Compact Space-Borne Telescope for Efficient HE and VHE Gamma-Ray Detection with Oriented Crystals

CRIS-MAC 2024

Ferrara, 6th June 2024

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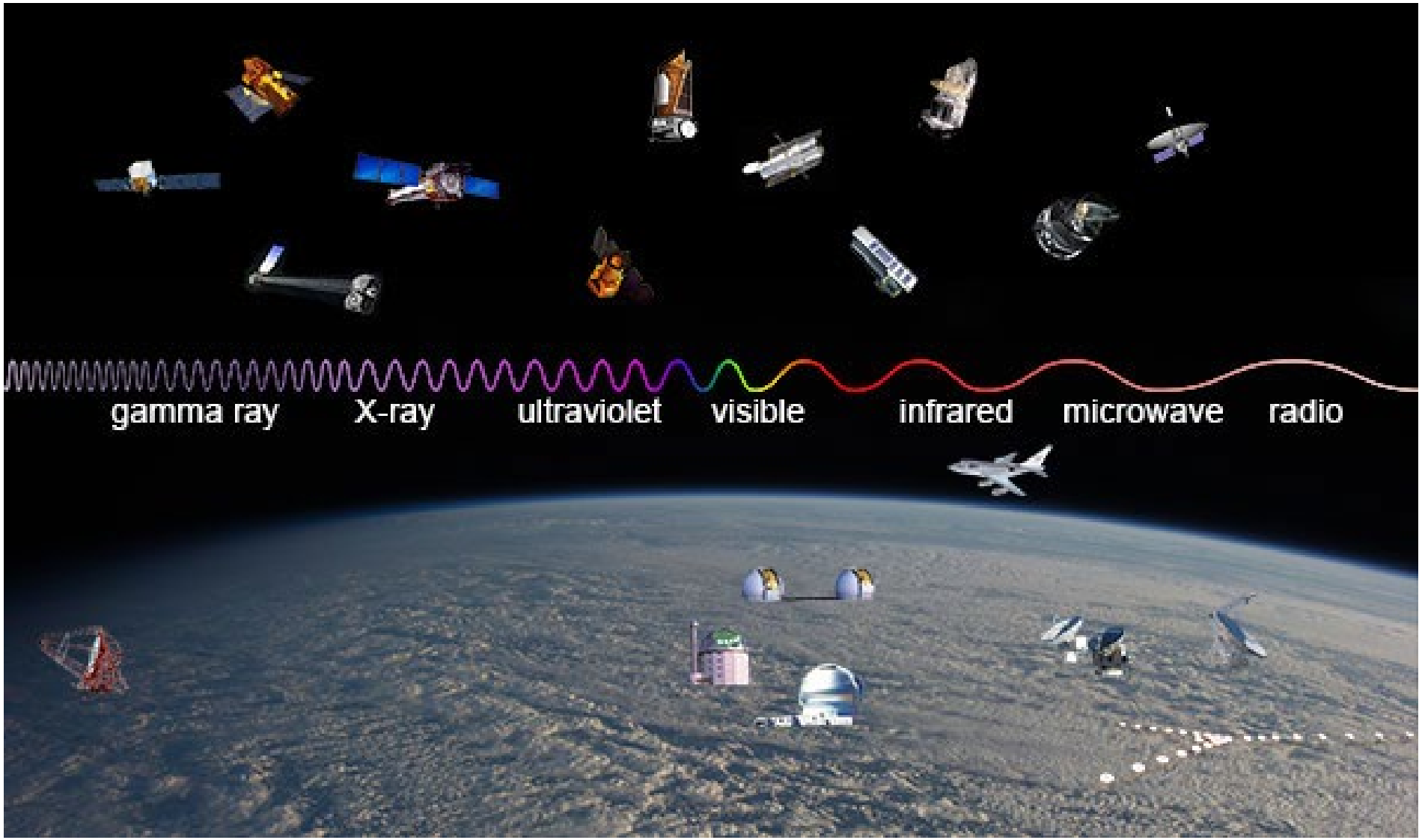
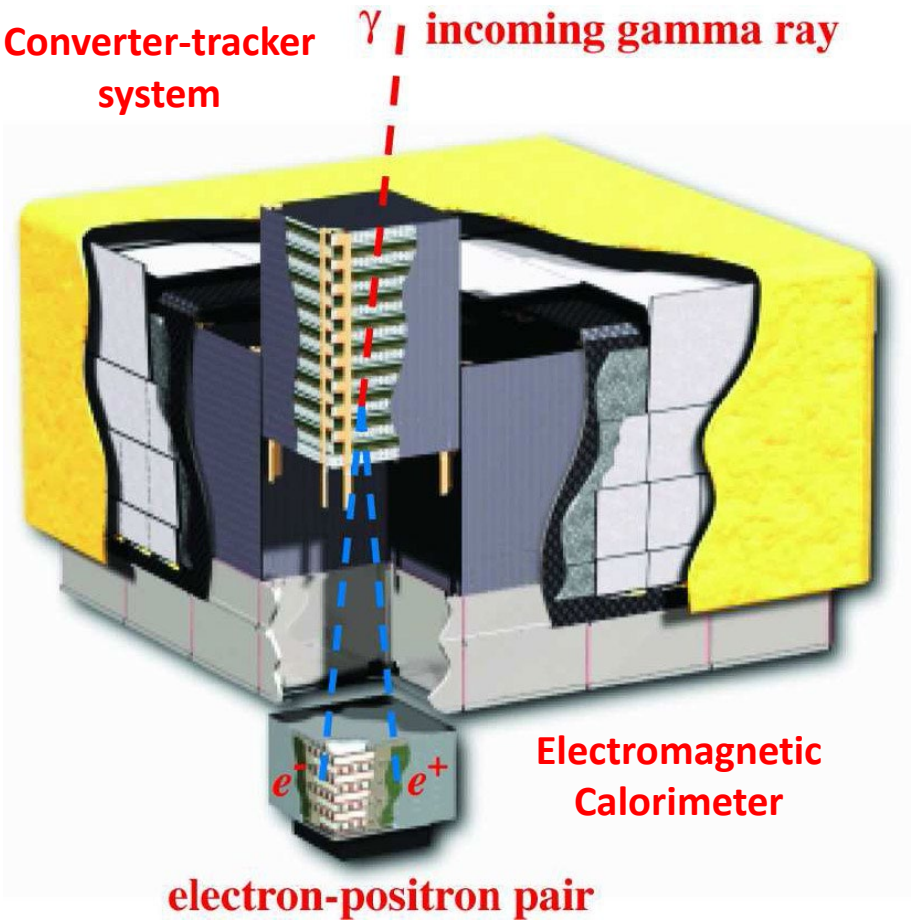
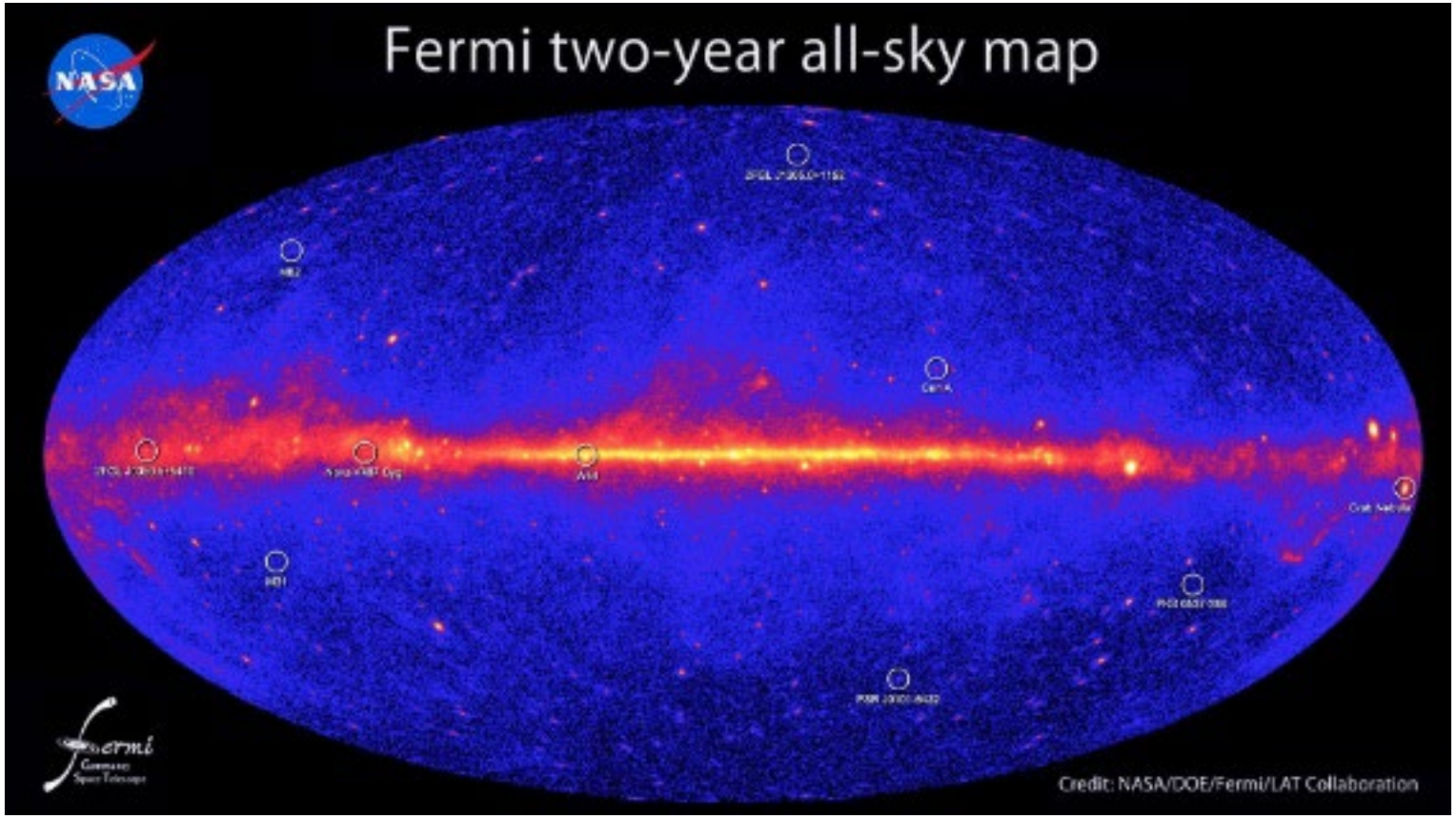
HE and VHE gamma-ray observation from Space



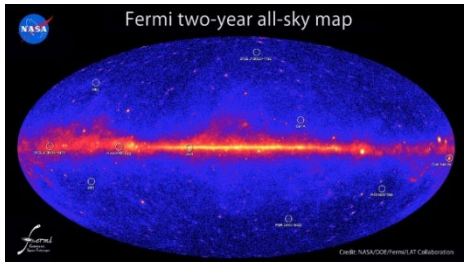
HE and VHE gamma detectors in space

Take the FERMI-Large Area Telescope..

