



Faculty of Physics
Warsaw University of Technology

Quantum sensing concepts for HEP

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INSTR 26, Hefei 12—17 October



- Clarification of terms
- Quantum sensors for high energy particle physics
 - Timing and tracking
 - Scintillation: fast and high yield and calorimetry
- Open software and hardware for quantum instrumentation
- Detector R&D collaboration at CERN

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.

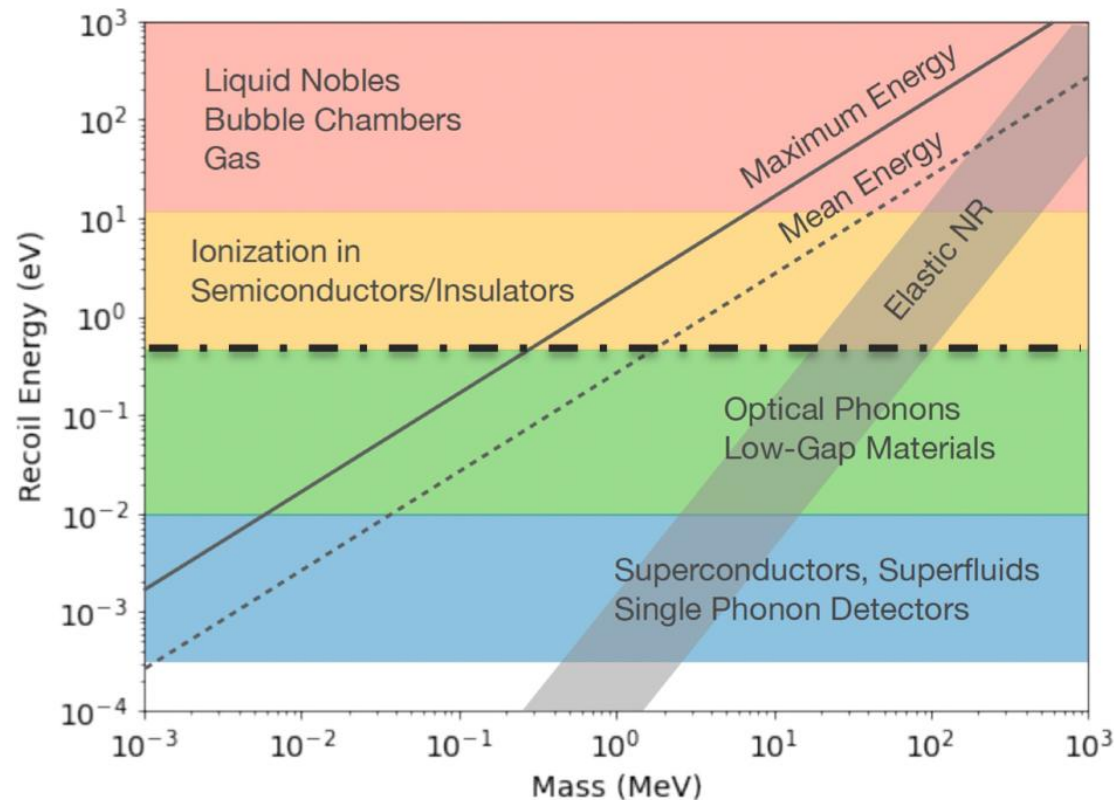
and because the commensurate energies are very low, unsurprisingly, quantum sensors are ideally matched to low energy (particle) physics;

→ 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

quantum sensing & particle physics



$$\Delta E \sim 1 \text{ eV}$$

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

$$\Delta E \sim 10 - 100 \text{ meV}$$

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

$$\Delta E \sim 1 \text{ meV}$$

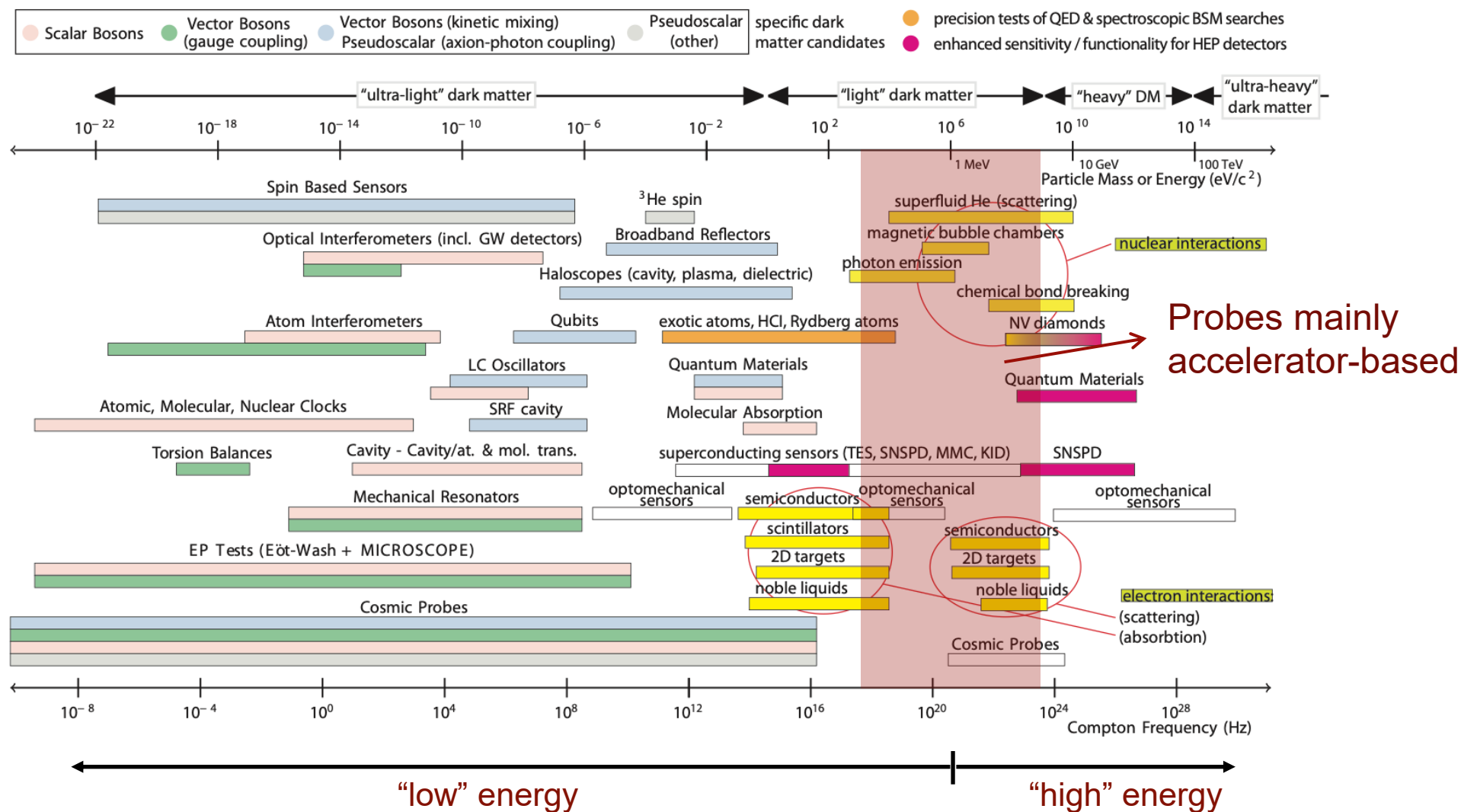
e.g. superfluids,
superconductors

Daniel Baxter | 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: Nanoscintillators, superconductors, Rydberg atoms...

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



quantum technologies

- ① superconducting devices (TES, SNSPD, ...) / cryo-electronics
- ② spin-based, NV-diamonds, SiC
- 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

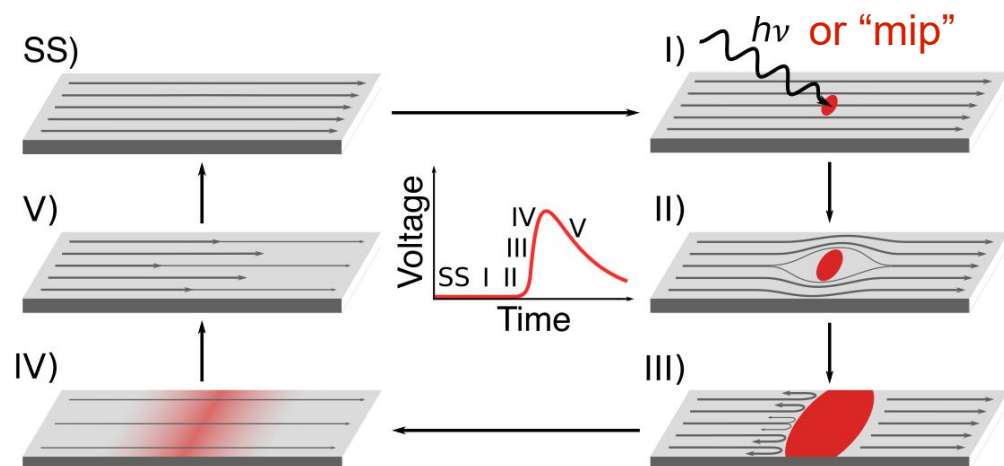
Development of new detectors for future accelerator experiments

ECFA Detector R&D Roadmap
Quantum and Emerging Technologies

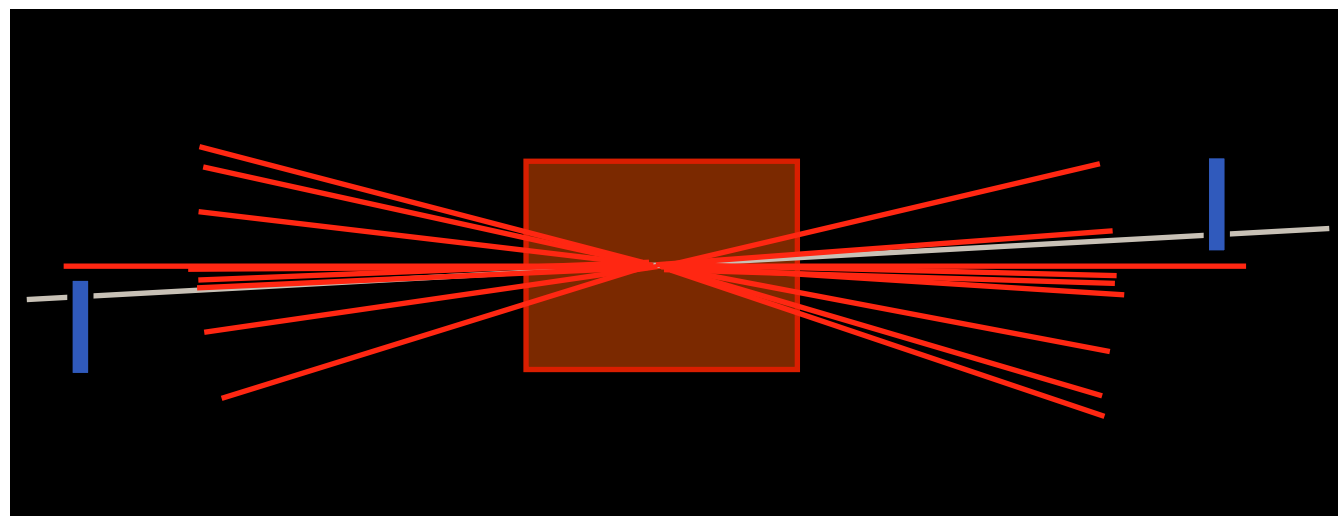
→ <https://indico.cern.ch/event/999818/>

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

Extremely fast detectors: SNSPD



diffractive scattering via ps-resolution tracking in Roman pots



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

Parameter	SOA 2020	Goal by 2025
Efficiency	98% @ 1550nm	>80 % @ 10 μ m
Energy Threshold	0.125 eV (10 μ m)	12.5 meV (100 μ m)
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

mip: ~20 keV/100 μ m

$\times 10^6$
sensitivity

Snowmass2021 - Letter of Interest

Superconducting Nanowire Single-Photon Detectors

Moving to SC strips conventional lithography $\rightarrow$ scale up
Development towards SC SSPM

