Quantum sensor applications to (low and high)-energy physics at CERN

M. Doser, CERN

EP seminar, 13.5.2022

Some words on the landscape

Clarification of terms

Quantum sensors for low energy particle physics

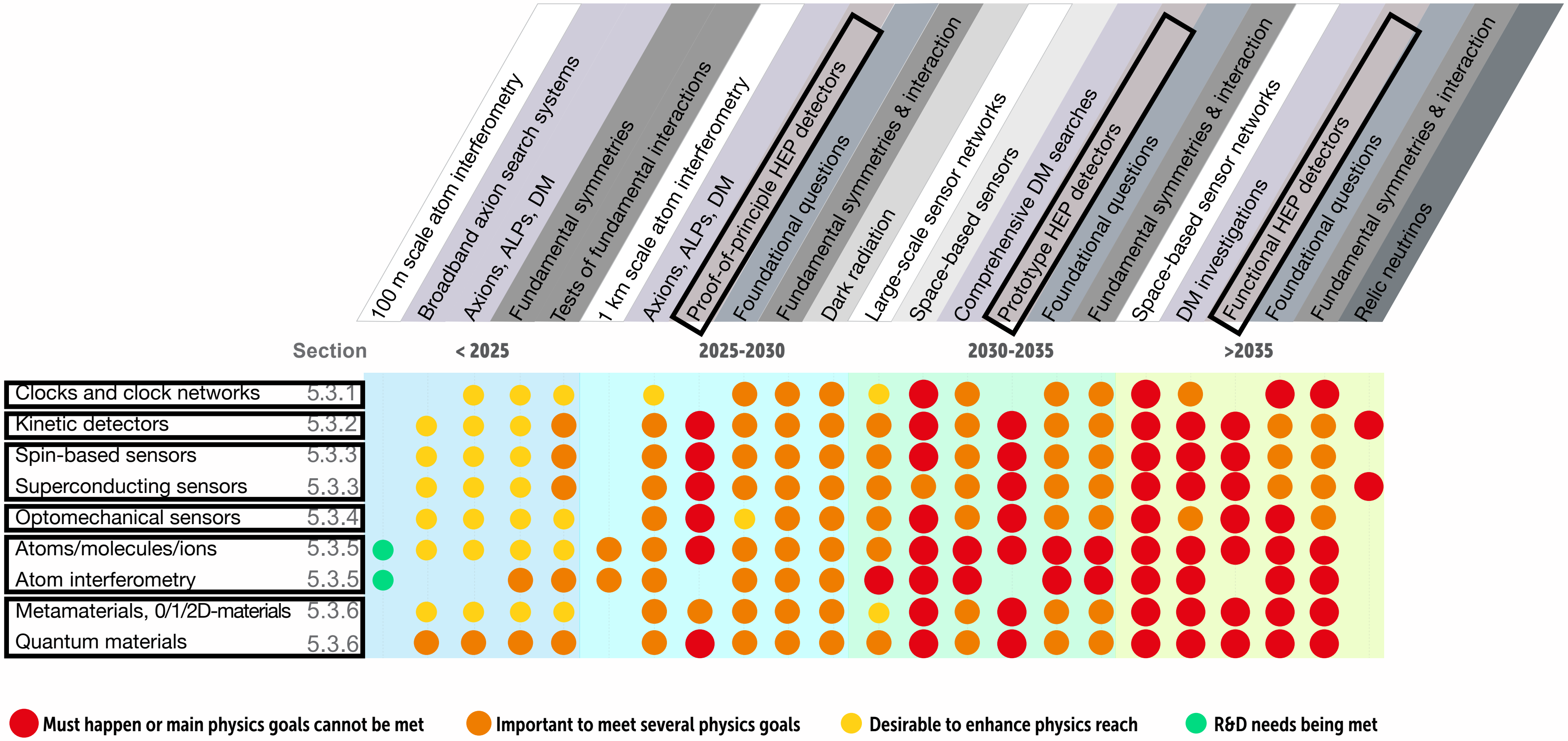
Quantum sensors for new particle physics experiments

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	< 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

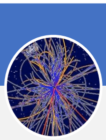
Chapter 4: Particle Identification and Photon Detectors

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.

CERN quantum initiative

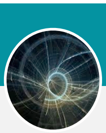
https://quantum.web.cern.ch/

Scientific Objectives



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

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

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

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

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

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

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

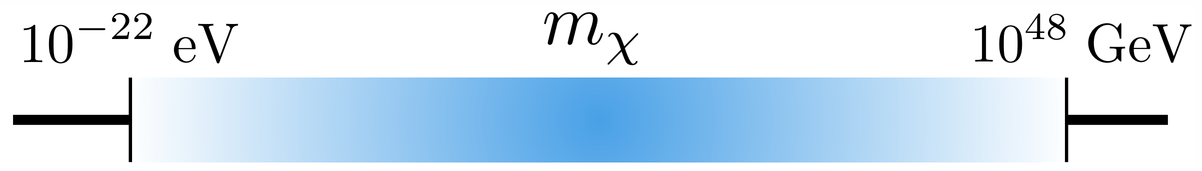
- superconducting devices (TES, SNSPD, …) / cryo-electronics
- spin-based, NV-diamonds
- optical clocks
- ionic / atomic / molecular
- optomechanical sensors
- metamaterials, 0/1/2-D materials

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

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

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

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

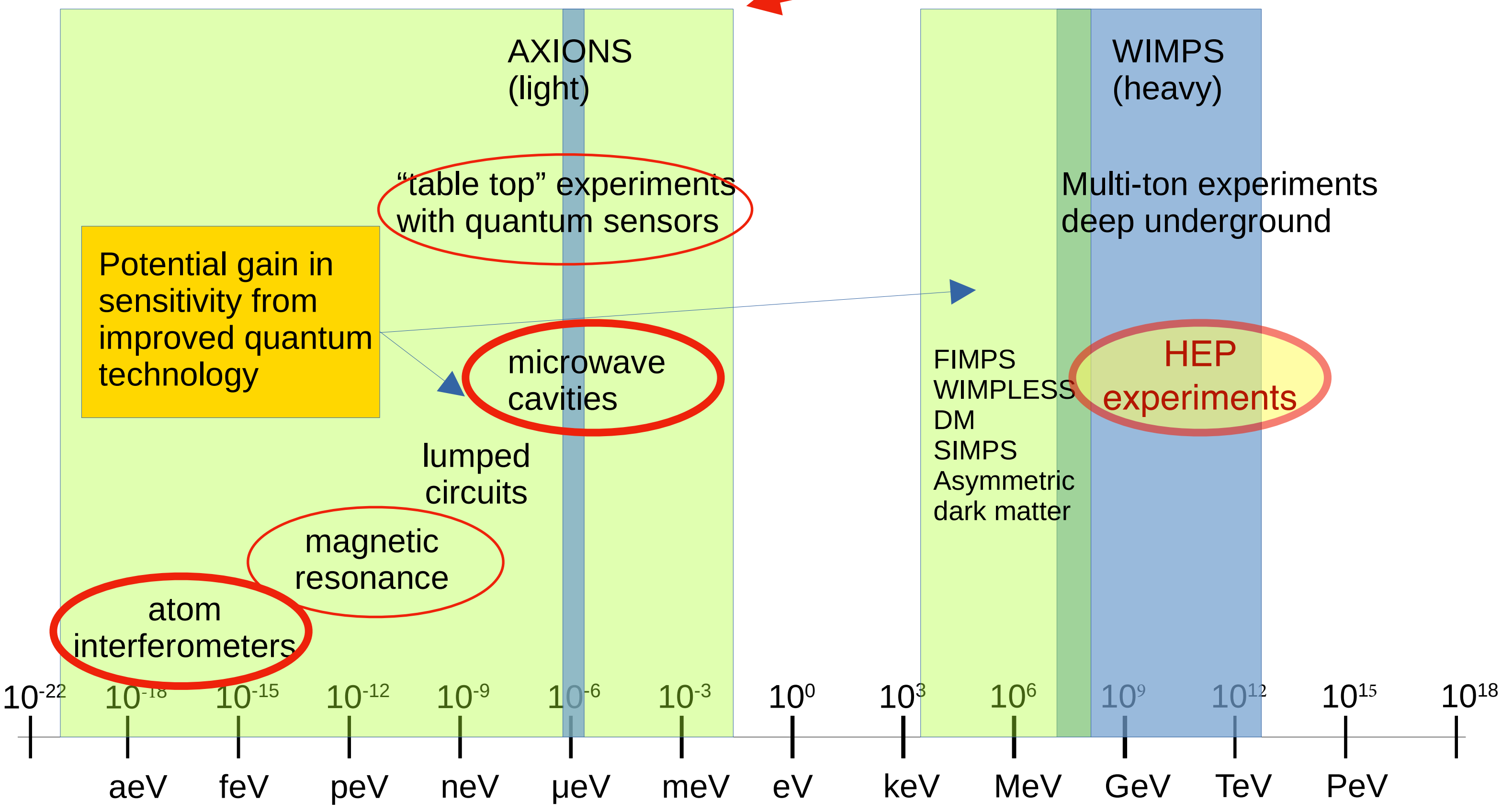


cavity size = axion size

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



AXIONS
(light)

"table top" experiments
with quantum sensors

Potential gain in sensitivity from improved quantum technology

microwave
cavities

lumped
circuits

magnetic
resonance

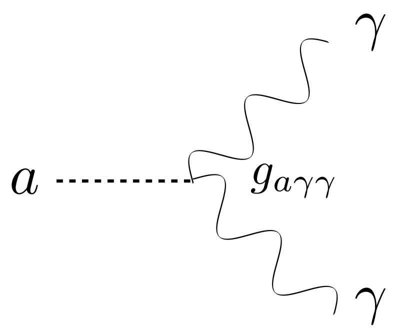
atom
interferometers

WIMPS
(heavy)

Multi-ton experiments
deep underground

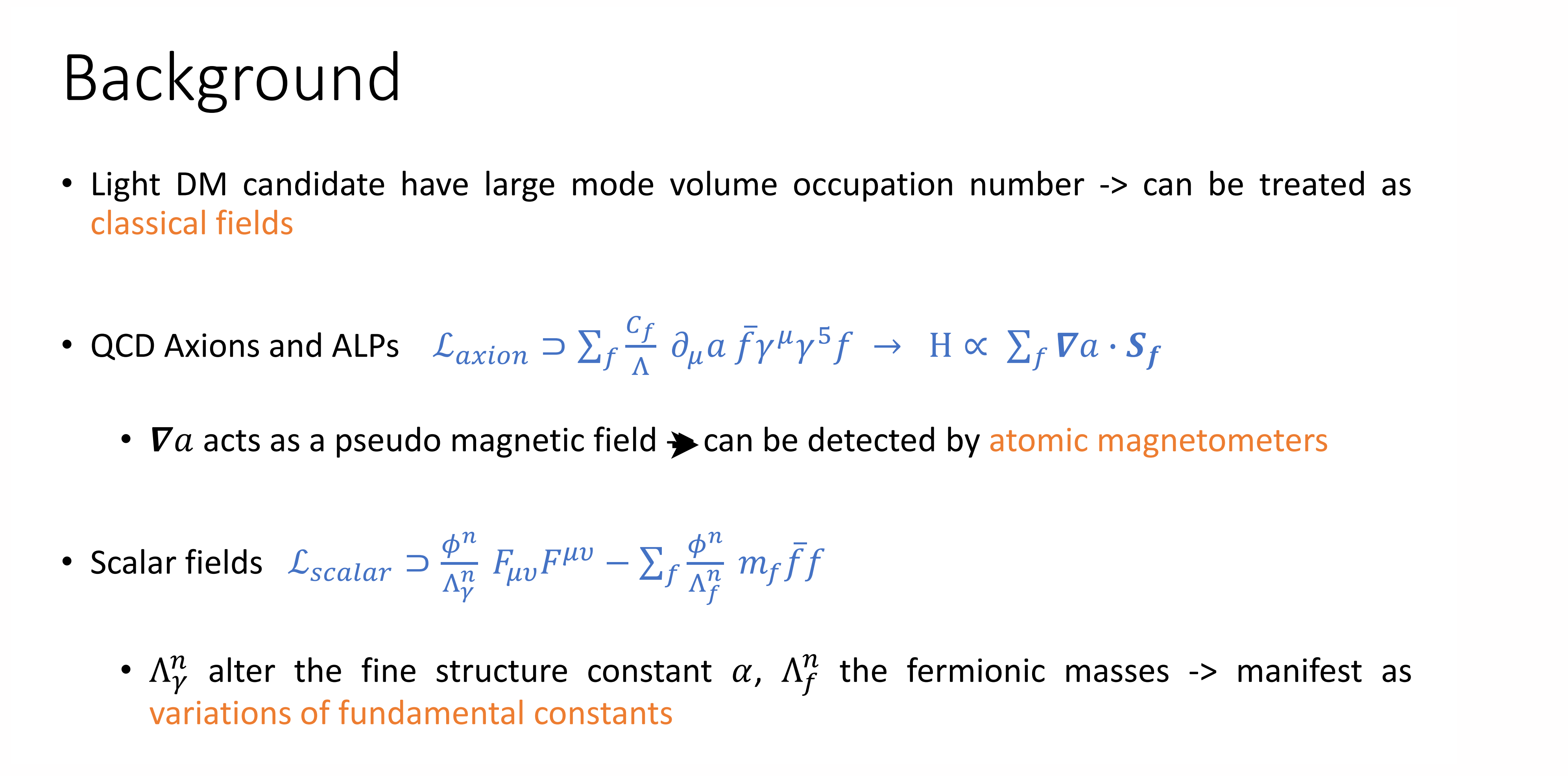
FIMPS
WIMPLESS
DM
SIMPS
Asymmetric
dark matter

HEP
experiments



(but not only…)

particle physics: what are we talking about?