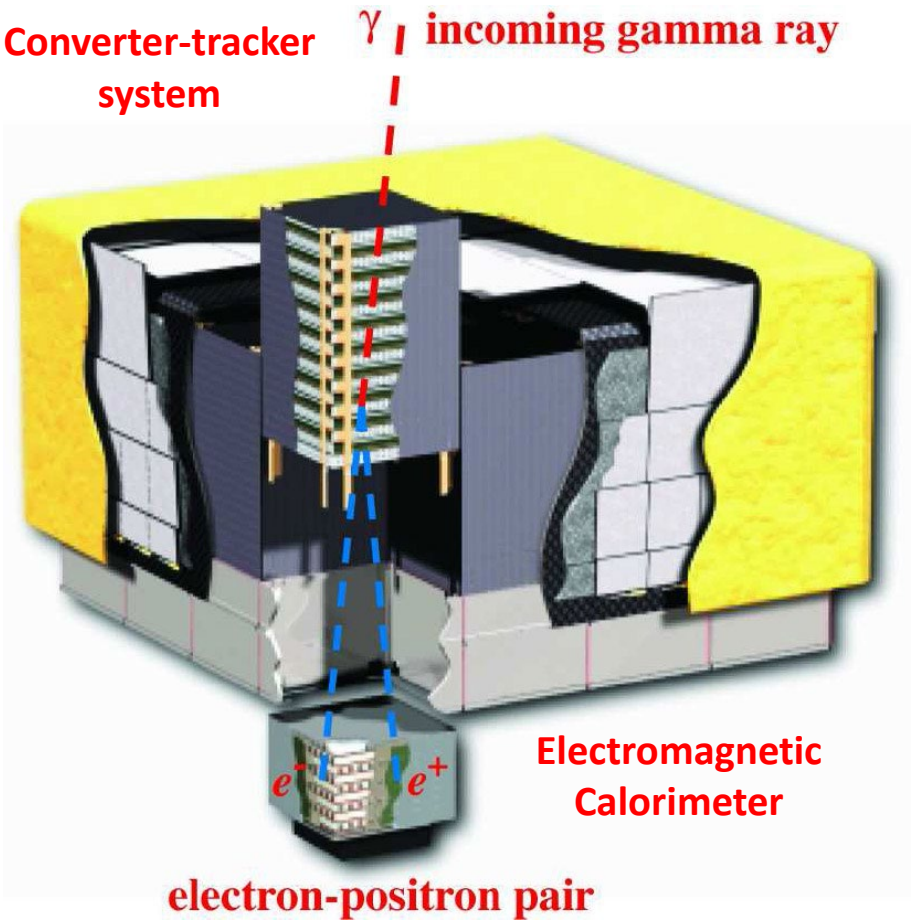




HE and VHE gamma detectors in space



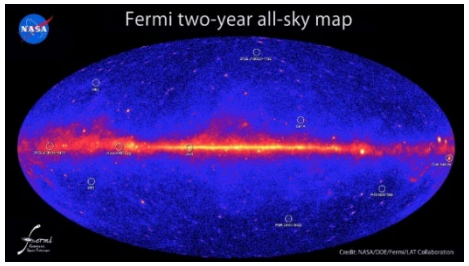
Take the FERMI-Large Area Telescope..



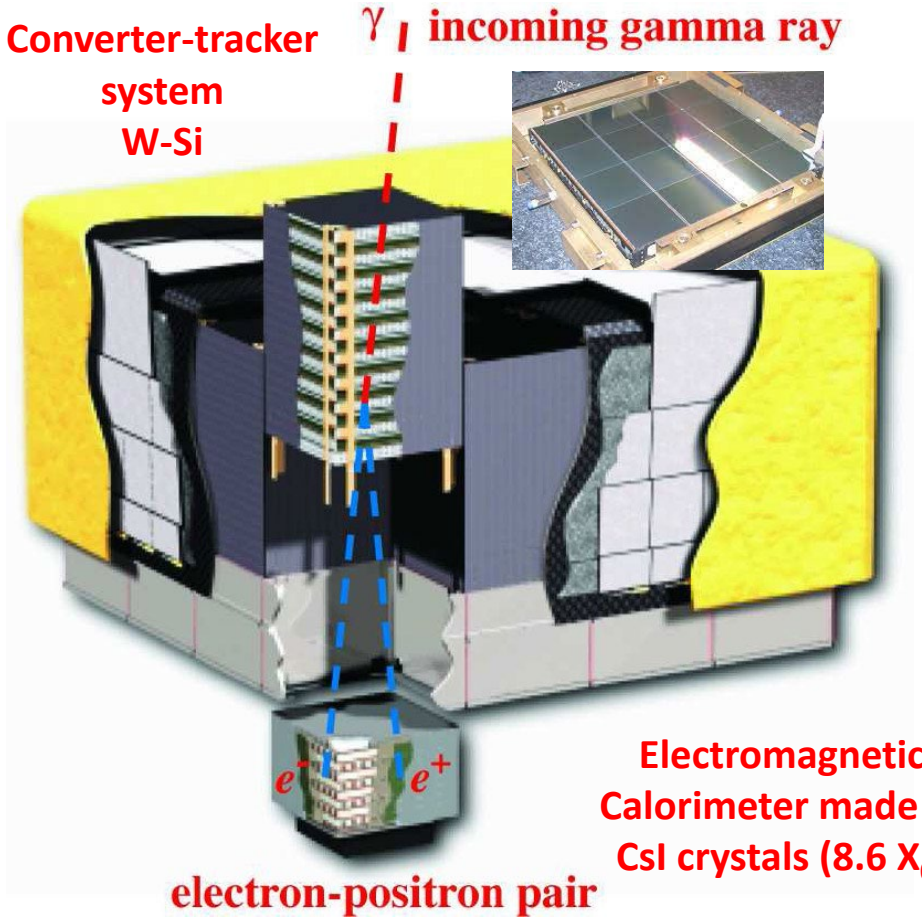
Fermi-LAT is currently doing a great job and will continue for the next years.

Nevertheless, there are **still open questions** (e.g., unidentified gamma-ray sources, the nature of the GeV γ excess from the Galactic Center).

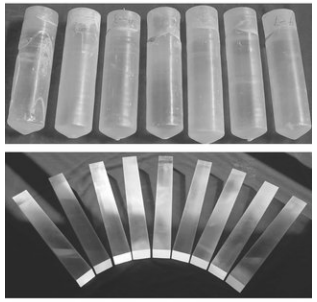
HE and VHE gamma detectors in space



Take the FERMI-Large Area Telescope..

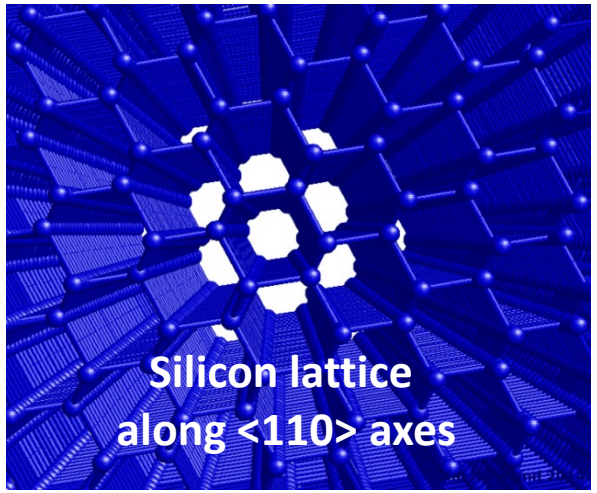


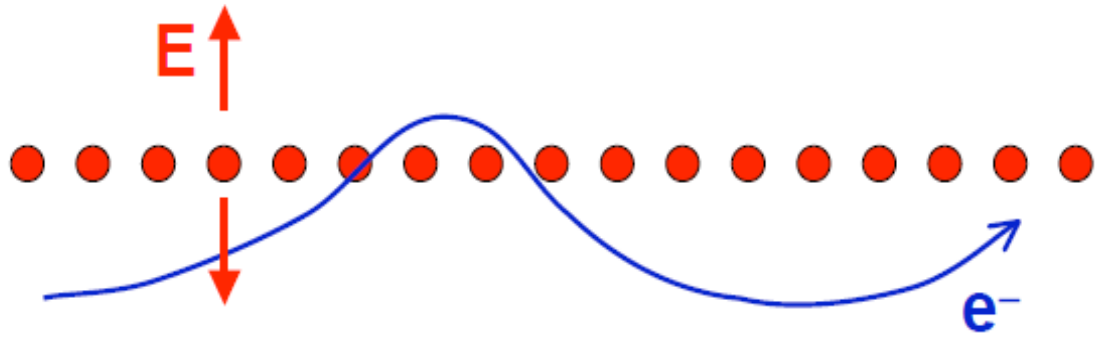
Electromagnetic Calorimeter made of CsI crystals (8.6 X_0)



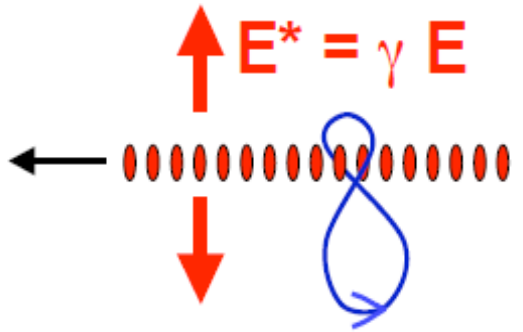
All of these materials have a crystalline structure and can be oriented along some preferred lattice direction

Electromagnetic processes in oriented crystals



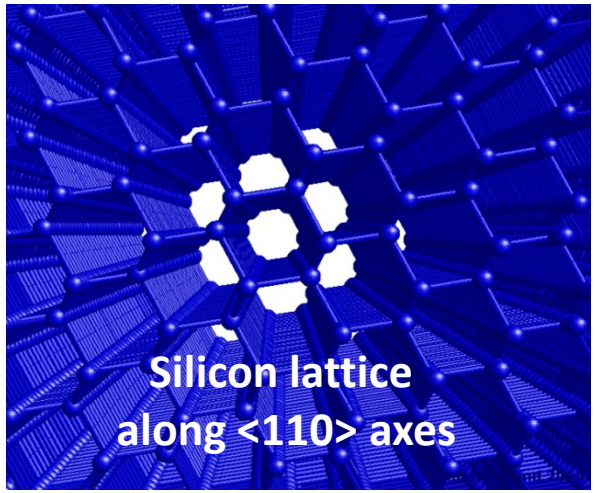


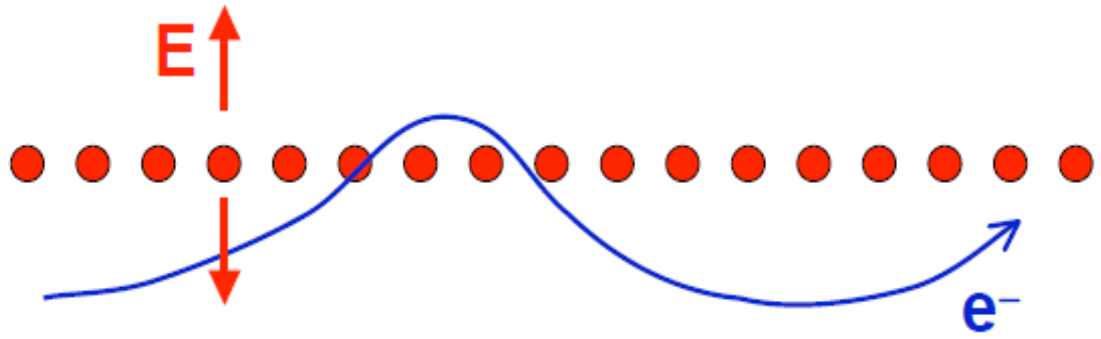
lab. frame



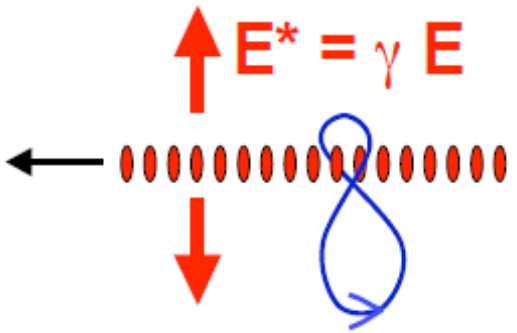
e⁻ - comoving frame

Electromagnetic processes in oriented crystals





lab. frame

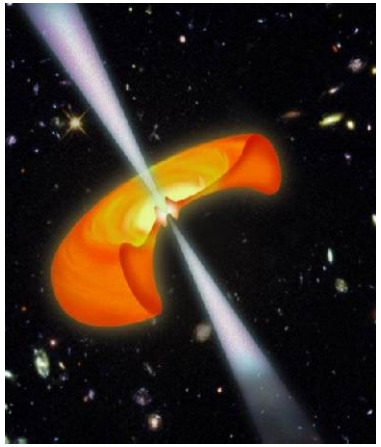


e⁻ - comoving frame

In the comoving frame, the **Lorentz contracted Electric field** can be computed as:

$$E^* = \gamma E$$

Being the Axial field of high-Z crystals $E \approx 10^{11}$ V/cm



Magnetars
B ≈ 10^{10} T

At beam energies > 10 GeV, E* can reach the **Critical Schwinger QED Strong Field**:

