DRD5:

A global initiative on R&D on quantum sensors and emerging technologies for particle physics*

Marcel Demarteau, Michael Doser (and *many* contributors)

with a special thanks to the UK community in general and Ian Shipsey in particular

* low energy *and* high energy particle physics

Goals of DRD5:

Among the *very* many areas and technologies being worked on worldwide,

- Identify key quantum/emerging technologies (within the ECFA roadmap) (*where is collaboration relevant?*)

- Within these, identify key topics which would most benefit the corresponding communities but that are not being addressed because they go beyond what individual groups can tackle (*where is collaboration useful?*)

- On these topics, identify groups that are willing to participate in a global collaborative effort (*where is collaboration welcome?*)

Challenge 1: non-HEP communities, need to establish trust, mutual interest, benefits

Challenge 2: need to grow a corresponding community (unlike other DRD's)

Timeline:

2021-2022: ECFA roadmap (*top-down*)

- Identify key quantum/emerging technologies

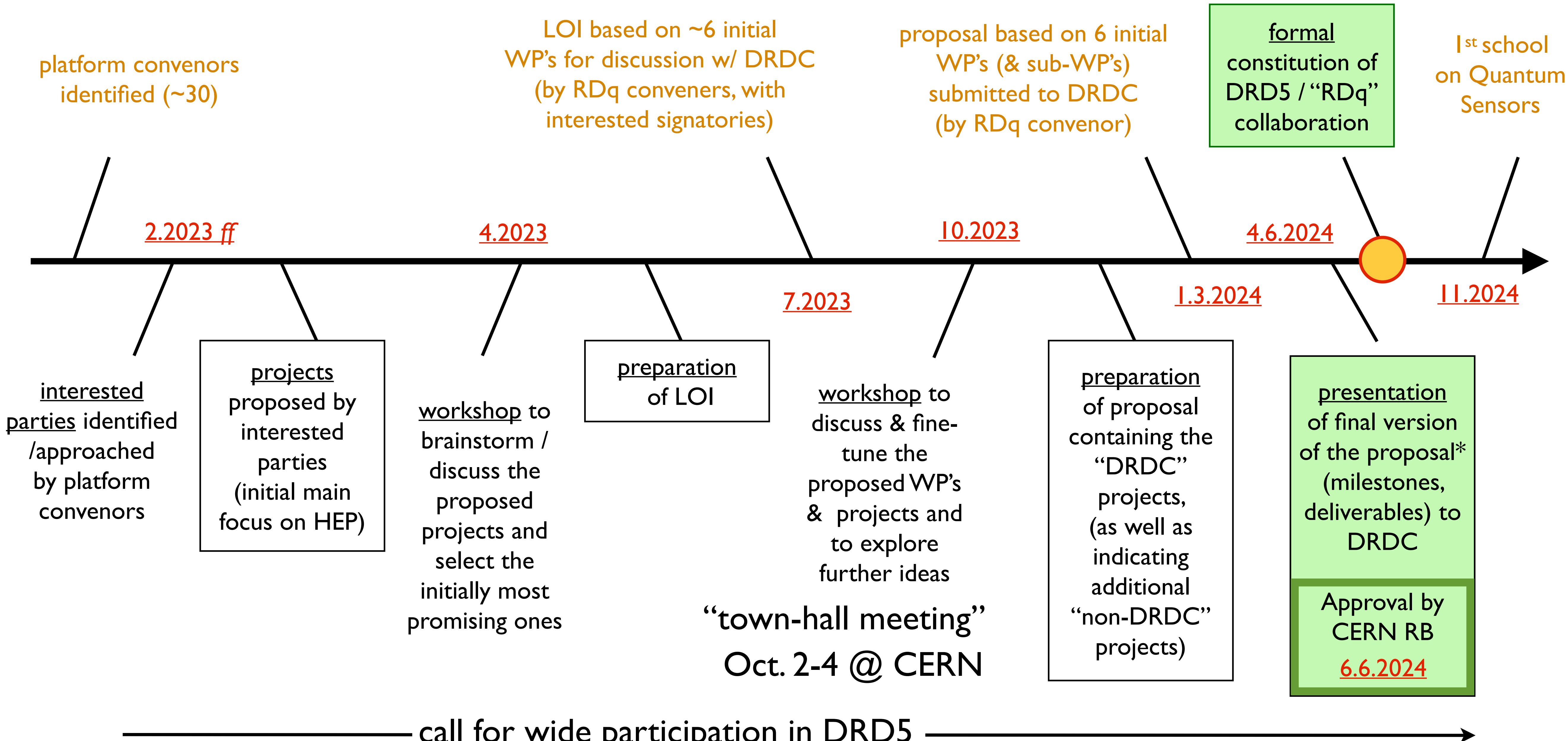
2023: transform roadmap into proposal (*bottom-up*)

