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Istituto Nazionale di Fisica Nucleare

European Commission

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Korea Institute of
Science and Technology Information

Trillion

Application of crystalline calorimeters for the detection of cosmic γ-rays rays
Project TRILLION GA n. 101032975

Dr. Alexei Sytov

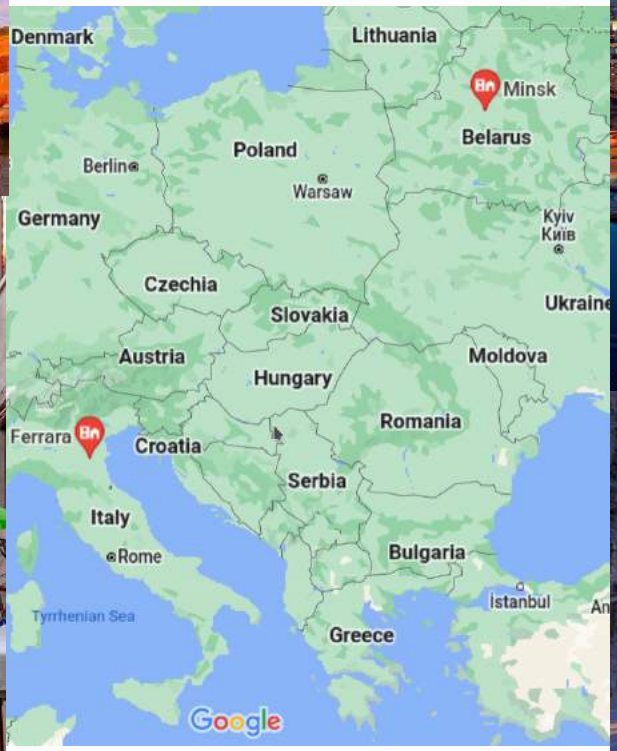
Daejeon, 04/07/22

Outline

- **Briefly about me**
- **TRILLION - Marie Curie Individual Global Fellowships project**
  - The idea of the project
  - Main applications
- **The idea of oriented crystals for γ-ray astronomy**
  - Radiation and pair production in oriented crystals
  - Electromagnetic shower in oriented crystals
  - The concept of γ-ray astronomy space telescope
- **Investigations in progress**
  - Briefly about my group
  - Experimental results
  - Simulations
  - Implementation of the new physics into Geant4
- **What can be observed with** γ-ray space telescopes

Where I am from?

I work in
Italy, Ferrara

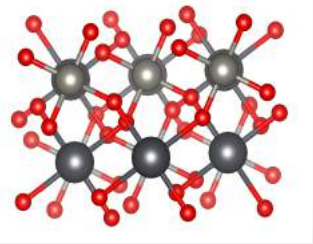


Originally I am from
Belarus, Minsk

Briefly about me

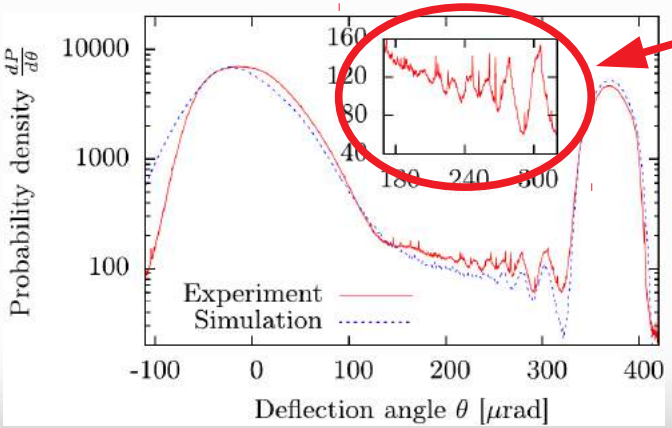
- **2018: 2 PhDs –** in Experimental Physics, University of Ferrara and in Theoretical Physics, Belarusian State University
- **2019-2021**: **Post-doctoral Fellow** in Experimental Physics at the INFN Division of Ferrara.
- Since **2020** involved in **MC_INFN** – INFN **Geant4** project
- Since **02/09/2021**: Marie Sklodowska-Curie Action Global Individual Fellowships, GA n. 101032975 – project Trillion
- **My field**: **Electromagnetic effects** of charged particles interaction with **oriented crystals** (deflection, radiation and pair production) and their applications in **accelerator physics**, **detector physics**, **nuclear physics**, **medical physics**.
- **Effects**: **Channeling**, channeling radiation, coherent pair production

e+/e-/γ; hadrons



Briefly about me

- **New effect predicted and observed experimentally**: **Quasichanneling oscillations** in the deflection angle distribution*
- **Software designed**: **CRYSTALRAD** simulation code – simulations of channeling, channeling radiation and crystal-based extraction from an accelerator.
- **High Performance Computing experience**: HPC Monte Carlo simulations, usage of **CINECA** supercomputing center resources since 2015, **PI** of 5 projects.
- **Additionally**: Fortran, C/C++, Mathematica, Python, Geant4, Keras deep learning framework.



Quasichanneling oscillations

*T. N. Wistisen, …, and A. Sytov. Phys. Rev. Lett. 119, 024801 (2017)

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Marie Sklodowska-Curie Action Global Individual Fellowships by A. Sytov in 2021-2024, Project TRILLION GA n. 101032975

Main goal: The **implementation** of both physics of **electromagnetic processes in oriented crystals** and the design of specific applications of crystalline effects into **Geant4** simulation toolkit as Extended Examples to bring them to a large scientific and industrial community and under a free Geant4 license.

Group:

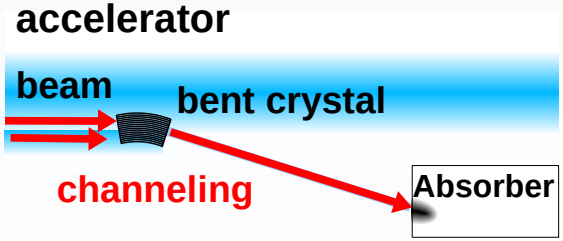
- **A. Sytov** – project coordinator
- **L. Bandiera** – INFN supervisor
- **K. Cho** – KISTI supervisor
- **G. Kube** – DESY supervisor
- **I. Chaikovska** – IJCLab Orsay supervisor

Location:

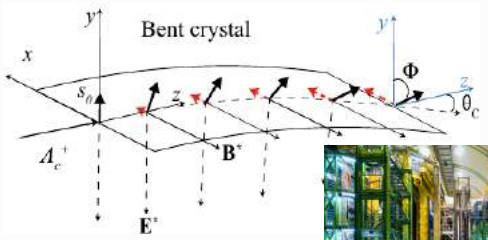
- 2 years at **KISTI** (partner organization)
- 1 year at **INFN Section of Ferrara** (host organization)
- 1 month of secondment at **DESY** (partner organization)
- 1 month of secondment at **IJCLab Orsay** (partner organization)

Applications of oriented crystals*

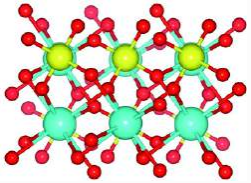
Crystal-based collimation or beam extraction from an accelerator



Measurement of dipole magnetic and electric moments of exotic particles

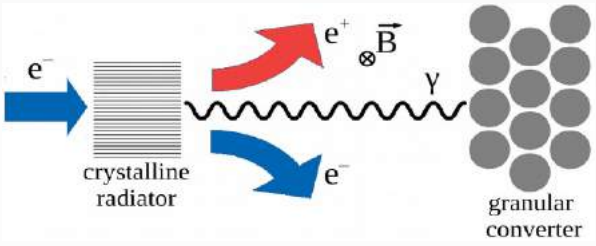


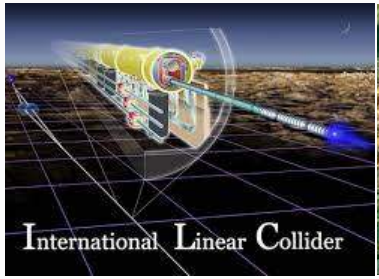
Ultrashort crystalline calorimeter

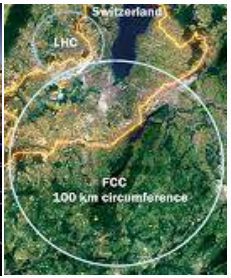


Gamma-ray Space Telescope

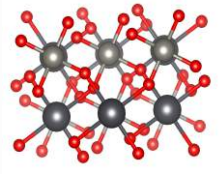
Positron source for future e+/e- and muon colliders



