Quantum Detectors
for particle physics

(focus on applying quantum sensors to
both “HEP” *and* low energy particle physics)

Michael Doser / CERN/MIT/Oxford

1 Clarification of terms

2 Some words on the landscape

3 Quantum sensors for low energy particle physics

4 Quantum sensors for high energy particle physics

5 “DRD5”

①

Clarification of terms

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

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

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

bottom line: quantum sensors measure result of *a single* individual interaction

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;

①

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

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

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

bottom line: quantum sensors measure result of *a single* individual interaction

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

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

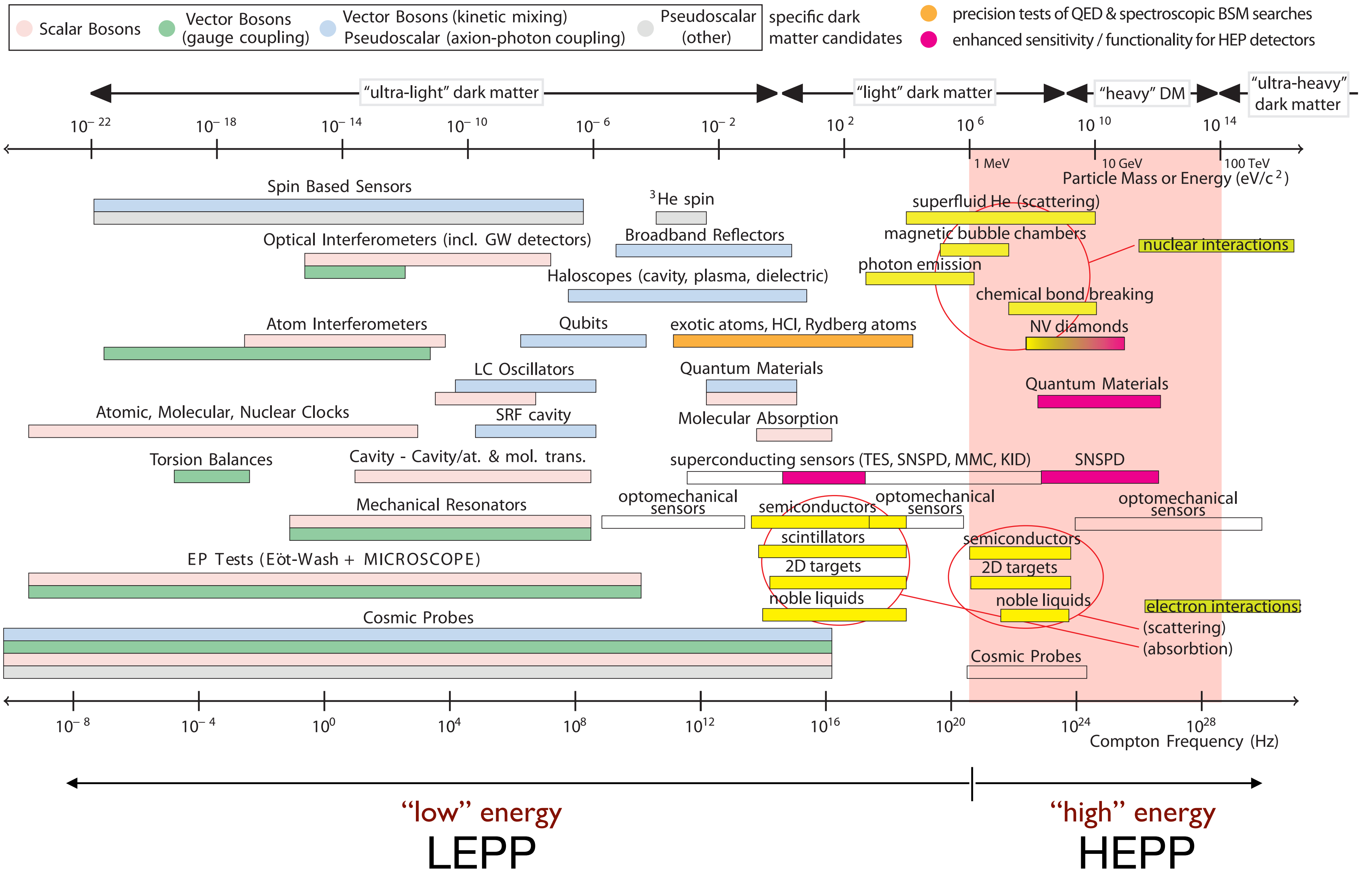
→ focus on activities in both in low energy and high energy particle physics

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

①

“Quantum” is everywhere

Landscape: quantum sensing applied to an extremely wide range of DM searches



②

ECFA Detector R&D Roadmap: *Quantum and Emerging Technologies*

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

→ https://indico.cern.ch/event/957057/page/23281-the-roadmap-document

domains of physics

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

roadmap 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

Qbit-relevant technologies

②

Many initiatives related to HEP world-wide;

Three initiatives at CERN:

- CERN Quantum Technology Initiative
- Physics Beyond Colliders
- R&D on quantum sensors for particle physics (DRD5)

pilot

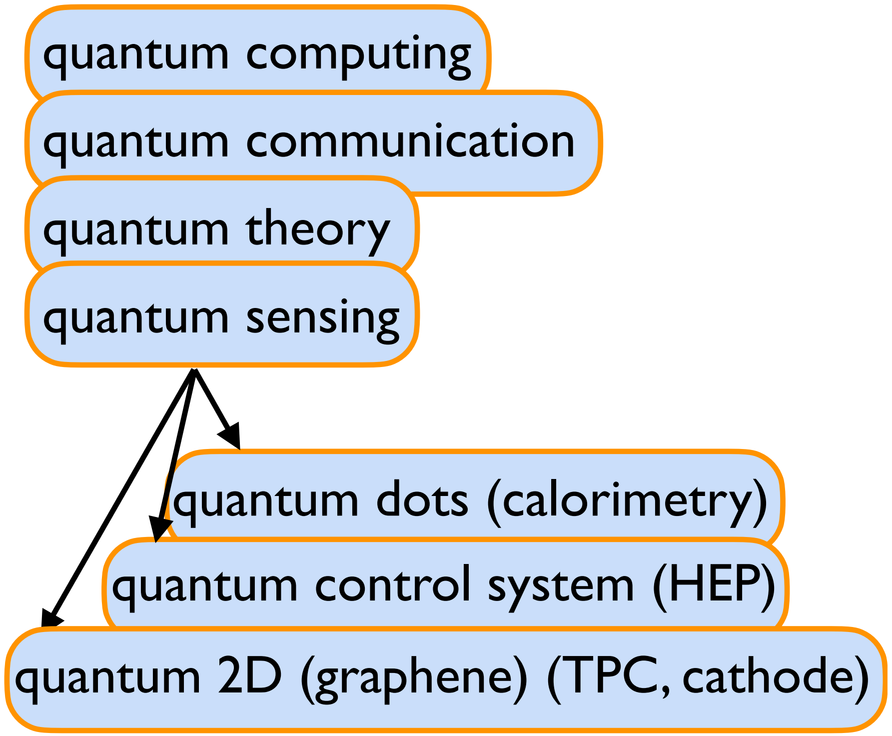
CERN quantum initiative (v1)

QUANTUM TECHNOLOGY INITIATIVE

focus on technology

CERN quantum initiative (v2)

DRD5 WP's ① ③ ⑥


quantum computing

quantum communication

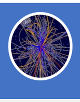
quantum theory

quantum sensing

quantum dots (calorimetry)

quantum control system (HEP)

quantum 2D (graphene) (TPC, cathode)


Objective 2.1a: Exotic atoms as qubits and Dark Matter sensors (Rydberg states characterisation, spectroscopy; atom interferometry; entangled Rydberg states as quantum demonstrators for qubits)

Objective 2.2a: RF cavities and coating for axion searches; designing, building and operating a tuneable RF cavity for axion and GW searches

Objective 2.2b.1: Development of a multi-qubit demonstrator platform (cryogenic infrastructure and RF cavity technology; design intermediate control software layer)

Objective 2.3a: Quantum Sensors and Quantum Data Acquisition (TES as quantum sensors for millicharged DM searches in beam dumps, test bed for Quantum DAQ)

Core goals


Objective 2.1b: Evaluation of the interplay between interferometric inertial sensors and cosmology to improve understanding of properties of Dark Matter and sources of GWs

Objective 2.2b.2: Develop device-aware algorithms for qubits with SRF cavities

Objective 2.3b: Cryogenic veto system, tuneable low-energy deposit calibration set-up; Monte Carlo simulation for tracks of backgrounds and signals, pushing the modeling towards low-energy deposits

Extended objectives


Objective 2.1c: Benchmark and comparison of Rydberg states as qubits in prototype systems

Objective 2.2b.3: Investigate scaling behavior of multiple qubits

Objective 2.3c: Read-out-free detection & DAQ via entanglement between TES voxels and another system; machine-learning-based anomaly detection of millicharged DM particles in TES

Long term objectives

③ WP1

particles, atoms, ions, nuclei:

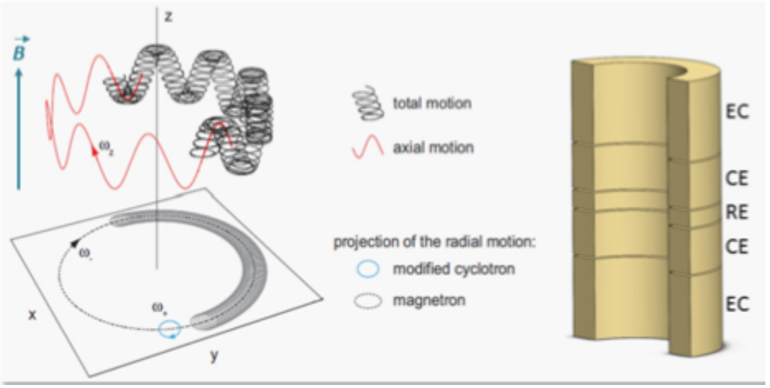
tests of QED, T-violation, P, Lorentz-violation, DM searches

eEDM's in molecules

nuclear clock (^{229}Th)

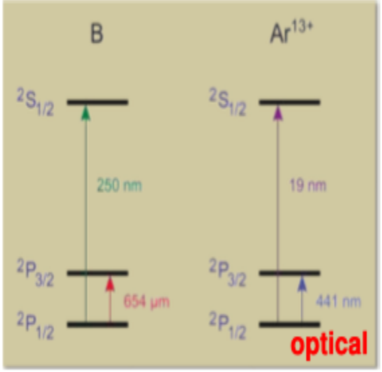
molecular / ion clocks

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^{-4}



K. Blaum et al., Quantum Sci. Technol. 6 014002 (2021)
J.C. Berengut et al., Phys. Rev. A 86, 02251 (2012)

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

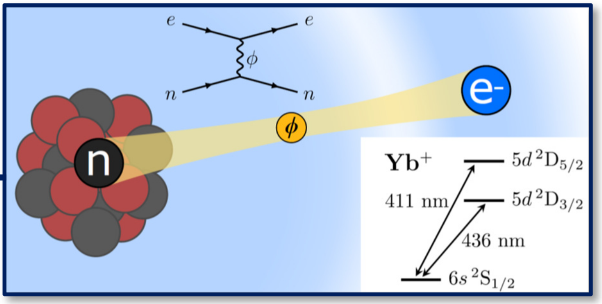
→ https://indico.cern.ch/event/999818/ Marianna Safronova (University of Delaware)

③ WP1

Quantum sensors for new particle physics experiments: Penning traps

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



WP-1 Atomic & nuclear physics (exotic atoms, neutrino physics, clocks)

Ions in traps: ✓ Antiprotons (AD), fully-stripped (radio)nuclei (AD), anions & cations (AD), cations (ISOLDE)

BASE collaboration, Coherent spectroscopy with a single antiproton spin
https://www.nature.com/articles/s41586-025-09323-1

Rydberg atoms: ✓ Positronium (AD), antiprotonic atoms (AD)

Hydrogen-like Rydberg ions: Single-electron highly charged ions in Rydberg states optical

Hydrogen-like GS ions: Single-electron GS optical HFS manipulation in HCI's optical

"Towards metrology with highly charged isomeric ions from antiproton annihilation"
Sara Alfaro et al 2025 J. Phys. B: At. Mol. Opt. Phys. **58** 215002
(qubits in a highly shielded environment, but with long-range interactions)

Antiprotonic atoms ➔ novel HCI systems

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

③ *Low energy quantum systems* (atoms, …) for QED, nuclear physics, …

Antiprotonic atoms → novel Highly Charged Ionic systems

S. Alfaro, L. Panzl et al., J. Phys. B: At. Mol. Opt. Phys. **58** 215002
"Towards metrology with highly charged isomeric ions from antiproton annihilation"

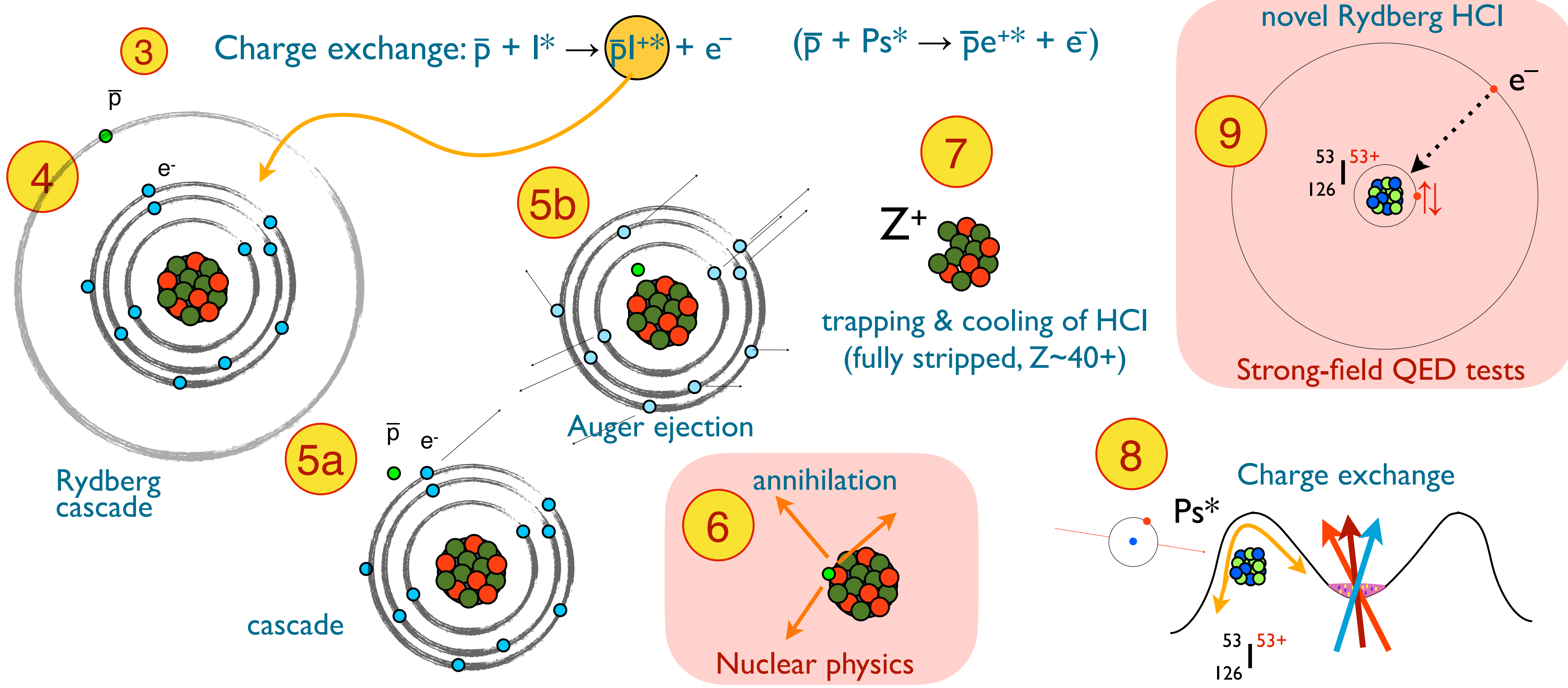
New systems building on *quantum manipulations* of atomic/ionic systems in traps

① formation and capture of HCI

① photo-detachment: $I^- \to I^0 + e^-$ (γ_1)

2_{opt} Rydberg excitation: $I^0 \to I^*$ ($\gamma_2 + \gamma_3$)

③ Charge exchange: $\bar{p} + I^* \to \bar{p}I^{+*} + e^-$ $(\bar{p} + Ps^* \to \bar{p}e^{+*} + e^-)$



trapping & cooling of HCI (fully stripped, Z~40+)

Nuclear physics

Strong-field QED tests

③

Low energy quantum systems (molecules, …) for symmetries, …

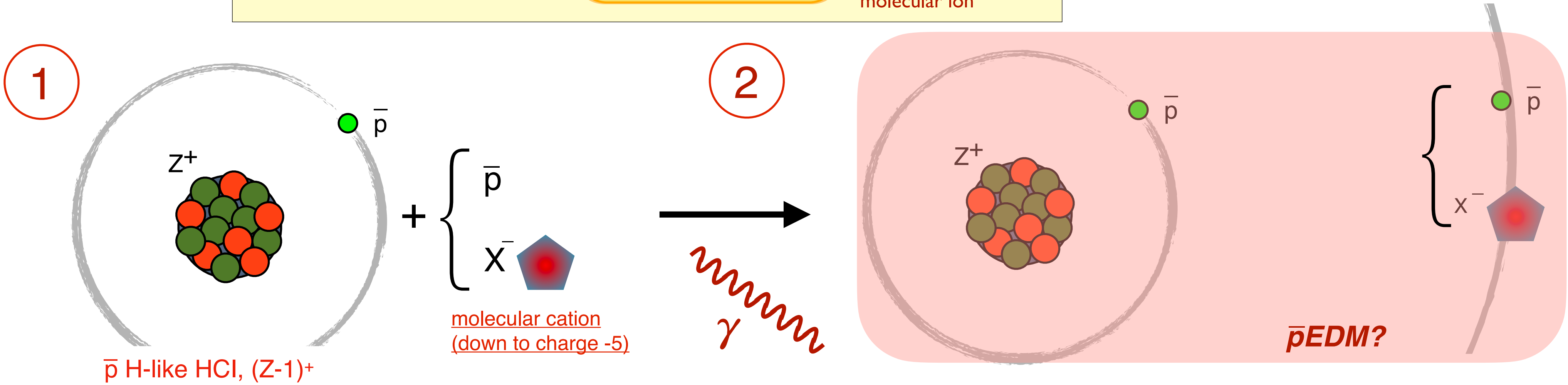
Antiprotonic Rydberg molecular ions

$\bar{p}$EDM? precision spectroscopy?