- Identify key figures in the communities ➔ ~30 contributors
- Workshop to identify relevant WP-able groupings (April)
- proto-proposal (September)
- public workshop to fine-tune *WP*'s, *milestones*, *deliverables* (October)
- final proposal formulated and circulated (January '24)
- call for participation (*ongoing*)
- in parallel, constant communication & community building

timeline

Two goals for DRD5 (Detector R&D on Quantum Sensors) in 2023/2024 :

- preparation of a proposal (LoI, White Paper) for detector R&D
- formation of a global collaboration (Europe, Americas, Asia)



* https://cds.cern.ch/record/2901426

Roadmap topics ⟶ Proposal themes ⟶ Proposal WP's

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

WP ⟶ sub-WP ⟶ sub-sub-WP

WP-1 ATOMIC, NUCLEAR AND MOLECULAR SYSTEMS IN TRAPS & BEAMS
- WP-1a Exotic systems in traps and beams
  - WP-1aa: Extension and improved manipulation of exotic systems
  - WP-1ab: Bound state calculations
  - WP-1ac: Global analysis in the presence of new physics
- WP-1b Interferometry
- WP-1c Networks, signal and clock distribution
  - WP-1ca: Large-scale clock network
  - WP-1c b: Portable references and sources

WP-2 QUANTUM MATERIALS (0-, 1- and 2-D materials)
- WP-2a Application-specific tailoring
- WP-2b: Extended functionalities
- WP-2c: Simulations

WP-3 CRYOGENIC MATERIALS, DEVICES AND SYSTEMS
- WP-3a: The 4K stage
- WP-3b: Cryogenic quantum sensors for particle and photon detection
- WP 3c: Resilient integration of superconducting systems

WP-4 DEVELOPMENT OF LARGE ENSEMBLES OF QUANTUM SYSTEMS
- WP-3a Multi-modal devices (e.g. Opto-mechanical systems, transduction)
- WP-3b Quantum-system-inspired parallel readout

WP-4 SCALING UP “QUANTUM”
- WP-4a Massive spin polarized ensembles
- WP-4b Hybrid devices
- WP-4c: Opto-mechanical sensors

WP-5 QUANTUM TECHNIQUES FOR SENSING
- WP-5a Squeezing
- WP-5b Back action evasion
- WP-5c Entanglement
- WP-5d Optimization of physics reach

WP-6 CAPACITY BUILDING
- WP-6a Education platforms
- WP-6b Exchange platforms
- WP-6c Shared infrastructures

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

community building

WP1: Atomic, ionic, nuclear and molecular systems and nanoparticles in traps and beams

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)

Visions:

Widely expanded set of systems, widely expanded set of tools to form, manipulate and study them (atoms, molecules, ions, trapped nanoparticles; improved production, trapping and cooling techniques)

