Warsaw University of Technology

Faculty of Physics

UCZELNIA BADAWCZA
INICJATYWA DOSKONAŁOŚCI

XVII Polish Workshop on Relativistic Heavy-Ion Collisions

Phase diagram and Equation of State of strongly interacting matter

14–15.12.2024 Warsaw Poland

Quantum sensors for HEP: DRD-5: Detector R&D Collaboration for quantum sensors at CERN

Georgy Kornakov

georgy.kornakov@pw.edu.pl

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Ministerstwo
Edukacji i Nauki

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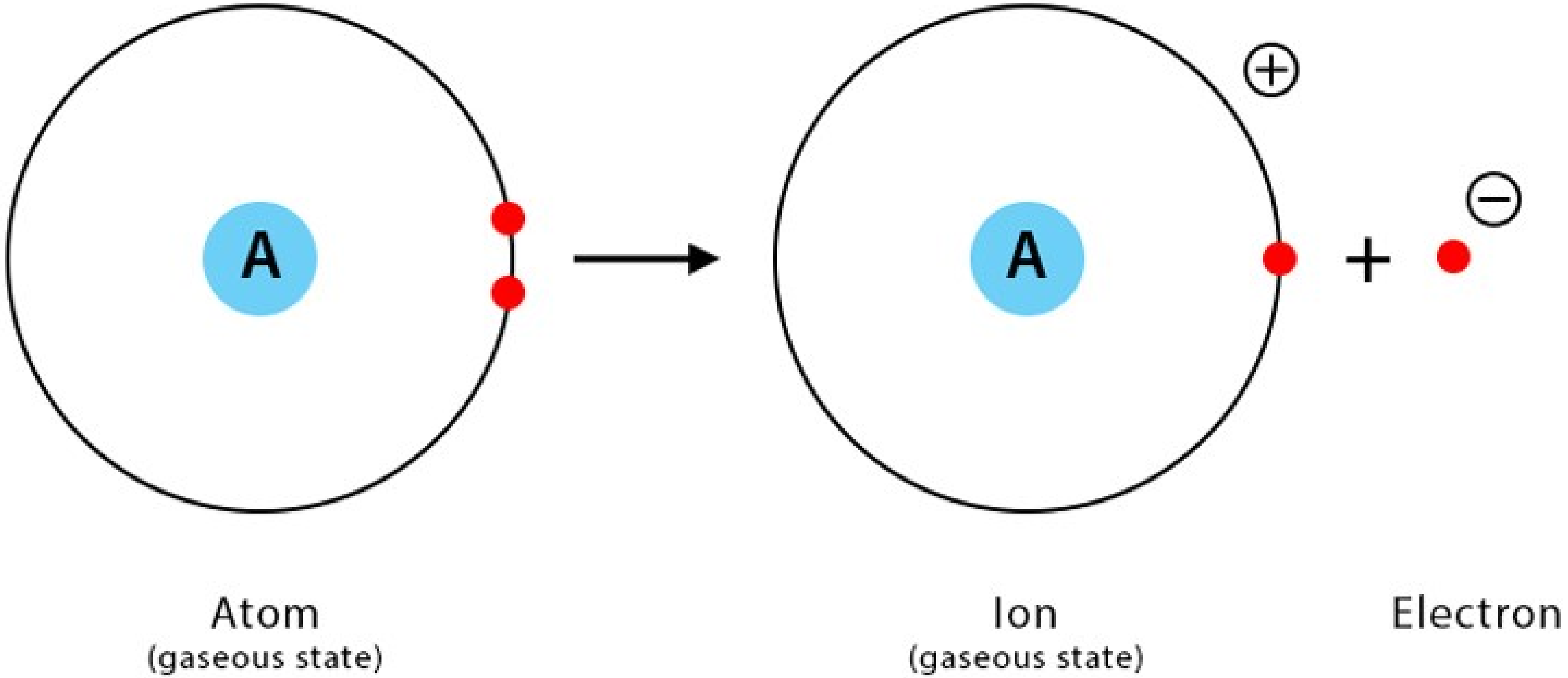
Ionization



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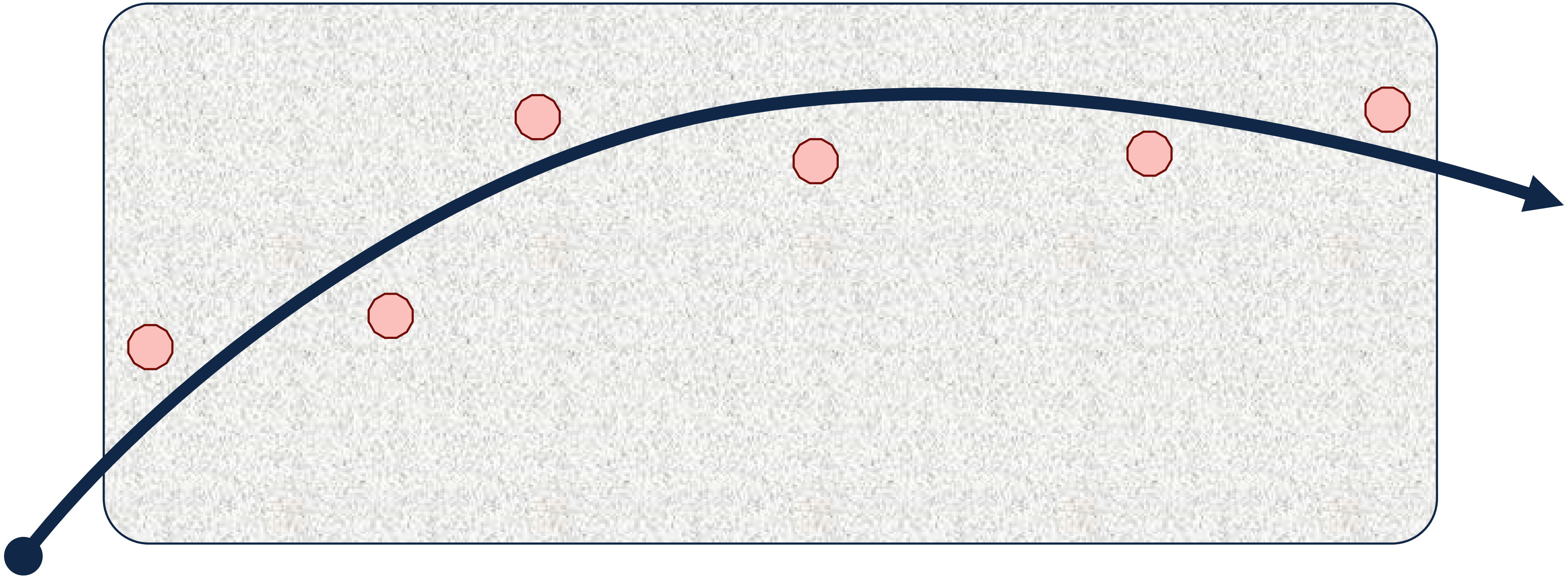
Ionization



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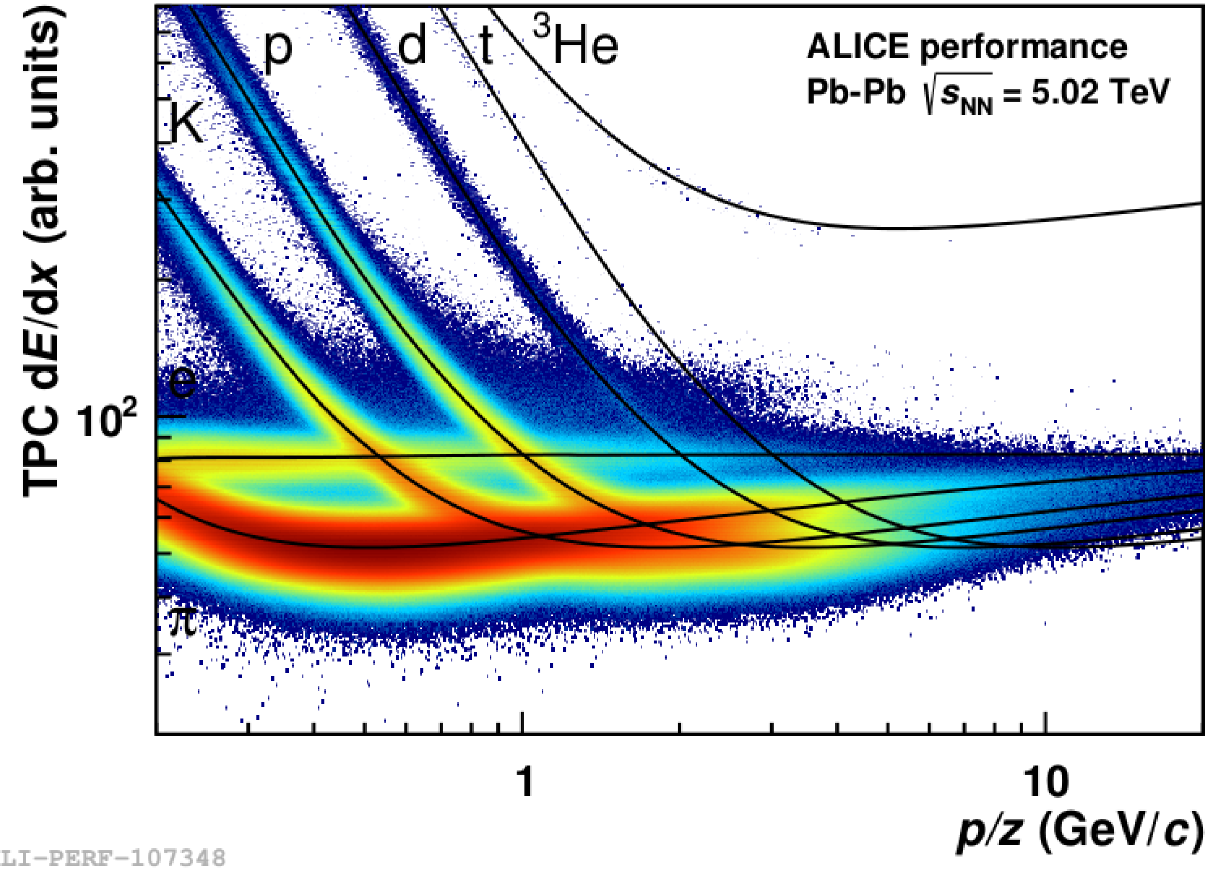
ionization



Very non-trivial way from ionization to particle identification…

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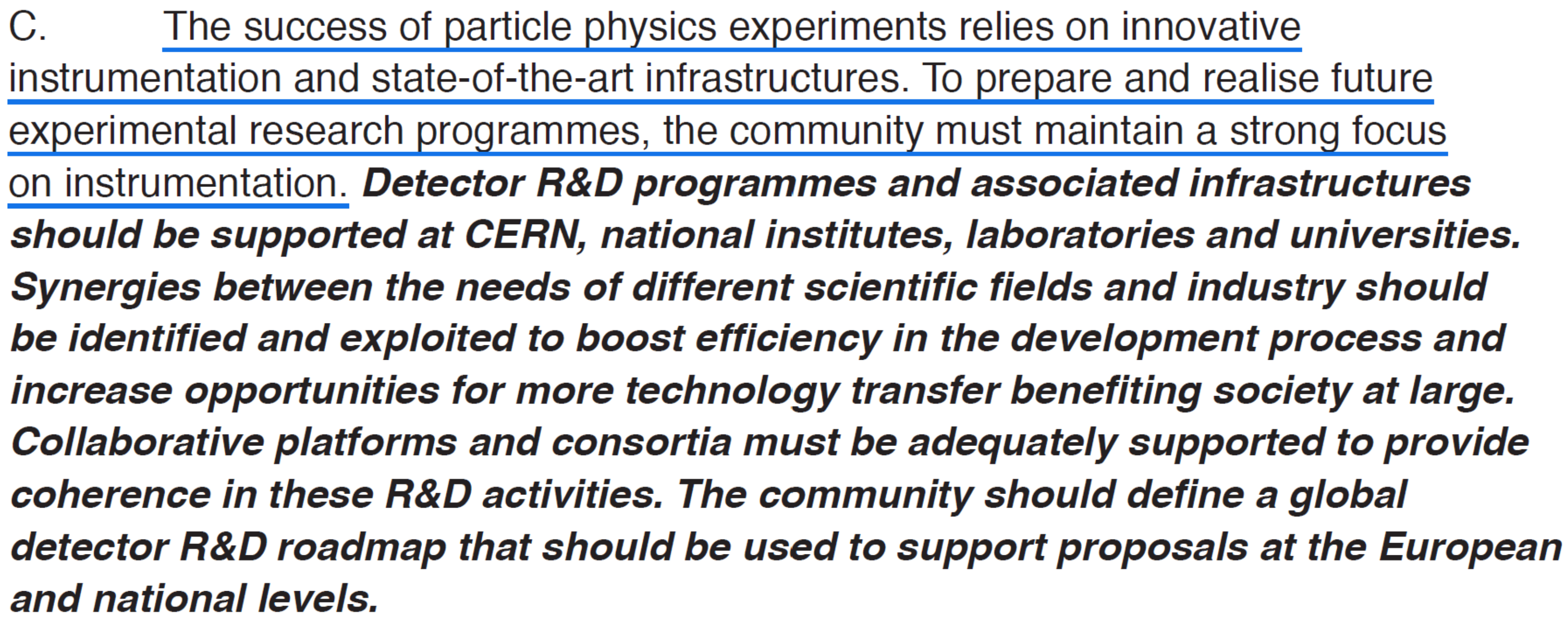
European Particle Physics Strategy 2020 Update



C. The success of particle physics experiments relies on innovative instrumentation and state-of-the-art infrastructures. To prepare and realise future experimental research programmes, the community must maintain a strong focus on instrumentation. ***Detector R&D programmes and associated infrastructures should be supported at CERN, national institutes, laboratories and universities. Synergies between the needs of different scientific fields and industry should be identified and exploited to boost efficiency in the development process and increase opportunities for more technology transfer benefiting society at large. Collaborative platforms and consortia must be adequately supported to provide coherence in these R&D activities. The community should define a global detector R&D roadmap that should be used to support proposals at the European and national levels.***

georgy.kornakov@pw.edu.pl

(low energy) particle detectors:

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.

