Quantum Particle Detectors

(focus on applying quantum sensors to HEP,
with *some* mention of low energy particle physics)

M. Doser, CERN

Clarification of terms

Some words on the landscape

Quantum sensors for low energy particle physics

Quantum sensors for high energy particle physics

(quantum sensor-based) 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 / 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;

→ focus on high energy particle physics ("*manipulate*")

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

bottom line: quantum sensors measure the result of *a single* individual interaction, but bulk quantum systems might also allow improved *multiple interaction* measurements

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

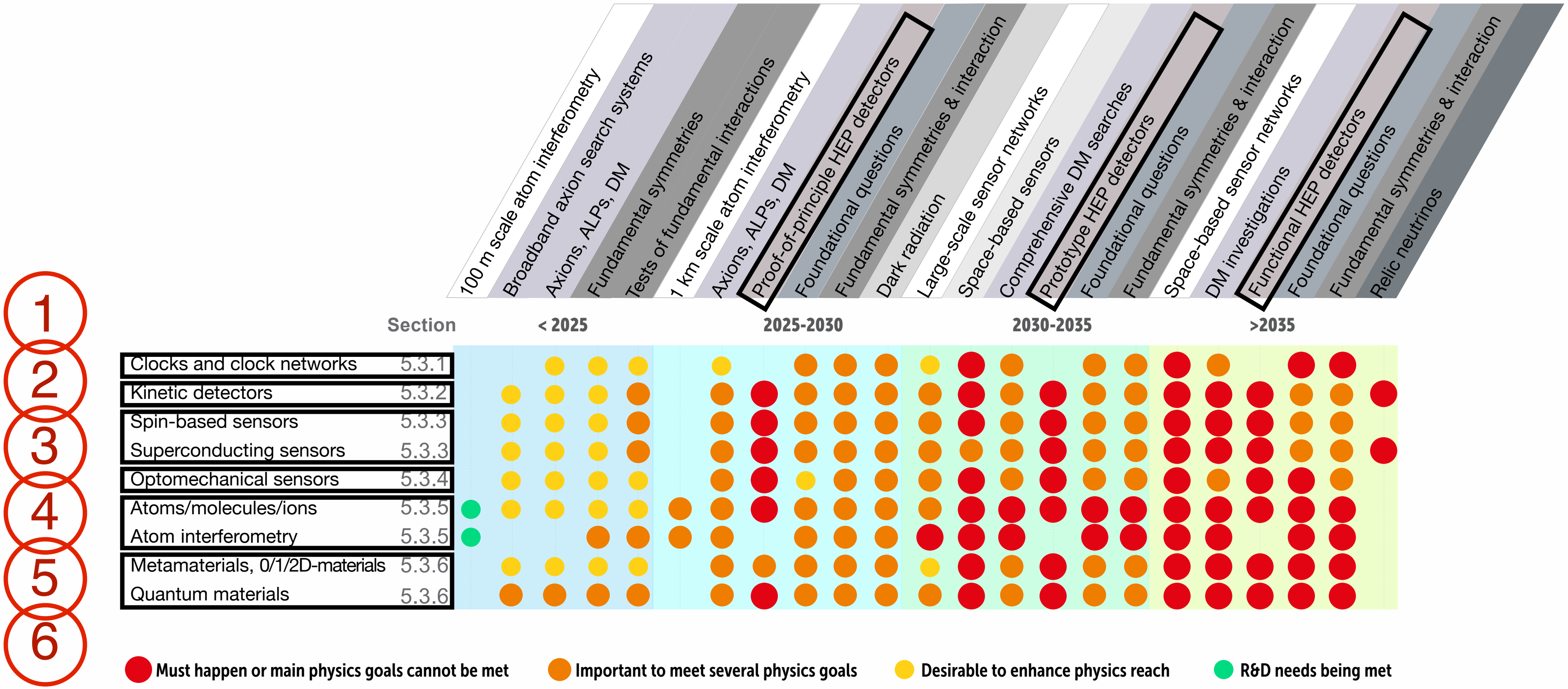
https://indico.cern.ch/event/999818/

quantum sensing & particle physics

RECFA Detector R&D roadmap 2021

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

Chapter 5: Quantum and Emerging Technologies Detectors



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 quantum initiative

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

CERN | QUANTUM TECHNOLOGY INITIATIVE

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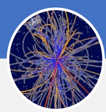


- Assess the **areas of potential quantum advantage** in HEP applications (QML, classification, anomaly detection, tracking)
- Develop **common libraries of algorithms, methods, tools**; benchmark as technology evolves
- Collaborate to the development of shared, **hybrid classic-quantum infrastructures**

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

- 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

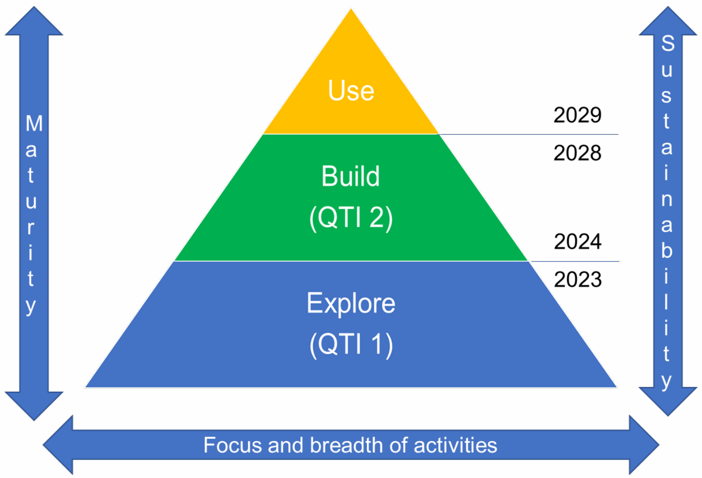
currently: 3 PhD's

- **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

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 characterization for axion and Gravitational Wave searches; development and characterization 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)

approved! (1.2024-12.2028)

CERN | QUANTUM TECHNOLOGY INITIATIVE

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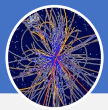
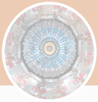


- Objective 2.1a: Exotic atoms as qubits and Dark Matter sensors (Rydberg states characterisation, spectroscopy; atom interferometry; entangled Rydberg states as quantum demonstrators for qubits)
- Objective 2.2a: RF cavities and coating for axion searches; designing, building and operating a tuneable 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

@ 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)

Highly active experimental community with quantum sensors world-wide
→ rapid investigation of new phase space w/ new types of quantum sensors

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

@ CERN

→ particles, atoms, ions, nuclei: tests of QED, symmetries

→ (cryogenic) RF cavities: axion searches

→ atom interferometers: DM searches, grav. waves 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 *

Atoms, molecules, ions

5.3.5 *

Rydberg TPC's

Spin-based sensors

5.3.3 *

helicity detectors

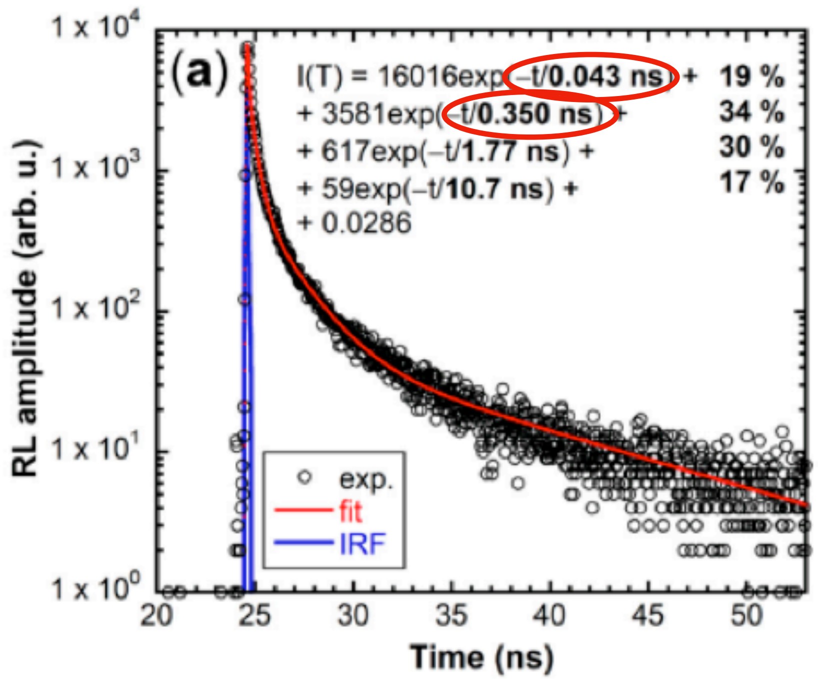
* https://cds.cern.ch/record/2784893

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

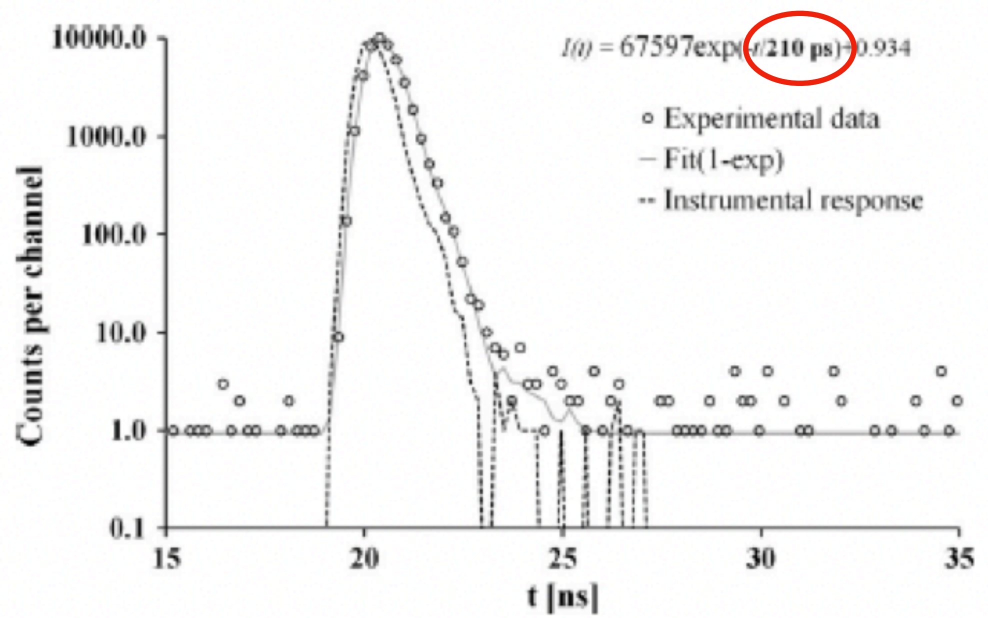


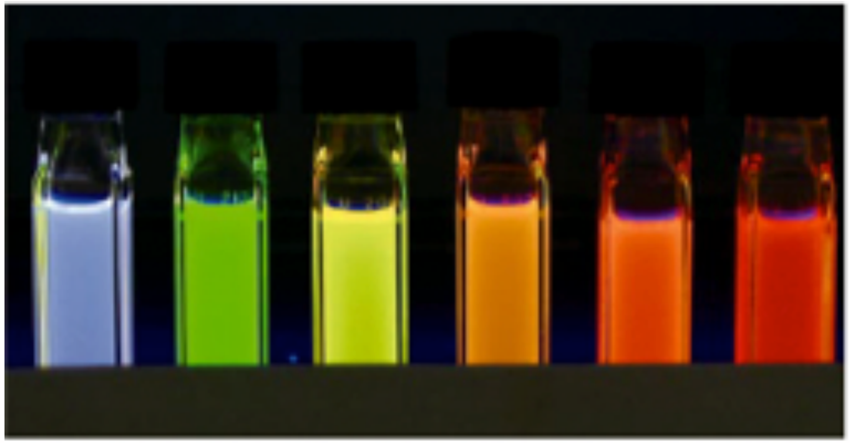
Fig. 9. Photoluminescence decay of ZnO:Ga sample at room temperature. Excitation nanoLED 339 nm, emission wavelength set at 390 nm. Decay curve is approximated by the convolution of instrumental response (also in figure) and single exponential function $I(t)$ provided in the figure.

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

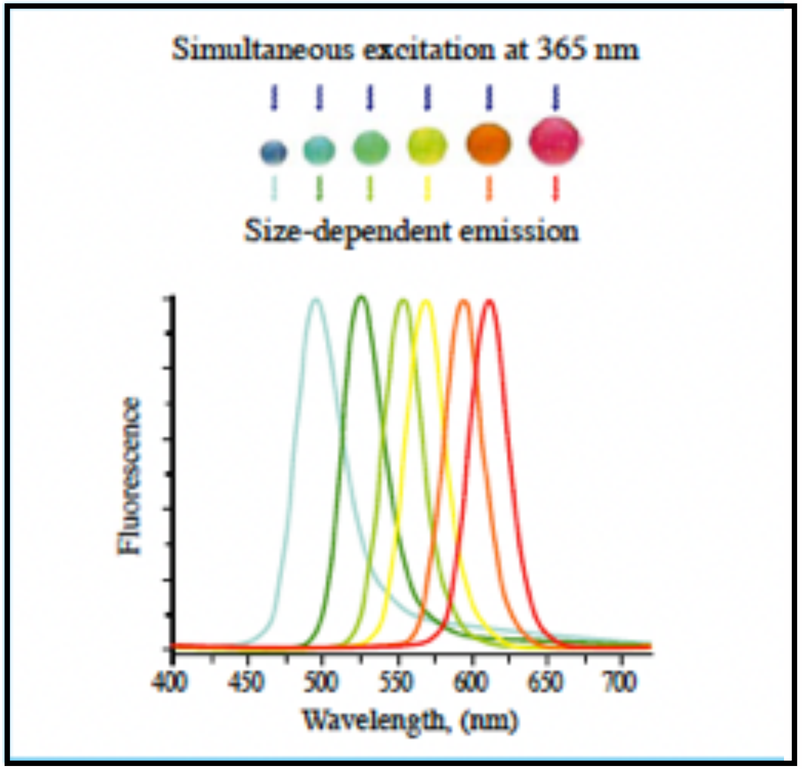
Concerns: integrated light yield (need many photons to benefit from rapid rise time)

