DRD5 for DRD6

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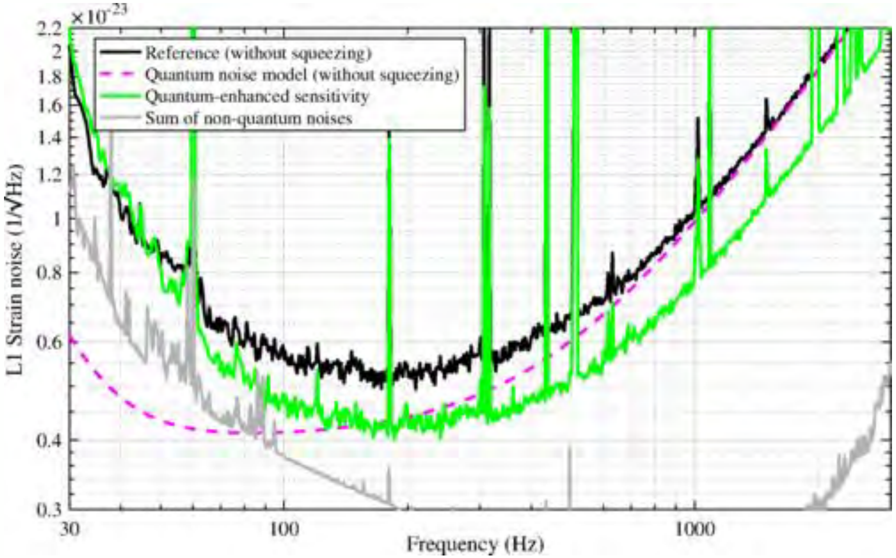
Michael Doser

October 31, 2024

ECFA Roadmap

- It has been shown that detectors based on quantum technologies can be engineered with significantly increased sensitivity
  - The best-known example to date is Advanced-LIGO:
    factor 2 better sensitivity – increased the size of the observable universe by a factor of 8!

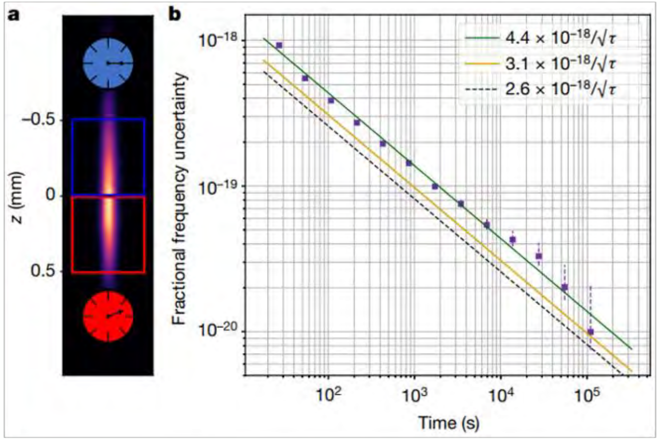


M. Tse et al., Phys. Rev. Lett. 123, 231107 (2019)

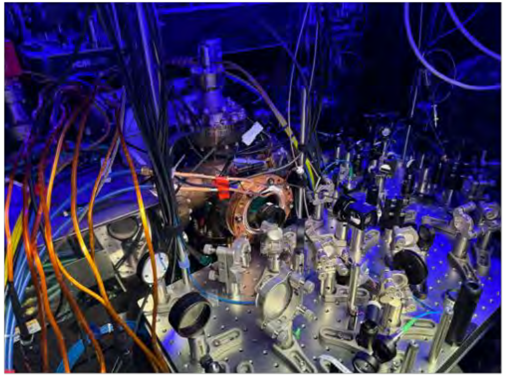
DRD5

Sensing has moved clock precision to 21st digit

QSA's advances in metrology deliver unprecedented accuracy in sensing, opened the doors to measuring the gravitational redshift using only a millimeter atomic sample instead of kilometer scale experiments



Measurement results



Experimental setup in Boulder

Measuring the gravitational redshift predicted by general relativity once required measurements separated by thousands of kilometers, now it can done over millimeter length scales

University of Colorado Boulder

Nature **602,** 420 (2022)

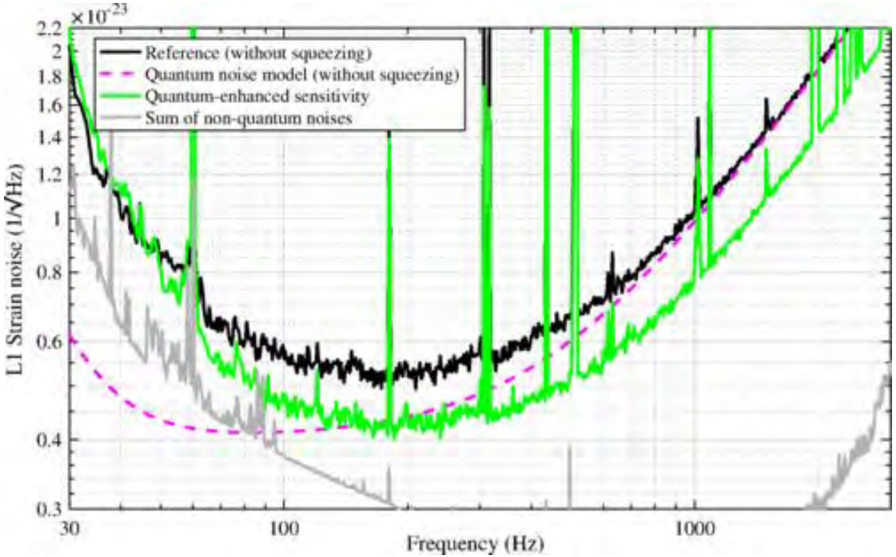
DRD5

ECFA Roadmap

- It has been shown that detectors based on quantum technologies can be engineered with significantly increased sensitivity
  - The best-known example to date is Advanced-LIGO: factor 2 better sensitivity – increased the size of the observable universe by a factor of 8!

- Quantum sensors, and in general emerging technologies, could hold great promise for the field.

