CHROMATIC CALORIMETRY

Yacine Haddad [(1)], Devanshi Arora[(2)], Etiennette Auffray [(3)], Michael Doser [(3)], Matteo Salomoni [(3,4)], and Michele Weber [(5)]

[(1)] Northeastern University, [(2)] Shizuoka University, [(3)] CERN, European Organization for Nuclear Research, [(4)] University of Milano-Bicocca. [(5)] University of Bern

INTRODUCTION

- **Why Quantum Technology for High Energy Physics?**
  - Increasingly ambitious physics goals necessitate innovative detector designs

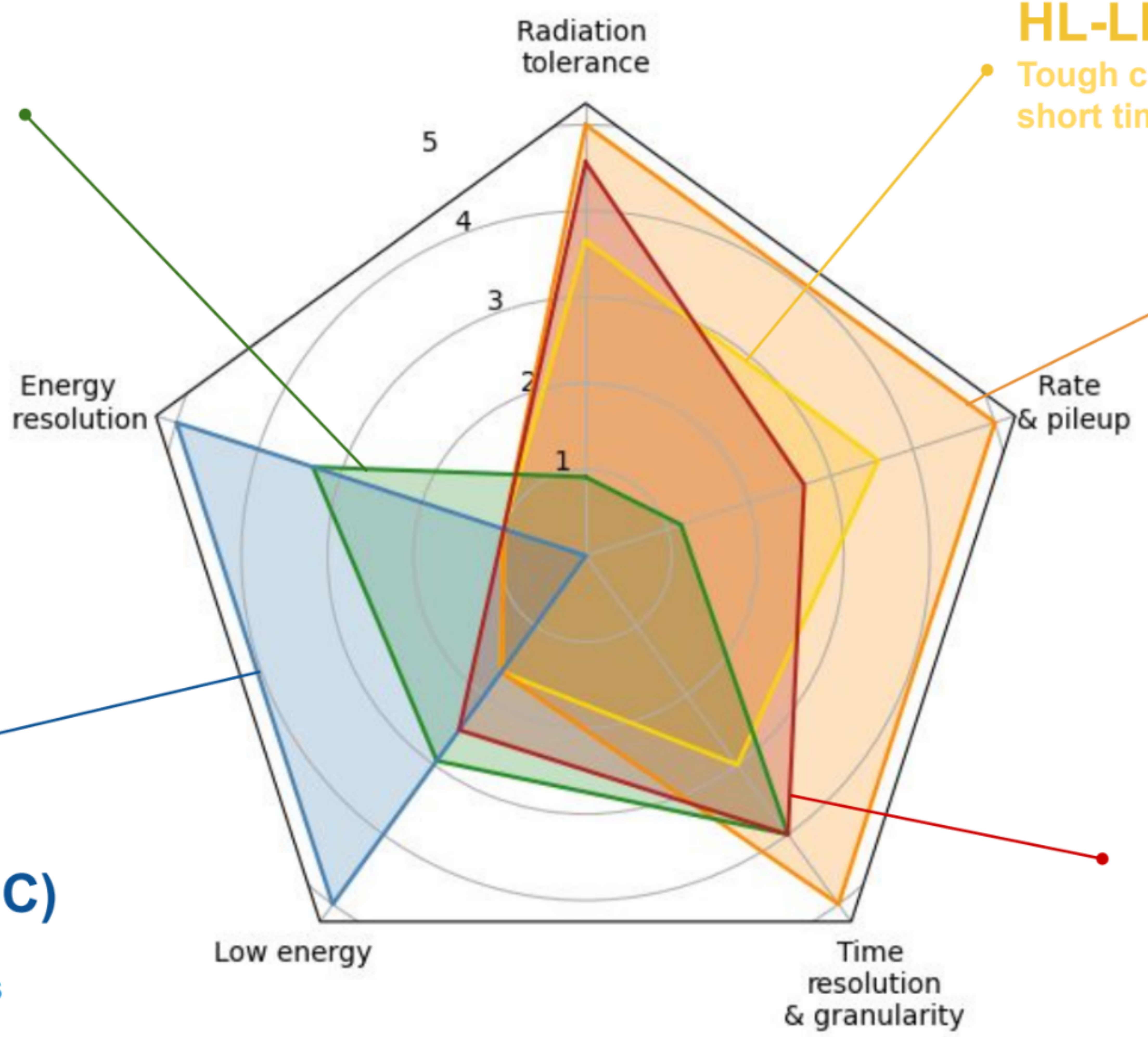
- **The future Calorimetry:**
  - **Demanding requirements** from HEP: radiation-hardness, improved electromagnetic energy and timing resolution, high-granularity with multi-dimensional readout for particle-flow algorithms
  - Traditional technologies could address these needs, but with significantly increased complexity in readout systems.

NEW FRONTIERS IN PARTICLE PHYSICS

e^+e^- colliders
Precision physics benefits from exploiting the best possible energy and time resolution

HL-LHC
Tough challenges on a short timescale

FCC-hh
Setting the toughest challenge on radiation tolerance and pileup conditions



Very high energy (longitudinal containment)

Strong interaction experiments (e.g. EIC)
Requiring the highest energy resolution for low energy photons

$\mu^+\mu^-$ colliders
High beam induced background and radiation levels, need for ambitious time resolution

M. Lucchini, INFN, "ECFA Detector R&D Roadmap Task Force 6: Calorimetry Community Meeting, 12.1.2023"

PROPOSAL FOR DRD5: R&D ON QUANTUM SENSING

Roadmap topics ⟶ Proposal themes ⟶ Proposal WP's

Roadmap topics

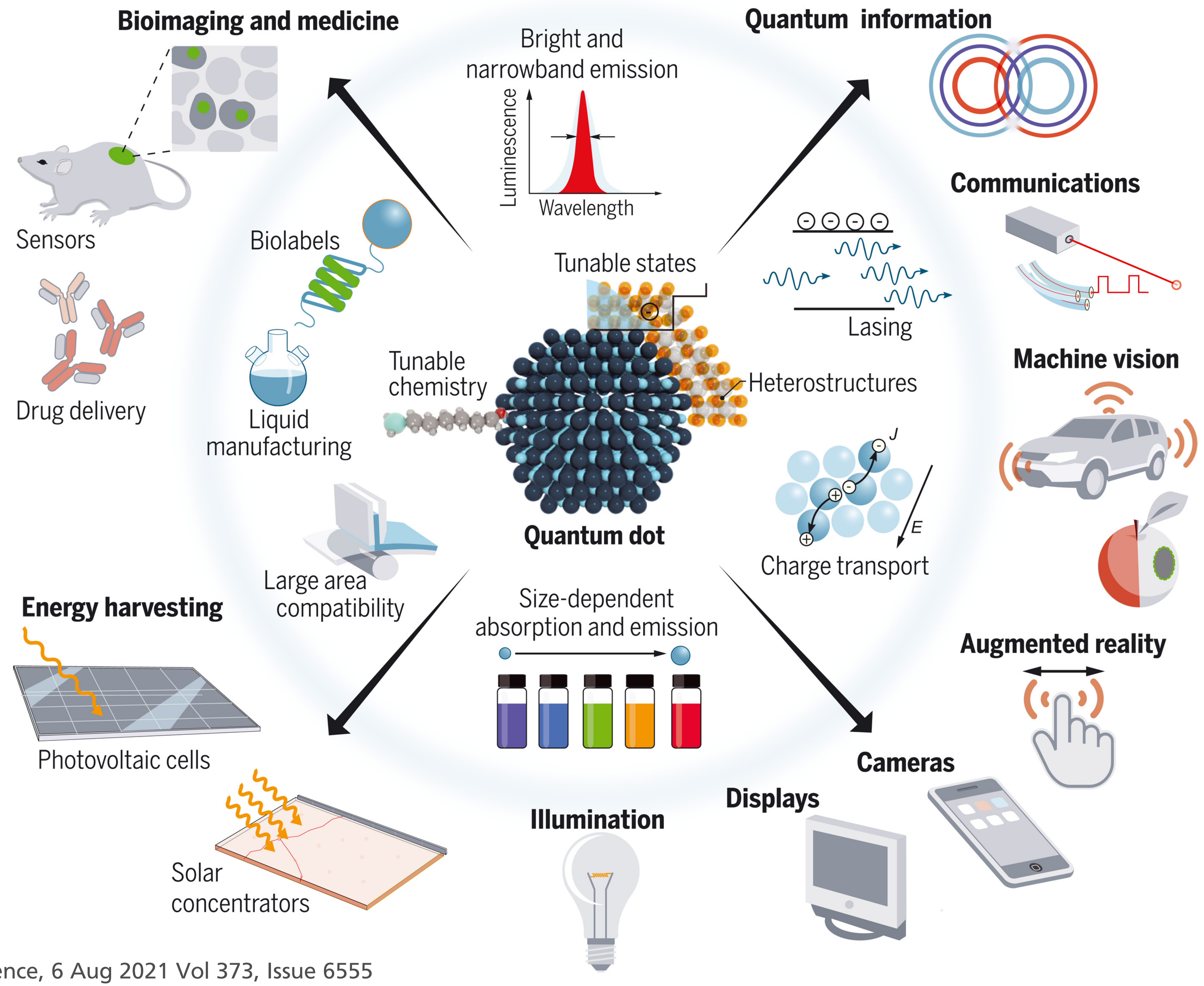
Proposal WP's

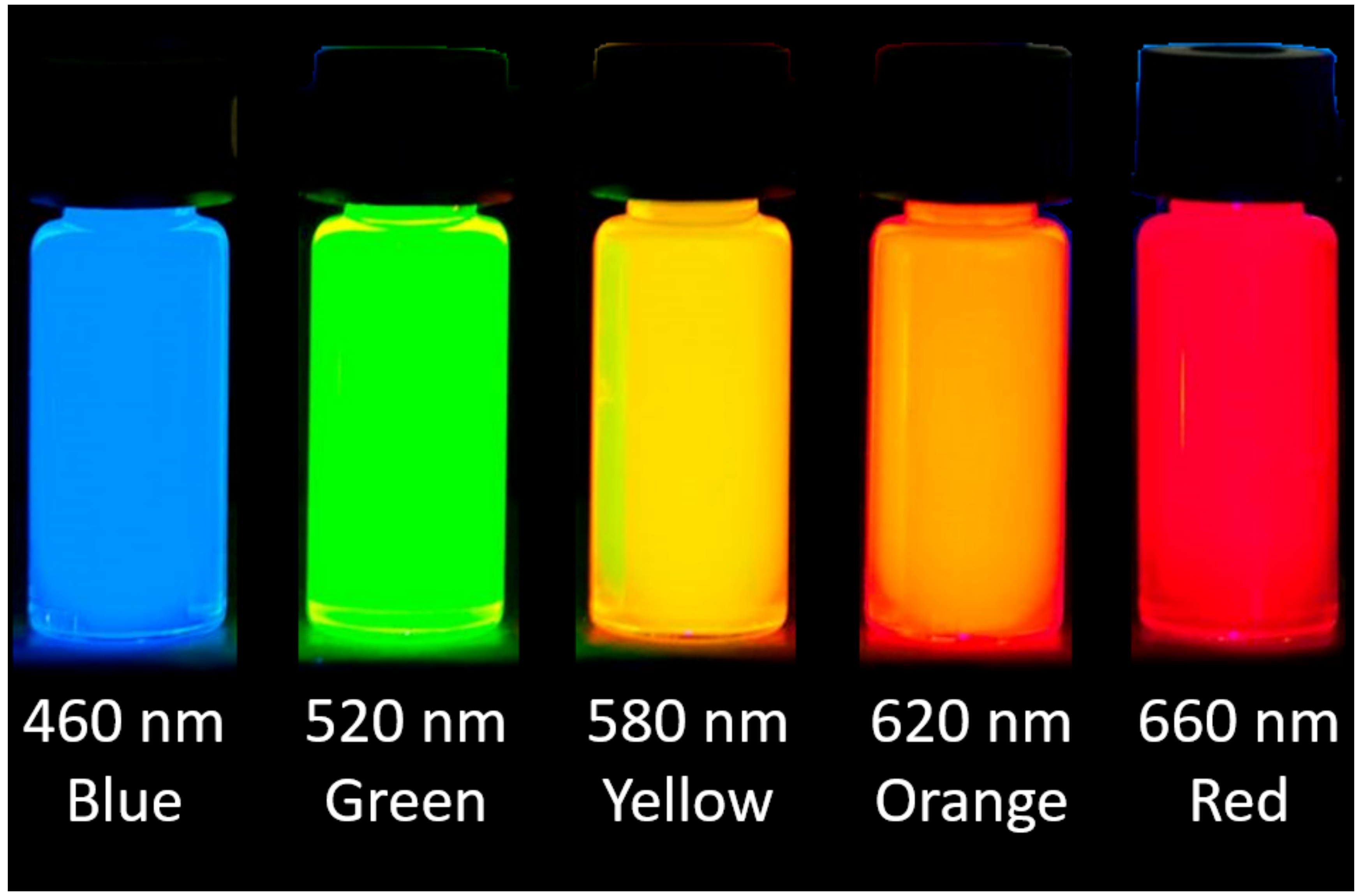
Sensor family → / Work Package ↓	clocks & clock networks	superconducting & spin-based sensors	kinetic detectors	atoms / ions / molecules & atom interferometry	opto-mechanical sensors	nano-engineered / low-dimensional / materials
WP1 *Atomic, Nuclear and Molecular Systems in traps & beams*	X			X	(X)	
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

Proposal on R&D on quantum sensors: the DRD5/RDq proto-collaboration
https://cds.cern.ch/record/2901426

QUANTUM DOTS

The invention of Quantum Dots received the Nobel Prize in Chemistry in 2023



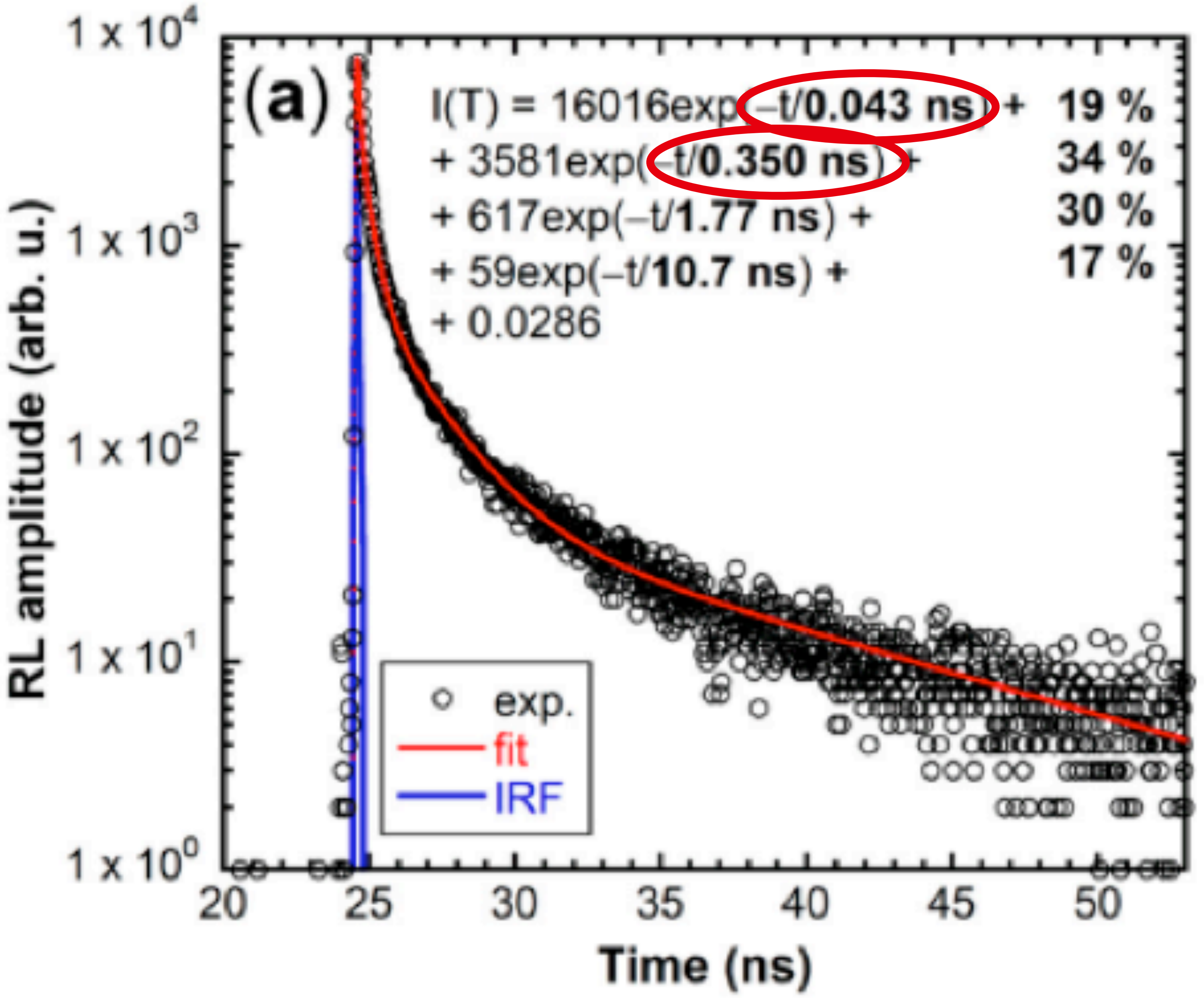


- Quantum dots are Semiconductor nanocrystals with size-tunable emission
- Narrow bandwidth (~20 nm) allows precise segmentation.
- **Potential to outperform traditional scintillators in timing and spectral resolution.**