Background

- Light DM candidate have large mode volume occupation number -> can be treated as classical fields
- QCD Axions and ALPs $\mathcal{L}_{axion} \supset \sum_f \frac{C_f}{\Lambda} \partial_\mu a\, \bar{f}\gamma^\mu\gamma^5 f \rightarrow \mathrm{H} \propto \sum_f \boldsymbol{\nabla} a \cdot \boldsymbol{S}_f$
  - $\boldsymbol{\nabla} a$ acts as a pseudo magnetic field → can be detected by atomic magnetometers
- Scalar fields $\mathcal{L}_{scalar} \supset \frac{\phi^n}{\Lambda_\gamma^n} F_{\mu v}F^{\mu v} - \sum_f \frac{\phi^n}{\Lambda_f^n} m_f \bar{f} f$
  - Λ_γ^n alter the fine structure constant α, Λ_f^n the fermionic masses -> manifest as variations of fundamental constants

- symmetry violations probed via precision measurements (C̸P, CP̸T, Lor̸enz, WE̸P, …) → SME

D. Colladay, V.A. Kostelecký, "CPT violation and the standard model". Physical Review D. 55 (11) (1997) 6760–6774. arXiv:hep-ph/9703464

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

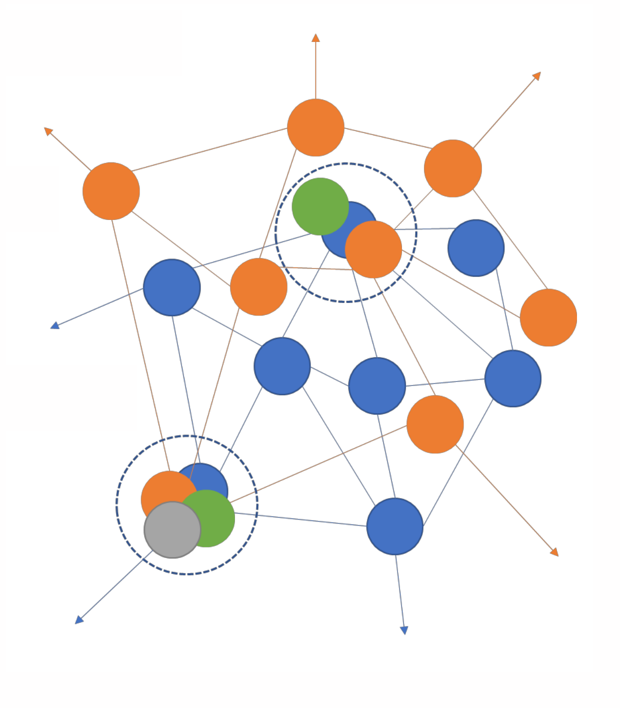
https://indico.cern.ch/event/999818/

Giovanni Barontini (Birmingham)

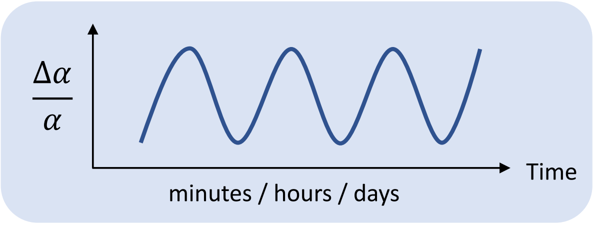
particle physics: what are we talking about?

search for NP / BSM

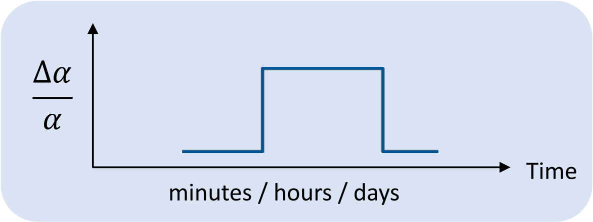
networks of sensors



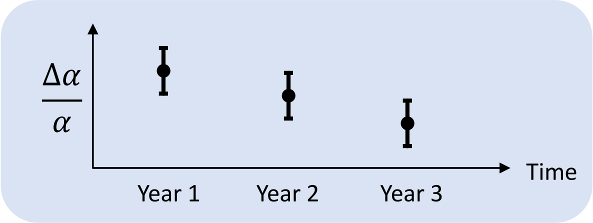
- Oscillations
- Fast transients
- Slow drifts



Very light DM



DM- topological defects



New physics

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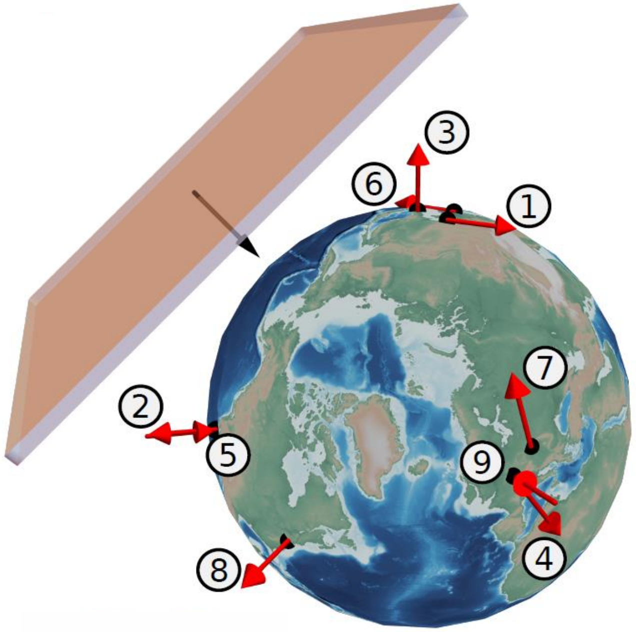
https://indico.cern.ch/event/999818/

Giovanni Barontini (Birmingham)

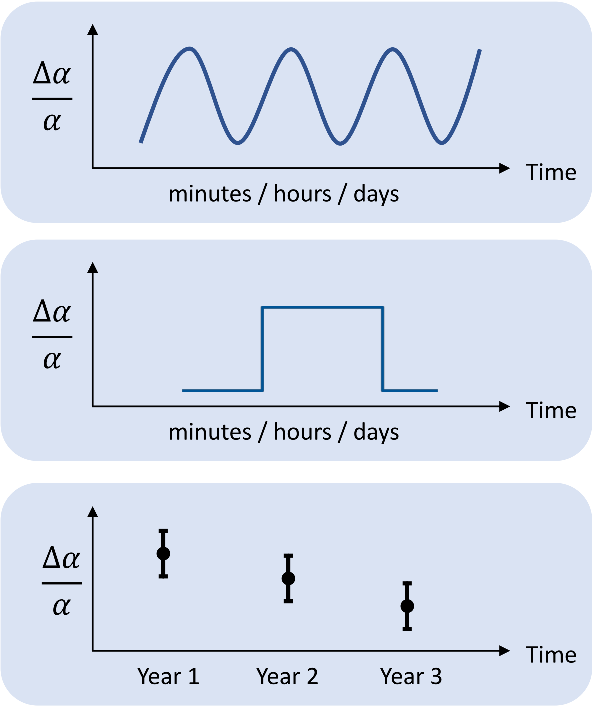
particle physics: what are we talking about?

search for NP / BSM



- Oscillations
- Fast transients
- Slow drifts

networks of sensors



→ Very light DM

→ DM- topological defects

→ 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

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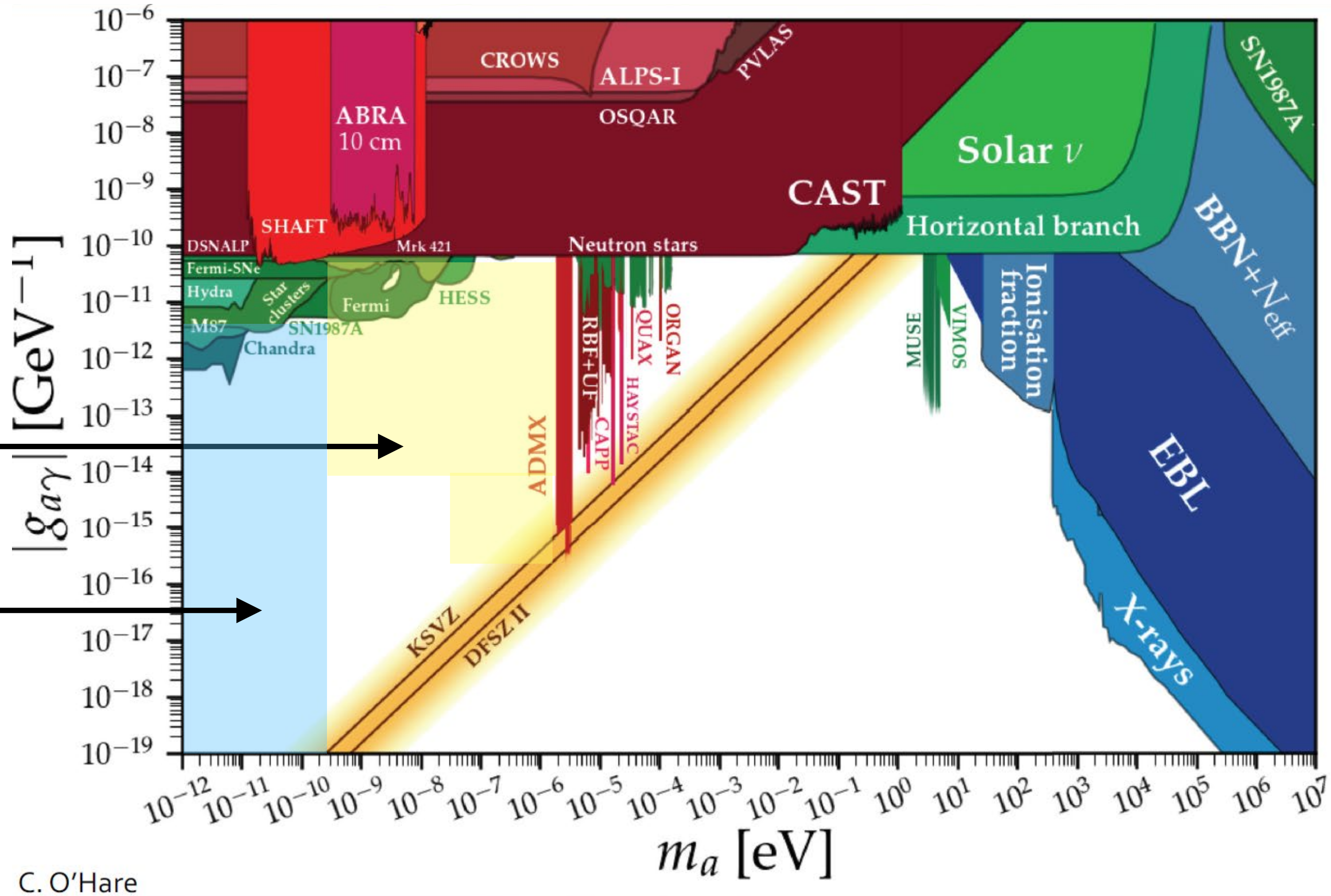
https://indico.cern.ch/event/999818/

particle physics: what are we talking about?



C. O'Hare

DMRadio →

CASPEr
electric
NMR →

spin-based, NMR

microwave cavities

electromagn.
resonators

bolometers, TES

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

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

Kent Irwin (Stanford University)

@ CERN: PBC, large low energy physics community…

https://indico.cern.ch/event/1002356/ PBC technology annual workshop 2021 (focus on quantum sensing)
https://indico.cern.ch/event/1057715/ PBC technology mini workshop: superconducting RF (Sep. 2021)

Initial experiments with quantum sensors world-wide
→ rapid investigation of new phase space

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

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

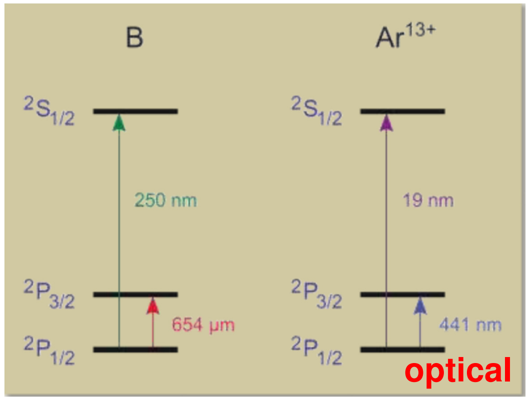
particle physics: what are we talking about?