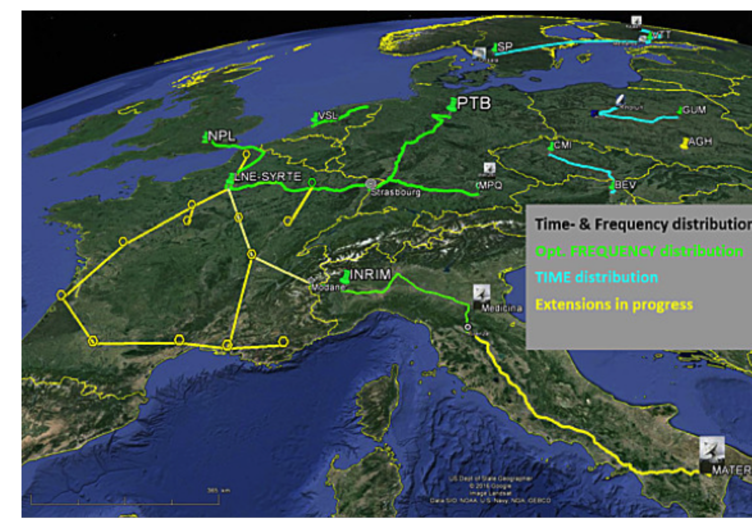
Match (future) experimental precision with improved precision in theory for simple 2 or 3 body systems, allowing testing QED, BSM, nuclear properties, fundamental symmetries, in all possible bound systems.

A birds-eye view on the landscape of well-motivated new physics scenarios and their effects on different measurements.

At least one km-scale detector operational by 2035, and preparation for a space-based atom-interferometry mission

Several orders of magnitude gain in sensitivity by:

- Increasing the source flux of ultra-cold Rb and Sr atoms
- Advance on large momentum transfer techniques
- High repetition rate set-ups
- Deployment of entangled atoms



Global network of high-stability and high-accuracy clocks: time-stamping to O(10ps) and distribution of a highly precise continuous clock signals as multiple references

Design and fabrication of standardized portable references (neutrals and charged); robust portable trapping systems.

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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)

WP-1a (exotic systems)

WP1a_a (exotic systems) → Trap advances (*Workshop*) → Extended nb of systems (*White paper*) → Cooling (all systems) (*Technology demonstrator*)

WP1a_b (calculations) → Improved bound state QED and nuclear structure theory calculations (*Continuous improvements (published)*)

WP1a_c (global analysis) → initial study → study report (*Publication(s)*) → updated study

WP-1b (interferometry)

WP1b_a (TVLBAI) → community building (*Proto-collaboration formation*) → instrumentation study (*White paper*) → atom flux study (*R&D roadmap*)

WP1b_b (high precision) → optics & high flux study (*Improved flux & probe time*) → high rate operation (*Squeezing & rate demo*)

WP-1c (clocks & networks)

WP1c_a (clock networks) → institute connection study (*Design report*) → hardware test (*Network testbed*) → cross-border link (*Technology demonstrator*)

WP1c_b (portable clocks) → define targets (*Parameters paper*) → tech design study (*Specifications*) → evaluate & recommend (*Prototype selection*)

WP2: Quantum materials (0-, 1- and 2-D materials)

(Building blocks: complex nanoscale "quantum materials")

WP-2a: Application-specific tailoring

WP-2b: Extended functionalities

WP-2c: Simulations

Visions:

WP-2a

Exploring the landscape of possible building blocks of the low dimensional devices:

Quantum dots, nanocrystals, nano-platelets

Nanowires (also WP-3)

Mono-layers, surface deposition, surface treatments (thin films, also of superconductors)

Optimized engineering for specific applications (e.g. scintillators)

Radiation hardness

WP-2b

Geometries, chemical composition, internal layout, environment: all play a role in shaping the properties of individual elements;

Extensive overview of what the design landscape enables on one hand, and what detector design benefits from.

Engineering of the building blocks of arbitrary nanocomposite material

WP-2c

Simulation packages need to go beyond the assumption of continuous media (G4) and incorporate processes at the local molecular scale;

Full understanding of performance requires accounting for interactions between the building blocks and their environment.

