DRD5 Collaboration

Warsaw University of Technology
Faculty of Physics

Quantum sensing developments for particle physics

Quantum sensors for both high and low energy particle physics

Georgy Kornakov

DIPC, San Sebastian, 16 July 2026

- Clarification of terms
- Quantum sensors for low energy particle physics
- Quantum sensors for high energy particle physics
- Detector R&D collaboration at CERN
- Control systems and electronics for QE

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

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

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

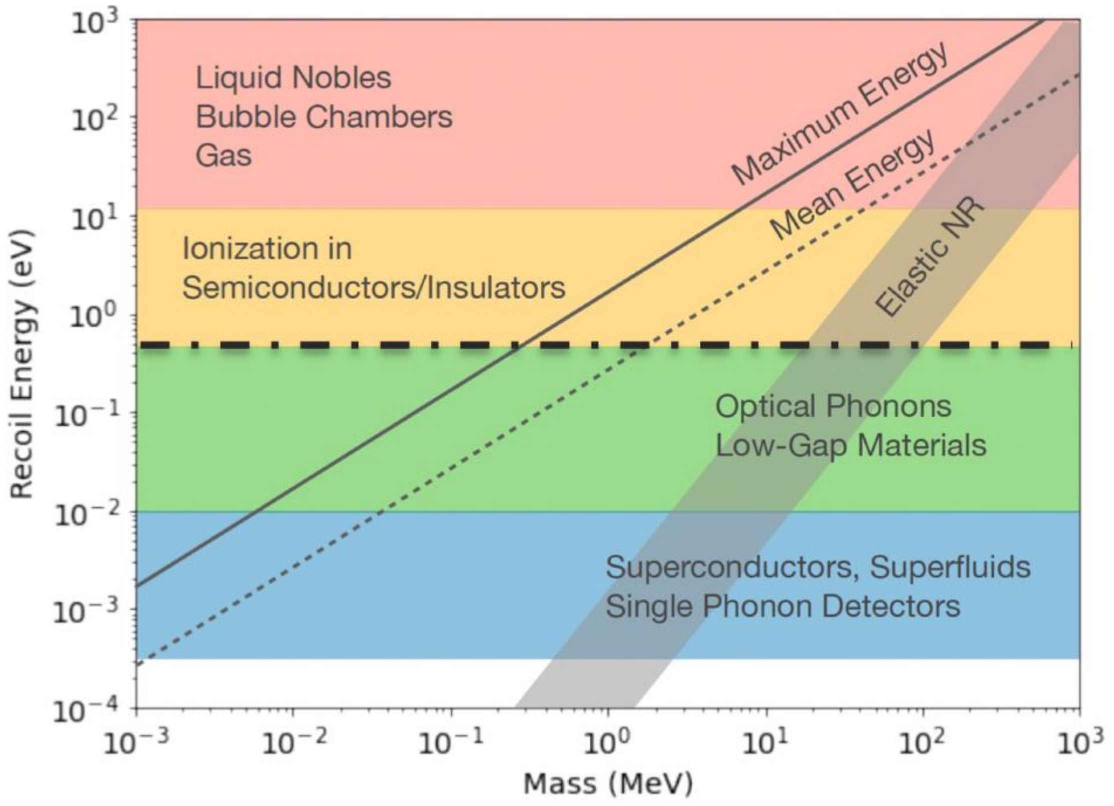
Then, a "quantum sensor" is a device, the measurement (sensing) capabilities of which are enabled by our ability to manipulate ***and/or*** *read out its quantum states.*

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

→ They can also form natural elements of HEP detectors

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

Start with an example: Energy deposited in detectors by particles



$\Delta E \sim 1$ eV

e.g. Si, Ge, GaAs, diamond, Quantum Dots, organic scintillators…

$\Delta E \sim 10 - 100$ meV

e.g. GaAs, sapphire, Dirac materials, doped s/c, …

$\Delta E \sim 1$ meV

e.g. superfluids, superconductors

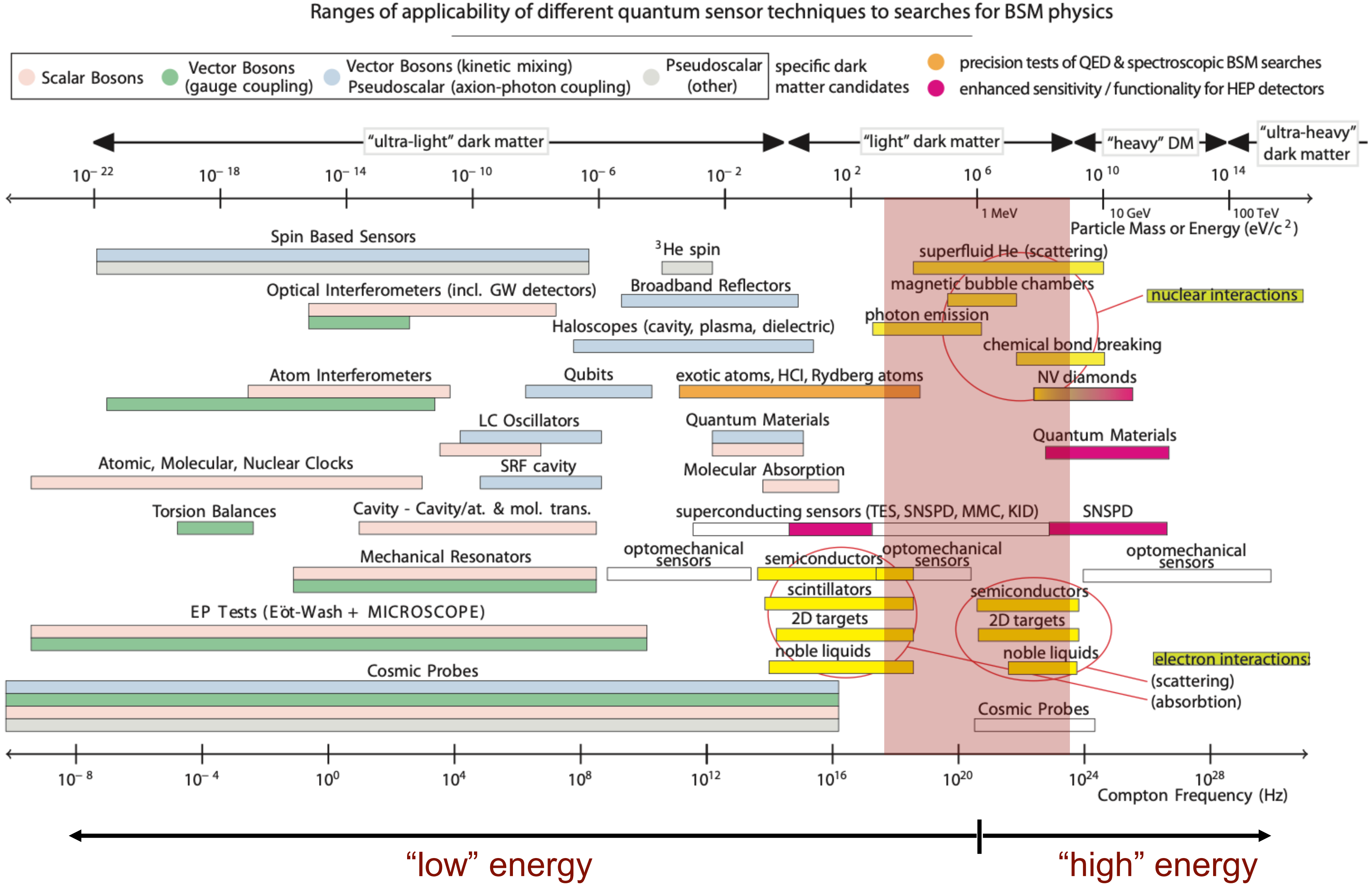
Daniel Baxter I IDM 2024

Essig et al, Snowmass CF1 WP2 (2022) [arXiv:2203.08297]

- What's the goal? MIP detection? or minute, sub-MIP energy deposits?
- Very low bandgap materials required to be sensitive to tiny energy deposits: milli-charged particles, nuclear recoil from very light DM, …
- For much higher (or lower) particle masses (or better, very weak fields), other quantum sensing technologies are more appropriate: Rydberg atoms, Qubits

quantum sensing & particle physics

S. Bass, M. Doser Nature Rev. Phys. 6 (2024) 5, 329-339



quantum technologies

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

domains of physics

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

ECFA Detector R&D Roadmap
Quantum and Emerging Technologies

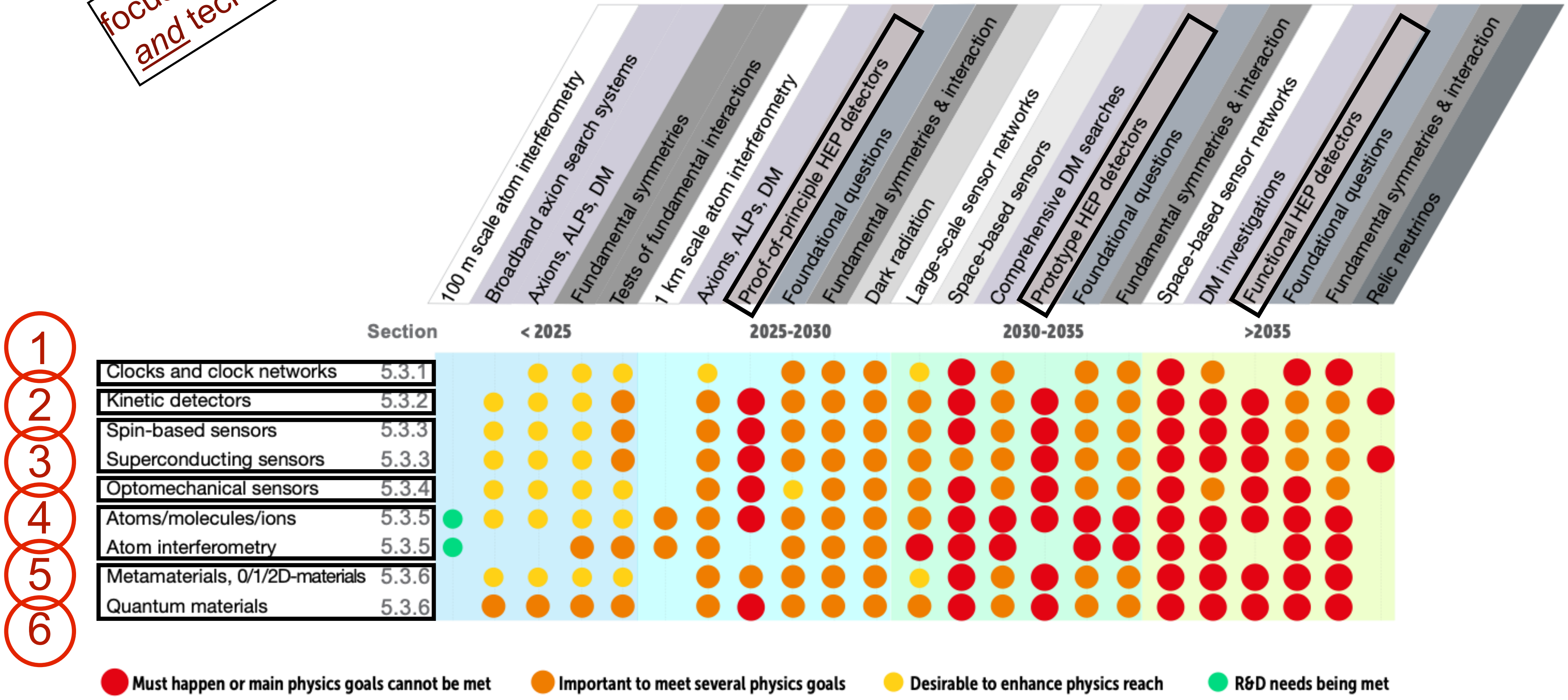
→ https://indico.cern.ch/event/999818/
→ https://indico.cern.ch/event/957057/page/23281-the-roadmap-document