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

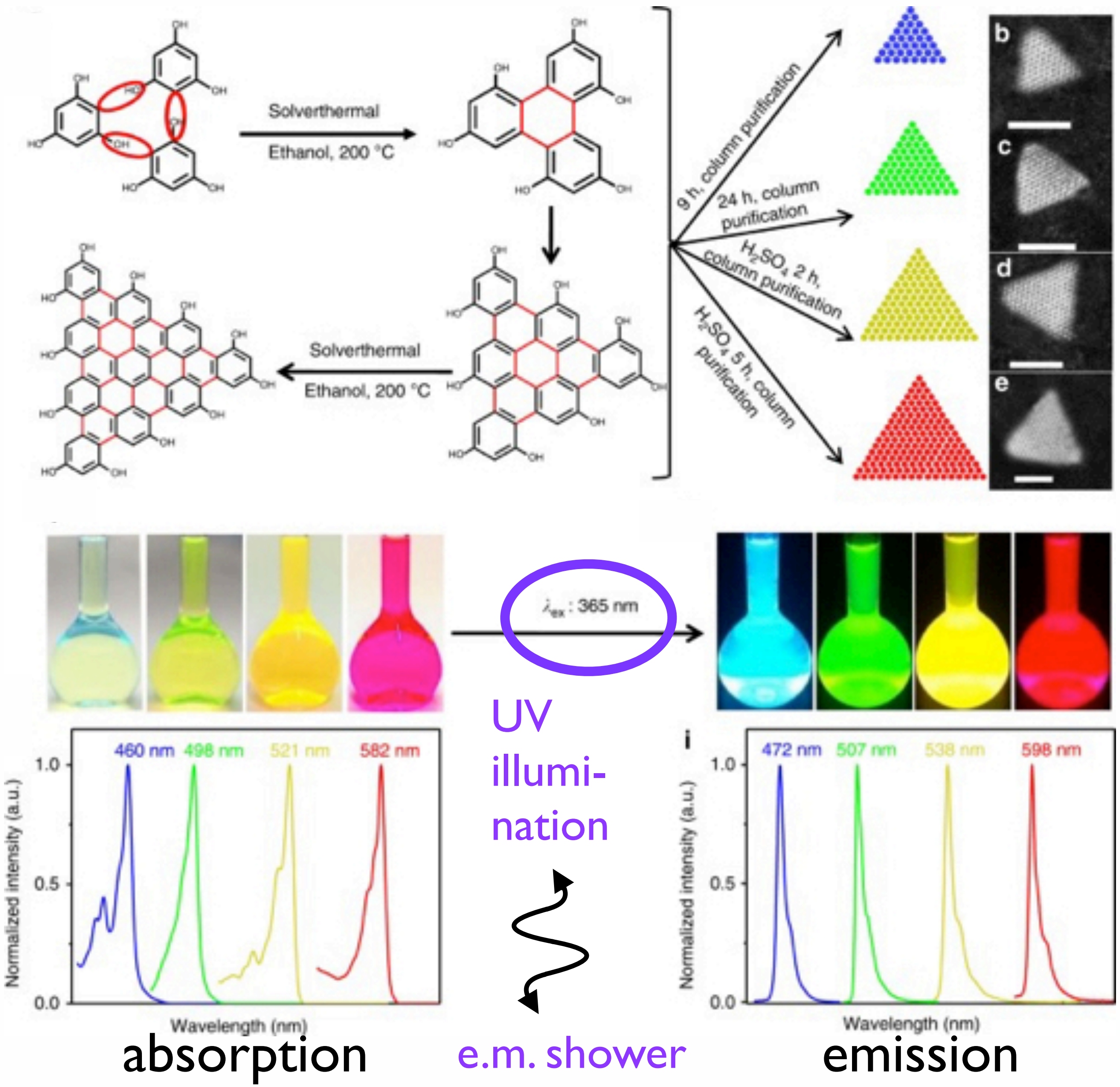


chromatic tunability → optimize for quantum efficiency of PD (fast, optimizable WLS)

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



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

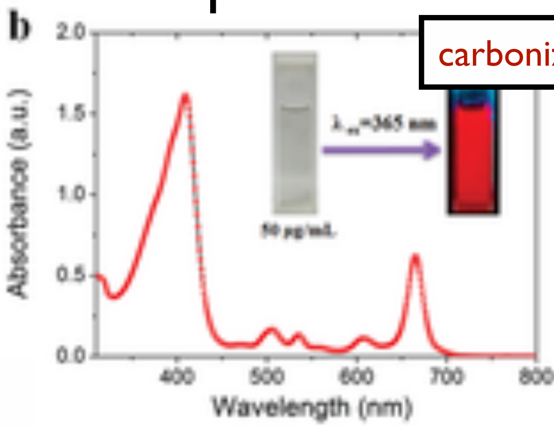
select appropriate nanodots

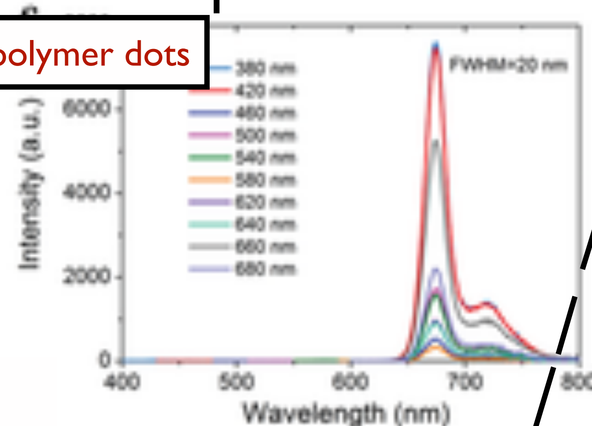
e.g. triangular carbon nanodots

absorption spectrum

emission spectrum

carbonized polymer dots





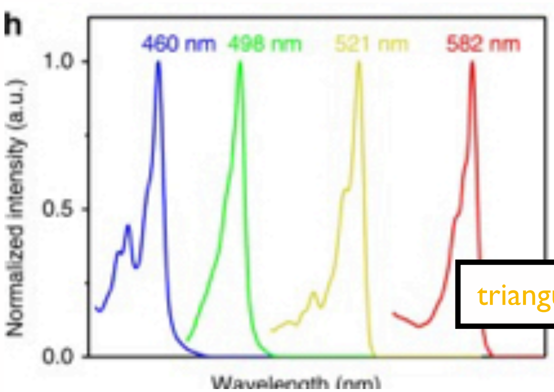
leftmost nanodots:
absorb wavelengths < 650 nm
emit at > 680 nm

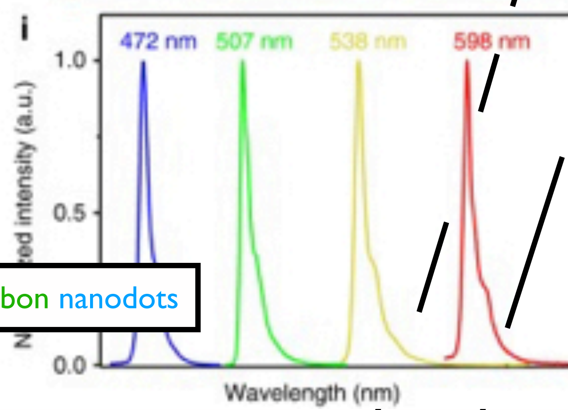
next band:
absorb wavelengths < 590 nm
emit at > 590 nm

…

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

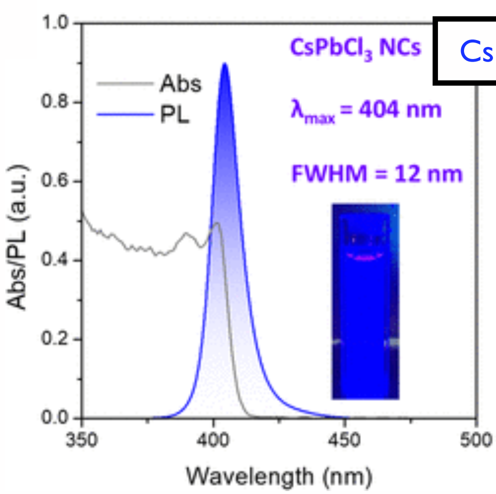
triangular carbon nanodots

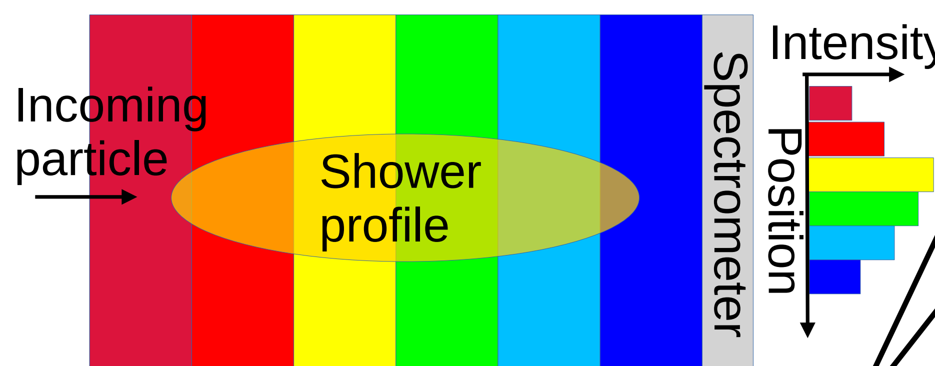




if high-Z substrate transparent in 400-700 nm, then no re-absorption of emitted light

CsPbCl3 nanocrystals





Monochromators + PD?

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

Metalenses?

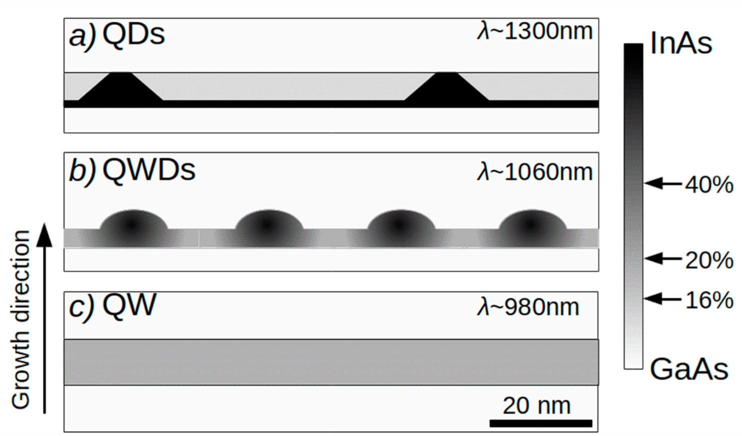
M. Khorasaninejad & F. Capasso, Science 358, 6367 (2017)

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

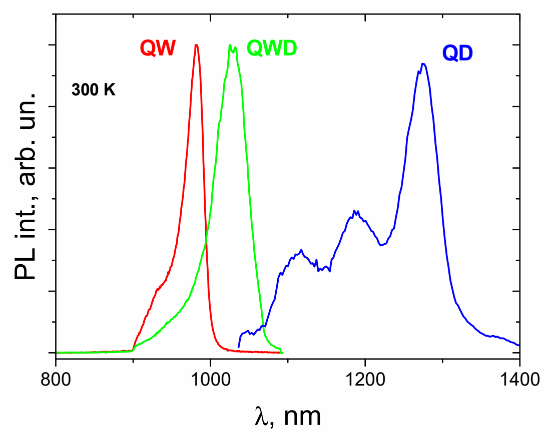
Active scintillators (QWs, QDs, QWDs, QCLs)

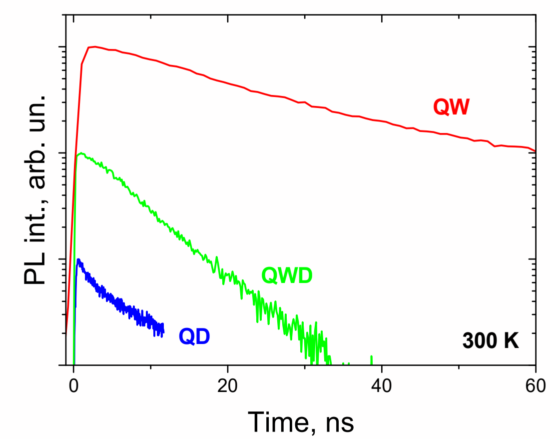
standard scintillating materials are passive
- can not be amplified
- can not be turned on/off
- can not be modified once they are in place

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

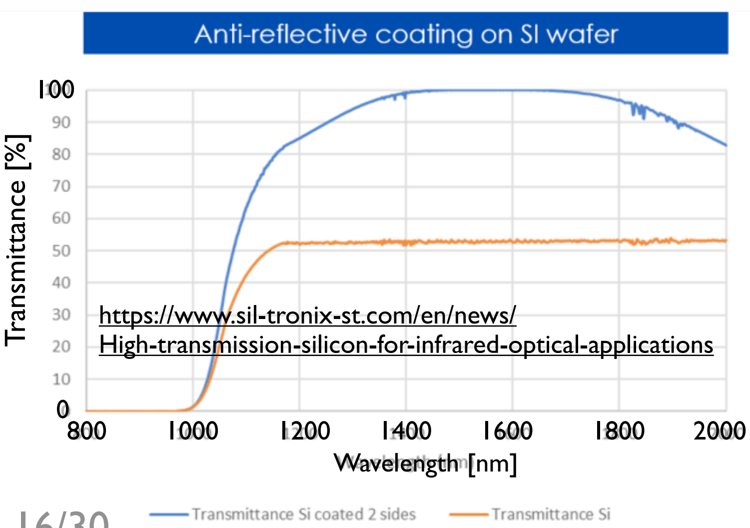


existing QD's, QWD's are elements of optoelectronic devices, typically running at 10 GHz, quite insensitive to temperature





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

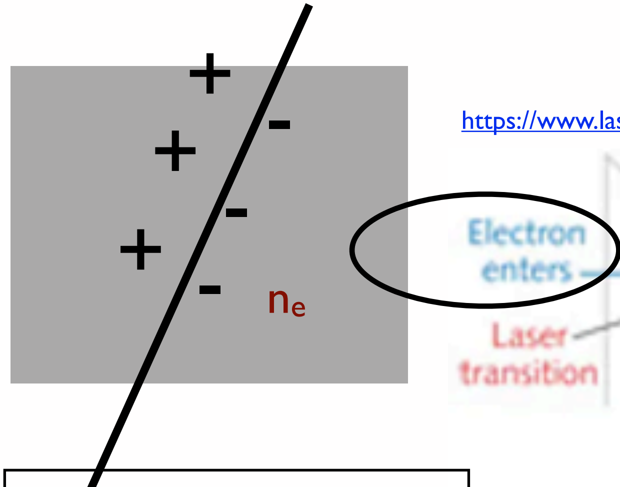


Emission in IR! Silicon is ~transparent at these wavelengths…
Can this IR light be transported *through* a tracker to outside PDs?