WP3: Cryogenic materials, devices and systems

WP-3a: The 4K stage

WP-3b: Cryogenic quantum sensors for particle and photon detection

WP 3c: Resilient integration of superconducting systems

Visions:

Optimized, standardized and robust electronics for superconducting devices with minimal degradation of performance (ultra-low-noise amplifiers, arrayable high dynamic range amplifiers, integrated system building blocks, multiplexing for mega-pixel devices)

Goal: <u>Library of validated modules</u>

Improved devices for photon and massive particle detection; improved modeling of charged-particle impact on full devices

Fabrication of large arrays of such devices beyond the existing photon sensors

Investigation of role of high-Tc superconductors for HEP applications

(There is also a need for a forest of high-resolution calibration lines between 50 keV and 300 keV)

Optimized, standardized and robust packaging approaches; shielding against stray light, EMI, magnetic fields, operation in harsh environments; optimal thermal design

WP4: Scaling up quantum ("Bulkification")

WP-4a: Massive spin polarized ensembles

WP-4b: Hybrid devices

WP-4b a: Scintillators

WP 4b b: Ensembles of heterostructures

WP-4b c: Heterodox devices

WP-4c: Opto-Mechanical Sensors

Visions:

Go beyond building blocks

Large ensembles of spin-polarized samples:

- Levitated ferromagnetic torque sensors
- Molecules with radio-isotopes (for EDM searches)
- High-spin-polarization "targets" and "scattering planes" for HEP
- High-spin-polarization ensembles for spin-dependent interactions

Goal: <u>Optimization</u> of polarization

HEP (Scintillators): full optimization of the complete chain: not just of the quantum dots but also of surface treatments, novel types of scintillators (e.g. quantum wells in semiconductors), embedding materials and photon detection

Composite structure engineered for optimal performance and potentially combining different dimensionalities or compositions or geometries (work-function engineering, fine-tuning of charge transport in gaseous detectors, …)

Novel devices that use individual quantum elements to engineer new types of behavior, e.g. QCL coupled to silicon strip detectors.

Bulk systems of quantum-behavior exhibiting individual elements: levitated nanospheres, levitated torque sensors, arrays of cantilevered detectors, superfluid He sensors whose detection modality (mechanical) is different from the readout modality (optical)

Goal: <u>Optimization</u> of sensors & interconnects

WP5: Quantum techniques for sensing

WP-5a: Squeezing	WP-5b: Back action evasion	WP-5c: Entanglement	WP-5d: Optimization of physics reach

Visions:

WP-5a

Beyond gravitational wave detection:

- opto-mechanical resonators
- Atom interferometers

Need: versatile and scalable sources of squeezed light

Applicability to particle physics?

WP-5b

Extraction of information without modifying the observed system:

Develop a theoretical framework for implementation in experiments beyond gravitational wave experiments

Perform proof-of-principle experiments as validation

WP-5c

Beyond two-sensor entanglement:

- scaling up to networks of sensors
- distribution of entanglement over networks

Relevance to HEP?

WP-5d

How far can one go?

WP6: Capacity building

WP-6a: Education platforms

Quantum Sensing and Technology Schools

Education based on micro-credentials

WP-6b: Exchange platforms

WP-6c: Shared infrastructures

Visions:

Growing a workforce of quantum technology savvy individuals, both for research and for society

Sharing and exchange of expertise and of research questions / opportunities

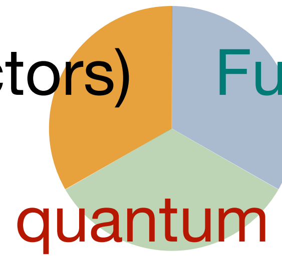
Sharing of infrastructures (test beams, dilution refrigerators, fab labs, …) via agreed-upon standardized protocols

Cross-WP synergies

work package	WP1	WP2	WP3	WP4	WP5	WP6
WP 1 (Quantum systems in traps and beams)	-					
WP 2 (Quantum materials: 0-, 1- and 2-D)	(X)	-				
WP 3 (Superconducting quantum devices)	(X)	(X)	-			
WP 4 (Scaled-up bulk systems for mip's)		X	X	-		
WP 5 (Quantum techniques)	X	(X)	X	(X)	-	
WP 6 (Capacity building)	X	X	X	X	X	-

