“Quantum low-dimensional systems as particle detectors”

M. Doser, CERN

Quantum Sensing School, Nov. 2024

(low energy) particle detectors:

quantum sensors register a change of quantum state caused by the interaction with an external system:

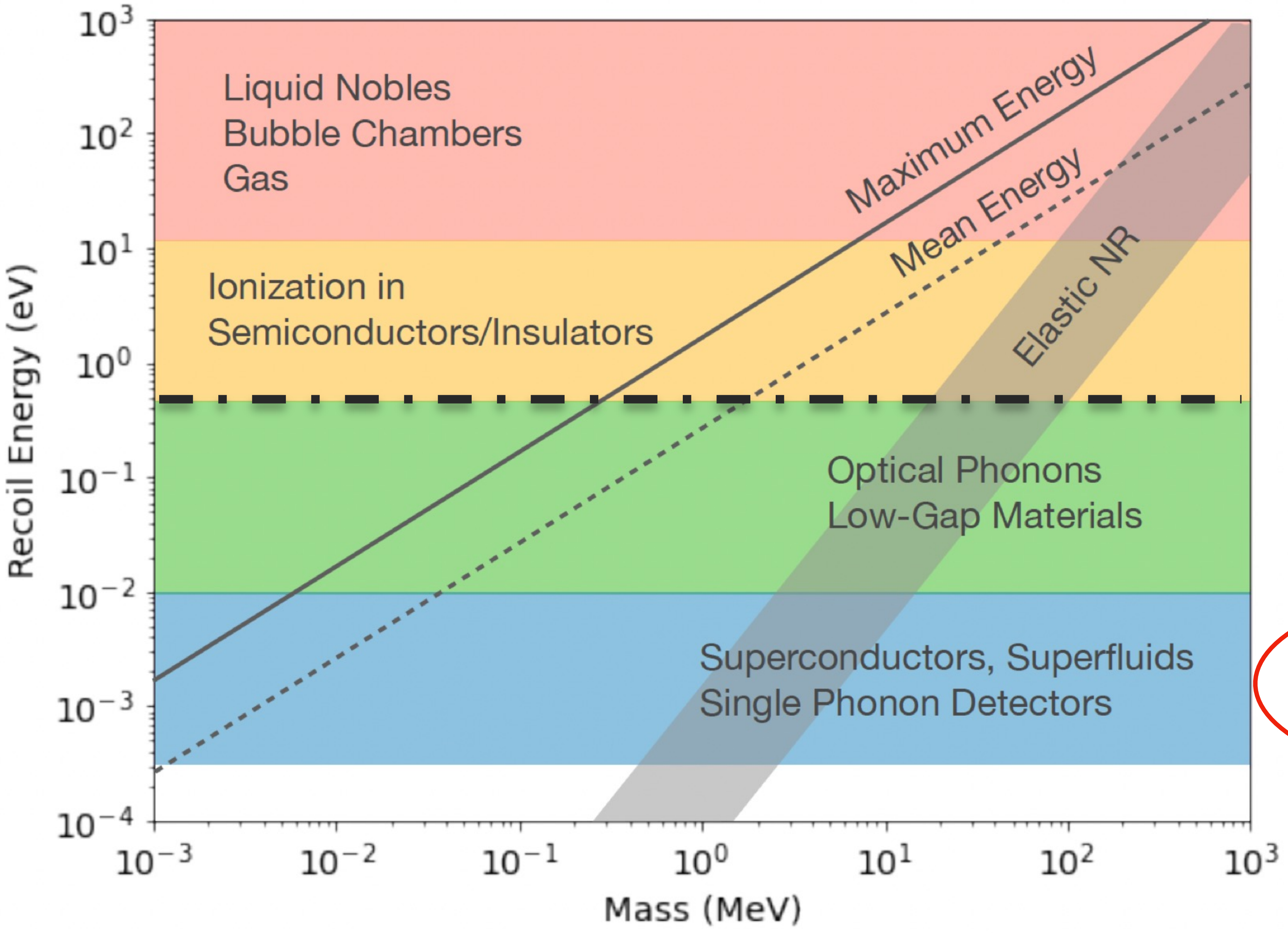
- transition between superconducting and normal-conducting
- transition of an atom from one state to another
- change of resonant frequency of a system (quantized)

} 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 → focus on these

Start with an example: Energy deposited in detectors by particles



Daniel Baxter I IDM 2024 Essig et al, Snowmass CF1 WP2 (2022) [arXiv:2203.08297]

$\Delta E \sim 1$ 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

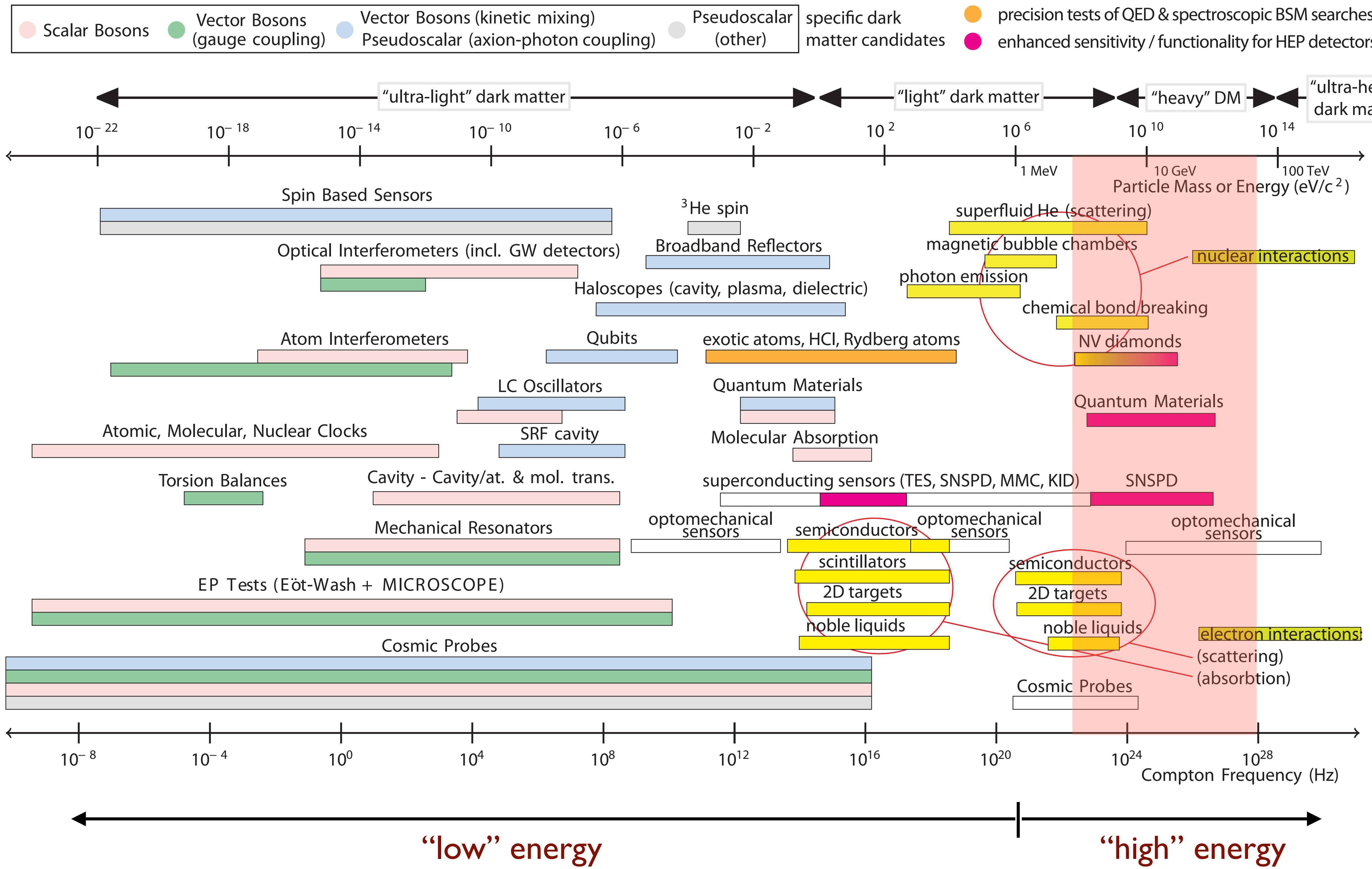
What's the goal? mip detection? or minute, sub-mip energy deposits?

Very low bandgap materials required to be sensitive to tiny energy deposits: milli-charged particles, nuclear recoil from very light DM, IR photons, precise photon #

For much higher (or lower) particle masses (or better, very weak fields), other quantum sensing technologies are more appropriate:

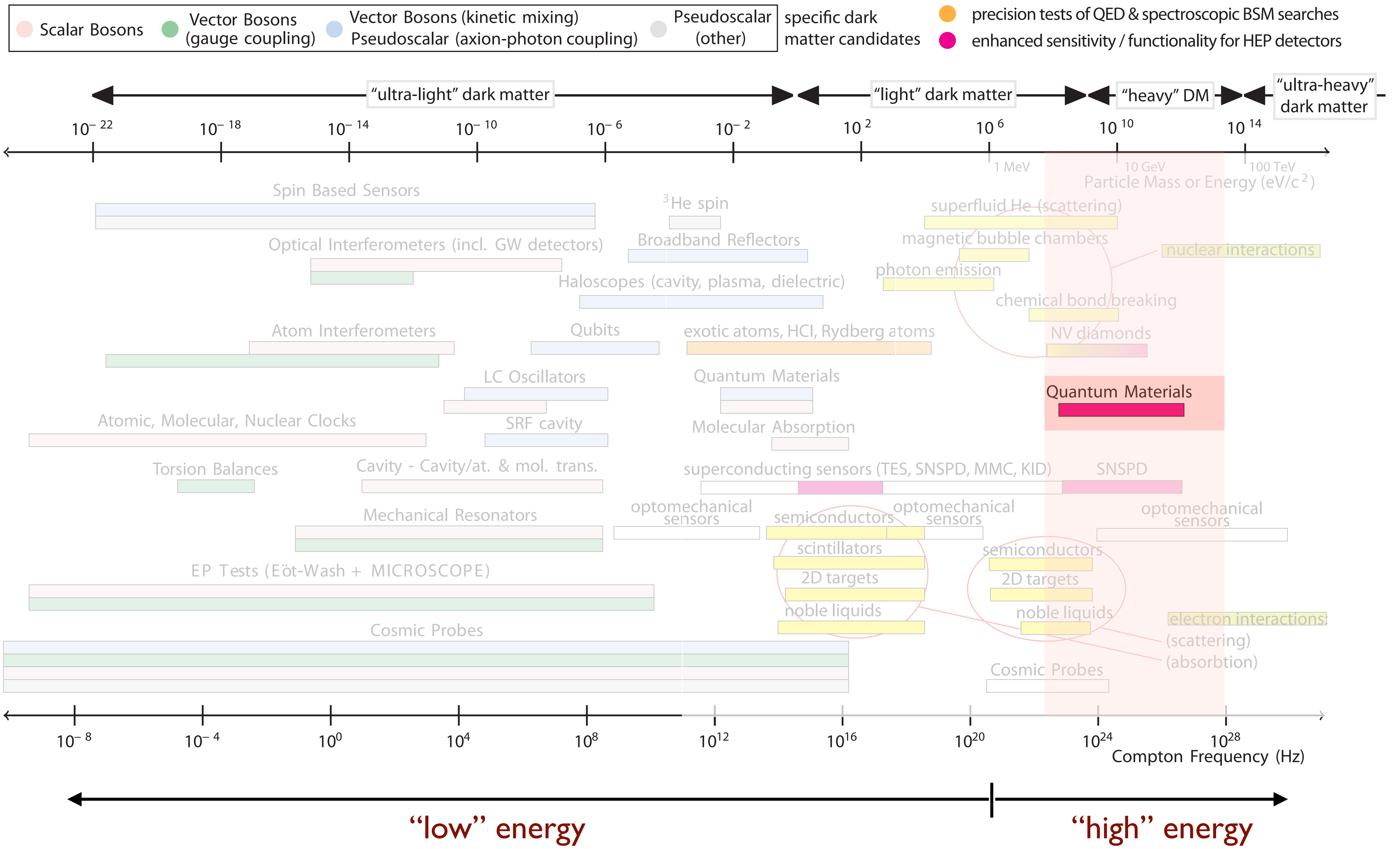
quantum sensing & particle physics

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

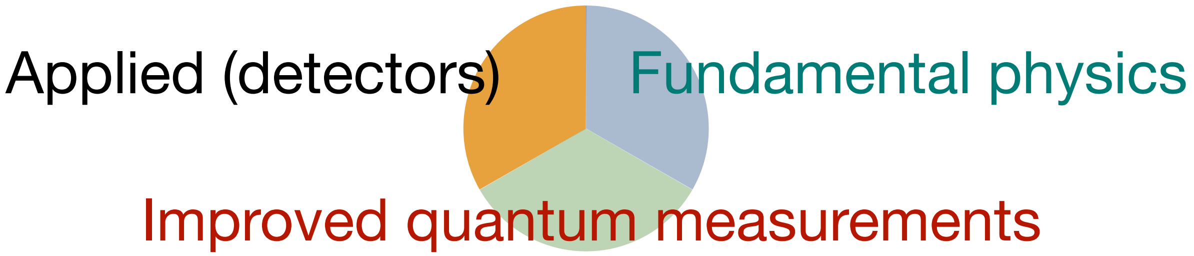


quantum sensing & particle physics

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



Potential HEP impact



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)

Metamaterials, 0 / 1 / 2-dimensional materials

quantum dots for calorimetry	chromatic calorimetry
quantum dots for tracking	chromatic tracking

Atoms, molecules, ions

quantum-boosted dE/dx	Rydberg TPC's

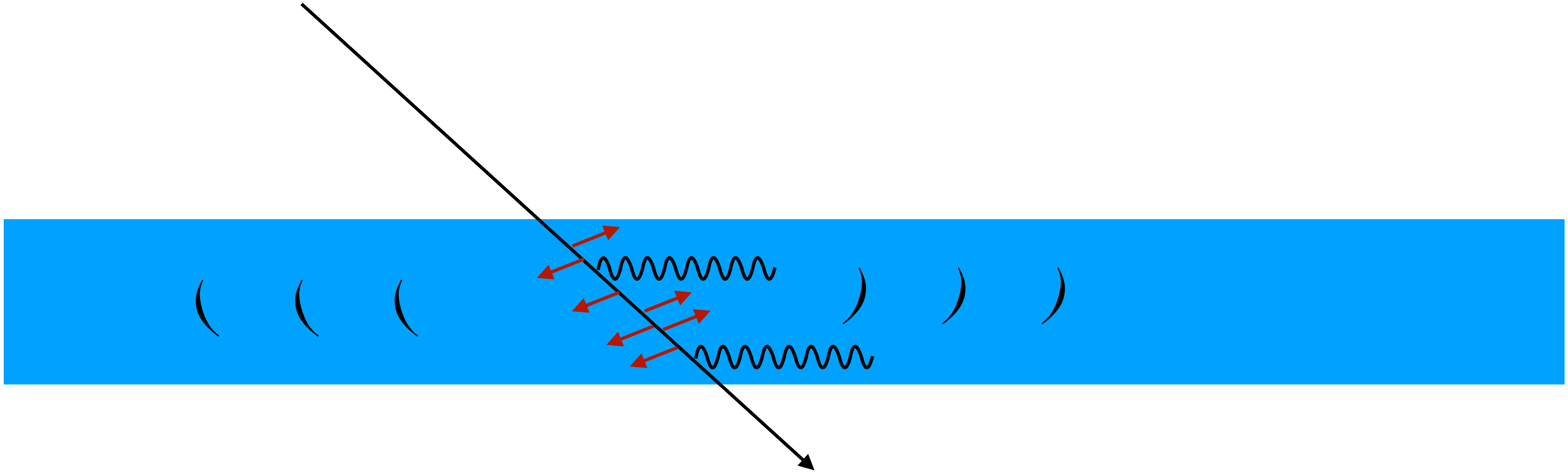
Spin-based sensors

quantum-polarized helicity detection	helicity detectors

Superconducting sensors

microcalorimeters	X-ray spectroscopy
quantum pixel ultra-sensitive tracking	milli-charge trackers

Particle detection through production of secondaries



Detect:

n_e E_e

n_γ E_γ

n_{phonon} E_{phonon}

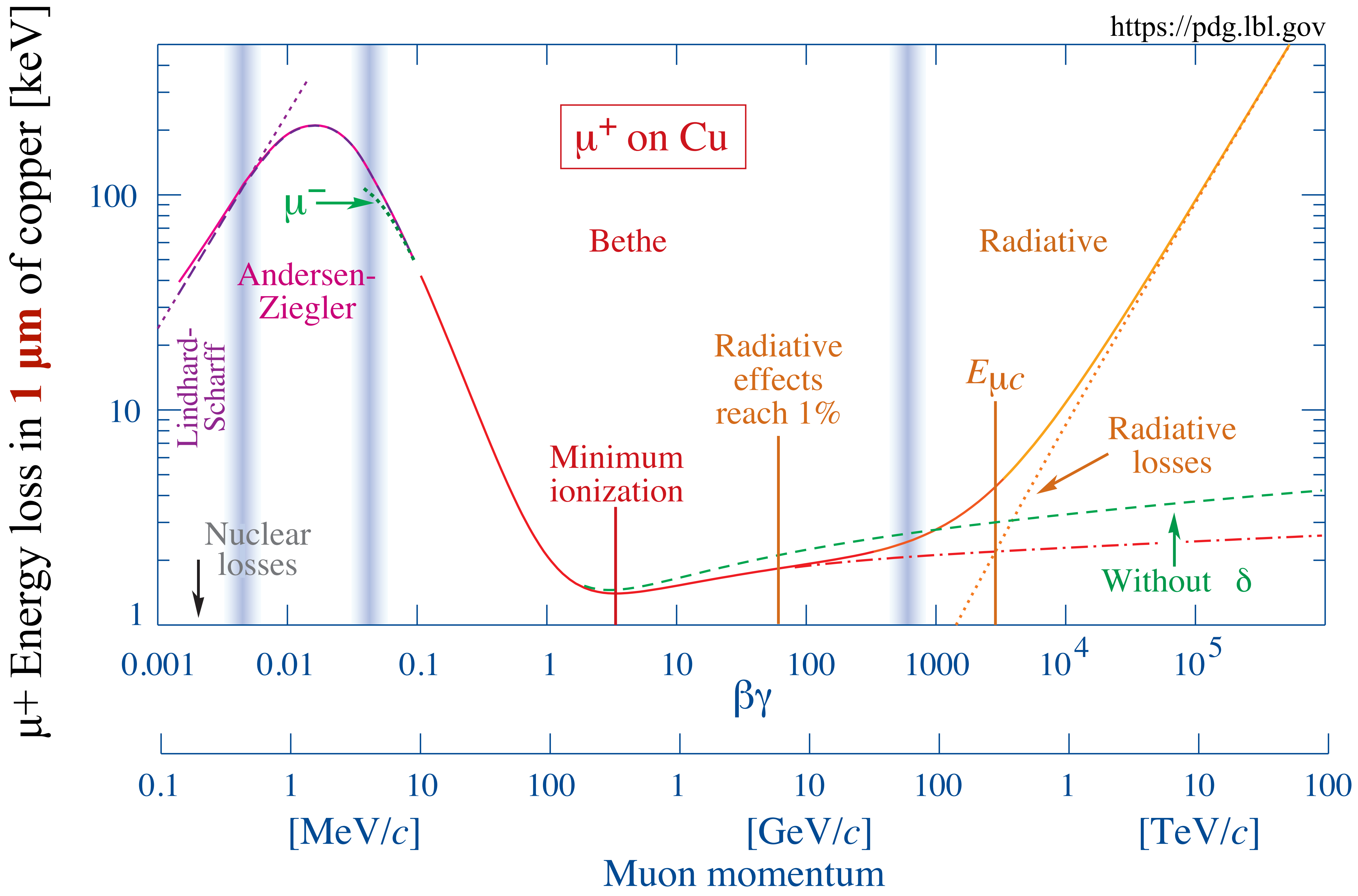
invisible except at ultra-low temperatures

