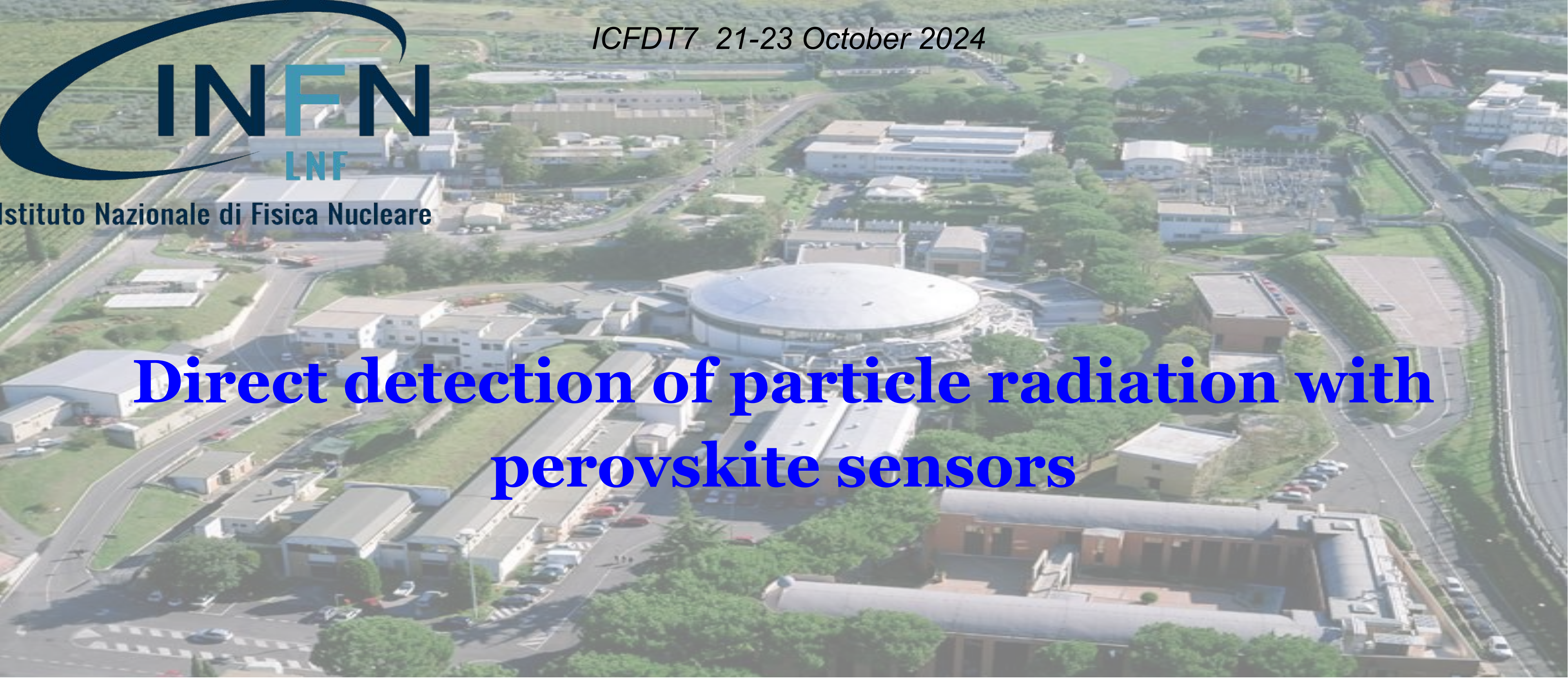


ICFDT7 21-23 October 2024

Istituto Nazionale di Fisica Nucleare

Direct detection of particle radiation with perovskite sensors

Gemma Tinti

on behalf of the **PEROV collaboration**

(M. Auf der Maur, Z. Chubinidze, A. De Santis, G. Felici, L. Lo Presti, F. Matteocci, S. Morganti, A. Paoloni, G. Papalino, S. Rizzato, C. Rovelli, M. Testa, G. Tinti, I. Viola)

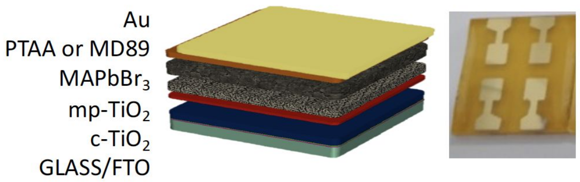
$MAPbBr_3$ properties

$MAPbBr_3$ (or CH_3NH_3 (MA)$PbBr_3$, i. e. Methylammonium lead bromide) properties:

- Large # of carriers, carrier transport capabilities (large $\boldsymbol{\mu \cdot \tau}$ ~ $O(10^{-4}\ cm^2V^{-1})$)
- High density and effective atomic number
- Solution processing: low costs, scalable to large areas

Semiconductor		Silicon	$MAPbBr_3$
Density		2.33 g/cm^3	3.8 g/cm^3
Band gap (eV)		1.12 (indirect)	2.24 (direct)
Mobility $\boldsymbol{\mu}$ (cm^2/Vs)	electrons	1400	25-140
	holes	450	13-220
Average energy for e/h creation (eV)		3.6	5.8
Radiation length X0 (cm)		9.36	2.33
Z_{eff}		14	62