WP cross-influences and impacts

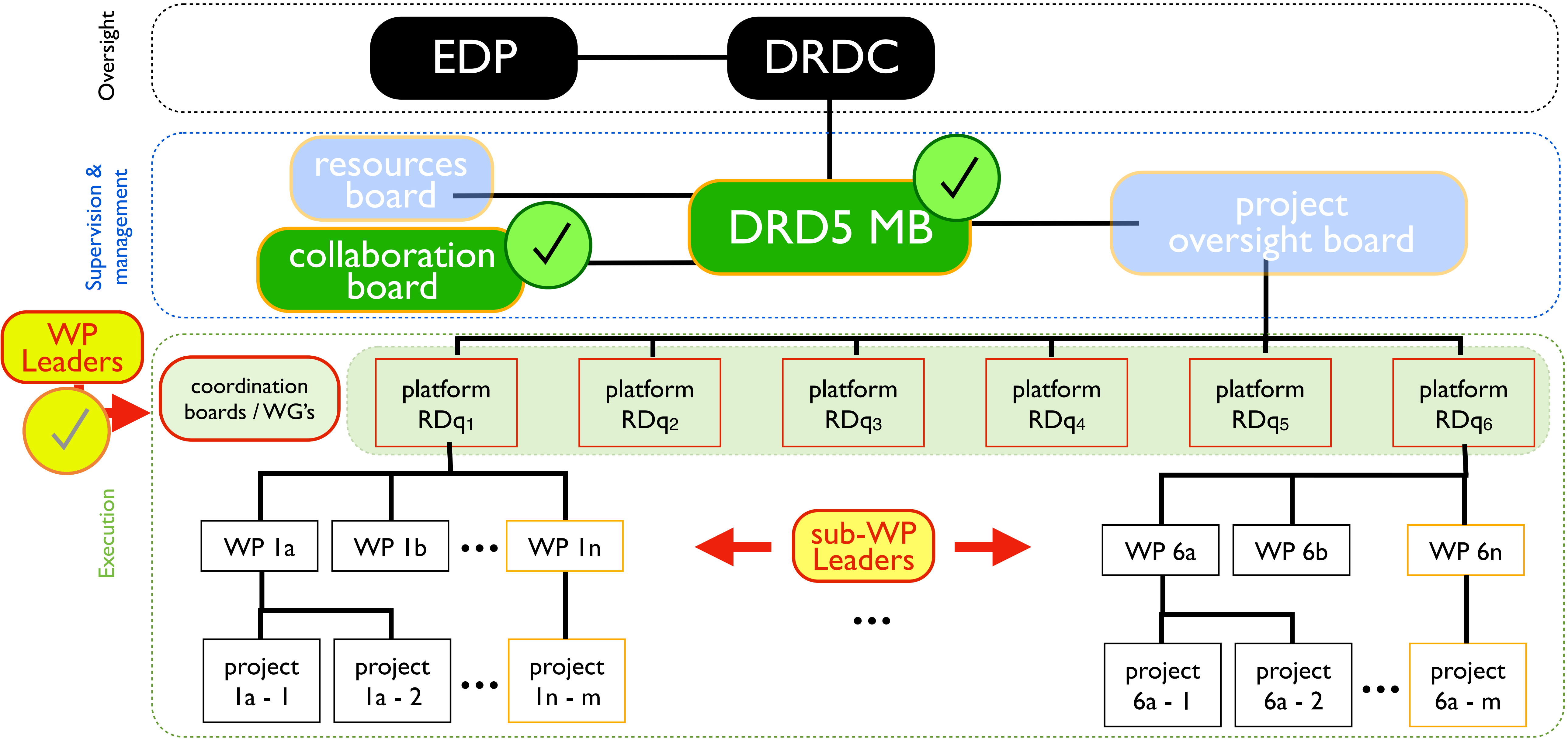
Potential HEP impact



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 (Roman pot)	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)				

