Quantum sensors for particle identification in HEP

Michael Doser / CERN

PHOSE2023

Focus on photon detection for:

- high energy photons: energy measurements
- low energy particles: x-ray measurements
- use of photon detectors for other HEP applications

photon detection in the framework of calorimeters

long chain between

- photon generation by particles in material ← simulation beyond G4!
- photon transport
- WLS (optimizing QE for PD)
- transformation into electronic signals

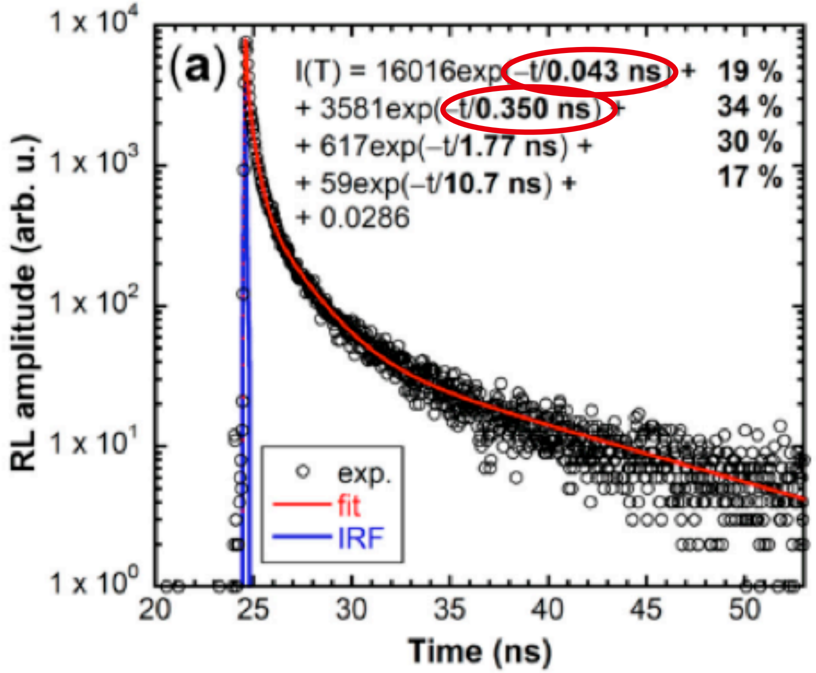
what we're interested in is:

- timing
- total energy deposited
- where energy is deposited

Quantum dots: timing

Etiennette Auffray-Hillemans / CERN

Scintillation decay time spectra from $CsPbBr_3$ nanocrystal deposited on glass



K. Decka et al., Scintillation Response Enhancement in Nanocrystalline Lead Halide Perovskite Thin Films on Scintillating Wafers. Nanomaterials 2022, 12, 14. https://doi.org/ 10.3390/nano12010014

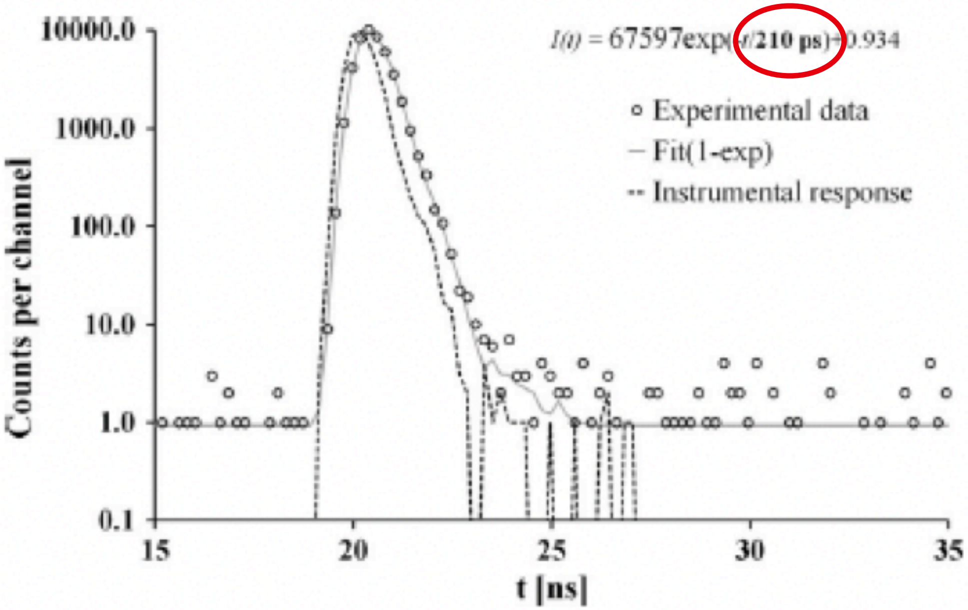


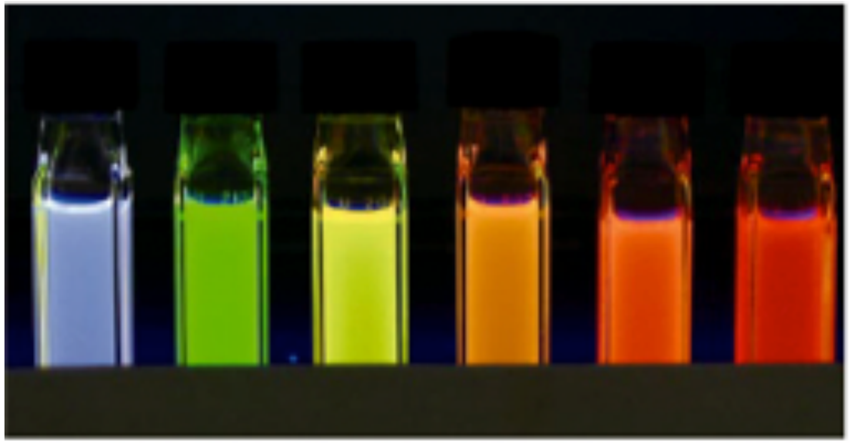
Fig. 9. Photoluminescence decay of ZnO:Ga sample at room temperature. Excitation nanoLED 339 nm, emission wavelength set at 390 nm. Decay curve is approximated by the convolution of instrumental response (also in figure) and single exponential function $I(t)$ provided in the figure.

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

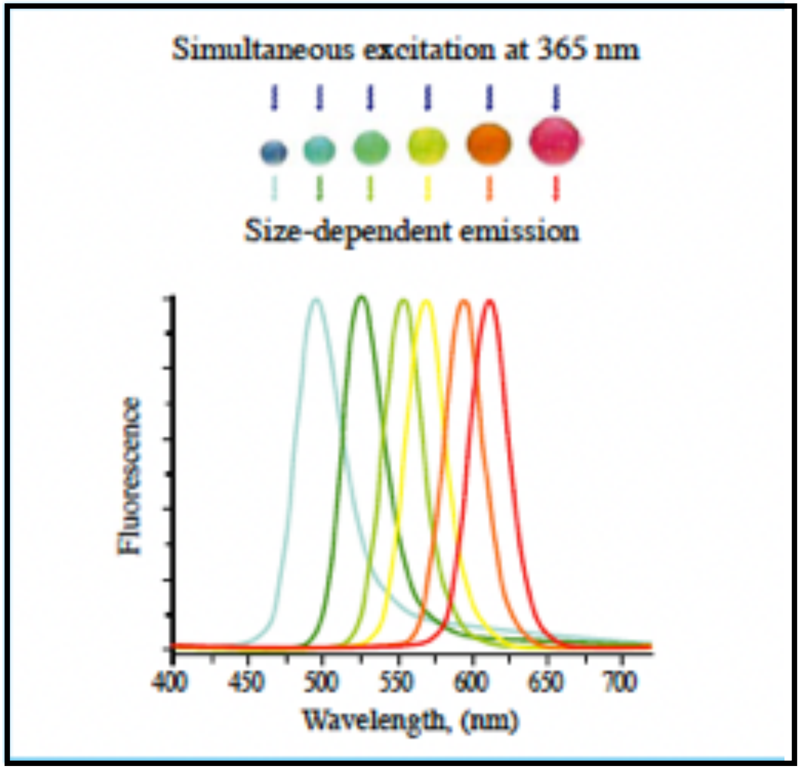
Concern: integrated light yield (need many photons to benefit from rapid rise time)

Quantum dots: chromatic tunability

Etiennette Auffray-Hillemans / CERN



Hideki Ooba, "Synthesis of Unique High Quality Fluorescence Quantum Dots for the Biochemical Measurements," AIST TODAY Vol.6 , No.6 (2006) p.26- 27

