Quantum Sensors & Emerging Technologies

<u>What's covered:</u>

1. Brief overview of the landscape (submissions, activities)

2. Which quantum sensors and emerging technologies are we talking about? (focus on HEP, mainly)

3. What's the status of relevant DRD activities?

1

"Quantum" is popular

quick overview of (266) submissions

By national submissions: Quantum sensing mentioned in 25 out of 53 submissions

By labs: Quantum sensing happening in 5 out of 8 submissions

By HEPP / LEPP§: HEPP (5 of 71) / LEPP (14 of 27)

LEPP/HEPP (0 of 6)

HEPP: SNSPD's, Quantum Dots, 5D calorimetry*
LEPP: many different technologies*

"by necessity"

"by lack of familiarity"

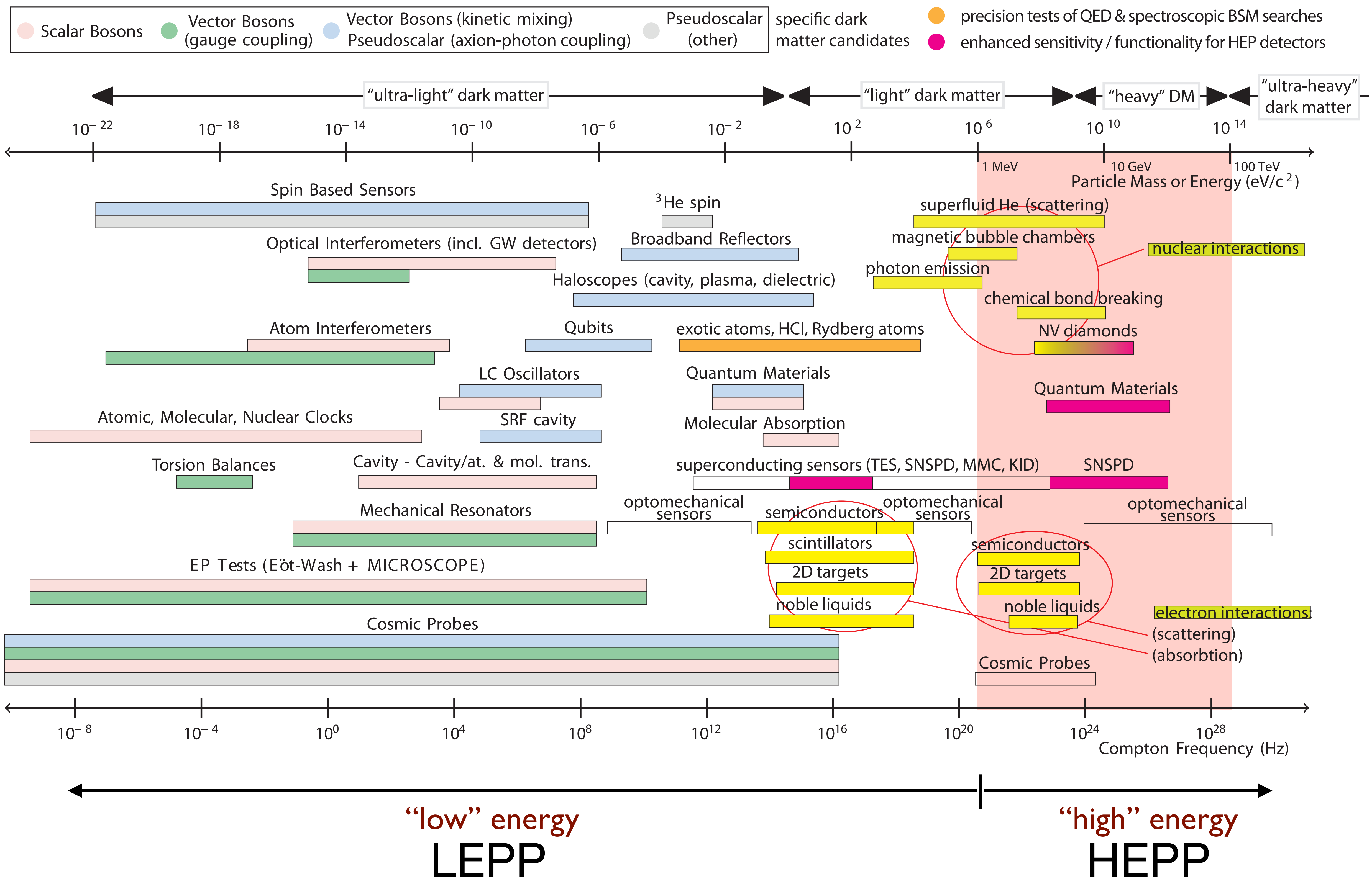
§ only a small number of known low energy particle physics groups submitted a document to the ESPP update

*most topics addressed by DRD5

1

"Quantum" is everywhere

Landscape: quantum sensing applied to an extremely wide range of DM searches



1

"Quantum" is relevant

Focus on potential HEP impact

DRD5 WP

Work package \ HEP function	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)

Examples of LEPP & HEPP applications

all of these need dedicated R&D to achieve their expected potential!

Quantum dots (HEP calorimetry)

- 155: KOTO
- 11: Fermilab / Higgs factory @ CERN
- 140: linear collider

Superconducting devices (HEP, astroparticle)

Nano- and Microwires

- 211: ALLEGRO / FCC-ee
- 95: luminosity @ FCC

TES, MMC (cryo-spectrometry)

- 132: KATRIN: 3.3.3: large arrays of quantum sensors' (MMC's)
- 197: AMoRE: MMC's, Squids
- 258: electron capture in Ho-163: MMC's, Squids
- 72: DESY: TES
- 181: HOLMES+: TES, TWPA's
- 28: TES / PTOLEMY

RF cavities

- 260: DM & gravitational waves

Cryoelectronics, packaging …

- 54: RF amplifiers @ 50 mK
- 225: ultra-low noise quantum electronics / Project 8

Atomic & nuclear physics (exotic atoms, neutrino physics, clocks)