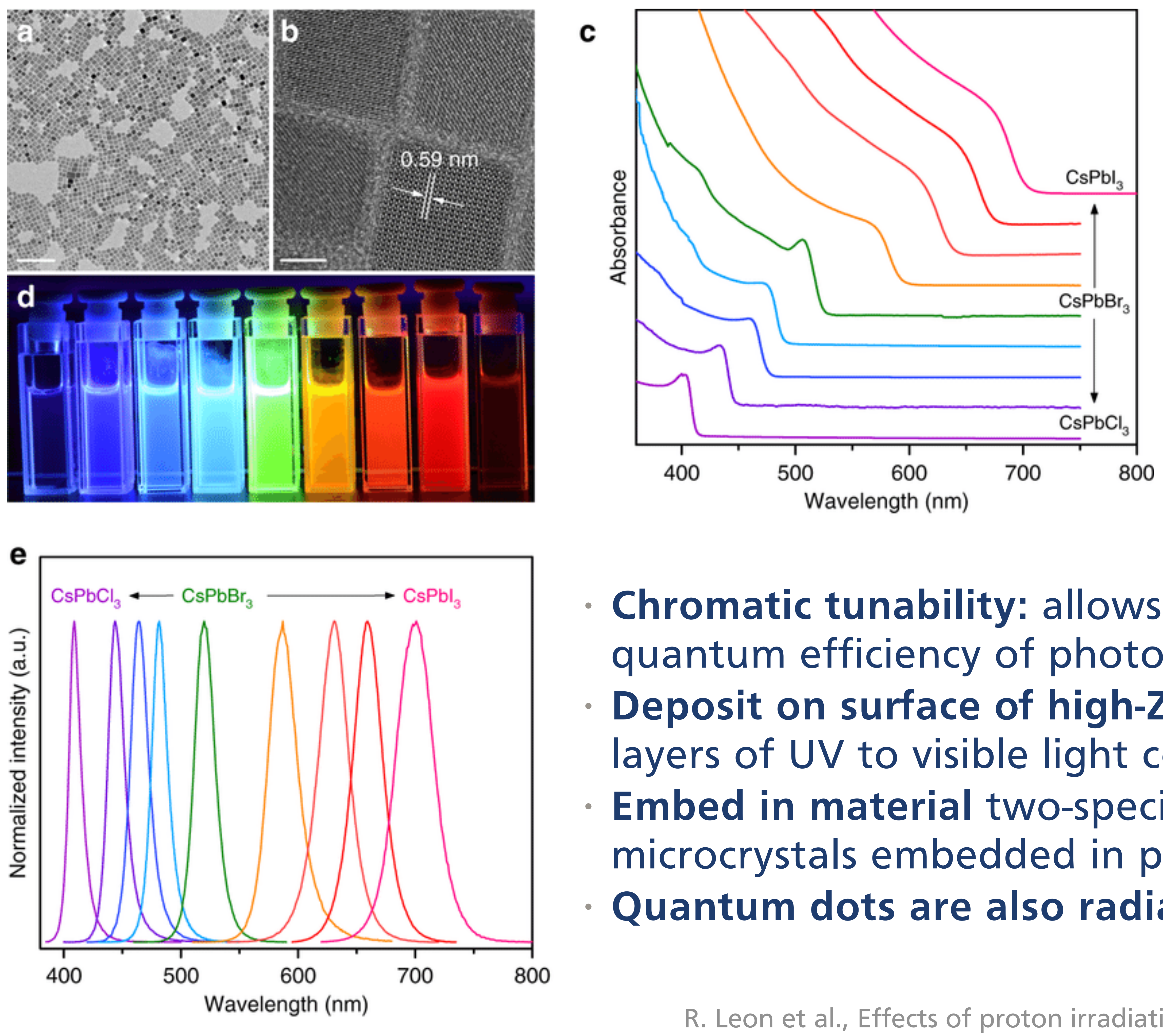
Science, 6 Aug 2021 Vol 373, Issue 6555
DOI: 10.1126/science.aaz8541

QUANTUM DOTS: TIMING & CHROMATIC TUNABILITY

Scintillation decay time spectra from CsPbBr3 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

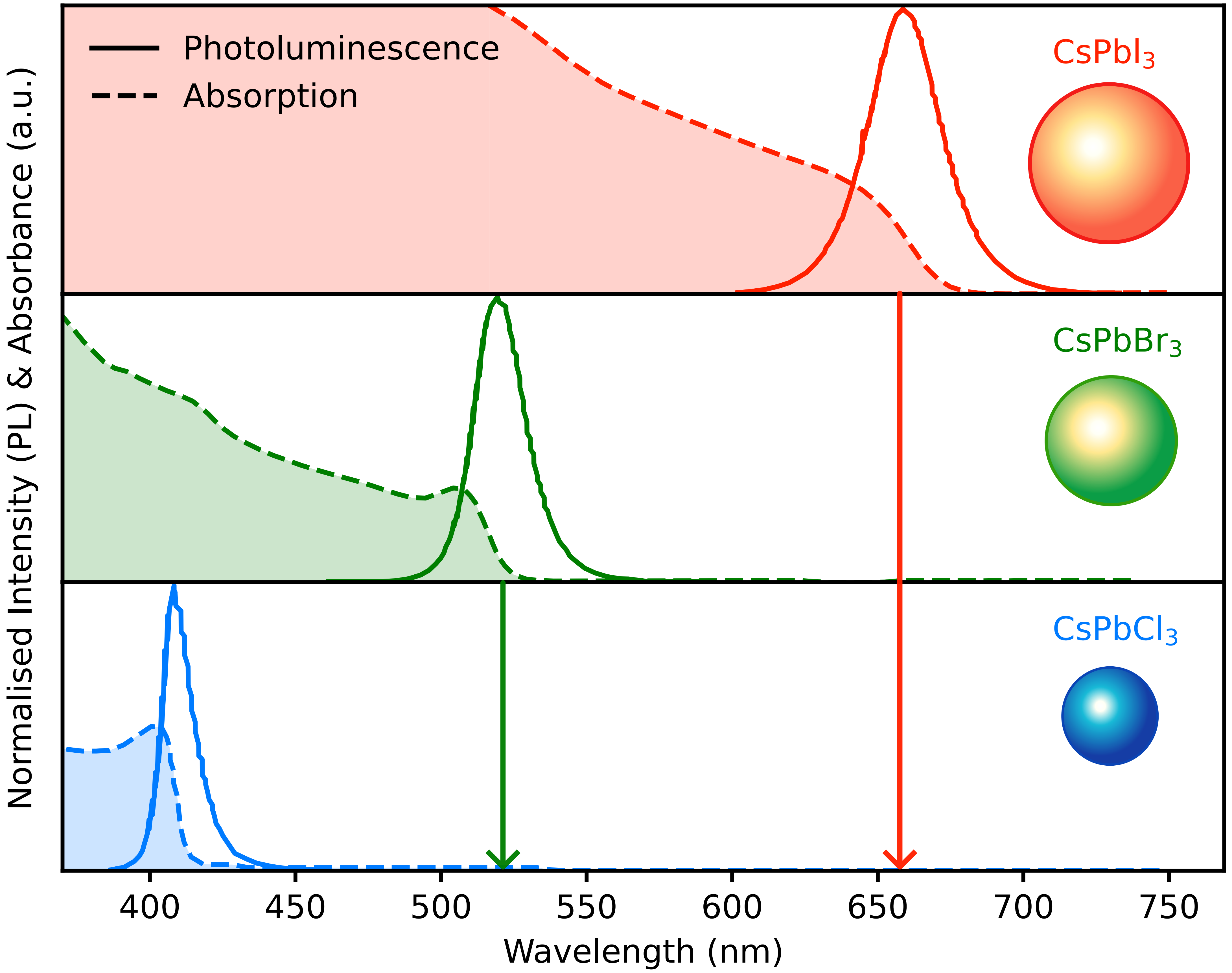


- **Chromatic tunability:** allows to optimise for quantum efficiency of photo detectors
- **Deposit on surface of high-Z material**: thin layers of UV to visible light converter
- **Embed in material** two-species, nanodots and microcrystals embedded in polymer matrix
- **Quantum dots are also radiation hard !!**

R. Leon et al., Effects of proton irradiation on luminescence emission and carrier dynamics of self-assembled III-V quantum dots, https://ieeexplore.ieee.org/document/1134230

QUANTUM DOT BASED CHROMATIC CALORIMETRY (CCAL)

Example with perovskite QD



- **THE 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

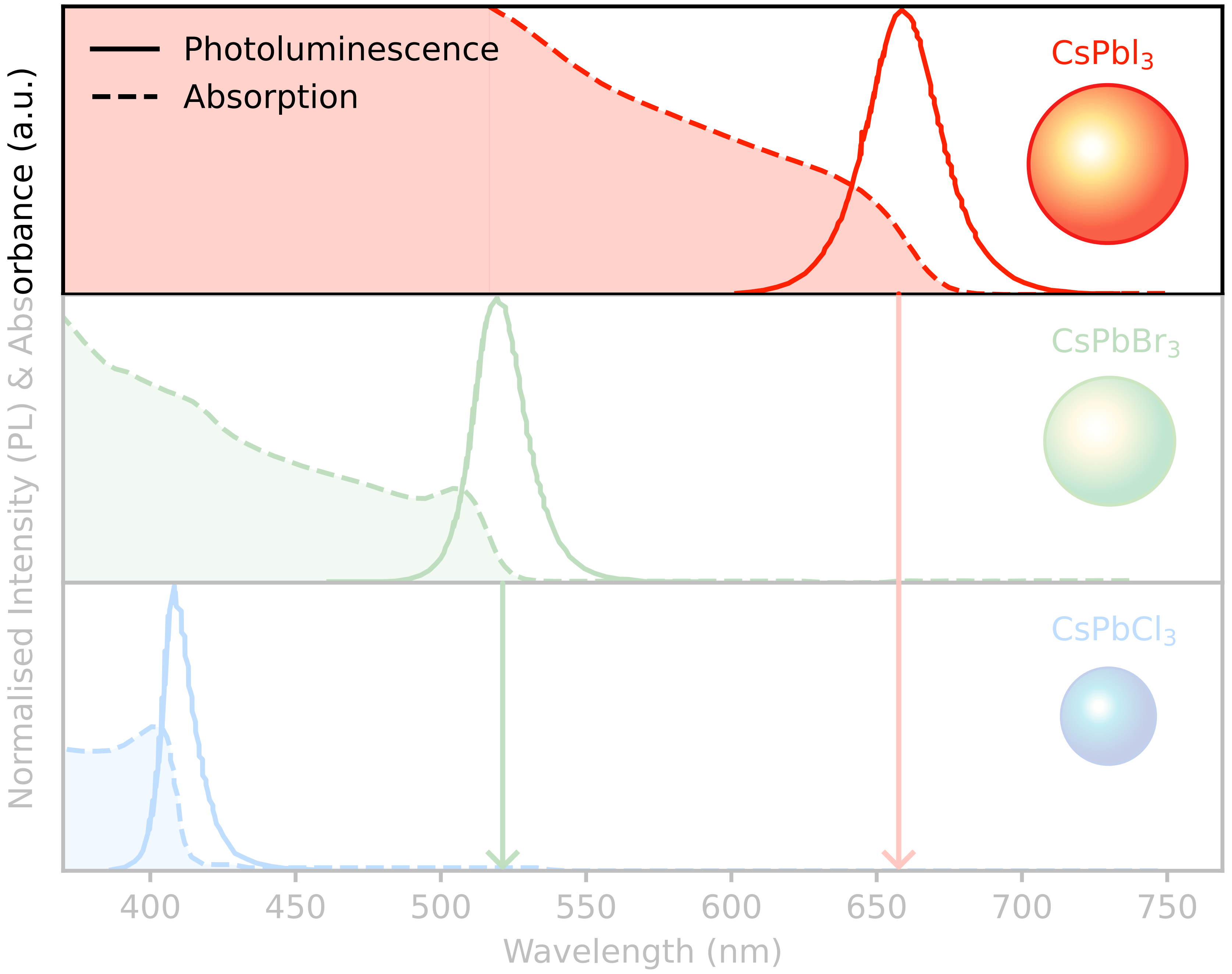
- **Main features (on top of classic calorimeter):**
  - Longitudinally segmented, each layer with a certain emission wavelength and absorption band
  - single readout capable of providing spectral information
  - Unidirectional spectral transparency.

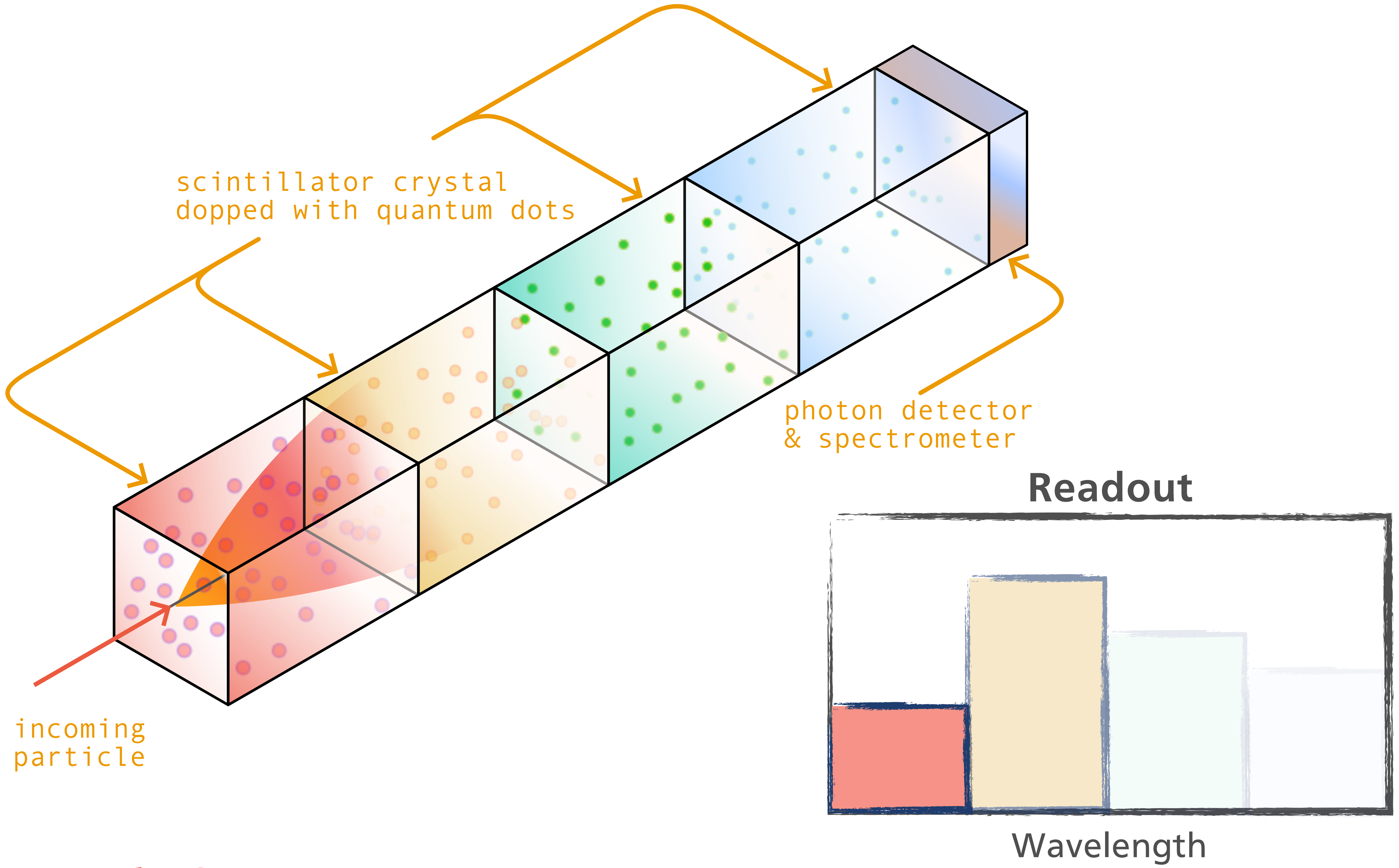
The longitudinal segmentation can be as fine as the materials allow → many layers with 20 nm QD narrow band emission!