→

Position (x,y,z)

Time (t)

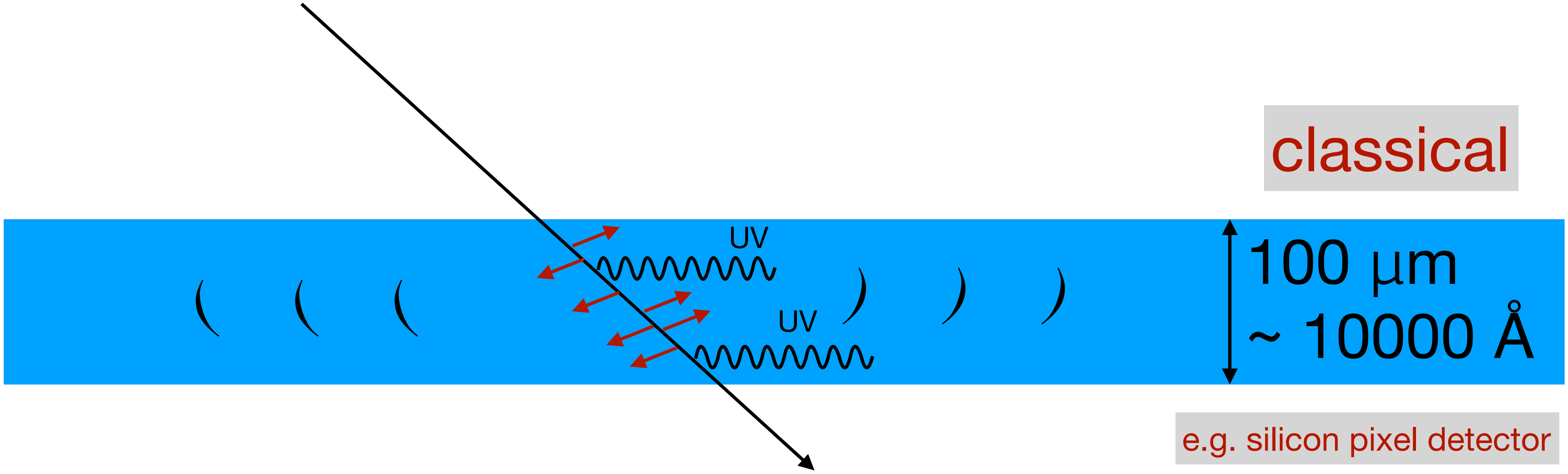
Energy (dE/dx)



~ **keV** energy deposit = ***n*** x *ionization energy of atoms* [O(10 eV)]

Particle detection through production of secondaries

classical



e.g. silicon pixel detector

Detect:

$n \sim 10^4$

n_e E_e

n_γ E_γ

n_{phonon} E_{phonon}

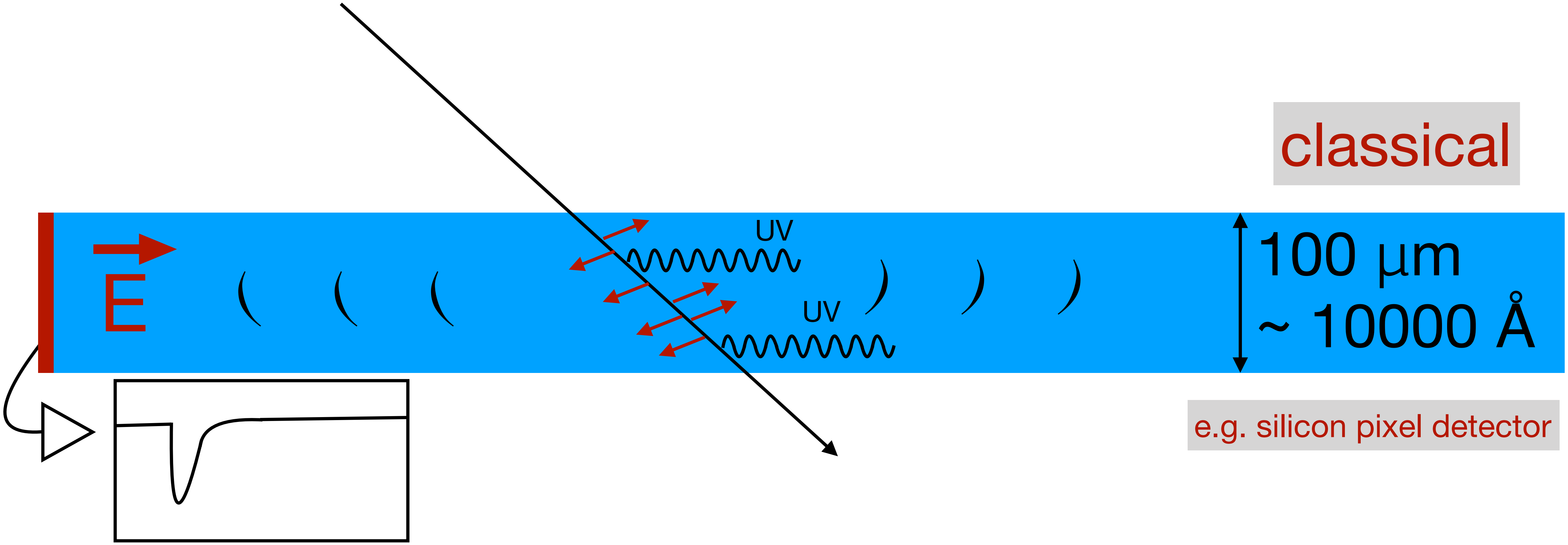
→

Position (x,y,z)

Time (t)

Energy (dE/dx)

Particle detection through production of secondaries



Detect:

$n \sim 10^4$

n_e E_e

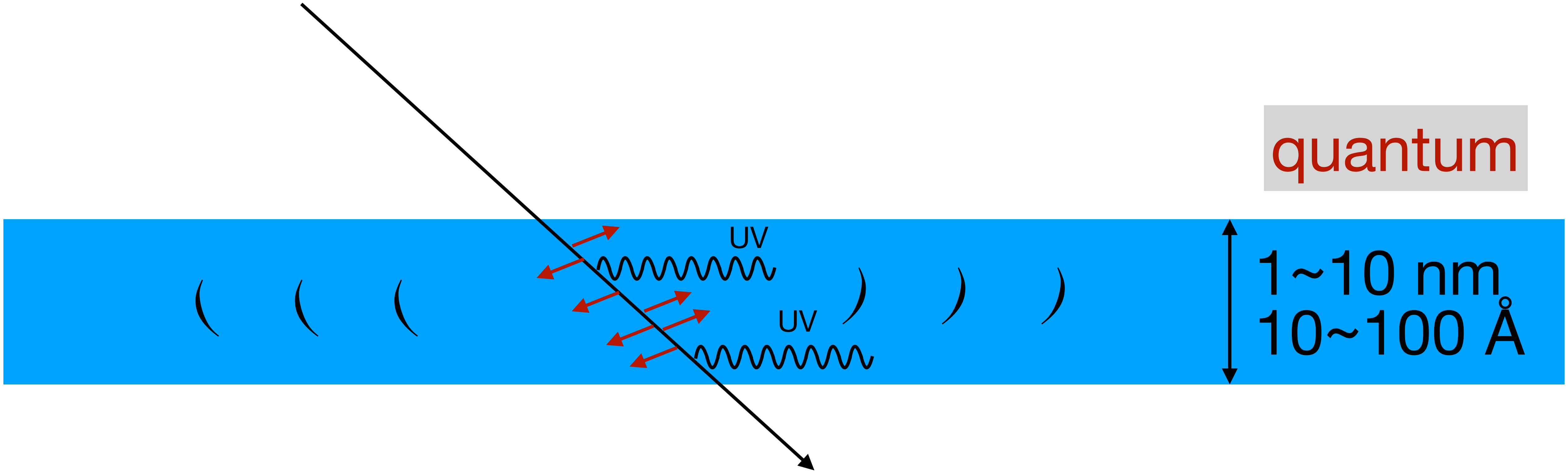
n_γ E_γ

n_{phonon} E_{phonon}

→

Position (x,y,z)	~ 10 µm
Time (t)	~ 30 ps
Energy (dE/dx)	~ 10 %

Particle detection through production of secondaries



Detect:

$n \sim 10$

$\boxed{n_e \quad E_e}$

$n_\gamma \quad E_\gamma$

$n_{\text{phonon}} \quad E_{\text{phonon}}$

→

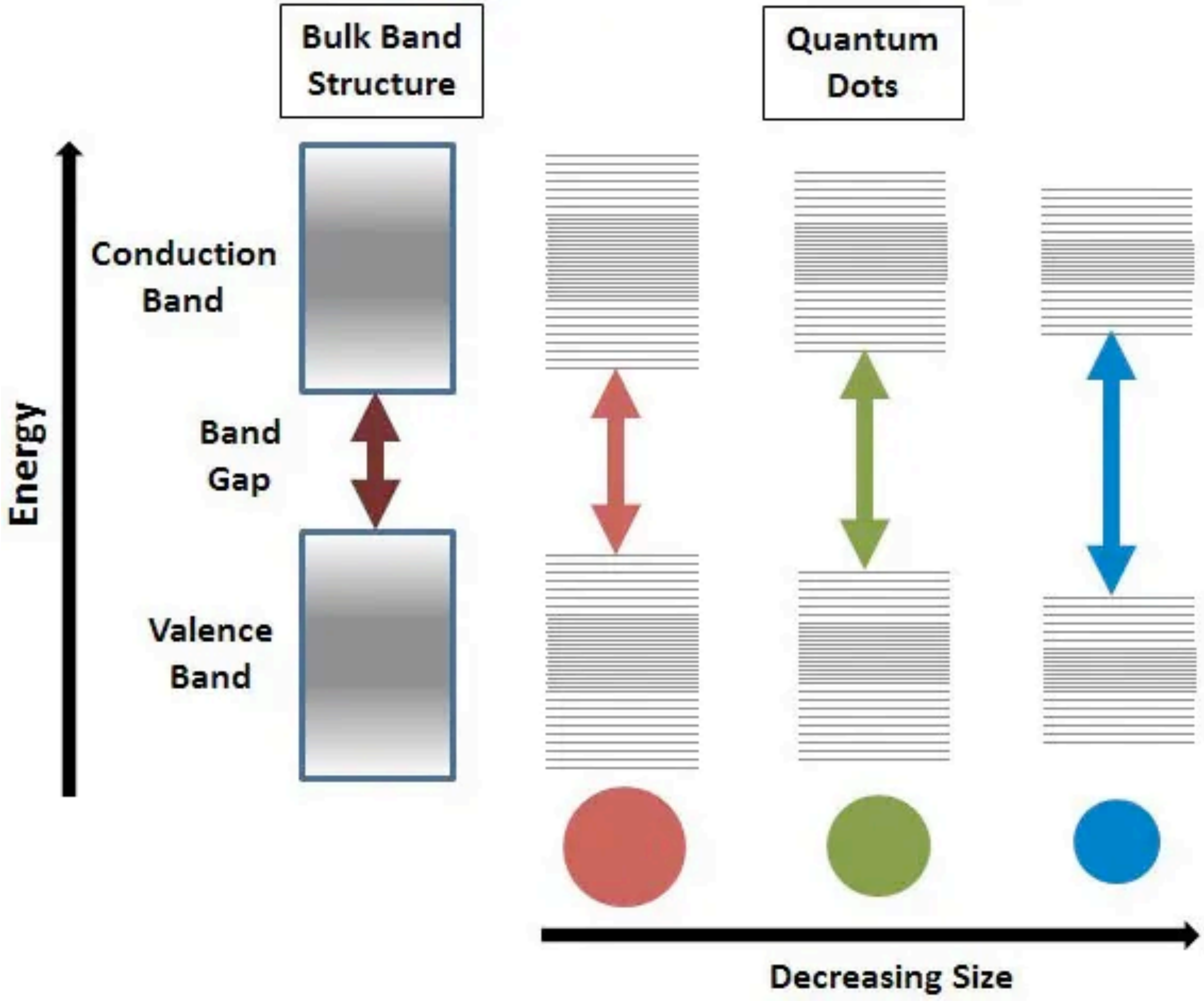
Position (x,y,z) ~ 10 Å

Time (t) ≪ 30 ps

Energy (dE/dx) ?

few eV energy deposit = few atoms ionized

The size of the band gap depends on the overall mass of the quantum dot. As the quantum dot gets smaller, the size of the conduction and valence bands decrease which makes the band gap increase.



$\Delta E \sim 1$ eV

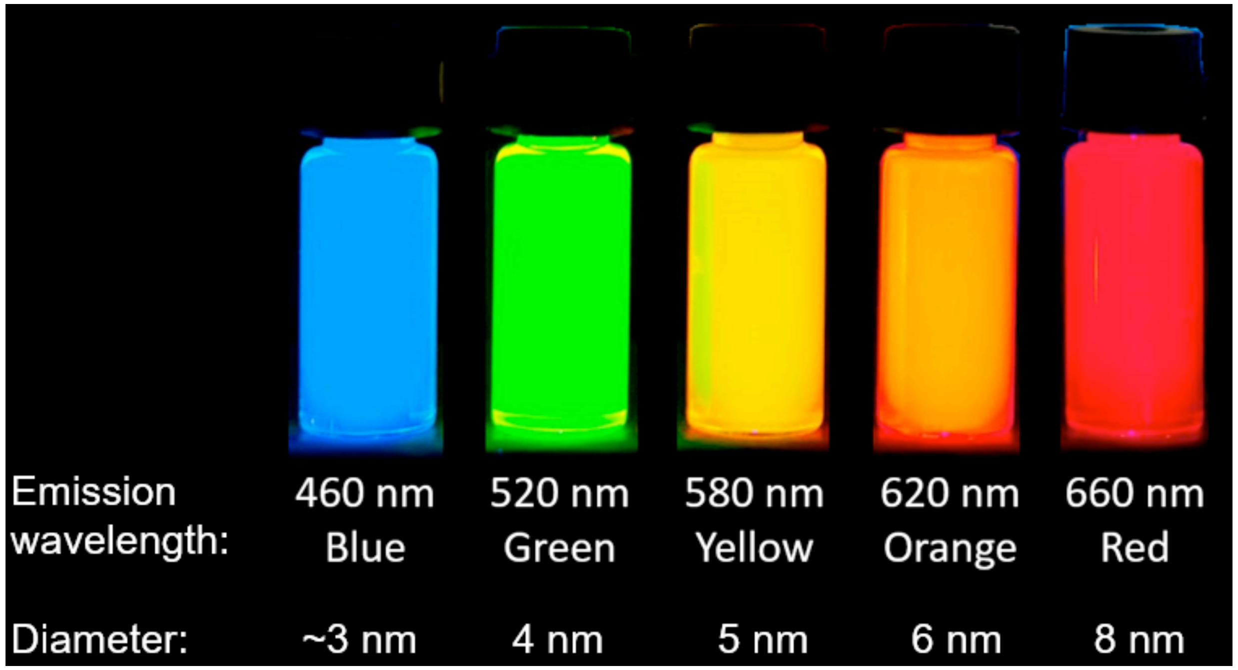
e.g. Si, Ge, GaAs, diamond, Quantum Dots, organic scintillators…

Anything that can excite a transition (e^-, γ) will be transformed into visible light = WLS

https://www.sigmaaldrich.com/CA/en/technical-documents/technical-article/materials-science-and-engineering/biosensors-and-imaging/quantum-dots

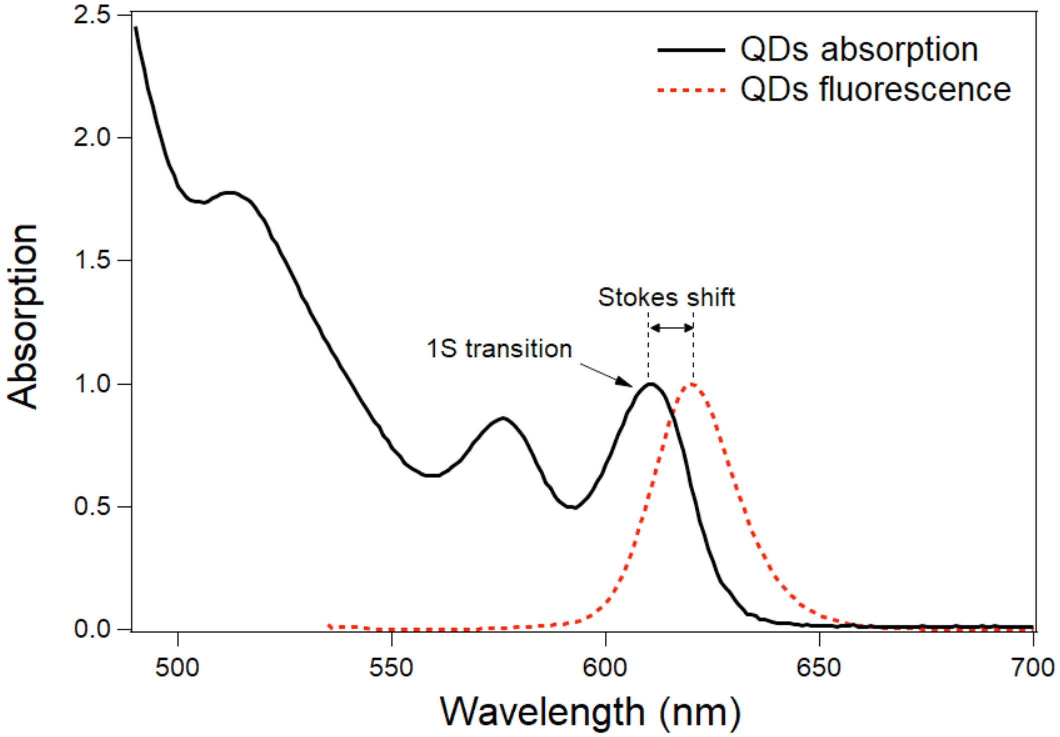
Band gap doesn't only depend on size, but also composition

Size-dependent emission properties



Multicomponent dots offer an alternative method to tune properties without changing crystallite size.

