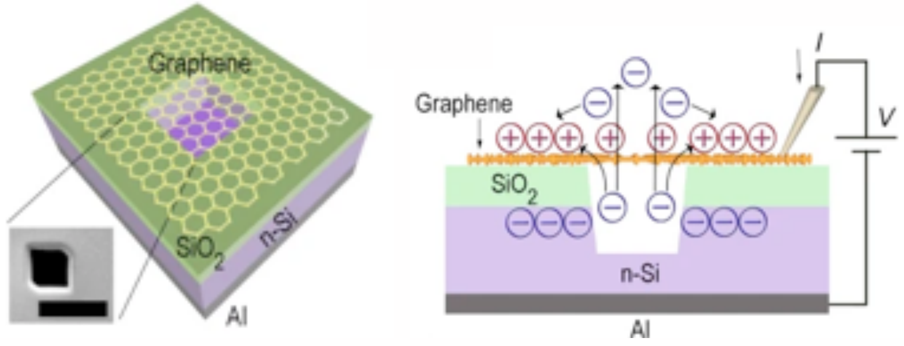
amplification

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 (?)



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



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

Metamaterials, 0 / 1 / 2-dimensional materials (quantum dots, nanolayers)

ultra-fast scintillators based on perovskytes

chromatic calorimetry (QDs)

active scintillators (QCL, QWs, QDs) 5.3.6

GEMs (graphene)