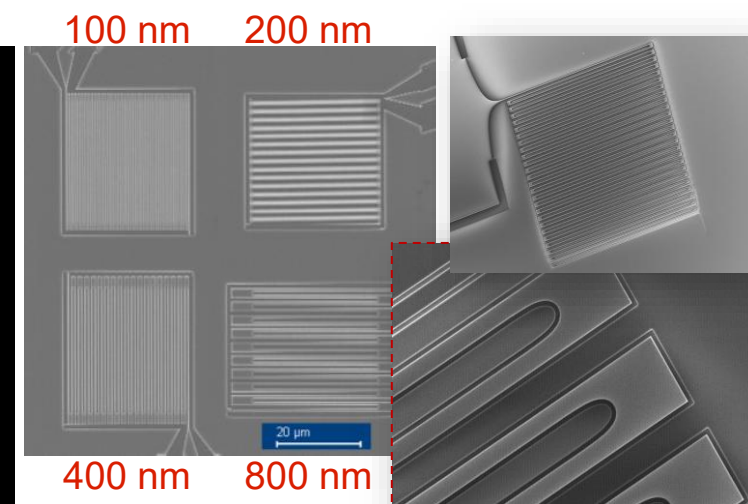
QT4HEP22-- I. Shipsey

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125

@ 2.8 K

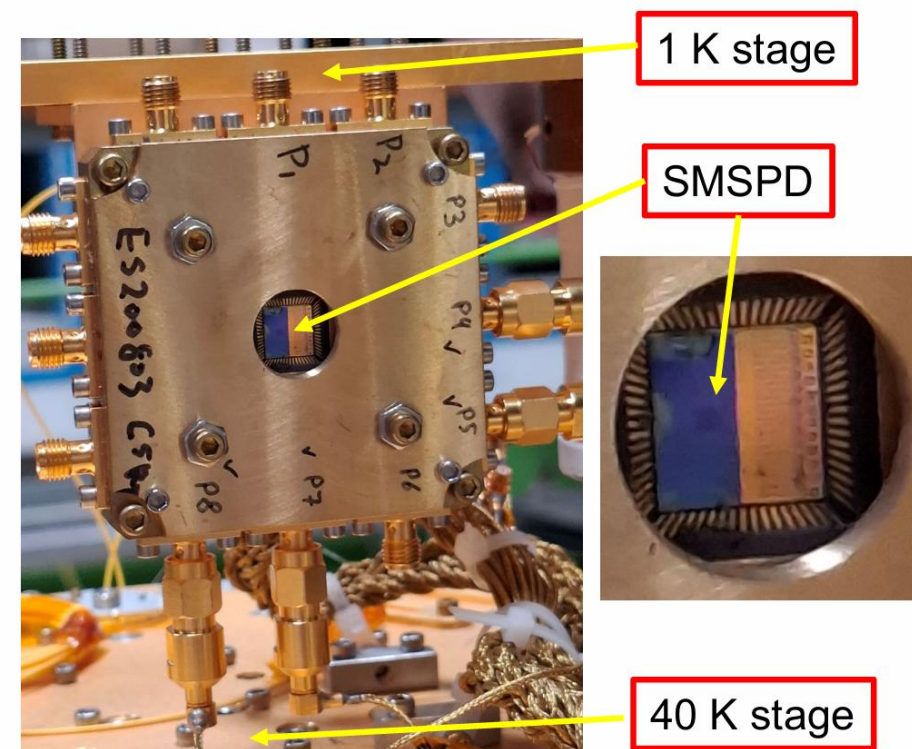
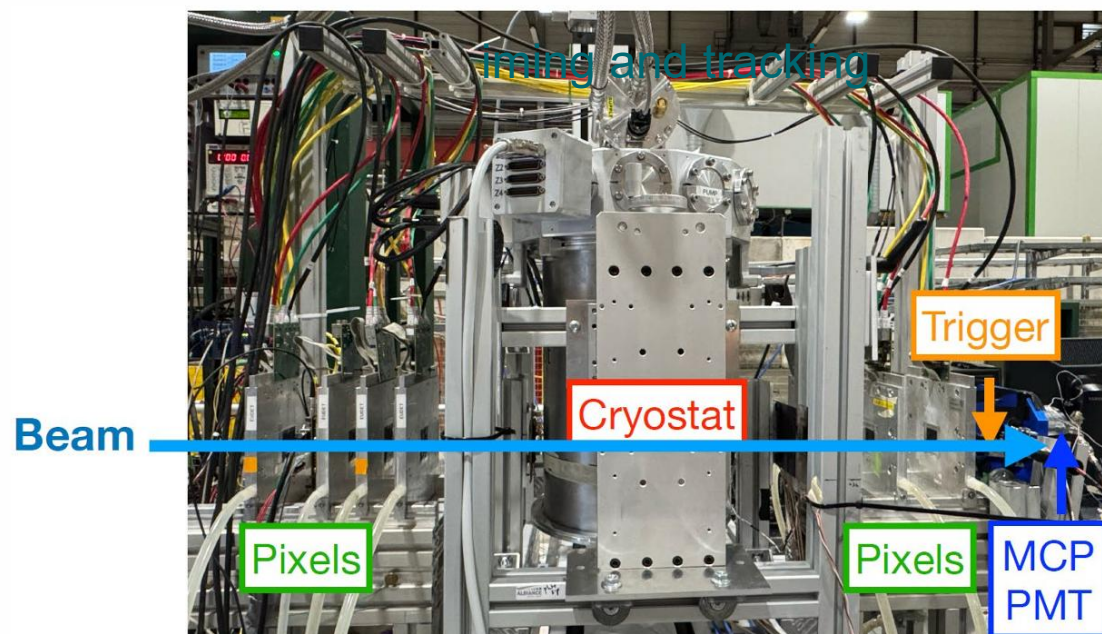


S. Lee et al., (2024)
arXiv:2312.13405v2
SNSPD w/ p@120 GeV
for use e.g. at EIC

SMSPDs for Ionizing Particle Detection



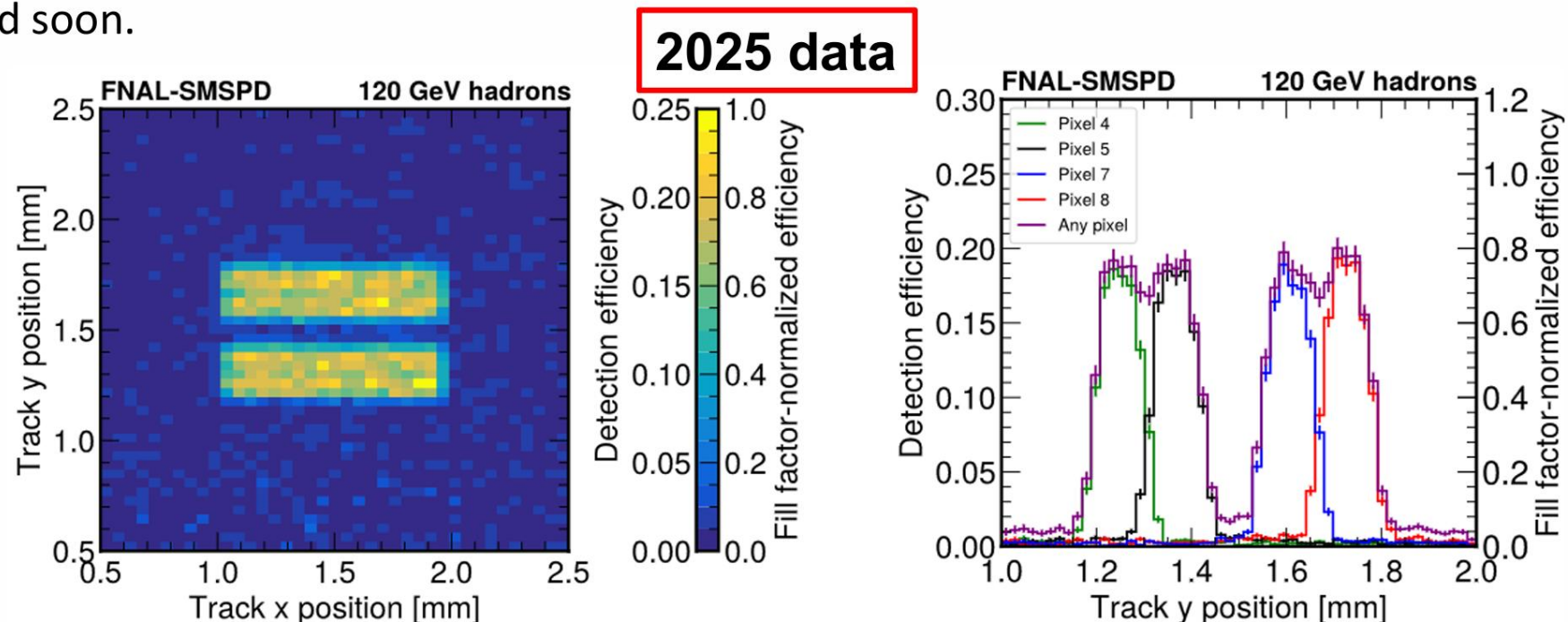
- Superconducting Nanowire Single Photon Detectors (SNSPD) are very low noise, highly efficient and fast photo sensors widely used in quantum applications.
- In 2024, [C. Pena et al.](#) demonstrated “High energy particle detection with large area superconducting microwire array” at FNAL test beam.
- Setup : Cryostat at 0.8 K, particle beam of 120 GeV protons, pixel tracker, TOF reference with MCP PMT.
- SMSPD: 3nm thick, 1.5 μm wide WSi from $\text{W}_{50}\text{S}_{50}$ target

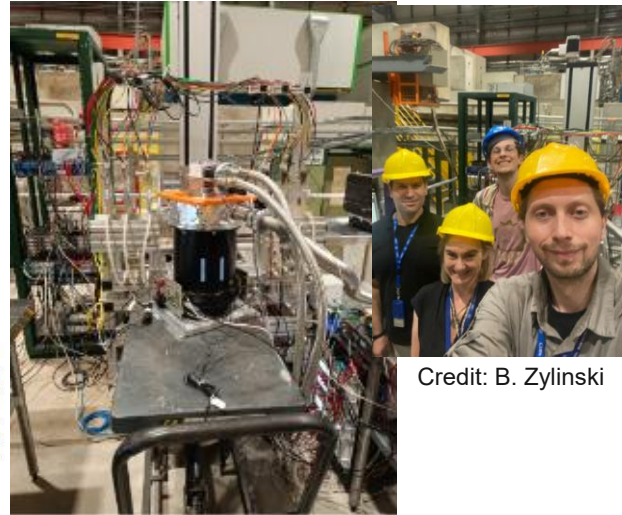
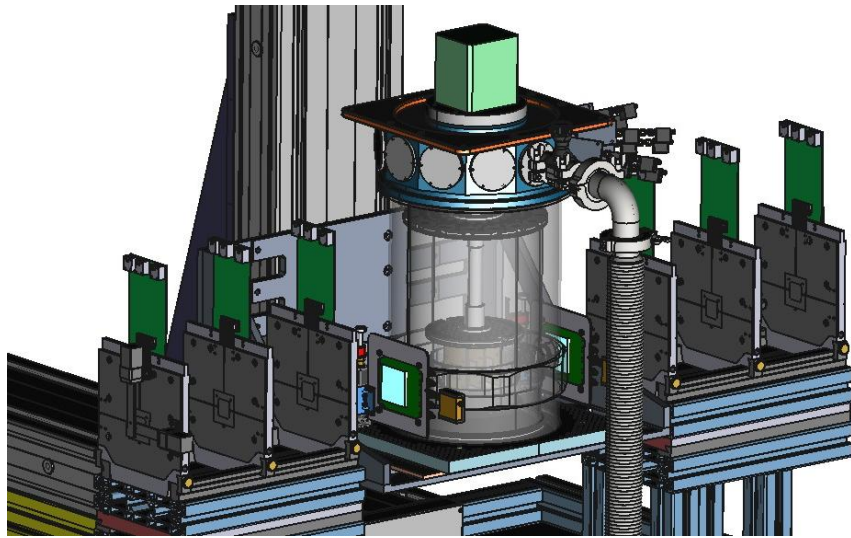