Result: longitudinal tomography of the shower profile.

Doser M, et al. (2022) Quantum Systems for Enhanced High Energy Particle Physics Detectors. Front. Phys. 10:887738. doi: 10.3389/fphy.2022.887738

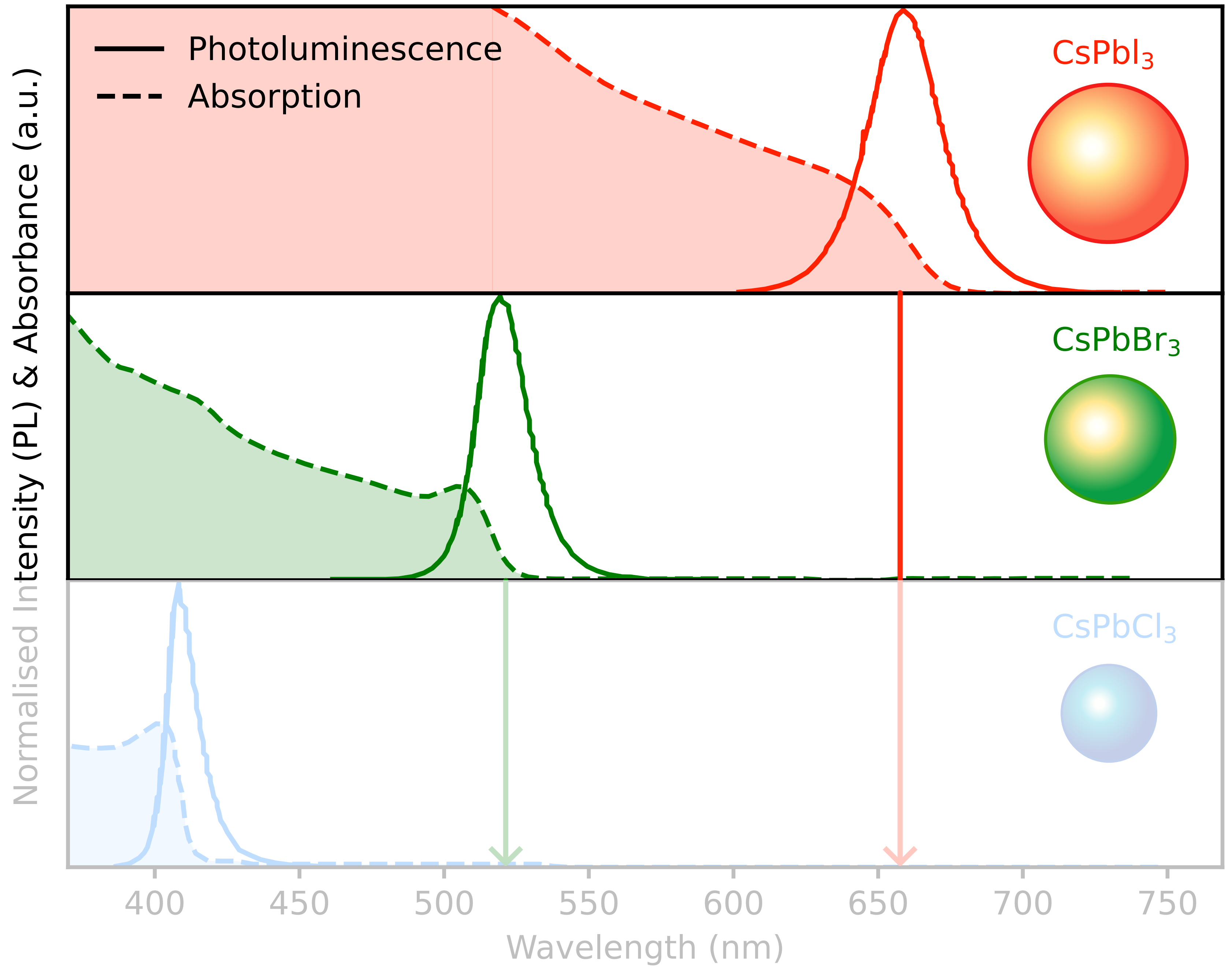
HOW DOES A CCAL WORK?

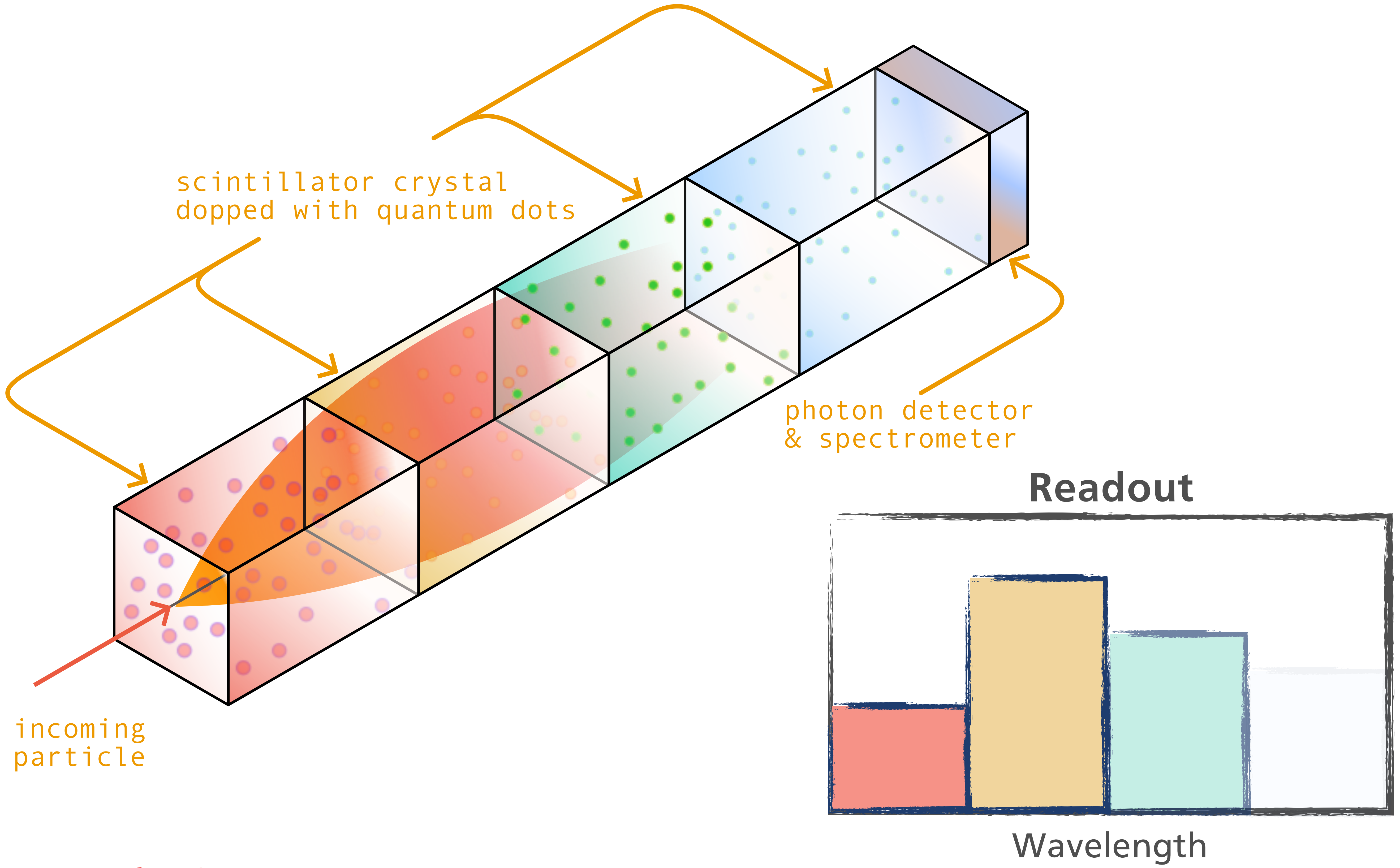




- **1st layer:** QDs absorb $\lambda \leq 650$ nm emit at 670 nm

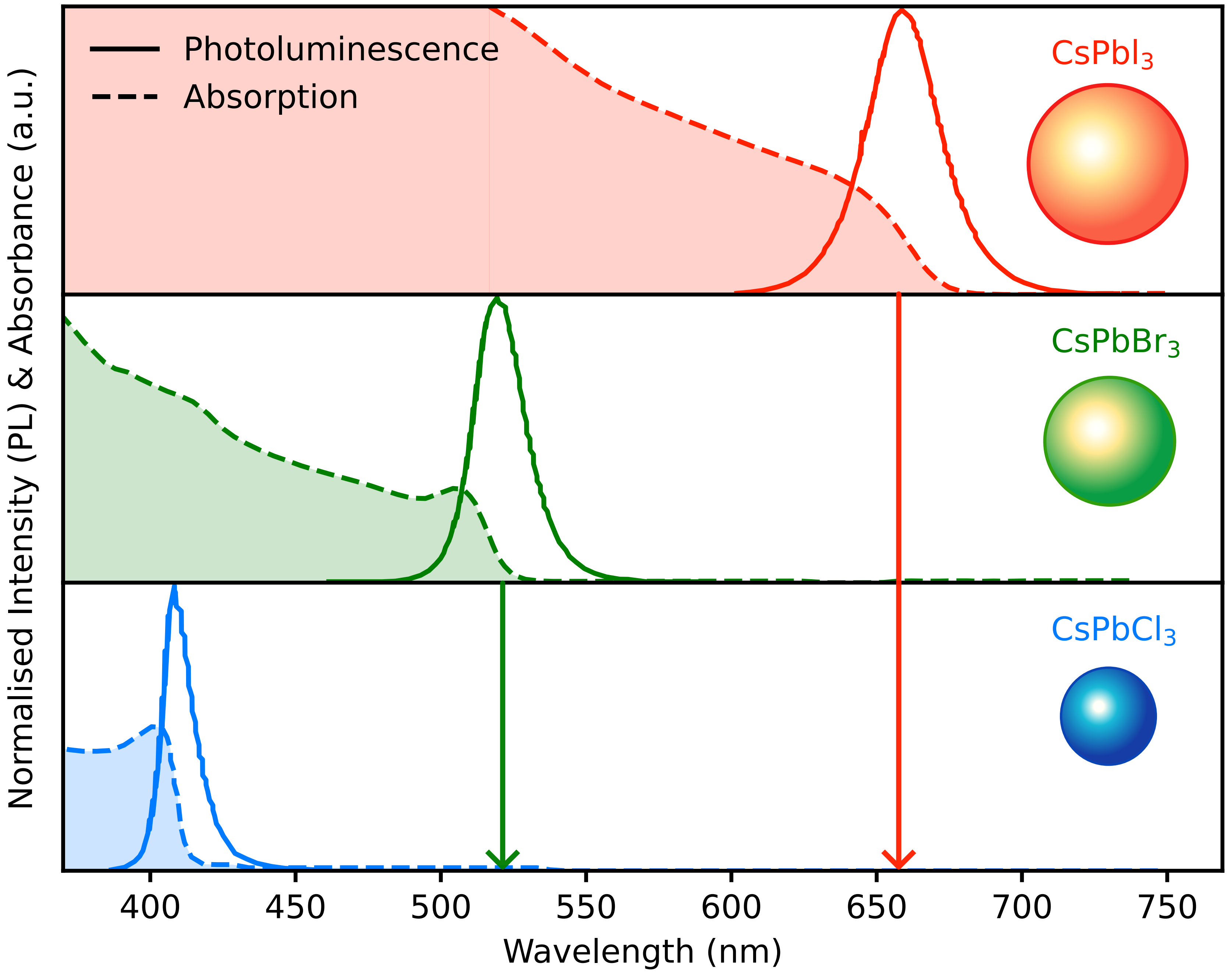
HOW DOES A CCAL WORK?