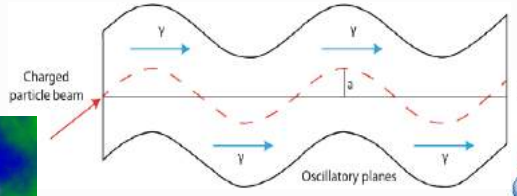


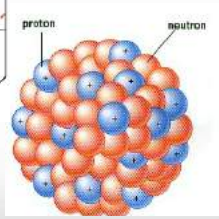


Oriented crystals

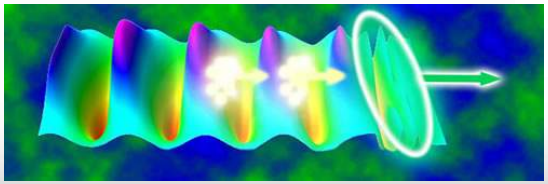


X and γ-ray source for nuclear and medical physics





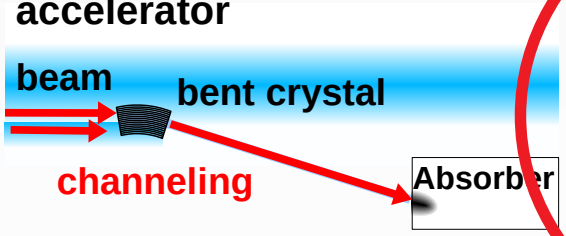
Plasma acceleration



*From A. Sytov presentation at the European Researchers' Night 2021 and IPAC22

Applications of oriented crystals*

Crystal-based collimation or beam extraction from an accelerator



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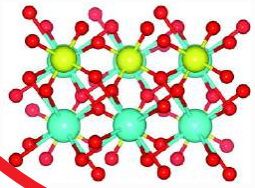

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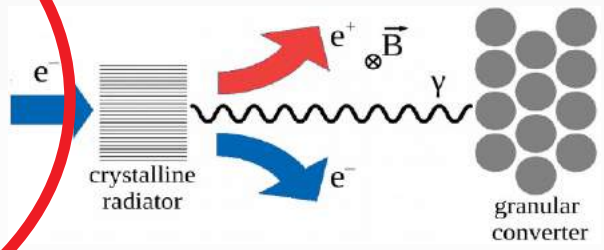

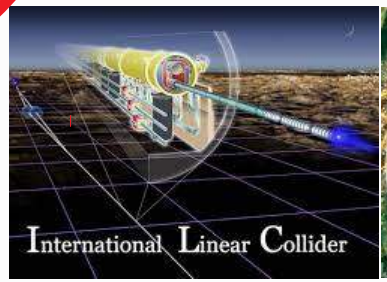

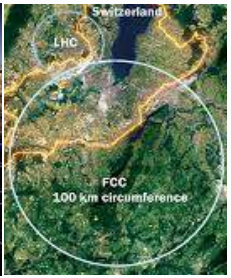

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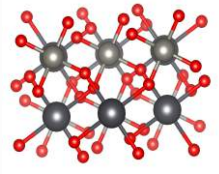

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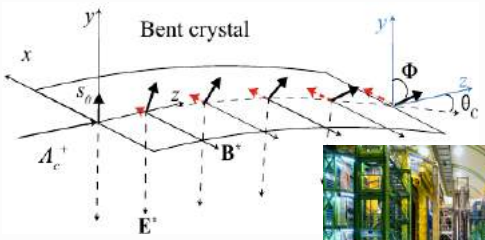

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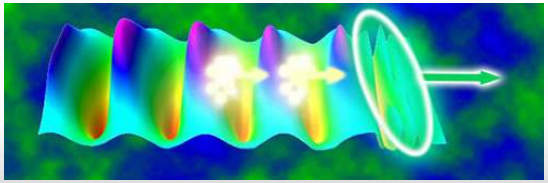
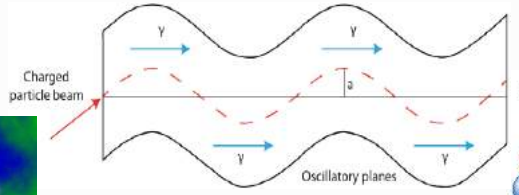
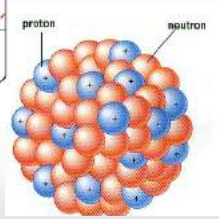


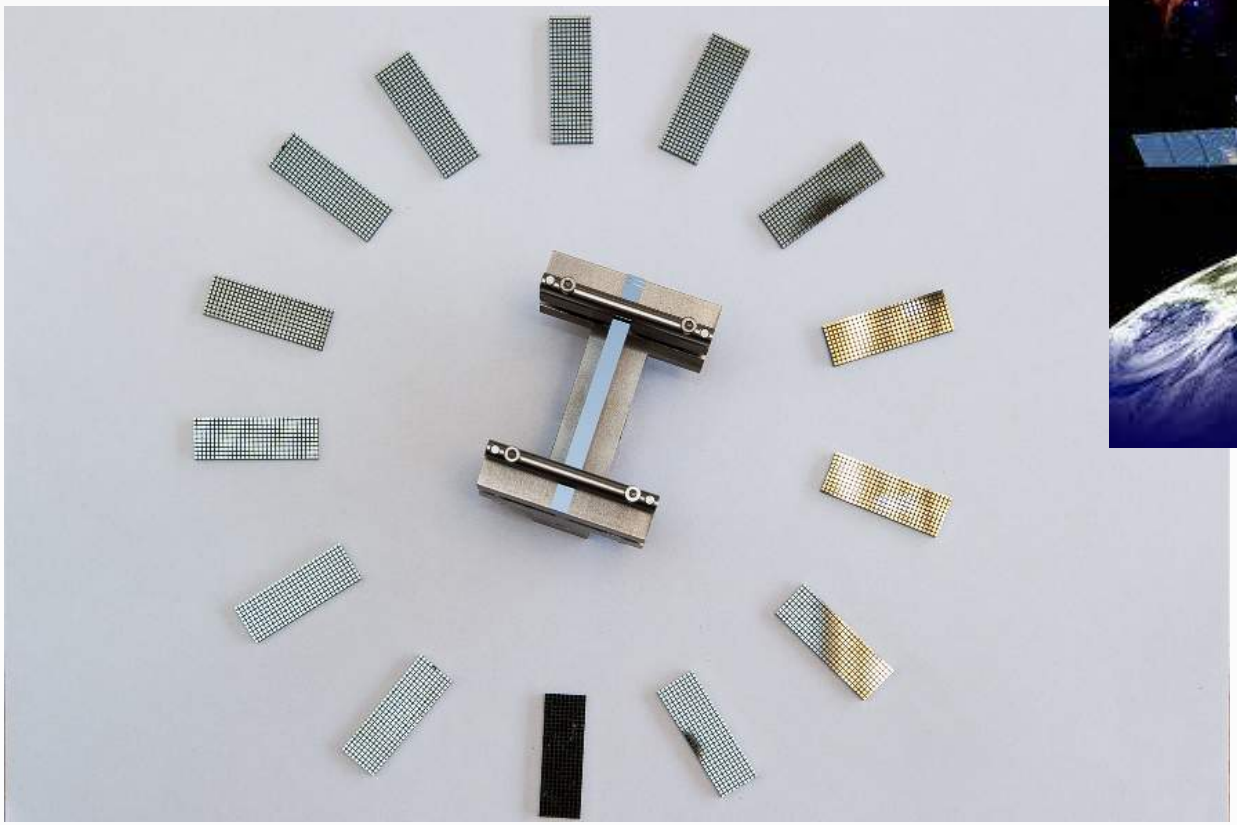
X and γ-ray source for nuclear and medical physics