RECFA Detector R&D roadmap 2021

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

focus on physics *and* technology

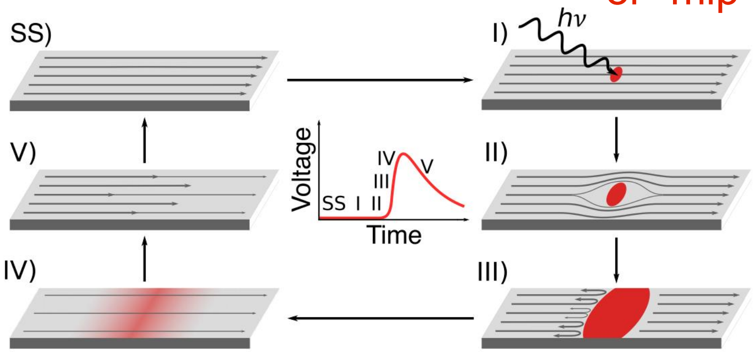
Chapter 5: Quantum and Emerging Technologies Detectors



Extremely low energy threshold detectors: SNSPD

quantum pixel ultra-sensitive tracking

or “mip”



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

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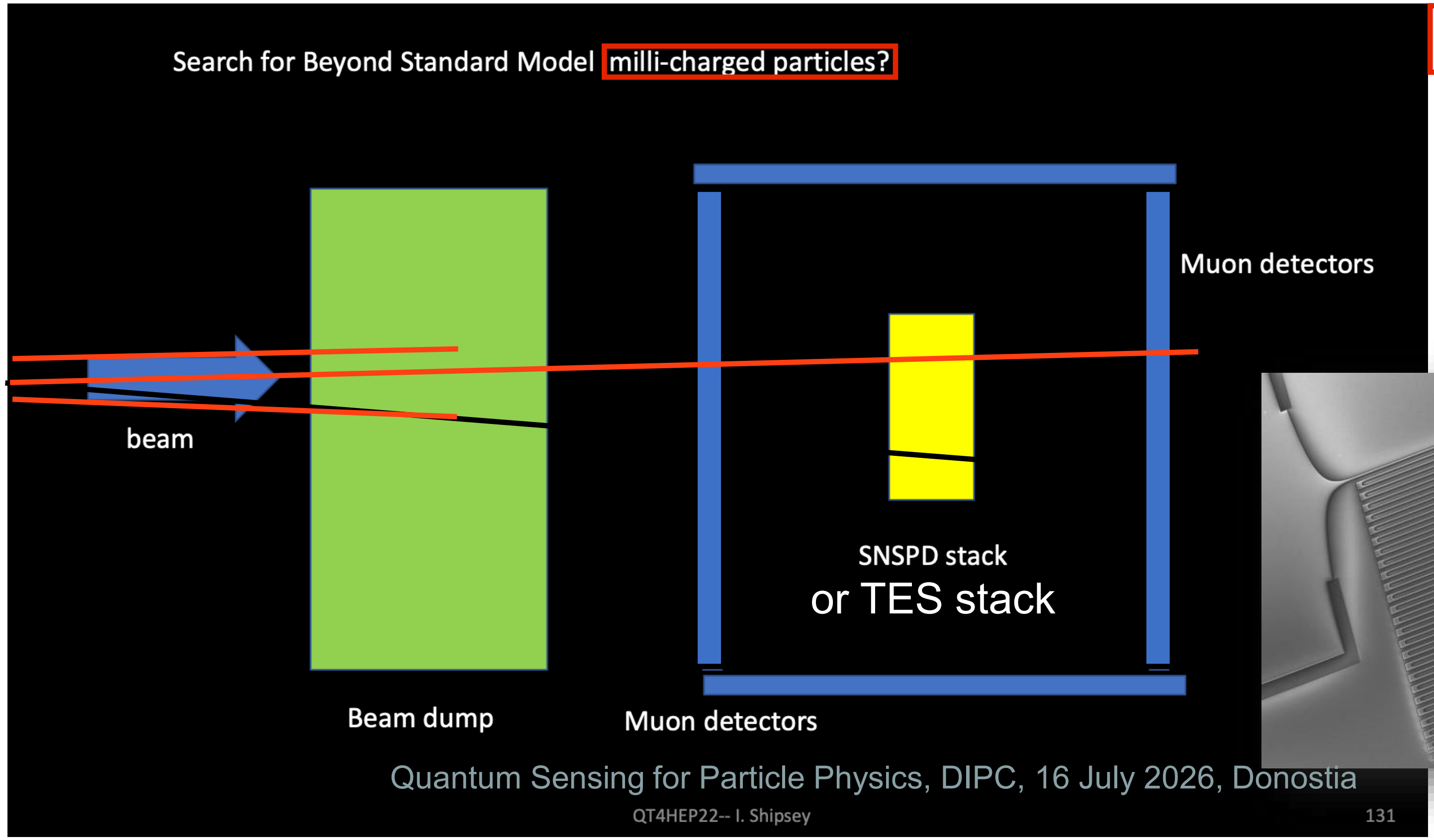
Moving to SC strips conventional lithography → scale up
Development towards SC SSPM

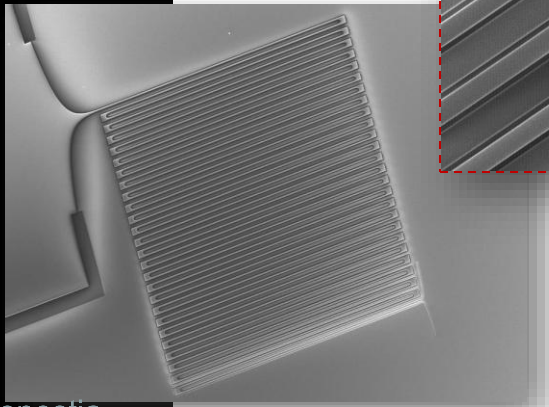
QT4HEP22-- I. Shipsey 125

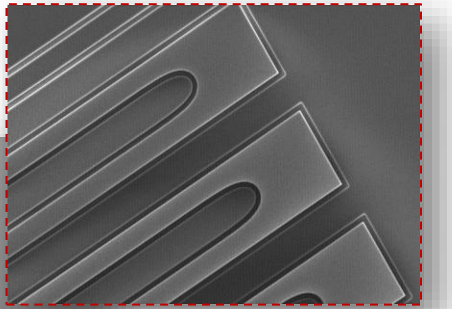


mip: ~20 keV/100 μm

x 10^6 sensitivity

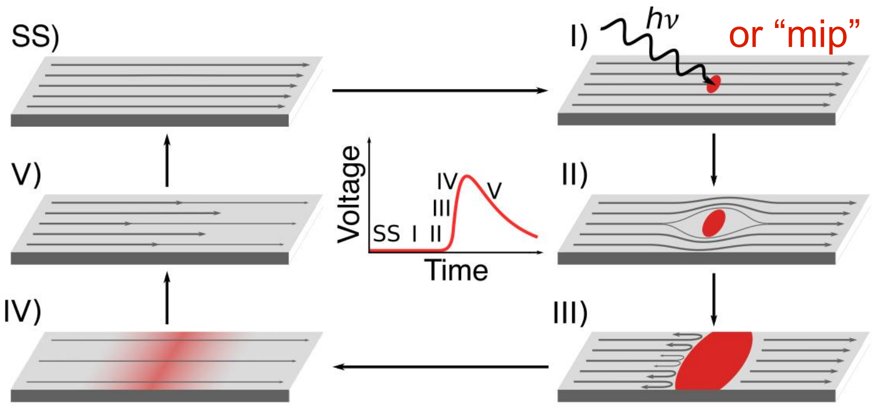
Thick → slow (ns)





quantum pixel ultra-sensitive tracking

Extremely fast detectors: SNSPD



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Snowmass2021 - Letter of Interest

Superconducting Nanowire Single-Photon Detectors

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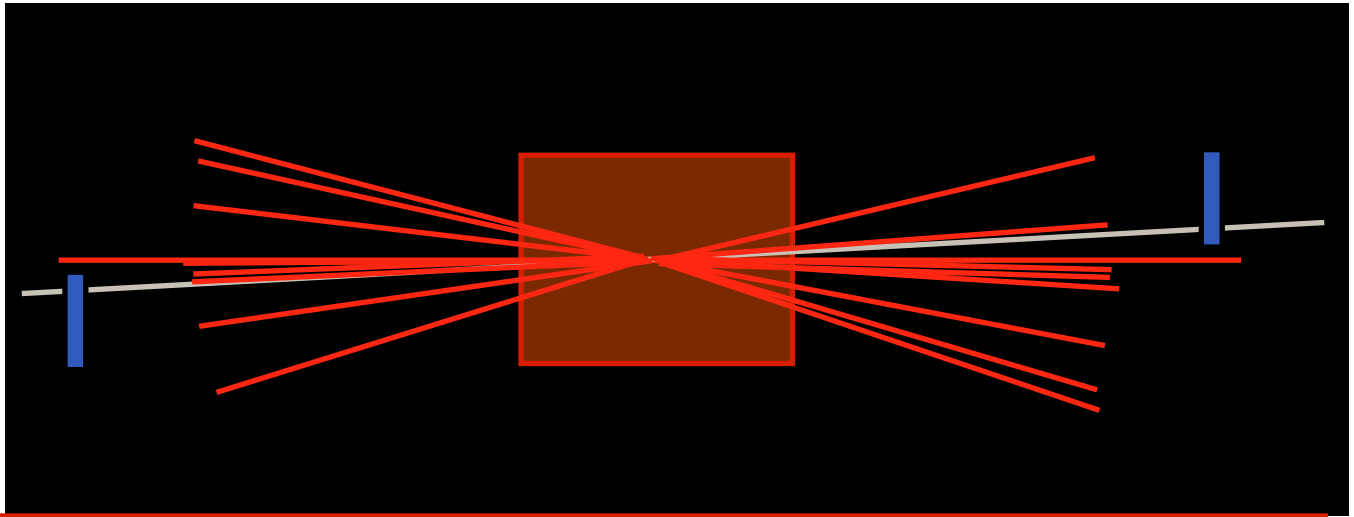
Moving to SC strips conventional lithography → scale up
Development towards SC SSPM

