"Quantum Sensors for particle physics, dark matter and GW searches"

M. Doser, CERN

Patras, Sept. 2024

Clarification of terms

Quantum sensors for low energy particle physics

Quantum sensors for high energy particle physics

Some words on the landscape and the outlook

(low energy) particle detectors:

quantum sensors register a change of quantum state caused by the interaction with an external system:

- transition between superconducting and normal-conducting
- transition of an atom from one state to another
- change of resonant frequency of a system (quantized)

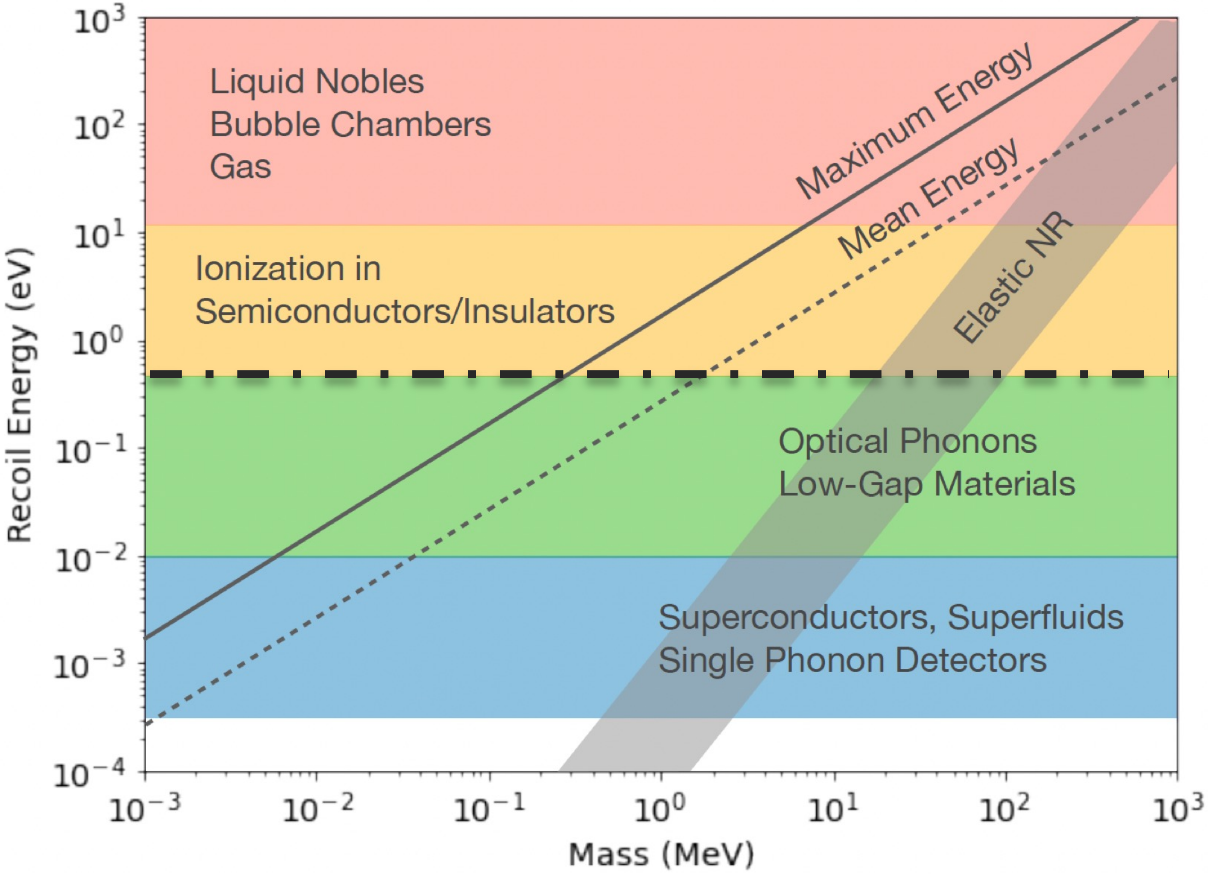
} highly sensitive and highly specific sensors for minute perturbations of the environment in which they operate

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

and because the commensurate energies are very low, unsurprisingly, quantum sensors are ideally matched to low energy (particle) physics; nevertheless, they can also form natural elements of HEP detectors → touch upon both

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

Start with an example: Energy deposited in detectors by particles



$\Delta E \sim 1$ eV
e.g. Si, Ge, GaAs, diamond, Quantum Dots, organic scintillators…

$\Delta E \sim 10 - 100$ meV
e.g. GaAs, sapphire, Dirac materials, doped s/c, …

$\Delta E \sim 1$ meV
e.g. superfluids, superconductors

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

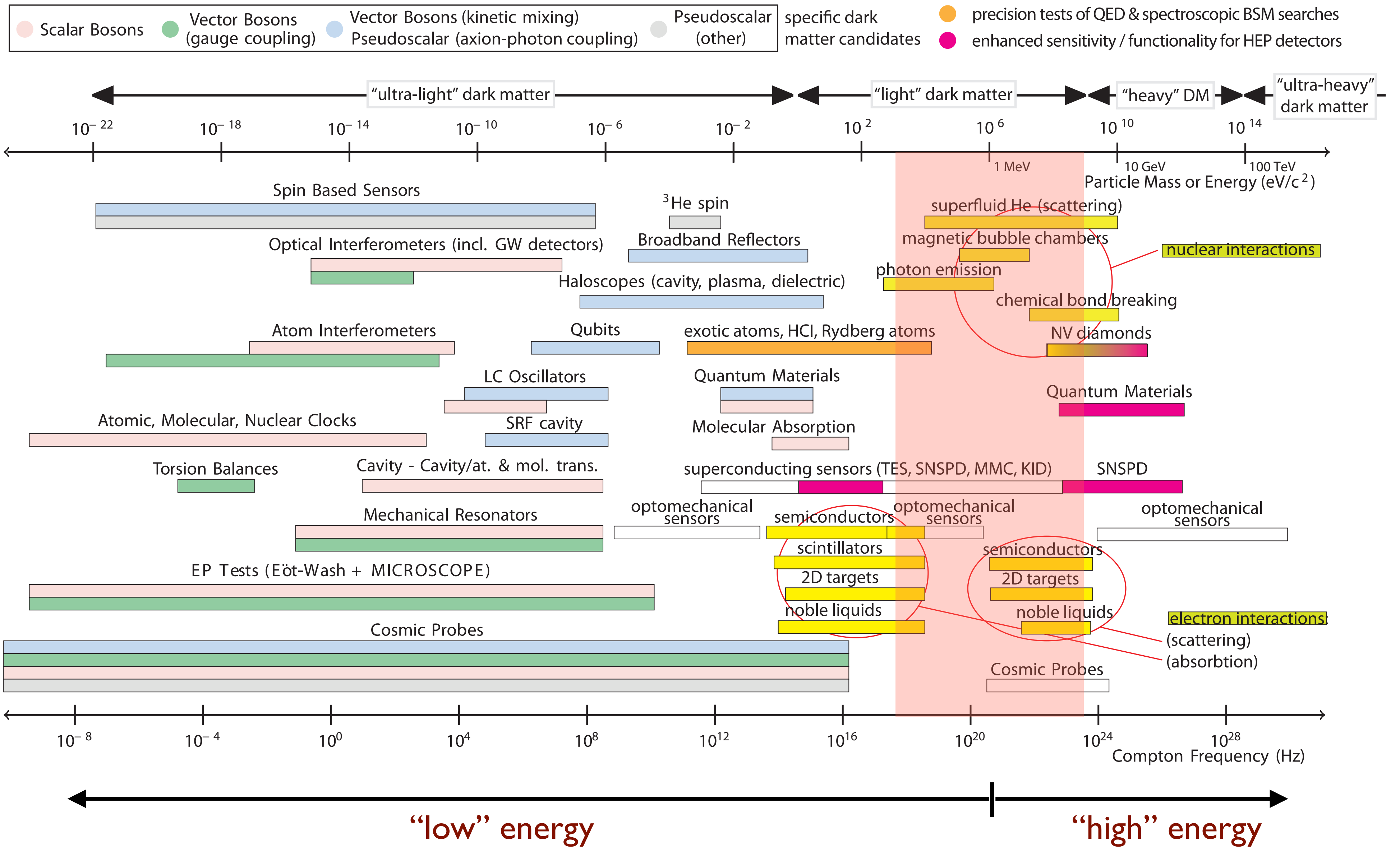
What's the goal? mip detection? or minute, sub-mip energy deposits?

Very low bandgap materials required to be sensitive to tiny energy deposits: milli-charged particles, nuclear recoil from very light DM, …

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

quantum sensing & particle physics

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



quantum sensors & particle physics: what are we talking about?

quantum technologies

1. superconducting devices (TES, SNSPD, …) / cryo-electronics
2. spin-based, NV-diamonds
3. optical clocks
4. ionic / atomic / molecular
5. optomechanical sensors
6. metamaterials, 0/1/2-D materials

domains of physics

- search for NP / BSM
- Axions, ALP's, DM & non-DM UL-particle searches
- tests of QM — wavefunction collapse, decoherence
- EDM searches & tests of fundamental symmetries
- *Development of new detectors*

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

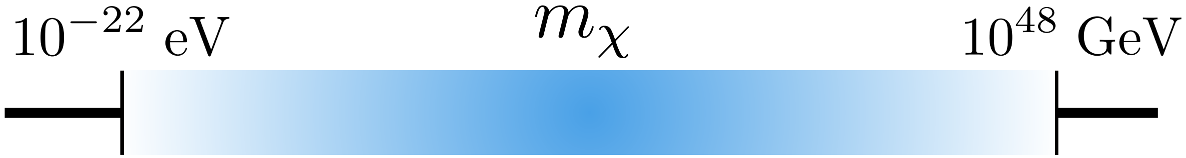
A *ridiculously* rapid overview of a selection of particle physics at low energy enabled by Quantum Sensors

- RF cavities, cryodetectors (DM searches)
- field sensors (DM searches)
- atom interferometry, clocks, networks (DM, gravity)
- exotic systems (QED, BSM, gravity, symmetries, DM)

These and many others are covered here → Marianna S Safronova and Dmitry Budker 2021 *Quantum Sci. Technol.* **6** 040401

Superconducting sensors: RF cavities

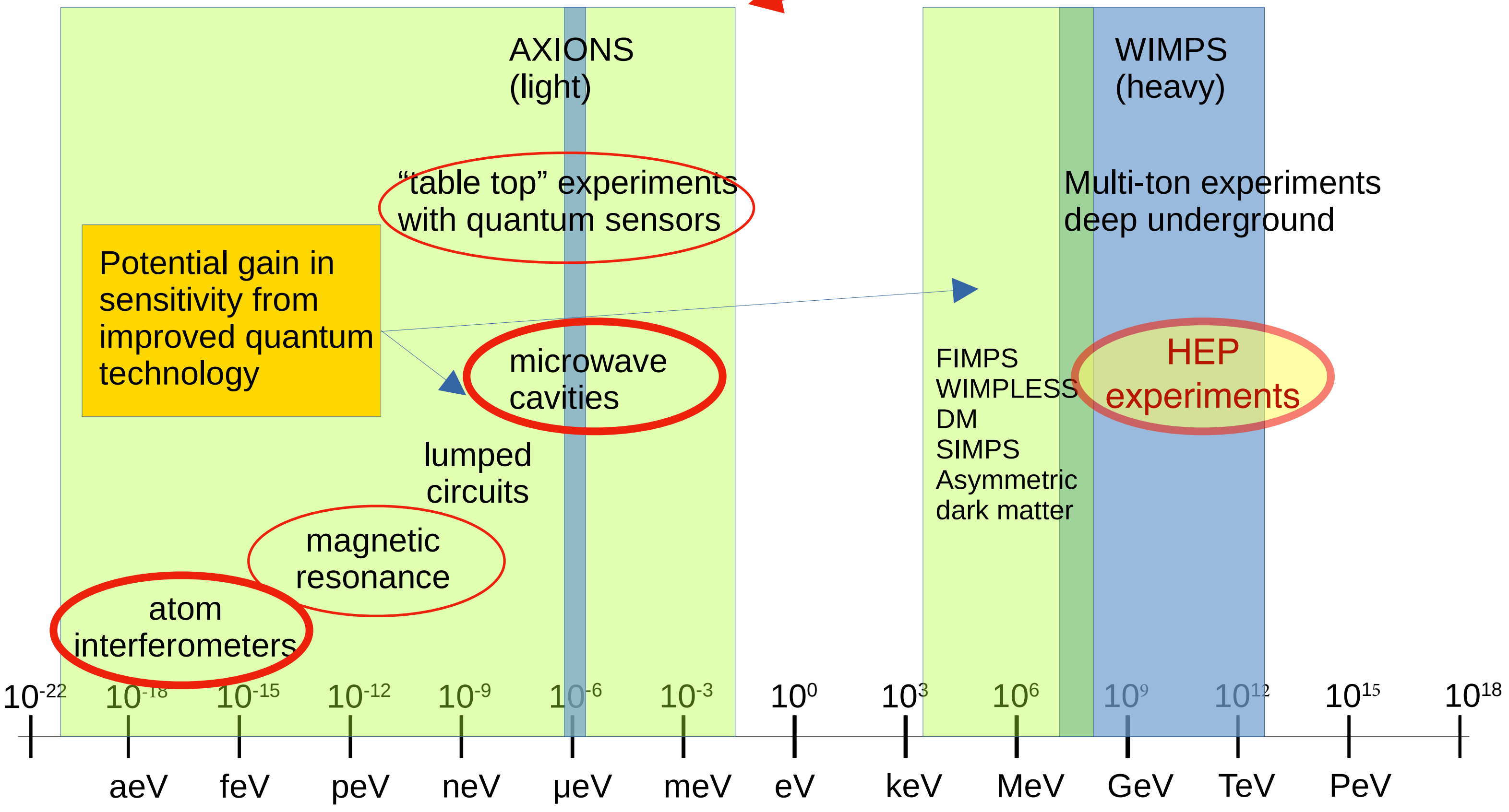
Axions, ALP's, DM & non-DM UL-particle searches

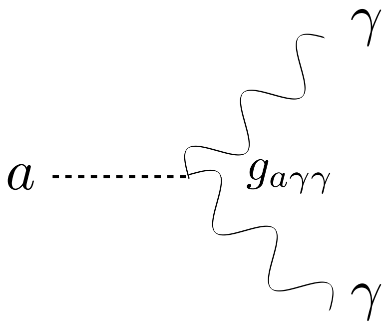


cavity size = axion size
axion mass = unknown

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

system noise temperature
cryo-amplifiers JJPA





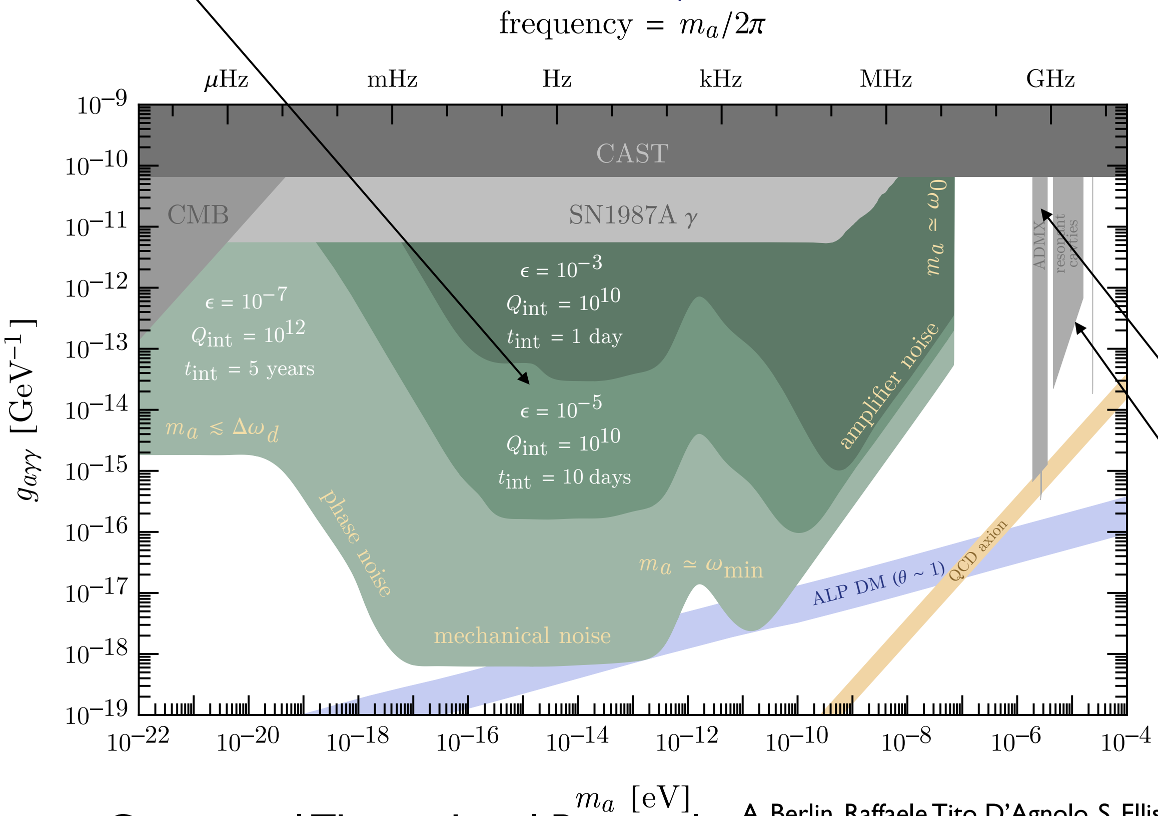
(but not only…)