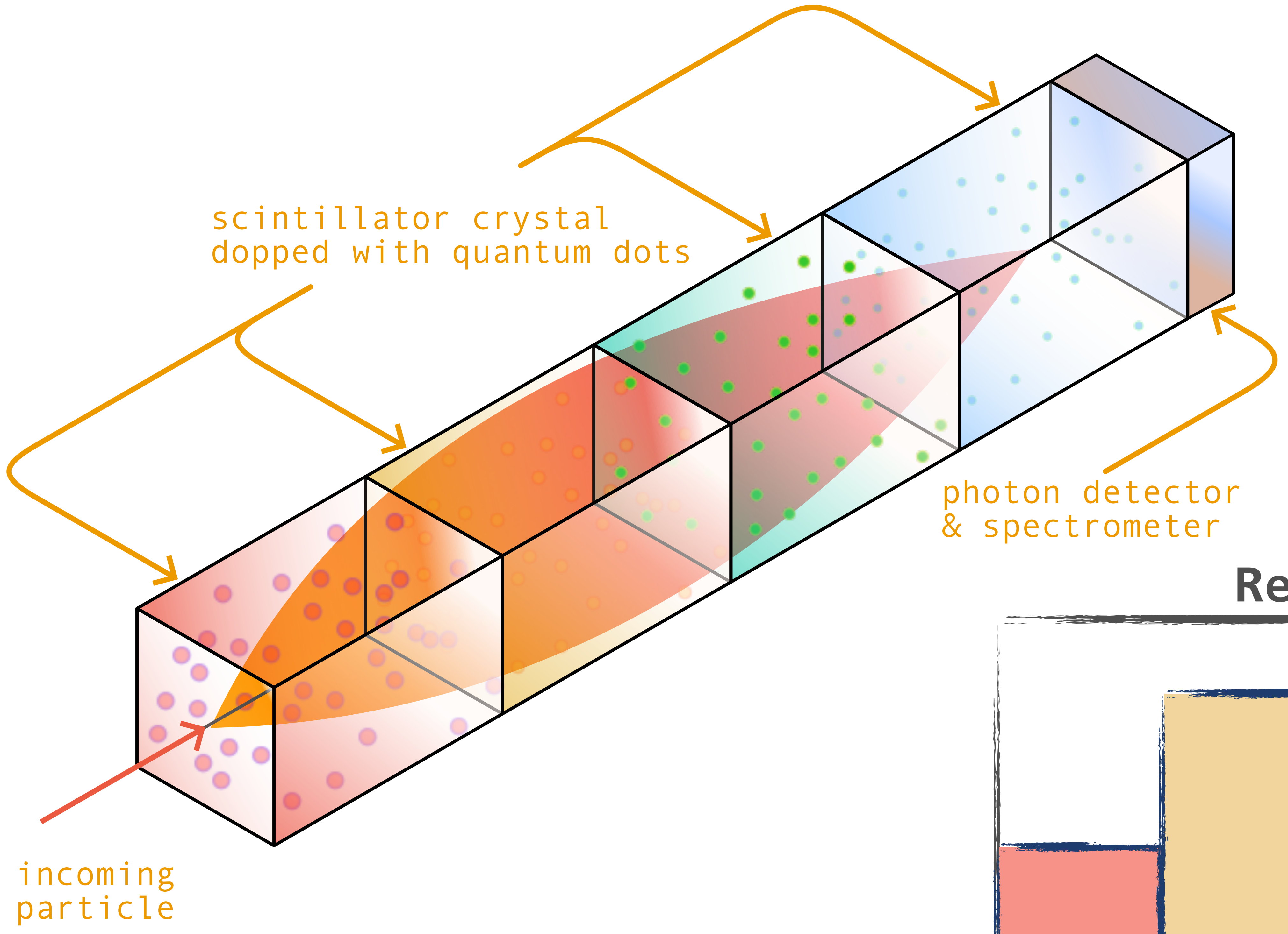


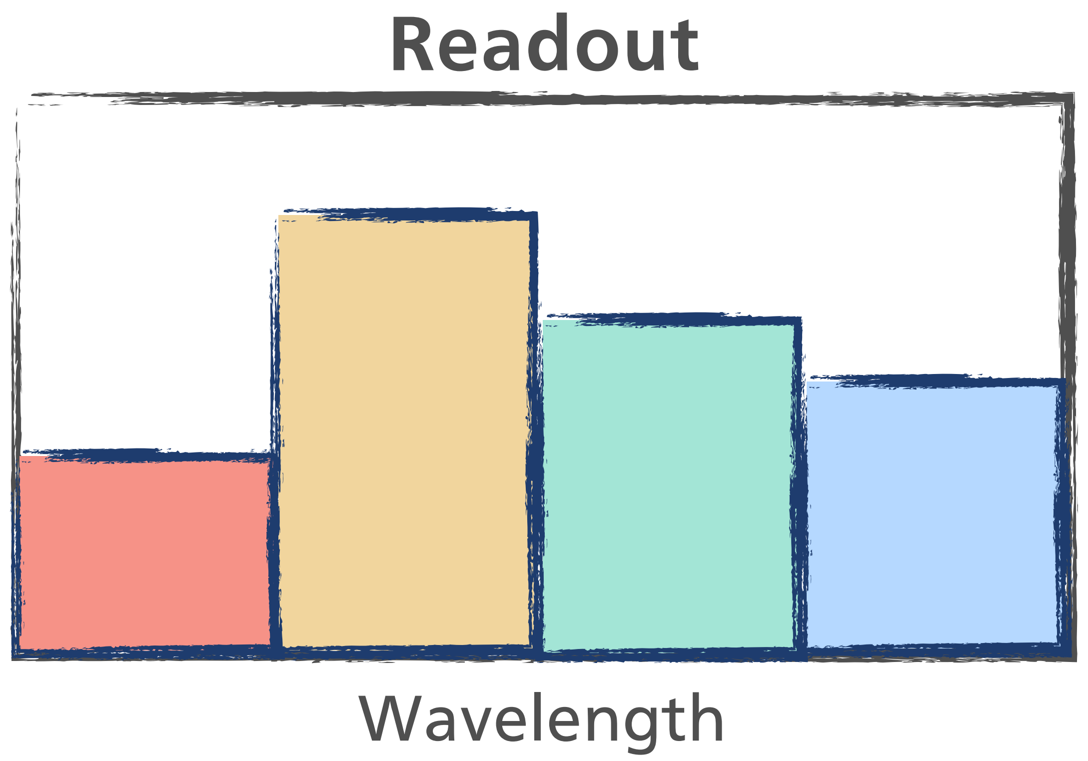


- **1st layer:** QDs absorb $\lambda \leq 650$ nm emit at 670 nm
- **2nd layer:** QDs absorb $\lambda \leq 529$ nm emit at 530 nm, 670 nm passes through

HOW DOES A CCAL WORK?





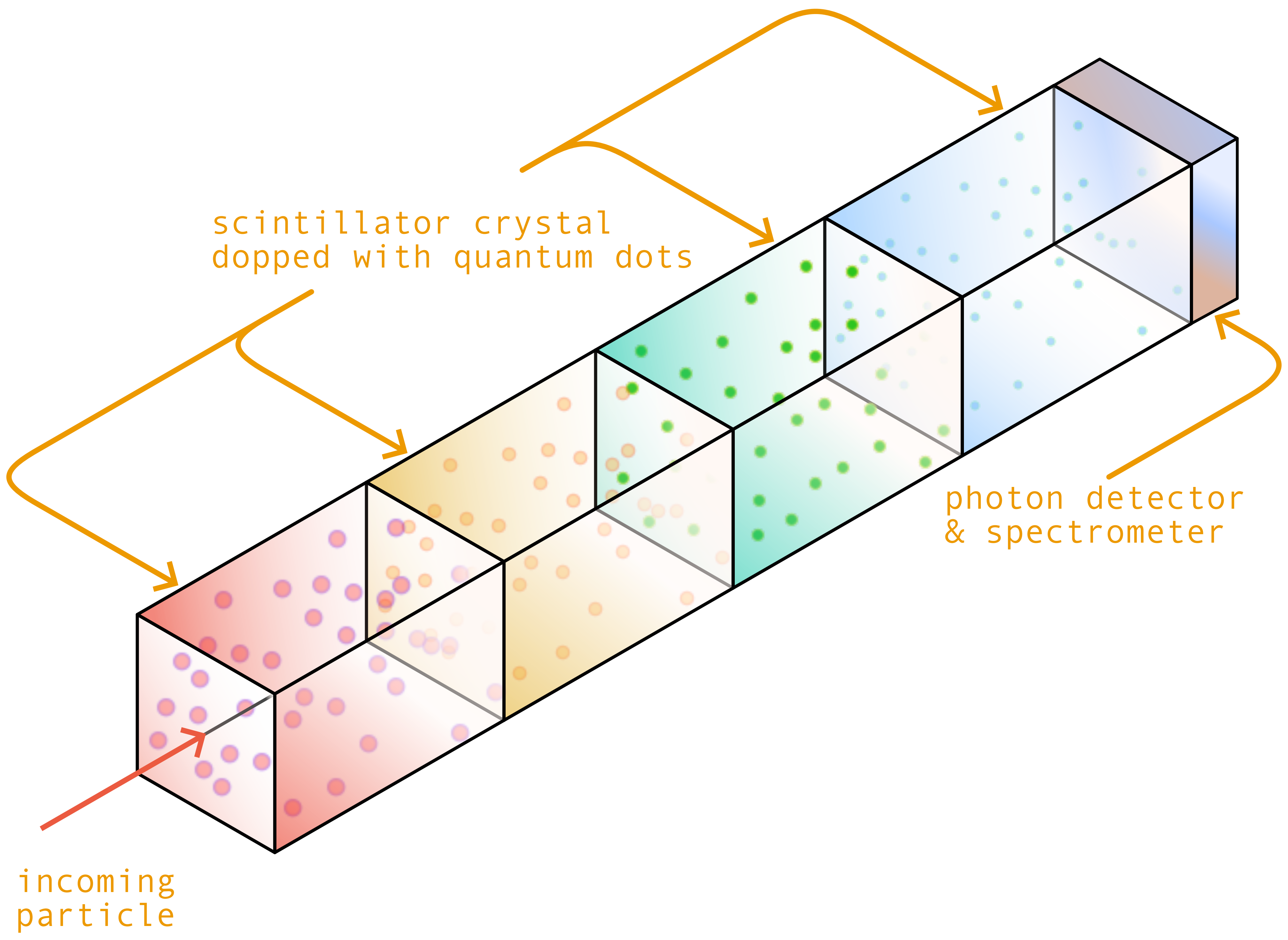


- **1st layer:** QDs absorb $\lambda \leq 650$ nm emit at 670 nm
- **2nd layer:** QDs absorb $\lambda \leq 529$ nm emit at 530 nm, 670 nm passes through
- **3rd layer:** QDs absorb $\lambda \leq 410$ nm emit at 420 nm, 670 nm and 530 nm pass through

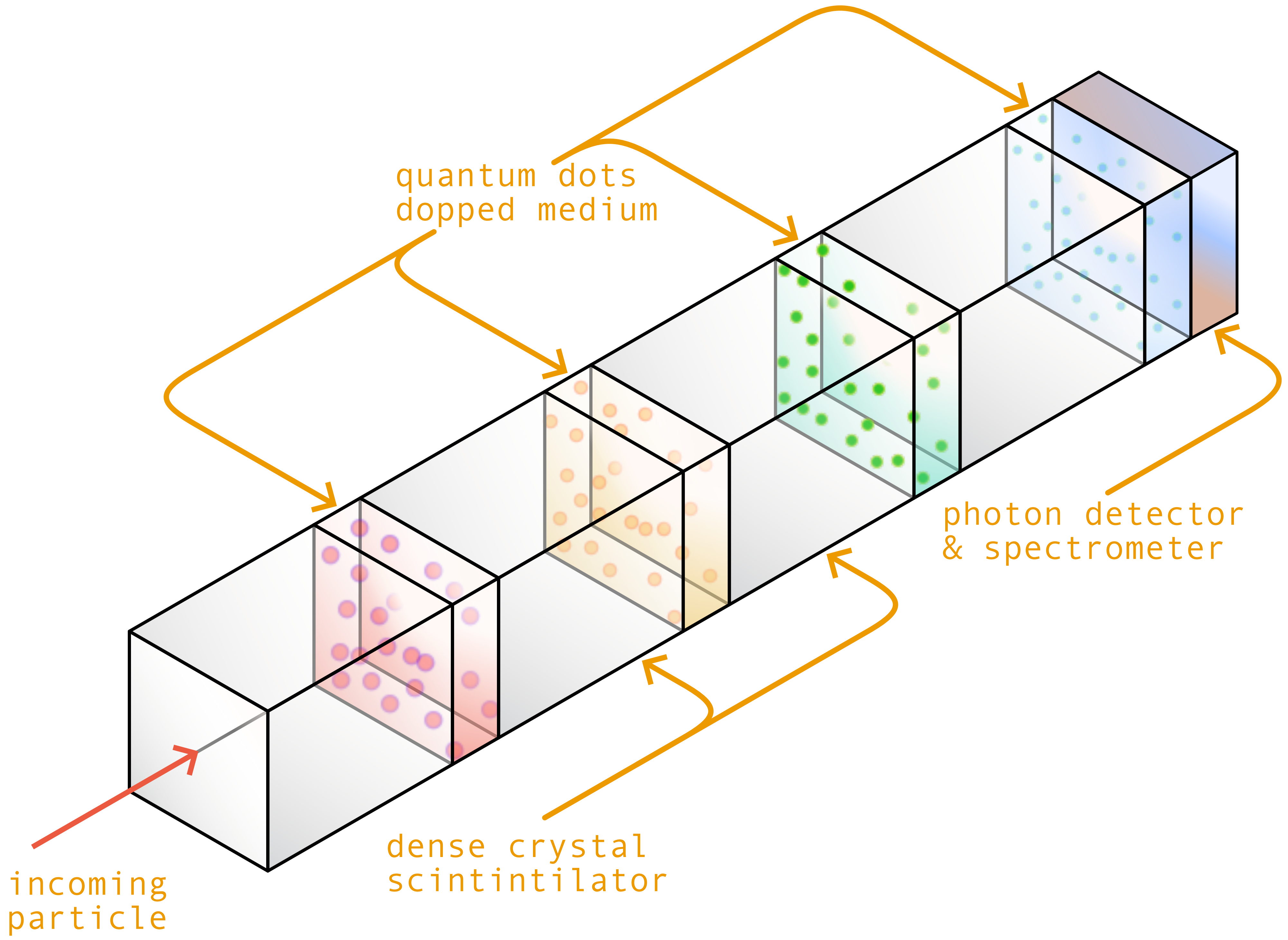
*** If high-Z substrate transparent in 400-700nm*

→ no re-absorption of emitted light

HOW TO BUILD A CCAL: TWO POSSIBILITIES



Option 1: Directly embedding QDs in high-Z crystals



Option 2: Hybrid approach polymer layers doped with QDs interleaved with crystals.

Key challenge: Balancing QD integration with material stability.

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

HOW TO BUILD A CCAL: READOUT

Ideally we want to **count photons to measure the energy** deposited in the calorimeter module **while measuring their wavelengths to reconstruct the longitudinal segmentation** of the shower.

Few Possibilities:

Metalenses

- Compact, nanostructured optical devices for precise light focusing. Requires further development for scalability in HEP

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

Pixel-Based Spectral Reconstruction

- RGB-based photodetectors, requires advanced algorithms to reconstruct spectrum from RGB measurements

Y.T. Lin & G. Finlayson, *Sensors* 2023, *23*(8), 4155

Bandpass Optical Filters with Photodetectors

- Photomultipliers (e.g SiPMs) coupled with bandpass optical filters
- Challenges: Angular acceptance and filter

SIMULATION FOR PROOF OF PRINCIPLE

Geant4 used to simulate hybrid CCAL single module

- Four PbWO4 blocks (6cm each) ~ 25 X_0
- Interleaved 2 mm PMMA layers doped with QDs.
- SiPM detectors with bandpass filters at the rear tuned to the QD emission peaks

Materials

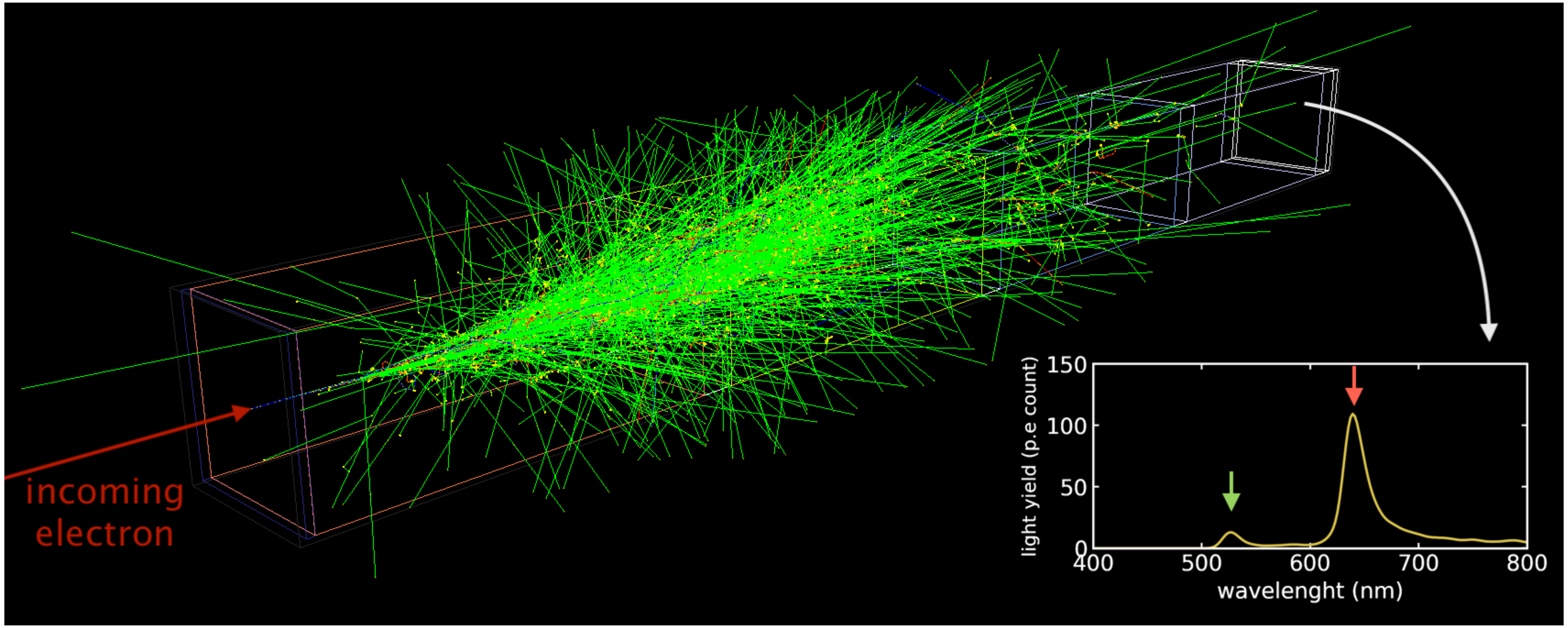
	ρ g/cm^3	X_0 cm	λ_I cm	$n^\dagger$	λ_{max} nm	Light Yield
PMMA	1.19	34.07	69.54	1.49	⋆	-
$PbWO_4$	8.30	0.89	20.7	2.20	425	200/MeV