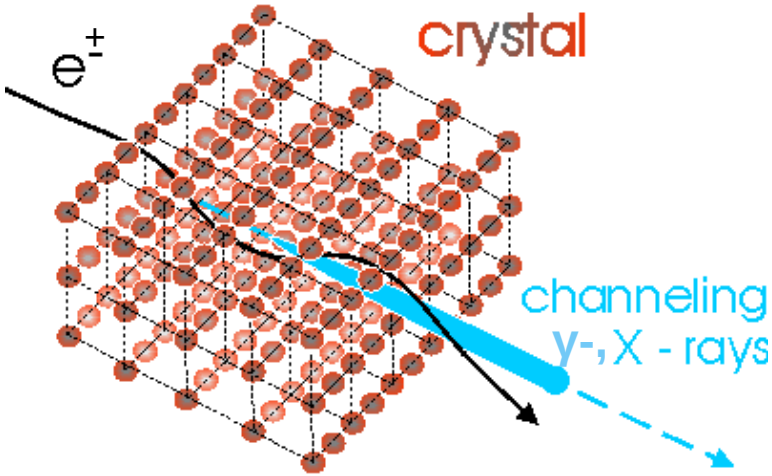
*From A. Sytov presentation at the European Researchers' Night 2021 and IPAC22

The idea of oriented crystals for γ-ray astronomy



Coherent effects in a crystal

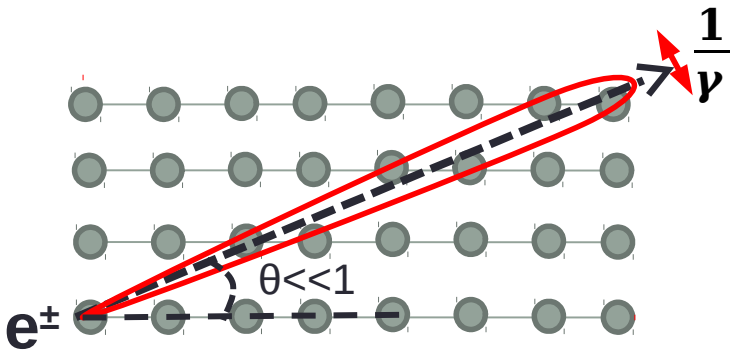
Channeling radiation*



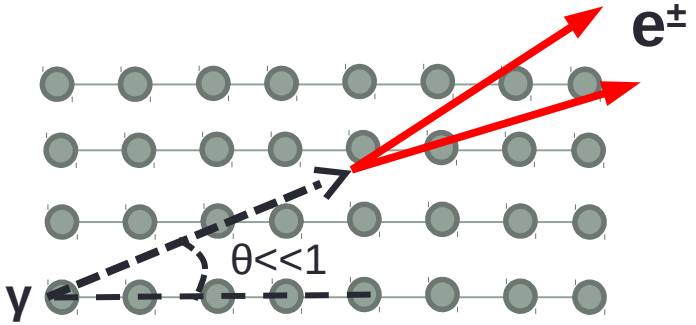
Planar/Axial field $10^9/10^{11}$ V/cm

Coherent effects preserve **up to few mrad** of particle direction vs the crystal axis

Coherent bremsstrahlung**



Coherent pair production***

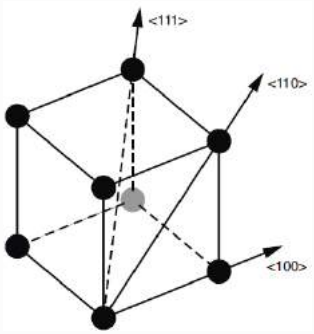


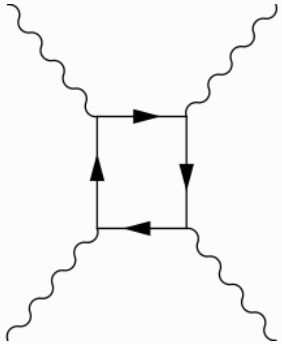
*M.A. Kumakhov, Phys. Lett. A 57(1), 17–18 (1976)
**B. Ferretti, Nuovo Cimento 7, 118 (1950).
**M. Ter-Mikaelian, Sov. Phys. JETP 25, 296 (1953).
*** H. Überall, Phys. Rev. 103, 1055 (1956).

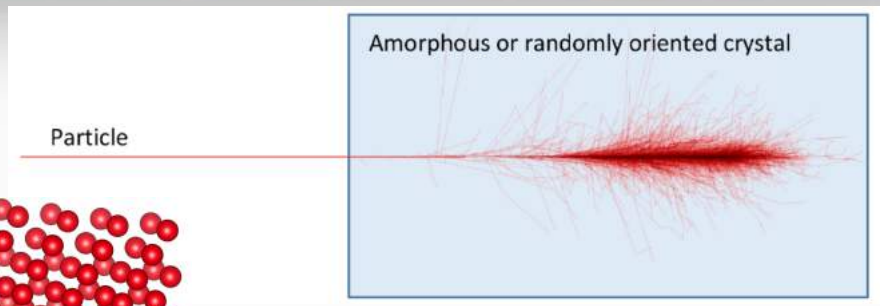
Electromagnetic shower acceleration: Schwinger limit at laboratory conditions

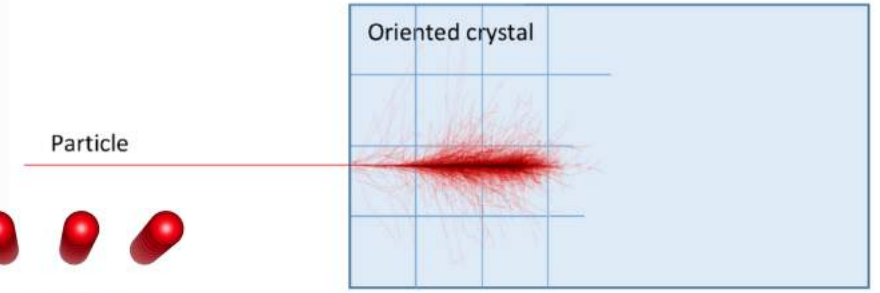
Axial field
10^{11} V/cm * y

Approaching the **Schwinger limit** starting from few **GeV** for **e+/e-**







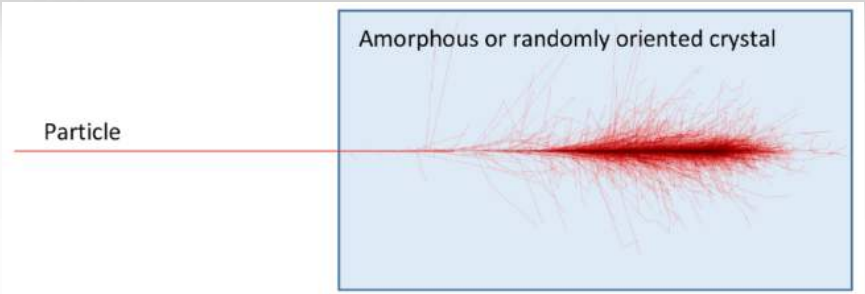


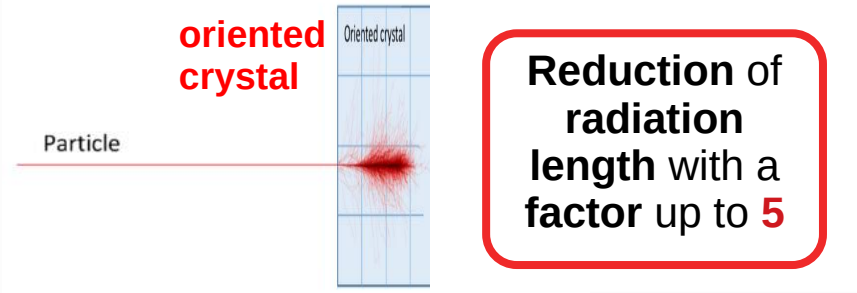
The **radiation** intensity and the **pair production** cross-section **drastically increase** in **oriented crystals!**

Strong field effects **like at magnetars**

Shower development in the field of axes is **accelerated**. The radiation length is considerably reduced.

