Quantum sensors for (low and high-energy) particle physics experiments at CERN

M. Doser, CERN

Kitzbühel, 28.6.2022

Some words on the landscape

Clarification of terms

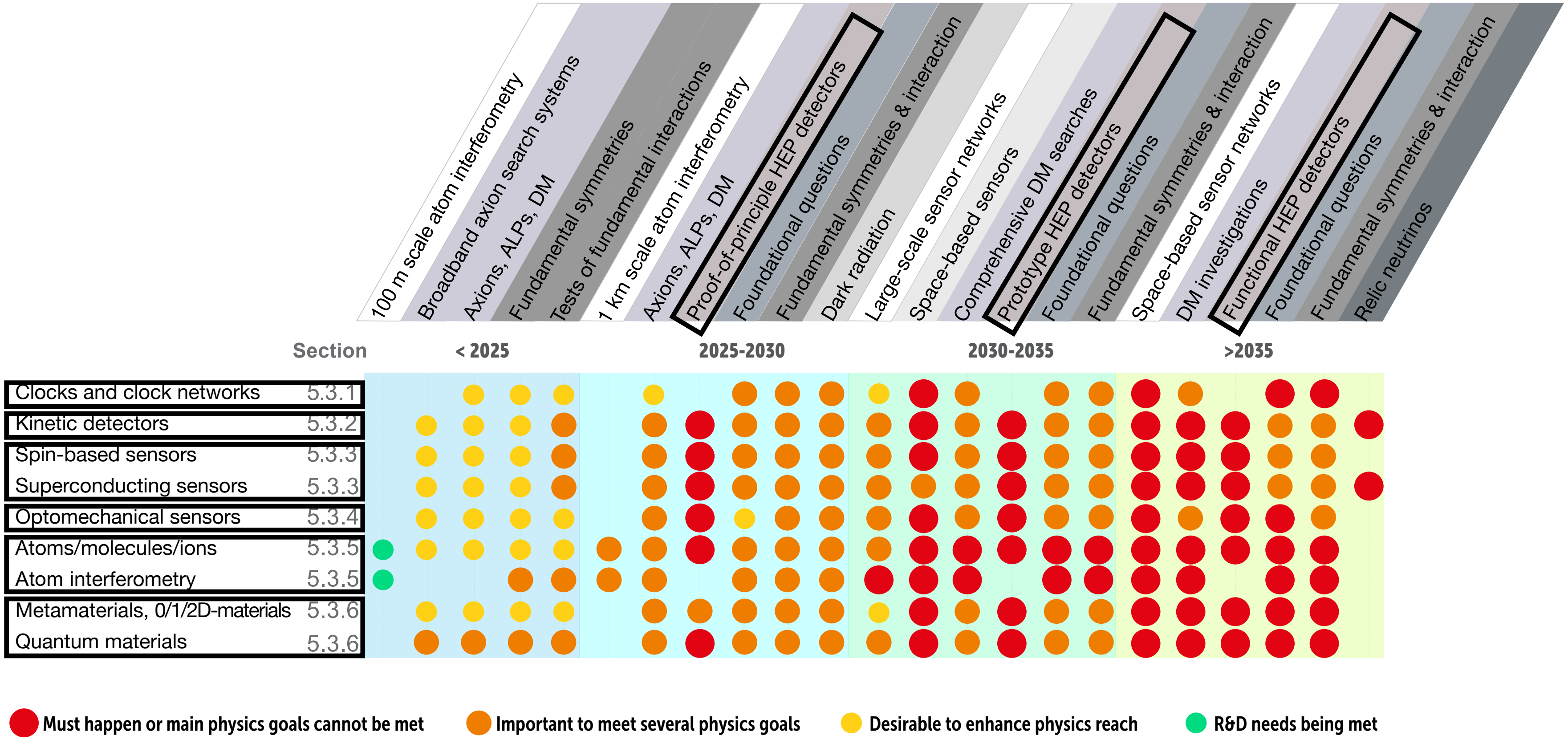
Quantum sensors for low energy particle physics

Quantum detectors for high energy particle physics

RECFA Detector R&D roadmap 2021

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

Chapter 5: Quantum and Emerging Technologies Detectors



	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

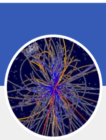
@ CERN: PBC, large low energy physics community…

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)

CERN quantum initiative

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

CERN | 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

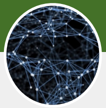
- Identify and develop techniques for **quantum simulation** in collider physics, QCD, cosmology within and beyond the SM
- Co-develop quantum computing and sensing approaches by providing **theoretical foundations** to the identifications of the areas of interest

Simulation & Theory

- 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: 2.5 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/

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

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

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

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

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

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)

start with low energy particle physics

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

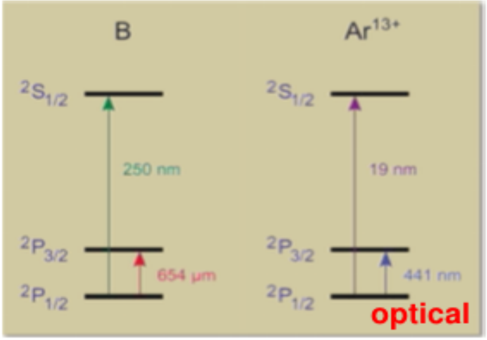
particles, atoms, ions, nuclei:

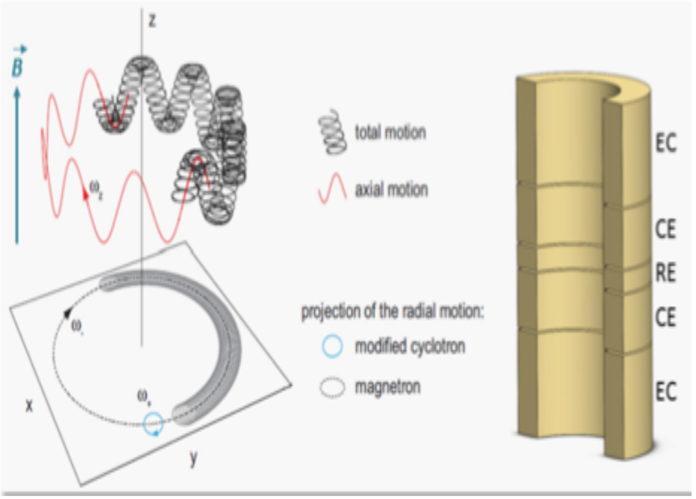
tests of QED, T-violation, P, Lorentz-violation, DM searches

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

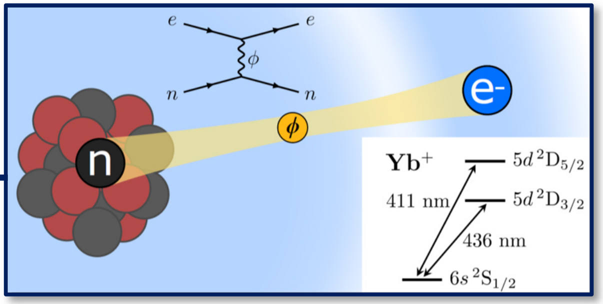
https://iopscience.iop.org/journal/2058-9565/page/Focus-on-Quantum-Sensors-for-New-Physics-Discoveries

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

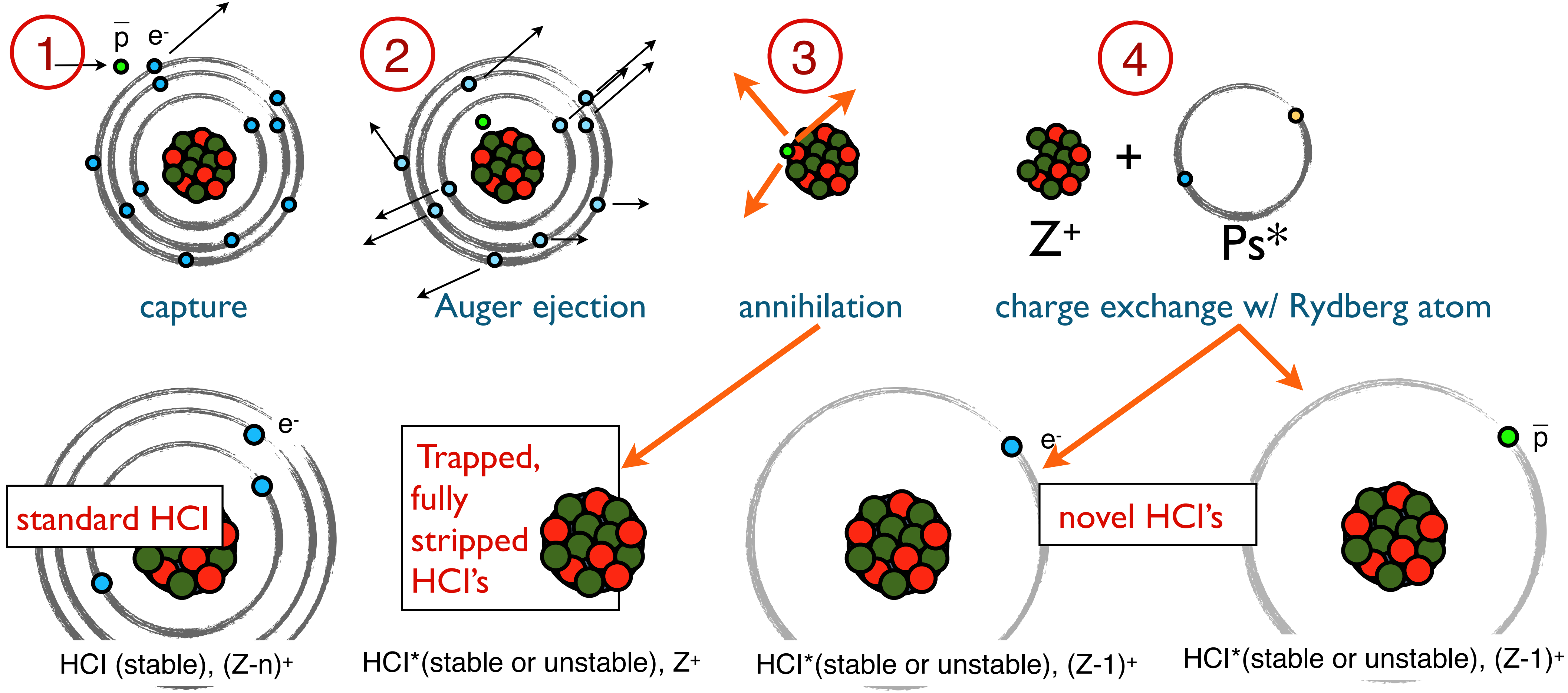
https://indico.cern.ch/event/999818/ Marianna Safronova (University of Delaware)

