4th Jennifer2 General Meeting
Pisa, 3-4 April 2025

Study of Innovative Organic Photosensors

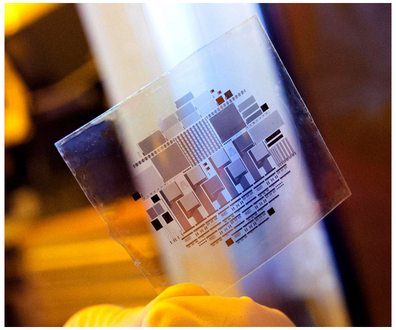
Marco Ruggieri
LASR3 (Rome) – INFN Roma 3

EU grant n.822070

Outline

- Introduction
    - Organic Electronics
    - Advantages (and problems)
    - Large-Area Fabrication
    - Organic Photodetectors
- Organic Photodetectors
    - Indirect Fully-Organic Phototransistor Detector
- Hybrid Scintillators with Quantum Dots
    - Quantum Dots
    - Hybrid OPD with embedded Perovskite QD Scintillator
    - QD-loaded Scintillators
    - Epoxy on PbS QD Photodetector
- Conclusions

Organic Electronics: Advantages

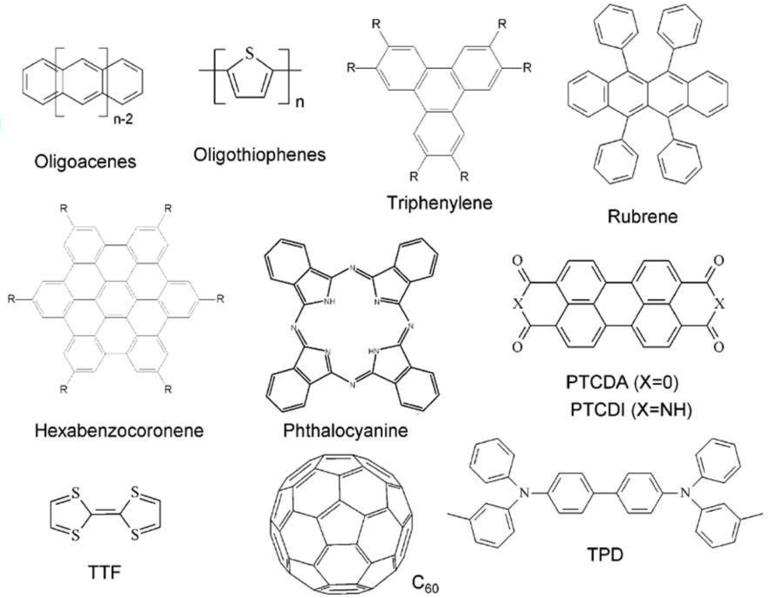


Organic Semiconductors (OSC)

Carbon-based molecules with semiconducting properties

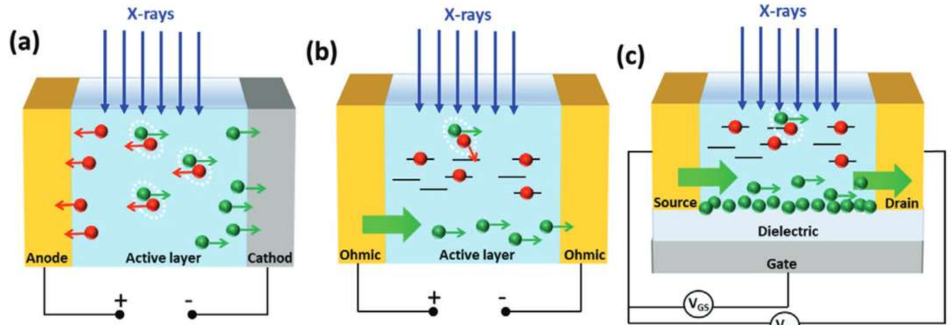
Organic Electronics

Design, Synthesis and Development of Devices/Systems based on OSC and Polymers



Several Advantages

- Low-cost production
- Large-area manufacturing
- Flexibility
- Material Tunability →Optimisation!



Basiricò, Laura, et al. Advanced Materials Technologies 6.1 (2021): 2000475.

Introduction

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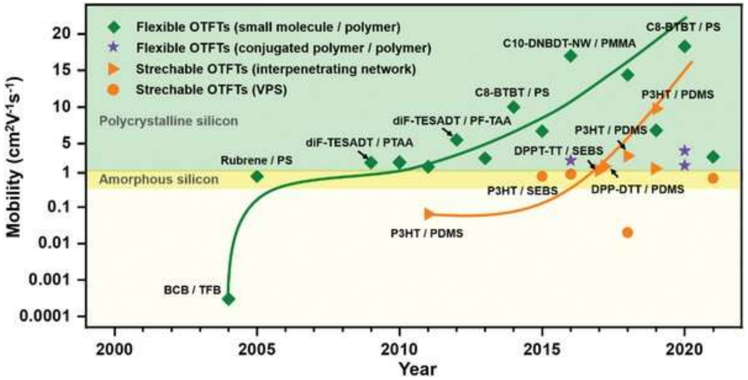
Organic Electronics- … and Problems

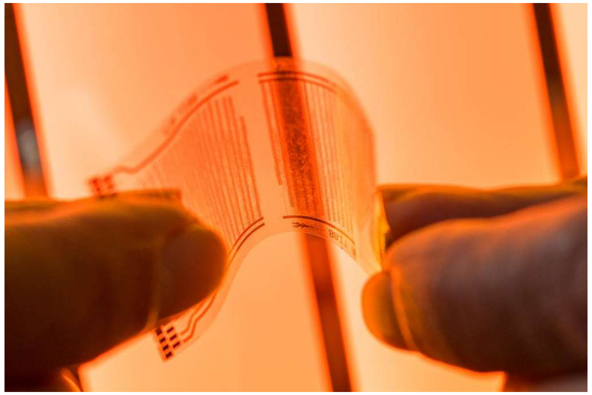
Low Carrier Mobility



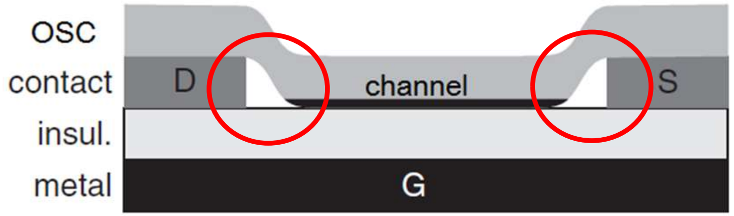
Yin, Xiaowen, Junliang Yang, and Haibo Wang,Advanced Functional Materials 32.27 (2022): 2202071.

Oxygen/Moisture

- Degradation of devices (mobility, traps, Vth etc…)
- O_2 and H_2O easily diffuse in multilayers



High Contact Resistance



Thermal Stability

- Polymers can melt or degrade at High Temperatures
- Thermal cycles can induce degradation or ion diffusion in OSC

Introduction

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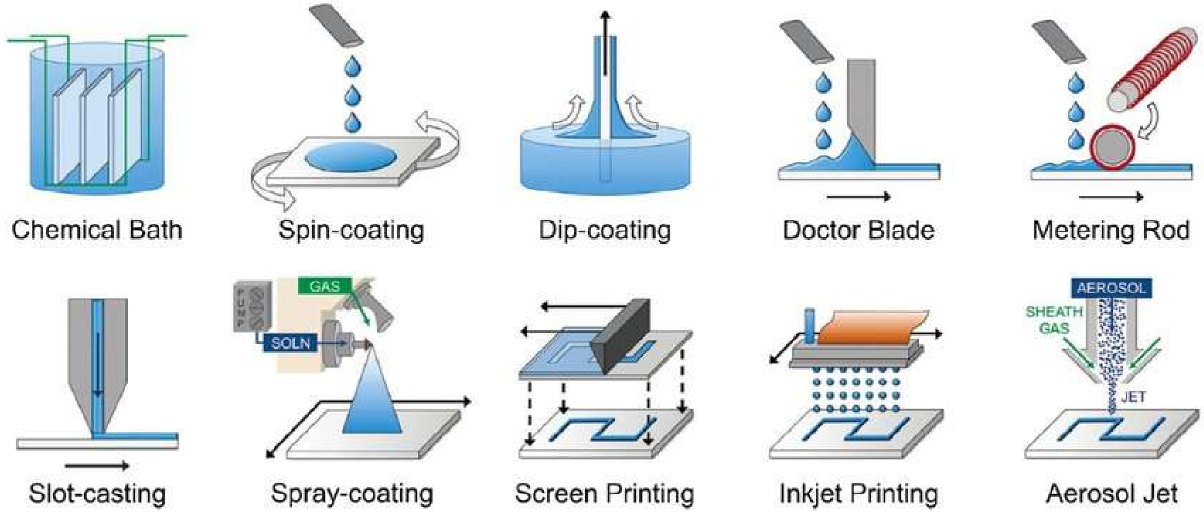
Large-Area Fabrication of Organic Electronics

Techniques for Solution-Processable Mat.