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)



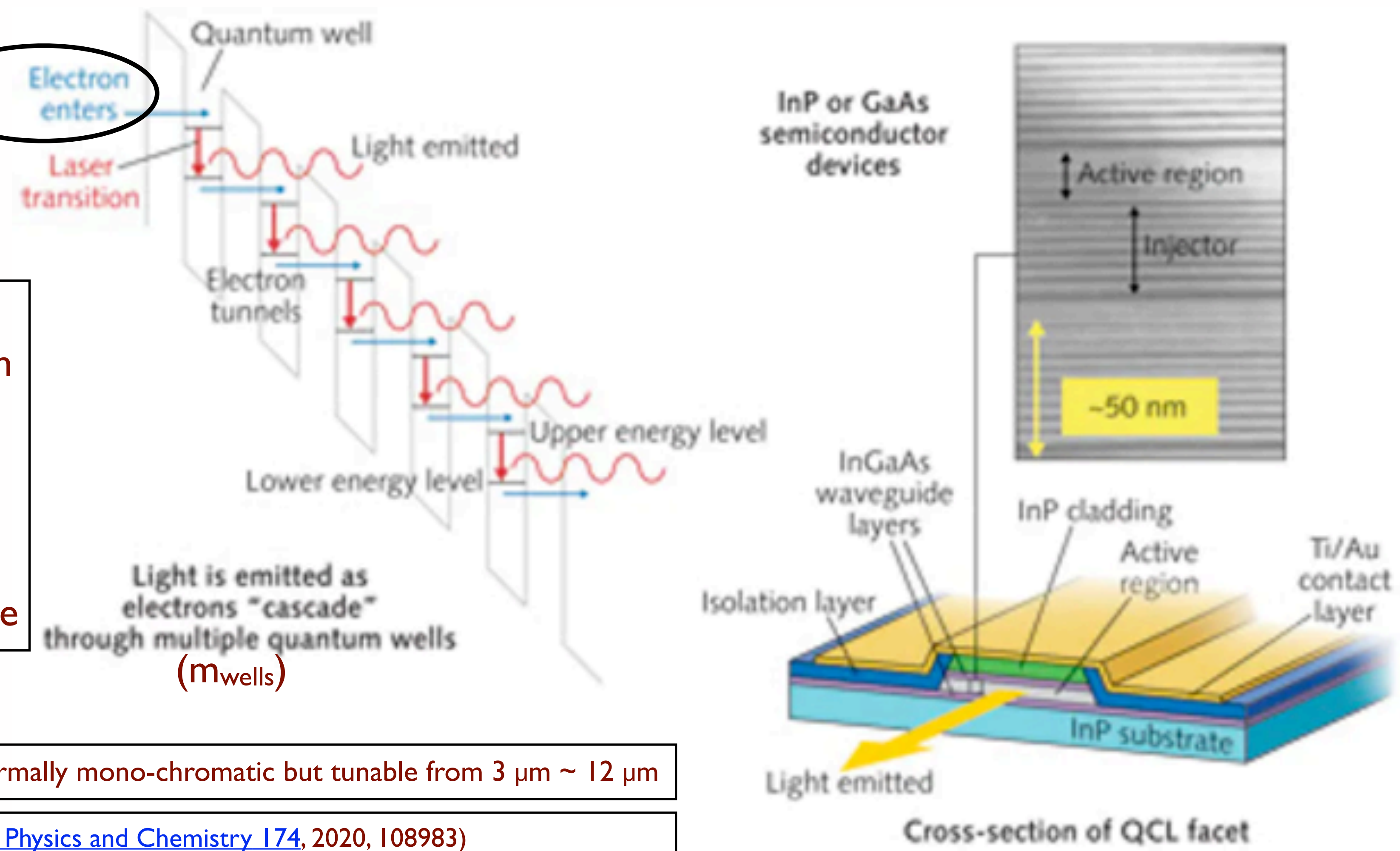
Couple bulk semi-conductor to electron injection layer:

n_γ = m_{wells} x n_e

furthermore:

E_γ is (locally) tunable

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



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

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

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 *

Atoms, molecules, ions

- Rydberg TPC's 5.3.5 *

Spin-based sensors

- helicity detectors 5.3.3 *

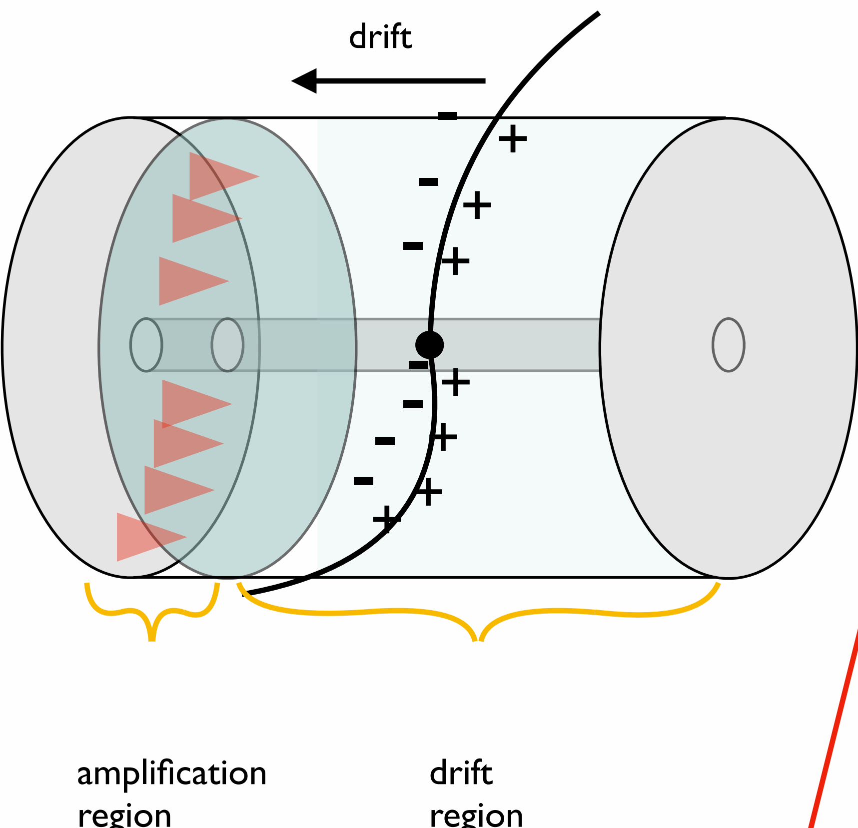
* https://cds.cern.ch/record/2784893

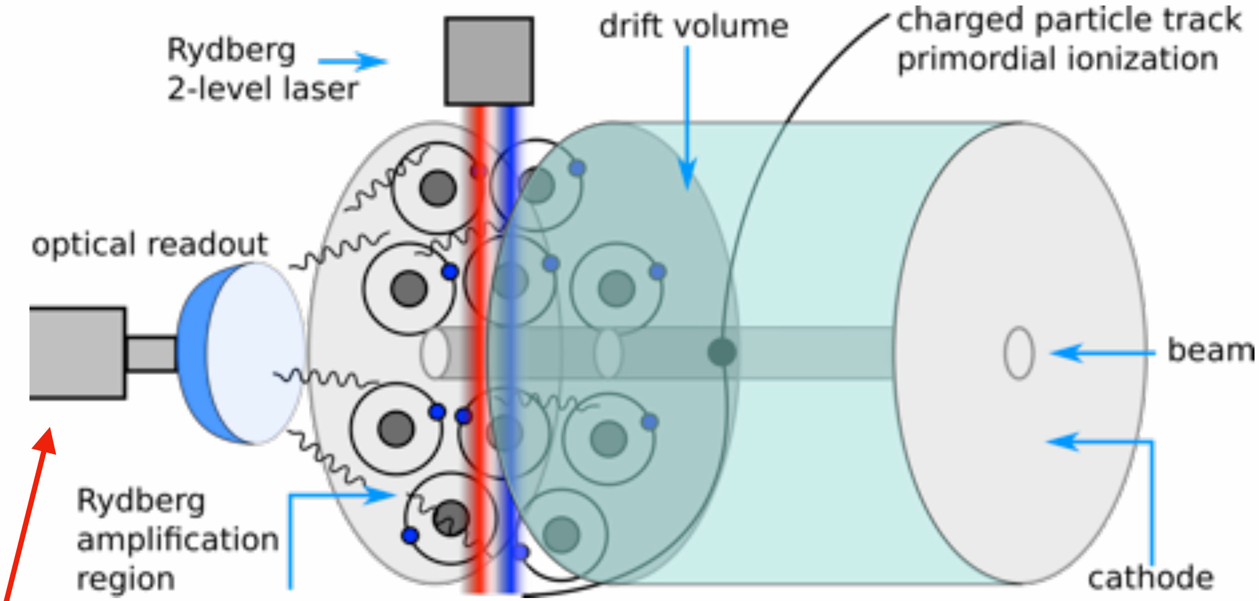
Superconducting sensors

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

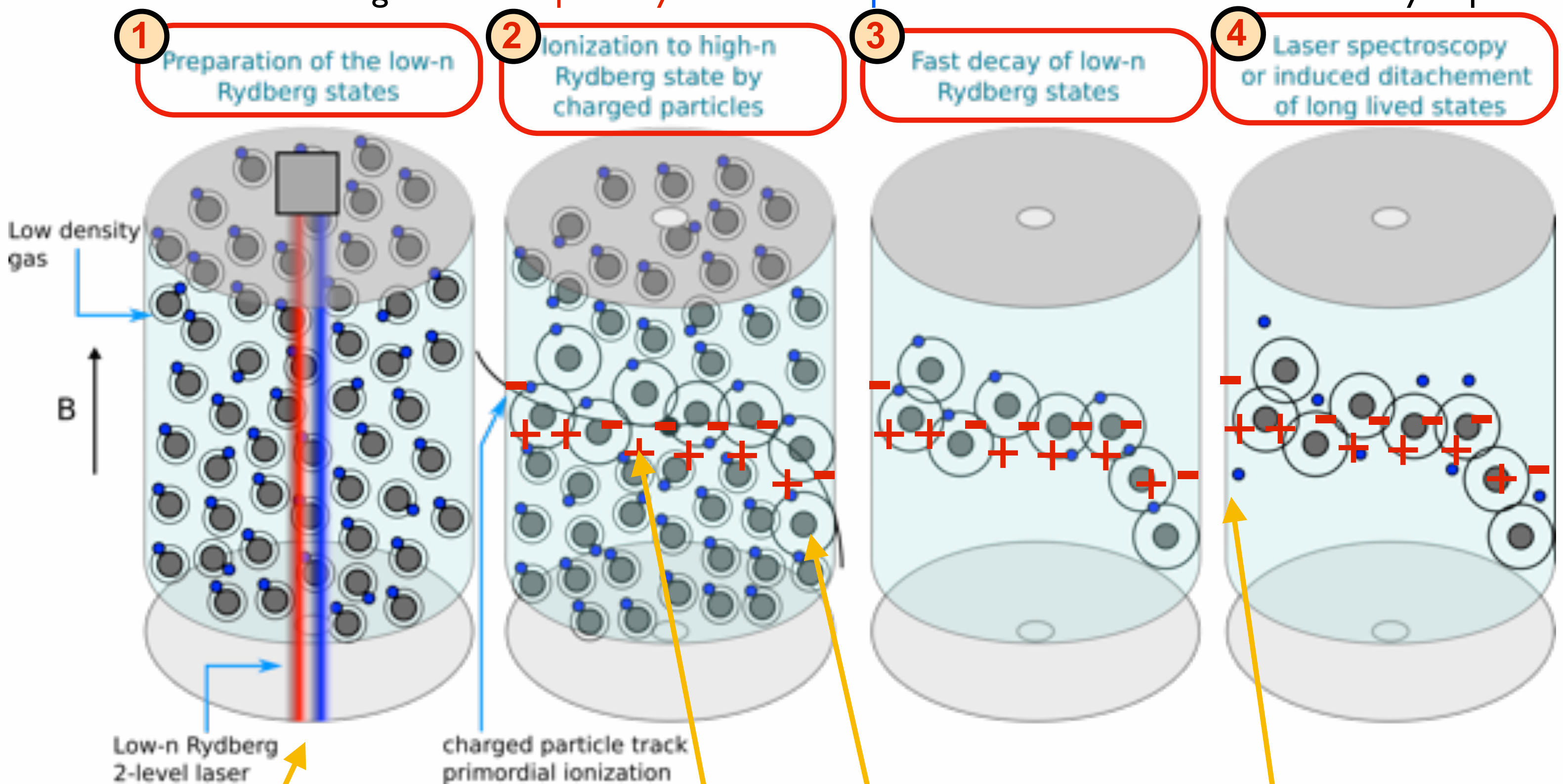
Rydberg atoms can serve to up-convert THz / GHz radiation into the optical regime ⟶ optical R/O of avalanche intensities

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



reduction of ionization and atomic excitation threshold

ionization + excitation;
natural decay of unmodified atoms

photo-ionization of excited atoms

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Superconducting sensors

HEP

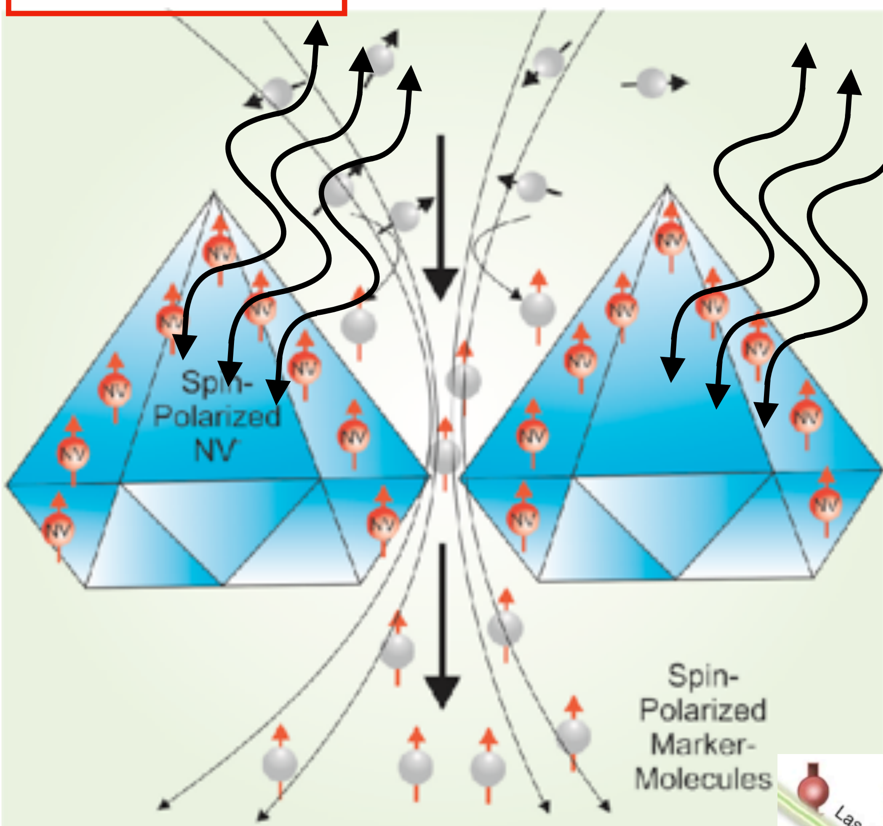
optically polarizable elements: Nitrogen-vacancy diamonds (NVD)