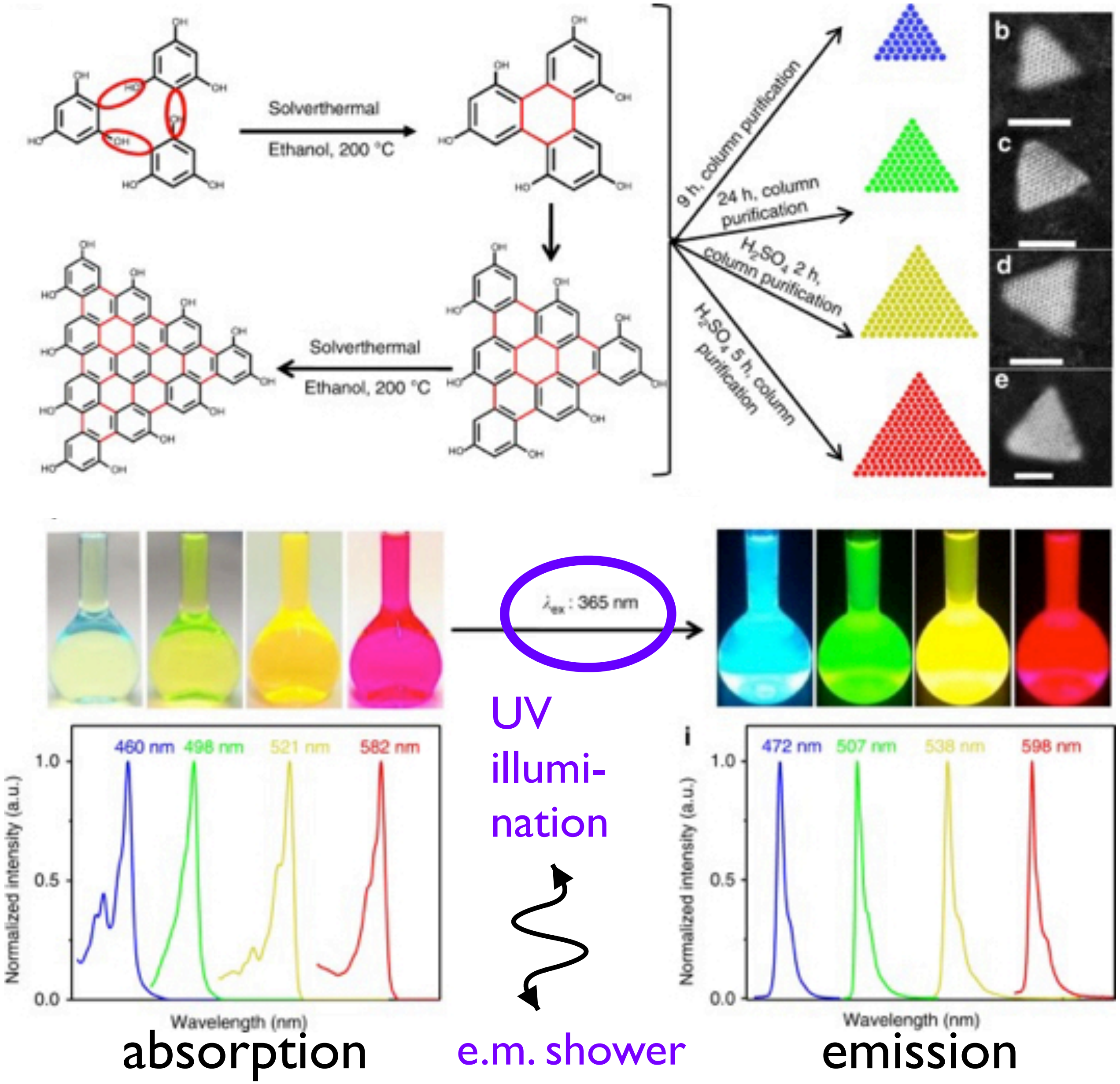


chromatic tunability → optimize for quantum efficiency of PD (fast, optimizable WLS)

deposit on surface of high-Z material → thin layers of UV → VIS WLS

embed in high-Z material ? two-species (nanodots + microcrystals) embedded in polymer matrix?
→ quasi continuous VIS-light emitter (but what about re-absorbtion?)

Quantum dots: chromatic calorimetry



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

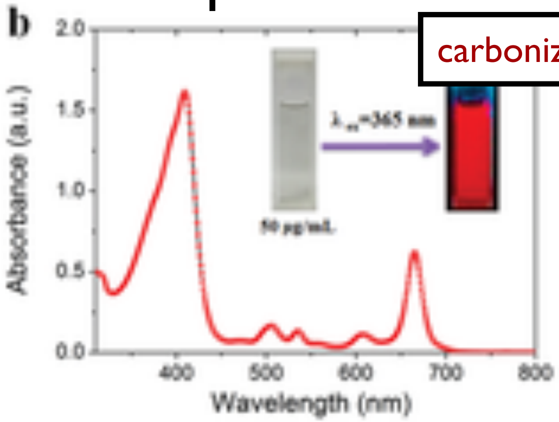
select appropriate nanodots

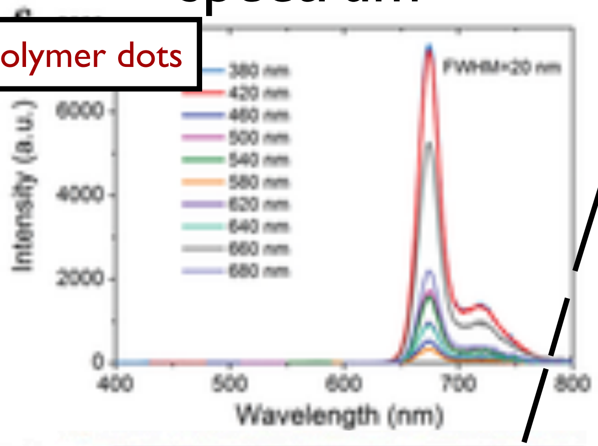
e.g. triangular carbon nanodots

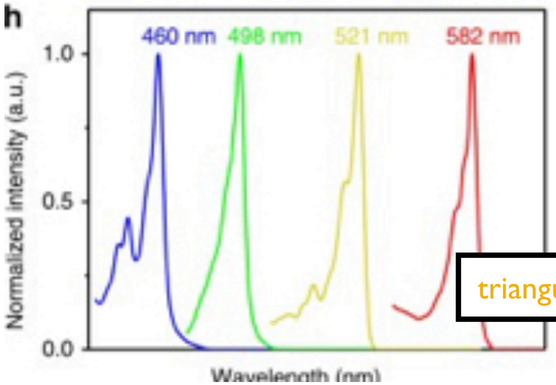
absorption spectrum

emission spectrum

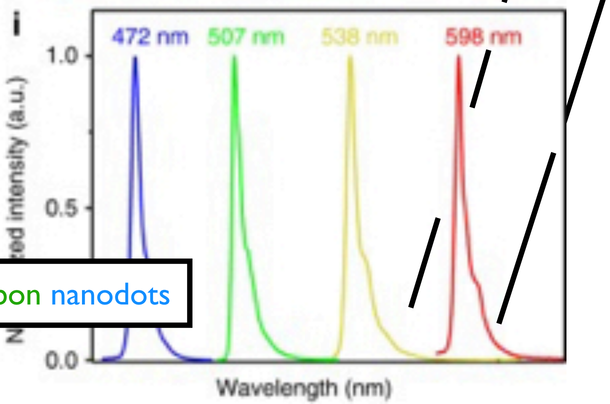
carbonized polymer dots

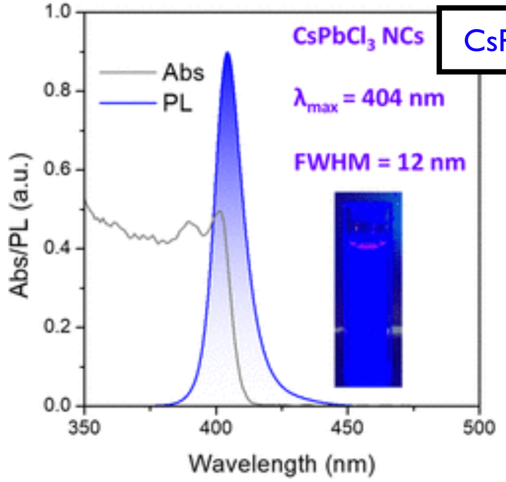






triangular carbon nanodots





CsPbCl$_3$ nanocrystals

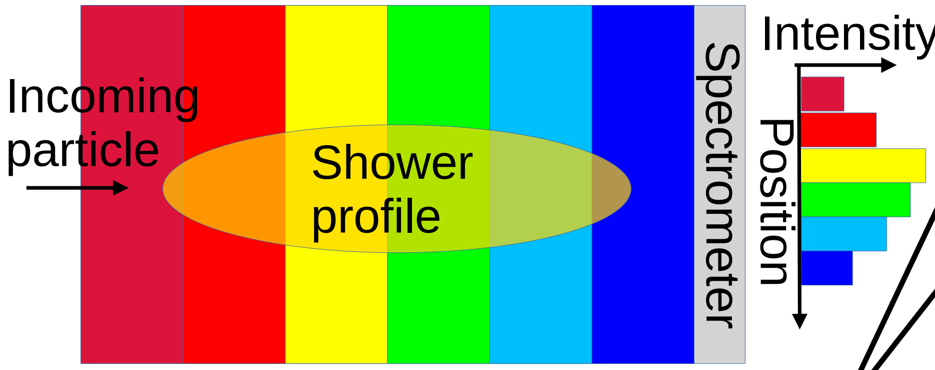
leftmost nanodots:
absorb wavelengths < 650 nm
emit at > 680 nm

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

…

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

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



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

Monochromators + PD?

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

Metalenses?

