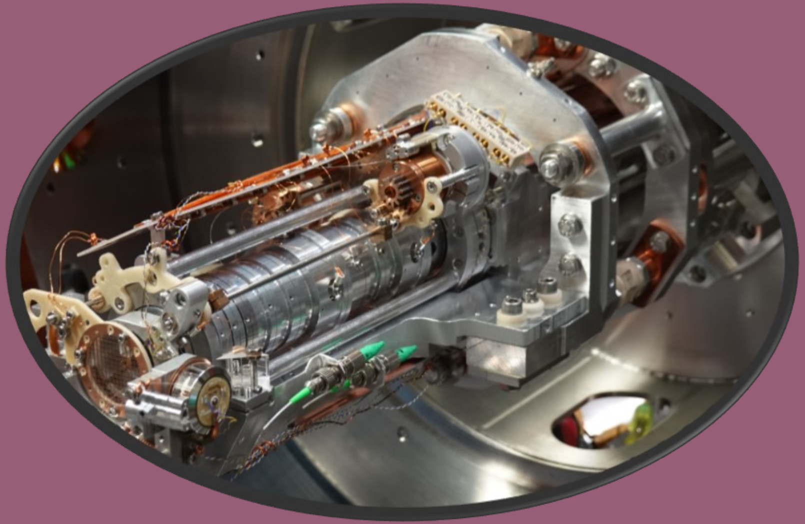
CERN



Faculty of Physics
WARSAW UNIVERSITY OF TECHNOLOGY

Quantum systems for enhanced detectors for High Energy Particle Physics

Georgy Kornakov

Quantum Information in Spain (ICE-8)
Compostela, 29.5-1.6 2023

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UCZELNIA BADAWCZA
INICJATYWA DOSKONAŁOŚCI

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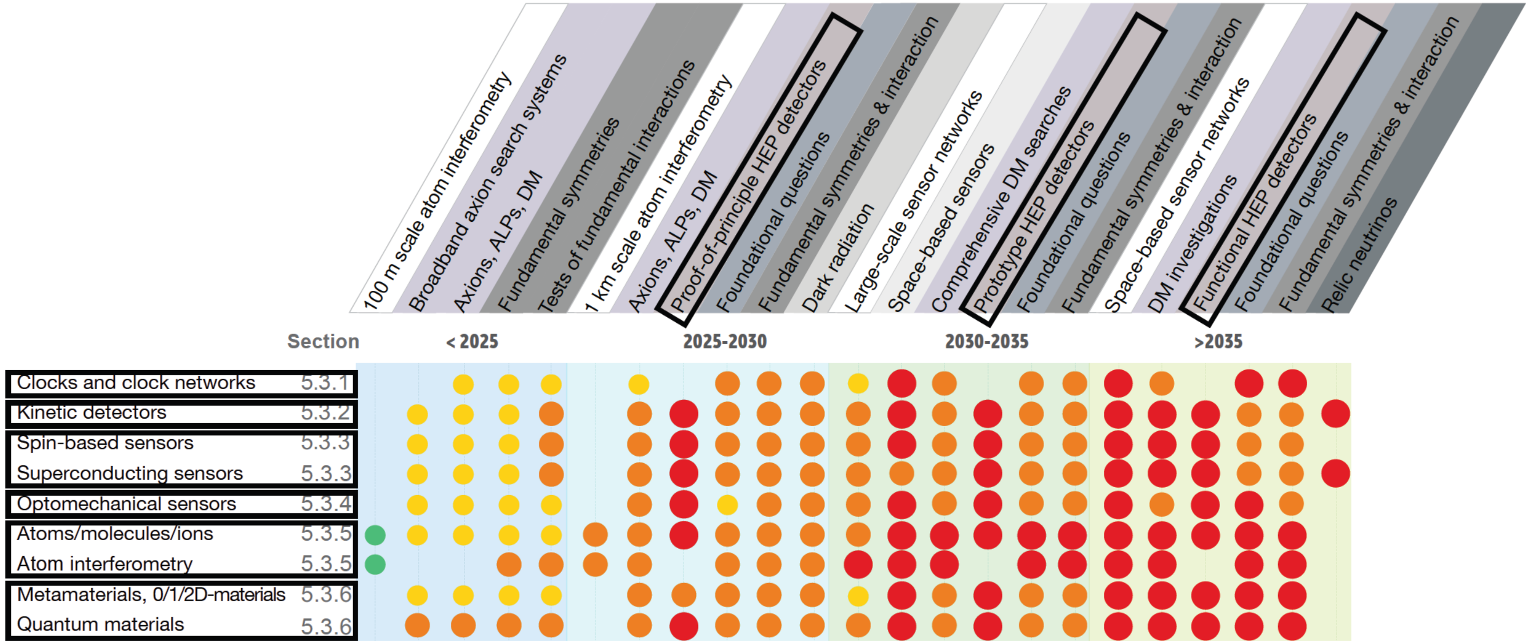
*European Committee for Future accelerators

quantum sensing & particle physics

RECFA Detector R&D roadmap 2021

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

Chapter 5: Quantum and Emerging Technologies Detectors



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

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

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.