3-body formation: combine with nearby cold anions ($\bar{p}$, X^{n-})

$$X^{n-} + (\bar{p}\ HCl^{Z+})^{*} \rightarrow (\bar{p}\ HCl^{Z+*}X^{n-}) + \gamma$$

molecular ion



molecular cation (down to charge -5)

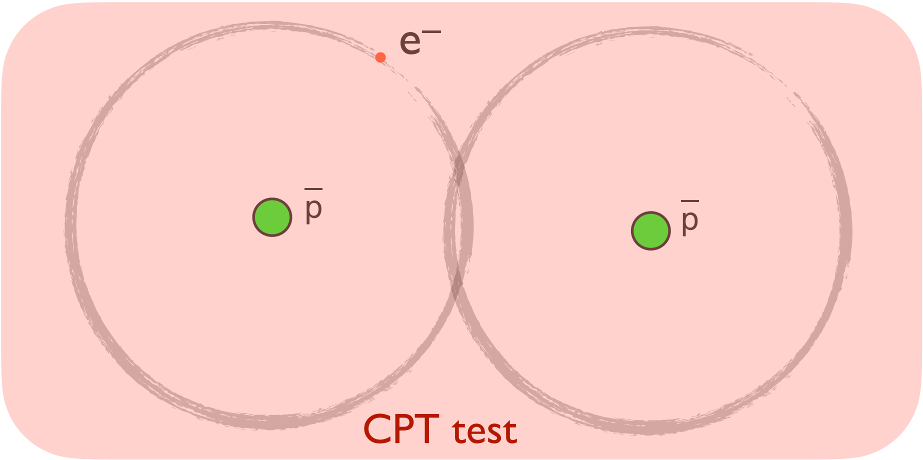
$\bar{p}$ H-like HCI, $(Z-1)^+$

Fang, Hong, and Puru Jena. "Stable tetra-and penta-anions in the gas phase." *Angewandte Chemie International Edition* 58.33 (2019): 11248-11252. https://doi.org/10.1002/anie.201903044

Antimatter molecular ions ($\bar{H}_2^-$)

precision spectroscopy

Formation through $\bar{H}$ + $\bar{H}$? $\bar{H}$* + ($\bar{p}$p)* ?



③④

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

Topological Dark Matter (TDM)

~ 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: search for daily variations of the relative frequency difference between 2 clocks with different spatial orientation

Local Position Invariance (LPI)

independence of any local test experiment from when and where it is performed in the Universe; here,compare atomic clocks based on different transitions to constrain the time variation of fundamental constants and their couplings

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

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

① atom interferometry at macroscopic scales:

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

AION$^{\text{UK}}$ MIGA$^{\text{France}}$ MAGIS$^{\text{Fermilab}}$ ZAIGA$^{\text{China}}$

CERN?

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

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

② satellite missions:

ACES (Atomic Clock Ensemble in Space)

ESA mission for ISS 2025-2028

On 28 April 2025, ACES was successfully switched on on the ISS for the first time

pathfinder / technology dev. 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;

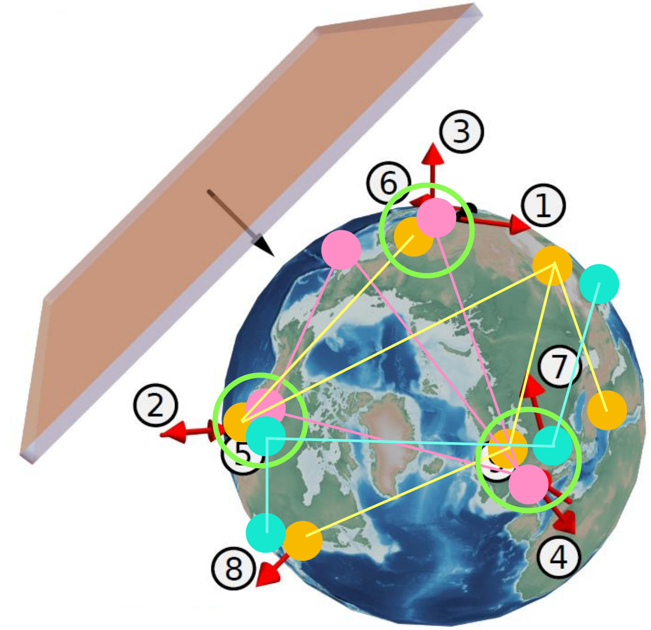
FOCOS (Fundamental physics with an Optical Clock Orbiting in Space): Yb optical lattice clock with 1×10^{-18} stability

AEDGE: ~2045

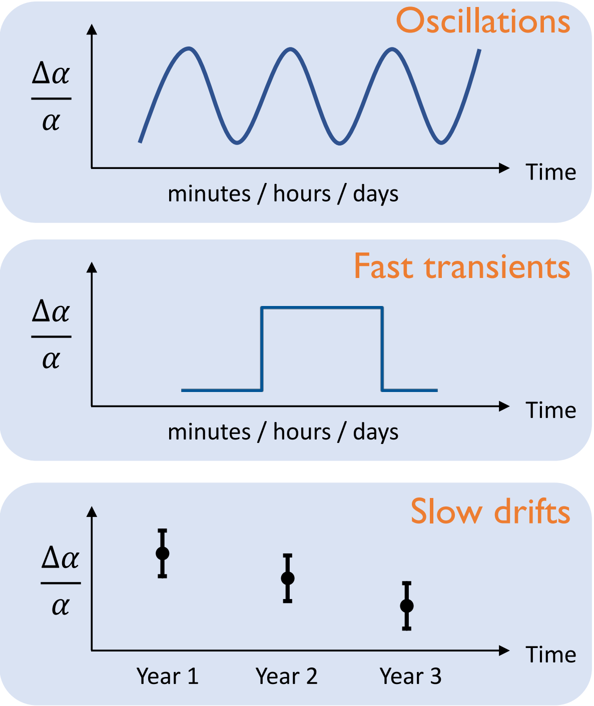
El-Neaj, Y.A., Alpigiani, C., Amairi-Pyka, S. *et al.* AEDGE: Atomic Experiment for Dark Matter and Gravity Exploration in Space. *EPJ Quantum Technol.* **7,** 6 (2020). https://doi.org/10.1140/epjqt/s40507-020-0080-0

③ WP1 WP4 Quantum sensors for low energy particle physics

search for NP / BSM



networks of sensors



Oscillations → Very light DM

Fast transients → DM- topological defects

Slow drifts → New physics

magnetometers

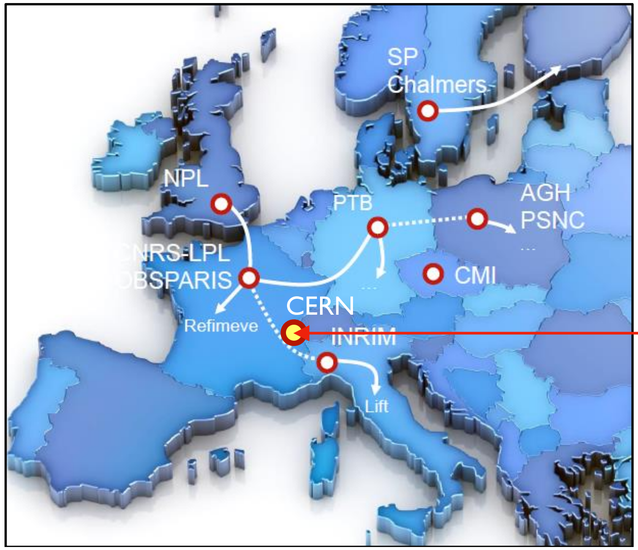
Afach et al, arXiv:2102.13379v2

atomic clocks nuclear, HCI, molecules

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

optical fiber networks

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



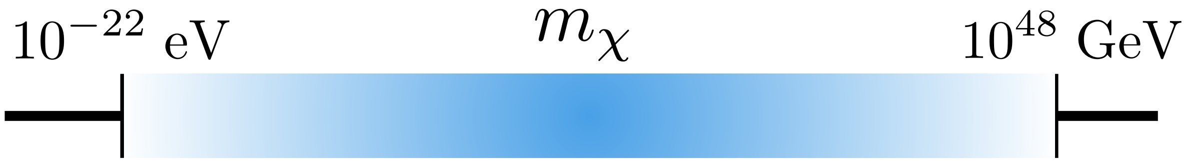
Investigate very light scalar and pseudo-scalar DM candidates over ~10 orders of magnitude in mass and different couplings

@ CERN: CPT, QED, QCD tests

Precision spectroscopy of antihydrogen, $\bar{p}$He, Ps @ 10^{-15}ΔE/E

Superconducting sensors: RF cavities

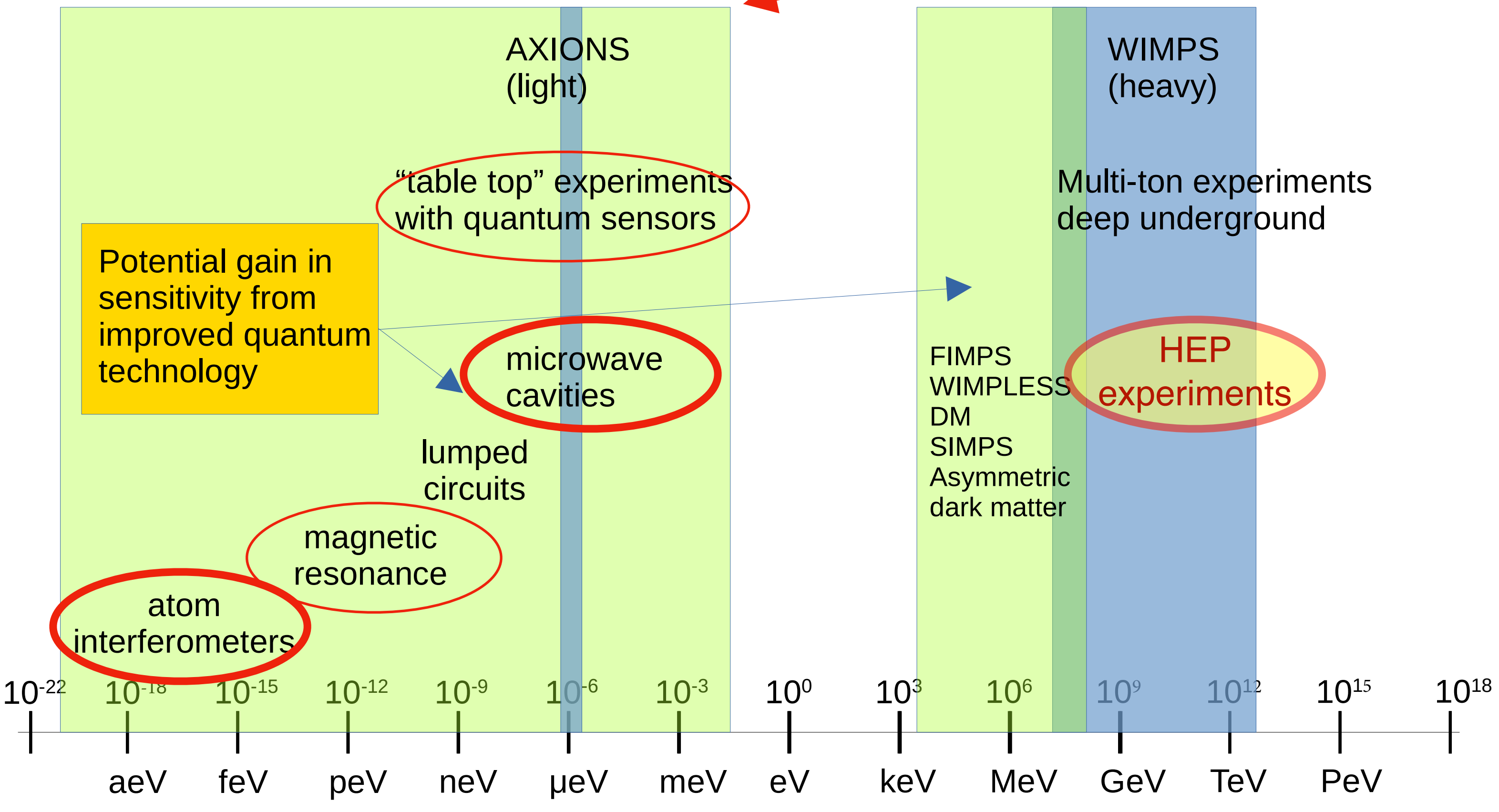
Axions, ALP's, DM & non-DM UL-particle searches

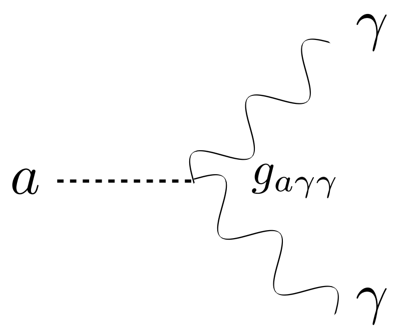


cavity size = axion size
axion mass = unknown

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

system noise temperature
cryo-amplifiers JJPA



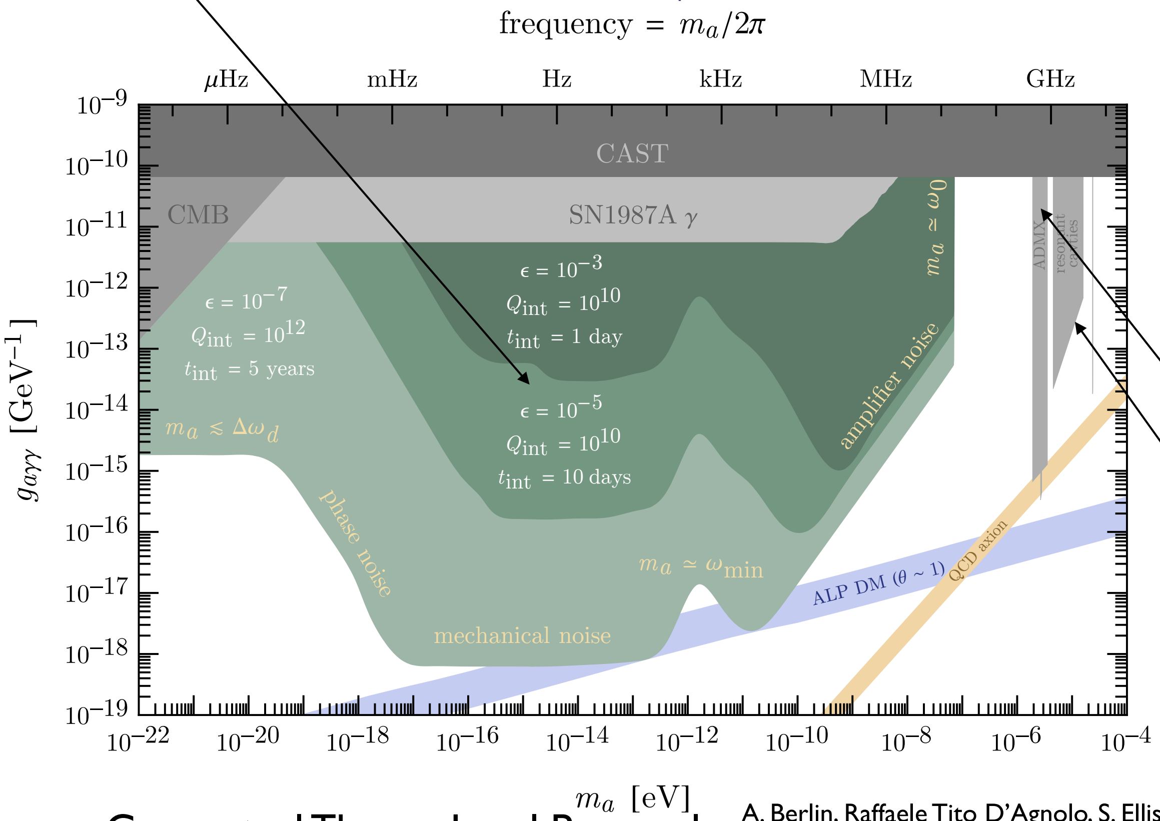


(but not only…)

Axion heterodyne detection

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

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



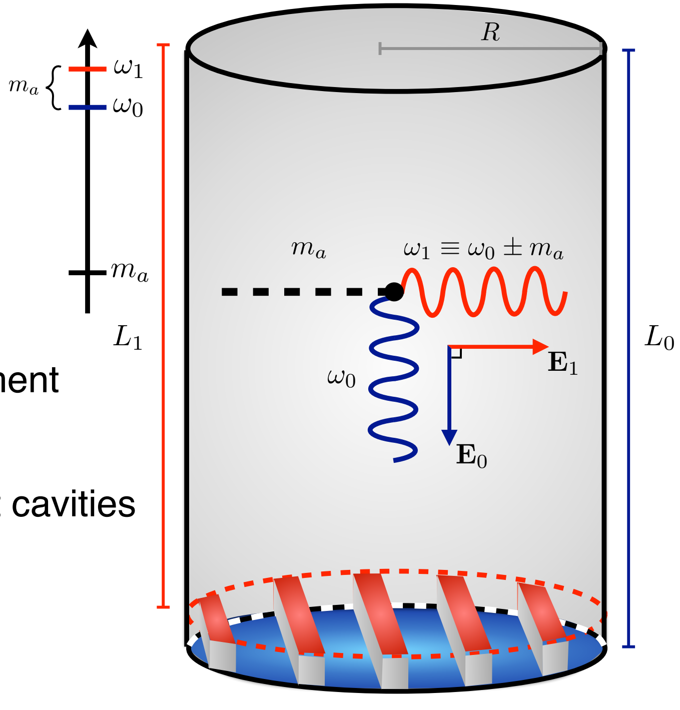
ADMX experiment

resonant cavities

problem: cavity resonance generally fixed

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

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



(a) Cartoon of cavity setup.