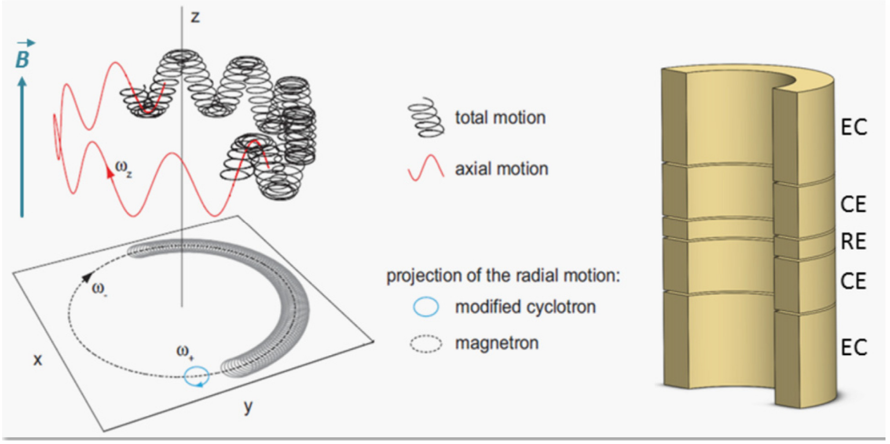
tests of QED, T-violation, P, Lorentz-violation, DM searches

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)

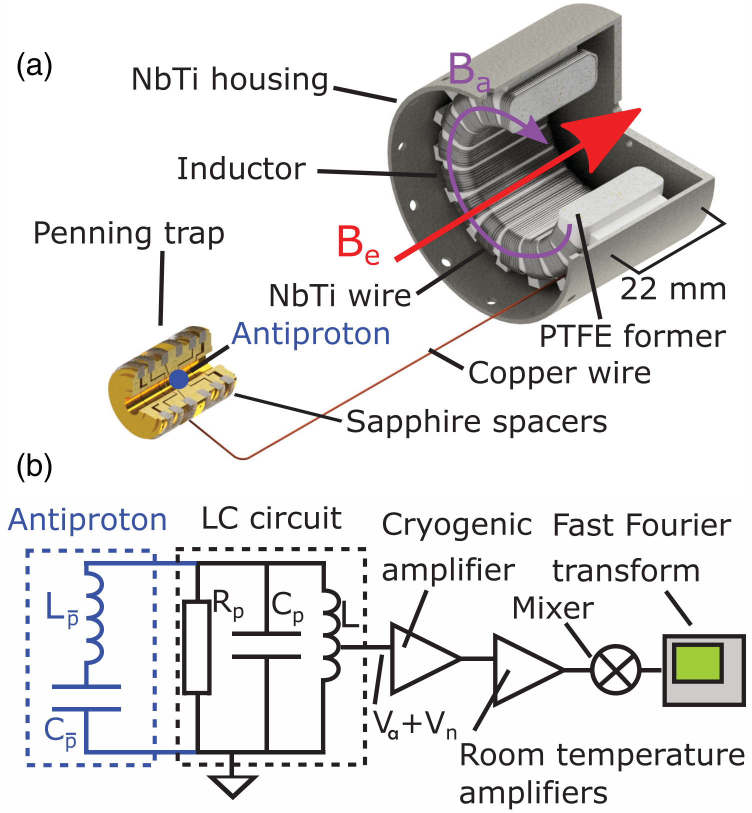
Quantum sensors for new particle physics experiments: Penning traps

search the noise spectrum of fixed-frequency resonant circuit for peaks caused by dark matter ALPs converting into photons in the strong magnetic field of the Penning-trap magnet

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

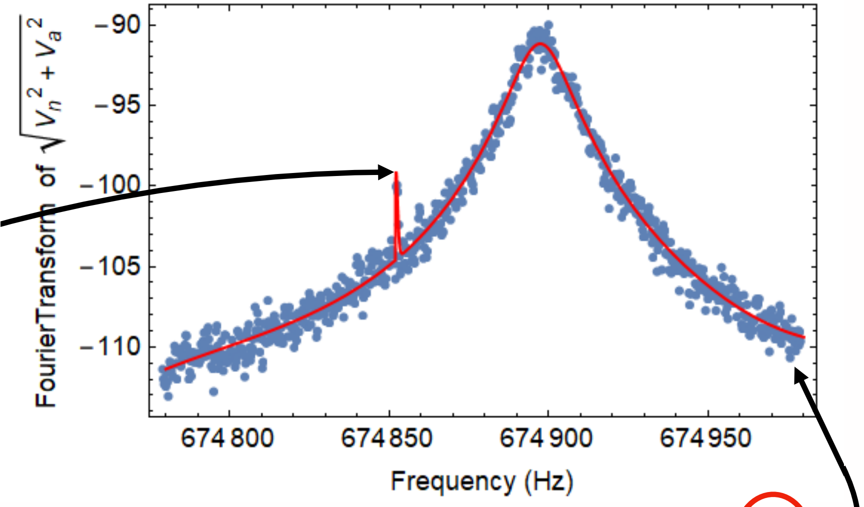
Constraints on the Coupling between Axion-like Dark Matter and Photons Using an Antiproton Superconducting Tuned Detection Circuit in a Cryogenic Penning Trap

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

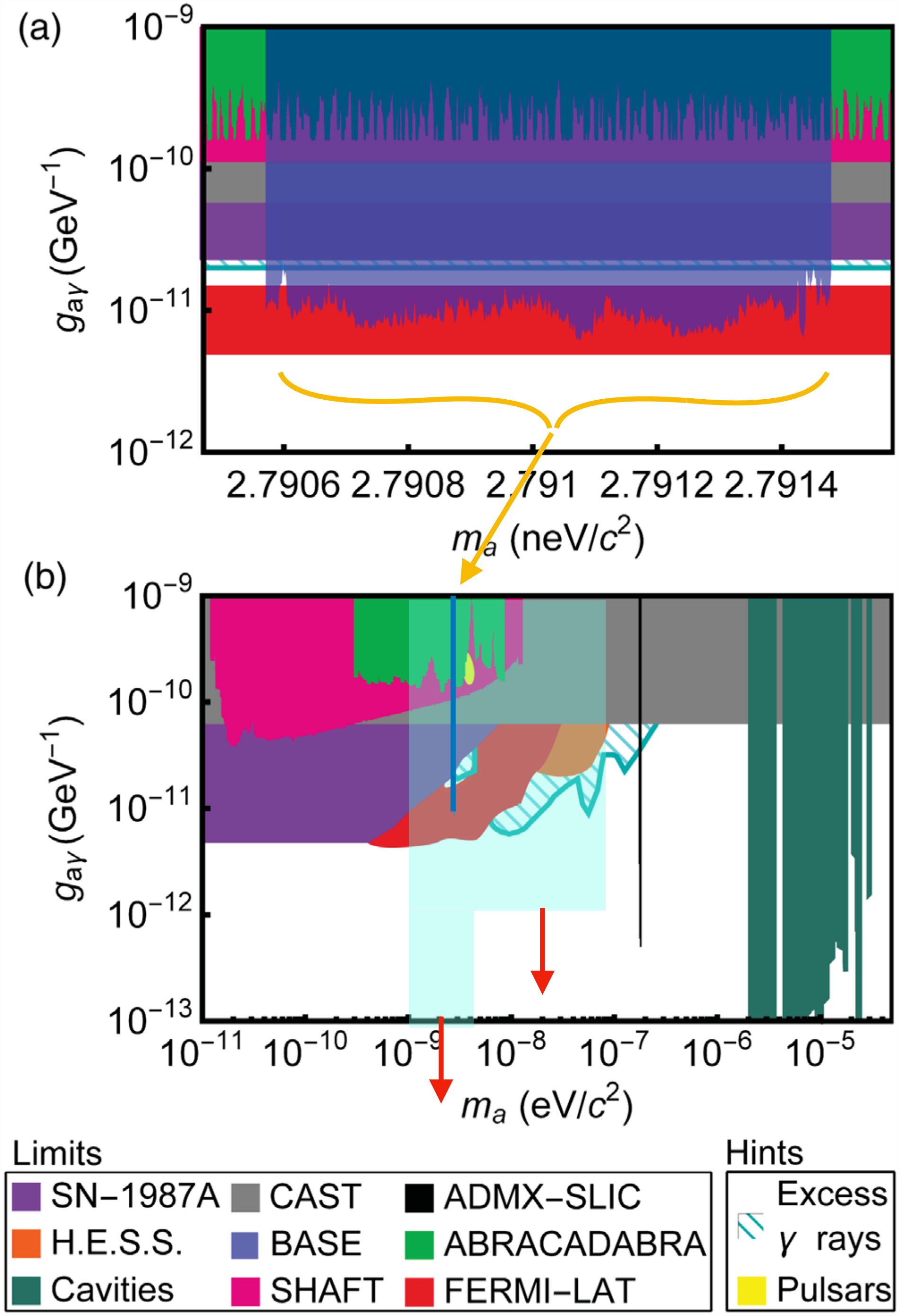
The axion signal

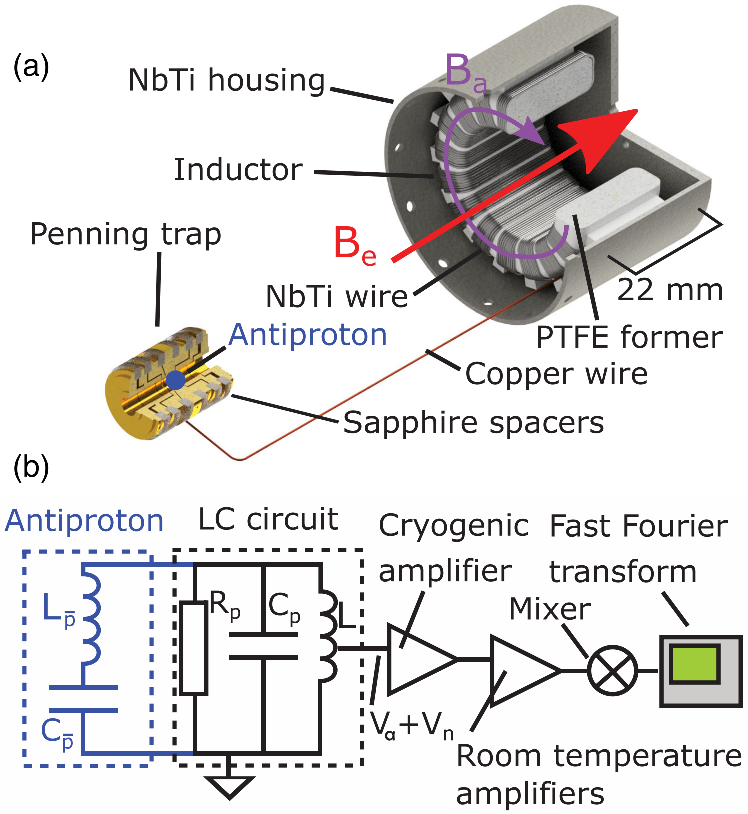
$$V_a = \frac{\pi}{2} Q \sqrt{f(\nu, Q, \mathbf{q})}\kappa \nu_a l N_\mathrm{T} (r_2^2 - r_1^2) g_{a\gamma} |\mathbf{B}_e| \sqrt{\rho_a \hbar c}\,.$$

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

Tunability!





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

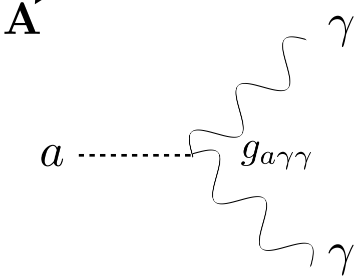
vector potential

Axion DM coupling to electromagnetism through

$$-\mathcal{L} \supset \frac{1}{4}\, g_{a\gamma\gamma}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} \supset \frac{1}{2}\,\mathbf{J}_{\rm eff}\cdot\mathbf{A}$$

In the presence of **B**, axion → effective current density

$$\mathbf{J}_{\rm eff} \simeq g_{a\gamma\gamma}\,\partial_t a\,\mathbf{B}\,.$$



Static **B** → $\mathbf{J}_{\rm eff}$ oscillates with the same frequency as the axion field

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

Tunability!