Atoms, molecules, ions

Rydberg TPC's 5.3.5

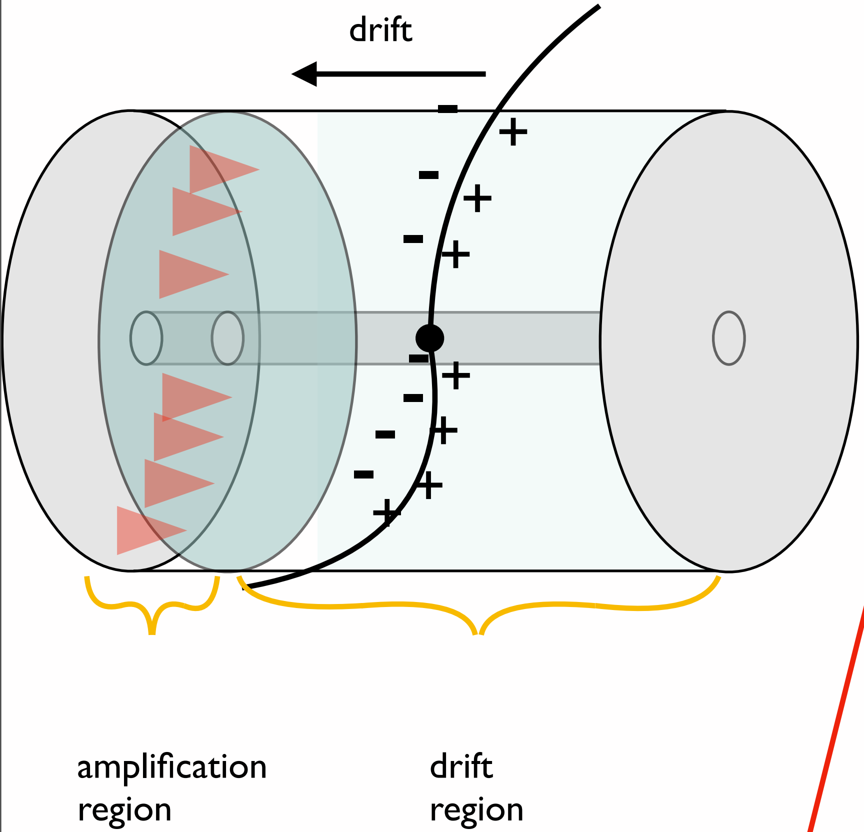
Spin-based sensors

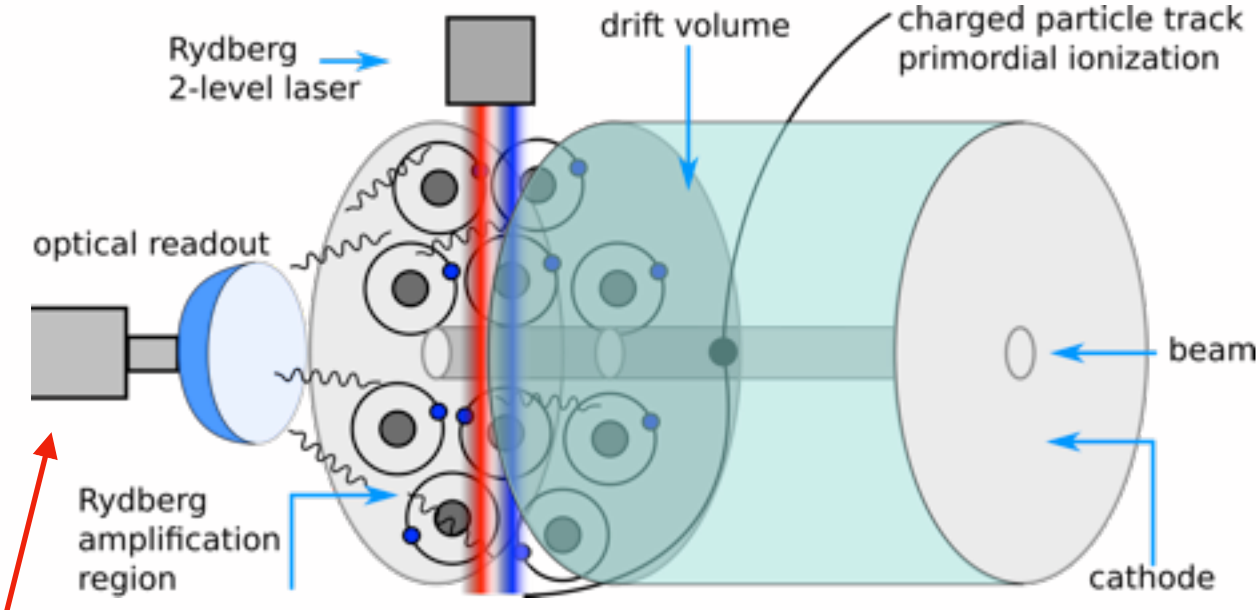
helicity detectors 5.3.3

Rydberg atom TPC's

Georgy Kornakov / WUT

Act on the amplification region





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

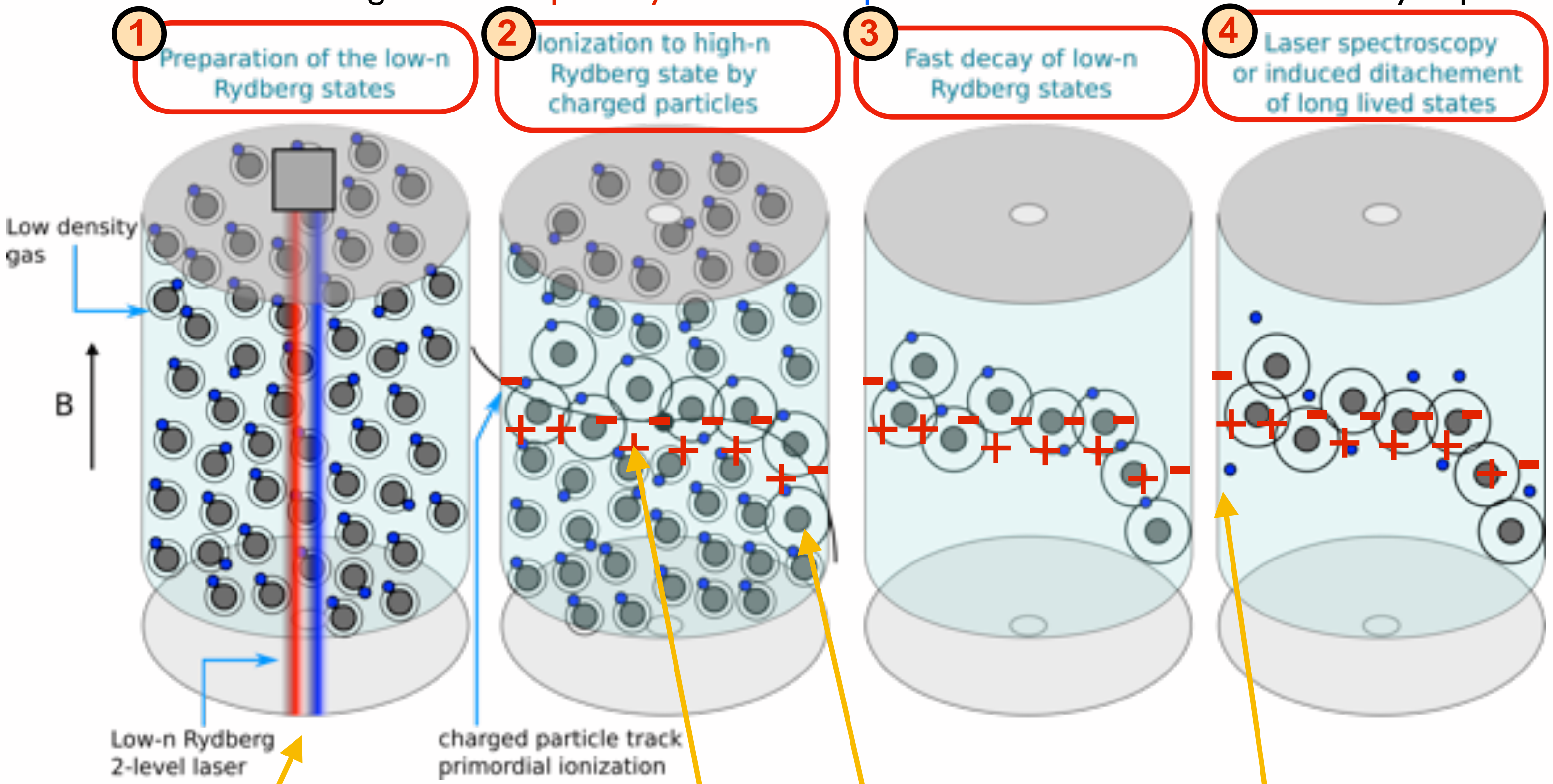
Rydberg atoms can serve to up-convert THz / GHz radiation into the optical regime ⟶ optical R/O of avalanche intensities

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



ionization + excitation;
natural decay of unmodified atoms

reduction of ionization and
atomic excitation threshold

photo-ionization of excited atoms

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HEP

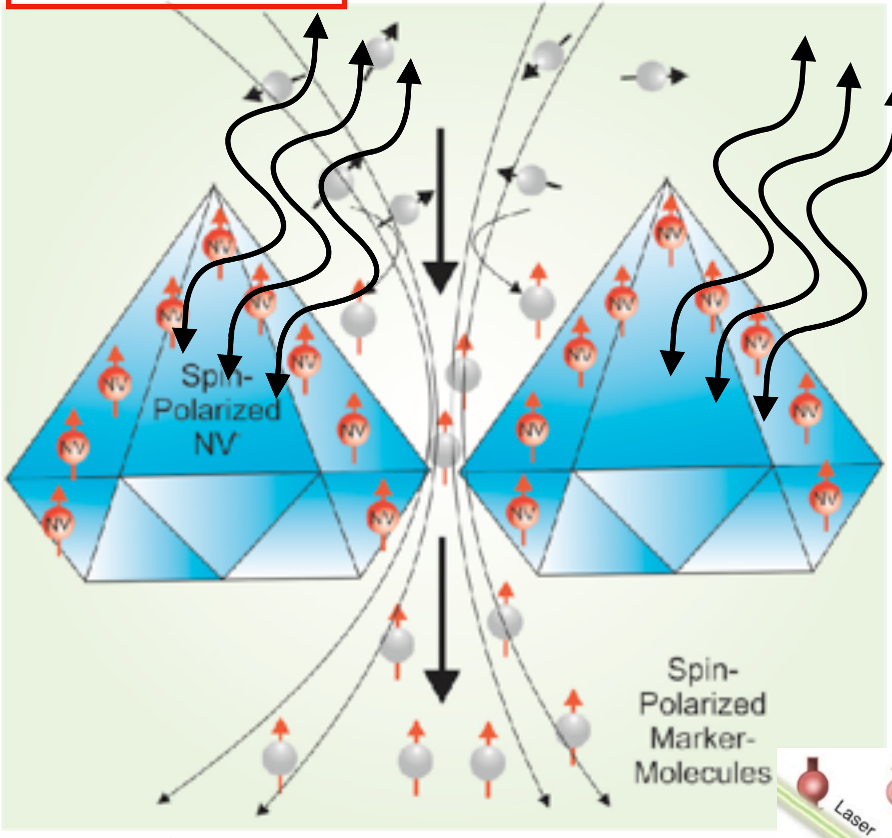
optically polarizable elements: Nitrogen-vacancy diamonds (NVD)