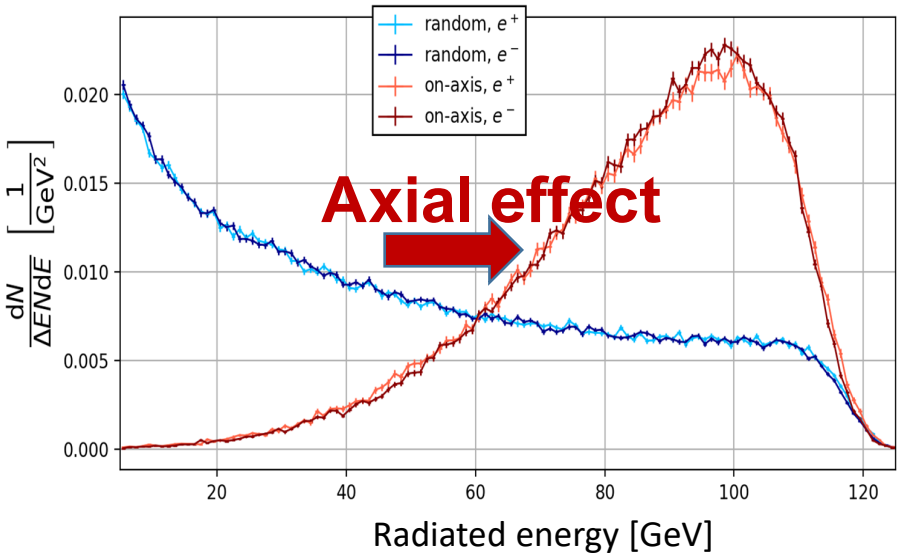
$$E_0 = m^2c^3/e\hbar \simeq 1.3 \times 10^{16} V/cm$$

above which electrodynamics becomes non linear

Ulrik I. Uggerhøj, REVIEWS OF MODERN PHYSICS, VOLUME 77, OCTOBER 2005

Radiation and pair production in axial alignment

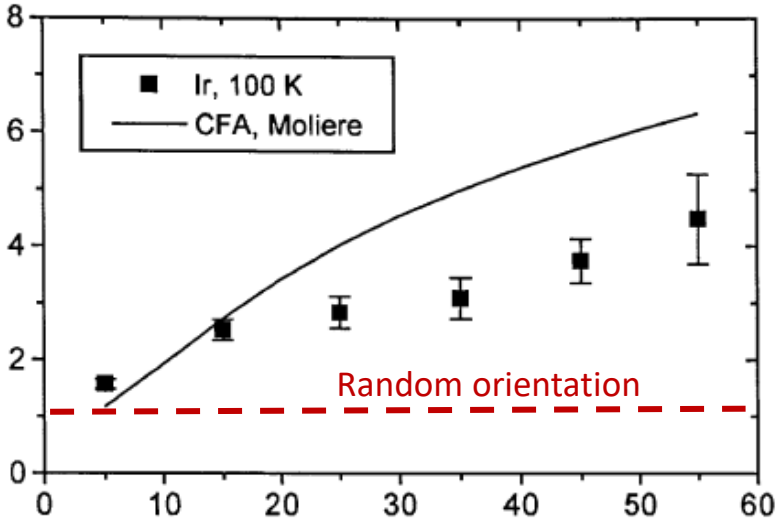
Radiative energy loss spectrum of 120 GeV e± aligned with the <001> axis of a 4 mm PWO scintillator crystal



L. Bandiera et al., Phys. Rev. Lett. 121 (2018) 021603

Enhancement of pair production in a 3 mm Ir crystal axially oriented – compared to random orientation Vs. photon energy

(NA48 exp. @CERN)



Strong field regime

$$E^* \geq E_0$$

- ***Radiation length reduction***
  - **X_0 decreases with initial energy increase.**
- ***Angular range:***
  - **$\Theta_{max} = V_0/m$ (0.1° for W, 0.06° for PWO)**
  - **few mrad up to 0.5°-1°** of misalignment between particle direction and crystal axes;
  - Depends weakly on particle energy.

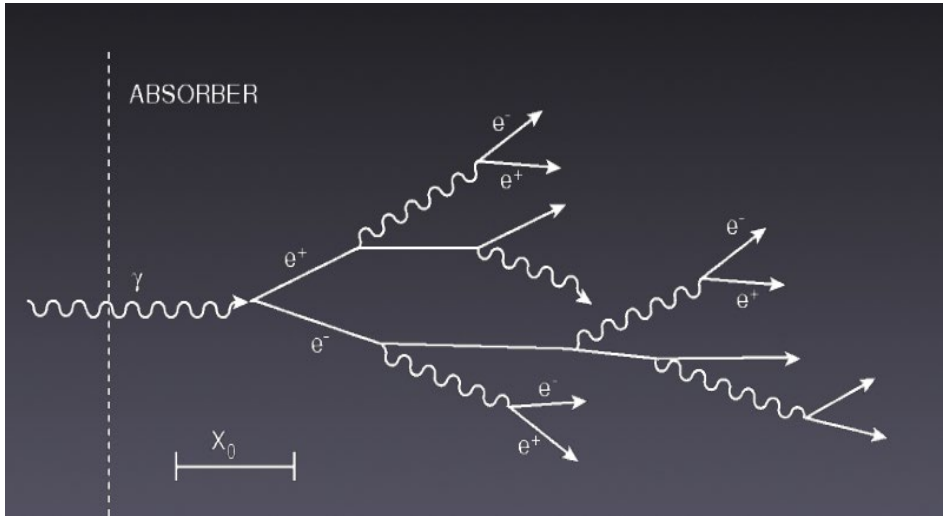
Strong increase in the energy radiated by e± and in the pair production probability by high-energy gamma-rays!

Electromagnetic shower acceleration

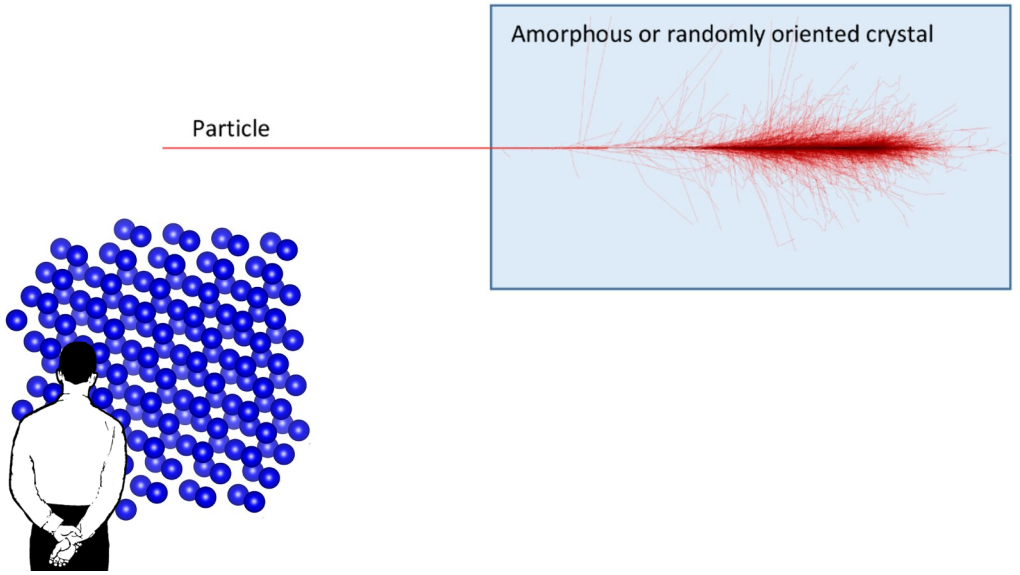
electromagnetic shower is way more compact