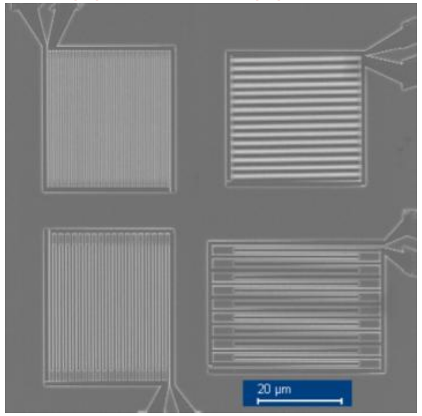
QT4HEP22-- I. Shipsey 125

diffractive scattering via ps-resolution tracking in Roman pots



@ 2.8 K

100 nm 200 nm



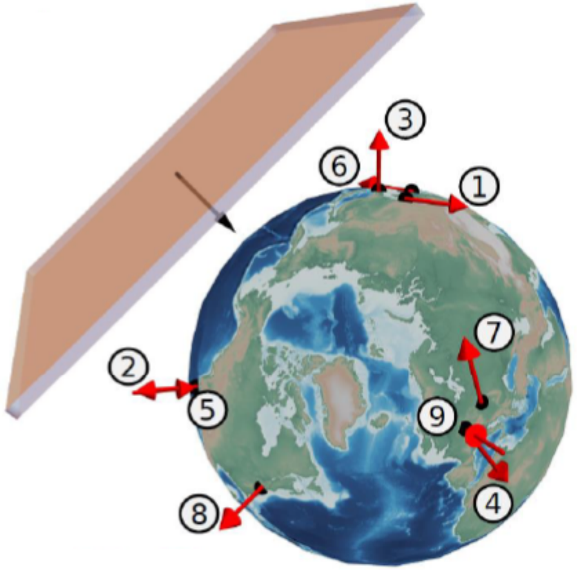
400 nm 800 nm

S. Lee et al., (2024)
arXiv:2312.13405v2
SNSPD w/ p@120 GeV
for use e.g. at EIC

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

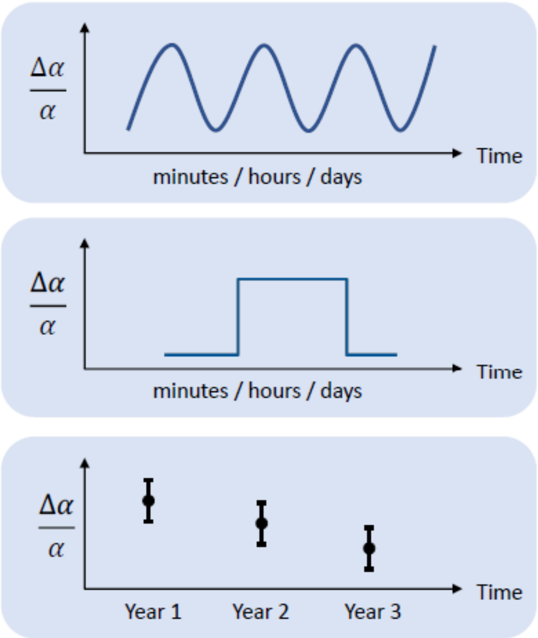
particle physics: what are we talking about?

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

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

https://indico.cern.ch/event/999818/ Giovanni Barontini (Birmingham)

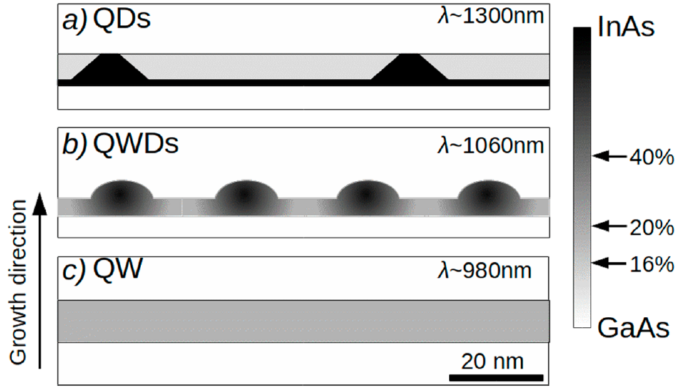
Active scintillators (QWs, QDs, QWDs, QCLs)

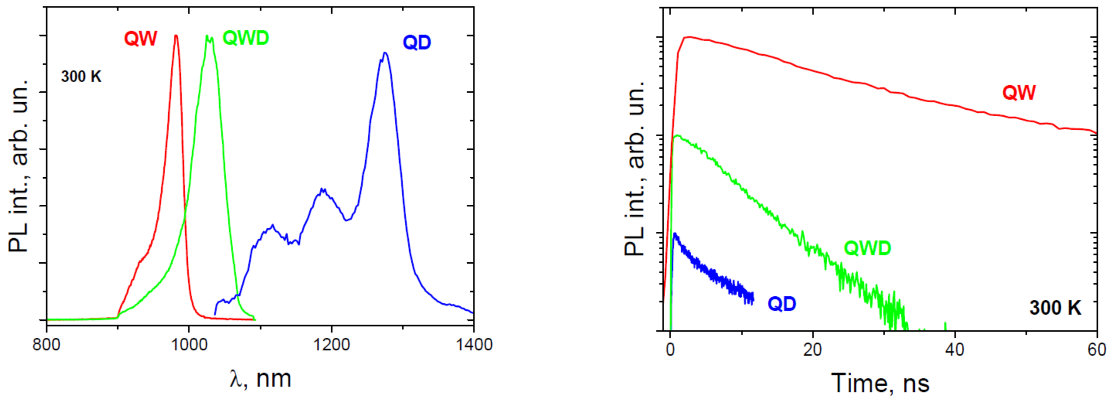
M. Doser, CERN

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

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

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





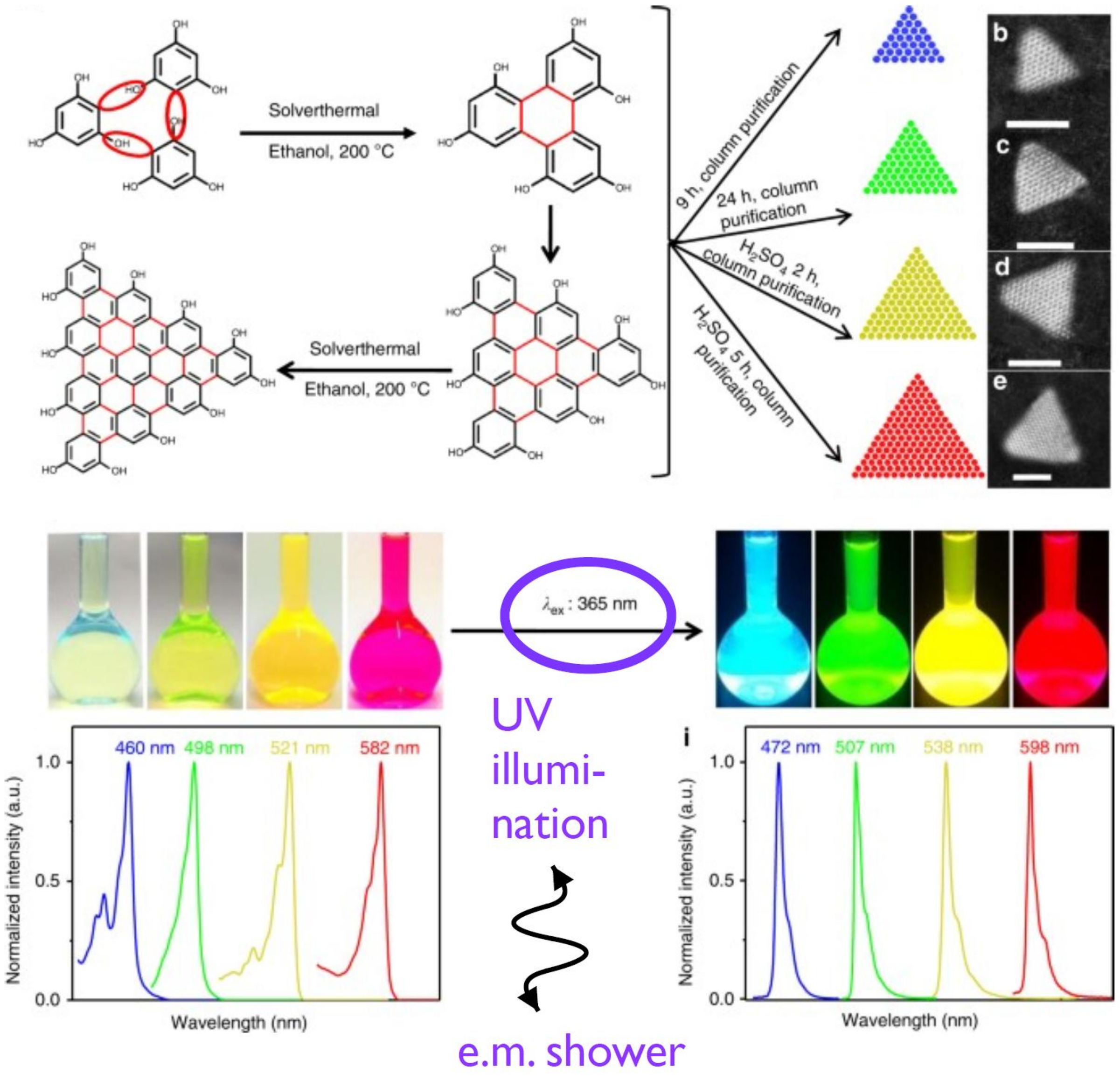
Light Emitting Devices Based on Quantum Well-Dots, Appl. Sci. 2020, 10, 1038; doi:10.3390/app10031038

QD's are radiation resistant

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

Quantum dots: chromatic calorimetry

M. Doser, CERN



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

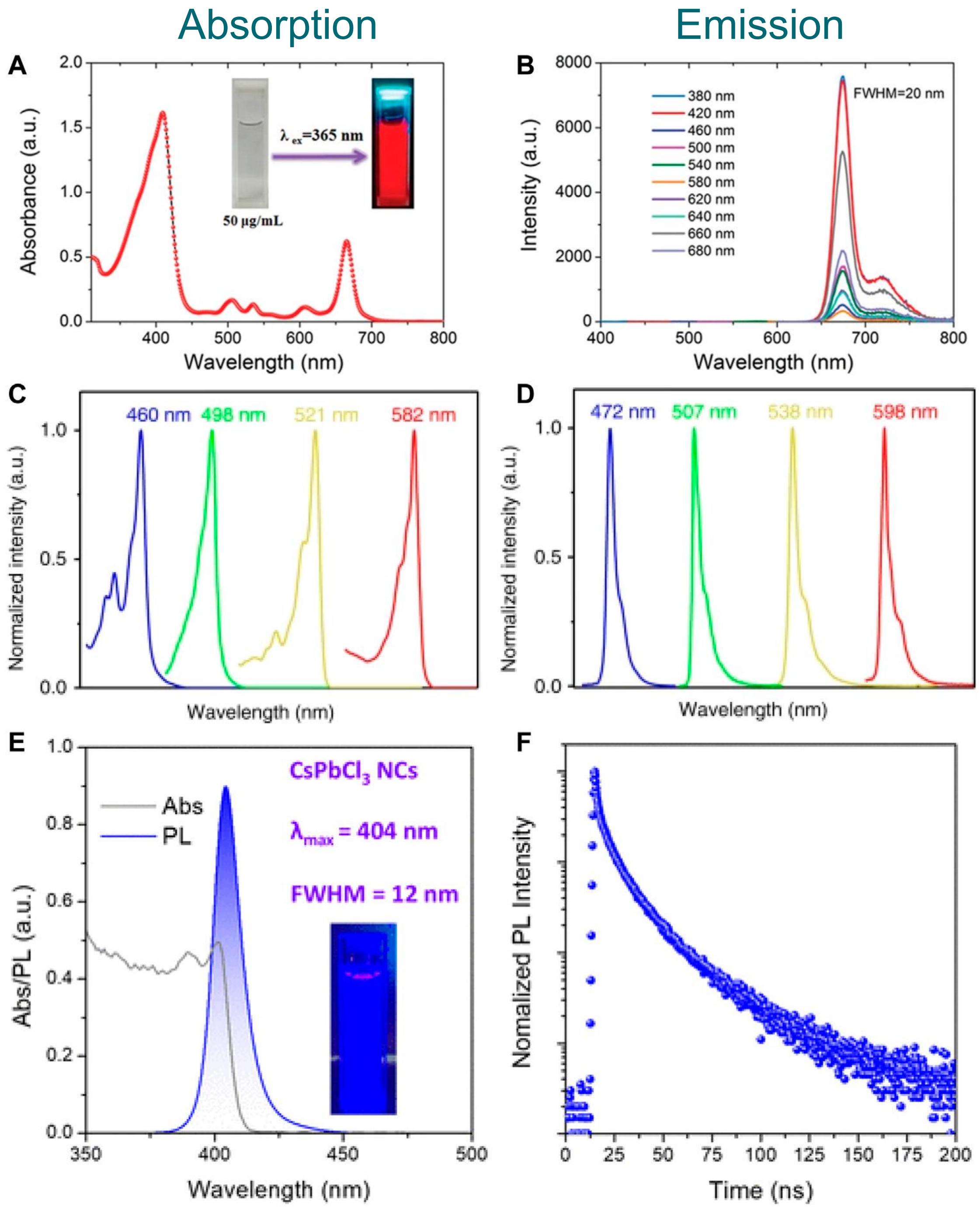
idea: seed different parts of a "crystal" with nanodots emitting at different wavelengths, such that the wavelength of a stimulated fluorescence photon is uniquely assignable to a specific nanodot position

requires:

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

select appropriate nanodots

e.g. triangular carbon nanodots



M. Doser, CERN

carbonized polymer dots

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

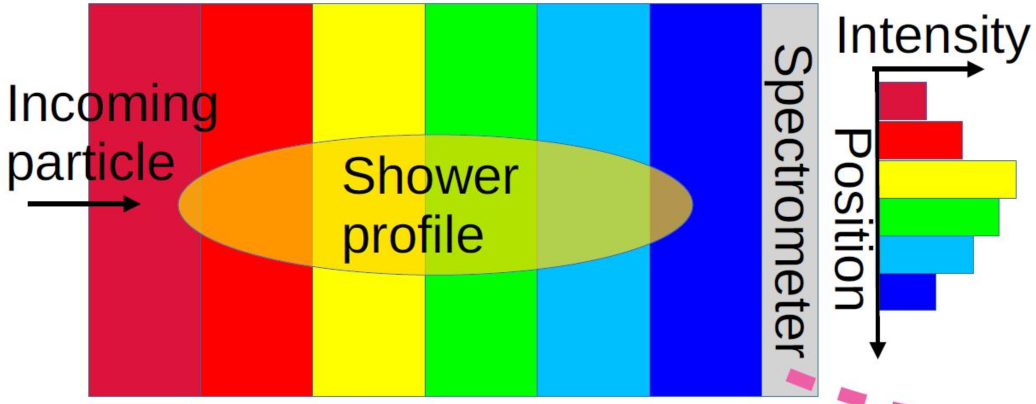
triangular carbon nanodots

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

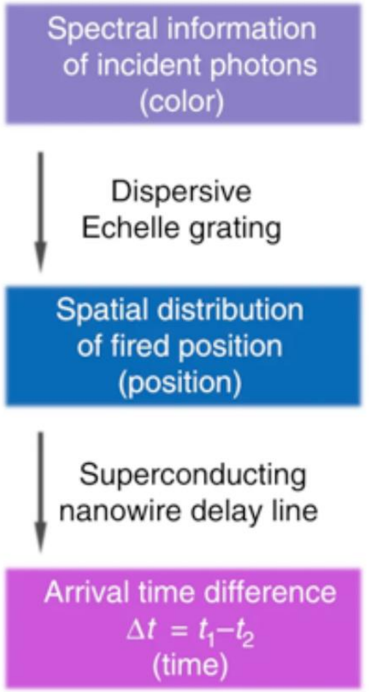
CsPbCl3 nanocrystals

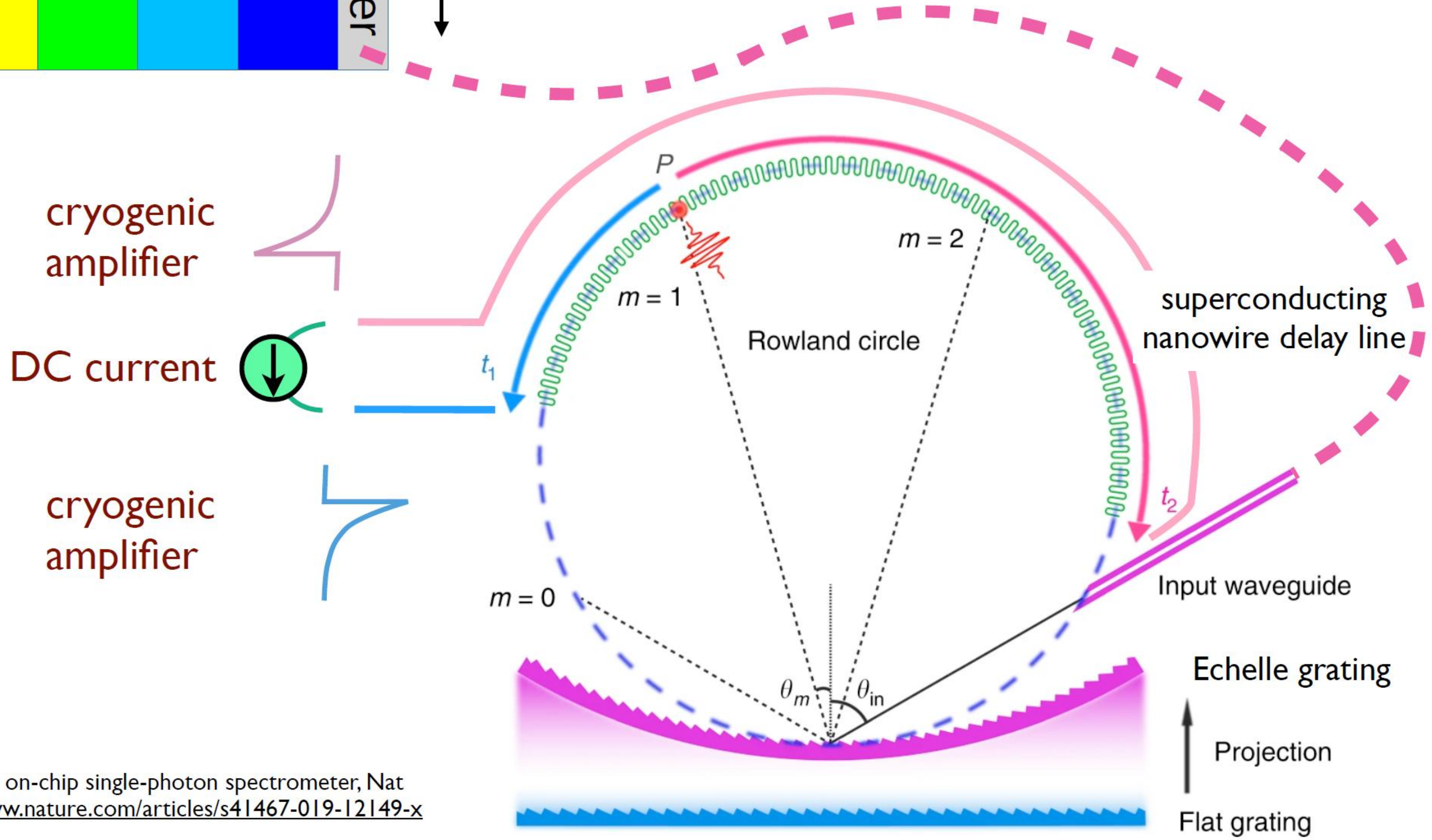
C. Zhang, L. Li, Y. Qi, et al., ACS Energy Lett. 6 (2021) 3545–3554.

M. Doser, CERN



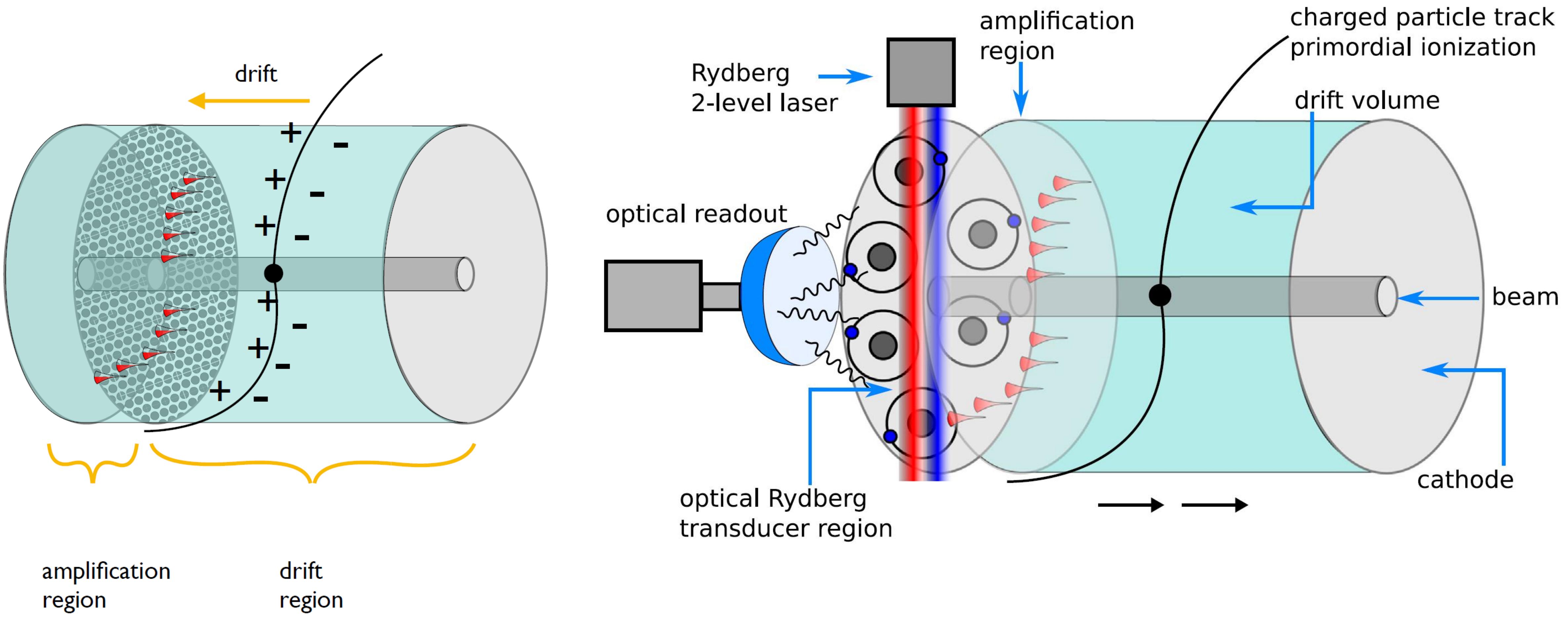
different options for spectrometry:
- monochromators + PD
- light guiding fiber / each layer
- light guiding fiber to spectrometer