Georgy Kornakov / WUT

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

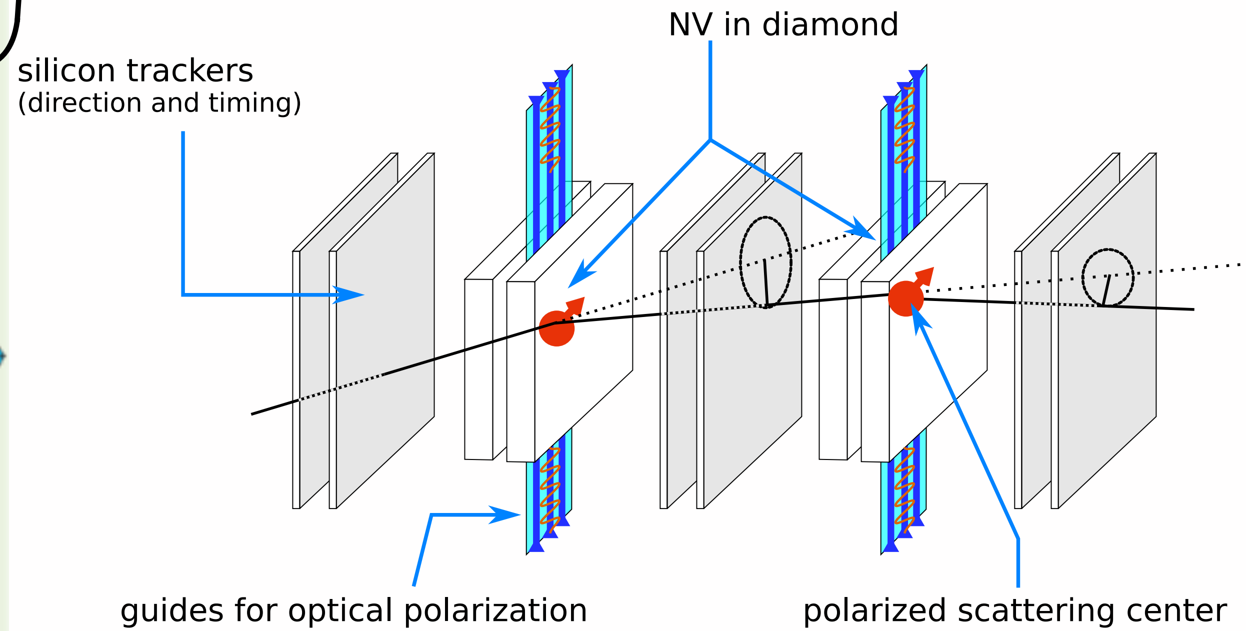
introduce polarized scattering planes to extract track-by-track particle helicity

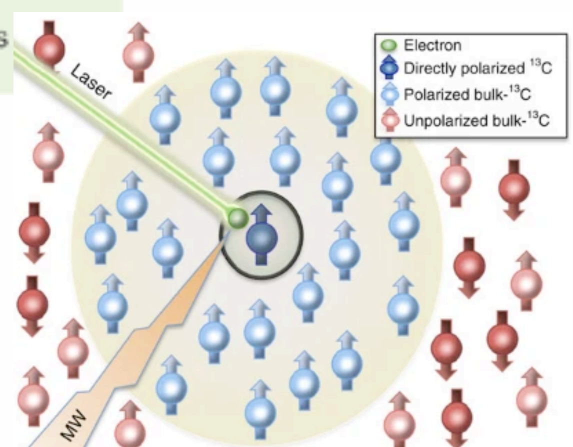
$10^{16} \sim 10^{18}$ / cm^3



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

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





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

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

x 10^2

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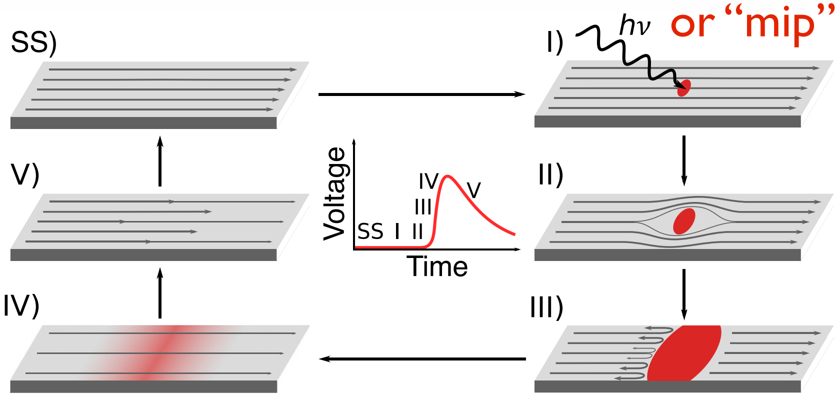
Superconducting sensors

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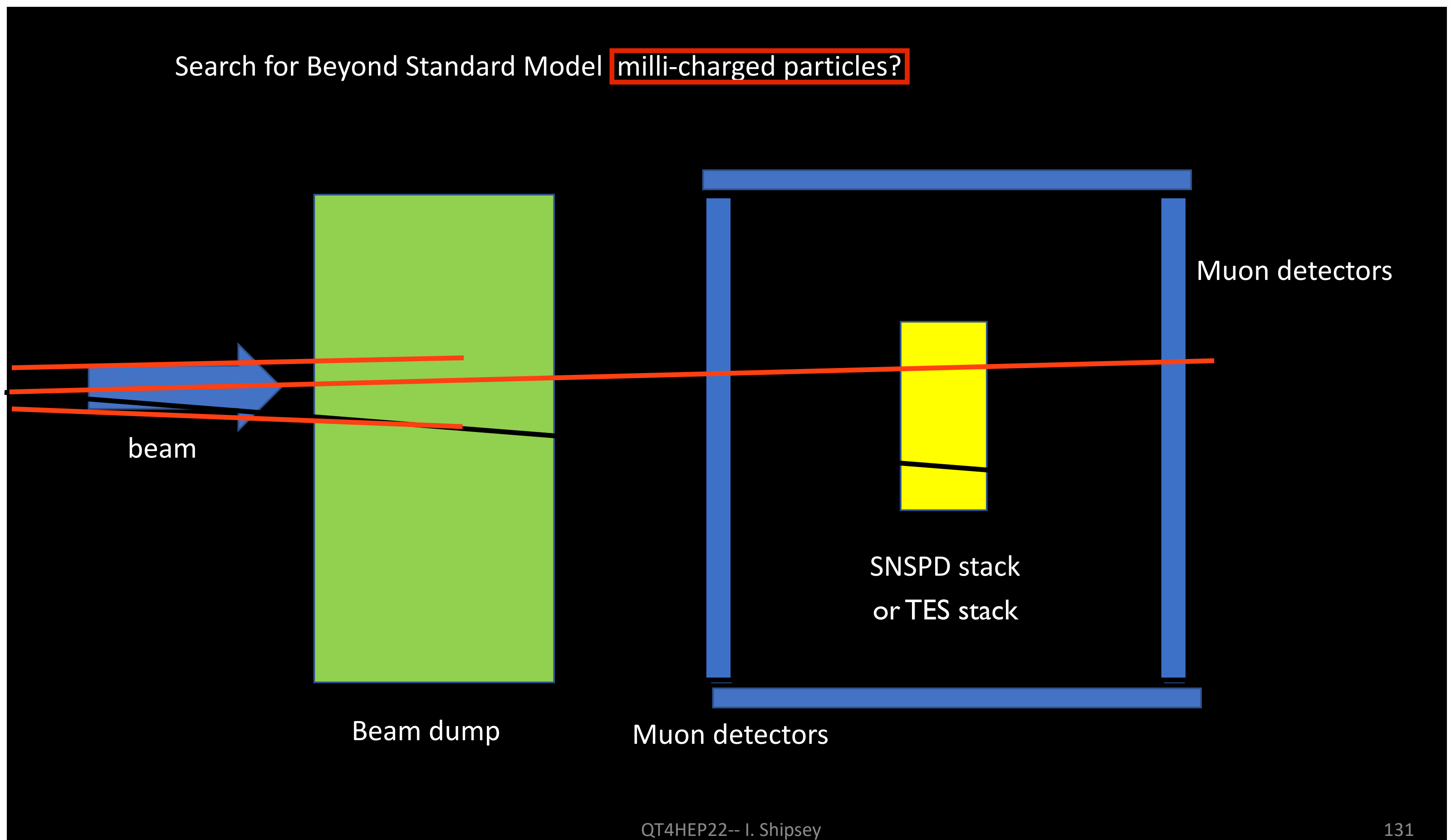
Moving to SC strips conventional lithography → scale up
Development towards SC SSPM



mip: ~20 keV/100 μm

x 10^6 sensitivity

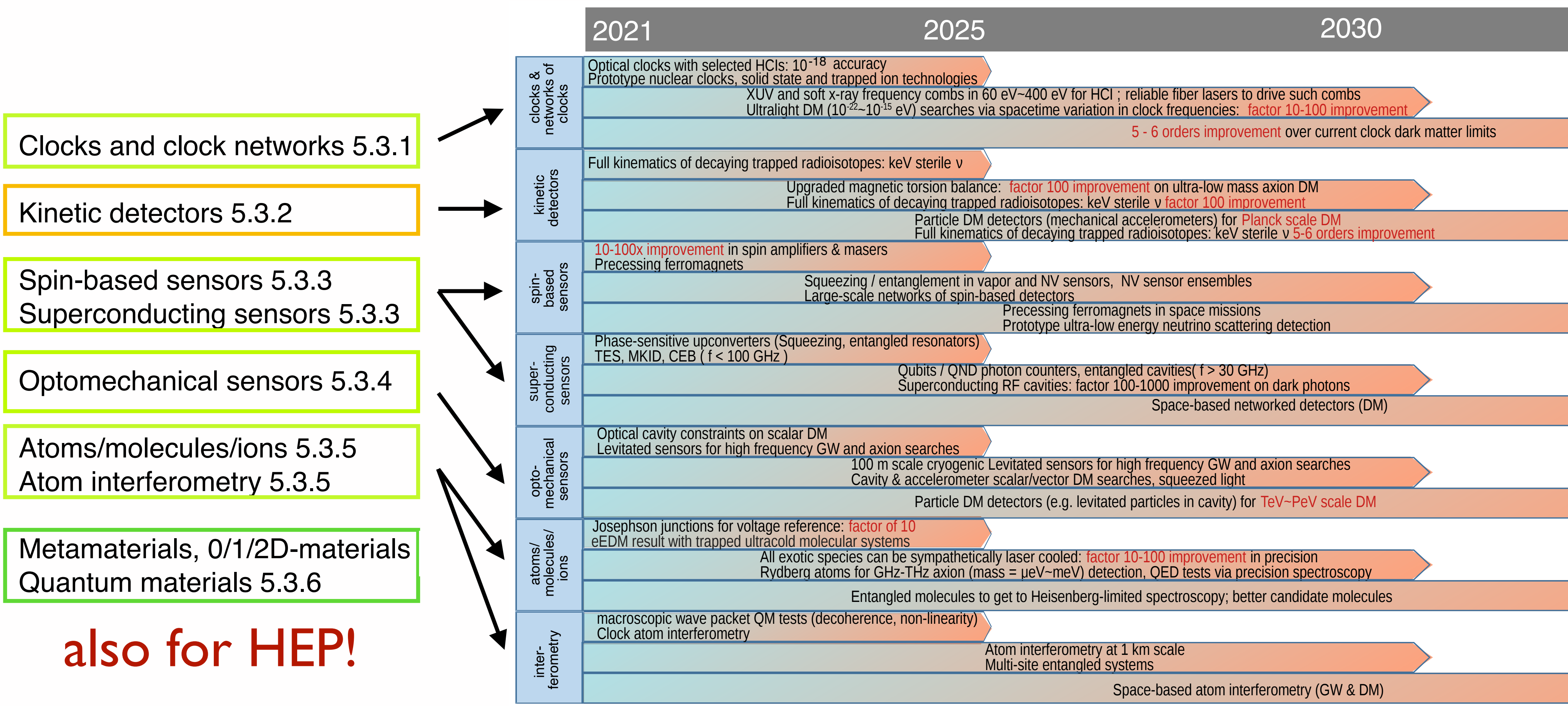
further systems
(also for γ detection):

TES
TWPA
...

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:



also for HEP!

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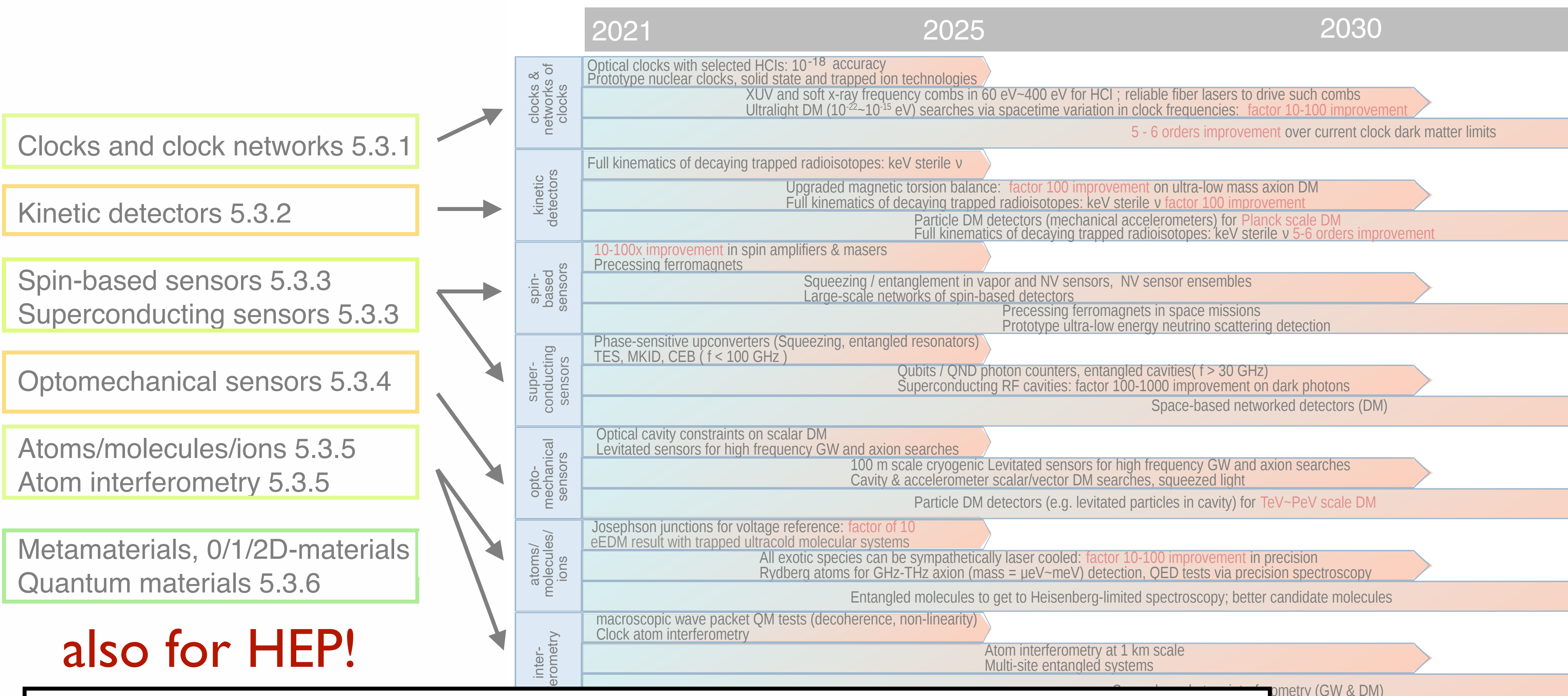


also for HEP!