Axion heterodyne detection

$Q_{int} \gtrsim 10^{10}$ achieved by DarkSRF collaboration

(sub-nm cavity wall displacements)

A. Grassellino, "SRF-based dark matter search: Experiment," 2019. https://indico.fnal.gov/event/19433/session/2/ contribution/2/material/slides/0.pdf



problem: cavity resonance generally fixed

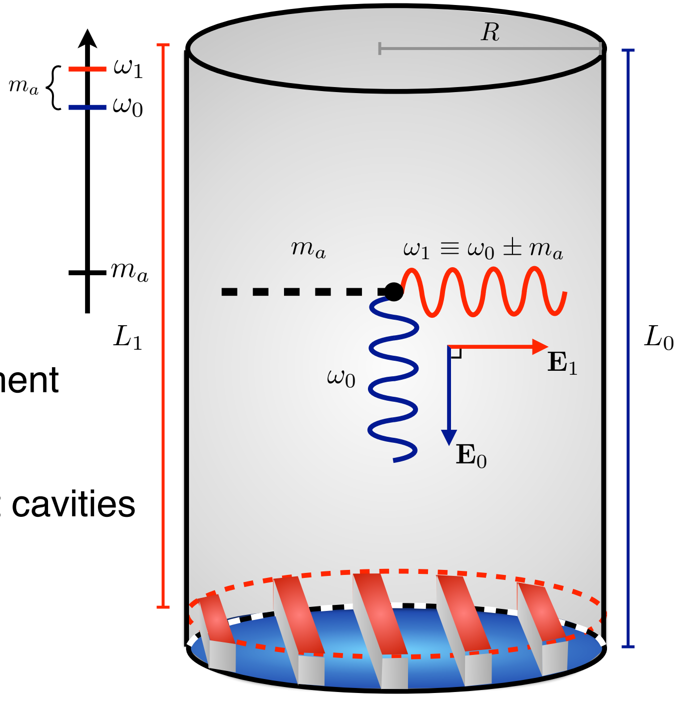
Resonant cavities possible down to μeV;
below that, need huge volume

driving "pump mode" at ω_0 ~ GHz allows axion to resonantly drive power into "signal mode" at $\omega_1 \sim \omega_0 \pm m_a$

solution for tuning: mechanical deformation; field tuning (SRF)

ADMX experiment

resonant cavities



(a) Cartoon of cavity setup.

Conceptual Theory Level Proposal:

A. Berlin, Raffaele Tito D'Agnolo, S. Ellis, C. Nantista, J. Nielson, P. Schuster, S. Tantawi, N. Toro, K. Zhou, *JHEP* 07 (2020) 07, 088

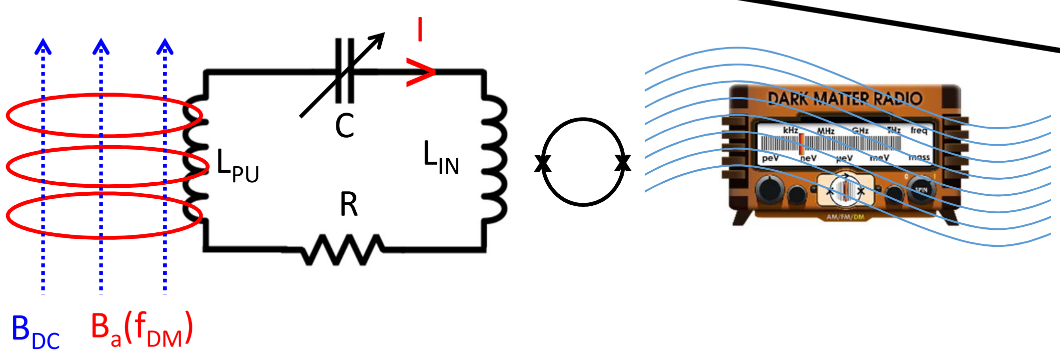
Asher Berlin, Raffaele Tito D'Agnolo, Sebastian A. R. Ellis, Christopher Nantista, Jeffrey Neilson, Philip Schuster, Sami Tantawi, Natalia Toro, Kevin Zhou, https://arxiv.org/abs/1912.11048

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

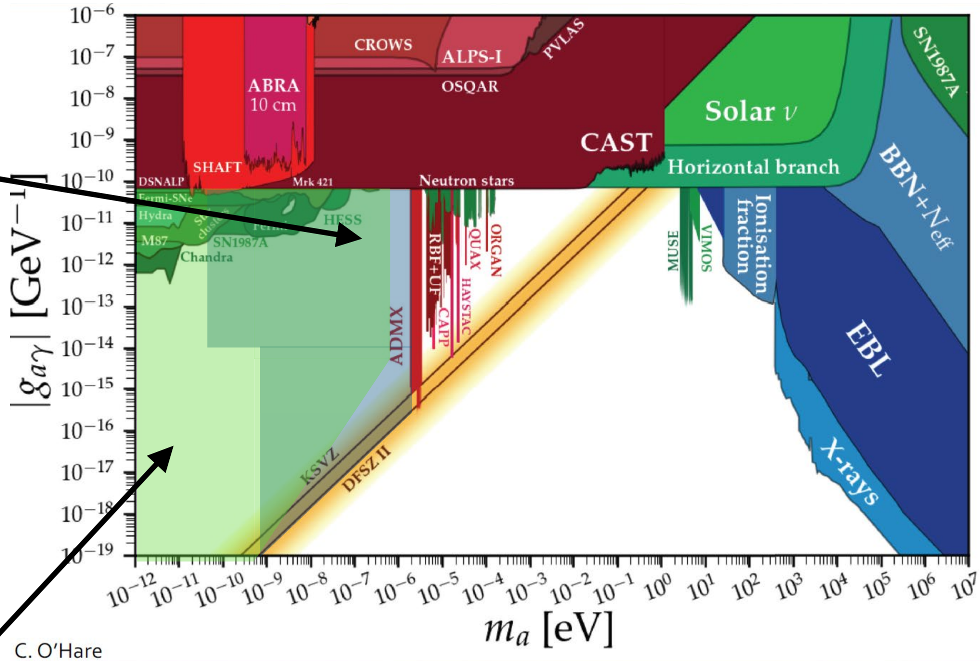
Focus on detecting not a particle (a photon), but a field

Quantum sensors for DM searches: field-sensitive devices

DMRadio



- Axion field converts to oscillating EM signal in background DC magnetic field
- Detect using tunable resonator
- Signal enhancement when resonance frequency matches rest-mass frequency $\nu_{DM}=mc^2/h$
- SQUID's, RF Quantum upconverters, cryoamplifiers

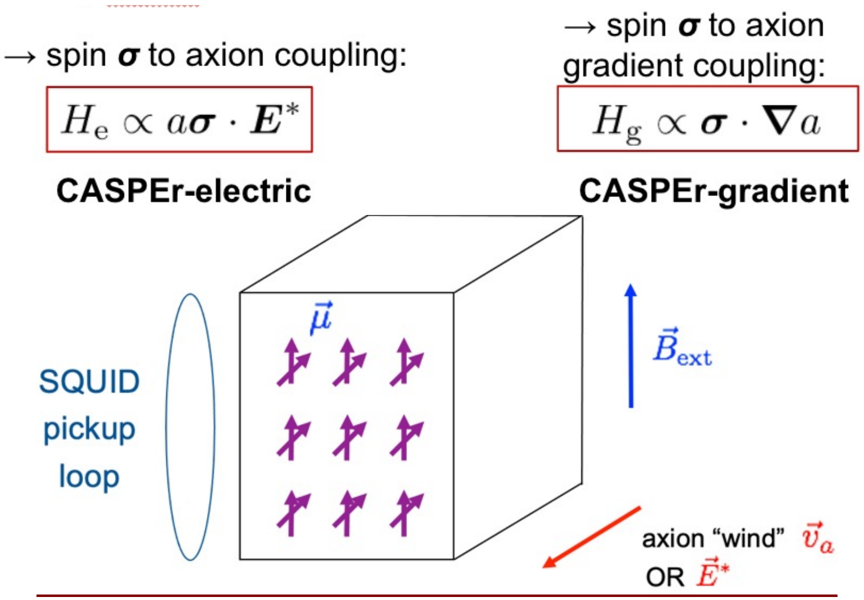


C. O'Hare

CASPEr electric NMR (Gen. 3)

Axion-like dark matter can exert an oscillating torque on ^{207}Pb nuclear spins via the electric dipole moment coupling g_d or via the gradient coupling g_{aNN}.

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



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

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

CASPEr-electric

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

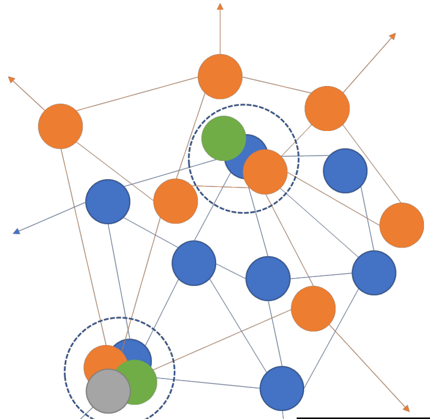
$\boxed{H_g \propto \boldsymbol{\sigma}\cdot\boldsymbol{\nabla}a}$

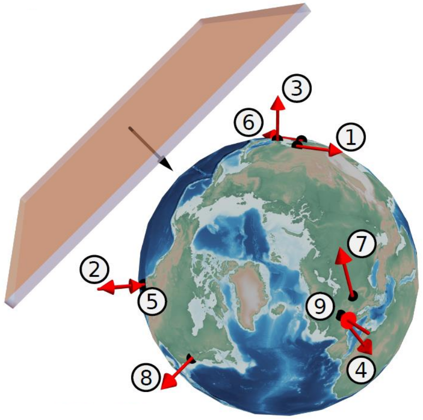
CASPEr-gradient

ECFA Detector R&D Roadmap Symposium of Task Force 5 Quantum and Emerging Technologies
https://indico.cern.ch/event/999818/ Kent Irwin (Stanford University), Dima Budker (Mainz University)

Networked quantum sensors for DM and NP searches

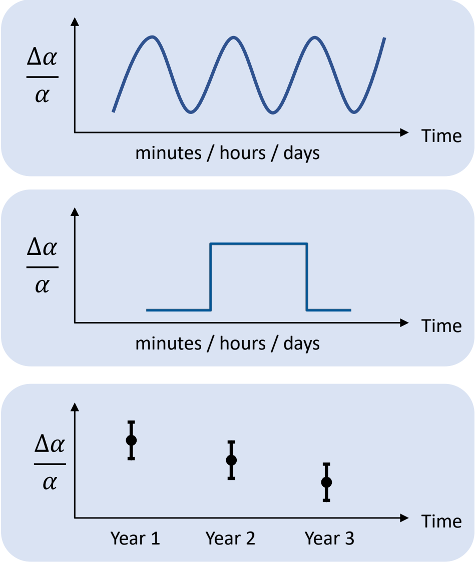
search for NP / BSM





Time- & Frequency distribution:
Opt. FREQUENCY distribution
TIME distribution
Extensions in progress

networks of sensors



- Oscillations → Very light DM
- Fast transients → DM- topological defects
- Slow drifts → New physics

magnetometers

Afach et al, arXiv:2102.13379v2

atomic clocks nuclear, HCI, molecules

Wcislo et al, Sci. Adv. 4, 4869 (2018)

optical fiber networks

Roberts et al, New J. Phys. 22, 093010 (2020)

Investigate very light scalar and pseudo-scalar DM candidates over ~10 orders of magnitude in mass and different couplings

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

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

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

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

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

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

MIGA France

AION UK

ZAIGA China

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

MAGIS Fermilab

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

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

satellite missions:

ACES (Atomic Clock Ensemble in Space): 2024-2025

ESA mission for ISS

two on-board clocks rely on atomic transitions in the microwave domain

probe time variations of fundamental constants, and to perform tests of the Lorentz-Violating Standard Model Extension (SME). Possibly topological dark matter

pathfinder / technology development missions: ~2030

I-SOC: key optical clock technology (laser cooling, trapping, optical resonators) for space; Sr optical lattice clock / Sr ion clock; microwave and optical link technology;

FOCOS (Fundamental physics with an Optical Clock Orbiting in Space): Yb optical lattice clock with 1×10^{-18} stability

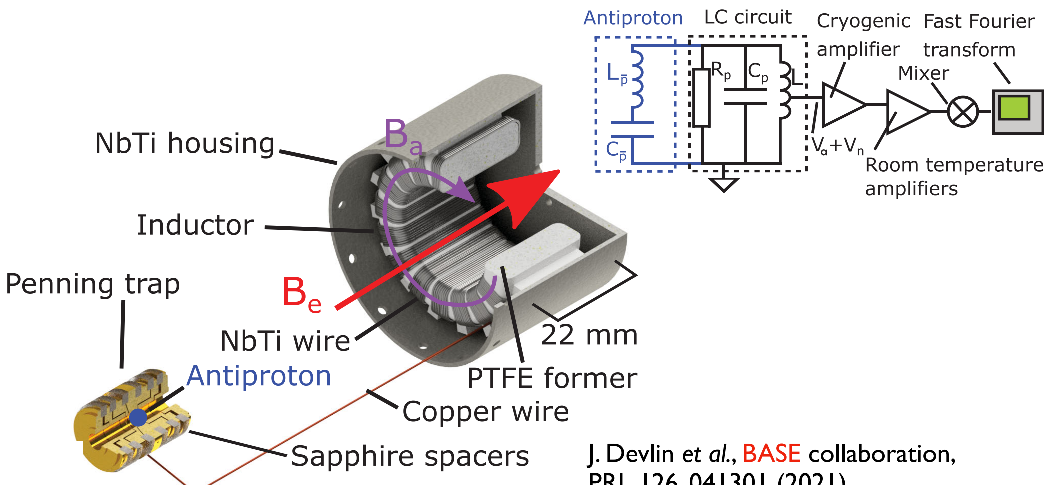
AION: ~2045 satellite mission

AEDGE: ~2045 satellite mission

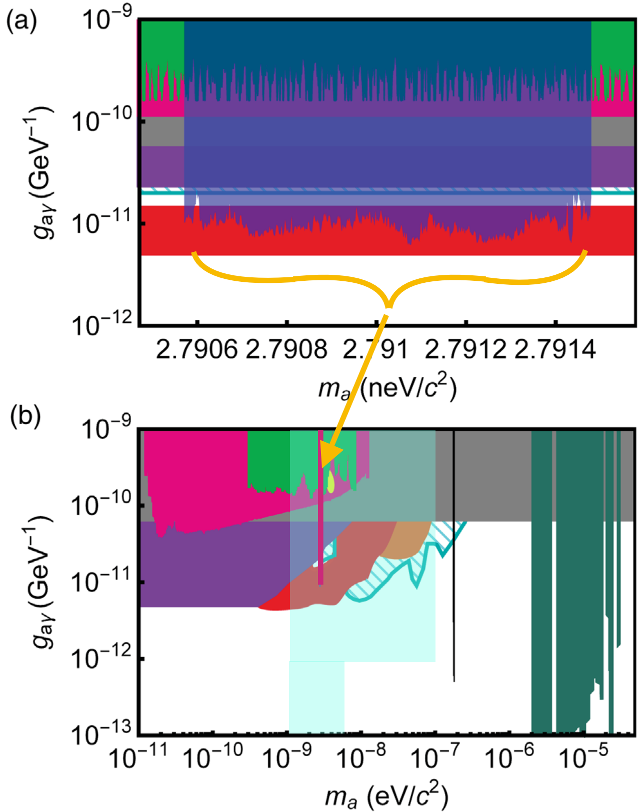
El-Neaj, Y.A., Alpigiani, C., Amairi-Pyka, S. *et al*. AEDGE: Atomic Experiment for Dark Matter and Gravity Exploration in Space. *EPJ Quantum Technol*. **7,** 6 (2020). https://doi.org/10.1140/epjqt/s40507-020-0080-0