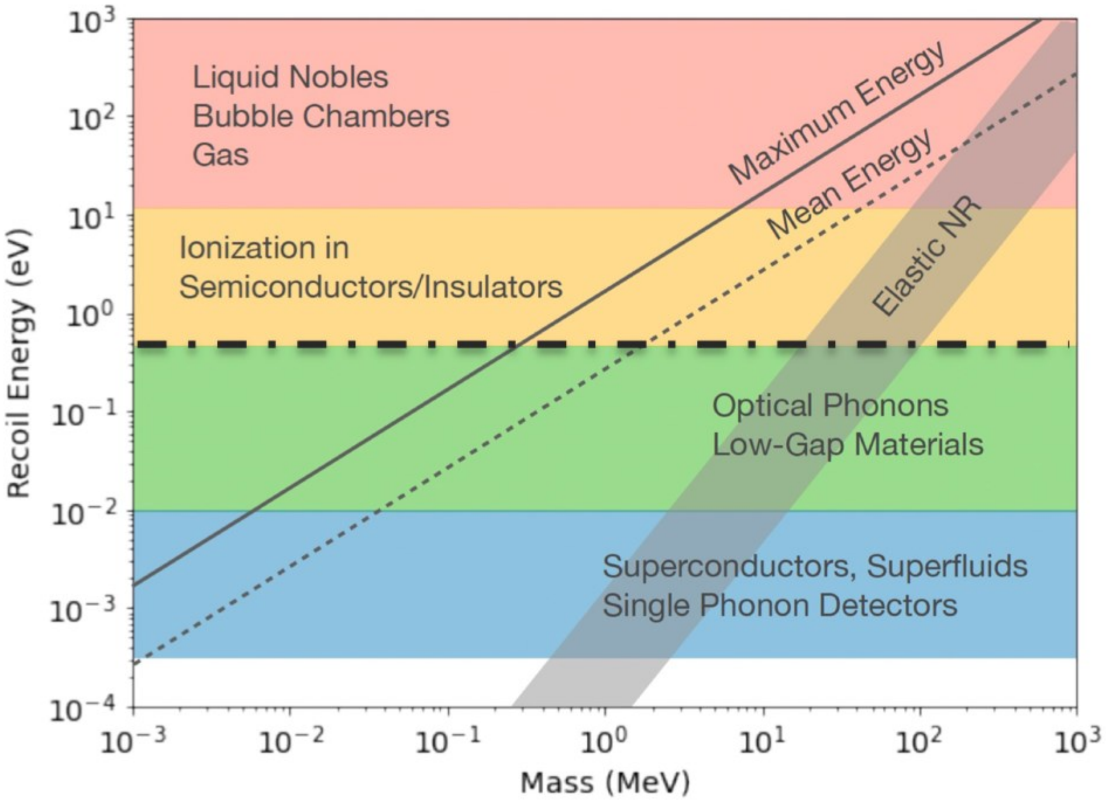
and because the commensurate energies are very low, unsurprisingly, quantum sensors are ideally matched to low energy (particle) physics; nevertheless, they can also form natural elements of HEP detectors

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

georgy.kornakov@pw.edu.pl

Start with an example: Energy deposited in detectors by particles

quantum sensing & particle physics



$\Delta E \sim 1$ 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

georgy.kornakov@pw.edu.pl

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

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

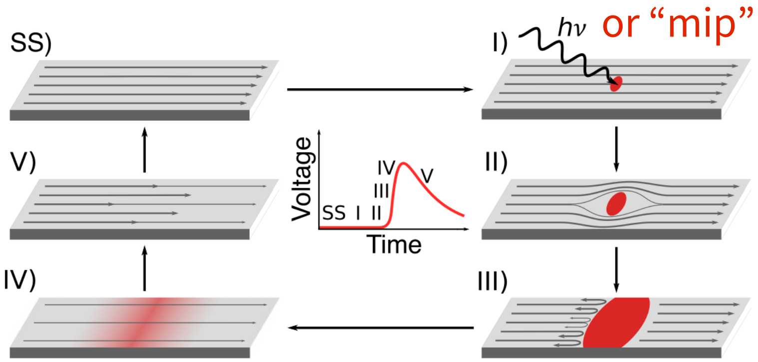
- search for NP / BSM
- Axions, ALP's, DM & non-DM UL-particle searches
- tests of QM — wavefunction collapse, decoherence
- EDM searches & tests of fundamental symmetries
- *Development of new detectors*

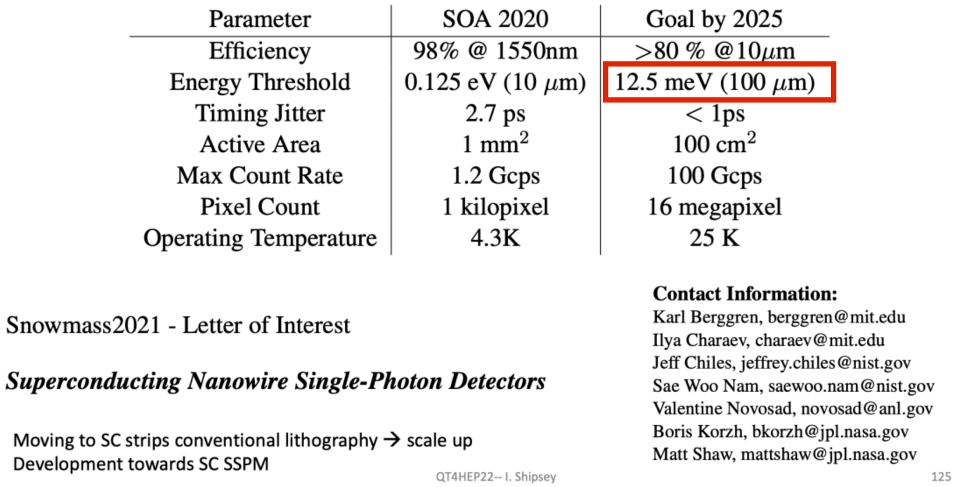
→ ECFA Detector R&D Roadmap Symposium of Task Force 5 Quantum and Emerging Technologies
https://indico.cern.ch/event/999818/

georgy.kornakov@pw.edu.pl

Extremely low energy threshold detectors: SNSPD

quantum pixel ultra-sensitive tracking





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

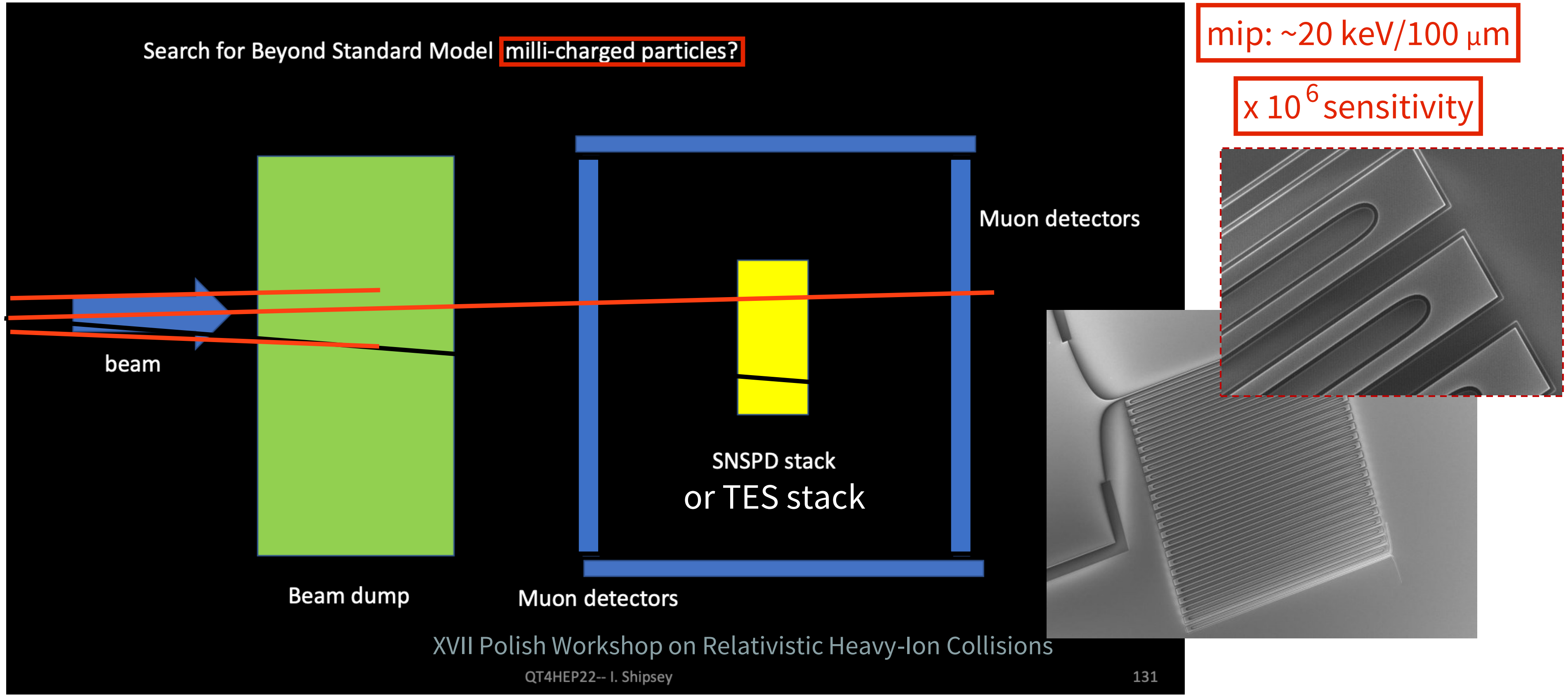
Snowmass2021 - Letter of Interest

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



Search for Beyond Standard Model milli-charged particles?