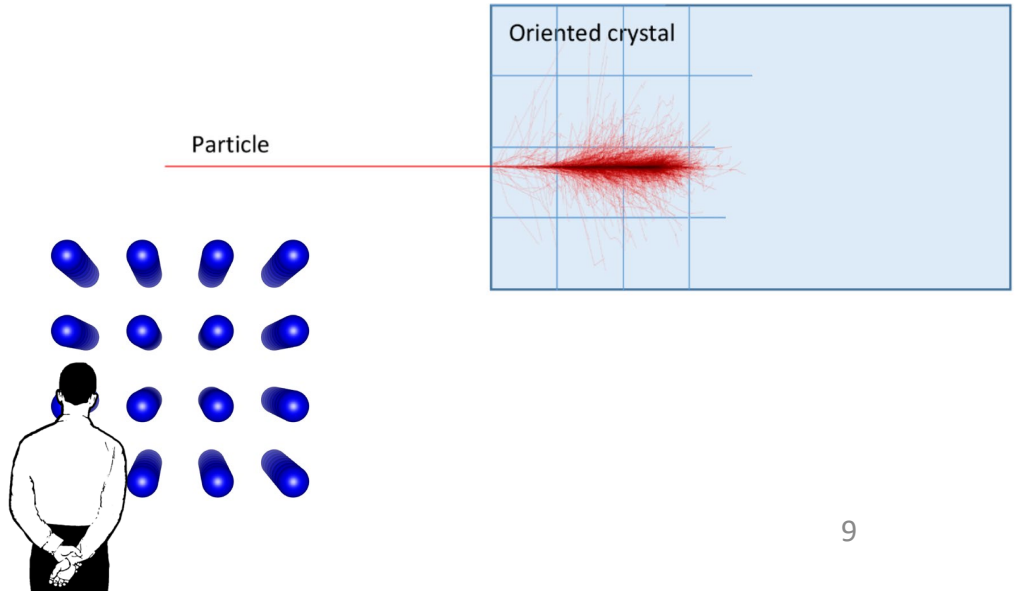
or equivalently

effective radiation length X_0 is much shorter



L. Bandiera et al., Phys. Rev. Lett. 121 (2018) 021603



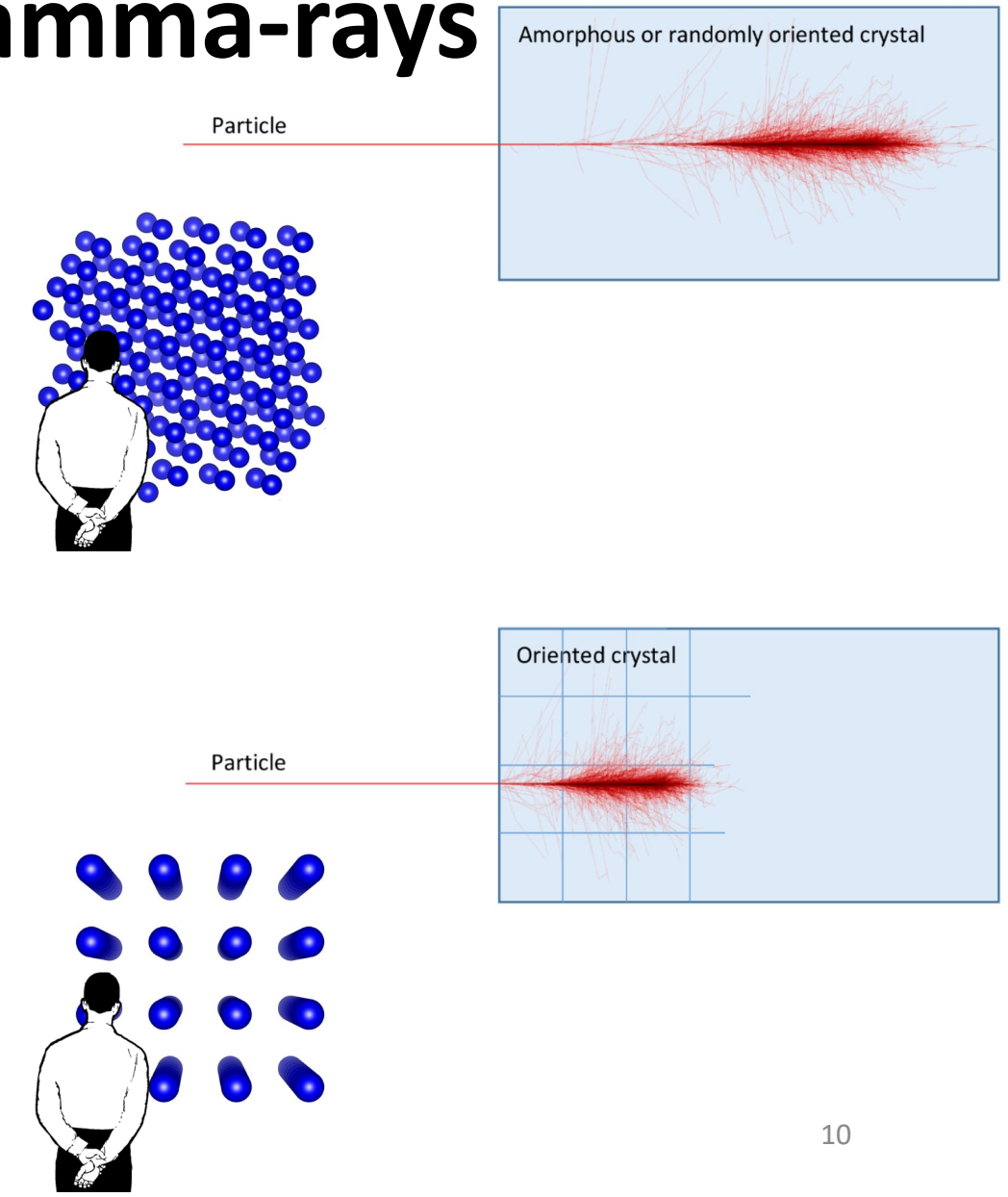


Novel idea: ultra-compact space-borne satellite to detect VHE gamma-rays

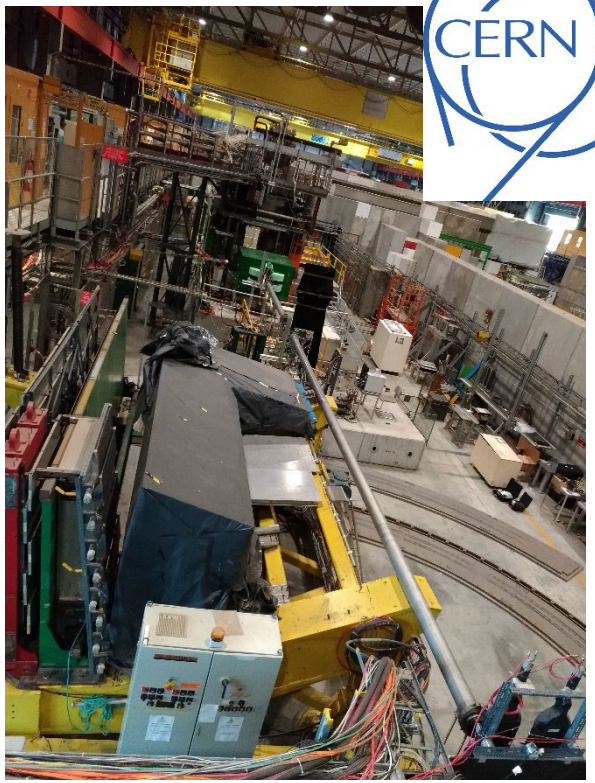
If we point the telescope toward a gamma-ray source..

- **enhance the sensitivity to gamma-rays above GeV;**
- **containing e.m. showers initiated by particles with energies even above 100 GeV in a reduced volume/weight ->**
  - ***cost reduction!!!***
  - *possibility to* ***increase the transverse area (to see more photons!!!)***
  - *could* ***improve*** *the* ***energy resolution***
- **increase the signal-to-background discrimination when the gamma direction is within one or few mrad**

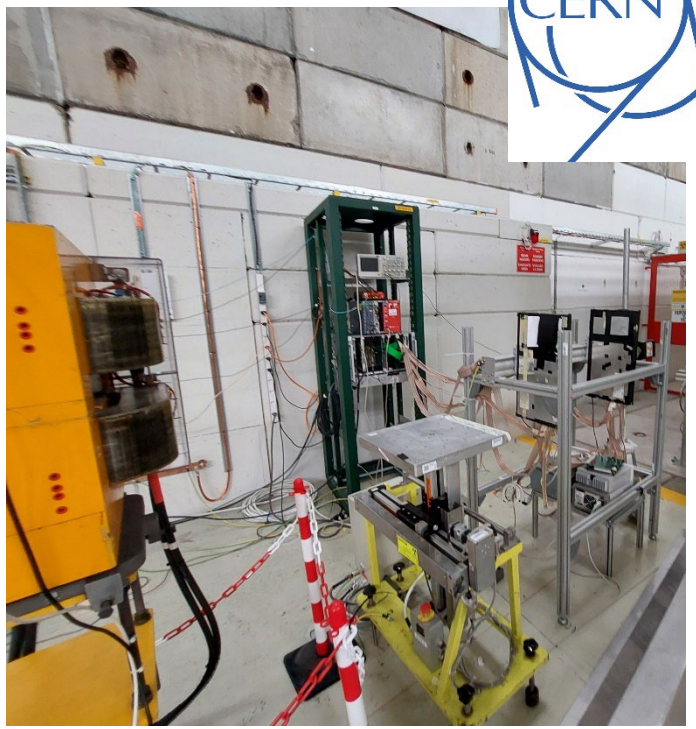
N.B. the system would continue to operate in a standard way in the absence of pointing!



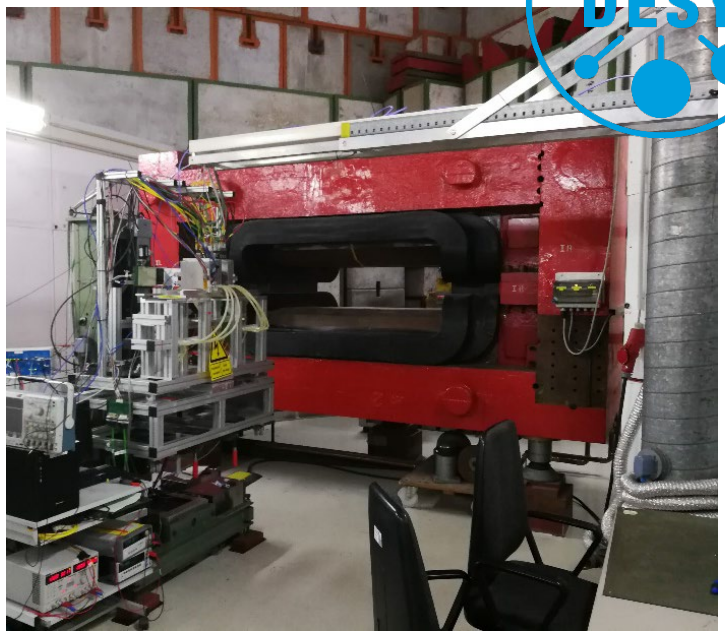
Experimental tests…



e^- & γ @ 10-120 GeV
CERN SPS NA H2
(Geneve, Switzerland)

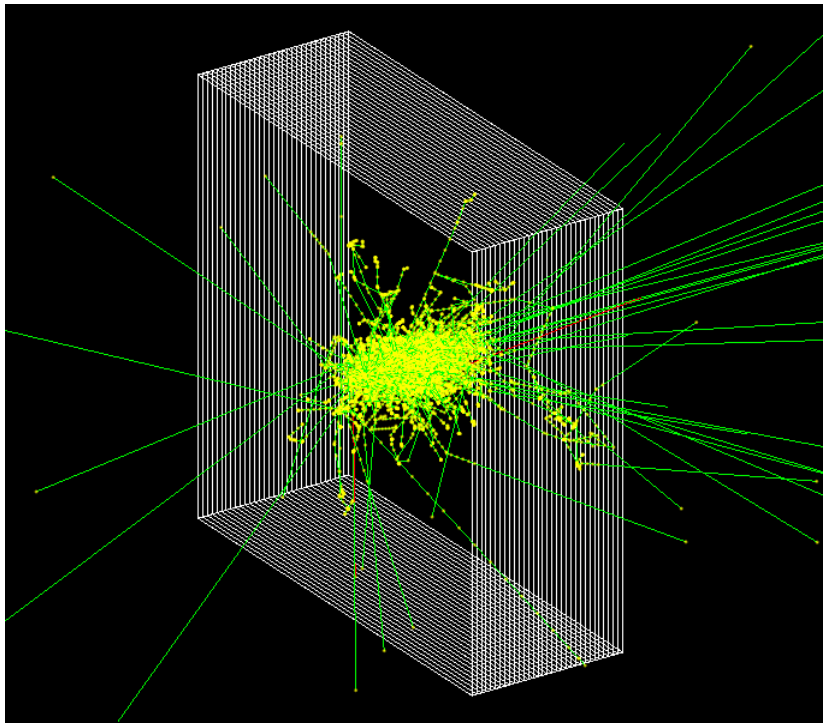


e^- @ 6 GeV
CERN PS EA T9
(Geneve, Switzerland)

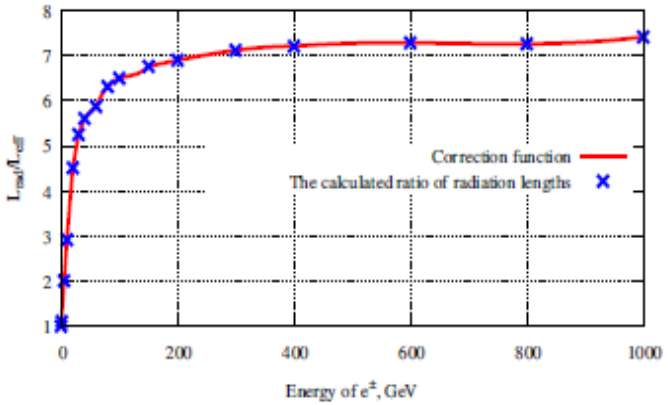


e^- @5.6 GeV
DESY TB (Hamburg, Germany)

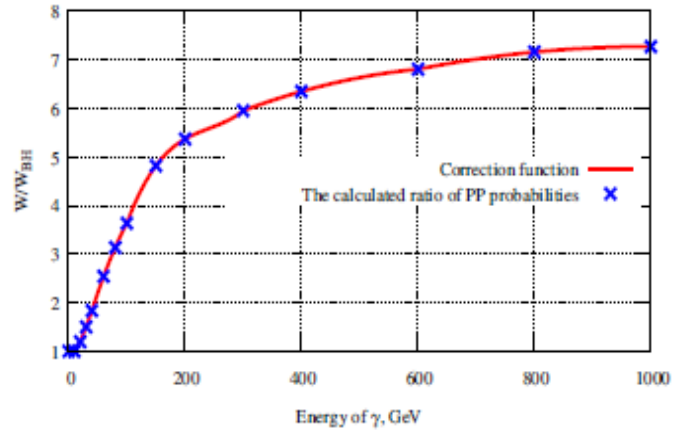
…and Monte Carlo simulations



bremsstrahlung



Pair production



The electromagnetic shower is simulated using the **Geant4** toolkit in which the cross sections for **bremsstrahlung and pair production are rescaled** in agreement with full Monte Carlo including the strong field effects in crystals*.