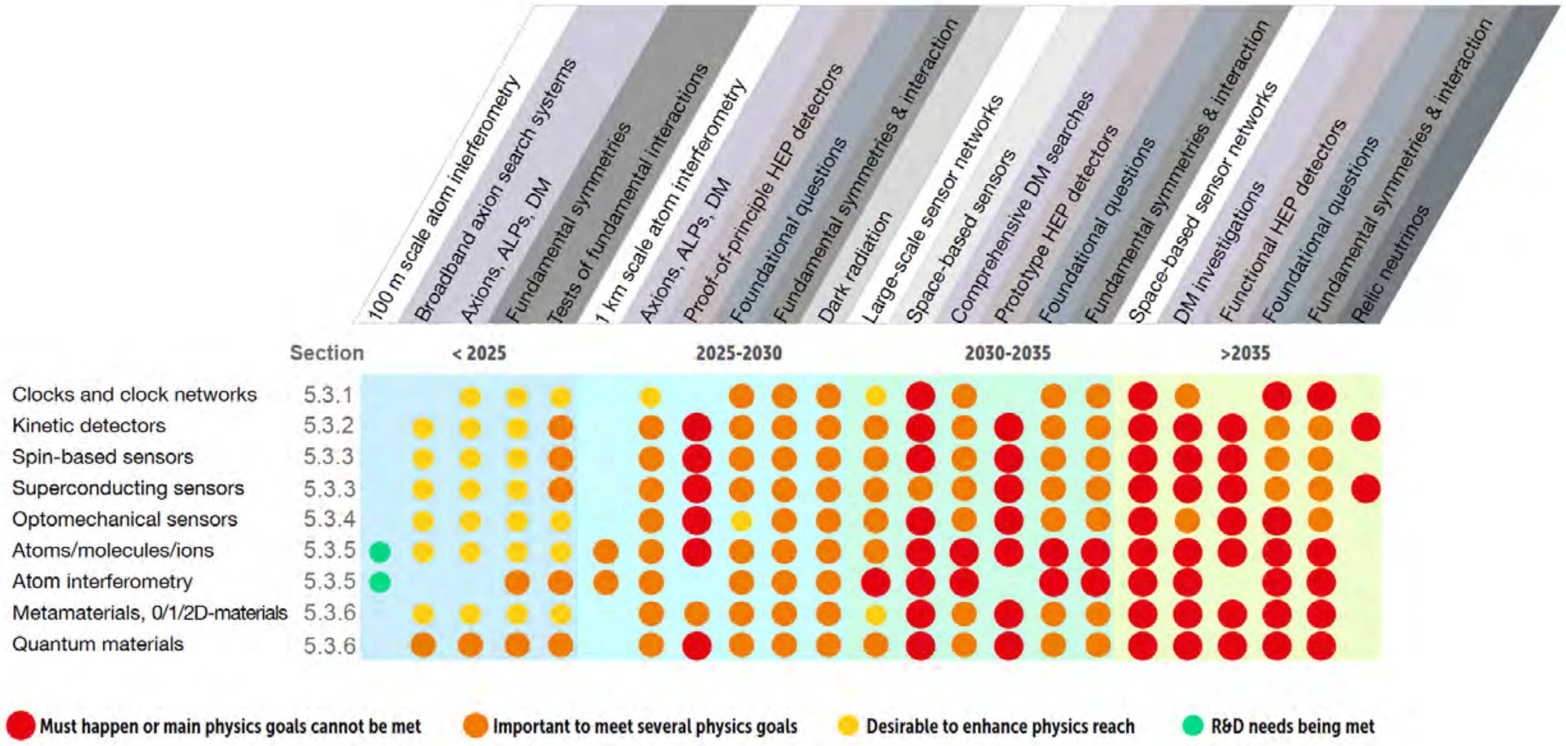
- Given that the ECFA Detector R&D Roadmap covered a broad spectrum of particle physics experiments, **quantum sensors and emerging technologies** included in the ECFA Detector R&D roadmap.



M. Tse et al., Phys. Rev. Lett. 123, 231107 (2019)

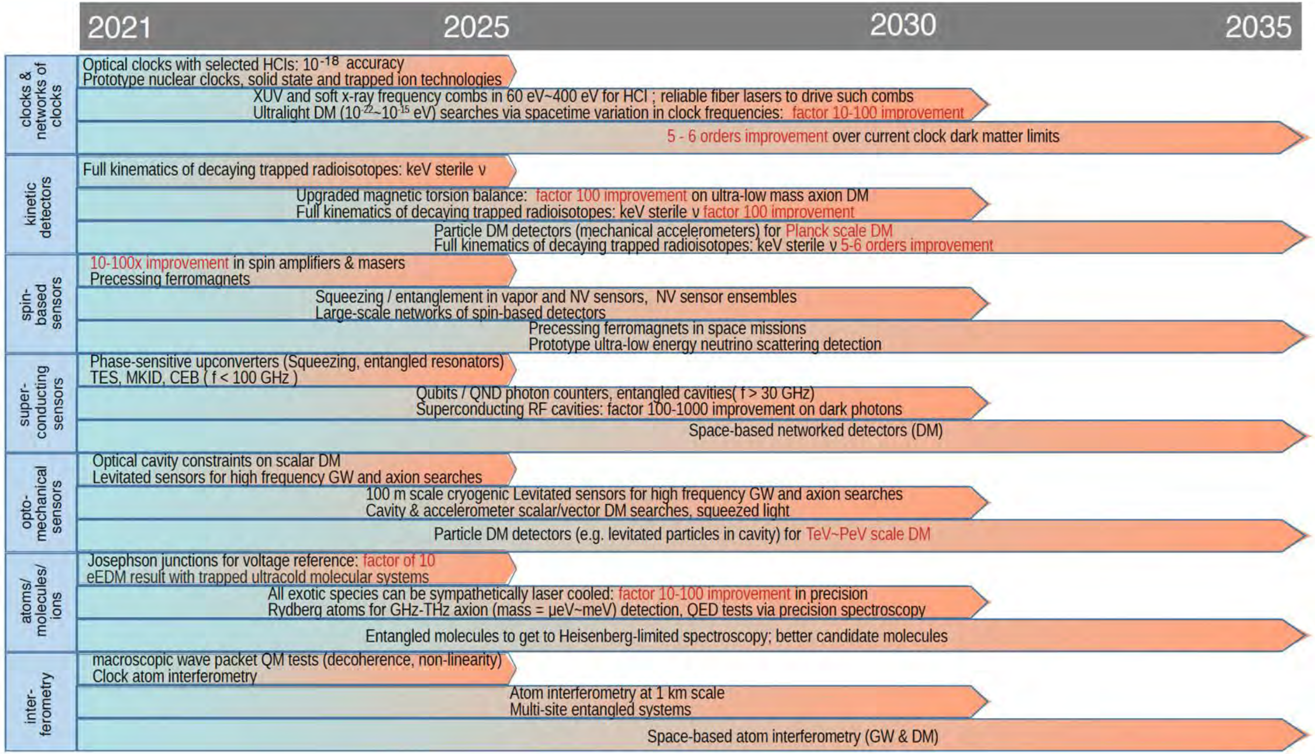
DRD5

ECFA Roadmap 2021



- Schematic timeline of categories of experiments employing detectors from the quantum sensing and emerging technology areas

ECFA Roadmap 2021



- *Prospective timeline for selected developments for a range of quantum and emerging technologies with deliverables; increases in sensitivity or accessible range are highlighted in red.*

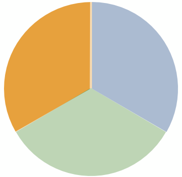
Broad range of application for quantum sensing

Applied (detectors)

- Novel designer materials
- Extreme sensitivity: candidate techniques for ultra-low interaction energy scales
- Gravitational wave detection
  Novel types of detectors

Fundamental physics

- Searches for dark matter
- Probing of fundamental symmetries:
  - via particle, atomic, molecular EDM's, spectroscopy)
- Gravitational waves
- Searches for novel couplings