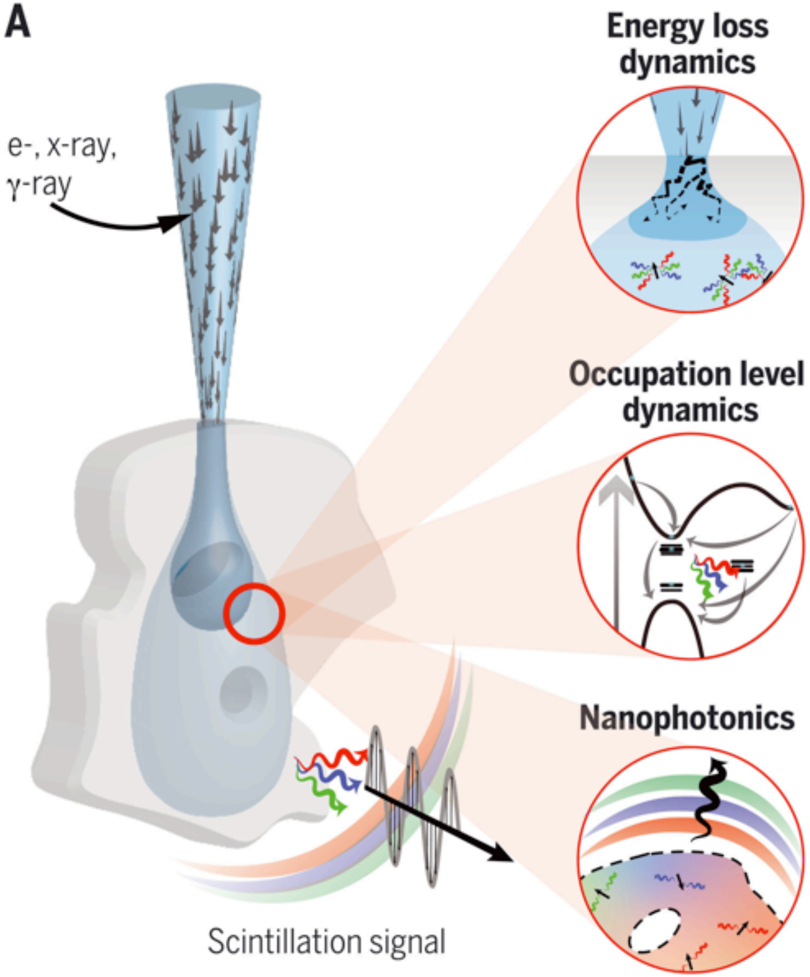
M. Khorasaninejad & F. Capasso, Science 358, 6367 (2017)

Scintillation with nanophotonics: simulation beyond G4

(the importance of a detailed understanding of the full chain)

A framework for scintillation in nanophotonics,
Charles Roques-Carmes , Nicholas Rivera, Ali Ghorashi, Steven E. Kooi *et al.*,
Science, 25 Feb 2022, Vol 375, Issue 6583, DOI: 10.1126/science.abm9293

https://www.science.org/doi/full/10.1126/science.abm9293



electron-beam induced scintillation from silicon-on-insulator nanophotonic structures

general framework to model, tailor, and enhance scintillation by means of nanophotonic structures integrated into scintillating materials (nanophotonic scintillators)

spectral shaping and enhancement of scintillation;
could be extended to angular and polarization control

by considering different emission linewidths and frequencies, one can selectively ***design*** optimized nanophotonic structures that enhance one of the scintillating peaks, at a single frequency or over the entire scintillation bandwidth.

Focus on photon detection for:

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- low energy particles: x-ray measurements
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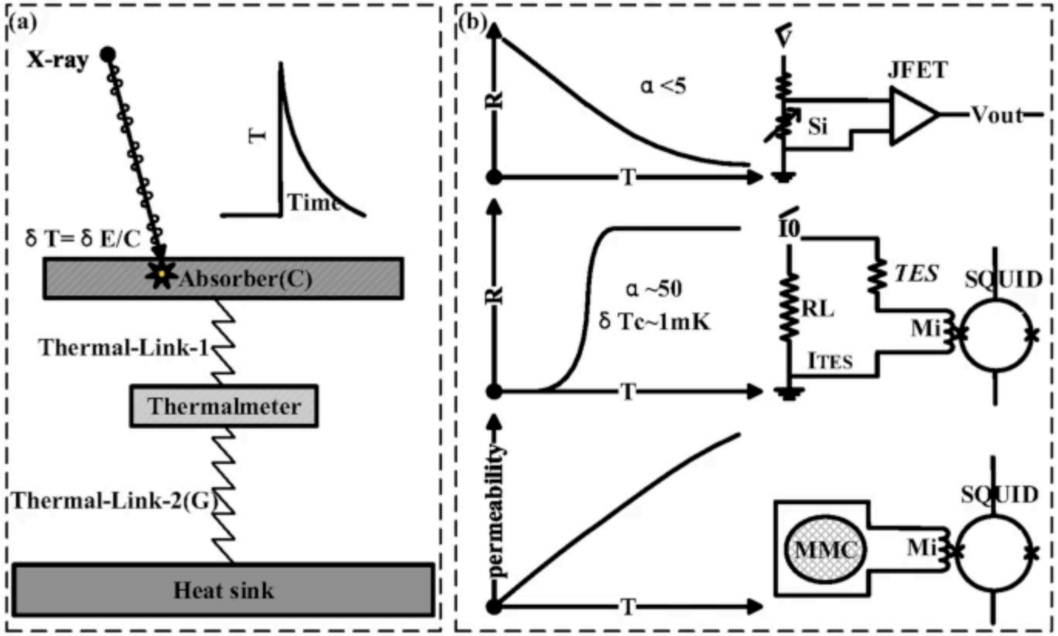
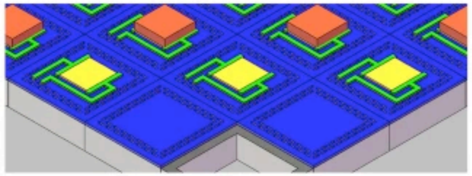
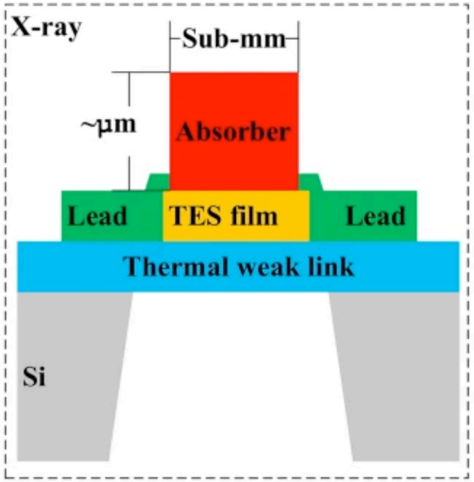
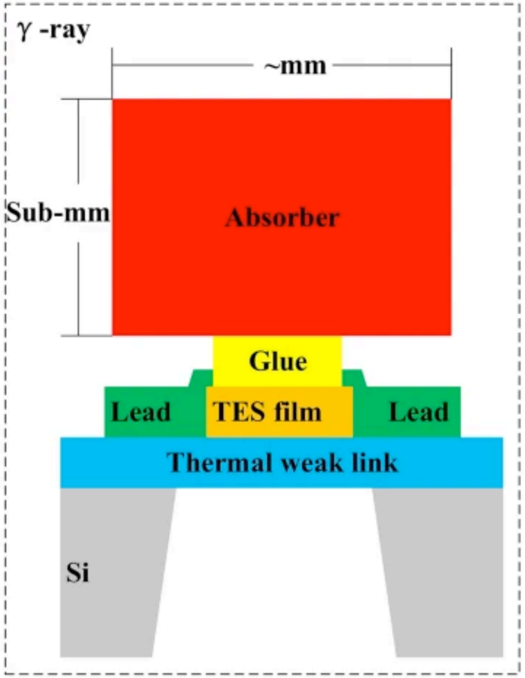
TES: Transition Edge Sensors (x-rays)