Conceptual Theory Level Proposal:

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

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

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

Needed! : major developments on integrated cryoelectronics (4K)

4

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

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

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

Quantum Technology		Technical application	
Metamaterials, 0 / 1 / 2-dimensional materials	WP-2	chromatic calorimetry (QDs)	QTI@CERN
Atoms, molecules, ions	WP-1	TPC	
Spin-based sensors	WP-4	helicity detectors	
Superconducting sensors	WP-3	cryogenic ps luminosity monitors	QTI@CERN

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

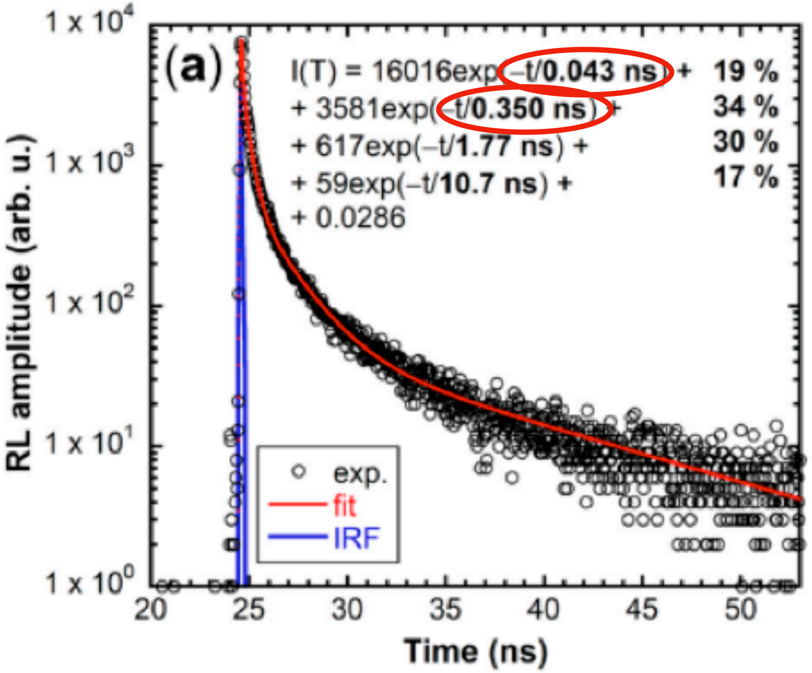
Mostly speculative!

4

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

ZnO:Ga embedded in SiO_2 or polystyrene

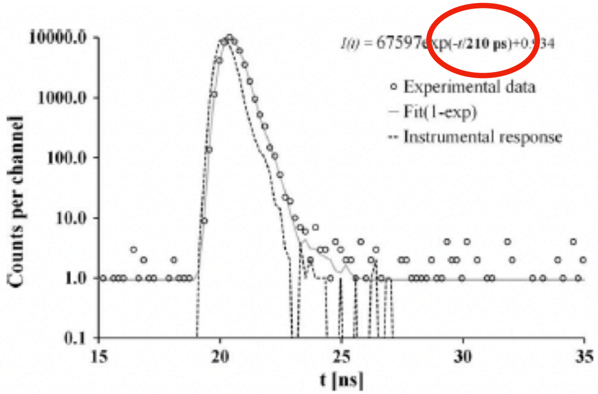
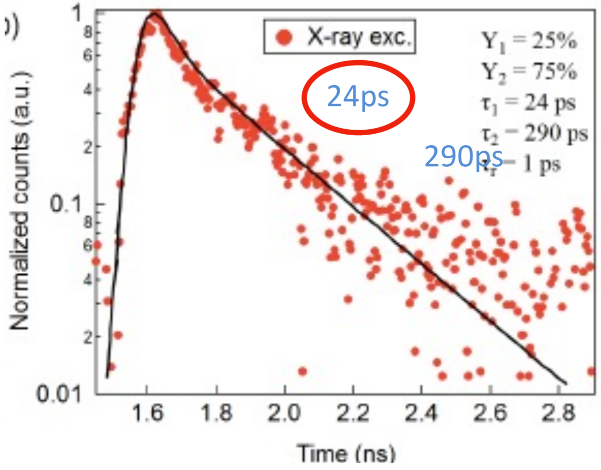


Fig. 9. Photoluminescence decay of ZnO:Ga sample at room temperature. Excitation nanoLED 339 nm, emission wavelength set at 390 nm. Decay curve is approximated by the convolution of instrumental response (also in figure) and single exponential function $I(t)$ provided in the figure.

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

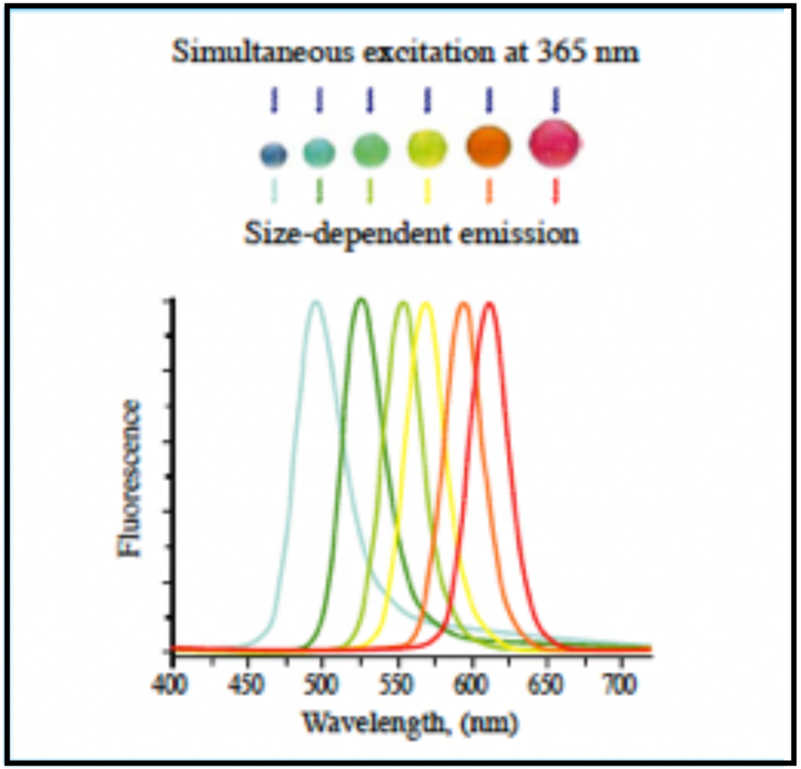
CdSe nanoplatelet,



J. Grim et al., *Nature Nanotechnology,* **9**,2014, 891–895
R. Martinez Turtos et al., 2016 JINST_11 (10) P10015

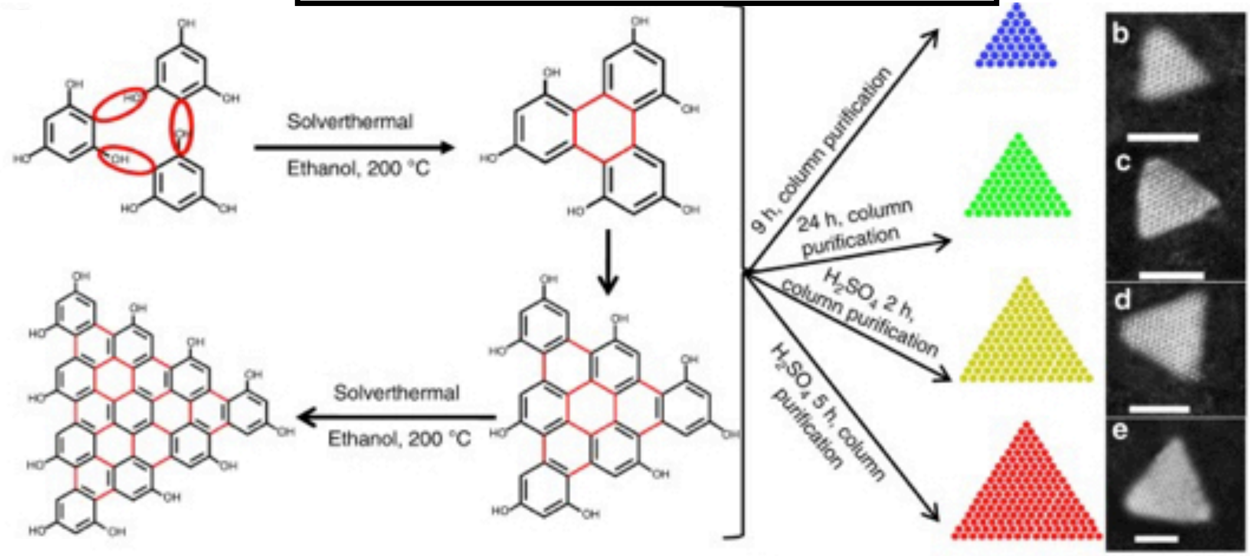
Concerns: integrated light yield (need many photons to benefit from rapid rise time)

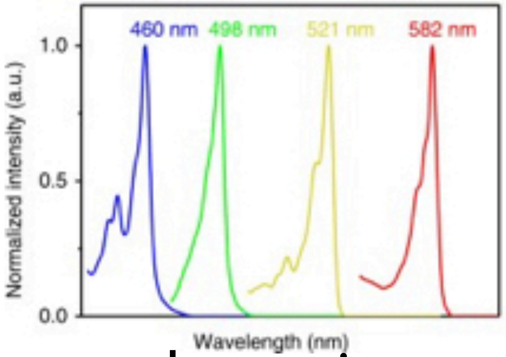
4 Quantum dots: chromatic tunability



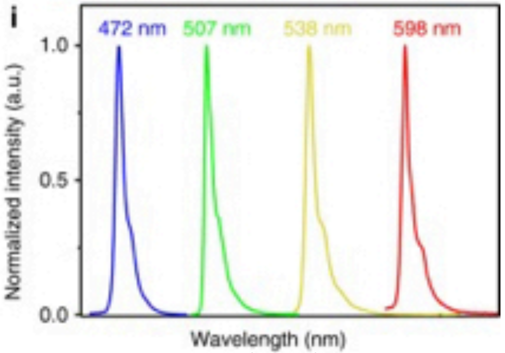
by size, composition, geometry

e.g. triangular carbon nanodots





UV illumination



absorption e.m. shower emission

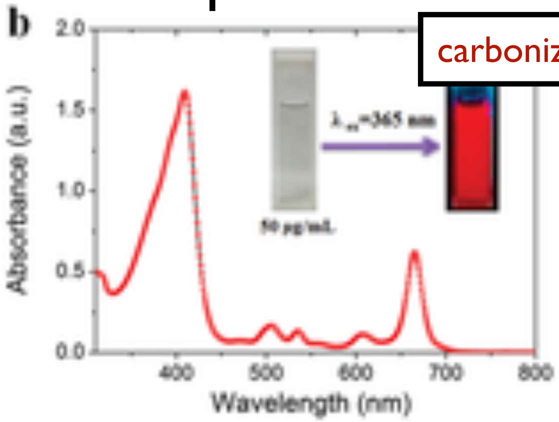
F. Yuan, S. Yang, et al., Nature Communications 9 (2018) 2249

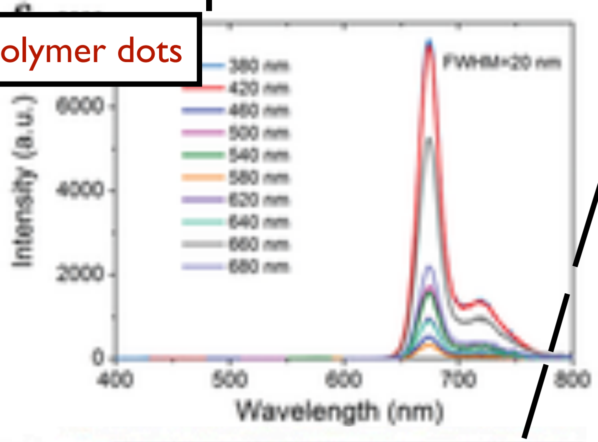
4

absorption spectrum

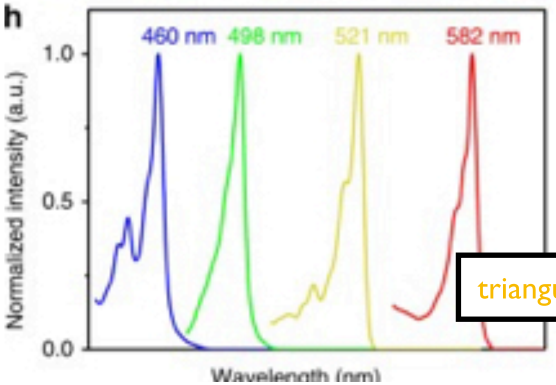
emission spectrum

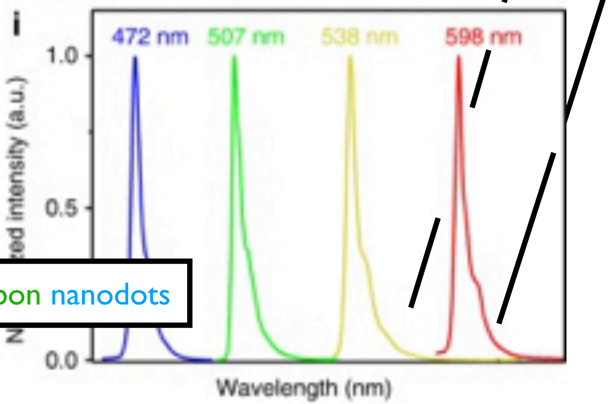
carbonized polymer dots



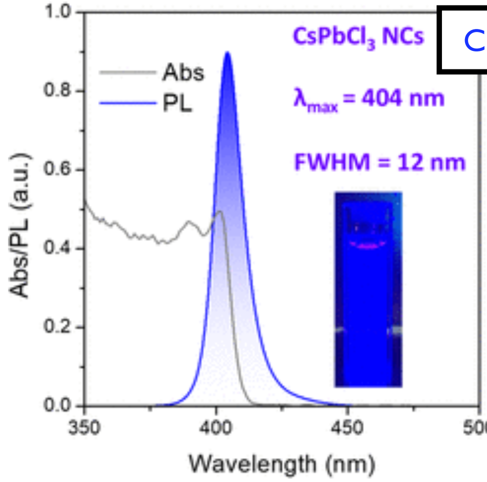


triangular carbon nanodots





CsPbCl₃ nanocrystals



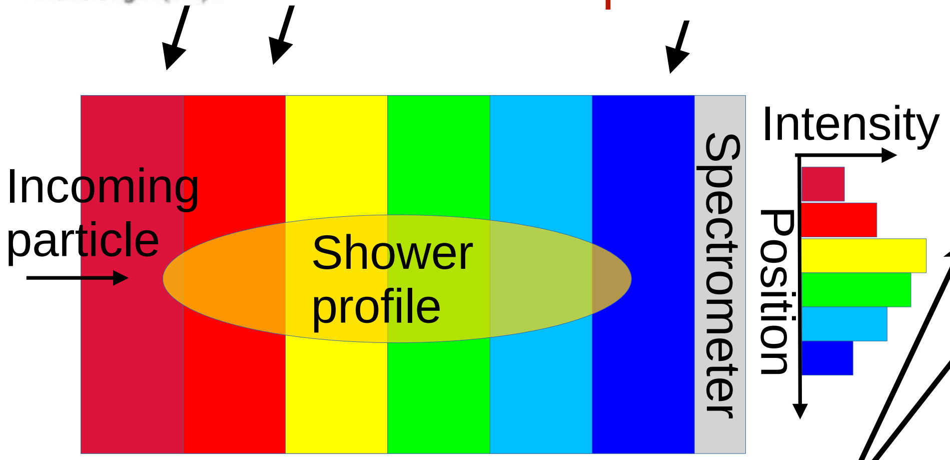
leftmost nanodots:
absorb wavelengths < 650 nm
emit at > 680 nm

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

…

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

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



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

Monochromators + PD?