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

Trapped, fully stripped HCI's

novel HCI's

HCI (stable), (Z-n)+

HCI*(stable or unstable), Z+

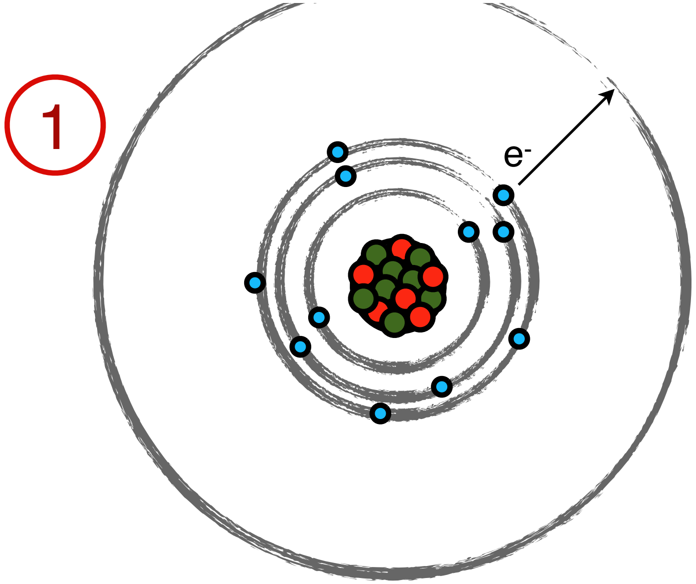
HCI*(stable or unstable), (Z-1)+

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

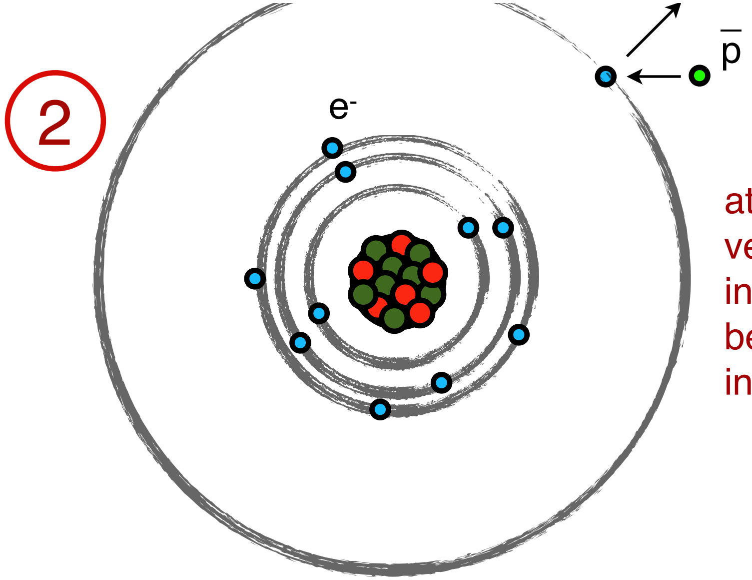
M. Doser, Prog. Part. Nucl. Phys, (2022), https://doi.org/10.1016/j.ppnp.2022.103964

Quantum sensors for new particle physics experiments: Penning traps

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



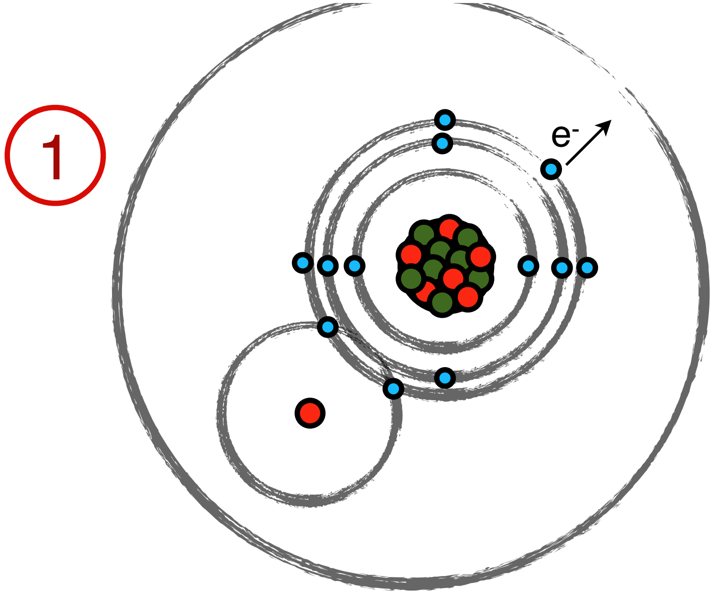
Rydberg excitation



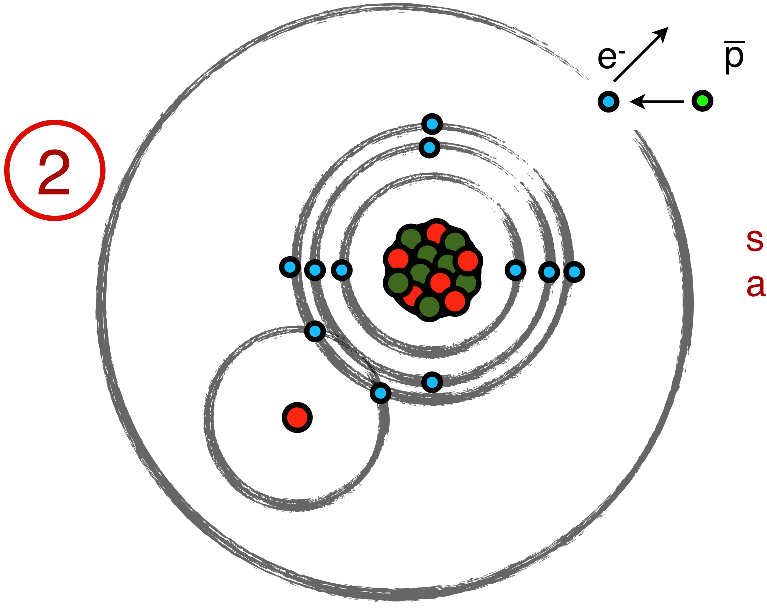
charge exchange

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

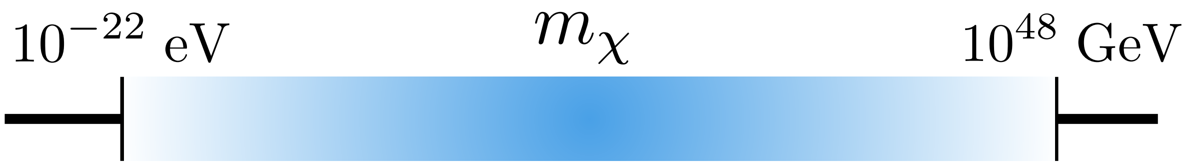


charge exchange

similar approach as eEDM in molecules

RF cavities:

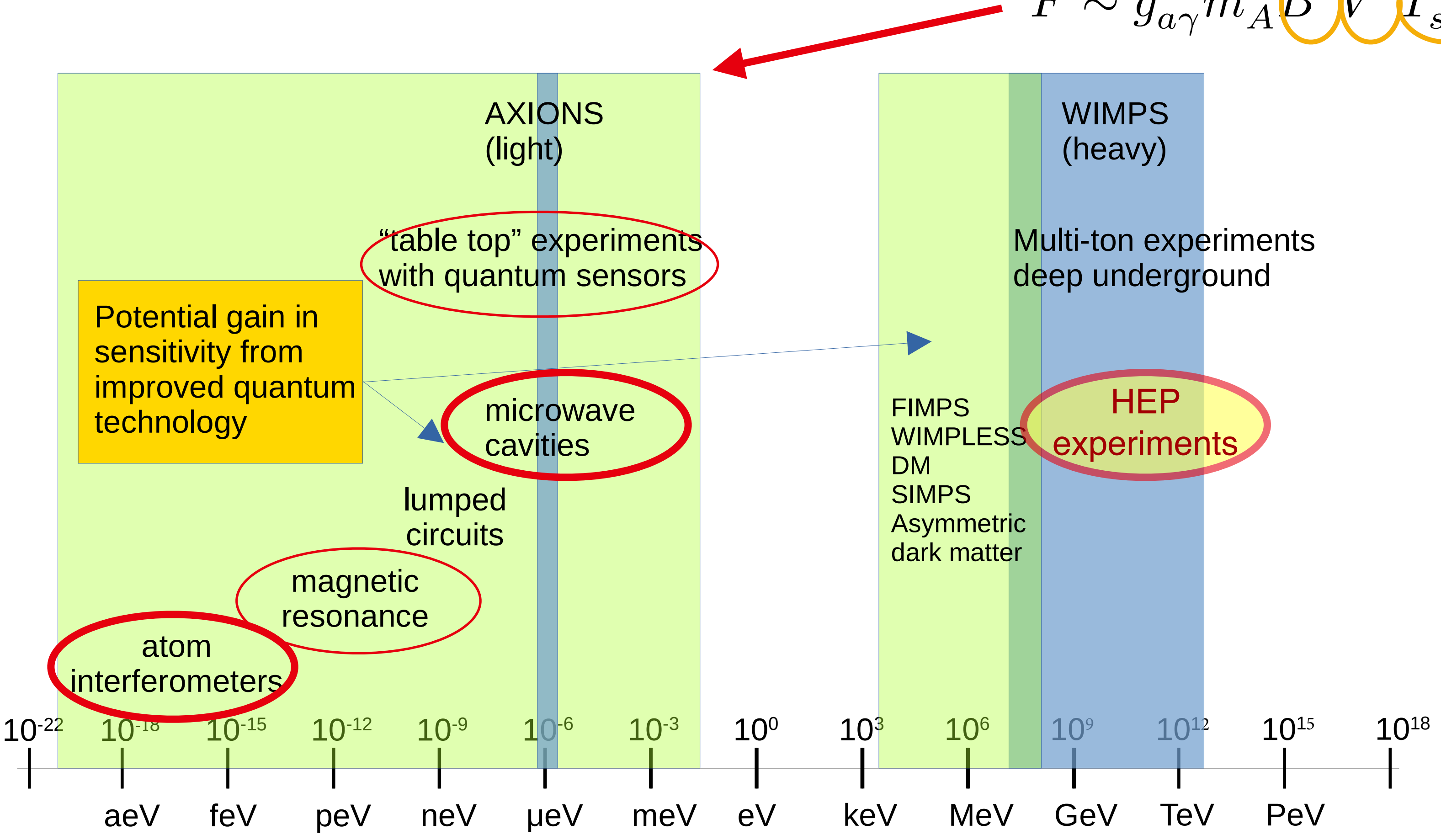
Axions, ALP's, DM & non-DM UL-particle searches

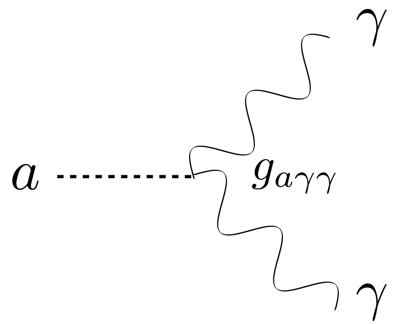


cavity size = axion size
axion mass = unknown

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

system noise temperature
cryo-amplifiers JJPA





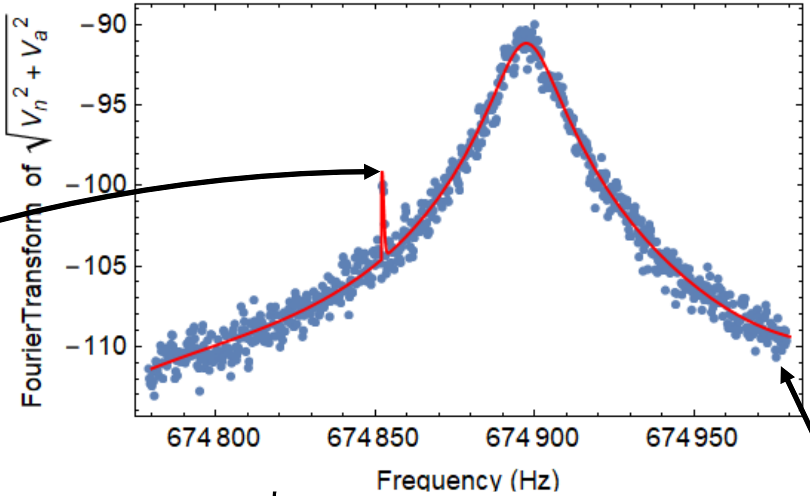
(but not only…)

Tunability!