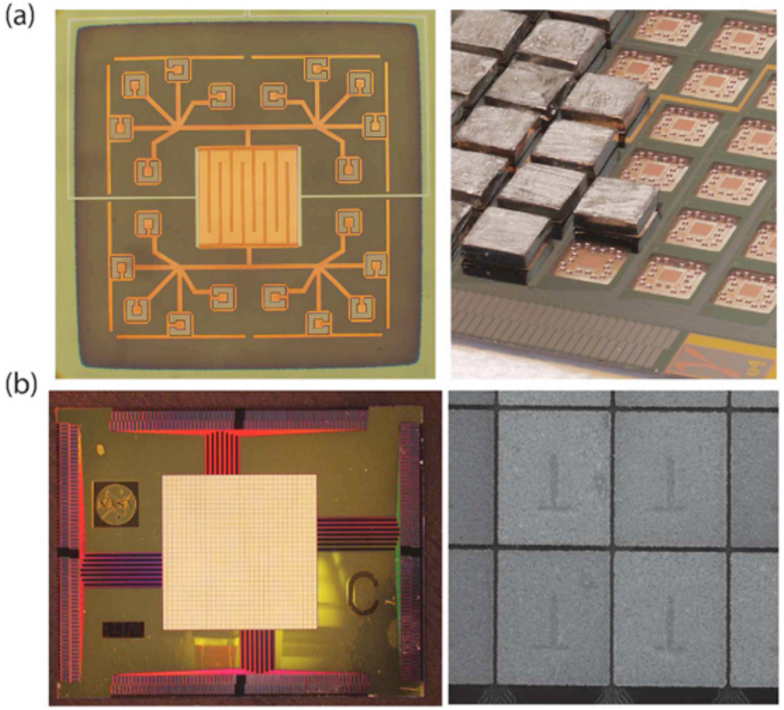


https://link.springer.com/article/10.1007/s41365-022-01071-5

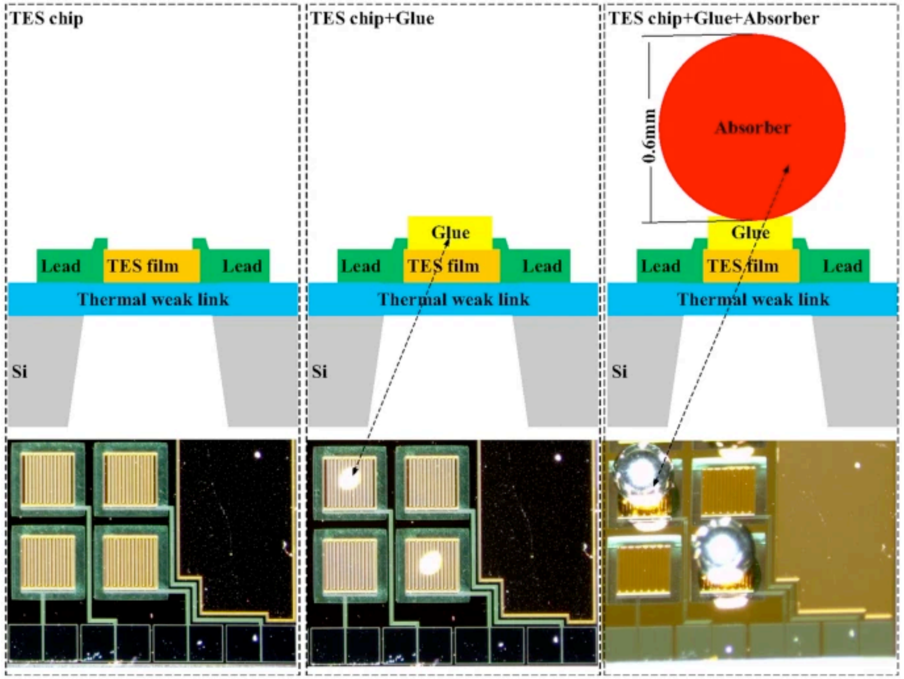
X-rays with energies below 10 keV have a weak penetrating ability, hence, only gold or bismuth of a few micrometers in thickness can guarantee a quantum efficiency higher than 70%. Therefore, the entire structure of the TES X-ray detector in this energy range can be realized using a microfabrication process. However, for X-rays or γ-rays from 10 keV to 200 keV, submillimeter absorber layers are required, which cannot be realized using the microfabrication process. This paper first briefly introduces a set of TES X-ray detectors and their auxiliary systems, and then focuses on the introduction of the TES γ-ray detector with an absorber based on a submillimeter lead-tin alloy sphere. The detector achieved a quantum efficiency above 70% near 100 keV and an energy resolution of approximately **161.5 eV at 59.5 keV.**

$T_{operation}$ ~ 0.1 K: dilution refrigerator!

TES: Transition Edge Sensors (x-rays)



https://iopscience.iop.org/article/10.1088/0953-2048/28/8/084003



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$T_{operation} < 0.1$ K: dilution refrigerator!

MMC: Magnetic Microcalorimeters (x-rays)

J Low Temp Phys (2018) 193:365–379
https://doi.org/10.1007/s10909-018-1891-6

massive particle absorber

paramagnetic temperature sensor in weak magnetic field → temperature dependent sensor magnetization

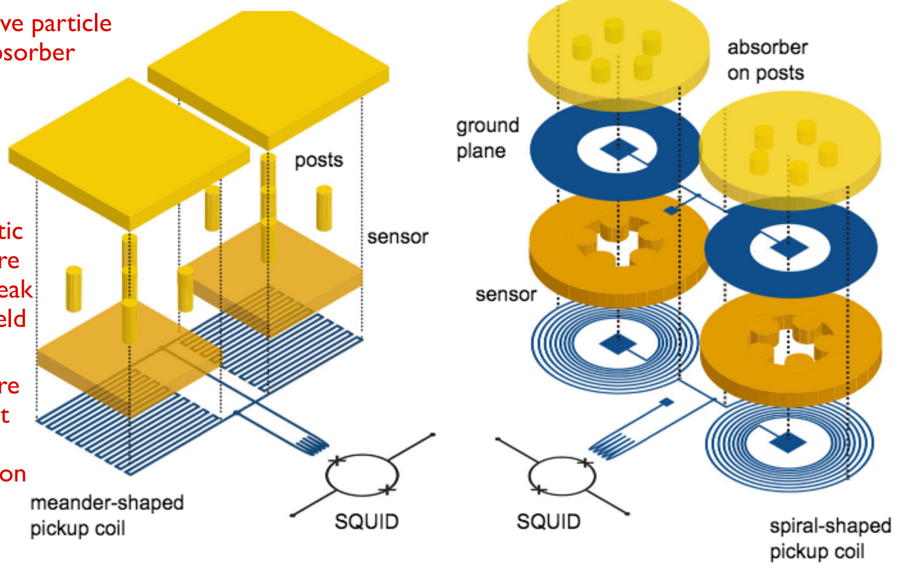


Fig. 2 Schematics of two state-of-the-art transformer-coupled detector geometries using (Left) meander-shaped and (Right) spiral-shaped pickup coils (Color figure online)

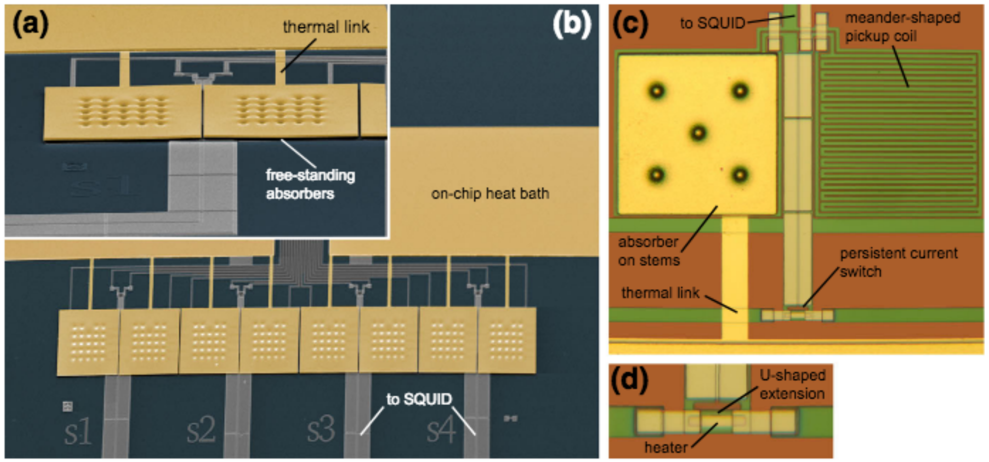
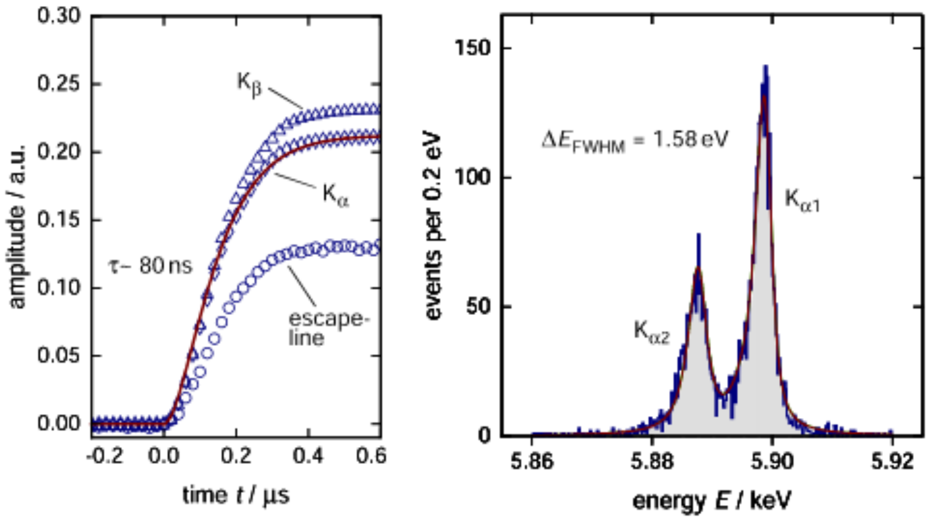


Fig. 4 Colorized SEM pictures as well as microscope photographs of the maXs-20 detector array having meander-shaped pickup coils and being optimized for high-resolution spectroscopy of photons with energy up to 20 keV [18] and a single-channel high-resolution detector that was developed for the ECHo experiment [19,20]. **a** Single two-pixel detector of the maXs-20 detector array. **b** Overview of the full maXs-20 detector array. **c** Overview of a single ECHo detector. **d** Magnification of the persistent current switch used within the ECHo detector (Color figure online)



$T_{\mathrm{operation}}$ ~ 0.02 K: dilution refrigerator!