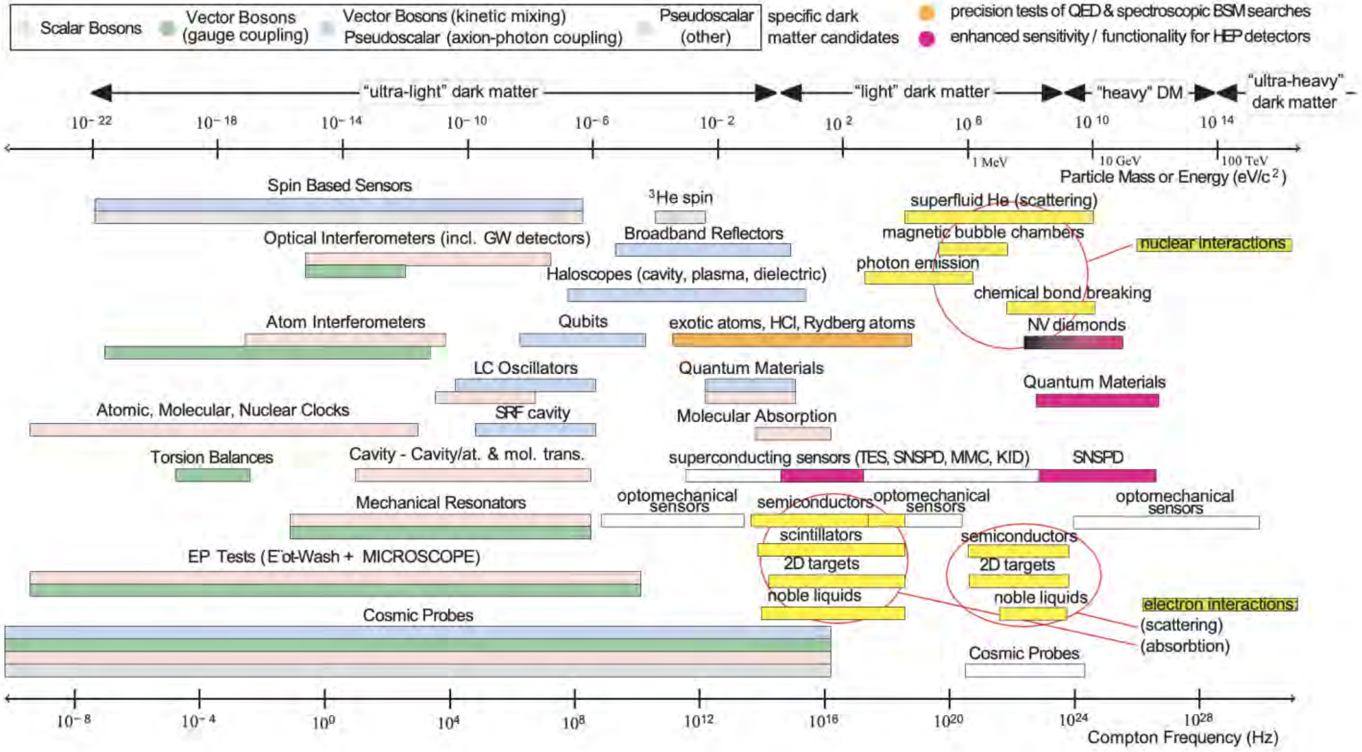


Improved quantum measurements

Tests of fundamental symmetries and interactions
Foundational Physics questions
Exploit full power of Quantum Mechanics

Example: Dark Matter Searches

- Many fundamental physics areas where quantum sensing can have a real impact, but for e.g. UL-DM, QS is essential



Possible Applications to Collider Physics

HEP function / Work package	Tracking	Calorimetry	Timing	PID	Helicity
WP 1 (Quantum systems in traps and beam)	Rydberg TPC	BEC WIMP scattering (recoil)	O(fs) reference clock for time-sensitive synchronization (photon TOF)	Rydberg dE/dx amplifiers	
WP2 (Quantum materials: 0-, 1- and 2-D)	"DotPix"; improved GEM's; chromatic tracking (sub-pixel); active scintillators	Chromatic calorimetry	Suspended / embedded quantum dot scintillators	Photonic dE/dx through suspended quantum dots in TPC	
WP 3 (Superconducting quantum devices)	O(ps) SNSPD trackers for diffractive scattering (Roman pot)	FIR, UV & x-ray calorimetry	O(ps) high Tc SNSPD	Milli- & microcharged particle trackers in beam dumps	
WP 4 (scaled-up bulk systems for mip's)	Multi-mode trackers (electrons, photons)	Multi-mode calorimeters (electrons, photons, phonons)	Wavefront detection (e.g. O(ps) embedded devices)		Helicity detector via ultra-thin NV optically polarized scattering / tracking stack
WP 5 (Quantum techniques)				Many-to-one entanglement detection of interaction	
WP 6 (capacity building)	Technical expertise of future workforce (detector construction); broadened career prospects and thus enhanced attractiveness; cross-departmental networking and collaboration; broadened user base for infrastructure (beam tests, dilution refrigerators, processing technologies)				

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

Goals of DRD5

- Among the many areas and technologies being worked on worldwide:
  - Identify key quantum/emerging technologies (within the ECFA roadmap).

- Within these,
  - Identify key topics which would most benefit the corresponding communities but that are not being addressed because they go beyond what individual groups can tackle.

- On these topics,
  - Identify groups that are willing to participate in a global collaborative effort.

Note: DRD5 does not have the benefit of long-established collaborative efforts within the community. Quantum efforts are mainly based in non-traditional HEP communities. DRD5 needs to establish trust, mutual interest, benefits for all involved and grow a corresponding community.

DRD5 WP Structure

ECFA Roadmap topics

DRD5 Work Packages

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

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

- N-dimensional materials are the building blocks for complex nanoscale "quantum materials". Work package has three focus areas:

- WP-2a: Application-specific tailoring
  - Exploring the landscape of possible building blocks of the low dimensional devices:
    - Quantum dots, nanocrystals, nano-platelets
    - Nanowires (also WP-3)
    - Mono-layers, surface deposition, surface treatments (thin films, also of superconductors)
    - …
  - Deliverables:
    - Optimized engineering for specific applications (e.g. scintillators)
    - Radiation hardness

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

- WP-2b: Extended functionalities
  - Geometries, chemical composition, internal layout, environment: all play a role in shaping the properties of individual elements;
  - Deliverables:
    - Extensive overview of what the design landscape enables on one hand, and what detector design benefits from on the other hand.
    - Engineering of the building blocks of arbitrary nanocomposite material

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

- WP-2c: Simulation
  - Simulation packages need to go beyond the assumption of continuous media (G4) and incorporate processes at the local molecular scale;
  - Deliverables:
    - Full understanding of performance requires accounting for interactions between the building blocks and their environment.