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

Trapped p̄: symmetry tests, DM searches



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

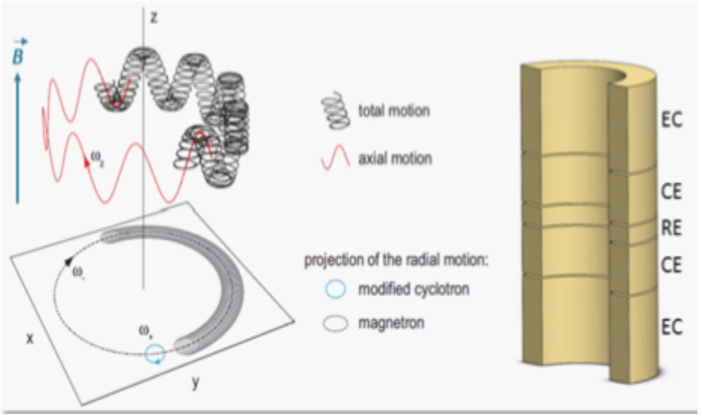


Trapped ions: tests of QED, symmetry tests, DM searches

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

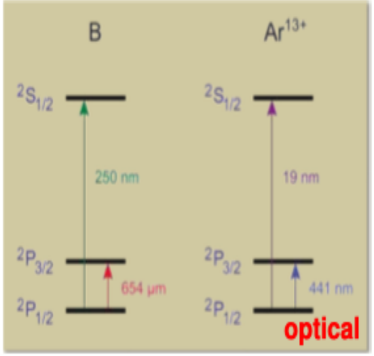
- Searches for the variation of fundamental constants
- Tests of QED: precision spectroscopy
- Fifth force searches: precision measurements of isotope shifts with HCIs to study non-linearity of the King plot

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



Scaling with a nuclear charge Z

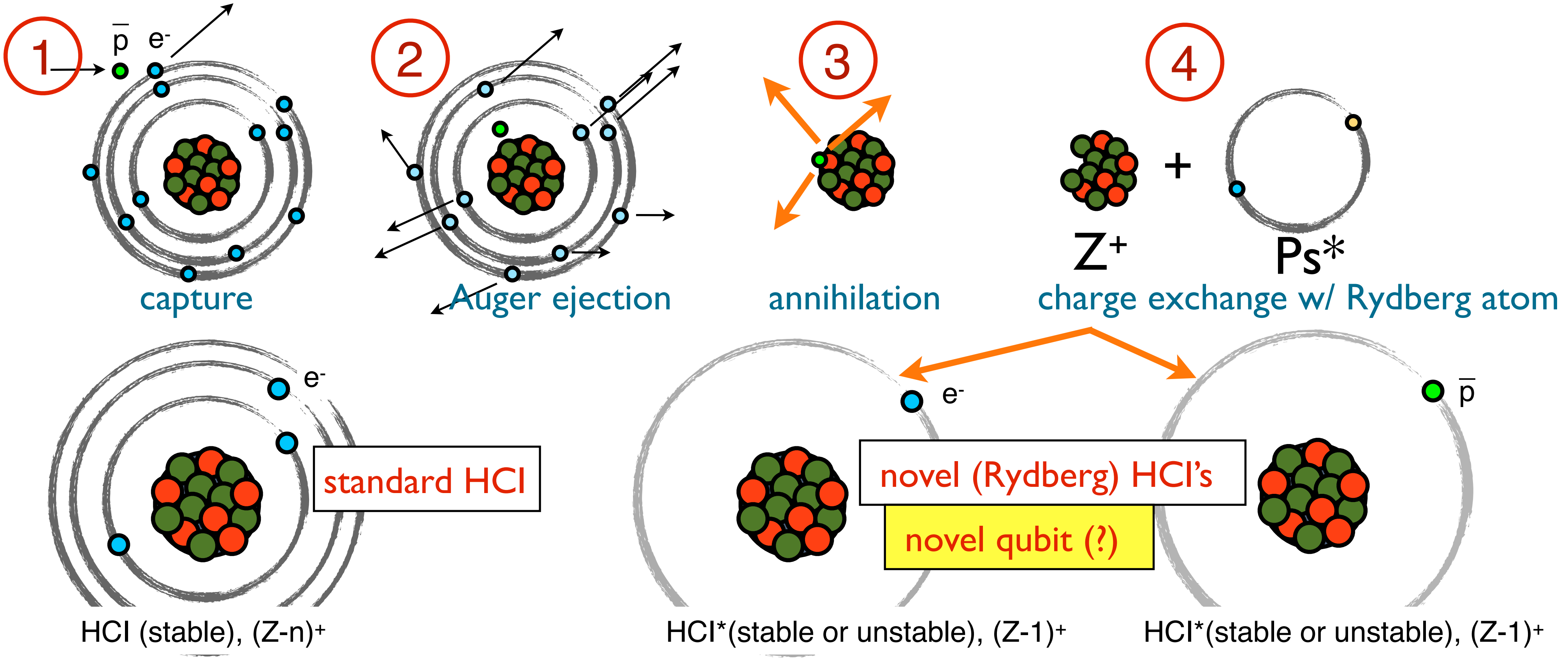
Binding energy	~ Z^2
Hyperfine splitting	~ Z^3
QED effects	~ Z^4
Stark shifts	~ Z^{-6}



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

Antiprotonic atoms → novel HCI systems

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



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

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

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

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

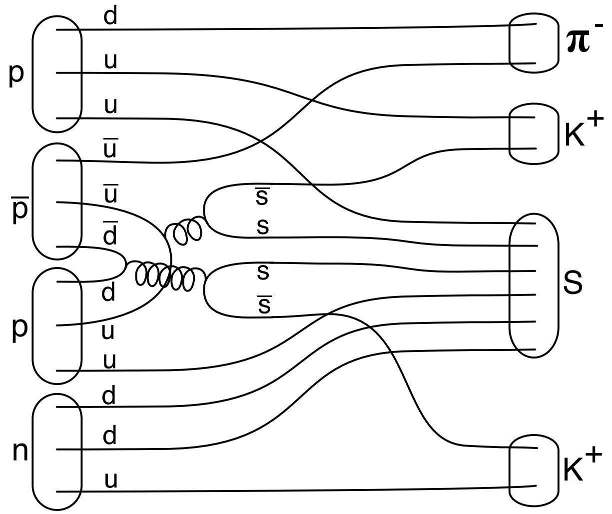
G. Farrar, G. Kornakov, M. Doser, EPJC 83, 1149 (2023)

sexaquark: (u↑u↓d↑d↓s↑s↓) scalar QCD bound state

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

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

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

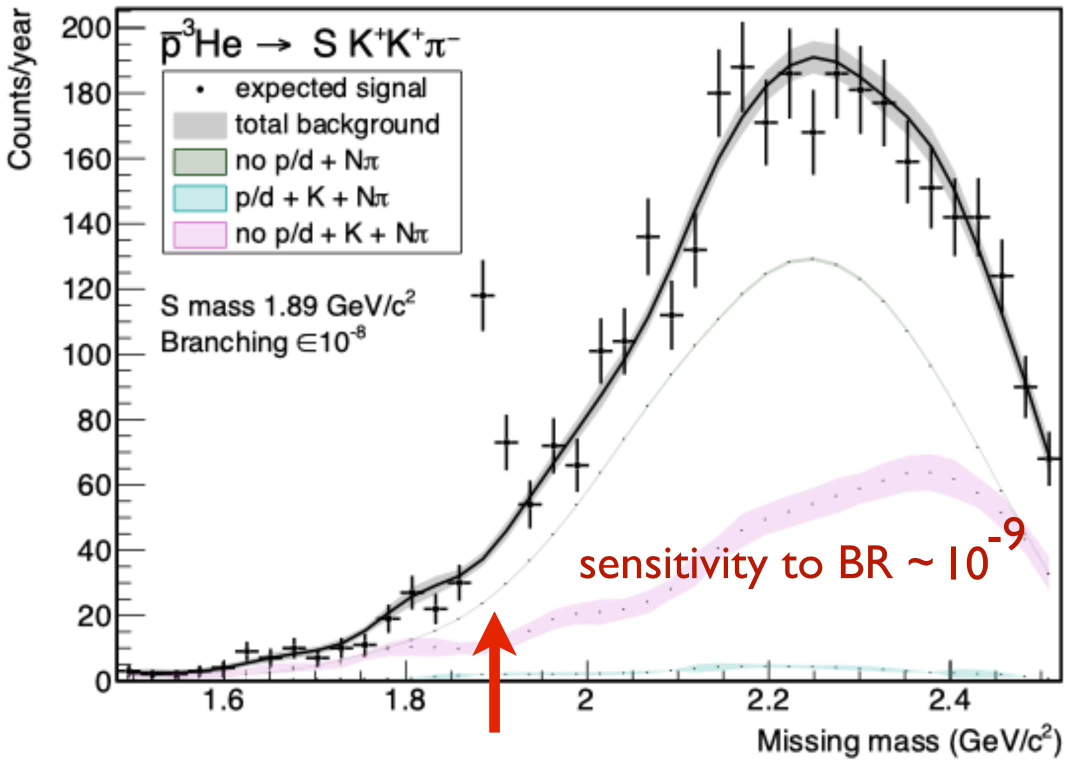


S= +2, Q= +1

Tracking detector with good particle ID

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

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



sensitivity to BR ~ 10^{-9}

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

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

typically not obvious, given that most detectors rely on detecting the product of many interactions between a particle and the detector (ionization, scintillation, Čerenkov photons, …)

handful of ideas that rely on quantum devices, or are inspired by them. not necessarily used as quantum detectors per se, but rather their properties to enhance / permit measurements that are more difficult to achieve otherwise

main focus on tracking / calorimetry / timing / novel observables / PU ...

closely related: nanostructured materials

→ Frontiers of Physics, M. Doser et al., 2022
doi: 10.3389/fphy.2022.887738

these are not fully developed concepts, but rather the kind of approaches one might contemplate working towards

very speculative!

Metamaterials, 0 / 1 / 2-dimensional materials

quantum dots for calorimetry	chromatic calorimetry
quantum dots for tracking	chromatic tracking

Atoms, molecules, ions

quantum-boosted dE/dx	Rydberg TPC’s

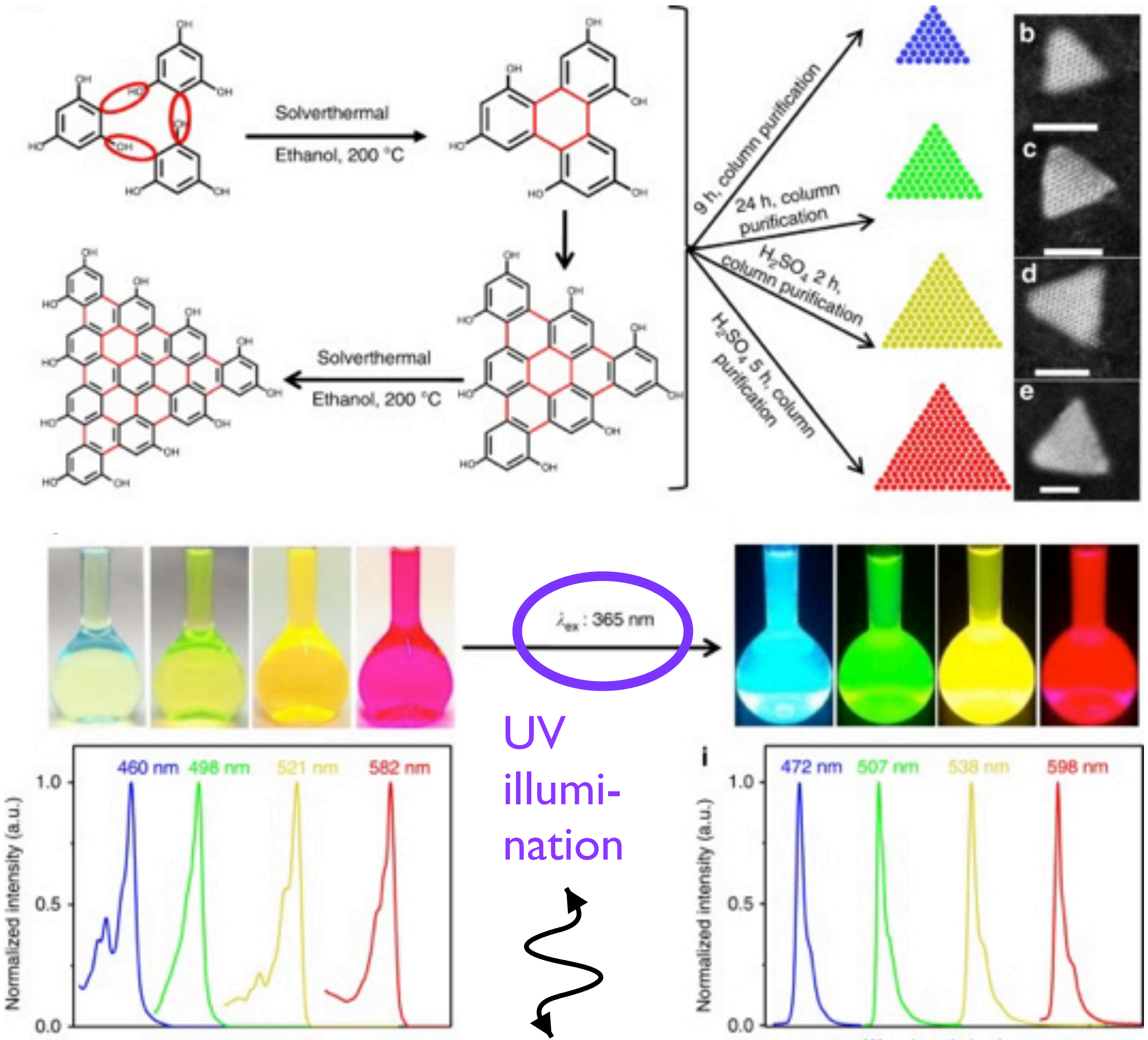
Spin-based sensors

quantum-polarized helicity detection	helicity detectors

Superconducting sensors

quantum pixel ultra-sensitive tracking	milli-charge trackers

Quantum dots: chromatic calorimetry



UV illumi-nation

e.m. shower

absorption

emission

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

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

requires:

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

select appropriate nanodots

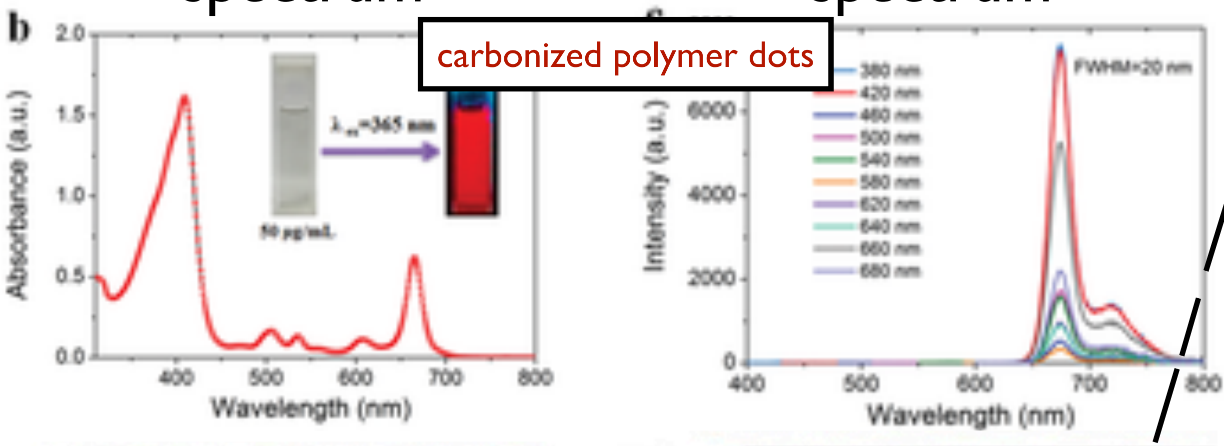
e.g. triangular carbon nanodots

quantum dots for calorimetry

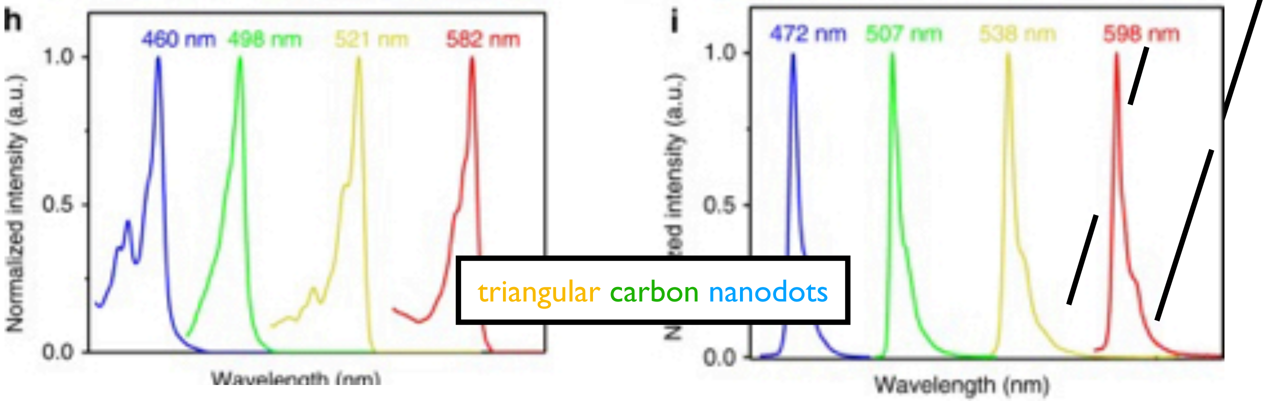
absorption spectrum

emission spectrum

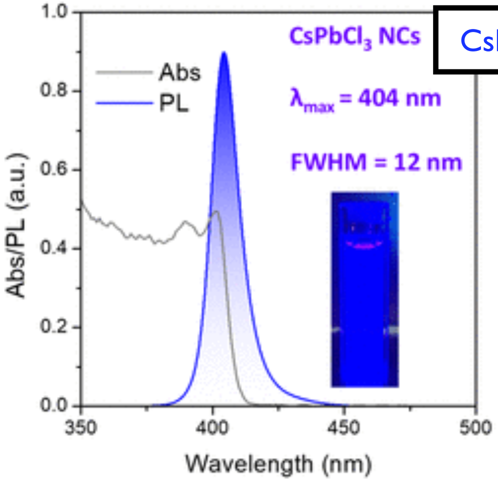
carbonized polymer dots



triangular carbon nanodots



CsPbCl₃ nanocrystals



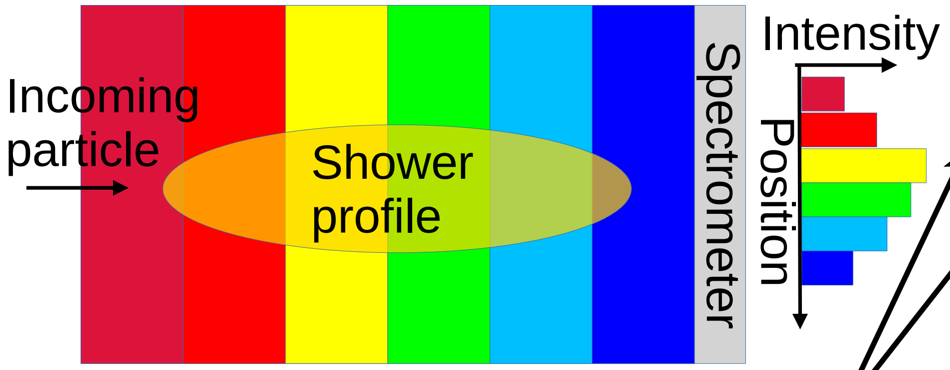
leftmost nanodots:
absorb wavelengths < 650 nm
emit at > 680 nm

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

…

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

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



Monochromators + PD?

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

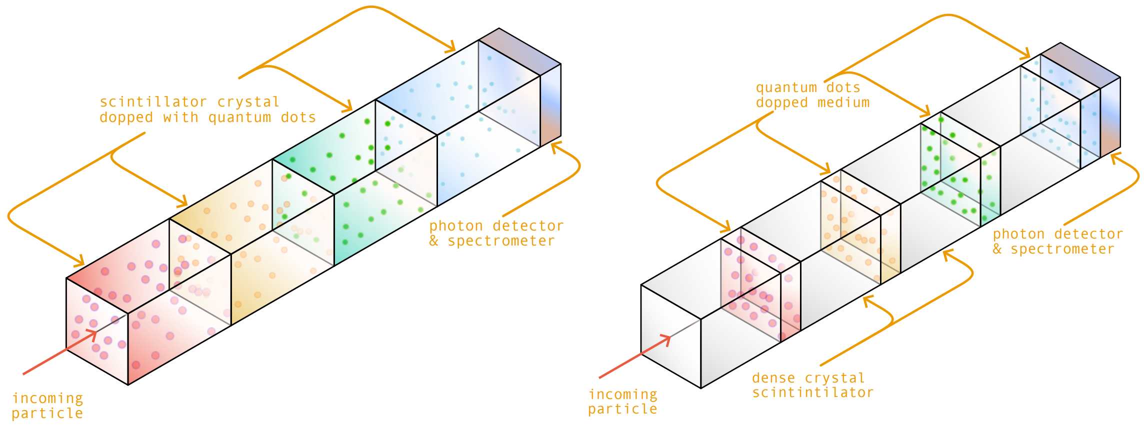
Metalenses?

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

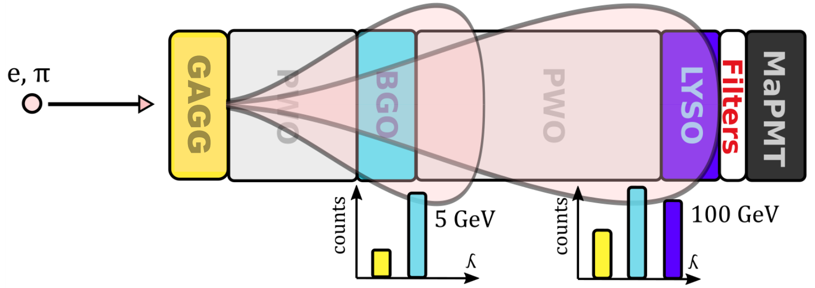
(shower profile via ***spectrometry***)

This slide courtesy Devanshi Arora, CALOR'24

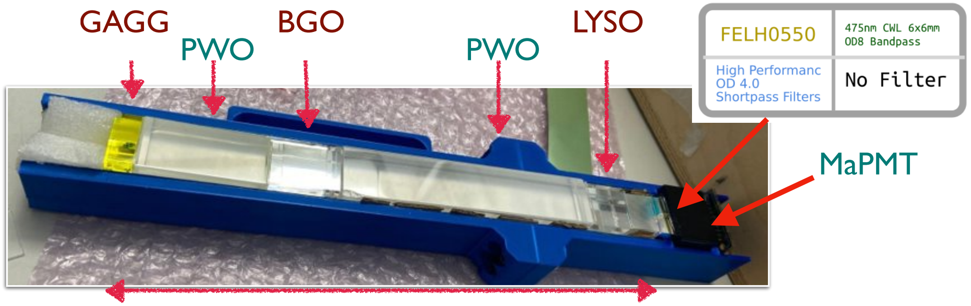
quantum dots for calorimetry



courtesy Y. Haddad, N U, Boston, USA



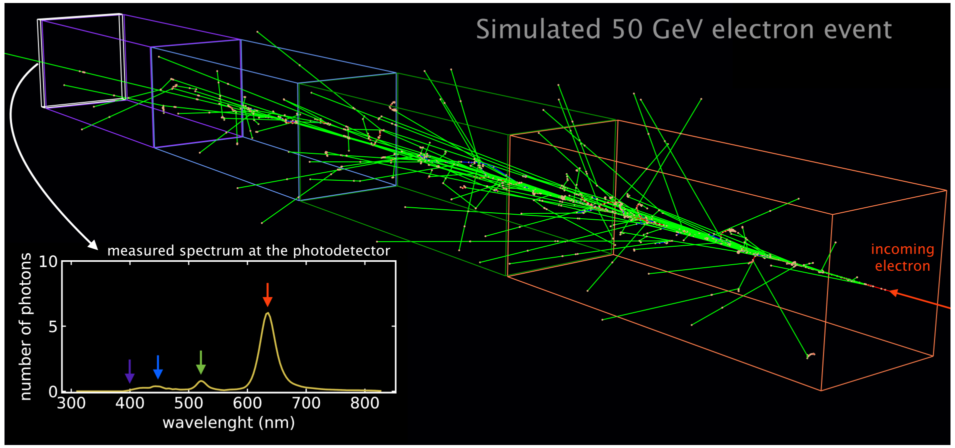
Beam test results (SPS) 2023

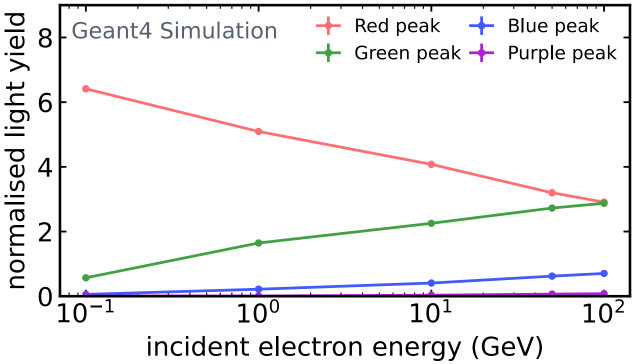


Light filters

FELH0550	475nm CWL 6x6mm OD8 Bandpass
High Performanc OD 4.0 Shortpass Filters	No Filter

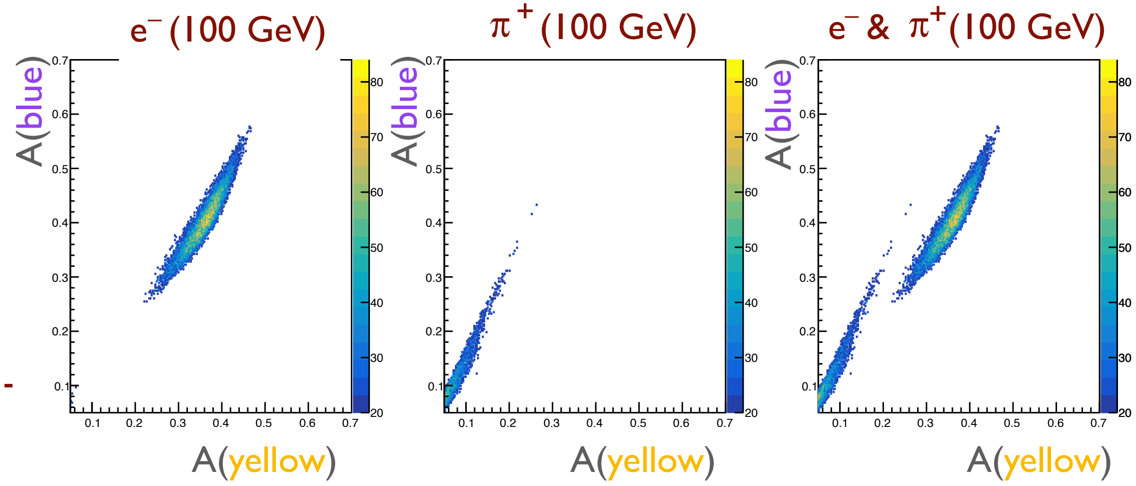
24 cm





"Chromatic" energy measurement

"Chromatic" electron - pion discrimination

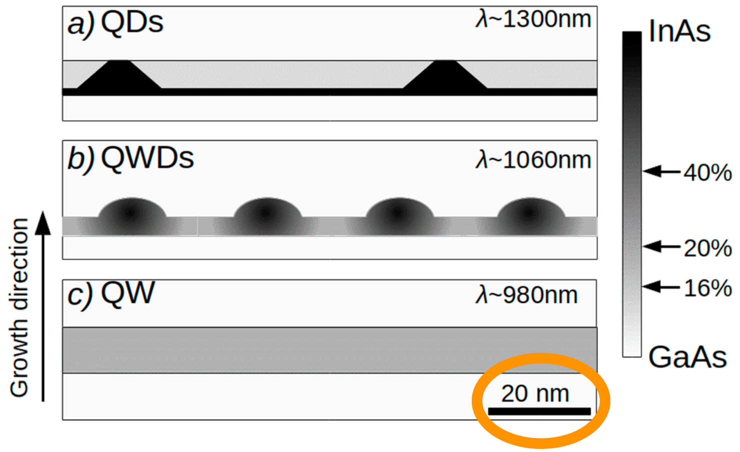


86% "chromatic" electron - pion discrimination

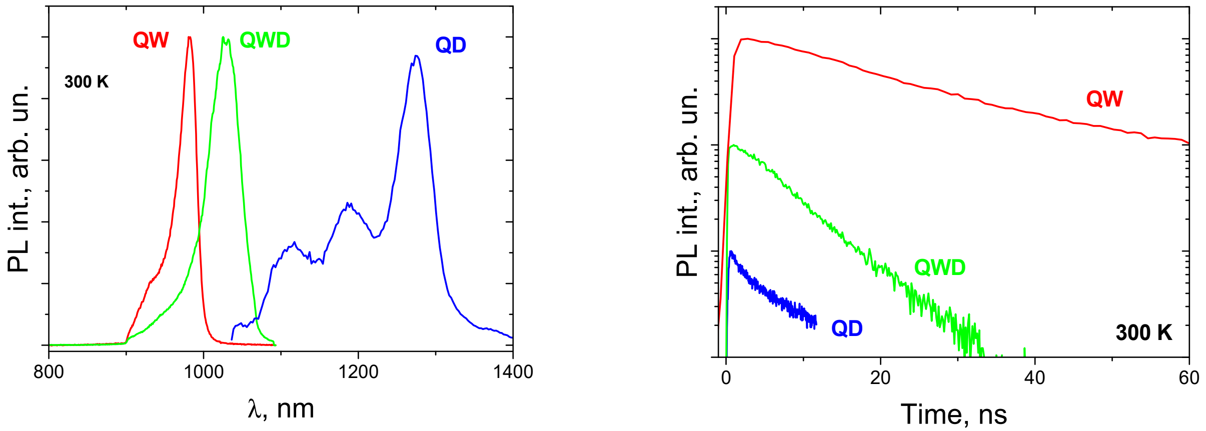
Active scintillators (QWs, QDs, QWDs, QCLs)