Quantum sensors for new particle physics experiments: Penning traps

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

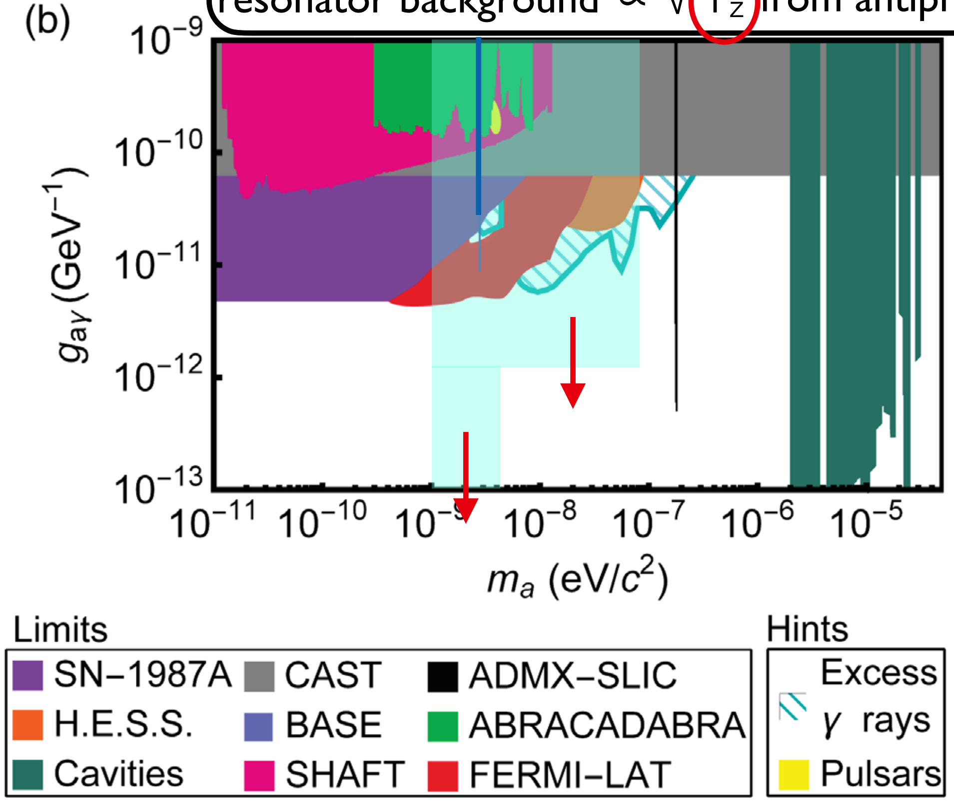
J. Devlin *et al.*, BASE collaboration, Physical Review Letters 126, 041301 (2021)

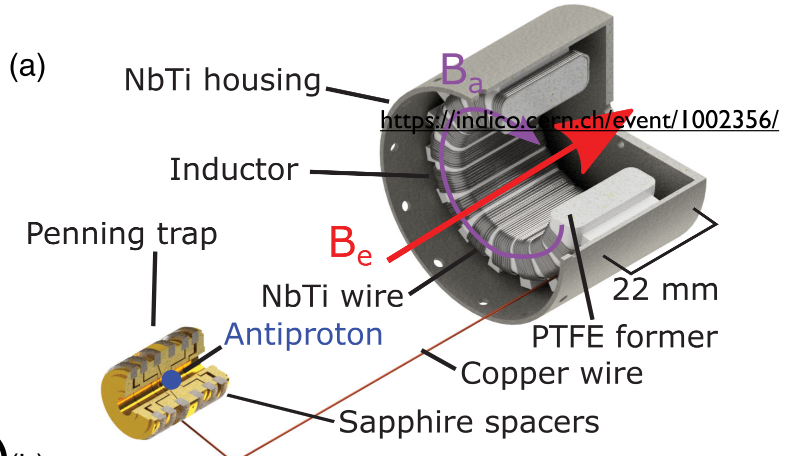


The axion signal

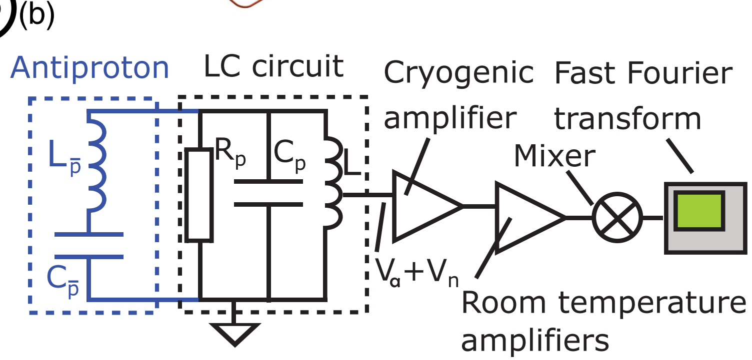
$$V_a = \frac{\pi}{2} Q\sqrt{f(\nu,Q,\mathbf{q})}\,\kappa\nu_a l N_{\mathrm{T}}(r_2^2 - r_1^2)\, g_{a\gamma}|\mathbf{B}_e|\sqrt{\rho_a\hbar c}\,.$$

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





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



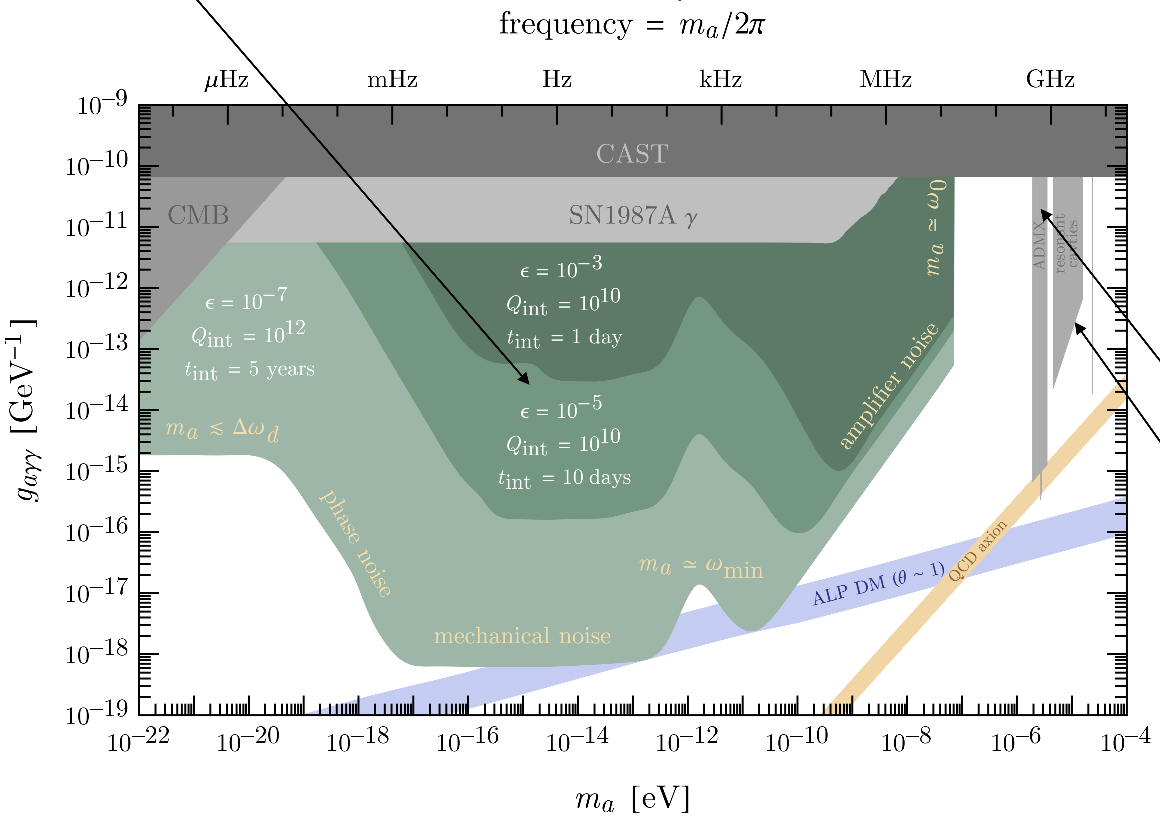
currently developing superconducting tunable capacitors & laser-cooled resonators

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

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



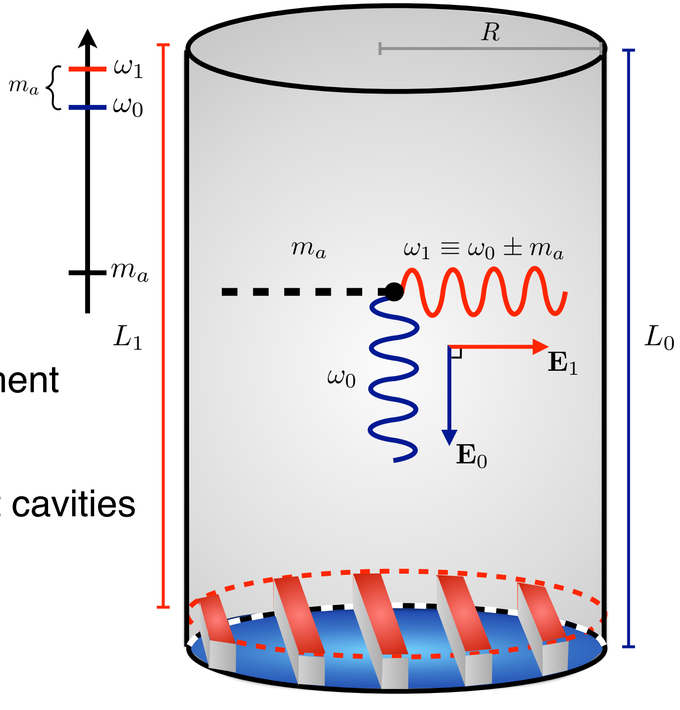
ADMX experiment

resonant cavities

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 $\omega_1 \sim \omega_0 \pm m_a$



(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."