SMSPDs for Ionizing Particle Detection

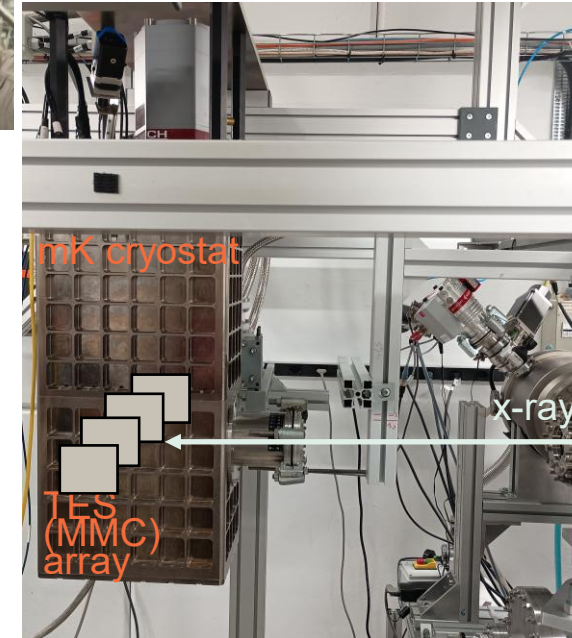
- Team led by [C. Pena @ FNAL](#) now conducts a comprehensive program to understand detection mechanism in detail and optimize efficiency and timing performance.
- Results from 2025 test beam by [C. Wang et al.](#) demonstrate progress "Towards high-efficiency particle detection using superconducting microwire arrays".
- 2025 data from multi pixel SMSPD with 4.7nm thick wire, 1 um wide WSi from $W_{30}S_{70}$ target, 25% fill factor.
- The fill factor corrected efficiency reaches 80%, the time resolution is 130 ps across one pixel.
- Measurements with 5 different SMSPD geometries measured in test beam 2026 at CERN. Results to be published soon.





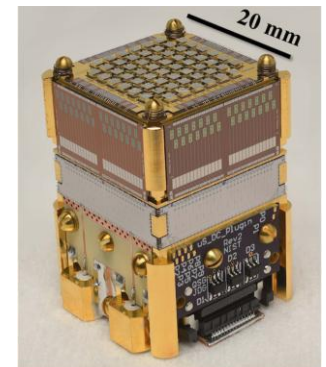
Credit: B. Zylinski

but also TELMAX $\bar{p}$ test beam line
 $\bar{p}A$ x-ray spectroscopy (PAX)
 Nancy Paul / LKB



FWHM resolution of MMC's is approximately **20eV at 33keV**

[O. Eizenberg et al., arXiv:2607.13690](#)

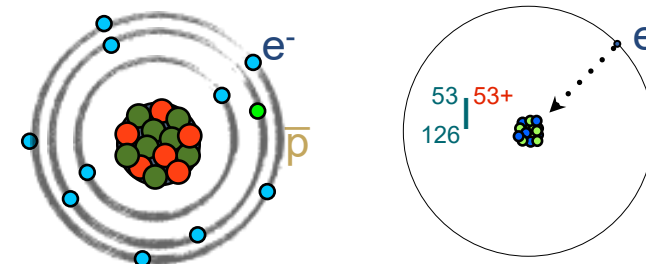


- Second prototype (K2): B. Korzh Uni Geneva (boris.korzh@cern.ch)
- All components purchased and received by UNIGE in 2026
 - Modifications requested by DRD5 community beyond K1:
 - Increase pre-cooler cooling power to: 0.9 W
 - Increase width of lowest stage from 20 cm to 40 cm
 - Accessible stages for sample mounting in front of beam path:
 - 300 mK
 - 800 mK
 - 3 K - with heaters such that it can be warmed up to 20 K and stabilized

- CERN prototype (C1): CERN Quantum Technology Initiative - II
- Clone of K2
 - With minor improvements/fixes following prototyping
 - Commissioning by mid-2028 ready for test beams
 - Procurements will start as soon as DRD5 approves

- Future CERN prototype (C2):
- If community maintains interest
 - Accessible stages for sample bracket mounting in front of beam path:
 - 60-100 mK
 - 3 K - with heaters such that it can be warmed up to 20 K and stabilized
 - Form factor: same as K2 / C1
 - Potential timeline: 2029/2030 Beam telescopes, controls systems, DAQ

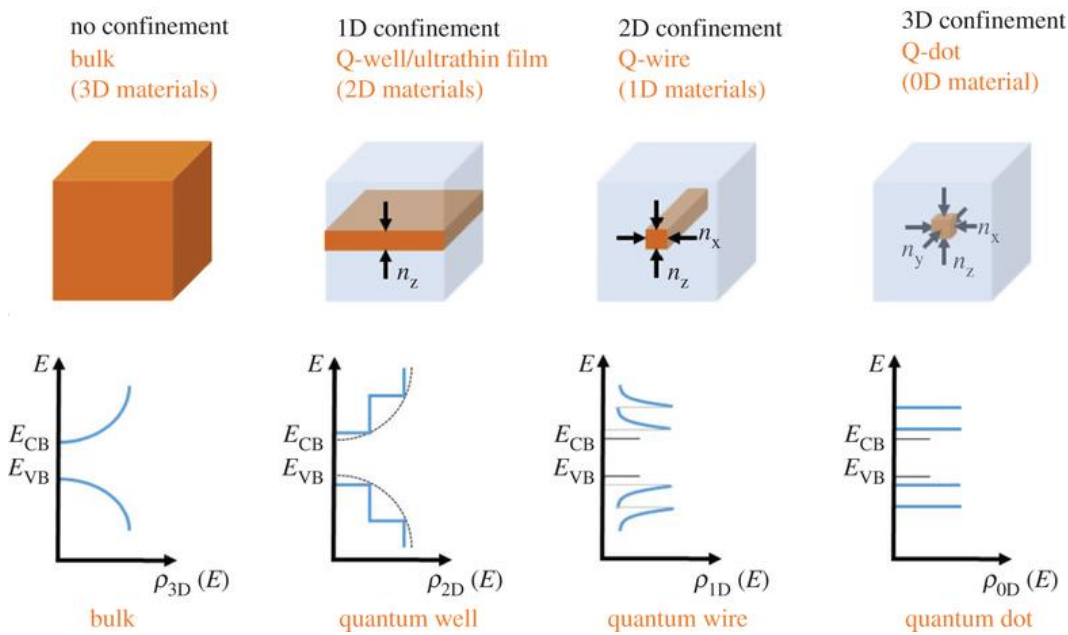
Precision tests of QED in strong field ($\Delta E/E \sim 1\text{eV} @ 10\text{keV}$)



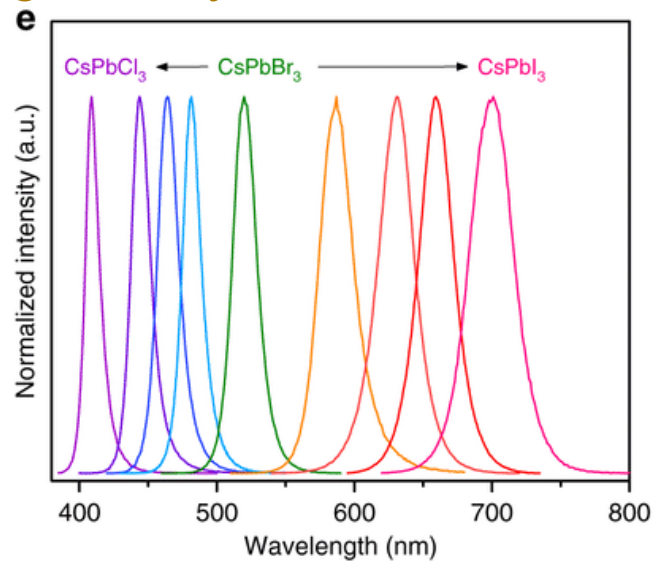
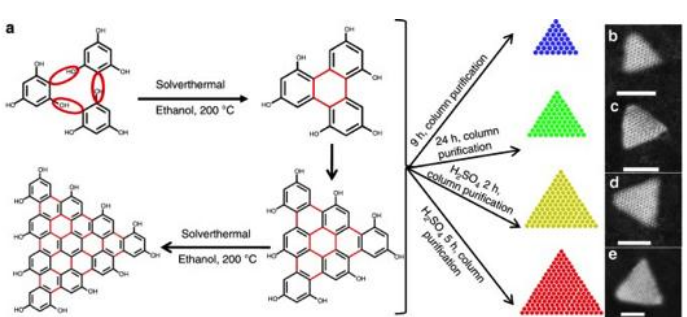
TES at 122.1 keV was **76.3 eV FWHM**
 K. Morgan et al., IEEE T.A.S, VOL.36, NO. 6,

Scintillation

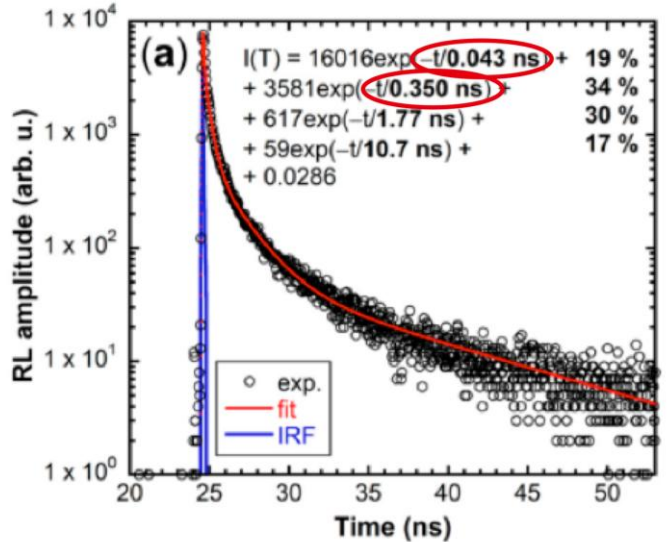
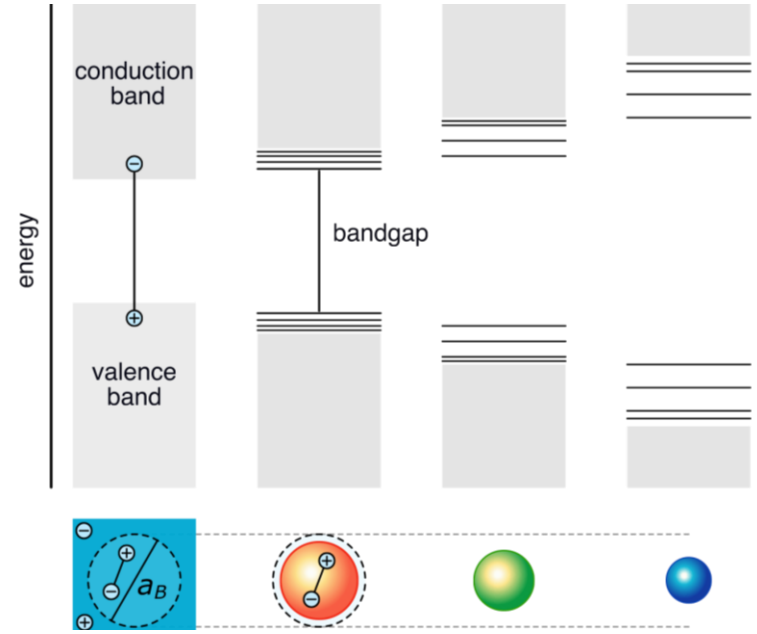
nano Scintillators



by size, composition, geometry



Goyal, R.K., Maharaj, S., Kumar, P. *et al.* Exploring quantum materials and applications: a review. *J Mater. Sci: Mater Eng.* **20**, 4 (2025).