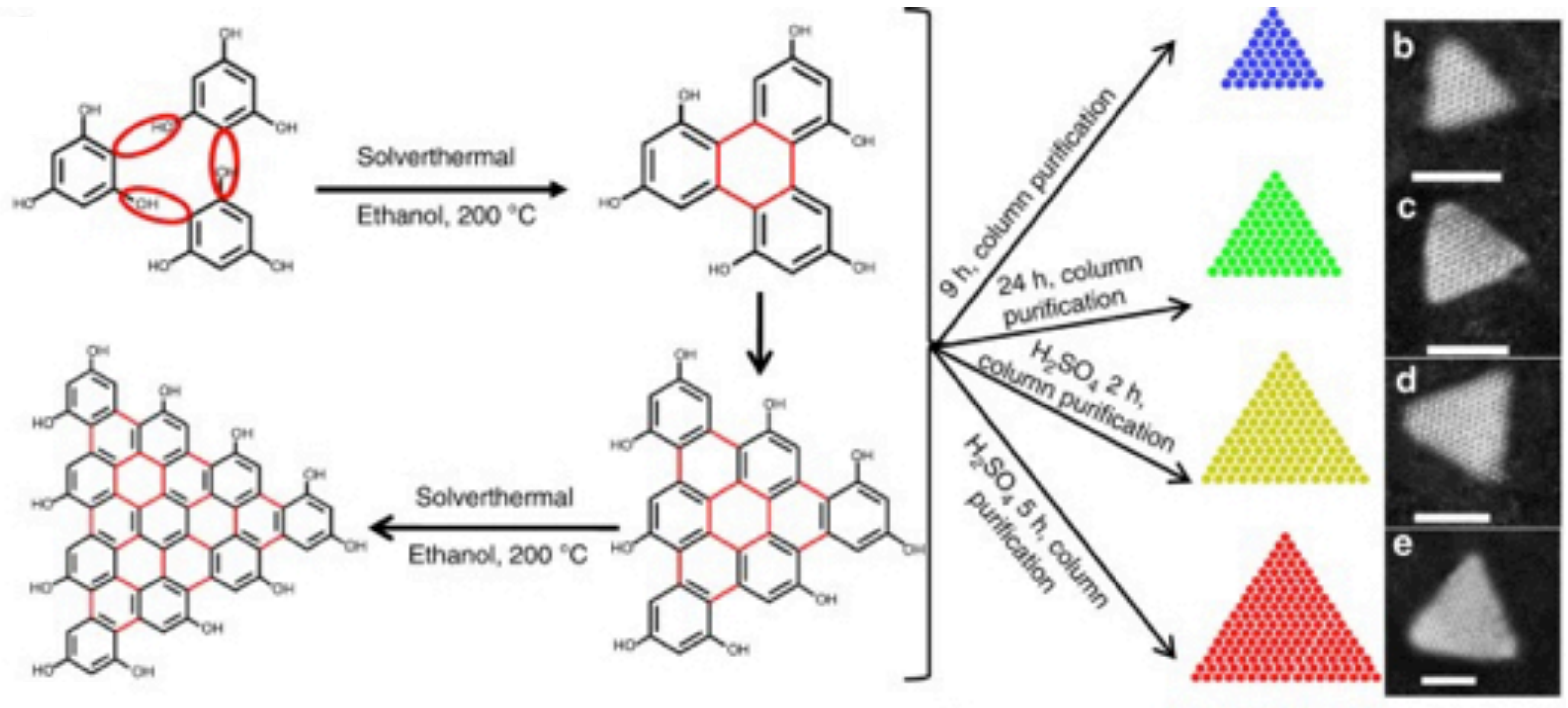
Photoluminescence of alloyed CdSxSe1-x/ZnS quantum dots of 6 nm diameter. The material emits different color of light by tuning the composition.

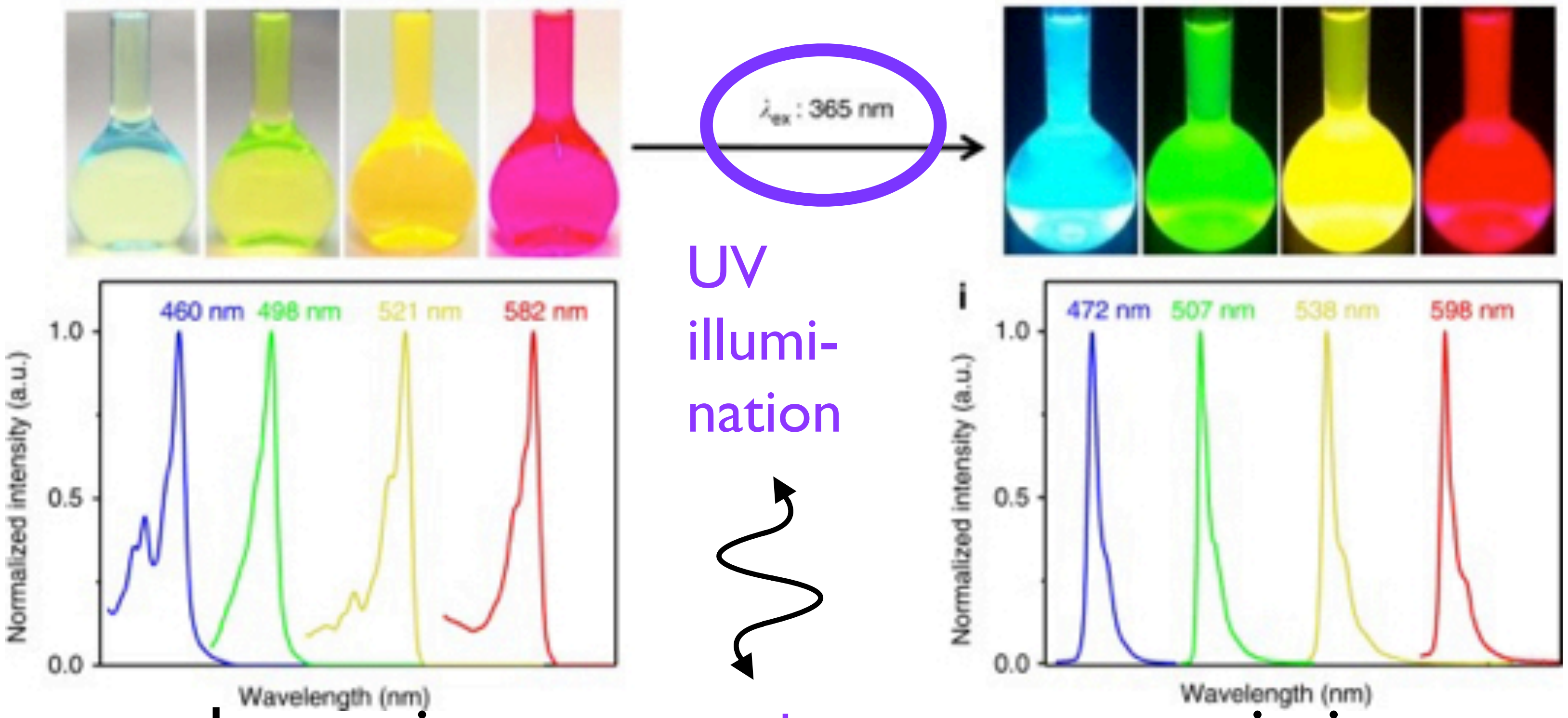


Stokes shift: (mostly) monochromatic emission but broad-band absorption spectrum that may overlap with the emission spectrum (in which case, emitted light may be re-absorbed).

Large Stokes shift = bright emission

Quantum dots: chromatic calorimetry





UV illumination

absorption

e.m. shower

emission

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

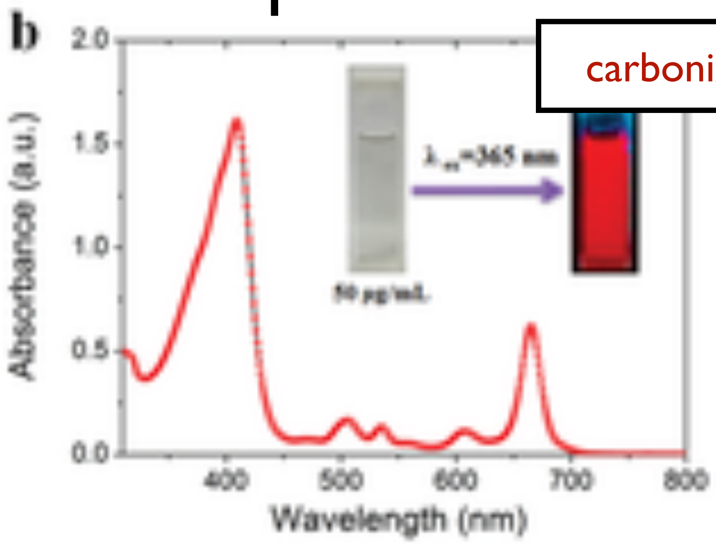
requires:

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

select appropriate nanodots

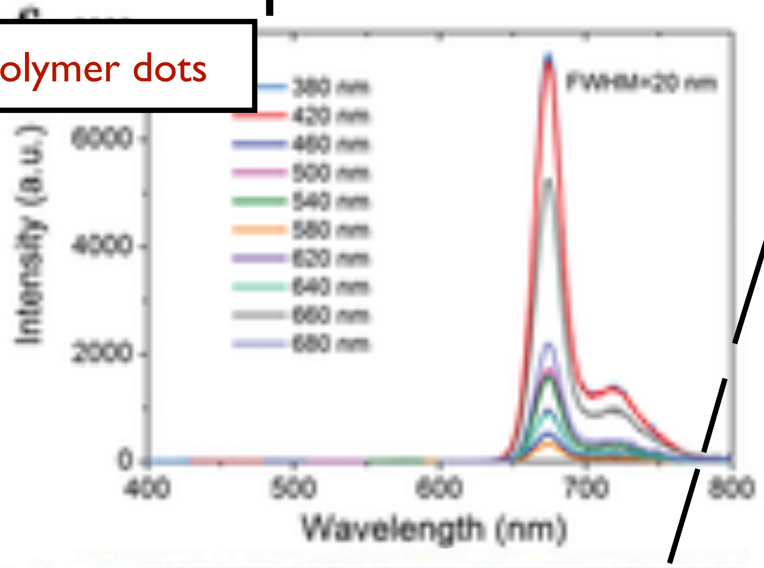
e.g. triangular carbon nanodots

absorption spectrum



carbonized polymer dots

emission spectrum

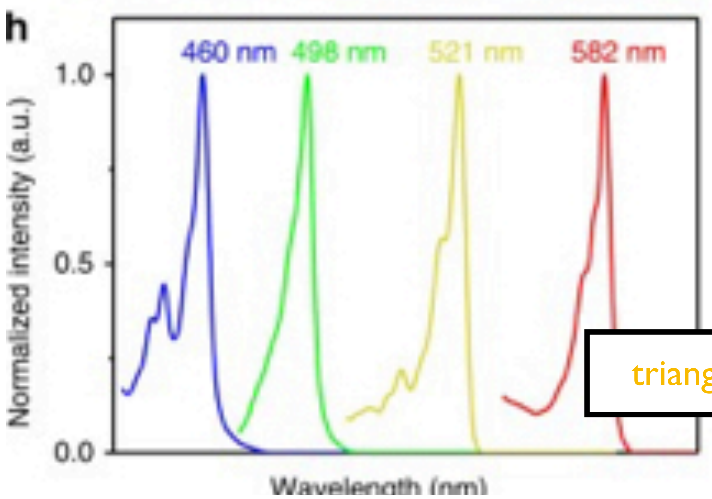


leftmost nanodots:
absorb wavelengths < 650 nm
emit at > 680 nm

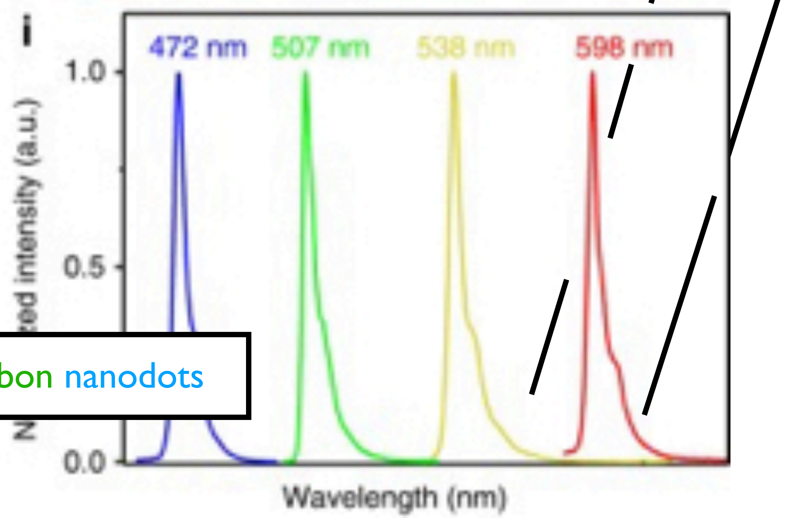
next band:
absorb wavelengths < 590 nm
emit at > 590 nm

…

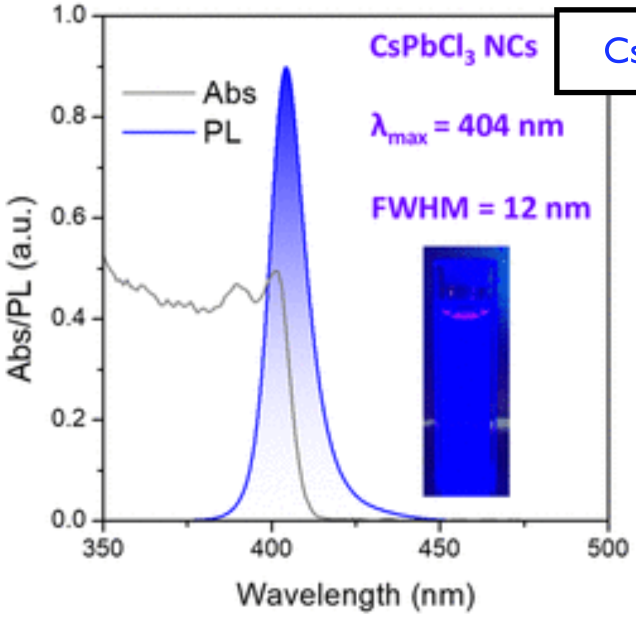
rightmost nanodots:
absorb wavelengths < 410 nm
emit at > 420 nm



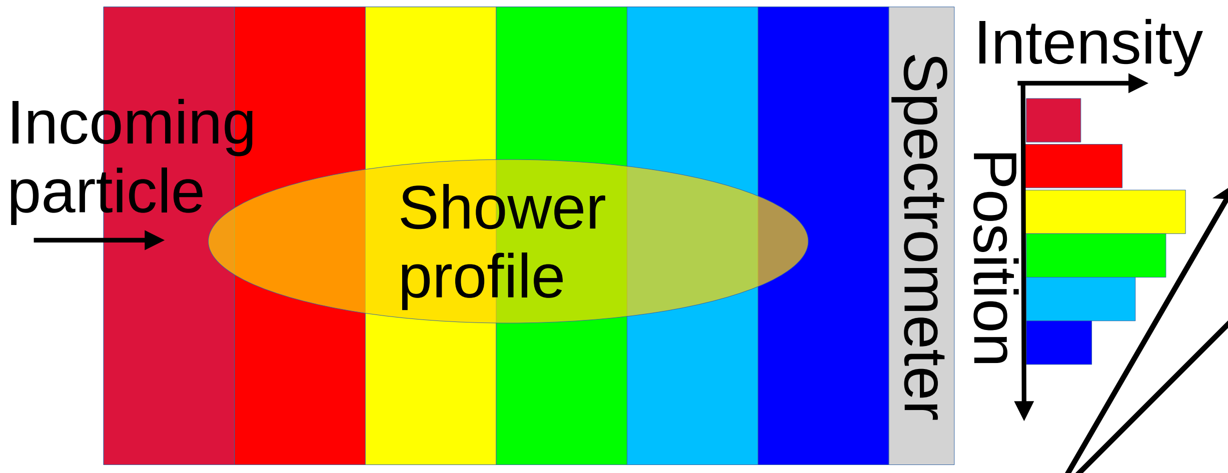
triangular carbon nanodots



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



CsPbCl$_3$ nanocrystals



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

Monochromators + PD?

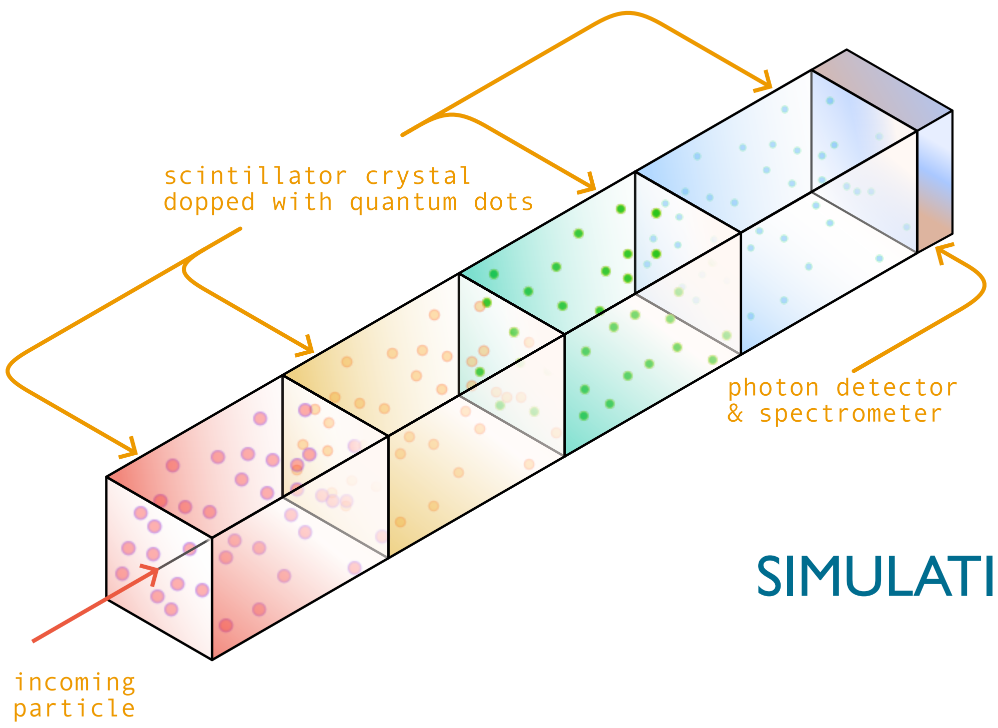
Y.T. Lin & G. Finlayson, Sensors 23, 4155 (2023)

Metalenses?