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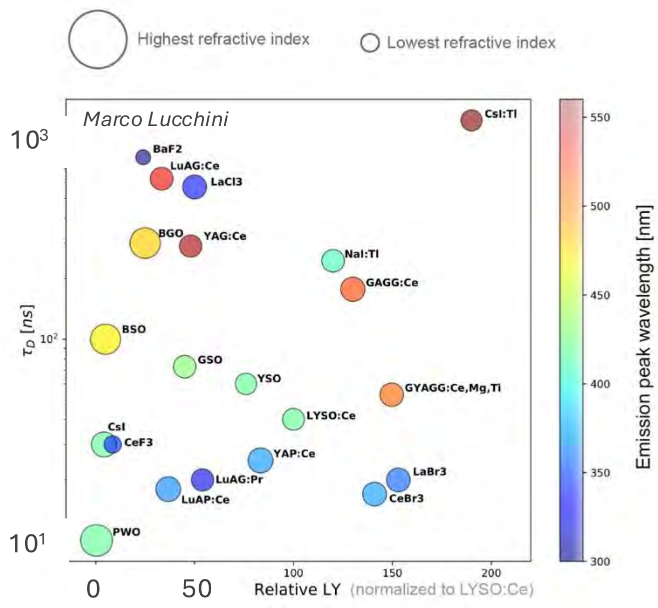
Milestone Deliverable

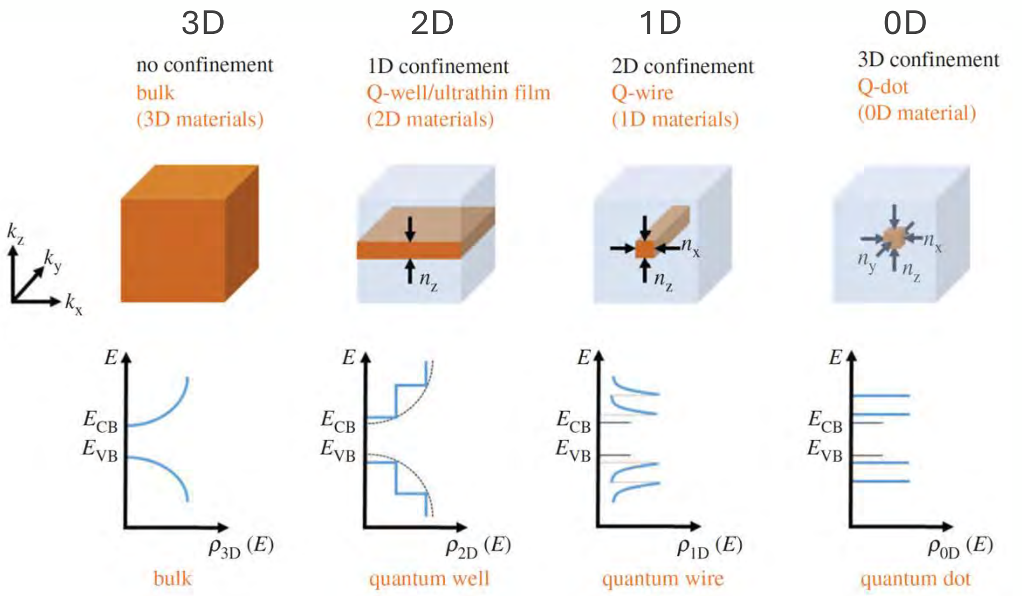
WP-2 (0-,1- and 2-D materials)

WP-2a	characterization protocol	database definition	populated db
(application-specific tailoring)	*protocol*	*Database prototype*	*Functional database*
WP-2ab	workshop/conference	device designs	novel hybrid devices
(extended functionalities)	*Device concepts*	*Prototype devices*	*Functional devices*
WP-2c	status & desiderata	prototype model	benchmarked simulations
(simulations)	*Report*	*Simulation SW designs*	*Validation report*

Crystal Calorimetry

- Traditionally, crystal – fully absorbing – calorimetry has obtained the best energy resolution





- Huge range of possibilities through **quantum engineering** of materials

rsos.royalsocietypublishing.org R. Soc. open sci. 5: 180387

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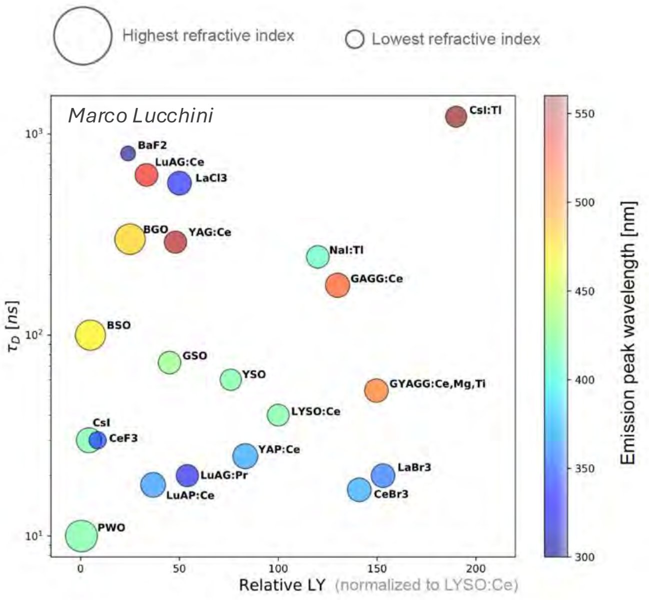
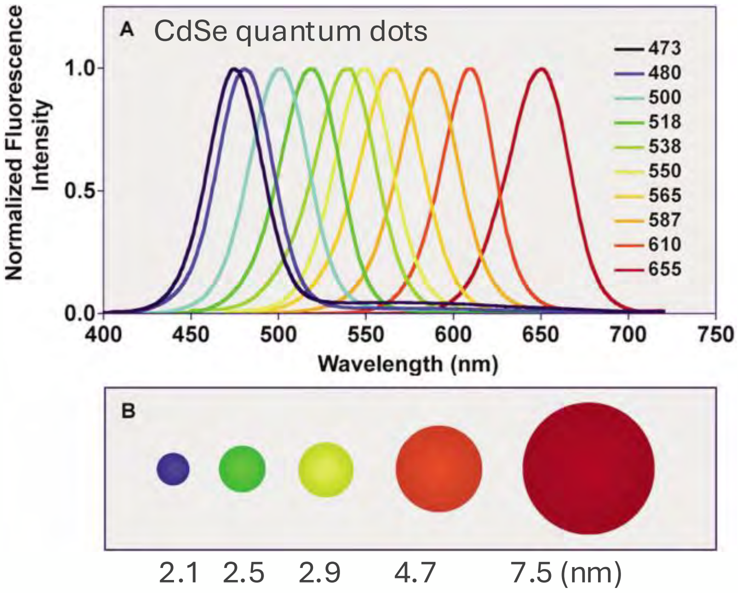