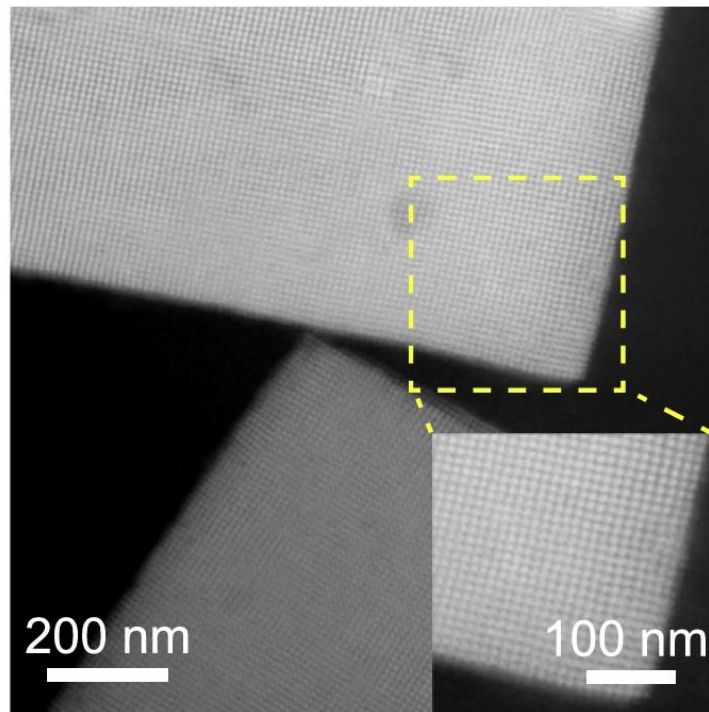


Scintillation decay time spectra from CsPbBr₃ nanocrystal deposited on glass

Scintillation Scintillation - overcoming the limitations: fast and high yield

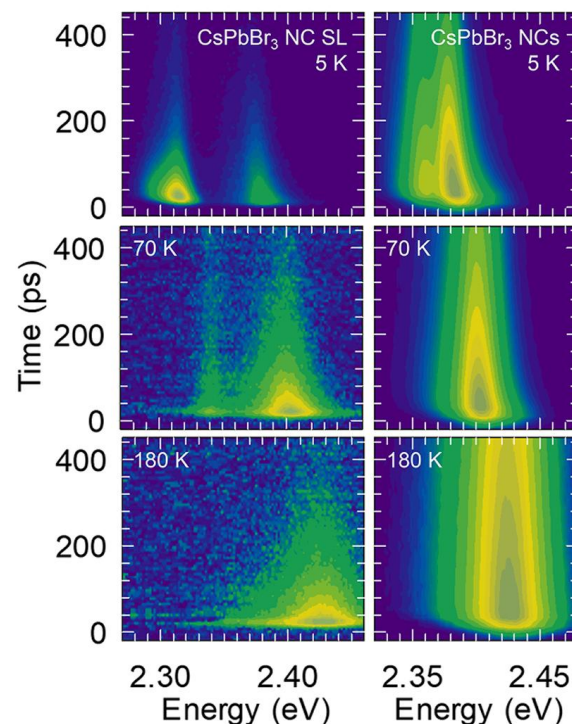
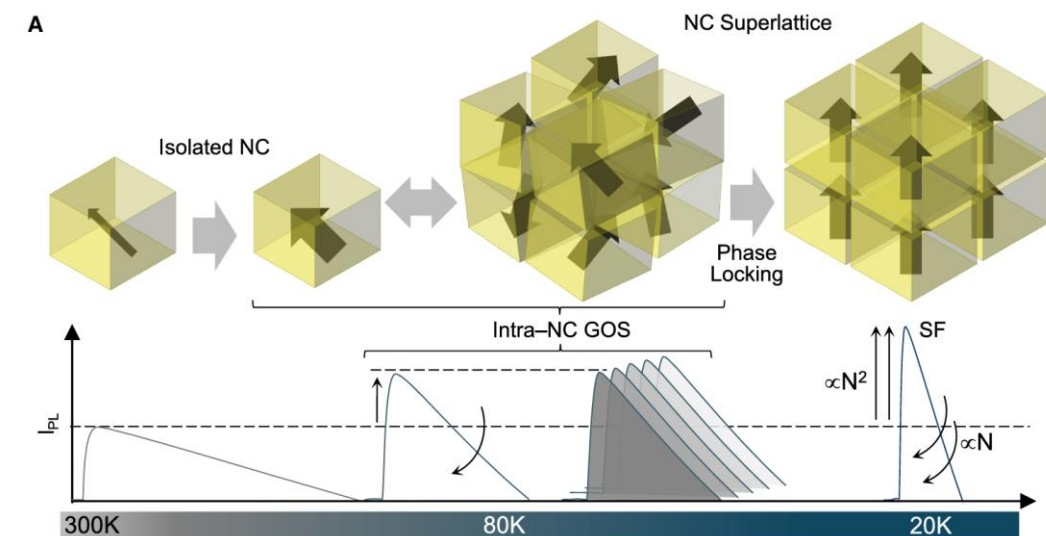
Superluminescence

Zaffalon et al., 2026, Matter 9, 102659 April 1, 2026.
<https://doi.org/10.1016/j.matt.2026.102659>

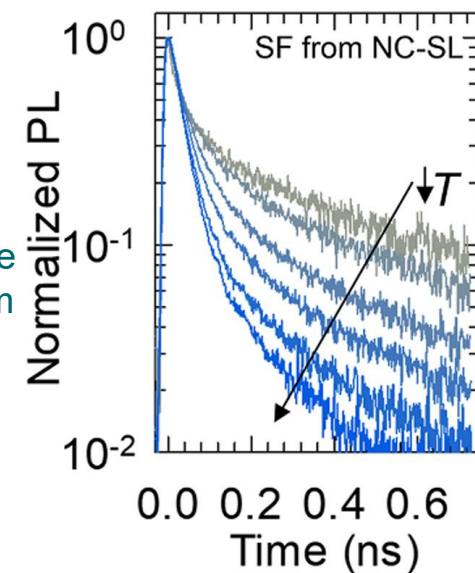


Low-magnification dark-field STEM image of two neighboring SL domains with (inset) dark-field STEM image of the area outlined with a dashed yellow line, demonstrating highly ordered NCs in simple cubic (sc) packing.

Cooperative processes in isolated NCs and in NC SLs at cryogenic temperatures. At lower temperatures, quantum phase-locking of excited states within the coherence volume of a NC SL produces an SF photon burst whose intensity and decay rate scale proportionally to the number of coupled dipoles, N .



Spectrally and time-resolved luminescence at controlled temperature (5, 70, and 180 K from top to bottom) of (A) CsPbBr (B) isolated CsPbBr NCs dispersed in polystyrene.

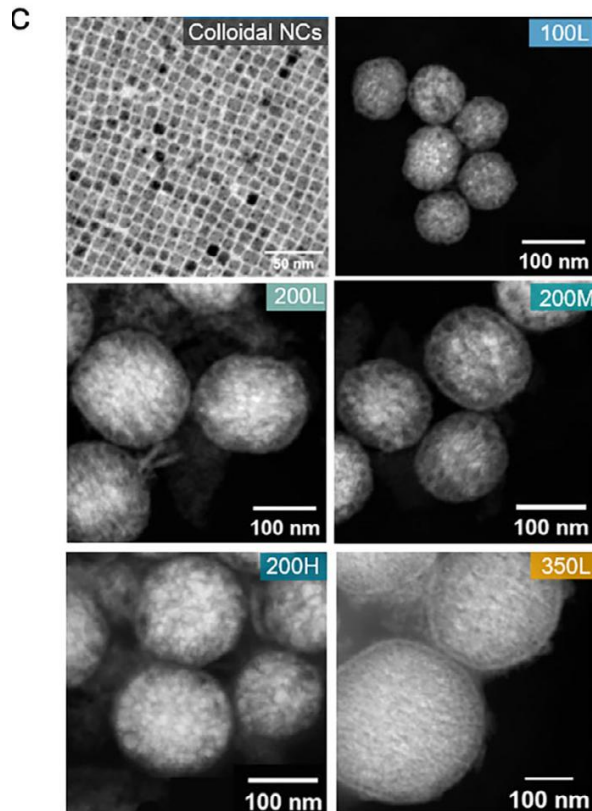


Lifetime down to ~40 ps

Normalized Photoluminescence Spectroscopy (PL) decay traces of the superfluorescence (SF) component from CsPbBr₃ NC SL in the 5–40 K temperature range.

Sample name	d (nm)	ρ (NC/MSN)
100L	100	77
200L	200	660
200M	200	1200
200H	200	1800
350L*	350	2100

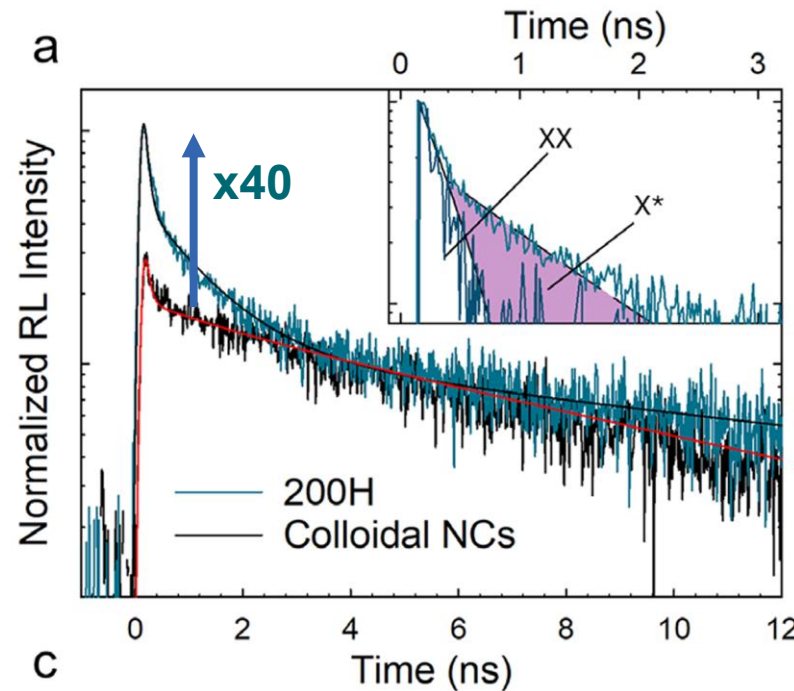
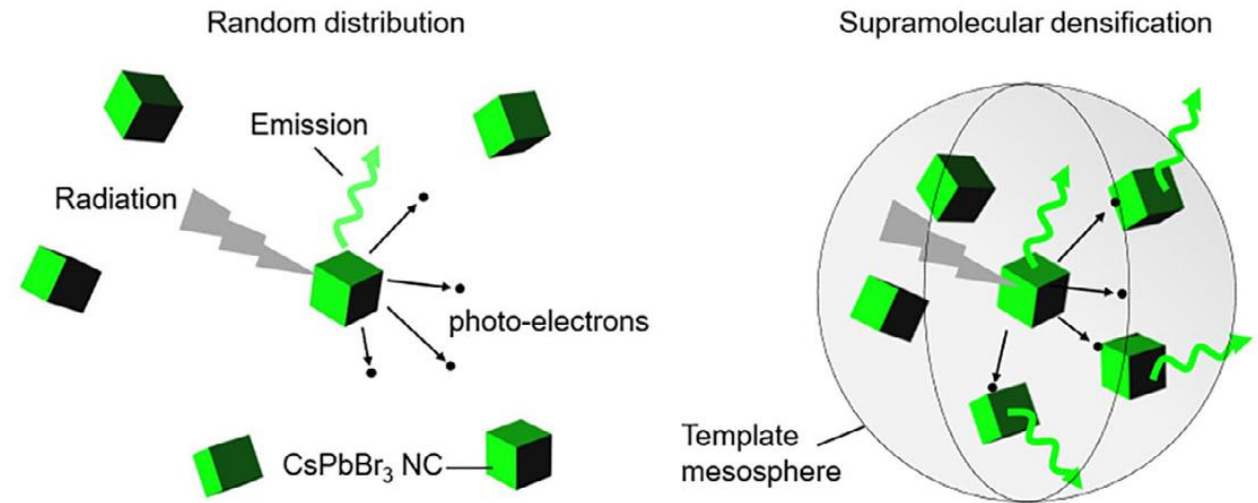
* PVK content was lower than expected