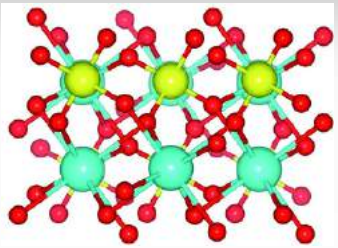
Crystalline ultrashort electromagnetic calorimeter*





Reduction of **radiation length** with a **factor** up to **5**

Cristalline calorimeter extends observation **γ energy range** up to **multi-TeV scale**



PWO

Advantage:

- Considerably shorter thickness
- More transparent for other particles (hadrons)
- Potentially lower time resolution

Crystalline calorimeter can be applied at:

- Fixed-target experiments including **dark matter search**
- **Space gamma telescopes => GRB** observation

Gamma-ray Space Telescope (like Fermi)

CERN North Area

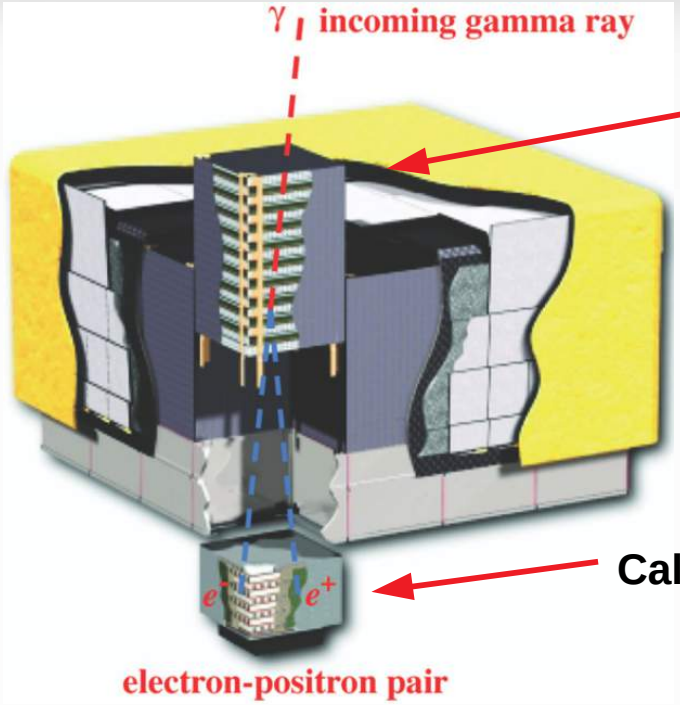
KLEVER

$$K_L \rightarrow \pi^0 \nu\nu$$

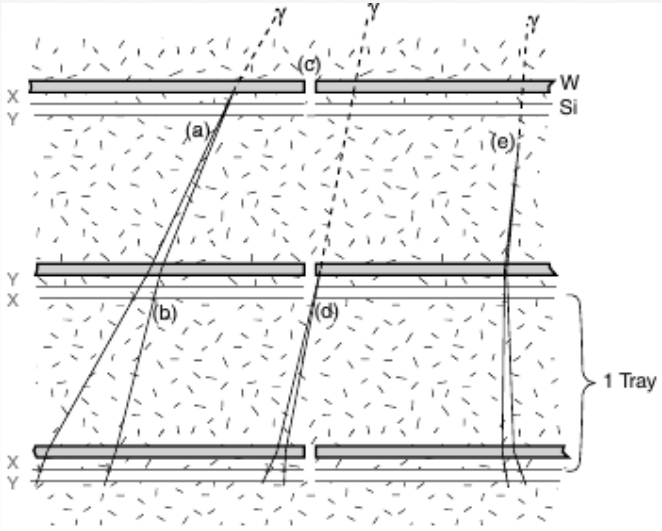
+ dark photon search

*L. Bandiera, …, A. Sytov et al. Phys. Rev. Lett. 121, 021603 (2018)

How a gamma-ray space telescope looks like? (Fermi-LAT example*)



Tracker



New γ-ray space telescopes reaching TeV scale

- DAMPE, Chang J. et al., (The DAMPE Collaboration), Astropart. Phys. 95, 6-24 (2017)
- CALET (ISS). S. Torii et al. (The CALET Collaboration), Adv. in Space Res. 64, Iss. 12, 2531-2537 (2019)

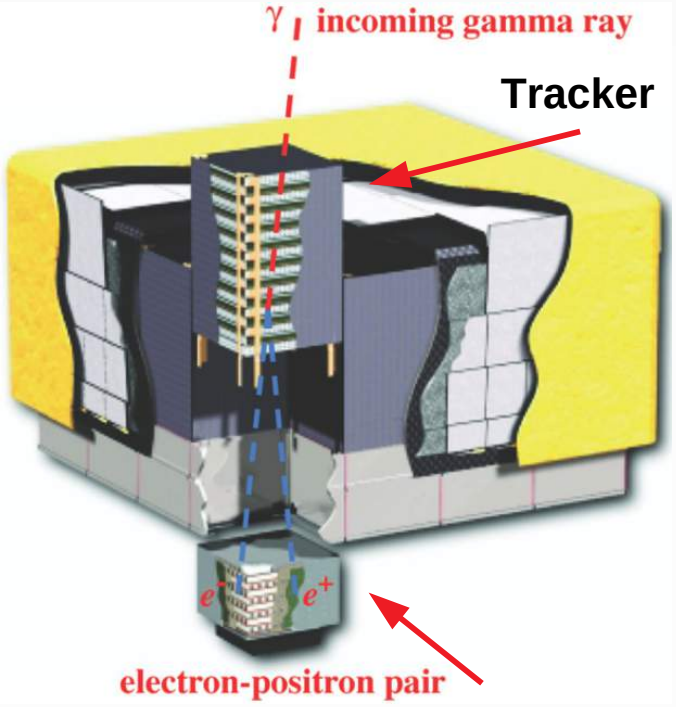
Calorimeter parameters

- 96 CsI(Tl) crystals * 16 modules
  2.7 cm×2.0 cm×32.6 cm each crystal
- 8.6 radiation lengths (segmentation helps)
- **Energy range 20 MeV–300 GeV**
- **Total weight > 1 tonne**

*W.B. Atwood et al. The Astrophysical Journal, 697, 1071–1102 (2009)

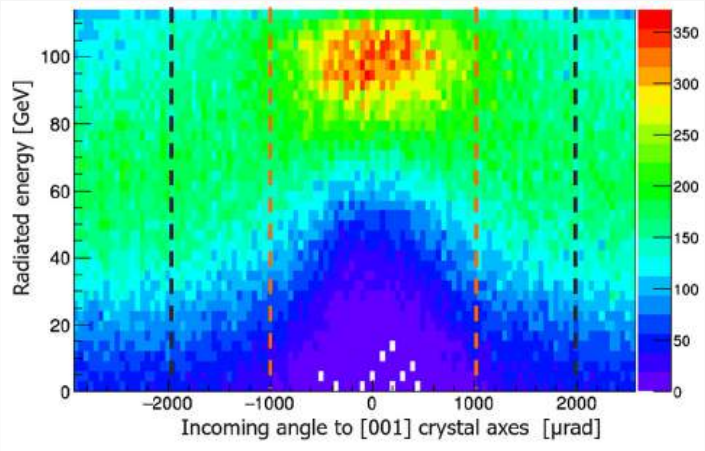
How a gamma-ray space telescope with a crystalline calorimeter will look like?