M. Doser, VCI 21-25 Feb 2022

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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

superconducting devices (TES, SNSPD, ...) / cryo-electronics

spin-based, NV-diamonds

optical clocks

ionic / atomic / molecular

optomechanical sensors

metamaterials, 0/1/2-D materials

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

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Status and Implementation of the ECFA roadmap in QS for HEP

https://indico.cern.ch/event/1278425/ ← follow updates

- The White Paper in preparation and release **May/June**

- LoI to be submitted to the DRDC* **July**

- Open symposium at CERN (**2-4 October**)

- Proposal to DRDC **December**

*Detector Research & Development Committee

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

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

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

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

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

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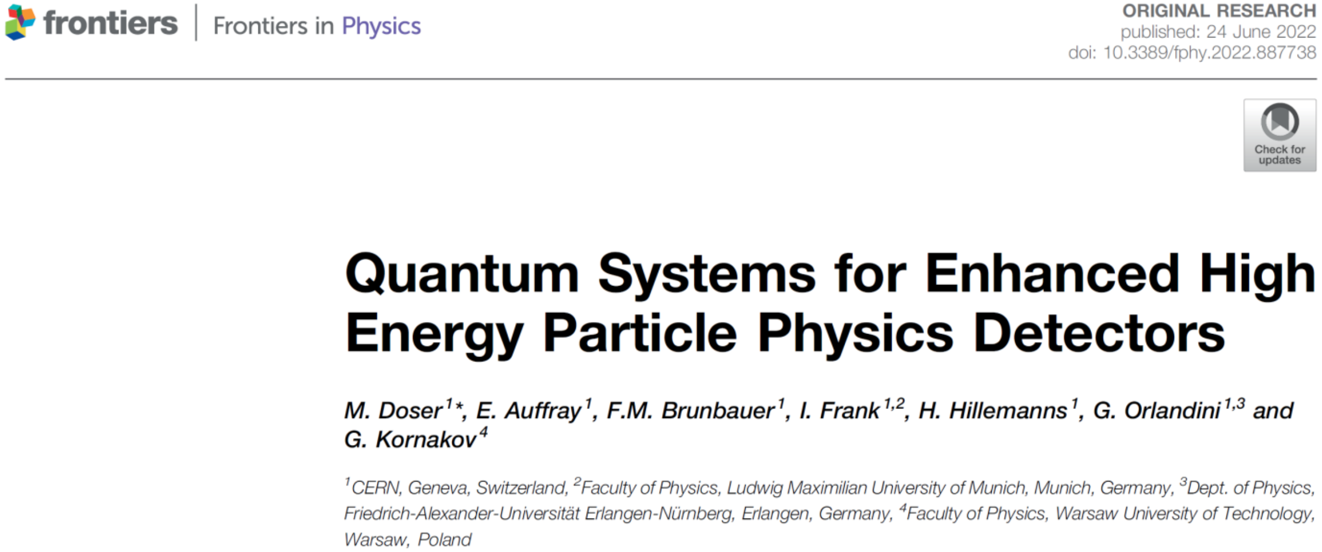

frontiers | Frontiers in Physics

ORIGINAL RESEARCH
published: 24 June 2022
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Check for updates

Quantum Systems for Enhanced High Energy Particle Physics Detectors

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handful of ideas that rely on quantum devices, **but do not use them as quantum detectors per se**

properties enhanced of:

- tracking
- calorimetry
- timing

- **LOW-DIMENSIONAL MATERIALS**
- ATOMS MOLECULS AND IONS
- SPIN BASED SENSORS

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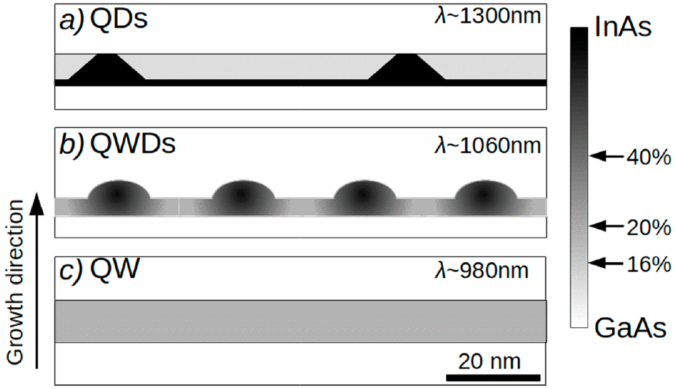
Active scintillators (QWs, QDs, QWDs, QCLs)