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

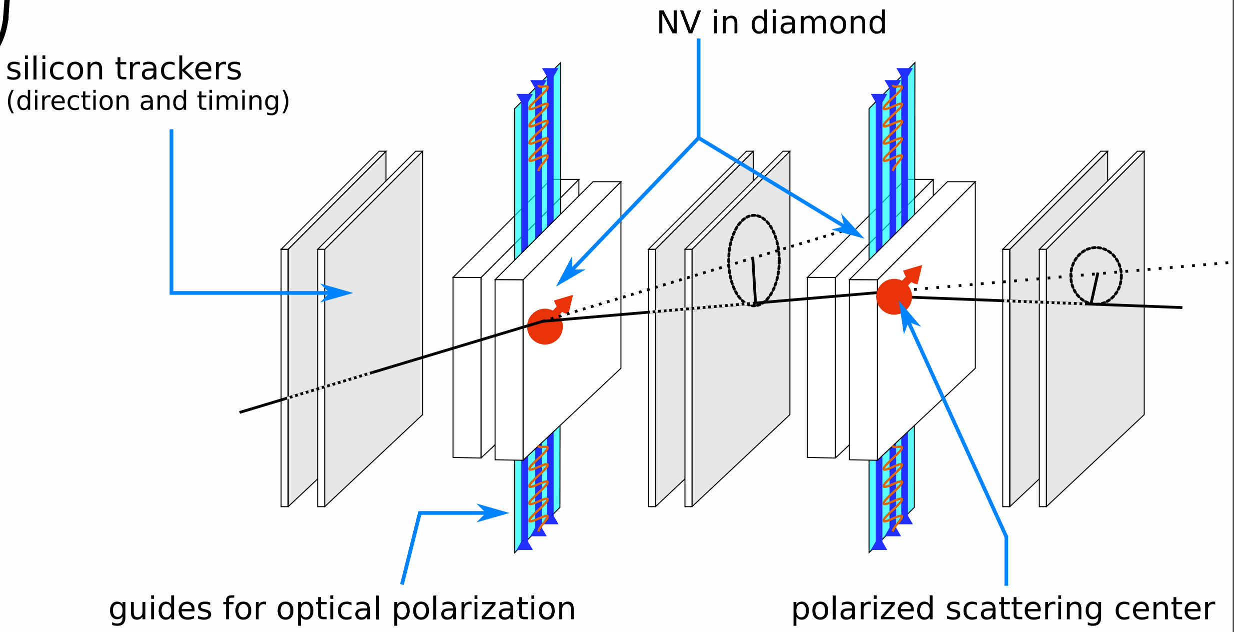
$10^{16} \sim 10^{18}$ / cm^3



© Dr. Christoph Nebel, Fraunhofer IAF

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

Diamond plates of up to 8 × 8 mm² in size, fabricated by Element Six

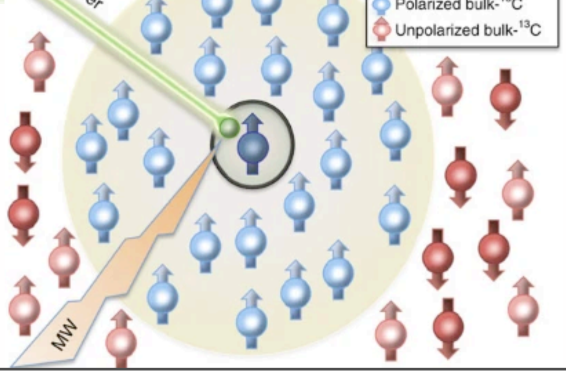


silicon trackers
(direction and timing)

NV in diamond

guides for optical polarization

polarized scattering center

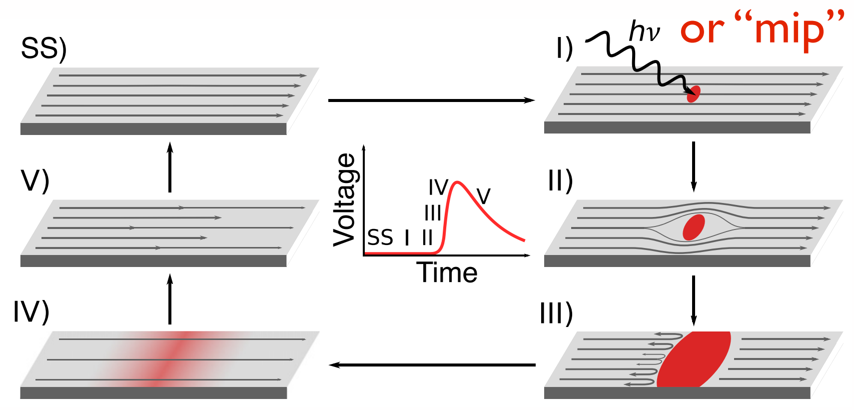


Local and bulk ^{13}C hyperpolarization in nitrogen-vacancy centred diamonds at variable fields and orientations, G. Alvarez et al., *Nature Communications* **6**, 8456 (2015)