- **Perovskite studied as light, X-ray detectors, fewer works on different types of radiation**
- R&D challenge posed by highly mobile defects (Br^-)

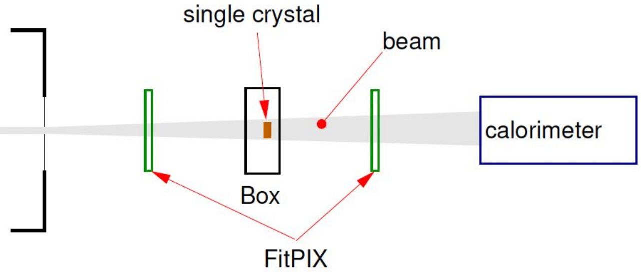


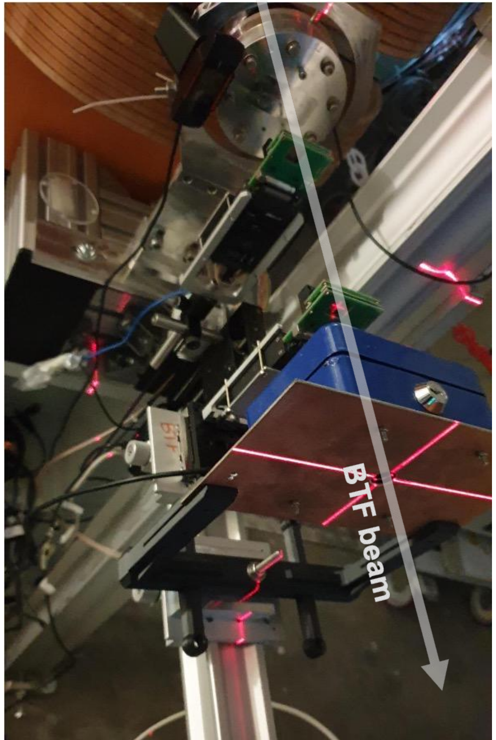
300 nm thick films: **Appl. Phys. Lett. 120, (2022),113505**

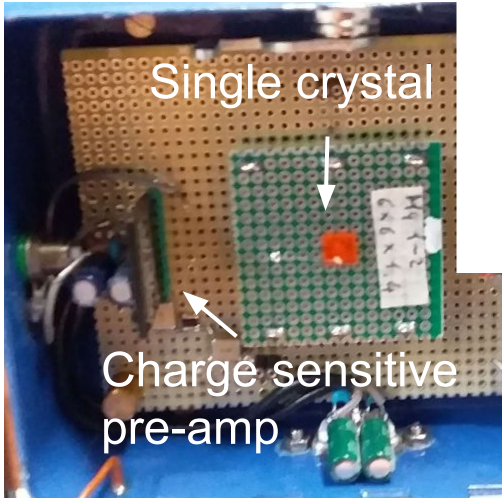
2-6 μm thick crystals: **Adv. Mater. Technol. (2023), 8, 2300023**

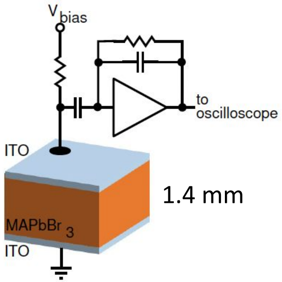
Minimum ionising particle setup

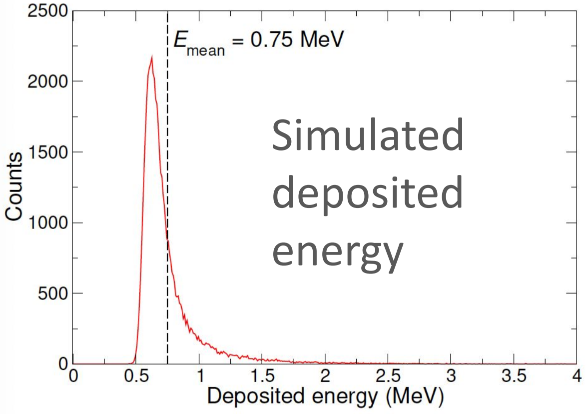
- Test beam performed at the **Beam Test Facility** @LNF (Nov 23)
- Electron beam (300 MeV): e^- behaves as minimum ionising particles (MIPs)
- Tested a **single crystal** grown from solution (University of Milano, submitted to Journal of Crystal Growth) with dimensions 6 x 6 x 1.4 mm^3 , symmetric Indium Tin Oxide (ITO) contacts