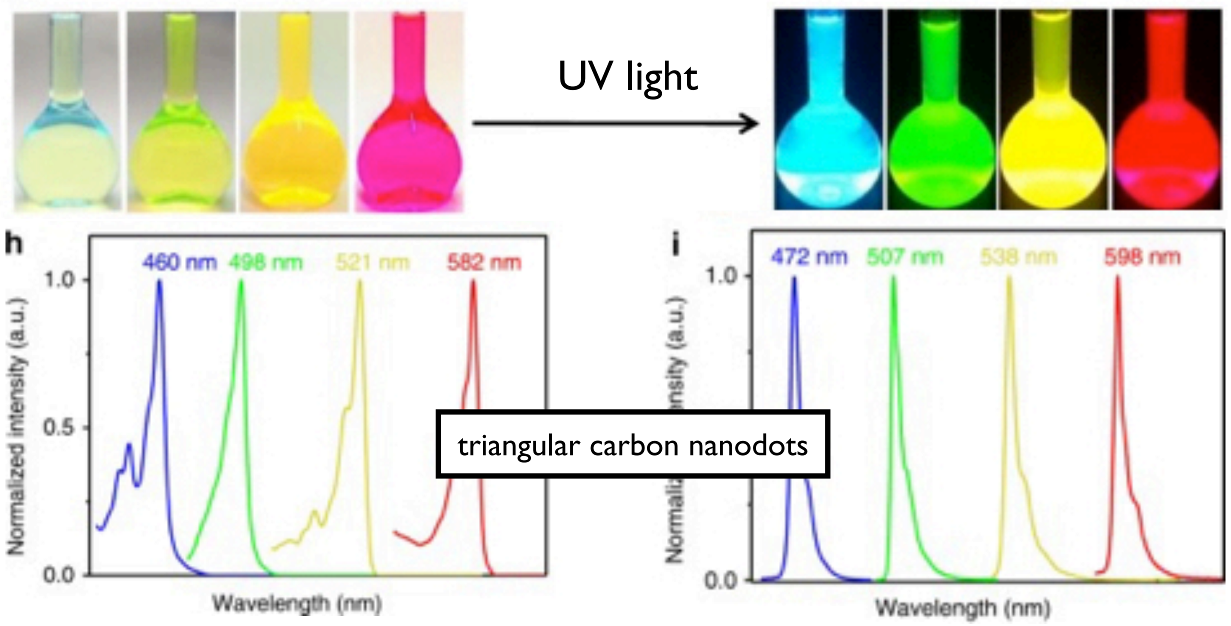
- 71: AD
- 6: ISOLDE
- 37: TVLBAI

Spin-based sensors

- 260: DM & gravitational waves
- 271: spin-based search for quantum gravity

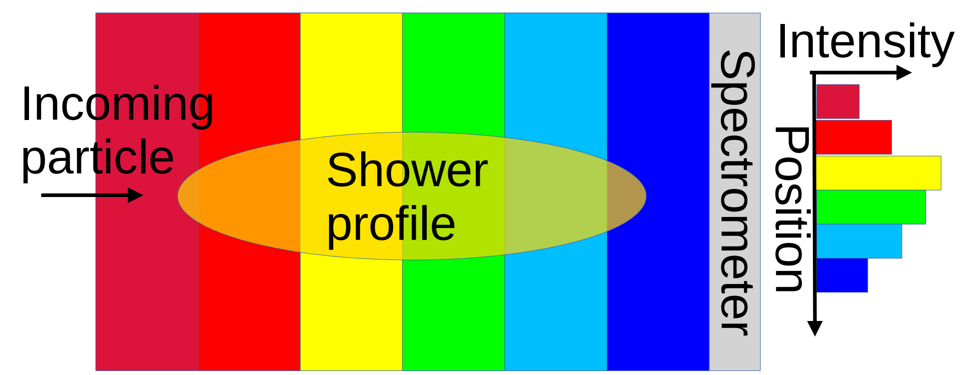
Specific examples for potential particle physics impact: chromatic calorimetry

fast, narrowband emitters (20nm), large Stokes shift



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

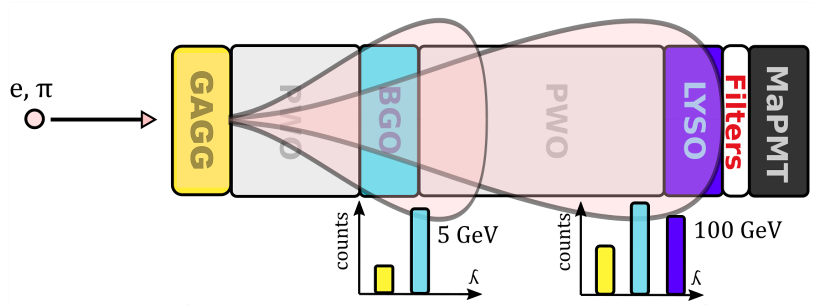


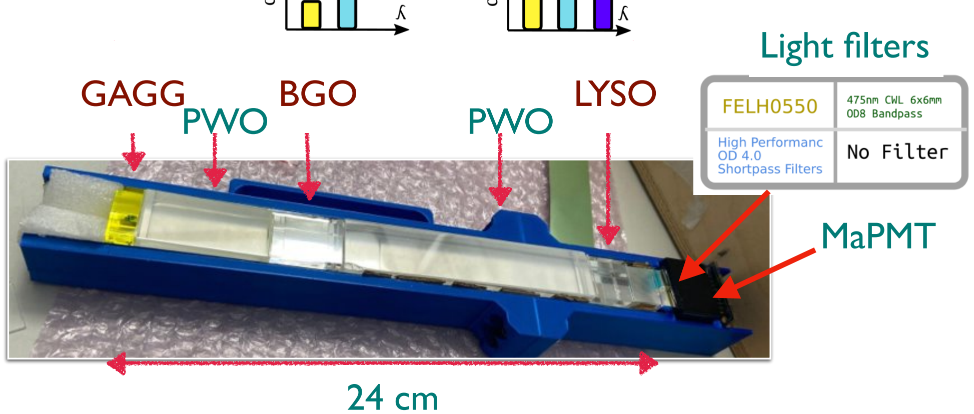
(shower profile via ***spectrometry***)

→ chromatic energy measurement
→ shower profile
→ PID

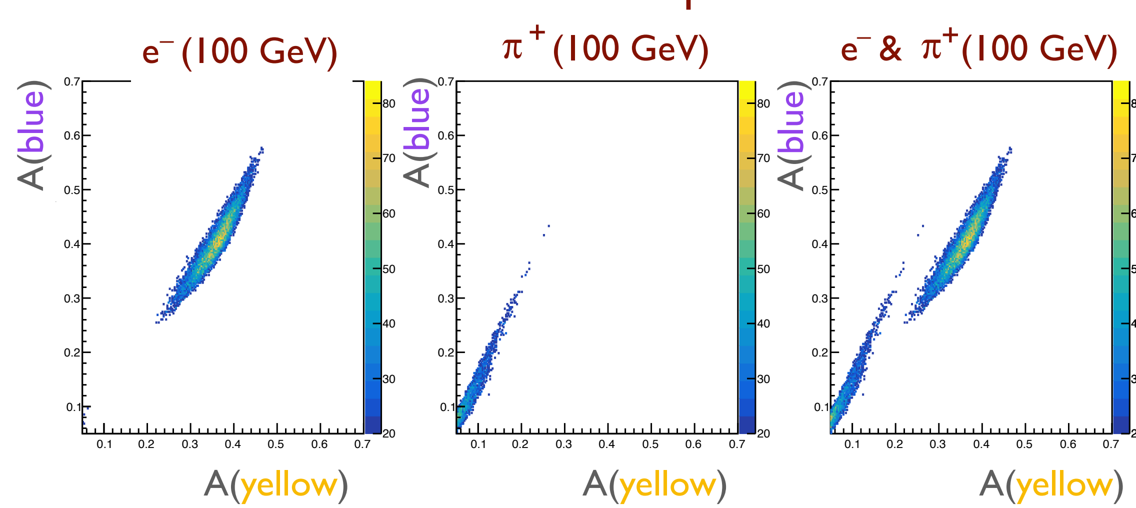
test of chromatic concept in beam (SPS, 2023)

Devanshi Arora et al., 2025, JINST 20 P06019



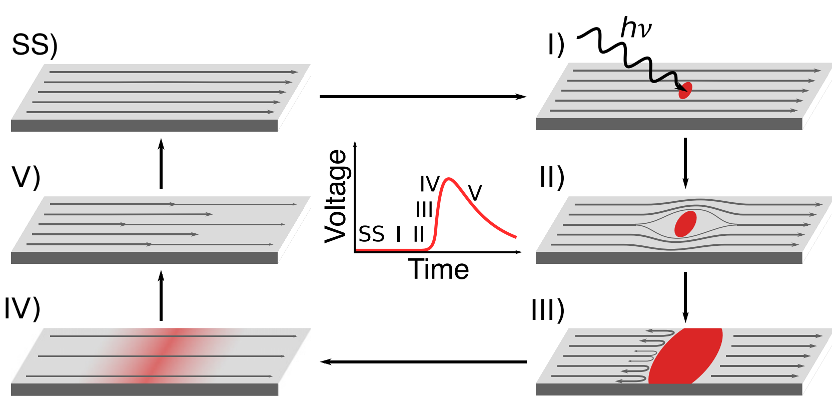


86% "chromatic" electron - pion discrimination



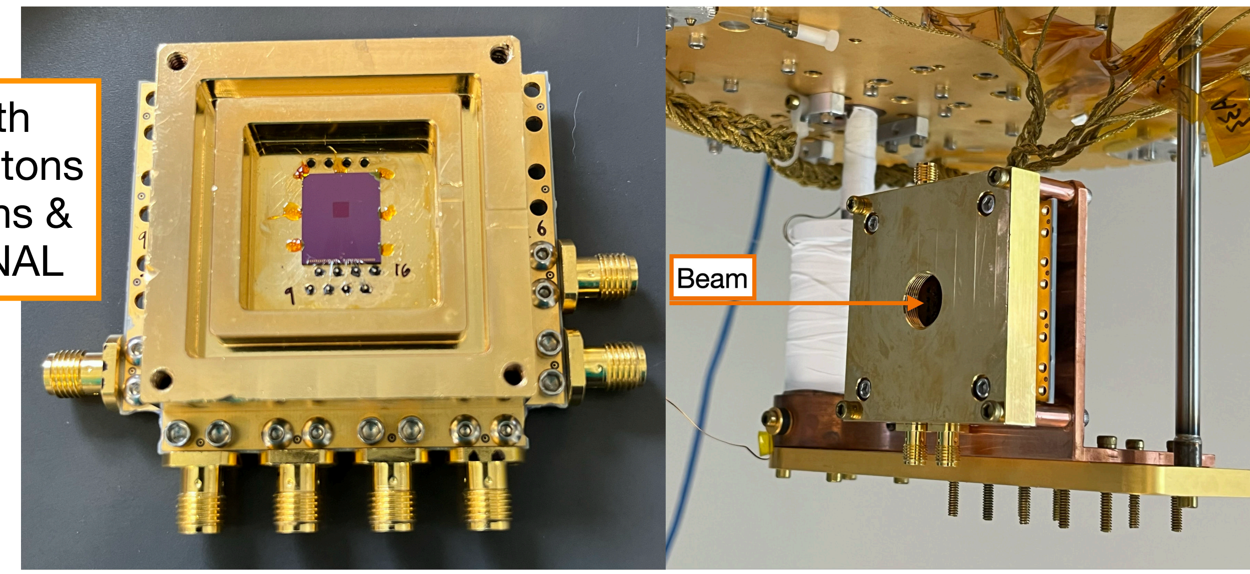
2 WP-3 Cryopixel arrays for HEP tracking