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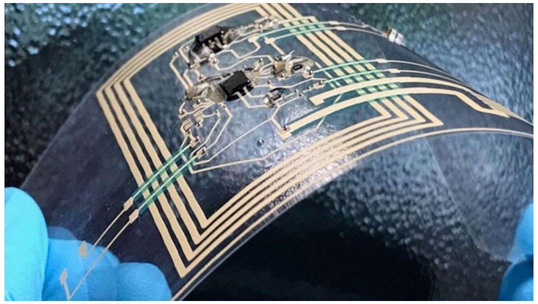
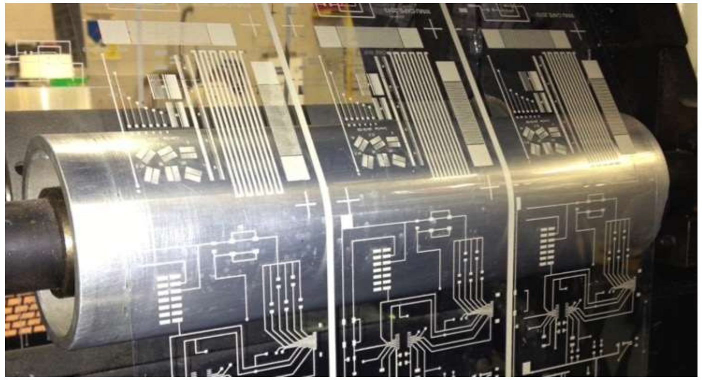
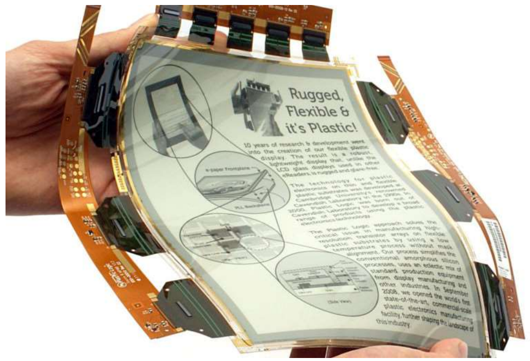


Electronics

Large-Area Fabrication





Introduction

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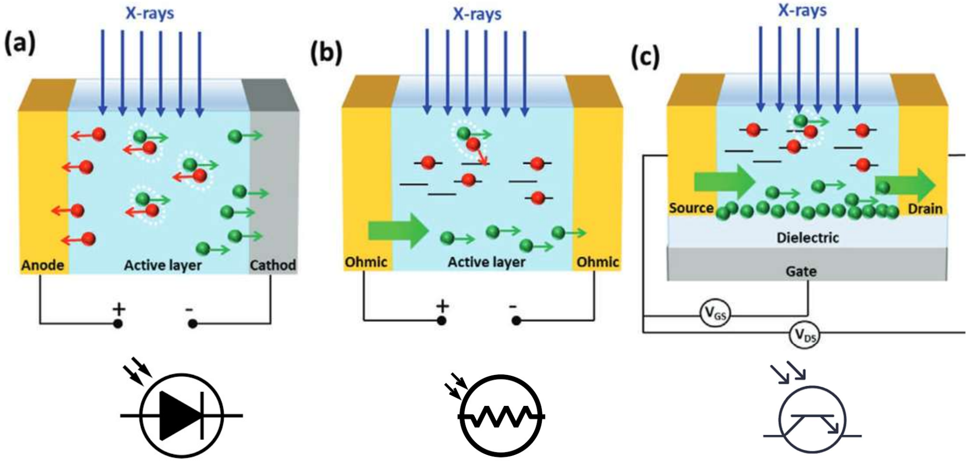
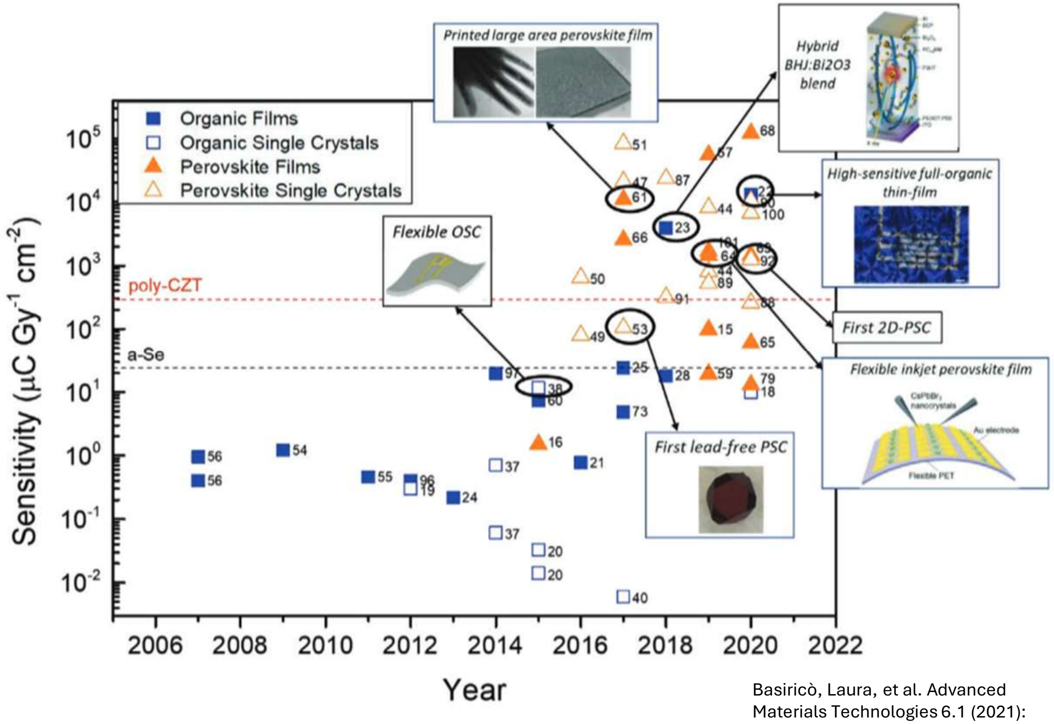
Organic Photodetectors



Advantages

- Organic → Tissue Equivalence
- Biocompatibility
- Flexibility
- High Sensitivity, low Limit of Detection



Basiricò, Laura, et al. Advanced Materials Technologies 6.1 (2021): 2000475.

However…

- Low-Z → Small X-ray absorption
- Radiation hardness
- Response speed

OPD *Organic PhotoDetectors*

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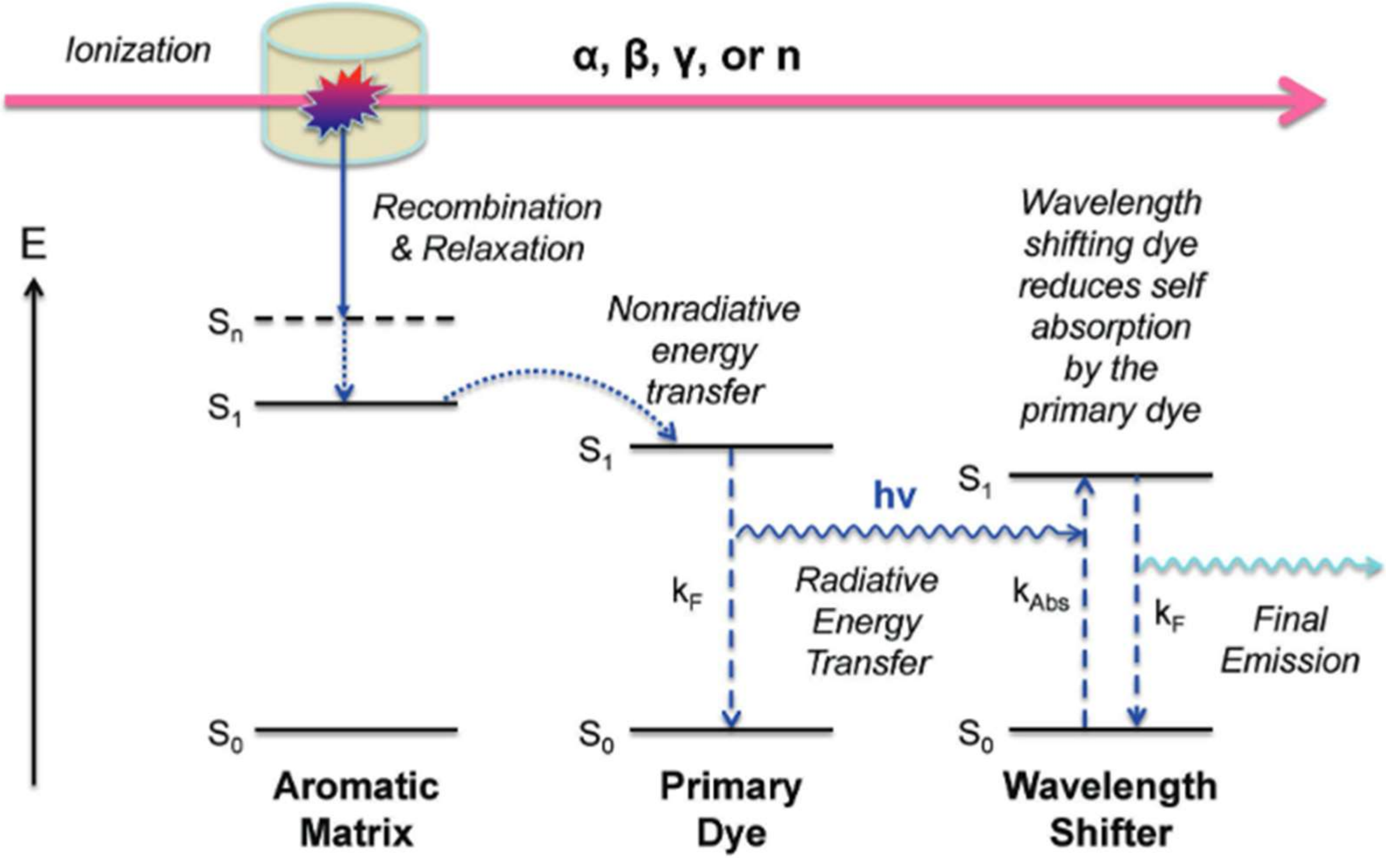
Organic Photodetectors