High Q in high B!

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

Relic Axion Detector Exploratory Setup (RADES) searches for axion dark matter with $m_a > 30$ µeV

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

figure of merit   magnetic field   quality factor

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

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

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

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

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

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

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

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

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

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 topologocal 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

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

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)

GEMs (graphene)

closely related: nanostructured materials
Frontiers of Physics, M. Doser et al., 2022
doi: 10.3389/fphy.2022.887738

Atoms, molecules, ions

Rydberg TPC's

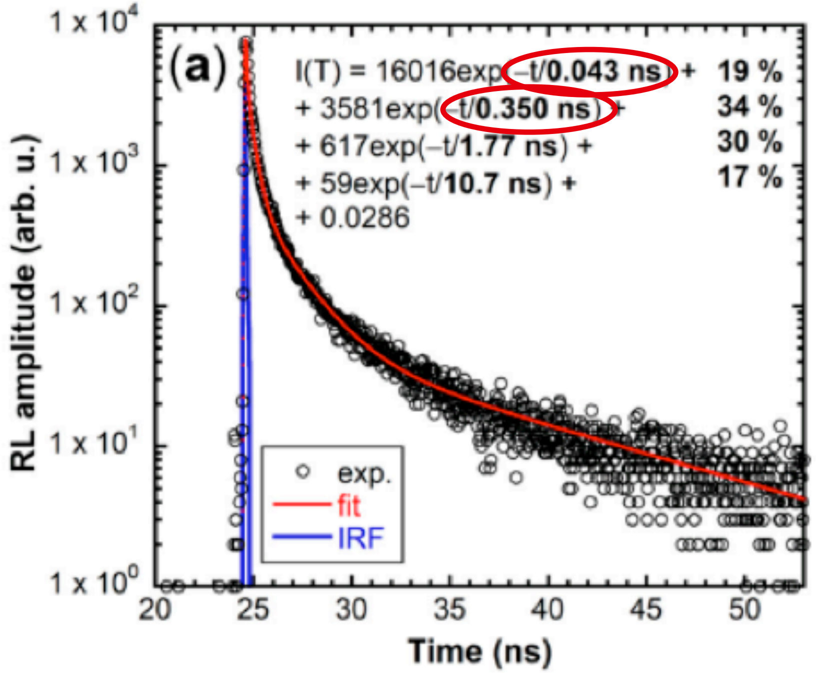
Spin-based sensors

helicity detectors

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

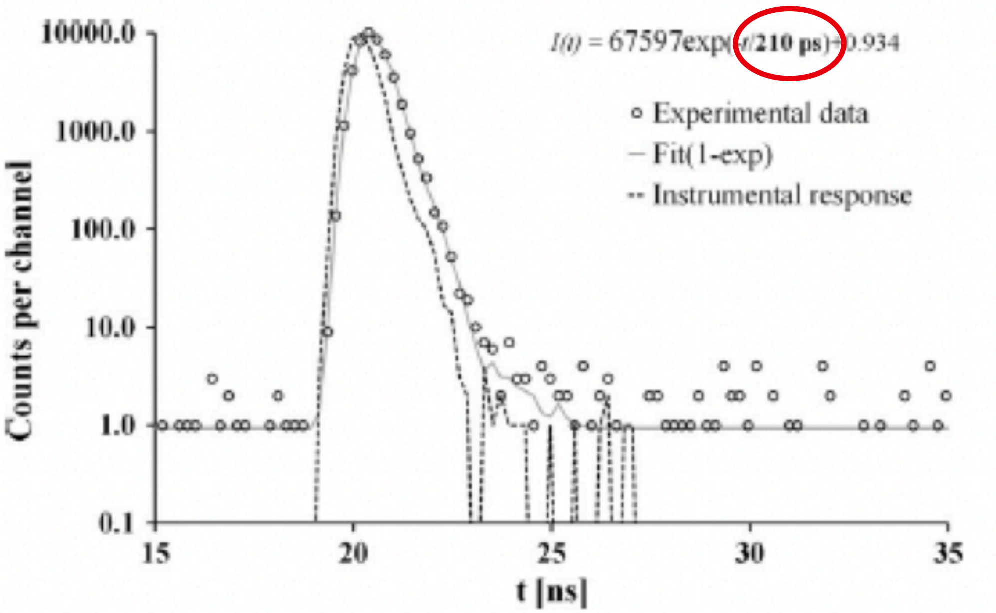


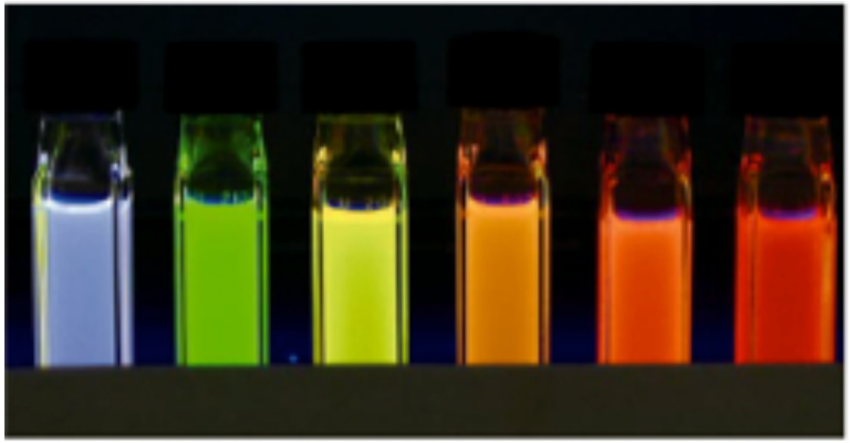
Fig. 9. Photoluminescence decay of ZnO:Ga sample at room temperature. Excitation nanoLED 339 nm, emission wavelength set at 390 nm. Decay curve is approximated by the convolution of instrumental response (also in figure) and single exponential function *I*(*t*) provided in the figure.

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

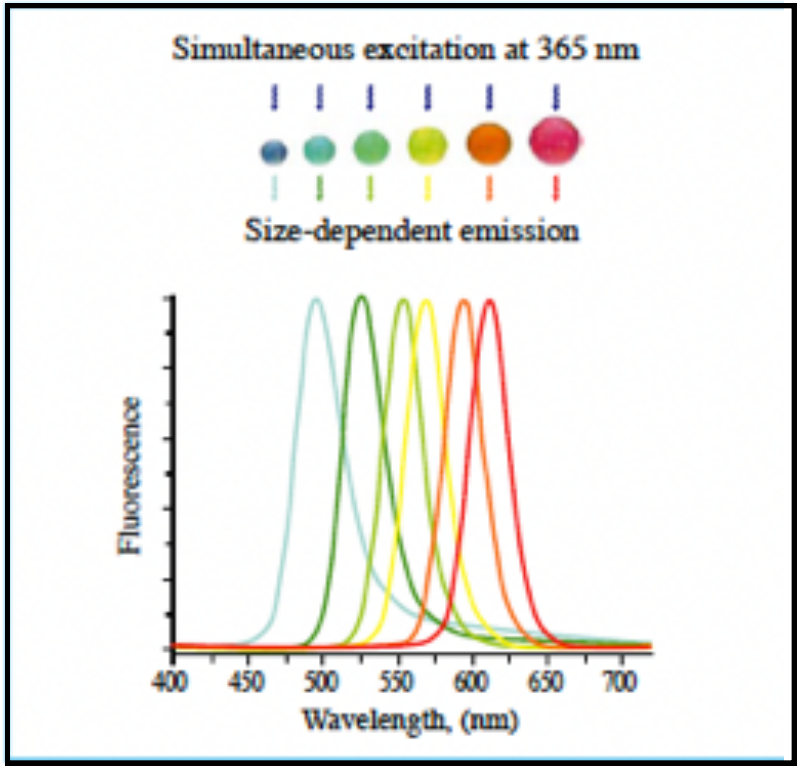
Concerns: integrated light yield (need many photons to benefit from rapid rise time)

Quantum dots: timing

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

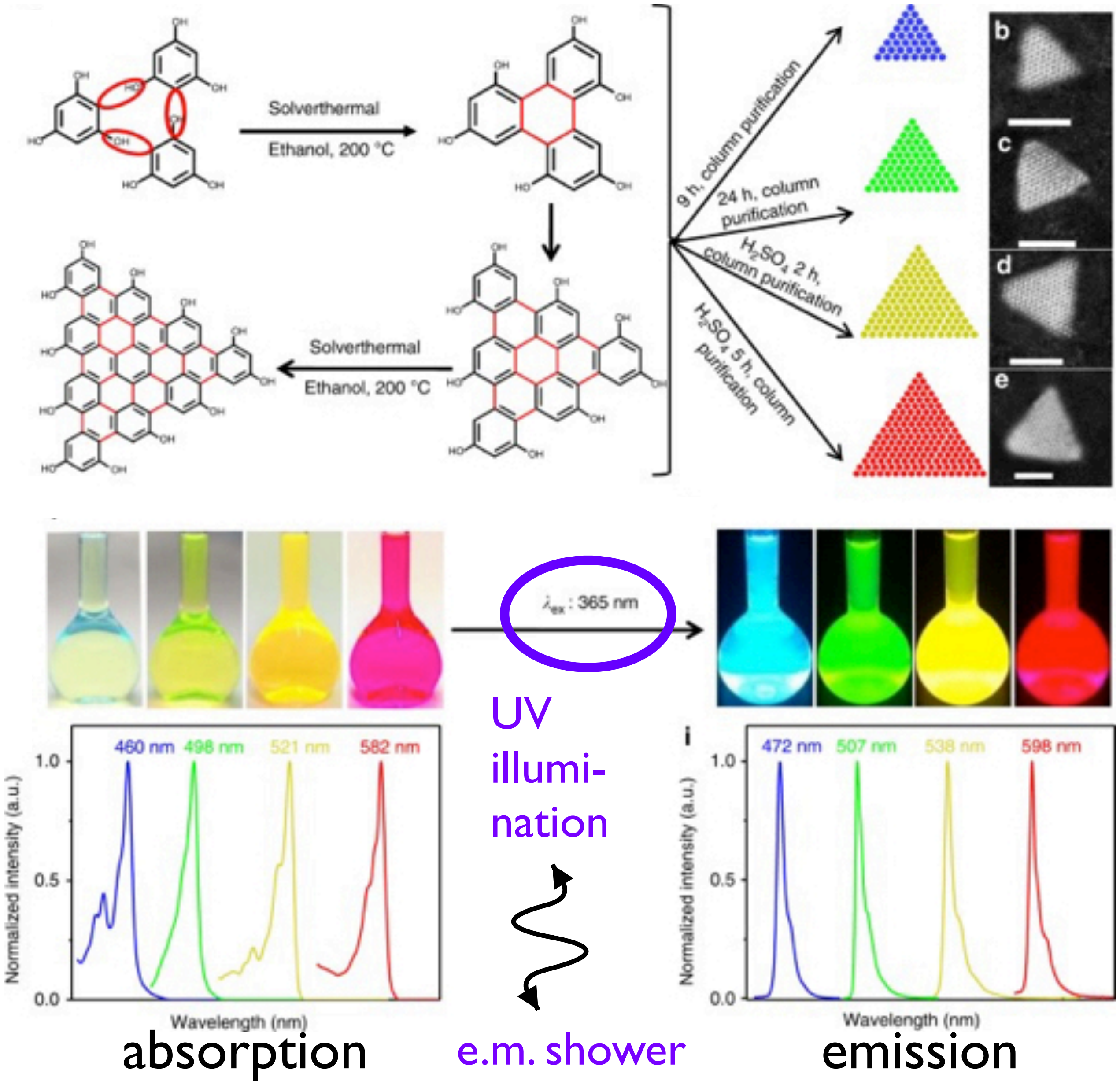


chromatic tunability → optimize for quantum efficiency of PD (fast, optimizable WLS)