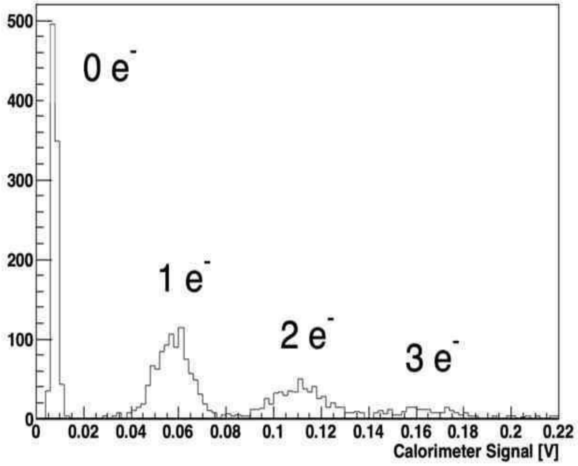


MPV = 0.63 MeV

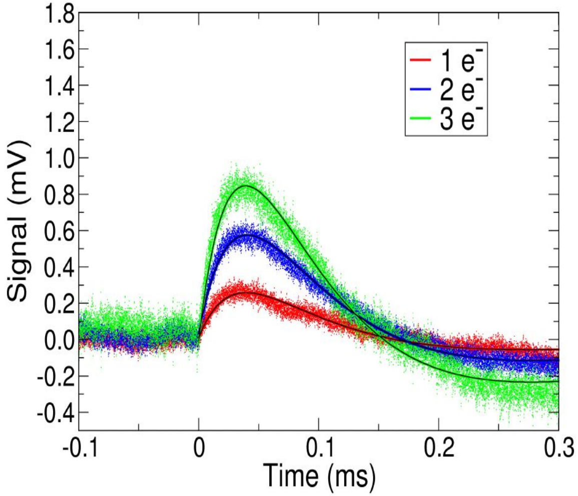
Low multiplicity

- Multiplicity of the electron beam monitored with a calorimeter: electron distribution follows a Poisson distribution with mean <***μ***>
- Published in <u>***Nanoscale*****, 2024,16, 12918-12922:**</u> **first time MIPs are detected by a perovskite sensor**
- Average waveforms for the PEROV single crystal (SC) with bias voltage 5V at different multiplicities