Similar to Fermi-LAT but with **specific parameters** and **features**



$$t_{max} = \frac{x_{max}}{X_0} = \ln\frac{E_0}{\varepsilon} \pm 0.5$$

Experimental* radiated energy distribution by 120 GeV e⁻



Main features

- **Pointing calorimeter**: must be **oriented** towards cosmic object within **few mrad** => tracker is necessary
- Still works as a **conventional calorimeter outside** this **angular region**
- **Drastic reduction** of a crystal **thickness** in the pointing mode => **minus ~1 tonne** of Fermi-LAT weight

AND/OR

- Exponential increase of the **maximal energy limit** => **multi-TeV** energy scale with a drastic **reduction** of **costs**

*L. Bandiera, …, A. Sytov et al. Phys. Rev. Lett. 121, 021603 (2018)

Investigations in progress

INFN Ferrara team and collaborators on coherent effects in crystals

Prof. Vincenzo Guidi

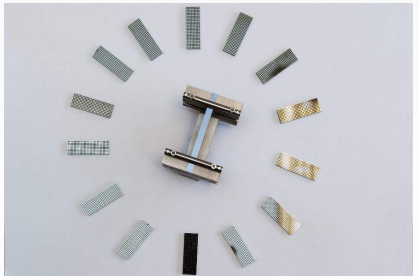
Dr. Laura Bandiera

INFN and University of Ferrara
INFN Legnaro Lab and University of Padua
INFN of Milan Bicocca and Insubria University
INFN and University of Milan
INFN and Sapienza University of Rome
INFN Frascati Lab

Main external collaborations
CERN, MAMI, DESY, MBN Center,
ESRF, Kharkiv, INP Minsk, IJCL Orsay

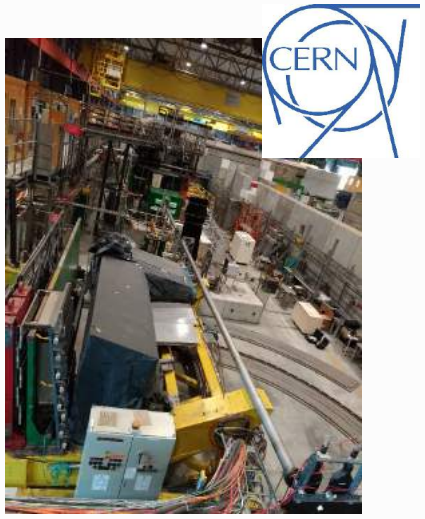
INFN Ferrara expertise

- **Combination of high-energy, accelerator and solid state physics**
  - Development of innovative ideas and research activities
  - Design of setups for channeling experiments
  - Crystals manufacturing and characterization
  - Data analysis
  - Simulations of channeling in crystals



$e^{\pm}$ @6 GeV DESY (Hamburg, Germany)

e^{-} @ subGeV MAMI (Mainz, Germany)



p, $e^{\pm}$, $\pi^{\pm}$ @ (20-400) GeV CERN (Geneve, Switzerland)

Experiments by INFN

INFN
Istituto Nazionale di Fisica Nucleare

CERN
Collimation & beam steering
Innovative radiation sources
Pair production studies
Innovative detectors

MAMI MAINZER MIKROTRON
Beam steering
Innovative radiation sources

DESY.
Innovative radiation sources
Innovative detectors
Beam extraction

JLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis
Innovative radiation sources
Beam steering

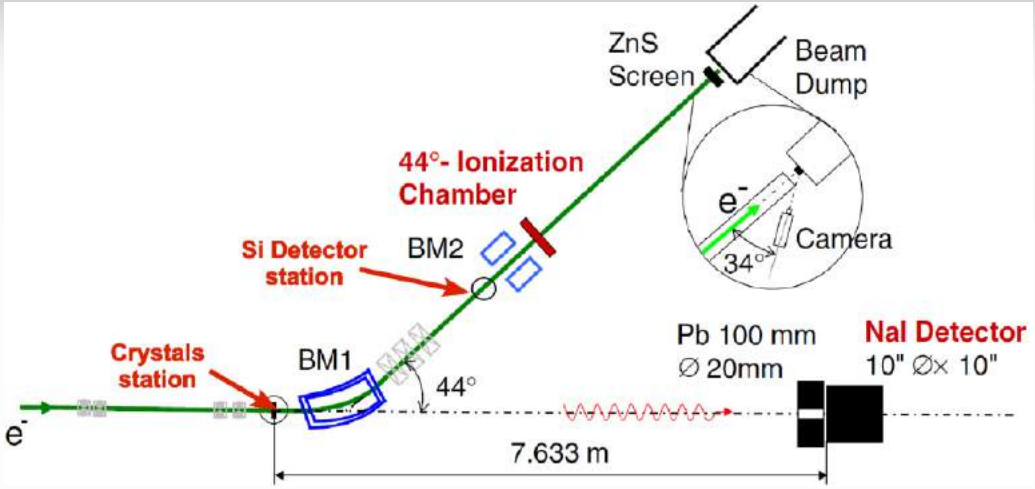
SLAC

erc European Research Council Established by the European Commission

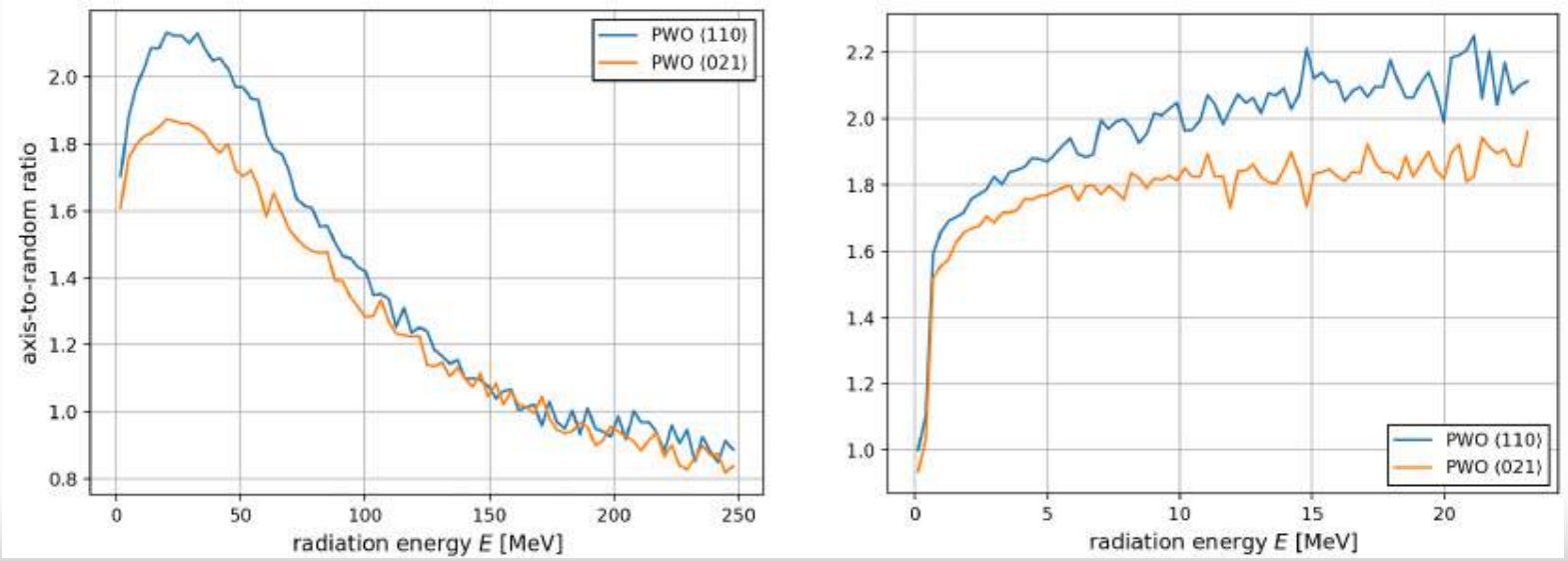
ERC-CoG CRYSBEAM (LHC beam extraction)
ERC-CoG SELDOM (Studies of MDM and EDM of charmed baryons)
MCA-IRSES CUTE (crystalline undulators)
MSCA-RISE PEARL (crystalline undulators)
MSCA-RISE N-LIGHT (crystalline radiation sources)
INFRAIA AIDAInnova (crystal calorimeters)