Focus on photon detection for:

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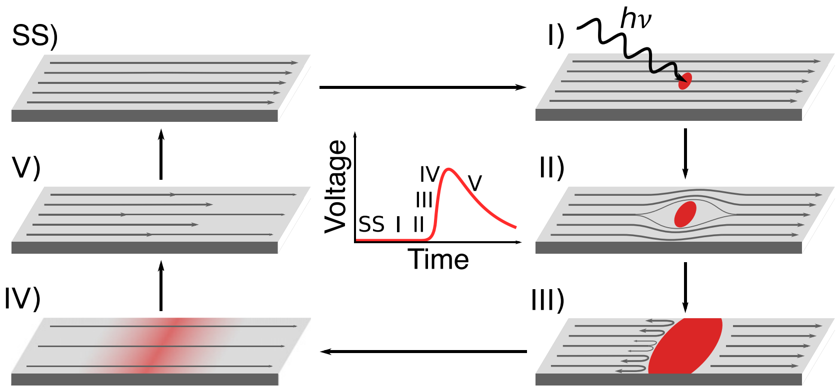
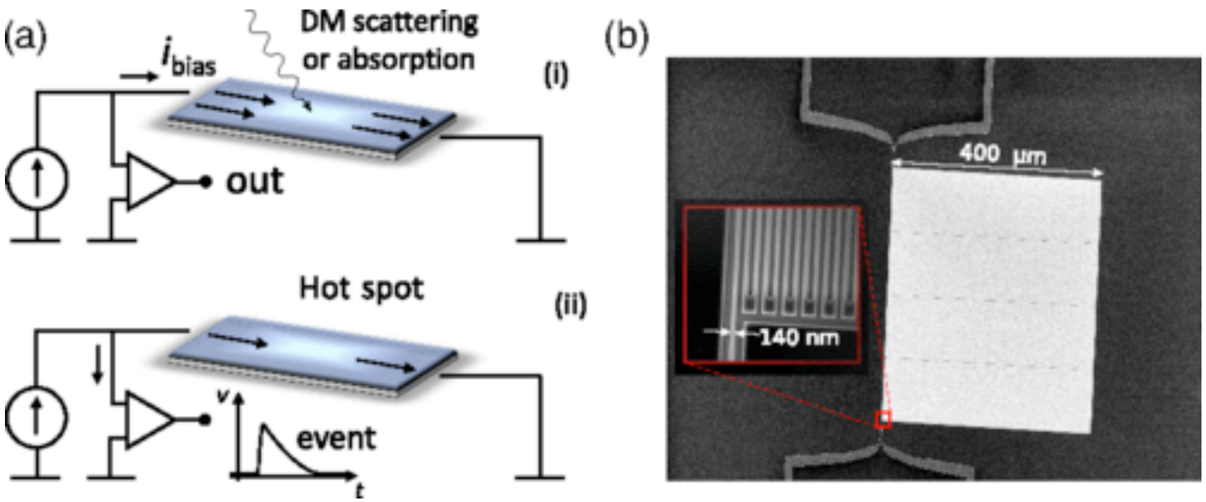
- low energy particles: energy measurements
- use of photon detectors for other HEP applications

SNSPD: superconducting nanowire single photon detectors





Detecting Sub-GeV Dark Matter with Superconducting Nanowires, Yonit Hochberg, Ilya Charaev, Sae-Woo Nam, Varun Verma, Marco Colangelo, and Karl K. Berggren, Phys. Rev. Lett. 123, 151802 (2019)

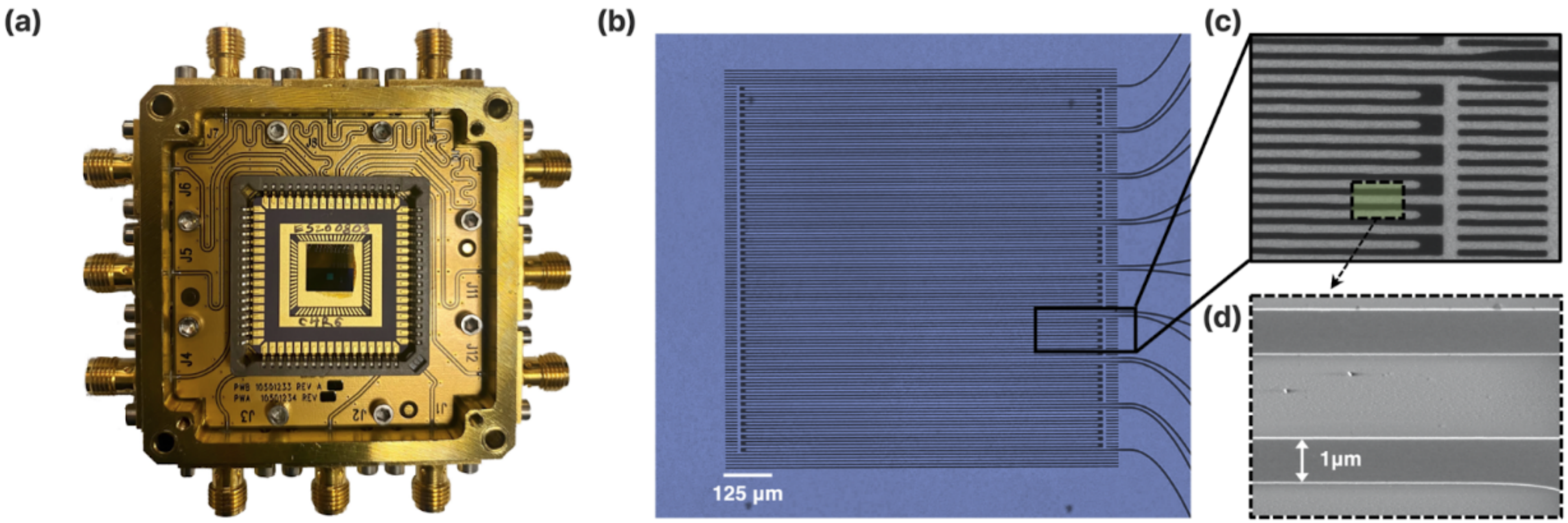
(SS) The detector is biased at a current close to the critical value. (I) When the energy is absorbed by the nanowire, the electrons depart from equilibrium and diffuse (II) out of the formed hot spot (flux squeezed out, critical current in neighboring regions). A resistive region formed across the nanowire then leads to a measurable voltage pulse in the readout.

The SEM image of the prototype WSi device after fabrication. The active area is 400×400 µm^2.

The long wavelength sensitivity of the SNSPD extends far beyond that of the Si single-photon avalanche photodiode (SPAD) [11] and the SNSPD is superior to the InGaAs SPAD [12] in terms of signal-to-noise ratio.

$T_{\text{operation}}$ ~ 4 K: dilution refrigerator!

SNSPD: superconducting nanowire single photon detectors



J. Luskin et al, Applied Phys Lett 122, 243506 (2023)

Figure 4: Superconducting nanowire single photon detectors.

arXiv:2311.01930

Large active-area superconducting microwire detector array with single-photon sensitivity in the near-infrared

- sensitive to single photons
- time resolution ~ 2ps
- no energy resolution
- high rate capability (MHz)
- radiation hard (expected, yet to be measured)
- work also for high Tc materials

B. Korzh, Q.-Y. Zhao, J. P. Allmaras, et al., “Demonstration of sub-3 ps temporal resolution with a superconducting nanowire single-photon detector,” Nature Photonics, no. 14, Mar. 2020.

potentially useful for non-resolving (soft) photon counting devices (e.g. shower size determination in concert with a charged-particle detector)

Esmaeil Zadeh, J. Chang, J. W. N. Los, et al., “Superconducting nanowire single-photon detectors: A perspective on evolution, state-of-the-art, future developments, and applications,” Applied Physics Letters, vol. 118, no. 19, p. 190 502, (2021) doi: 10.1063/5.0045990

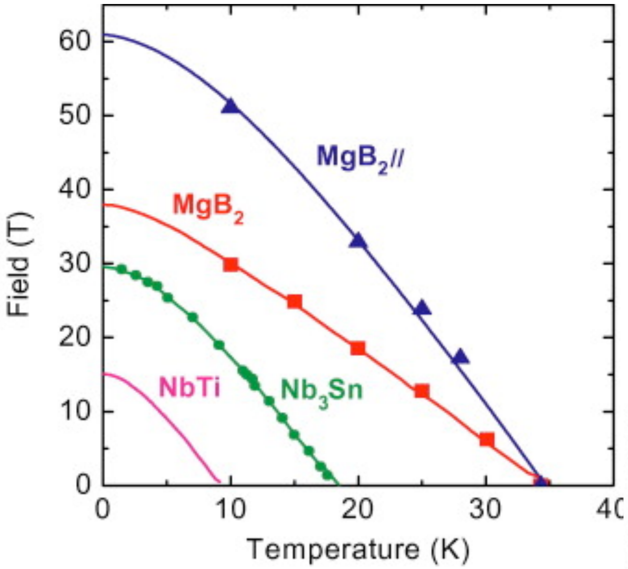
SNSPD: superconducting nanowire single photon detectors

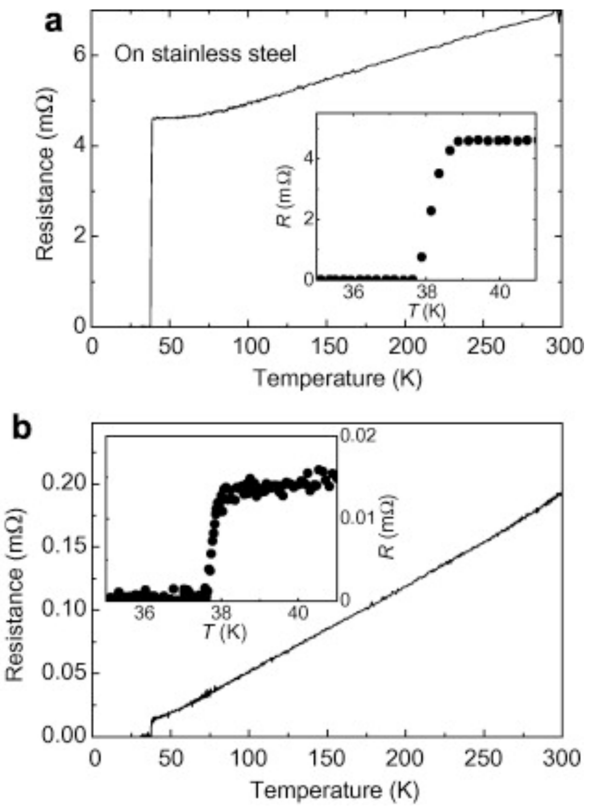
~~dilution refrigerator~~

Low kinetic inductance superconducting MgB_2 nanowires with a 130 ps relaxation time for single-photon detection applications