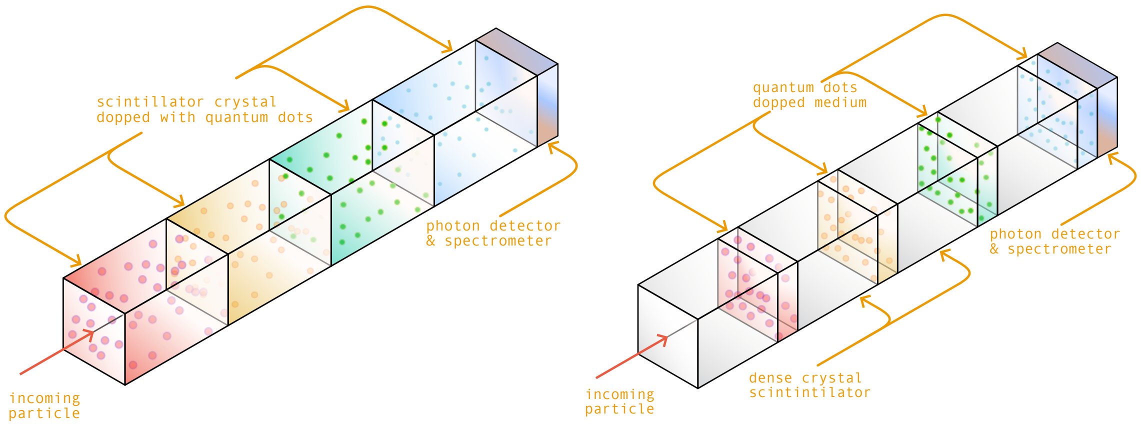
Y.T. Lin & G. Finlayson, Sensors 23, 4155 (2023)

Metalenses?

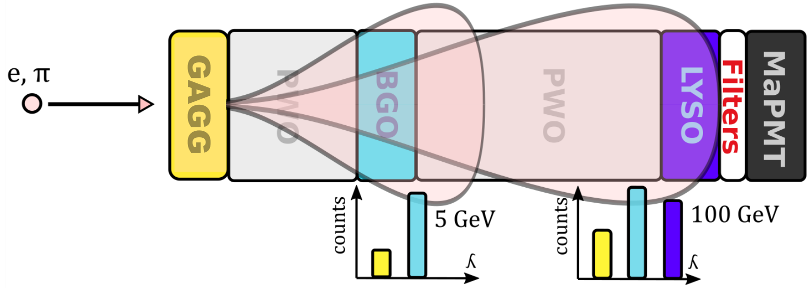
M. Khorasaninejad & F. Capasso, Science 358, 6367 (2017)

④ This slide courtesy Devanshi Arora, CALOR'24

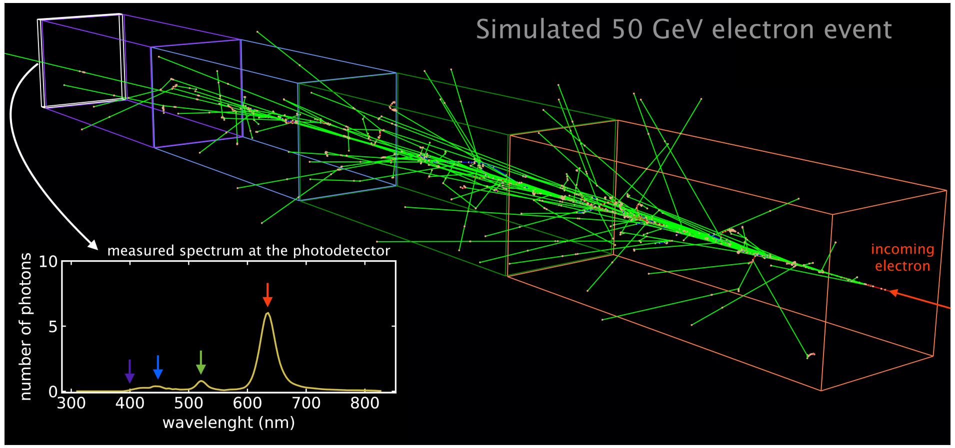
Quantum sensors for high energy particle physics

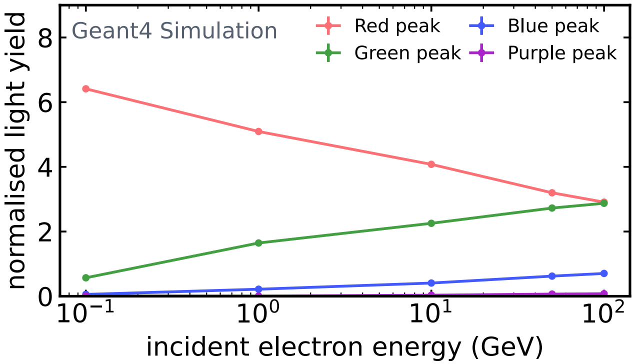


courtesy Y. Haddad, N U, Boston, USA



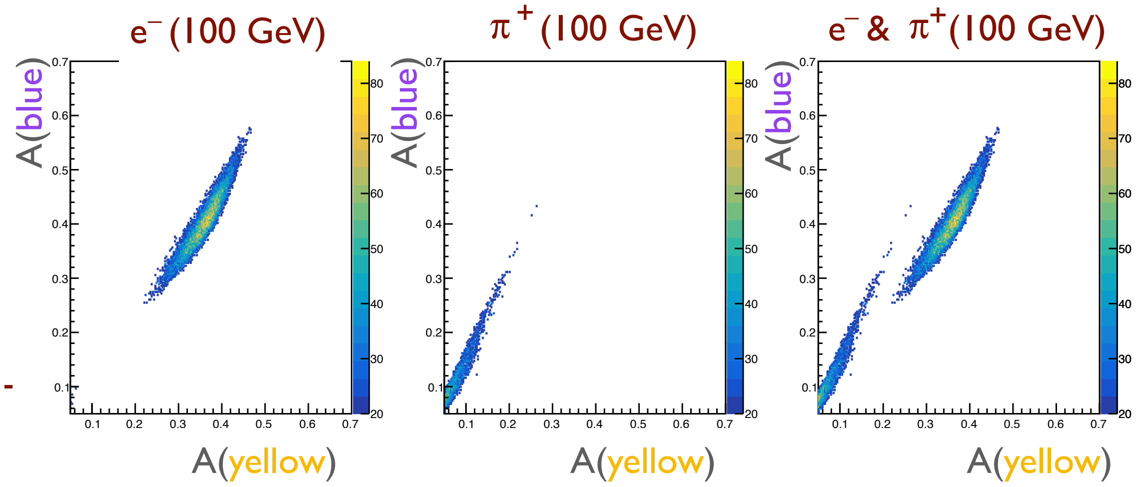
Beam test results (SPS) 2023





"Chromatic" energy measurement

"Chromatic" electron - pion discrimination



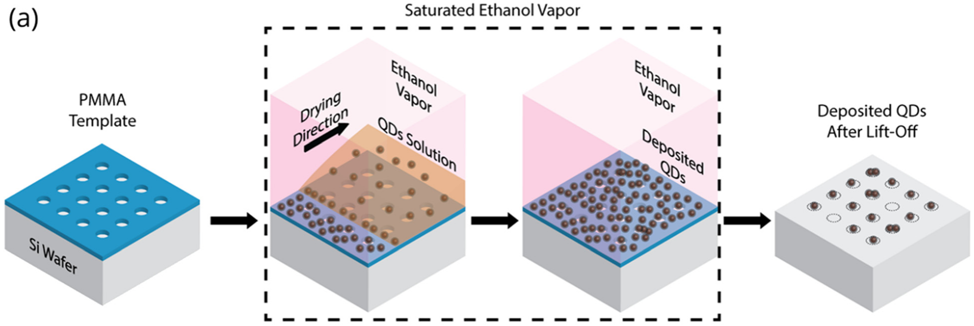
86% "chromatic" electron - pion discrimination

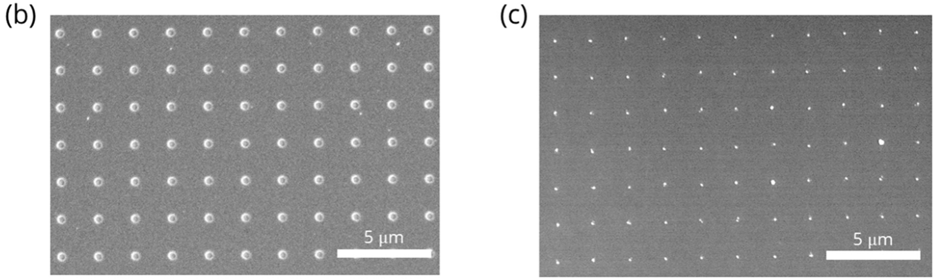
② (IR) Quantum dots for HEP charged particle tracking

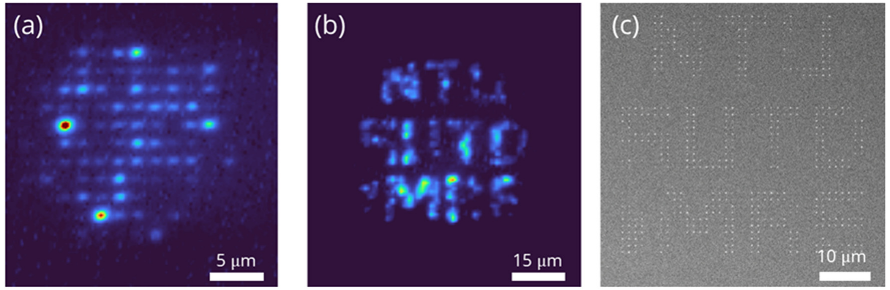
WP-2

Deterministic positioning of few aqueous colloidal quantum dots

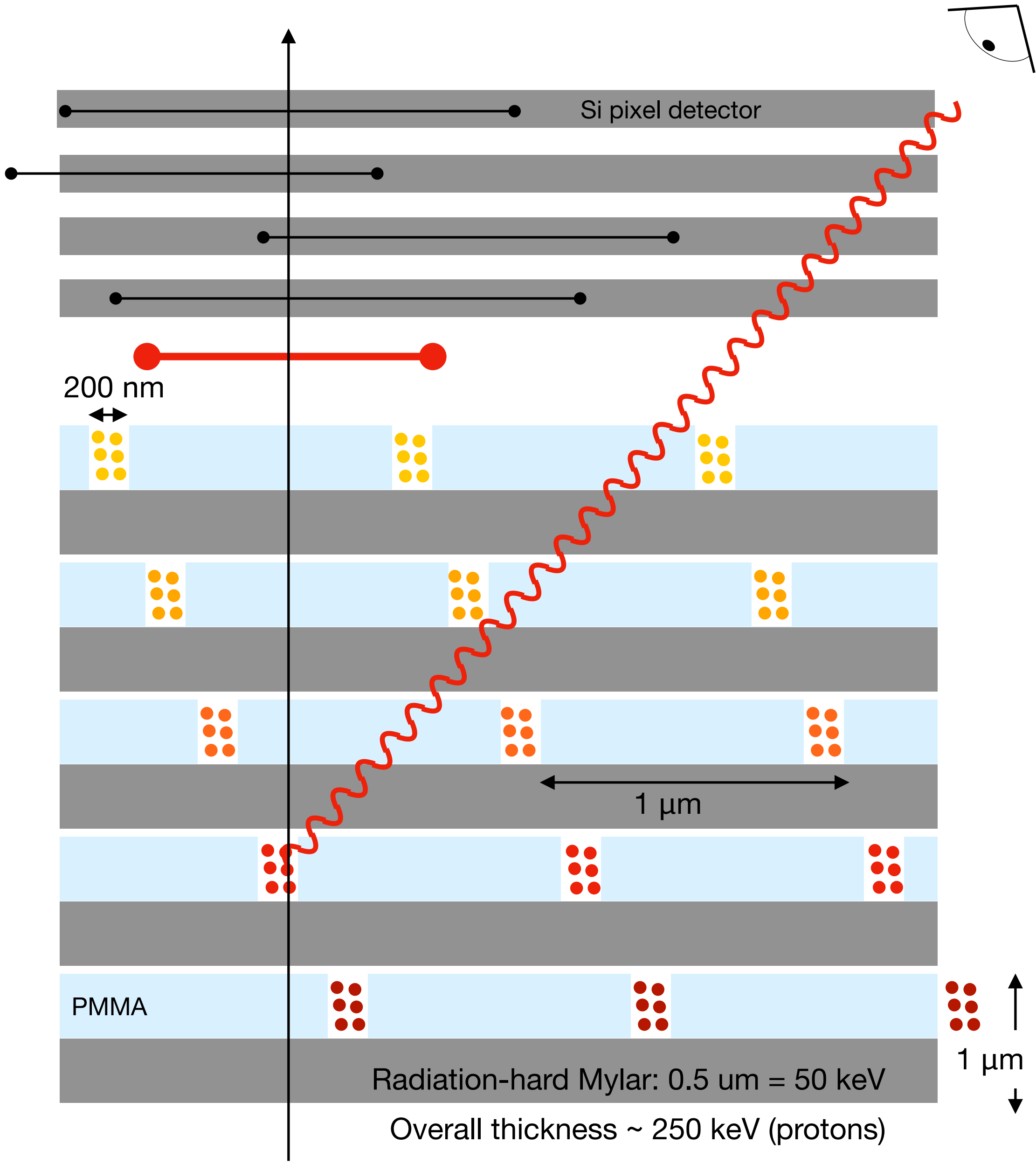
Drying Process of Drop-Cast QDs Under Saturated Ethanol Vapor







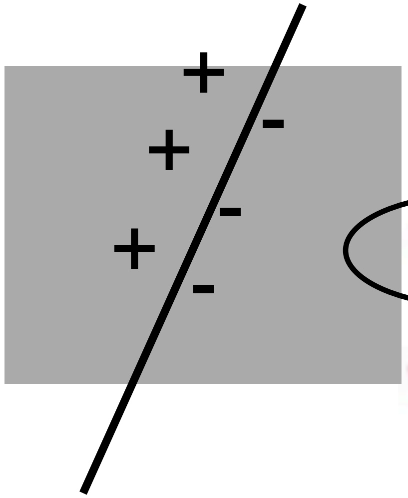
Nanoscale, 2024, 16, 18339
https://ds.bilkent.edu.tr/wp-content/uploads/2024/10/Nanoscale1_2024_HVD.pdf



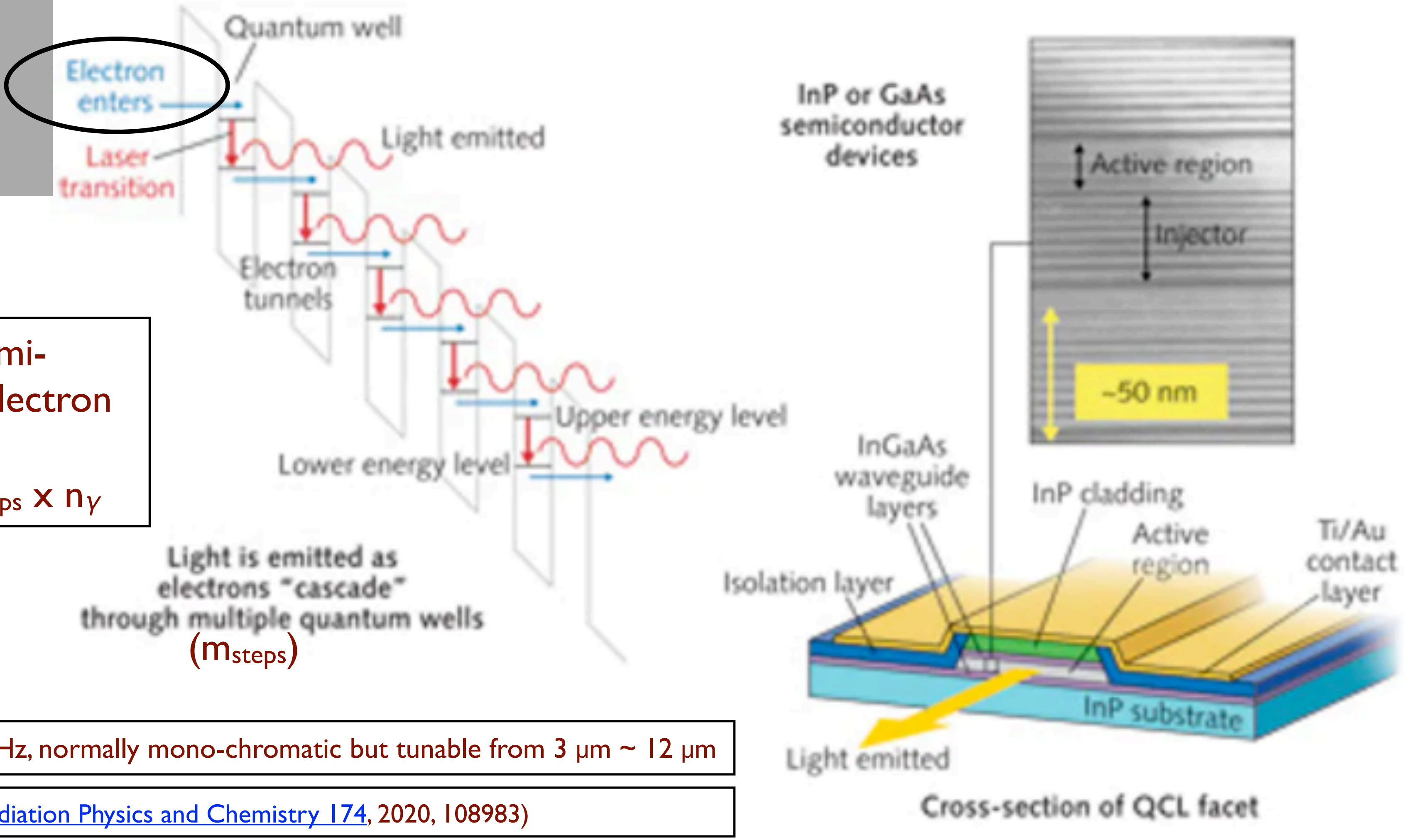
Assembly positioning to < 100 nm

https://xeryon.com/products/precision-linear-stages/xls-ultrasonic-linear-piezo-stage/