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

x 10^2

Extremely low energy threshold detectors: SNSPD



SNSPD's Near term future

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

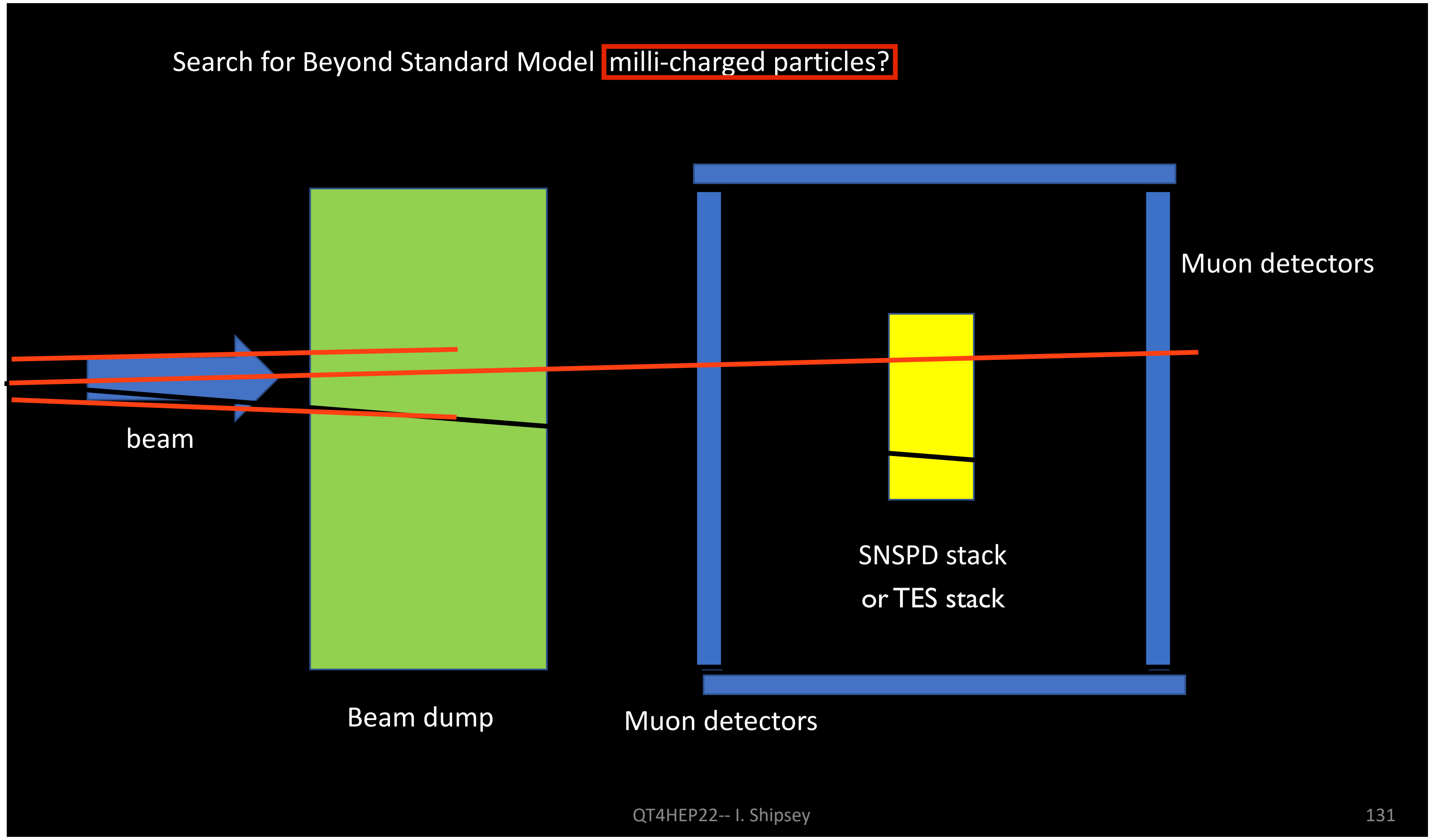
Snowmass2021 - Letter of Interest

Superconducting Nanowire Single-Photon Detectors

Contact Information:
Karl Berggren, berggren@mit.edu
Ilya Charaev, charaev@mit.edu
Jeff Chiles, jeffrey.chiles@nist.gov
Sae Woo Nam, saewoo.nam@nist.gov
Valentine Novosad, novosad@anl.gov
Boris Korzh, bkorzh@jpl.nasa.gov
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

Tokyo, Aug. 2023

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

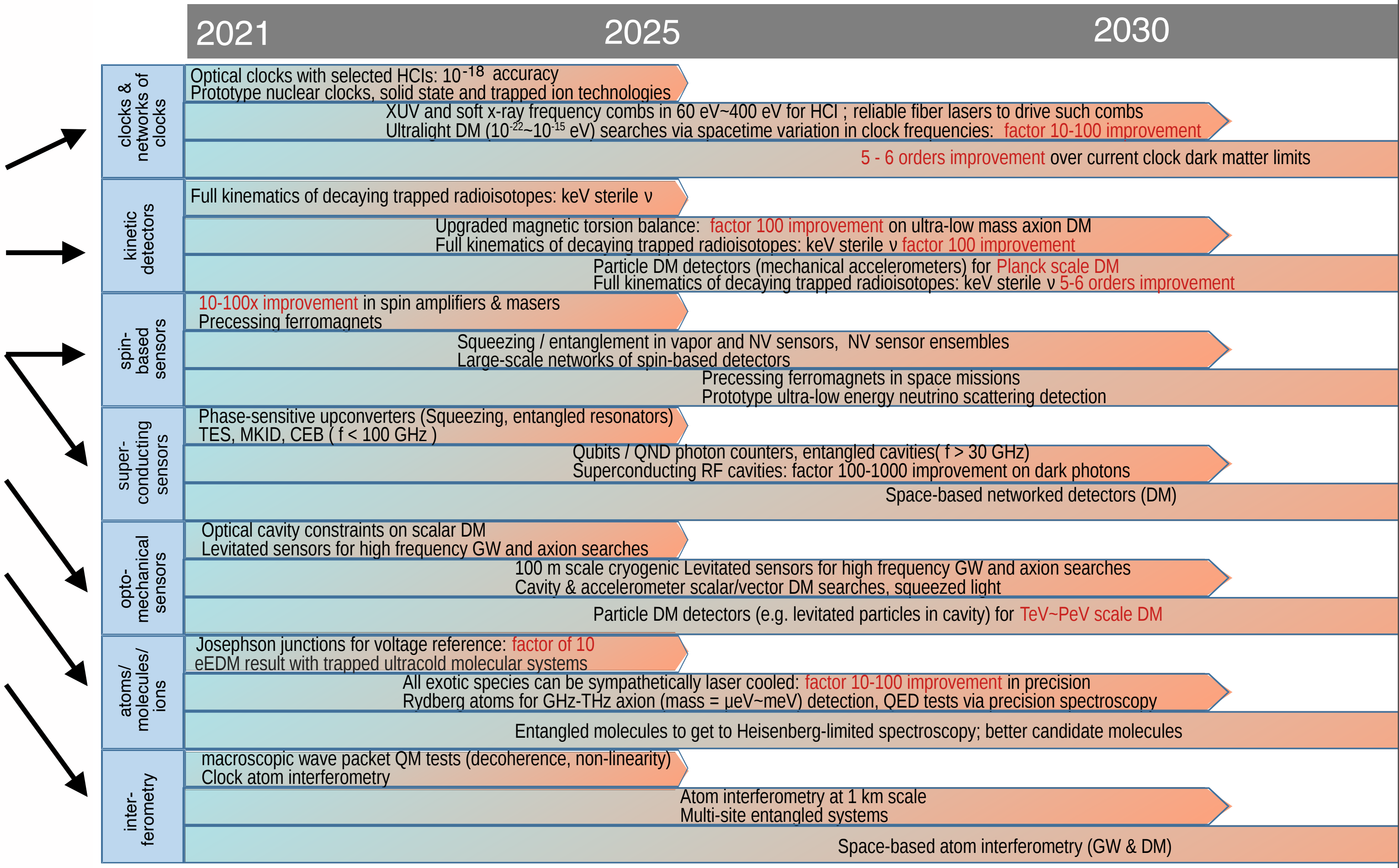
Kinetic detectors 5.3.2

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



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)

also for HEP!

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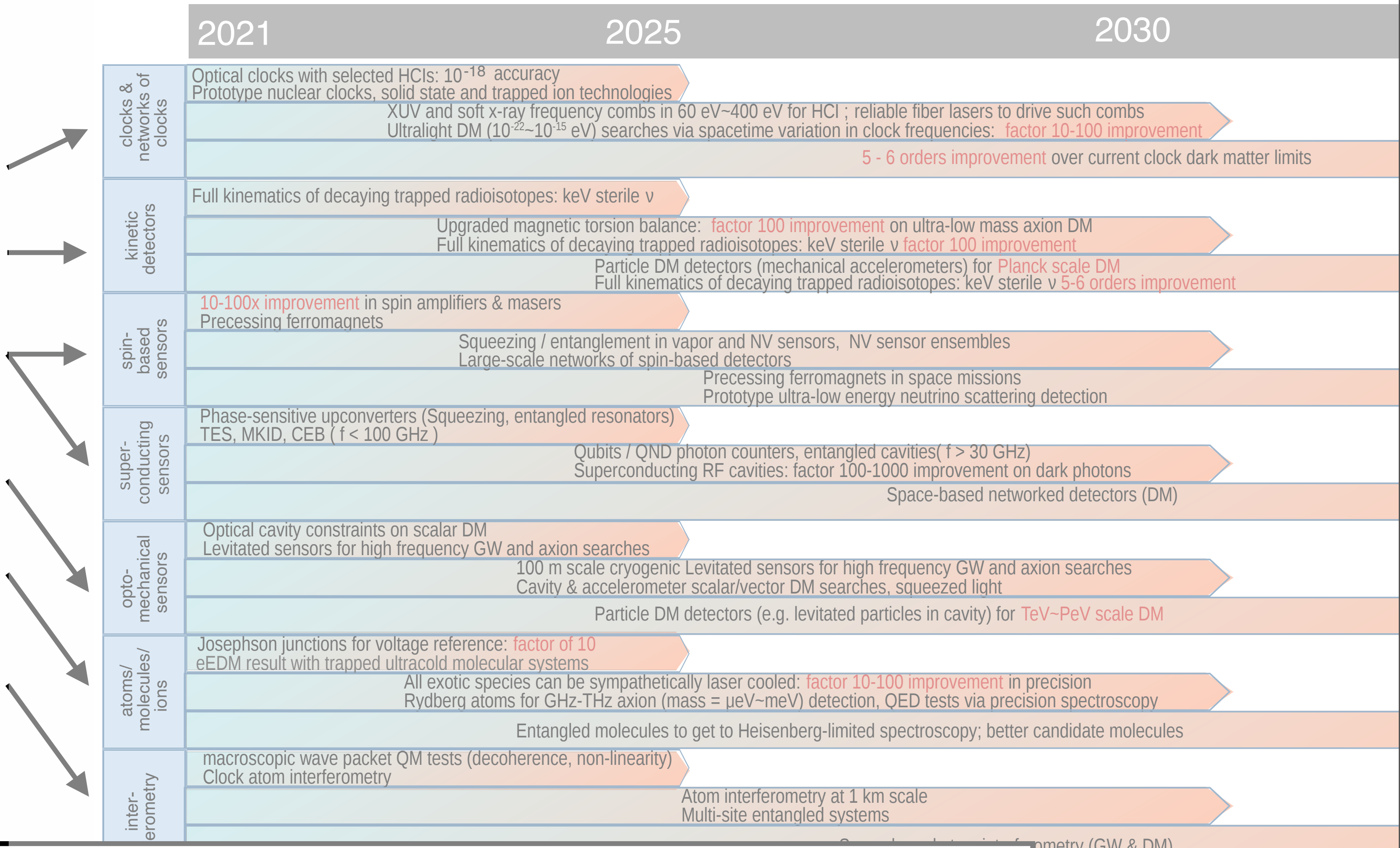