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:

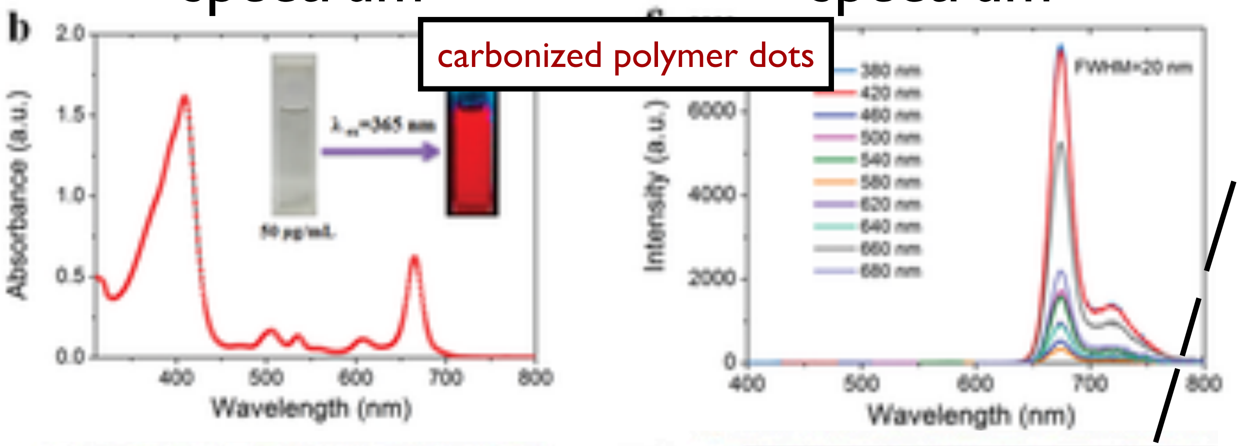
- narrowband emission (~20nm)
- only absorption at longer wavelengths
- short rise / decay times

select appropriate nanodots

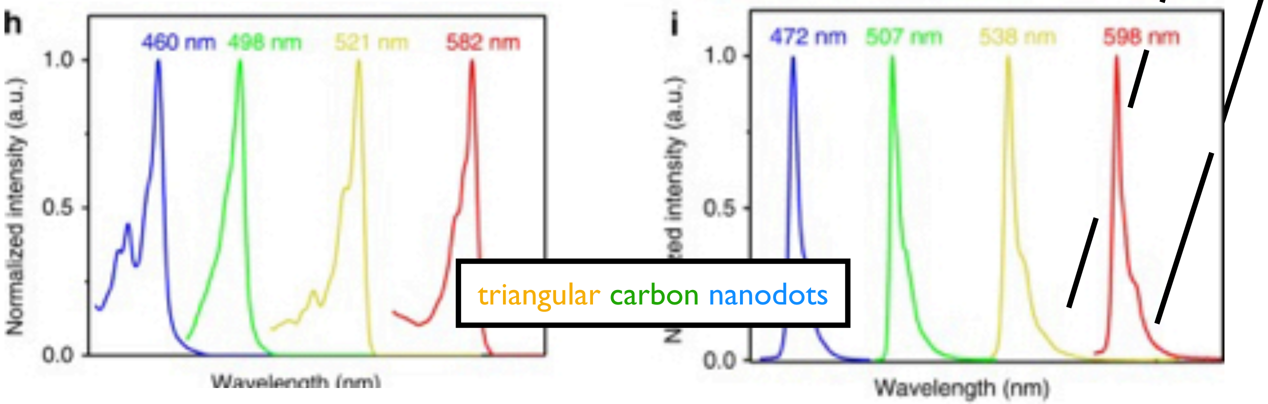
e.g. triangular carbon nanodots

absorption spectrum

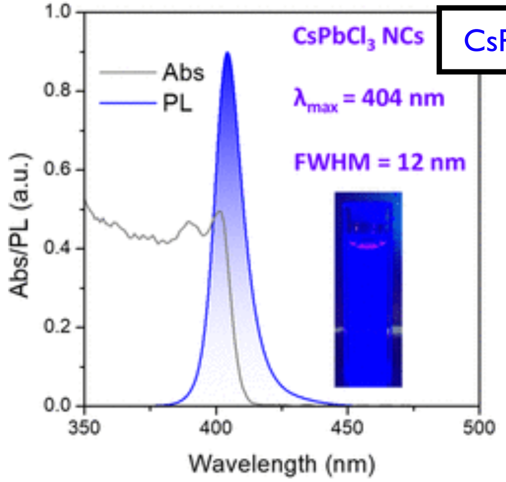
emission spectrum



carbonized polymer dots



triangular carbon nanodots



CsPbCl$_3$ nanocrystals

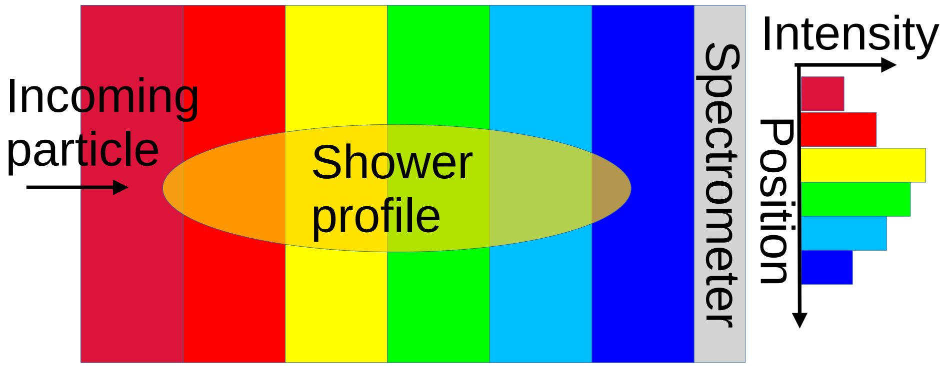
leftmost nanodots:
absorb wavelengths < 650 nm
emit at > 680 nm

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



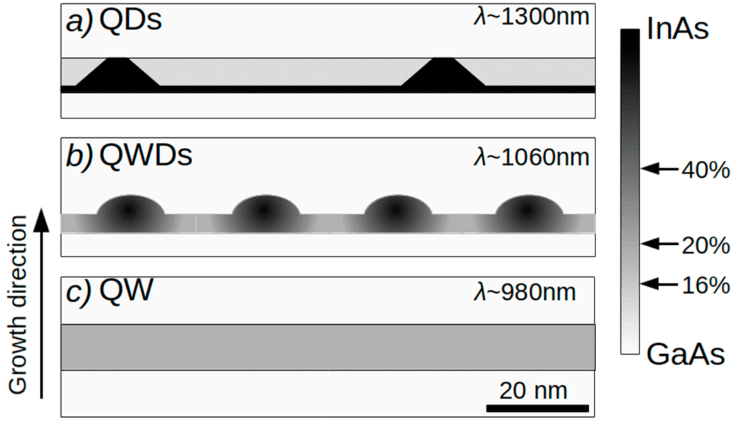
(shower profile via ***spectrometry***)

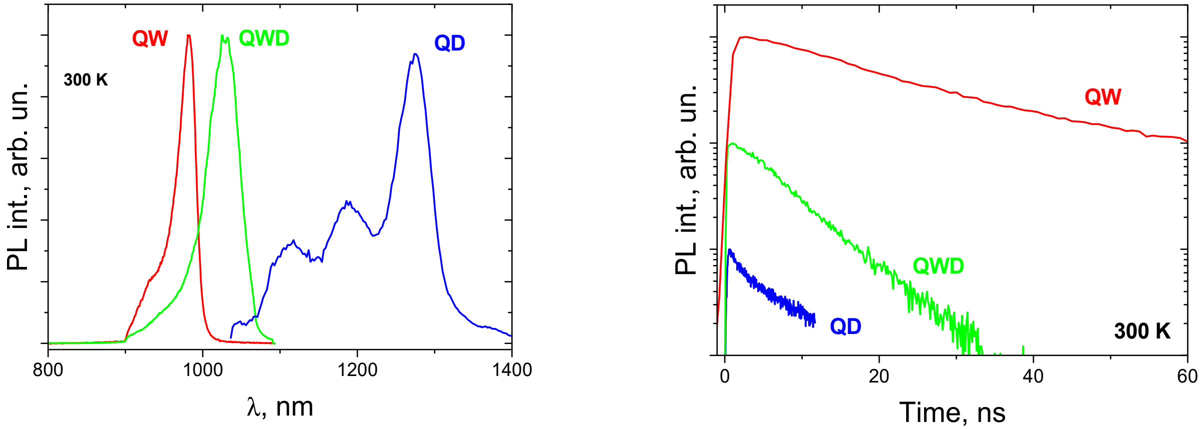
Active scintillators (QWs, QDs, QWDs, QCLs)

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





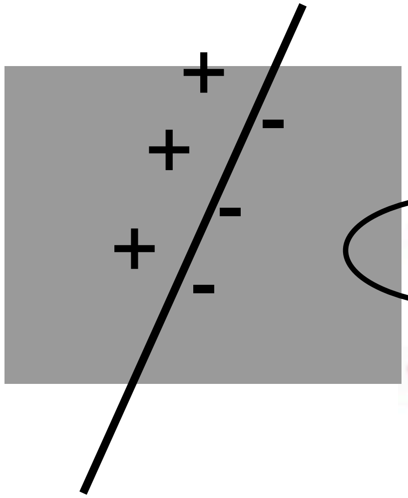
Light Emitting Devices Based on Quantum Well-Dots, Appl. Sci. 2020, 10, 1038; doi:10.3390/app10031038