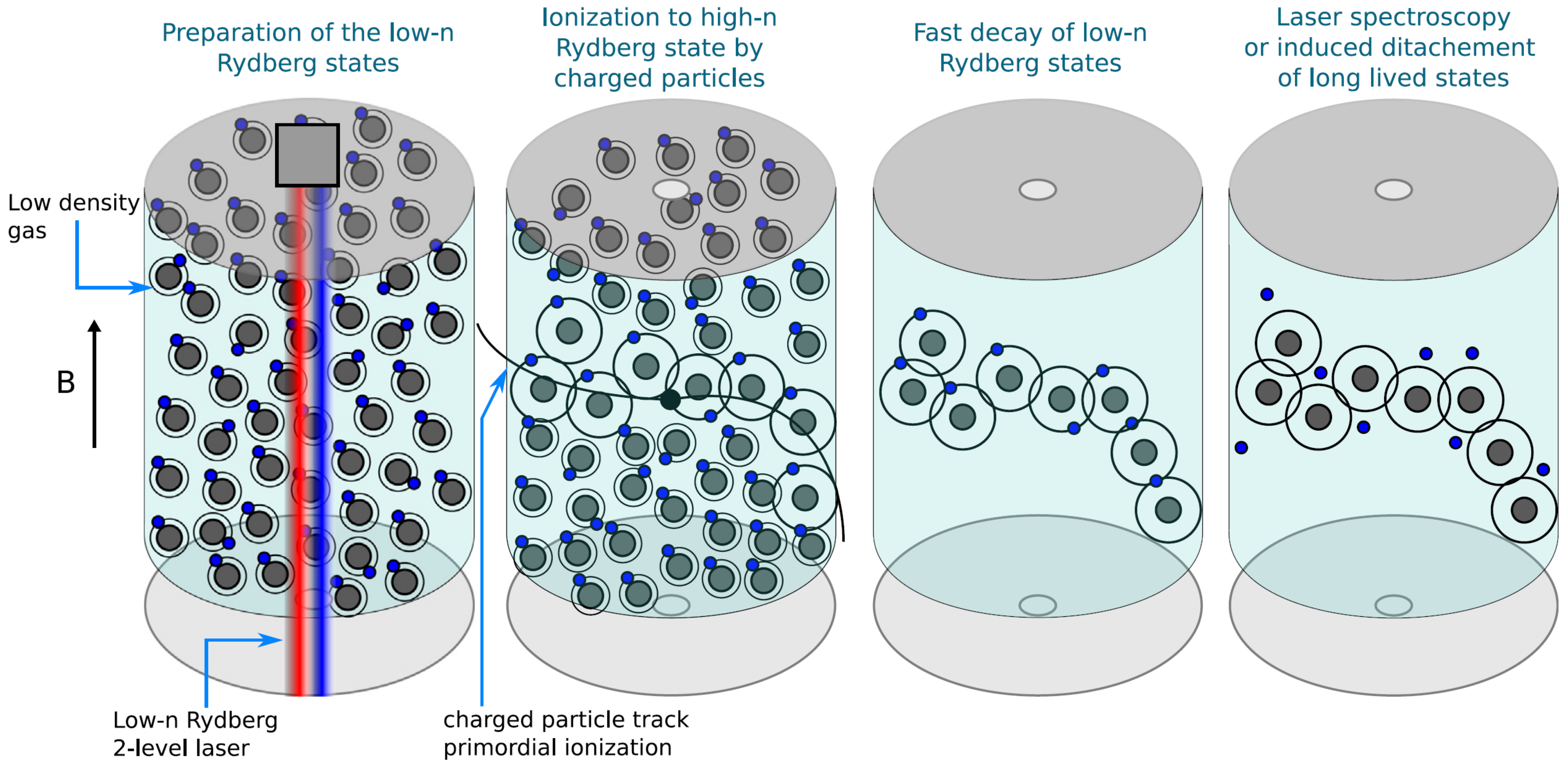


R. Cheng, H. X. Tang, et al., Broadband on-chip single-photon spectrometer, Nat Commun 10 (2019) 4104; https://www.nature.com/articles/s41467-019-12149-x

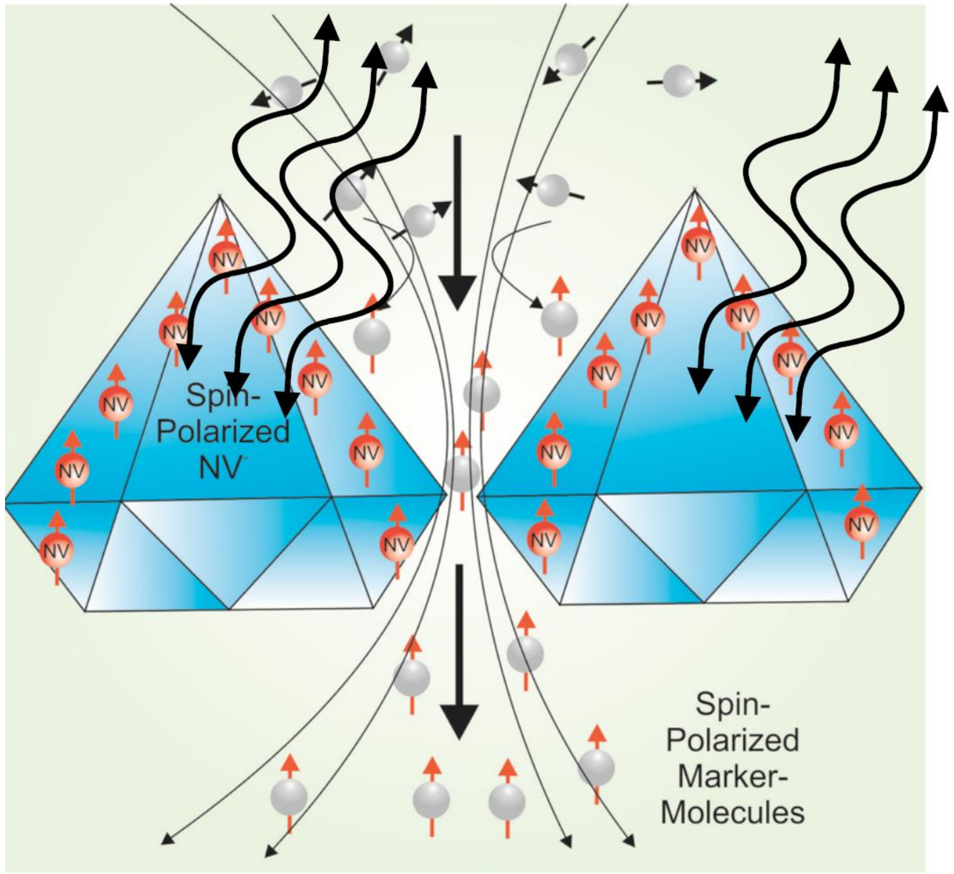
Rydberg-enhanced Time projection Chambers



Rydberg Time projection Chamber



Helicity trackers



© Dr. Christoph Nebel, Fraunhofer IAF

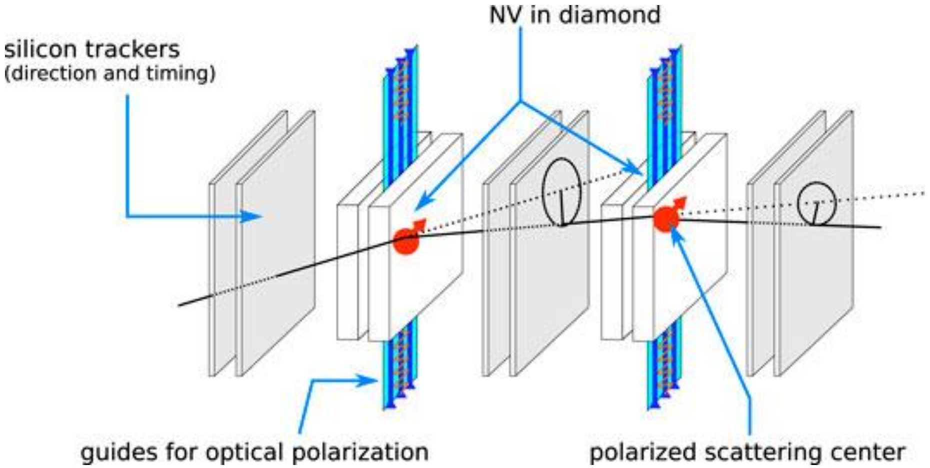
https://www.metaboliqs.eu/en/news-events/MetaboliQs_PM_first_year.html

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

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

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

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



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)

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

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

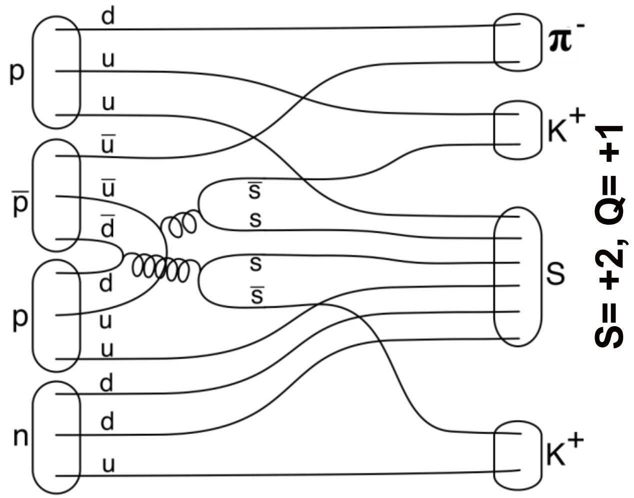
state sexaquark: (u↑u↓d↑d↓s↑s↓) scalar QCD bound

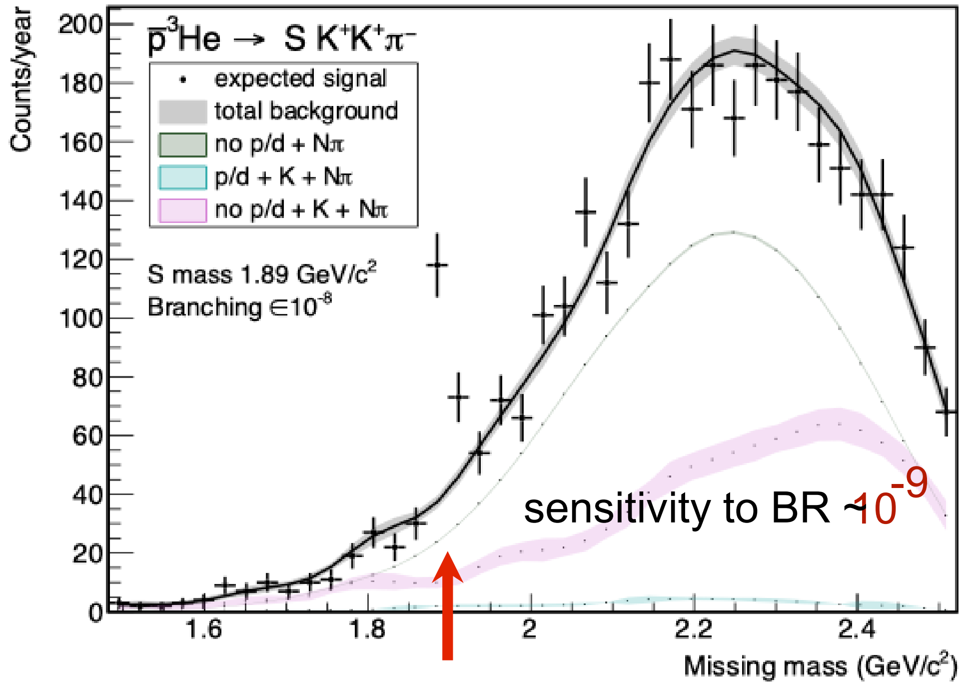
($m \sim 2m_n$, $< 2m_\Lambda$) Glennys Farrar, arxiv:1808.08951v2 (2017)