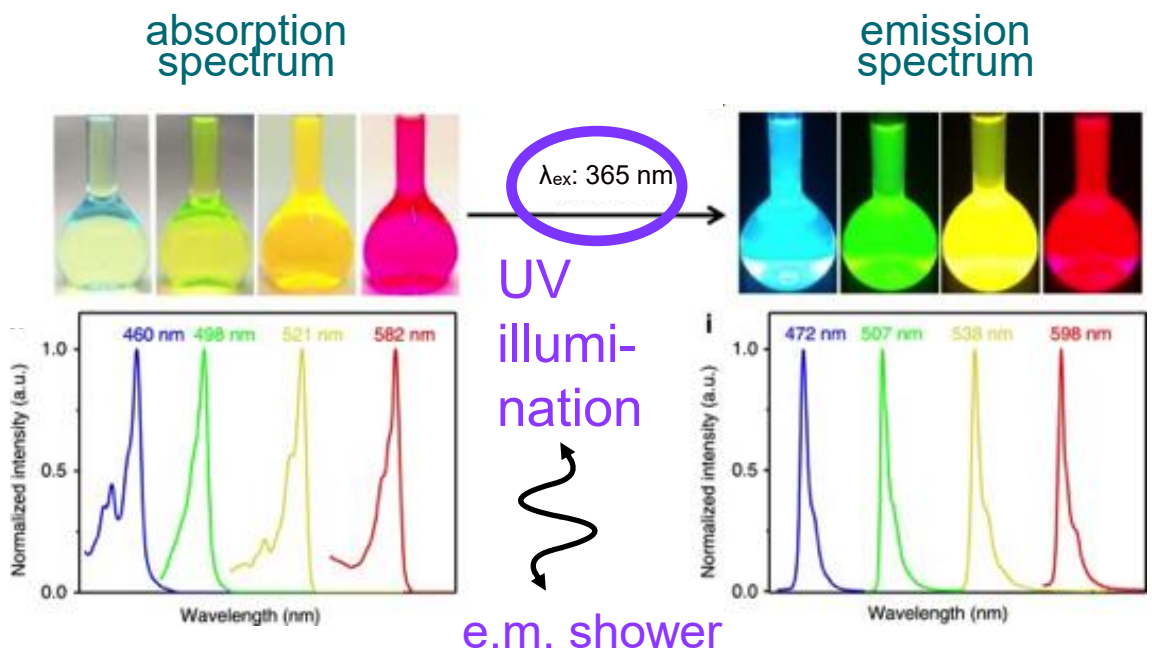
TEM images of NC-MSNs of sizes $d = 100, 200$, and 350 nm.

NCs organized into densely packed domains within porous SiO₂ mesospheres (MSNs).

40-fold increase in radioluminescence intensity compared to colloidal NCs



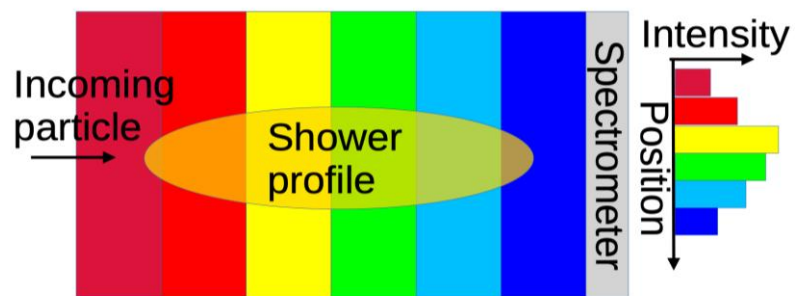
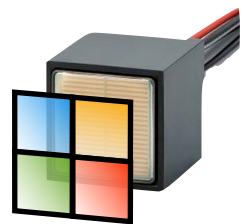
Time-resolved RL of colloidal NCs (black line) and 200H (dark green line), normalized to single exciton tail.



Narrowband emission: **large Stokes shift**
e.g. absorb wavelengths < **585 nm**
emit at > **595 nm**

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

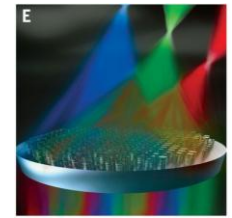
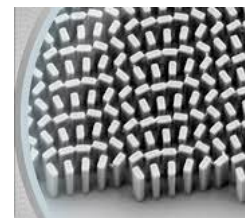
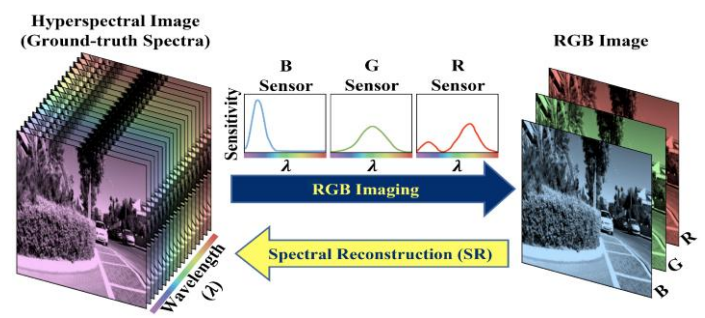
Optical filters
Inefficient; angular acceptance...



(shower profile via spectrometry)

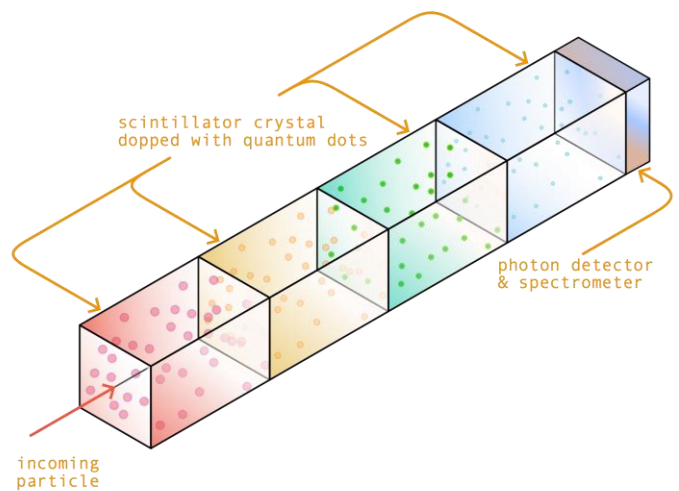
Pixel-based reconstruction
RGB-based photodetectors, require advanced algorithms to extract spectrum from RGB values
Y.T. Lin & G. Finlayson, Sensors 2023, 23(8), 4155

Metalenses
Compact, nanostructured optical devices for precise light focusing. Requires further development for scalability in HEP.
R. Cheng, M. Khorasaninejad & F. Capasso, Science 358, 6367 (2017)

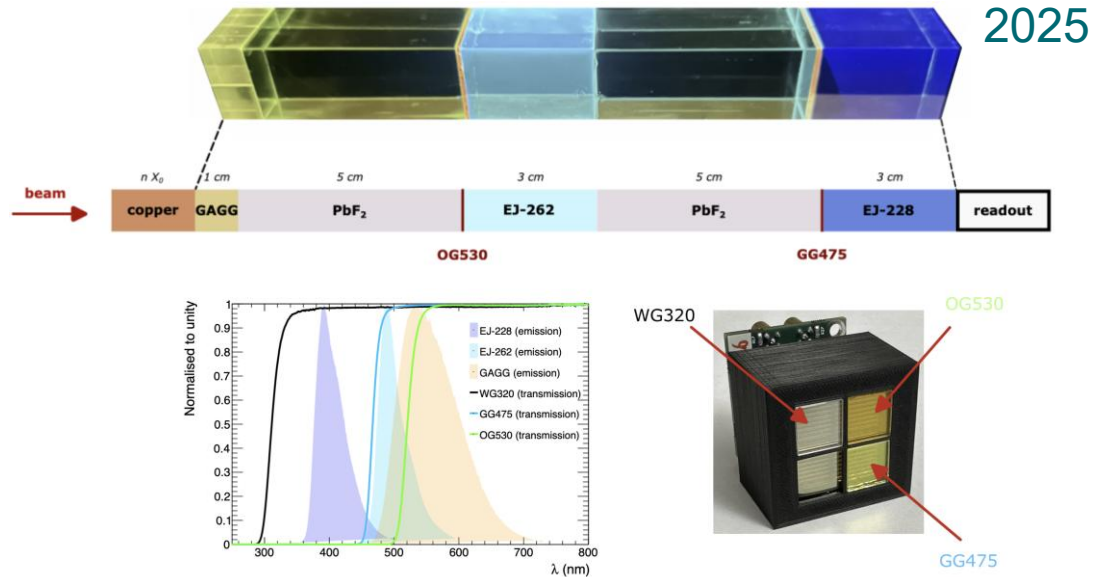


Building a CCAL needs quantum-dot-based scintillators either organic or inorganic

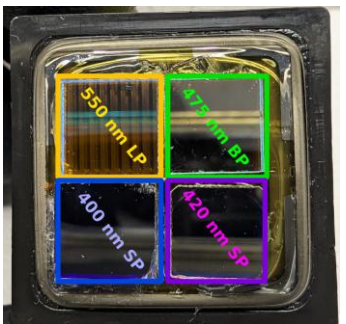
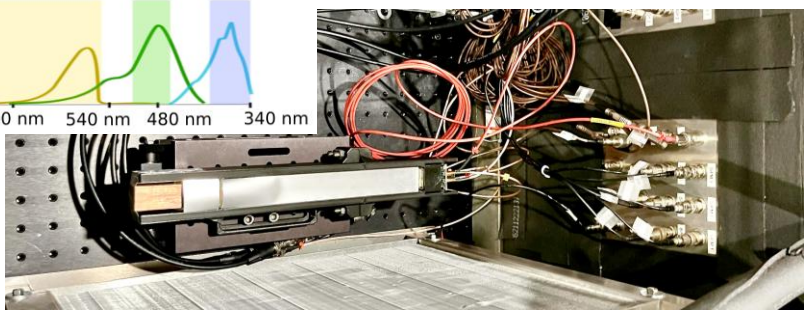
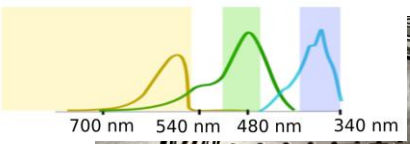
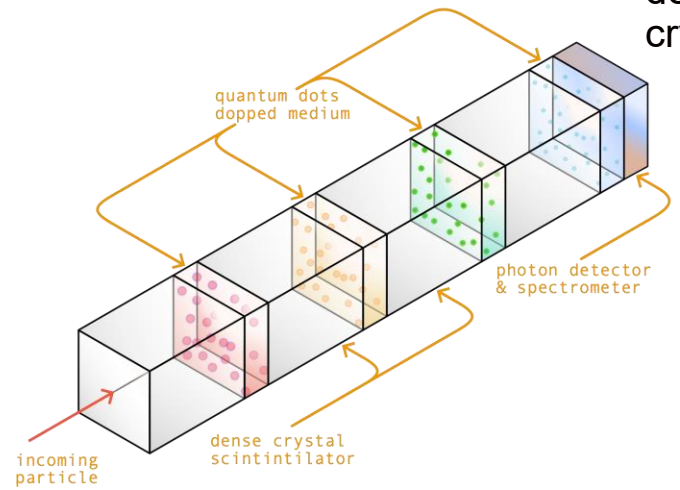
Devanshi Arora *et al* 2025 JINST 20 P06019



Option 1: Directly embedding QDs in high-Z crystals



Option 2: Hybrid approach (heterostructure*) polymer layers doped with QDs interleaved with crystals.