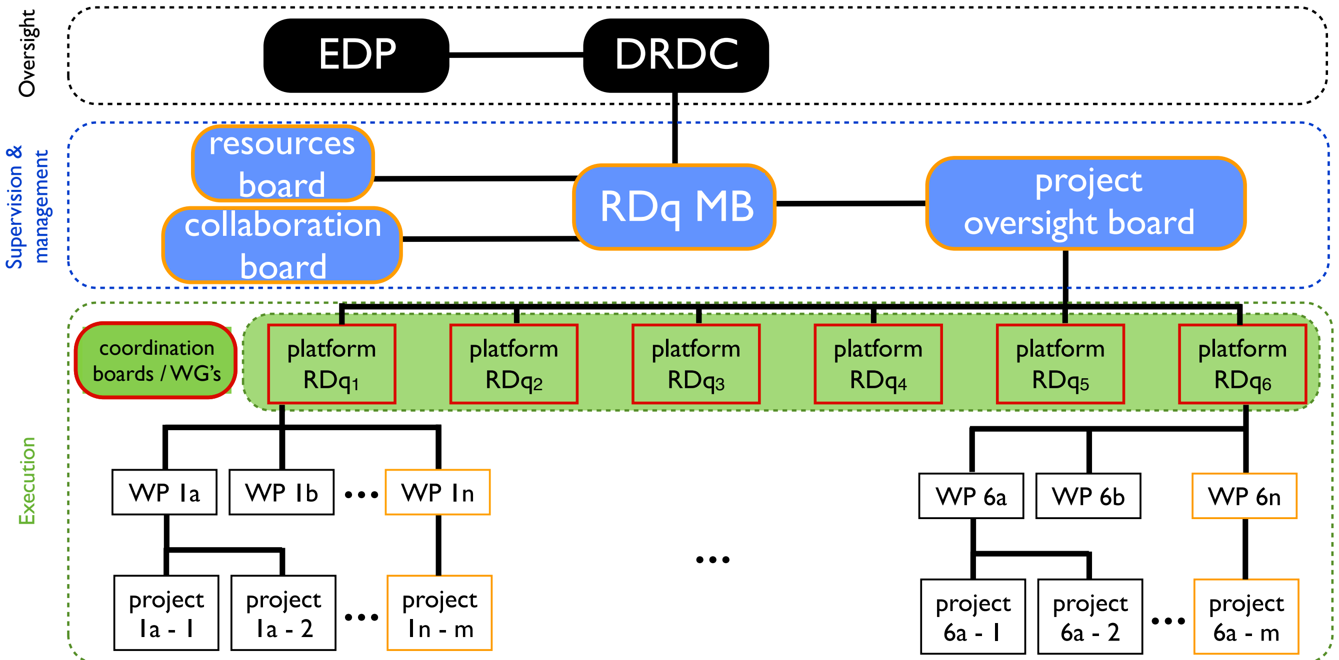
(under way; in preparation; under discussion or imaginable applications; long-range potential)

DRD5: WP's and structure



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

Structure of DRD5:



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

WP leaders

WP1		
WP2		
WP3		Stafford Withington (UK)
WP4		Hendrik Ulbricht (UK)
WP5		
WP6		

Membership is free (no common fund contributions)! (Only for academics! industry?)

Simple membership access (via request to CB) / leave (inform CB) process;

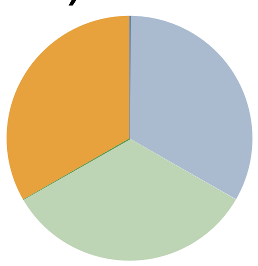
MB, POB, WG: by election through CB (1 institute = 1 vote) (Attention to balance!)

MB = spokesperson + deputy + CB, RB and POB chairs

Total number of institutes (as of 3.6.2024): 96

Total number of participants (as of 3.6.2024): 344 (= 100 FTE, assuming 30% scaling)

	FTE	Total number of institutes
WP 1	21	45
WP 2	16	26
WP 3	18	40
WP 4	19	35
WP 5	18	42
WP 6	9	18



Widespread (geographically and community-wise) interest & participation

DRD5: 100 involved groups

(and another 10 in discussions)