https://iopscience.iop.org/article/10.1088/1361-6668/abdeda/meta

Sergey Cherednichenko *et al* 2021 *Supercond. Sci. Technol.* **34** 044001

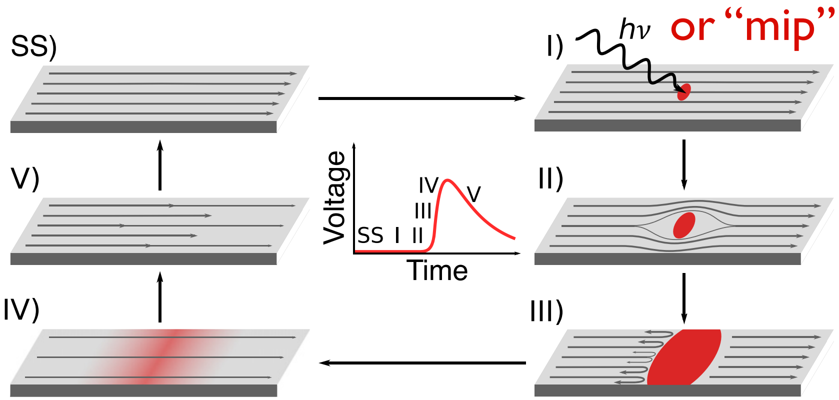




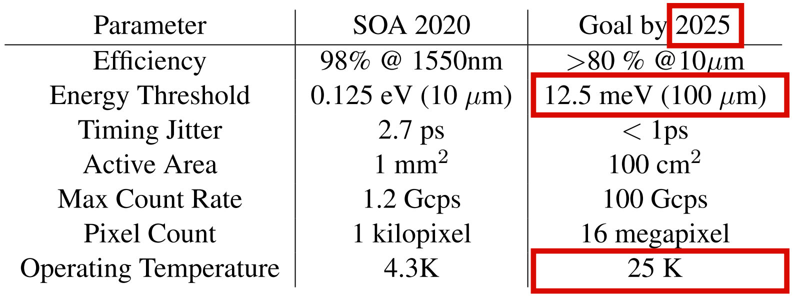
… **reset time in 35 nm × 120 μm MgB_2 nanowires is 130 ps**, which is more than a factor of 10 shorter than in NbN nanowires of similar length-to-width ratios. Depending on the bias current, **such MgB_2 nanowires function as single-, double, or triple-photon detectors for both visible (λ = 630 nm) and infrared (λ = 1550 nm) photons, with a dark count rate of <10 cps**.

…

Extremely low energy threshold detectors: SNSPD



SNSPD's Near term future



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

Snowmass2021 - Letter of Interest

Superconducting Nanowire Single-Photon Detectors

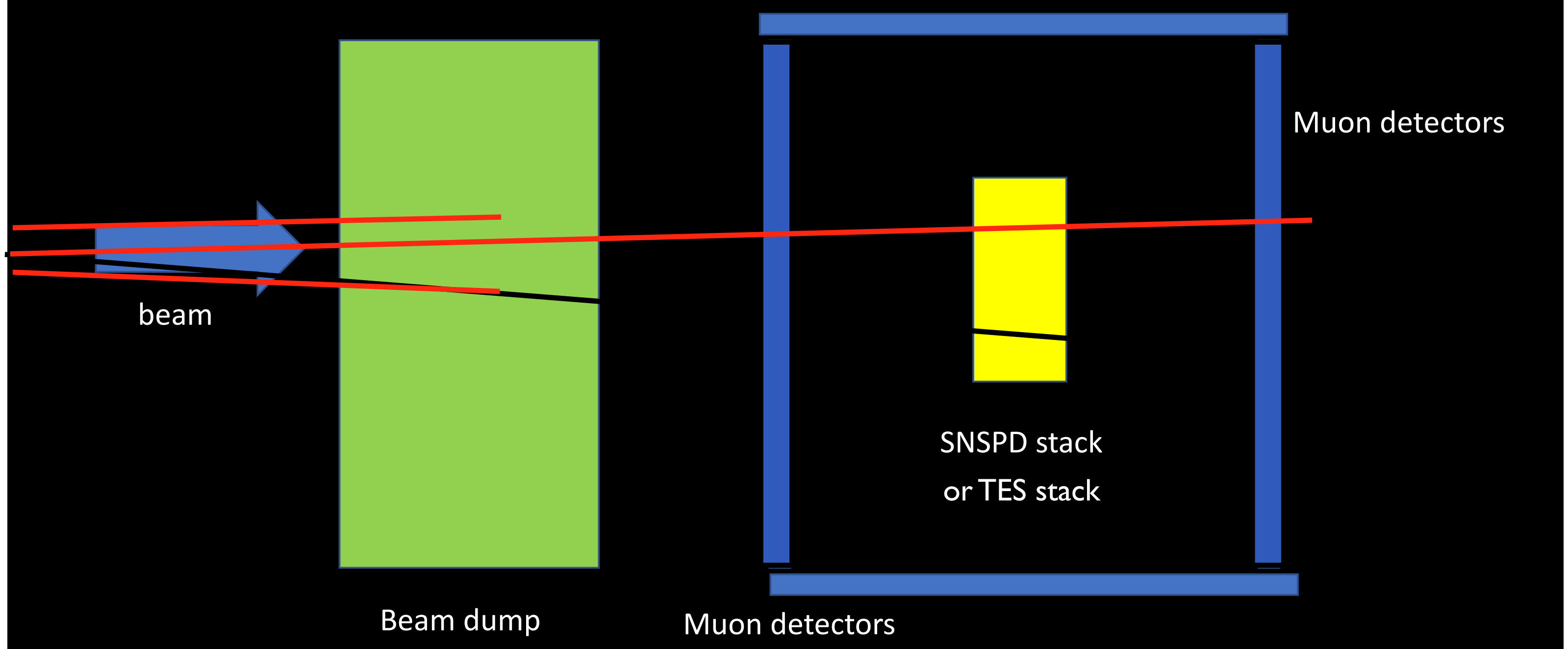
Contact Information:
Karl Berggren, berggren@mit.edu
Ilya Charaev, charaev@mit.edu
Jeff Chiles, jeffrey.chiles@nist.gov
Sae Woo Nam, saewoo.nam@nist.gov
Valentine Novosad, novosad@anl.gov
Boris Korzh, bkorzh@jpl.nasa.gov
Matt Shaw, mattshaw@jpl.nasa.gov

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

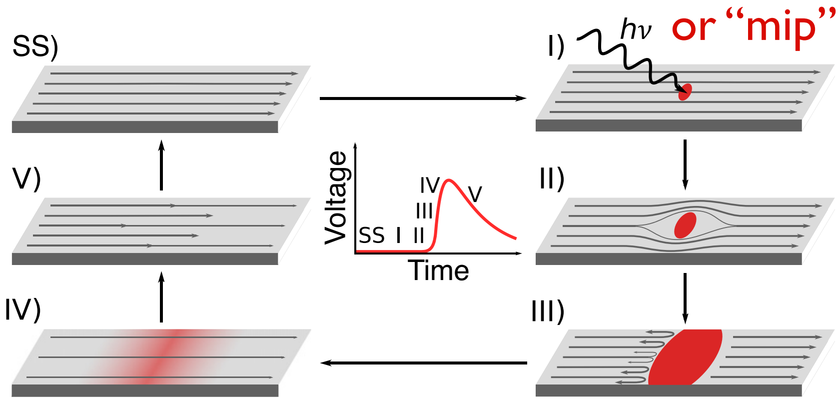
mip: ~20 keV/100 μm

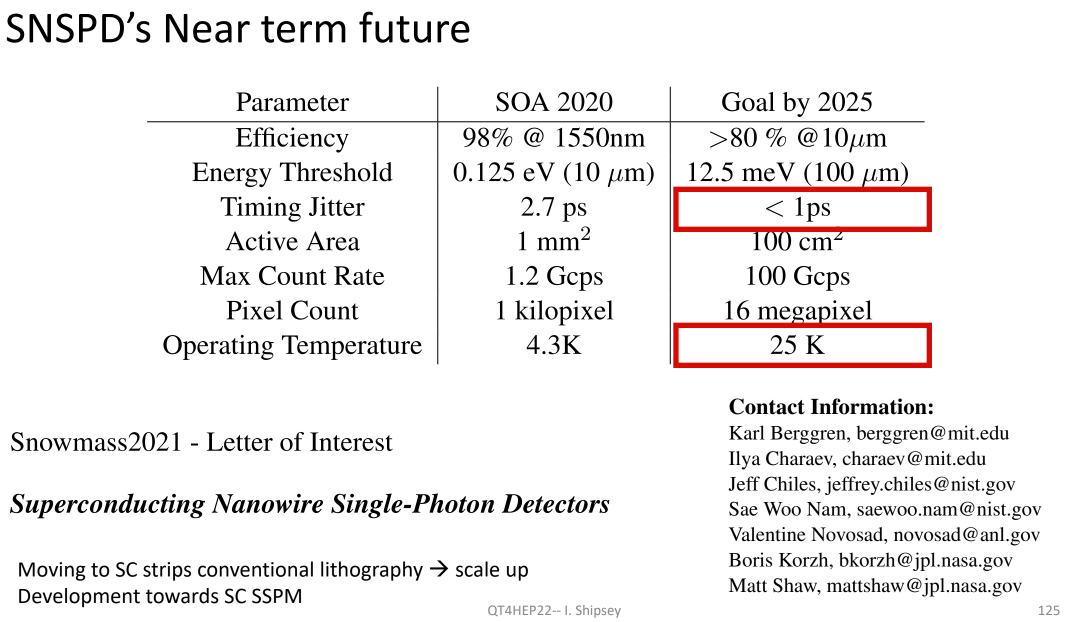
x 10^6 sensitivity

Search for Beyond Standard Model milli-charged particles?