***L. Bandiera, V. Haurylavets and V. Tikhomirov NIM A 936 (2019) p.124-126**

European Commission

Alexei Sytov (INFN-FE)
Marie Curie Individual fellow
TRILLION coordinator

Trillion https://www.fe.infn.it/trillion/

The project TRILLION is dedicated to the implementation of electromagnetic processes in oriented crystals into Geant4

Pointing the tracker-converter system…..

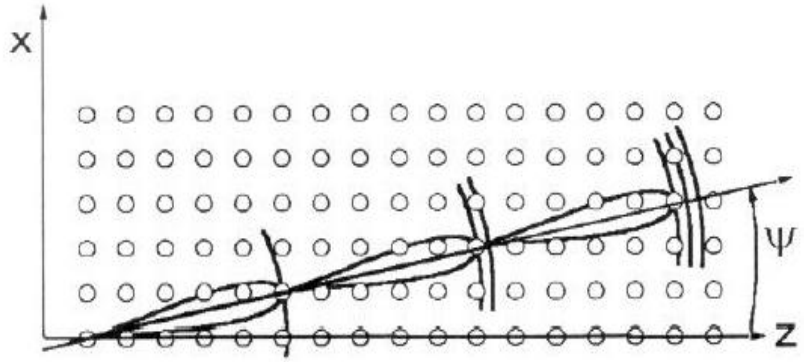
In case of pointing gamma sources within 0.5°-1°, one may **substitute the W amorphous foils with crystalline W**, leading to:

- **Possible reduction of tracker length**, while maintaining or **even increase the sensitivity to gamma with E > few GeV**

- **Pair production enhancement possible also for Silicon and <u>for lower energy photons (hundreds of MeV) in case of off-axes orientation due to Coherent Pair Production</u>**

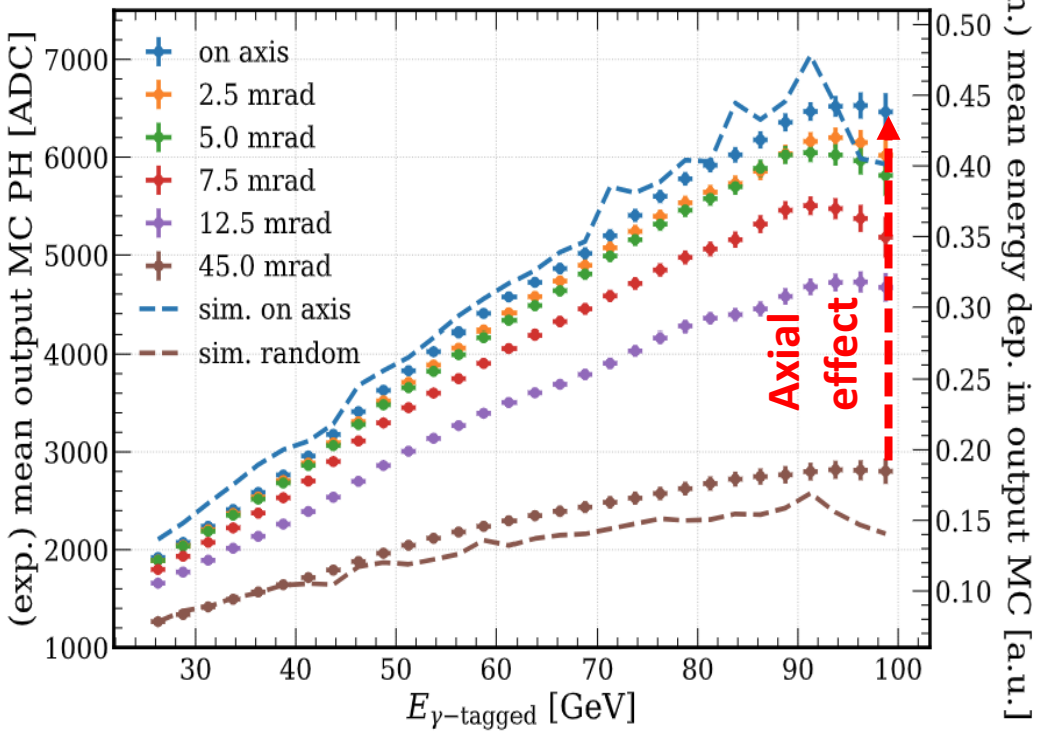
Interference of pair production on different atomic strings gives rise to pair production enhancement.

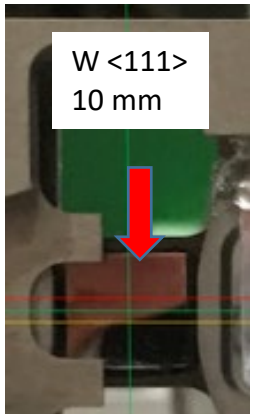
G. Diambrini Palazzi, Rev. Mod. Phys. 40 (1968) 611



Pair Production in W crystal by a VHE gamma beam @CERN SPS

*Energy deposited in a plastic scintillator after the crystal (i.e. **the pair production enhancement**)*





Gamma-ray energy: 25-100 GeV
Crystal: W <111>, 10 mm long (~2.85 X_0)

- **The gamma conversion in pairs in an aligned W crystal increases with photon energy**
- The enhancement is maximal in the case of axial alignment and diminishes as the misalignment between the gamma direction and crystal axes increases.
- **A measurable enhancement is visible up to 0.7°**

M. Soldani, L. Bandiera, M. Moulson et al., Eur. Phys. J. C 83, 101 (2023)

…and orienting the e.m. calorimeter

Simulation of the e.m. shower of HE electrons in a PWO crystal

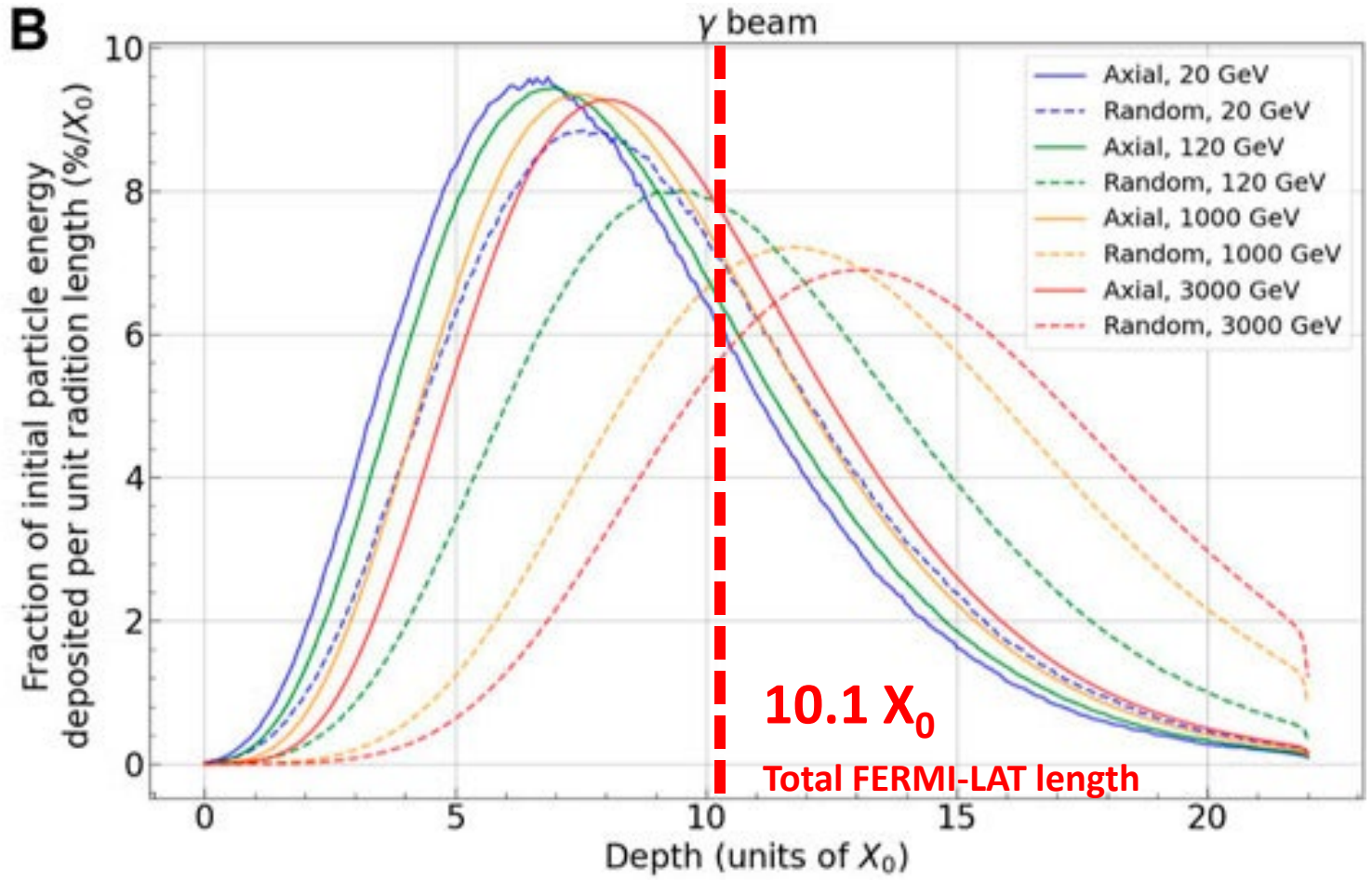
scintillators emitters commonly employed in electromagnetic calorimetry (CsI, BGO, PWO..)

the input electromagnetic showers can <u>fully develop in a much lower thickness with respect to the current state-of-the-art detectors</u>

→ enhanced compactness

→ budget-saver

→ n/γ discrimination



Longitudinal development of the e.m. shower in 21 X_0 PWO axial vs. random

OREO - ORiEnted calOrimeter **L. Bandiera et al., Front. Phys. 2023 11:1254020. doi: 10.3389/fphy.2023.1254020**

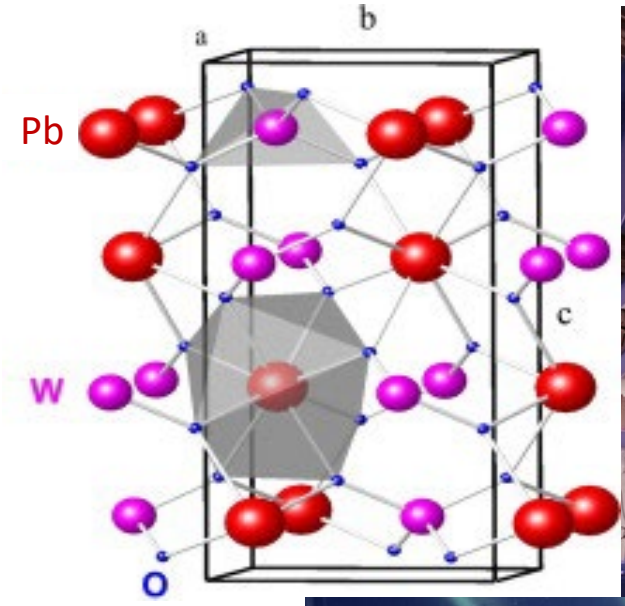
Crystal investigated: Lead tungstate ($PbWO_4$)