Tracking detector with good particle ID

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

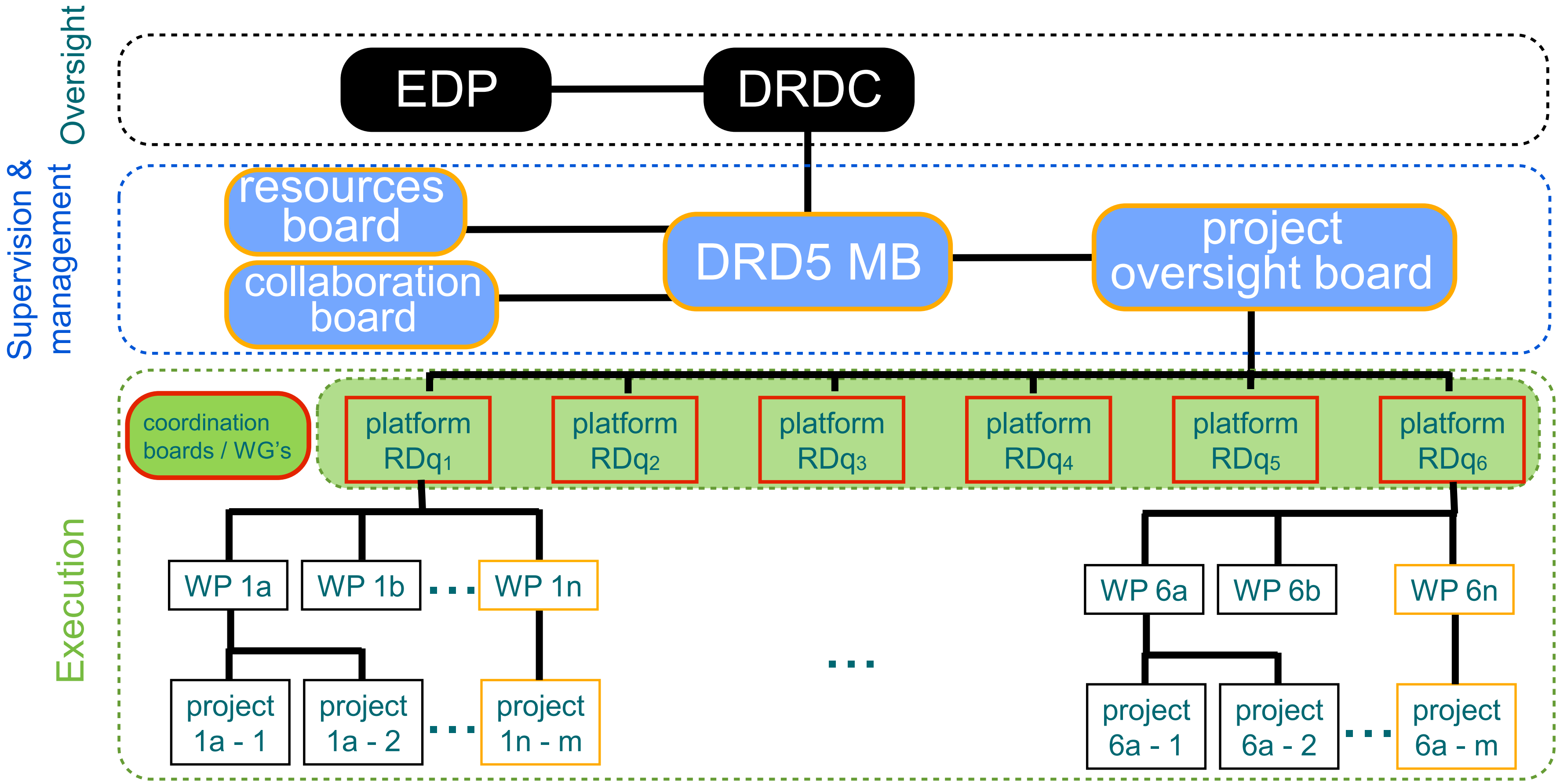
formation reaction:
$(\bar{p}\,^3He)^* \rightarrow S(uuddss) + K^+K^+\pi^-$





DRD5: WP's and structure

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



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

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

(some) HEP applications

WP-2 • Quantum dots (**HEP calorimetry**)

• Superconducting devices (**HEP, astroparticle**)

WP-3
  • Nano- and Microwires
  • TES, MMC (cryo-spectrometry)

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

WP-4 • Spin-based sensors

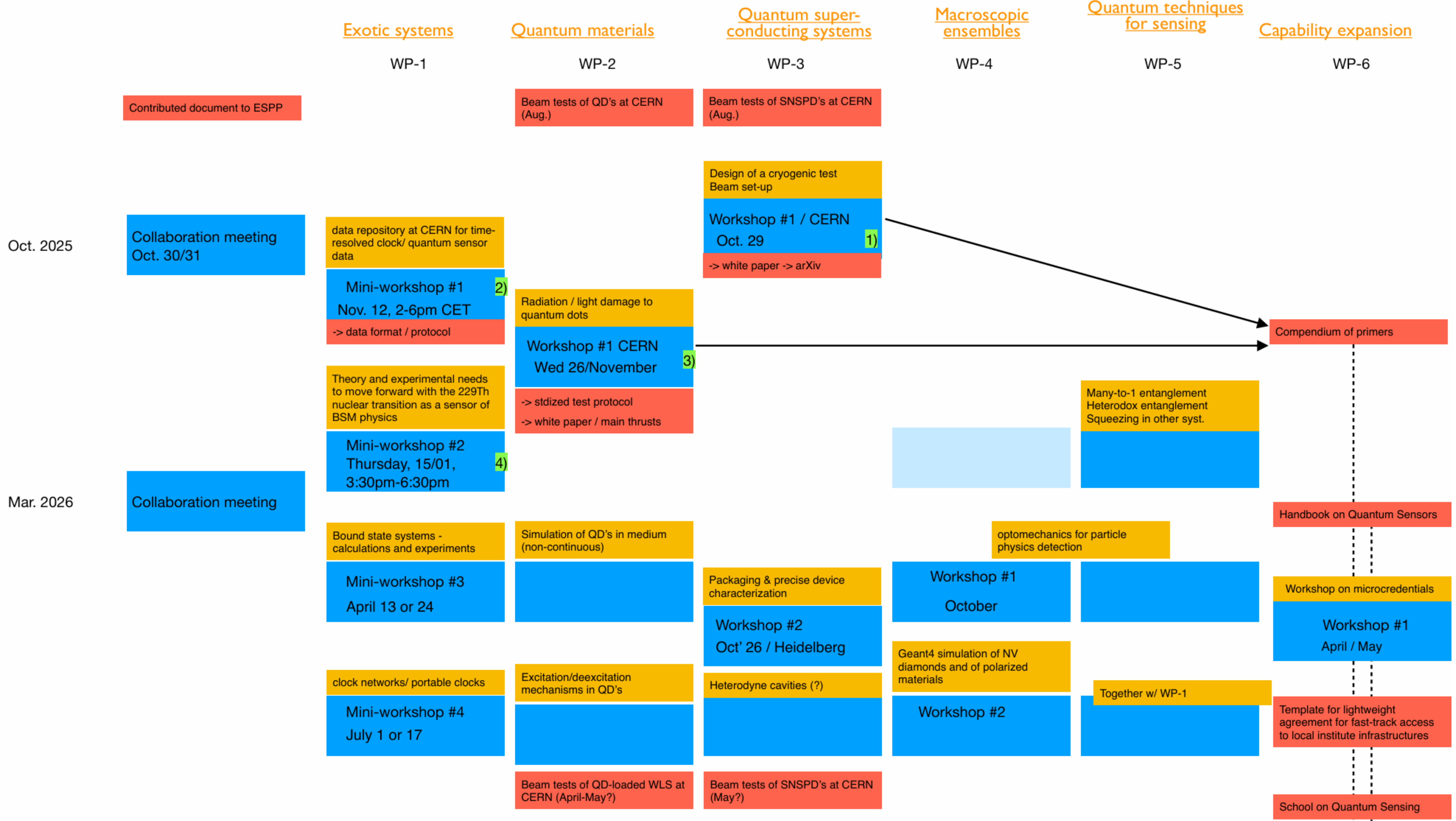
DRD5 : putting together a global collaboration ab initio

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
- …

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**, …)



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

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)

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 ... active ... ators	segmented calorimeter	Suspended / embedded quantum dot scintillators	Ph... dE/dx ... TPC ... qu... C	
WP 3 (Superconducting quantum devices)	t... Luminosity monitor ... scat... sity)	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 ... 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)				

DRD5 WP

Identify at least one potential HEP-relevant project per WP

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., Yale, 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, U Bern

Netherlands: U. of Groningen

Norway: Oslo University

Sweden: Stockholm Uni

Denmark: Aarhus Uni

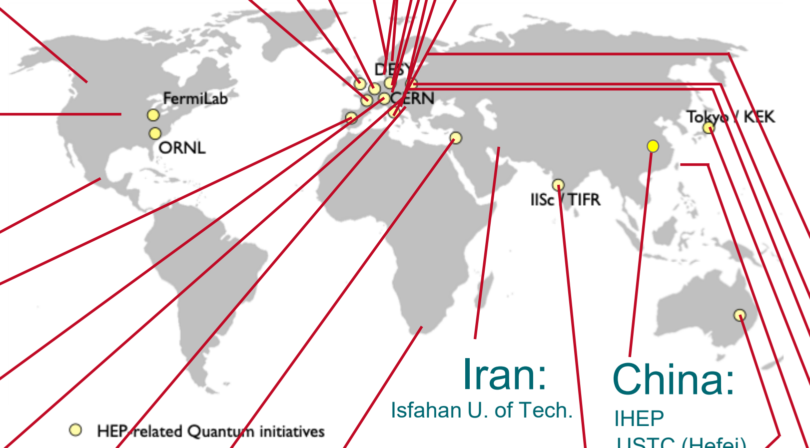
Lithuania:

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

Iran: Isfahan U. of Tech.

China: IHEP, USTC (Hefei)

Austria: IQOQI Vienna, TU Wien

Israel: Technion, Haifa

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

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

Czech Republic: Czech Tech. University, University of West Bohemia

Croatia: Inst. of Physics, Zagreb

South Africa: U. of Cape Town

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

Taiwan: Academia Sinica and NTU

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., Yale, 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, U Bern

Netherlands: U. of Groningen

Norway: Oslo University

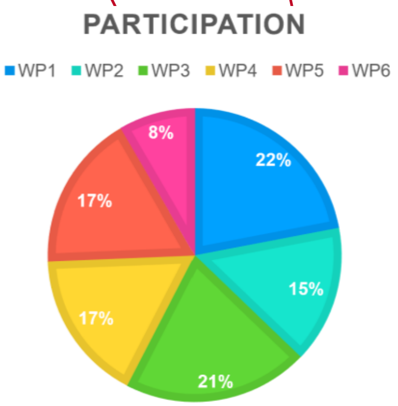
Sweden: Stockholm Uni

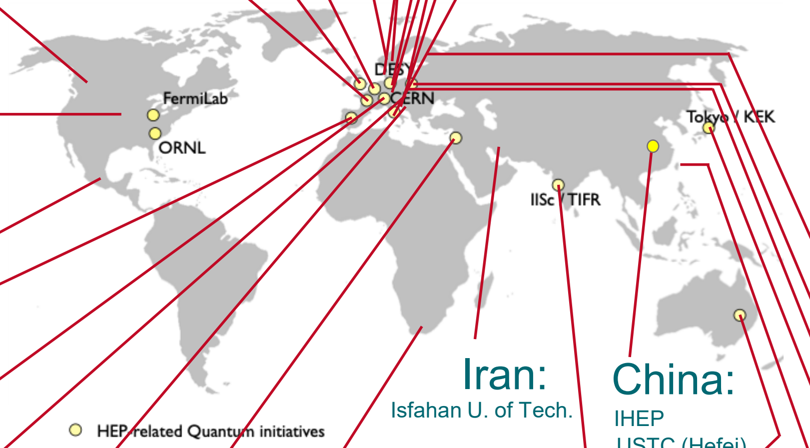
Denmark: Aarhus Uni

Lithuania:

Hungary: Wigner Institute

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





Austria: IQOQI Vienna, TU Wien

Croatia: Inst. of Physics, Zagreb

Israel: Technion, Haifa

South Africa: U. of Cape Town

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

Iran: Isfahan U. of Tech.