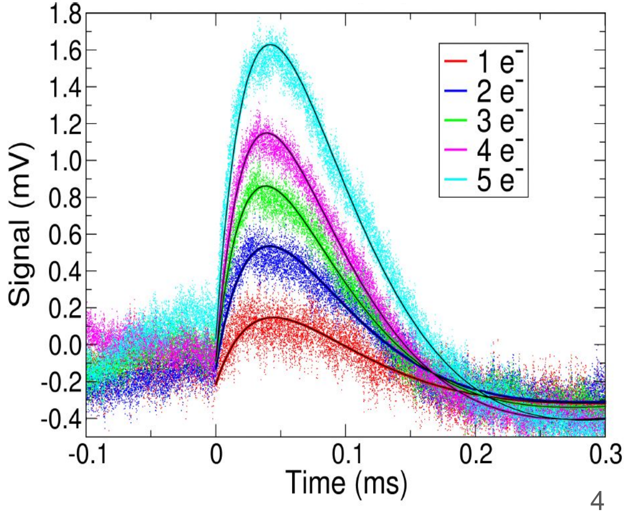
Calorimeter signal <***μ***>=1.4



SC waveforms <***μ***>=1.4

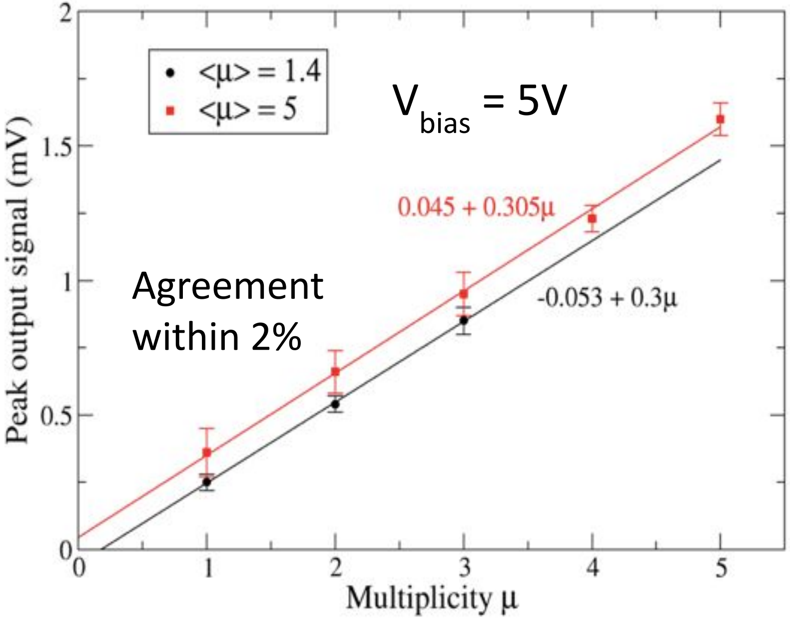


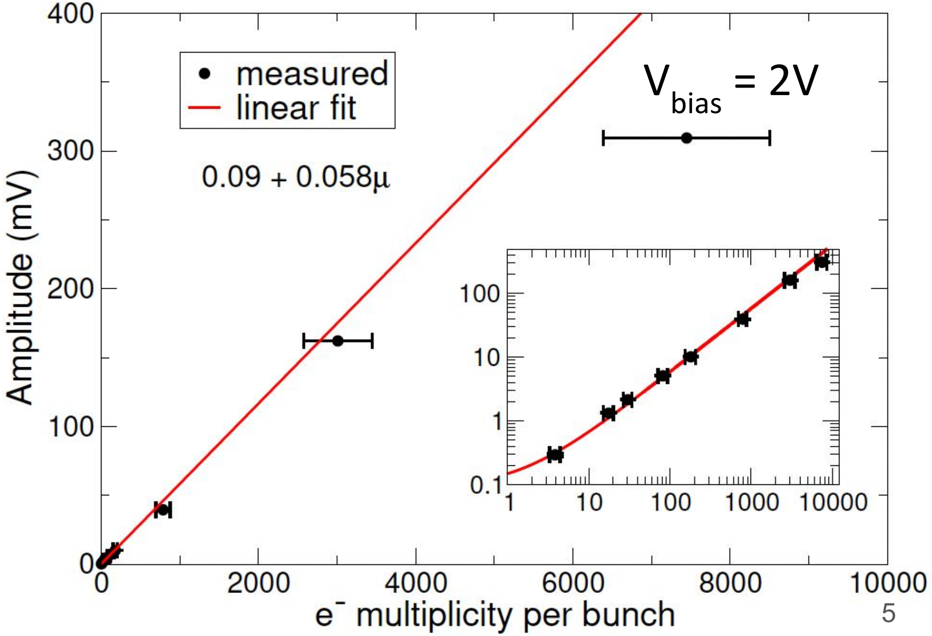
SC waveforms <***μ***>=5



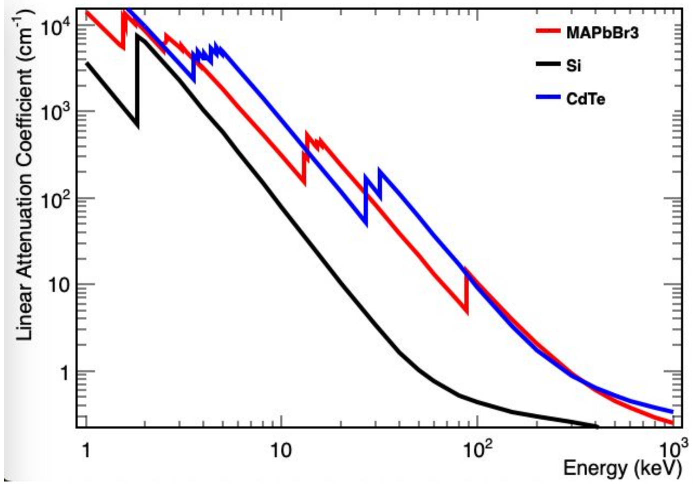
Linearity at low and high multiplicity

- Scan at high multiplicity performed at 2V bias voltage not to saturate electronics
- Effective multiplicity on the SC has been calculated (~70% geometrical acceptance)
- Good linearity over a dynamic range of 5 10^3 makes perovskite sensors attractive for dosimetry applications for charge particles at high intensity
- **Deposited patent 102023000012477 on a perovskite based tracking/dosimetry device**



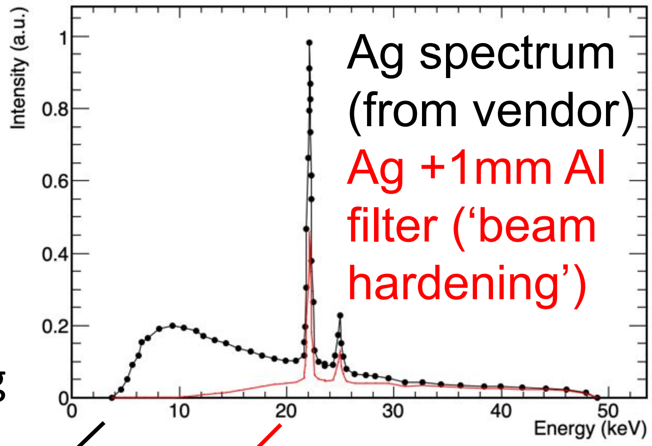


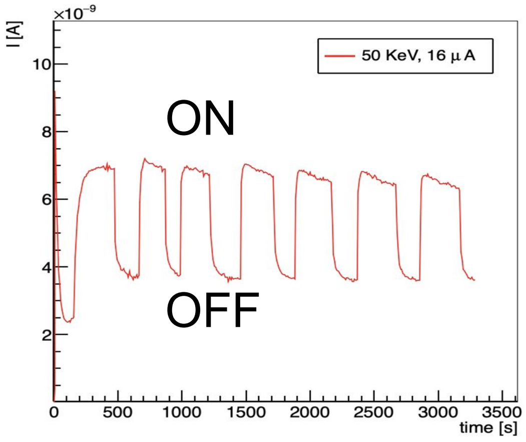
R&D for X-ray detection

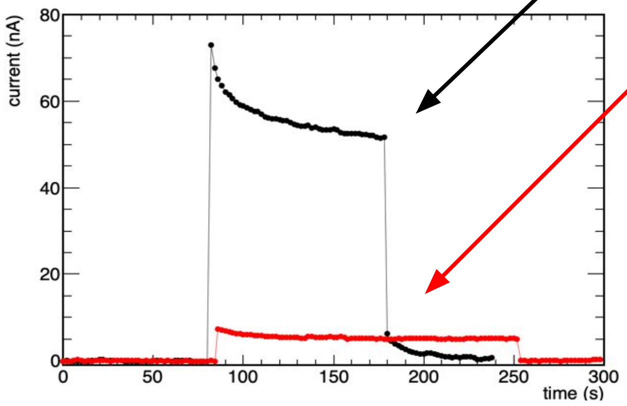


MAPbBr3 is interesting as an X-ray sensor above 30 keV thanks to the high Z_{eff} and density and low costs