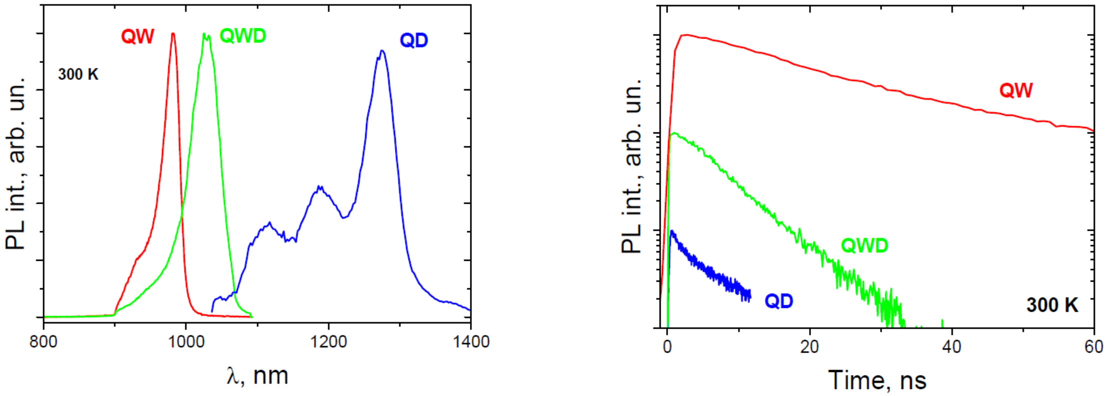
M. Doser, CERN

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





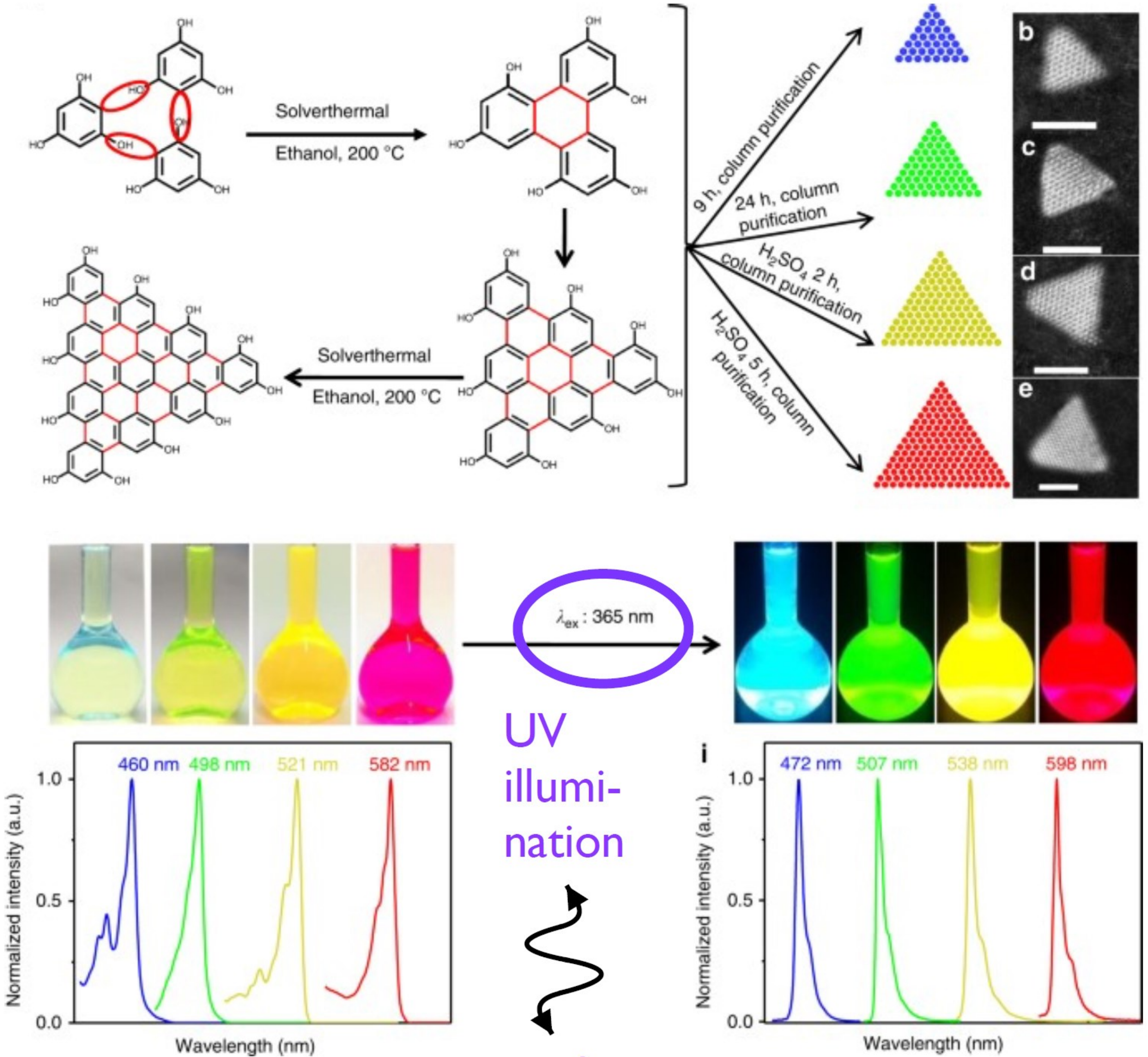
Light Emitting Devices Based on Quantum Well-Dots, Appl. Sci. 2020, 10, 1038; doi:10.3390/app10031038

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.

Quantum dots: chromatic calorimetry

M. Doser, CERN



UV illumi-nation

e.m. shower

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

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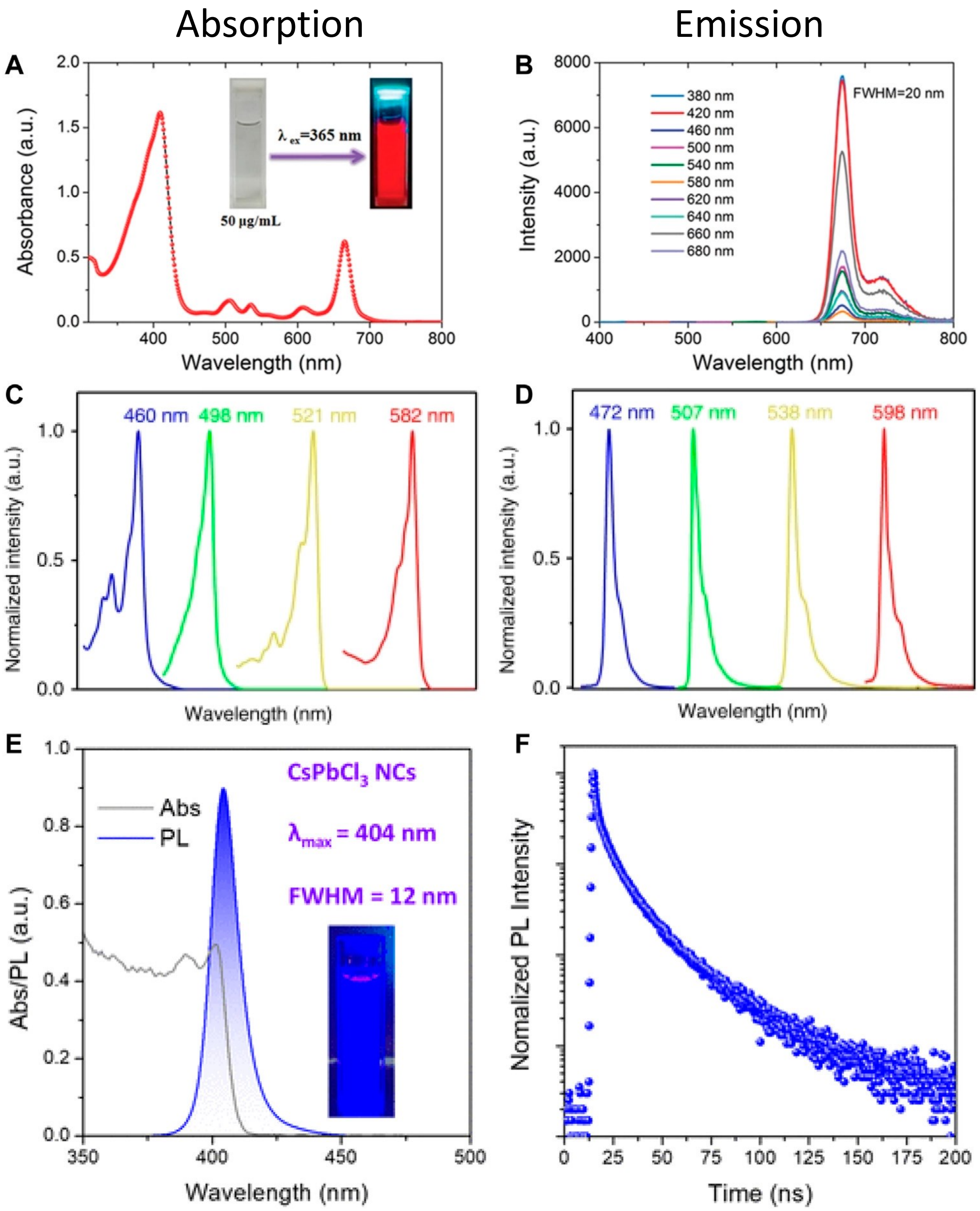