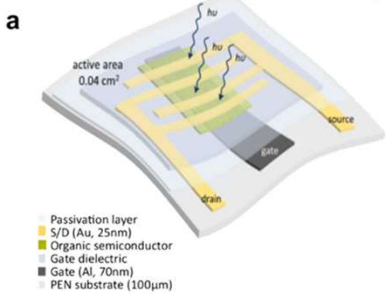
Hajagos, Tibor Jacob, et al. *Advanced Materials* 30.27 (2018): 1706956.

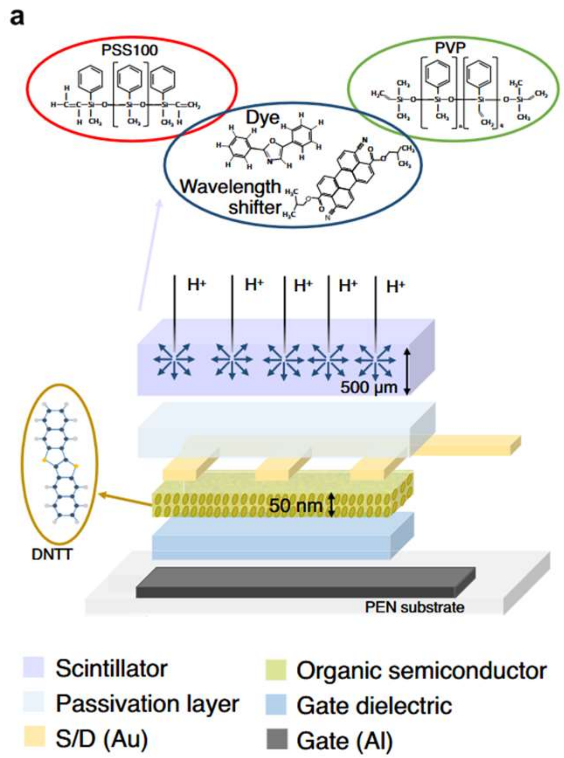
Fully-Organic Phototransistor Detector

"Flexible fully organic indirect detector for megaelectronvolts proton beams"

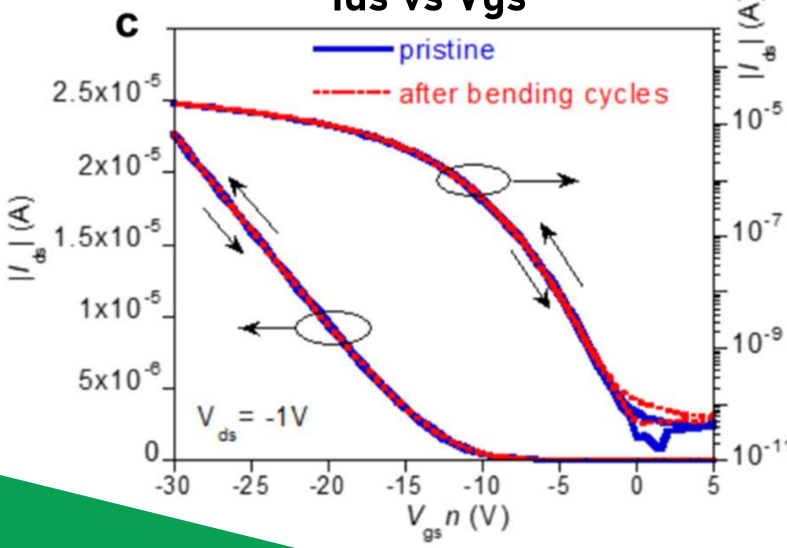
Calvi, Sabrina, et al.
npj Flexible Electronics 7.1 (2023): 5.

- Dose monitoring in Proton Therapy
- Indirect Detector – Organic Scintillator
- Coupled to Organic Phototransistor
- Low-Power (1V)

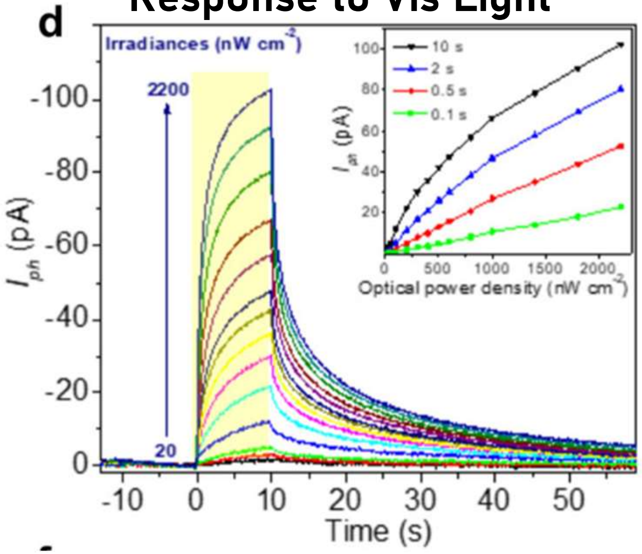




Ids vs Vgs



Response to Vis Light



OPD *Organic PhotoDetectors*

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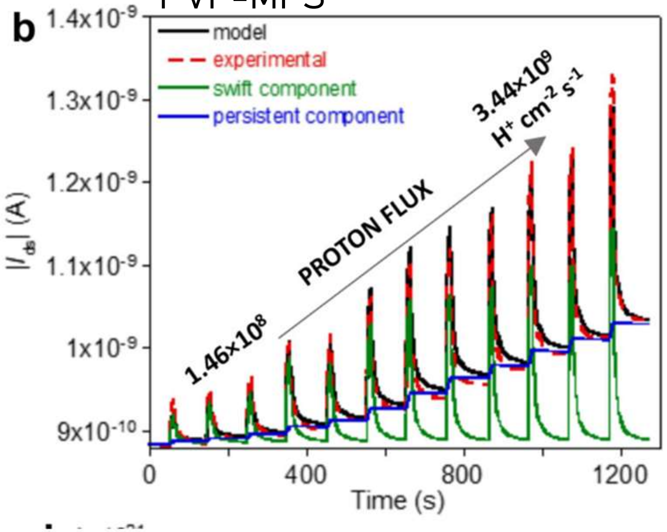
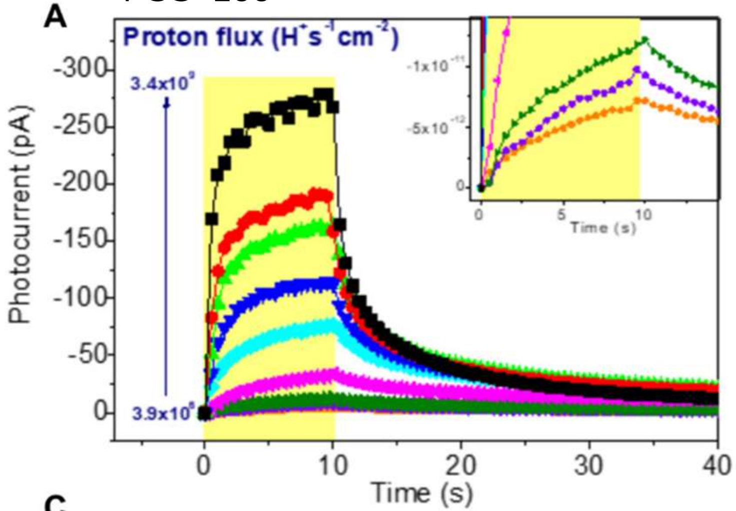
Fully-Organic Phototransistor Detector