Contact: Stafford Withington

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

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

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

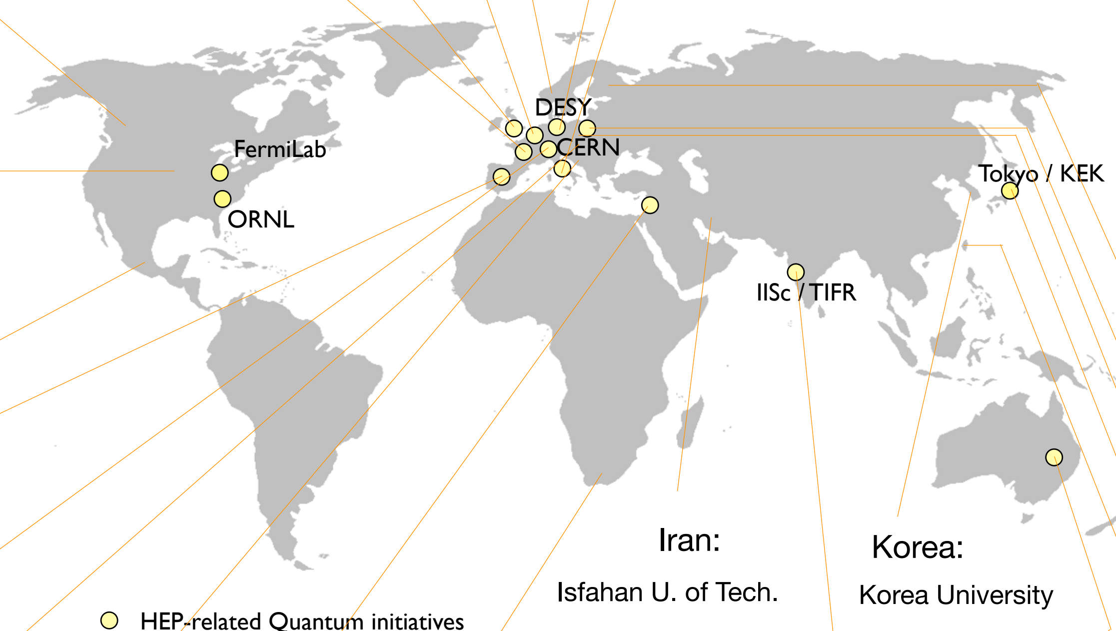
Mexico: U. de Aguascalientes

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

Switzerland: U. of Geneva, U. of Zürich, CERN, ETHZ

Netherlands: U. of Groningen

Norway: Oslo University



Austria: IQOQI Vienna

Croatia: Inst. of Physics, Zagreb

Israel: Technion, Haifa

South Africa: U. of Cape Town

Iran: Isfahan U. of Tech.

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

Korea: Korea University

Australia: University of Western Australia, Swinburne University of Technology

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: Czech Tech. University, University West Bohemia

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

CERN involvement: quantum initiative

(2021-2023)

focus on technology

QUANTUM TECHNOLOGY INITIATIVE

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

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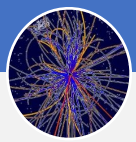


- Assess the **areas of potential quantum advantage** in HEP applications (QML, classification, anomaly detection, tracking)
- Develop **common libraries of algorithms, methods, tools**; benchmark as technology evolves
- Collaborate to the development of shared, **hybrid classic-quantum infrastructures**

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

- Quantum dots
- Graphene
- AMO control systems for HEP

Sensing, Metrology & Materials

currently: 3 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

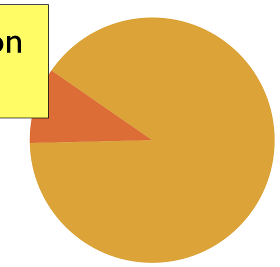
(2024-2028)

CERN involvement: quantum initiative v2

focus on technology

QUANTUM TECHNOLOGY INITIATIVE

CERN contribution to DRD5



DRD5 WP's

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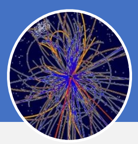
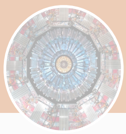


- Objective 2.1a: Exotic atoms as qubits and Dark Matter sensors (Rydberg states characterisation, spectroscopy; atom interferometry; entangled Rydberg states as quantum demonstrators for qubits)
- Objective 2.2a: RF cavities and coating for axion searches; designing, building and operating a tuneable 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