Involved in channeling activities for about 20 years

Experimental results at MAMI with 855 MeV e⁻

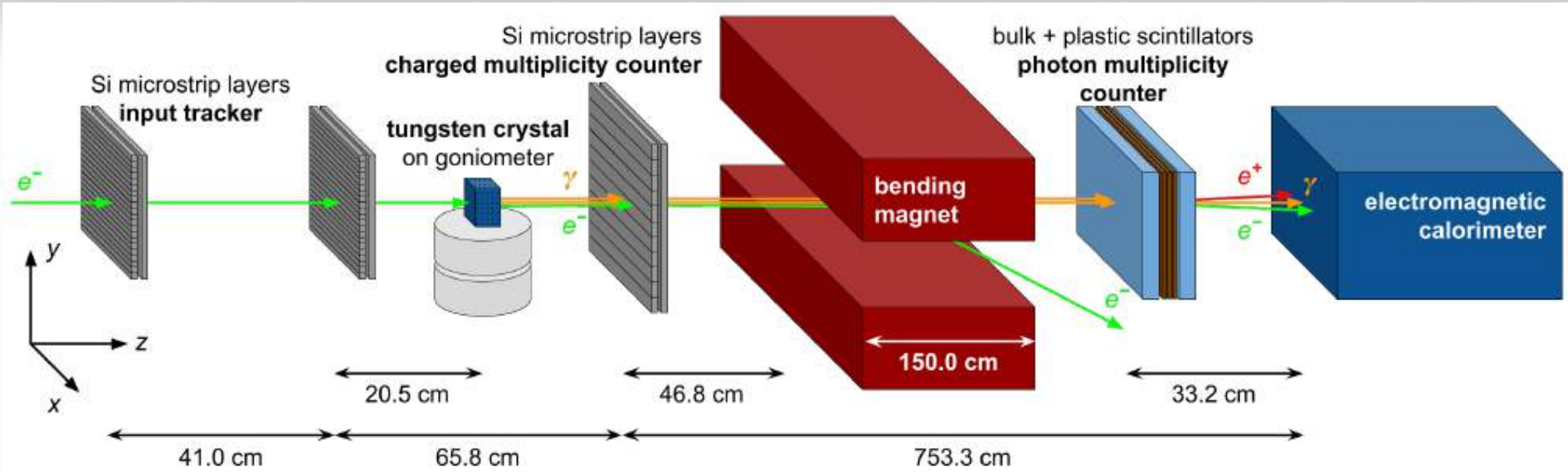


Experimental radiated energy distribution by 855 MeV e⁻

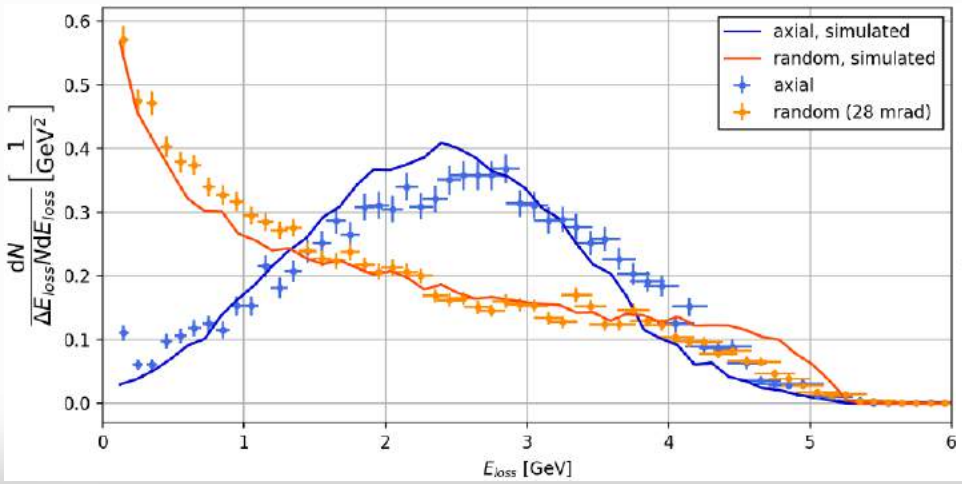


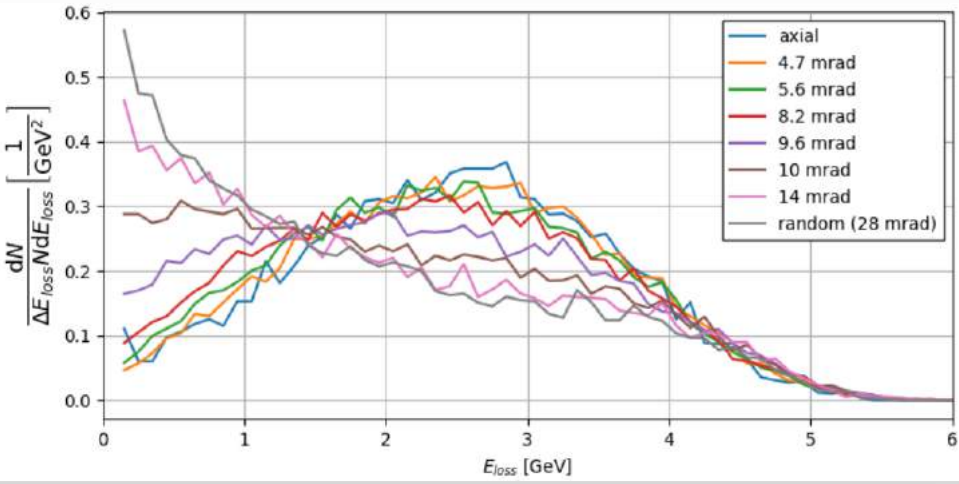
*M. Soldani, et al. Proc. of Science, EPS-HEP 2021, 853

Experimental results at DESY with 5.6 GeV e⁻



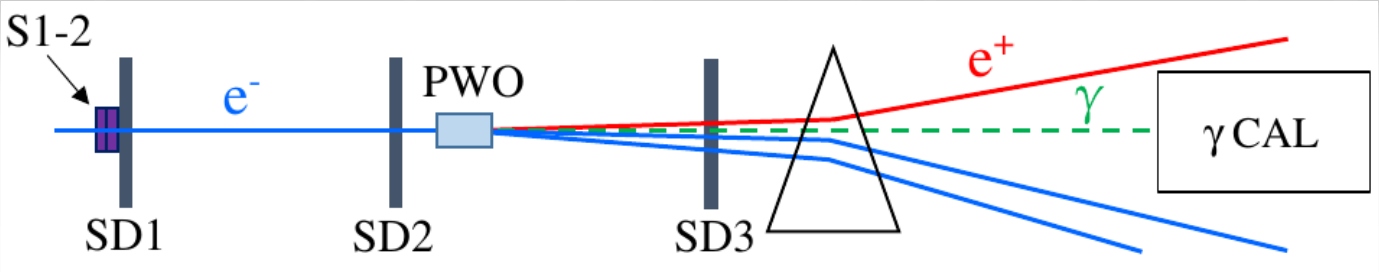
Experimental and simulated radiated energy distribution by 5.6 GeV e⁻