next step: implementation of ECFA detector R&D pgm

Two goals for end of 2023: the DRD5 / RDq collaboration

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

focus on technical developments that go beyond what a single group can do

platform convenors identified

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

→ WP's

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

preparation of LOI

7.2023

10.2023

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

"town-hall meeting"
Oct. 2-4 @ CERN
https://doser.web.cern.ch

formal constitution of DRD5 / "RDq" collaboration

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

1.1.2024

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

call for wide participation in RDqi

WP's & structure

WP1 — Network, signal & clock distribution (clock network; std. 'portable' clocks)

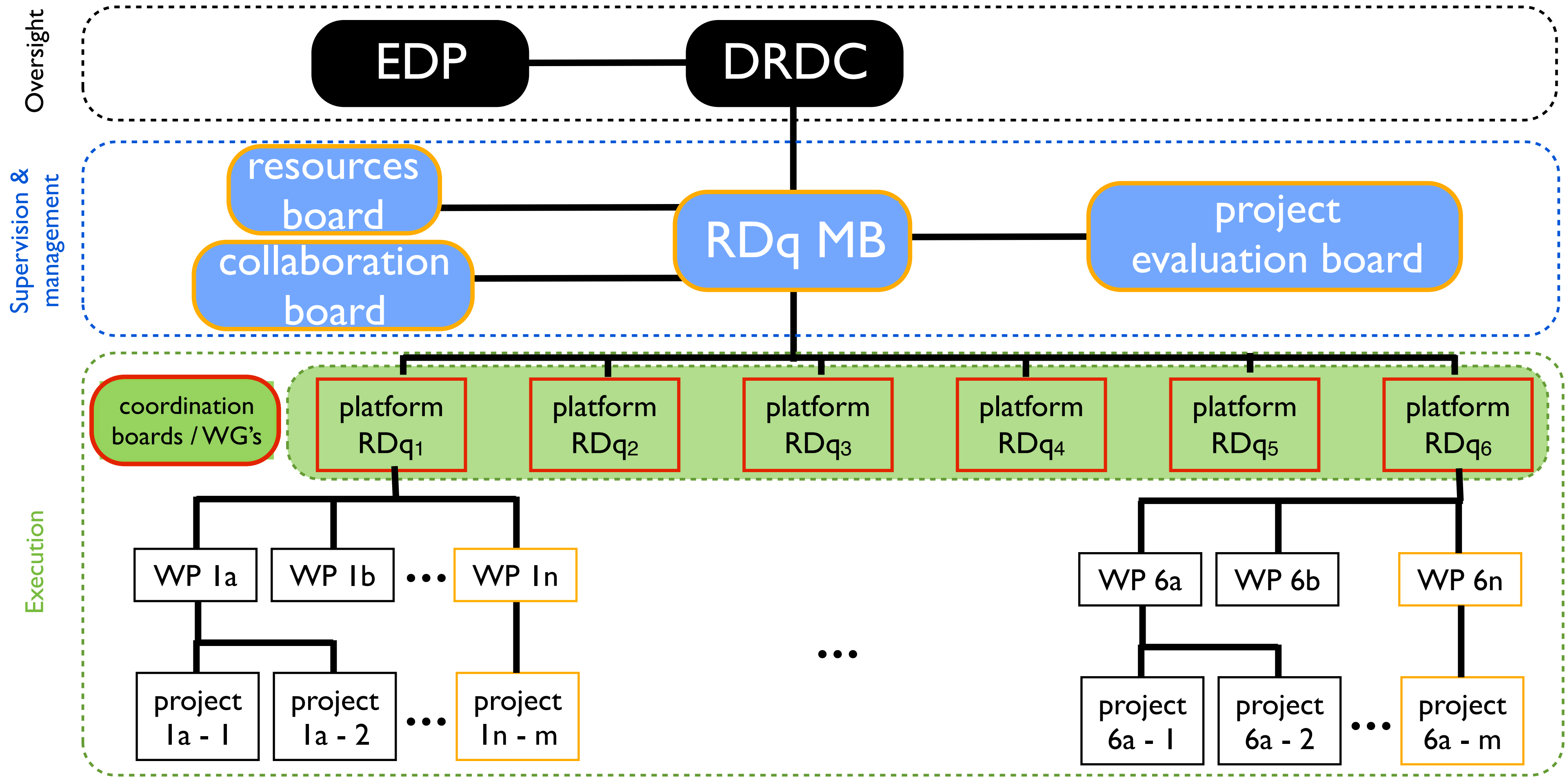
WP2 — Exotic systems in traps & beams (HCI's, Rydberg systems & molecules; beam-beaker-beam)

WP3 — Cryogenic systems (4K electronics; TES/KID's/...; integration challenges)

WP4 — Theory (bound state calculations; Heisenberg limit; parameter space comparators)

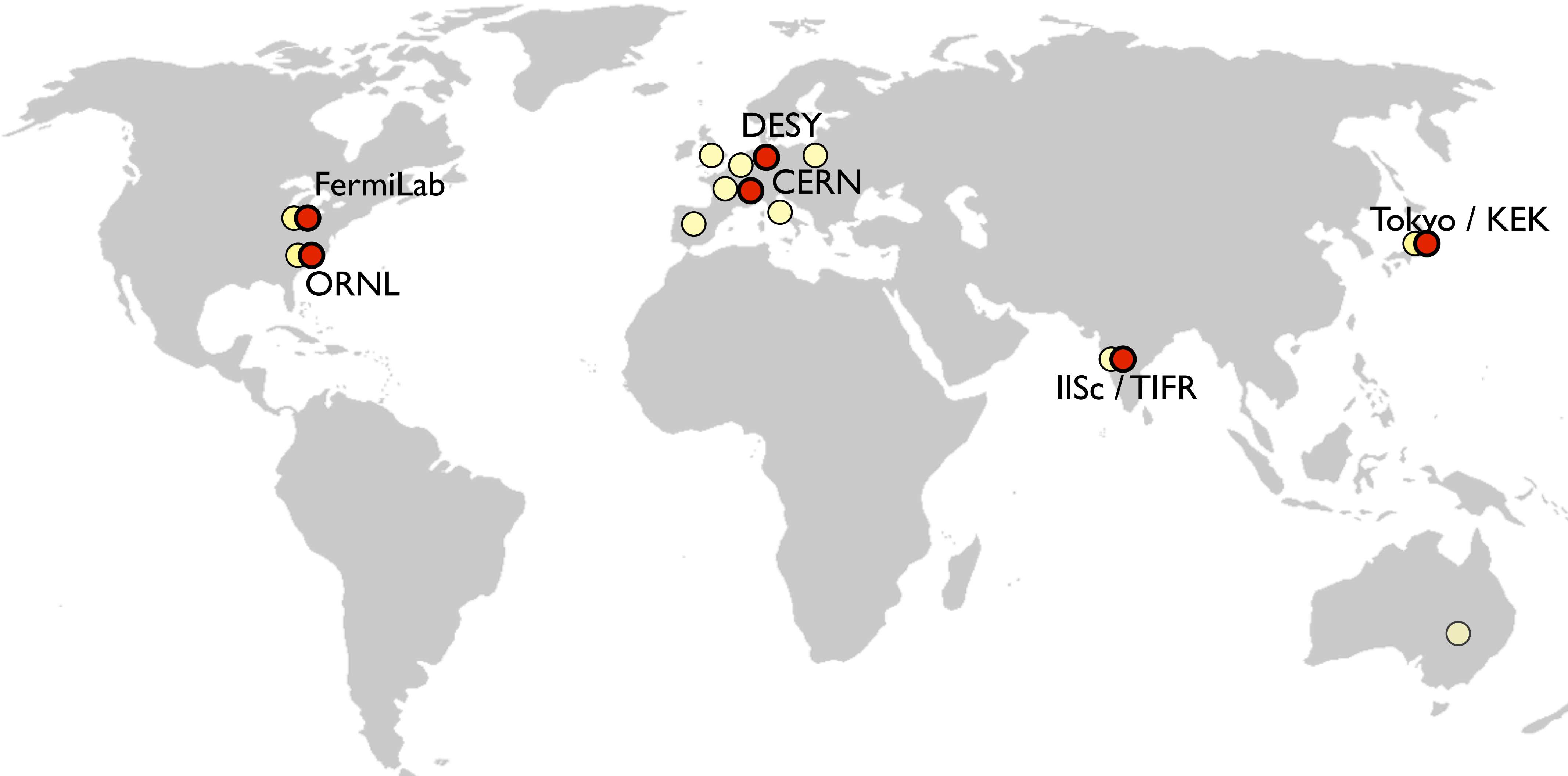
WP5 — Scaling up to macroscopic ensembles (spins; nano-structured materials; ...)

WP6 — Capability driven design (cross-disciplinary exchanges; test infrastructure; education)



(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

Sharing of responsibilities for coordinating the technical work of the WP's



possible DRD5 hosting platforms

HEP-related Quantum initiatives

Two goals for end of 2023: the DRD5 / RDq collaboration

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

focus on technical developments that go beyond what a single group can do

DRD5 / RDq:

platform c
ident

if you are interested / curious / intruigued, please let me know or sign up via http://doser.web.cern.ch

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 → WP's

7.2023 — preparation of LOI

10.2023 — workshop to discuss & fine-tune the proposed WP's & projects and to explore further ideas

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

https://doser.web.cern.ch

1.1.2024 — preparation of proposal containing the "DRDC" projects, (as well as indicating additional "non-DRDC" projects)

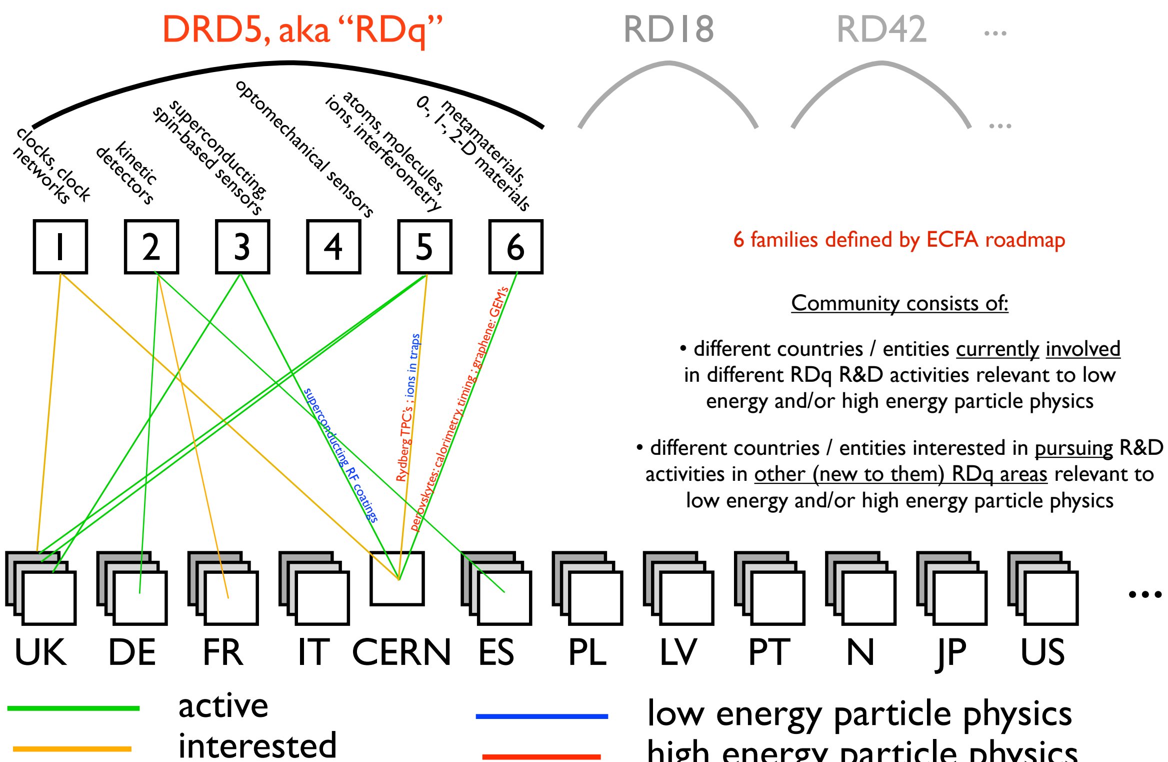
call for wide participation in RDqi

thank you!

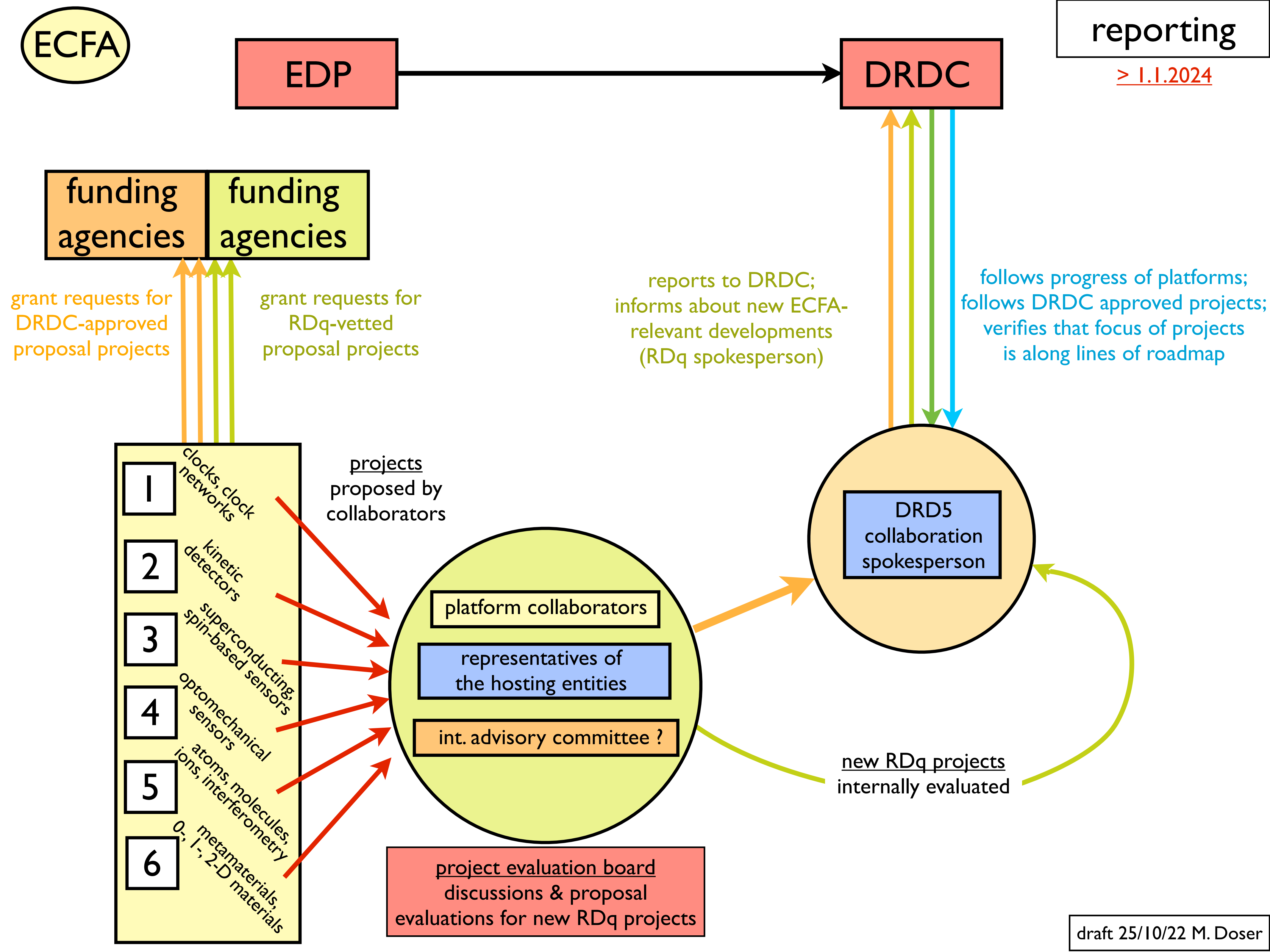
next step: implementation of ECFA-wide R&D pgm