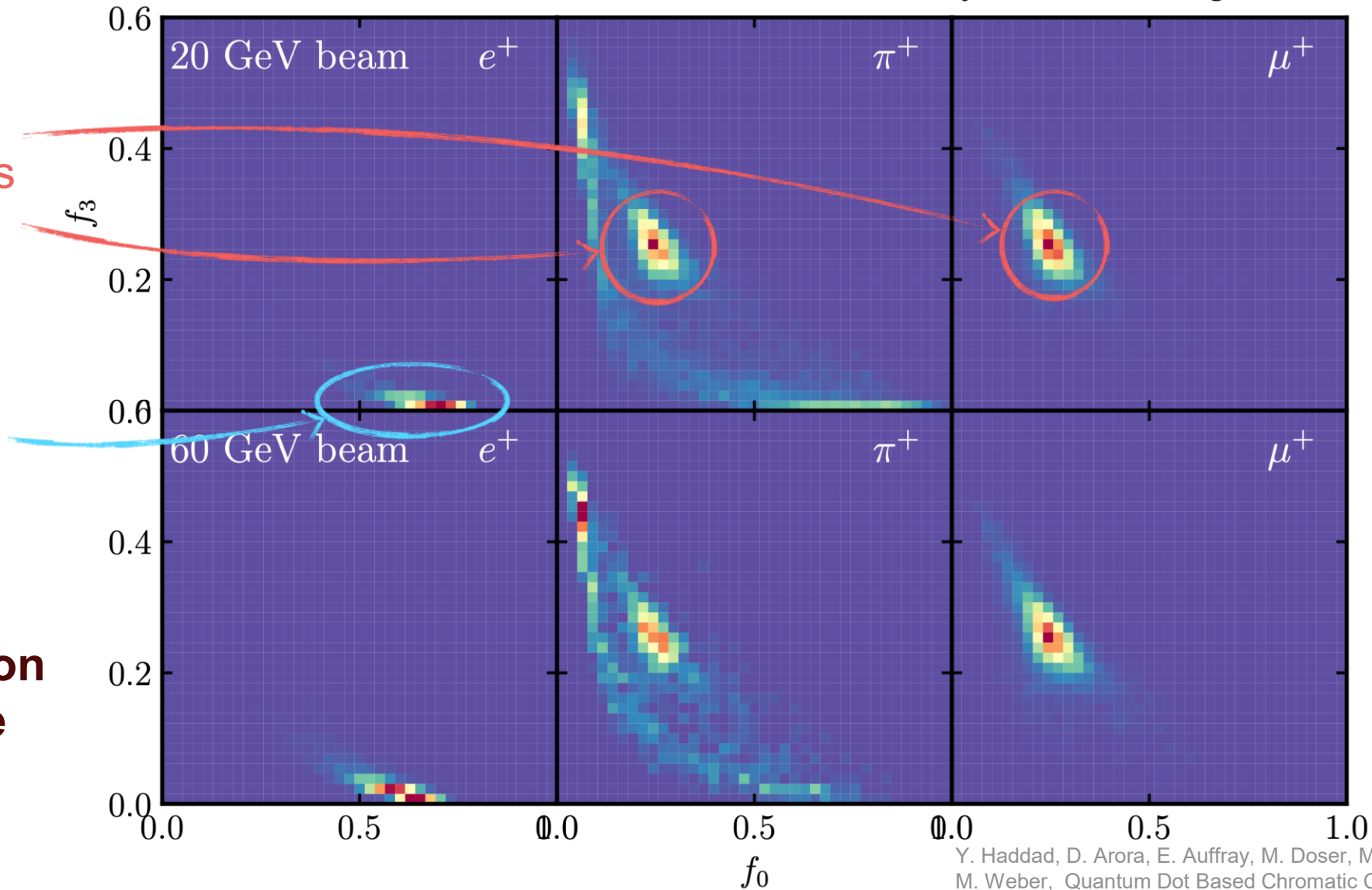
Y. Haddad, D. Arora, E. Auffray, M. Doser, M. Salomoni, M. Weber, Quantum Dot Based Chromatic Calorimetry: A proposal, arXiv:2501.12738

Geant4 used to simulate hybrid CCAL single module

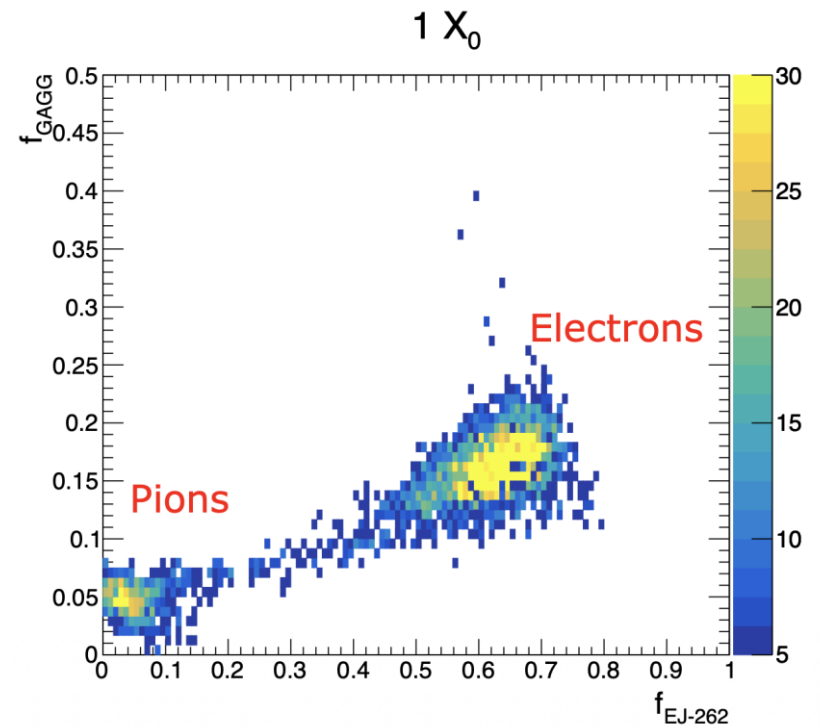
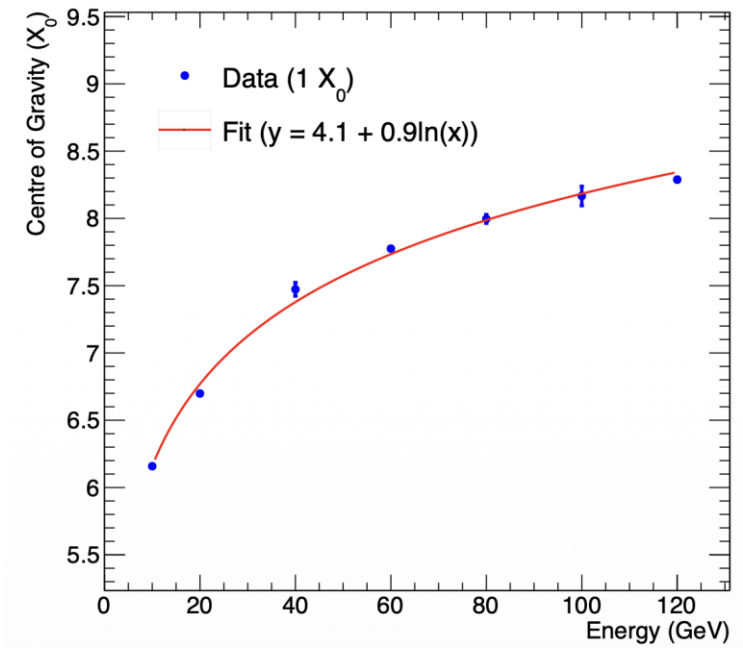
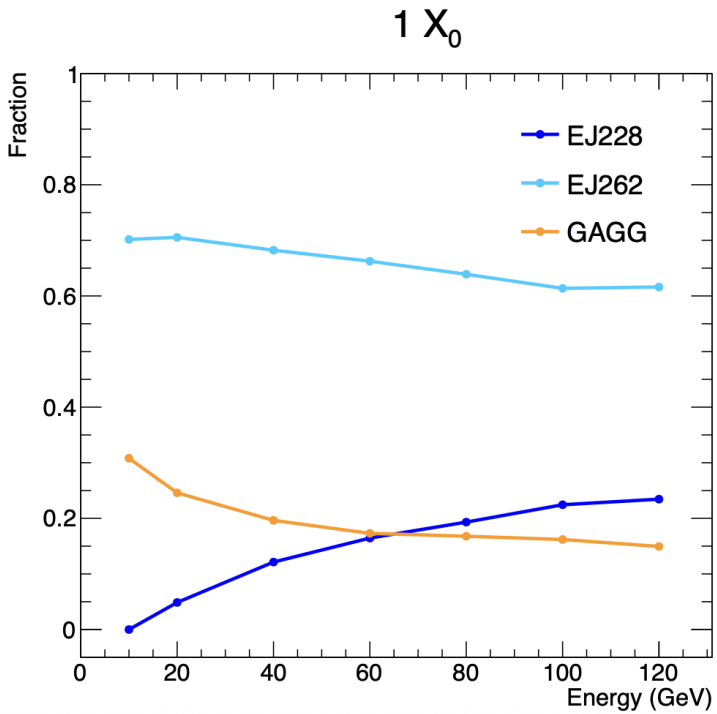
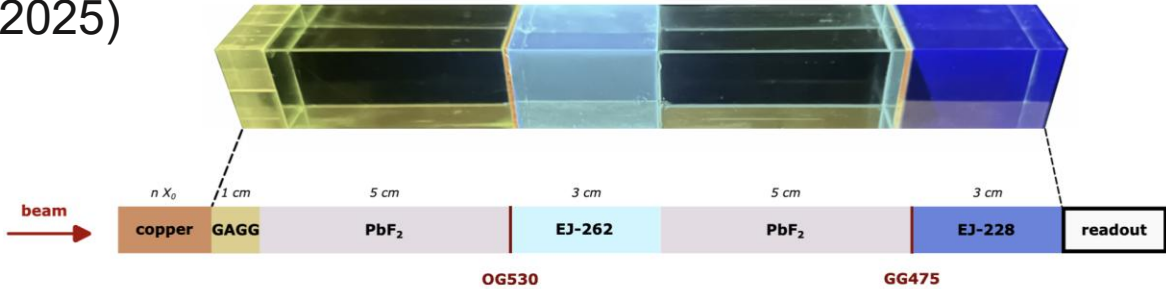
Minimum
Ionising
Particles