Specific examples for potential particle physics impact: cryogenic tracking

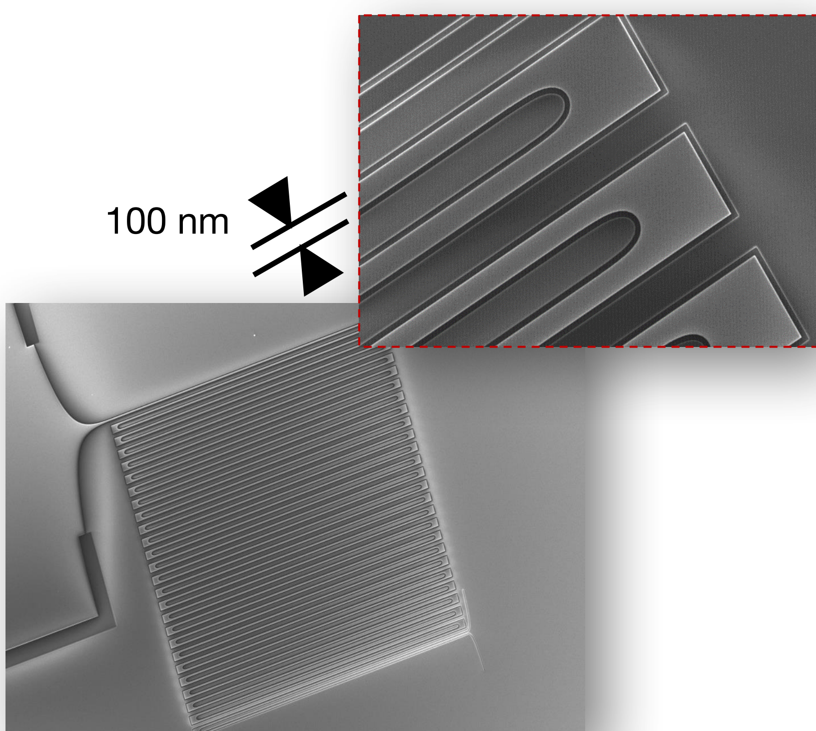


'Large area' 2×2 mm² 8-channel SMSPD array (pixel size: 0.25×2 mm²)

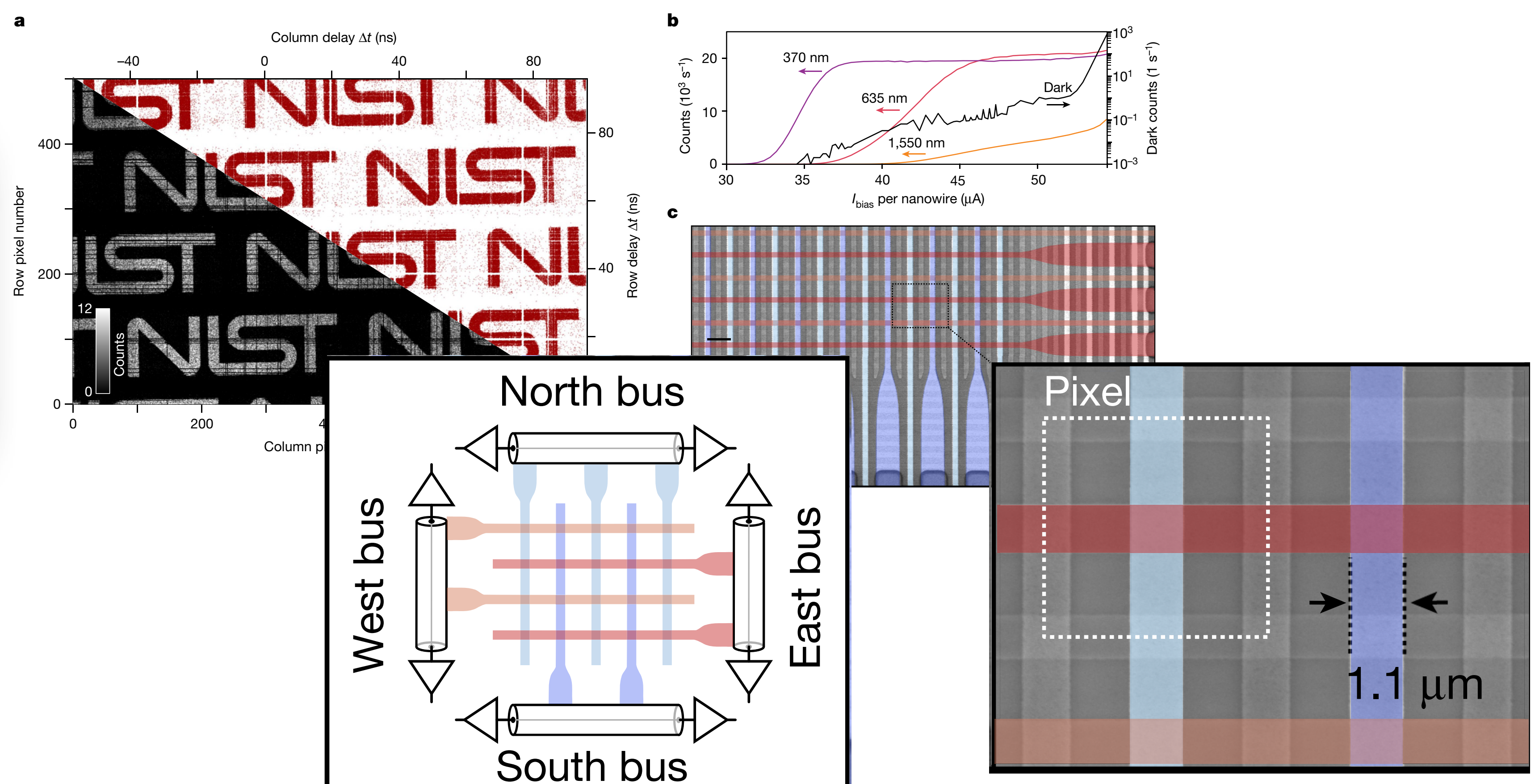
Beam tests with 120 GeV/c protons & 8 GeV/c pions & electrons @ FNAL



Cristián Peña et al 2025 JINST 20 P03001



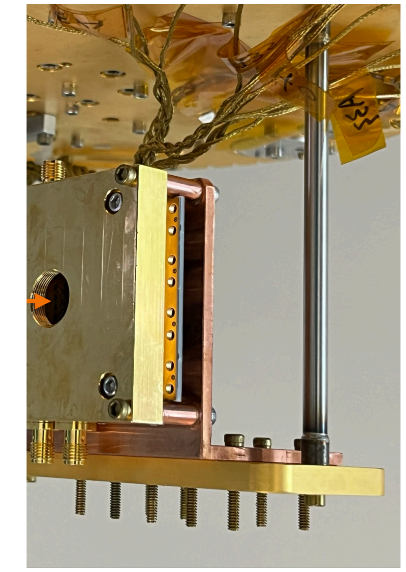
Fabrication and operation of a 800 × 500 SNSPD element camera



Oripov, B.G., Rampini, D.S., Allmaras, J. *et al.* *Nature* **622**, 730–734 (2023). https://doi.org/10.1038/s41586-023-06550-2