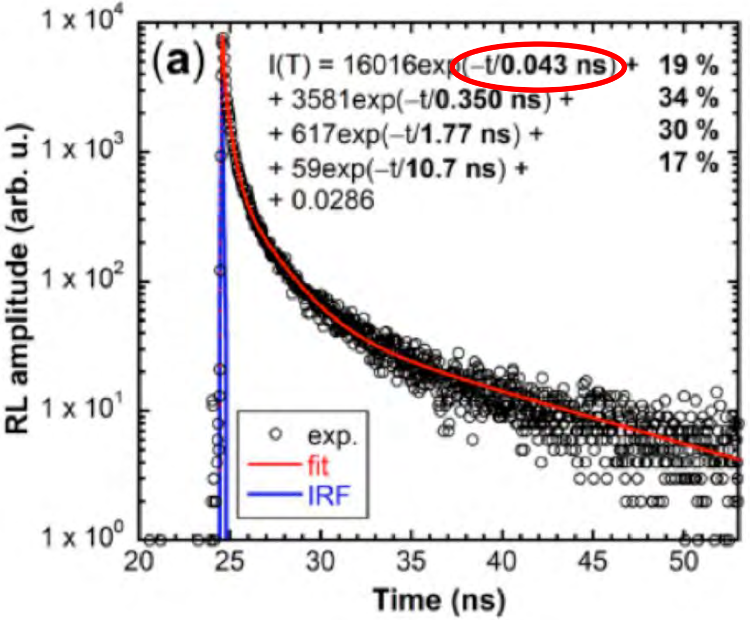
A. Smith, https://doi.org/10.1039/B404498N

- Huge range of possibilities through **quantum engineering** of materials

DRD5

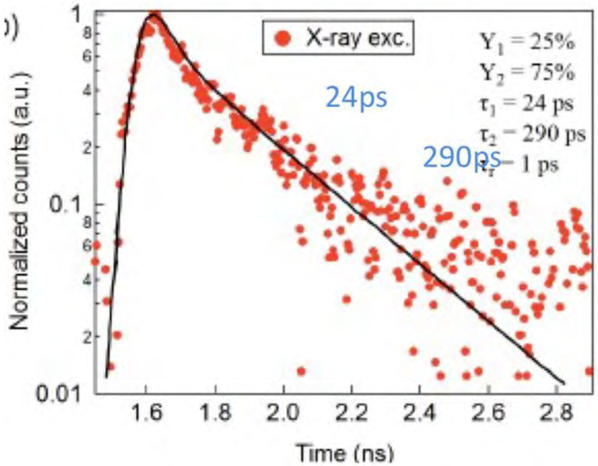
Quantum Dots for Timing

- Fast light emission through QD engineering



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

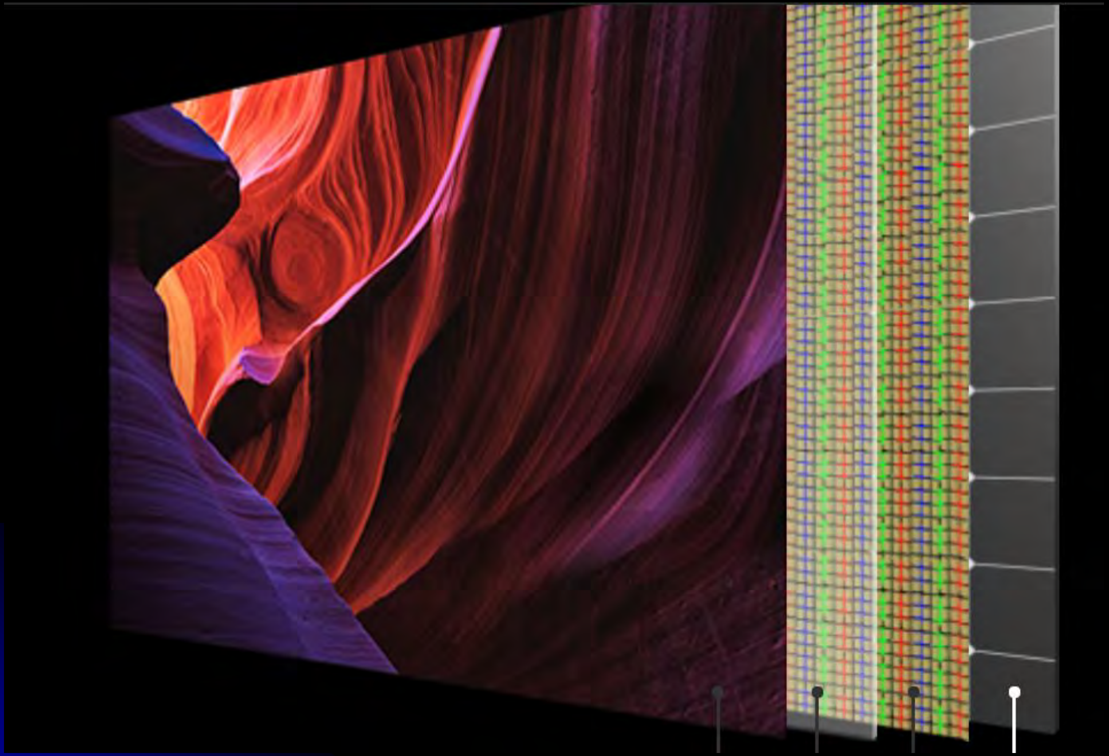
CdSe nanoplatelet,



J. Grim et al., *Nature Nanotechnology*, **9**,2014, 891–895
R. Martinez Turtos et al., 2016 JINST_11 (10) P10015

DRD5

Digression



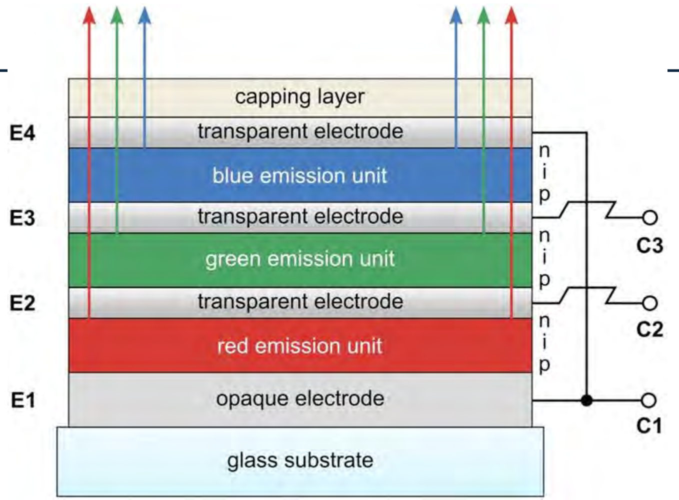
A closer look at technologies at industrial scale like Organic Light Emitting Diode (OLED)

- A series of organic thin films ink-jet printed between two conductors emitting light when a voltage is applied.
- Ubiquitous used in laptops, monitors, automotive, cell phones, …
- Anisotropic Conductive Film drives the pixels.