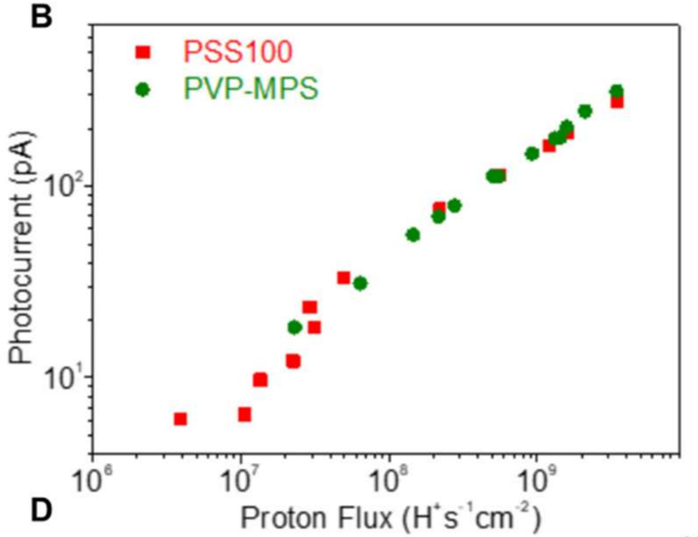
Calvi, Sabrina, et al.
npj Flexible Electronics 7.1 (2023): 5.

PVP-MPS

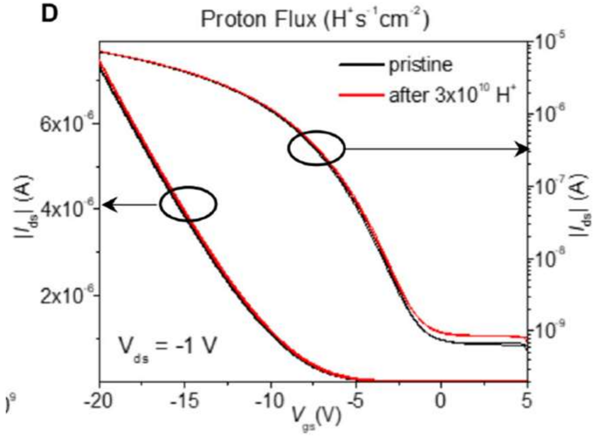


PSS-100





- $5 MeV$ Proton Beam
- Proton Exposure time: $10 s$
- Low Bias: Vds = Vgs = -1V



PSS-100

- Limit of Detection: $43\ mGy/s$

PVP-MPS

- Limit of Detection: $26\ mGy/s$

OPD *Organic PhotoDetectors*

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Hybrid Detectors – Quantum Dots

Advantages

- ❌ Organic → Tissue Equivalence
- ❌ Biocompatibility
- Flexibility
- High Sensitivity, low Limit of Detection

However…

- ❌ Low-Z → Small X-ray absorption
- Radiation hardness
- Response speed

Hybrid Detectors – Quantum Dots

Advantages

- ✗ Organic → Tissue Equivalence
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- Flexibility
- High Sensitivity, low Limit of Detection

However…

- ✗ Low-Z → Small X-ray absorption
- Radiation hardness
- Response speed

Advantages

- ✓ High(er)-Z → Better X-ray Absorption
- Flexibility
- High Sensitivity, low Limit of Detection
- ✓ Tunable Optical Characteristics

However…

- Radiation hardness
- Response speed
- Biocompatibility Issues ✗
- Limited Tissue Equivalence ✗

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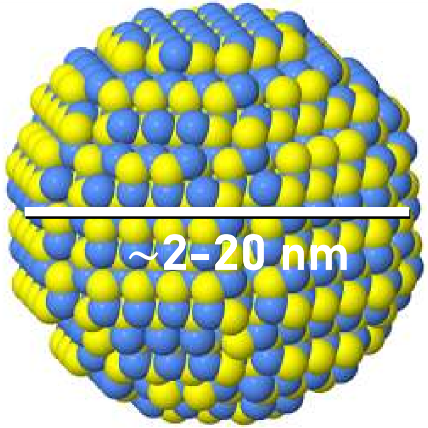
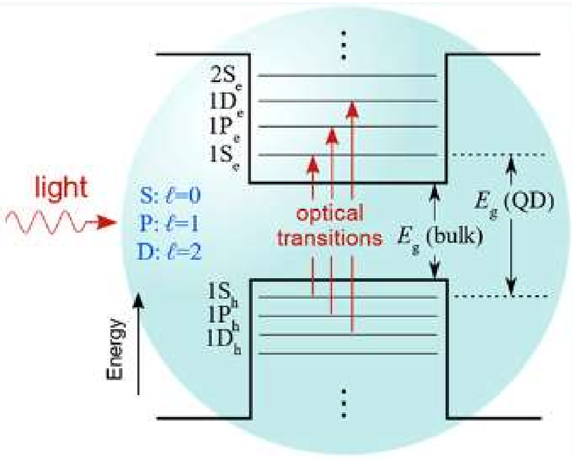
Hybrid Detectors – Quantum Dots

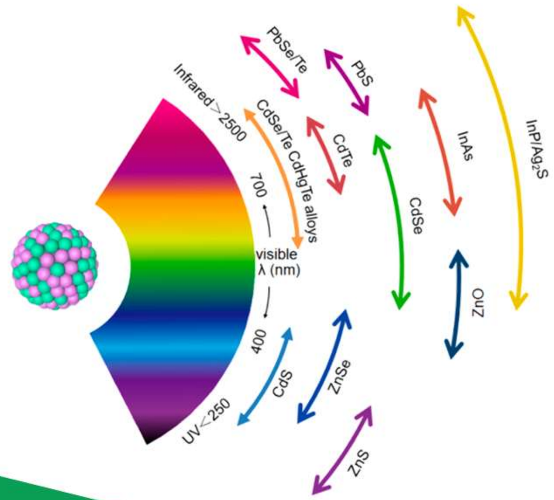
Colloidal Quantum Dot (QD)

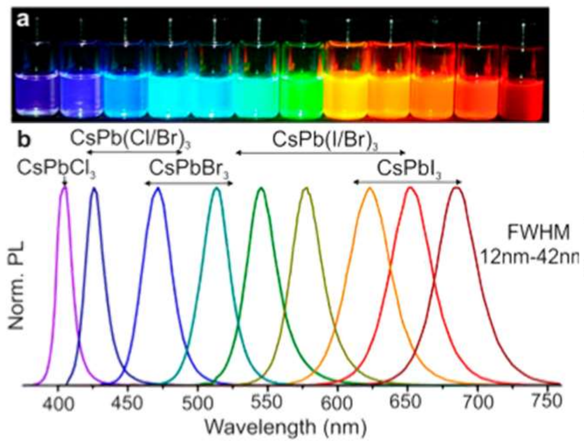
Nanocrystal (2-20 nm) of semiconducting materials that exhibit quantum confinement effects

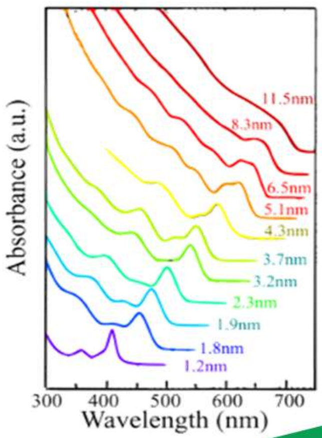
- **Solution-processable** materials
- **Size is tunable** during synthesis
- **Size-dependent** Optoelectr. Properties
- **High-Z** Materials
- **QD photoconductors** with high IR-Vis responsivity