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

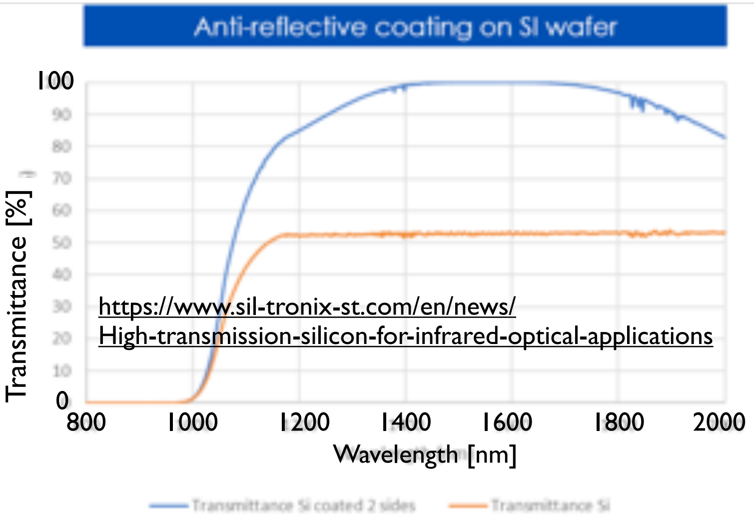
is it possible to produce active scintillating materials?
- electronically amplified / modulable
- pulsed / primed
- gain adapted in situ



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



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



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

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

QD’s are radiation resistant

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

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

Quantum dots and wells:

https://arxiv.org/abs/2202.11828

submicron pixels

DoTPiX

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

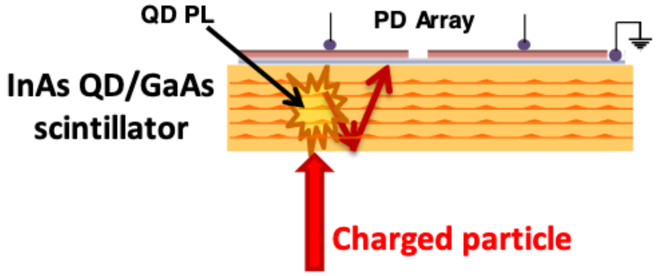
- as a hole-collecting electrode and
- as a channel current modulation gate

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

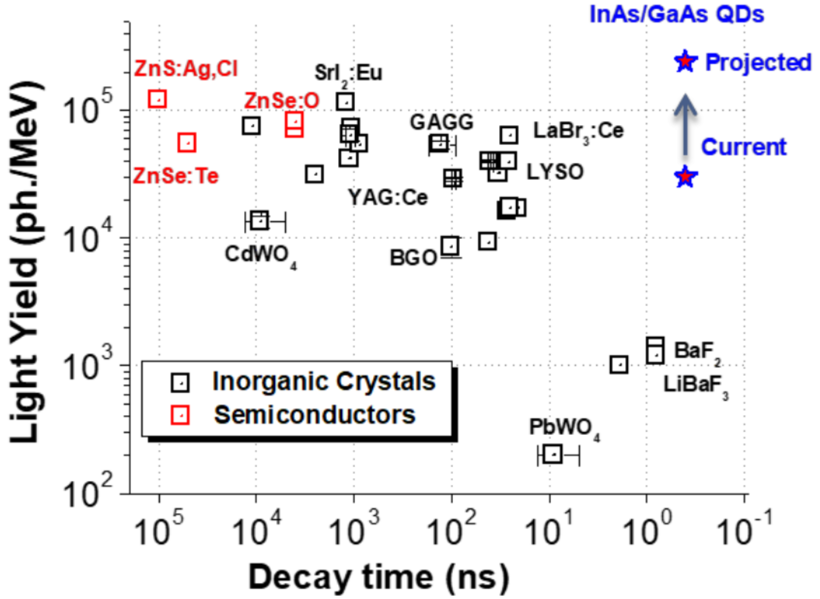
Novel Sensors for Particle Tracking: a Contribution to the Snowmass Community Planning Exercise of 2021, M.R. Hoeferkamp et al., arXiv:2202.11828

scintillating (chromatic) tracker

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



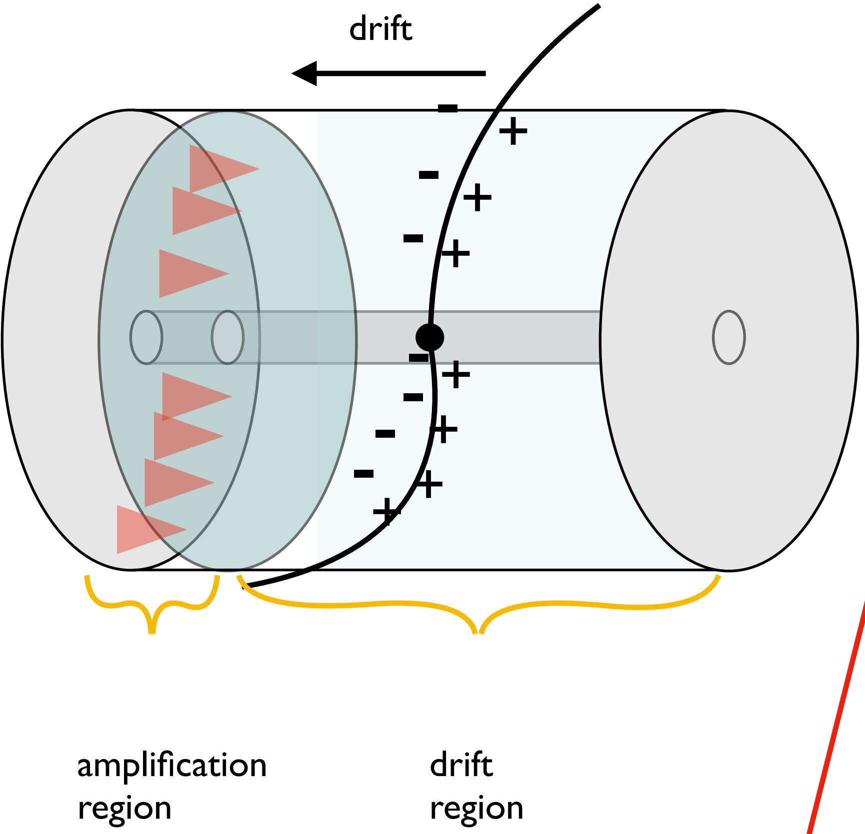
IR emission from InAs QD's integrated PD's (1-2 μm thick)

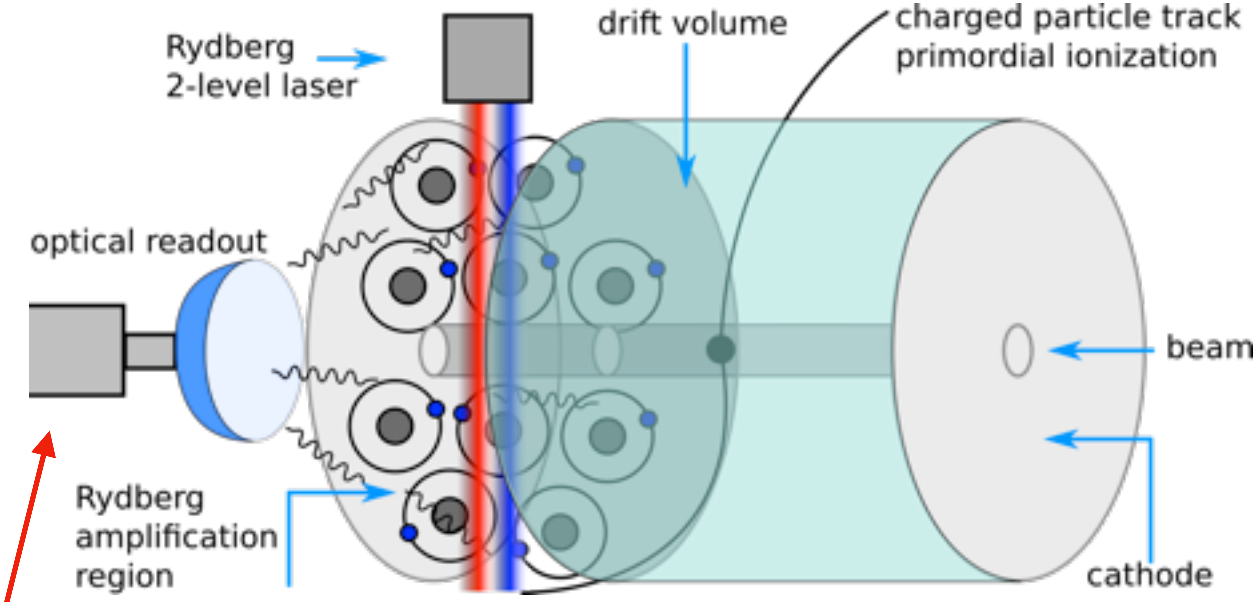


Rydberg atom TPC's

Georgy Kornakov / WUT

Act on the amplification region





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

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

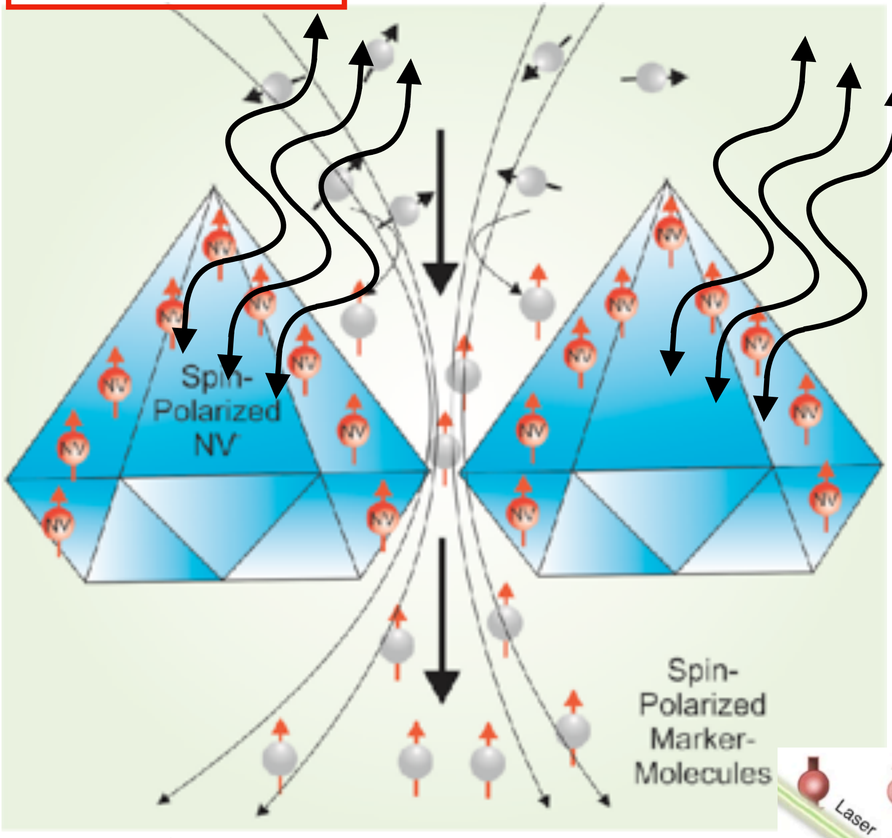
optically polarizable elements: Nitrogen-vacancy diamonds (NVD)

Georgy Kornakov / WUT

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

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

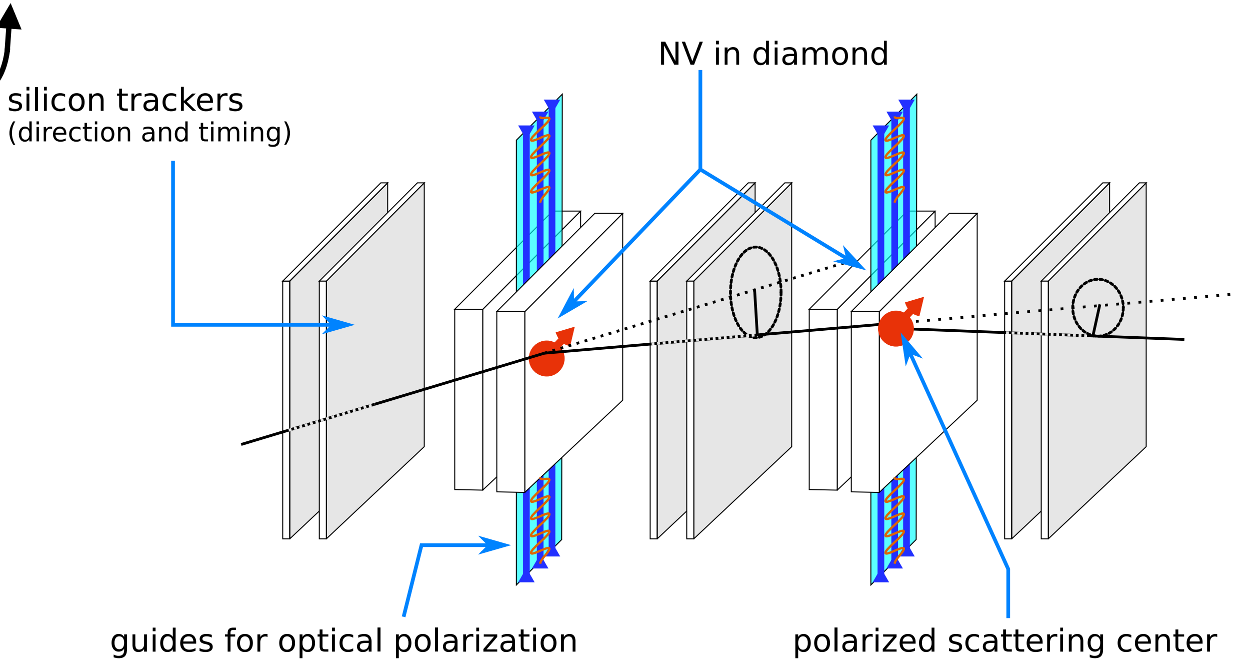
$10^{16} \sim 10^{18}$ / cm^3



© Dr. Christoph Nebel, Fraunhofer IAF

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

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

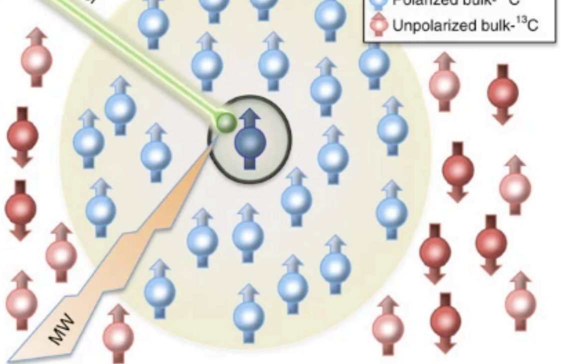


NV in diamond

silicon trackers
(direction and timing)

guides for optical polarization

polarized scattering center

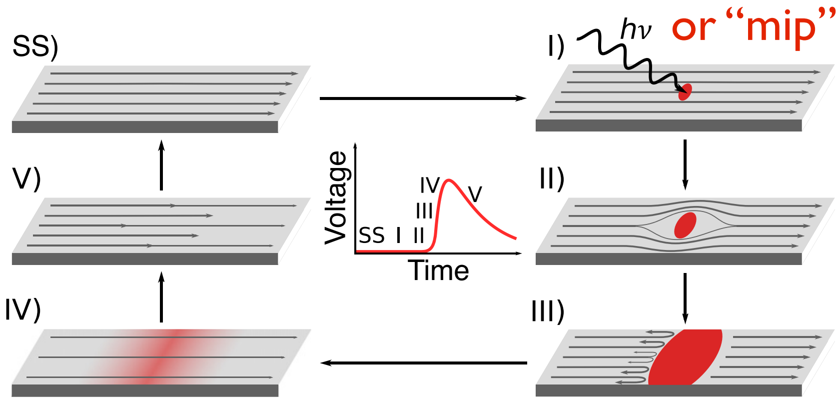


Local and bulk ^{13}C hyperpolarization in nitrogen-vacancy centred diamonds at variable fields and orientations, G. Alvarez et al., *Nature Communications* **6**, 8456 (2015)

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

x 10^2

Extremely low energy threshold detectors: SNSPD



quantum pixel ultra-sensitive tracking

Parameter	SOA 2020	Goal by 2025
Efficiency	98% @ 1550nm	>80 % @10μm
Energy Threshold	0.125 eV (10 μm)	12.5 meV (100 μm)
Timing Jitter	2.7 ps	$<$ 1ps
Active Area	1 mm^2	100 cm^2
Max Count Rate	1.2 Gcps	100 Gcps
Pixel Count	1 kilopixel	16 megapixel
Operating Temperature	4.3K	25 K