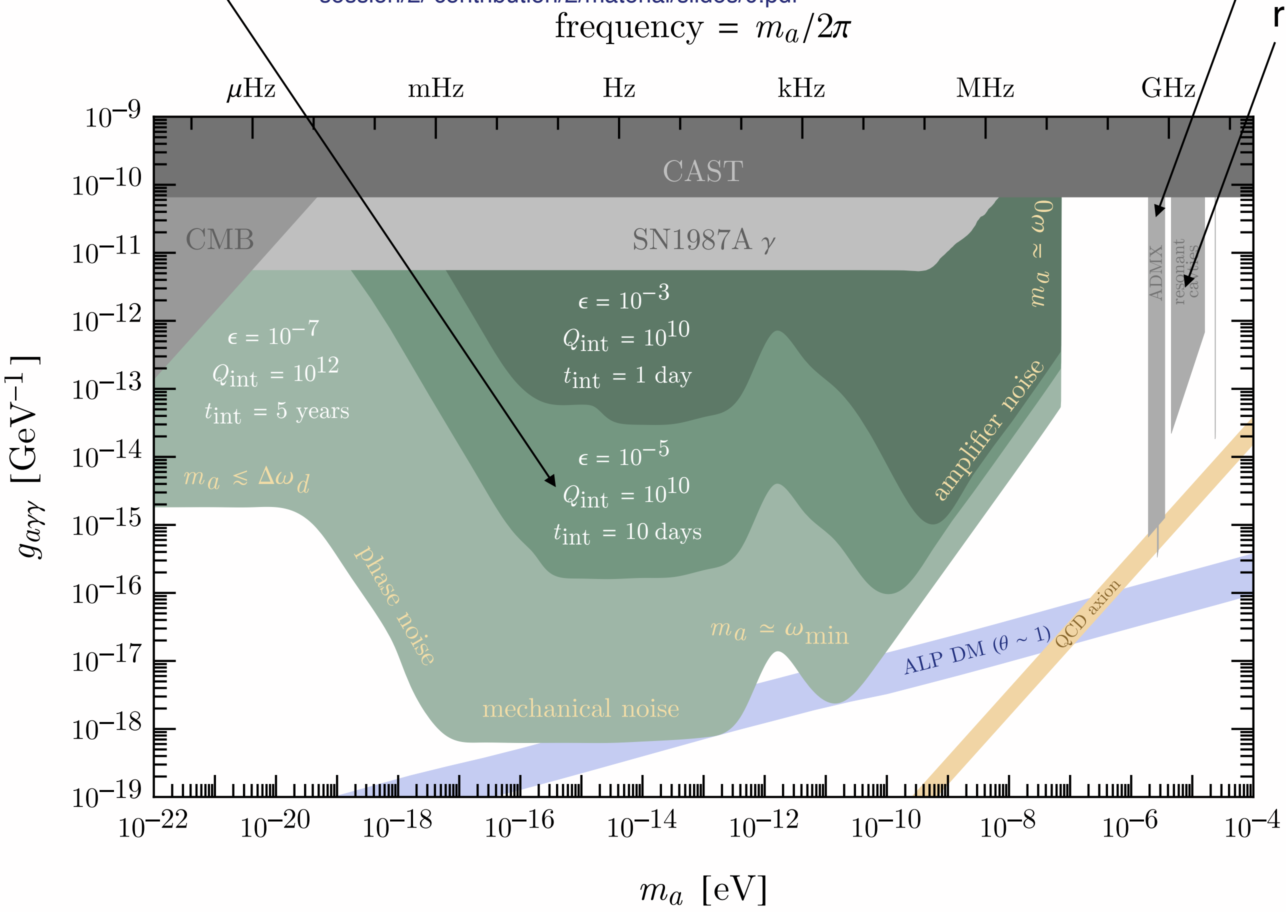
Quantum sensors for new particle physics experiments: tunable RF cavities

$Q_{int} \gtrsim 10^{10}$ achieved by DarkSRF collaboration (sub-nm cavity wall displacements)

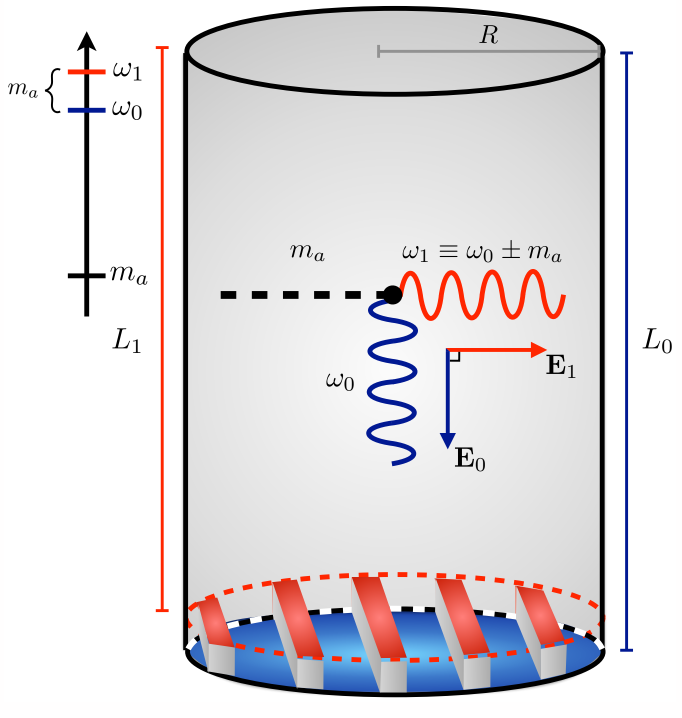
A. Grassellino, “SRF-based dark matter search: Experiment,” 2019. https://indico.fnal.gov/event/19433/session/2/ contribution/2/material/slides/0.pdf

ADMX experiment

resonant cavities



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) Cartoon of cavity setup.

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

$$\underset{\text{figure of merit}}{F} \sim g_{a\gamma}^2 m_A^2 \underset{\text{magnetic field}}{B^4} V^2 T_{sys}^{-2} G^4 \underset{\text{quality factor}}{Q},$$

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 ☐

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].

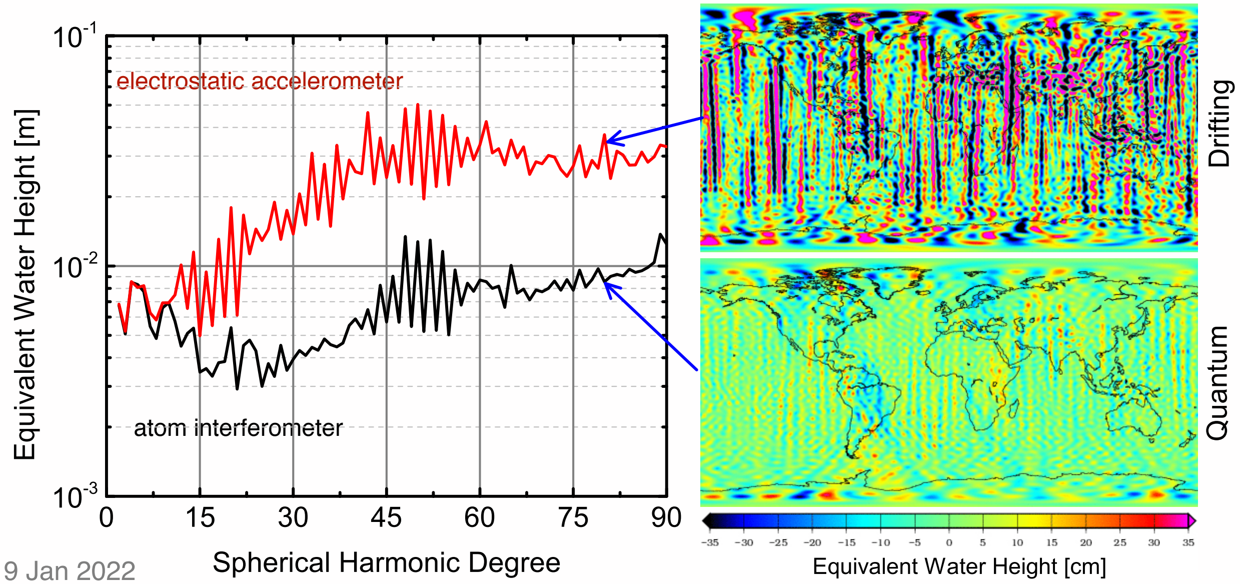
Topological Dark Matter (TDM)	TDM can be expressed as a scalar field that couples to fundamental constants, thus producing variations in the transition frequencies of atomic clocks at its passage.
Ultralight Dark Matter	spatial variation of the fundamental constants associated with a change in the gravitational 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

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

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:

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

~2030

AION: ~2045 satellite mission

AEDGE: ~2045 satellite mission

El-Neaj, Y.A., Alpigiani, C., Amairi-Pyka, S. *et al*. AEDGE: Atomic Experiment for Dark Matter and Gravity Exploration in Space. *EPJ Quantum Technol*. **7**, 6 (2020). https://doi.org/10.1140/epjqt/s40507-020-0080-0 typically not obvious, given that most detectors rely on detecting the product of many interactions between a particle and the detector (ionization, scintillation, Cerenkov photons, …)

handful of ideas that rely on quantum devices, or are inspired by them, but do not necessarily use them 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

closely related: nanostructured materials
→ Frontiers of Physics, M. Doser et al., 2022

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

very speculative!

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

ultra-fast scintillators based on perovskytes

chromatic calorimetry (QDs)

active scintillators (QCL, QWs, QDs) 5.3.6 *

GEMs (graphene)

Atoms, molecules, ions

Rydberg TPC's 5.3.5 *

Spin-based sensors

helicity detectors 5.3.3 *

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

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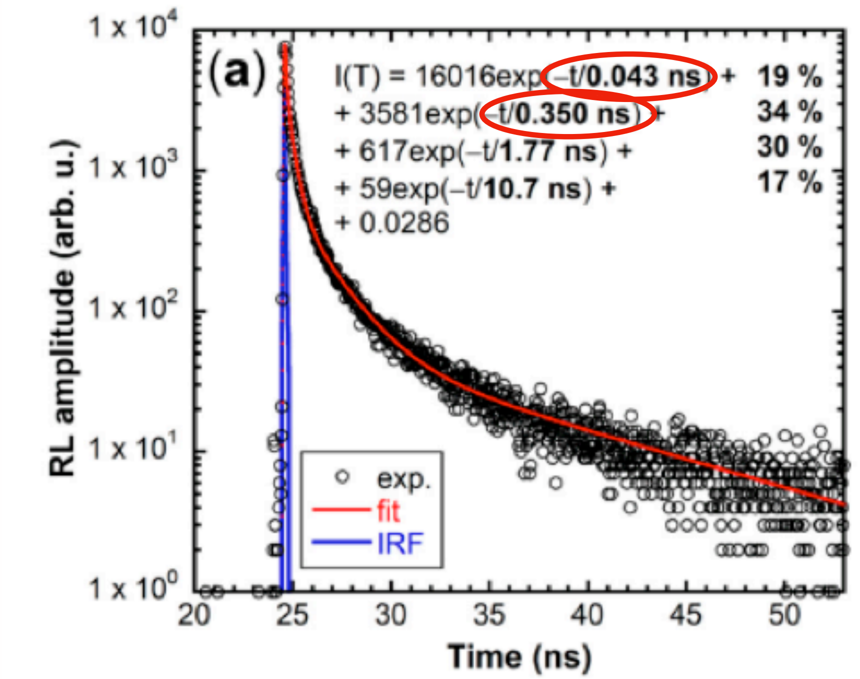
helicity detectors 5.3.3

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

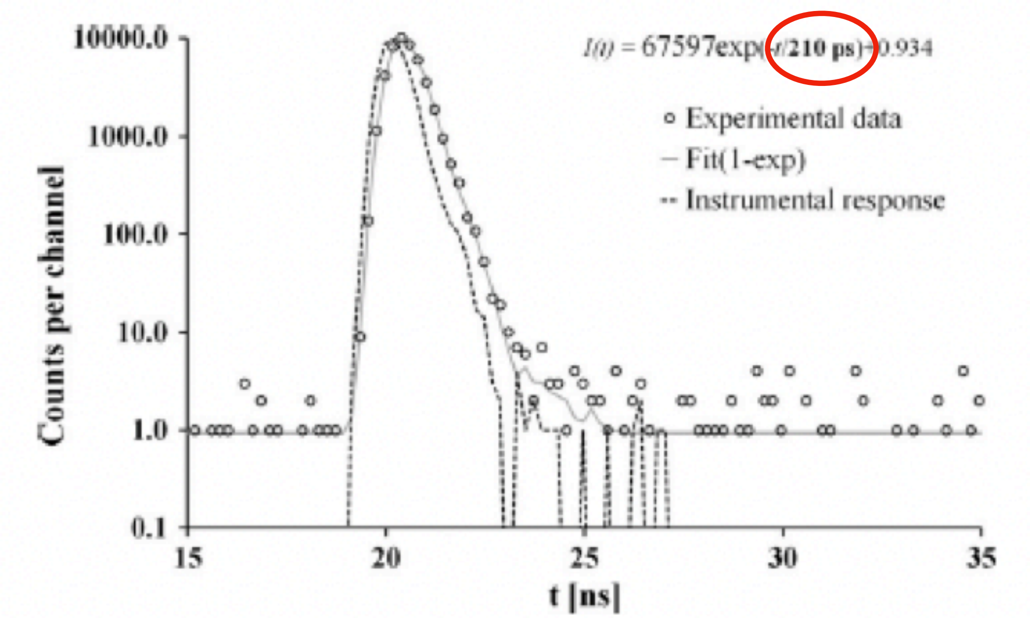


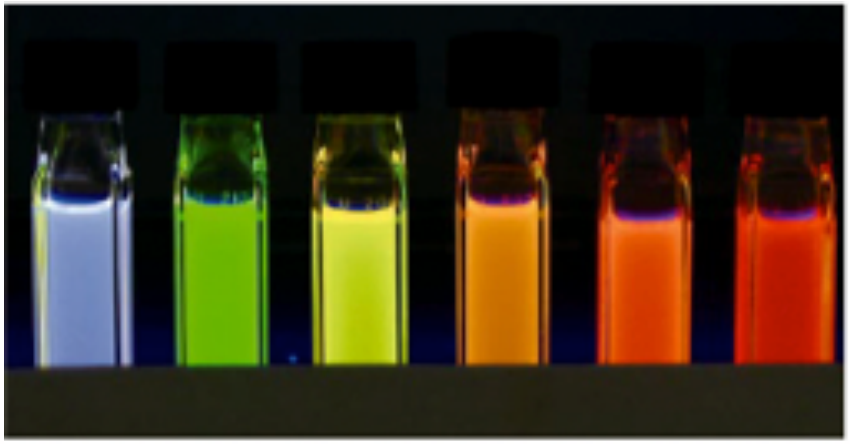
Fig. 9. Photoluminescence decay of ZnO:Ga sample at room temperature. Excitation nanoLED 339 nm, emission wavelength set at 390 nm. Decay curve is approximated by the convolution of instrumental response (also in figure) and single exponential function $I(t)$ provided in the figure.