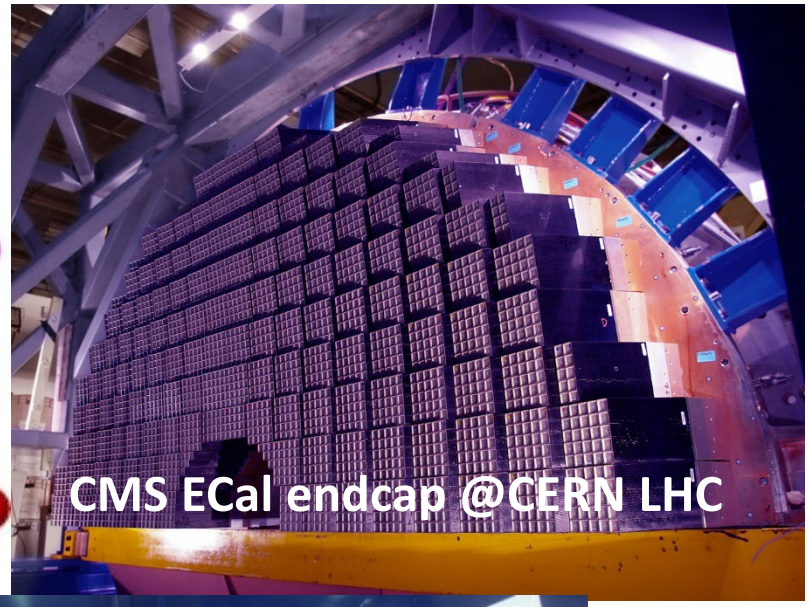
- scintillator, with well-peaked light emission in the blue
- optically transparent
- exploited by the CALET ECal → well known
- high density, high *Z* ***X_0 = 8.9 mm***
- radiation hard
- cheap fabrication into big samples and with good crystalline quality
- axes properties

	[100]	[001]
interatomic pitch	5.456 Å	6.01 Å
U_0	~700 eV	~500 eV
SF threshold	~25 GeV	

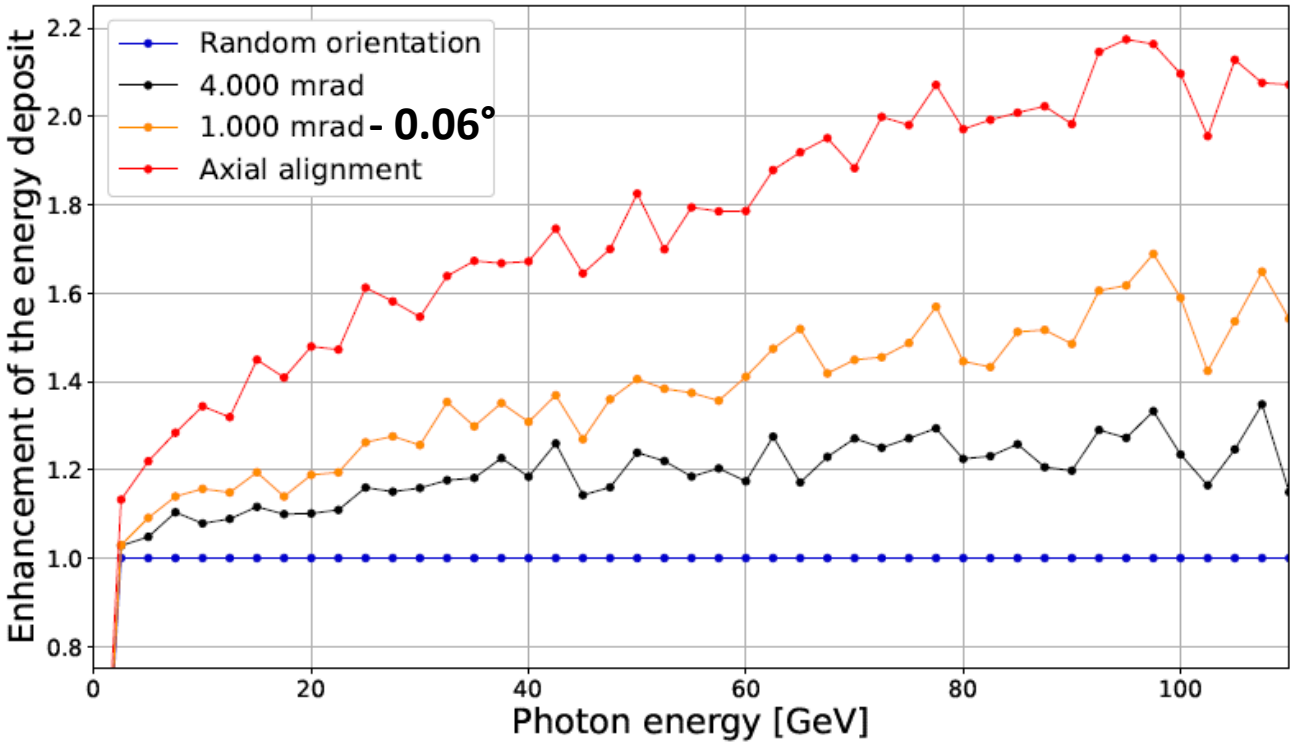
High-Z crystal for compact detectors

Maximum of Strong Field within $\Theta_{max} = V_0/m \approx 1$ mrad

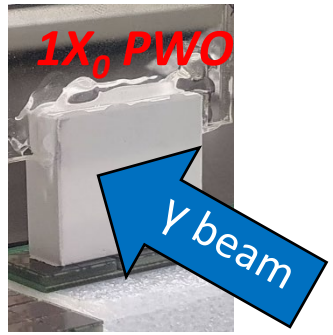


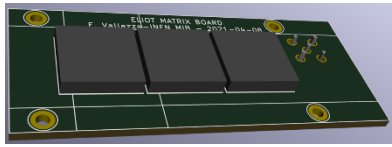


Deposited energy inside an oriented scintillator crystal by a HE gamma beam



CERN SPS NA H2 beamline
Beam: γ @5-100 GeV
Crystal: PWO , 1 X_0 (9 mm)
(CALET, CMS @LHC, PANDA @FAIR)





SiPM matrix readout

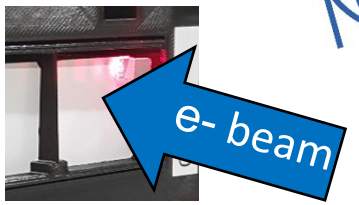
Enhancement *of the* ***energy deposited inside the crystal*** *by the photon beam in axial orientation as* ***measured by SiPM*** *vs. the photon energy*

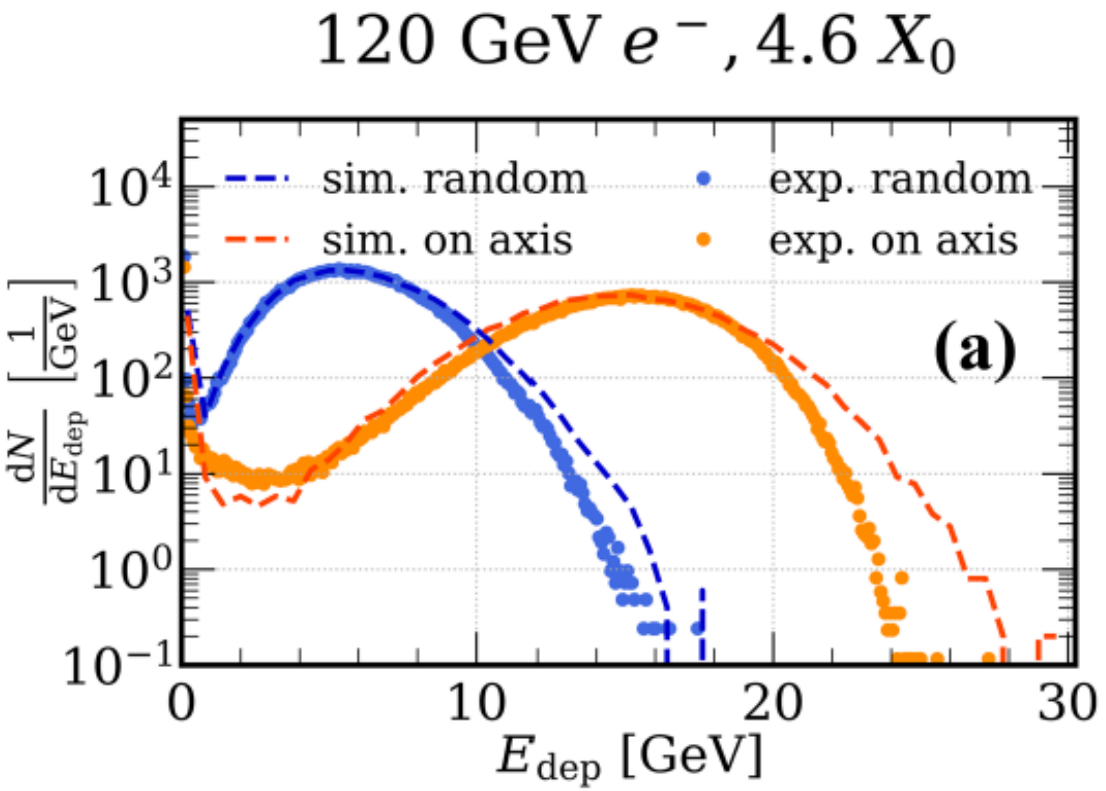
M. Soldani et al., arXiv:2404.12016v1

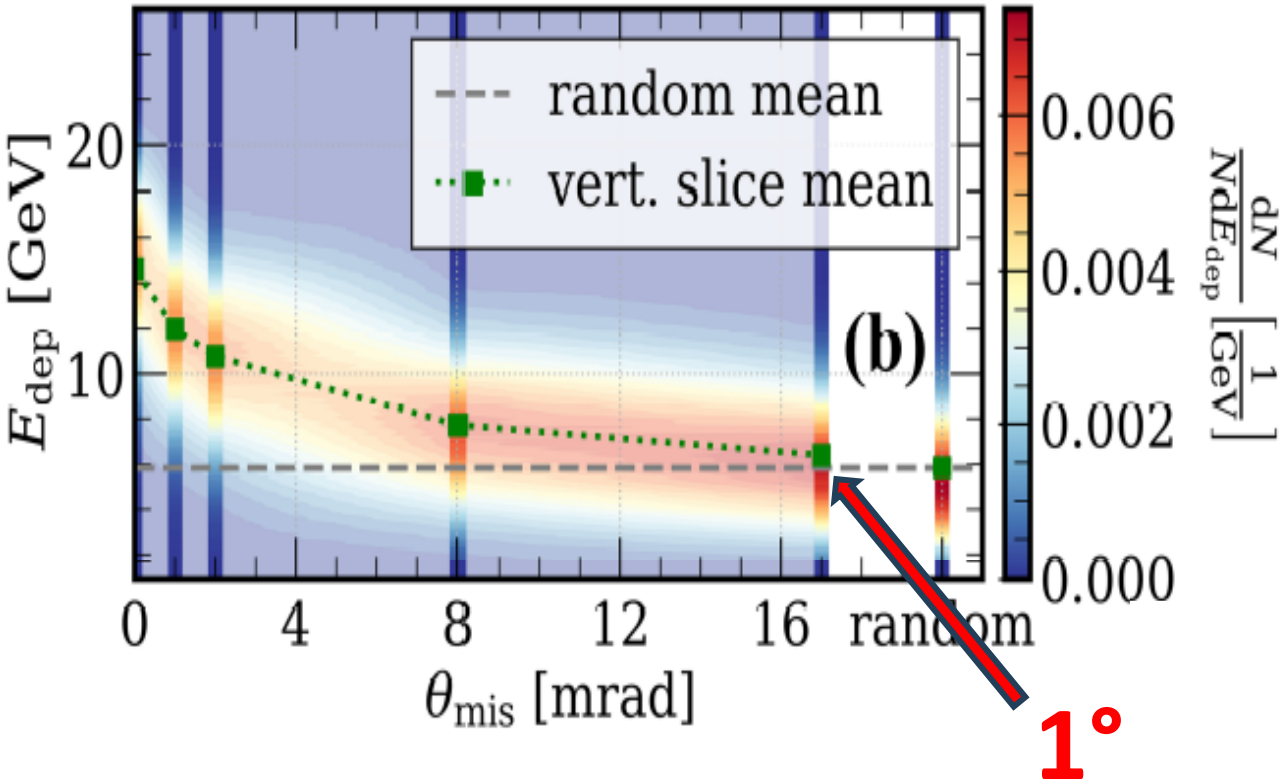
Work done in collaboration with the HIKE/KLEVER&CRILIN team