2021 2025 2030

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Multi-site entangled systems

ometry (GW & DM)

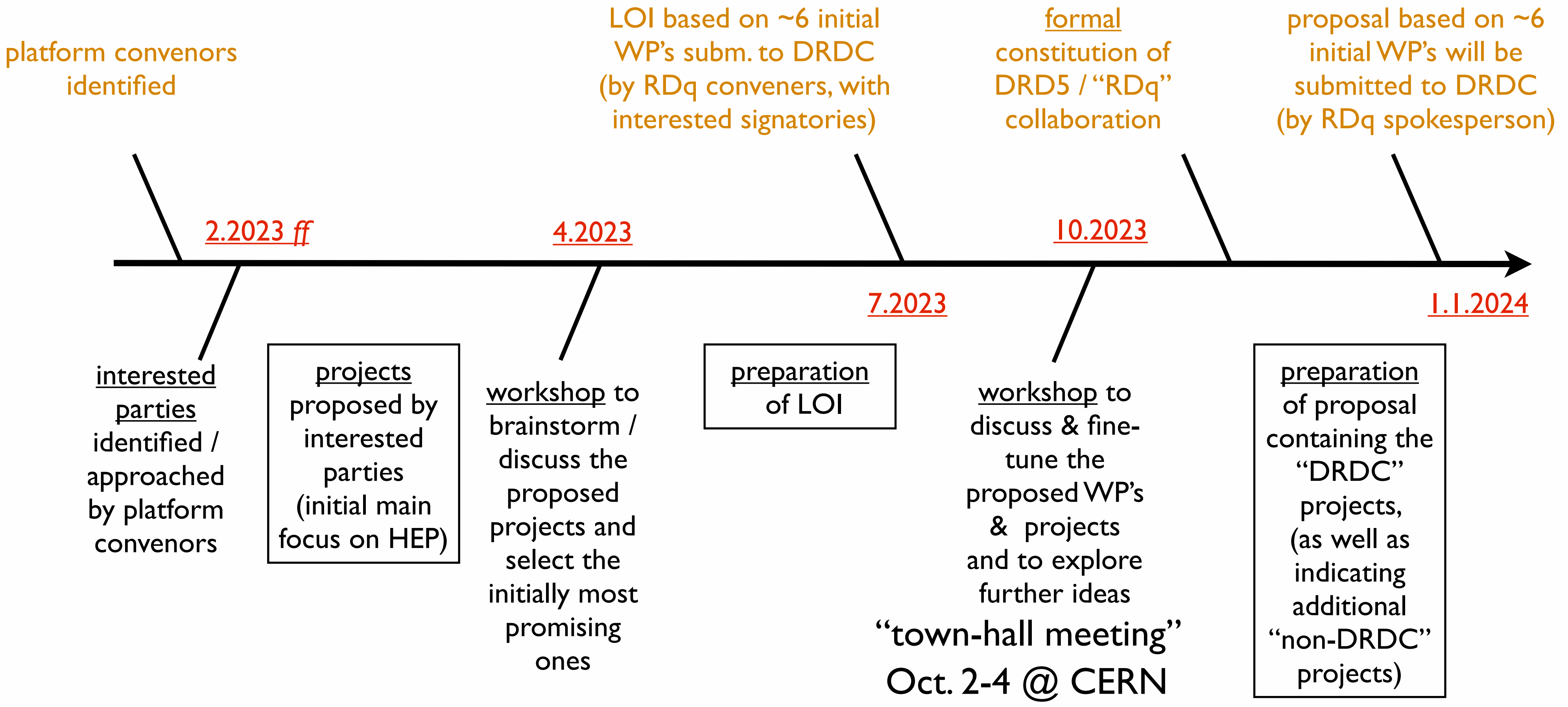
also for HEP!

next step: implementation of ECFA detector R&D pgm

timeline

Two goals:

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



platform convenors identified

2.2023 ff

<u>interested parties</u> identified / approached by platform convenors

<u>projects</u> proposed by interested parties (initial main focus on HEP)

4.2023

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

<u>preparation</u> of LOI

LOI based on ~6 initial WP's subm. to DRDC (by RDq conveners, with interested signatories)