Active scintillators (QCLs, QWs, QDs, QWDs)



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



(m_{steps})

Couple bulk semi-conductor to electron injection layer:

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

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

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

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)

Atoms, molecules, ions

- Rydberg TPC's

Spin-based sensors

- helicity detectors

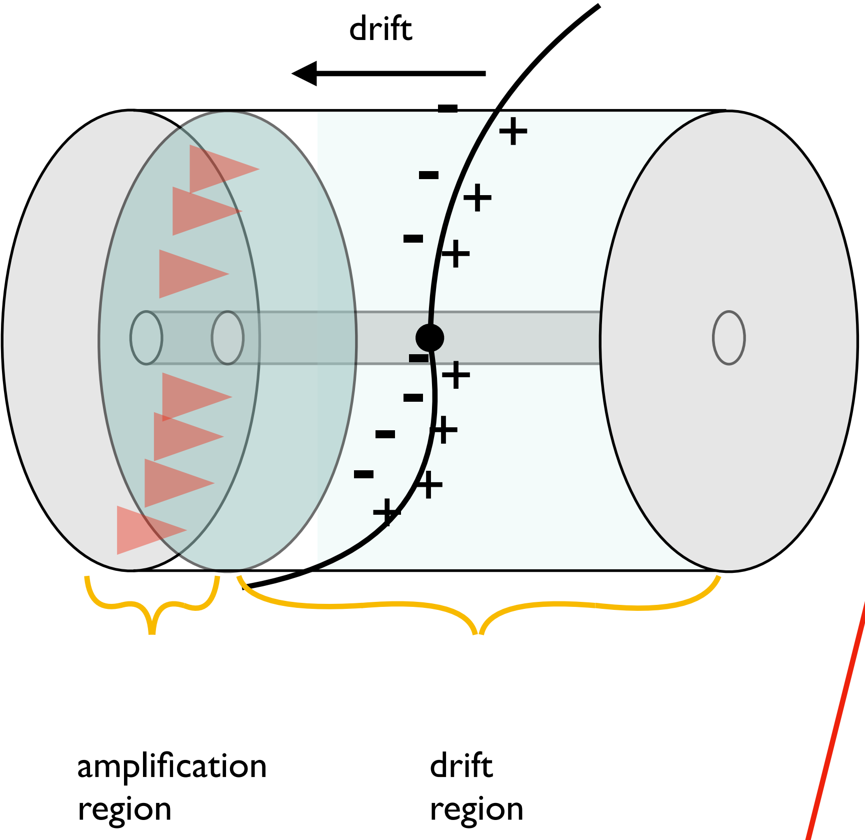
Superconducting sensors

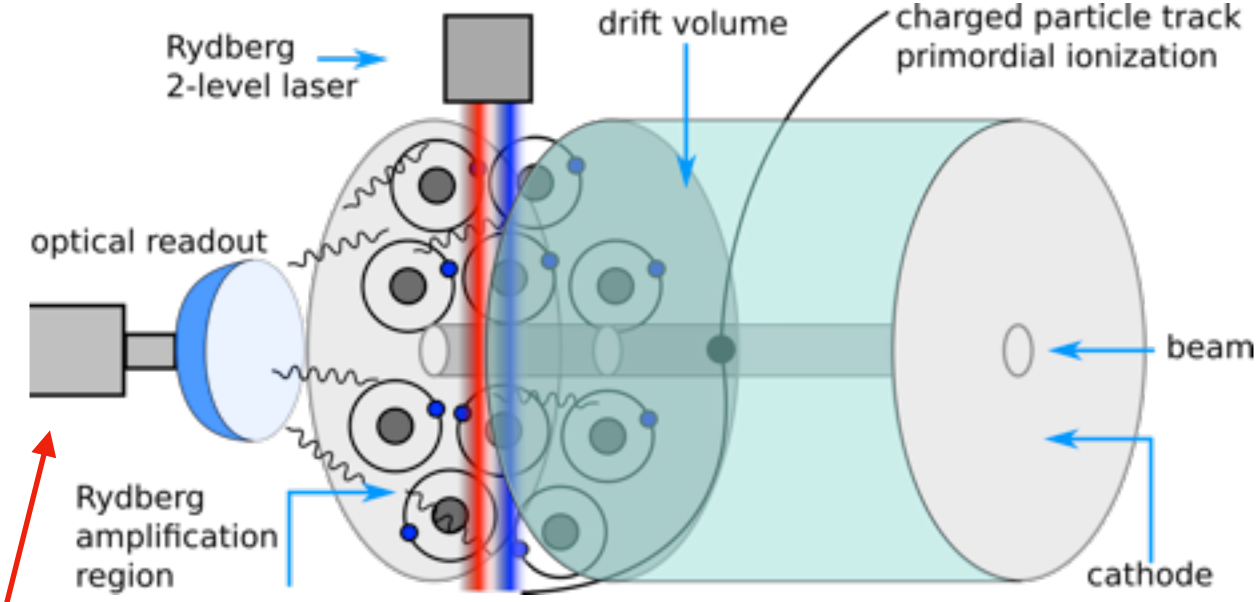
④

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

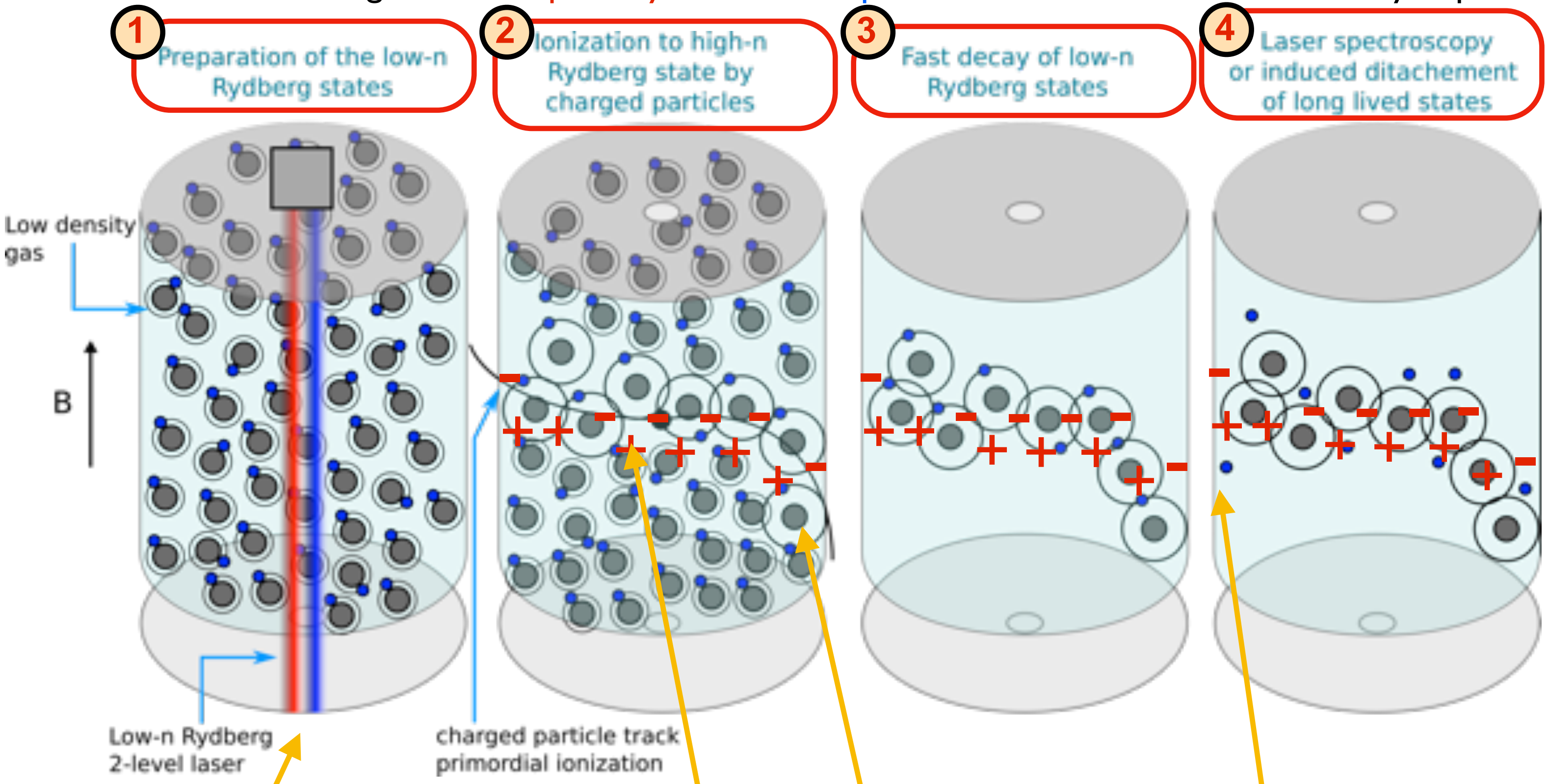
④

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



ionization + excitation;
natural decay of unmodified atoms

reduction of ionization and
atomic excitation threshold

photo-ionization of excited atoms

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)

Atoms, molecules, ions

Rydberg TPC's

Spin-based sensors

helicity detectors

Superconducting sensors

④

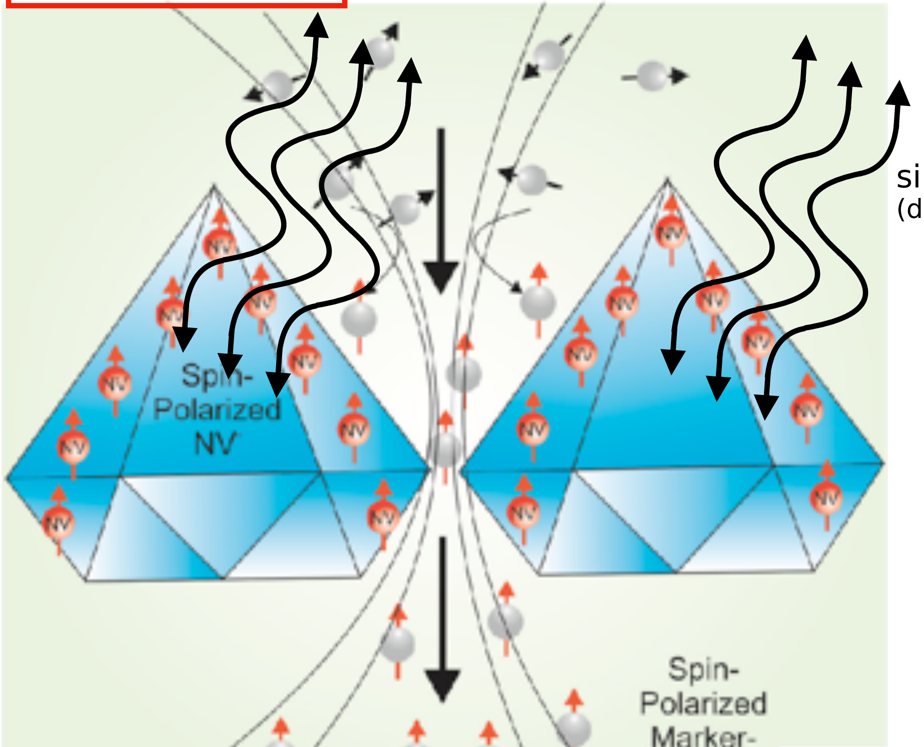
optically polarizable elements: Nitrogen-vacancy diamonds (NVD)

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

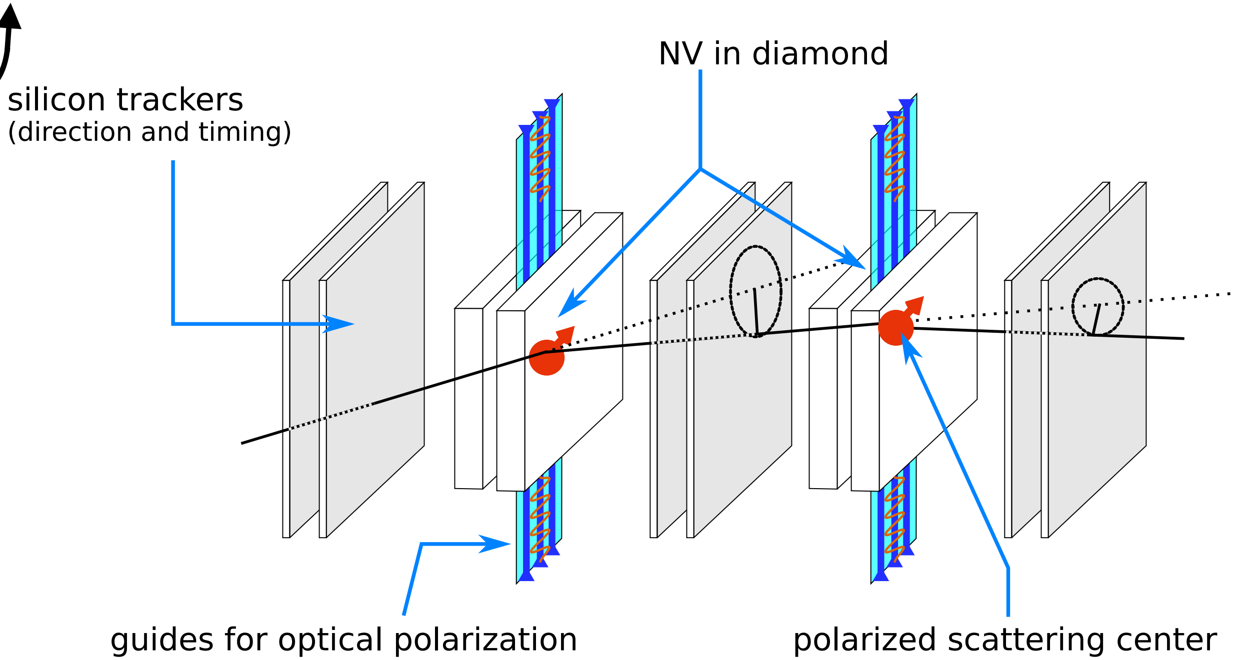
$10^{16} \sim 10^{18}$ / cm^3

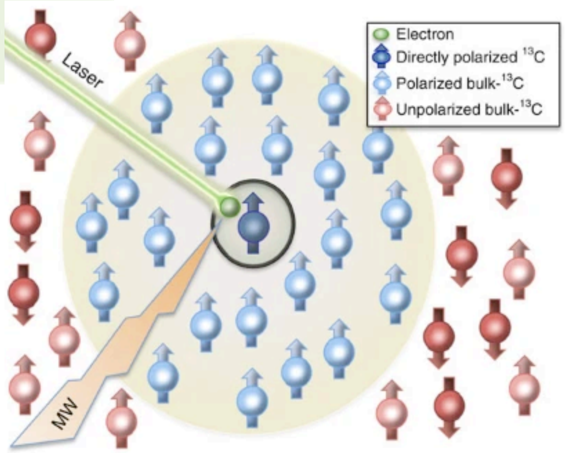


© Dr. Christoph Nebel, Fraunhofer IAF

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





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

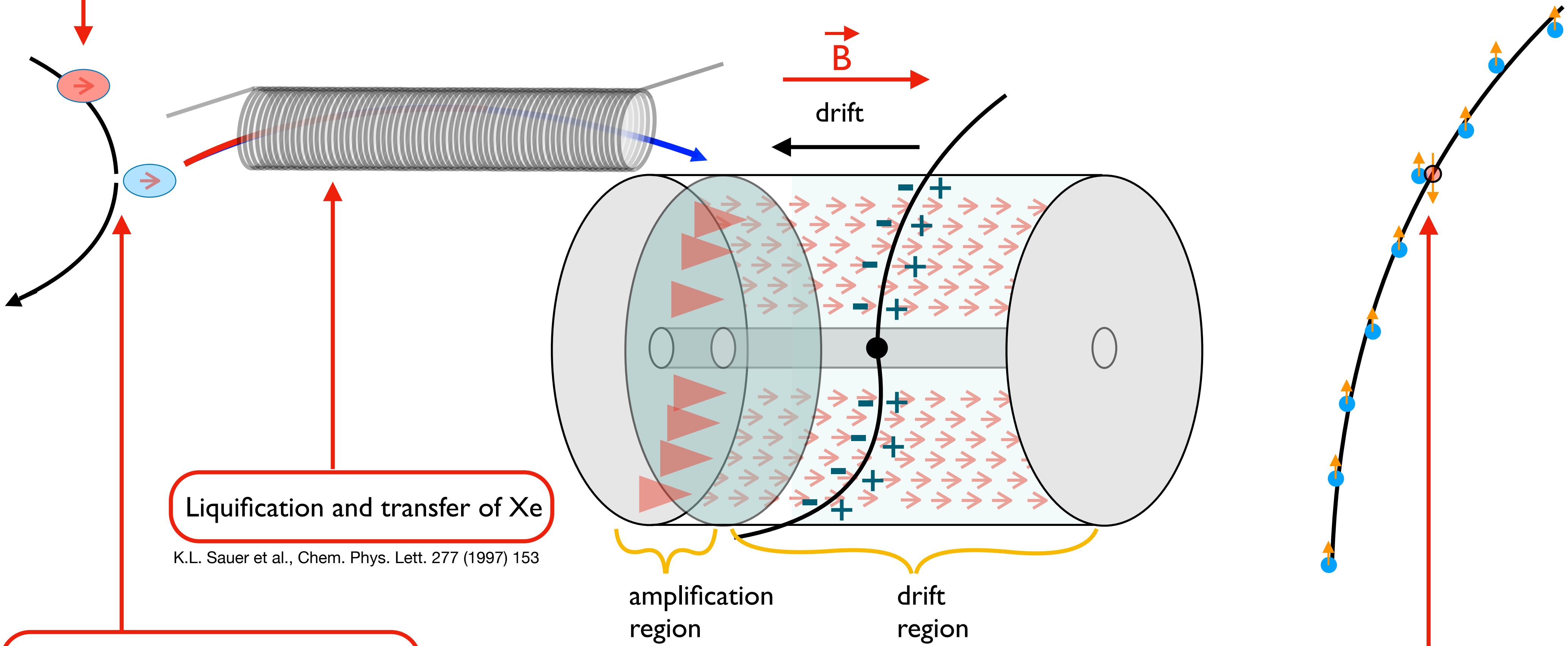
x 10^2

④

Polarized TPC’s

Xe (Kr, Ar) can be sympathetically polarized by interaction with optically polarized Rb