M. Doser, CERN

carbonized polymer dots

J. Liu, B. Yang, et al., Advanced Materials 32 (2020) 1906641

triangular carbon nanodots

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

$CsPbCl_3$ nanocrystals

C. Zhang, L. Li, Y. Qi, et al., ACS Energy Lett. 6 (2021) 3545–3554.

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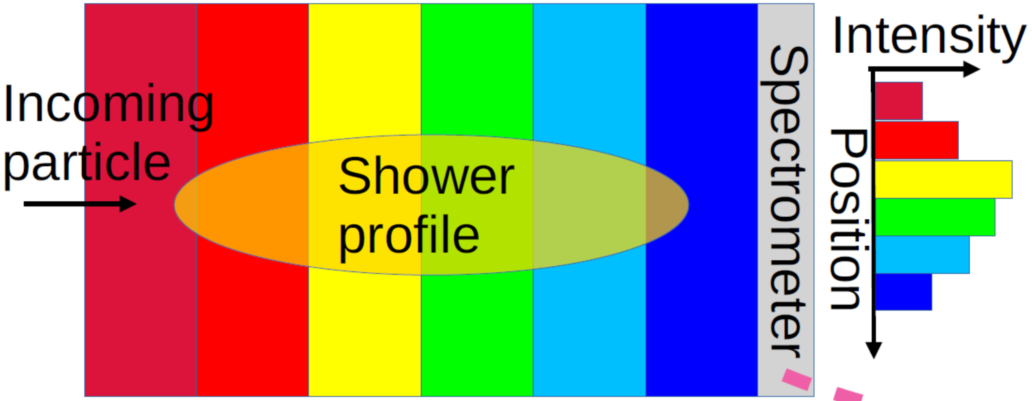


different options for spectrometry:
- monochromators + PD
- light guiding fiber / each layer
- light guiding fiber to spectrometer

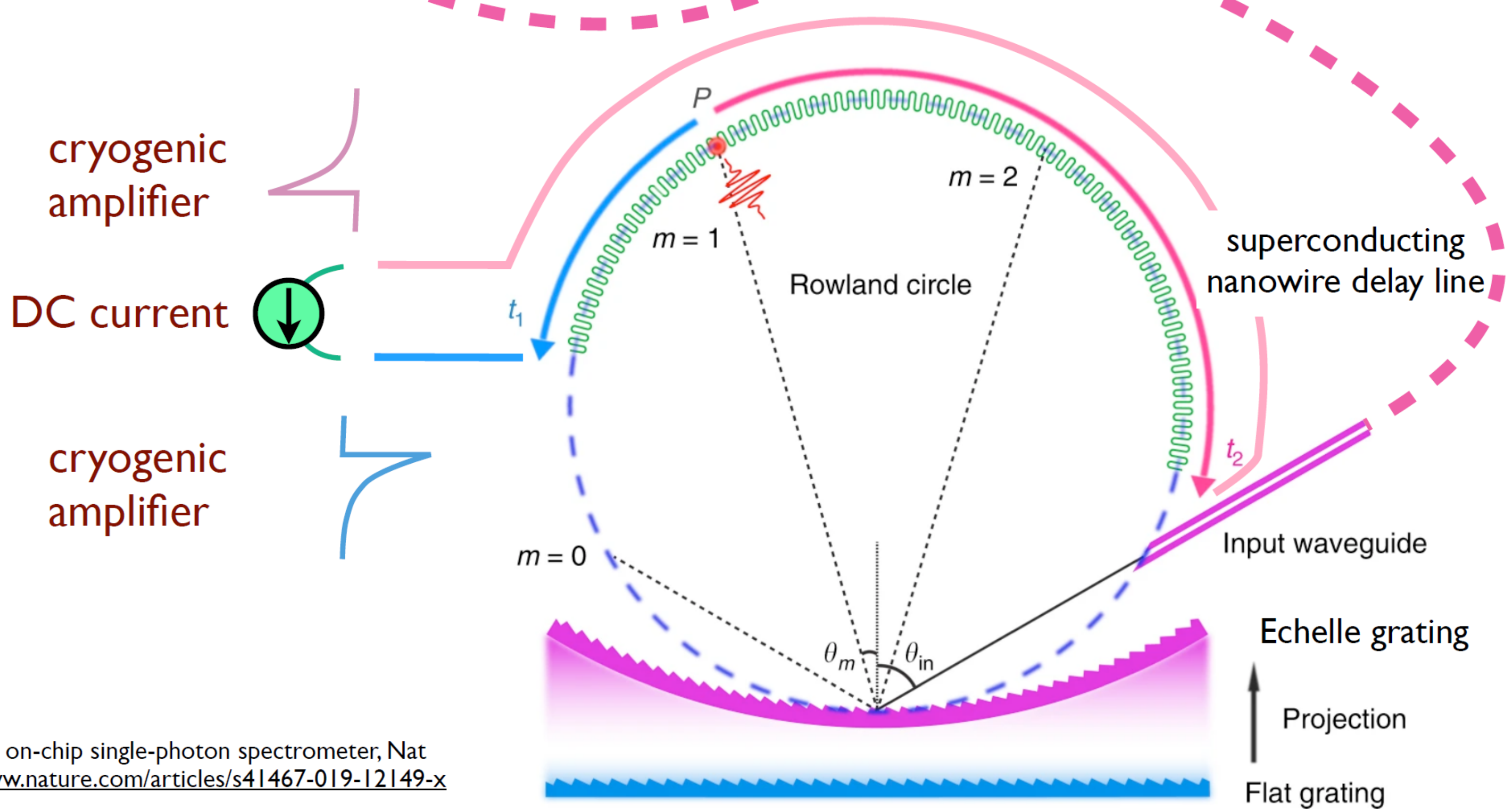
Spectral information of incident photons (color)