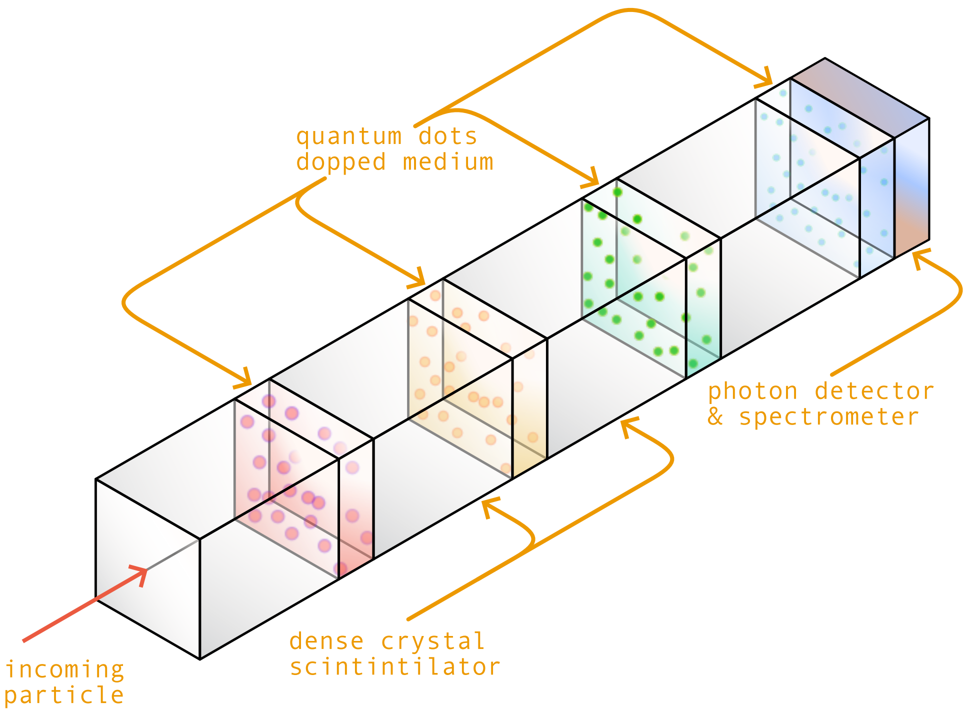
M. Khorasaninejad & F. Capasso, Science 358, 6367 (2017)

This slide courtesy Devanshi Arora, CALOR’24

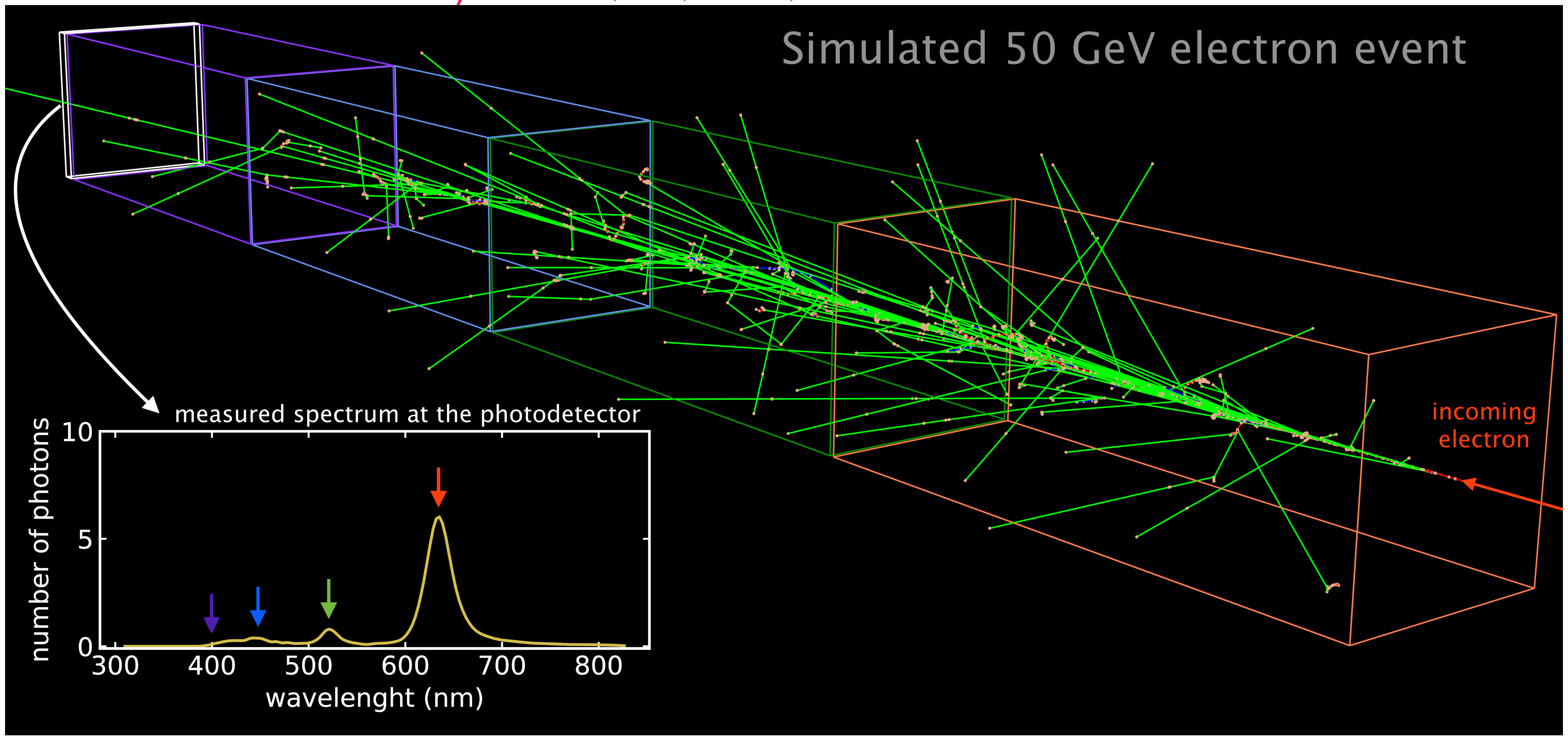
quantum dots for calorimetry



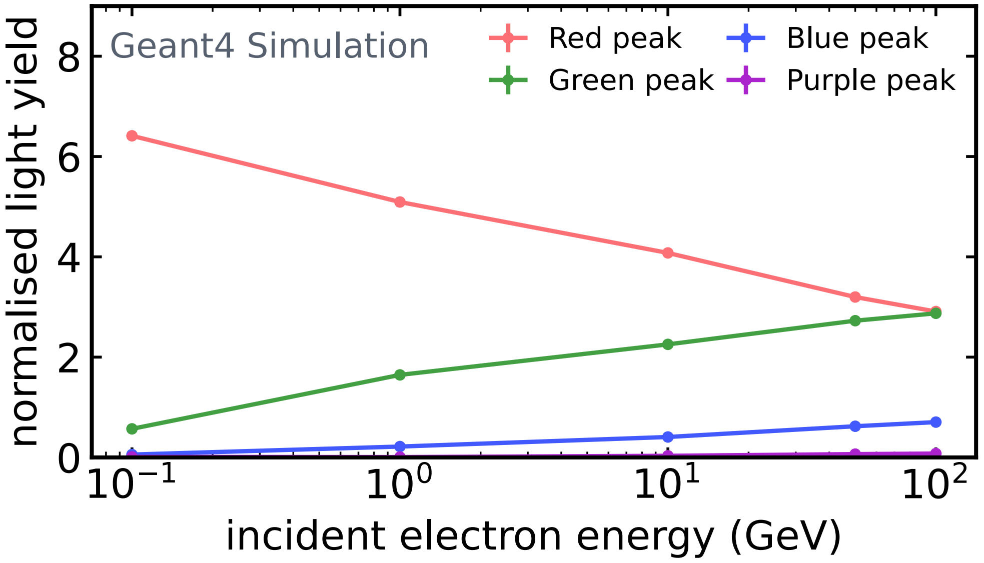
SIMULATION



courtsey Y. Haddad, N U, Boston, USA



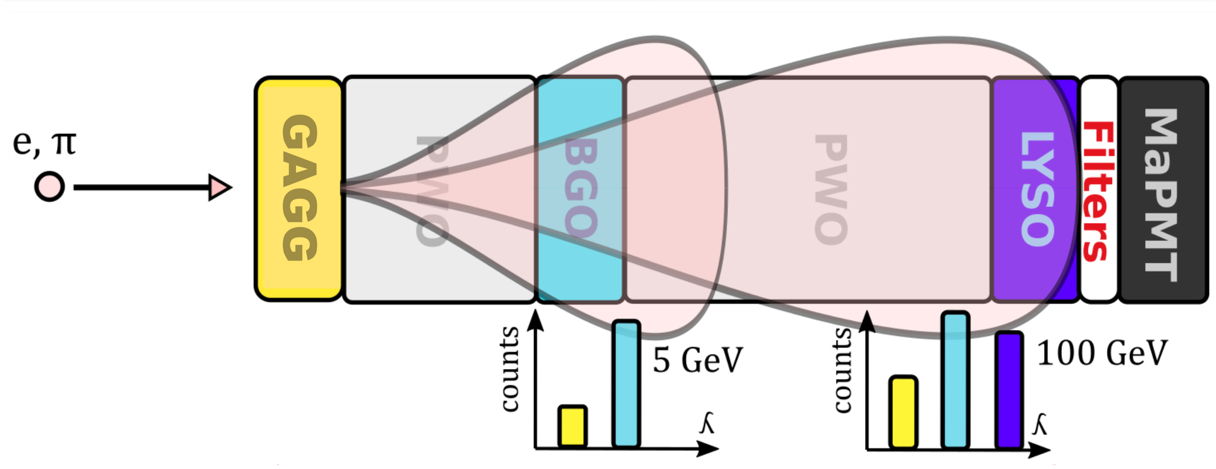
OUTCOME

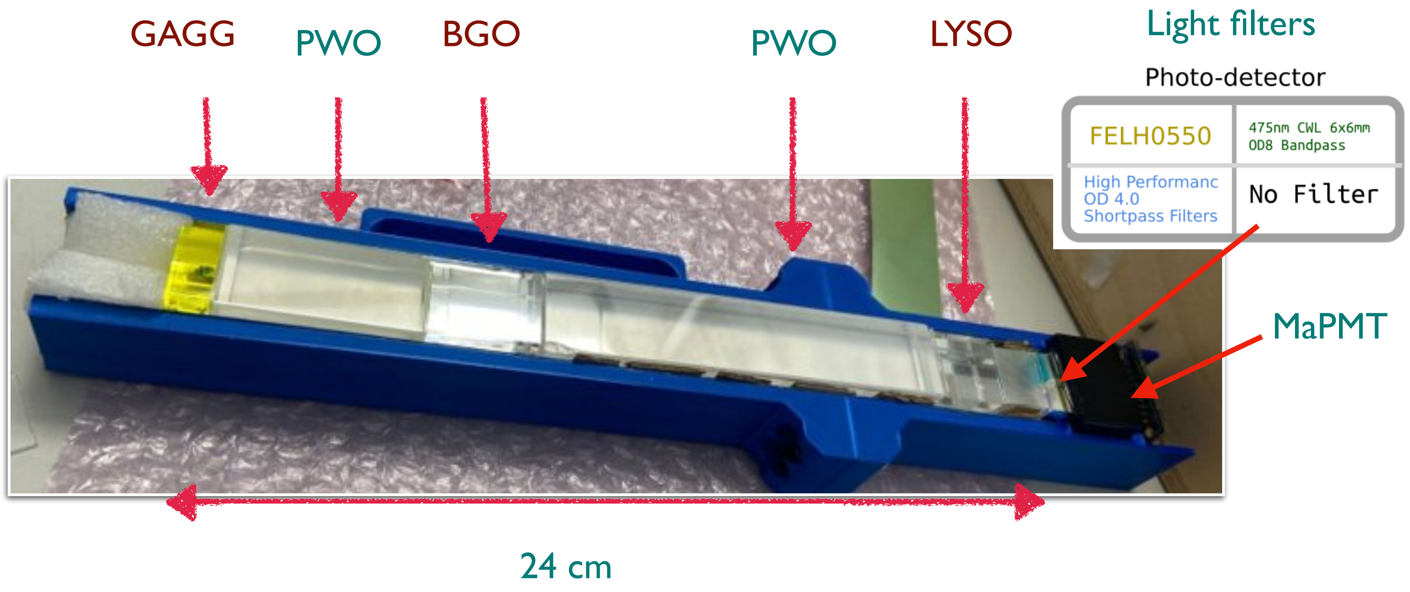


→ “Chromatic” energy measurement

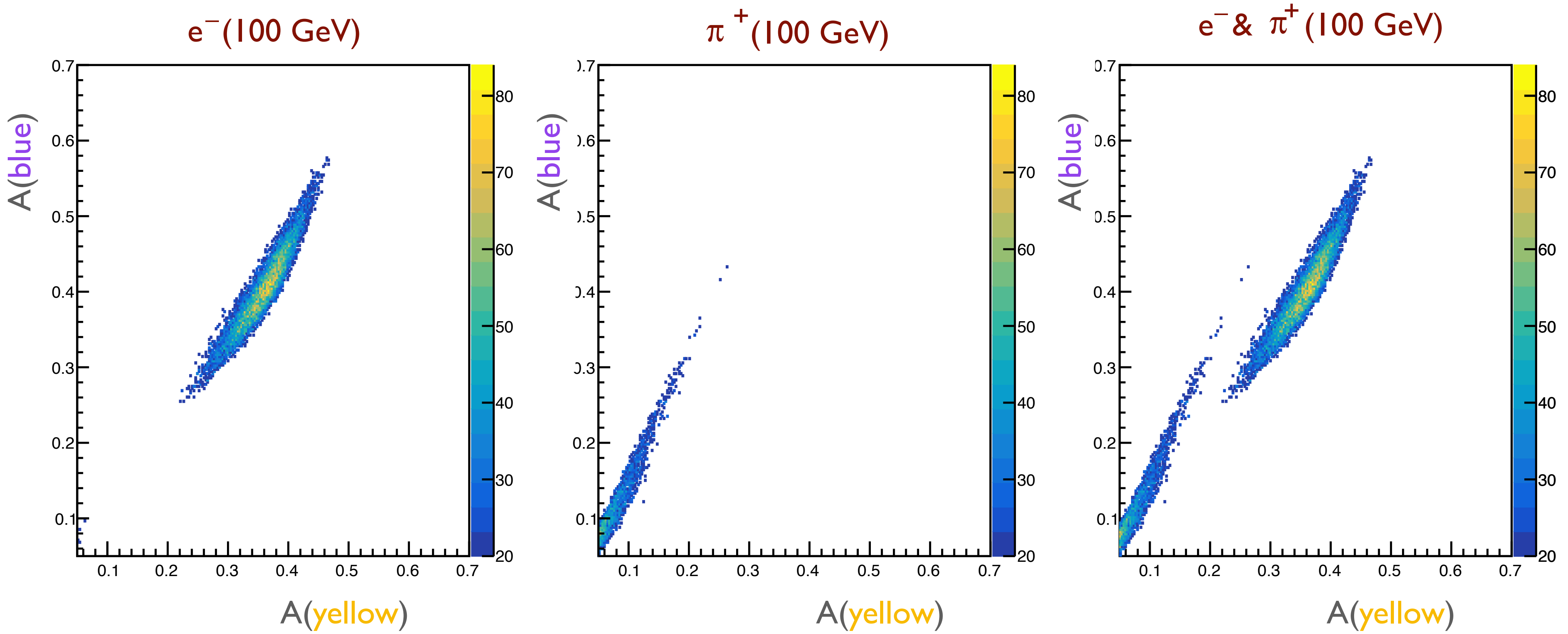
This slide courtesy Devanshi Arora, CALOR’24

quantum dots for calorimetry





Beam test results (SPS) 2023



“Chromatic” electron - pion discrimination

(86% “chromatic” electron - pion discrimination)

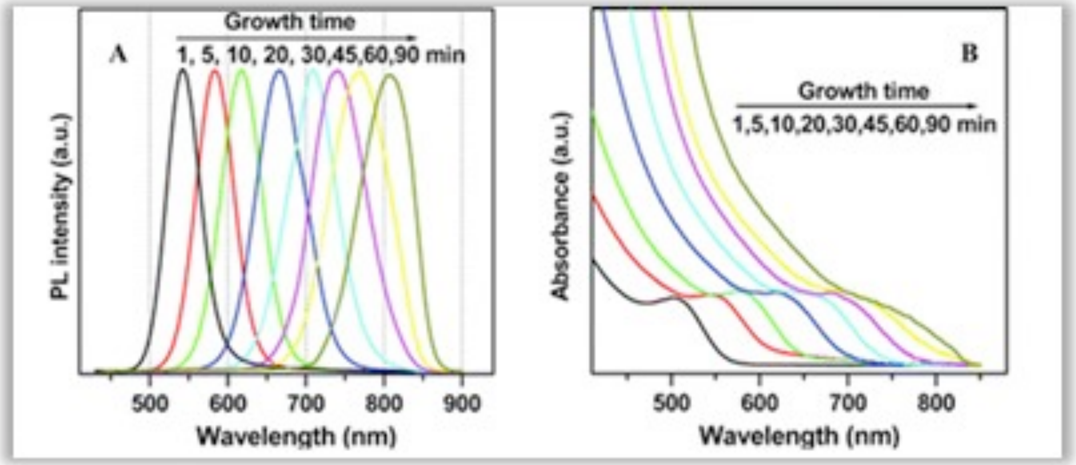
“Chromatic” energy measurement

OK, so how does one get quantum dots?

1 Buy them: many (!) suppliers www.sigmaaldrich.com


https://www.mesolight.com/

https://www.cd-bioparticles.com/



https://quantumdotz.com/

2 Make them in your kitchen

OK, so how does one *make* nanodots?

Disclaimer: This is as dangerous as making candy. This is simply cooking, be safe and use common sense, molten sugar is the worst thing to burn yourself with.

Equipment Needed

Microwave
Tempered Glass bowl(I prefer Borosilicate but we aren't rapidly changing temperatures)
Heat resistant gloves(perhaps with silicone for grip)
A few containers for your samples
Plastic Pipettes
Glass vials to store
UV or Blacklight

Supplies

Water(I used tap water)
Baking soda(Sodium Bicarbonate)
Cane sugar(Sucrose)
White Vinegar(Acetic Acid)

1. Combine 1 of cup water, 80 grams of cane sugar, and ¼ cup of vinegar in a bowl and microwave for 5 mins.
2. After microwaved, slowly pour in 20 grams of baking soda into the solution. This makes the sugars start to form the quantum dots.
3. Microwave for another 5 mins. The added heat speeds up the quantum dot formation process.
4. Once microwaved, dilute the quantum dots in water and shine a UV light onto the solution.
5. The solution should glow a blue colour, indicating the quantum dots have been synthesized.

https://www.instructables.com/DIY-Quantum-DotsNanotech-in-Your-Kitchen/

https://lanyutachandran.medium.com/synthesizing-my-own-colour-changing-nanomaterial-quantum-dots-36640e4a5d7c

OK, so how does one make nanodots?