Spin Hyperpolarization in Modern Magnetic Resonance, J. Eills et al., Chem. Rev. 123 (2023), https://doi.org/10.1021/acs.chemrev.2c00534



Laser polarization of Rb

Liquification and transfer of Xe

K.L. Sauer et al., Chem. Phys. Lett. 277 (1997) 153

Transfer of Rb polarization to Xe
Spin exchange optical pumping hyperpolarization

G. Norquay et al., Phys. Rev. Lett. 121, 153201

Spin-spin scattering of helicity +1/-1 particle on polarized “target” ⟶ helicity determination

N. Lockyer et al., Phys. Rev. D 30 (1984) 860;
C.X. Lin et al., arXiv:2512.02804v1 (2025);
Y.T. Liang et al., Phys. Rev. D 112 (2025) L031502

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)

Atoms, molecules, ions

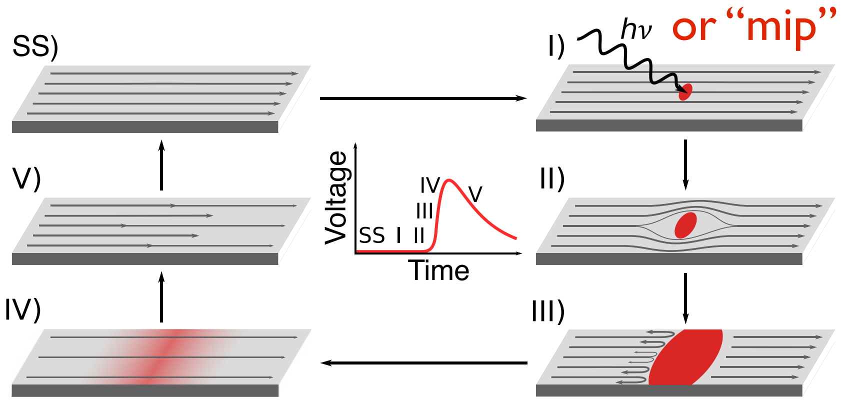
Rydberg TPC's

Spin-based sensors

helicity detectors

Superconducting sensors

④ Extremely low energy threshold detectors: SNSPD



SNSPD's Near term future

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

Snowmass2021 - Letter of Interest

Superconducting Nanowire Single-Photon Detectors

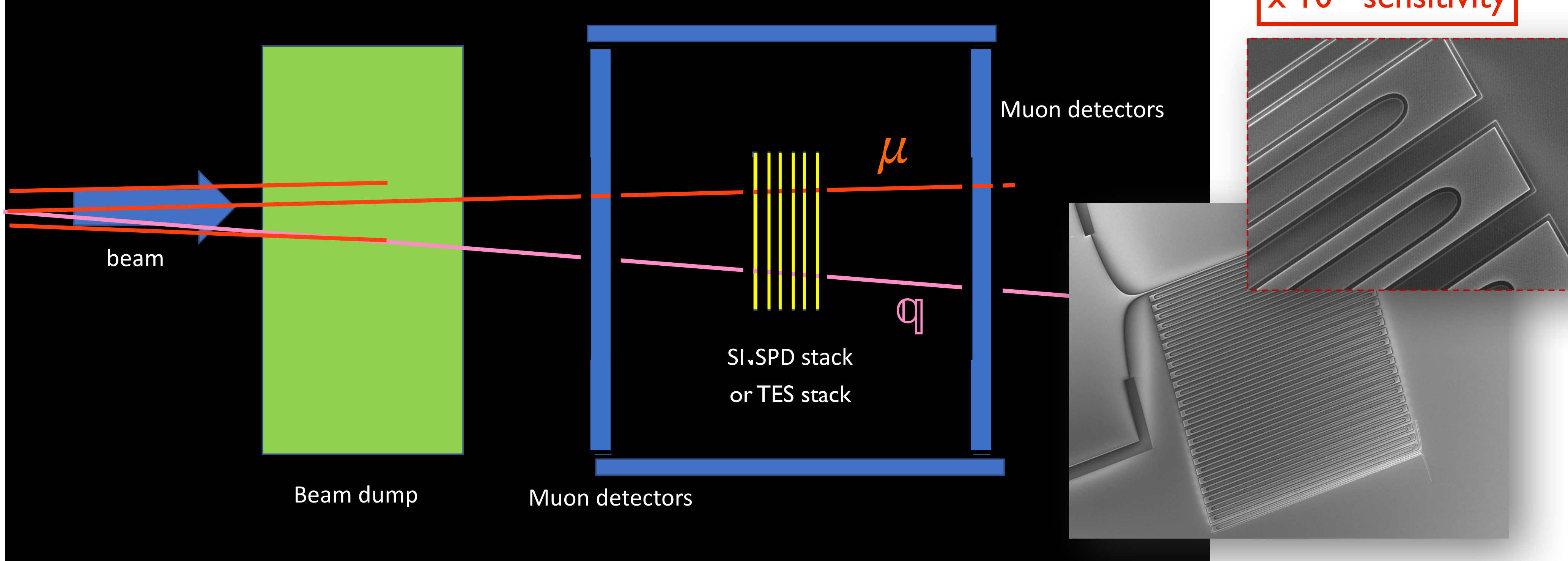
Contact Information:
Karl Berggren, berggren@mit.edu
Ilya Charaev, charaev@mit.edu
Jeff Chiles, jeffrey.chiles@nist.gov
Sae Woo Nam, saewoo.nam@nist.gov
Valentine Novosad, novosad@anl.gov
Boris Korzh, bkorzh@jpl.nasa.gov
Matt Shaw, mattshaw@jpl.nasa.gov

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

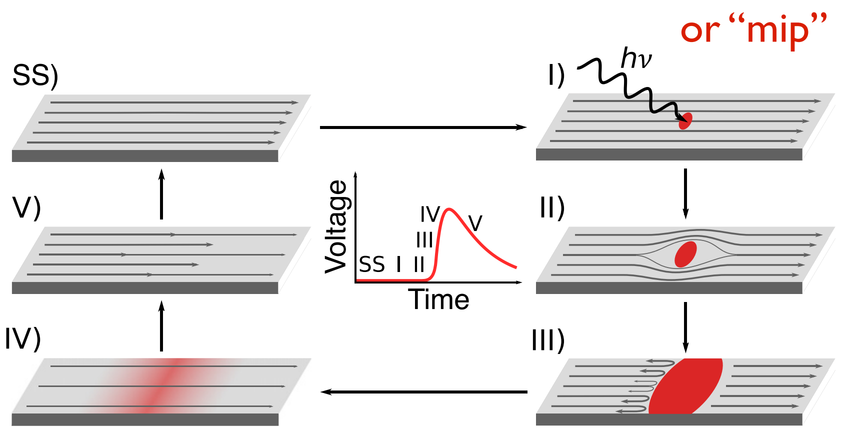
Search for Beyond Standard Model milli-charged particles?

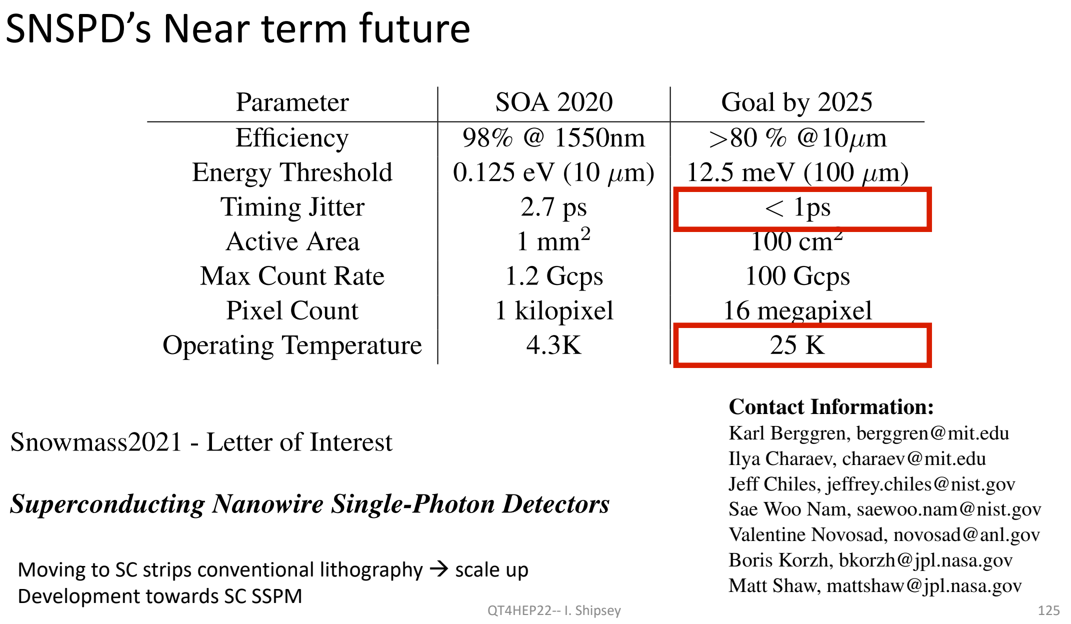
mip: ~20 keV/100 µm

x 10^6 sensitivity



④ Extremely fast detectors: SNSPD





SNSPD's Near term future

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

Snowmass2021 - Letter of Interest

Superconducting Nanowire Single-Photon Detectors

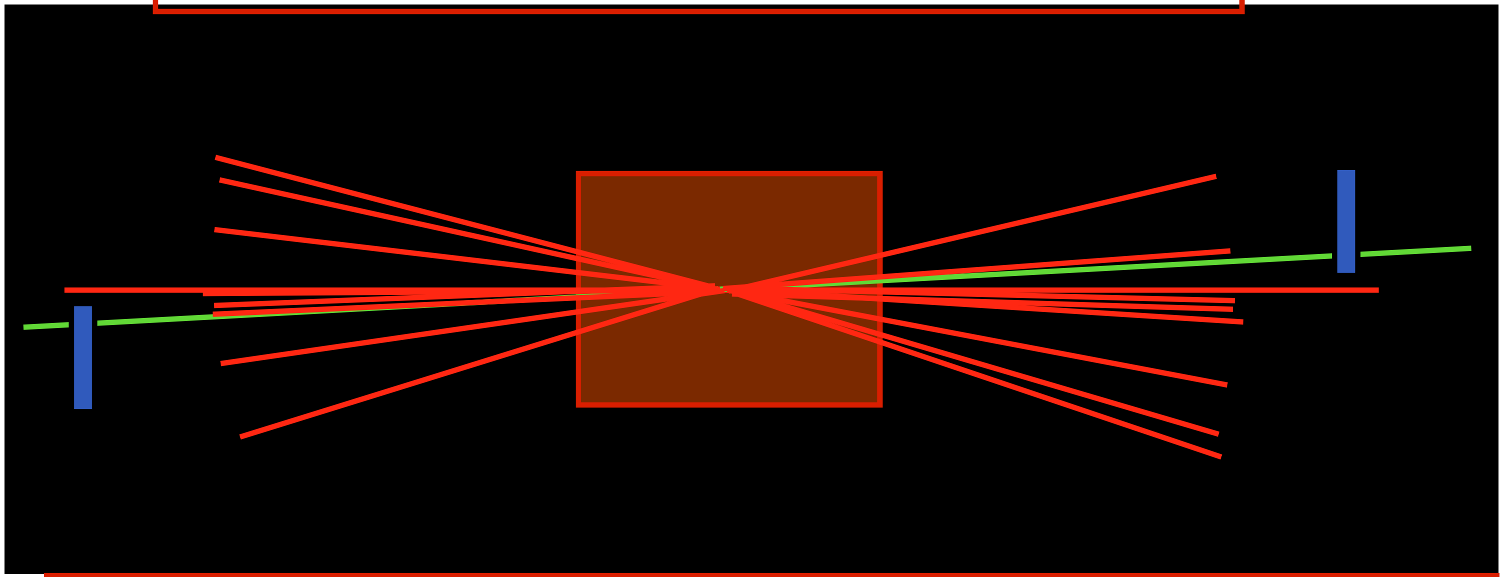
Contact Information:
Karl Berggren, berggren@mit.edu
Ilya Charaev, charaev@mit.edu
Jeff Chiles, jeffrey.chiles@nist.gov
Sae Woo Nam, saewoo.nam@nist.gov
Valentine Novosad, novosad@anl.gov
Boris Korzh, bkorzh@jpl.nasa.gov
Matt Shaw, mattshaw@jpl.nasa.gov

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

QT4HEP22-- I. Shipsey

125

diffractive scattering via ps-resolution tracking in Roman pots

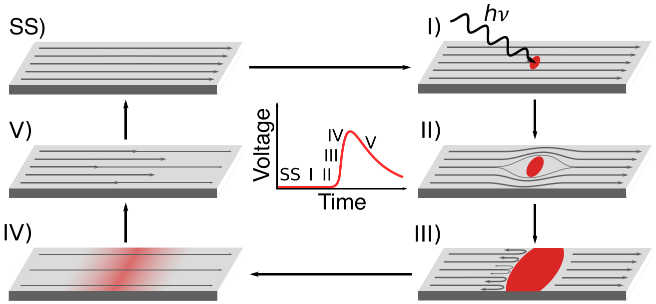


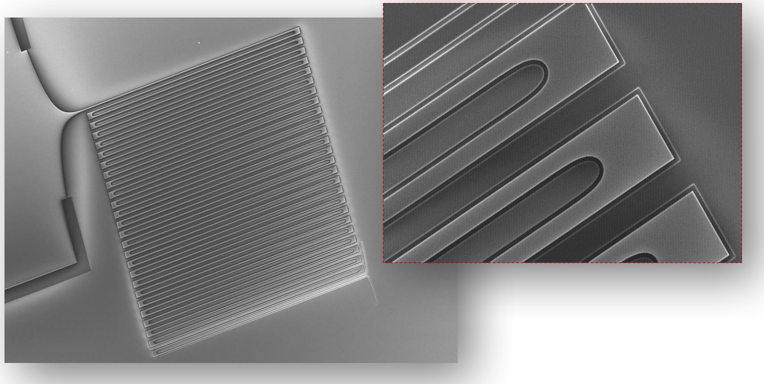
@ 2.8 K

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

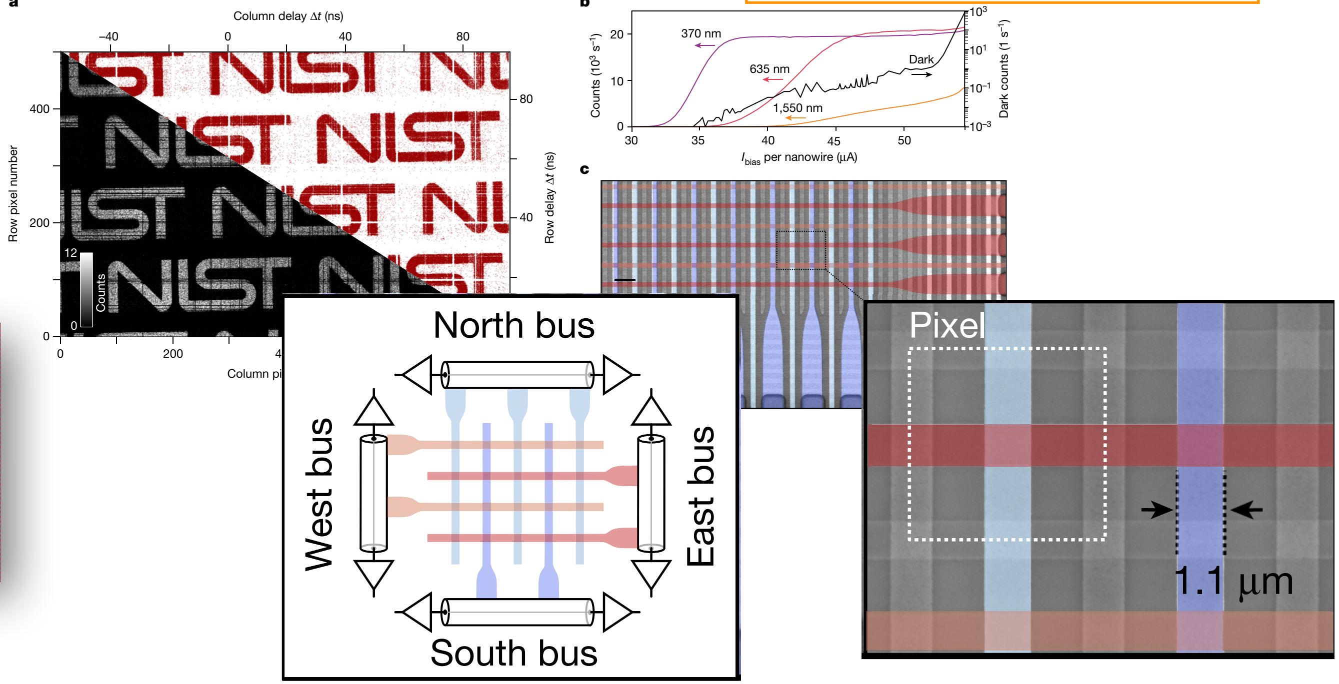
low energy particle physics: dark count rate is critical !
high energy particle physics: dark count rate is not a problem: high Tc is imaginable