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

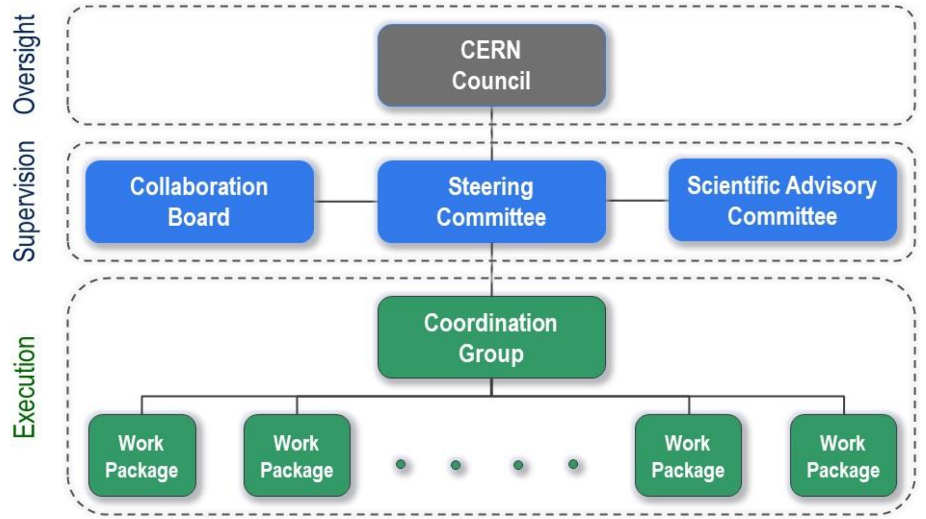


- spread load by hosting families in several platforms / institutions

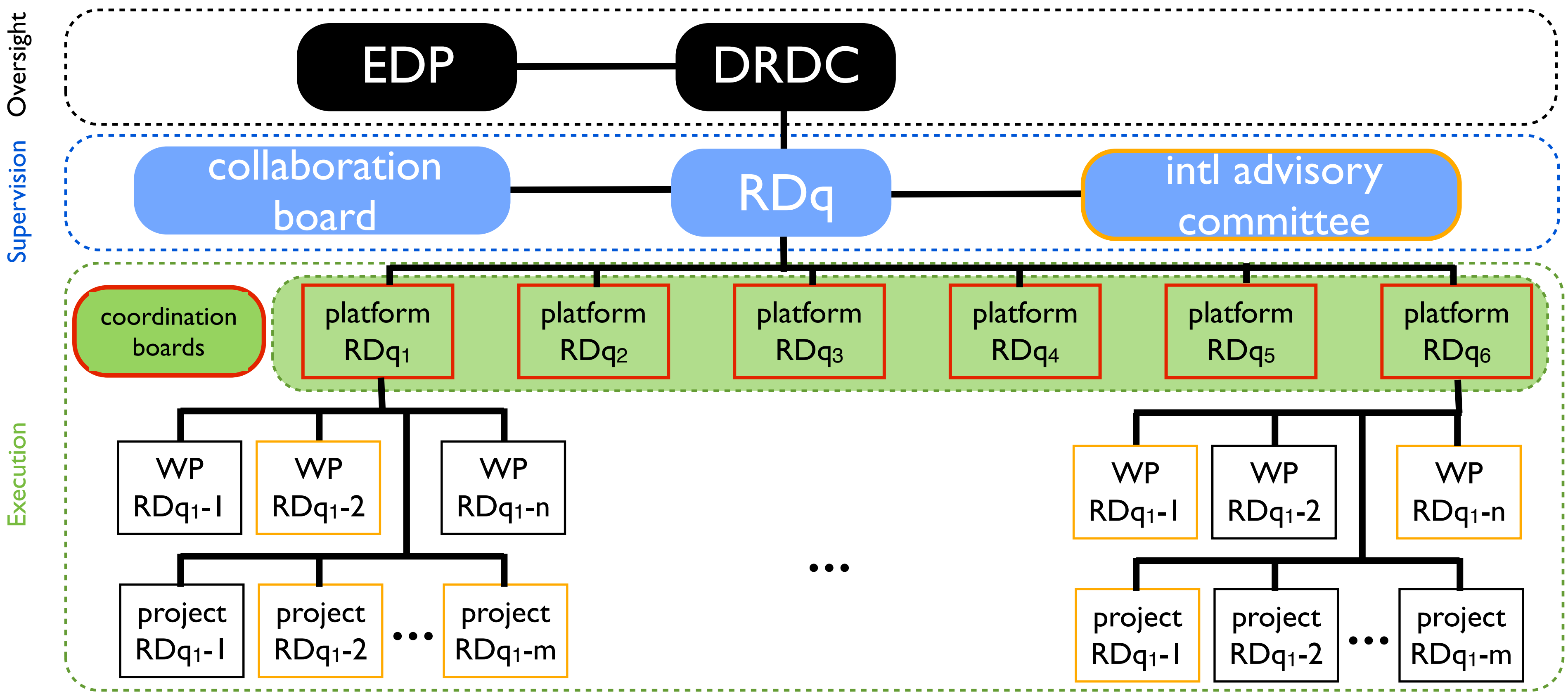

ECFA
EDP
DRDC
reporting
> 1.1.2024
funding agencies
funding agencies
grant requests for DRDC-approved proposal projects
grant requests for RDq-vetted proposal projects
reports to DRDC; informs about new ECFA-relevant developments (RDq spokesperson)
follows progress of platforms; follows DRDC approved 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
projects proposed by collaborators
platform collaborators
representatives of the hosting entities
int. advisory committee ?
DRD5 collaboration spokesperson
new RDq projects internally evaluated
project evaluation board
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



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)

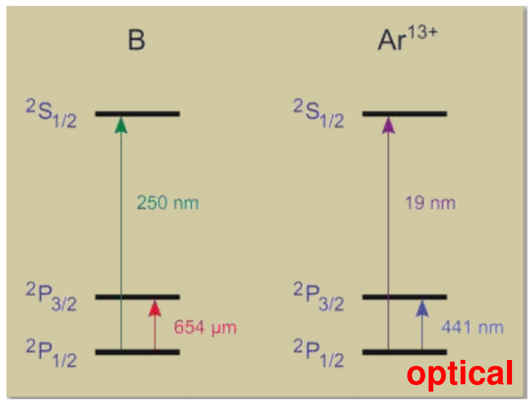
particles, atoms, ions, nuclei:

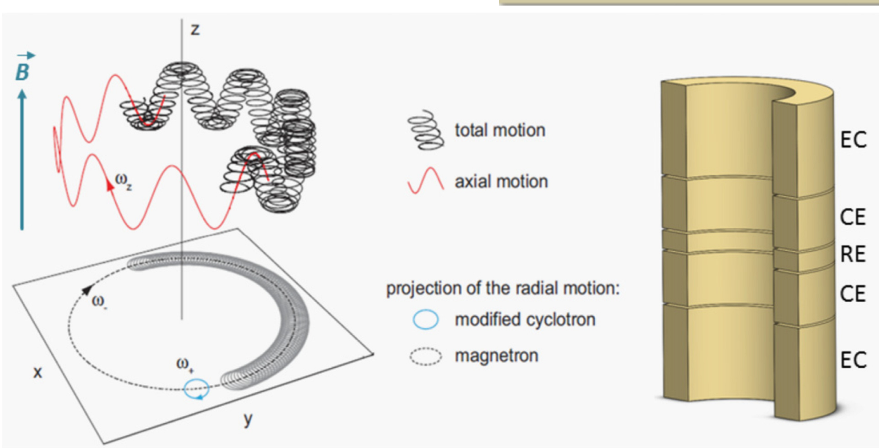
tests of QED, T-violation, P, Lorentz-violation, DM searches

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

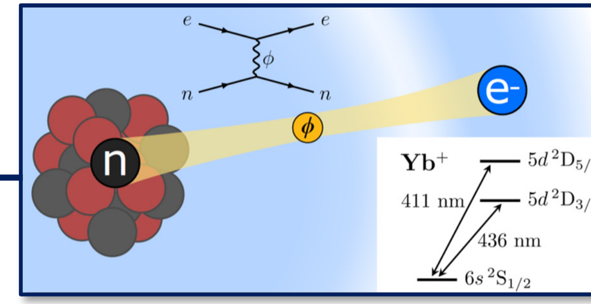
https://iopscience.iop.org/journal/2058-9565/page/Focus-on-Quantum-Sensors-for-New-Physics-Discoveries

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

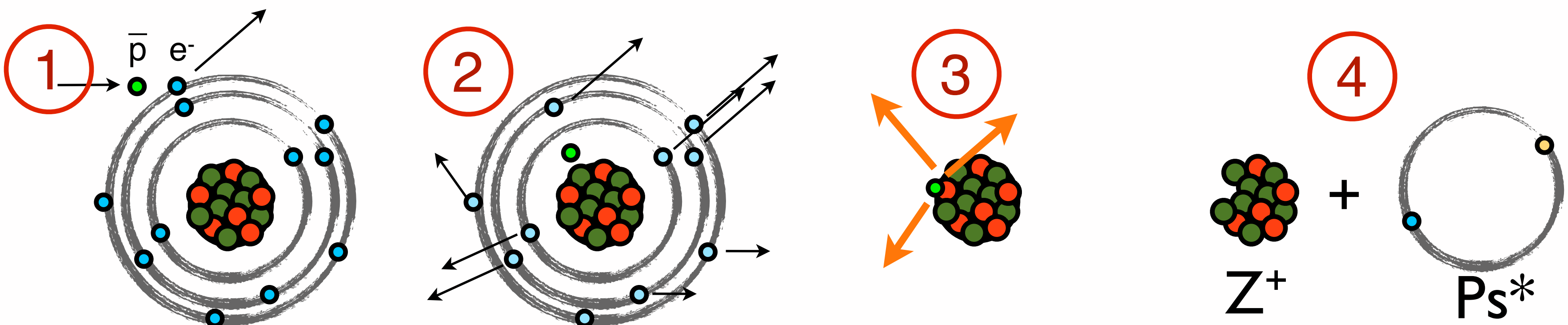
→ https://indico.cern.ch/event/999818/ Marianna Safronova (University of Delaware)

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

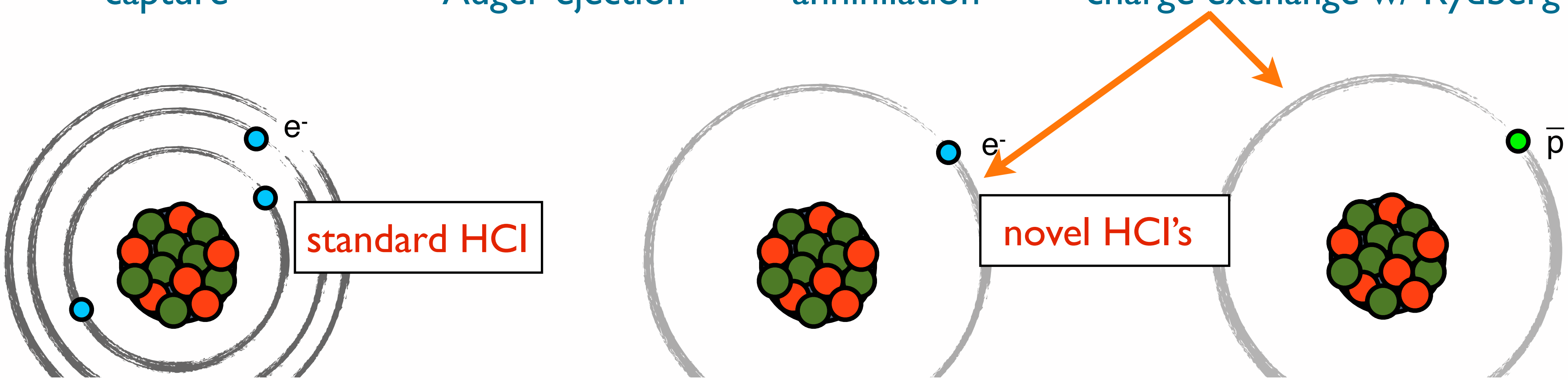
- Searches for the variation of fundamental constants
- Tests of QED: precision spectroscopy
- Fifth force searches: precision measurements of isotope shifts with HCIs to study non-linearity of the King plot



Antiprotonic atoms → novel HCI systems



capture | Auger ejection | annihilation | charge exchange w/ Rydberg atom

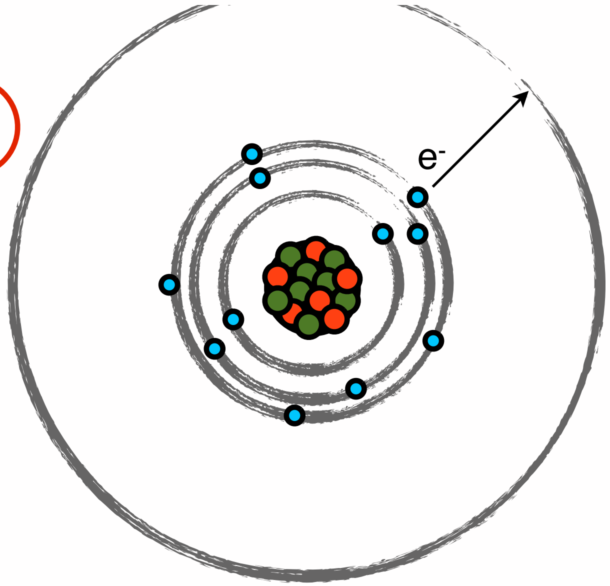


HCI (stable), $(Z\text{-}n)^+$ | HCI*(stable or unstable), $(Z\text{-}1)^+$ | HCI*(stable or unstable), $(Z\text{-}1)^+$