Disclaimer: This experiment uses toxic and carcinogenic reagents and directly handles extremely hot liquids. Gloves, protective clothing and a fume hood should be used. This should be performed by, or under the direct supervision of, an experienced chemist.

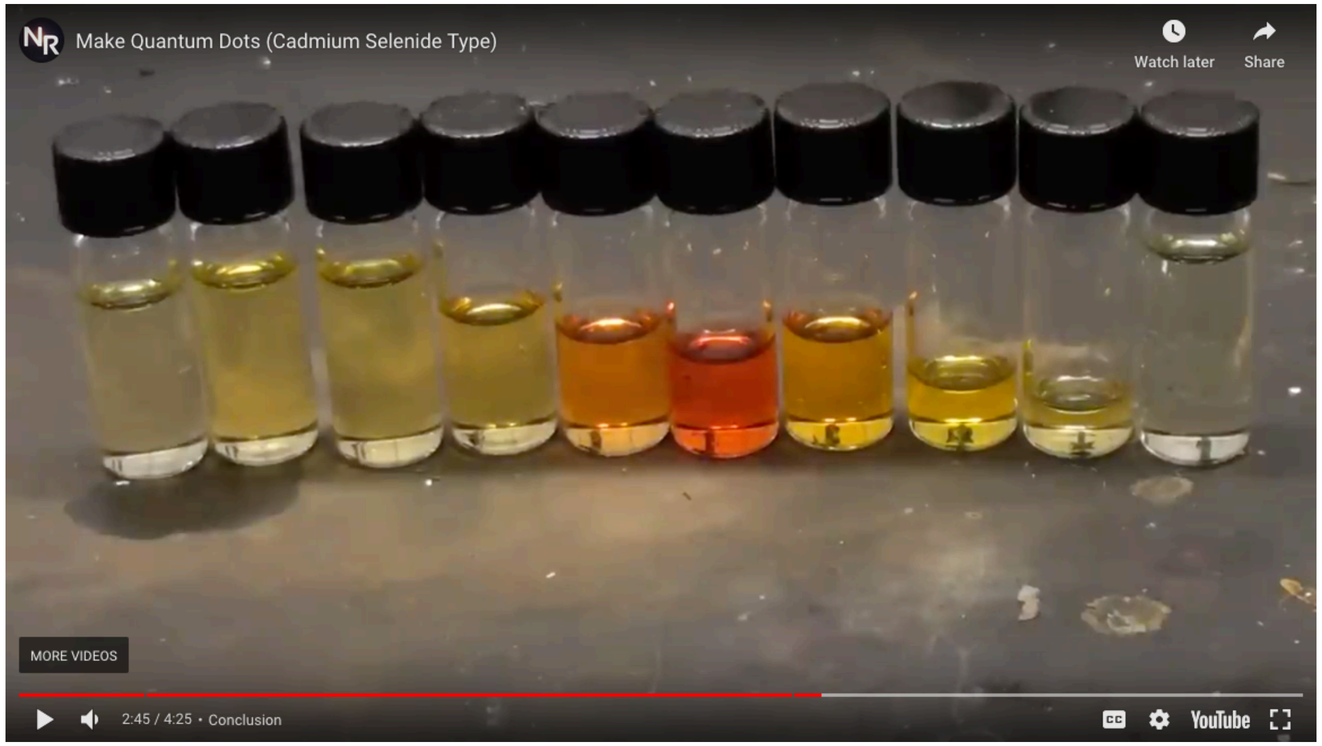
Make trioctylphosphine selenide solution:
Combine 30mg of pure selenium powder, 5mL of 1-octadecene and 0.4mL of trioctylphosphine. Gently heat it until all the selenium dissolves into a clear liquid. Once it's ready, take off heating, seal it and let it cool.

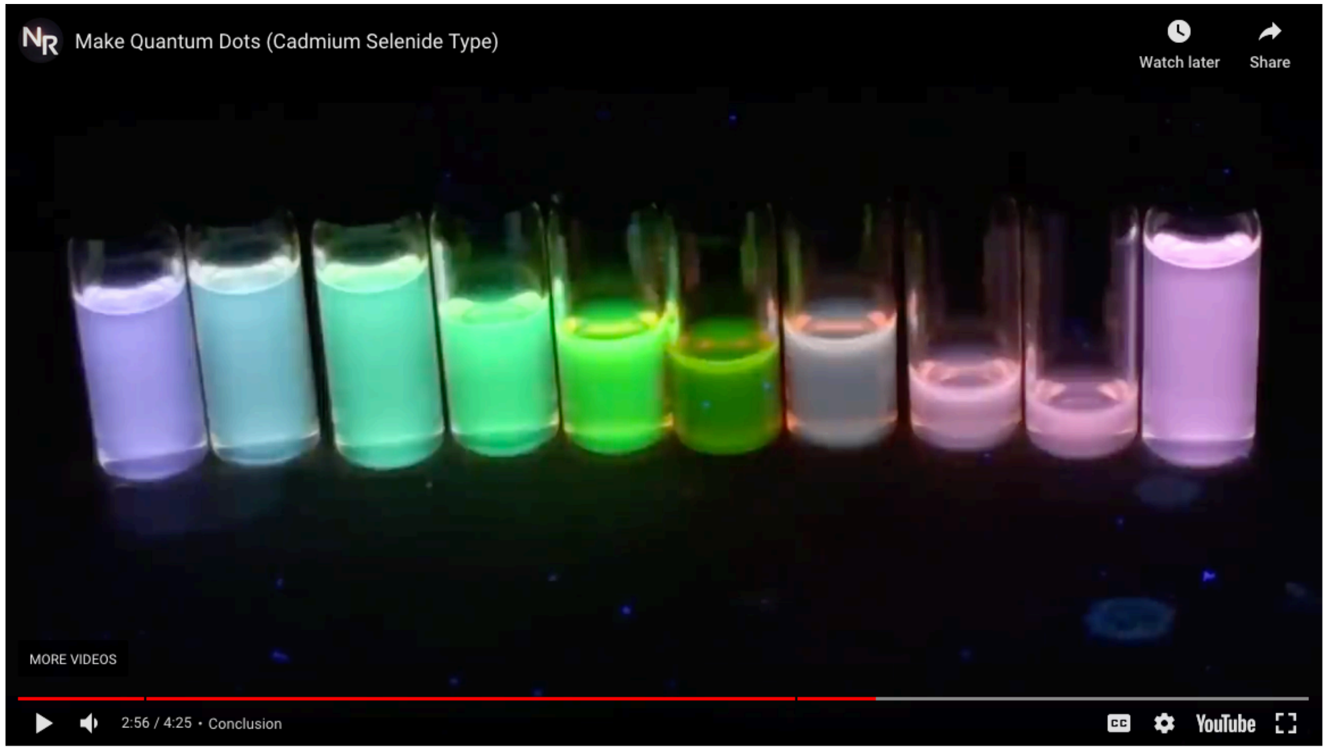
Make quantum dots:
Combine 13mg of cadmium oxide, 0.6mL of oleic acid and 10mL of 1-octadecene. Heat the mixture until the cadmium oxide completely dissolves to form cadmium oleate. After the cadmium oxide dissolves keep heating until the mixture hits 225 degrees celsius.

Inject 1mL of the trioctylphosphine selenide solution from before and shake. Quickly withdraw small ~0.5mL portions of liquid and quench by placing it into vials at room temperature. A more narrow particle size distribution can be obtained if the vials are cooled on dry ice. The first several portions should be removed as fast as possible. The remaining portions may be withdrawn when there is a visible color change.

What's happening is the cadmium oleate is reacting with the trioctylphosphine selenide to form cadmium selenide. These particles start small but grow in size the longer the solution reacts. Now this growth only continues if the temperature is maintained so withdrawing it at regular intervals and placing it in a room temperature vial stops the reaction and locks the particles into their current size. The oleic acid surrounds, or "caps", the particles and keeps them from aggregating.

https://www.instructables.com/Make-Quantum-Dots-Cadmium-Selenide-Type/





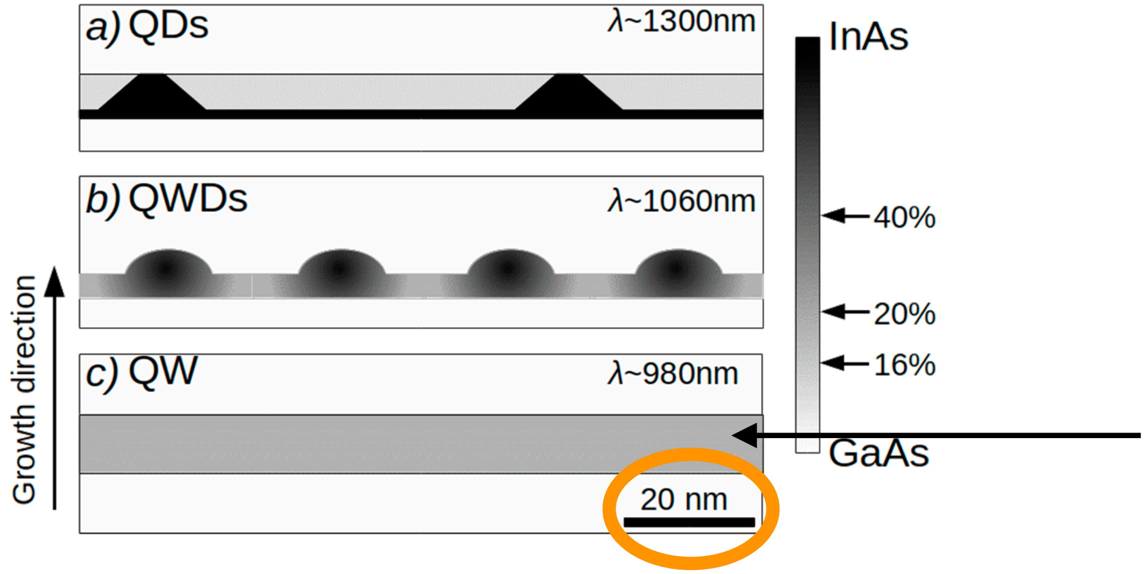
Active scintillators (QWs, QDs, QWDs, QCLs)

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

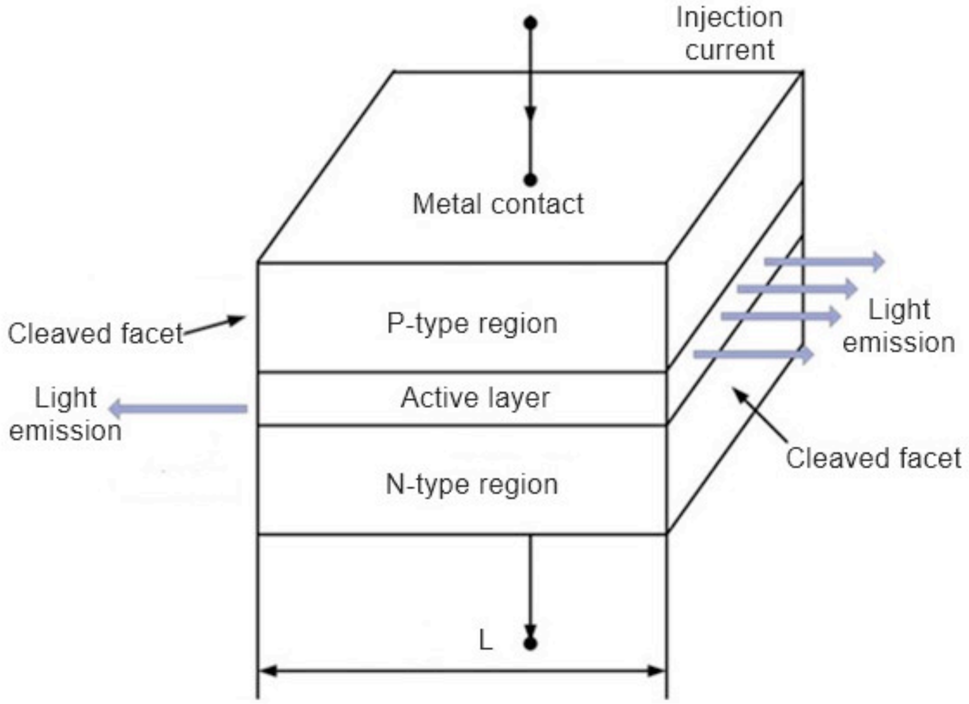
existing QD's, QWD's are elements of optoelectronic devices, typically running at 10 GHz

growth through molecular beam epitaxy (MBE) or metal-organic chemical vapor deposition (MOCVD)



thickness lower than the de Broglie wave-length of the charge carrier

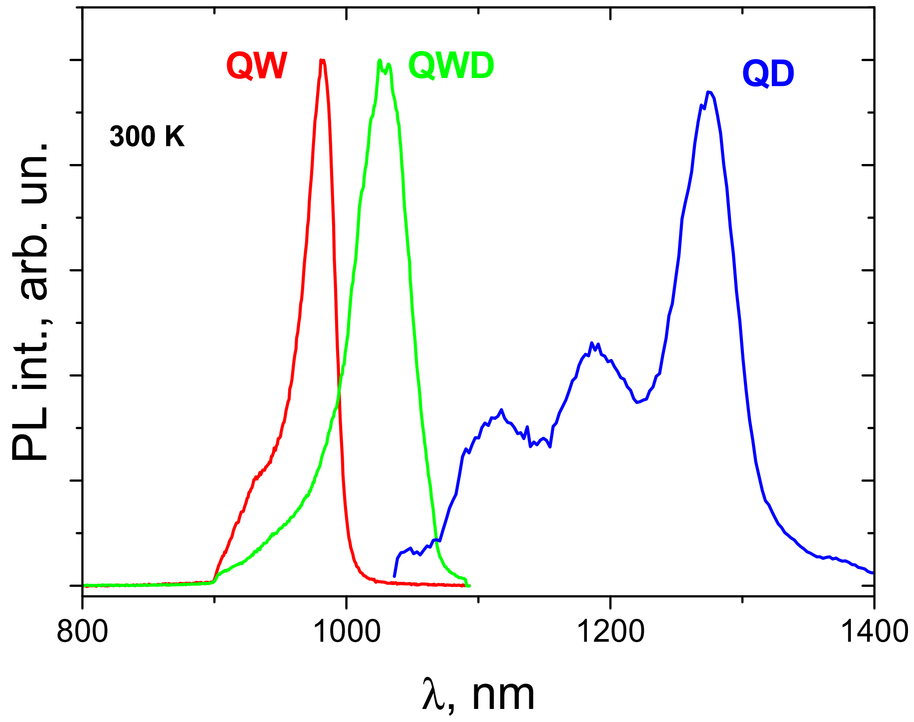
Schematic representation of InGaAs structures of different dimensionalities—**self-organized** Stranski–Krastanow quantum dots, QDs (**a**); quantum well-dots, QWDs (**b**); and quantum wells, QW (**c**).



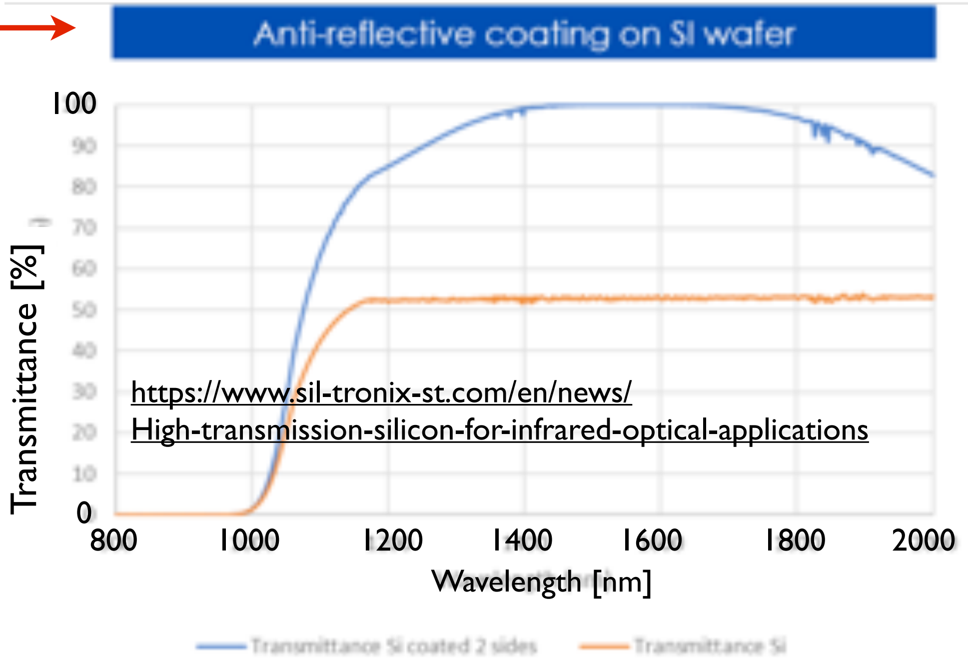
Active scintillators (QWs, QDs, QWDs, QCLs)

Emission in IR! Silicon is ~transparent at these wavelengths…
Can this IR light be transported *through* a tracker to outside PDs?

1300 nm: telecoms band
1555 nm: optical telecoms C-band



The (In,Ga,Al)As material system allows design and fabrication of single-photon emitters within a wide spectral range between ~900 nm (InGaAs/GaAs QDs) and ~1.55 μm (InAs/InGaAs QDs); lower wavelengths are however also possible…



https://www.sil-tronix-st.com/en/news/High-transmission-silicon-for-infrared-optical-applications

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.

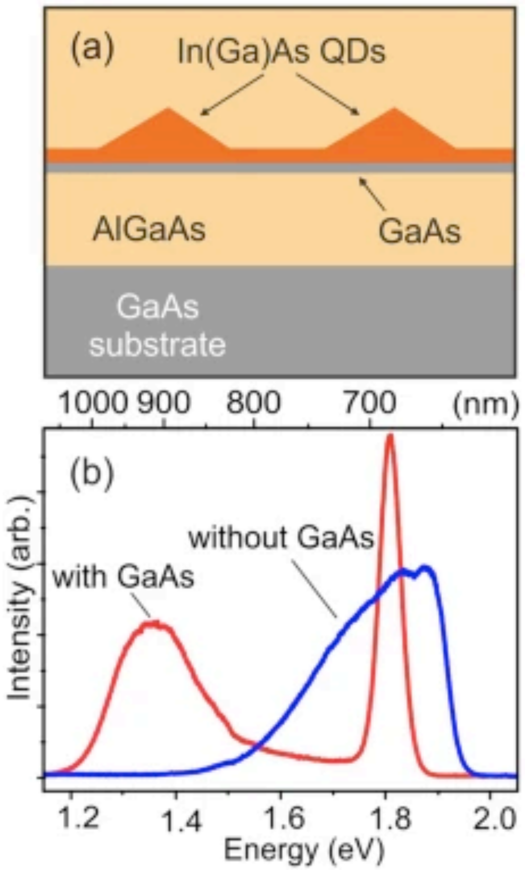
N. Sobolev, https://doi.org/10.1016/B978-0-08-046325-4.00013-X : "The QD heterostructures and QD lasers are generically more resistant to radiation damage than their bulk and two-dimensional (2D) counterparts, which is caused not only by the localization of the wavefunction of the confined carriers but also by the expulsion of the mobile defect components to the surface/interface of the nanocrystals."