Deposited energy inside an oriented scintillator crystal by 120 GeV electrons

CERN SPS NA H2 beamline
Beam: electron @120 GeV
Crystal: PWO , 4.6 X_0

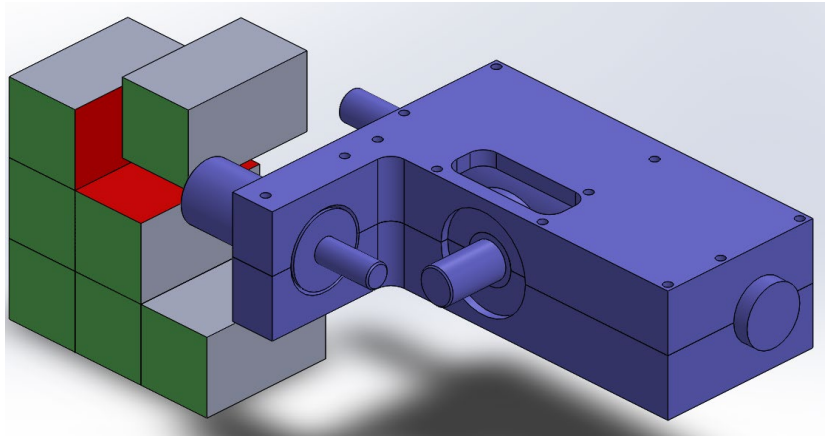




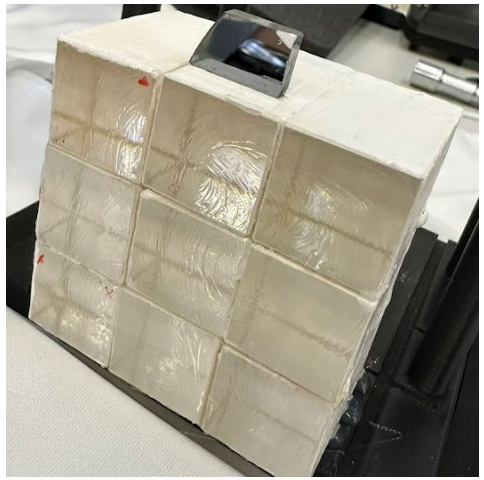


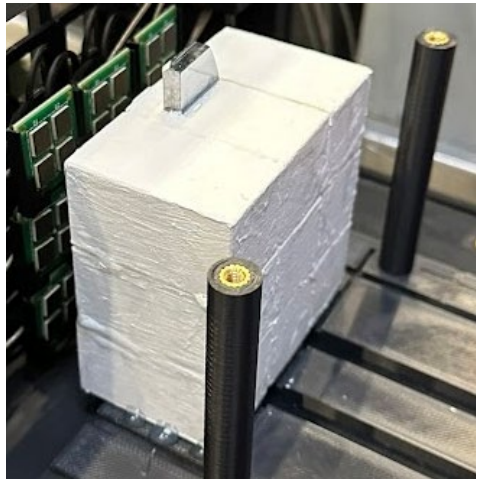
M. Soldani et al., arXiv:2404.12016v1

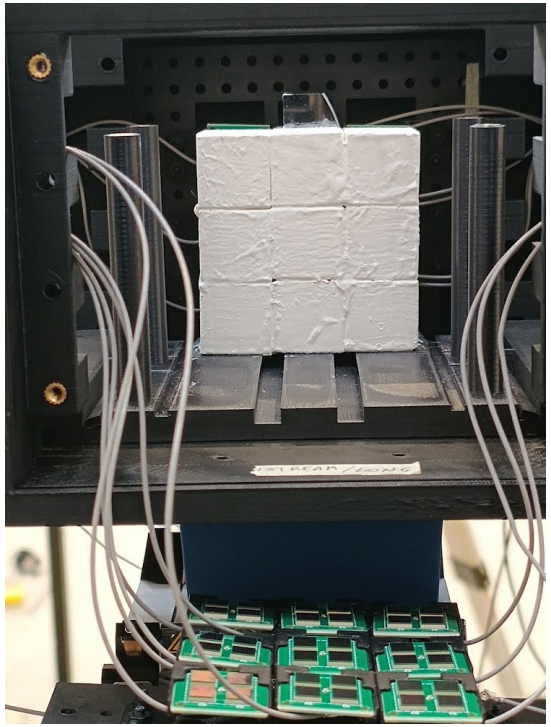
Construction of the OREO prototype
3x3 matrix



Orientation control: handling system based on motorized optomechanical components (Thorlabs) and autocollimator laser







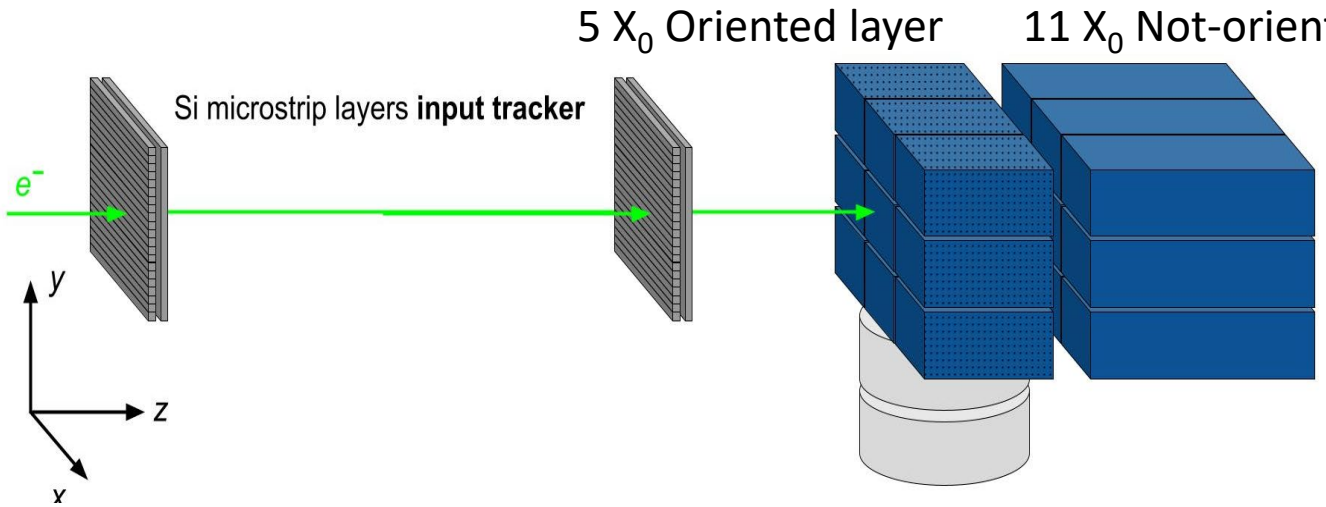
Crystals were coated with a reflective paint and the glued together.

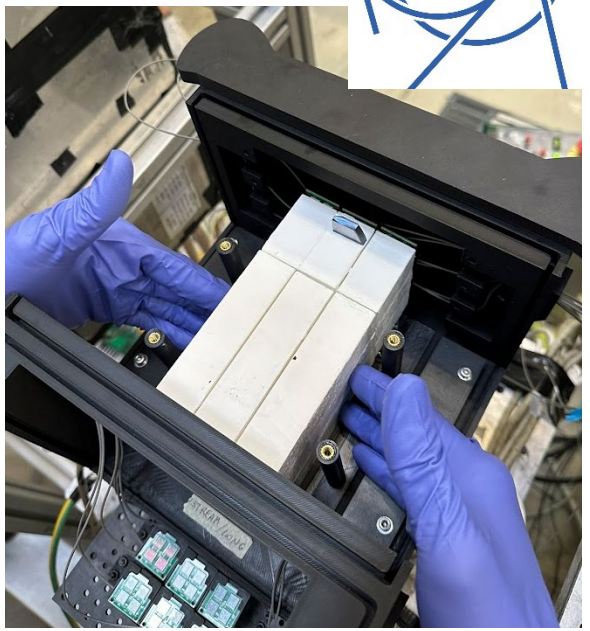
Misalignment < 0.3 mrad ($< \Theta_{max}$)

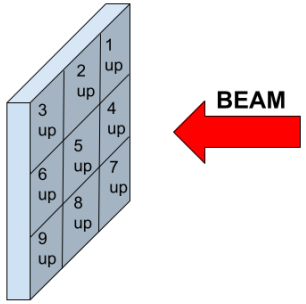
Readout: SiPM matrix, each coupled to one of the three crystals

Experimental test of the OREO prototype

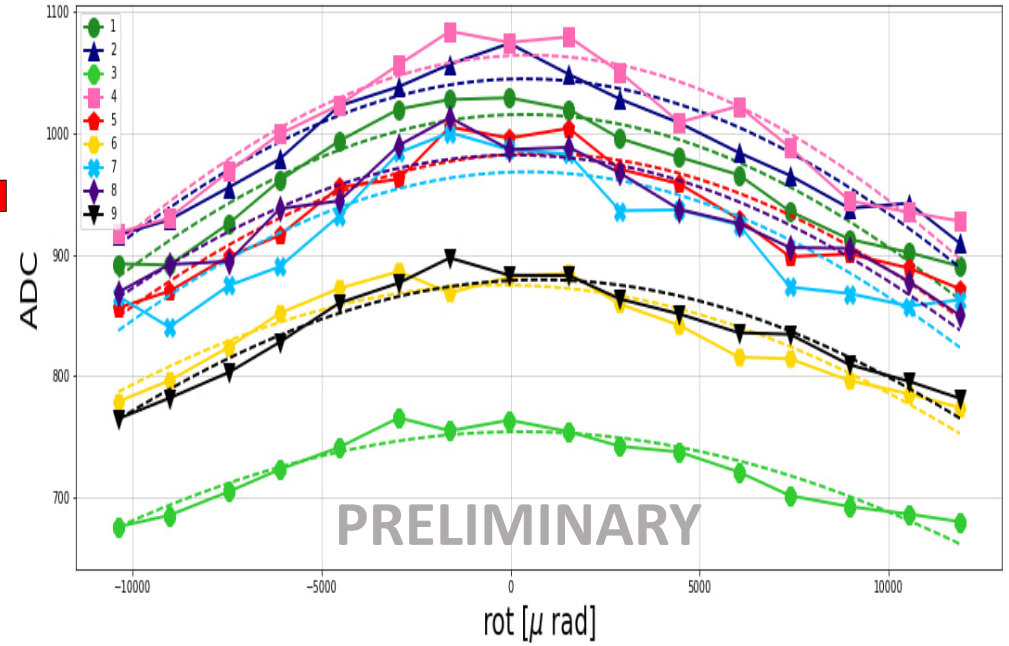
3x3 matrix







BEAM

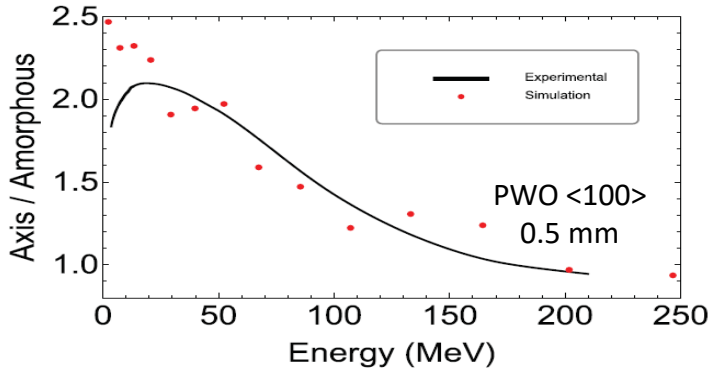


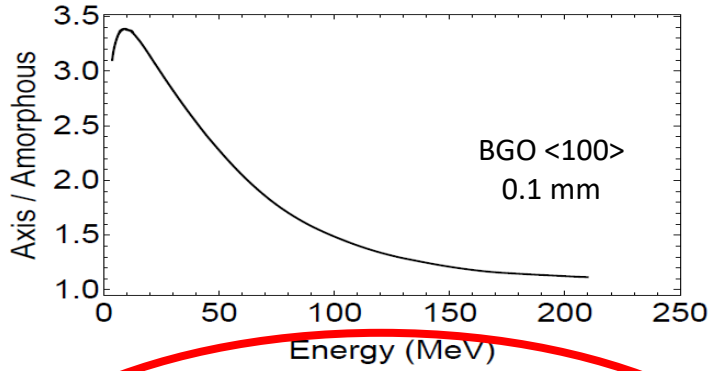
Tested @CERN PS/SPS last week with 6 GeV electrons