Dispersive Echelle grating

Spatial distribution of fired position (position)

Superconducting nanowire delay line

Arrival time difference $\Delta t = t_1 - t_2$ (time)



R. Cheng, H. X. Tang, et al., Broadband on-chip single-photon spectrometer, Nat Commun 10 (2019) 4104; https://www.nature.com/articles/s41467-019-12149-x

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- LOW-DIMENSIONAL MATERIALS
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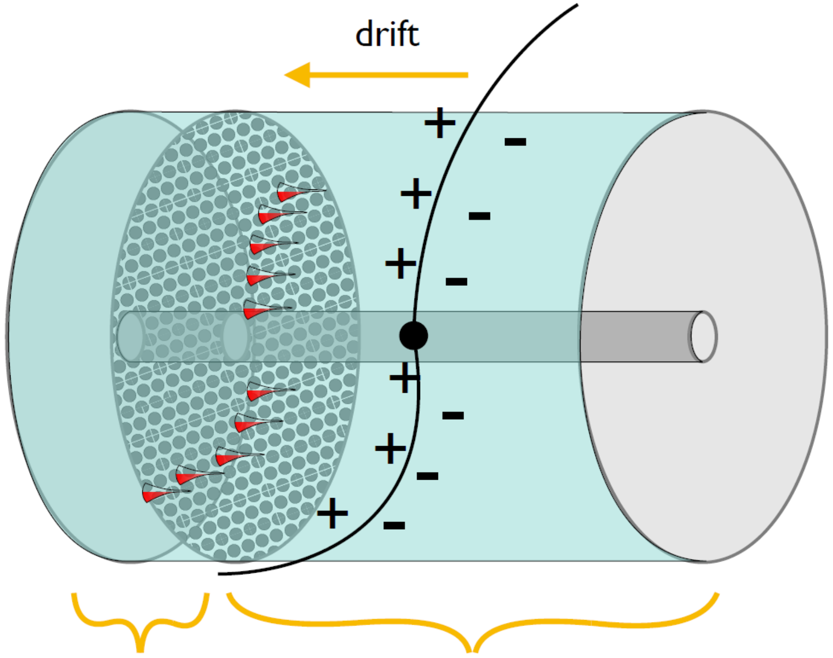
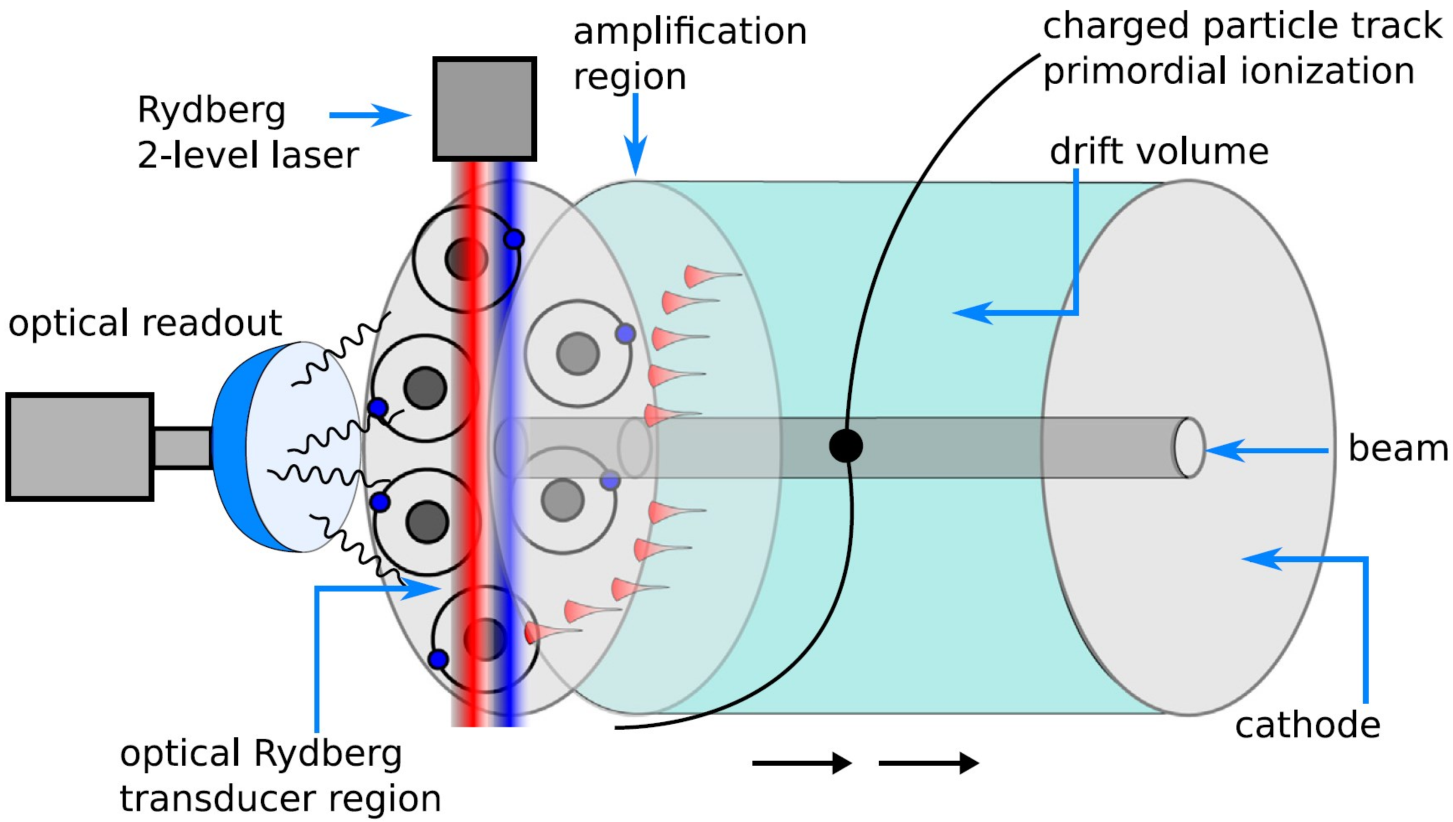
Rydberg-enhanced Time projection Chambers