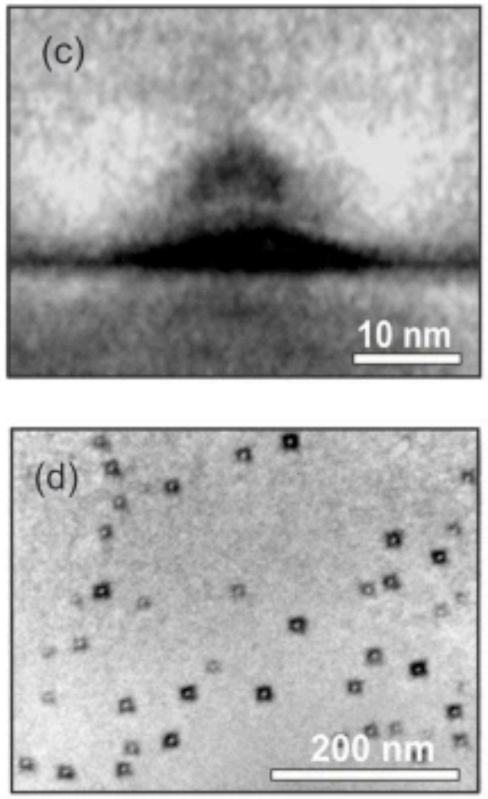
quantum dots for TOF?

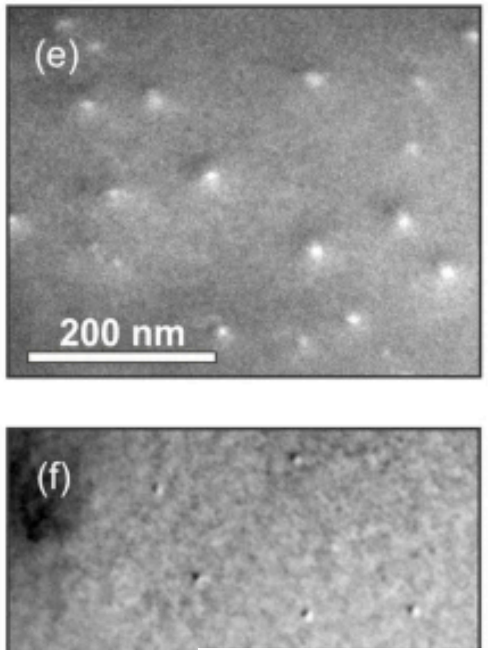
InAs/AlGaAs Stranski-Krastanov QDs fabricated by molecular beam epitaxy (MBE).

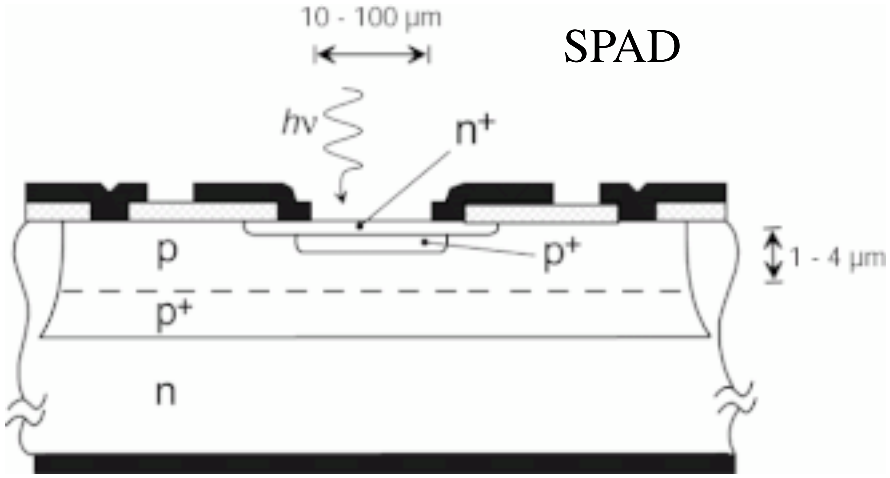
In these structures, the shift of the emission wavelength towards shorter wavelengths as compared with the most studied InAs/GaAs QDs arises from a combination of the larger barrier band gap and possible interdiffusion of Al into the QD material.

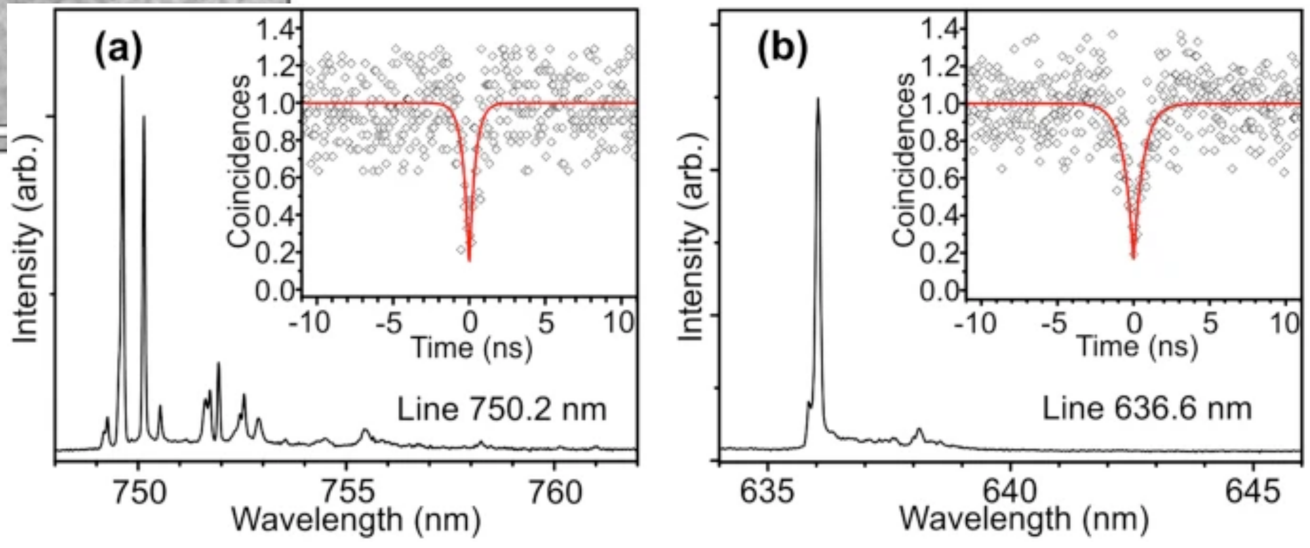
Particular focus on the practically important range 630–750 nm, which corresponds to the region of the highest sensitivity of modern single-photon avalanche diodes (SPAD), with timing resolution of 7.5-100 ps*.







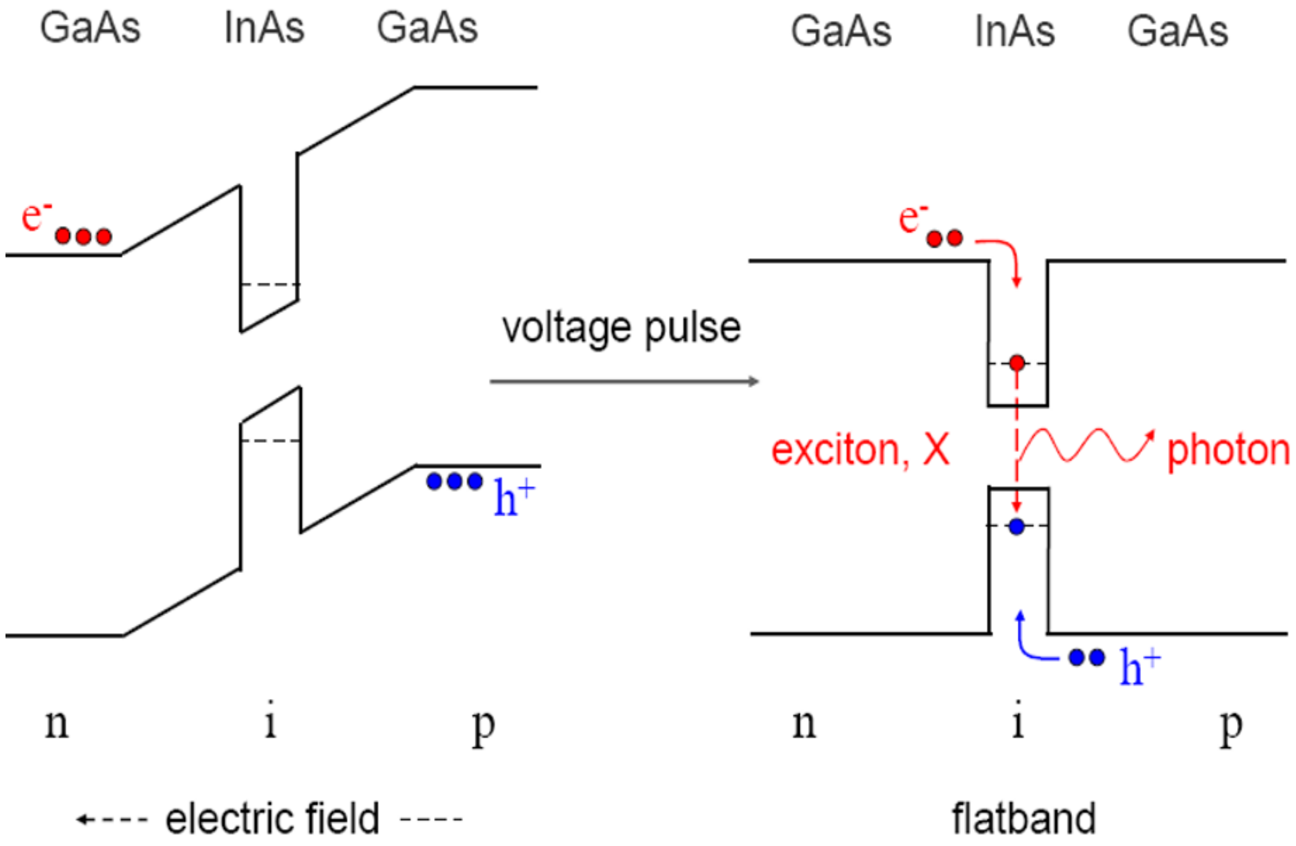




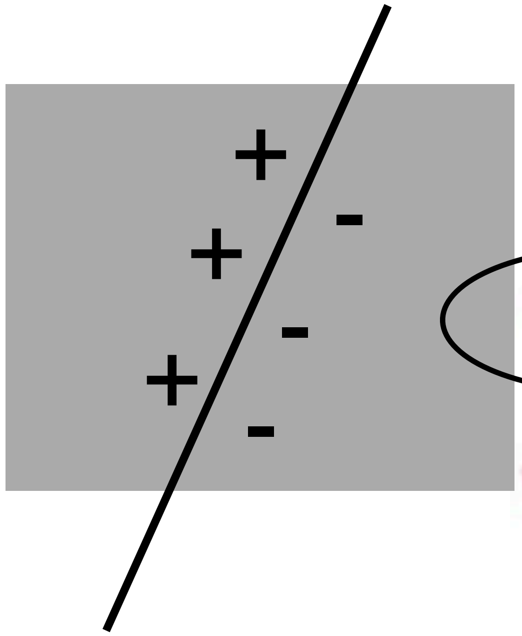
https://www.nature.com/articles/s41598-018-23687-7

* remote / contactless Time-of-Flight measurement?

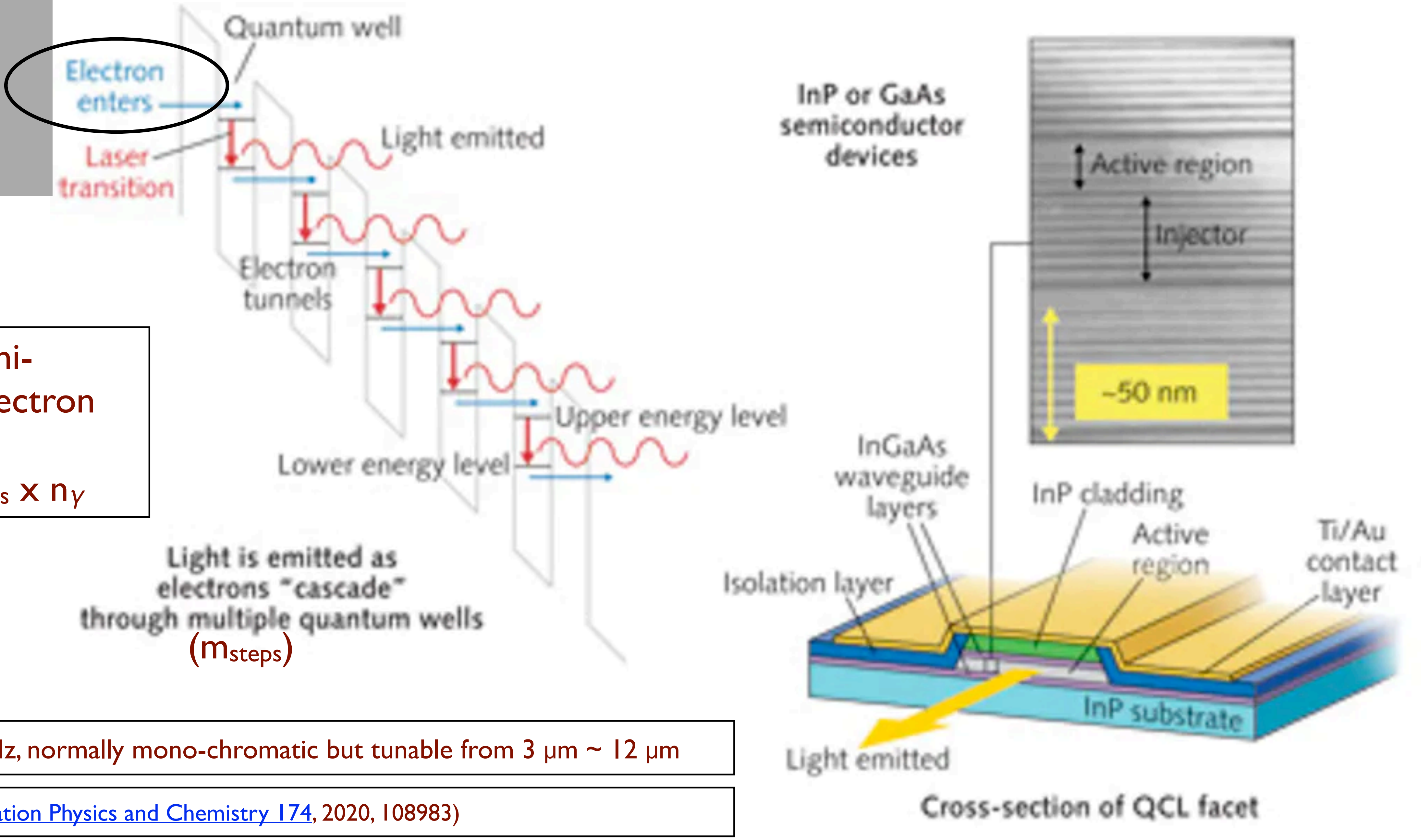
Active scintillators (QWs, QDs, QWDs, QCLs): switching on/off



Active scintillators (QCLs, QWs, QDs, QWDs)



https://www.laserfocusworld.com/test-measurement/spectroscopy/article/16556856/quantumcascade-lasers-qcls-enable-applications-in-ir-spectroscopy



(m_{steps})

Couple bulk semi-conductor to electron injection layer:

$n_e \longrightarrow m_{steps} \times n_\gamma$

Emitted light is IR~THz, normally mono-chromatic but tunable from 3 μm ~ 12 μm

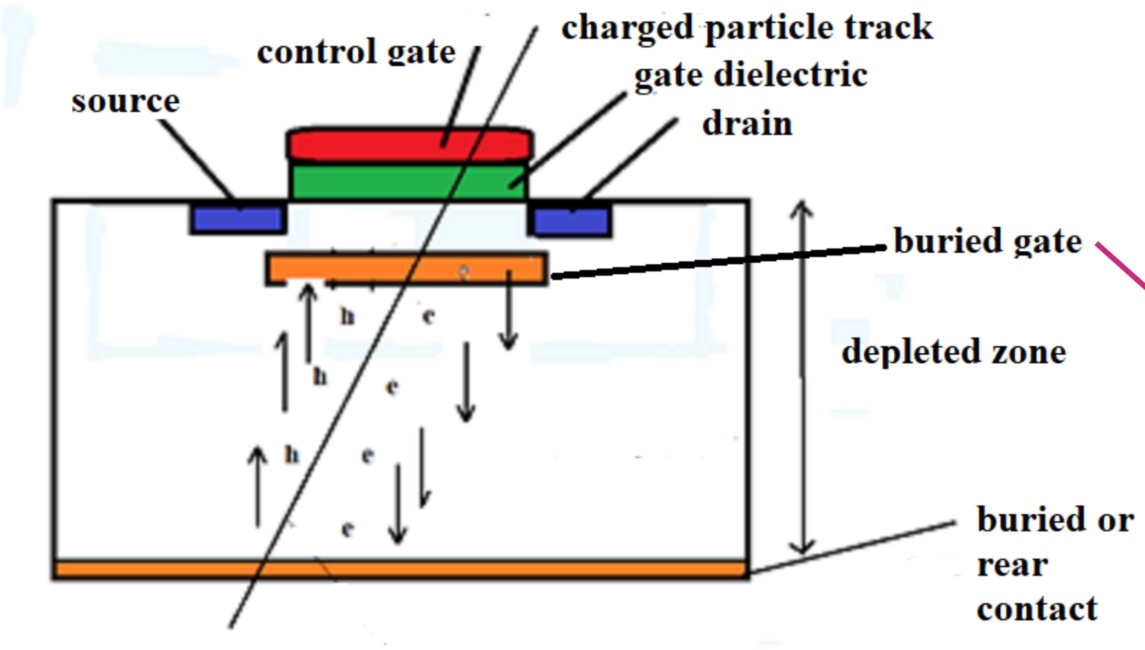
Radiation resistant ([Radiation Physics and Chemistry 174](https://doi.org/10.1016/j.radphyschem.2020.108983), 2020, 108983)

Quantum dots and wells:

https://arxiv.org/abs/2202.11828

submicron pixels DoTPiX (quantum Dot pixel)