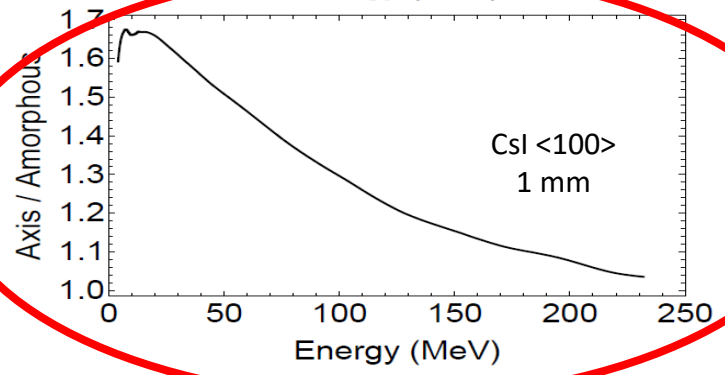
Energy deposited in the 9 OREO oriented crystals (ADC) vs. crystal orientation (zero is for axial positon)

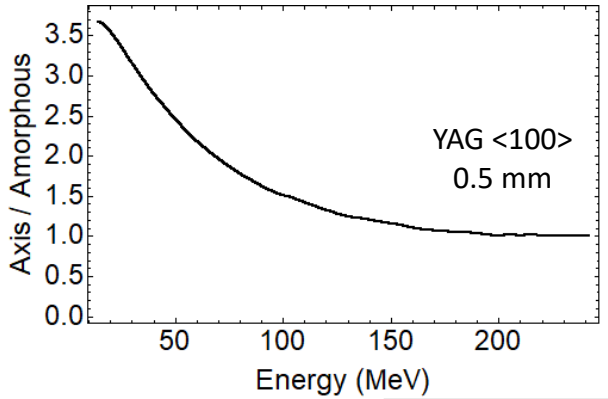
All the crystals respond in the same way-> perfectly aligned with each other.

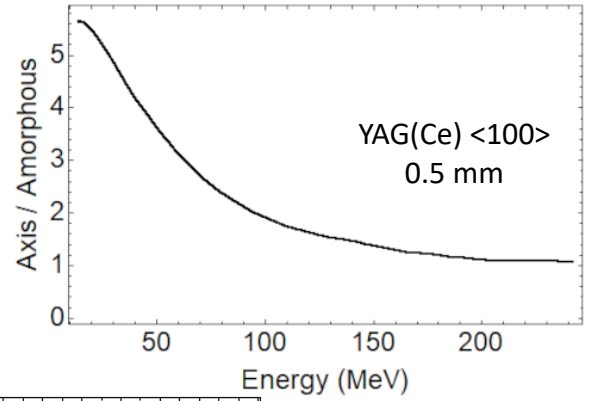
Just to mention: electromagnetic processes are modified not only in PWO..

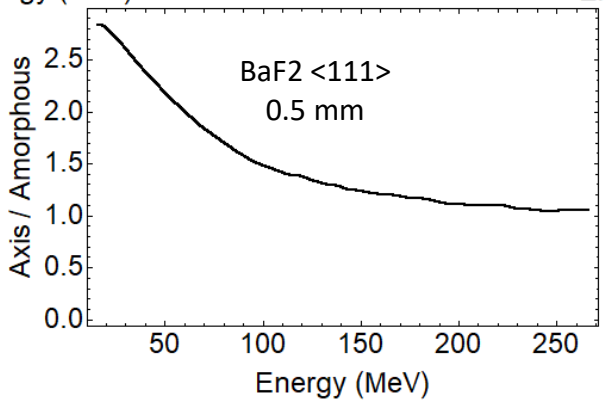












- Bremsstrahlung radiation enhancement in axial orientation in the [0, 150] MeV range (e- beam @855 MeV – below Strong Field threshold), which **indicates an enhancement of the electromagnetic processes inside the axially oriented crystals.**
- **First measurements ever of radiation enhancement** due to coherent orientational effects for all these **scintillator crystals (PWO, BGO, CsI, YAG(Ce), BaF2)**.

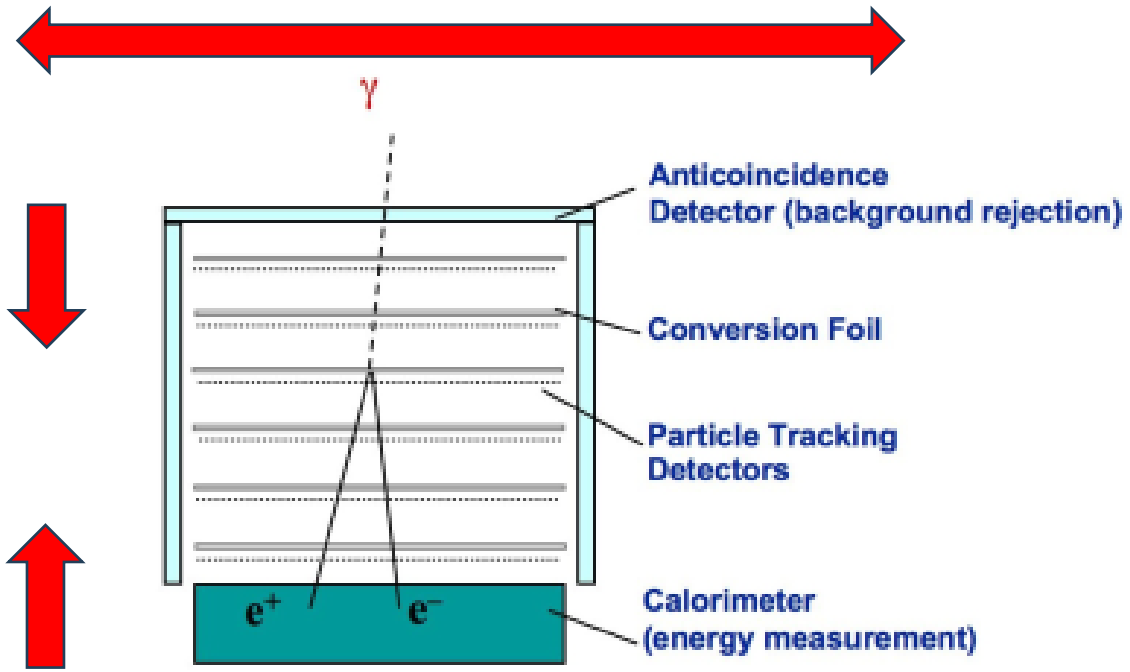
R. Negrello et al. Investigation of radiation emitted by sub GeV electrons in oriented scintillator crystals, NIM A(2024)

Summarizing.. A compact oriented crystals based satellite may be useful in future missions…

- To **increase the sensitivity in the pointing direction** above few GeV (better signal-to-background)
- To **improve the shower containmen**t up to TeV and more **-> cost reduction!**
- To **increase the detector area** with a reduced volume

Summarizing.. A compact oriented crystals based satellite may be useful in future missions…

- **Above 1 GeV**, the primary challenge is the **very limited photon flux**. Reducing the longitudinal dimension of the calorimeter would enable **the increase of the detector area** (to **see more photons**!) at no net cost in weight
- **or to realize lighter detectors**, thus increasing the space mission feasibility and/or that can be rotated fast enough to measure HE/VHE transient/multi messenger signals.

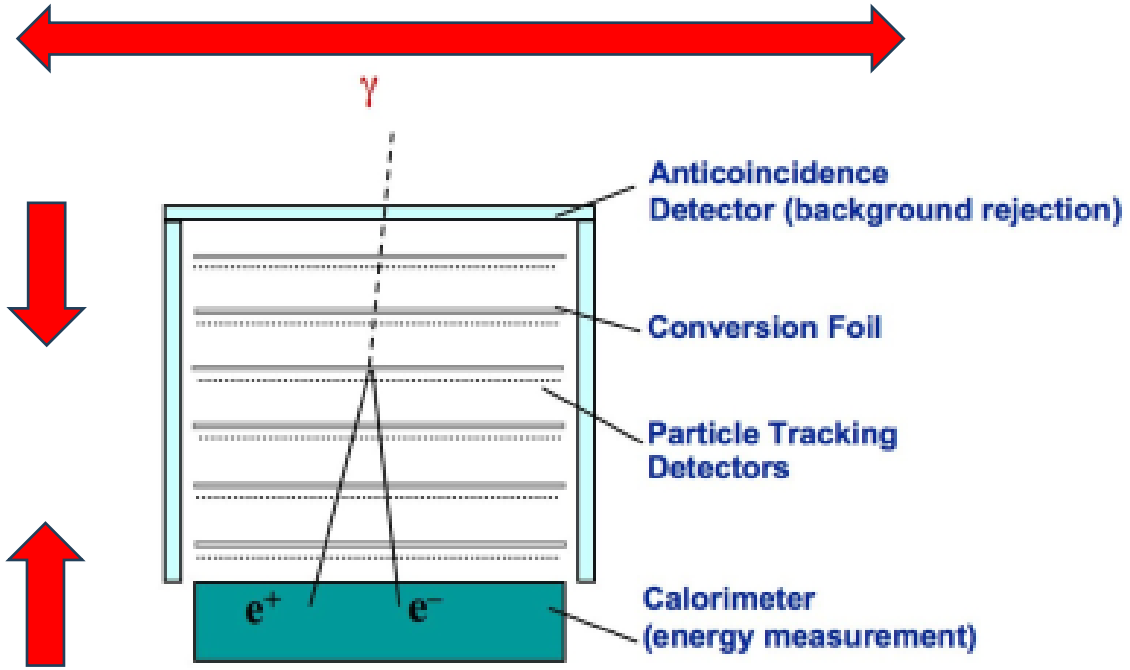


Summarizing.. A compact oriented crystals based satellite may be useful in future missions…

Possible applications:

- measurement of **unidentified γ-ray sources**
- **or investigate the γ excess in GC for indirect dark matter (DM) search…**
- **Follow up** of flaring/transient and multimessenger sources;

Tailored **for joint strategy observation with the new IACTs observatories** in the energy range above GeV up to hundreds GeV - TeV



Acknowledgment

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Other: R. Gaitskell and S. Koushiappas (Brown University); Kihyeon Cho (KISTI); V. Haurylavets and V. Tikhomirov

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Thank you for your attention!