China: IHEP, USTC (Hefei)

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

Taiwan: Academia Sinica and 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: Czech Tech. University, University of West Bohemia

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

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 Pa, LKB, ILM - University Lyon 1, IRFU/ CEA Saclay

Canada: McGill Univ., TRIUMF

USA: UCLA, ORNL, Northwestern Univ., Caltech, MIT, Arizona State Univ., Yale, 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, U Bern

Netherlands: U. of Groningen

Norway: Oslo University

Sweden: Stockholm Uni

Denmark: Aarhus Uni

Lithuania:

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Collaboration ramping up, combines diverse communities, including HEP.

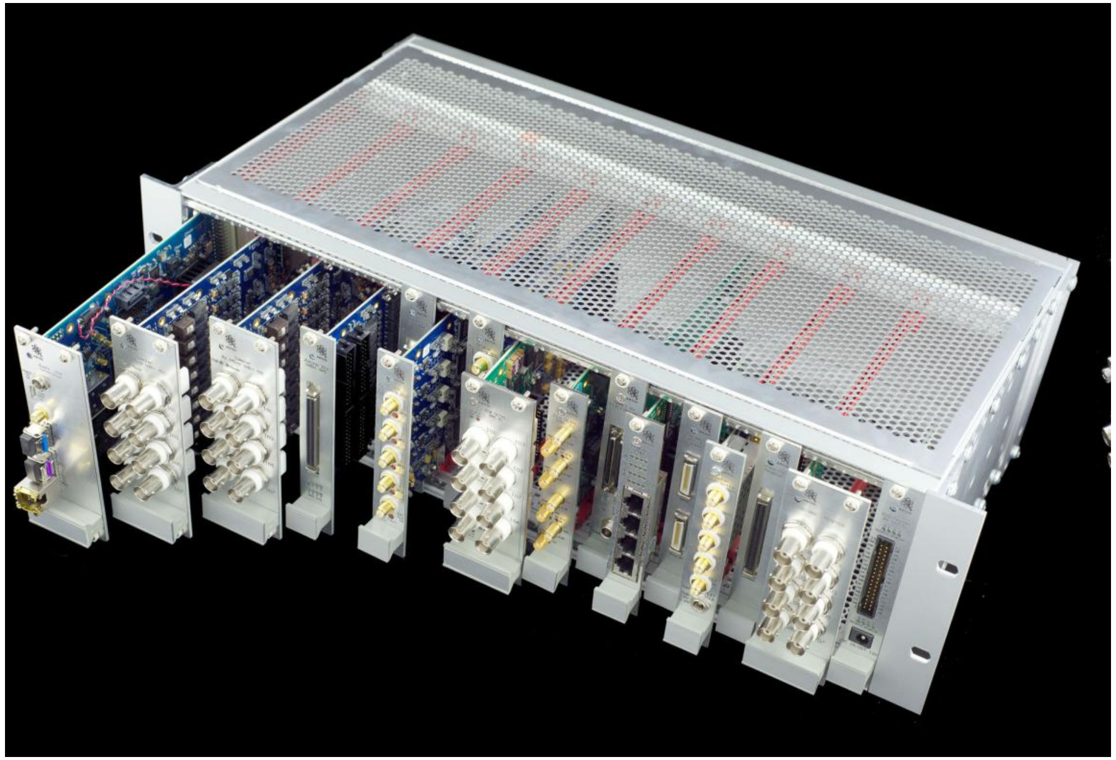
Many novel developments that benefit both quantum technologies and particle physics.

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

Sinara and ARTIQ

Open software and Open hardware for Quantum (and beyond!)

https://github.com/sinara-hw/meta/wiki and https://m-labs.hk/artiq/

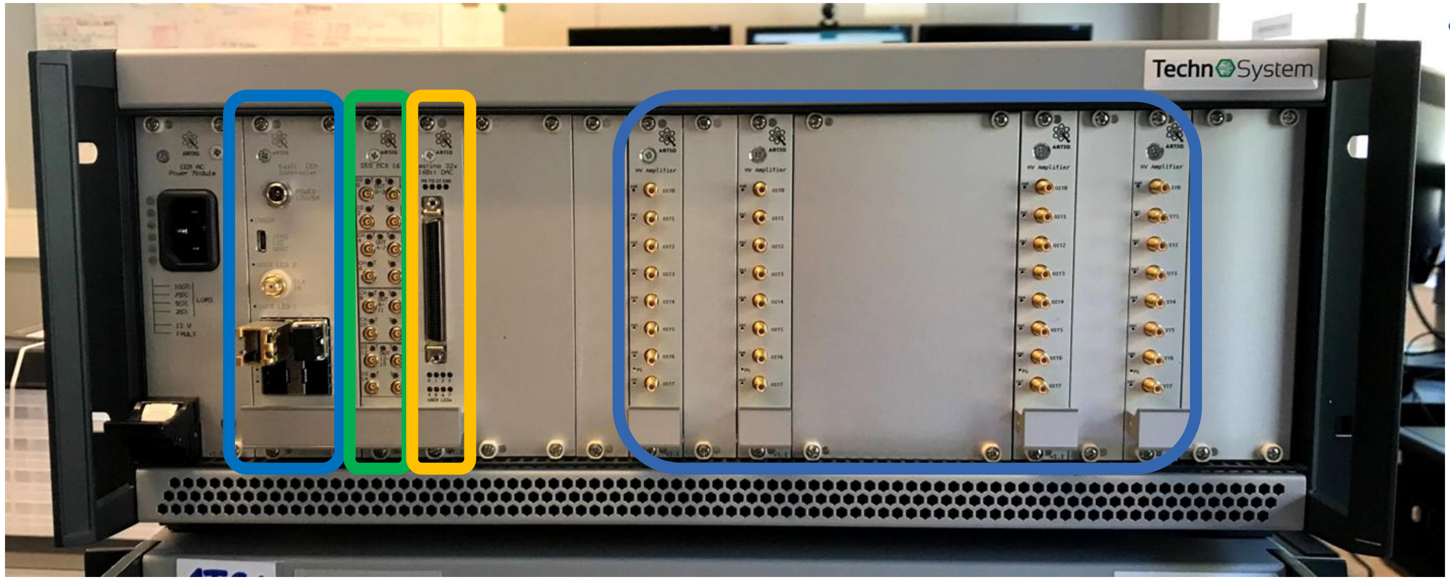


Sinara, an **open-source hardware ecosystem**,

- Designed for quantum experiments
- CERN Open Hardware License,
- over 50 modules (commercially available).
- Integration with the Advanced Real-Time Infrastructure for Quantum physics (ARTIQ) control system.
    - 1 ns timing resolution.
    - management of experiment scheduling,
    - versioning,
    - results storage,
    - and hardware management.

SINARA @ AEgIS

- **Kasli controller**
  - Artix-7 FPGA
  - PSU connector
  - JTAG port
  - External clock input (SMA)
  - 4 SFP ports (DRTIO receiver/distributor, allowing for master/satellite use)
  - Can control up to 12 extension modules

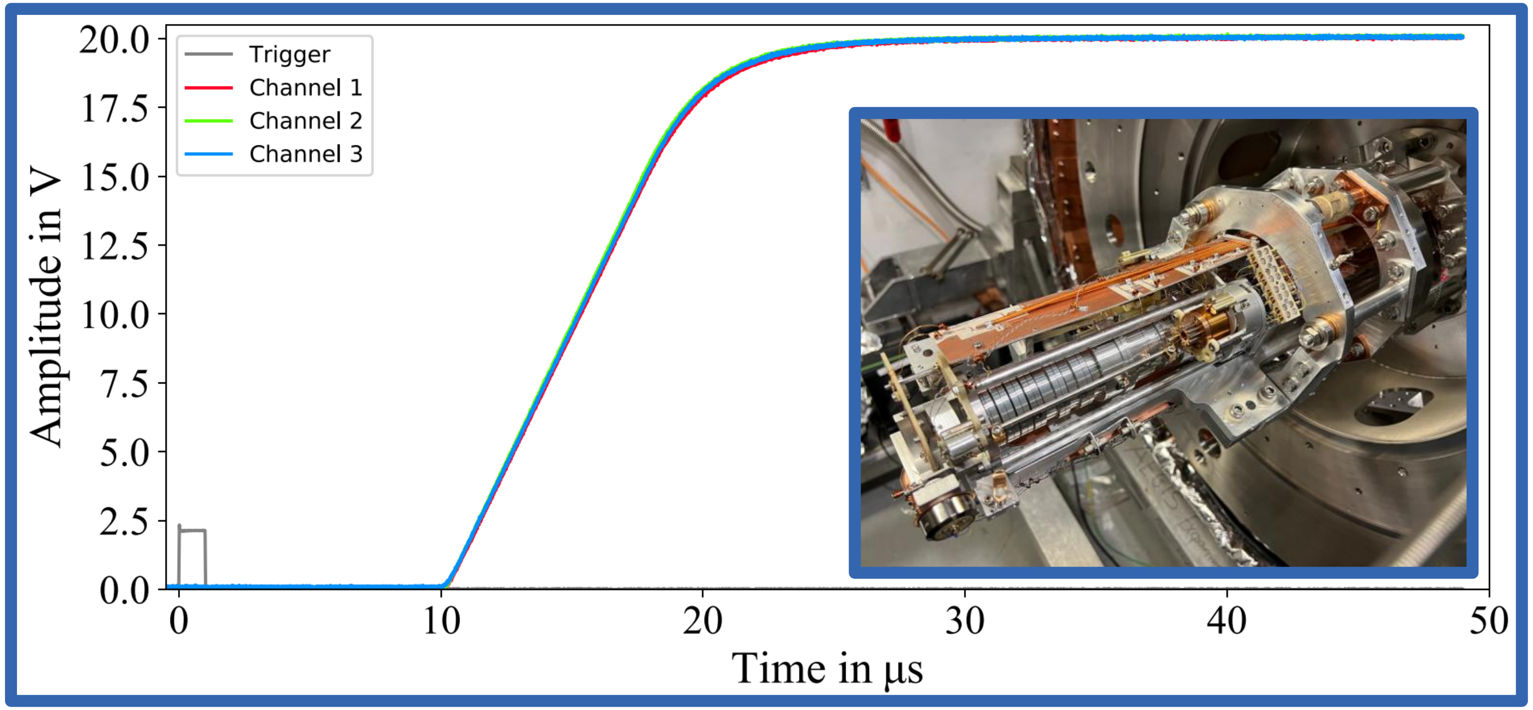


- **Amplifiers**
  - 20-fold amplifictation (± 10 V to ± 200 V)
  - Custom design
  - Individual OptoMOS isolation
  - 8 channels per board (SMC)

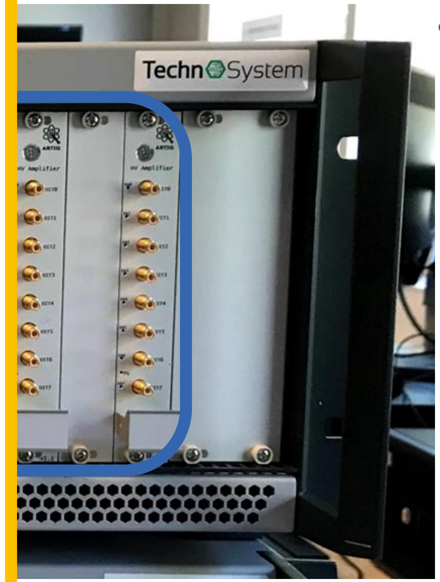
- **DIO units**
  - Individual in/out configuration
  - 16 channels (MCX)