Exposed to X-rays from an AMPTEK Mini-X tube with Ag cathode (courtesy of CMS-LNF)



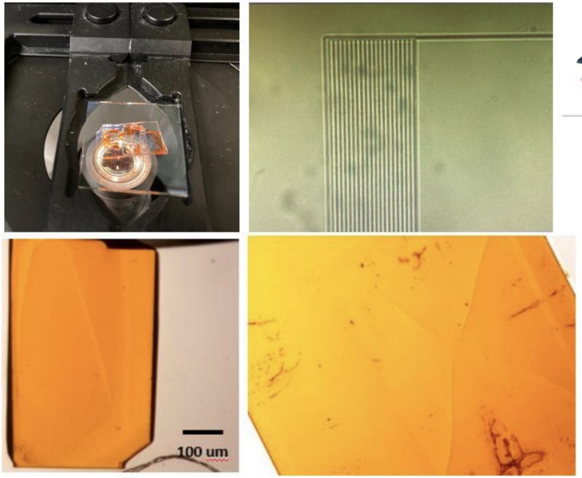


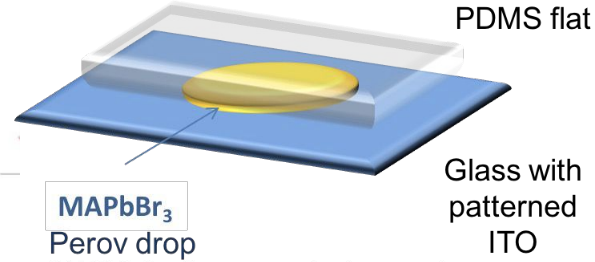


Shows sensitivity to X-rays above 20 keV

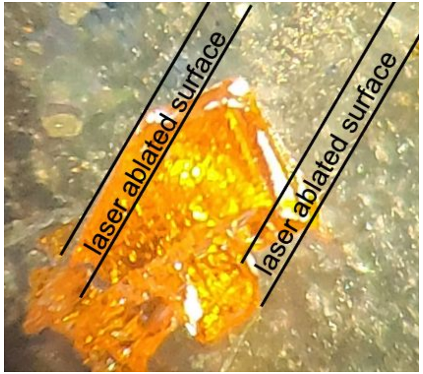
R&D of thinner sensors on patterned substrate

- PEROV project continuation: micropad crystal grown on a patterned ITO substrate: W 200 x L 500 x H 500 μm





MAPbBr3 micrometer single crystals grown by dewetting technique on a patterned ITO substrate.



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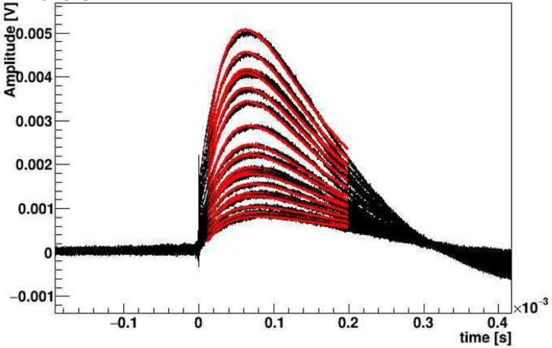
V_{bias} scan from 10 to 80 V

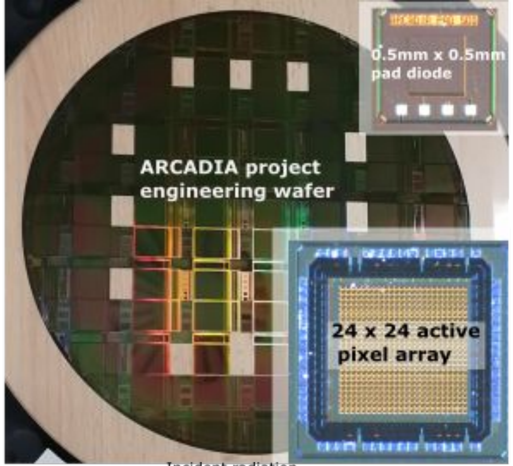


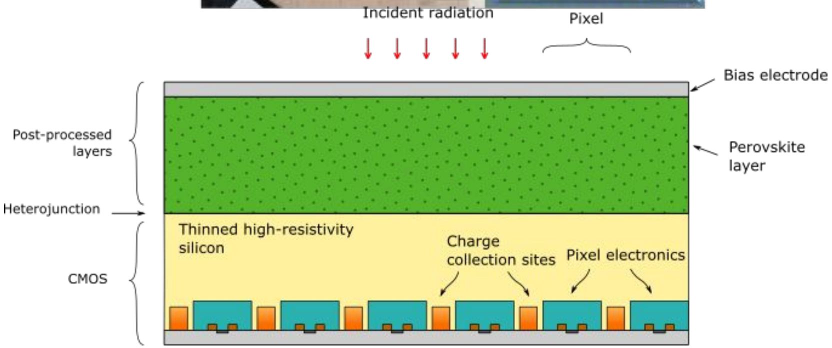
Exposed to 300 MeV electrons @ BTF (MIP-like)