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

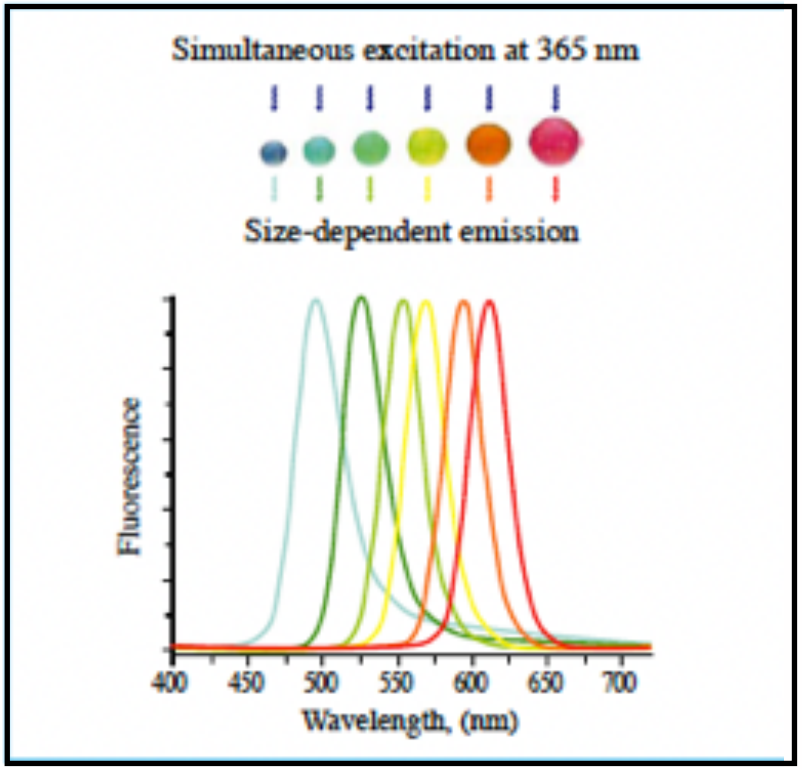
Concerns: integrated light yield (need many photons to benefit from rapid rise time)

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

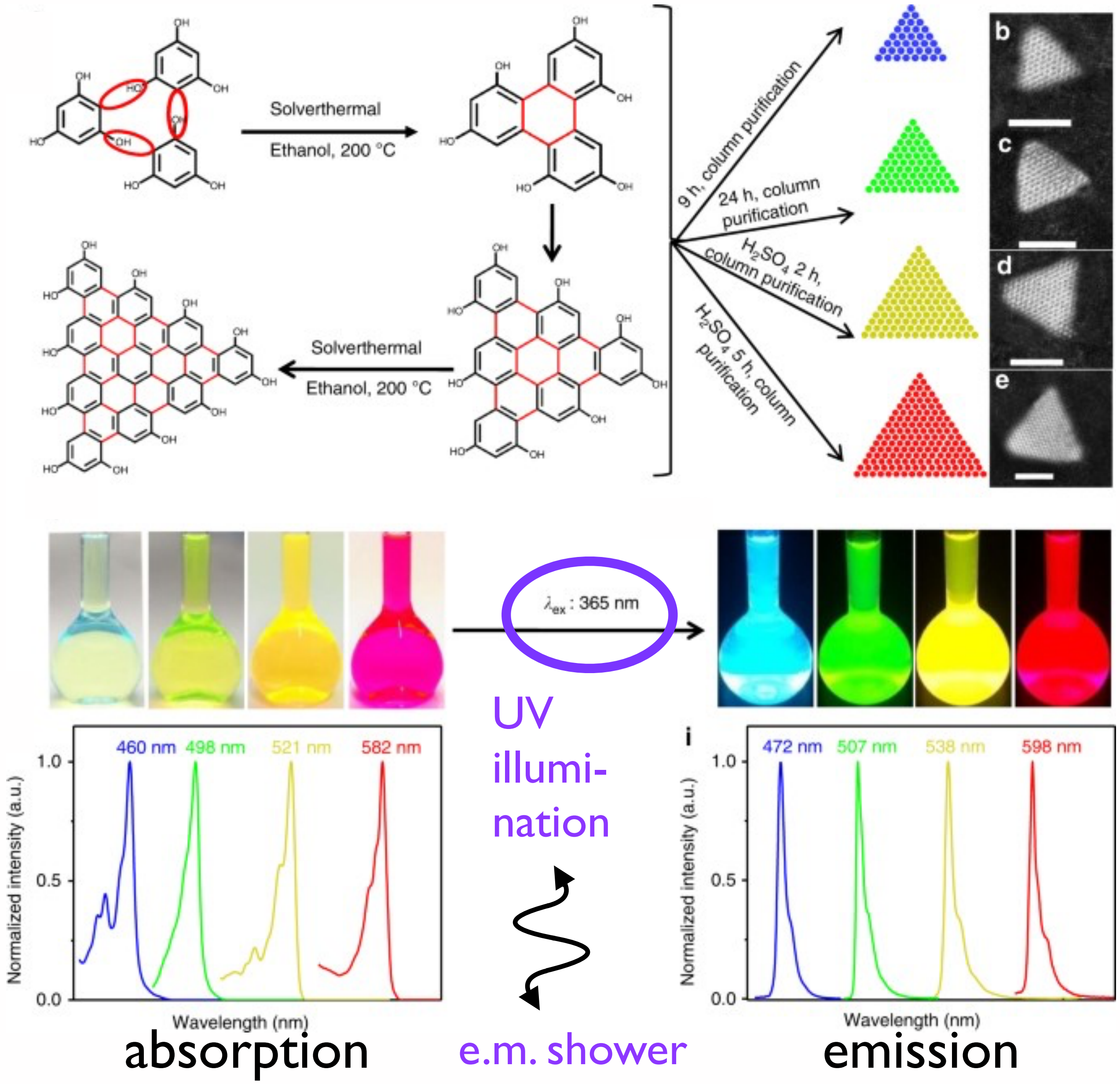


chromatic tunability → optimize for quantum efficiency of PD (fast, optimizable WLS)

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

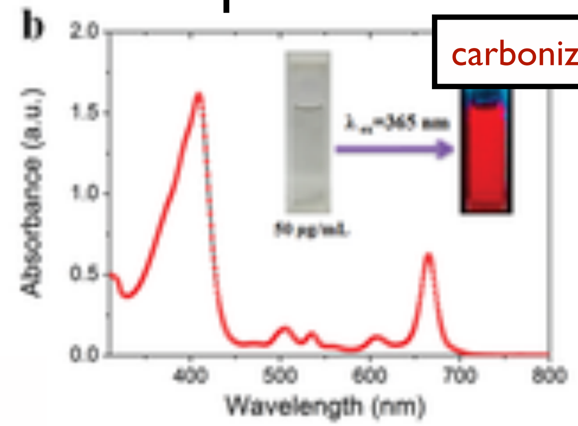
requires:

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

select appropriate nanodots

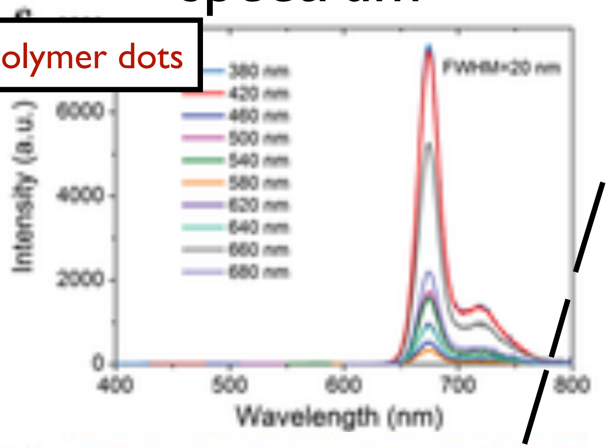
e.g. triangular carbon nanodots

absorption spectrum



carbonized polymer dots

emission spectrum



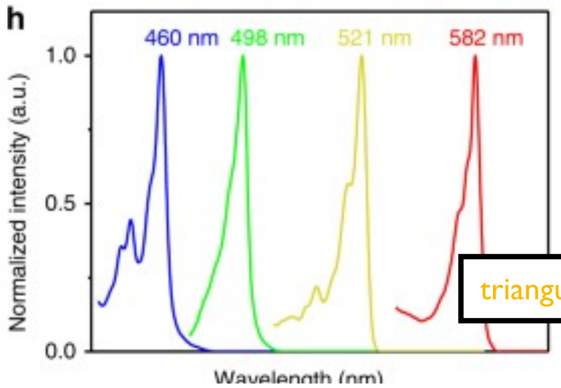
leftmost nanodots:
absorb wavelengths < 650 nm
emit at > 680 nm

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

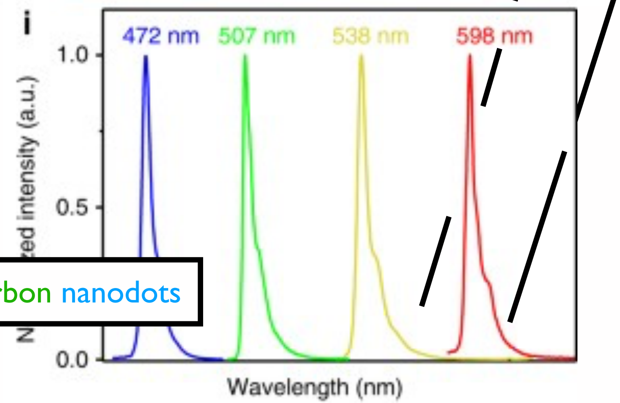
…

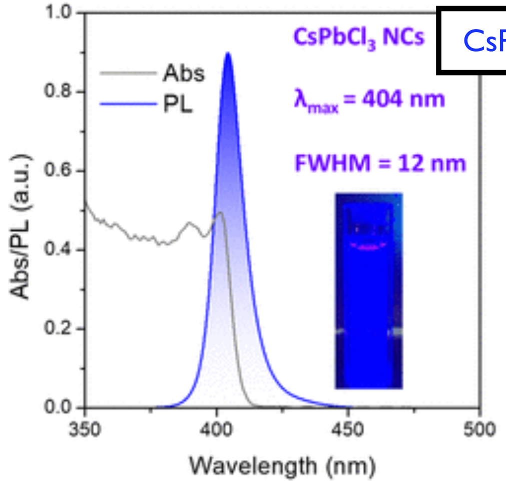
rightmost nanodots:
absorb wavelengths < 410 nm
emit at > 420 nm