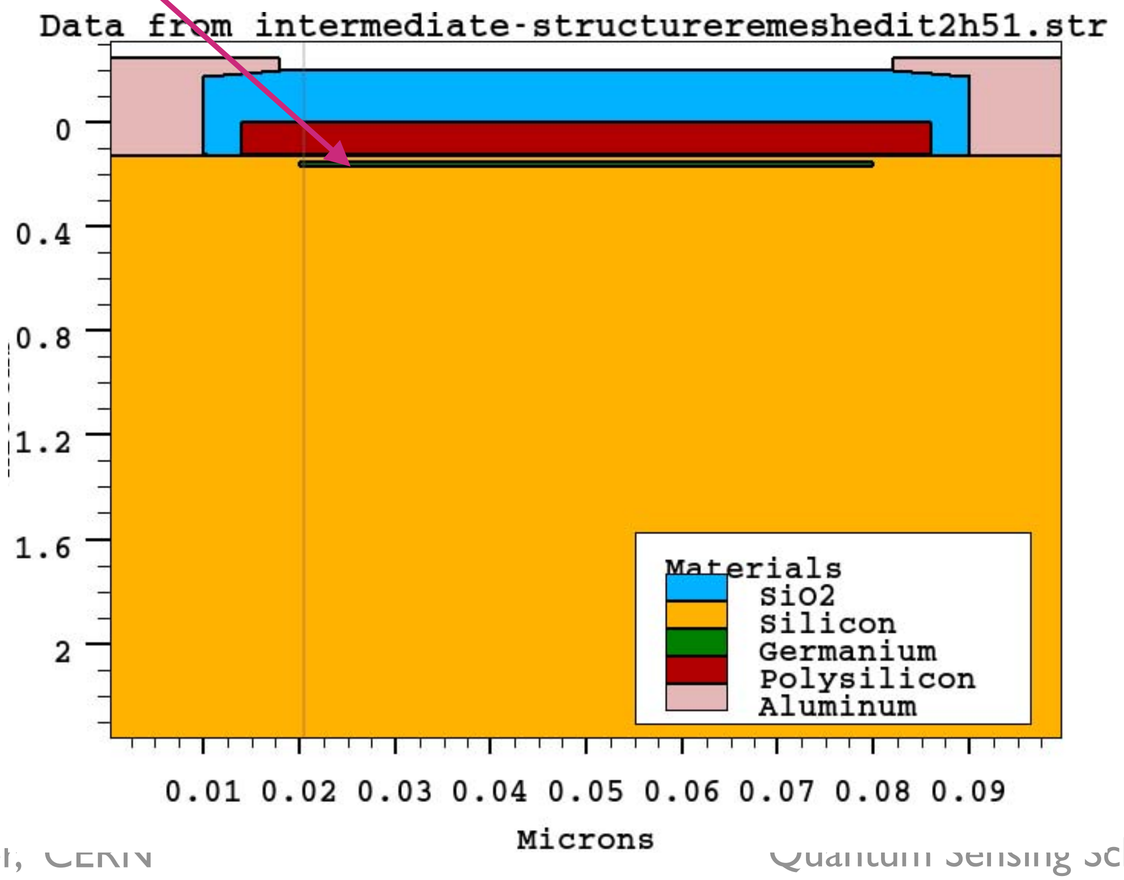
https://ieeexplore.ieee.org/document/7867862



= single n-channel MOS transistor, in which a buried quantum well gate performs two functions:

- as a hole-collecting electrode and
- as a channel current modulation gate

Electron-hole (e-h) pairs generated in the active volume, under the buried gate, are separated: as electrons flow to the substrate, holes flow to the buried gate and become localized in the valence band QW, for a lapse of time much more than 1 µs at room temperature (with a valence band well of 0.35 eV deep).



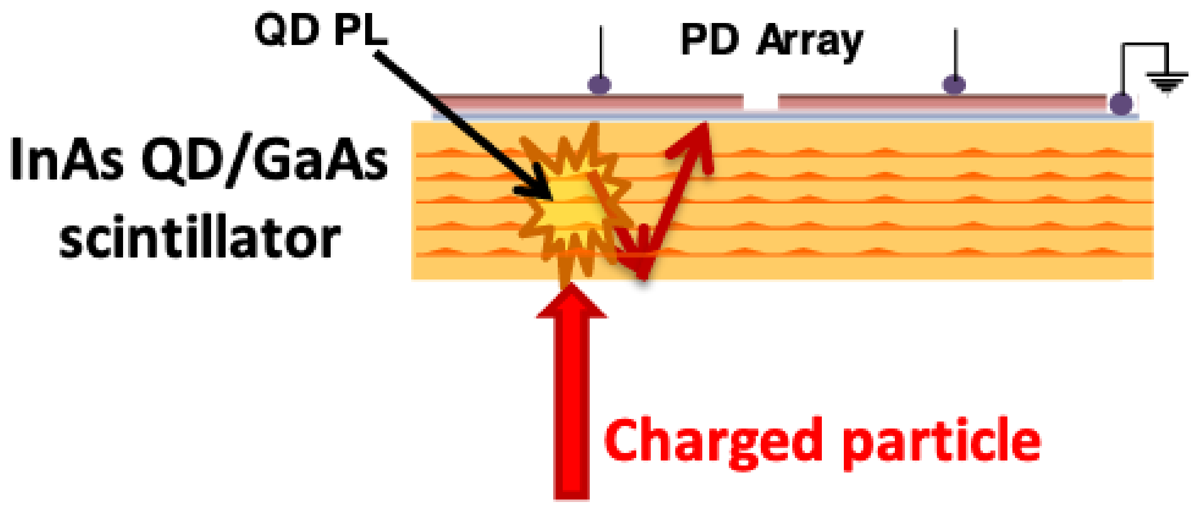
Quantum dots and wells:

https://arxiv.org/abs/2202.11828

scintillating (chromatic) tracker

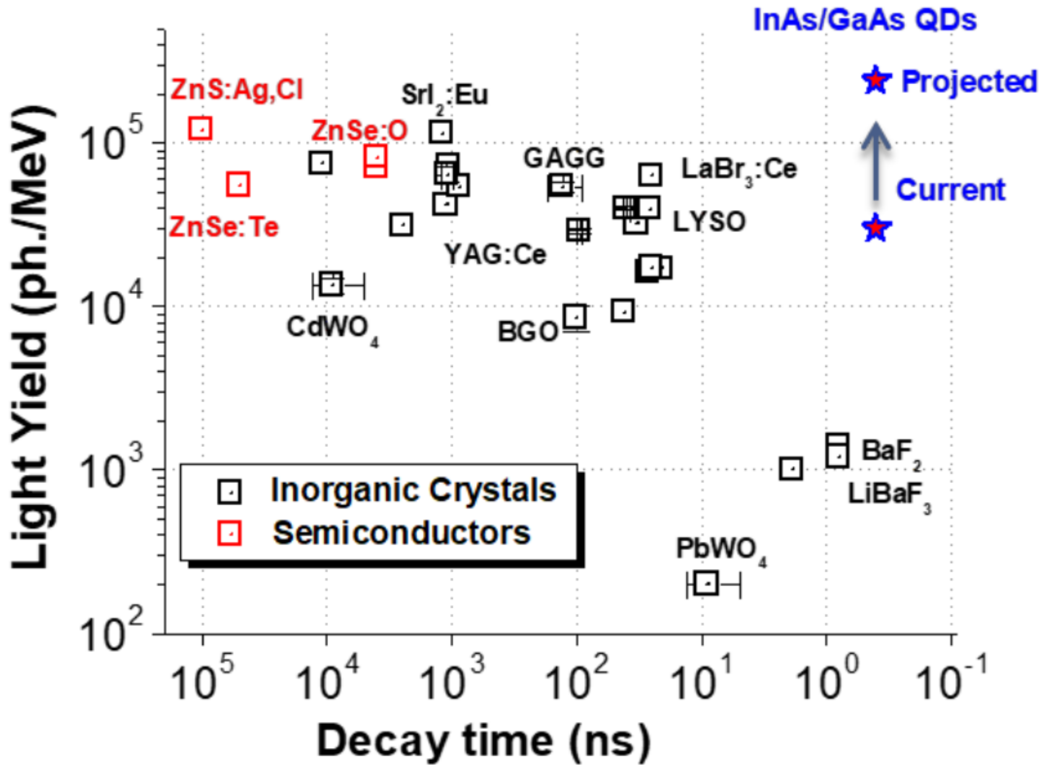
https://link.springer.com/article/10.1557/s43580-021-00019-y

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



A charged particle enters the GaAs bulk, producing electron-hole pairs. The electrons are then quickly (2-5ps) 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 (no emission into air, high refraction index).

IR emission from InAs QD's integrated PD's (1-2 μm thick)



Quantum dots and wells:

https://arxiv.org/abs/2202.11828

submicron pixels

DoTPiX

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scintillating QD (chromatic) tracker

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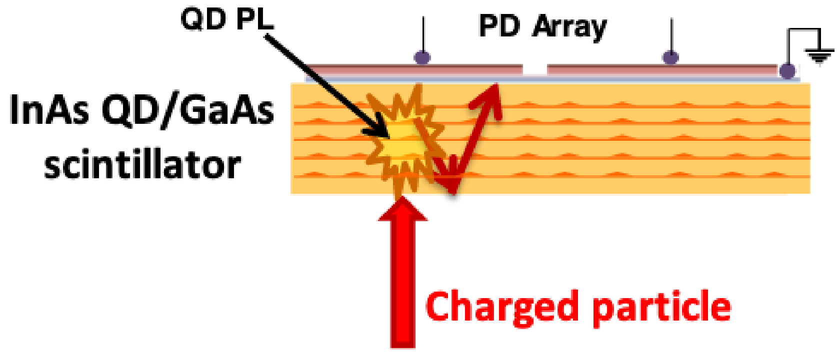
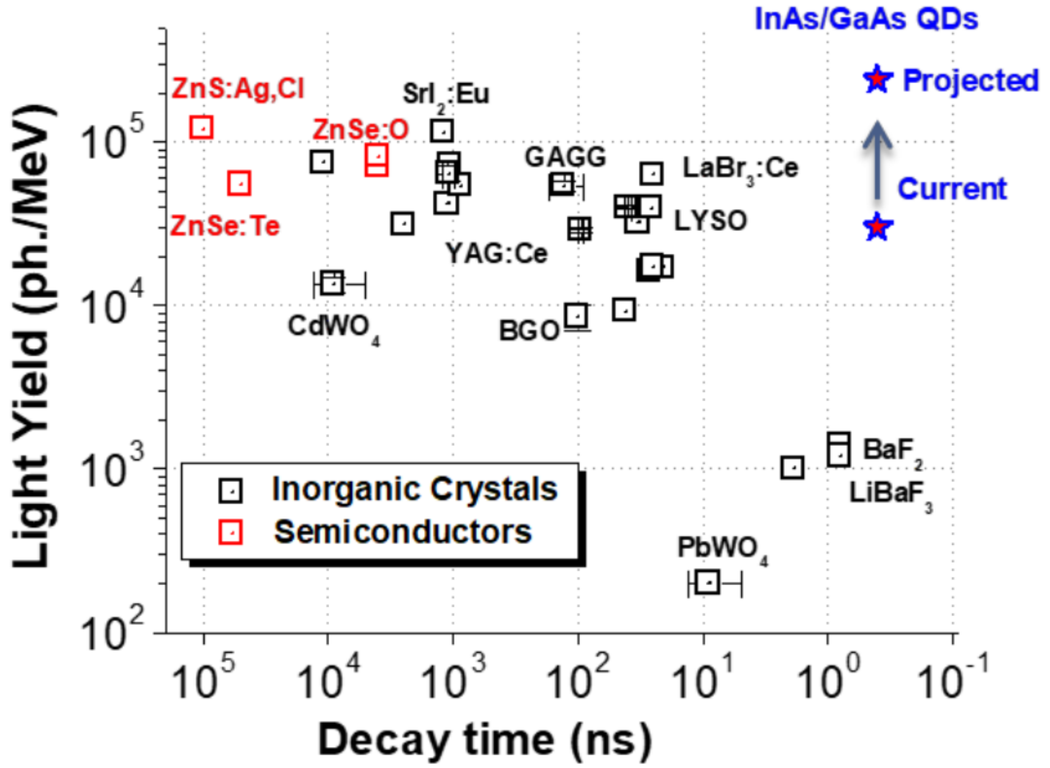


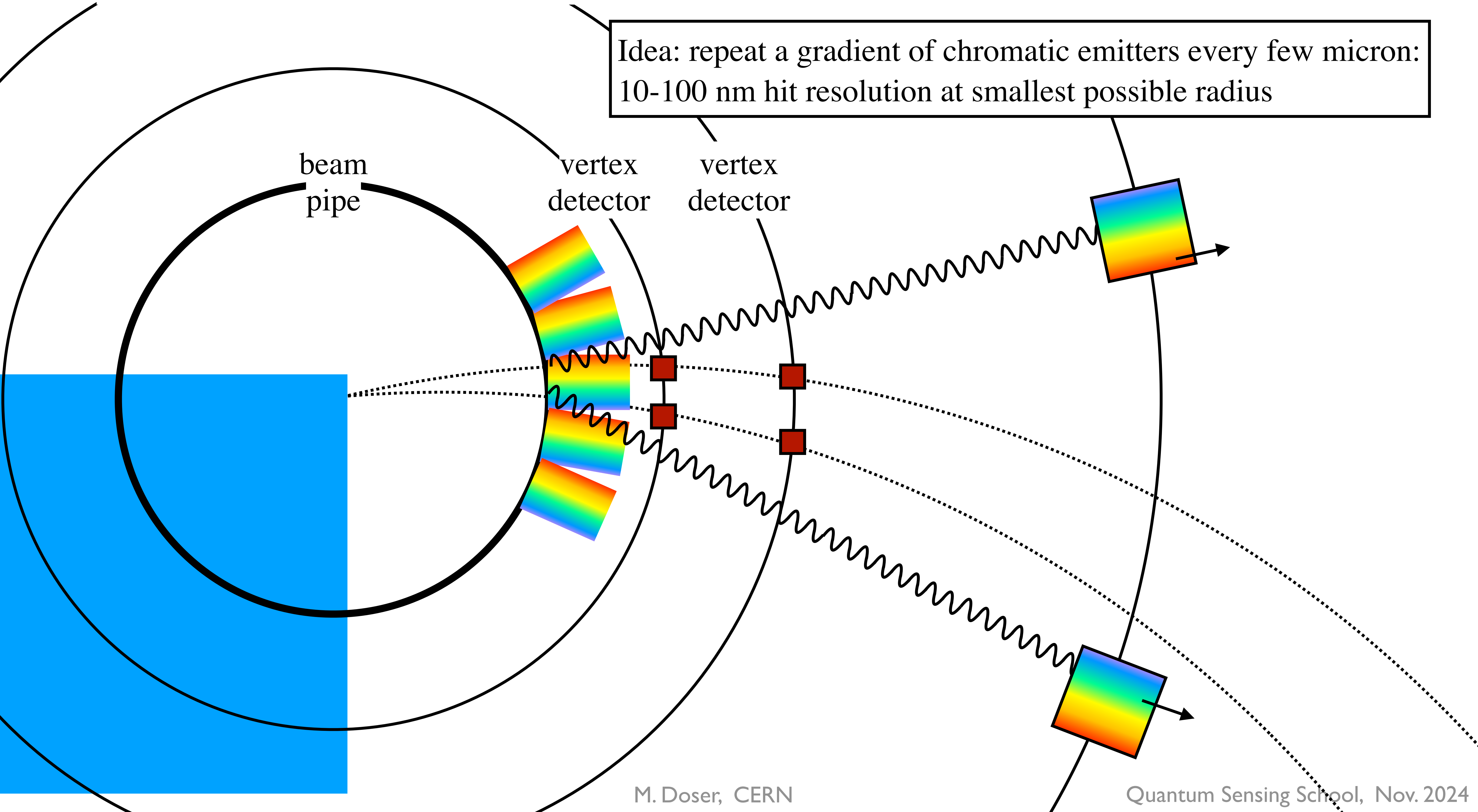
IR emission from InAs QD's

integrated PD's (1-2 μm thick)



Jump into the future: ordering nanodots to build new types of detectors

"Building ordered and defect-free two- and three-dimensional structures on the nanometer scale is essential for the construction of next-generation optical, electronic, and magnetic materials and devices."