Spectroscopic photosensors

- Reverse the OLED design: spectroscopic photodetectors
  - Engineer organic materials that absorb the light with a specific wavelength
  - Transparent electrodes collect the signal
  - Cherenkov vs. scintillation separation
  - No loss of photosensor coverage
- Can be made on rigid and flexible substrates
- Organic semiconductors good starting point
  - Low cost & highly scalable
- Integrate with 3D printed scintillators
- Requires multi-disciplinary collaboration

Stacked OLED

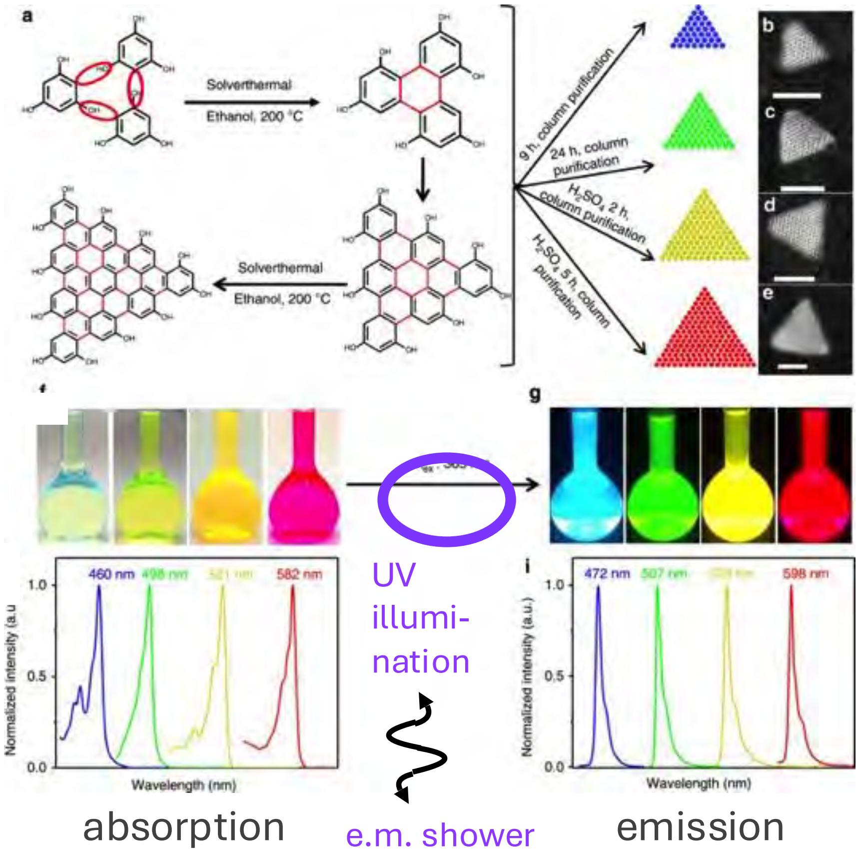


https://www.nature.com/articles/s41598-018-27976-z

https://www.sammobile.com/news/samsungs-new-foldable-and-udc-panels-reveal-an-exciting-future/

DRD5

Chromatic Calorimetry



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

Seed different parts of a medium 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>

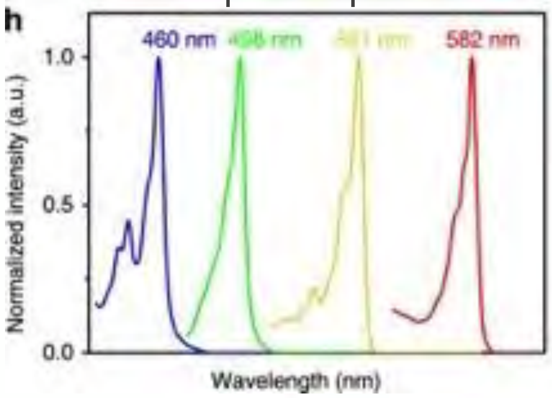
select appropriate nanodots

e.g. triangular carbon nanodots

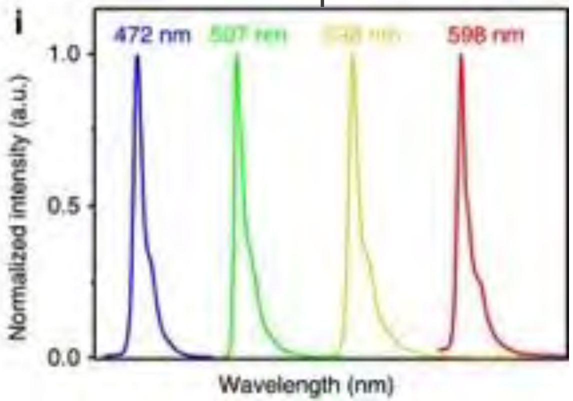
DRD5

Chromatic Calorimetry

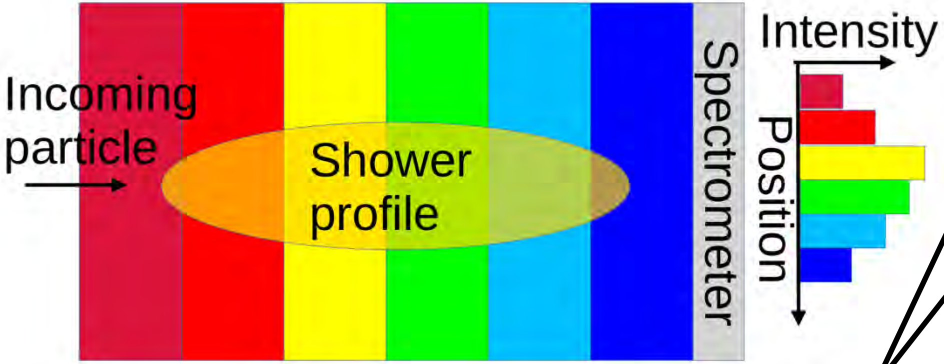
Absorption spectrum



Emission spectrum



triangular carbon nanodots



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

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

Metalenses?

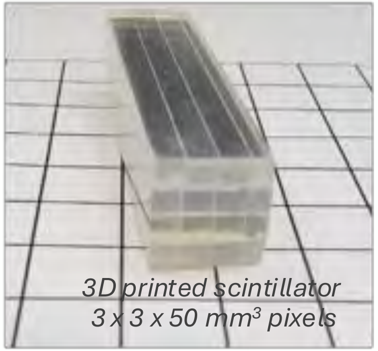
M. Khorasaninejad & F. Capasso, Science 358, 6367 (2017)

DRD5

Creation of Scintillators with Light

- Light-based **3D Stereolithography** (SLA):
  - Part is produced layer-by-layer from a liquid resin vat using just light
  - Near contactless manufacturing! Background free!
  - Significantly better optical properties than Fused Deposition Modeling
- Photocurable resins allows using UV or visible light:
  - Curing time from seconds to hours; large-scale production
  - Can be performed at room temperature
  - Resin formulations allows for embedding
- Can build **Optically Active** structural materials:
  - Polyethylene naphthalate (PEN) shifts 128 nm LAr scintillation light to ~440 nm and scintillates
  - Yield strength higher than copper at cryogenic temperatures