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

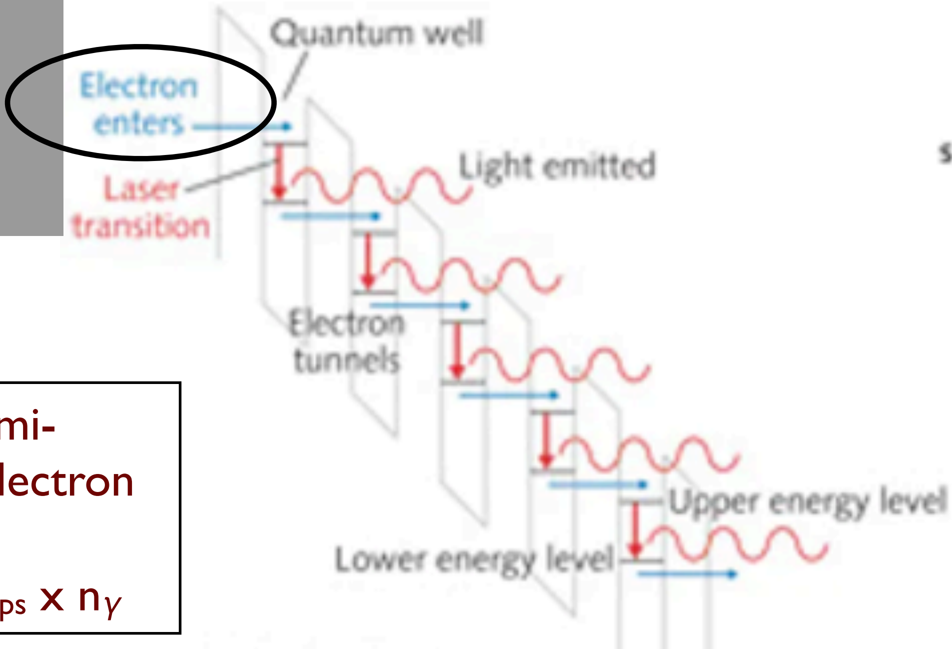
QD's are radiation resistant

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)



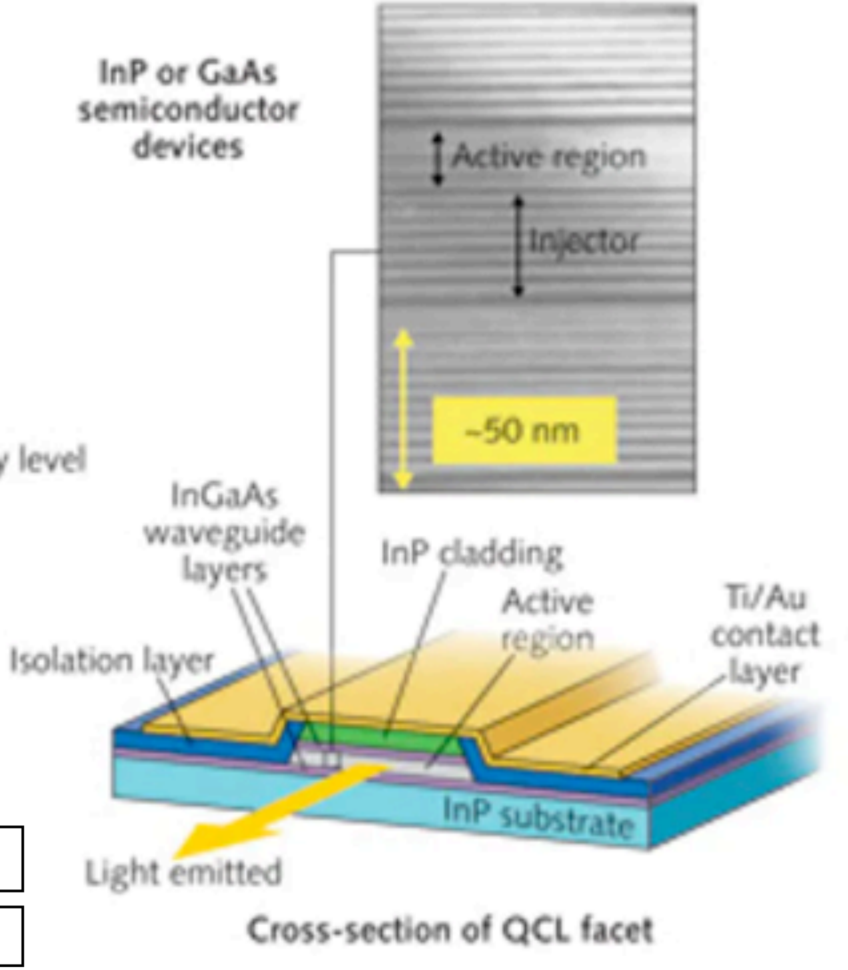
https://www.laserfocusworld.com/test-measurement/spectroscopy/article/16556856/quantumcascade-lasers-qcls-enable-applications-in-ir-spectroscopy



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

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)

Quantum dots and wells: https://arxiv.org/abs/2202.11828

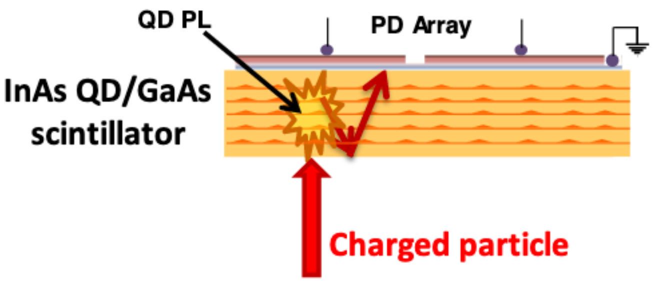
submicron pixels

scintillating (chromatic) tracker

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

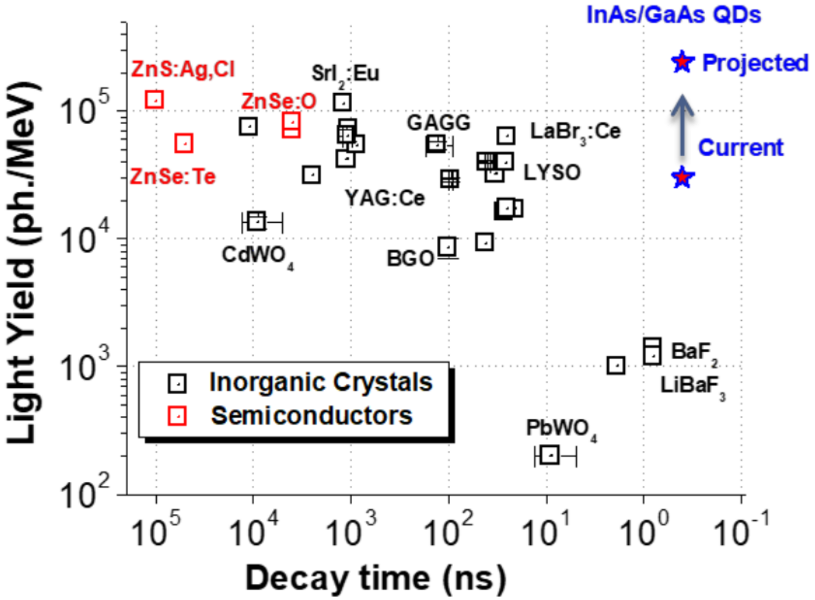


IR emission from InAs QD's integrated PD's (1-2 μm thick)

Novel Sensors for Particle Tracking: a Contribution to the Snowmass Community Planning Exercise of 2021

M.R. Hoeferkamp, S. Seidel, S. Kim, J. Metcalfe, A. Sumant, H. Kagan, W. Trischuk, M. Boscardin, G.-F. Dalla Betta, D.M.S. Sultan, N.T. Fourches, C. Renard, A. Barbier, T. Mahajan, A. Minns, V. Tokranov, M. Yakimov, S. Oktyabrsky, C. Gingu, P. Murat, M.T. Hedges

https://arxiv.org/abs/2202.11828



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

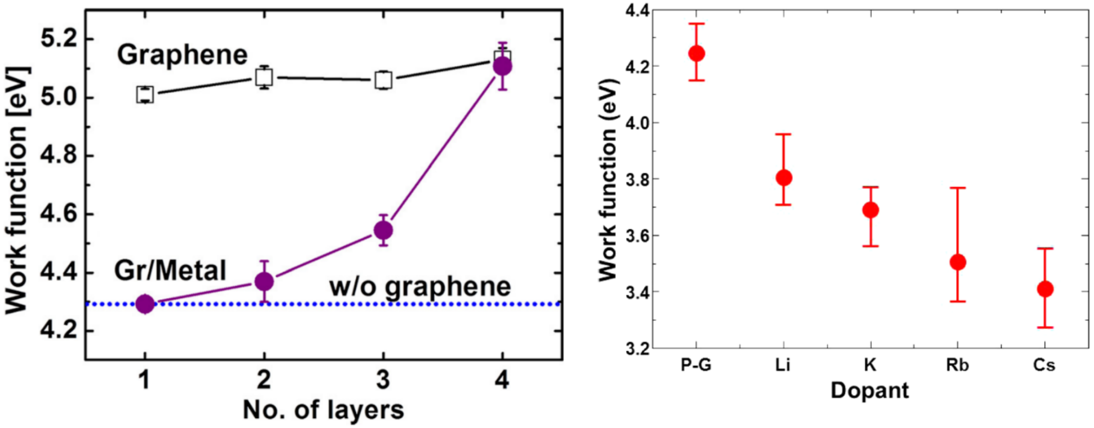
efficiency of the photocathode → timing resolution; QE
tune via resonant processes in low dimensional coating structures