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

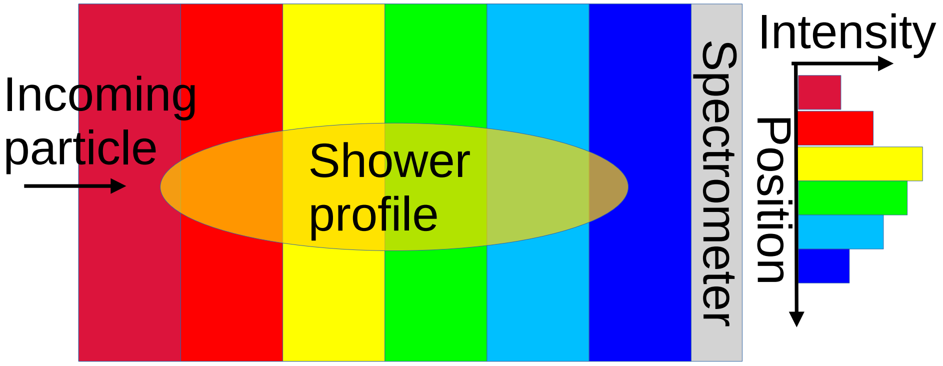


triangular carbon nanodots

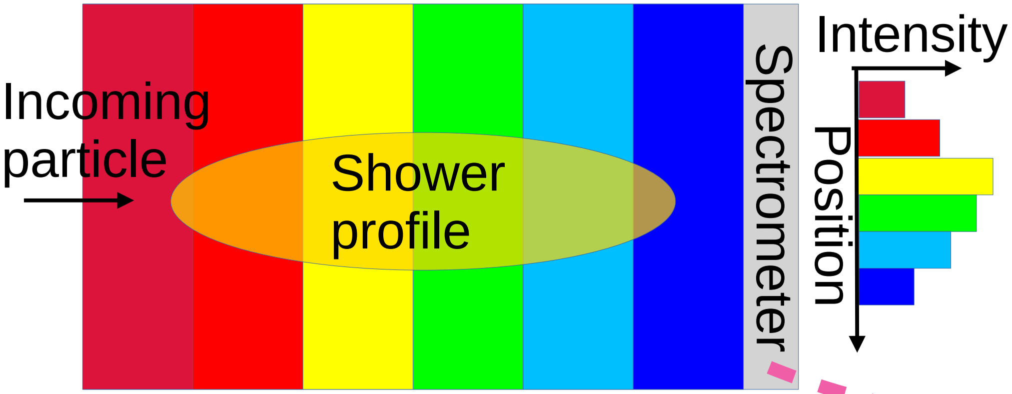




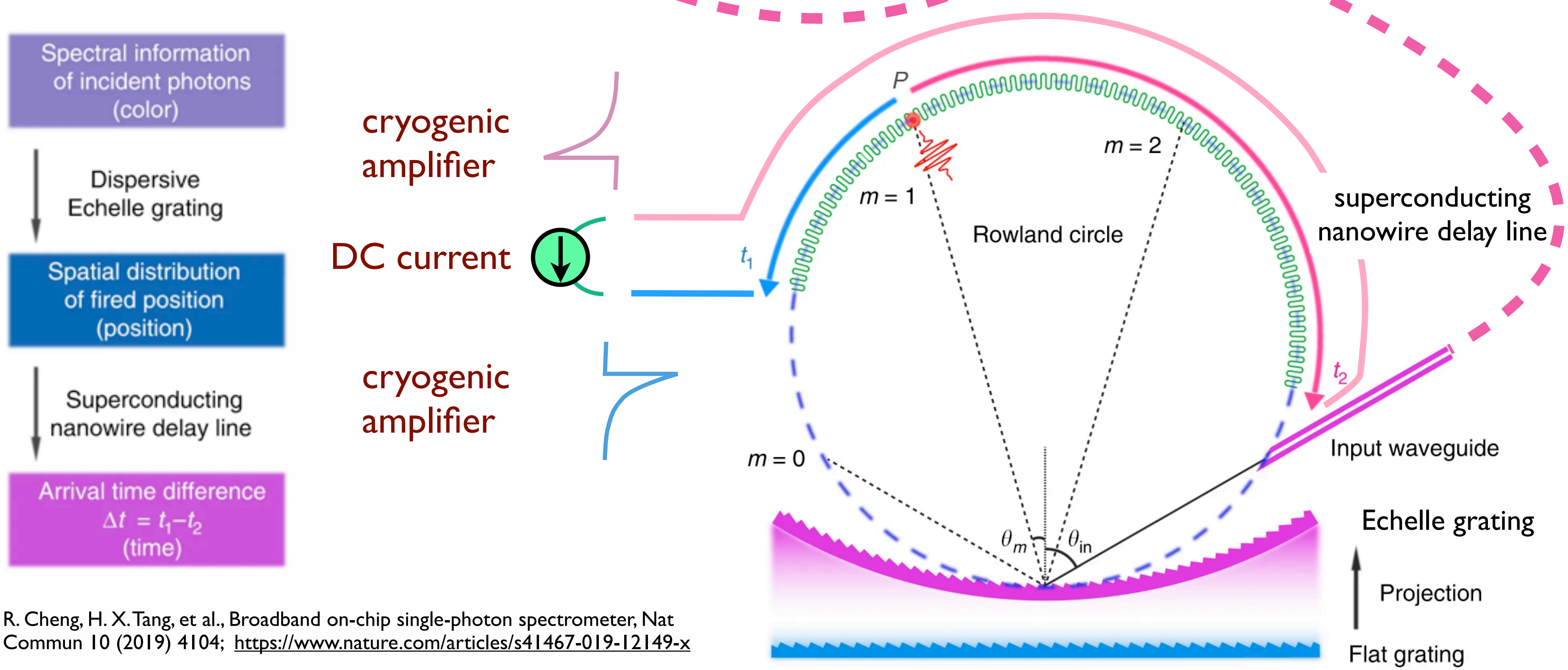
CsPbCl$_3$ nanocrystals



Quantum dots: chromatic calorimetry (shower profile via ***spectrometry***)



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



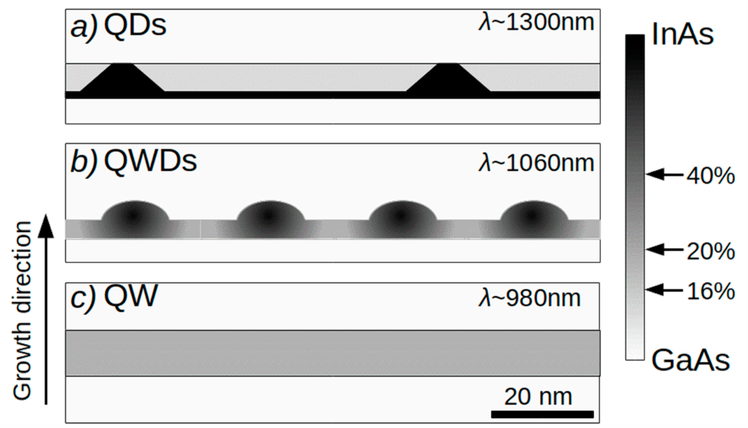
R. Cheng, H. X. Tang, et al., Broadband on-chip single-photon spectrometer, Nat Commun 10 (2019) 4104; https://www.nature.com/articles/s41467-019-12149-x

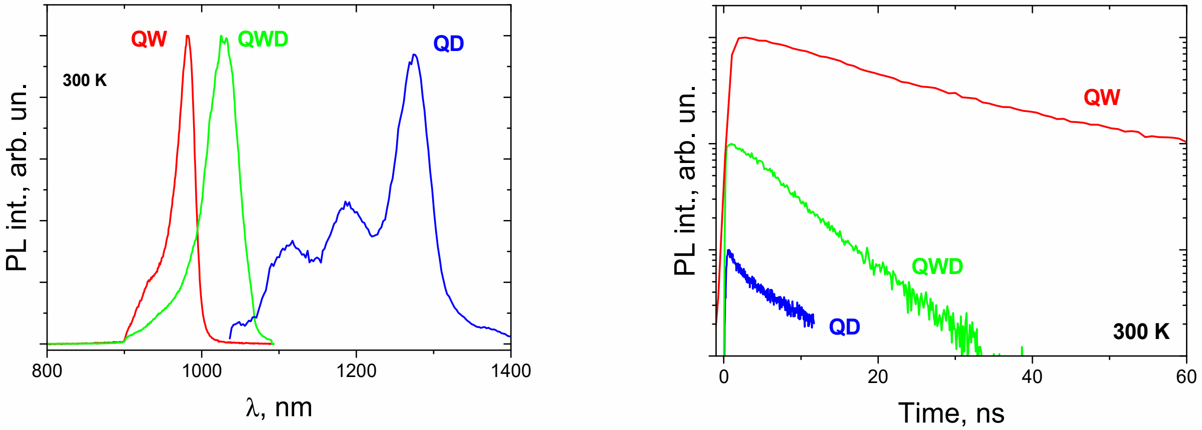
Active scintillators (QWs, QDs, QWDs, QCLs)

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





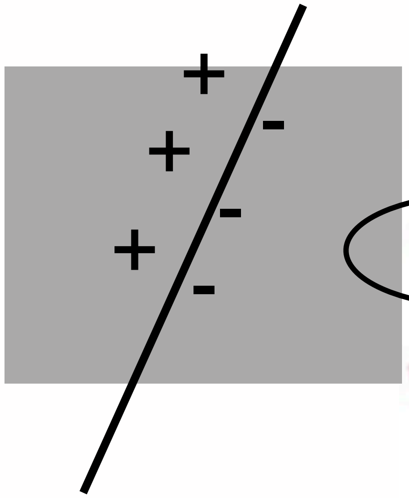
Light Emitting Devices Based on Quantum Well-Dots, Appl. Sci. 2020, 10, 1038; doi:10.3390/app10031038

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.

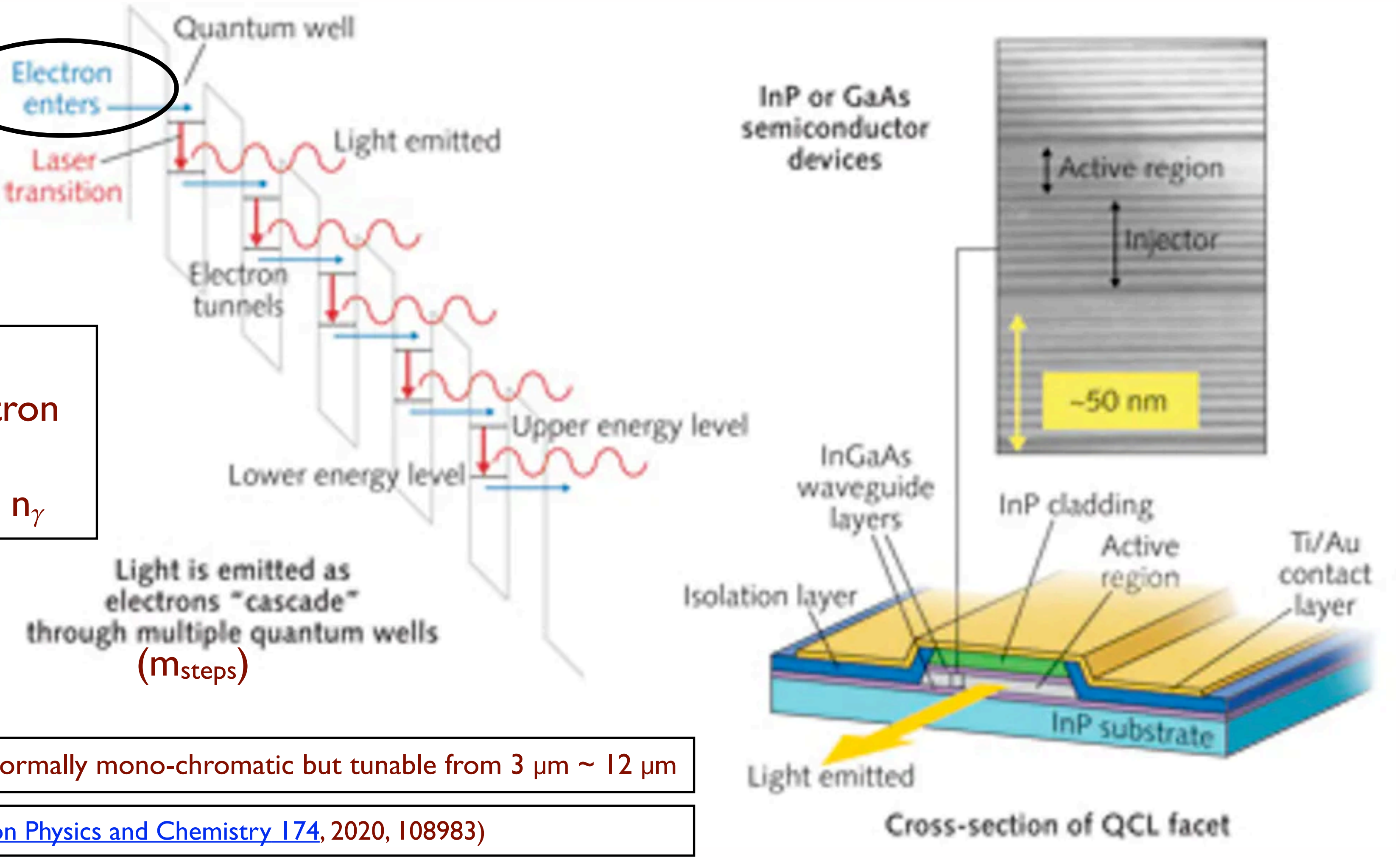
Active scintillators (QCLs, QWs, QDs, QWDs)



Couple bulk semi-conductor to electron injection layer:

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

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



(m_{steps})