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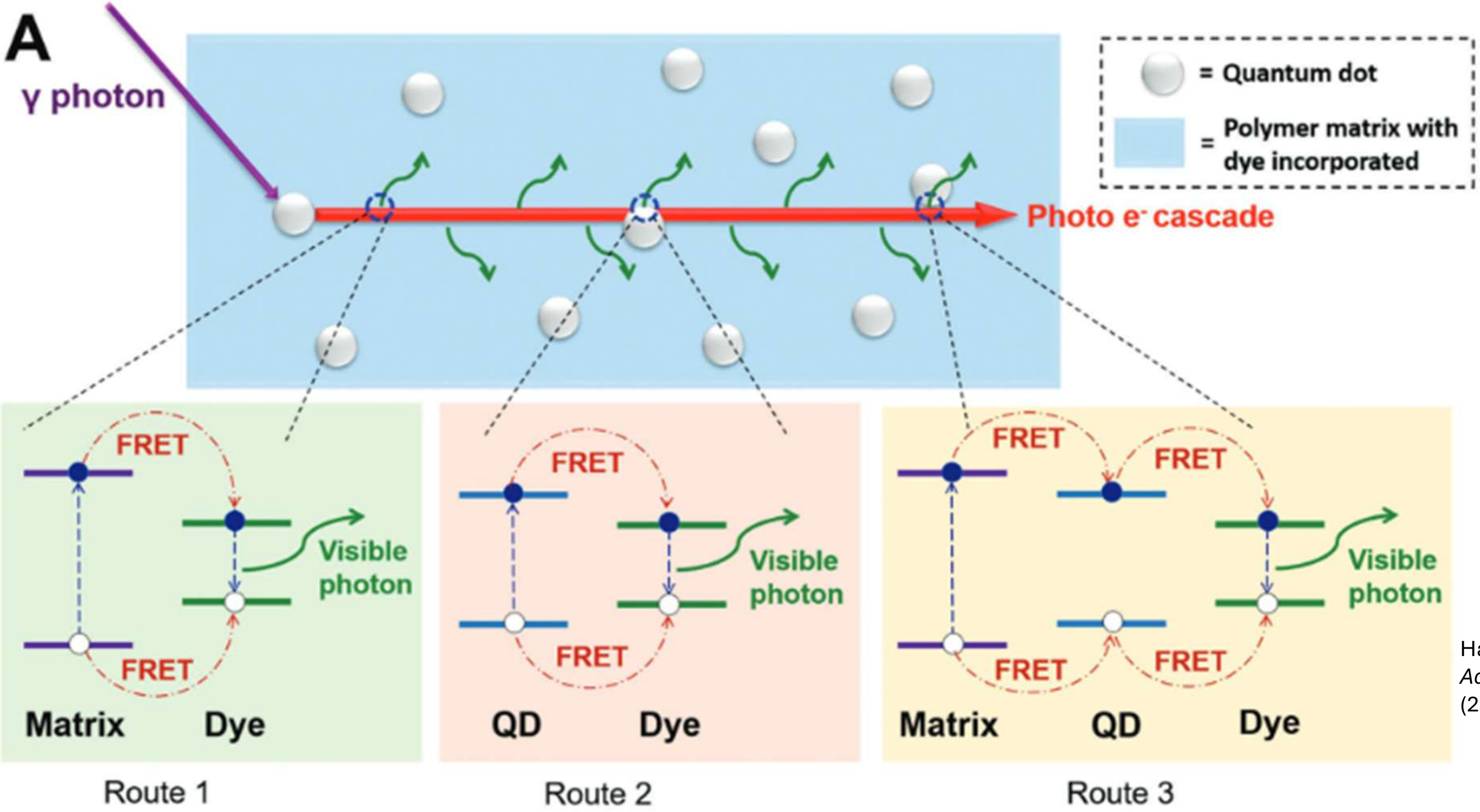
Hybrid Detectors – Quantum Dots



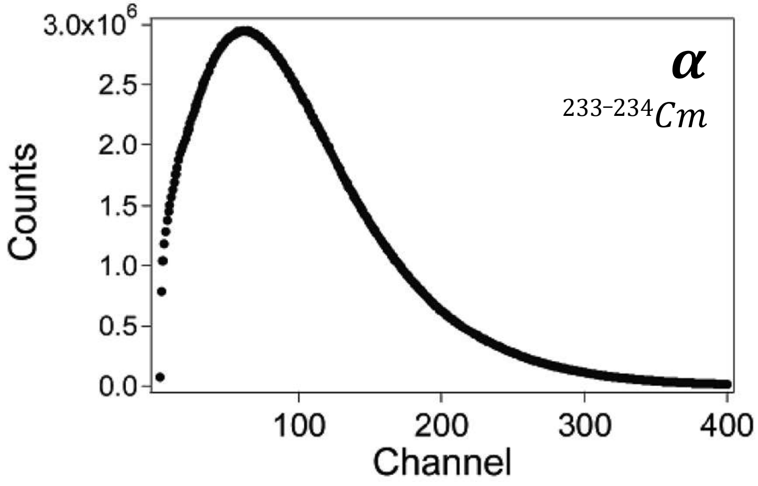
Hajagos, Tibor Jacob, et al. *Advanced Materials* 30.27 (2018): 1706956.

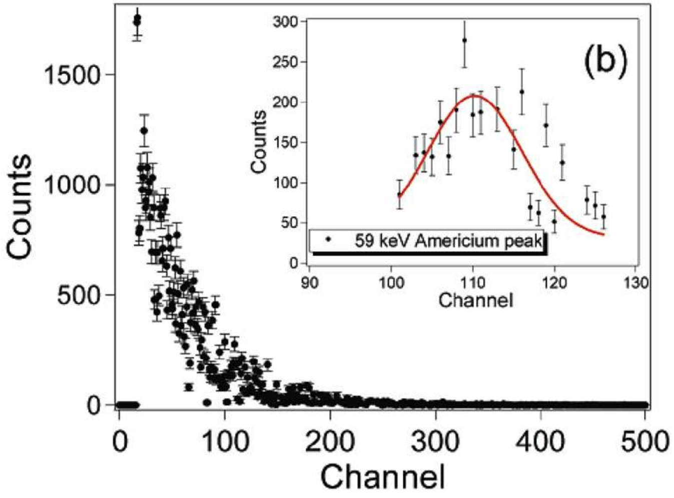
QD-Loaded Scintillators

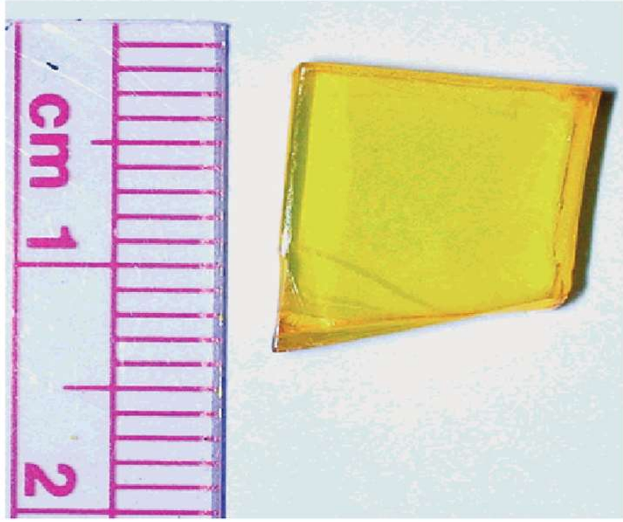
"Semiconductor quantum dot scintillation under γ-ray irradiation." **(2006)**

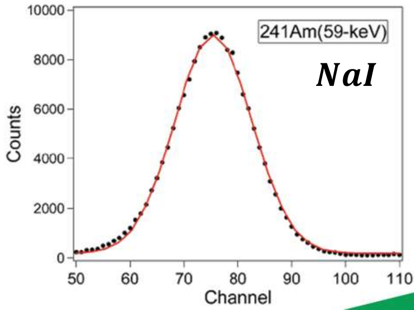
Létant, S. E., and T-F. Wang.
Nano Letters 6.12 (2006): 2877-2880.

- Glass loaded with Cds/ZnS QD
- Core-Shell QD with 510nm Photoluminescence
- Inorganic