QD and filters

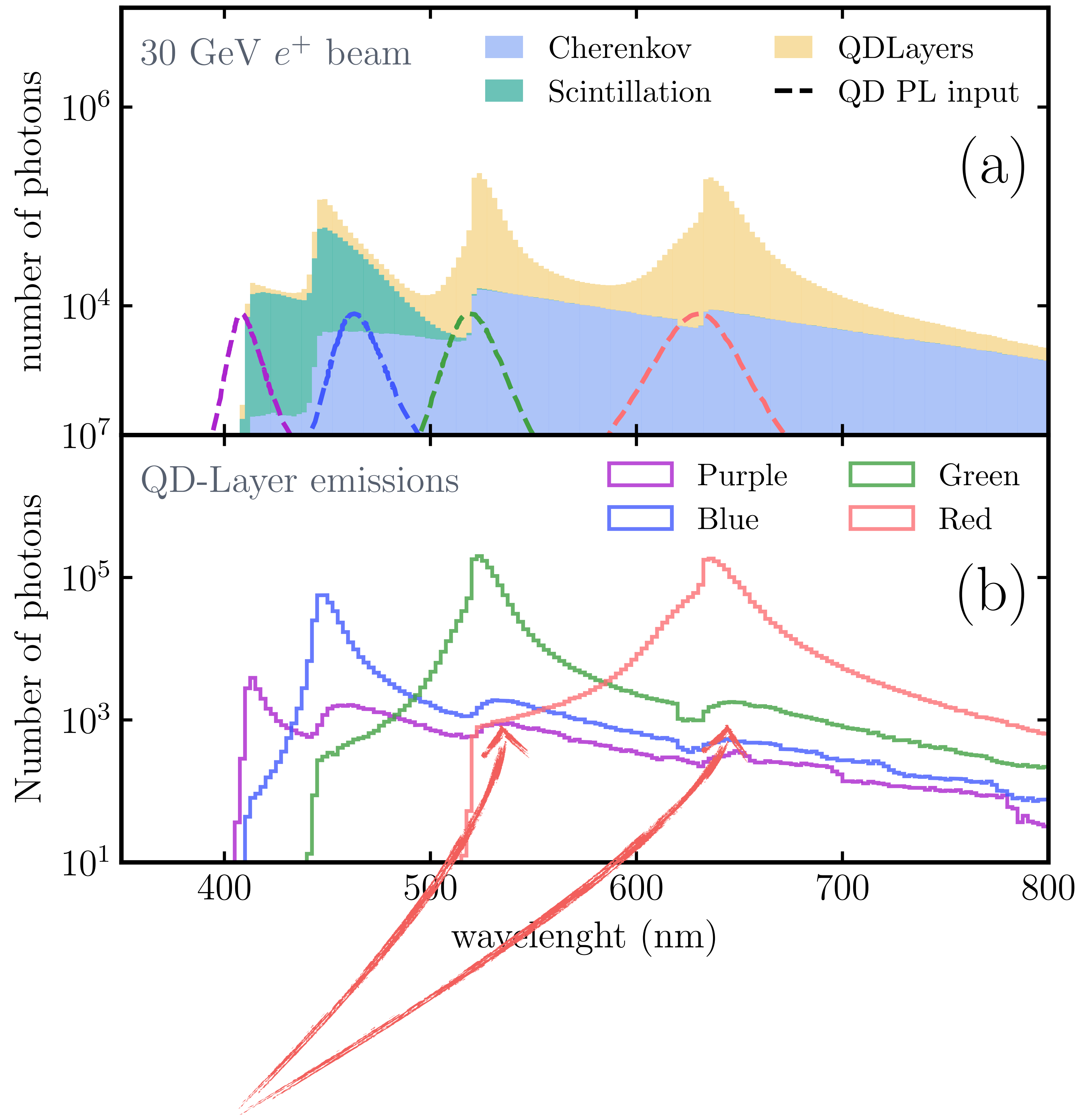
Label	λ^{QD}_{max} nm	Filter nm	PDE	σ_{abs}(400nm) 10^{-14} cm^2	ℓ_{abs}(400nm) cm
Red	630	630 ± 30	25%	31.69	0.03
Green	519	520 ± 30	42%	14.79	0.07
Blue	463	450 ± 30	51%	6.94	0.14
Purple	407	400 ± 30	47%	5.78	0.17

Simplified optical properties are assumed:

- **Neglecting detailed sub-keV interaction dynamics and surface effects**
- Tuning the absption based on the QD concetration in PMMA
- Absorption and re-emission spectra are approximated based on literature

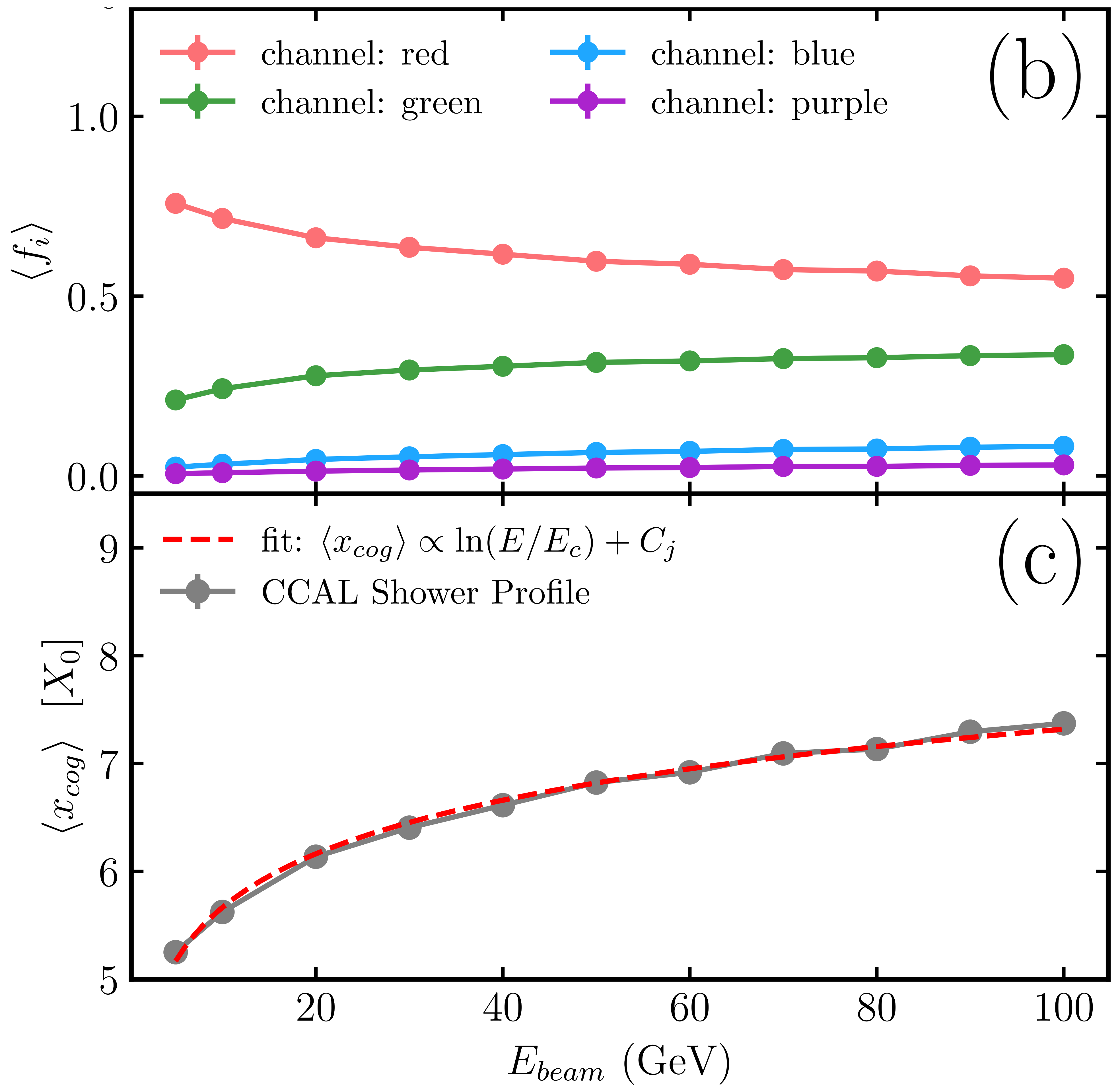


SIMUJLATION RESULTS: ENERGY RESPONSE



Echo photons: Backward propagating photons can get re-absorbed and re-emitted in the wavelength of the previous layers

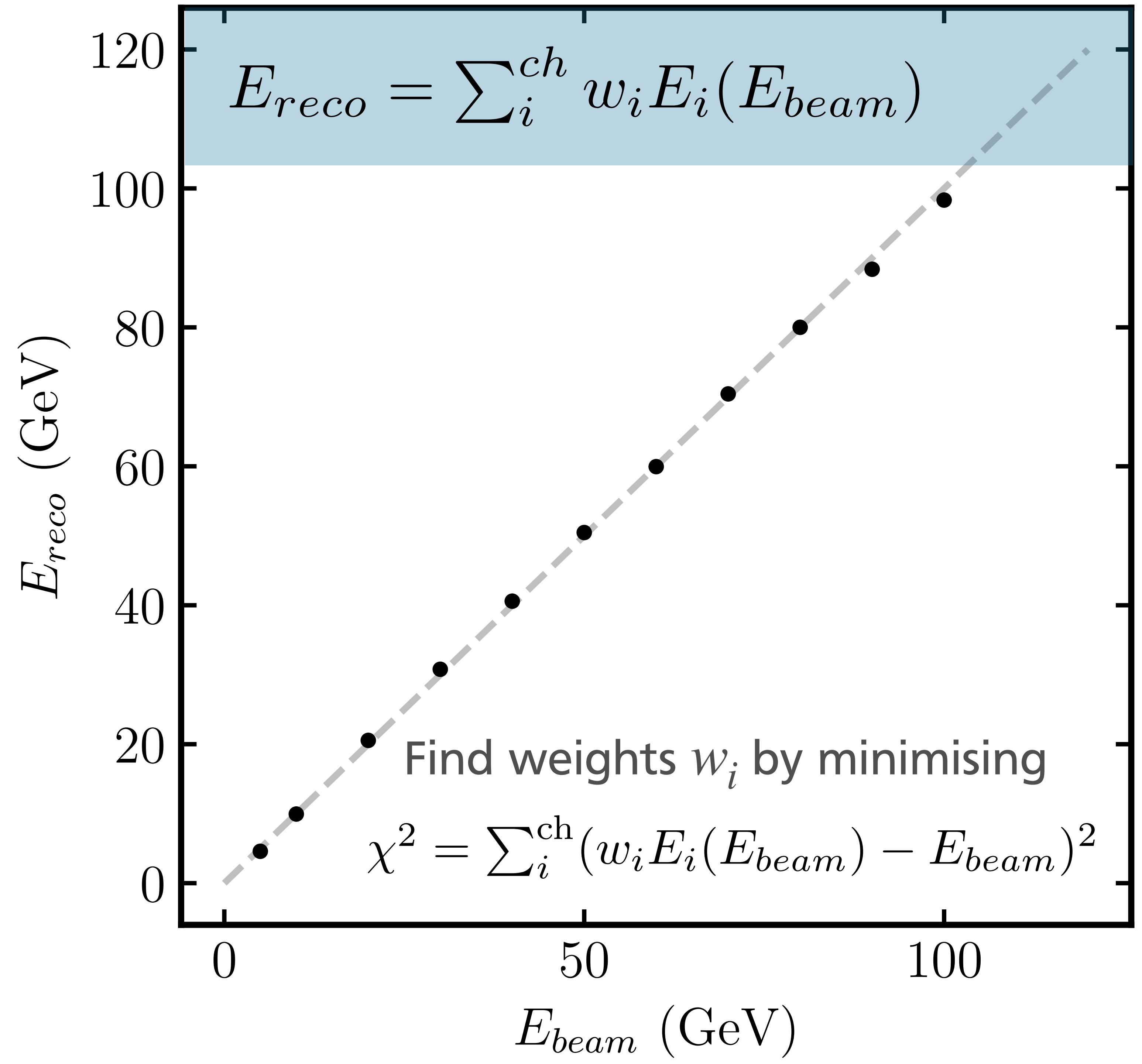
Fraction of energy as function of the electron energy

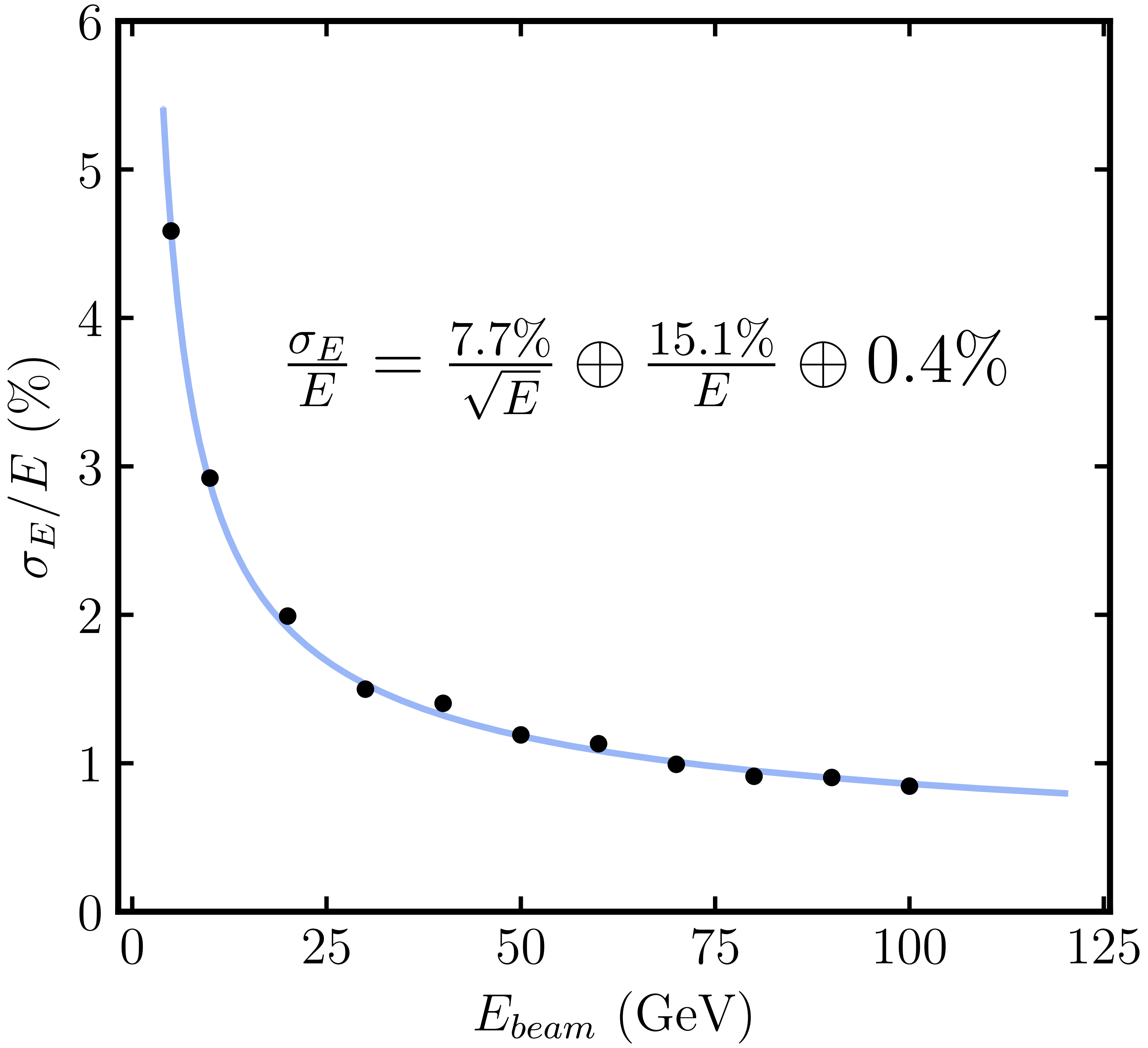


Logarithmic trend of the center of gravity as a function of the energy.

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

CHROMATIC CALORIMETRY: SIMULATION





Linear total energy response: weighted energy reconstruction achieves resolution comparable to current LHC-experiments benchmarks for single crystal modules

Advantage: Chromatic segmentation provides additional spatial information (e.g., center of gravity of the shower).