Snowmass2021 - Letter of Interest

Superconducting Nanowire Single-Photon Detectors

Contact Information:
Karl Berggren, berggren@mit.edu
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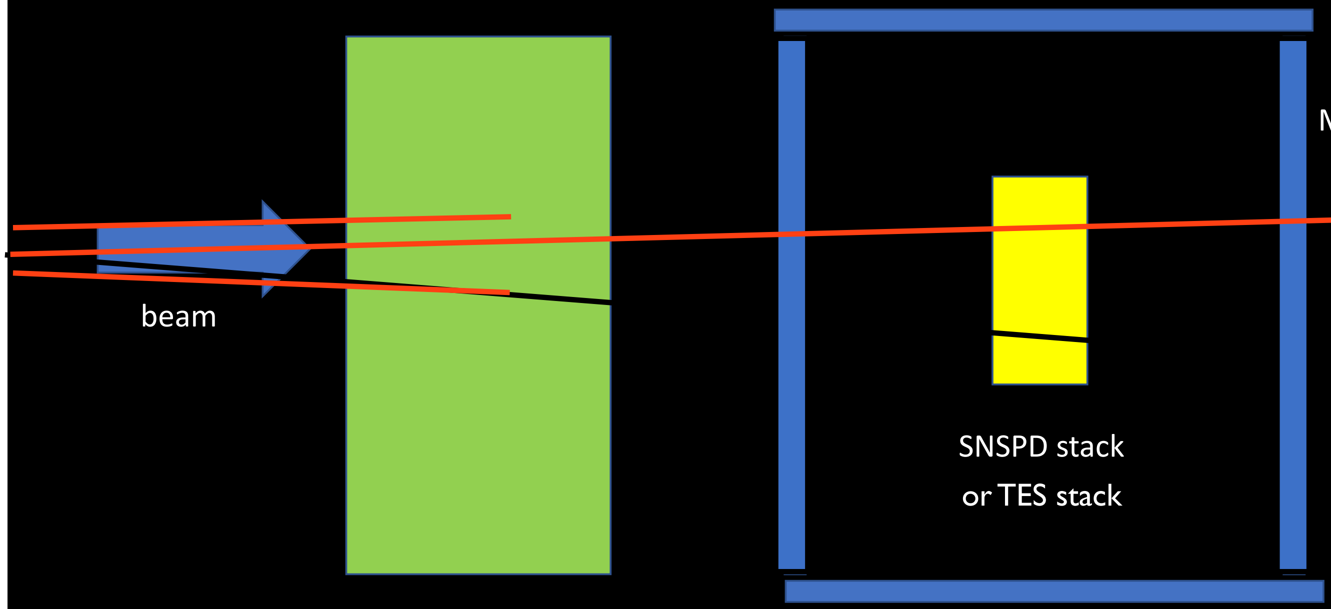
Matt Shaw, mattshaw@jpl.nasa.gov

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

Search for Beyond Standard Model milli-charged particles?



beam

Beam dump

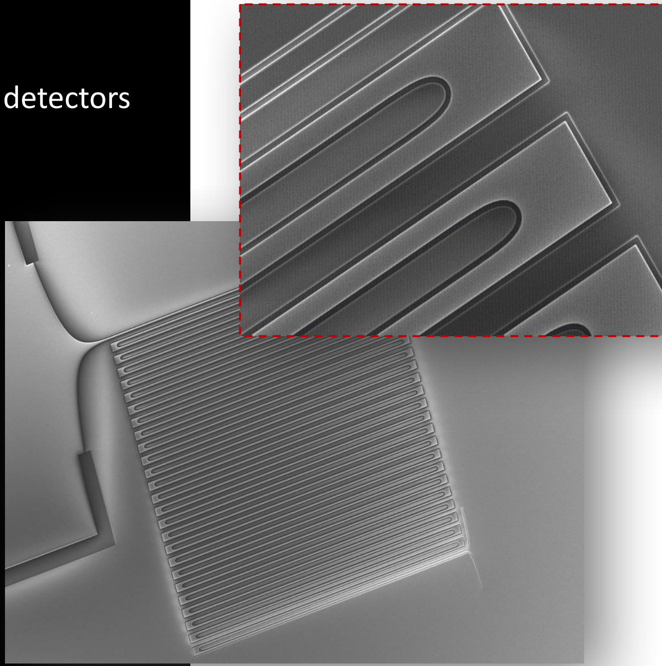
Muon detectors

Muon detectors

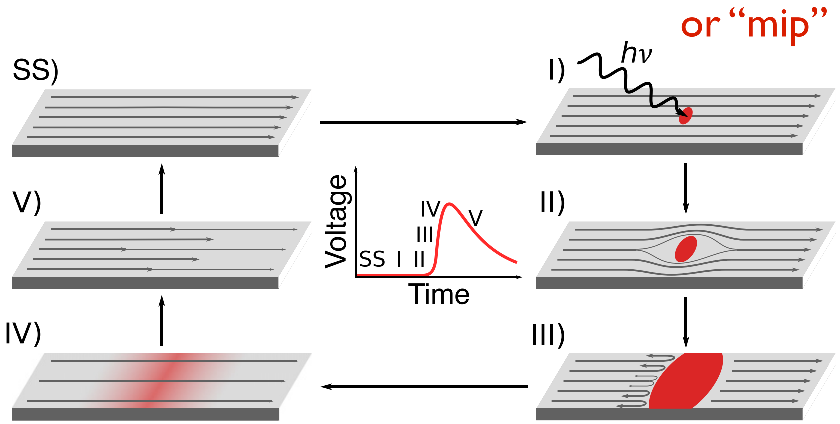
SNSPD stack
or TES stack

mip: ~20 keV/100 μm

x 10^6 sensitivity



Extremely fast detectors: SNSPD



or “mip”

quantum pixel ultra-sensitive tracking

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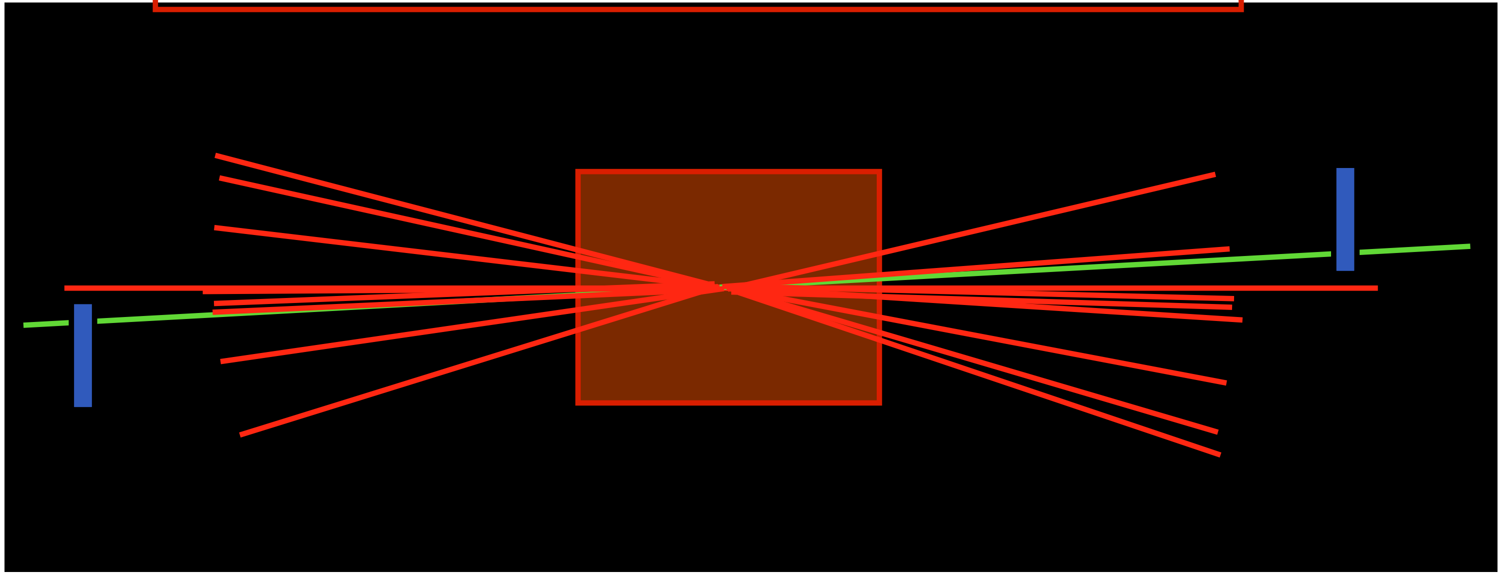
Matt Shaw, mattshaw@jpl.nasa.gov

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

QT4HEP22-- I. Shipsey

125

diffractive scattering via ps-resolution tracking in Roman pots



@ 2.8 K

arXiv:2312.13405v2
[physics.ins-det]
5 Apr 2024

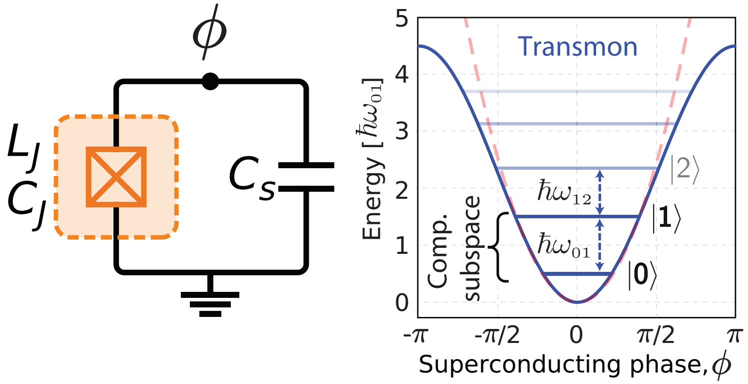
low energy particle physics: dark count rate is critical !
high energy particle physics: dark count rate is not a problem: high Tc is imaginable

quantum pixel ultra-sensitive tracking

Beyond existing sensors: using (superconducting) qubits

commonly used qubits: transmons

Josephson junction qubit



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

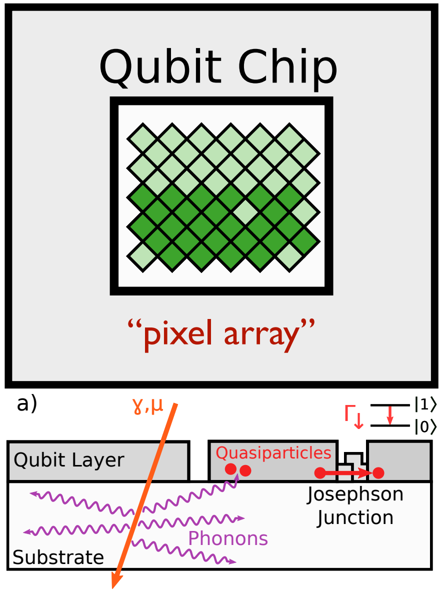
need to be able to define a computational subspace consisting of only two energy states (usually the two-lowest energy eigenstates) in between which transitions can be driven without also exciting other levels in the system: $|0\rangle$ and $|1\rangle$

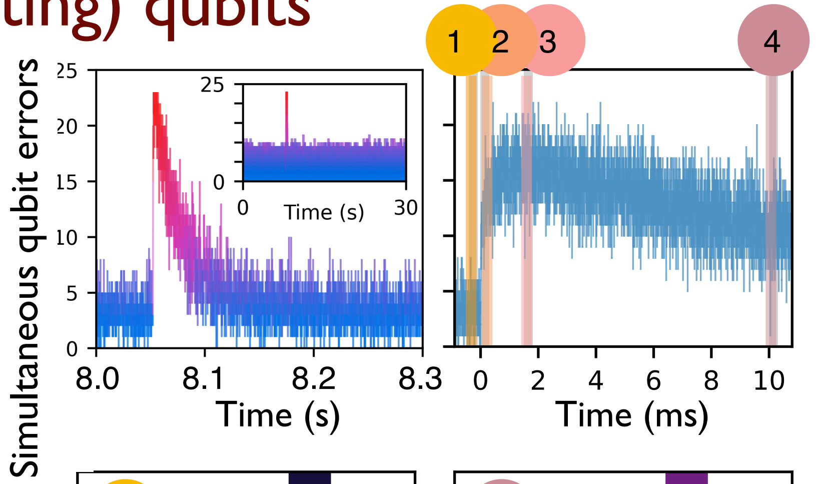
Energy scale: 25μeV (cosmic: 0.1~1 MeV)

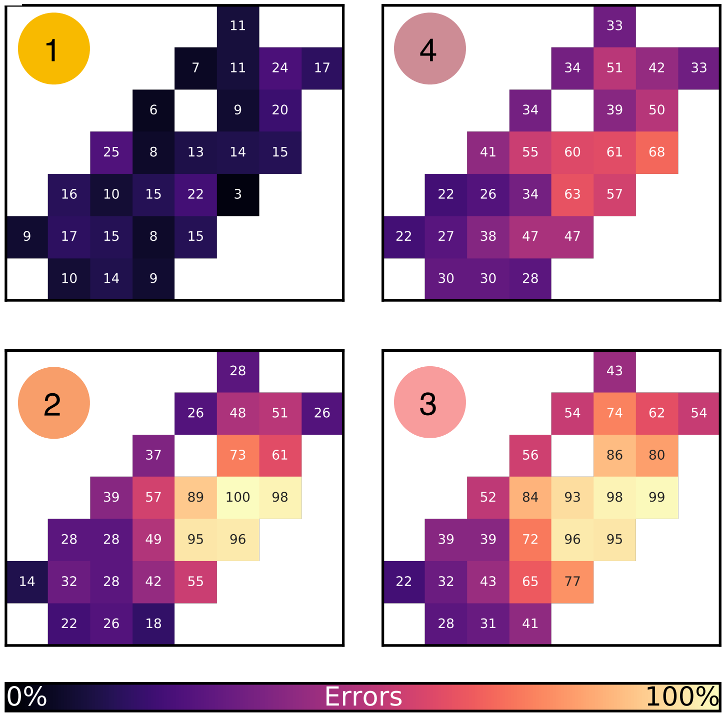
10^7 millicharged particles

A quantum engineer's guide to superconducting qubits, P. Krantz et al., https://arxiv.org/pdf/1904.06560

Google Sycamore processor (Quantum Computer)







Correlated errors in neighboring qubits in a 26 qubit sub-array: cosmic ray "tracker"