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

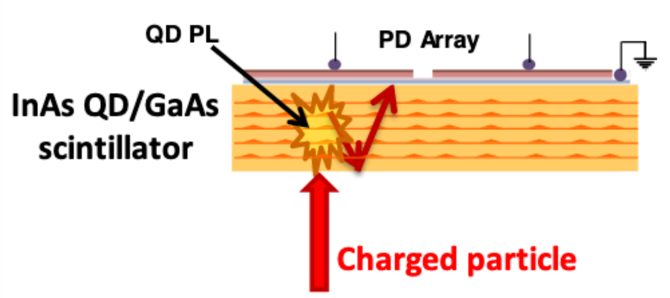
submicron pixels

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

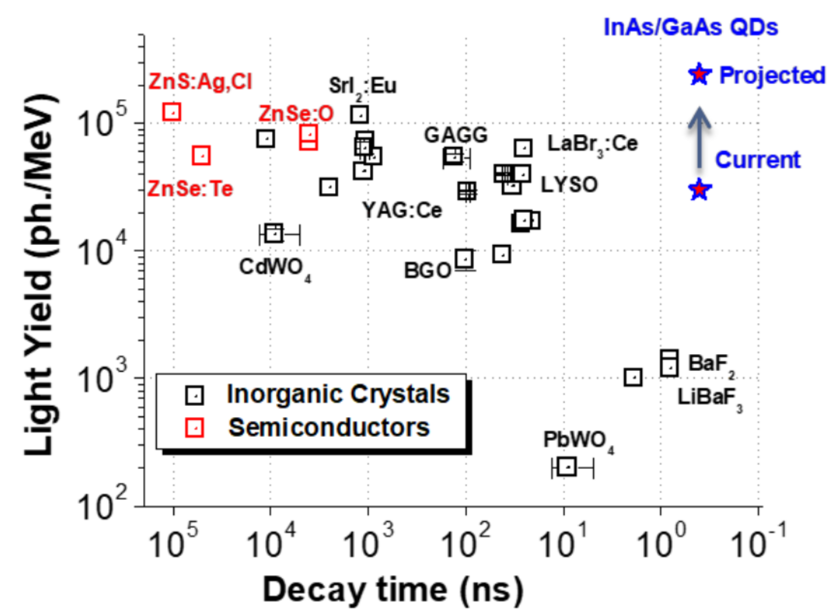


IR emission from InAs QD's integrated PD's (1-2 μm thick)

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

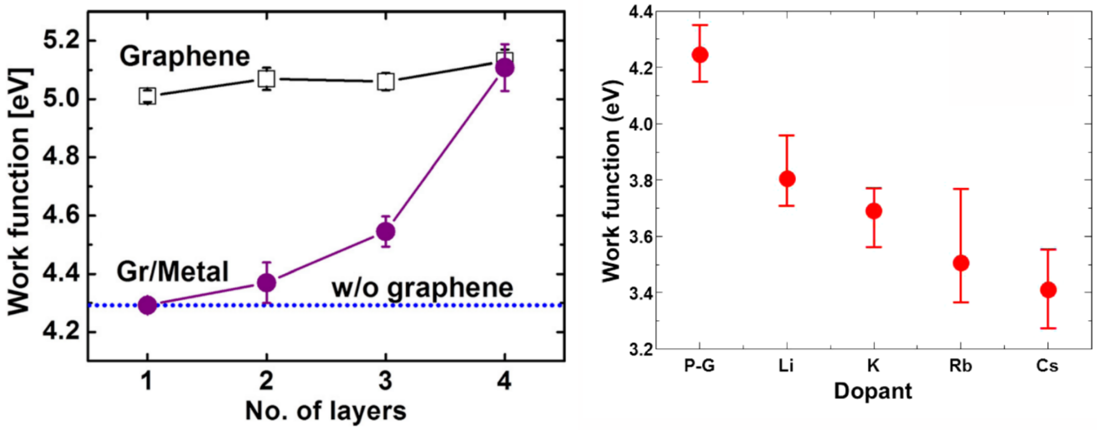
efficiency of the photocathode → timing resolution; QE
tune via resonant processes in low dimensional coating structures

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

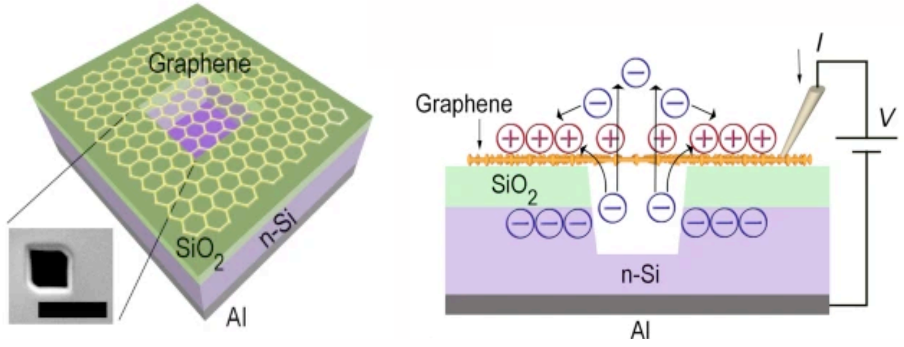
amplification

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)

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GEMs (graphene)

Atoms, molecules, ions

5.3.5

Rydberg TPC's

Spin-based sensors

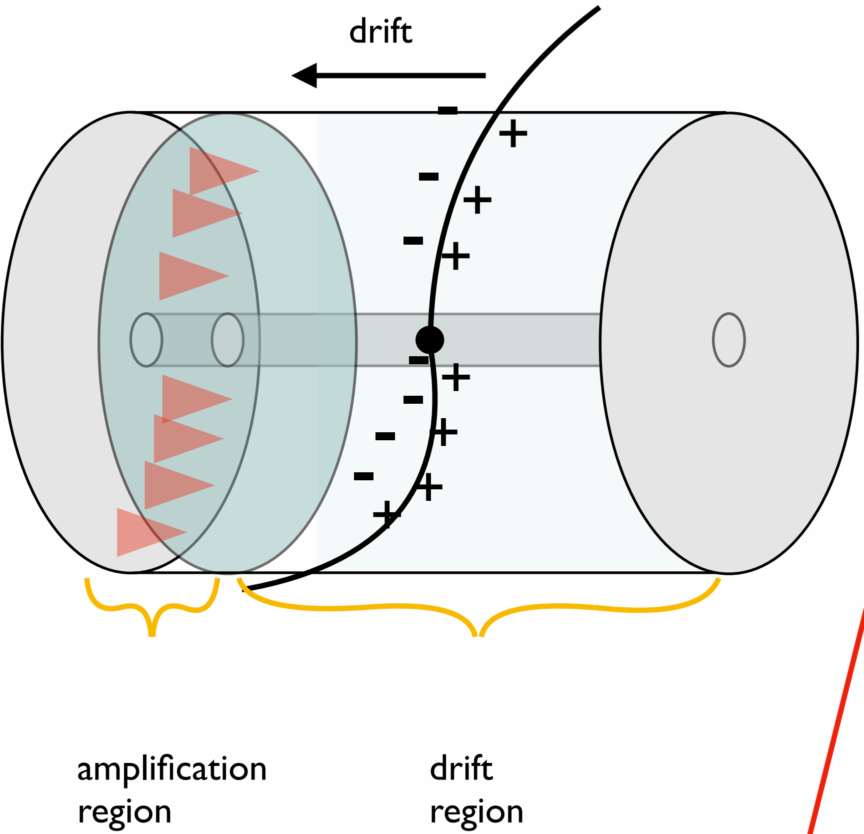
5.3.3

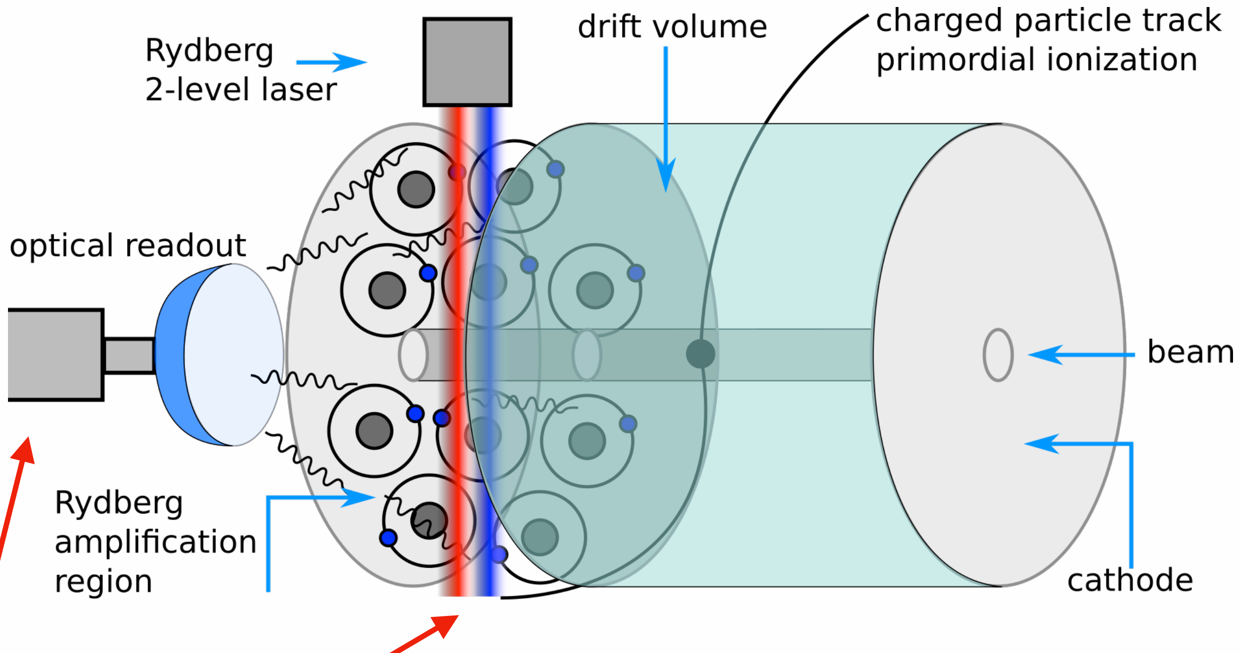
helicity detectors

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

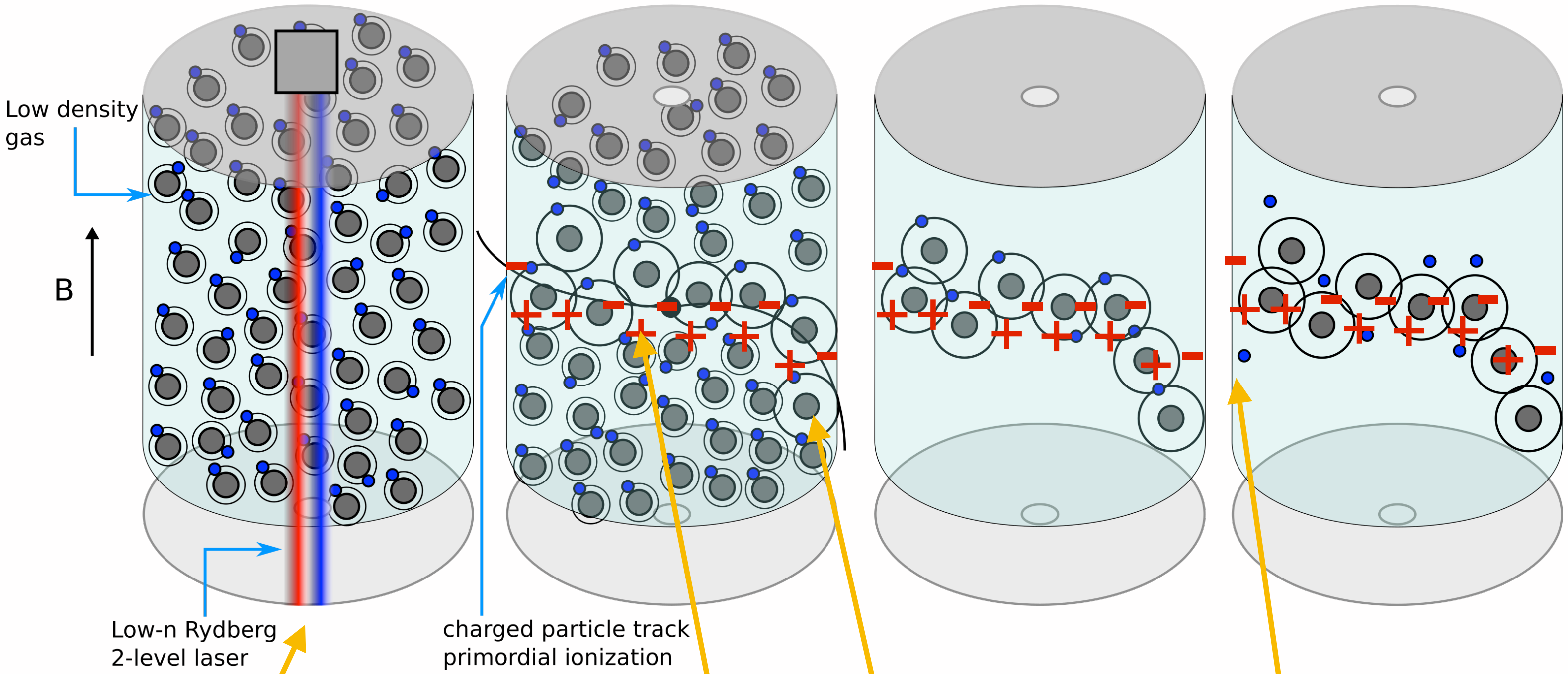
principle carries over to drift region:
enhanced electron signal through "priming" of gas in drift region:
effective reduction of ionization threshold of gas in amplification region
increased dE/dx through standard primary ionization + photo-ionization of atoms excited by mip's