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

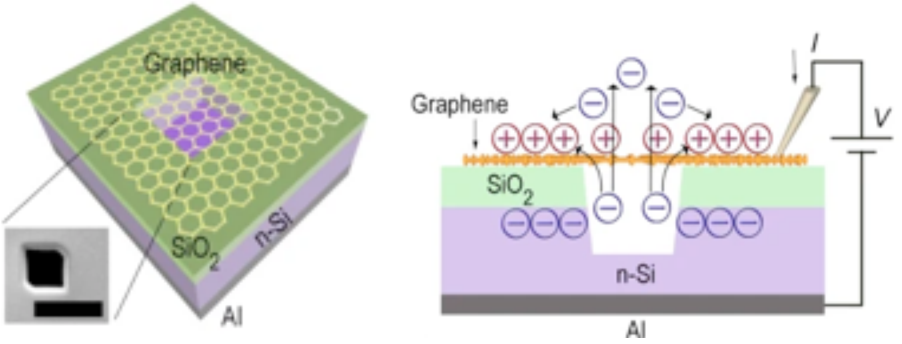
amplification

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

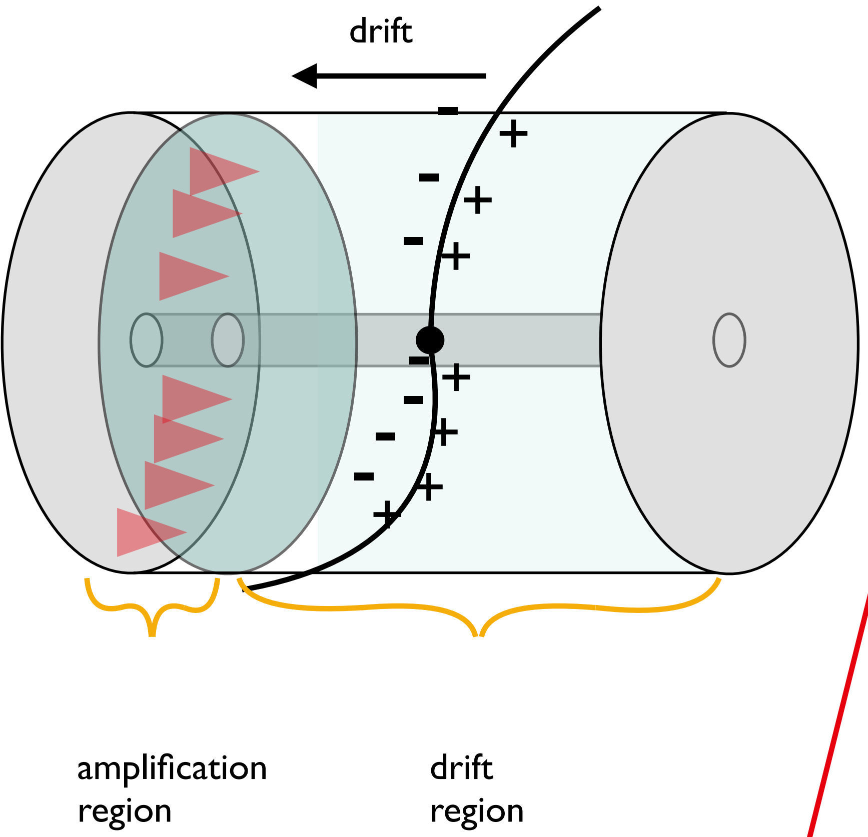
Spin-based sensors

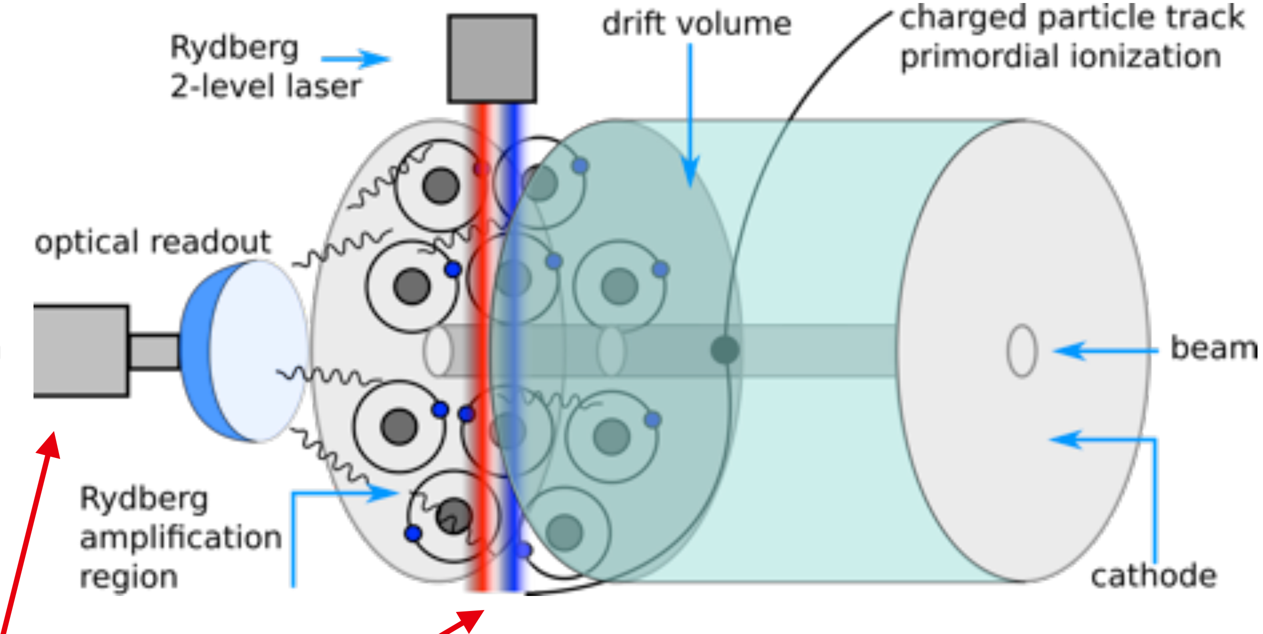
- helicity detectors 5.3.3

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

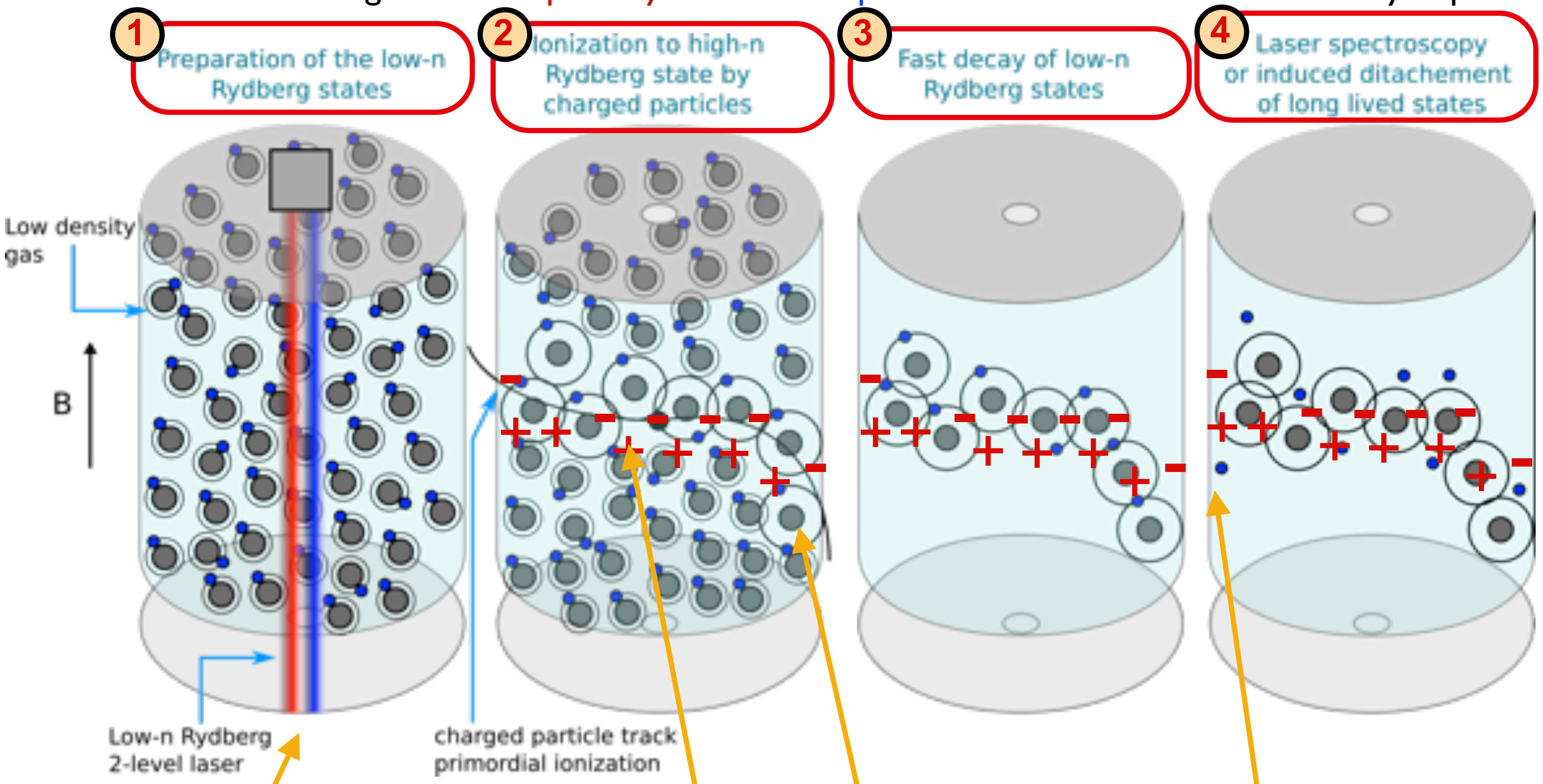
Rydberg atoms can serve to up-convert THz / GHz radiation into the optical regime ⟶ optical R/O of avalanche intensities

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



reduction of ionization and
atomic excitation threshold

ionization + excitation;
natural decay of unmodified atoms

photo-ionization of excited atoms

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

ultra-fast scintillators based on perovskytes

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5.3.5

Rydberg TPC's

Spin-based sensors

5.3.3

helicity detectors

HEP

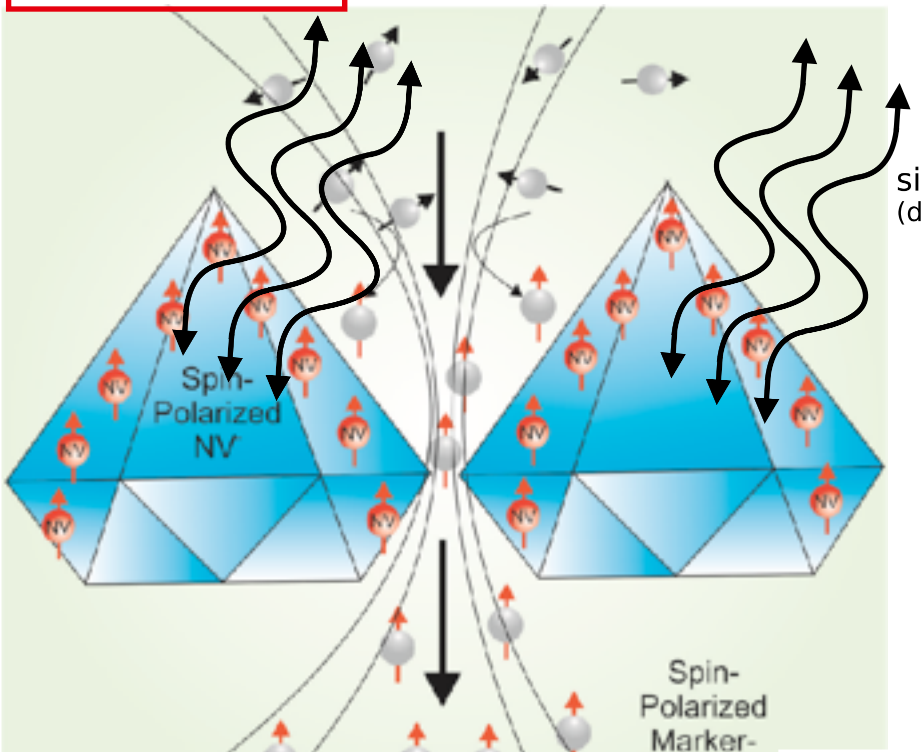
optically polarizable elements: Nitrogen-vacancy diamonds (NVD)