Preliminary multiplicity O(50) electrons but exact geometrical acceptance needs more studies

Future developments and conclusions

- The ability to grow the perovskite SC on patterned surface opens up to the possibility to integrate with silicon based technology (CMOS readout chip)
- Microfluidic technologies allow to reach sensor thickness suitable for medical X-rays O(100-500 μm), with controlled height to surface ratio and multi pixels
- CMOS technology developed for the INFN ARCADIA project; 50 μm pixel pitch 50 e^- RMS noise



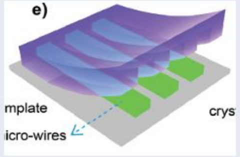
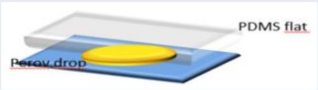
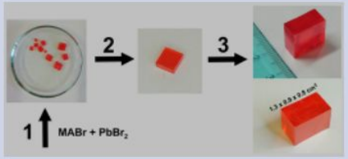


L.Pancheri, M. Testa, I. Viola (Italian PRIN 2022 project granted HyPoSiCX = Hybrid Perovskite on Silicon CMOS X-ray Detectors)

- The PEROV collaboration has demonstrated the ability both to produce and successfully characterize perovskite sensors for light, X-ray and ionising radiation detection

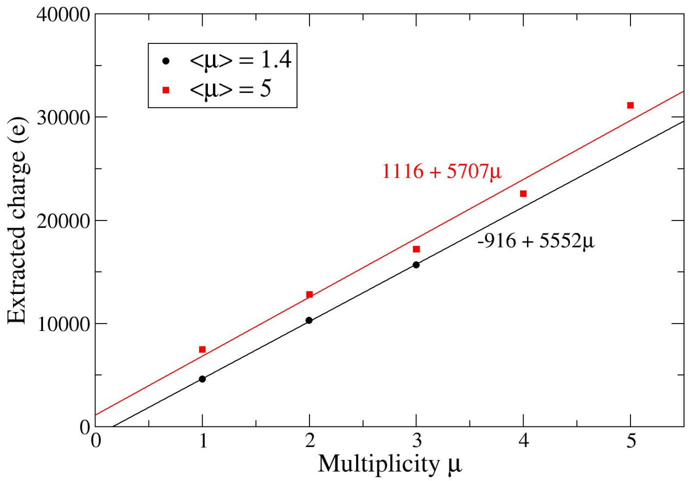
Backup slides

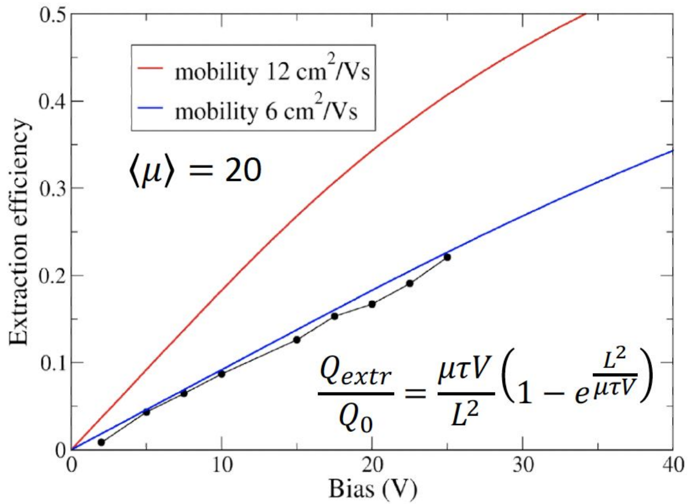
PEROV project: sensor technology

Technology	Pro	Contra
Film 300 nm thickness	• large area • small transit time due to low thickness • flexible substrate	• polycristalline • grain boundaries • large variability between samples
Micro wires (2-6 mm)  Micro pads (100 mm) 	• large flexibility in dimension • moderate area • pixelization • flexible substrate • Deposited directly on substrate	• need high optimization of parameters (pressure, temperature)
Single crystals Up 3 mm minimum 	• ideal for single crystal large dimension, up to O(1) cm^3 • low defects	• No scalability to large area systems • Need to be cut mechanically for low thickness