Extremely fast detectors: SNSPD





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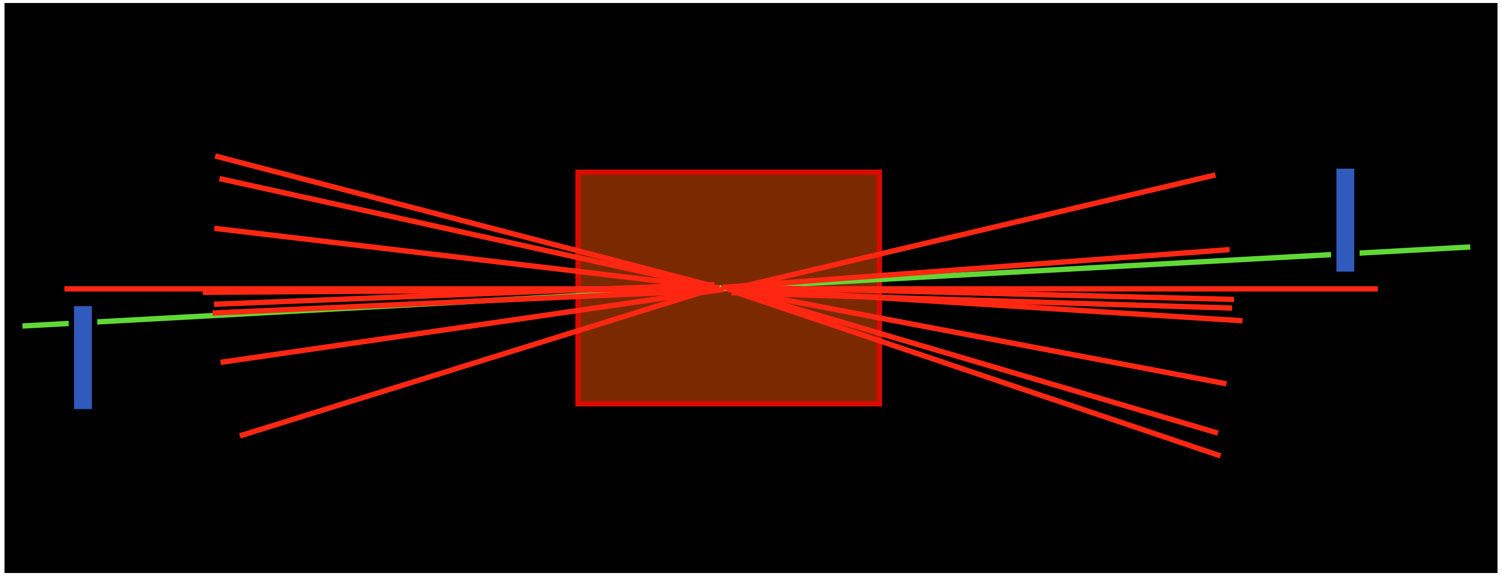
Matt Shaw, mattshaw@jpl.nasa.gov

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

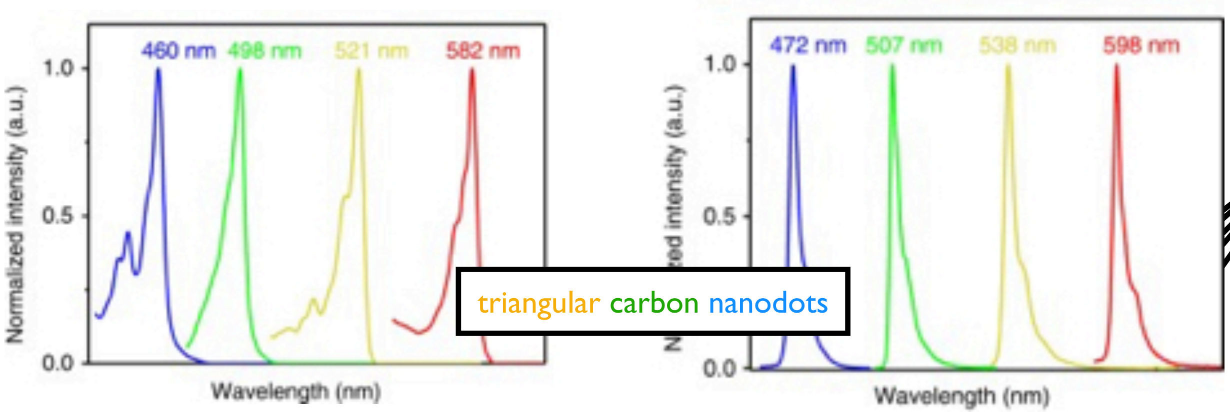
diffractive scattering via ps-resolution tracking in Roman pots



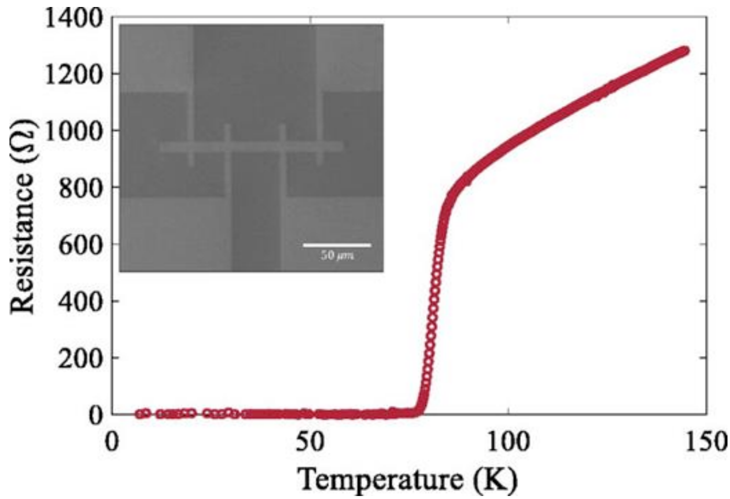
proposed for exactly this for the EIC

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

chromatic calorimetry & O(ps) shower timing

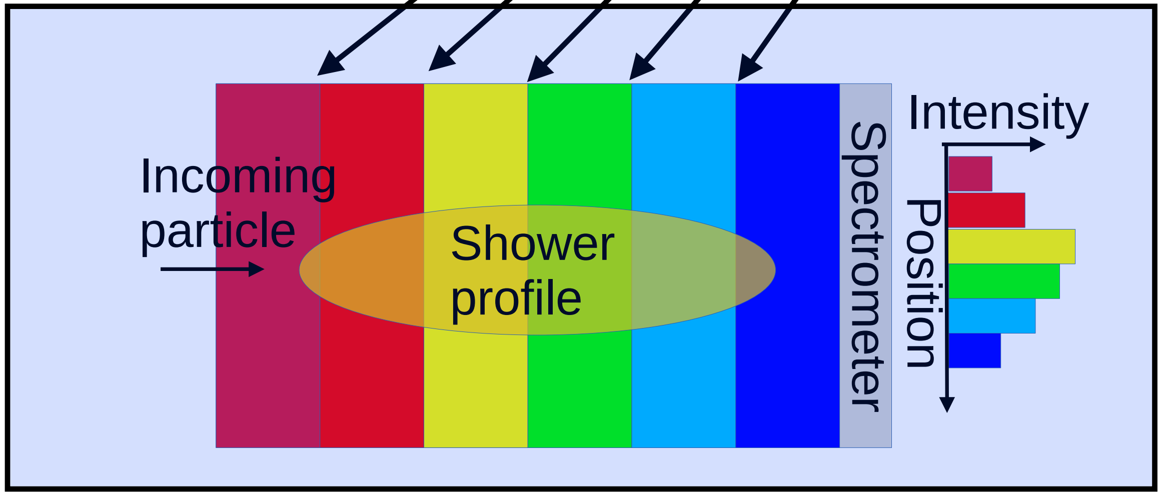


triangular carbon nanodots



Ultrafast low-jitter optical response in high-temperature superconducting microwires
A. Kumar et al., *Appl. Phys. Lett.* 122, 192604 (2023), https://doi.org/10.1063/5.0150805

segmented calorimeter
with intercalated very
thin timing layers ?