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

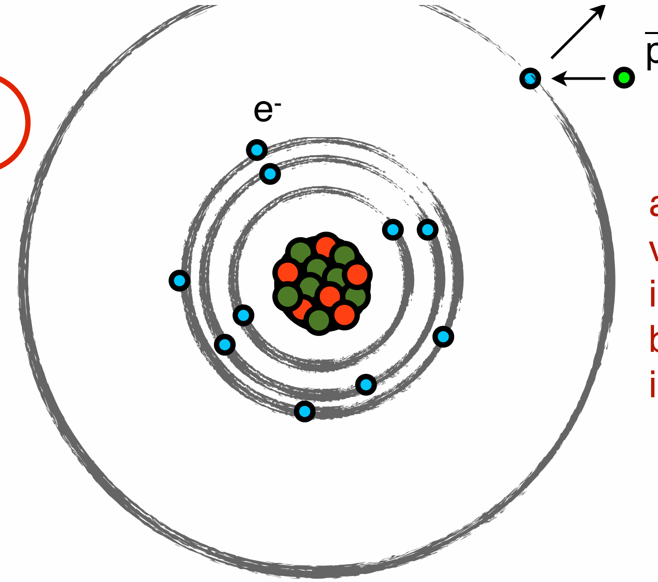
Antiprotonic Rydberg atoms: exotic couplings, similar approach as spectroscopy of muonic atoms, CPT tests

1



Rydberg excitation

2

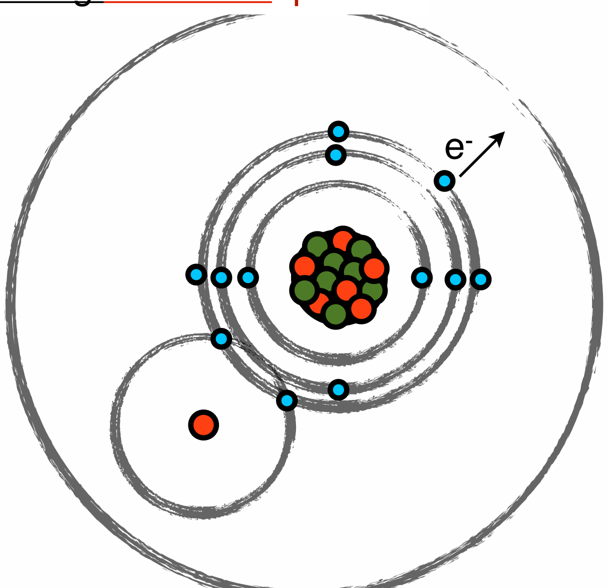


charge exchange

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

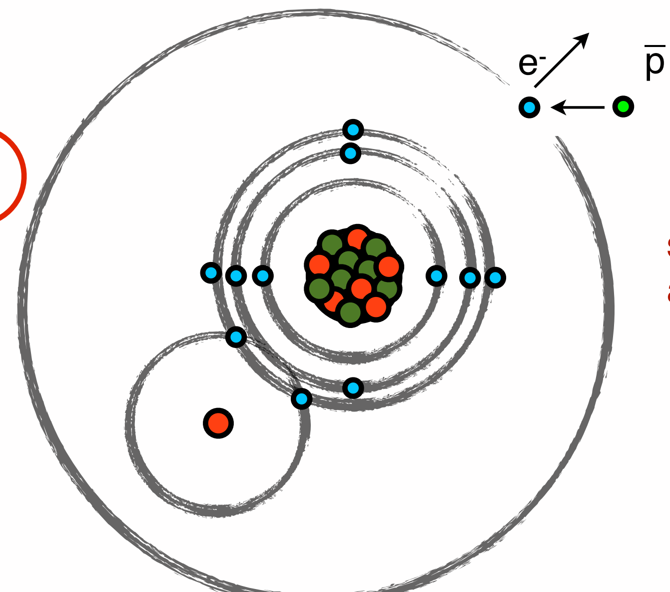
Antiprotonic Rydberg molecules: $\bar{p}$EDM?

1



Rydberg excitation

2



charge exchange

similar approach as eEDM in molecules

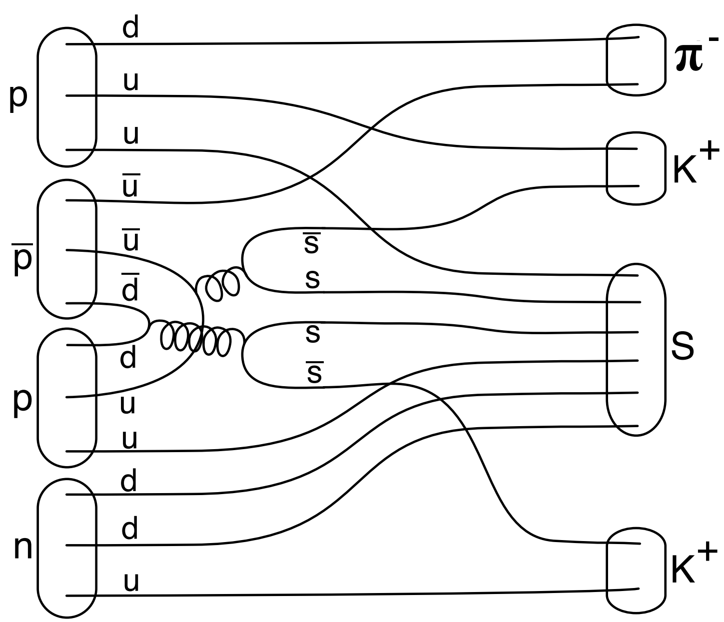
AEḡIS : a novel dark matter search

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

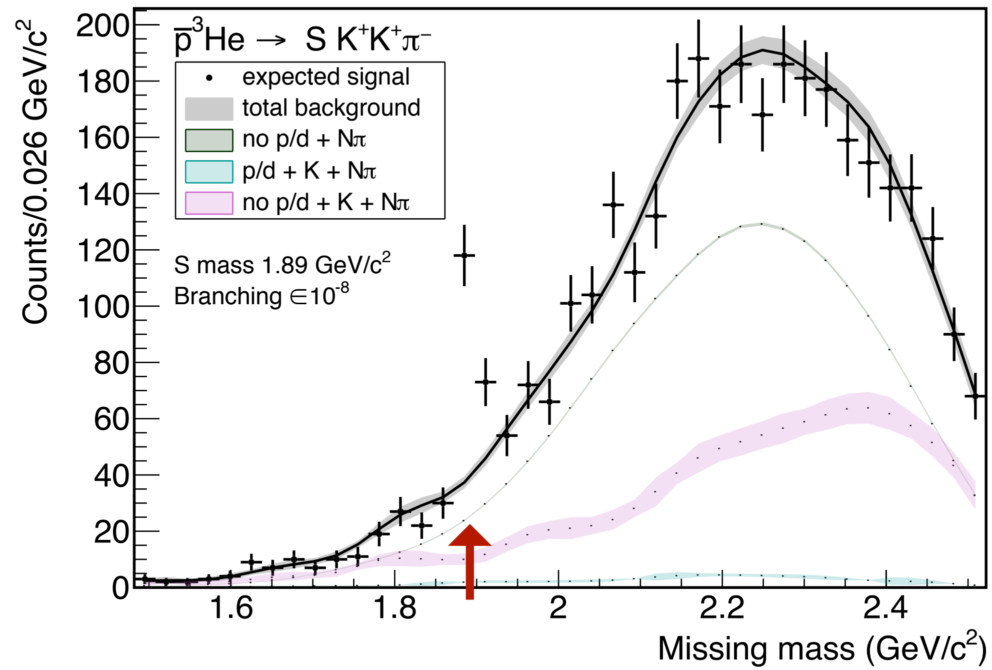
not excluded by prior searches for similar states (among them, the H dibaryon) in the GeV region
astrophysical bounds can be evaded
standard model compatible (uuddss bound state)

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

S= +2, Q= +1



Geant-4 simulation

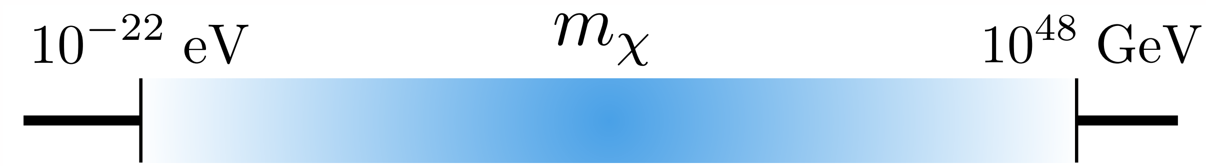


→ ***in-trap formation of antiprotonic atoms***
charged particle tracking, PID
detection of spectator p, d

→ ***sensitivity down to 10^{-9}***

RF cavities:

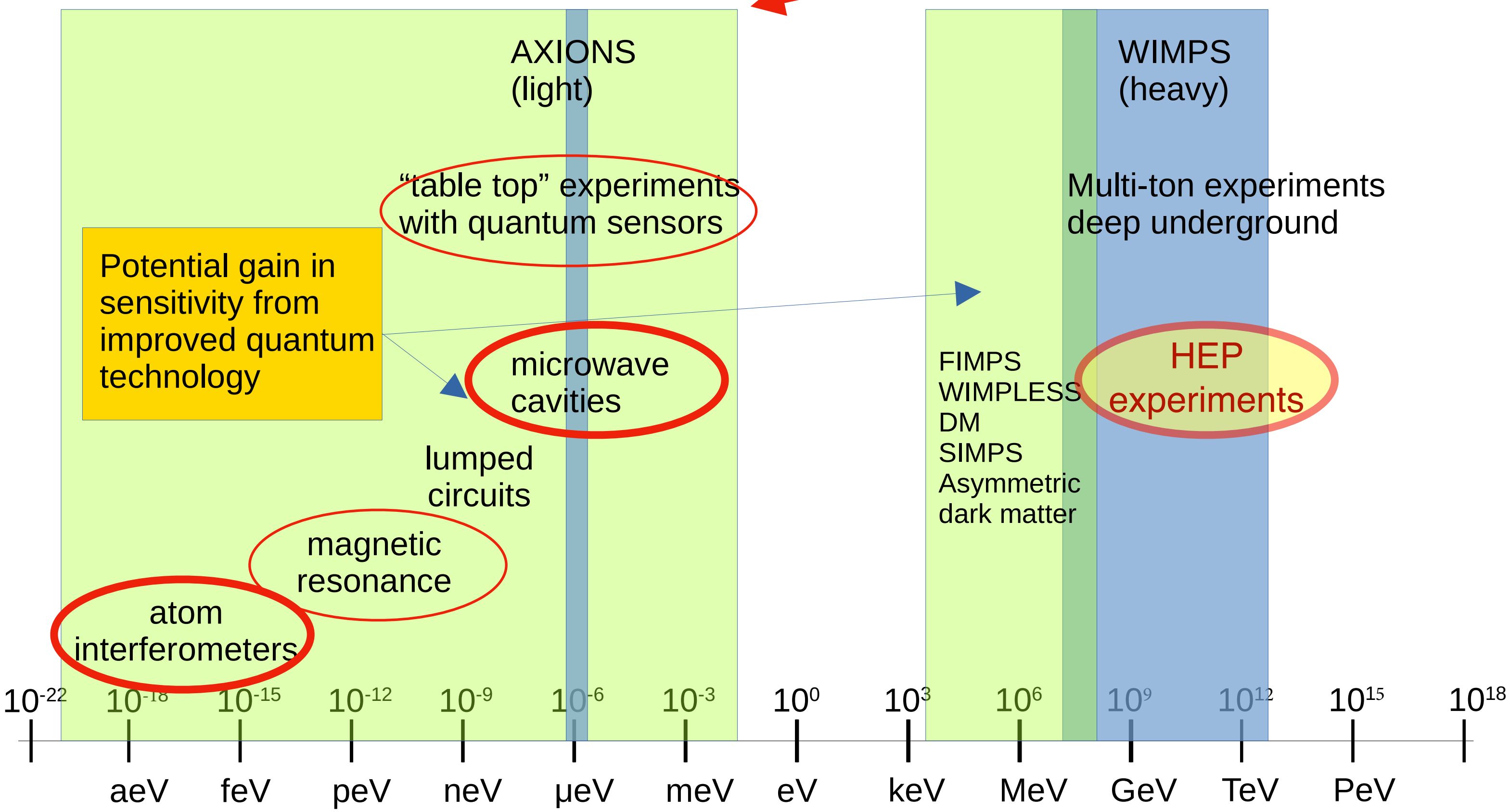
Axions, ALP's, DM & non-DM UL-particle searches

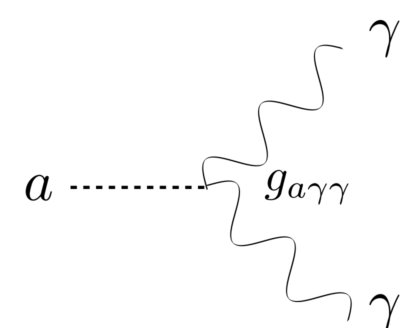


cavity size = axion size
axion mass = unknown

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

system noise temperature
cryo-amplifiers JJPA





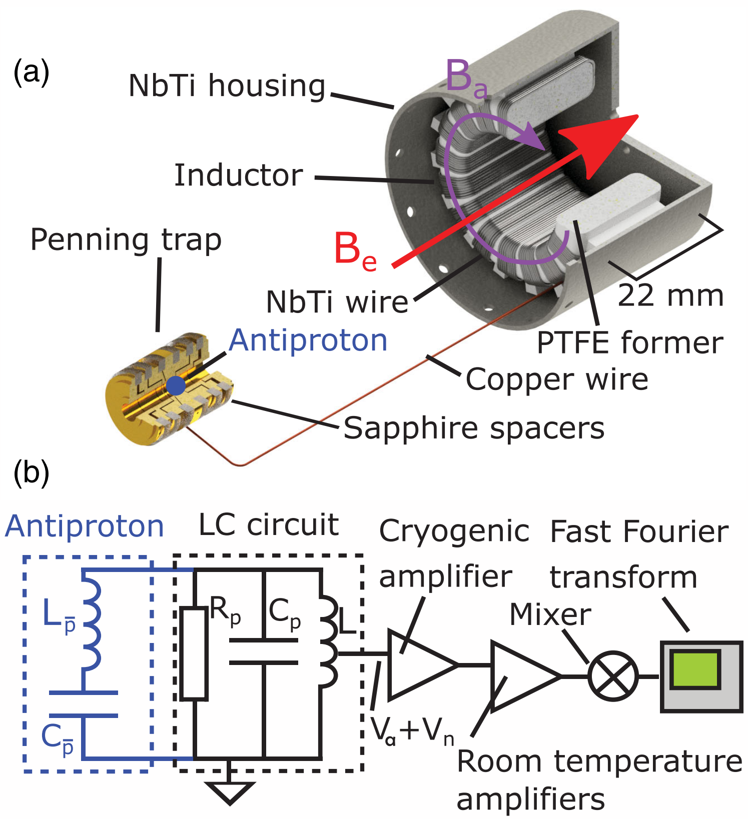
(but not only…)