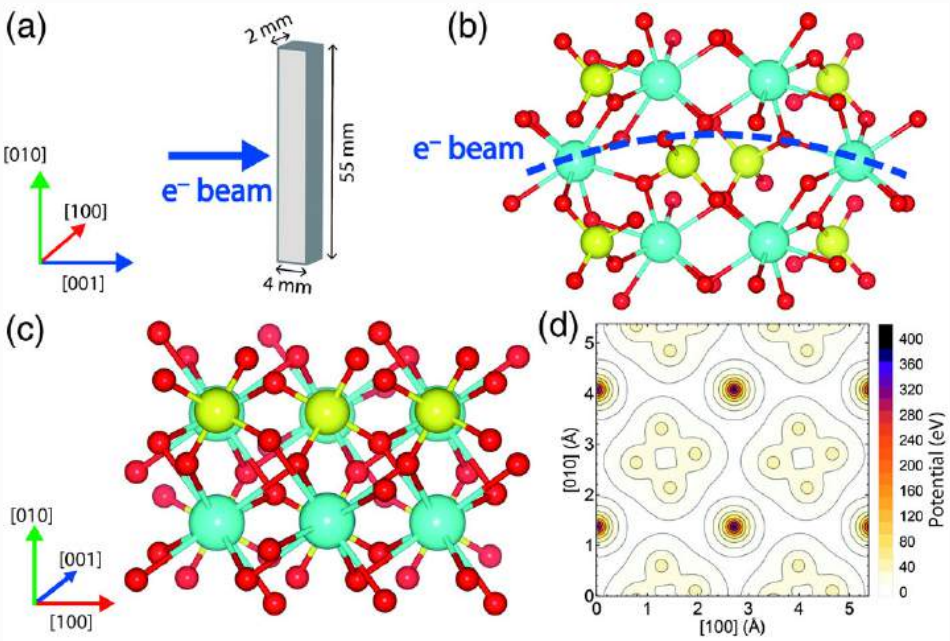




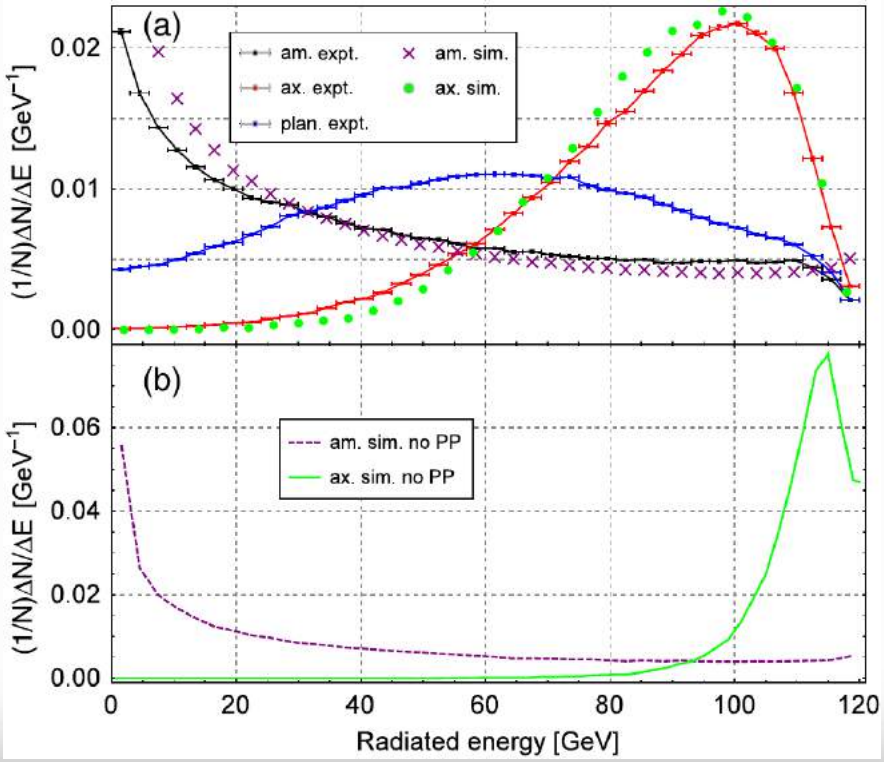
*L. Bandiera, …, A. Sytov et al. ArXiv 2203.07541v1, subm. to Eur. Phys. J. C (2022)

Experimental results at CERN North Area with 120 GeV e⁻





Experimental and simulated radiated energy distribution by 120 GeV e⁻



CRYSTALRAD simulation code

Main conception – tracking of charged particles in a crystal in averaged atomic potential

Program modes:

- **1D** model – particle motion in an interplanar potential
- **2D** model – particle motion in an interaxial potential

Simulation of the different physical processes:

- Multiple and single **Coulomb scattering** on nuclei and electrons.
- **Nuclear scattering**
- **Ionization energy losses**
- **Crystal geometry**

Unification of the **CRYSTAL*** code developed by **A. Sytov** and the **RADCHARM++**** code developed by **L. Bandiera** into the **CRYSTALRAD***** code to simulate the radiation spectra by **Baier-Katkov** formula

Advantages:

- High calculation speed
- **MPI** parallelization for high performance computing

***A.I. Sytov, V.V. Tikhomirov. NIM B 355 (2015) 383–386.**

****L. Bandiera, et al., Nucl. Instrum. Methods Phys. Res., Sect. B 355, 44 (2015)**

*****A. I. Sytov, V. V. Tikhomirov, and L. Bandiera. PRAB 22, 064601 (2019)**

The first step of TRILLION: Geant4 simulations of beam deflection by a bent crystal

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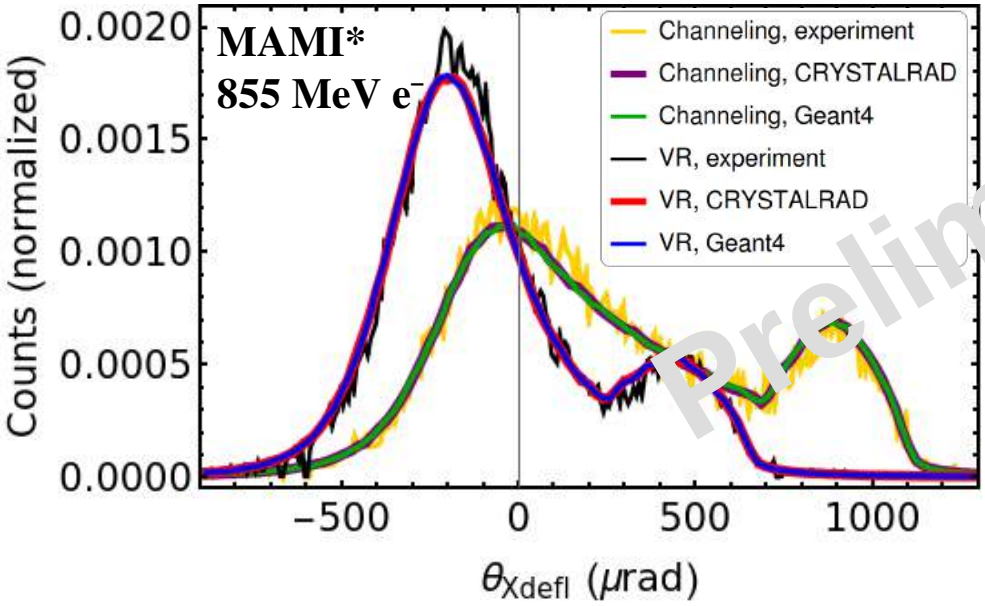
Korea Institute of Science and Technology Information