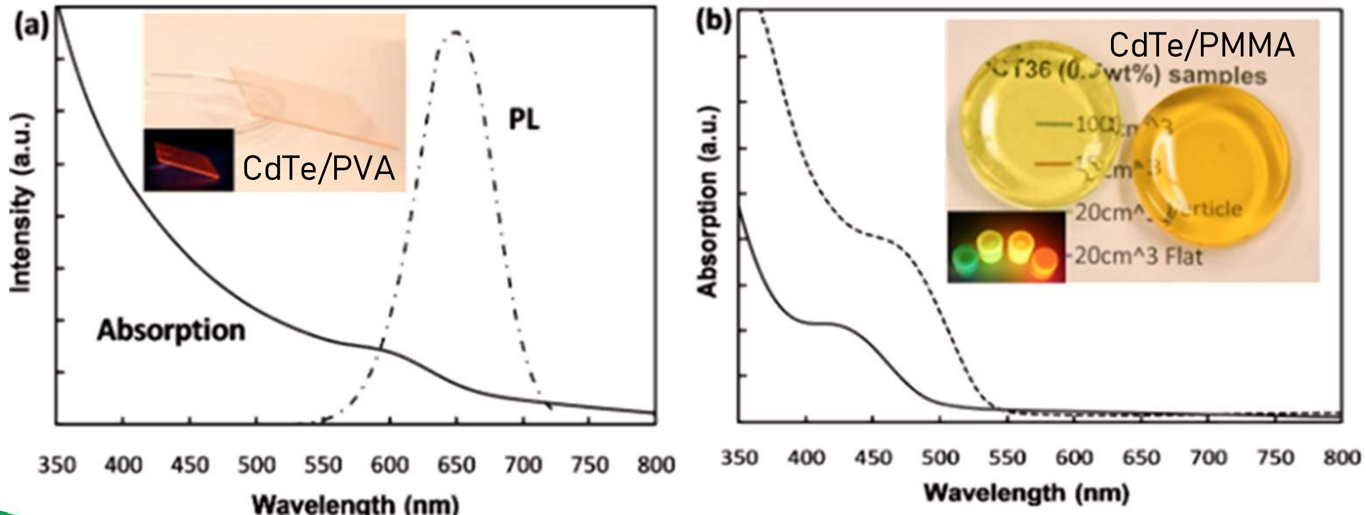


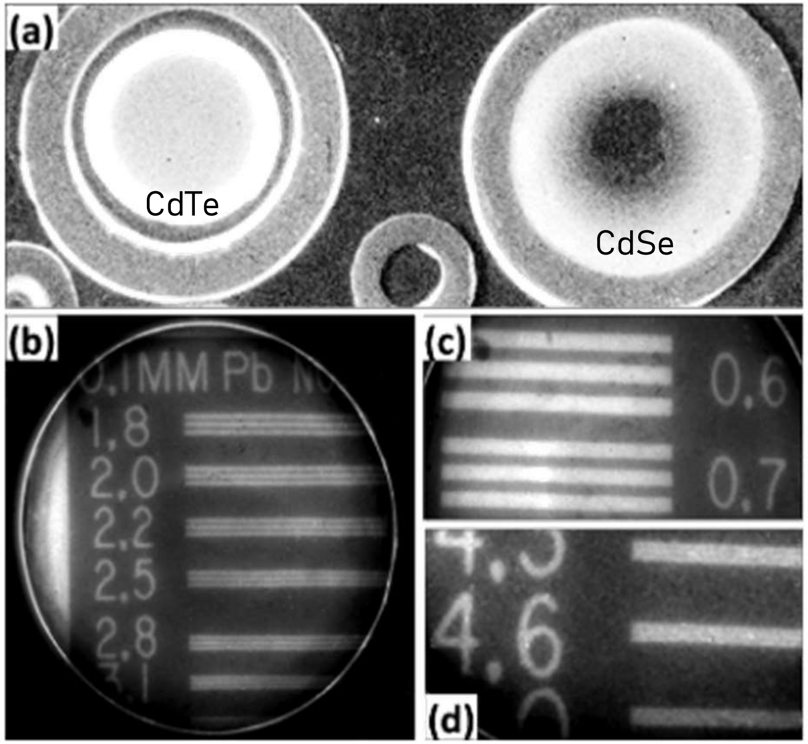
QD-Loaded Scintillators

"CdTe quantum dots and polymer nanocomposites for x-ray scintillation and imaging." **(2011)**

Kang, Zhitao, et al.
Applied physics letters 98.18 (2011).

- Cd-based QD loaded Plastic Scintillators (PMMA, PVA)
- excellent x-ray luminescence
- High resolution, fast decay, nonafterglow, high stopping power



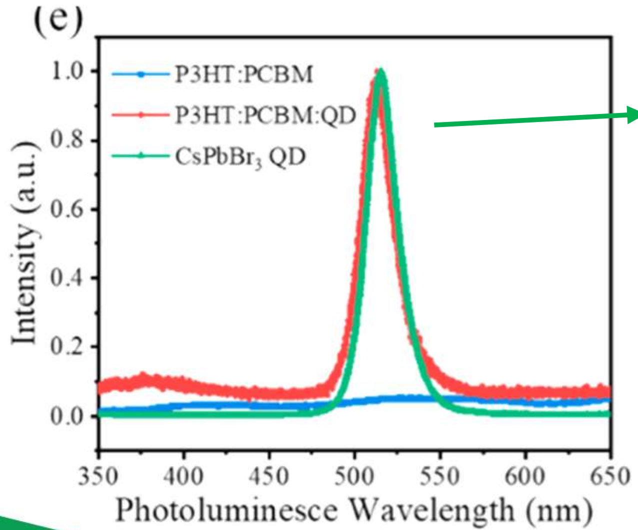


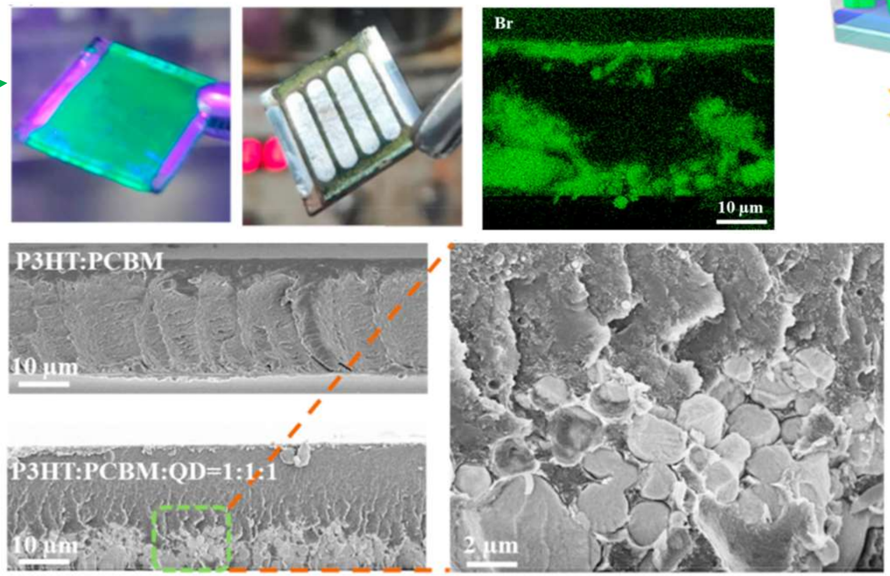
Hybrid OPD with Perovskite QD Scintillator

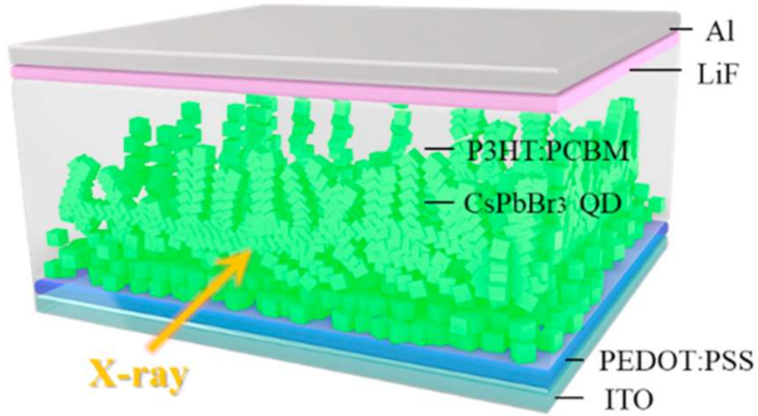
"X-ray Sensitive hybrid organic photodetectors with embedded CsPbBr3 perovskite quantum dots"

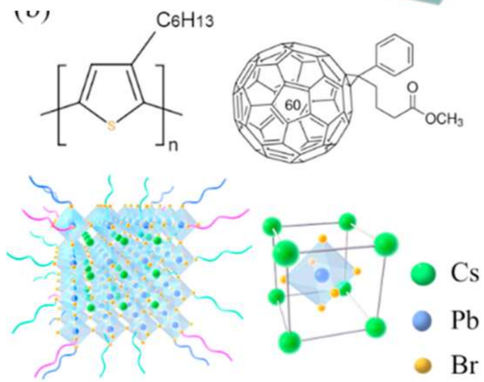
Xiang, Li, et al.
Organic Electronics 98 (2021): 106306.