DRD5: 100 involved groups

(and another 10 in discussions)

Collaboration currently being ramped up, combines diverse communities, *including* (but not mainly) 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

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

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

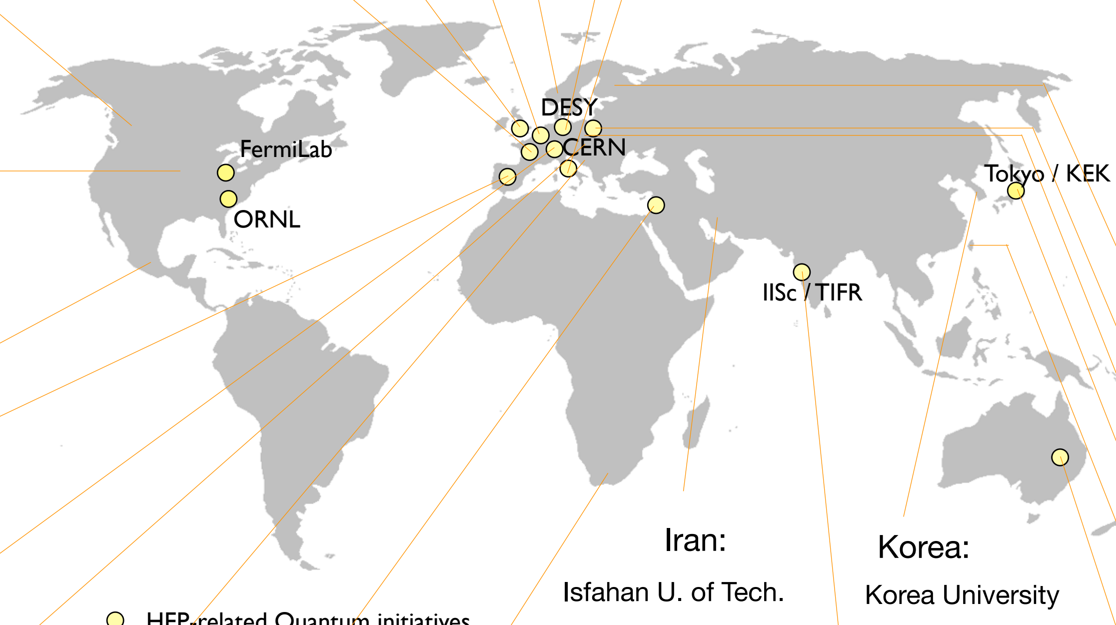
Mexico:
- U. de Aguascalientes

Spain:
- U. de Zaragoza
- U. de Cartagena
- U. de Valencia
- U. de Lleida

Switzerland:
- U. of Geneva
- U. of Zürich
- CERN
- ETHZ

Netherlands:
- U. of Groningen

Norway:
- Oslo University



Austria:
- IQOQI Vienna

Croatia:
- Inst. of Physics, Zagreb

Israel:
- Technion, Haifa

South Africa:
- U. of Cape Town

Iran:
- Isfahan U. of Tech.

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

Korea:
- Korea University

Australia:
- University of Western Australia
- Swinburne University of Technology

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:
- Czech Tech. University
- University West Bohemia

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

Conclusions:

- thanks to the involvement of key figures in the different Quantum Sensor and emerging technologies communities, we have identified a number of areas where a collaboration such as DRD5 can provide an added value to both particle physics and quantum technology activities

- we have managed to formulate WP's, milestones and deliverables in such a form that they are reasonable and acceptable to those communities

- we have started the process of growing a community; this process will require *time* and *trust*, both among the participants, but also from the side of the involved institutions (DRDC, CERN). It is also an ongoing process that will rely on successfully implementing first milestones in form of workshops, reports, agreements and technical co-developments

- we believe that the widespread response indicates that this endeavor addresses a real need and can build on an understanding that a CERN-style collaborative approach *can* benefit the different communities, as long as their idiosyncrasies are understood and accommodated

Thank you for your attention.