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

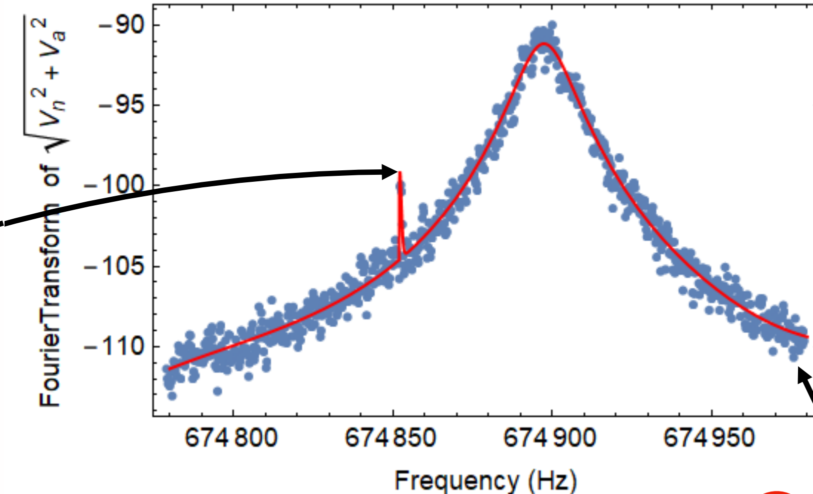
Constraints on the Coupling between Axion-like Dark Matter and Photons Using an Antiproton Superconducting Tuned Detection Circuit in a Cryogenic Penning Trap

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/



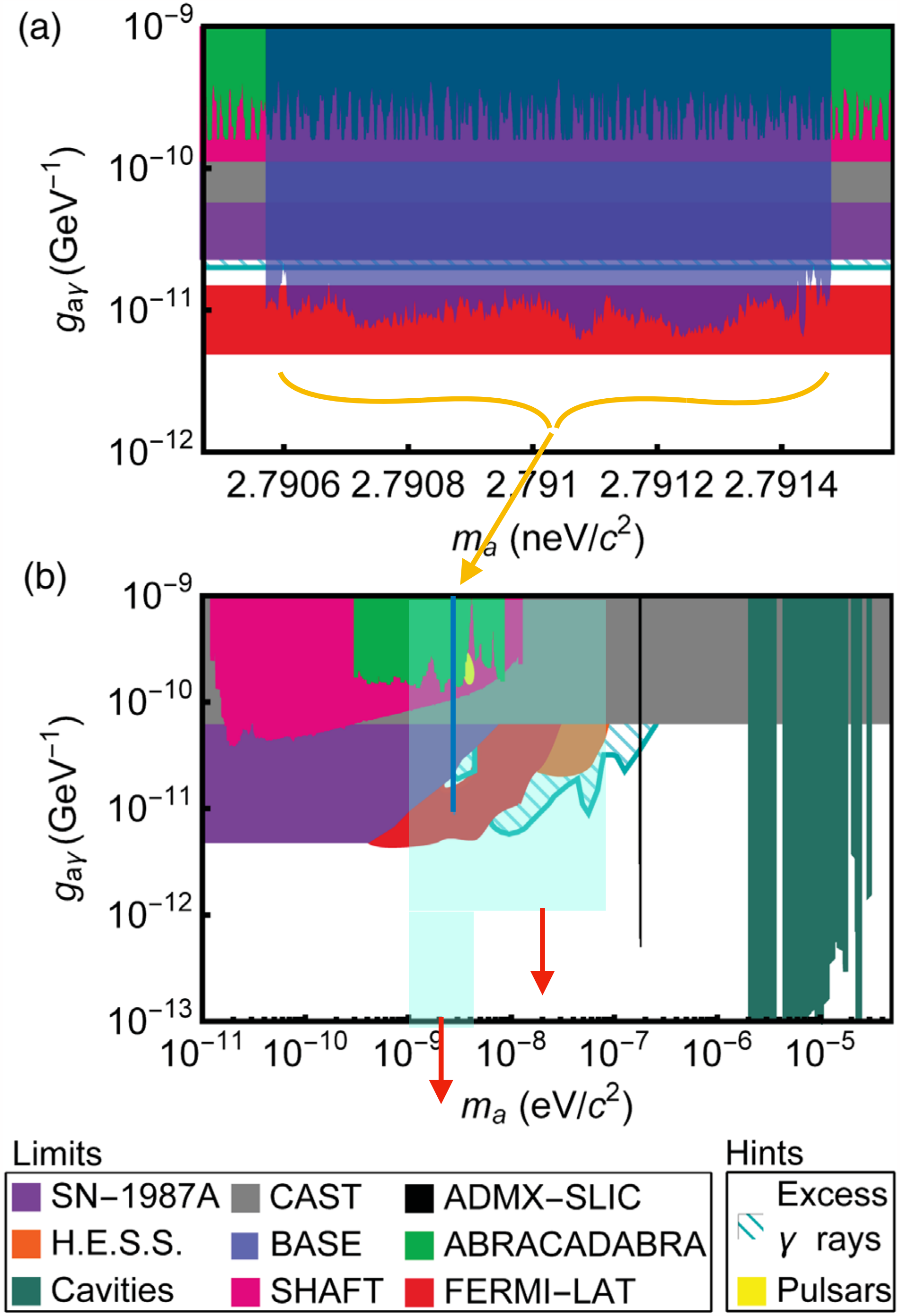
resonator background ∝ $\sqrt{T_z}$ from antiproton spin-flip

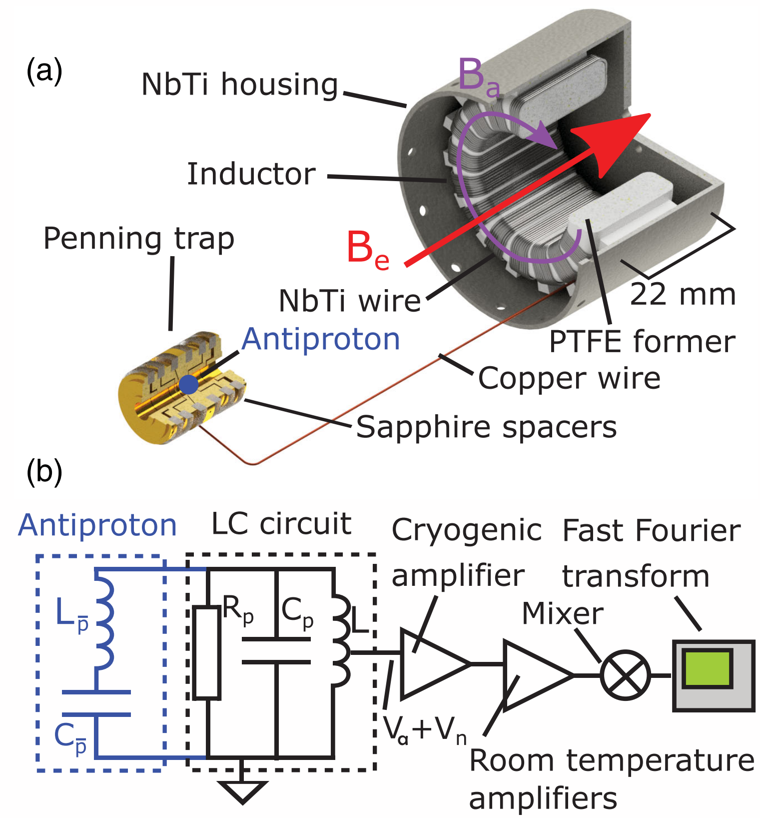
The axion signal

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

$f(\nu,Q,\mathbf{q})$ 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





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

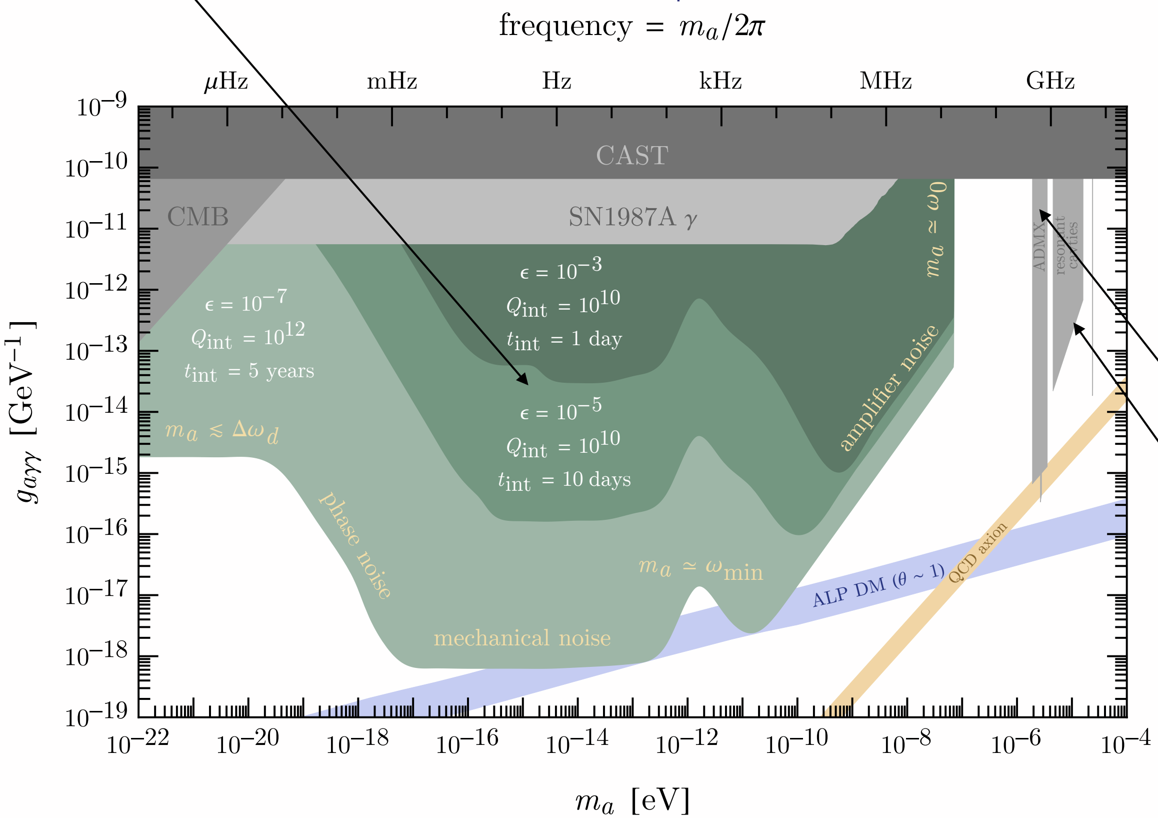
→ scan over axion masses m_a = slight perturbation of cavity geometry, which modulates the frequency splitting $\omega_0 - \omega_1$

→ superconducting RF cavities

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



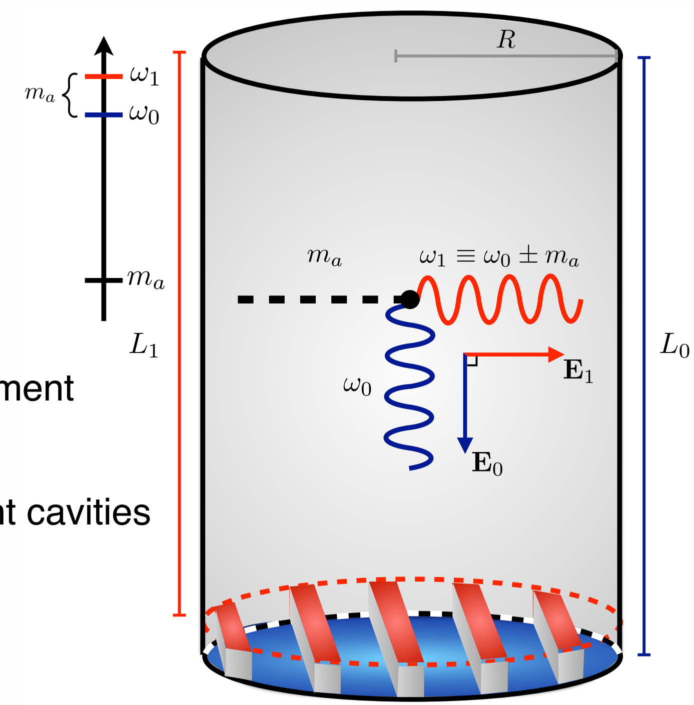
ADMX experiment

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 $\omega_1 \sim \omega_0 \pm m_a$



(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."

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

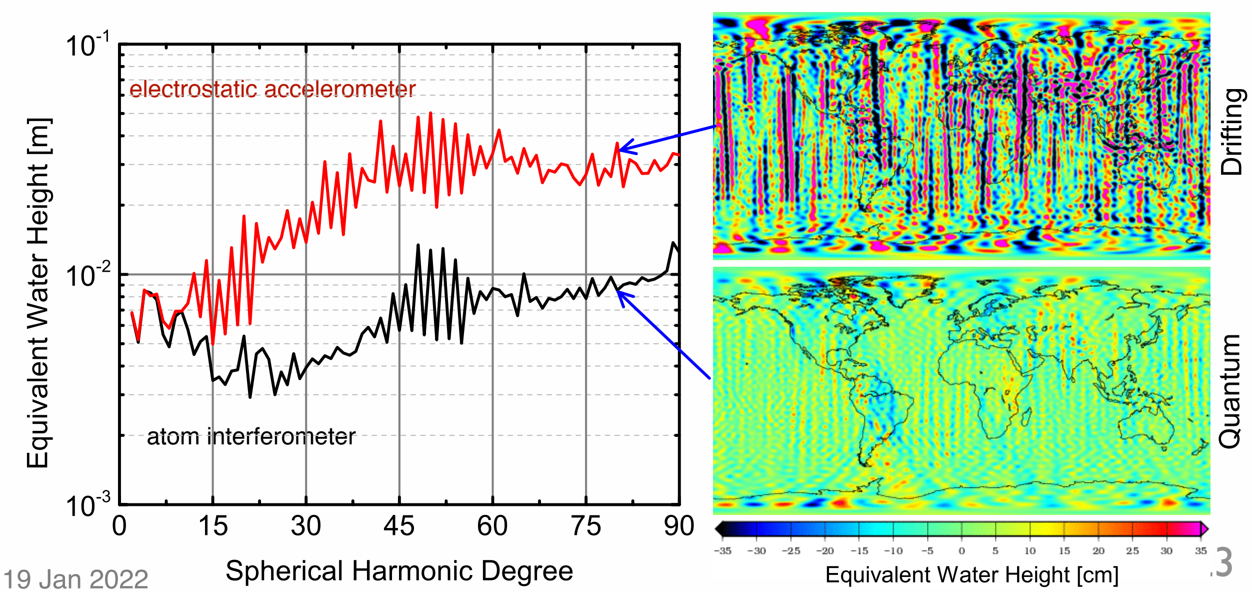
comparing atomic clocks based on different transitions can be used to constrain the time variation of fundamental constants and their couplings, comparison of two $^{171}Yb^+$ clocks and two Cs clocks -> limits on the time variation of the fine structure constant and of the electron-to-proton mass ratio

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

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