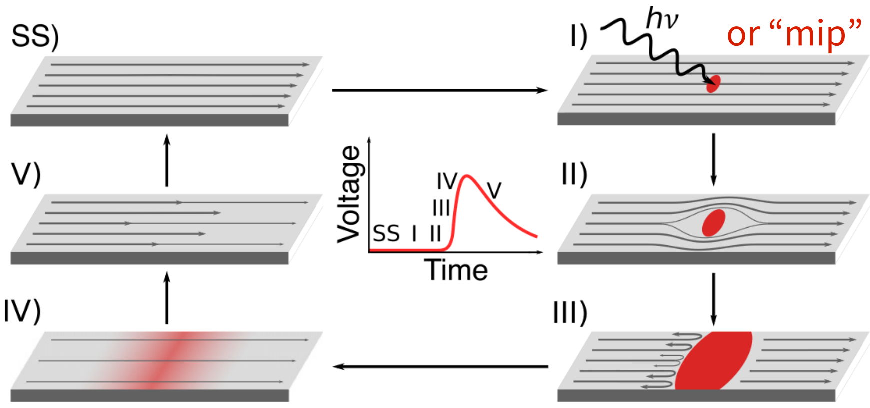
QT4HEP22-- I. Shipsey 131

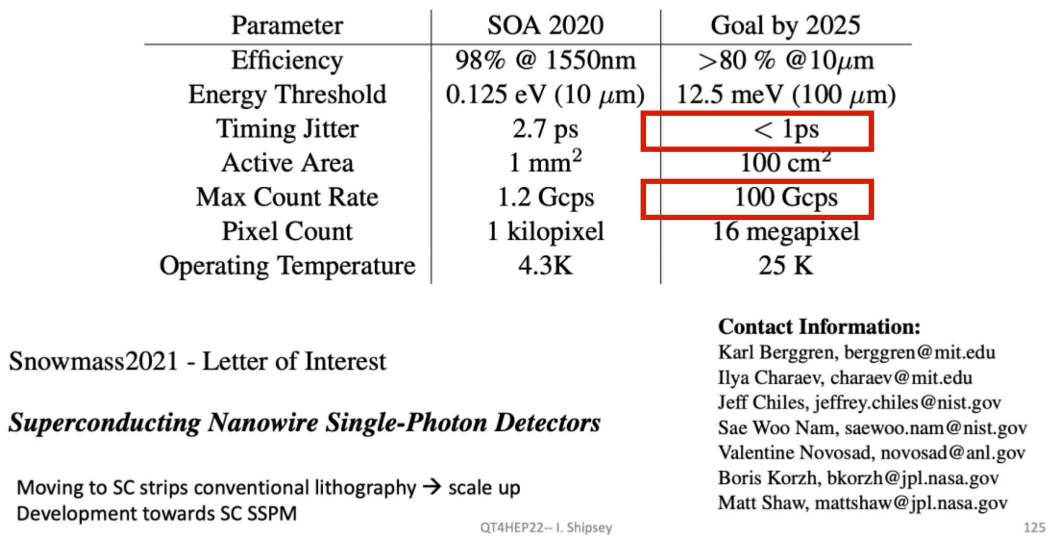
mip: ~20 keV/100 μm

x 10^6 sensitivity

Extremely fast detectors: SNSPD

quantum pixel ultra-sensitive tracking





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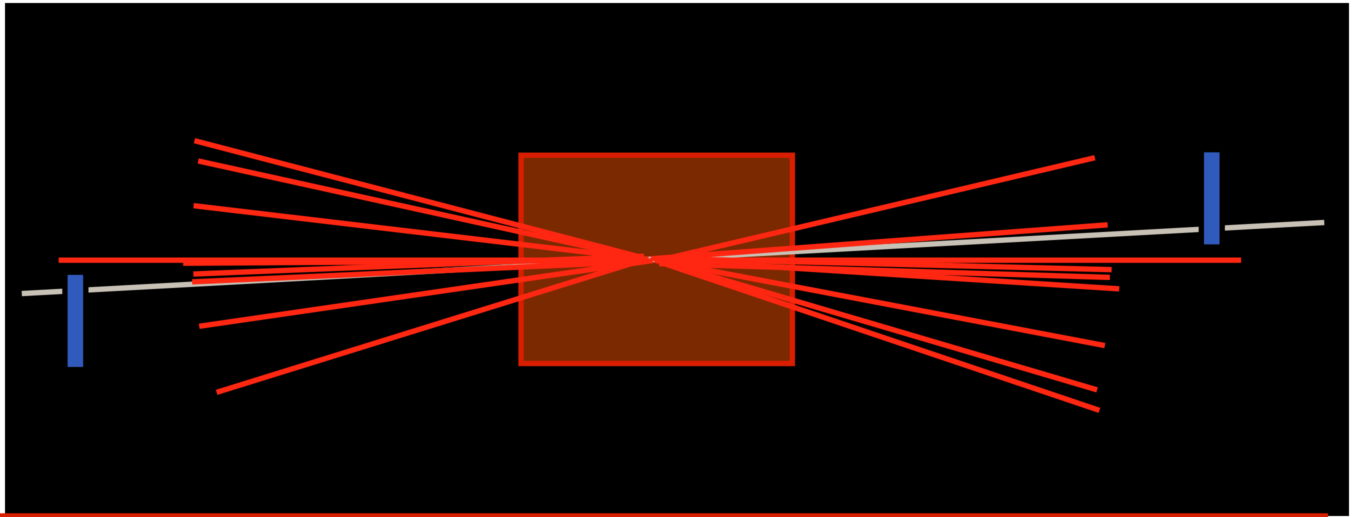
Moving to SC strips conventional lithography → scale up
Development towards SC SSPM

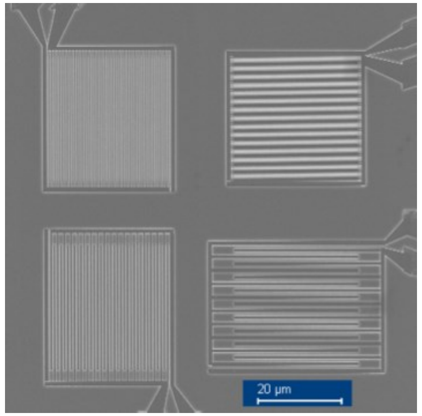
QT4HEP22-- I. Shipsey

125

@ 2.8 K

diffractive scattering via ps-resolution tracking in Roman pots



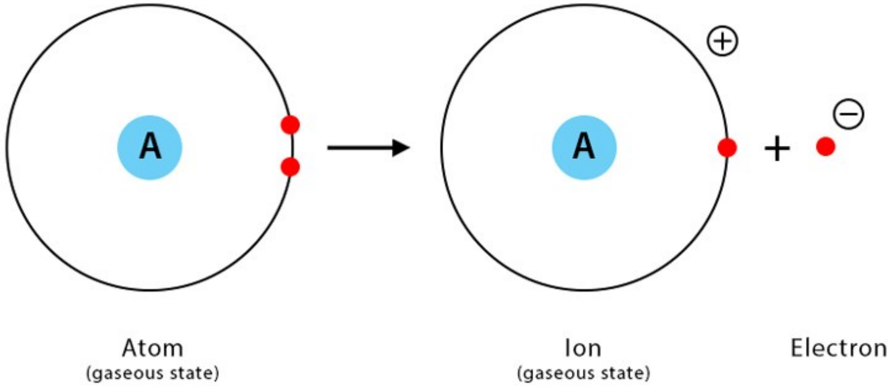


S. Lee et al., (2024)
arXiv:2312.13405v2
SNSPD w/ p@120 GeV
for use e.g. at EIC

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

georgy.kornakov@pw.edu.pl

Rydberg Time projection Chamber



How we could:

- reduce recoil
- increase energy sensitivity threshold
- reduce density of bulk
- increase read out speed
- increase locus accuracy…

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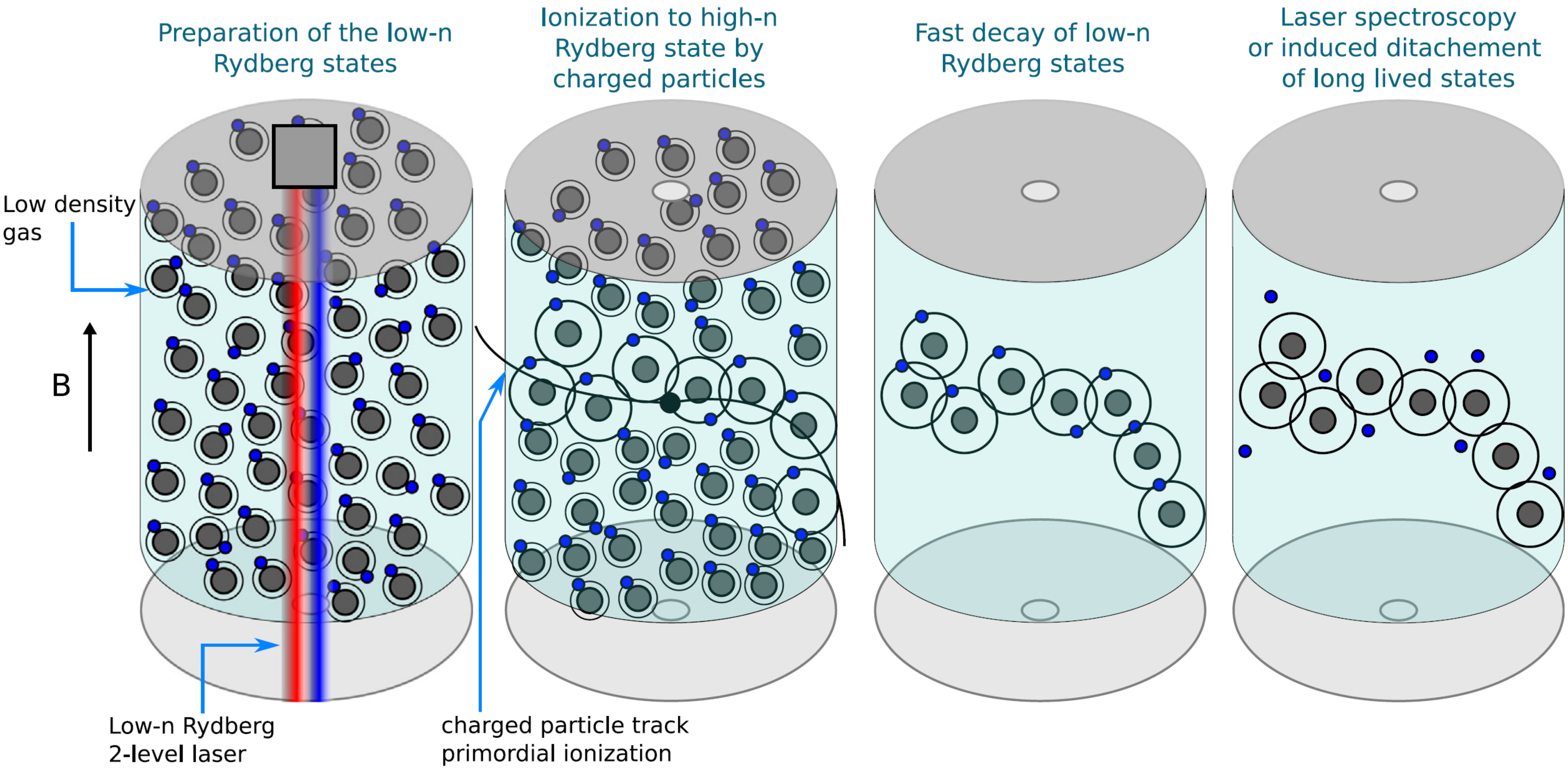
Rydberg Time projection Chamber