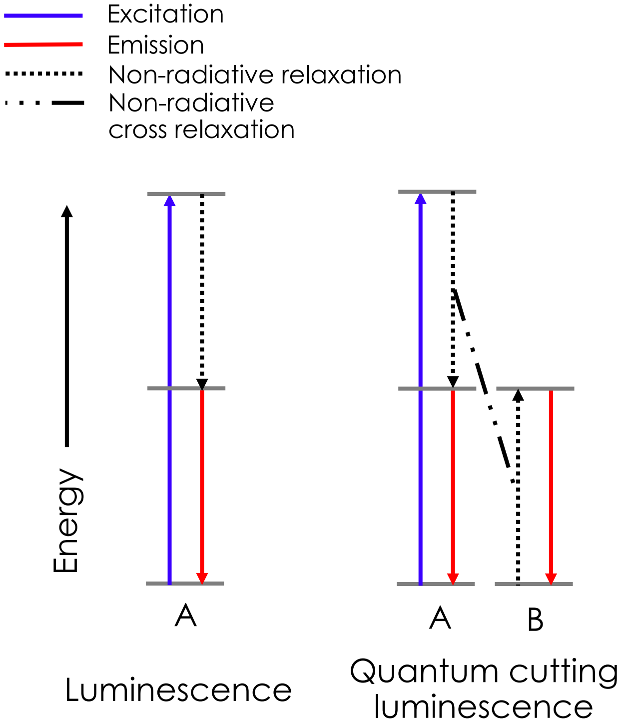
Plastic scintillator with embedded readout fiber



3D printed scintillator $3 \times 3 \times 50$ mm^3 pixels

Low mass detector holder design under UV illumination (LEGEND)

"Quantum amplification" – VUV to VIS



- Quantum Cutting Luminescence (QCL)
  - Two-photon luminescence process
  - Convert high energy photon to two low energy photons
  - Quantum efficiency > 100% possible

Visible Quantum Cutting in $LiGdF_4:Eu^{3+}$ Through Downconversion

René T. Wegh, Harry Donker, Koenraad D. Oskam, Andries Meijerink*
+ See all authors and affiliations

Science 29 Jan 1999:
Vol. 283, Issue 5402, pp. 663-666
DOI: 10.1126/science.283.5402.663

THE JOURNAL OF PHYSICAL CHEMISTRY C
Article
pubs.acs.org/JPCC

High Efficiency Green Phosphor $Ba_9Lu_2Si_6O_{24}:Tb^{3+}$: Visible Quantum Cutting via Cross-Relaxation Energy Transfers

Yongfu Liu,*[†] Jianxin Zhang,[†,‡] Changhua Zhang,[†,§] Jun Jiang,*[†] and Haochuan Jiang*[†]
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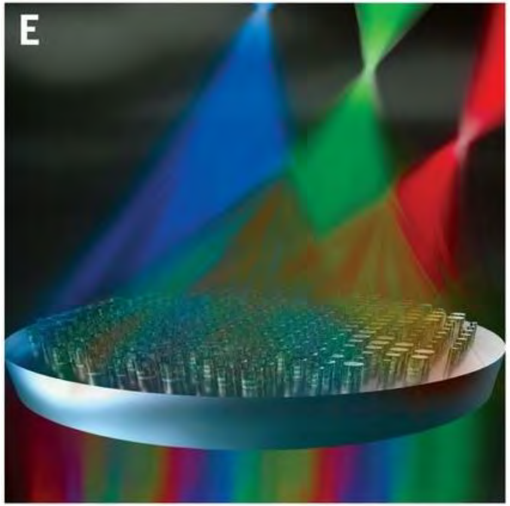
[‡]College of Electronic Information and Engineering, Hangzhou Dianzi University, Hangzhou 310018, China
[§]Department of Chemistry, College of Science, Shanghai University, Shanghai 200444, China

Traditional phosphors:	**QE ~90%**
$LiGdF_4:Eu^{3+}$	**QE 190%**
$BaF_2:Gd^{3+},Eu^{3+}$	**QE 194%**

Nanophotonics

- Arrays of sub-wavelength spaced nanostructures that can manipulate light wavefronts
- Control of phase, amplitude, polarization, wavelength, diffraction, …
- Large-areas through standard photo-lithographic process
- Low cost and very versatile

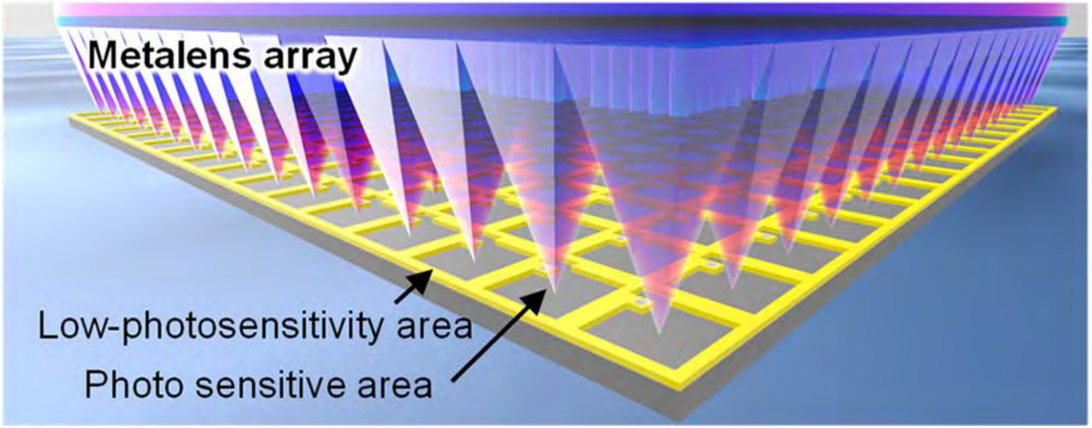


M. Khorasaninejad, F. Capasso,
Science 358 6367 (2017)
DOI: 10.1126/science.aam8100

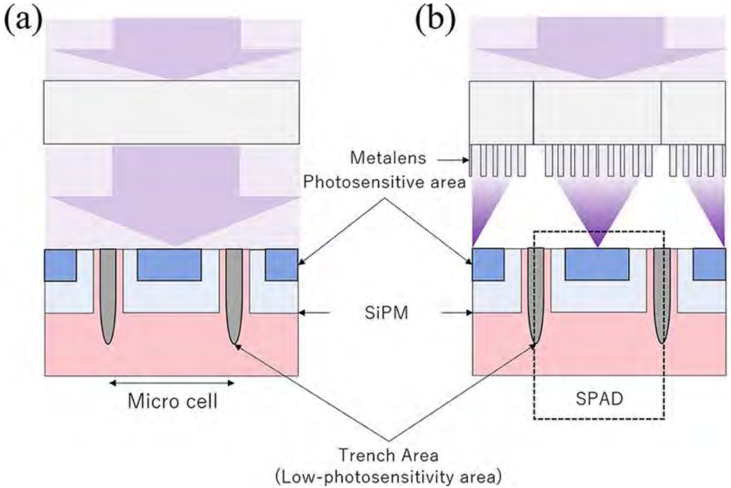
https://serious-science.org/federico-capasso-optical-properties-of-surfaces-3795

DRD5

Nanophotonics



S. Uenoyama, R. Ota, ACS Photonics 2021, 1548–1555
https://doi.org/10.1021/acsphotonics.1c00257



- Improved detection efficiency, timing resolution.
- Possibility for wavelength sensitivity?