shower profile via ***spectrometry***
shower timing via ***SNSPD***

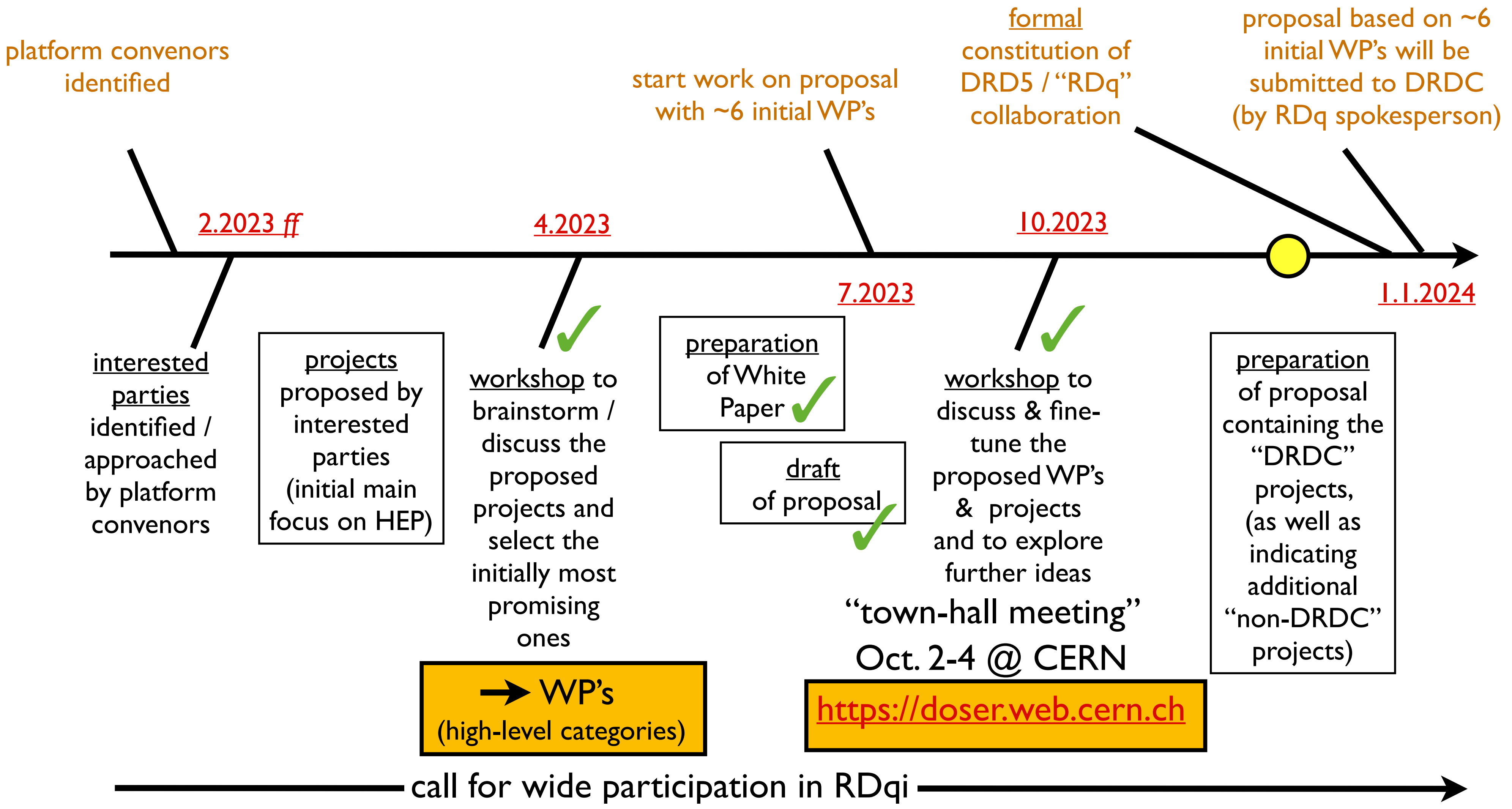
(requires operation in cryostat...)

ECFA: DRD5 / RD-q

Quantum sensing for particle physics

Very relevant *also* in the field of photon sensors

focus on technical developments that go beyond what a single group can do



platform convenors identified

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 ✓

→ WP's
(high-level categories)

start work on proposal with ~6 initial WP's

7.2023

preparation of White Paper ✓

draft of proposal ✓

10.2023

formal constitution of DRD5 / "RDq" collaboration

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

"town-hall meeting"
Oct. 2-4 @ CERN

https://doser.web.cern.ch

proposal based on ~6 initial WP's will be submitted to DRDC (by RDq spokesperson)

1.1.2024

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

call for wide participation in RDqi

continuous effort to inform & involve

WP's as of v 0.7

BOTH EXPERIMENTAL AND THEORETICAL
PHYSICS GROUPS INVOLVED IN WP's

WP1

ATOMIC, NUCLEAR AND MOLECULAR SYSTEMS IN TRAPS & BEAMS

- WP-1a: Exotic systems in traps and beams
  - WP-1aa: Extension & 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 networks
  - WP-1cb: Portable references and sources

WP2

QUANTUM COMPONENTS

- WP-2a: 0-, 1- and 2-D materials
  - WP-2aa: Application-specific tailoring
  - WP-2ab: Extended functionalities
- WP-2b: Cryogenic systems
  - WP-2ba: The 4K stage
  - WP-2bb: Cryogenic quantum sensors for particle and photon detection
  - WP-2bc: Resilient integration of superconducting systems

WP3

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 (for 'classical' detectors)

WP4

SCALING UP "QUANTUM" (FOR MIP's)

- WP-4a: Massive spin polarized ensembles
- WP-4b: Hybrid devices
  - WP-4ba: Scintillators
  - WP-4bb: Ensembles of heterostructures
  - WP-4bc: Heterodox devices

WP5

QUANTUM TECHNIQUES FOR SENSING

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

WP6

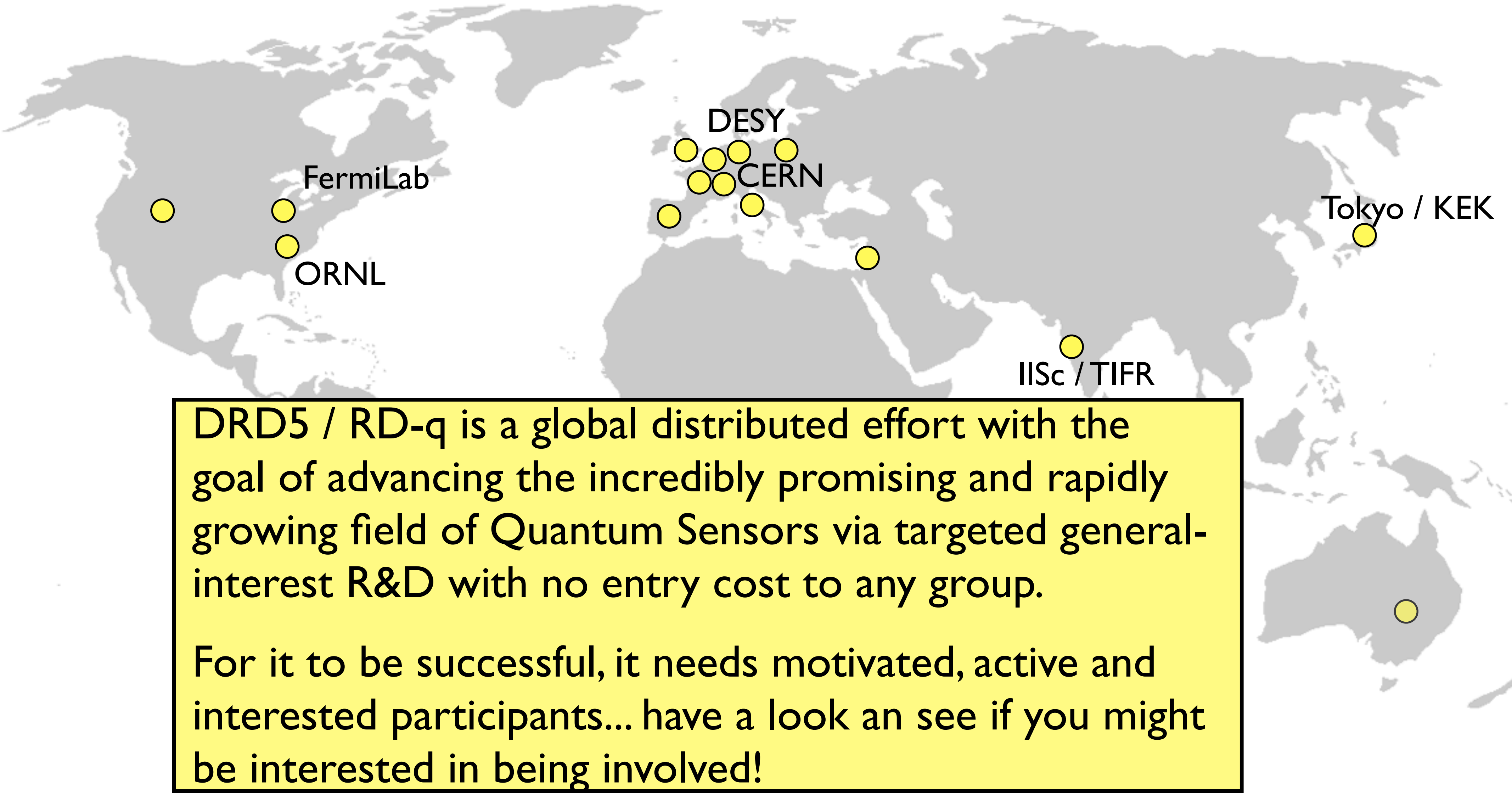
CAPACITY BUILDING

- WP-6a: Education platforms
- WP-6b: Exchange platforms
- WP-6c: Shared infrastructures

ECFA: DRD5 / RD-q

Two goals for end of 2023 for the future DRD5 / RDq collaboration:

- preparation of a proposal for detector R&D → CERN DRDC
- formation of a global collaboration (Europe, Americas, Asia) → MOU



DRD5 / RD-q is a global distributed effort with the goal of advancing the incredibly promising and rapidly growing field of Quantum Sensors via targeted general-interest R&D with no entry cost to any group.

For it to be successful, it needs motivated, active and interested participants... have a look an see if you might be interested in being involved!

● groups involved in RD-q process / HEP-related Quantum initiatives thank you!