Preparation of the low-n Rydberg states

Ionization to high-n Rydberg state by charged particles

Fast decay of low-n Rydberg states

Laser spectroscopy or induced ditachement of long lived states

Low density gas

B

Low-n Rydberg 2-level laser

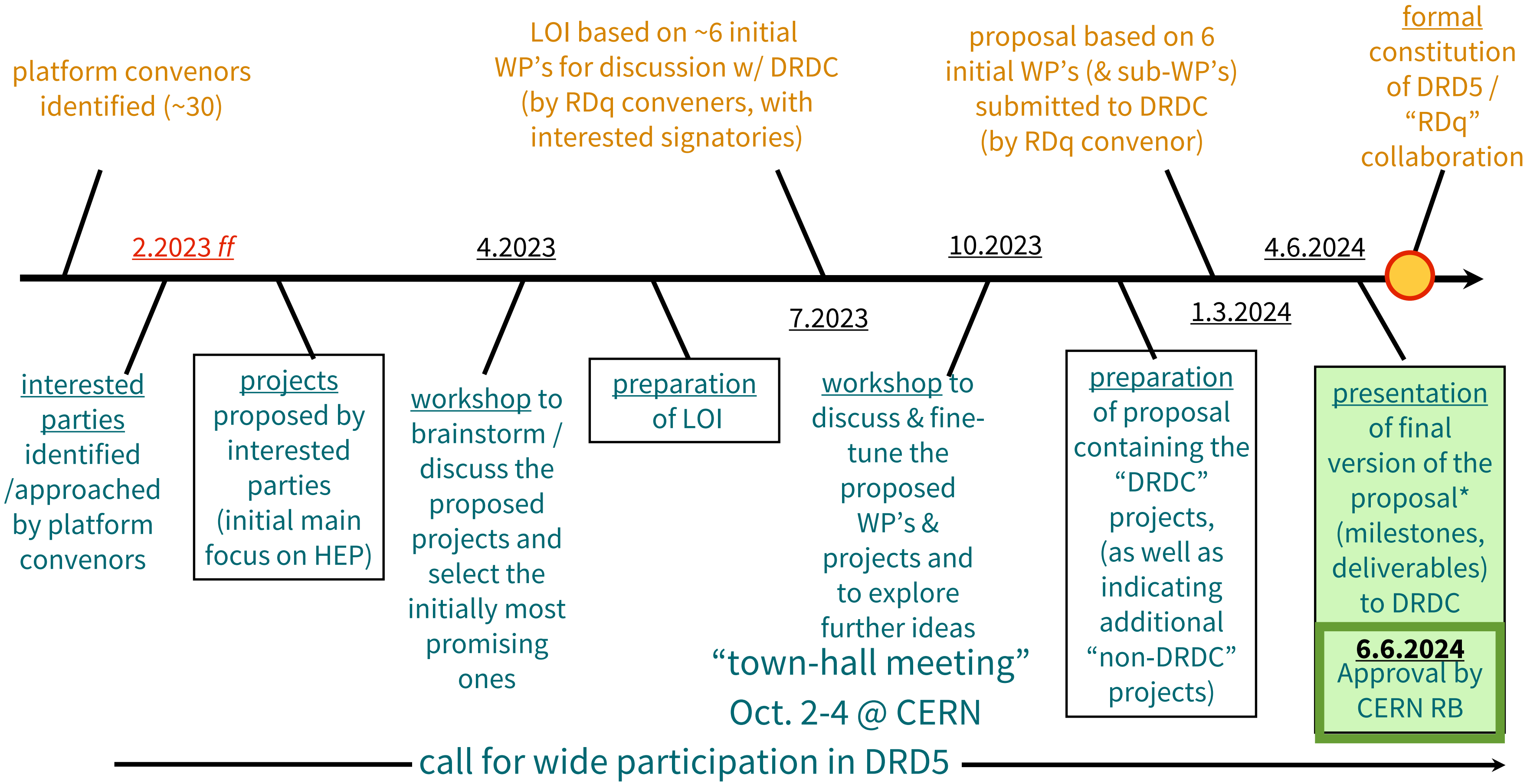
charged particle track primordial ionization

georgy.kornakov@pw.edu.pl

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)



platform convenors identified (~30)

2.2023 *ff*

interested parties identified /approached by platform convenors

projects proposed by interested parties (initial main focus on HEP)

4.2023

workshop to brainstorm / discuss the proposed projects and select the initially most promising ones

preparation of LOI

LOI based on ~6 initial WP's for discussion w/ DRDC (by RDq conveners, with interested signatories)

7.2023

workshop to discuss & fine-tune the proposed WP's & projects and to explore further ideas

"town-hall meeting"

Oct. 2-4 @ CERN

10.2023

preparation of proposal containing the "DRDC" projects, (as well as indicating additional "non-DRDC" projects)

proposal based on 6 initial WP's (& sub-WP's) submitted to DRDC (by RDq convenor)

1.3.2024

4.6.2024

presentation of final version of the proposal* (milestones, deliverables) to DRDC

6.6.2024
Approval by CERN RB

formal constitution of DRD5 / "RDq" collaboration

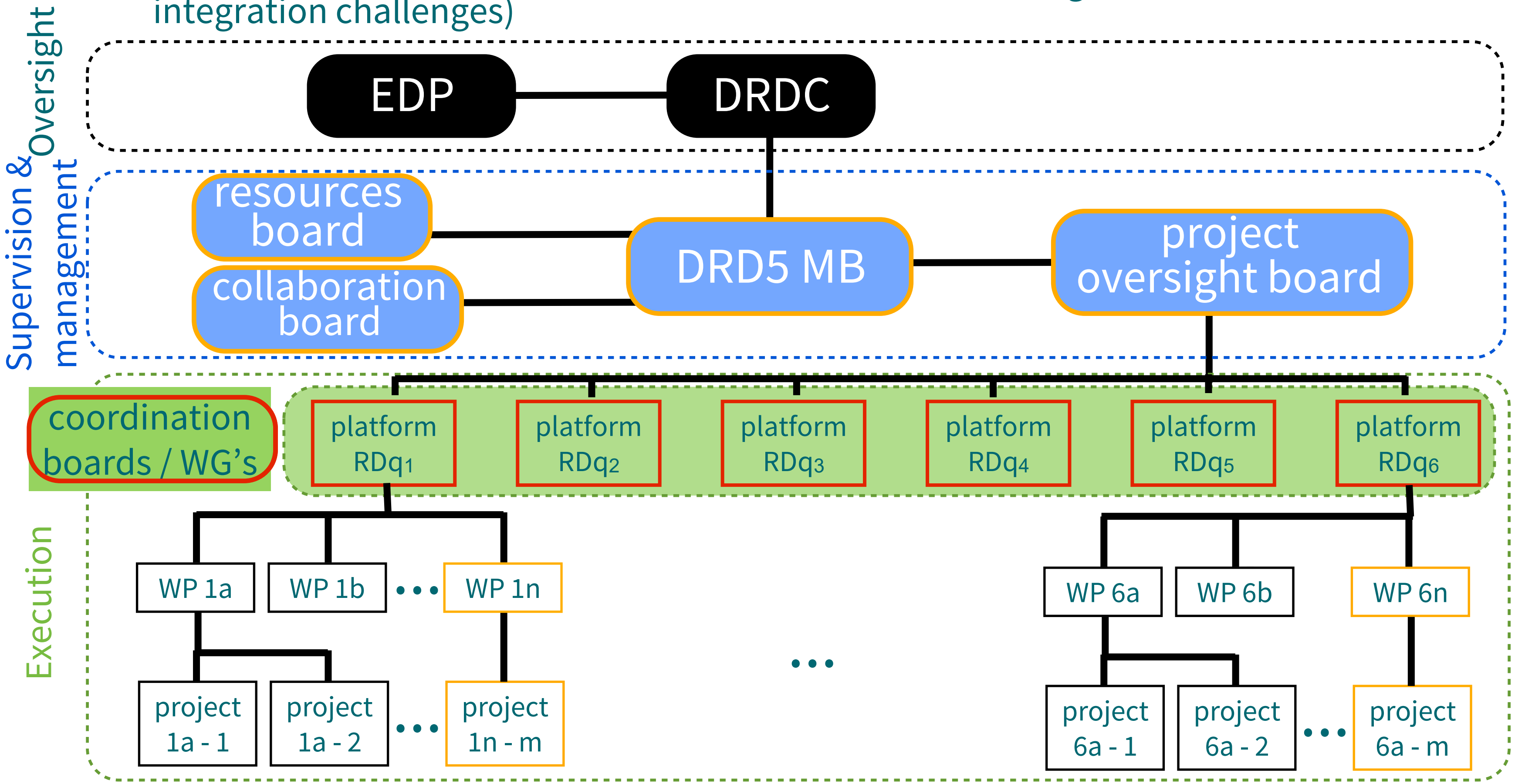
call for wide participation in DRD5

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

georgy.kornakov@pw.edu.pl

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)



Oversight

EDP

DRDC

Supervision & management

resources board

collaboration board

DRD5 MB

project oversight board

coordination boards / WG's

platform RDq1

platform RDq2

platform RDq3

platform RDq4

platform RDq5

platform RDq6

Execution

WP 1a

WP 1b

…

WP 1n

project 1a - 1

project 1a - 2

…

project 1n - m

…

WP 6a

WP 6b

WP 6n

project 6a - 1

project 6a - 2

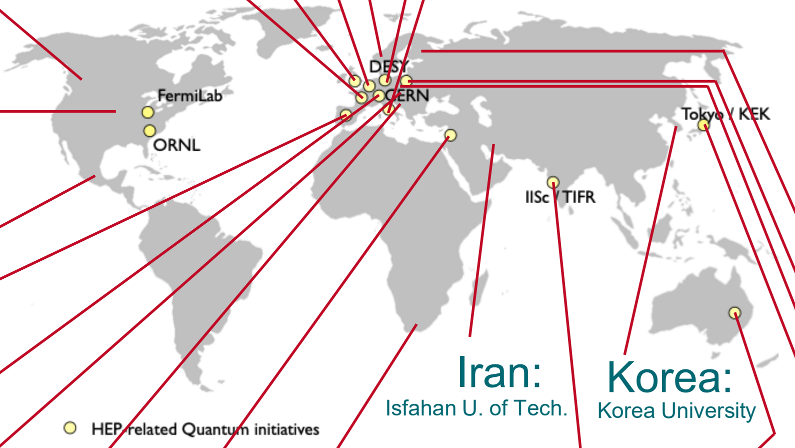
…

project 6a - m

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

georgy.kornakov@pw.edu.pl

DRD5: 96 involved groups (as of 3.6.2024)



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

Netherlands: U. of Groningen

Norway:
- Oslo University

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

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

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

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

Iran:
- Isfahan U. of Tech.

Korea:
- Korea University

Austria:
- IQOQI Vienna

Israel:
- Technion, Haifa

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

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

Croatia:
- Inst. of Physics, Zagreb

South Africa:
- U. of Cape Town

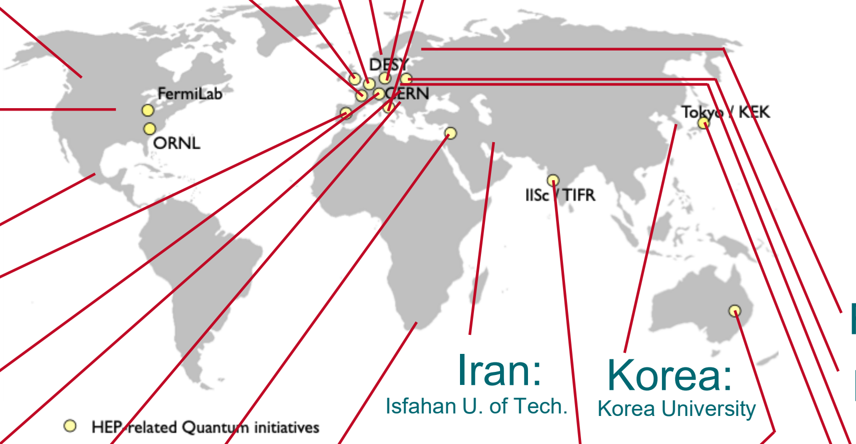
georgy.kornakov@pw.edu.pl

DRD5: 96 involved groups (as of 3.6.2024)

Collaboration currently being put together, 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!)



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South Africa: U. of Cape Town

Iran: Isfahan U. of Tech.

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- IISER, Kolkata
- TIFR, Mumbai
- University SOA Bhuvaneswar