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

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

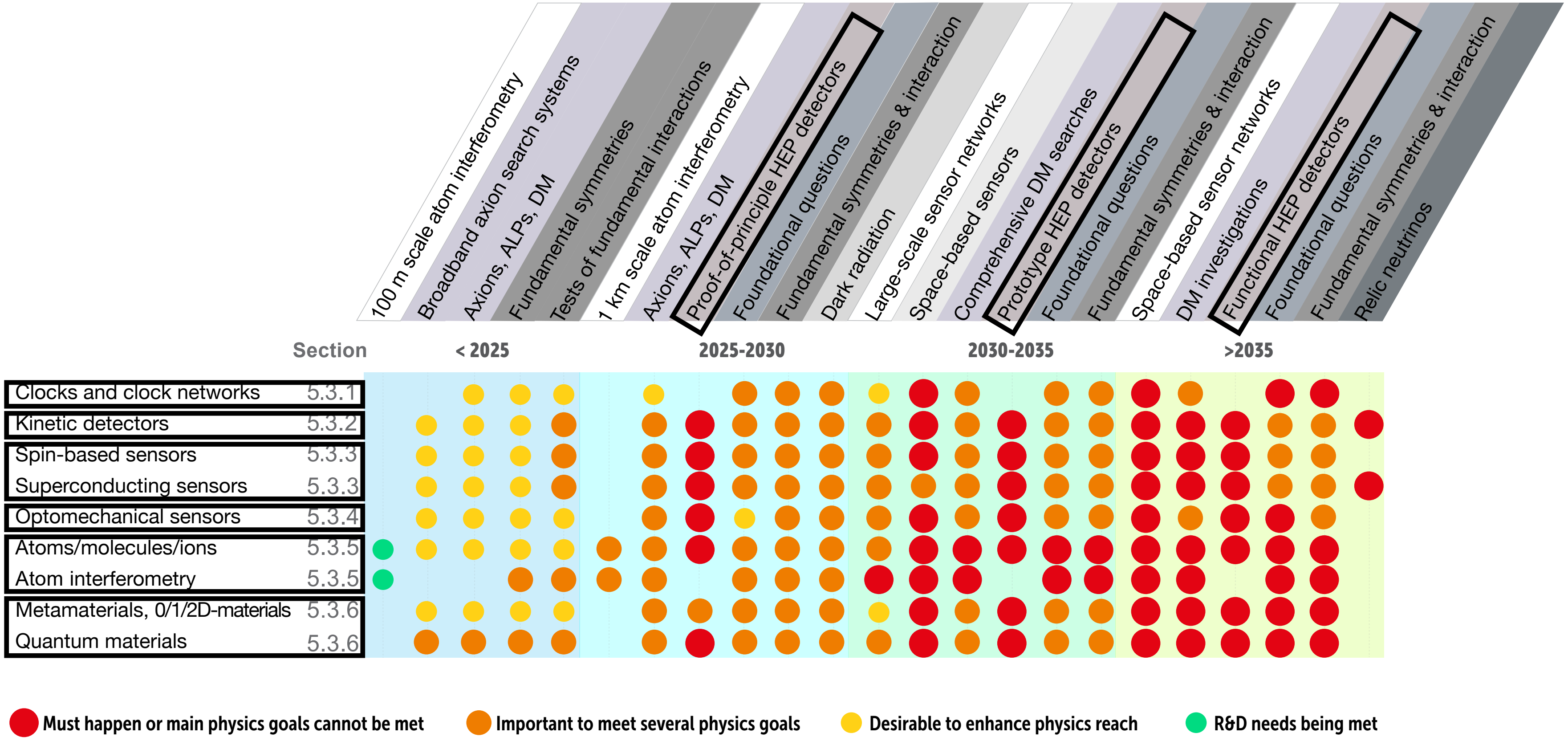
Quantum sensor R&D outlook

RECFA Detector R&D roadmap 2021

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

Chapter 5: Quantum and Emerging Technologies Detectors

focus on physics
<u>and</u> technology



① ② ③ ④ ⑤ ⑥

	Section	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
		< 2025					2025-2030						2030-2035						>2035					
Clocks and clock networks	5.3.1			🟡	🟡	🟡		🟡		🟠	🟠	🟠	🟡	🔴	🟠		🟠	🟠	🔴	🟠		🔴	🔴	
Kinetic detectors	5.3.2		🟡	🟡	🟡	🟠		🟠	🔴	🟠	🟠	🟠	🟠	🔴	🟠	🔴	🟠	🟠	🔴	🔴	🔴	🟠	🟠	🔴
Spin-based sensors	5.3.3		🟡	🟡	🟡	🟠		🟠	🔴	🟠	🟠	🟠	🟠	🔴	🟠	🔴	🟠	🟠	🔴	🔴	🔴	🟠	🟠	
Superconducting sensors	5.3.3		🟡	🟡	🟡	🟠		🟠	🔴	🟠	🟠	🟠	🟠	🟠	🟠	🔴	🟠	🟠	🔴	🔴	🔴	🟠	🟠	🔴
Optomechanical sensors	5.3.4		🟡	🟡	🟡	🟡		🟠	🔴	🟡	🟠	🟠	🟠	🔴	🟠	🔴	🟠	🟠	🔴	🟠	🔴	🔴	🟠	
Atoms/molecules/ions	5.3.5	🟢	🟡	🟡	🟡	🟡	🟠	🟠	🔴	🟠	🟠	🟠	🟠	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	
Atom interferometry	5.3.5	🟢			🟠	🟠	🟠	🟠		🟠	🟠	🟠	🔴	🔴	🔴		🔴	🔴	🔴	🔴		🔴	🔴	
Metamaterials, 0/1/2D-materials	5.3.6		🟡	🟡	🟡	🟡		🟠	🟠	🟠	🟠	🟠	🟡	🔴	🟠	🔴	🟠	🟠	🔴	🔴	🔴	🔴	🔴	
Quantum materials	5.3.6		🟠	🟠	🟠	🟠		🟠	🔴	🟠	🟠	🟠	🟠	🔴	🟠	🔴	🟠	🟠	🔴	🔴	🔴	🔴	🔴	

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

Proposal for DRD5: R&D on quantum sensors

ECFA Roadmap topics → Proposal themes → Proposal WP's

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

Roadmap topics

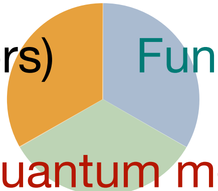
Proposal WP's

Sensor family → Work Package ↓	clocks & clock networks	superconducting & spin-based sensors	kinetic detectors	atoms / ions / molecules & atom interferometry	opto-mechanical sensors	nano-engineered / low-dimensional / materials
WP1 *Atomic, Nuclear and Molecular Systems in traps & beams*	X			X	(X)	
WP2 *Quantum Materials (0-, 1-, 2-D)*		(X)	(X)		X	X
WP3 *Quantum superconducting devices*		X				(X)
WP4 *Scaled-up massive ensembles* (spin-sensitive devices, hybrid devices, mechanical sensors)		X	(X)	X	(X)	X
WP5 *Quantum Techniques for Sensing*	X	X	X	X	X	
WP6 *Capacity expansion*	X	X	X	X	X	X

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

WP → sub-WP → sub-sub-WP

Potential HEP impact



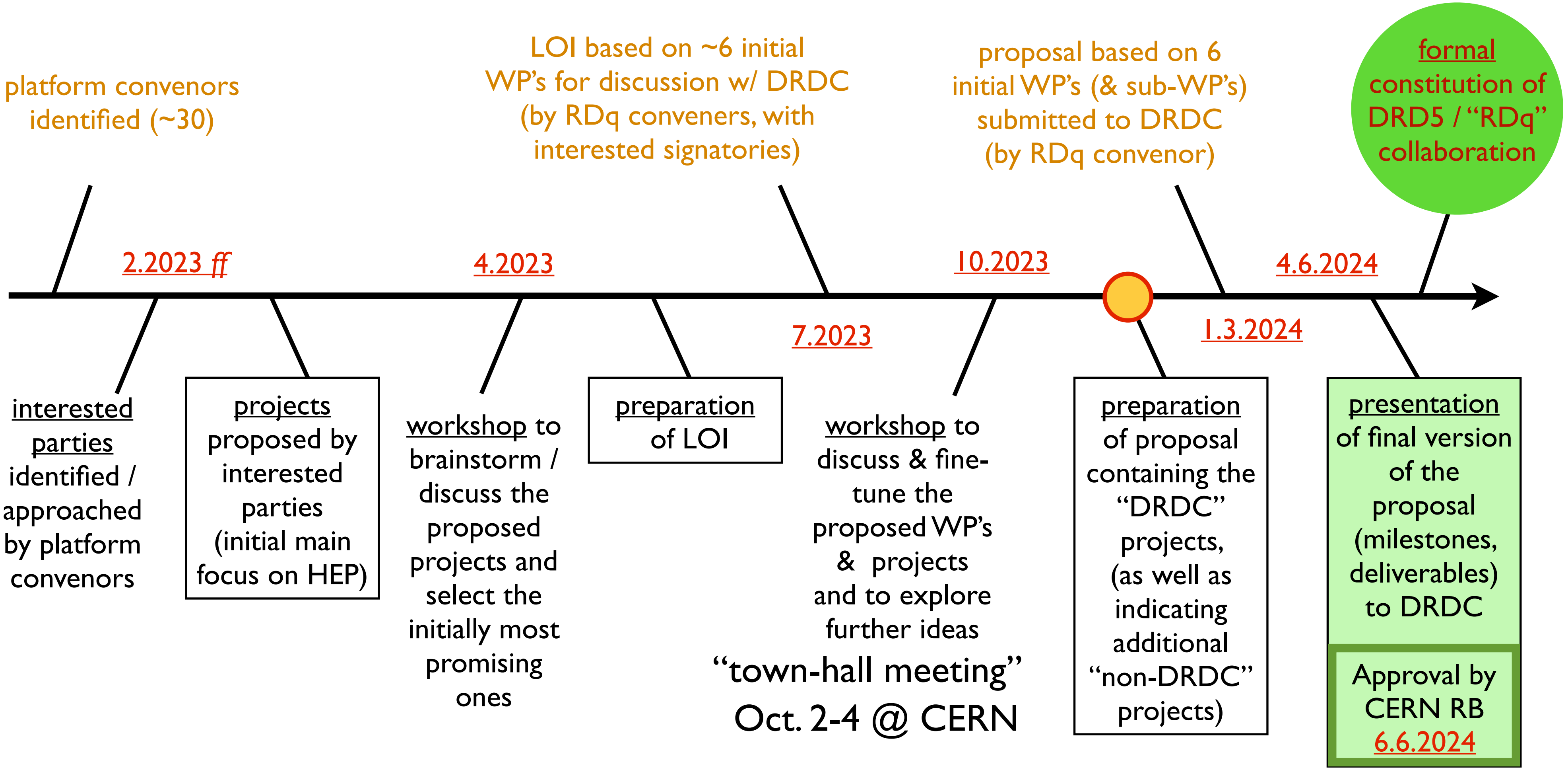
HEP function / Work package	Tracking	Calorimetry	Timing	PID	Helicity
WP 1 (Quantum systems in traps and beam)	Rydberg TPC	BEC WIMP scattering (recoil)	O(fs) reference clock for time-sensitive synchronization (photon TOF)	Rydberg dE/dx amplifiers	
WP2 (Quantum materials: 0-, 1- and 2-D)	“DotPix”; improved GEM’s; chromatic tracking (sub-pixel); active scintillators	Chromatic calorimetry	Suspended / embedded quantum dot scintillators	Photonic dE/dx through suspended quantum dots in TPC	
WP 3 (Superconducting quantum devices)	O(ps) SNSPD trackers for diffractive scattering (Roman pot)	FIR, UV & x-ray calorimetry	O(ps) high Tc SNSPD	Milli- & microcharged particle trackers in beam dumps	
WP 4 (scaled-up bulk systems for mip’s)	Multi-mode trackers (electrons, photons)	Multi-mode calorimeters (electrons, photons, phonons)	Wavefront detection (e.g. O(ps) embedded devices)		Helicity detector via ultra-thin NV optically polarized scattering / tracking stack
WP 5 (Quantum techniques)				Many-to-one entanglement detection of interaction	
WP 6 (capacity building)	Technical expertise of future workforce (detector construction); broadened career prospects and thus enhanced attractiveness; cross-departmental networking and collaboration; broadened user base for infrastructure (beam tests, dilution refrigerators, processing technologies)				

(under way; in preparation; under discussion or imaginable applications; long-range potential)

timeline

Two goals for DRD5 (Detector R&D on Quantum Sensors) in 2023/2024 :

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



2.2023 ff

platform convenors identified (~30)

interested parties identified / approached by platform convenors

projects proposed by interested parties (initial main focus on HEP)

4.2023

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

preparation of LOI

7.2023

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

10.2023

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

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

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

1.3.2024

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

4.6.2024

presentation of final version of the proposal (milestones, deliverables) to DRDC

Approval by CERN RB 6.6.2024

formal constitution of DRD5 / "RDq" collaboration

call for wide participation in DRD5

New opportunities for HEP and for low energy physics

WP's & structure

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

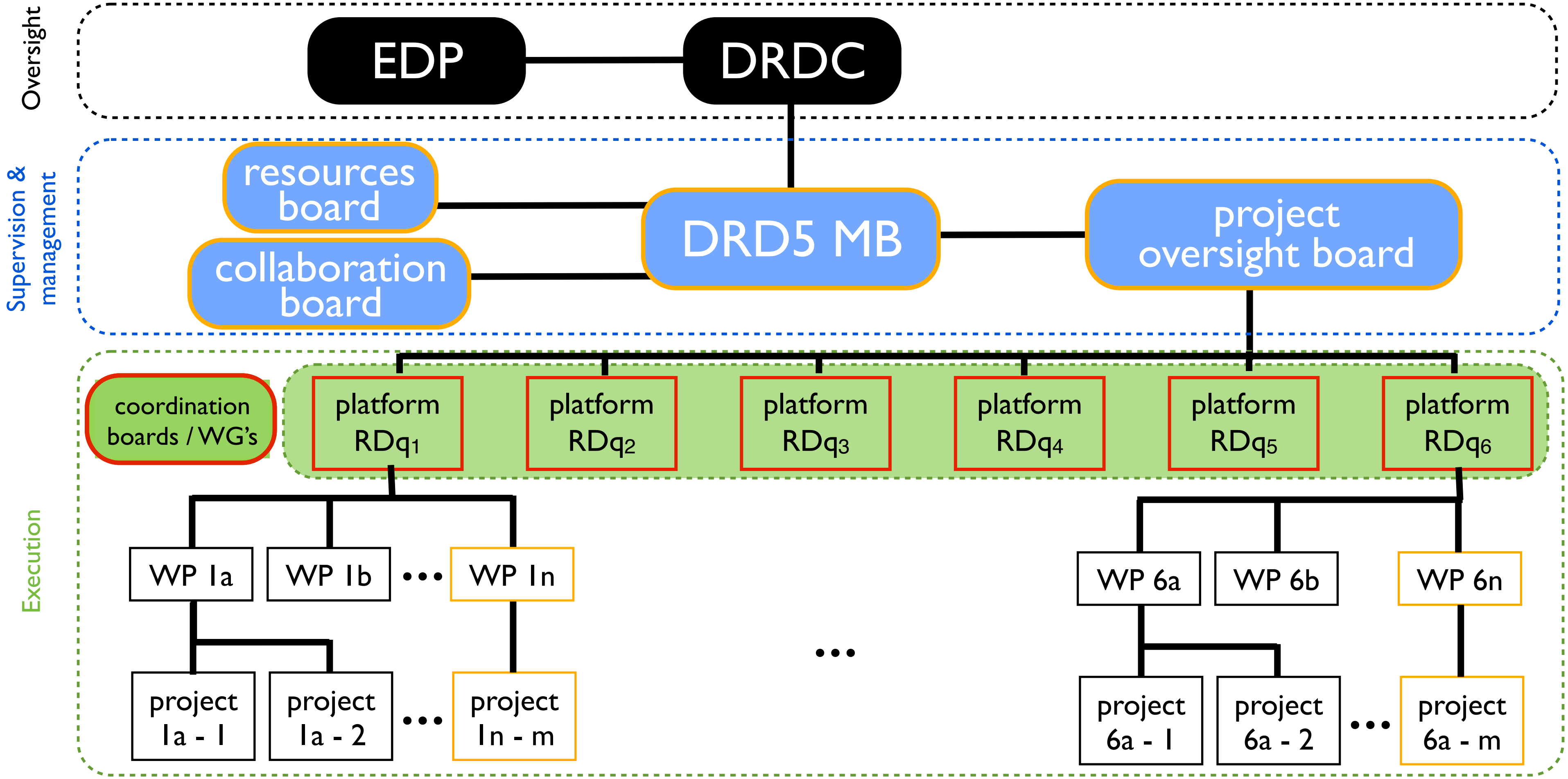
WP2 Quantum materials (0-, 1-, 2-D) (Engineering at the atomic scale)

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

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

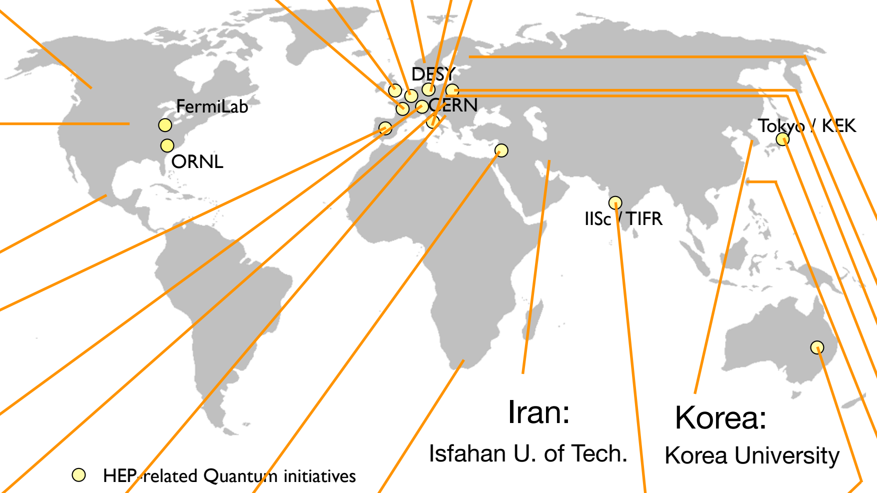
WP5 Quantum techniques for sensing (back action evasion, squeezing, entanglement, Heisenberg limit)