7.2023

10.2023

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

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

<u>formal</u> constitution of DRD5 / "RDq" collaboration

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

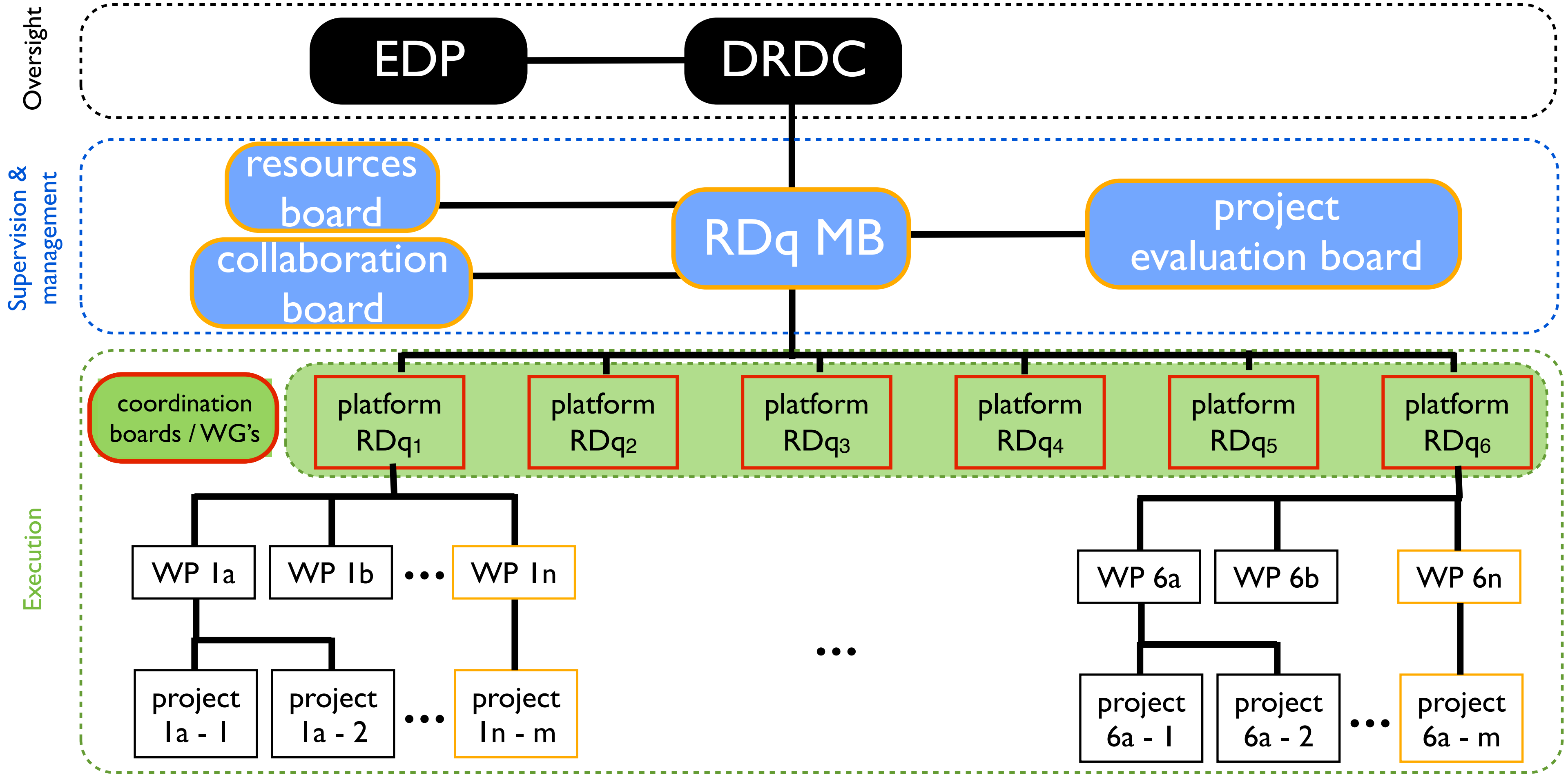
proposal based on ~6 initial WP's will be submitted to DRDC (by RDq spokesperson)

1.1.2024

call for wide participation in RDqi →

WP's & structure

WP1	Network, signal & clock distribution (clock network; std. 'portable' clocks)
WP2	Exotic systems in traps & beams (HCI's, Rydberg systems & molecules; beam-beaker-beam)
WP3	Cryogenic systems (4K electronics; TES/KID's/...; integration challenges)
WP4	Theory (bound state calculations; Heisenberg limit; parameter space comparators)
WP5	Scaling up to macroscopic ensembles (spins; nano-structured materials; ...)
WP6	Capability driven design (cross-disciplinary exchanges; test infrastructure; education)