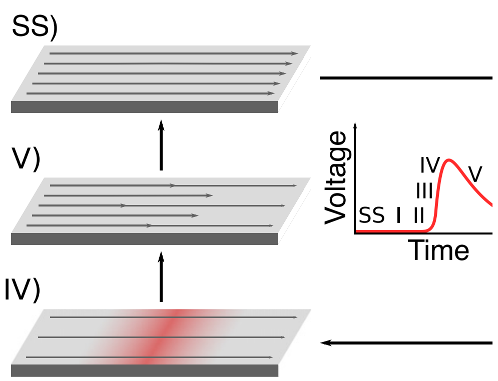
Specific examples for potential particle physics impact: cryogenic tracking

‘Large area’ 2×2 mm² 8-channel SMSPD array (pixel size: 0.25×2 mm²)



a et al 2025 JINST 20 P03001

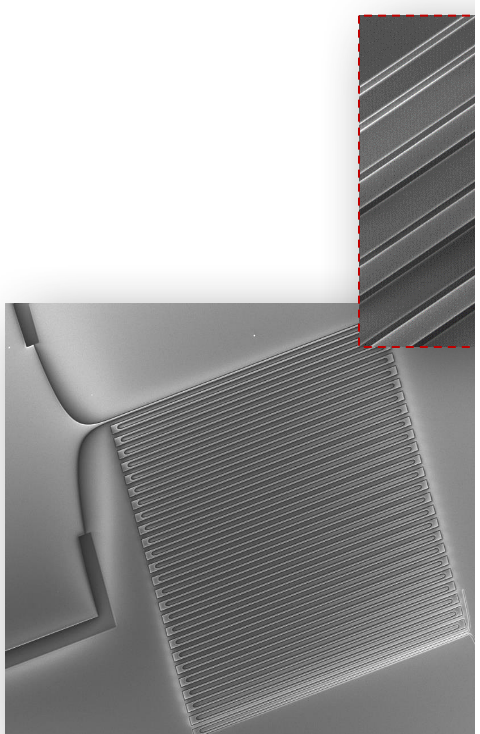
nera



SNSPD: Advances & Expected Performance

	Timing jitter	Intrinsic photon number resolution	Efficiency	Array size	Maximum count rate	Dark count rate	Active area	Cut-off wavelength
Records in 2016	18 ps	None	93%	64	1 Gcps	4 /s/mm²	0.001 cm²	5 µm
Current records for isolated devices	2.6 ps [1]	3-5 photons	98% [2]	4x10⁵ [3]	1.5 Gcps [4,5]	4x10⁻⁵ /s/mm² [6]	0.1 cm² [3]	29 µm [7]
Expected performance by 2030	1 ps	10	99 %	10⁷	10 Gcps	1x10⁻⁶ /s/mm²	1 cm²	100 µm

[1] Korzh, Zhao et al, ***Nature Photonics*** 14, 250 (2020)
[2] Reddy et al, ***Optica*** 7, 1649 (2020)
[3] Oripov, Rampini, Allmaras, Shaw, Nam, Korzh, and McCaughan, ***Nature*** 622, 730 (2023)
[4] Craiciu, Korzh et al, ***Optica*** 10, 183 (2023)
[5] Resta et al, ***Nano Letters*** (2023)
[6] Chiles, ***PRL*** 128, 231802 (2022)
[7] Taylor, Walter, Korzh et al, ***Optica***, (2023)

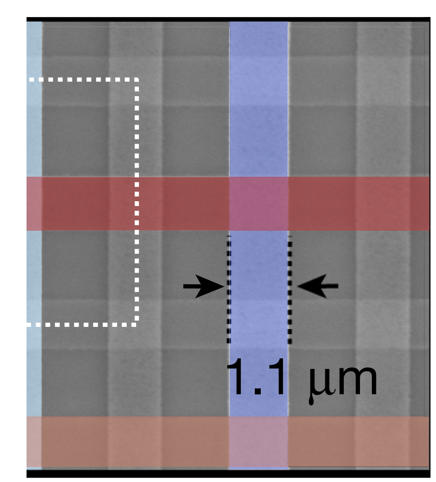


Multi-layer stacked superconducting pixel detector planes

- millicharged particles
- diffractive scattering
- luminosity monitors

(https://indico.cern.ch/event/1439855/contributions/6461493/)
(https://indico.cern.ch/event/1439855/contributions/6461614/)

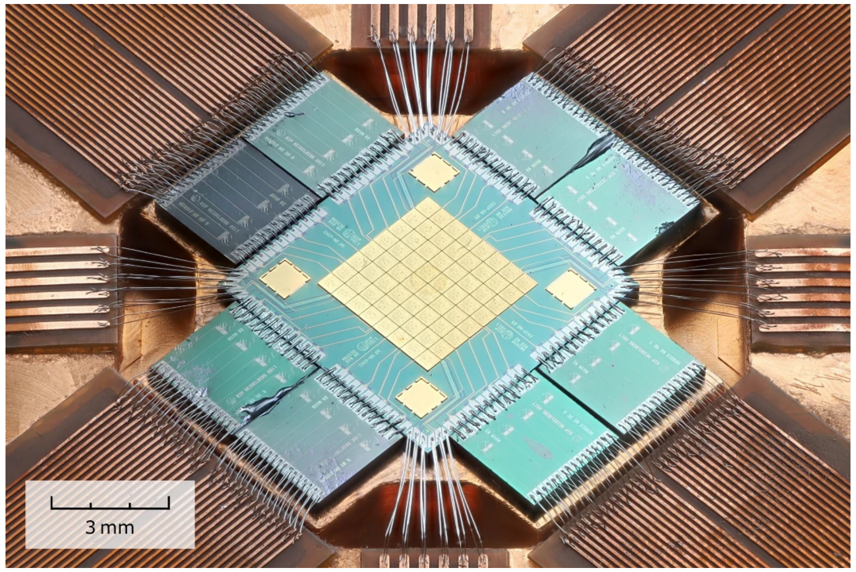
➢ ⁴He vs. high-Tc



.org/10.1038/s41586-023-06550-2

Specific examples for potential particle physics impact: cryogenic calorimetry

Transition Edge Sensors (TES)
Magnetic Microcalorimeters (MMC's)



QUARTETT Collaboration: Unger, D., Abeln, A., Cocolios, T.E. et al. MMC Array to Study X-Ray Transitions in Muonic Atoms. J Low Temp Phys 216, 344–351 (2024). https://doi.org/10.1007/s10909-024-03141-x

Cryo-spectroscopy: excellent σ(E)/E in the range of E_γ = 1~100 keV

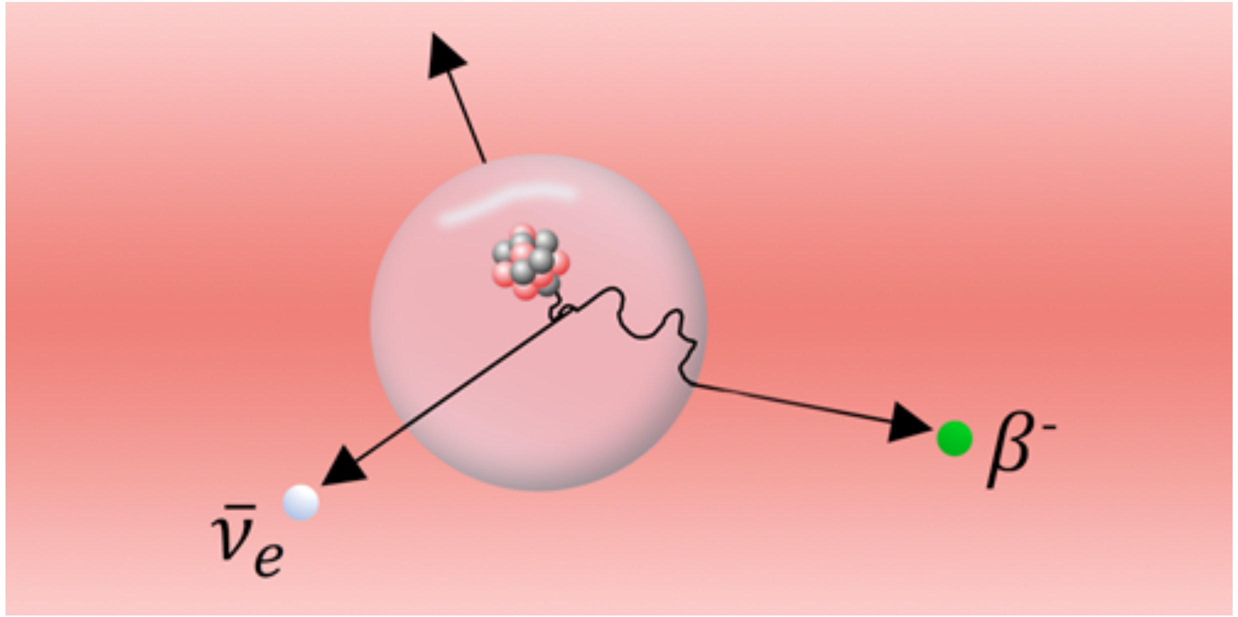
Synergy with IR sensing arrays in space

- **Nuclear charge radii** through x-ray spectroscopy of muonic, pionic, antiprotonic atoms
- Low temperature microcalorimeters for the measurement of the finite **neutrino mass** (spectrum endpoint): ^{163}Ho: Q=2.83 keV