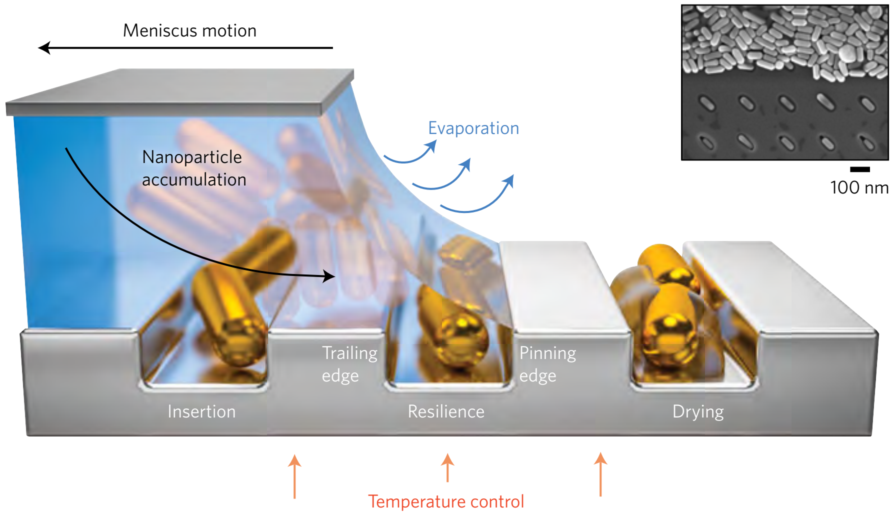


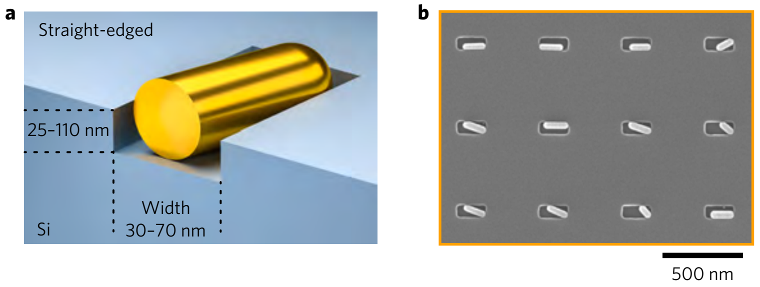
Idea: repeat a gradient of chromatic emitters every few micron: 10-100 nm hit resolution at smallest possible radius

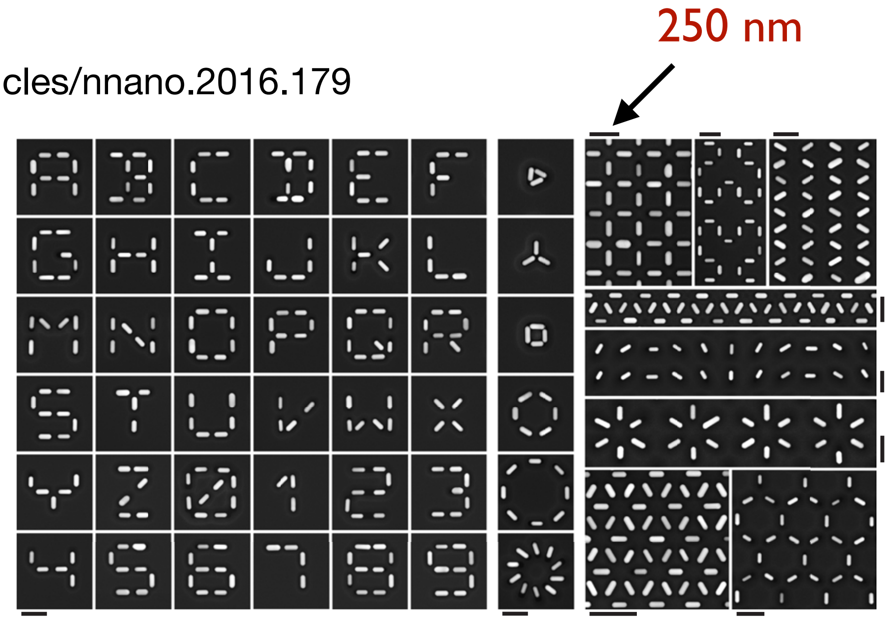
How to order nanodots at nm scale:

- "Classically": electrophoresis, capillary force assembly, …

https://www.nature.com/articles/nnano.2016.179

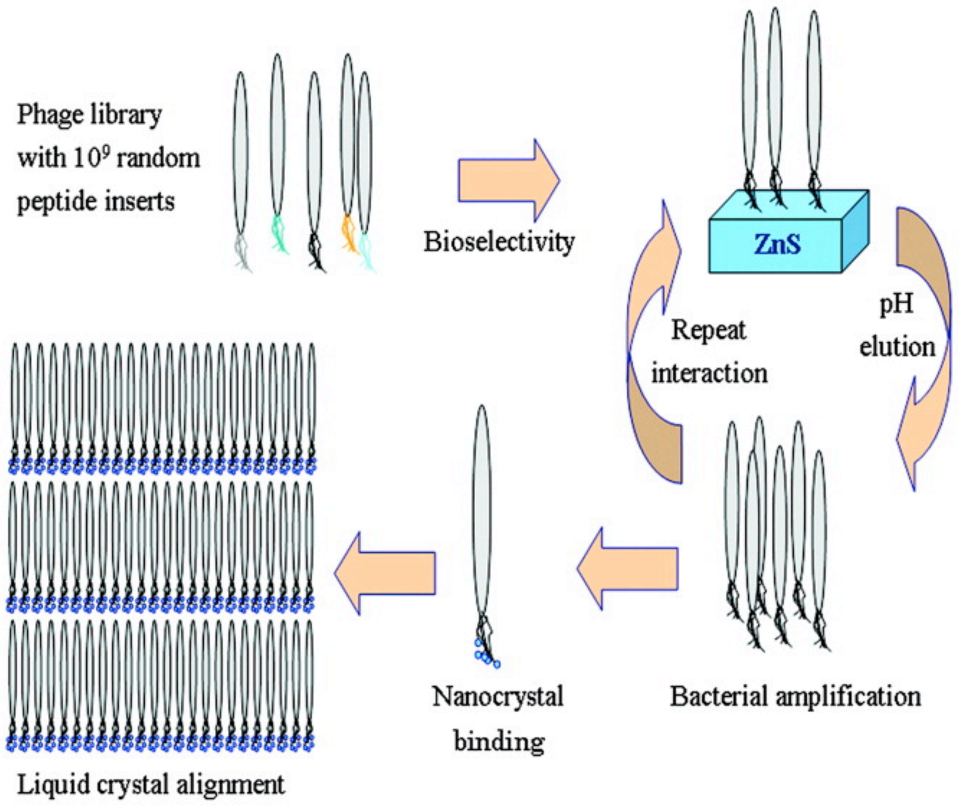


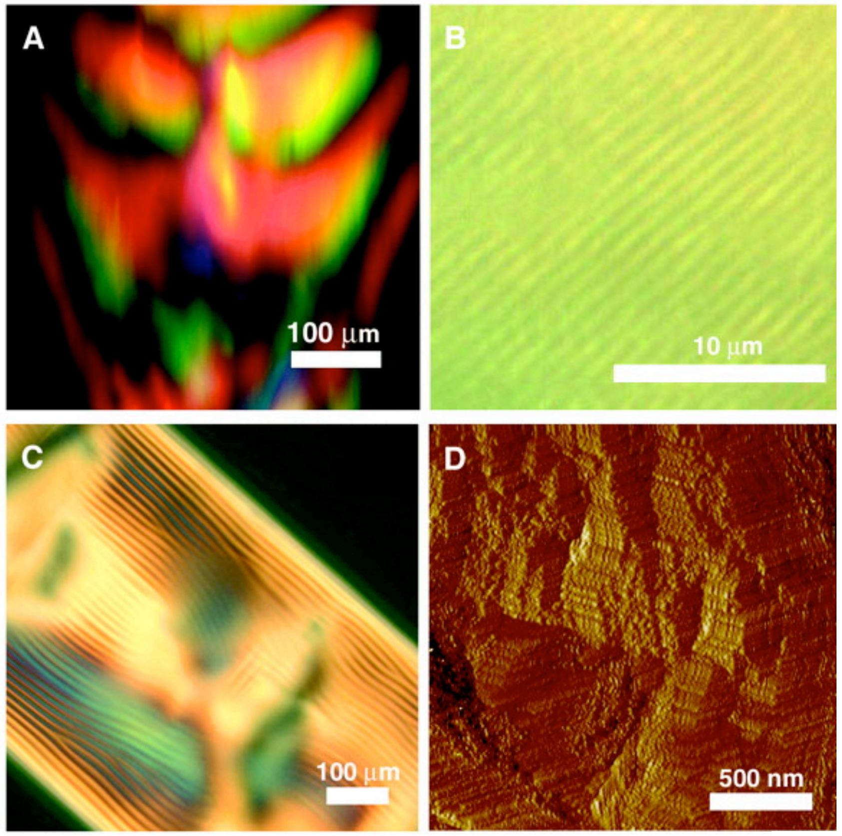


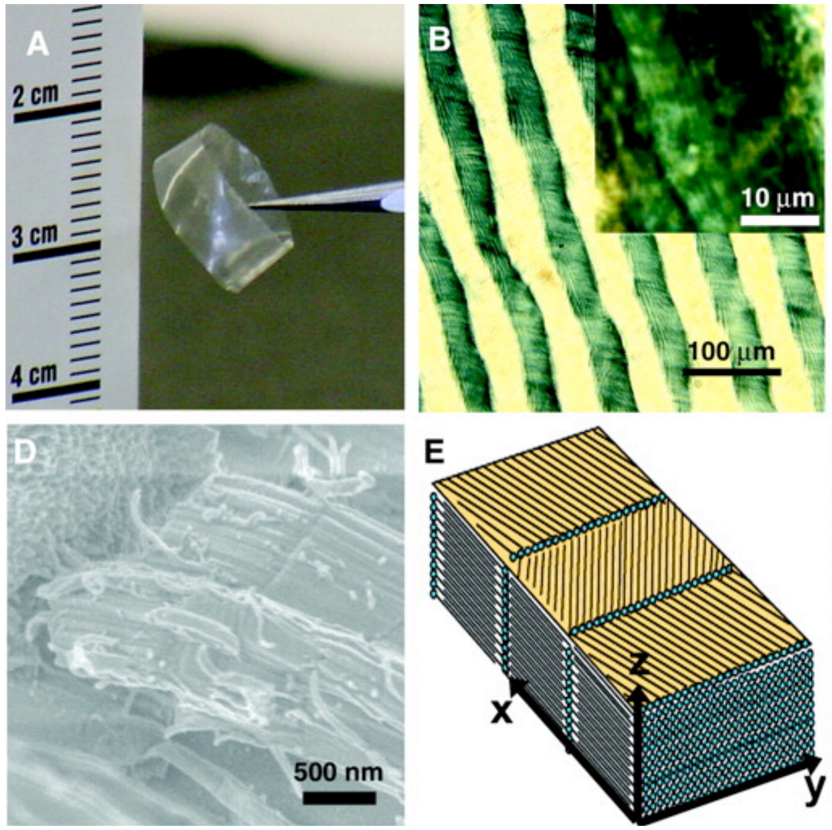


- We have evolved phage and ZnS precursor solutions to self-assemble highly oriented, self-supporting films. In this system, we can easily modulate both the length of bacteriophage and the type of inorganic materials through genetic modification and selection. Here we report our first effort to direct multi–length scale ordering of quantum dot (QD) hybrid self-supporting biocomposite structures using genetically engineered M13 bacteriophage, viruses with monodisperse size and shape. The resulting QD hybrid film material was ordered at the nanoscale and at the micrometer scale into 72-µm domains. These domains repeated continuously over a centimeter length scale.

https://www.science.org/doi/full/10.1126/science.1068054

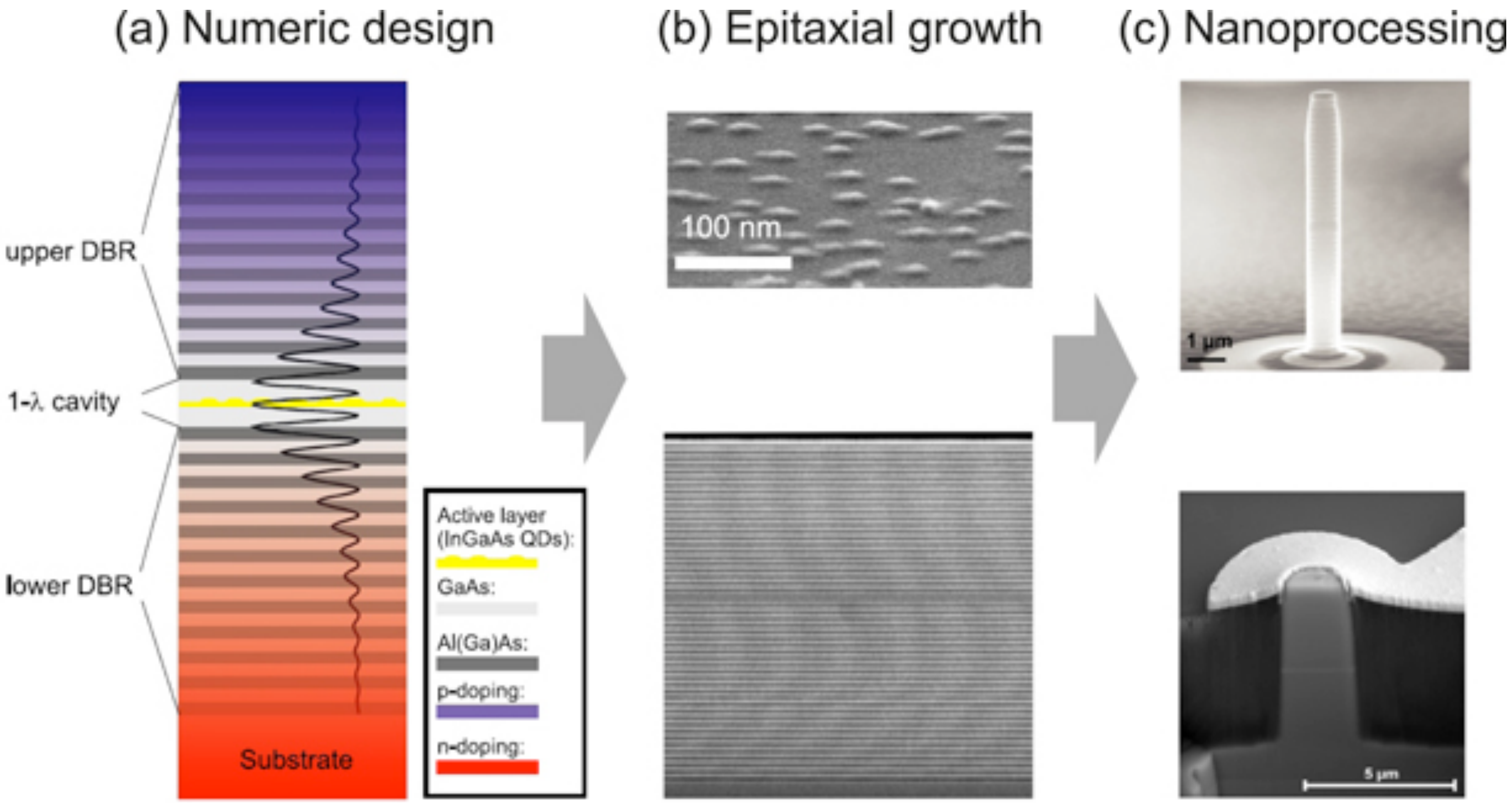


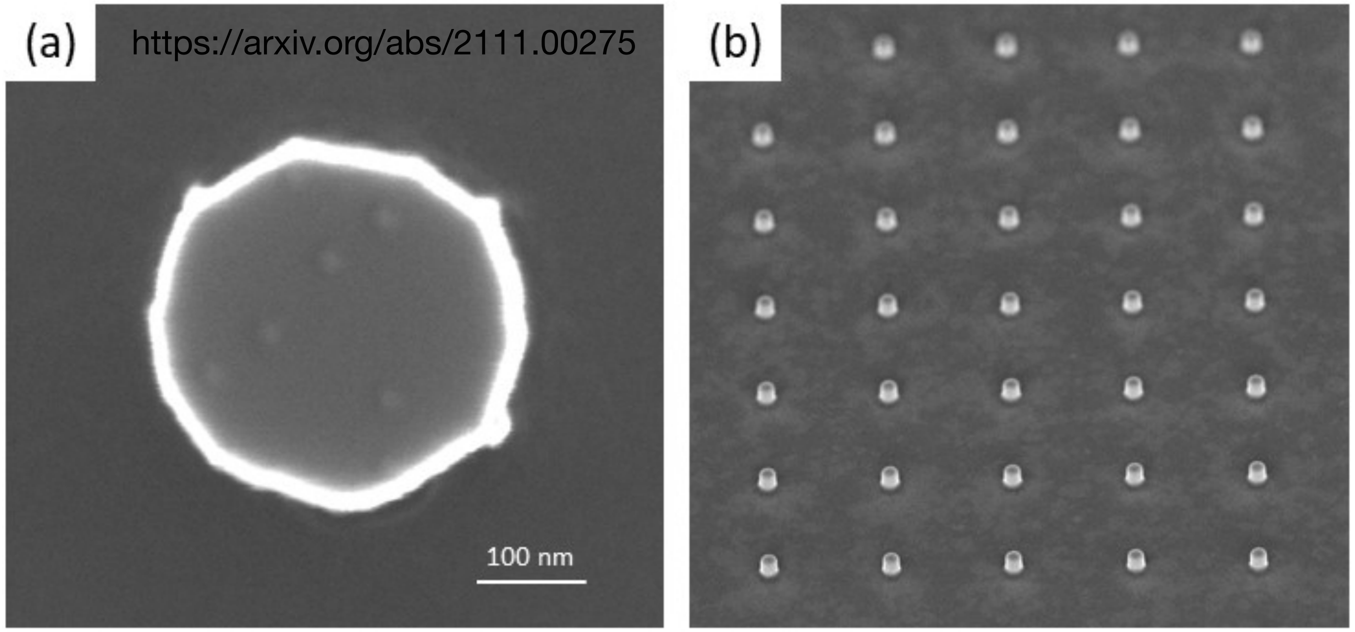




the end

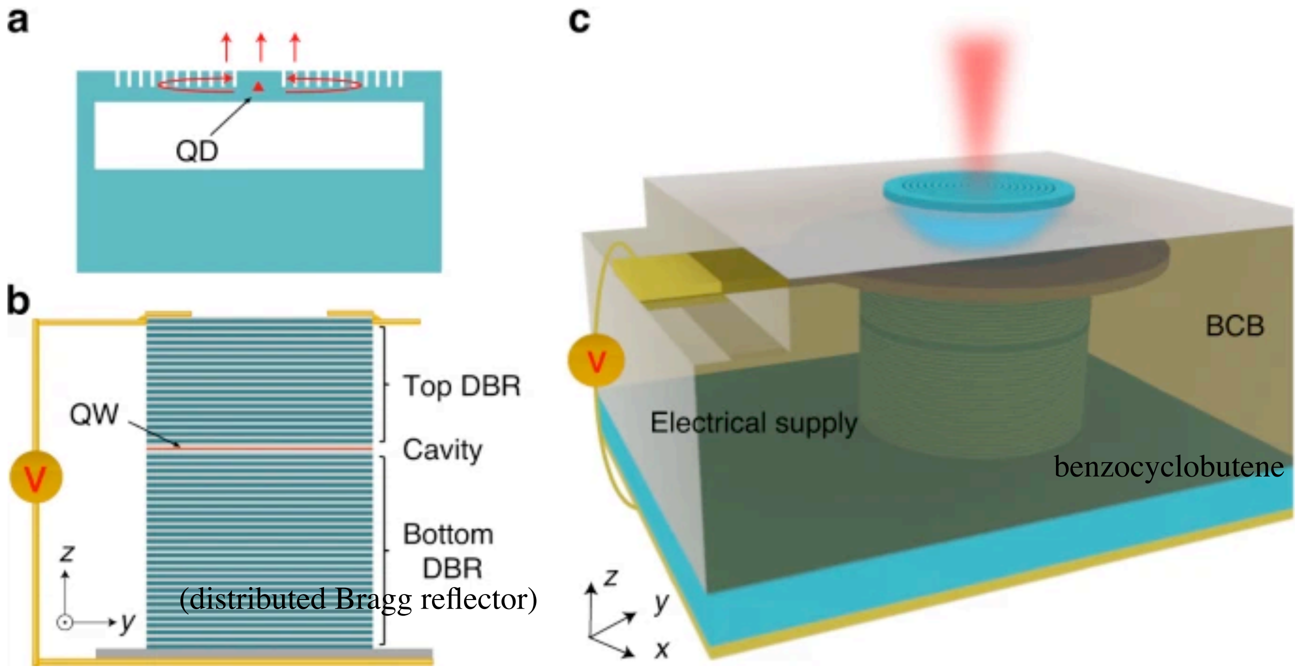
How to order nanodots at nm scale: micropillar arrays





https://arxiv.org/abs/2111.00275

FIGURE 1. (a) SEM image of a pillar. QDs on the top surface are for investigating QD growth condition. (b) Square lattice pillar array structure with a lattice constant of 2.5 µm.



(distributed Bragg reflector)

benzocyclobutene

https://www.nature.com/articles/s41377-023-01110-9