Oversight

EDP

DRDC

Supervision & management

resources board

collaboration board

RDq MB

project evaluation 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

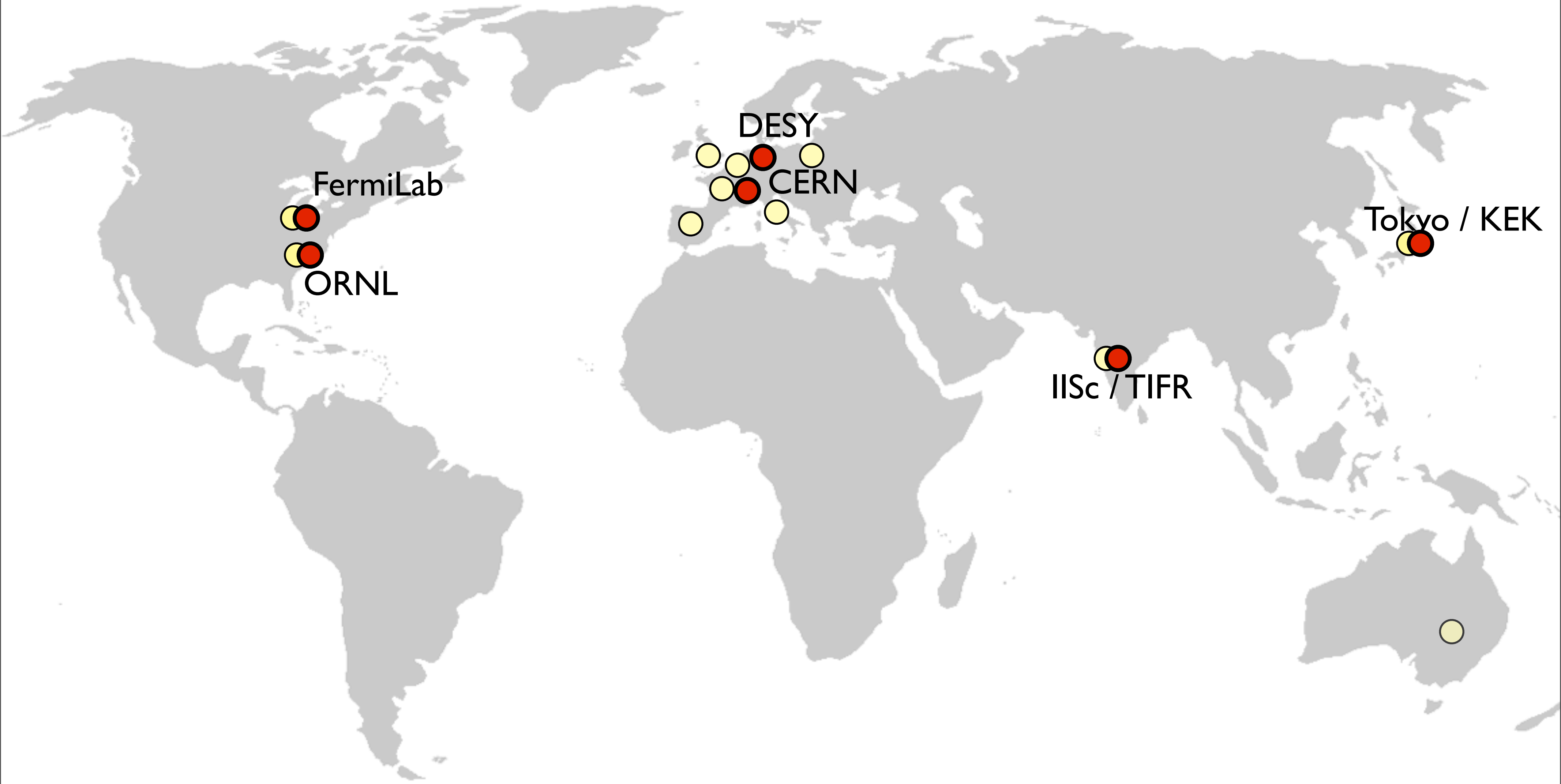
project 6a - 2

• • •

project 6a - m

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

possible platform hosting sites



● possible DRD5 hosting platforms

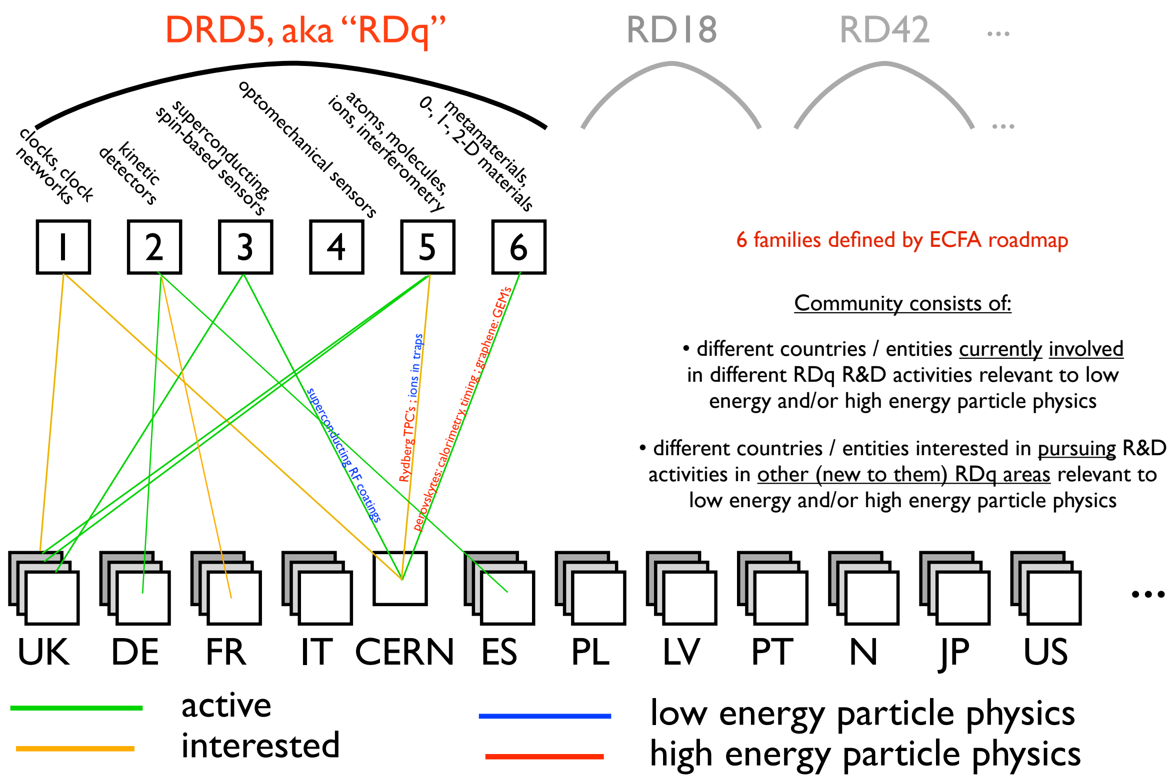
○ HEP-related Quantum initiatives

thank you!

next step: implementation of ECFA-wide R&D pgm

define structure of implementation of TF5:

- formal collaboration ("DRD5", a.k.a. "RDq")
- consists of 6 families of quantum technologies, each with many sub-activities and sub-collaborations

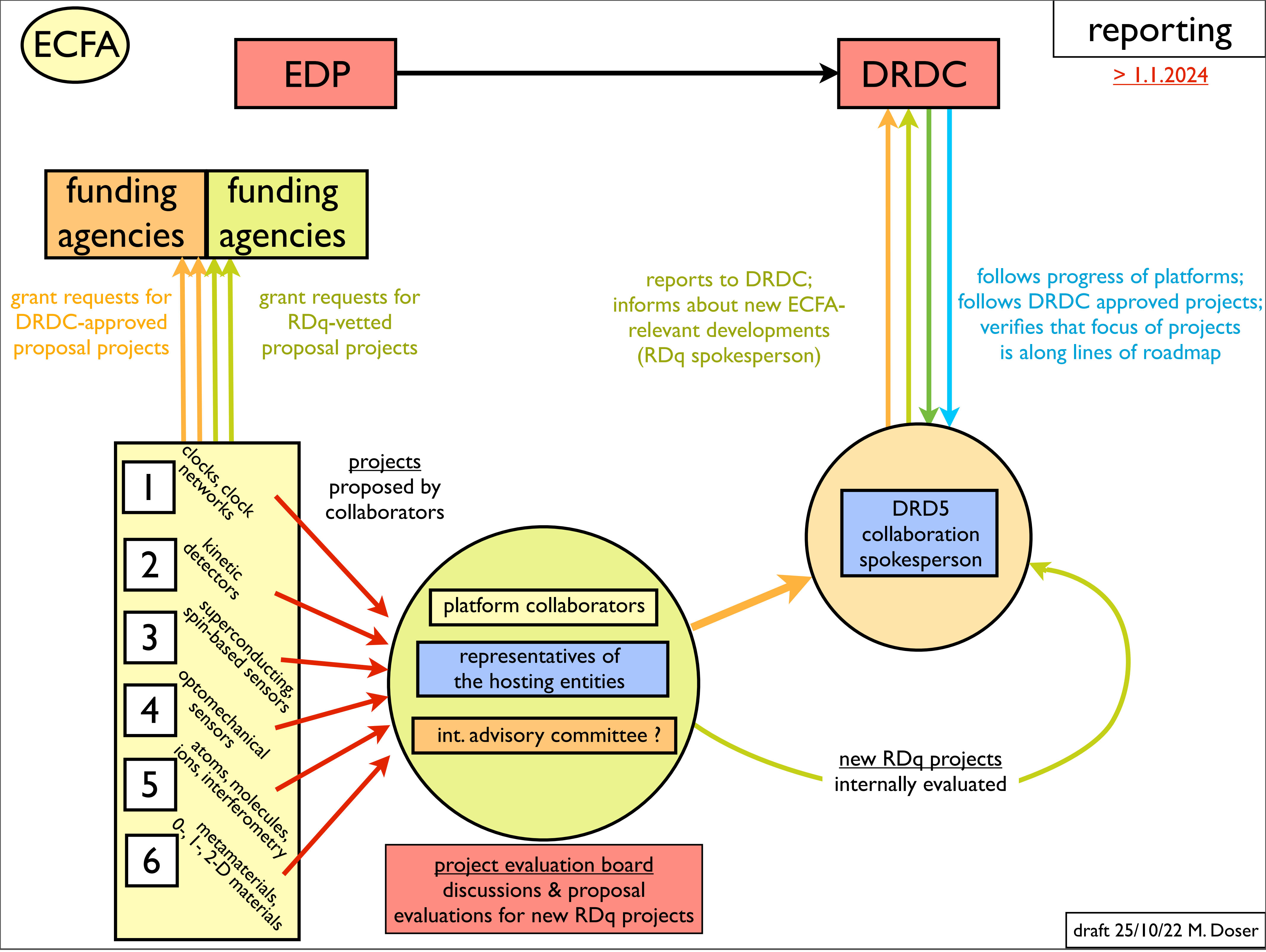


6 families defined by ECFA roadmap

Community consists of:

- different countries / entities currently involved in different RDq R&D activities relevant to low energy and/or high energy particle physics
- different countries / entities interested in pursuing R&D activities in other (new to them) RDq areas relevant to low energy and/or high energy particle physics

- spread load by hosting families in several platforms / institutions



ECFA

EDP

DRDC

reporting

> 1.1.2024

funding agencies

funding agencies

grant requests for DRDC-approved proposal projects

grant requests for RDq-vetted proposal projects

reports to DRDC; informs about new ECFA-relevant developments (RDq spokesperson)

follows progress of platforms; follows DRDC approved projects; verifies that focus of projects is along lines of roadmap

1 clocks, clock networks

2 kinetic detectors

3 superconducting, spin-based sensors

4 optomechanical sensors

5 atoms, molecules, ions, interferometry

6 metamaterials, 0-, 1-, 2-D materials

<u>projects</u> proposed by collaborators

platform collaborators

representatives of the hosting entities

int. advisory committee ?

DRD5 collaboration spokesperson

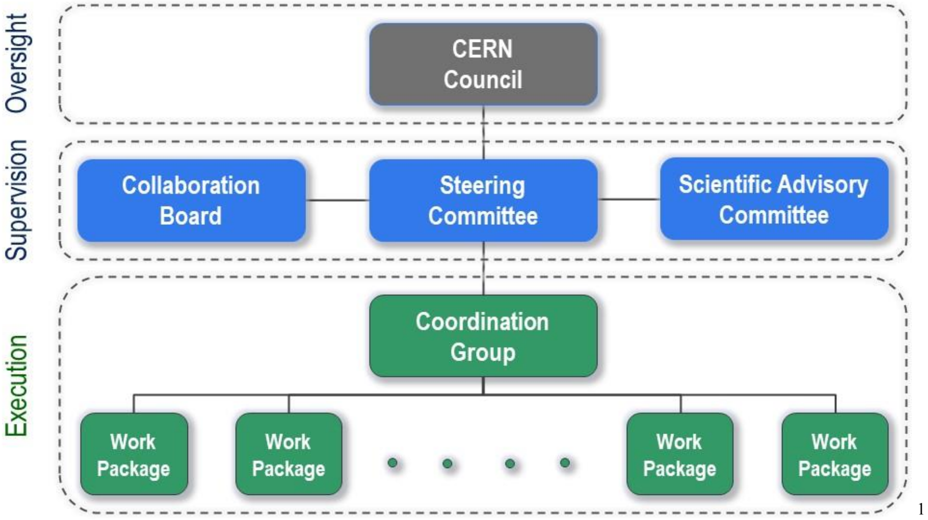
<u>new RDq projects</u> internally evaluated

<u>project evaluation board</u>
discussions & proposal evaluations for new RDq projects

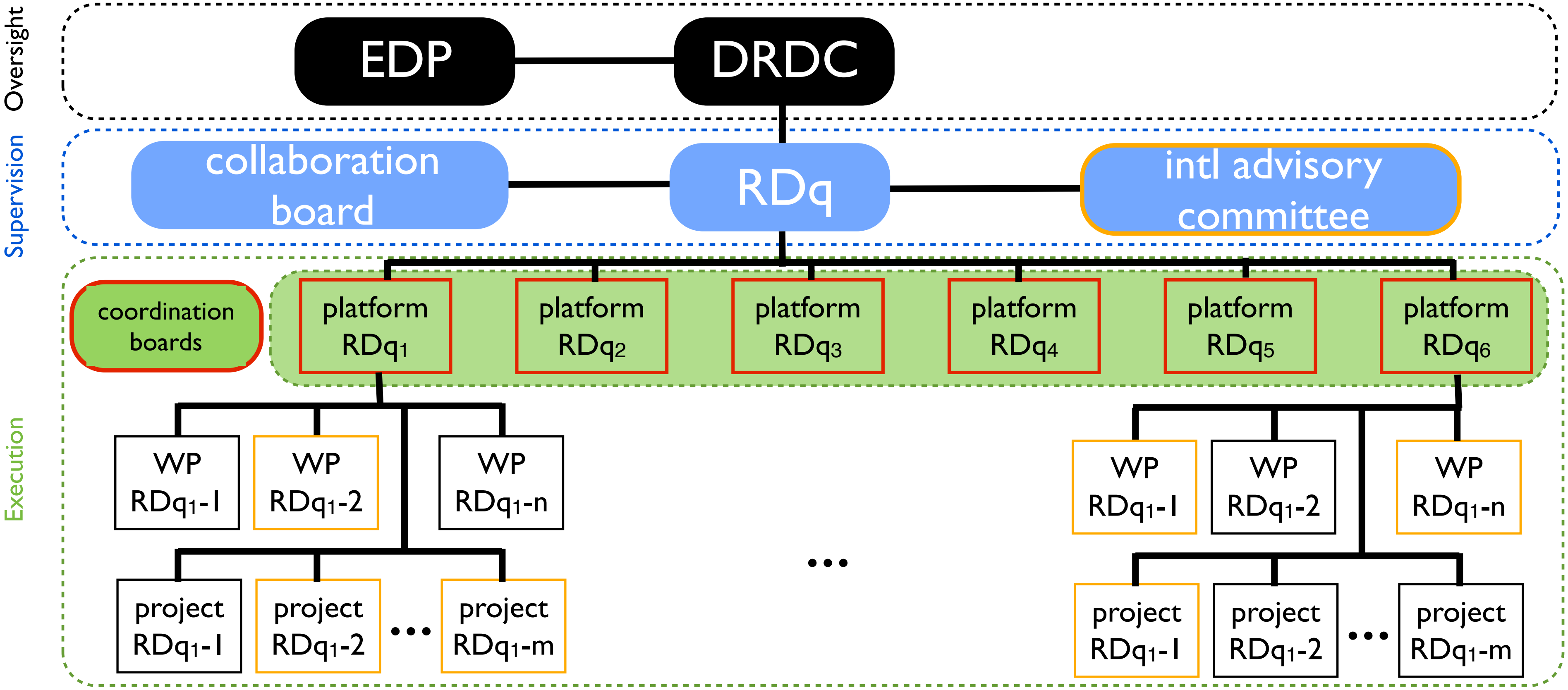
draft 25/10/22 M. Doser

structure of RDq

example from FCC



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



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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, superconductin 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)