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



reduction of ionization and atomic excitation threshold

ionization + excitation;
natural decay of unmodified atoms

photo-ionization of excited atoms

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helicity detectors 5.3.3

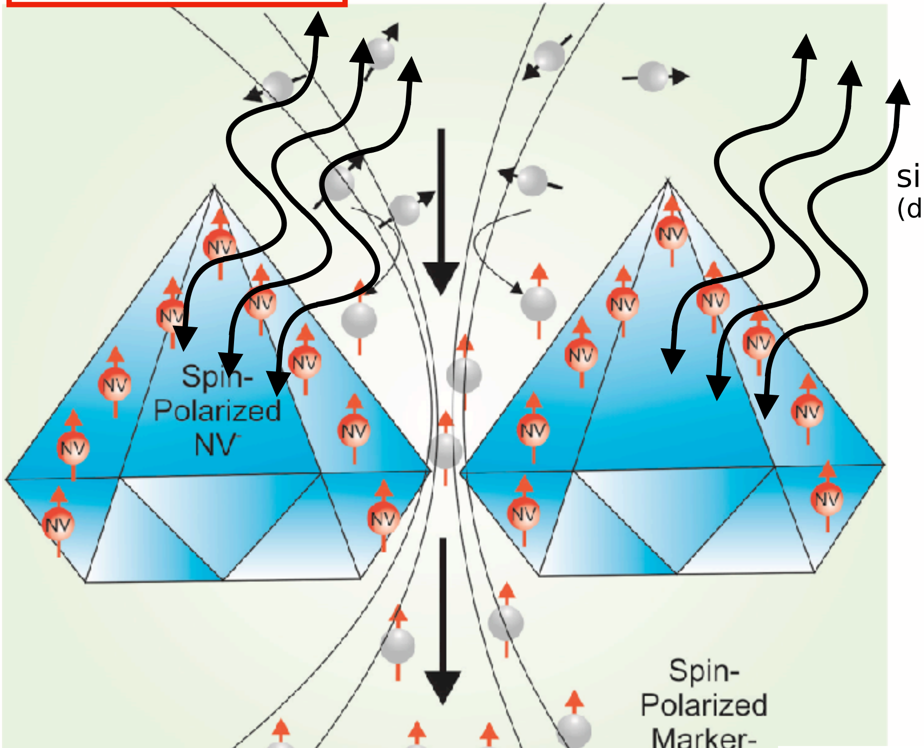
HEP
optically polarizable elements: Nitrogen-vacancy diamonds (NVD)

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

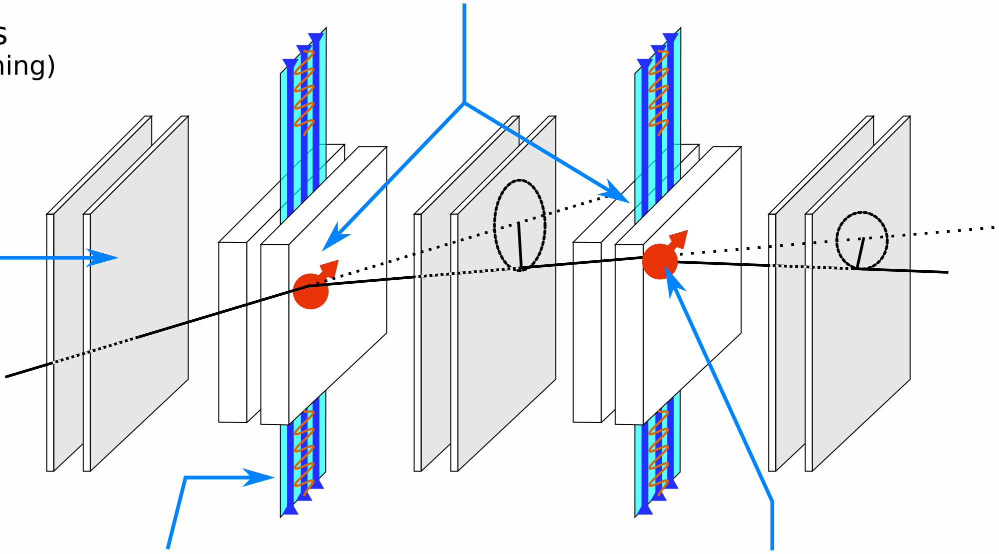
$10^{16} \sim 10^{18}$ / cm^3



© 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

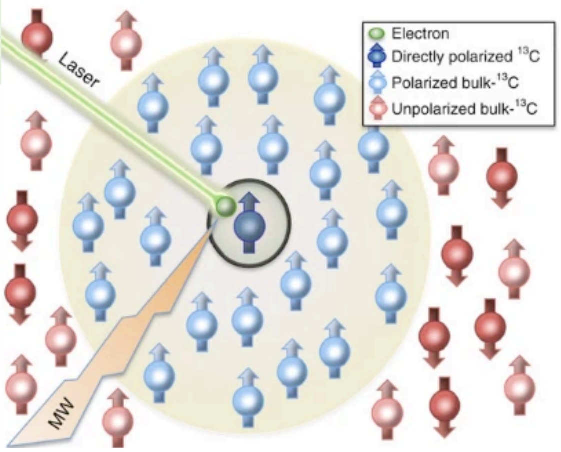


NV in diamond

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

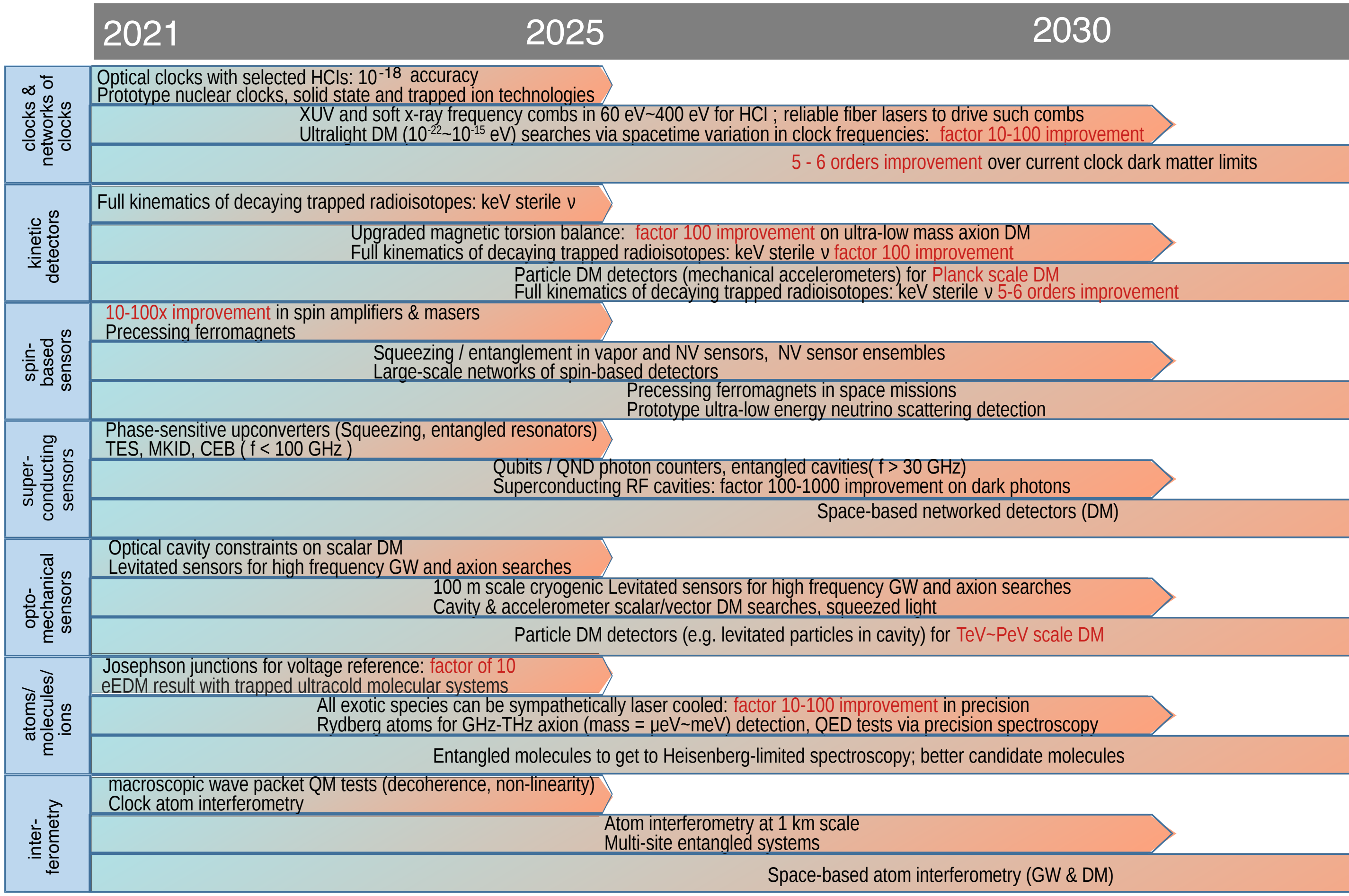
x 10^2

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



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

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

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

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)

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

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

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!

thank you!

Open symposium organized by TF5

Anna Grassellino,

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

Symposium: April 12, 2021

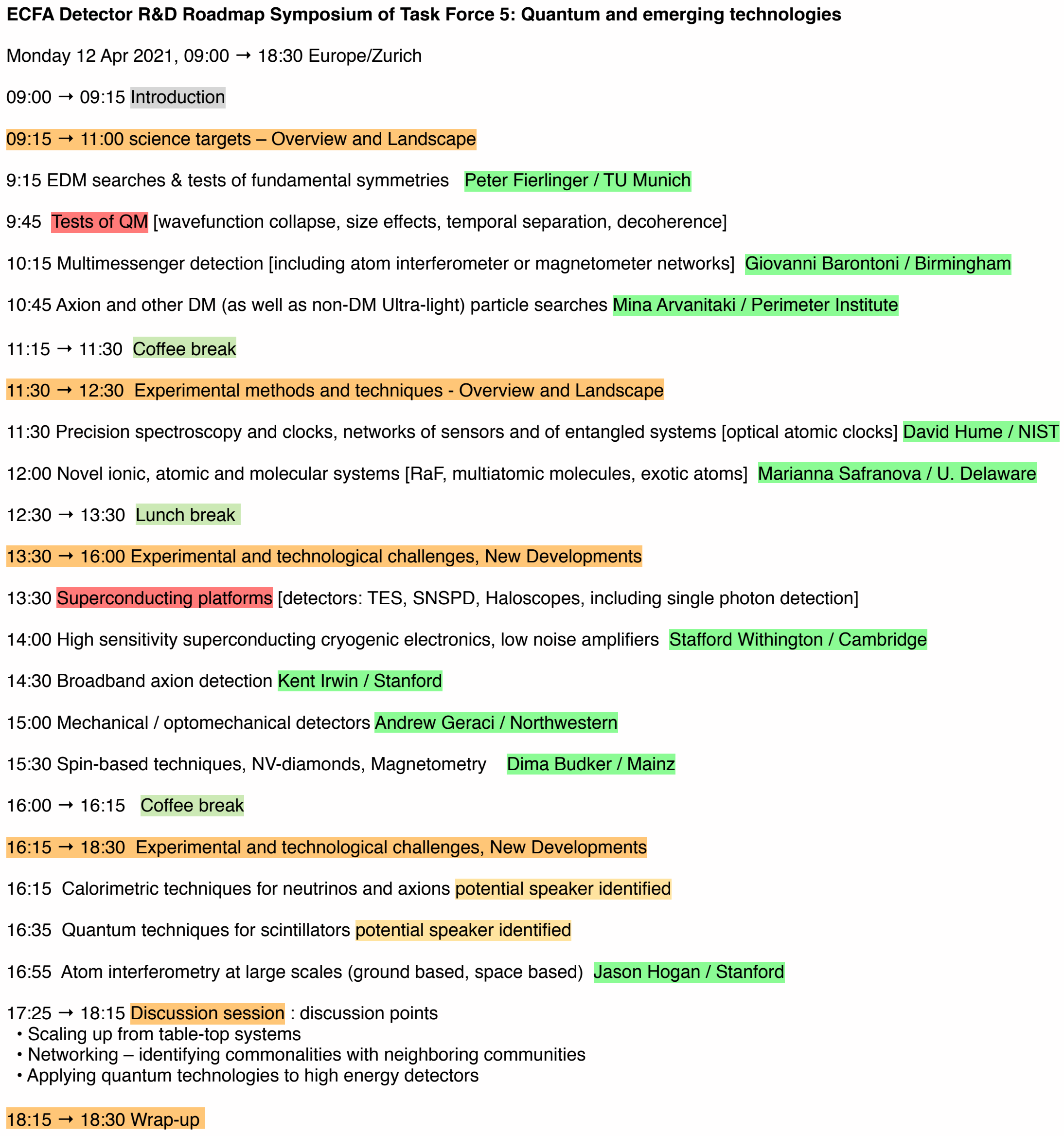
https://indico.cern.ch/event/999818/

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

Anna Grassellino, Marcel Demarteau, Michael

“Recommendations’

- many fascinating opportunities in nascent fields
- encourage <u>exploratory approaches</u>
- adapt funding profiles to both exploratory as well as consolidation approaches:
  - exploratory: funding cycle of 3 years, lightweight grant application, “fail early / fail often / proof-of-principle” mindset
  - consolidation: funding cycle of 10 years, after initial proof of principle, proposal
- <u>importance of interdisciplinarity</u>
  - training not only of early stage researchers but also of established researchers