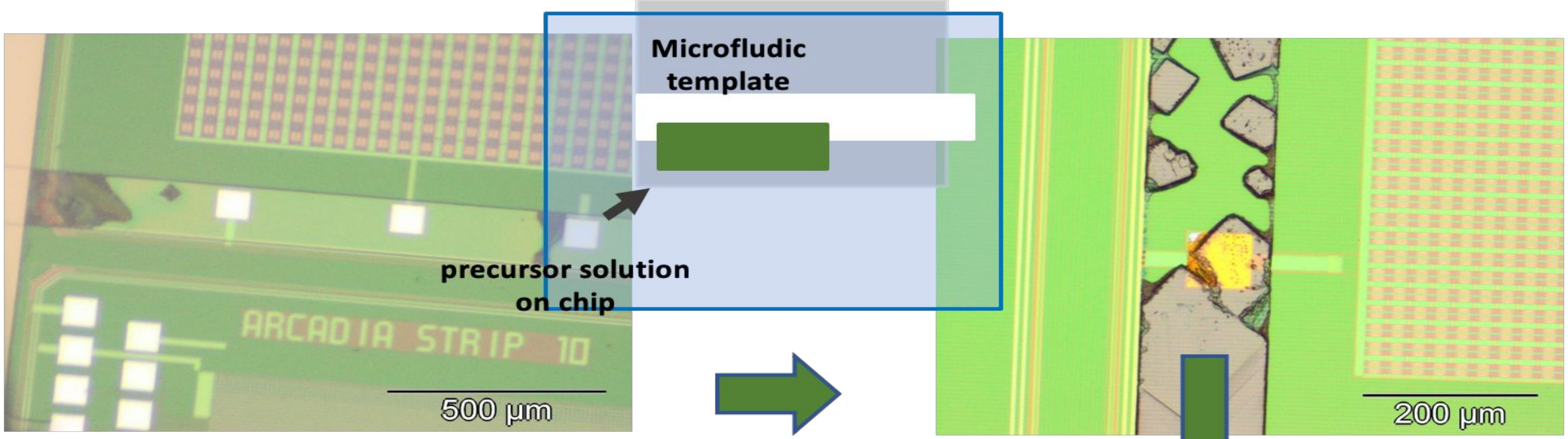
$MAPbBr_3$ sensor characteristic analysis

- **128k e/h pairs** are generated by the passage of a MIP through the SC sensor
- **5.6k e^-** are collected for a single MIP: the charge extraction efficiency is ~**4.3%**
- A low value of the extraction efficiency is expected given the low electric field and the sensor thickness which favour trapping and recombination of the charge carriers
- Voltage scan performed at <$\boldsymbol{\mu}$>=20 shows an increase of the extraction efficiency modelled with a mobility value of 6 cm^2/Vs
- $\boldsymbol{\mu \cdot \tau}$ ~ 3.8 $x10^{-4}$ cm^2V^{-1}, on the lower side of what reported in literature





Perovskite on CMOS: microfluidic-assisted growth



- High <u>crystalline quality</u> of each single crystal (SC);
- Controlled SC <u>dimensions</u> from 500 nm up to 200 µm;
- High <u>aspect ratios</u> for large area devices;
- Growth directly on the device interface;
- Tunability of precursor composition;
- Flexibility in the SC shapes.

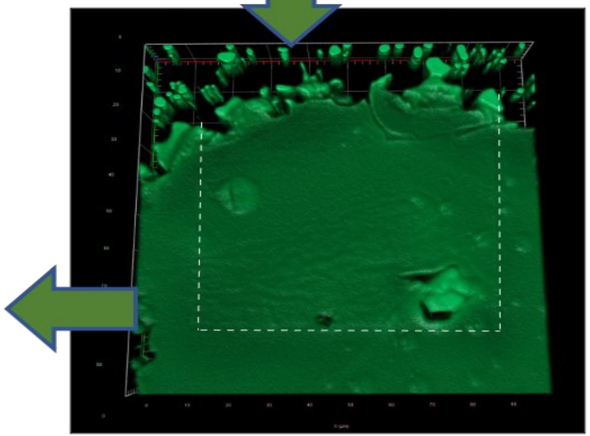
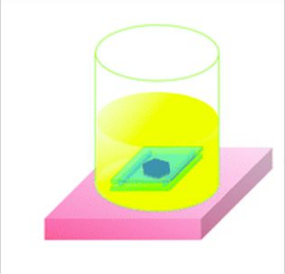


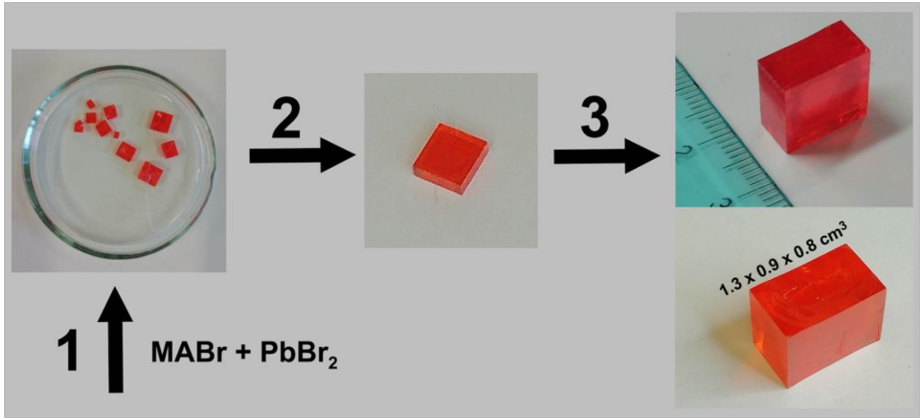
Photo courtesy: L. De Marco; R. Mastria; I. Viola – CNR-NANOTEC