> The HOLMES experiment will consist of 1000 TES detectors each loaded with about 300 Bq ^{163}Ho.
>
> The ECHo experiment is conceived with the goal to achieve sub-eV sensitivity on the effective electron neutrino mass using large arrays of multiplexed MMCs hosting ^{163}Ho.
>
> Given the need of having a total ^{163}Ho activity of the order of MBq to reach a neutrino mass sensitivity in the sub-eV region, a number of the order of 10^5 single pixels is required. The availability of a multiplexed readout scheme for thousands of detectors is essential.

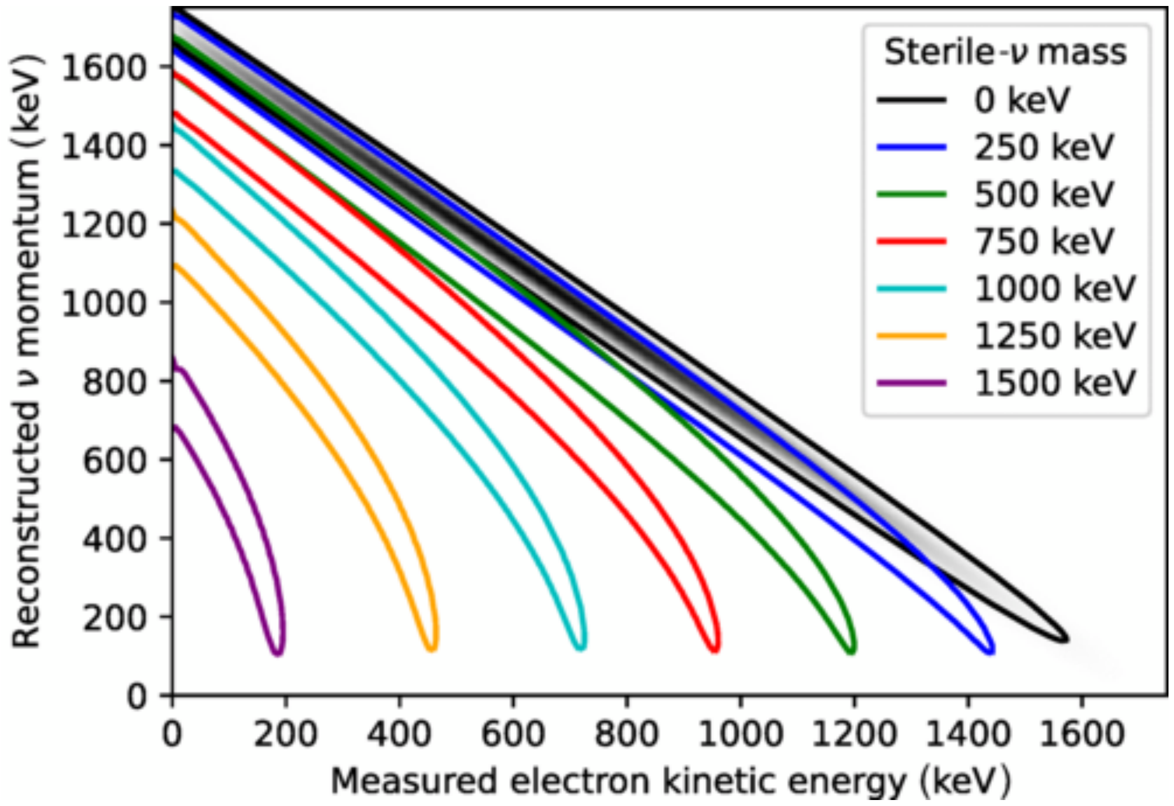
- The Ricochet experiment aims to make a detailed measurement of the coherent elastic neutrino-nucleus scattering (**CEvNS**) spectrum. A novel possibility is the Q-Array, which utilizes a readout based on Transition-Edge Sensors (TES) and radio frequency (RF) Superconducting Quantum Interference Devices (SQUIDs).

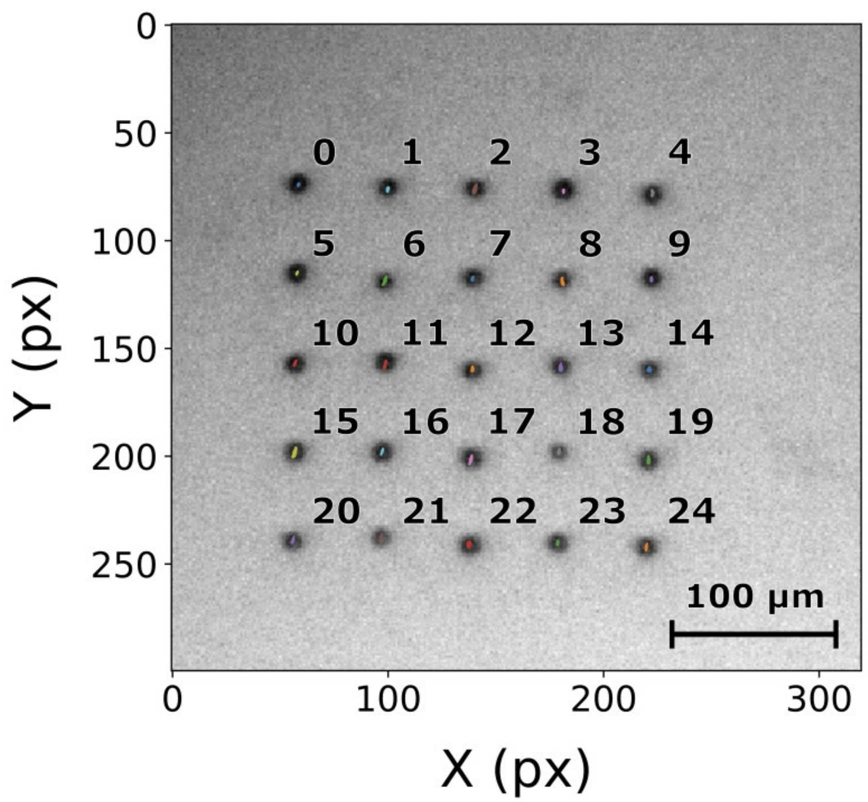
Specific examples for potential particle physics impact: neutrino mass



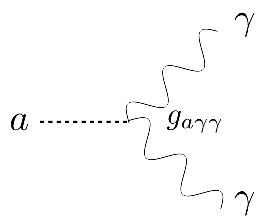
Radioactive material embedded in levitated microparticle → monitor positions → infer neutrino momentum and rest mass

Carney, Leach, Moore, PRX Quantum 4 010315 (2023)
Wang et al, PRL 133 023602 (2024)