Electromagnetic
Showers

Depth information
used for particle
identification



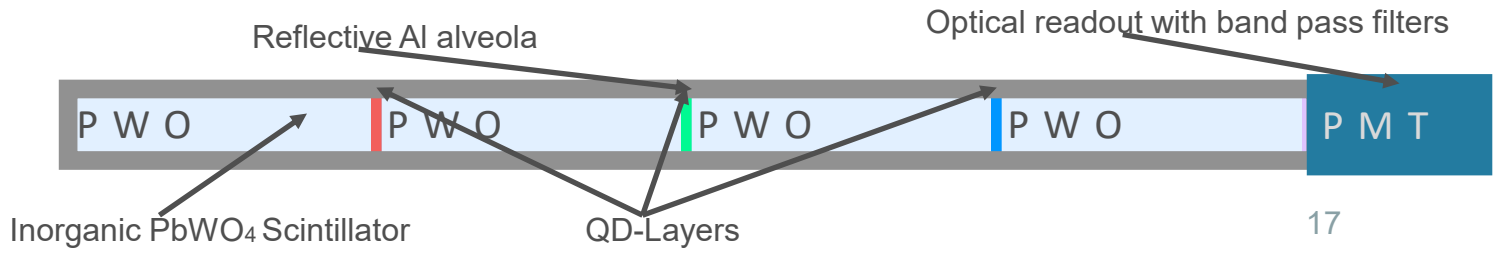
Y. Haddad, D. Arora, E. Auffray, M. Doser, M. Salomoni, M. Weber, Quantum Dot Based Chromatic Calorimetry: A proposal, arXiv:2501.12738



The trend in energy is logarithmic, as expected, demonstrating the capability of the CCAL to resolve the longitudinal shower profile

Particle-id based on the fraction correlations

In 2026 tests with nanodot based solution



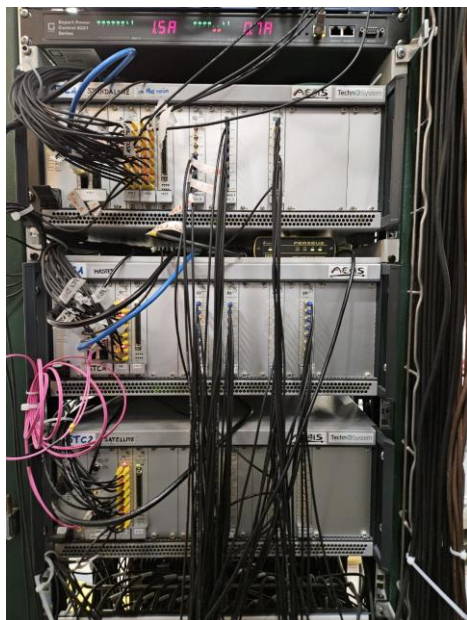
SINARA / ARTIQ

Real time ns control

An open, modular ecosystem

Scalable and flexible

More than 80 boards and hundreds of labs as users



Sinara crate and modules / TechnoSystem



Modular

Mix ADC, DAC, RF and I/O to fit your experiment.



Coordination

Unify control, clocks and triggers across peripherals.

ARTIQ

Python-based experiment definition

Versioned code, stored parameters and results support reproducibility.

Development in progress

DIOT integration

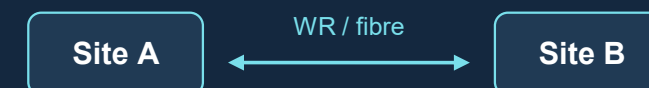
Easier servicing and reconfiguration

Backplane-based crate

White Rabbit

Common time base for remote experiment sites

Sub-ns time synchronization at distances >1000 km!



“Quantum” is relevant(also for HEP)→ DRD5

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	Helicity detector via transfer of atomic polarization to bulk
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 O(<ps) optical charged particle detection	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)	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)				
WP 6 (capacity building)					
(under way; in preparation; under discussion or imaginable applications; long-range potential)					

Infrastructure @ CERN

CERN QTI

DRD5: WP’s (particle physics > HEP)

WP1

Exotic systems in traps & beams (HCI’s, molecules, Rydberg systems, clocks, interferometry, ...)

WP4

Scaling up to macroscopic ensembles (spins; nano-structured materials; hybrid devices, opto-mechanical sensors,...)

WP2

Quantum materials (0-, 1-, 2-D) (Engineering at the atomic scale)

WP5

Quantum techniques for sensing (back action evasion, squeezing, entanglement, Heisenberg limit)

WP3

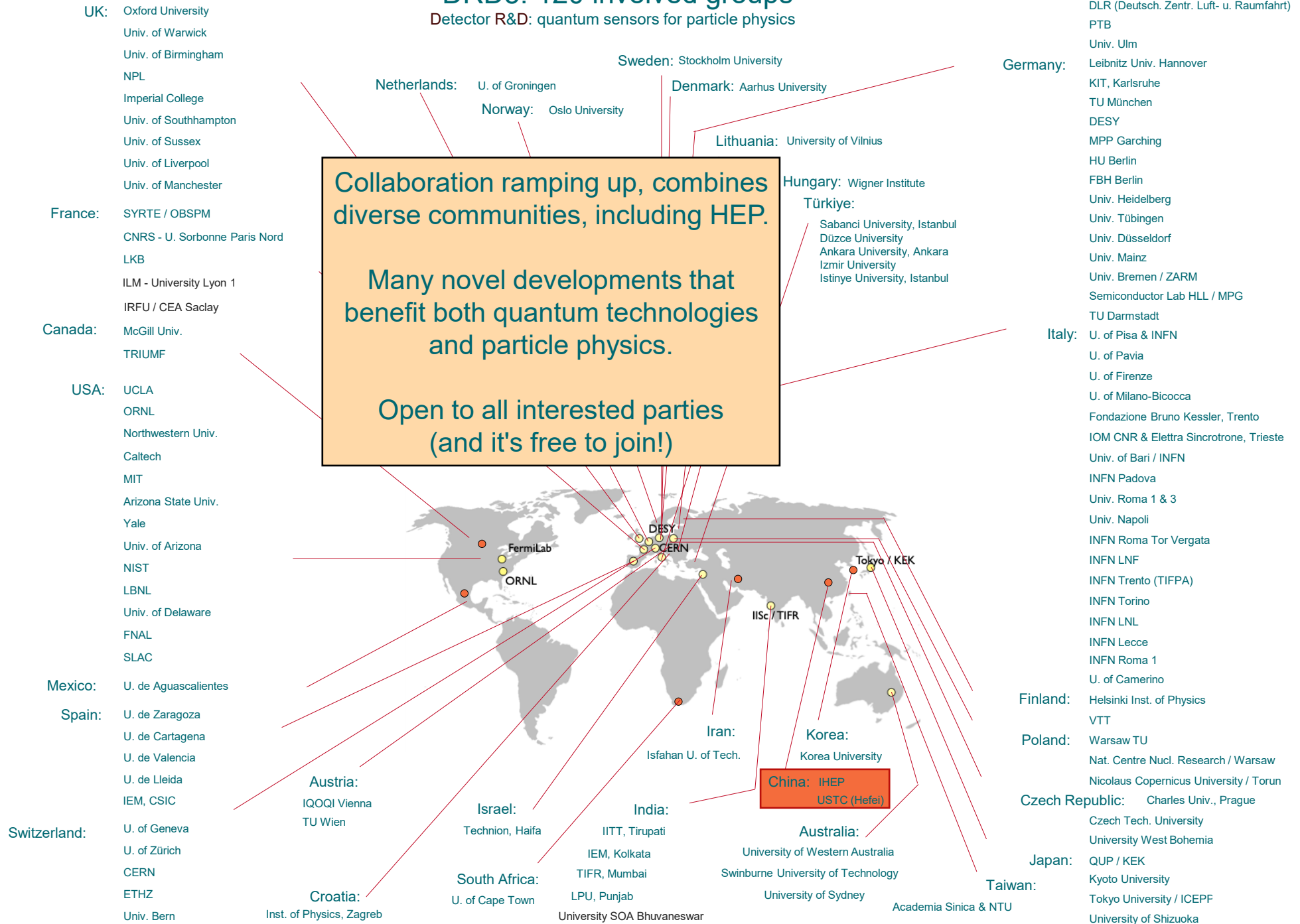
Quantum superconducting systems (4K electronics; MMC’s, TES, SNSPD, KID’s/...; integration challenges)

WP6

Capacity building (cross-disciplinary exchanges; infrastructures; education)

DRD5: 120 involved groups

Detector R&D: quantum sensors for particle physics



Oct. 13, 2026: WP-5: "Quantum sensing techniques in astro-particle searches" (Zoom)

Nov. 18, 2026: "Open Software and Hardware for Quantum Experiments"

Nov. 19-20, 2026: "Simulation of Nanocomposites and Nanodevices" (Bern)

Jan. 18-22, 2027: "Mechanical Quantum Sensors for New Physics Searches" (MITP Mainz);



backup

•SNSPDs as Particle Detectors

- Ultrathin, ~100-nm-wide superconducting strip on Si / SiN / SiC / sapphire / diamond substrate
- Current biased at a few K, operated just below it's transition point
- Single photon triggers brief resistive state, high efficiency at telecom bands, picosecond-scale timing, and ultra-low dark counts
- Absorbed photon locally breaks Cooper pairs forming nonequilibrium quasiparticle
- Current density increase round hotspot, superconductivity collapse

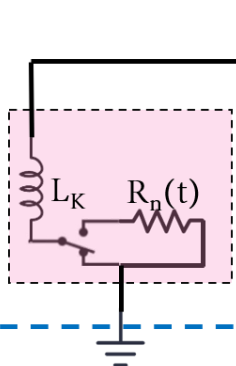
Cryostat

SNSPD

Bias-tee

Amplifier (G)

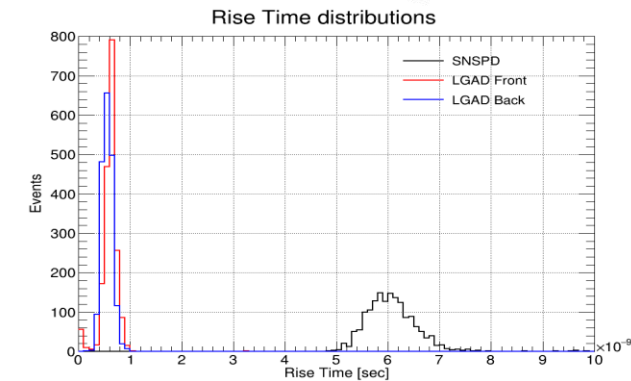
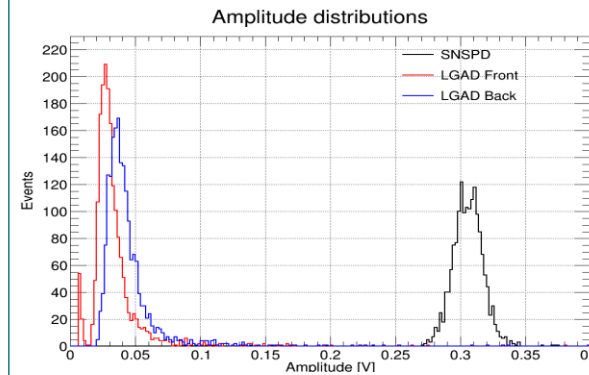
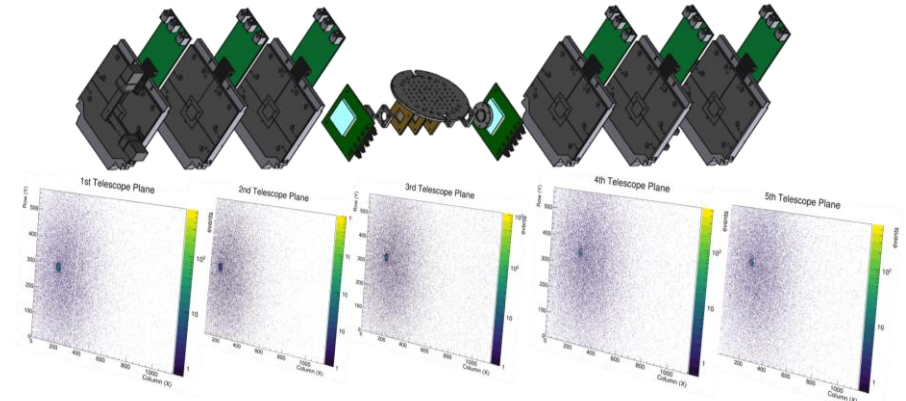
Read-Out Chain