Bulk single crystal

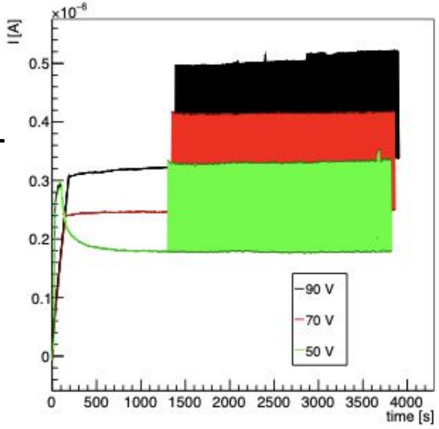
Seeding Techniques
Dip. Chimica Milano

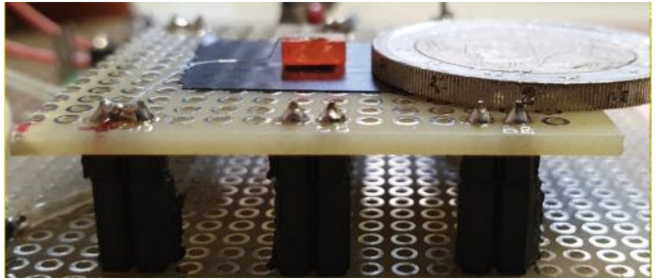


Large single crystal produced by low-cost solution processed at low temperatures and controlled ambient conditions.



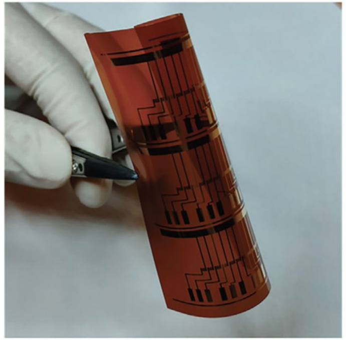
- Typical Dimensions: 5mm x 5mm x 2 mm (W x L x H)
- Device realized with Indium Tin Oxide / CH3NH3PbBr3 / Indium T Oxide
- Due to large thickness, not suitable for light detection but interesting as radiation detector

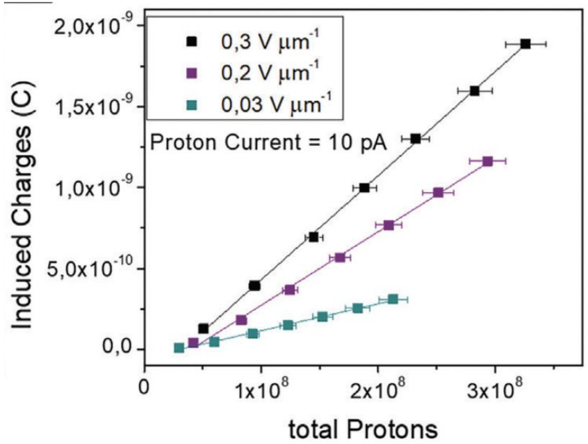




Perovskite active dosimeters

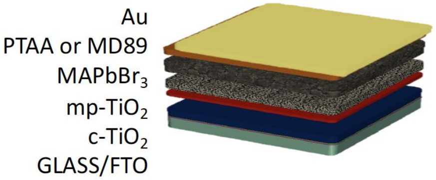
- 2D hybrid thin flexible perovskite films tested with 5MeV protons between 10^8 and 10^{10} H^+ s^{-1} cm^{-2}
  Taken from **Adv. Sci. 2024, 2401124**





Organo-Metal Halide perovskite

- **Organo Metal-Halide Perovskites (OMHP)** are a class of hybrid organic-inorganic semiconductor materials with a perovskite unit-cell structure **ABX_3** with A = $CH_3NH_3^+$,B = metallic cation (Pb^{2+}), X= halide anions (Cl^-, Br^-,I^-)
- OMHP are emerging as new generation photovoltaic material
- Band gap tunable changing halide (I,Br,Cl)
- Opto-electronic properties combine **advantages from organic and inorganic semiconductors**



300 nm thick films: **Appl. Phys. Lett. 120, (2022),113505**

2-6 μm thick crystals: **Adv. Mater. Technol. (2023), 8, 2300023**

- Disordered system
- Localized electronic states
- Hopping transport ⇒ low mobility
- Low cost, low temperature processing
- Can be solution processed
- Scalable to large area

- Ordered periodic crystal ⇒ band structure
- Delocalized Bloch states
- band transport ⇒ high mobility
- Usually wafer based technology
- Costly, high temperature processes

OMHP are studied as X-ray detectors, fewer works on different types of radiation

MAPbBr$_3$ properties

MAPbBr$_3$ (or CH_3NH_3 (MA)PbBr$_3$, i. e. Methylammonium lead bromide) characterized by:

- Carrier transport capabilities (large $\mu \cdot \tau$ ~ O(10^{-4} cm^{2}V^{-1}))
- High density and effective atomic number

R&D challenge posed by highly mobile defects (Br^-) which can cause hysteresis and degradation effects

		Silicon	CH_3NH_3 (MA)PbBr$_3$
Density		2.33 g/cm^3	3.8 g/cm^3
Band gap (eV)		1.12 (indirect)	2.24 (direct)
Mobility μ (cm^2/Vs)	electrons	1400	25-140
	holes	450	13-220
Absorption (cm^{-1})		< 10^4	> 4x10^4
Average energy for e/h creation (eV)		3.6	5.8
Radiation length X0 (cm)		9.36	2.33
Z_{eff}		14	62