Specific examples for potential particle physics impact: RF cavities



$$F \sim g_{a\gamma}^2 m_A^2 B^4 V^2 T_{sys}^{-2} G^4 Q,$$

system noise temperature
cryo-amplifiers JJPA

problem: cavity resonance generally fixed

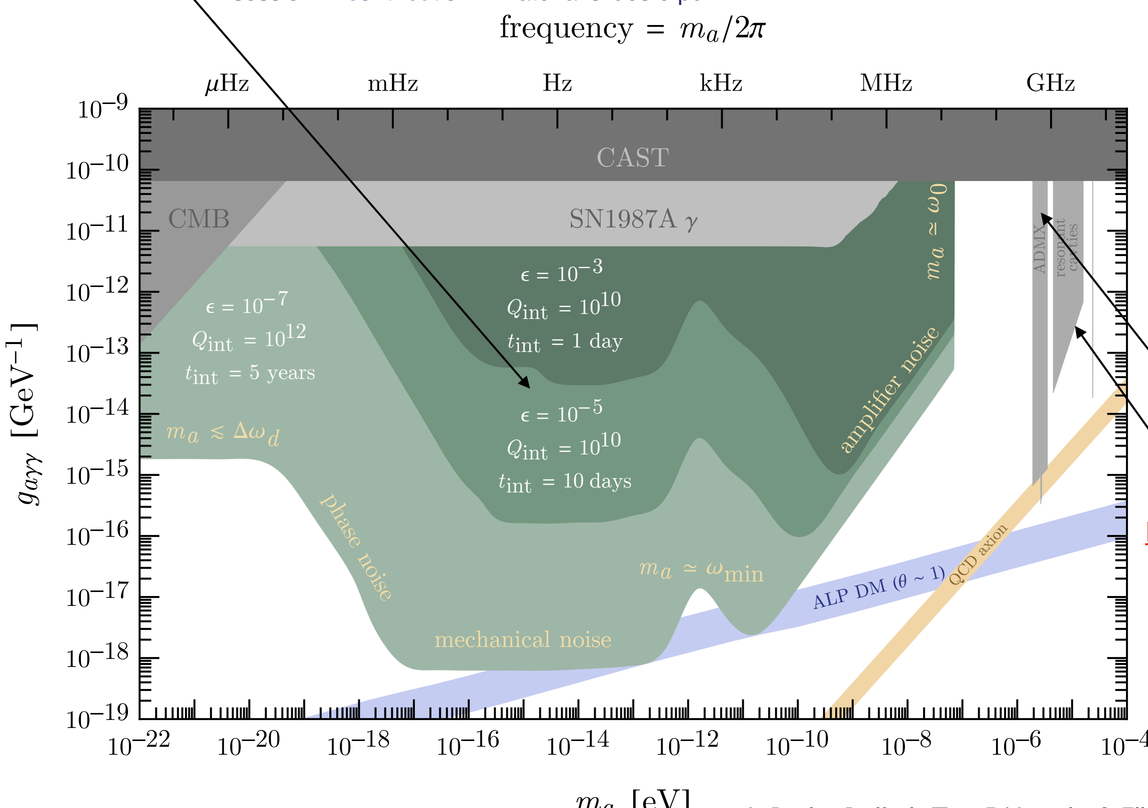
Resonant cavities possible down to μeV;
below that, need huge volume

driving "pump mode" at $\omega_0 \sim$ GHz allows axion to resonantly drive power into "signal mode" at $\omega_1 \sim \omega_0 \pm m_a$

solution for tuning: mechanical deformation; field tuning (SRF)

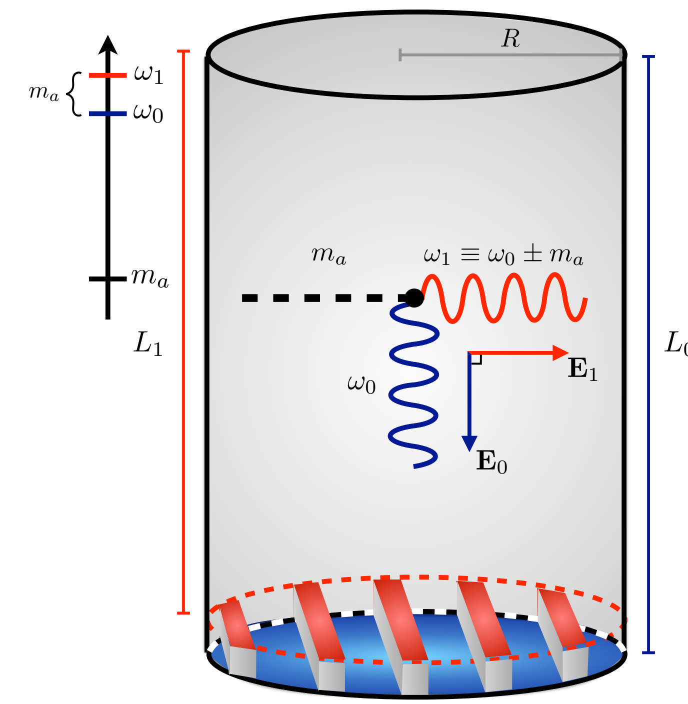
$Q_{int} \gtrsim 10^{10}$ achieved by DarkSRF collaboration
(sub-nm cavity wall displacements)

A. Grassellino, "SRF-based dark matter search: Experiment," 2019. https://indico.fnal.gov/event/19433/session/2/ contribution/2/material/slides/0.pdf



ADMX experiment

resonant cavities



(a) Cartoon of cavity setup.

Conceptual Theory Level Proposal:

A. Berlin, Raffaele Tito D'Agnolo, S. Ellis, C. Nantista, J. Nielson, P. Schuster, S. Tantawi, N. Toro, K. Zhou, *JHEP* 07 (2020) 07, 088
Asher Berlin, Raffaele Tito D'Agnolo, Sebastian A. R. Ellis, Christopher Nantista, Jeffrey Neilson, Philip Schuster, Sami Tantawi, Natalia Toro, Kevin Zhou, https://arxiv.org/abs/1912.11048

"The cavity is designed to have two nearly degenerate resonant modes at ω_0 and $\omega_1 = \omega_0 + m_a$. One possibility is to split the frequencies of the two polarizations of a hybrid HE_{11p} mode in a corrugated cylindrical cavity. These two polarizations effectively see distinct cavity lengths, L_0 and L_1, allowing ω_0 and ω_1 to be tuned independently."

2 WP-1 Atoms / HCI / molecules for DM, QED, BSM

Specific examples for potential particle physics impact: clocks and clock networks

BSM Ultralight scalar fields ↝ variations of fundamental constants that affect atomic clock frequencies.

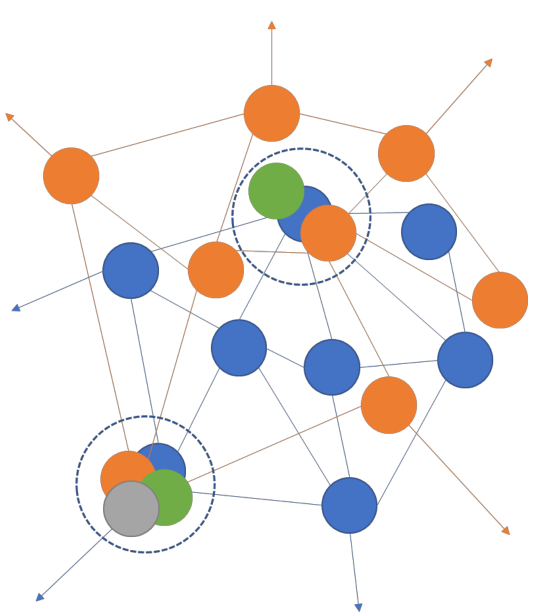
In our galaxy, such dark matter exhibits coherence and behaves like a wave with an amplitude ~ $\sqrt{\rho_{DM}}/m_{DM}$, (where ρ_{DM} = 0.4GeV/cm^3 is the local DM density and m_{DM} is the DM particle mass). The coupling of such DM to the Standard Model leads to oscillations of fundamental constants and, therefore, clock transition frequencies.