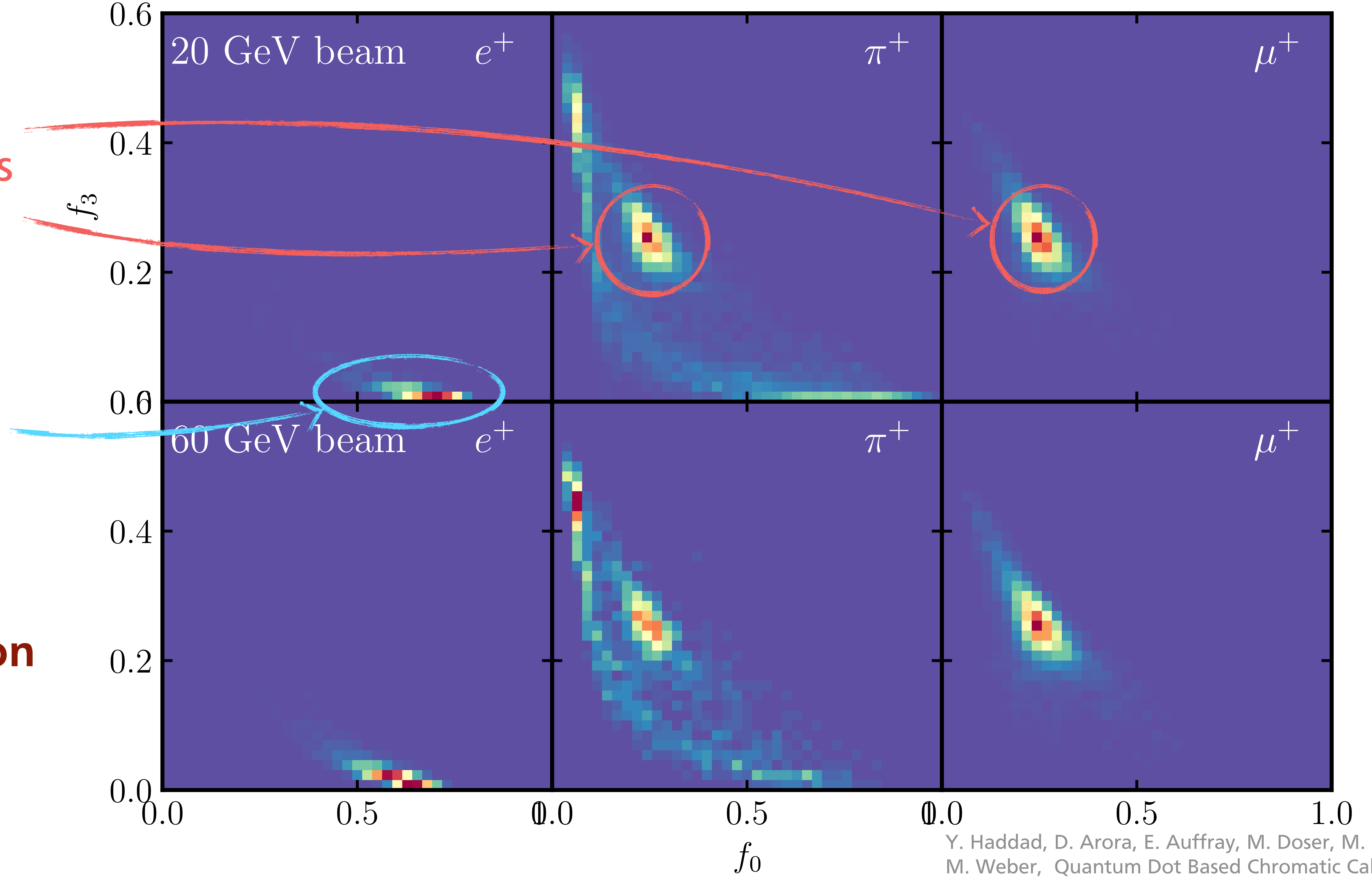
Y. Haddad, D. Arora, E. Auffray, M. Doser, M. Salomoni, M. Weber, Quantum Dot Based Chromatic Calorimetry: A proposal, arXiv:2501.12738

CHROMATIC CALORIMETRY: PARTICLE IDNETIFICATION

Minimum Ionising Particles

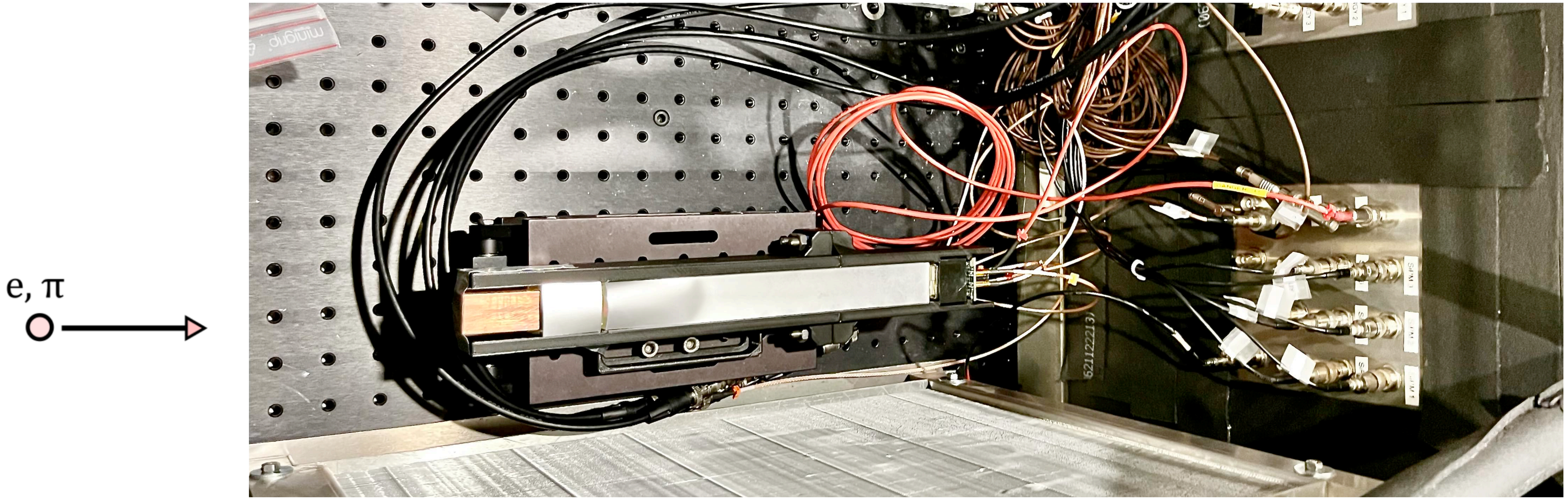
Electromagnetic Showers

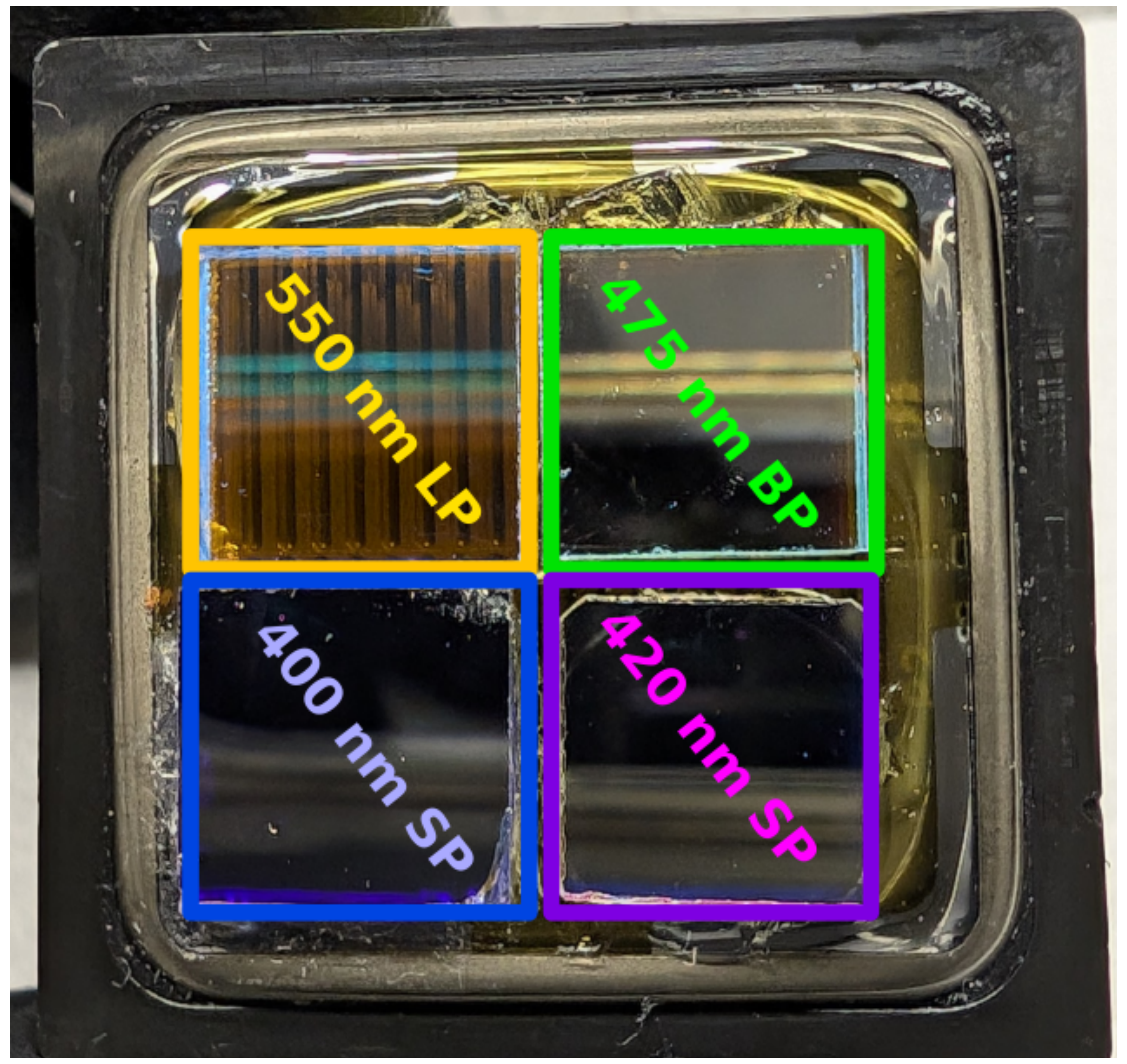
Depth information used for particle identification

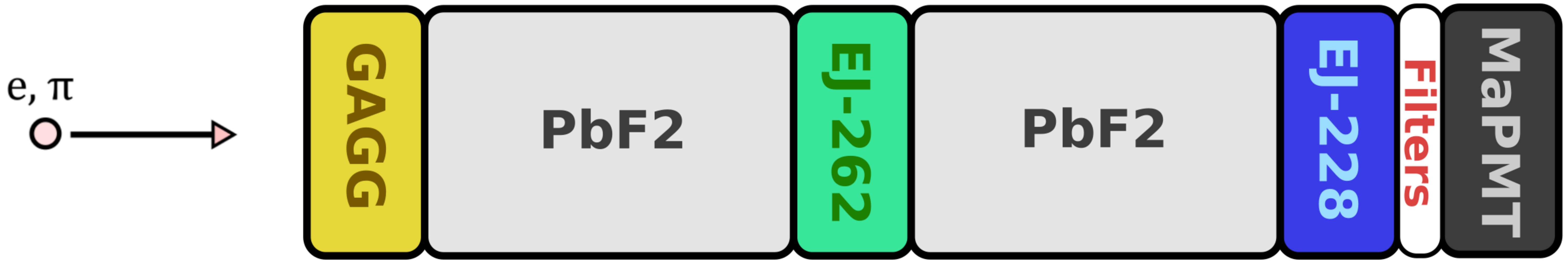


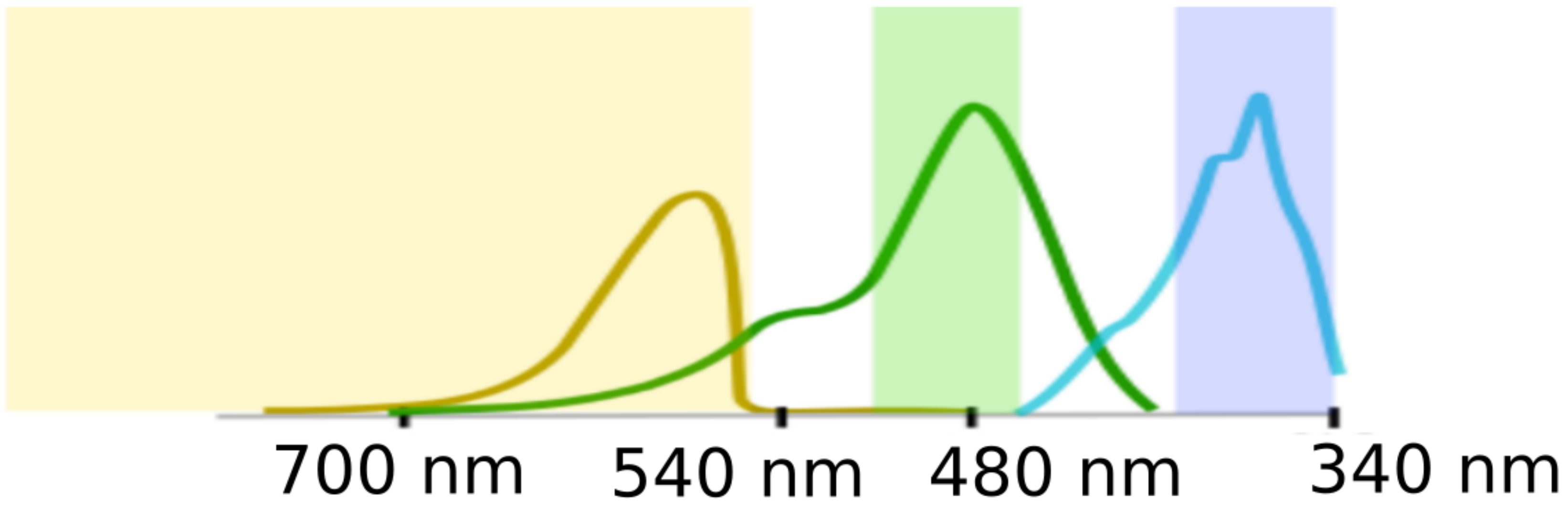
Y. Haddad, D. Arora, E. Auffray, M. Doser, M. Salomoni, M. Weber, Quantum Dot Based Chromatic Calorimetry: A proposal, arXiv:2501.12738

PROOF OF CONCEPT & BEAM TESTS (2024)









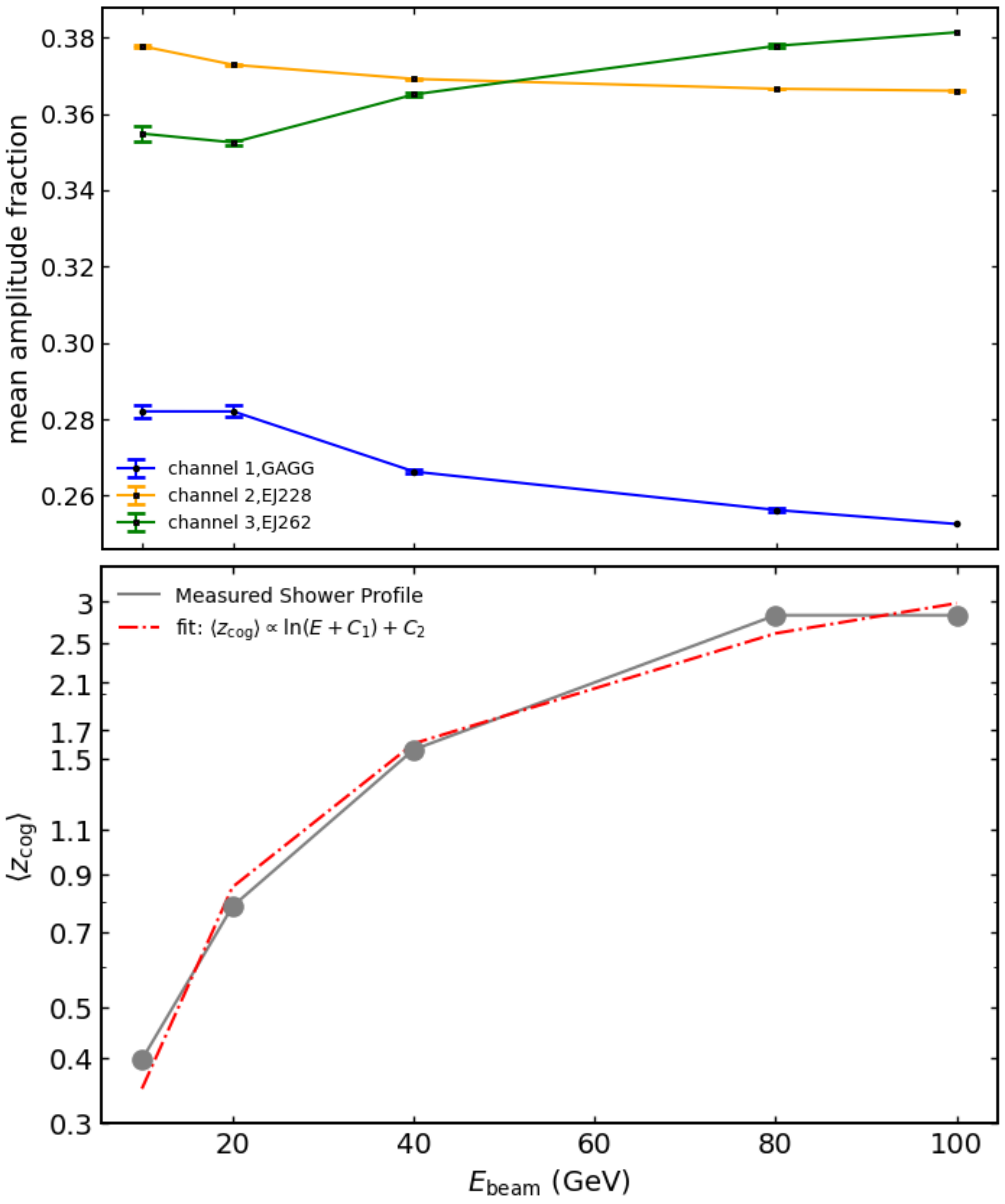
Materials: Standard inorganic and organic bulk scintillating materials with varying emission spectra were used. PbF_2 was selected as the dense light guide (25 X_0 and light propagation).