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

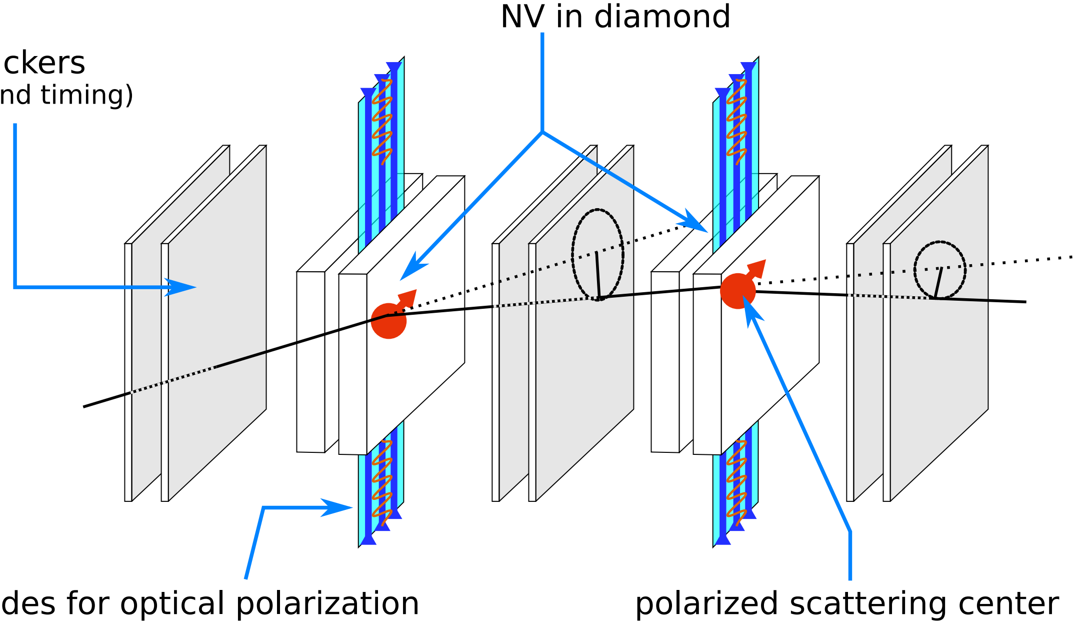
$10^{16} \sim 10^{18}$ / cm^3



© Dr. Christoph Nebel, Fraunhofer IAF

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

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

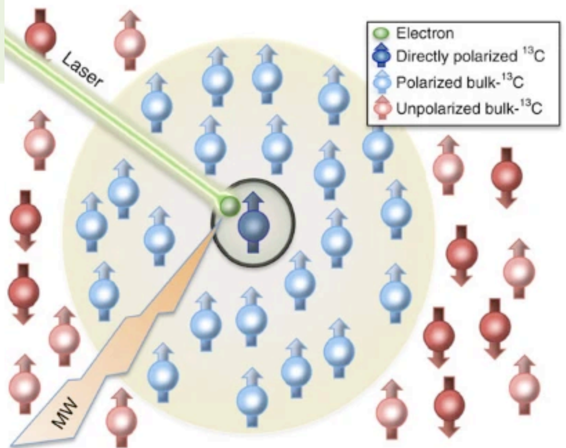


NV in diamond

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

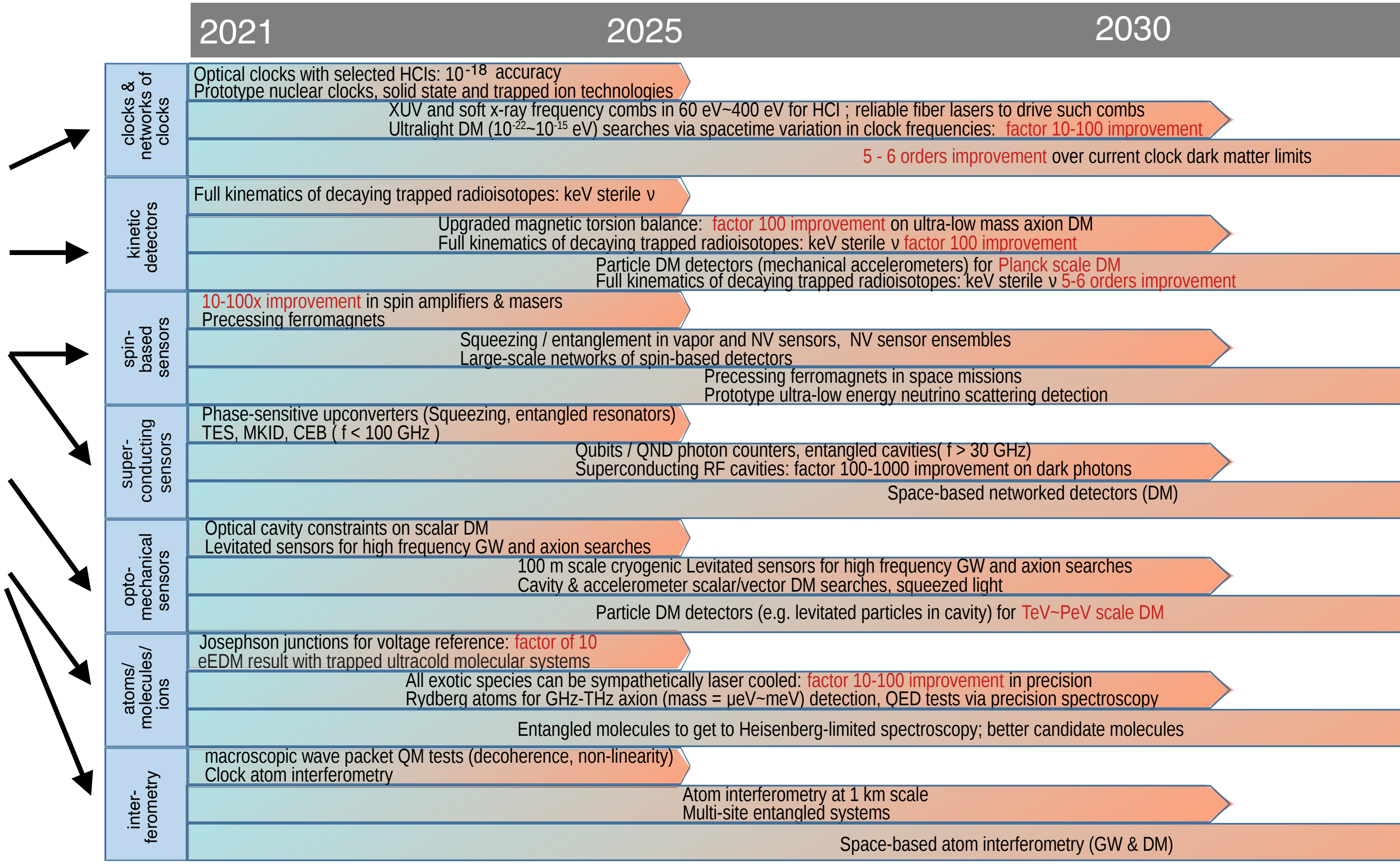
x 10^2

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



2021 2025 2030

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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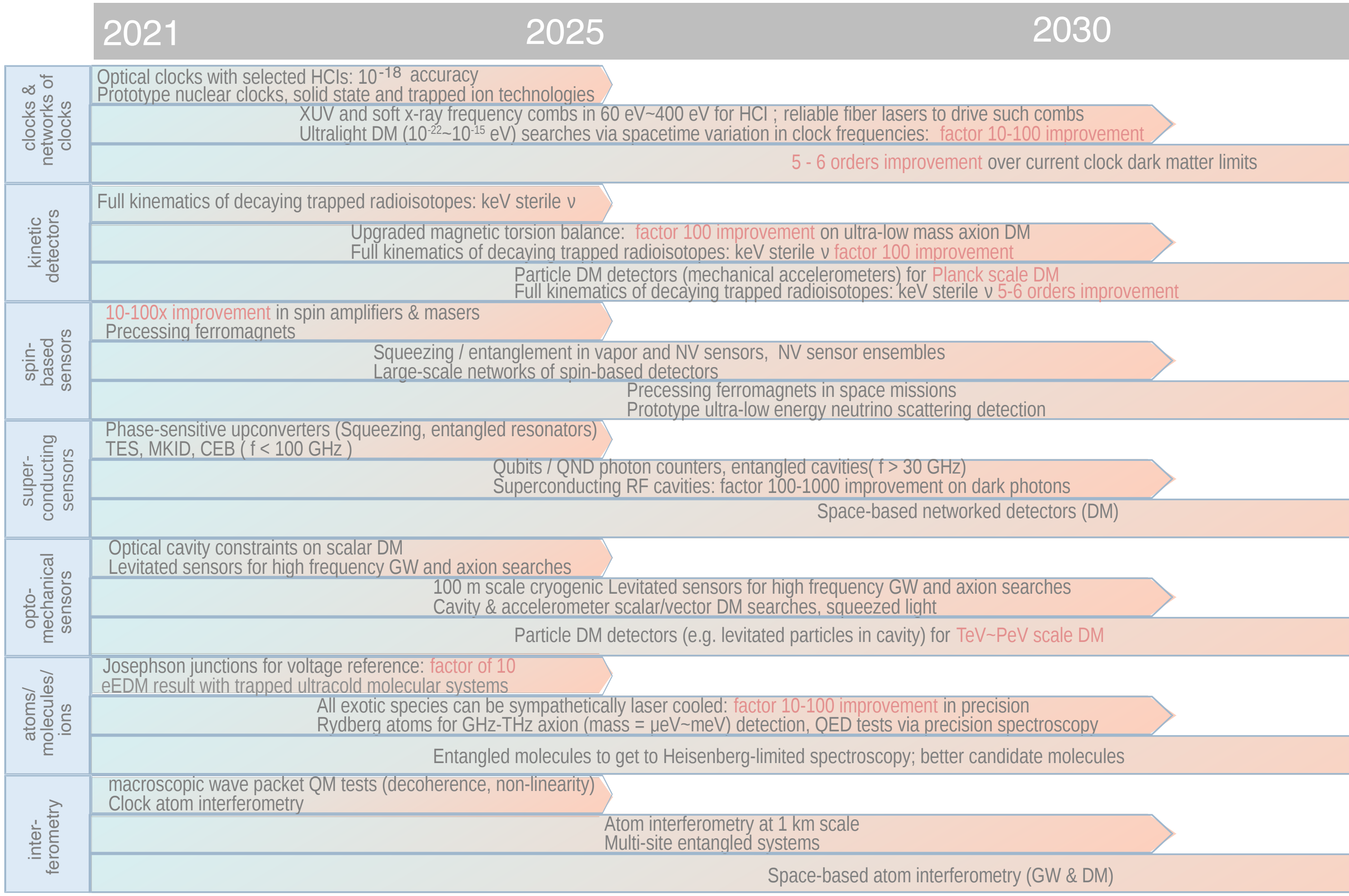

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also for HEP!

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