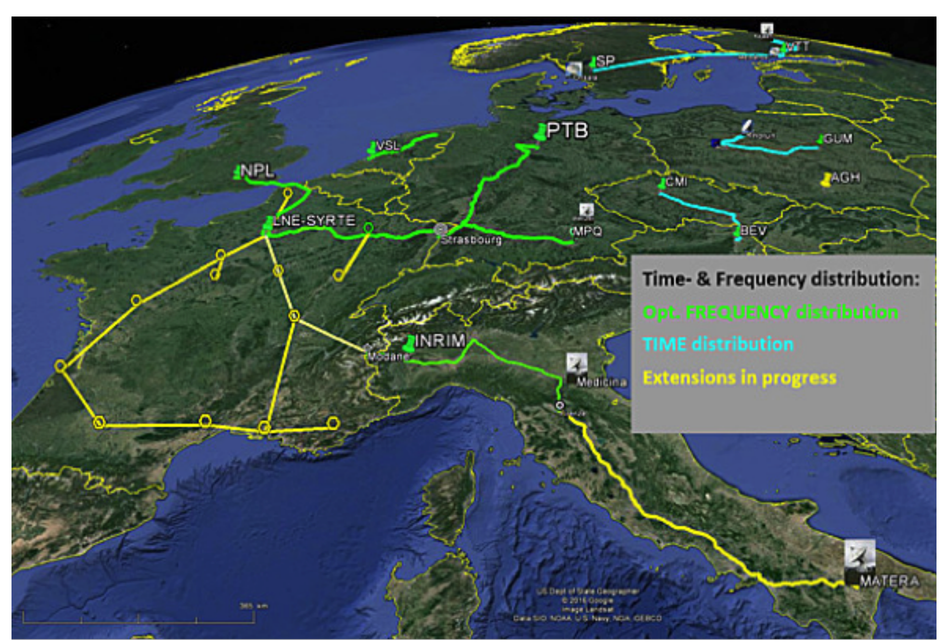
single clocks

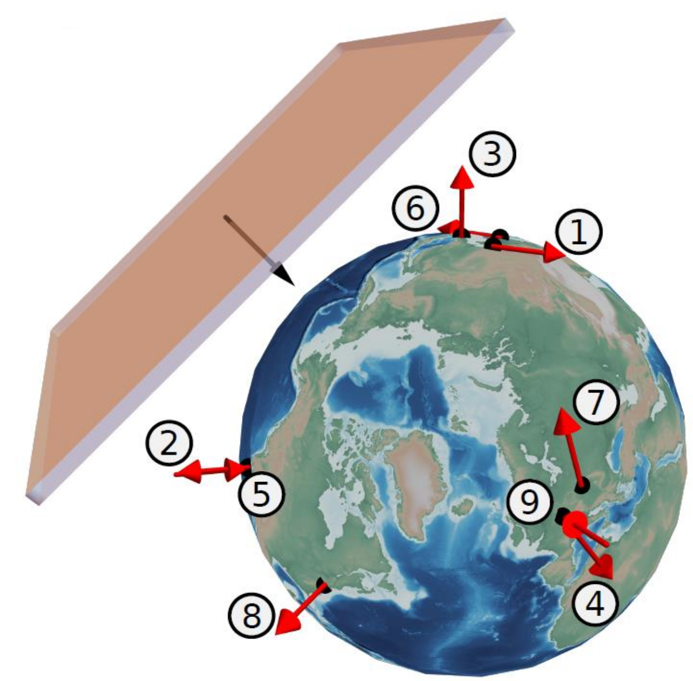
Thorium-based nuclear clock experiments will offer better sensitivity to ultralight scalar dark matter than any other existing or proposed experiments by many orders of magnitude for a large range of dark matter masses *in the long term*. Ion-based, molecule-based, atomic clocks currently define the frontier.

clock networks

A network of such clocks can *also* be used to search for transient signals of a hypothetical dark matter in the form of stable topological defects

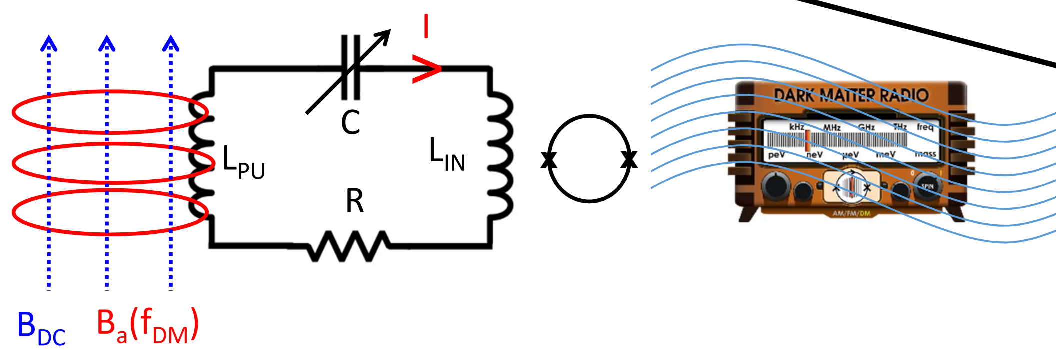




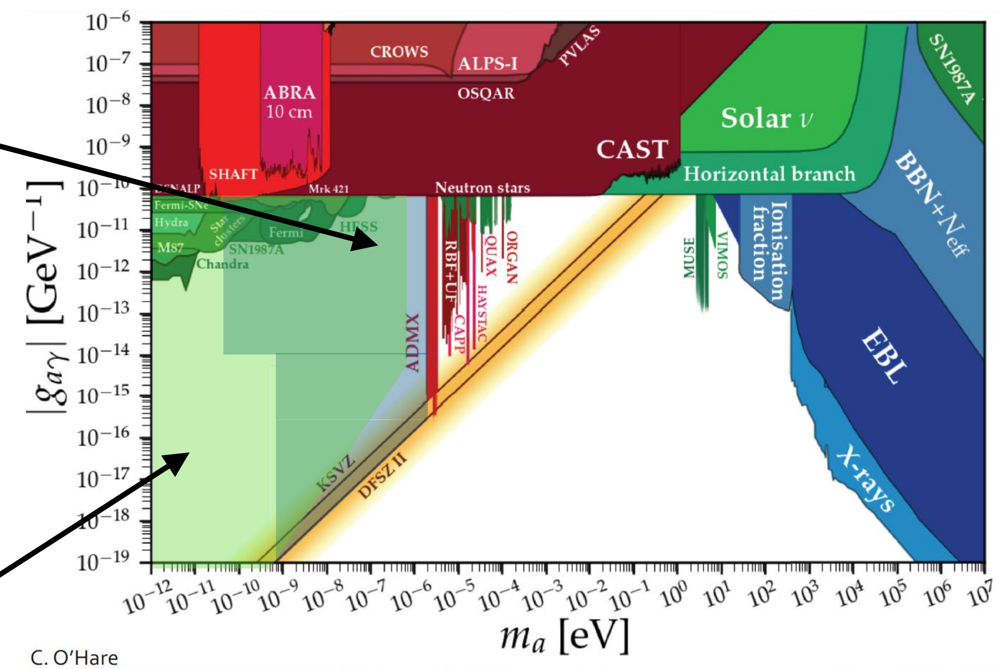


Specific examples for potential particle physics impact: Field and spin sensors

DMRadio



- Axion field converts to oscillating EM signal in background DC magnetic field
- Detect using tunable resonator
- Signal enhancement when resonance frequency matches rest-mass frequency $\nu_{DM}=mc^2/h$
- SQUID's, RF Quantum upconverters, cryoamplifiers



C. O'Hare

CASPEr

Axion-like dark matter can exert an oscillating torque on ^{207}Pb nuclear spins via the electric dipole moment coupling g_d or via the gradient coupling g_{aNN}.

Cosmic Axion Spin Precession Experiment is based on a precision measurement of ^{207}Pb solid-state nuclear magnetic resonance in a polarized ferroelectric crystal.

→ spin $\boldsymbol{\sigma}$ to axion coupling:

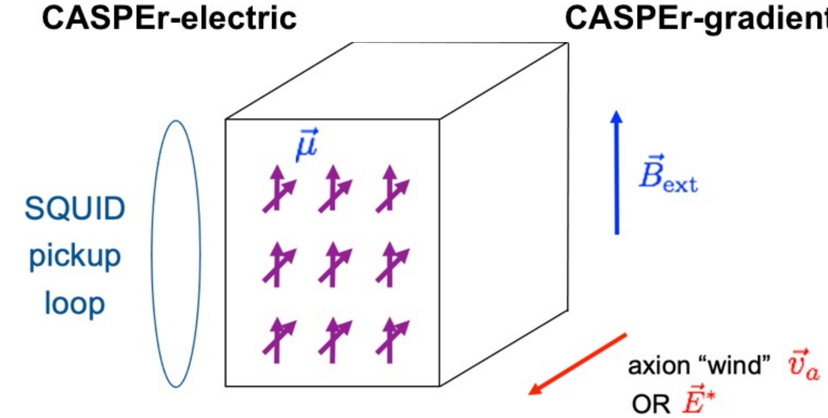
$$H_e \propto a\boldsymbol{\sigma}\cdot\boldsymbol{E}^*$$

CASPEr-electric

→ spin $\boldsymbol{\sigma}$ to axion gradient coupling:

$$H_g \propto \boldsymbol{\sigma}\cdot\boldsymbol{\nabla}a$$

CASPEr-gradient



3

Challenges to R&D on quantum sensors *in the context of particle physics*

- Organizational: multiple communities with little interactions
- Scale: going from individual devices to O(10^6) integrated elements
- Keeping up with very rapid growth in capabilities and range of quantum techniques: need for exploratory applications also for HEP
- Murkiness: need to identify critical aspects in specific applications that might hamper application to HEP (e.g. radiation damage, simulations, …)
- Education: rapid expansion in #'s of ESR's able to cover and apply broad range of expertise is needed

...in addition to the technical challenges of the dedicated R&D needed to achieve their expected potential!