Timing Characteristics

$$t_{\text{Rise}} = L_K / (Z_L + R_n(t)) \quad t_{\text{Decay}} = L_K / Z_L$$

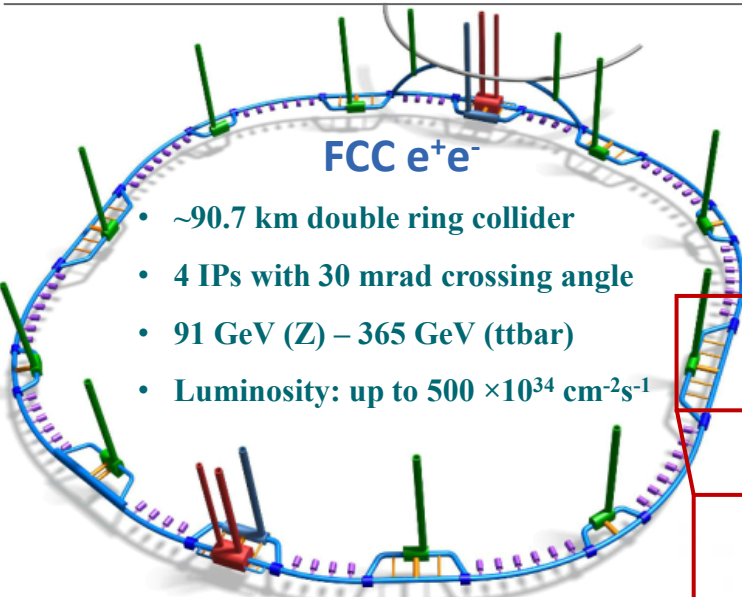
V. Gkougkousis, 33rd International Workshop ON Vertex Detectors
 “Tracking & timing performance of SNSPDs under 160 GeV SPS pion beams”



2025 period (August, 160 GeV $\pi^0, \pm$)

- First ever particle detection with **NbTiN** and **MbB₂** films
- 2.28 K operation within the AIDA telescope in H6B area
- 100 psec timing, 6 nsec rise times with 200 x 200 μm samples
- Two weeks beam time at DESY (March- April 2027)

•Superconductive Luminometer

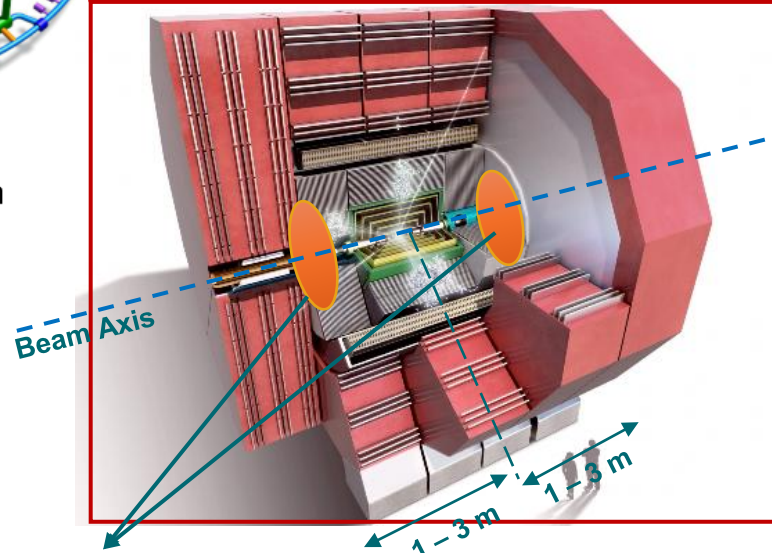


SN-SPDs based Luminometer

- ✓ Sub-per mill resolution through small angle Bhabha scattering

$$\sigma = \frac{16\pi\alpha^2}{s} \left(\frac{1}{\theta_{\min}^2} - \frac{1}{\theta_{\max}^2} \right)$$

- ✓ Goal of 10^{-4} precision on absolute luminosity
- ✓ Readout at Bunch-crossing rates with < 20ns shaping time
- ✓ 1.5 MGray dose at Z pole
- ✓ Pile-up ~ $1\text{E-}3$ / event
- ✓ $\sigma(\text{Z}) \sim 40\text{nb}$, $\sigma(\text{Bhabha}) \sim 14 \text{ nb}$



V. Gkougkousis, 14th International Conference on Position Sensitive Detectors
 “Towards a Superconducting Luminometer for FCC-ee”



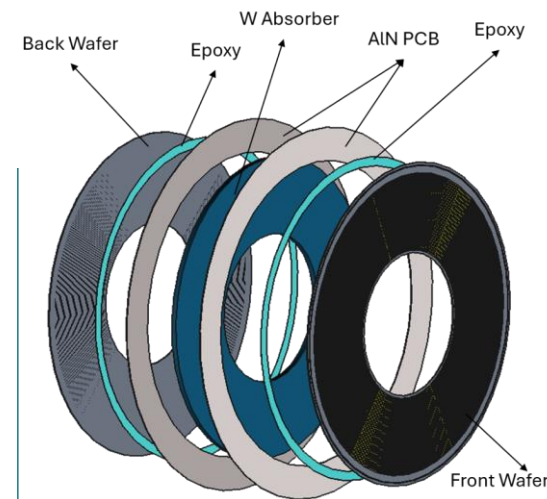
University of Zurich ^{UZH}



Warsaw University of Technology



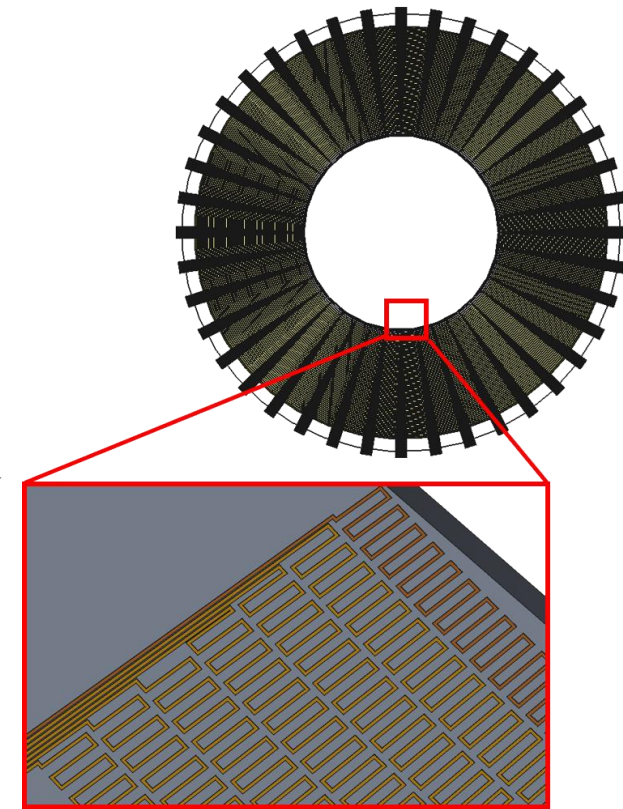
VTT Technical Research Centre of Finland



Sensor geometry: 100 % Fill Factor in multilevel staggered process

200 nm wide MgB₂ Film, 2 μm thickness

- 20 X 12” single wafers, 2 wafer per layer
- Sensors arranged in Tracks and Sectors
- 60 X 1 mm wide tracks spanning the perimeter of wafer from 54 mm to 114 mm
- 40 Sectors, each with 9° angular coverage
- Radial readout corridors between sectors, 1 mm wide
- Readout region is inherently active as nanowire extends to the periphery of the wafer



•Simulations & Common Framework

Contact: Vagelis Gkougkousis (egkougko@cern.ch)

- Custom implementation combining standard PAI model combined with Drude-Lorenz for low energy contribution:

$$\left(\frac{d\sigma}{d\Omega}\right)_{total} = \begin{cases} \left(\frac{d\sigma}{d\Omega}\right)_{DL,NbTiN} & 0.8 \text{ eV} < E_{tr} < 10 \text{ eV} \\ \left(\frac{d\sigma}{d\Omega}\right)_{PAI,NbTiN} & E_{tr} \geq 10 \text{ eV} \end{cases}$$

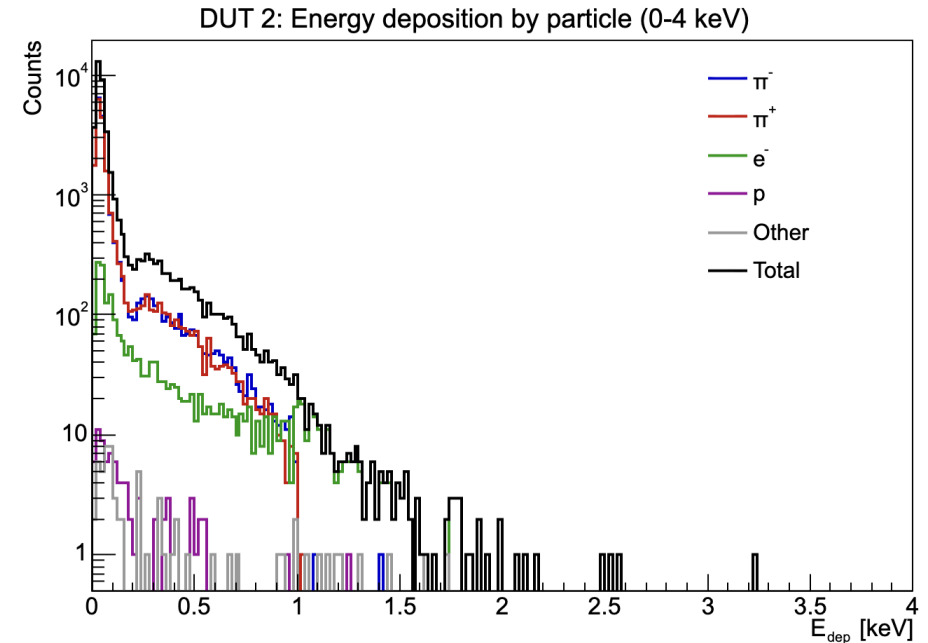
ELF -> Energy Loss Function

$$ELF(E_{tr}, q) = \text{Im} \left[-\frac{1}{\varepsilon(E_{tr}, q = 0)} \right]$$

$\varepsilon(E_{tr}, q)$ → Complex Dielectric Function

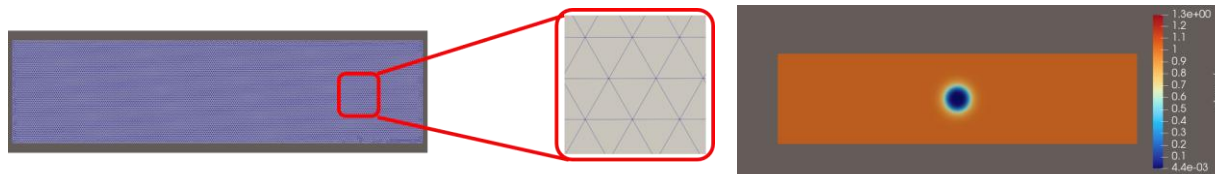
E_{tr} → Energy Transfer

q → Momentum Transfer (optical limit $q = 0$)



- 2-temperature model with quasiparticle diffusion / recombination, time-dependent Ginzburg - Landau model for hotspot:

$$\underbrace{\Gamma \left(\frac{\partial \psi}{\partial t} + i \frac{q^*}{\hbar} \phi \psi \right)}_{\text{Time evolution term}} = \underbrace{\frac{\hbar^2}{2m^*} \left(\nabla - i \frac{q^*}{\hbar} A \right)^2 \psi}_{\text{Kinetic (vortex)}} - \underbrace{\alpha \psi - \beta |\psi|^2 \psi}_{\text{GL free energy potential}}$$



- Synopsys full fabrication simulation
- Parameter tuning with geometry optimization and defat introduction
- Cross-feed with fabrication and re-optimization processes
- DFT Integration for BandGap

SYNOPSYS®