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- VTT

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

Czech Republic: Czech Tech. University

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

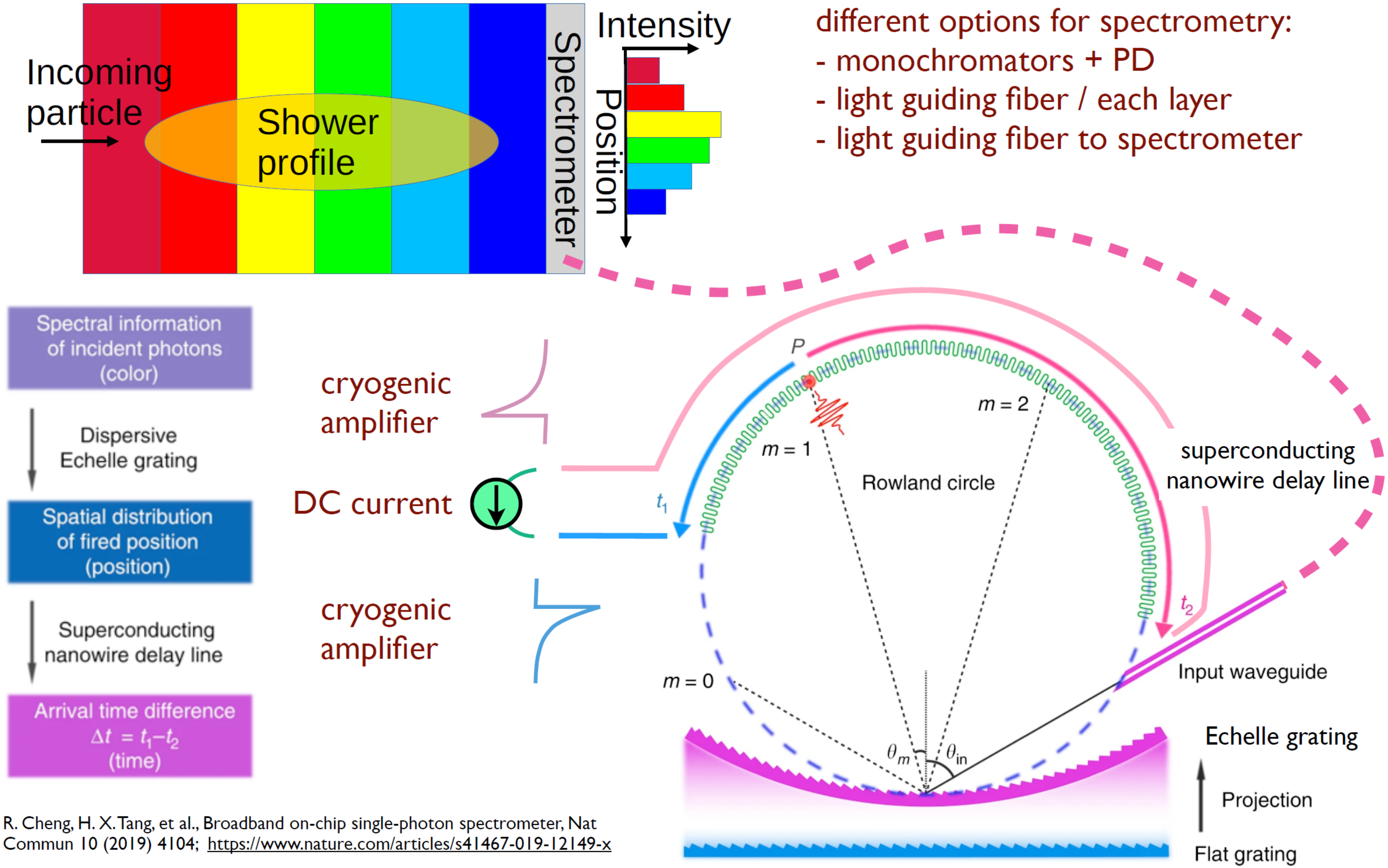
georgy.kornakov@pw.edu.pl

There is an ongoing revolution in the domain of quantum technologies and quantum sensing in particular.
The evolution from observation of fenomena to implementaiton of technological solution is now possible thanks to many enabling technologies which appeared in last decades.

The DRD-5 quantum sensing Collaboration at CERN is uniting researchers all over the worlds in a coherent effort to address some fundamental challenges in the development of quantum sensors and speed up their adpotion by a broader communities.

Thank you for your attention!

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



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

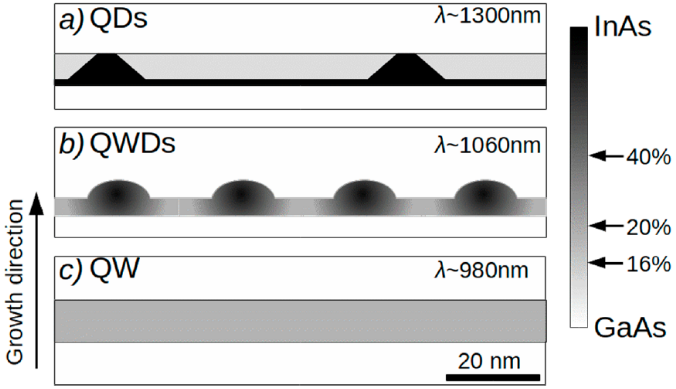
Active scintillators (QWs, QDs, QWDs, QCLs)

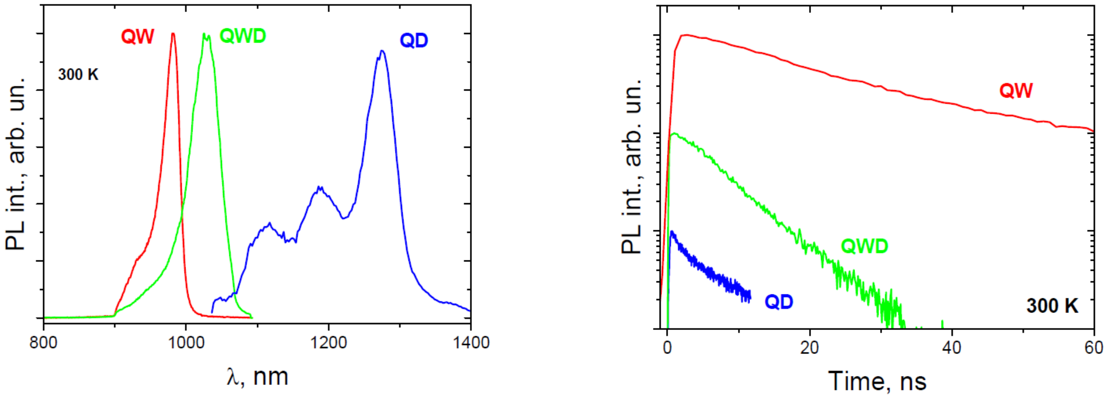
M. Doser, CERN

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

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

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





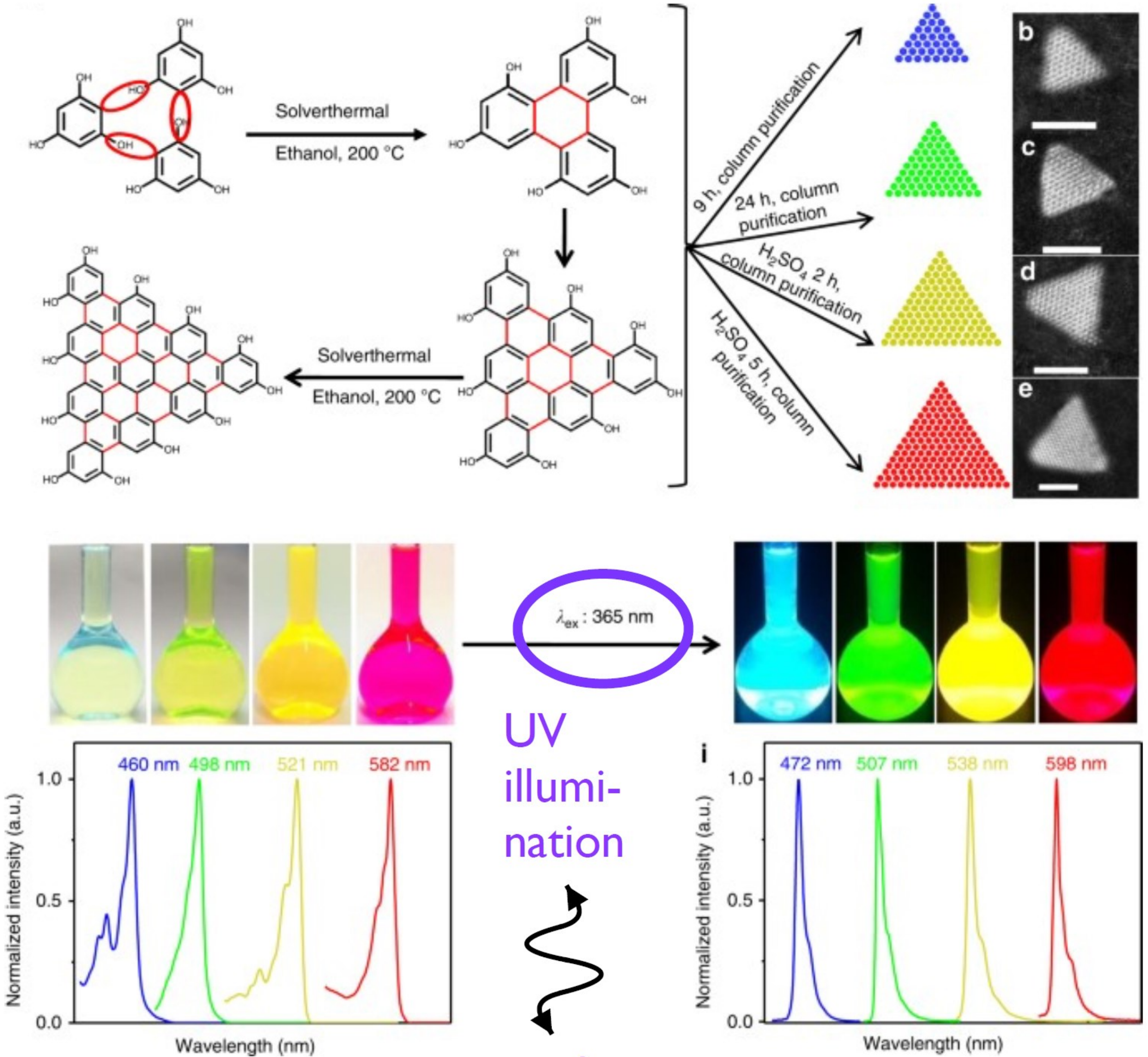
Light Emitting Devices Based on Quantum Well-Dots, Appl. Sci. 2020, 10, 1038; doi:10.3390/app10031038

QD's are radiation resistant

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

Quantum dots: chromatic calorimetry

M. Doser, CERN



UV illumi-nation

e.m. shower

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

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

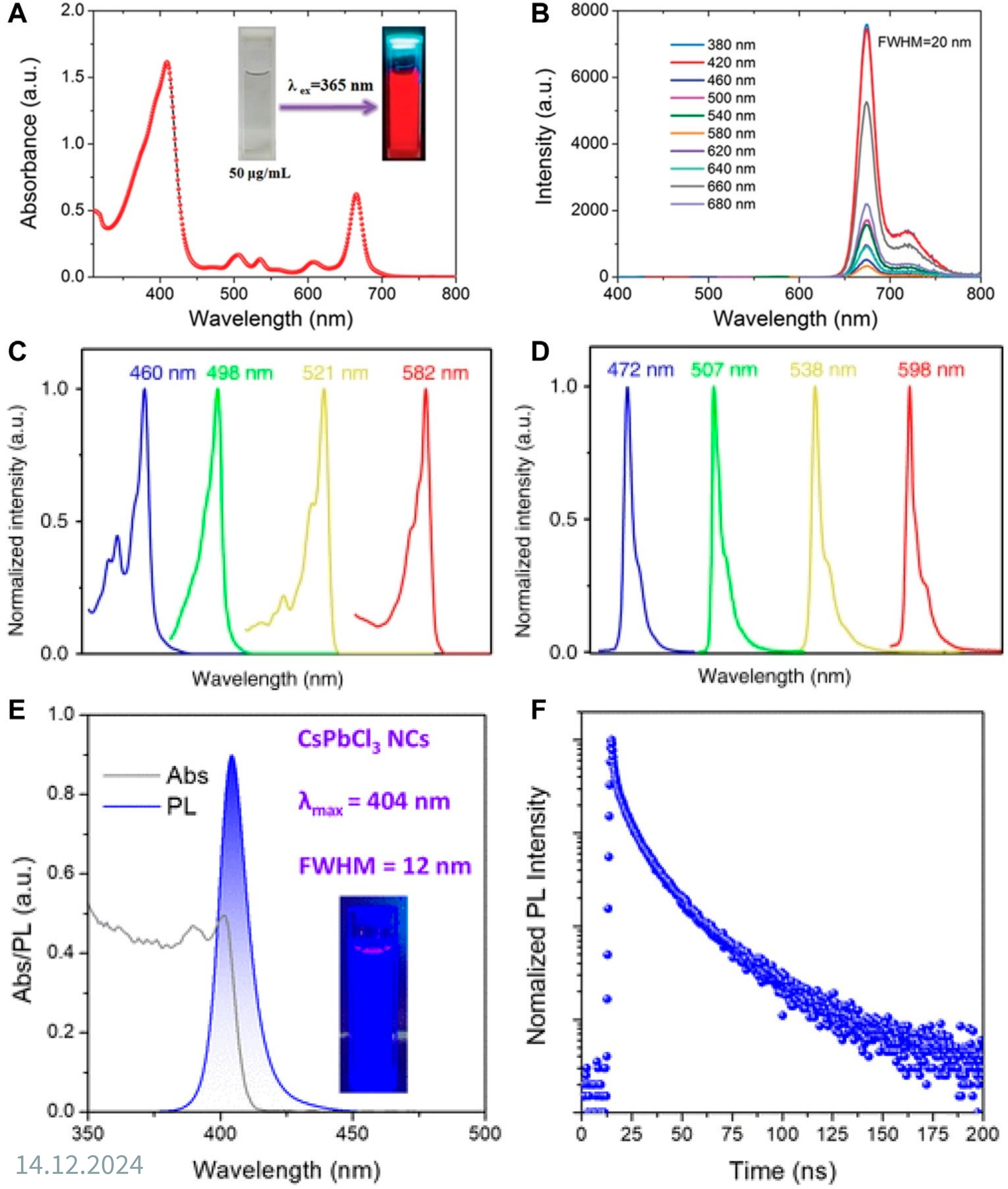
requires:

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

select appropriate nanodots

e.g. triangular carbon nanodots

Absorption Emission



M. Doser, CERN

carbonized polymer dots

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

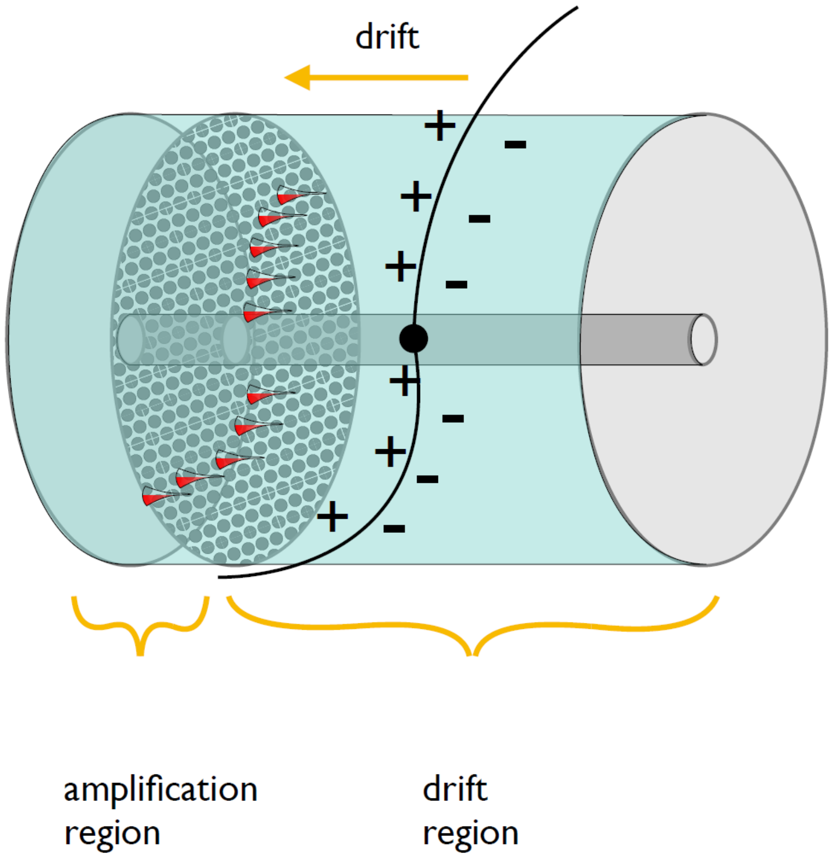
triangular carbon nanodots

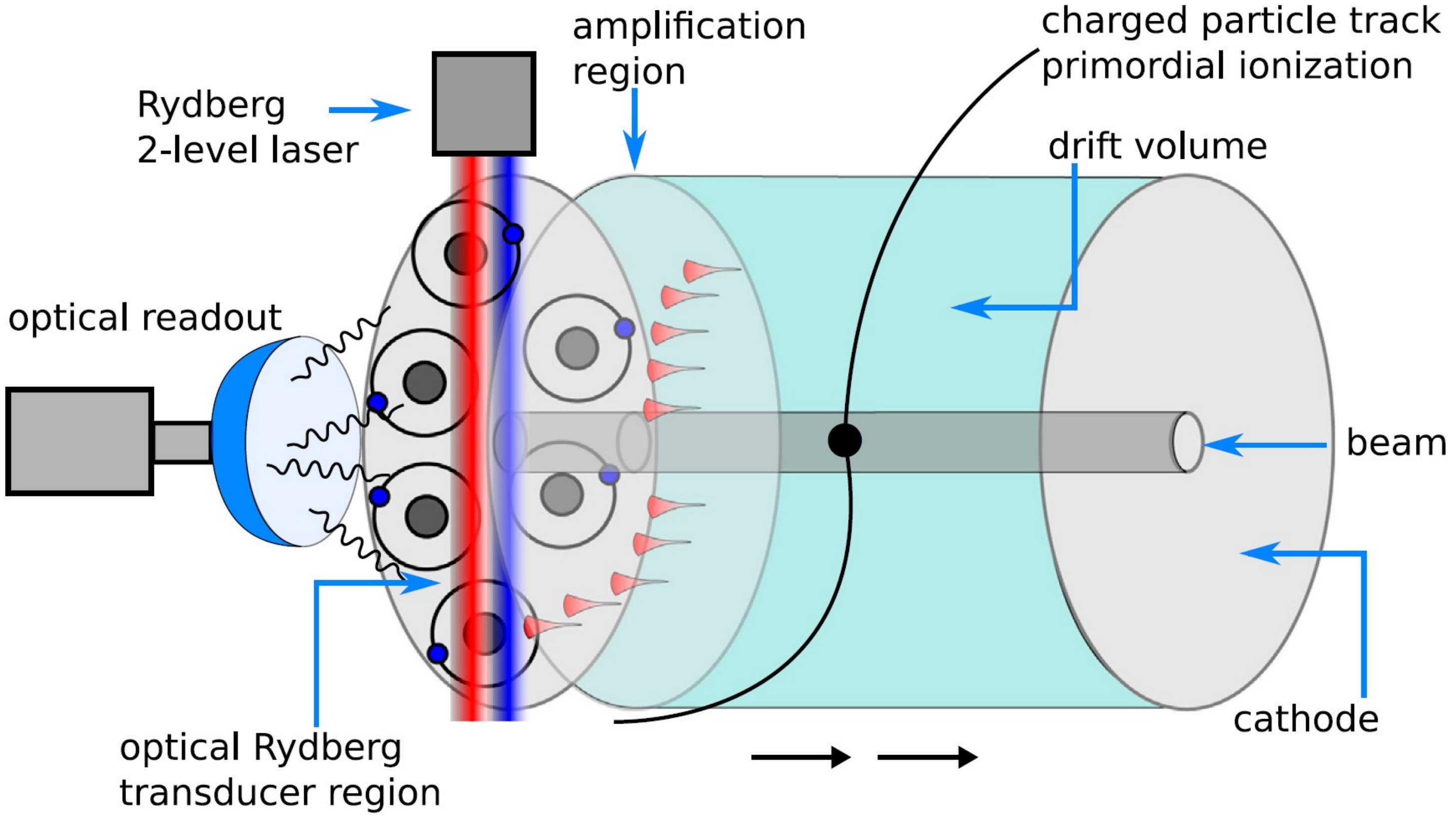
F. Yuan, S. Yang, et al., Nature Communications 9 (2018) 2249

$CsPbCl_3$ nanocrystals

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

Rydberg-enhanced Time projection Chambers

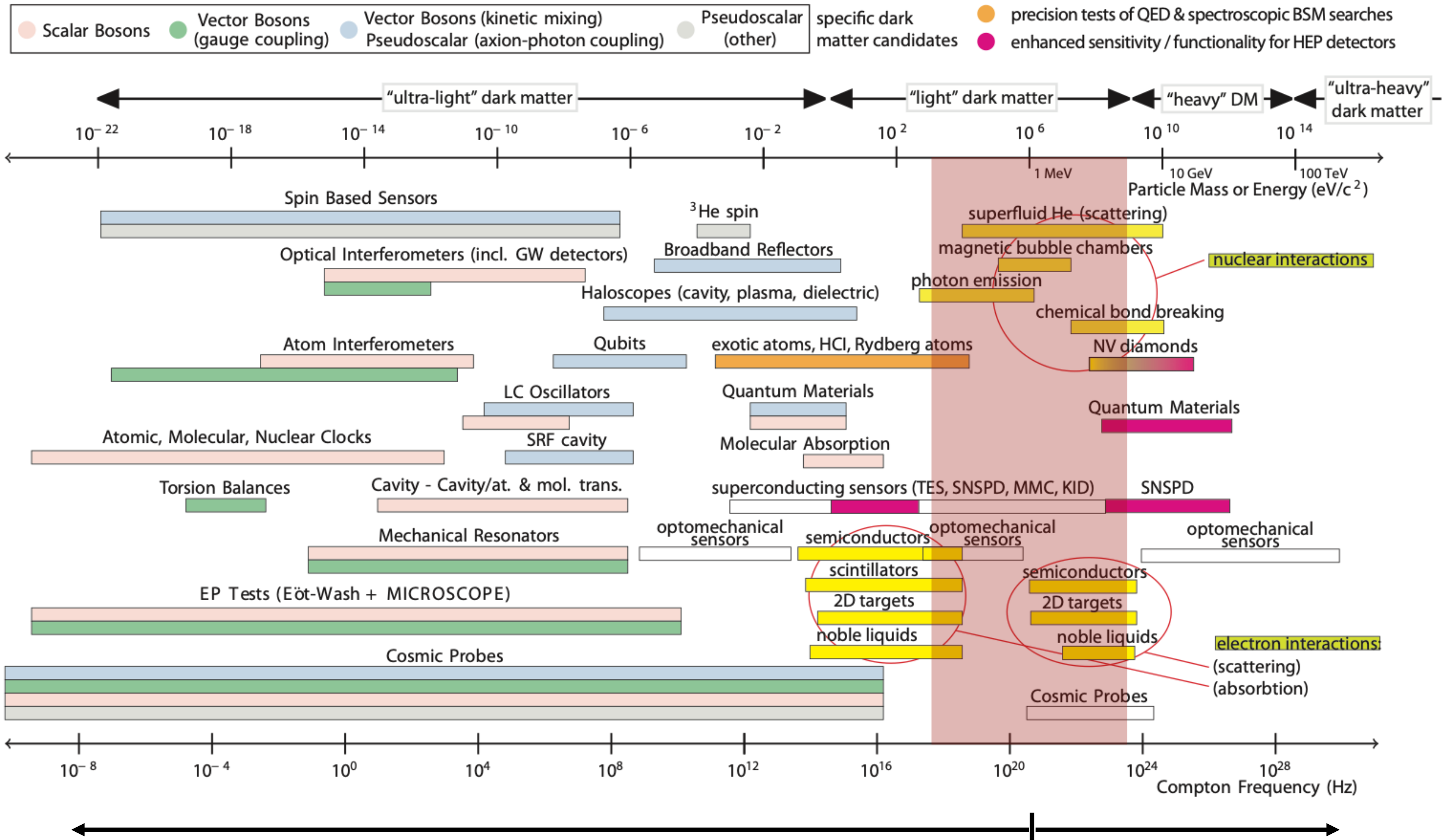




quantum sensing & particle physics

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

Ranges of applicability of different quantum sensor techniques to searches for BSM physics