Readout: Dichroic filters were employed on the readout side to enable spectral separation.

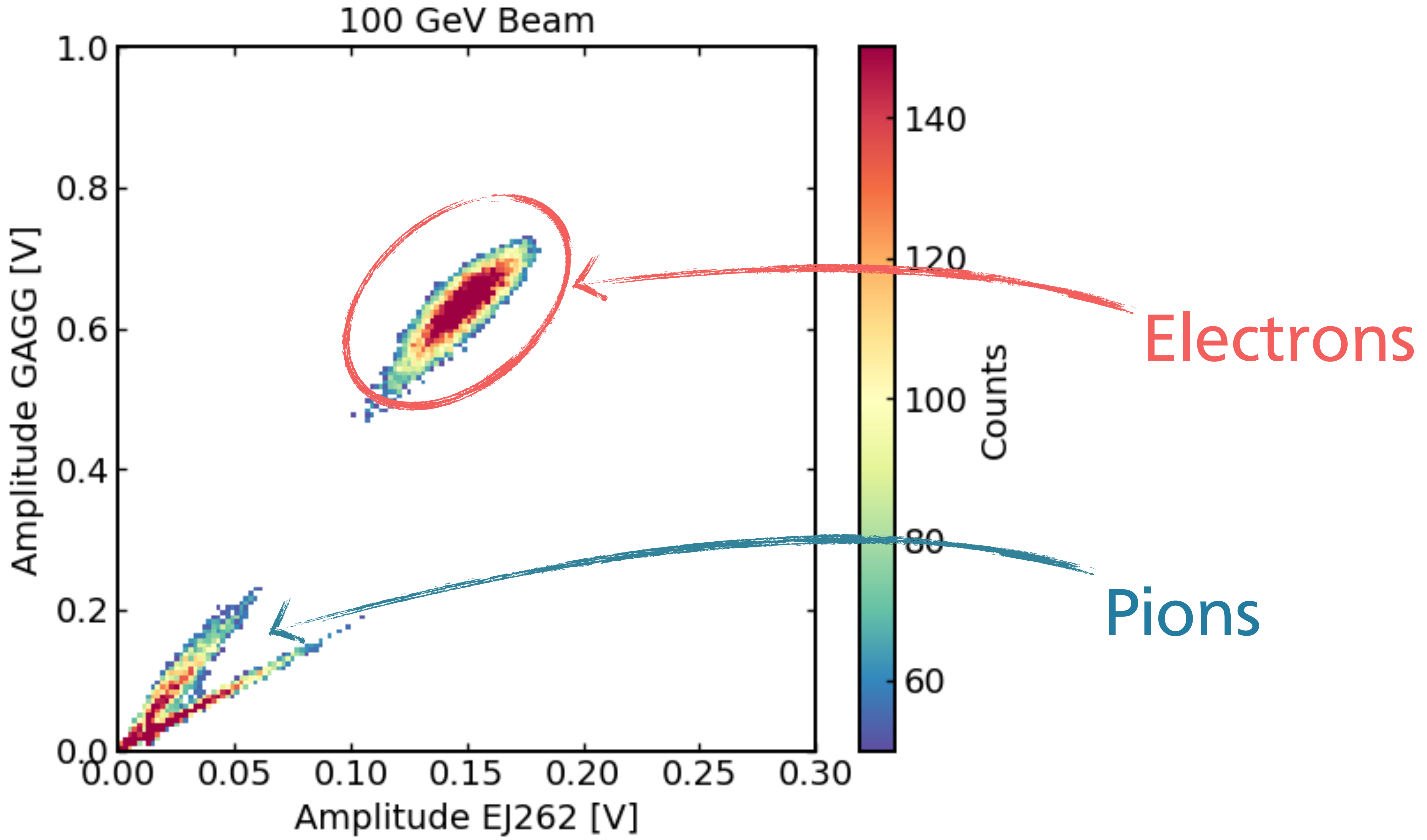
Progress in Chromatic Calorimetry Concept: Improved Techniques for Energy Resolution and Particle Discrimination, D. Arora, M Salomoni, Y Haddad, V Zabloudil, M Doser, et .al arXiv:2501.08483

PROOF OF CONCEPT & BEAM TESTS (2024)

Energy response and COG



Particle identification



Results: Longitudinal shower tomography. 100% separation between electrons and pions

Same results obtained for a $CsPbBr_3$ QD matrix used instead of EJ-262

Progress in Chromatic Calorimetry Concept: Improved Techniques for Energy Resolution and Particle Discrimination, D. Arora, M Salomoni, Y Haddad, V Zabloudil, M Doser, et .al arXiv:2501.08483

CONCLUSION

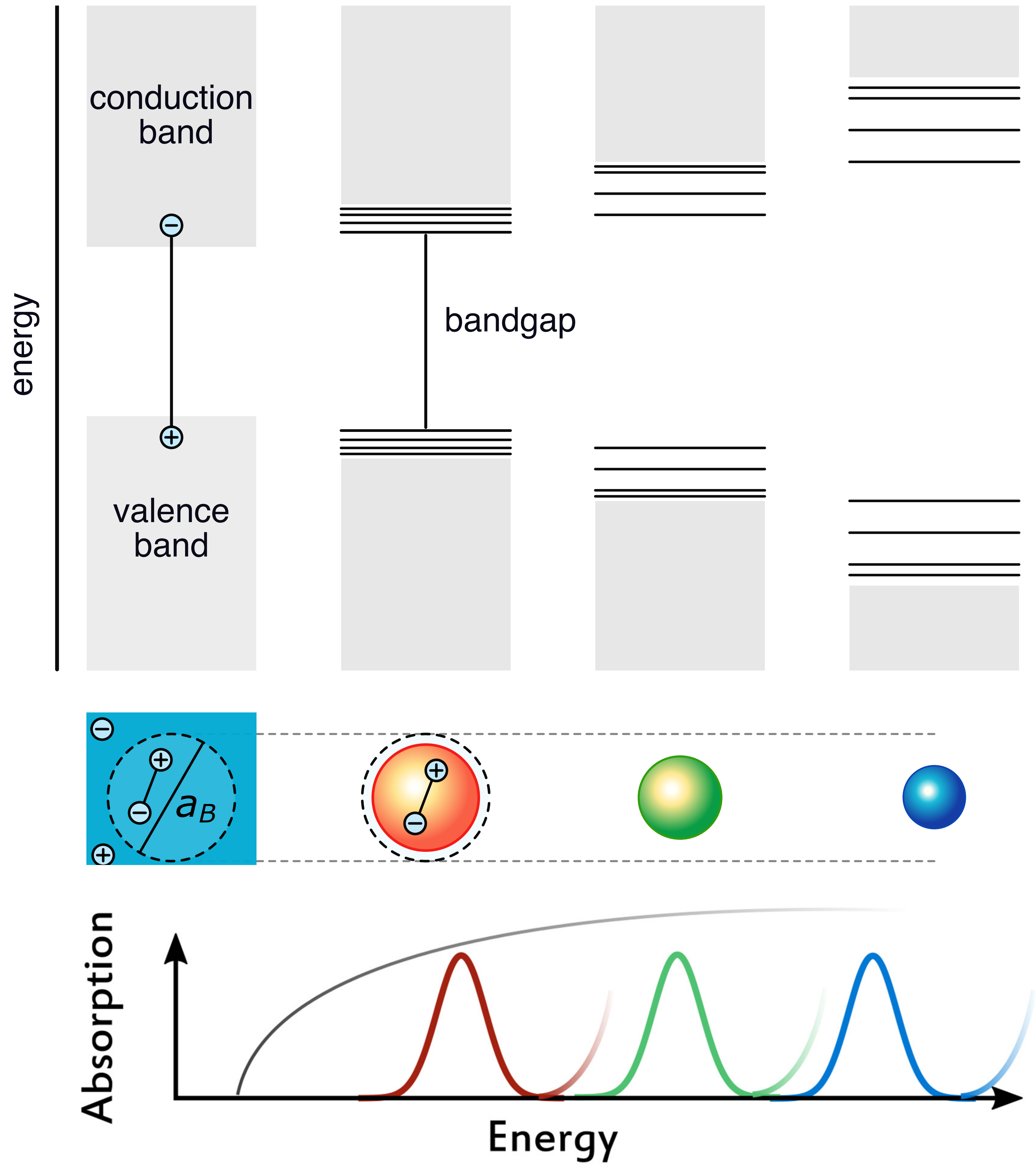
- **Quantum dots** with narrow-band emission and tunable properties provide a novel approach to calorimetry
- **Chromatic Calorimetry Achieves fine longitudinal tomography of particle showers,** enabling detailed shower profile and energy reconstruction.
- **Proof-of-principle simulations using Geant4** demonstrate that CCAL achieves linear energy response and energy resolution comparable to benchmarks like CMS ECAL, with added advantages of depth segmentation.
- **Proof of concept and beam tests at CERN:** Early results show effective spectral separation, demonstrating potential for electron-pion discrimination and shower reconstruction.
- **Next steps:** Test QD-doped materials and absorptive filters; explore time-of-arrival and pulse-shape information for further optimization. Obtain Eres vs E, comparative measurements.

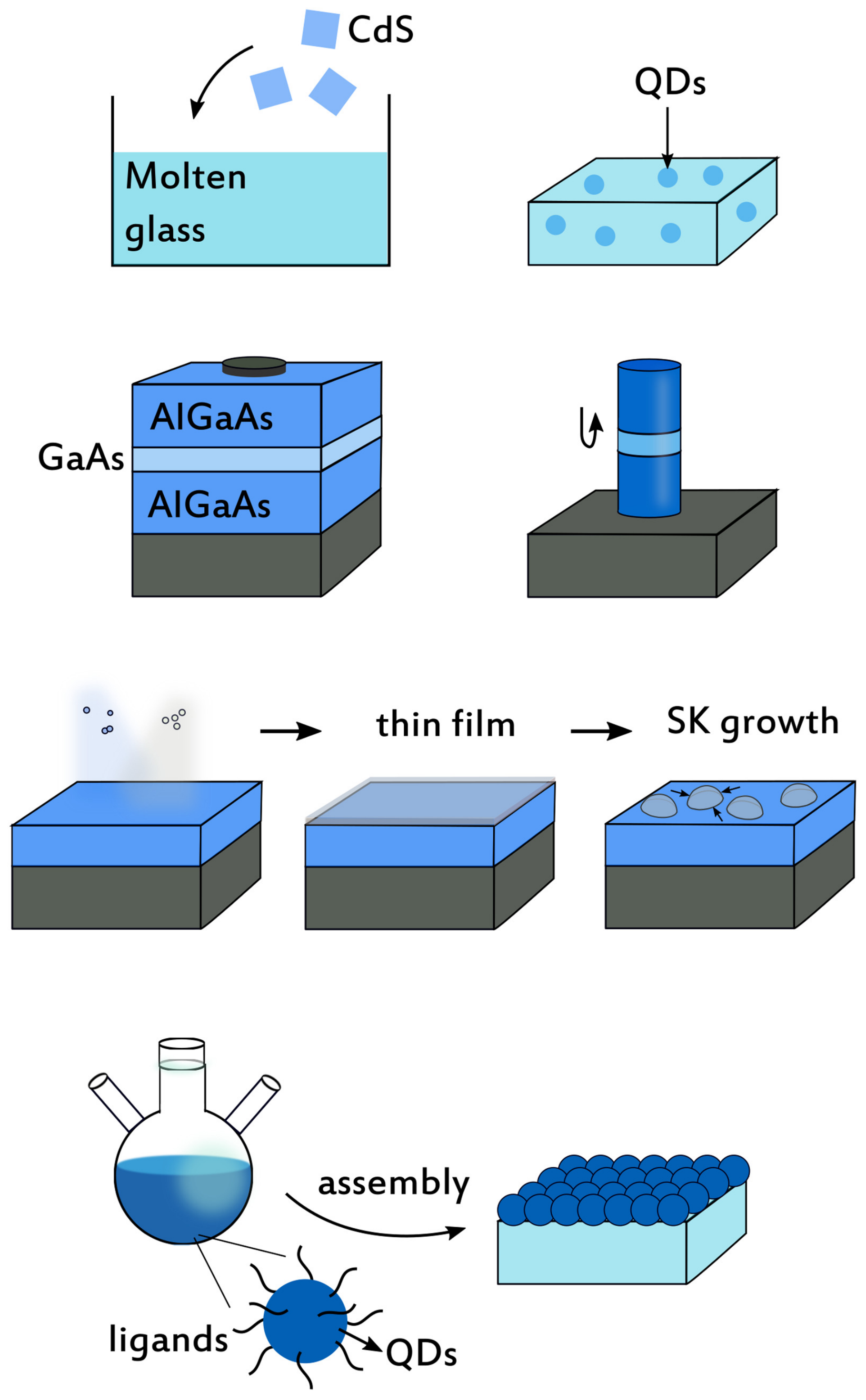
THANK YOU

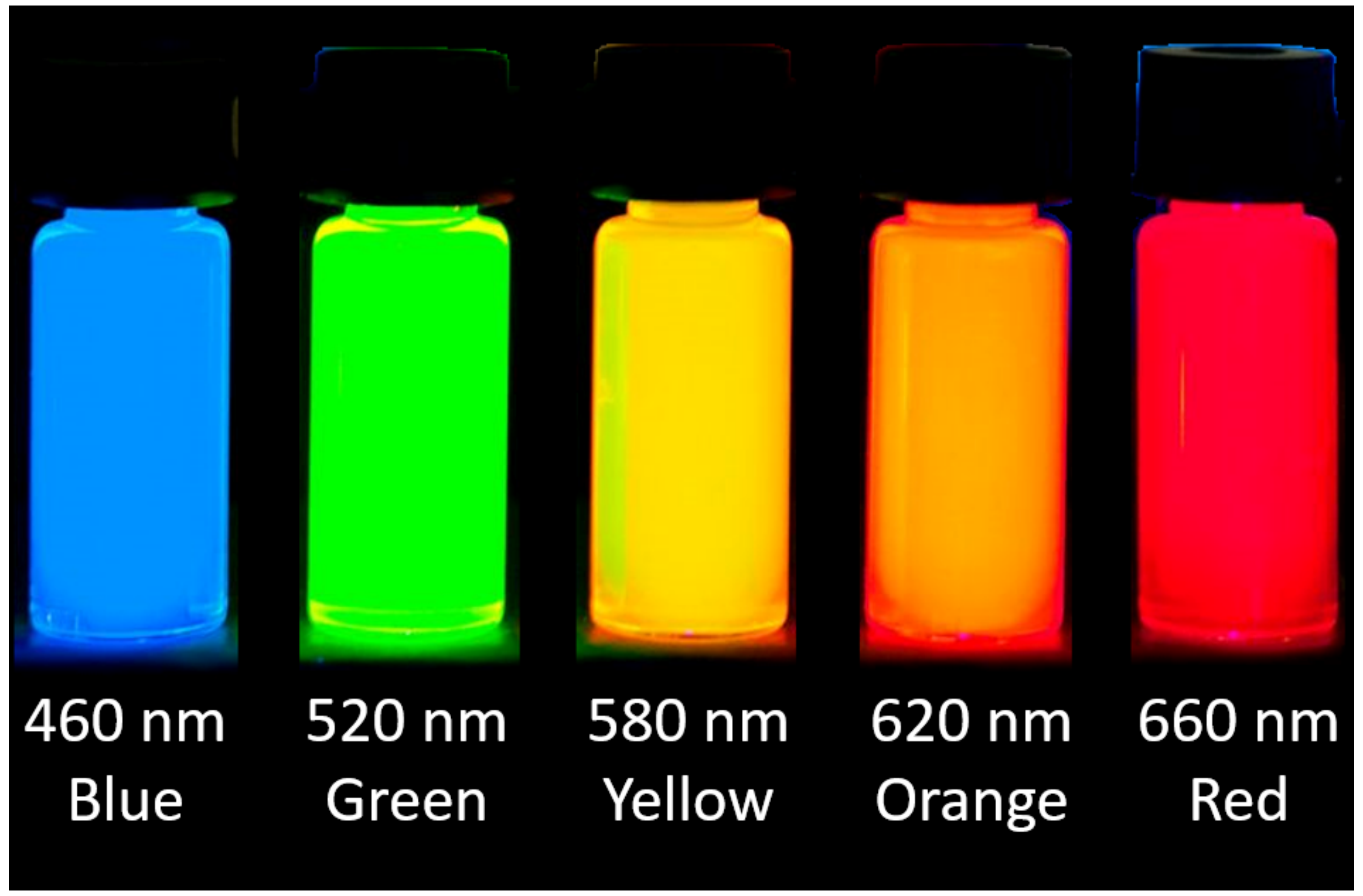
Many thanks to Crystal Clear Collaboration (RD18), Quantum Technology Initiative at CERN, and the ECFA DRD5 collaboration for their support in this research