amplification
region

drift
region



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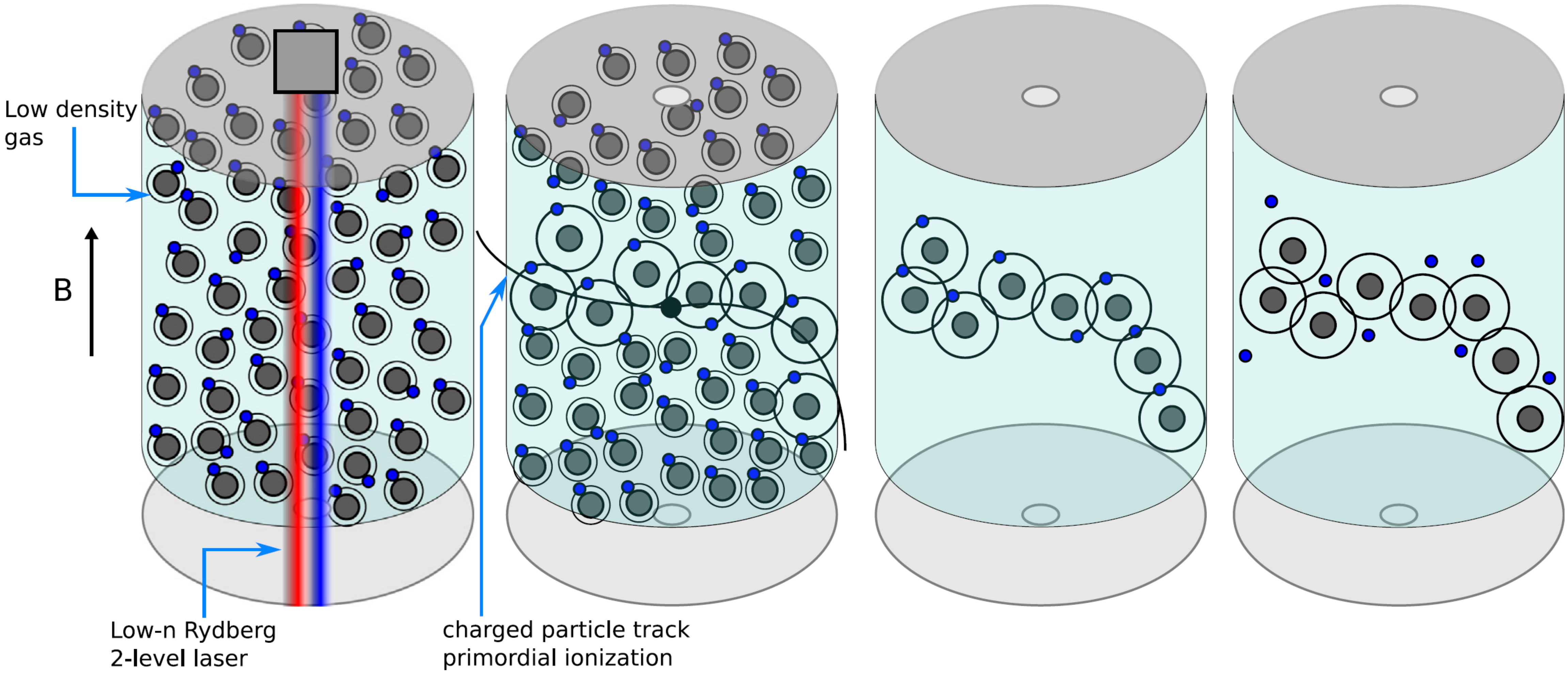
Rydberg Time projection Chamber