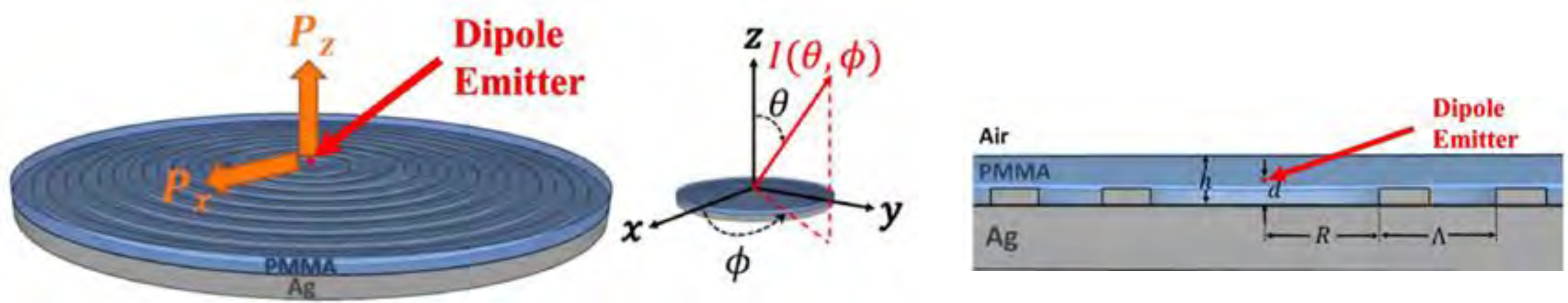
DRD5

Nano-plasmonics

- A lot of work is being done in the area of single photon emitters for quantum communication.
- Plasmonic nanomaterials or artificial surfaces can enhance spontaneous photon emission rates of nearby nanomaterial emitters– the Purcell Effect.
- Localized surface plasmon resonances (LSPR) need to overlap with the emitter's absorption or photoluminescence wavelength

Enhanced Photon Efficiency

- With metal-dielectric circular bullseye structures can create directional photomaterials
  - Photon source at center emits into a dielectric layer
  - Dielectric = slab waveguide that guides light radially toward circular gratings
  - In the far-field, the interference between various diffracted waves occurs only at low angles: Highly directional photon stream in broad spectral range

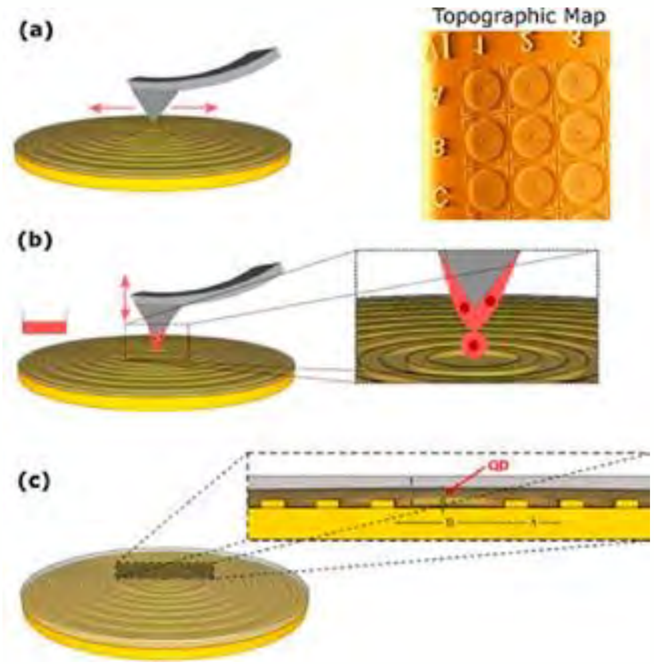


See original development by
R. Rapaport, H. Abudayyeh *Q. Sci. Tech.* (2017)

DRD5

Writing a single Quantum Dot

- Dip-pen nanolithography to directly write single QD at the center of a bullseye



- With dip-pen nanolithography creating a hybrid device and can precisely locate a single QD in the bullseye center
- Record-high collection efficiency: 85% of single photons.

Abudayyeh et al. APL Photonics 2021, 036109

WP4: Scaling Quantum

- Process of going from proof of principle to large-scale detectors
- WP-4b: Hybrid Devices
  - 4b-a: Scintillators
  - 4b-b: Ensembles of heterostructures
  - 4b-c: Heterodox devices
  - Vision:
    - **HEP Scintillators with full optimization** of the complete chain: not just of the quantum dots but also of surface treatments, novel types of scintillators (e.g. quantum wells in semiconductors), embedding materials and photon detection
    - **Composite structures engineered for optimal performance** and potentially combining different dimensionalities or compositions or geometries (work-function engineering, fine-tuning of charge transport in gaseous detectors, …)
    - **Novel devices that use individual quantum elements** to engineer new types of behavior, e.g. QCL coupled to silicon strip detectors.
    - …

Also connections to other DRDs

	Gaseous detectors	Liquid detectors	Solid state detectors	Photon detectors & PID	Calorimetry	Electronics/on-detector proc.	Integration	Training
work package	DRD1	DRD2	PDRD3	DRD4	DRD6	DRD7	PDRD8	DRD9
WP 1 (Quantum systems in traps and beams)	X			X				
WP 2 (Quantum materials: 0-, 1- and 2-D)		X	X		X			
WP 3 (Superconducting quantum devices)			X	X		X		
WP 4 (Scaled-up bulk systems for mip's)			X					
WP 5 (Quantum techniques)								
WP 6 (Capacity building)	X	X	X	X	X	X	X	X

Status

- DRD5 had to be built ”from scratch” and we are not as far advanced as the other DRDs. For example, not all work package leaders have been identified yet.
- Our first Collaboration Board meeting will take place next Monday, Nov. 4 with our first collaboration meeting in February, 2025.

Defining a Future Program for Europe is an Ambitious Goal

- **2021- 25:** Feasibility Study
- **2027/2028:** project approval by CERN Council
- **2032:** construction starts
- **2041:** HL-LHC ends
- **2045:** Operation of FCC-ee
- **2070:** Operation of FCC-hh

- The outcome of the process proposed will depend on many factors, with some important ones not under our control.

- We should build the strongest science case and demonstrate that we can meet the physics challenges with the **most advanced detectors** that we can design, to improve the likelihood that this very ambitious process be realized.

Conclusion

- Let's continue to "bounce ideas" for **new detector technologies**; we will all benefit.

- We are very much looking forward to a strong collaboration with DRD6.