- Hybrid device: Organic Photodiode+QD Scintillator
- QD Scintillator is embedded into the organic matrix
- Low Bias (-3V)
- Detection of Soft X-rays









QD *Quantum Dots*
Hybrid Detctors

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Hybrid OPD with Perovskite QD Scintillator

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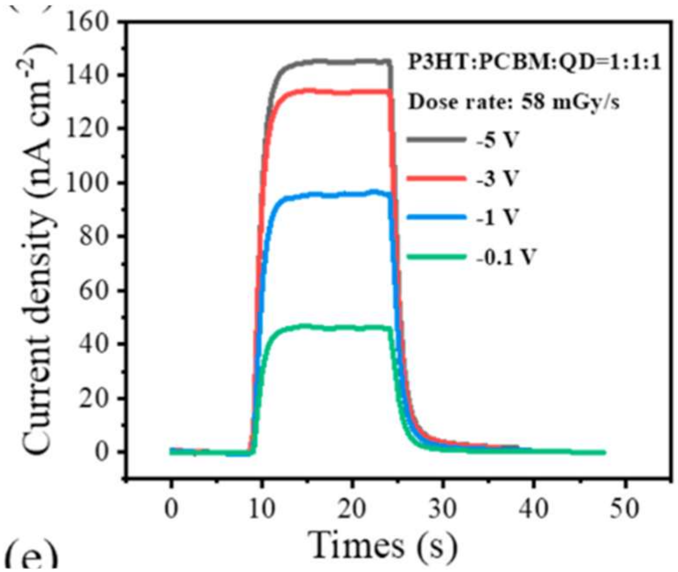
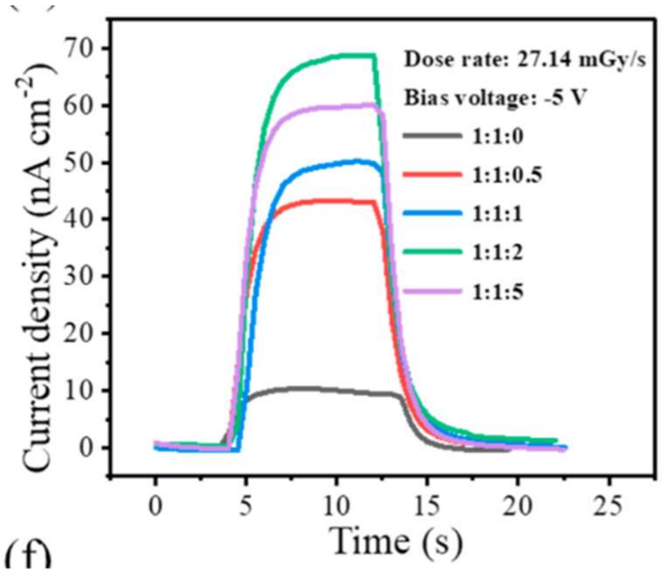
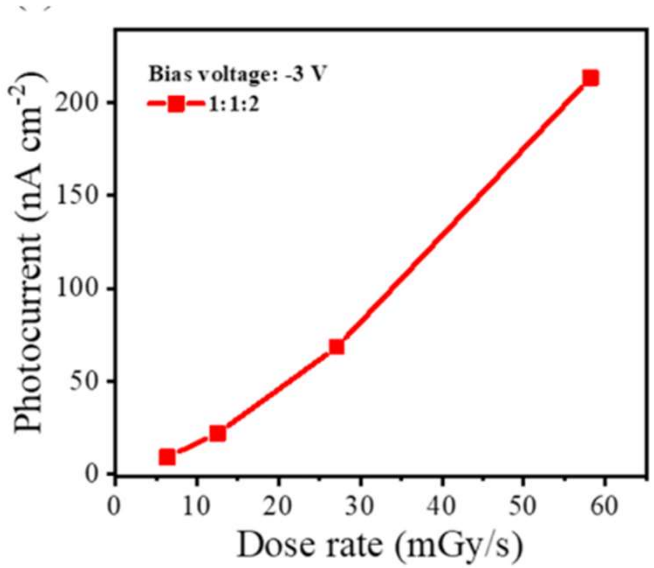
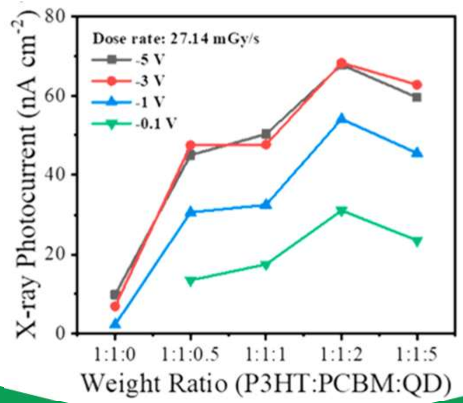
Organic Electronics 98 (2021): 106306.







- X-ray tube with Cu target
- Low Bias: |Vmax| = 5V
- Photocurrent vs. QD amount



Best device

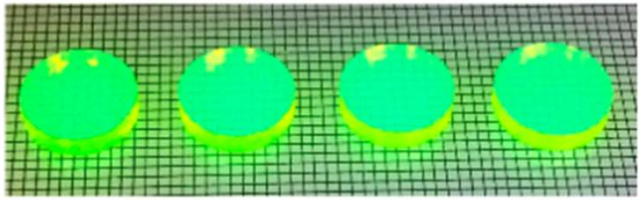
- Sensitivity: $3.67\mu CGy^{-1}cm^{-2}$

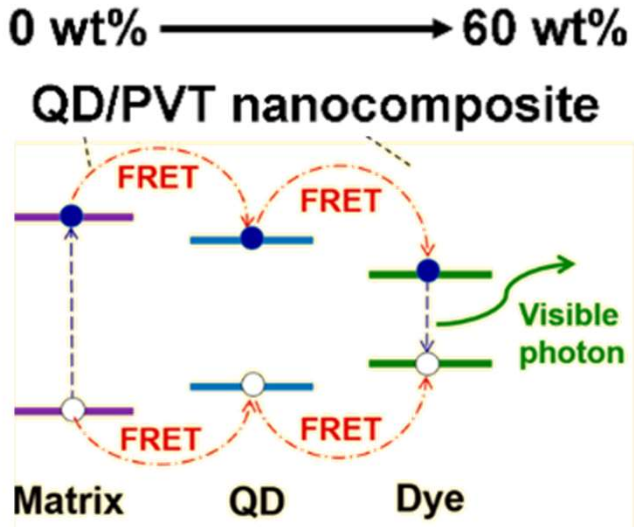
QD-Loaded Scintillators

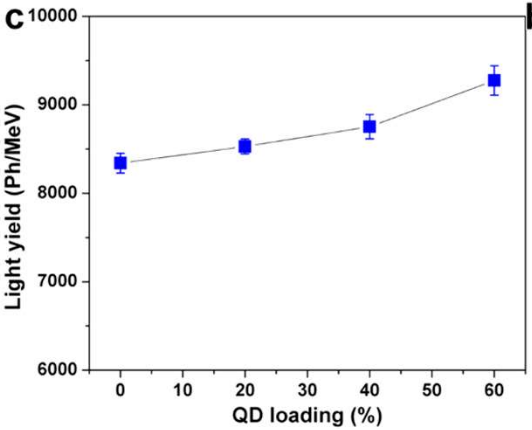
"Transparent ultra-high-loading quantum dot/polymer nanocomposite monolith for gamma scintillation."

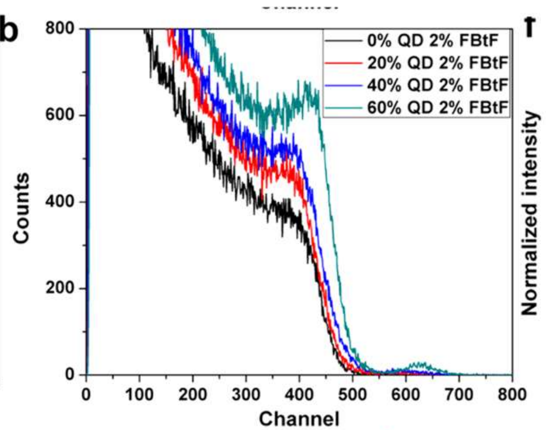
Liu, Chao, et al.
ACS nano 11.6 (2017): 6422-6430.