Preparation of the low-n Rydberg states

Ionization to high-n Rydberg state by charged particles

Fast decay of low-n Rydberg states

Laser spectroscopy or induced ditachement of long lived states

Low density gas

Low-n Rydberg 2-level laser

charged particle track primordial ionization

- LOW-DIMENSIONAL MATERIALS
- ATOMS MOLECULS AND IONS
- **SPIN BASED SENSORS**

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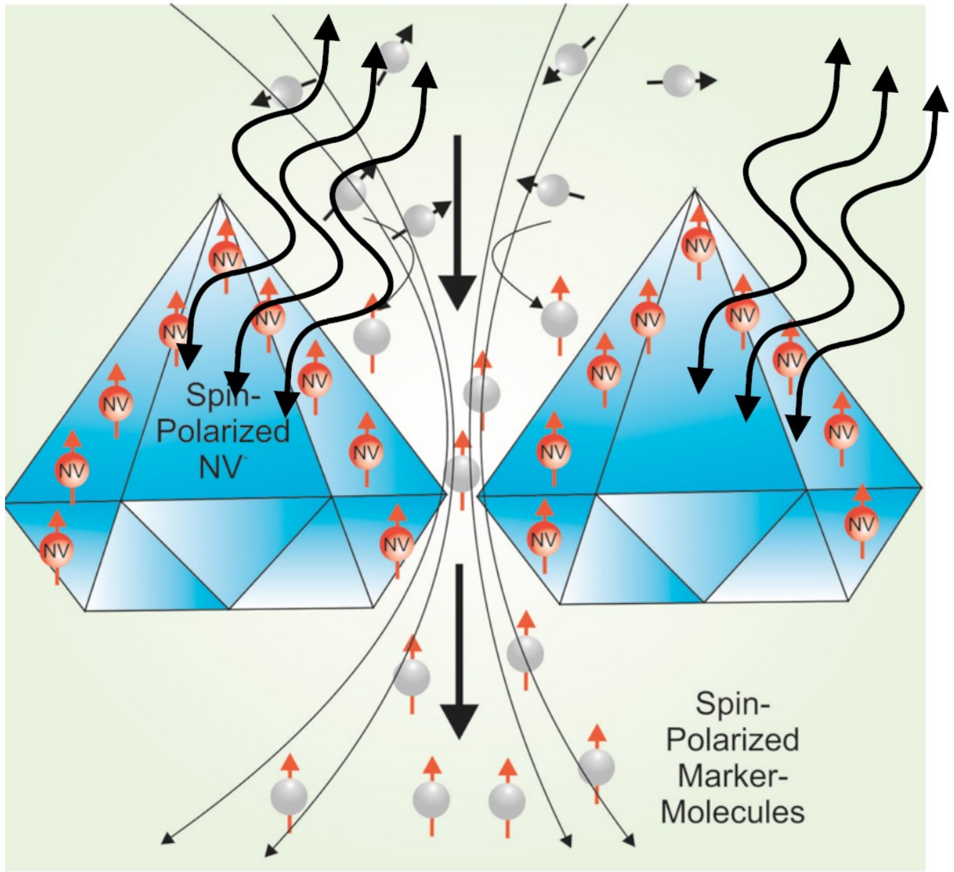
Helicity trackers

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



© Dr. Christoph Nebel, Fraunhofer IAF

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

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

- Polarization modify the helicity-dependent scattering direction probability of a charged particle crossing the polar tracker.
- The probability of scattering in a polarized atom is directly proportional to defect abundance in the diamond
- The density of defects is one of the parameters that is actively being optimized. Current state-of-the art: $10^{16\text{-}18}$ cm^{-3} (laser-created defects) with hyperpolarization 2 orderds of magnitude gain

Kurita T, et al., Appl Phys Lett (2021) 118(21):214001.

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)

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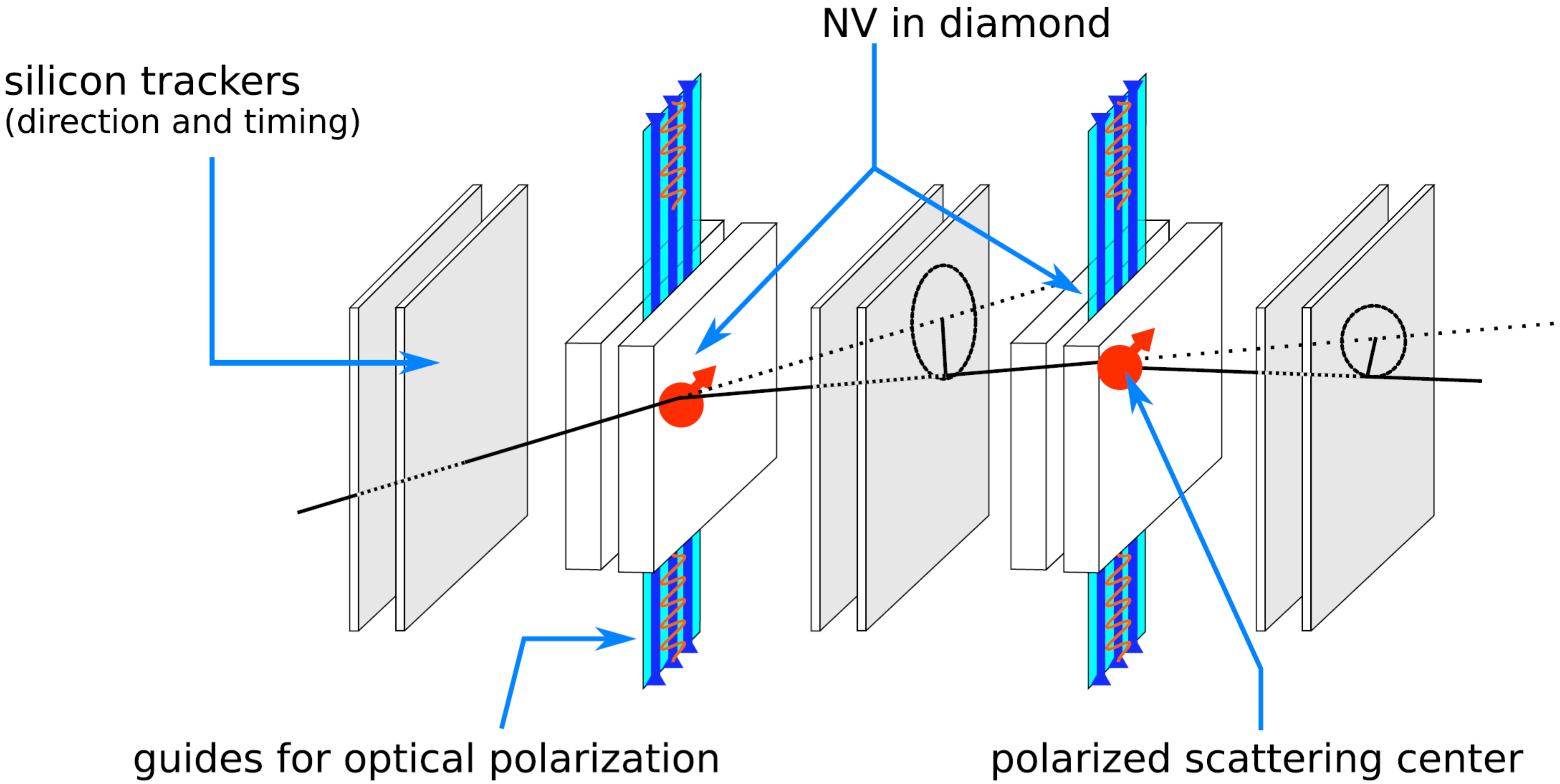
Helicity trackers