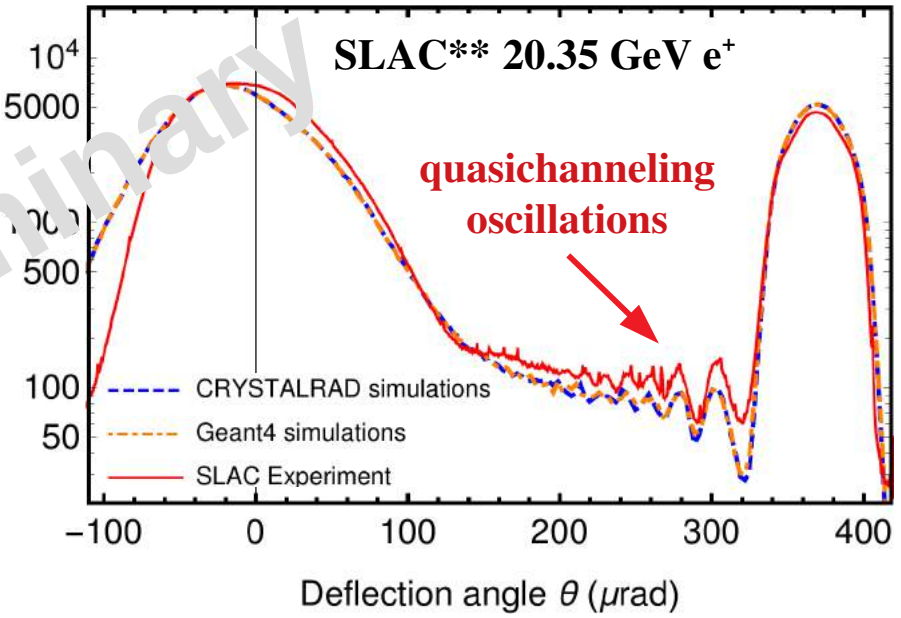
European Commission

Trillion

GEANT4 A SIMULATION TOOLKIT

Geant simulations vs experiment and CRYSTALRAD simulations





Preliminary

*A. Mazzolari et al. Phys. Rev. Lett. 112, 135503 (2014)

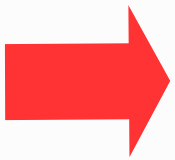
**T. N. Wistisen, …, and A. Sytov. Phys. Rev. Lett. 119, 024801 (2017)

New model implementation into Geant4

The channeling model is ready to be inserted into the next Geant4 release

To implement:

- **Channeling** model using FastSim interface: **DONE**
  (only trajectories)
- **Radiation** model (Baier-Katkov method)
- **Pair production** model
- **Radiation** and **positron source examples**
- **Beam extraction example**: requires the implementation of beam dynamics in an accelerator

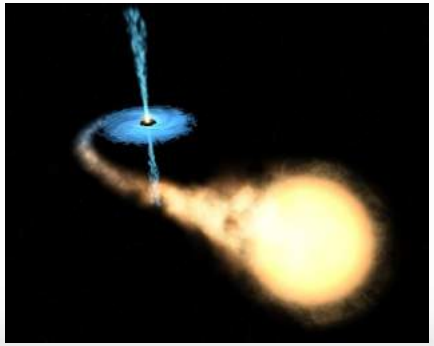


We have tools to simulate it

What can be observed with a gamma-ray space telescope?

- **Very High Energy γ-ray sources providing insights into lepton and hadron space acceleration**
- Pulsars and their nebulae
- Blazars
- Supernova remnants
- Gamma-ray binary systems
- Gamma-ray bursts
- Any misidentified sources

Element of multi-messenger astronomy



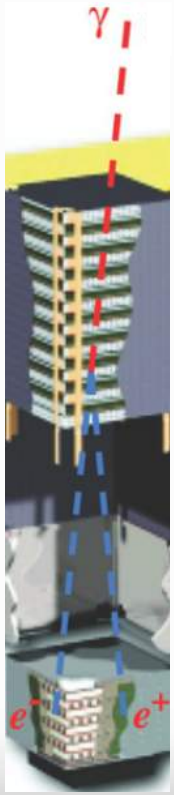
To understand better mechanisms of γ-rays production in space

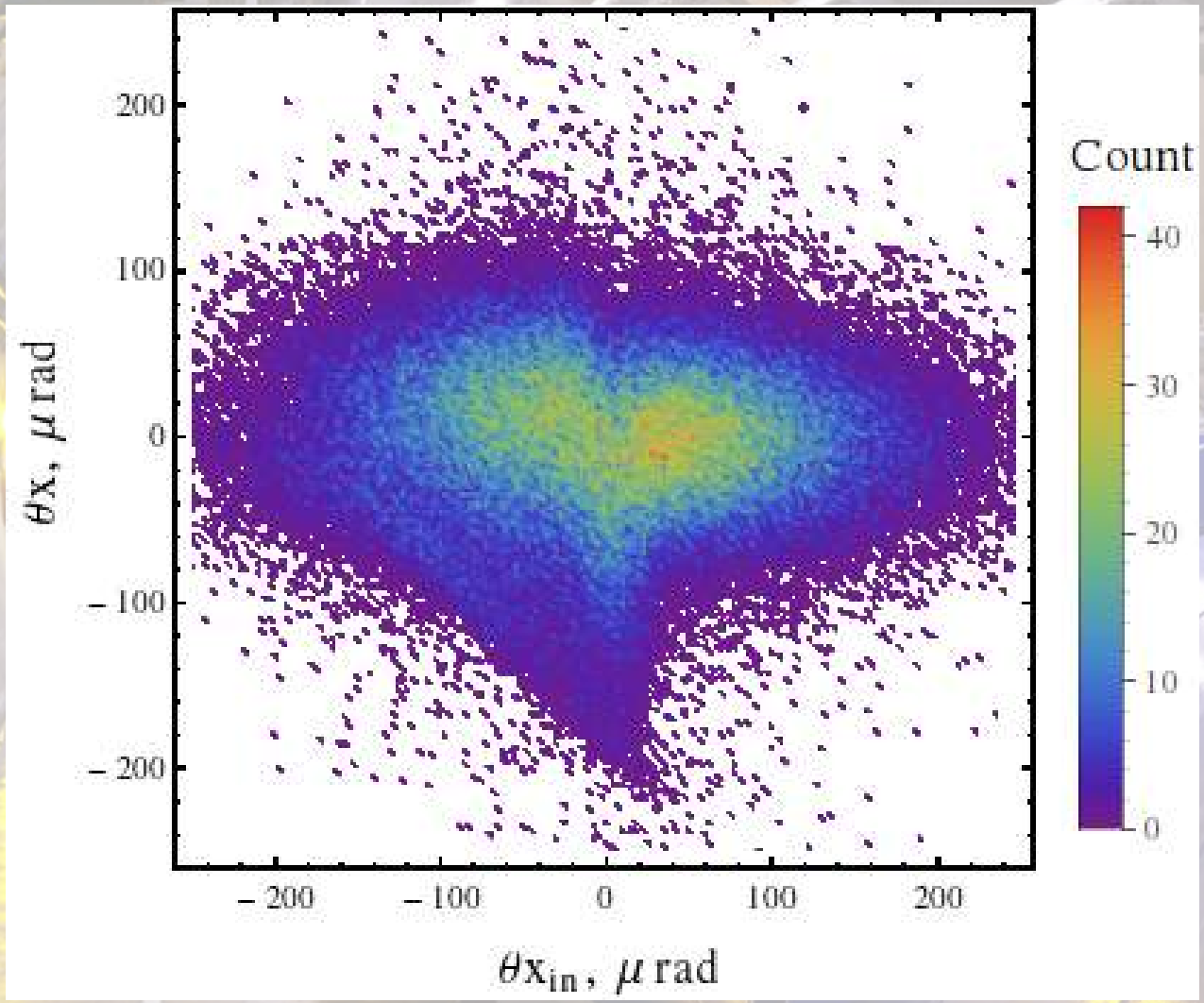
- p+p, p+γ, p+space gas reactions & π decay
- Inverse Compton scattering
- Synchrotron radiation of leptons and protons
- **Dark matter annihilation**

My proposal

- To simulate the **detection** of **y-rays** arriving from several types of sources as examples.
  - Simulations: our expertise.
  - Gamma-ray sources: your expertise.
- To **publish** a **paper** as a **proposal** describing the gamma-ray space telescope in GeV–TeV energy scale and simulations of its observations.
- We can start with a **nanosatellite** (for instance 1/16 part of Fermi-LAT) with a weight below 100 kg as a **proof-of-principle concept**.
- To think about **official collaboration** between our organizations and **funding request** for the **R&D** stage.

- **To launch this satellite into space!**





Thank you for attention!