3

What has happened since the ECFA roadmap ?

- concrete proposals for HEP-relevant uses of quantum sensors are appearing
- first beam tests with quantum dots and nano/microwires
- formation of a global multi quantum-technology community focusing on detector R&D under the umbrella of DRD5
- infrastructure needs have been identified and are starting to be addressed (cryogenic beam test facilities, quantum dot characterization infrastructure, …)
- almost all areas are covered by DRD5; this initiative has seen strong interest from multiple communities and has rapidly grown to now encompass 112 institutes worldwide, only 1/3 from traditional HEP

...in all the shown examples, dedicated R&D is under way, with involvement of DRD5

3

Main messages on quantum sensor R&D:

- Relevant for LEPP *and* HEPP. If quantum-sensor based devices are not critical for your applications, at least keep your toes in the water (in case something very useful comes out, but also to keep the next generation of detector experts interested and polyvalent: relevant for attractiveness of the field)

- Topical: first HEPP projects are starting to happen

- Complementary: Smaller scale experiments based on QS & emerging technologies complement (in timeline and expertise) the longer timescale large detector projects

- Synergies with neighboring fields & interest within HEP: Clear awareness and interest by the HEP community (national inputs, labs) & synergy with APPEC, NUPEC

- Actively used in LEPP; long term *potential* for HEPP; realizing the potential **requires investments**

> "Support at the national level for work on Quantum Sensing for Particle Physics is essential in order to fully achieve the potential of quantum technologies for a broad and fundamental impact on particle physics. The support is required to advance the five Quantum Sensor families that DRD5 focuses on, but also in order to develop an expert workforce through specific university programs, to ensure the fluid exchange of expertise, and to ensure efficient sharing of and access to infrastructure on a global level.
>
> Financial support is needed for both the workforce and on the technical fronts; the possibility of leveraging such support to achieve major advances in Quantum Sensors for Particle Physics is tightly tied to the fostering of open exchanges, to a willingness and ability to pool resources and to work across disciplines and borders."

https://indico.cern.ch/event/1439855/contributions/6461620/attachments/3045998/5381968/DRD5_submission_to_ESPP.pdf

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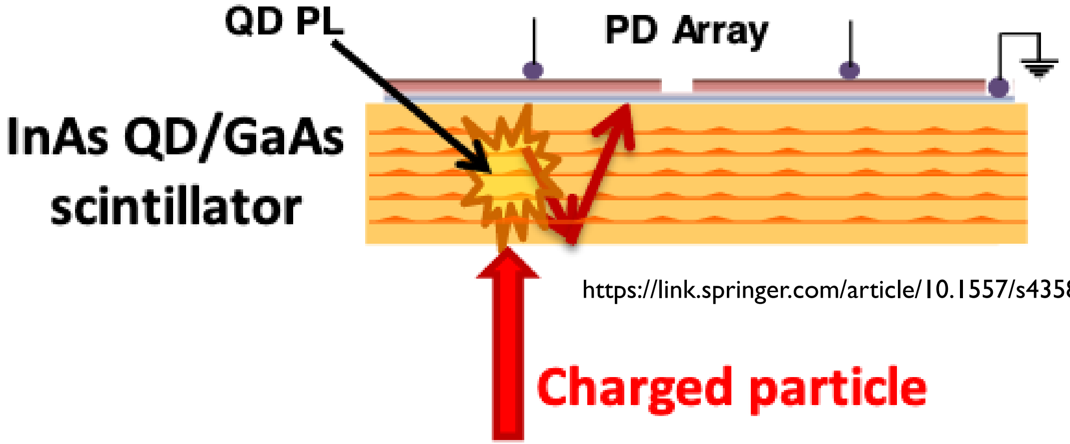
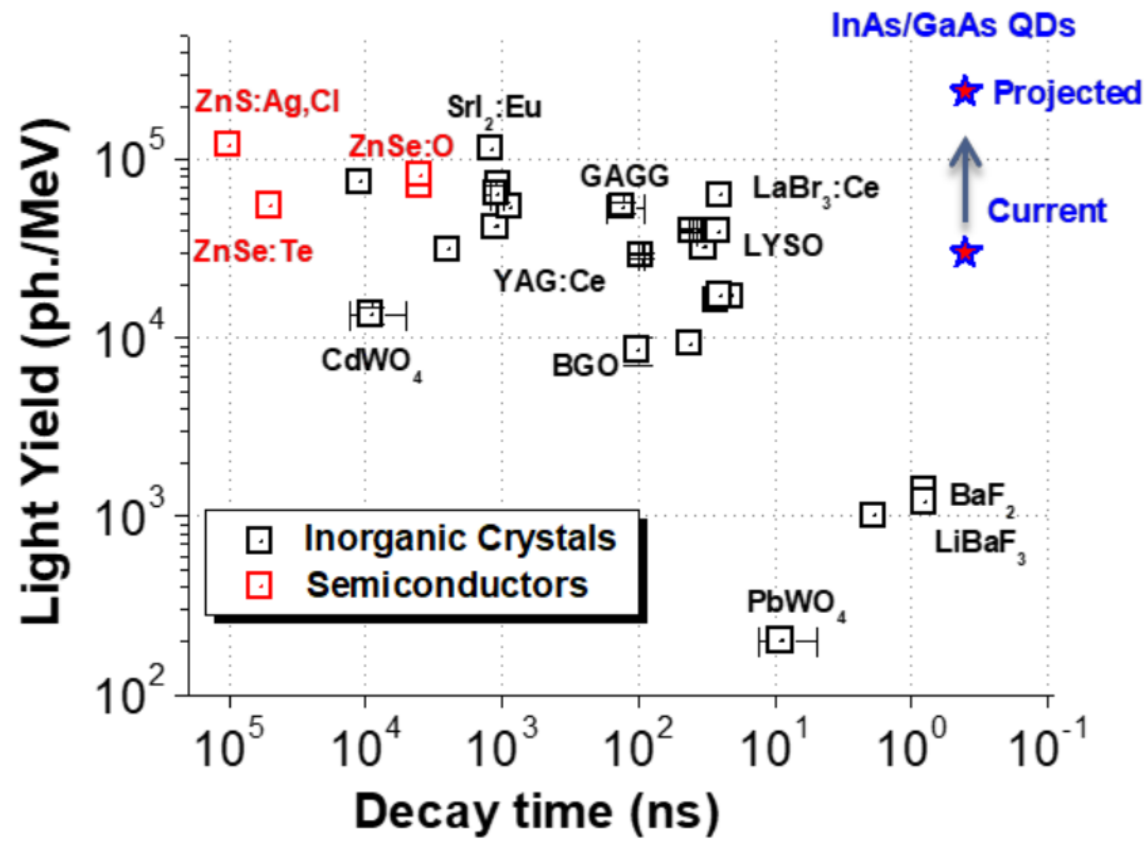
spare material

DotPix: Quantum dots for HEP tracking

scintillating (chromatic) tracker



https://link.springer.com/article/10.1557/s43580-021-00019-y



Novel Sensors for Particle Tracking: a Contribution to the Snowmass Community Planning Exercise of 2021, M.R. Hoeferkamp et al., arXiv:2202.11828

IR emission from InAs QD's

integrated PD's (1-2 μm thick)

A charged particle enters the GaAs bulk, producing electron-hole pairs. The electrons are then quickly trapped by the positively charged InAs quantum dots (QDs). The QDs undergo photoluminescence (PL) and emit photons that travel through the medium (GaAs absorption edge at 250 nm). The emitted photons are collected by a immediately adjoining photodiode (PD) array.