④ Specific examples for potential particle physics impact: WP-3





Overview of the 800 × 500 camera



SNSPD: Advances & Expected Performance

Operating Temperature	Timing jitter	Intrinsic photon number resolution	Efficiency	Array size	Maximum count rate	Dark count rate	Active area	Cut-off wavelength	
4.3 K	18 ps	None	93%	64	1 Gcps	4 /s/mm^2	0.001 cm^2	5 µm	Records in 2016
	2.6 ps [1]	**3-5 photons**	**98%** [2]	**4x10^5** [3]	**1.5 Gcps** [4,5]	**4x10^{-5} /s/mm^2** [6]	**0.1 cm^2** [3]	**29 µm** [7]	**Current records for isolated devices**
25 K	**1 ps**	**10**	**99 %**	**10^7**	**10 Gcps**	**1x10^{-6} /s/mm^2**	**1 cm^2**	**100 µm**	Expected performance by 2030

Multi-layer stacked dets

- millicharged particles
- diffractive scattering
- luminosity monitor

---

[1] Korzh, Zhao et al, ***Nature Photonics*** 14, 250 (2020)
[2] Reddy et al, ***Optica*** 7, 1649 (2020)
[3] Oripov, Rampini, Allmaras, Shaw, Nam, Korzh, and McCaughan, ***Nature*** 622, 730 (2023)
[4] Craiciu, Korzh et al, ***Optica*** 10, 183 (2023)
[5] Resta et al, ***Nano Letters*** (2023)
[6] Chiles, ***PRL*** 128, 231802 (2022)
[7] Taylor, Walter, Korzh et al, ***Optica***, (2023)

⑤ Quantum technology needs dedicated R&D to achieve its expected potential → DRD5

HEP applications

WP-2	Quantum dots (HEP calorimetry)
WP-3	Superconducting devices (HEP, astroparticle) Nano- and Microwires TES, MMC (cryo-spectrometry)
WP-1	Atomic & nuclear physics (exotic atoms, neutrino physics, clocks)
WP-4	Spin-based sensors

Infrastructure @ CERN

CERN QTI

DRD5: WP's (particle physics > HEP)

WP1	Exotic systems in traps & beams (HCI's, molecules, Rydberg systems, clocks, interferometery, …)
WP2	Quantum materials (0-, 1-, 2-D) (Engineering at the atomic scale)
WP3	Quantum superconducting systems (4K electronics; MMC's, TES, SNSPD, KID's/…; integration challenges)
WP4	Scaling up to macroscopic ensembles (spins; nano-structured materials; hybrid devices, opto-mechanical sensors,…)
WP5	Quantum techniques for sensing (back action evasion, squeezing, entanglement, Heisenberg limit)
WP6	Capability expansion (cross-disciplinary exchanges; infrastructures; education)

5

DRD5 : putting together a global collaboration ab initio

…in all the shown examples, dedicated R&D is under way, with involvement of DRD5

What is DRD5 built to do?

- focus on addressing topics that go *beyond what individual institutes* can do
- pool expertise, resources, create exchanges, educate
- create a global multi quantum-technology community focusing on quantum systems based detector R&D under the umbrella of DRD5

- Common R&D building on the extremely rapidly growing areas of quantum technologies
- Workshops
- Detector test facilities
- Education
- Agreements & standards
- …

5

DRD5 : putting together a global collaboration ab initio

...in all the shown examples, dedicated R&D is under way, with involvement of DRD5

What is DRD5 built to do?

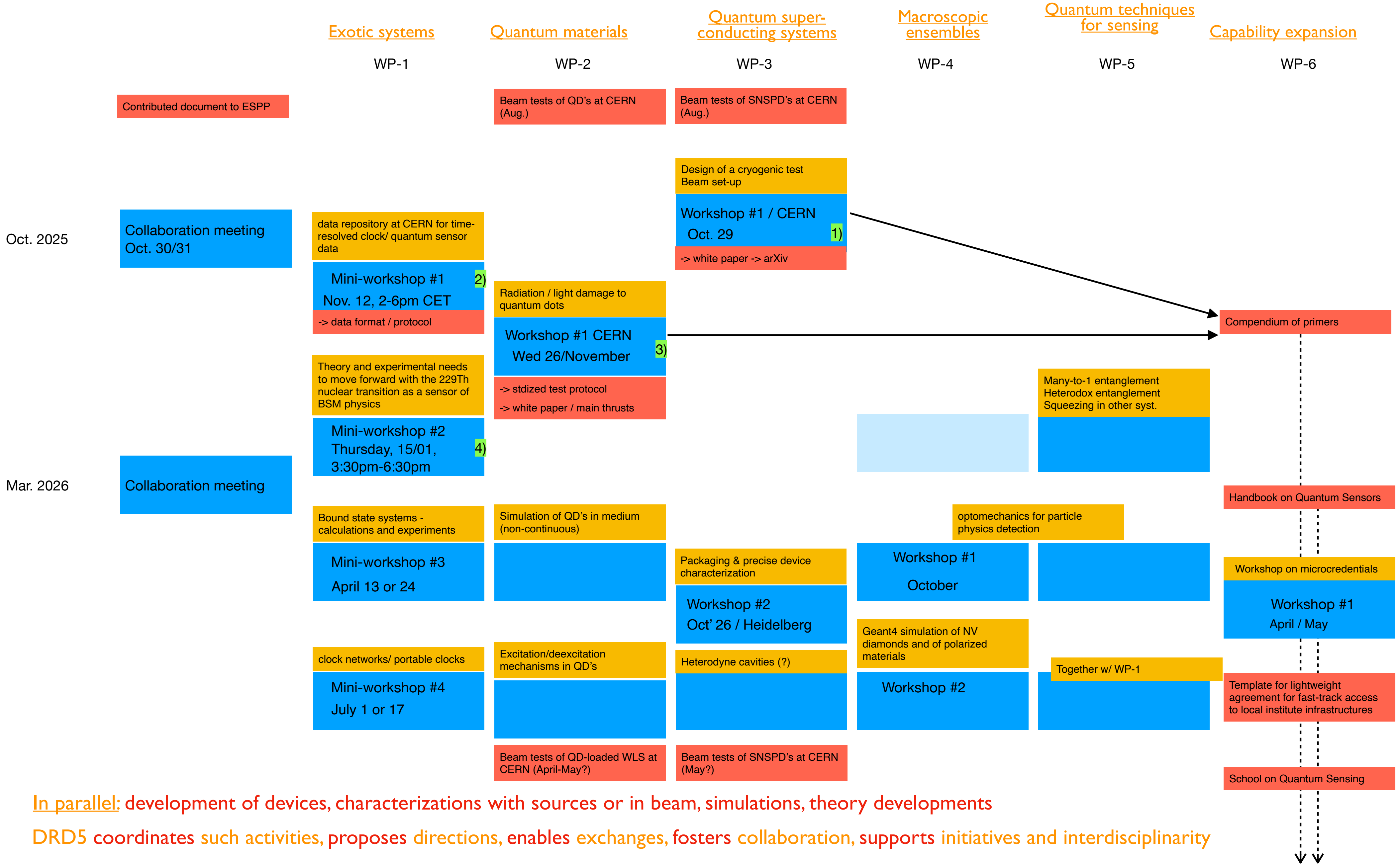
- focus on addressing topics that go *beyond what individual institutes* can do
- pool expertise, resources, create exchanges, educate
- create a global multi quantum-technology community focusing on quantum systems based detector R&D under the umbrella of DRD5

What has happened since the DRD5 was formed and approved in mid-2024?

- concrete proposals for *HEP-relevant* uses of quantum sensors are appearing
- first beam tests with quantum dots and nano/microwires
- formation of a global multi quantum-technology community focusing on detector R&D under the umbrella of DRD5
- infrastructure needs have been identified and are starting to be addressed (cryogenic beam test facilities, quantum dot characterization infrastructure, …)

5

DRD5 : ongoing and planned activities



Oct. 2025

Mar. 2026

Contributed document to ESPP

Collaboration meeting
Oct. 30/31

Collaboration meeting

Exotic systems
WP-1

data repository at CERN for time-resolved clock/ quantum sensor data
Mini-workshop #1 2)
Nov. 12, 2-6pm CET
-> data format / protocol

Theory and experimental needs to move forward with the 229Th nuclear transition as a sensor of BSM physics
Mini-workshop #2
Thursday, 15/01, 3:30pm-6:30pm 4)

Bound state systems - calculations and experiments
Mini-workshop #3
April 13 or 24

clock networks/ portable clocks
Mini-workshop #4
July 1 or 17

Quantum materials
WP-2

Beam tests of QD's at CERN (Aug.)

Radiation / light damage to quantum dots
Workshop #1 CERN
Wed 26/November 3)
-> stdized test protocol
-> white paper / main thrusts

Simulation of QD's in medium (non-continuous)

Excitation/deexcitation mechanisms in QD's

Beam tests of QD-loaded WLS at CERN (April-May?)

Quantum super-conducting systems
WP-3

Beam tests of SNSPD's at CERN (Aug.)

Design of a cryogenic test Beam set-up
Workshop #1 / CERN
Oct. 29 1)
-> white paper -> arXiv

Packaging & precise device characterization
Workshop #2
Oct' 26 / Heidelberg

Heterodyne cavities (?)

Beam tests of SNSPD's at CERN (May?)

Macroscopic ensembles
WP-4

optomechanics for particle physics detection
Workshop #1
October

Geant4 simulation of NV diamonds and of polarized materials
Workshop #2

Quantum techniques for sensing
WP-5

Many-to-1 entanglement
Heterodox entanglement
Squeezing in other syst.

Together w/ WP-1

Capability expansion
WP-6

Compendium of primers

Handbook on Quantum Sensors

Workshop on microcredentials
Workshop #1
April / May

Template for lightweight agreement for fast-track access to local institute infrastructures

School on Quantum Sensing

In parallel: development of devices, characterizations with sources or in beam, simulations, theory developments

DRD5 coordinates such activities, proposes directions, enables exchanges, fosters collaboration, supports initiatives and interdisciplinarity

1) https://indico.cern.ch/event/1580512/
2) https://indico.cern.ch/event/1598214
3) https://indico.cern.ch/event/1598214
4) https://indico.cern.ch/event/1624634

⑤

“Quantum” is relevant

(focus on potential HEP impact)

DRD5 WP

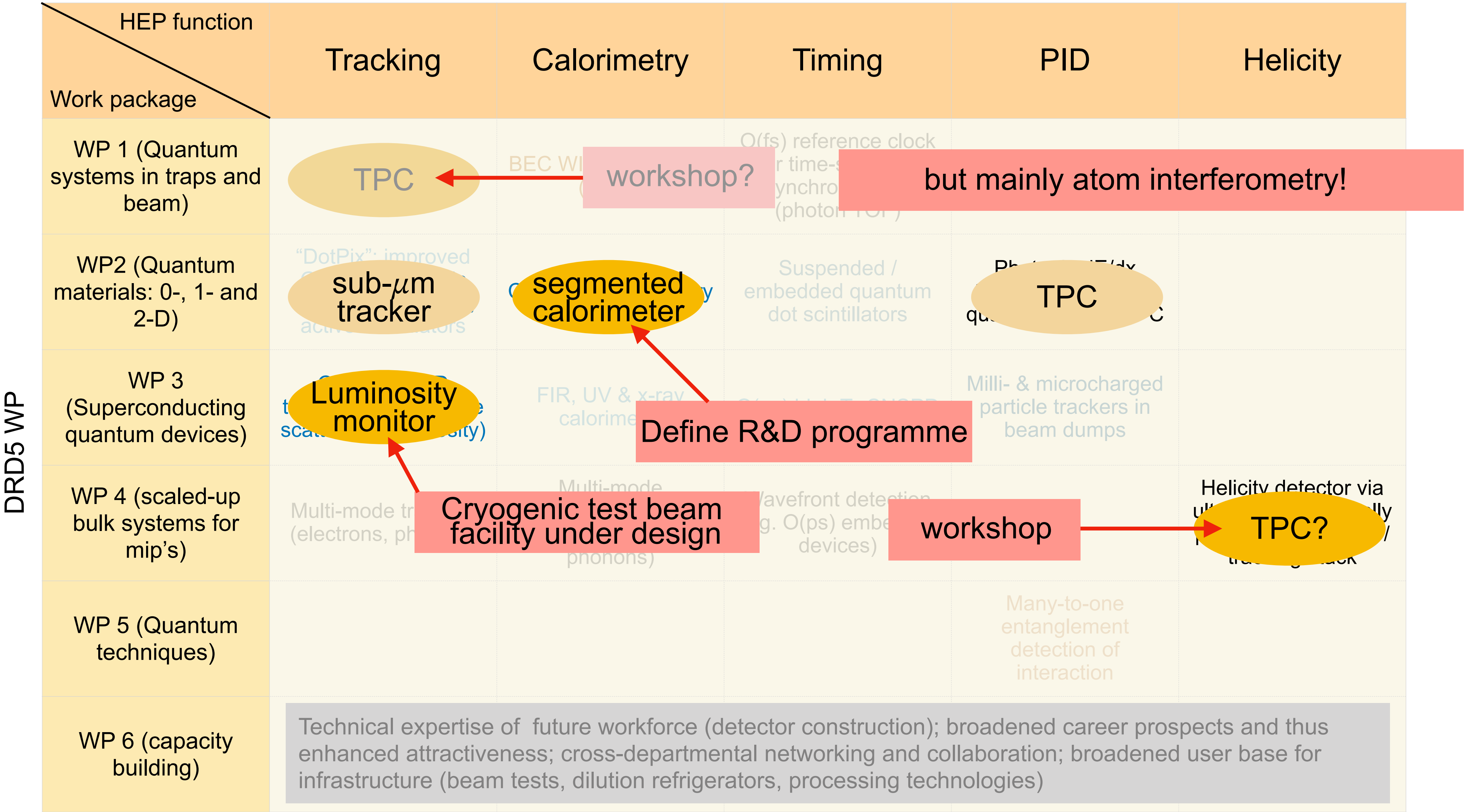
HEP function / Work package	Tracking	Calorimetry	Timing	PID	Helicity
WP 1 (Quantum systems in traps and beam)	Rydberg TPC	BEC WIMP scattering (recoil)	O(fs) reference clock for time-sensitive synchronization (photon TOF)	Rydberg dE/dx amplifiers	
WP2 (Quantum materials: 0-, 1- and 2-D)	“DotPix”; improved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

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

5

“Quantum” is relevant

(focus on potential HEP impact)



DRD5 WP

HEP function / Work package	Tracking	Calorimetry	Timing	PID	Helicity
WP 1 (Quantum systems in traps and beam)	TPC	BEC WI (workshop?	O(fs) reference clock r time-s ynchro (photon TOF)	but mainly atom interferometry!	
WP2 (Quantum materials: 0-, 1- and 2-D)	“DotPix”: improved sub-μm tracker acti ators	C y segmented calorimeter	Suspended / embedded quantum dot scintillators	Ph E/dx TPC qu C	
WP 3 (Superconducting quantum devices)	t e scat sity) Luminosity monitor	FIR, UV & x-ray calorime	Define R&D programme	Milli- & microcharged particle trackers in beam dumps	
WP 4 (scaled-up bulk systems for mip’s)	Multi-mode tr (electrons, ph	Cryogenic test beam facility under design Multi-mode phonons)	avefront detection g. O(ps) embe devices)	workshop	Helicity detector via ul lly / TPC? tra ack
WP 5 (Quantum techniques)				Many-to-one entanglement detection of interaction	
WP 6 (capacity building)	Technical expertise of future workforce (detector construction); broadened career prospects and thus enhanced attractiveness; cross-departmental networking and collaboration; broadened user base for infrastructure (beam tests, dilution refrigerators, processing technologies)				