- **Fastino DAC**
  - 16-bit resolution
  - Maximum voltage: ± 10 V
  - 32 channels

SINARA @ AEgIS



Synchronous application of a voltage on 3 electrodes using Fastino + 3 amplifier channels 10 µs after an incoming trigger pulse



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solution

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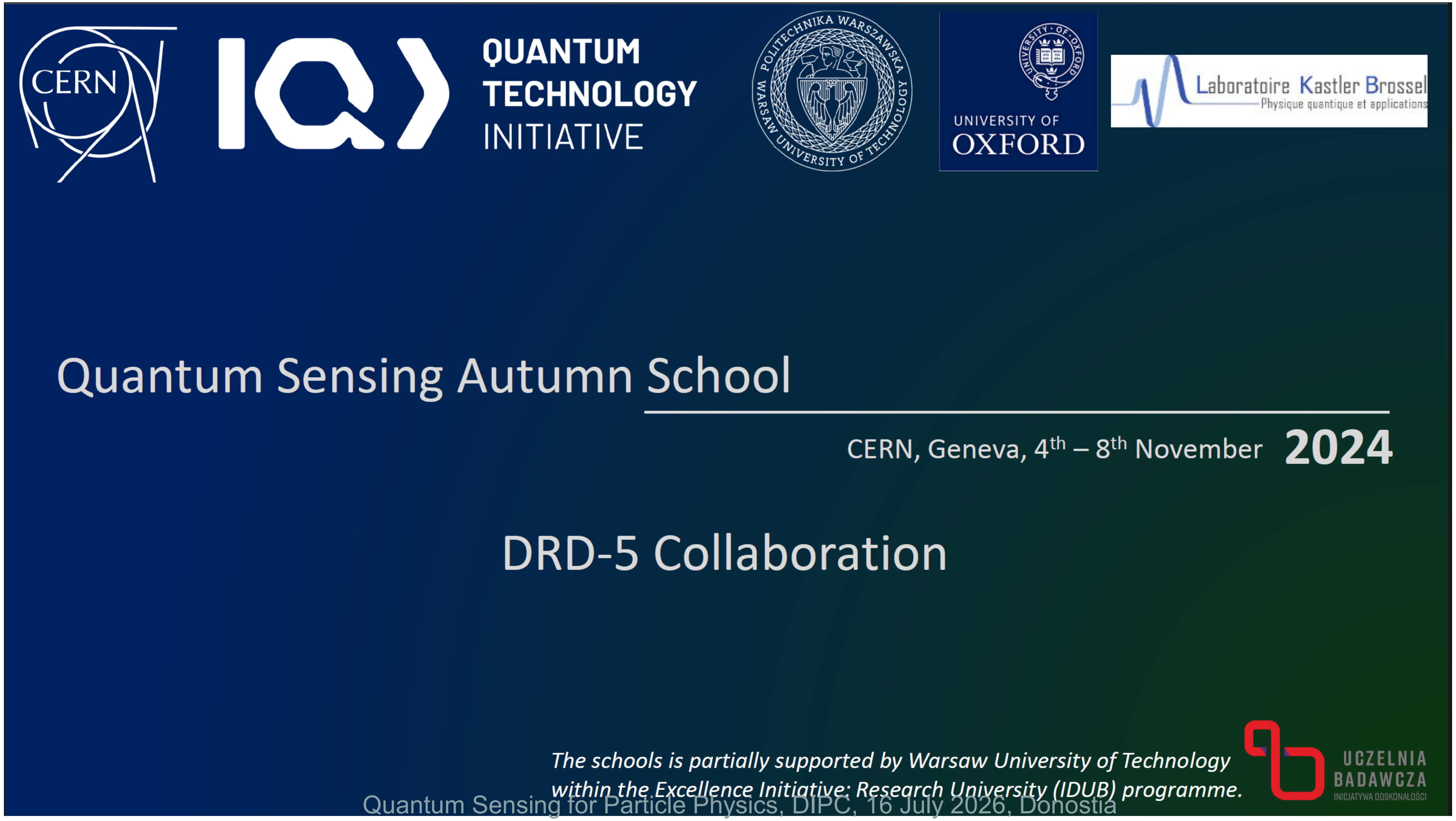
nels

Thank you!

Quantum sensing autumn school @CERN

Pilot school organized by:
Michael Doser (CERN), Stafford Withington (Oxford), Nancy Paul (LKB), and Georgy Kornakov (WUT)



Quantum sensing autumn school @CERN

Speakers and topics

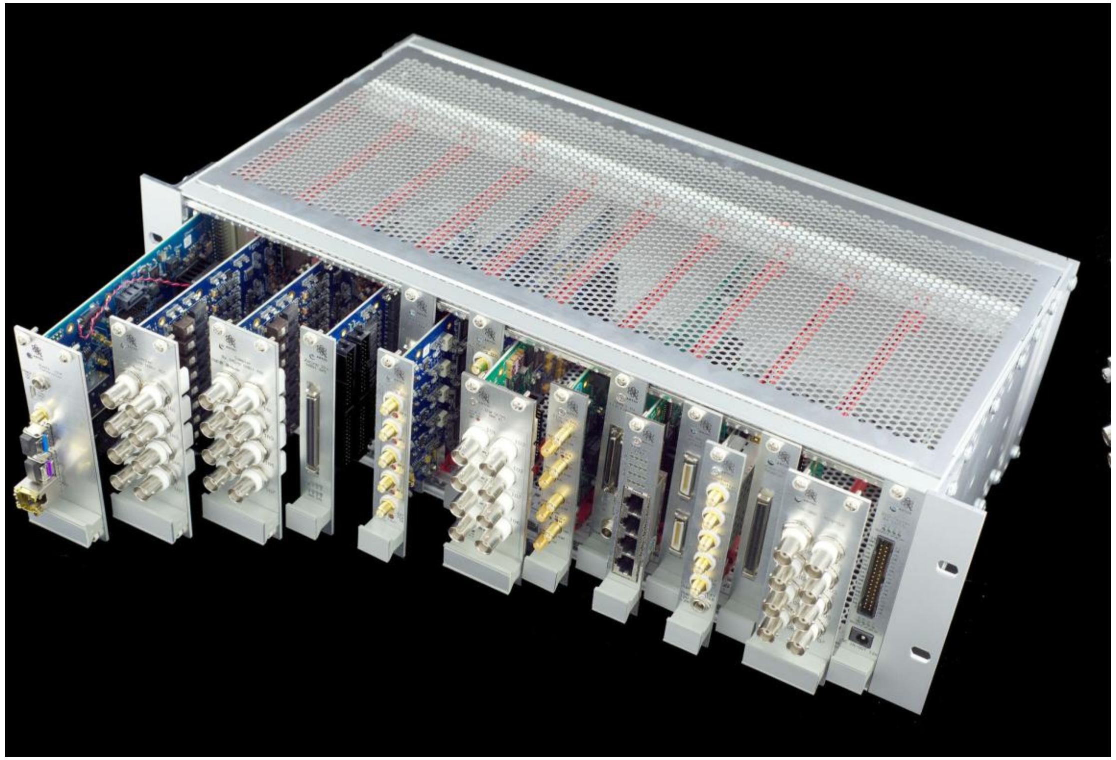
In total, the school has covered 10 topics in the domain of quantum sensors which were distributed in 5 morning sessions (3 hours and 30 minutes each), and 4 evening training sessions (3 hours each).

The topics were the following:

- Quantum Sensing implications for fundamental research (Prof. Marianna Safronova – University of Delaware)
- Atom Interferometry (Prof. John Ellis – Kings College London)
- Superconducting sensors (Prof. Stafford Withington - Oxford)
- Atomic Clocks (Prof. Steven Worm - DESY)
- Spin sensors (Prof. Dmitry Budker – Helmholtz Institute Mains and UC Berkeley)
- Molecules for HEP-related frontier measurements (Marianna Safronova - University of Delaware)
- Microcalorimeters (Prof. Loredana Gastaldo – Heidelberg University)
- Chromatic Calorimetry (Prof. Michael Doser – CERN)
- Quantum limit of measurements (Dr. Jan Kolodynski – IF PAN)
- Josephson parametric amplifier and Traveling Wave Parametric Amplifiers (Prof. Caterina Braggio – University of Padova and INFN)

Sinara

https://github.com/sinara-hw/meta/wiki and https://m-labs.hk/artiq/



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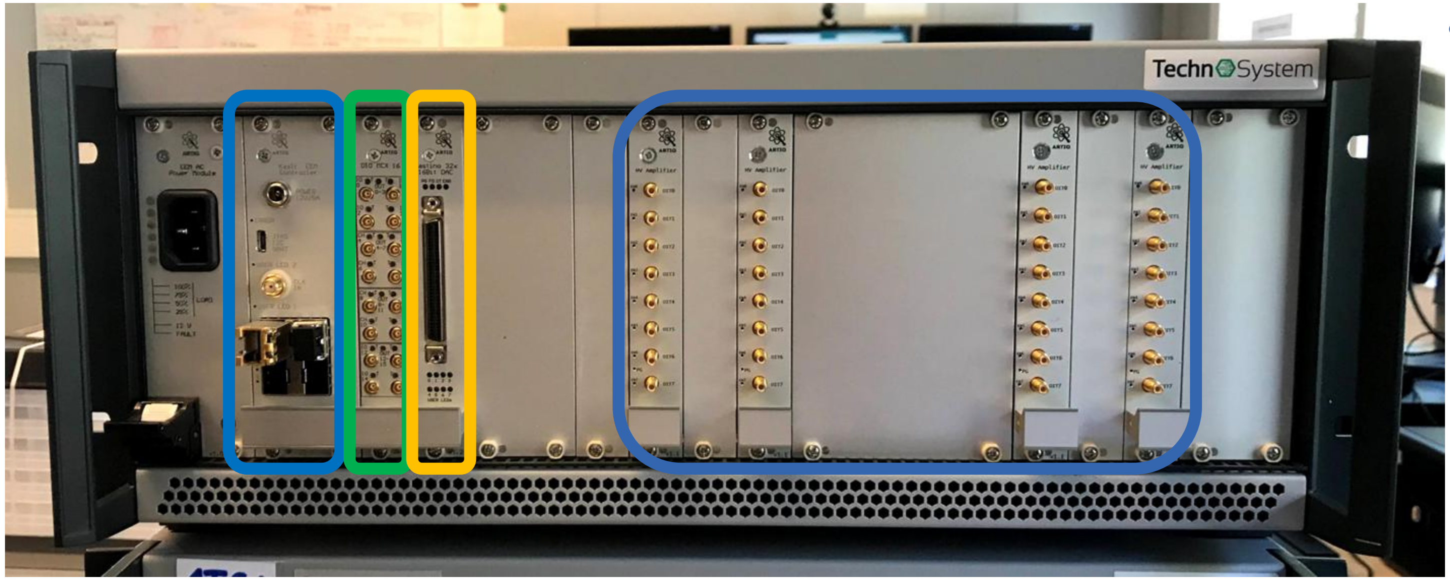

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Proposal for DRD5: R&D on quantum sensors

ECFA Roadmap topics → Proposal themes → Proposal WP's

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

Roadmap topics

Proposal WP's

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

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