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



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

DRD5: 100 involved groups



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

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

Canada:
McGill Univ.
TRIUMF

USA:
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ORNL
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Caltech
MIT
Arizona State Univ.
Yale
Univ. of Arizona
NIST
LBNL
Univ. of Delaware
FNAL
SLAC

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U. de Cartagena
U. de Valencia
U. de Lleida

Switzerland:
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U. of Zürich
CERN
ETHZ

Netherlands:
U. of Groningen

Norway:
Oslo University

Austria:
IQOQI Vienna

Croatia:
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Technion, Haifa

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INFN Padova
Univ. Roma 1 & 3
Univ. Napoli
INFN Roma Tor Vergata
INFN LNF
INFN Trento (TIFPA)
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U. of Camerino

Finland:
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VTT

Poland:
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Nat. Lab. FAMO / Torun

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University West Bohemia

Japan:
QUP / KEK
Kyoto University
Tokyo University / ICEPP

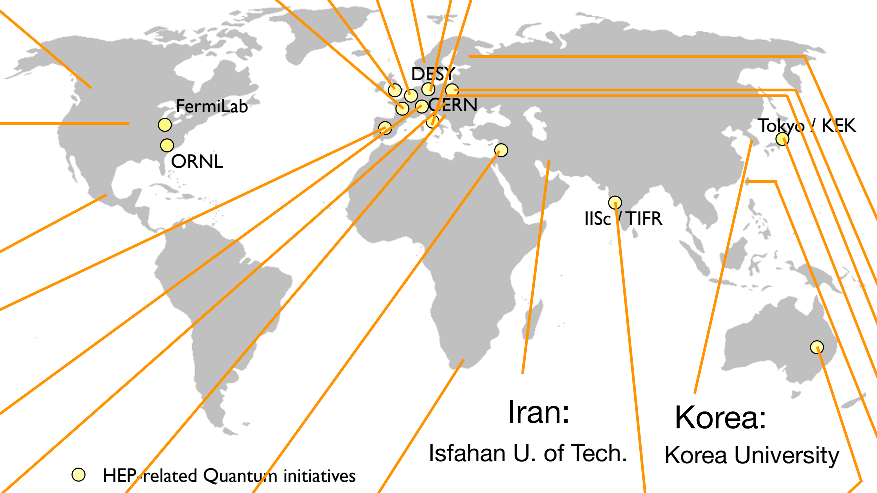
Taiwan:
Academia Sinica & NTU

DRD5: 100 involved groups

Collaboration currently being put together, combines diverse communities, including HEP.

Many novel developments that benefit both quantum technologies and particle physics.

Open to all interested parties (and it's free to join!)



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- Yale
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- U. de Lleida

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- ETHZ

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- IQOQI Vienna

Croatia:
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Israel:
- Technion, Haifa

South Africa:
- U. of Cape Town

Iran:
- Isfahan U. of Tech.

India:
- IITTP, Tirupati
- IISER, Kolkata
- TIFR, Mumbai
- University SOA Bhuvaneswar

Korea:
- Korea University

Australia:
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- Leibnitz Univ. Hannover
- KIT, Karlsruhe
- TU München
- DESY
- MPP Garching
- HU Berlin
- FBH Berlin
- Univ. Heidelberg
- Univ. Tübingen
- Univ. Düsseldorf
- Univ. Mainz
- Univ. Bremen / ZARM
- Semiconductor Lab HLL / MPG
- TU Darmstadt

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- INFN Lecce
- INFN Roma Tor Vergata
- U. of Camerino

Finland:
- Helsinki Inst. of Physics
- VTT

Poland:
- Warsaw TU
- Nat. Centre Nucl. Research / Warsaw
- Nat. Lab. FAMO / Torun

Czech Republic:
- Czech Tech. University
- University West Bohemia

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

Taiwan:
- Academia Sinica & NTU

thank you!

Ultralight Dark Matter

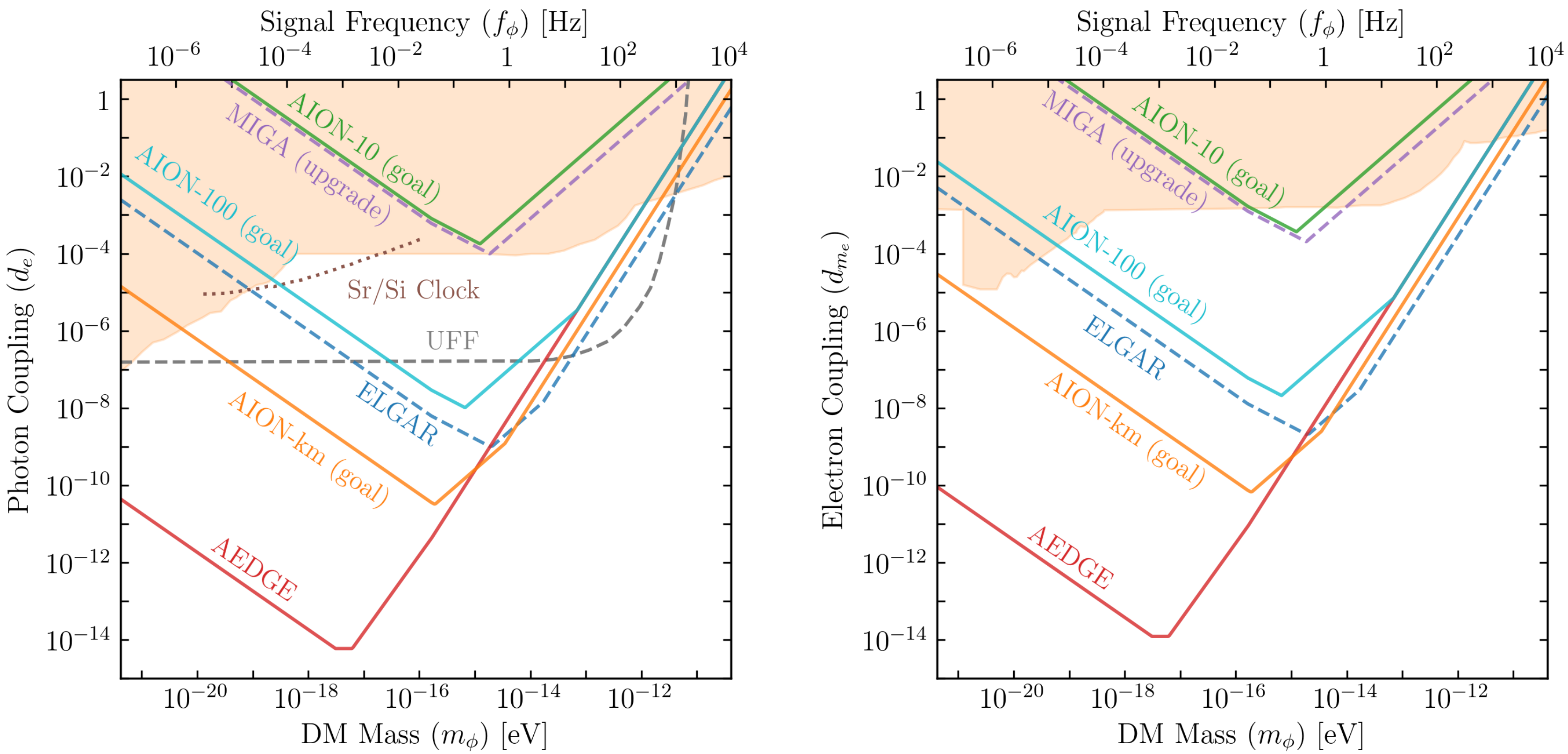


Figure 10. *Sensitivities to the possible couplings of scalar ULDM to photons (left panel) and to electrons (right panel) of the terrestrial AION [181], MIGA [182] and ELGAR [180] experiments, and of the AEDGE space-borne concept [5]. Also shown is a combination of the current constraints from MICROSCOPE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

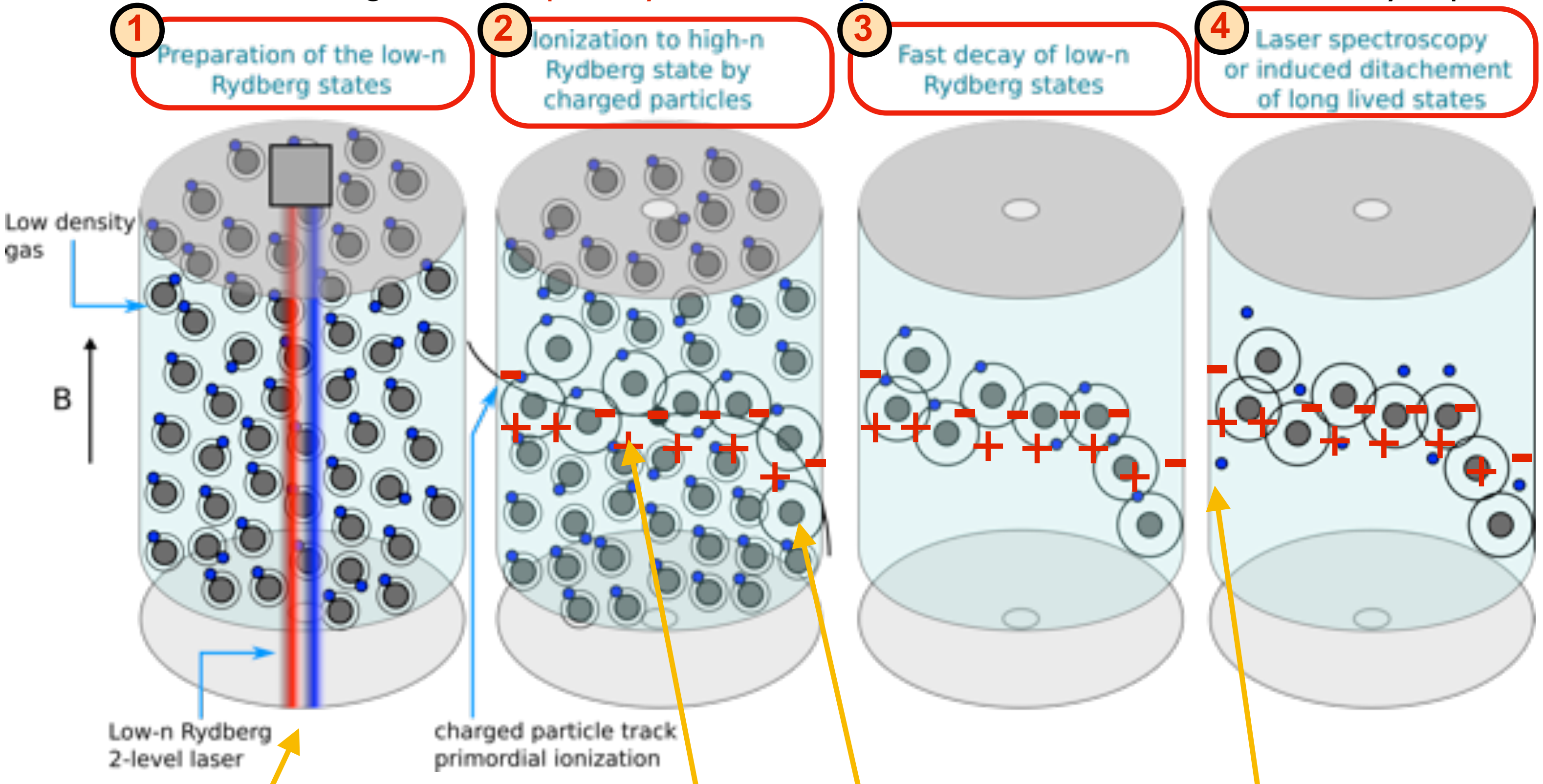
arXiv:2201.07789v1 [astro-ph.IM] 19 Jan 2022

Rydberg atom TPC’s

Georgy Kornakov / WUT

Act on the drift region

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



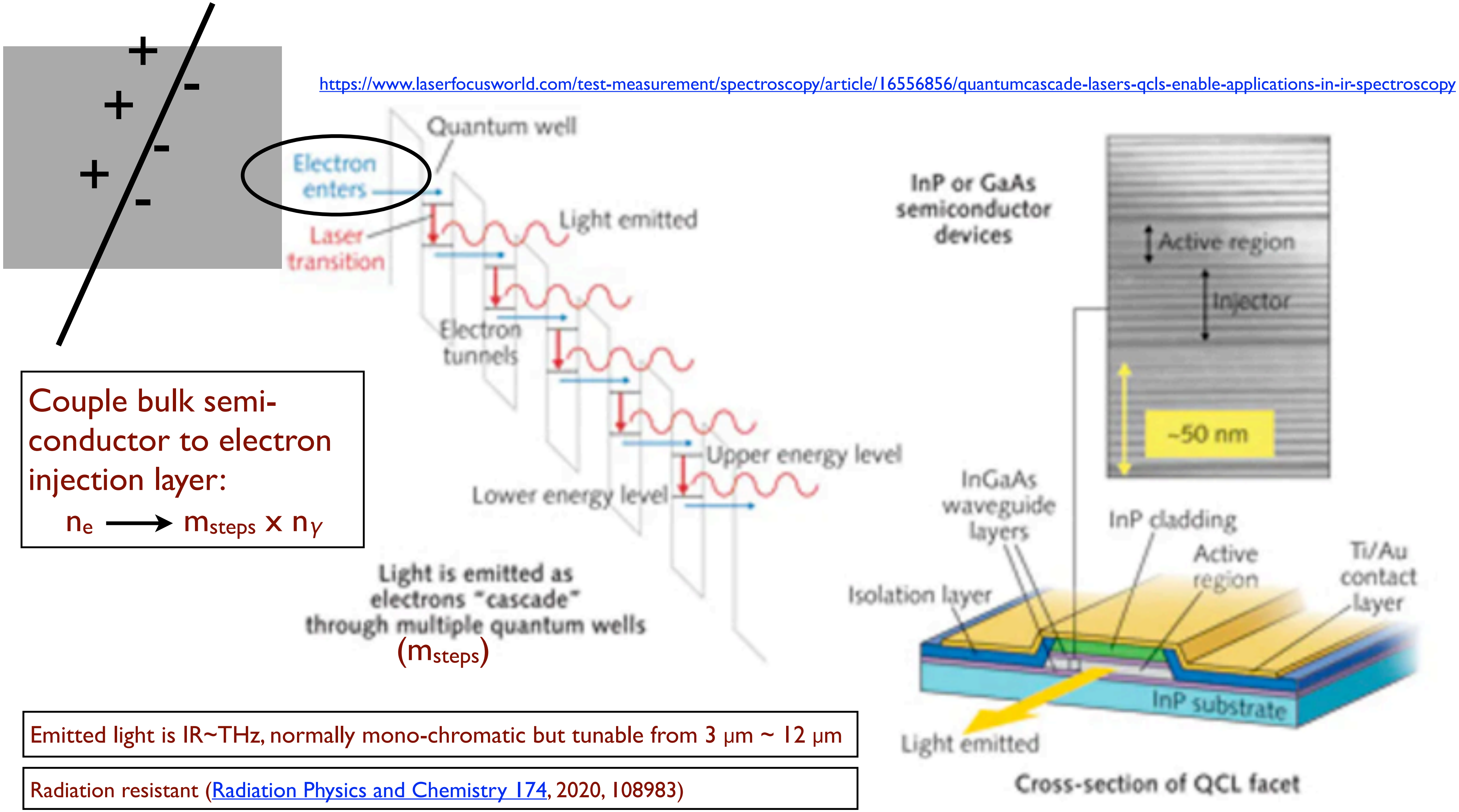
reduction of ionization and atomic excitation threshold

ionization + excitation;
natural decay of unmodified atoms

photo-ionization of excited atoms

Active scintillators (QCLs, QWs, QDs, QWDs)

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



Cross-section of QCL facet

Couple bulk semi-conductor to electron injection layer:

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

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

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

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

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

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

quantum sensors (an electromagnetic perspective)

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

Stafford Withington (Cambridge)