CERN QUANTUM TECHNOLOGY INITIATIVE CRYSTAL CLEAR

QUANTUM CONFINEMENT AND QUANTUM DOTS





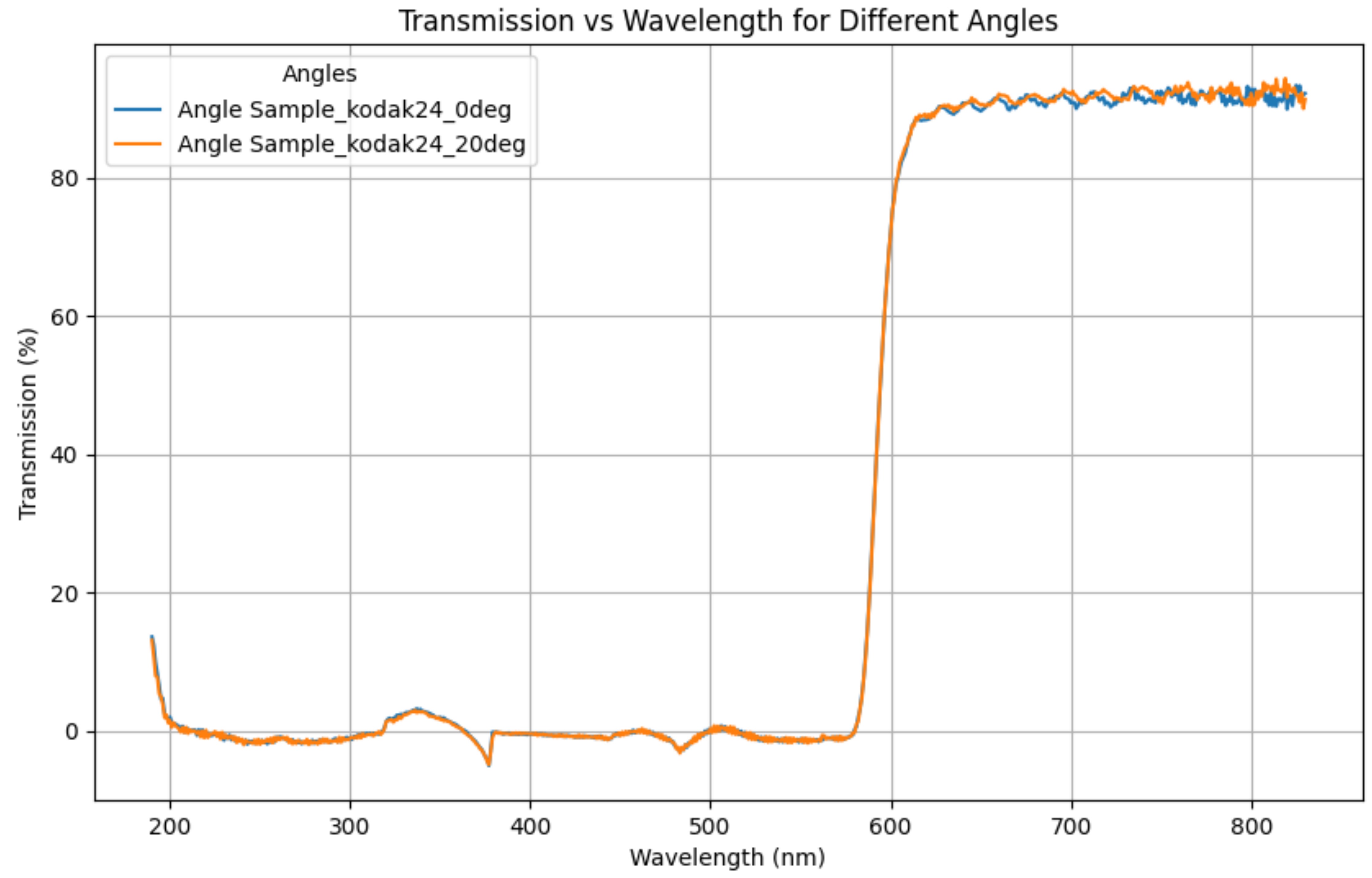


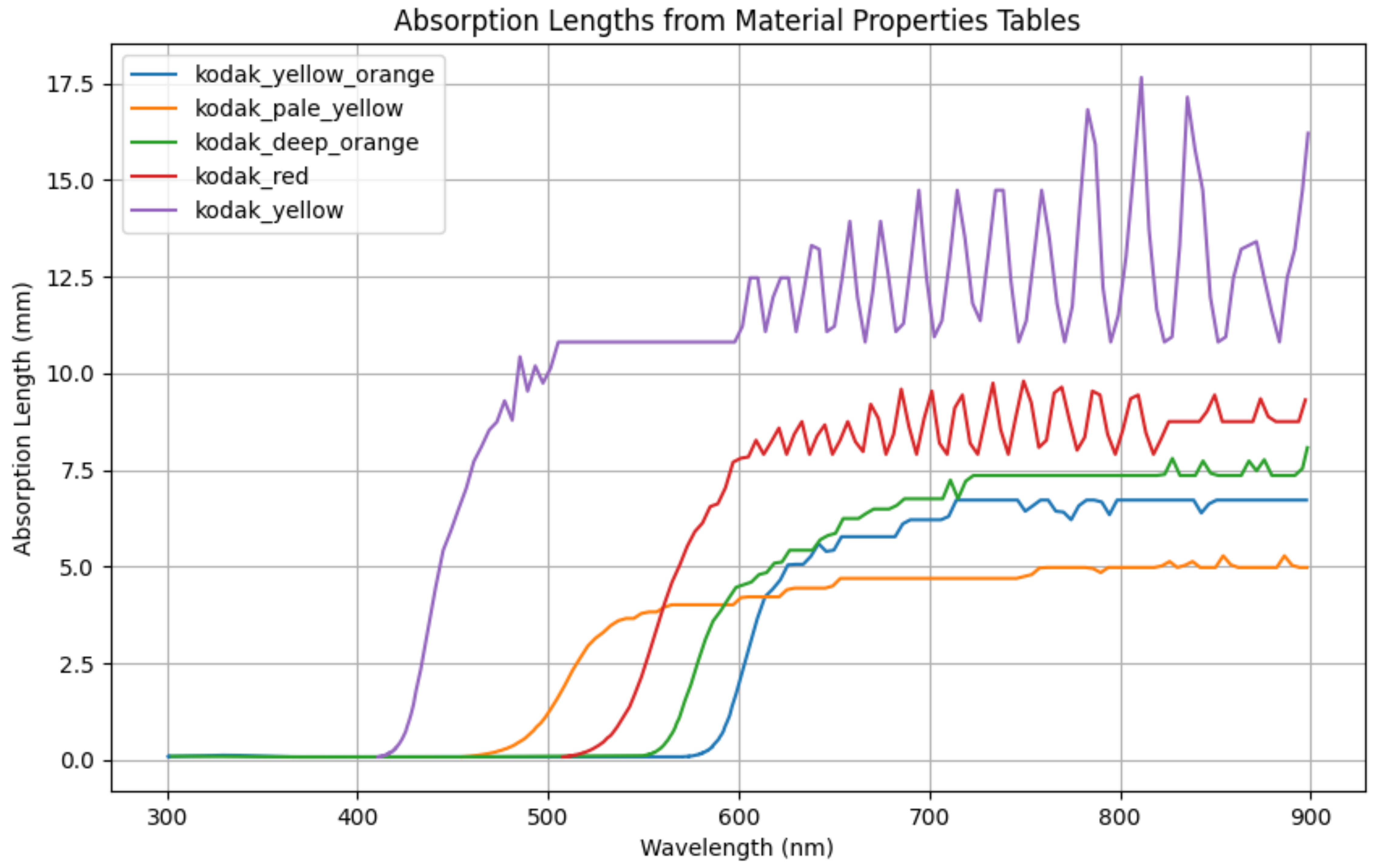
Quantum dots (QD) properties:

- Narrow-band emission (~20nm)
- Tunable emission
- Short rise/decay times
- Good light yield

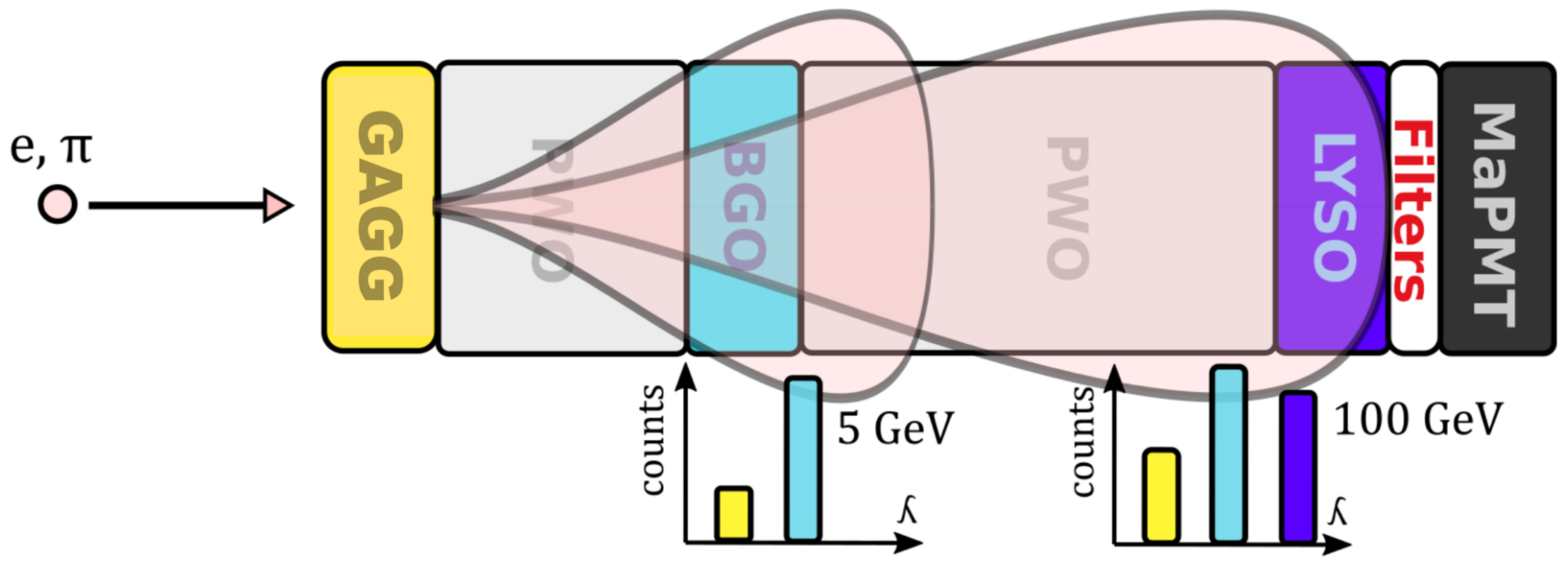
NEXT STEPS

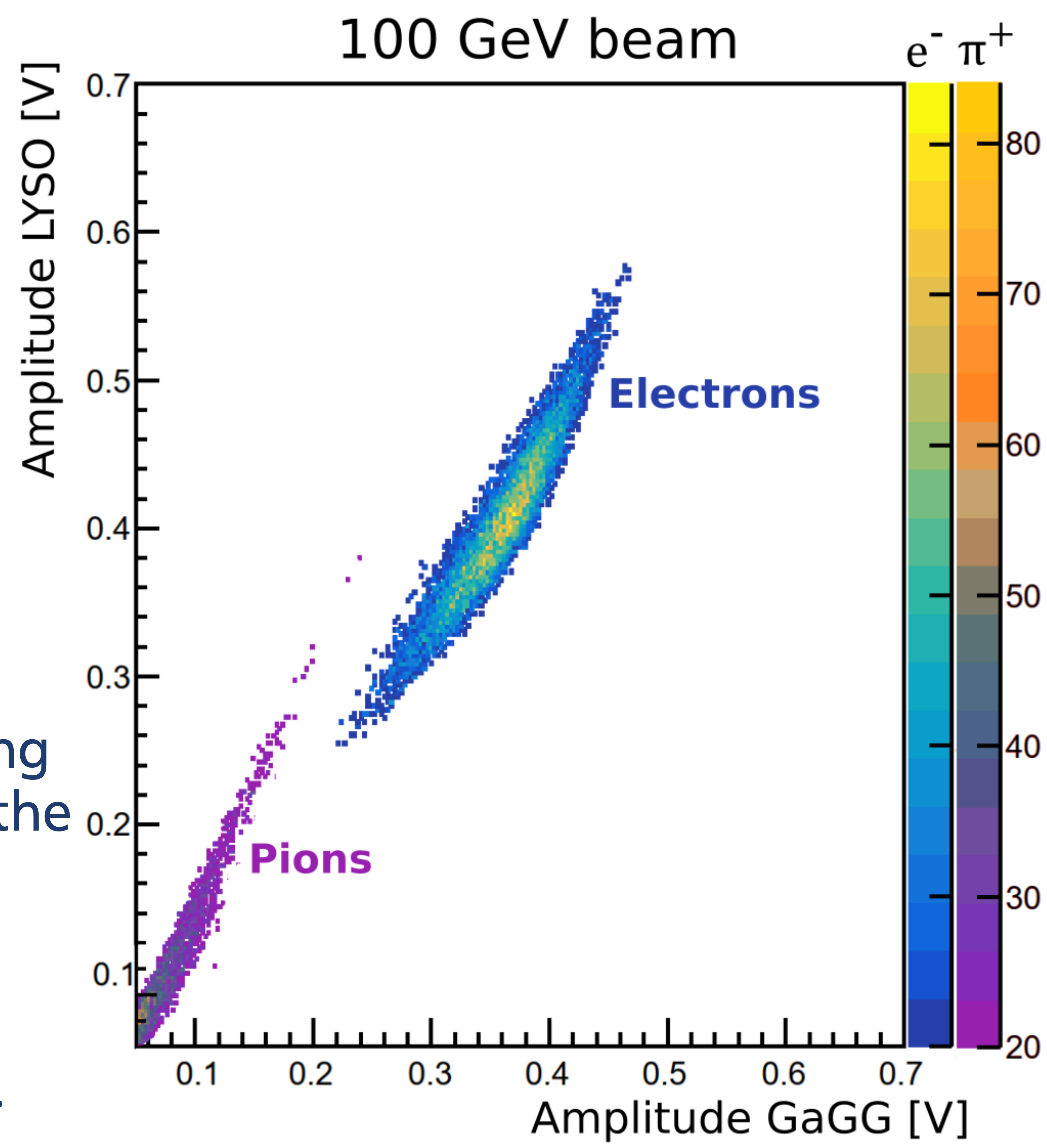
- **Filter Optimization:** Replace dichroic filters, which exhibit strong angular dependence, with absorptive filters in the next design iteration.
- **Material Testing:** Test quantum dot (QD) doped materials as a substitute for EJ-262, and implement a full stack using these new materials for improved performance.





CHROMATIC CALORIMETRY: 2023 BEAM TEST





Materials: Standard inorganic bulk scintillating materials with varying emission spectra were used. PWO (lead tungstate) was selected as the absorber.

Readout: Dichroic filters were employed on the readout side to enable spectral separation.

Results: Achieved a 90% separation between electrons and pions -> particle discrimination

Enhancing Energy Resolution and Particle Identification via Chromatic Calorimetry: A Concept Validation Study, D. Arora, M. Salomoni, Y. Haddad, et al, arXiv:2411.03685