Identify at least one potential HEP-relevant project per WP

⑤

DRD5: ~120 involved groups

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

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

Canada: McGill Univ.
TRIUMF

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

Mexico: U. de Aguascalientes

Spain: U. de Zaragoza
U. de Cartagena
U. de Valencia
U. de Lleida
IEM, CSIC

Switzerland: U. of Geneva
U. of Zürich
CERN
ETHZ
Univ. Bern

Austria: IQOQI Vienna
TU Wien

Croatia: Inst. of Physics, Zagreb

Netherlands: U. of Groningen

Norway: Oslo University

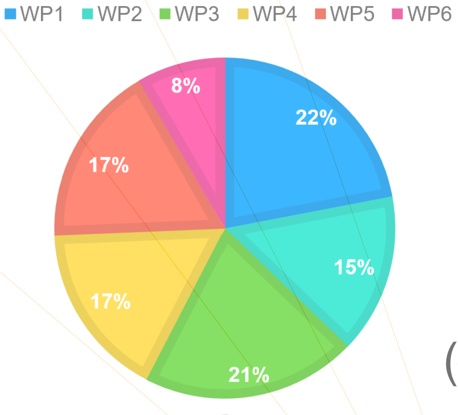
Sweden: Stockholm University

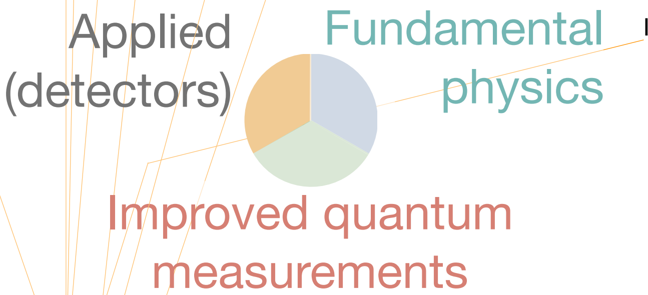
Denmark: Aarhus University

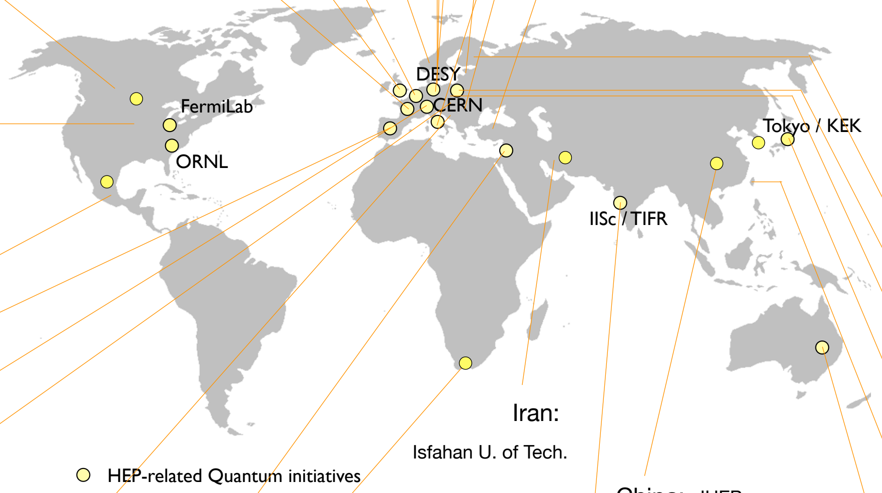
Lithuania: University of Vilnius

Hungary: Wigner Institute

Türkiye:
Sabanci University, Istanbul
Düzce University
Ankara University, Ankara
Izmir University
Istinye University, Istanbul




Applied (detectors)
Fundamental physics
Improved quantum measurements



HEP-related Quantum initiatives

Israel: Technion, Haifa

South Africa: U. of Cape Town

Iran: Isfahan U. of Tech.

India: IITT, Tirupati
IEM, Kolkata
TIFR, Mumbai
LPU, Punjab
University SOA Bhuvaneswar

China: IHEP
USTC (Hefei)

Australia:
University of Western Australia
Swinburne University of Technology
University of Sydney

Taiwan:
Academia Sinica & NTU

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

Italy: U. of Pisa & INFN
U. of Pavia
U. of Firenze
U. of Milano-Bicocca
Fondazione Bruno Kessler, Trento
IOM CNR, Elettra Sincrotrone, Trieste
Univ. of Bari / INFN
INFN Padova
Univ. Roma 1 & 3
Univ. Napoli
INFN Roma Tor Vergata
INFN LNF
INFN Trento (TIFPA)
INFN Torino
INFN LNL
INFN Lecce
INFN Roma Tor Vergata
U. of Camerino

Finland: Helsinki Inst. of Physics
VTT

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

Czech Republic: Charles Univ., Prague
Czech Tech. University
University West Bohemia

Japan: QUP / KEK
Kyoto University
Tokyo University / ICEPP
University of Shizuoka

5

DRD5: 120 involved groups

Collaboration ramping up, combines diverse communities, including HEP.

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

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

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

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

Canada: McGill Univ.
TRIUMF

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

Mexico: U. de Aguascalientes

Spain: U. de Zaragoza
U. de Cartagena
U. de Valencia
U. de Lleida
IEM, CSIC

Switzerland: U. of Geneva
U. of Zürich
CERN
ETHZ
Univ. Bern

Austria: IQOQI Vienna
TU Wien

Croatia: Inst. of Physics, Zagreb

Israel: Technion, Haifa

South Africa: U. of Cape Town

Iran: Isfahan U. of Tech.

India: IITT, Tirupati
IEM, Kolkata
TIFR, Mumbai
LPU, Punjab
University SOA Bhuvaneswar

China: IHEP
USTC (Hefei)

Australia: University of Western Australia
Swinburne University of Technology
University of Sydney

Taiwan: Academia Sinica & NTU

Netherlands: U. of Groningen

Norway: Oslo University

Sweden: Stockholm University

Denmark: Aarhus University

Lithuania: University of Vilnius

Hungary: Wigner Institute

Türkiye:
Sabanci University, Istanbul
Düzce University
Ankara University, Ankara
Izmir University
Istinye University, Istanbul

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

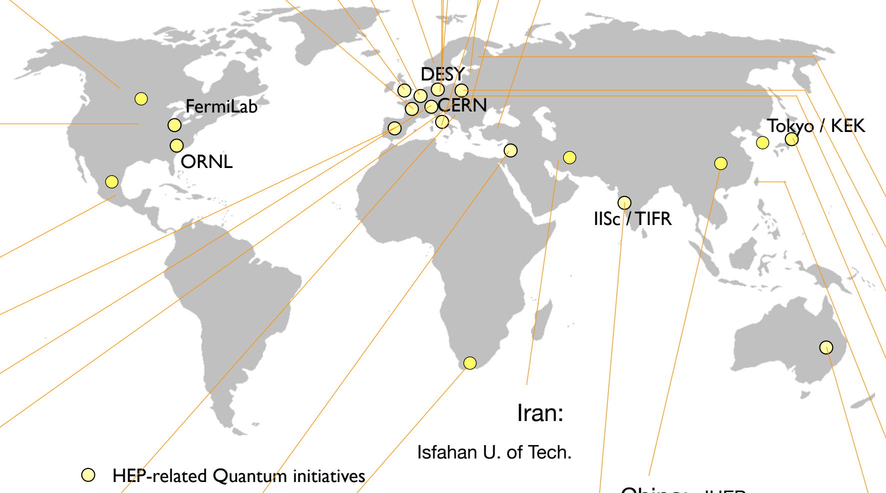
Italy: U. of Pisa & INFN
U. of Pavia
U. of Firenze
U. of Milano-Bicocca
Fondazione Bruno Kessler, Trento
IOM CNR, Elettra Sincrotrone, Trieste
Univ. of Bari / INFN
INFN Padova
Univ. Roma 1 & 3
Univ. Napoli
INFN Roma Tor Vergata
INFN LNF
INFN Trento (TIFPA)
INFN Torino
INFN LNL
INFN Lecce
INFN Roma Tor Vergata
U. of Camerino

Finland: Helsinki Inst. of Physics
VTT

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

Czech Republic: Charles Univ., Prague
Czech Tech. University
University West Bohemia

Japan: QUP / KEK
Kyoto University
Tokyo University / ICEPP
University of Shizuoka



thank you!

5

WP-1a : Exotic systems in traps and beams

WP-1a_a: extension and improved manipulation of exotic systems

WP-1a_b: Bound state calculations

WP-1a c: Global analysis in the presence of new physics

WP-1b : Atom Interferometry

WP-1b a: Terrestrial Very-Long-Baseline Atom Interferometry Roadmap

WP-1b b: High-Precision Atom Interferometry

WP-1c: Networks, Signal and Clock distribution

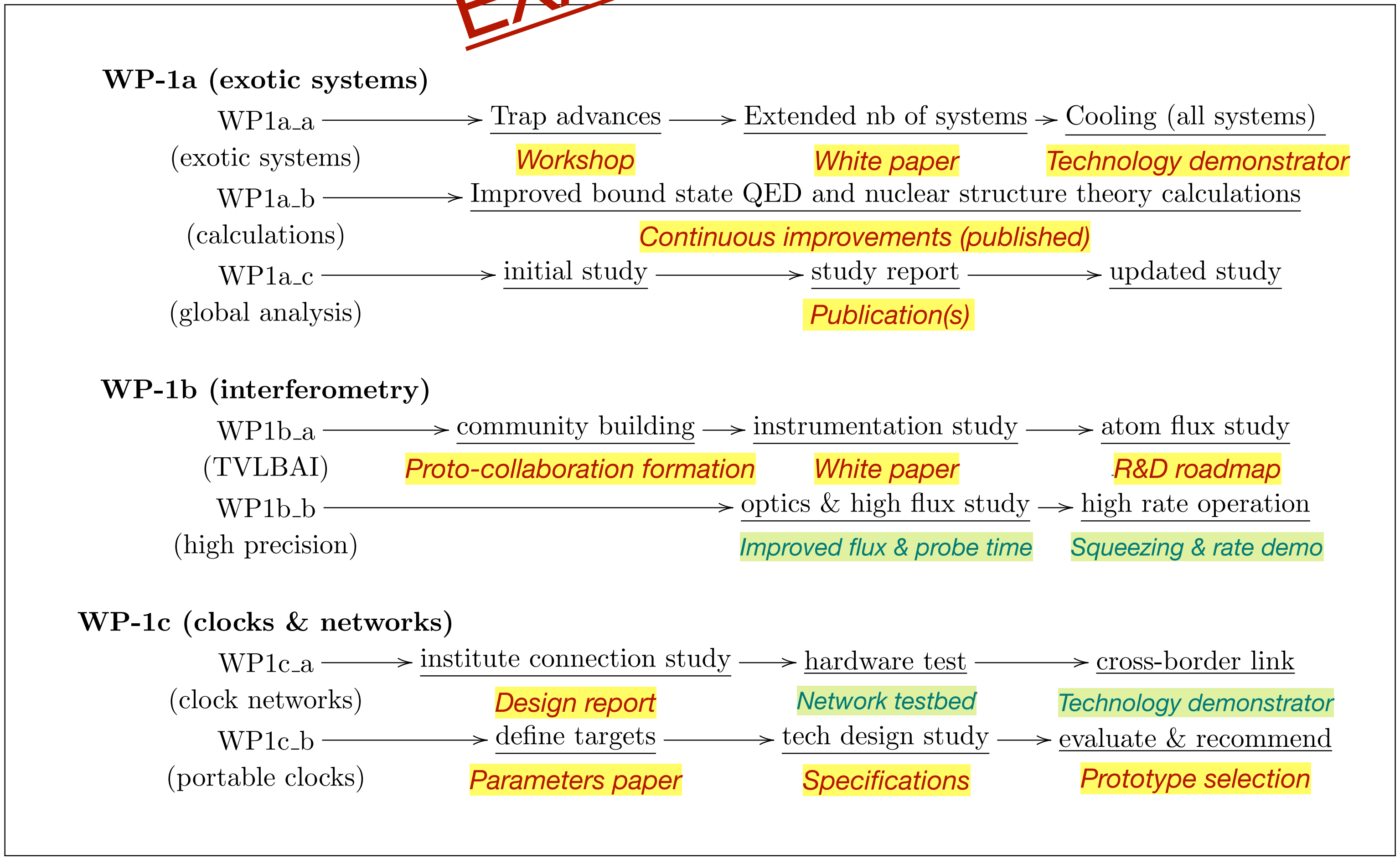
WP-1c a: Large-scale clock network

WP-1c b: Portable references and sources

cross-WP activity

(Time and frequency distribution via space)

EXAMPLE



WP-1a (exotic systems)

WP1a_a → Trap advances → Extended nb of systems → Cooling (all systems)
(exotic systems) *Workshop* *White paper* *Technology demonstrator*
WP1a_b → Improved bound state QED and nuclear structure theory calculations
(calculations) *Continuous improvements (published)*
WP1a_c → initial study → study report → updated study
(global analysis) *Publication(s)*

WP-1b (interferometry)

WP1b_a → community building → instrumentation study → atom flux study
(TVLBAI) *Proto-collaboration formation* *White paper* *R&D roadmap*
WP1b_b → optics & high flux study → high rate operation
(high precision) *Improved flux & probe time* *Squeezing & rate demo*

WP-1c (clocks & networks)

WP1c_a → institute connection study → hardware test → cross-border link
(clock networks) *Design report* *Network testbed* *Technology demonstrator*
WP1c_b → define targets → tech design study → evaluate & recommend
(portable clocks) *Parameters paper* *Specifications* *Prototype selection*

5

WP-1a : Exotic systems in traps and beams

WP-1a_a: extension and improved manipulation of exotic systems

WP-1a_b: Bound state calculations

WP-1a c: Global analysis in the presence of new physics

WP-1b : Atom Interferometry

WP-1b a: Terrestrial Very-Long-Baseline Atom Interferometry Roadmap

WP-1b b: High-Precision Atom Interferometry

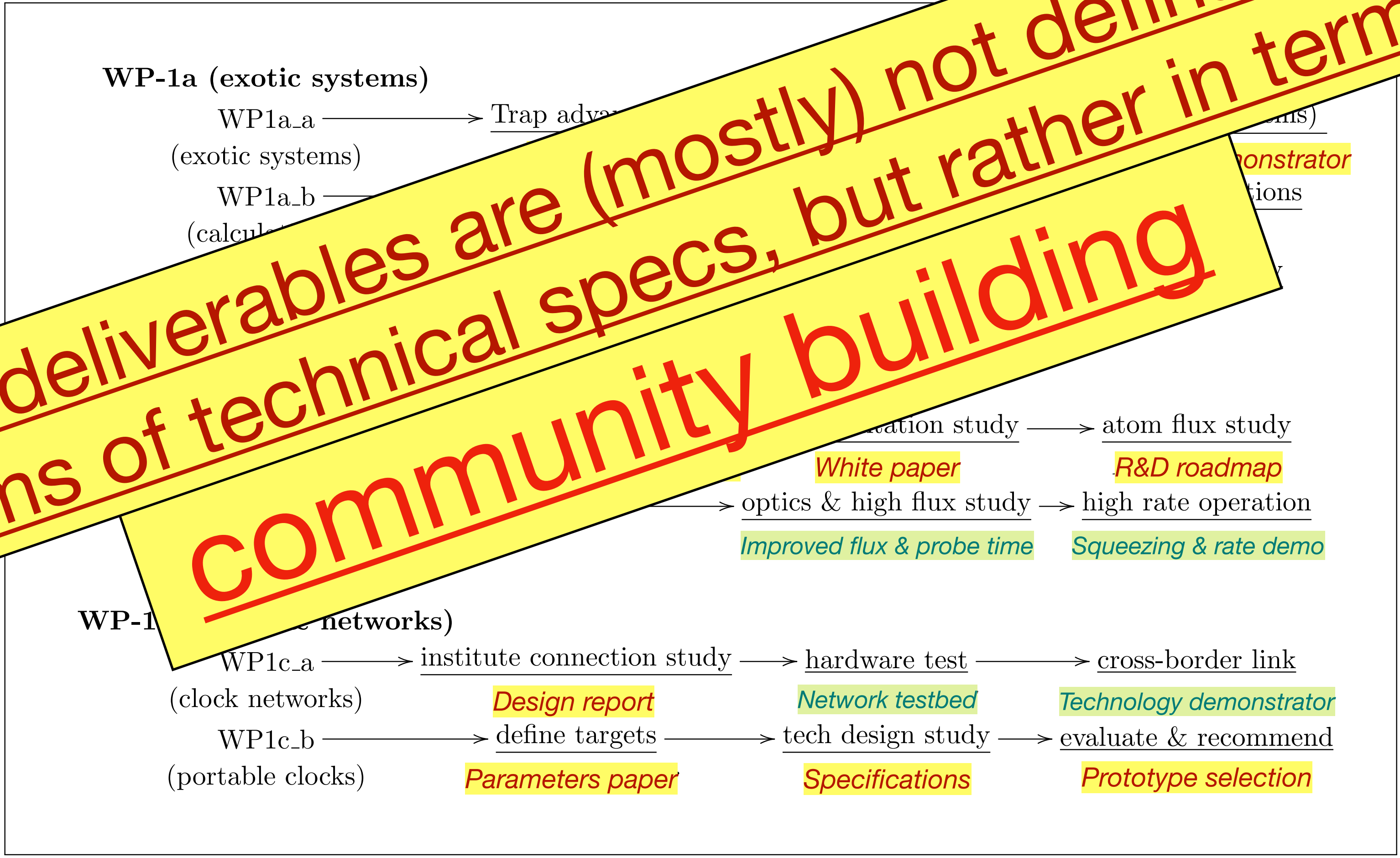
WP-1c: Networks, Signal and Clock distribution

WP-1c a: Large-scale clock network

WP-1c b: Portable references and

cross-WP activity

(Time and frequency distribution via sp



WP-1a (exotic systems)

WP1a_a → Trap adva

(exotic systems)

WP1a_b

(calcul

ns)

onstrator

tions

ation study → atom flux study

White paper

R&D roadmap

→ optics & high flux study → high rate operation

Improved flux & probe time

Squeezing & rate demo

WP-1 networks)

WP1c_a → institute connection study → hardware test → cross-border link

(clock networks)

Design report

Network testbed

Technology demonstrator

WP1c_b → define targets → tech design study → evaluate & recommend

(portable clocks)

Parameters paper

Specifications

Prototype selection

Our deliverables are (mostly) not definable in terms of technical specs, but rather in terms of community building

Other ideas:

Super-radiance-based detectors

Quantum dots suspended in liquid TPC’s