NV in diamond

silicon trackers
(direction and timing)

guides for optical polarization

polarized scattering center

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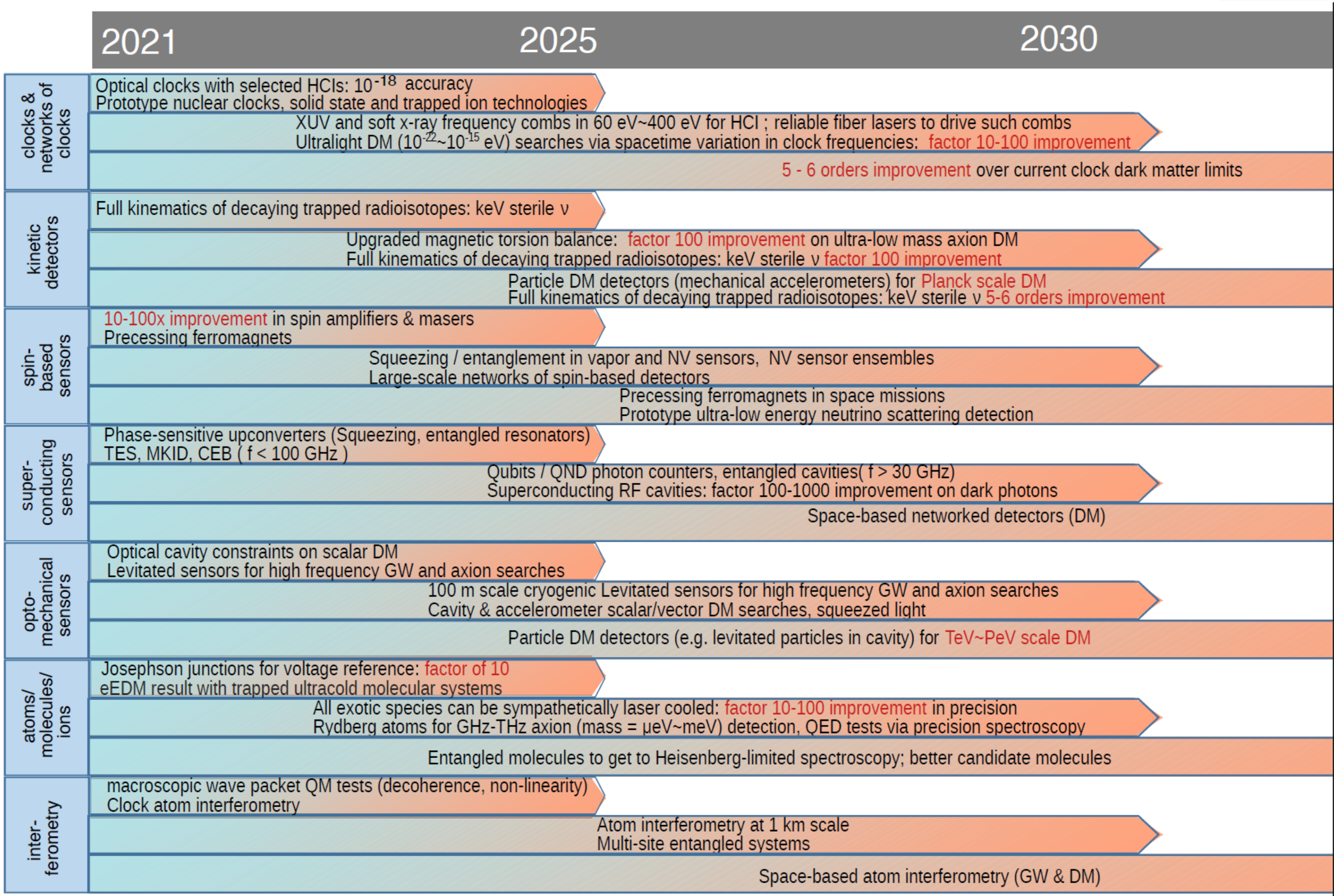
These potential applications of quantum sensors also in HEP require dedicated R&D to evaluate their potential and feasibility



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)

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Thanks