"low" energy

"high" energy

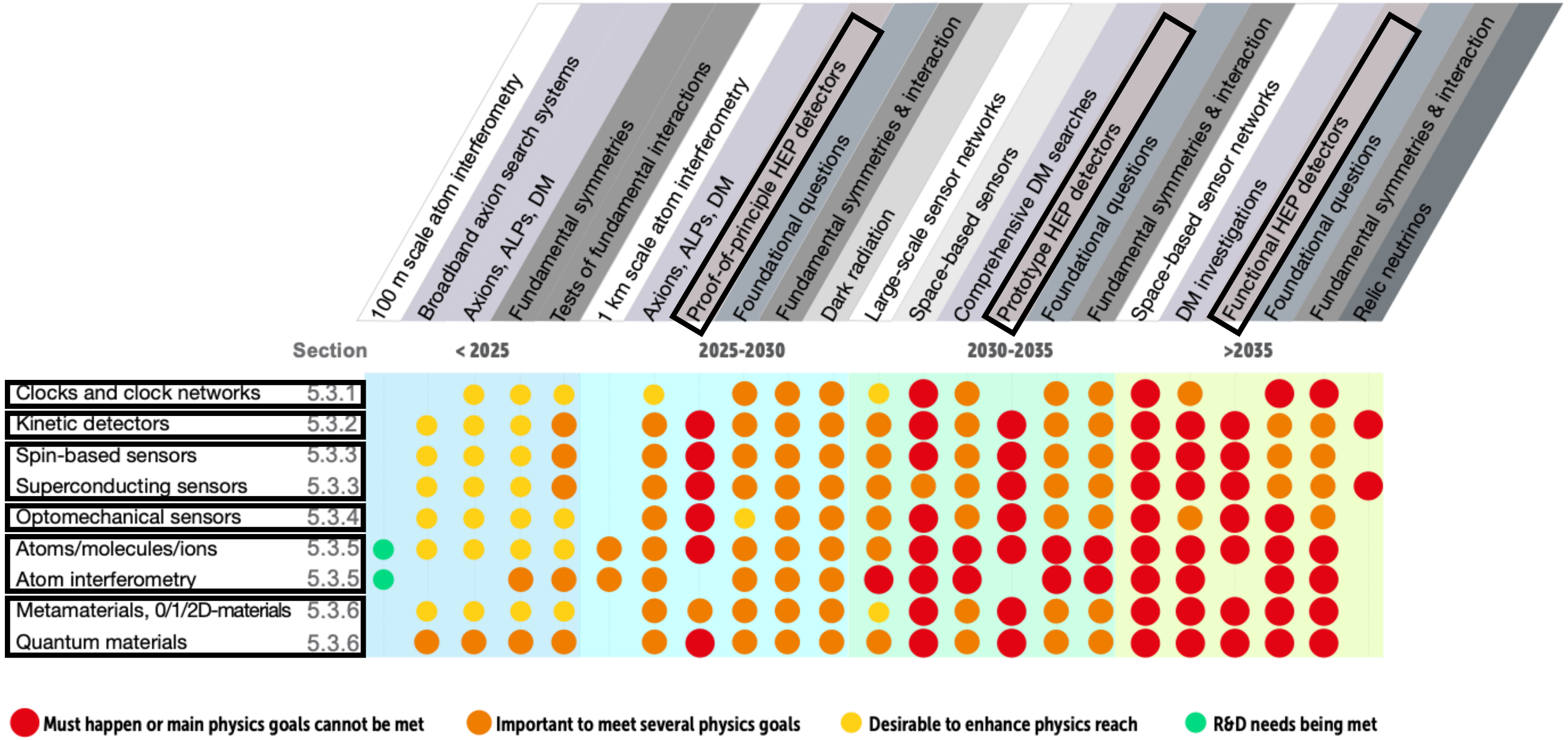
georgy.kornakov@pw.edu.pl

RECFA Detector R&D roadmap 2021

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

focus on physics
and technology

Chapter 5: Quantum and Emerging Technologies Detectors



①
②
③
④
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⑥

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

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

georgy.kornakov@pw.edu.pl

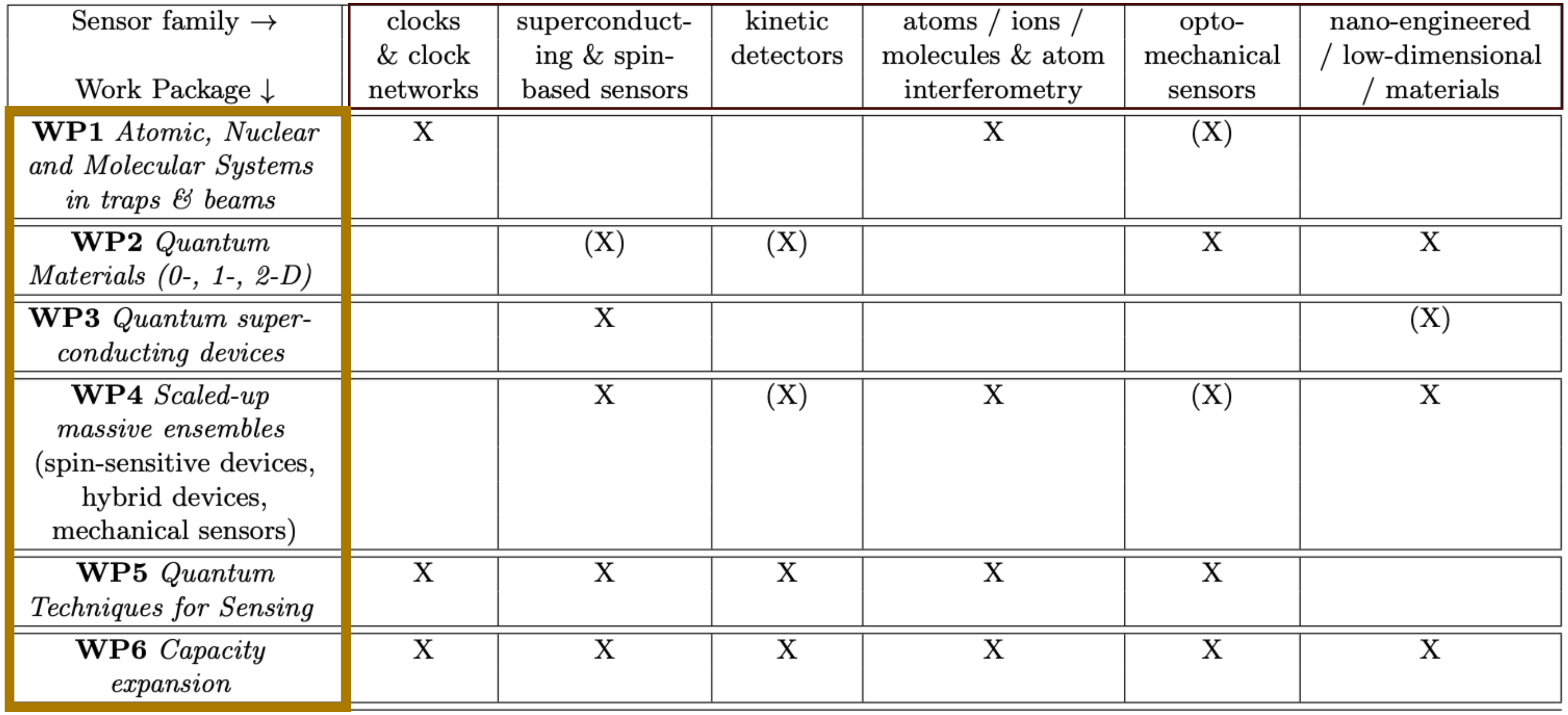
Proposal for DRD5: R&D on quantum sensors

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

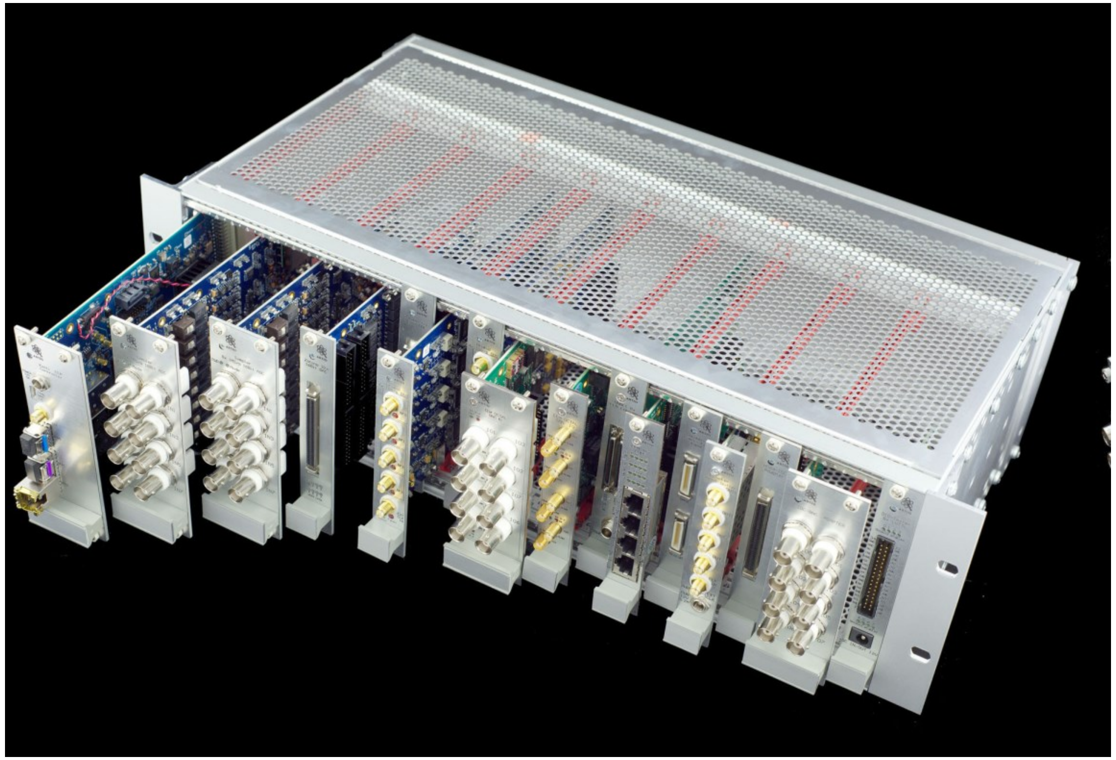


Sensor family → Work Package ↓	clocks & clock networks	superconducting & spin-based sensors	kinetic detectors	atoms / ions / molecules & atom interferometry	opto-mechanical sensors	nano-engineered / low-dimensional / materials
WP1 *Atomic, Nuclear and Molecular Systems in traps & beams*	X			X	(X)	
WP2 *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

Sinara

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



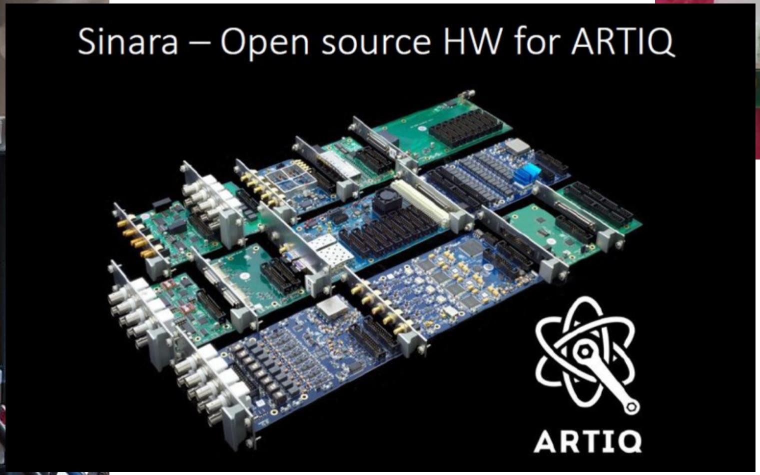
Sinara, an **open-source hardware ecosystem**,

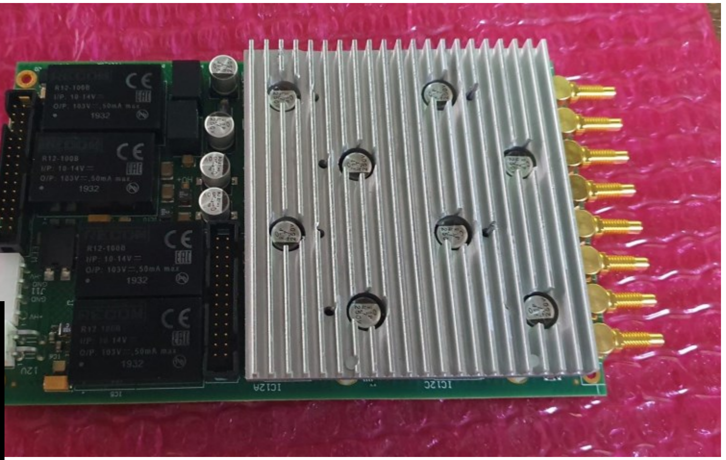
- Designed for quantum experiments
- CERN Open Hardware License,
- over 50 modules (commercially available).
- Integration with the Advanced Real-Time Infrastructure for Quantum physics (ARTIQ) control system.
  - 1 ns timing resolution.
  - management of experiment scheduling,
  - versioning,
  - results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