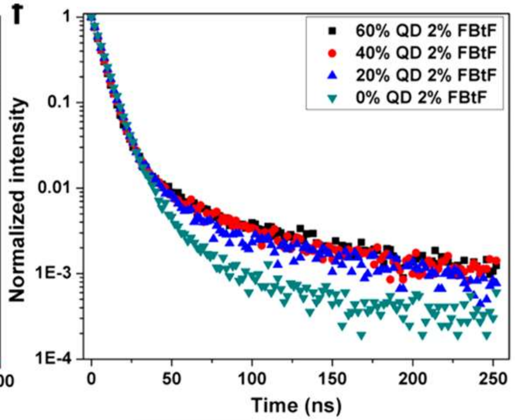
- CdZnS/ZnS in PVT with Dye for Forster Resonance Energy Transfer
- Optically transparent with High Light Yield (ph/MeV)
- Detection of 662 keV photopeak (Cs-137): FWHM = 9.8%

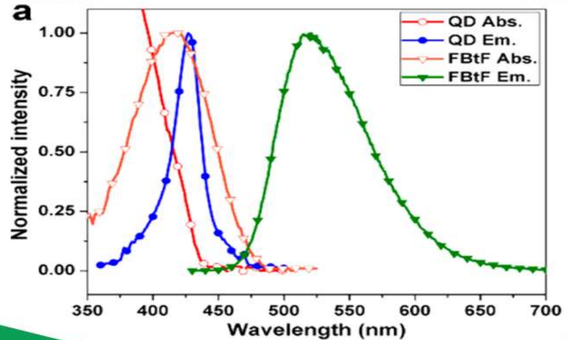












Epoxy on PbS QD Photodetector

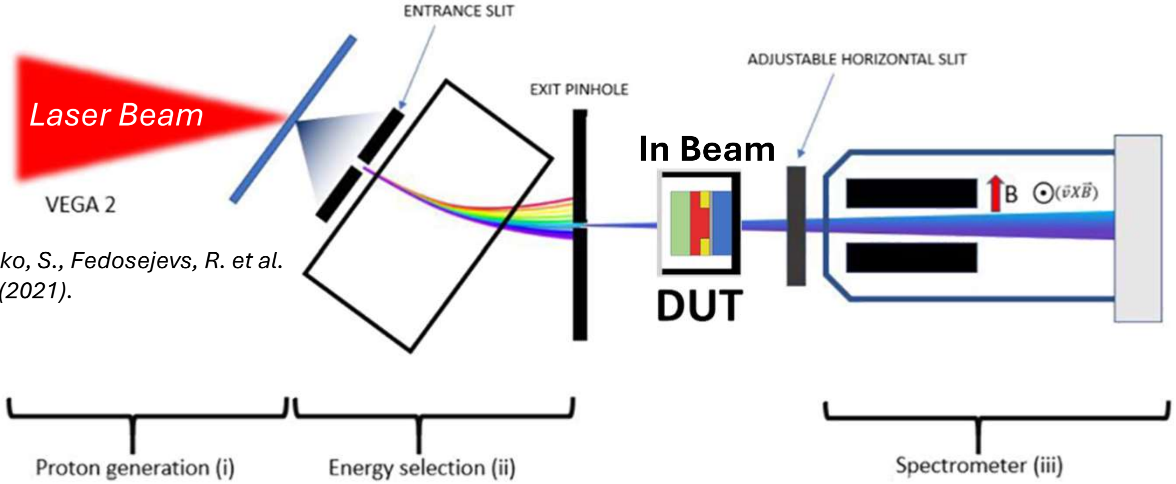
Ruggieri, Marco et al.
Nanoscience & Nanotechnology Conference, 2024

"From X-rays to accelerated particles: testing Lead Sulfide Quantum Dots-based detectors under laser-driven accelerated beams"

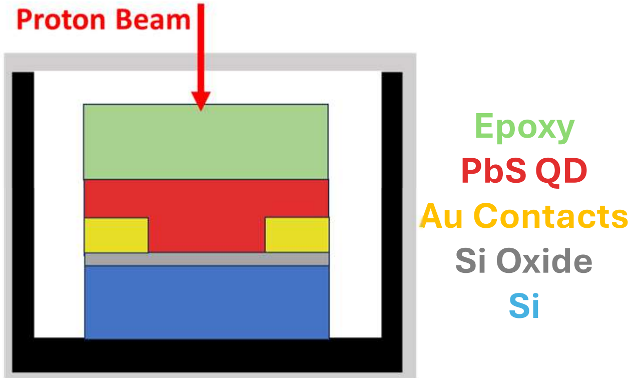
- PbS QD Photodetector with thick (3mm) Epoxy conversion slab
- Test with 10 MeV Proton shots in a Laser-Driven Facility
- Observation of a clear photocurrent signal on Proton Shots.

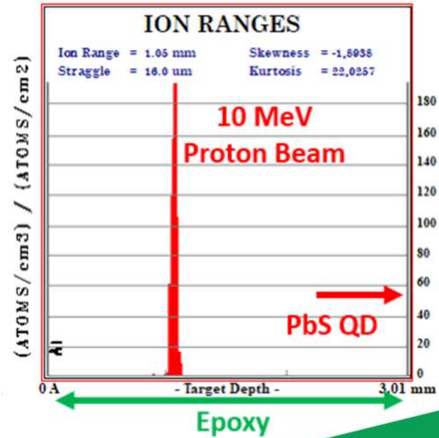
VEGA 2 Proton Acceleration System

*Apiñaniz, J.I., Malko, S., Fedosejevs, R. et al. Sci Rep **11**, 6881 (2021).*



	Peak Power	Energy/shot	Duration/pulse	Rep. Rate	Central @
VEGA 1	20 TW	600 mJ	30 fs	10 Hz	800 nm
VEGA 2	200 TW	6 J	30 fs	10 Hz	800 nm
VEGA 3	1 PW	30 J	30 fs	1 Hz	800 nm





QD *Quantum Dots Hybrid Detctors*

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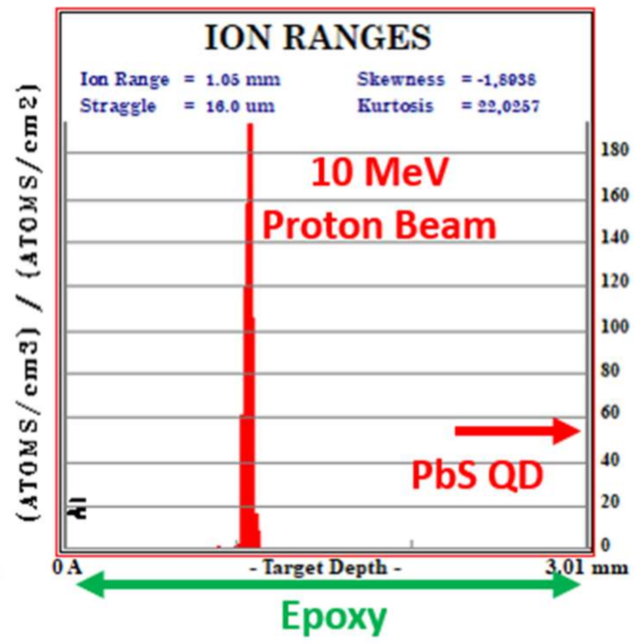
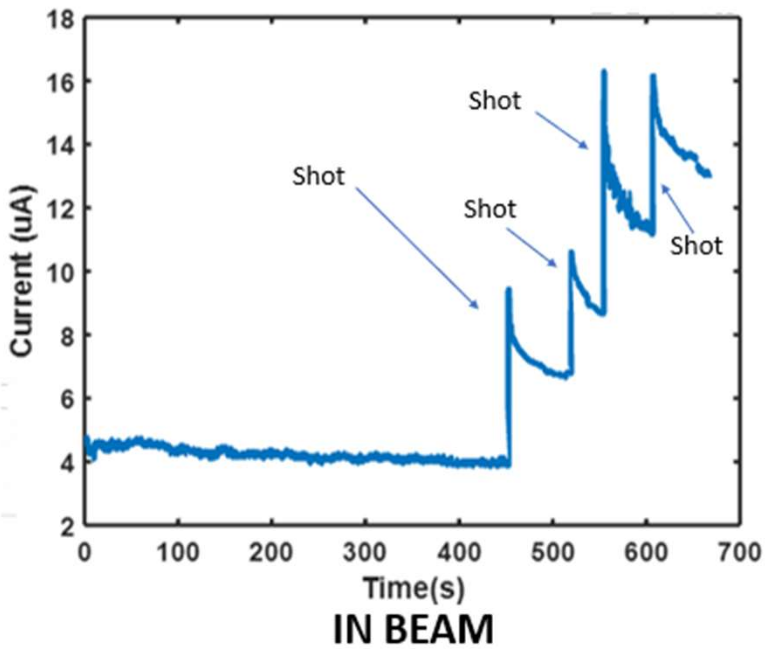
Epoxy on PbS QD Photodetector

Ruggieri, Marco et al.
Nanoscience & Nanotechnology
Conference, 2024

SRIM Simulation





QD *Quantum Dots*
Hybrid Detctors

JENNIFER²
EU grant n.822070

Conclusions

- **Organic Photodetectors and Scintillators** have been developed with **excellent detection** capabilities for photons and protons.
- **Fully-Organic** devices have many **desirable characteristics** (flexibility, solution-processability, low cost etc.) and **high sensitivity**
- **High-Z Quantum Dots** have tunable optoelectronic properties
- **QD-sensitized Scintillators** have been developed for X- and Gamma radiation
- The use of **embedded High-Z nanomaterials** is a **promising** strategy to increase the **absorption of organic scintillators**
- Even without embedding QDs, **nanomaterials can work in tandem** with **Organic scintillating** layers, exploiting and leveraging the **best of the two worlds**.

INFN ROMA TRE

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