georgy.kornakov@pw.edu.pl

A new control system: Sinara

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


Sinara – Open source HW for ARTIQ


https://github.com/sinara-hw/HV_AMP_8CH/wiki

Fast HV amplification for the trap electrodes

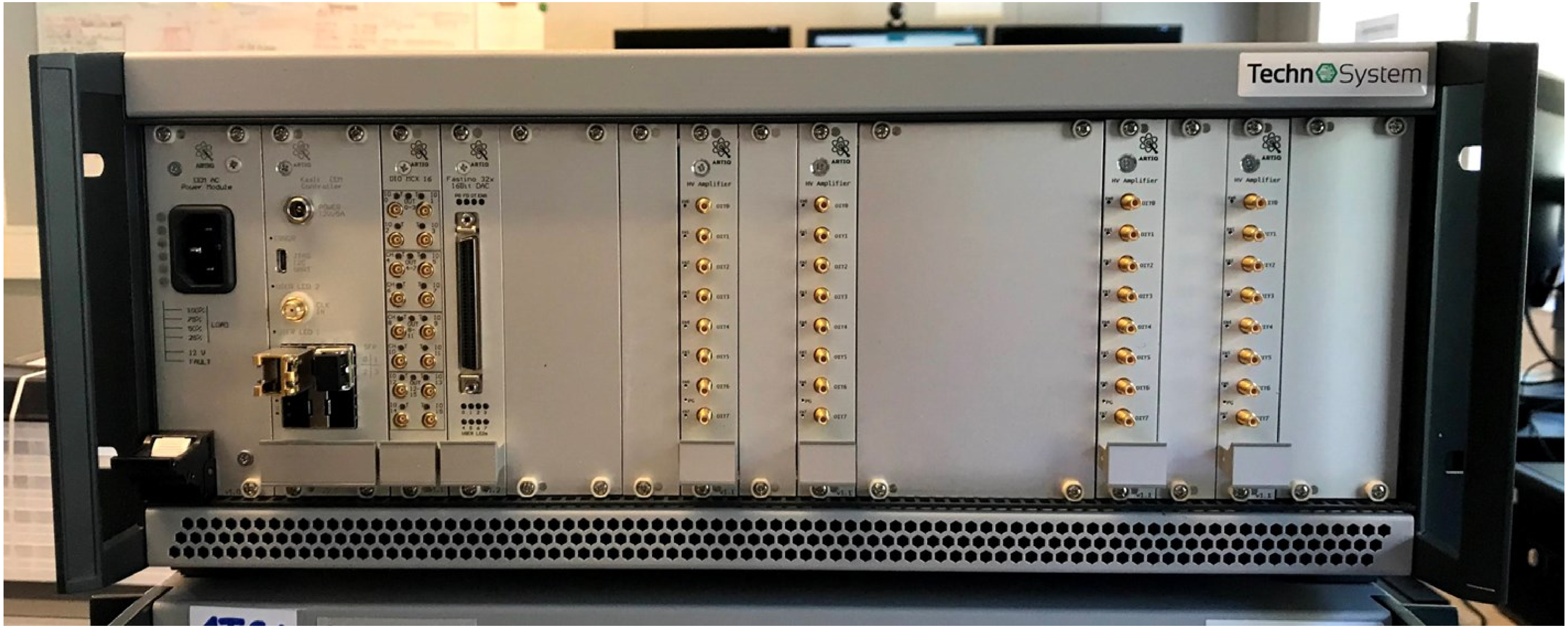
Characteristics:

- 8 channels
- +-200 V range
- 1 MHz
- 50R output impedance
- Overtemp protection
- quick output disconnect controlled via EEM using OptoMos to limit the noise

In 2022 the AEgIS experiment finalized the upgrade of the main control system. **Now it is based on SINARA** and it has been the key for successful operation in 2022.

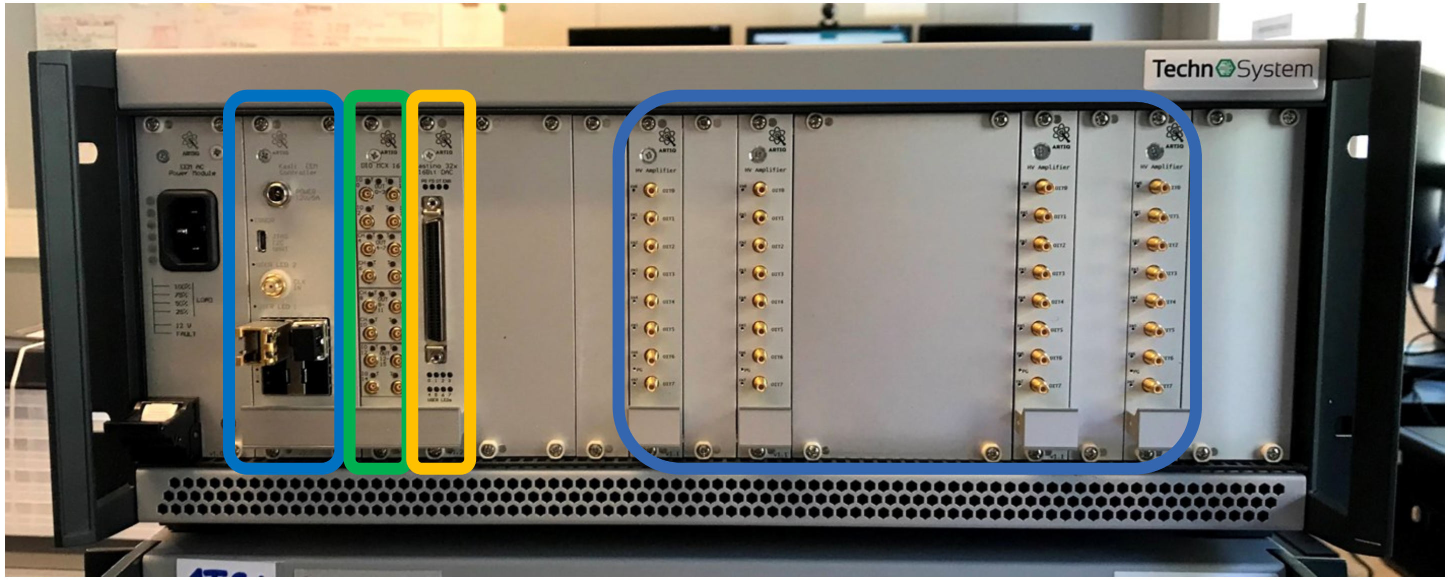
georgy.kornakov@pw.edu.pl

SINARA @ AEgIS



georgy.kornakov@pw.edu.pl

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

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

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

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

georgy.kornakov@pw.edu.pl

DM formation within Penning traps; starting from trapped p̄ and trapped $^3He^+$

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

state sexaquark: $(u\uparrow u\downarrow d\uparrow d\downarrow s\uparrow s\downarrow)$ scalar QCD bound

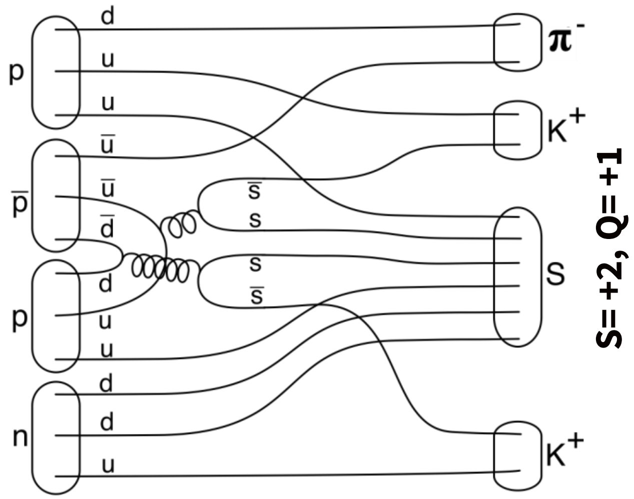
$(m \sim 2m_n, < 2m_\Lambda)$ Glennys Farrar, arxiv:1808.08951v2 (2017)

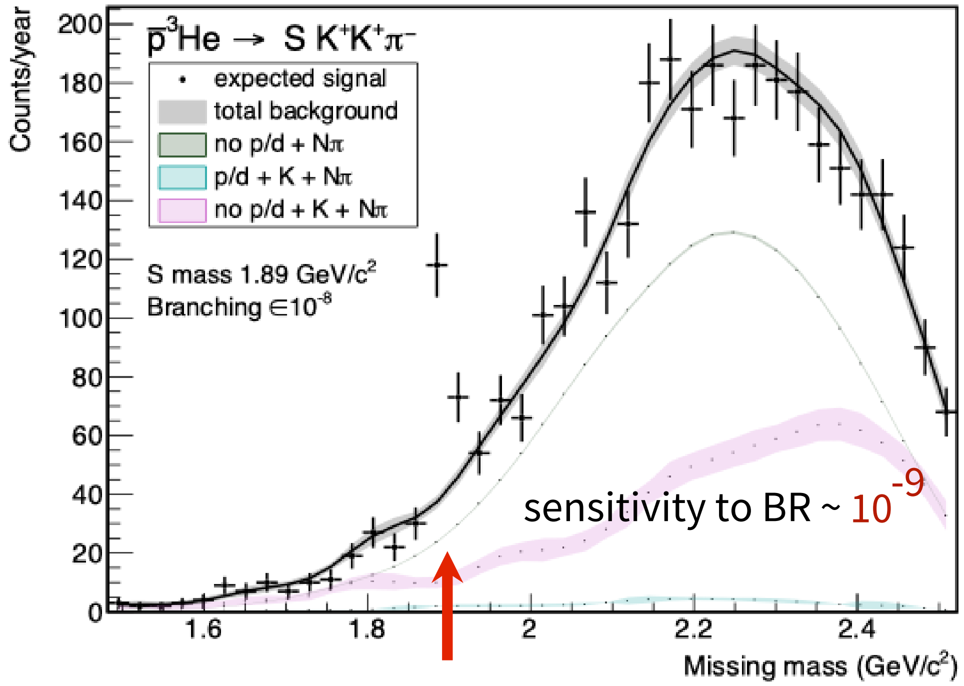
Tracking detector with good particle ID

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

formation reaction:

$(\bar{p}\,{}^3\mathrm{He})^* \longrightarrow S(uuddss) + K^+ K^+ \pi^-$



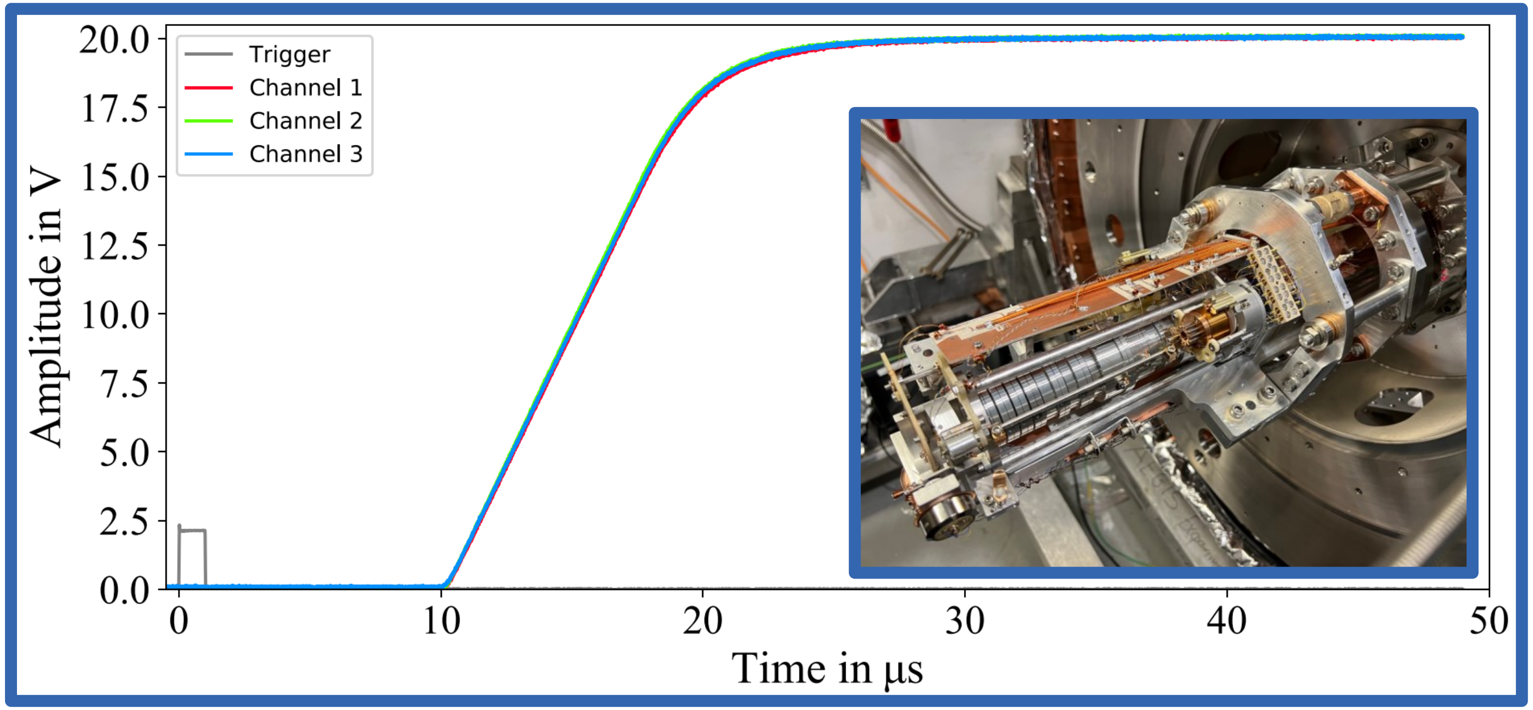


sensitivity to BR ~ 10^{-9}

georgy.kornakov@pw.edu.pl

ICHEP, Prague, July 2024

SINARA @ AEgIS



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

Fastino DAC

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

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

gergy.kornakov@pw.edu.pl