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Trillion

Marie Curie Global Fellowships, Project TRILLION GA n. 101032975

Dr. Alexei Sytov

Daejeon, 03/06/22

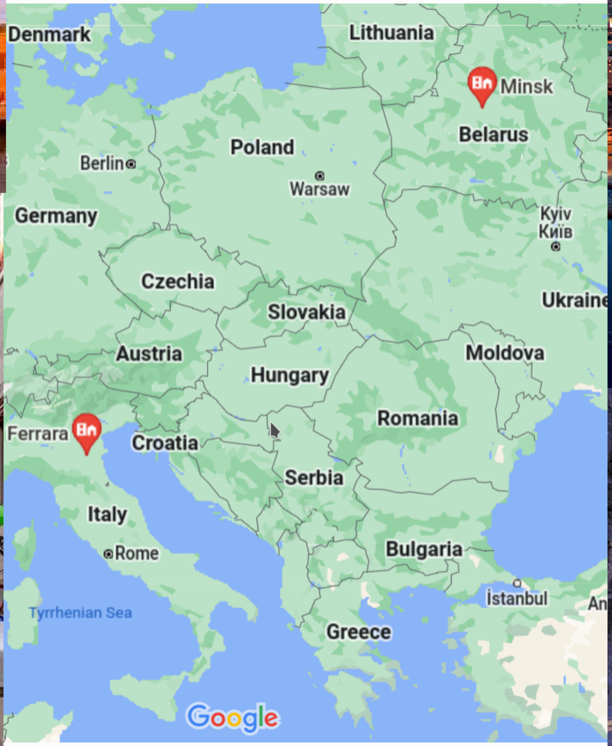
Outline

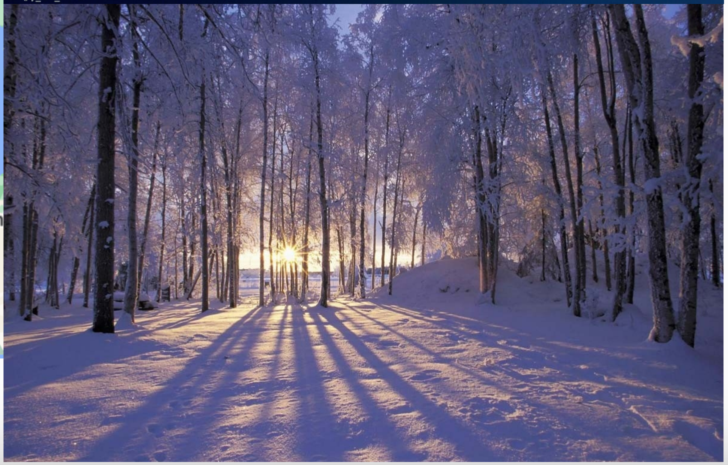
- **Briefly about me and my group**
- **The world of channeling effect**
  - Channeling, Radiation and pair production
  - Electromagnetic shower acceleration
  - INFN Ferrara Group
- **TRILLION - Marie Curie Individual Global Fellowships project**
  - The idea of the project
  - Main applications
  - Additional activities
- **TRILLION**: implementation of the new physics into Geant4
  - What has been done previously in Geant4?
  - Main conception: **FastSim** interface
  - What has been done by now?
- **High performance computing**
  - CINECA supercomputers
  - Project **MIRACLE**

Where I am from?

I work in
Italy, Ferrara

Originally I am from
Belarus, Minsk

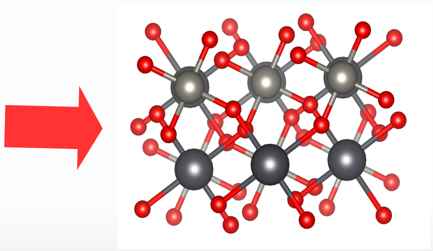




Briefly about me

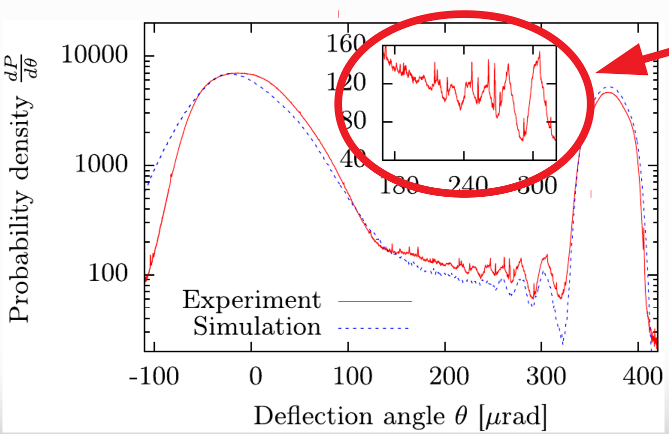
- **2018: 2 PhDs –** in Experimental Physics, University of Ferrara and in Theoretical Physics, Belarusian State University
- **2019-2021**: **Post-doctoral Fellow** in Experimental Physics at the INFN Division of Ferrara.
- Since **2020** involved in **MC_INFN** – INFN **Geant4** project
- Since **02/09/2021**: 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

INFN Ferrara team and collaborators on Crystal Channeling

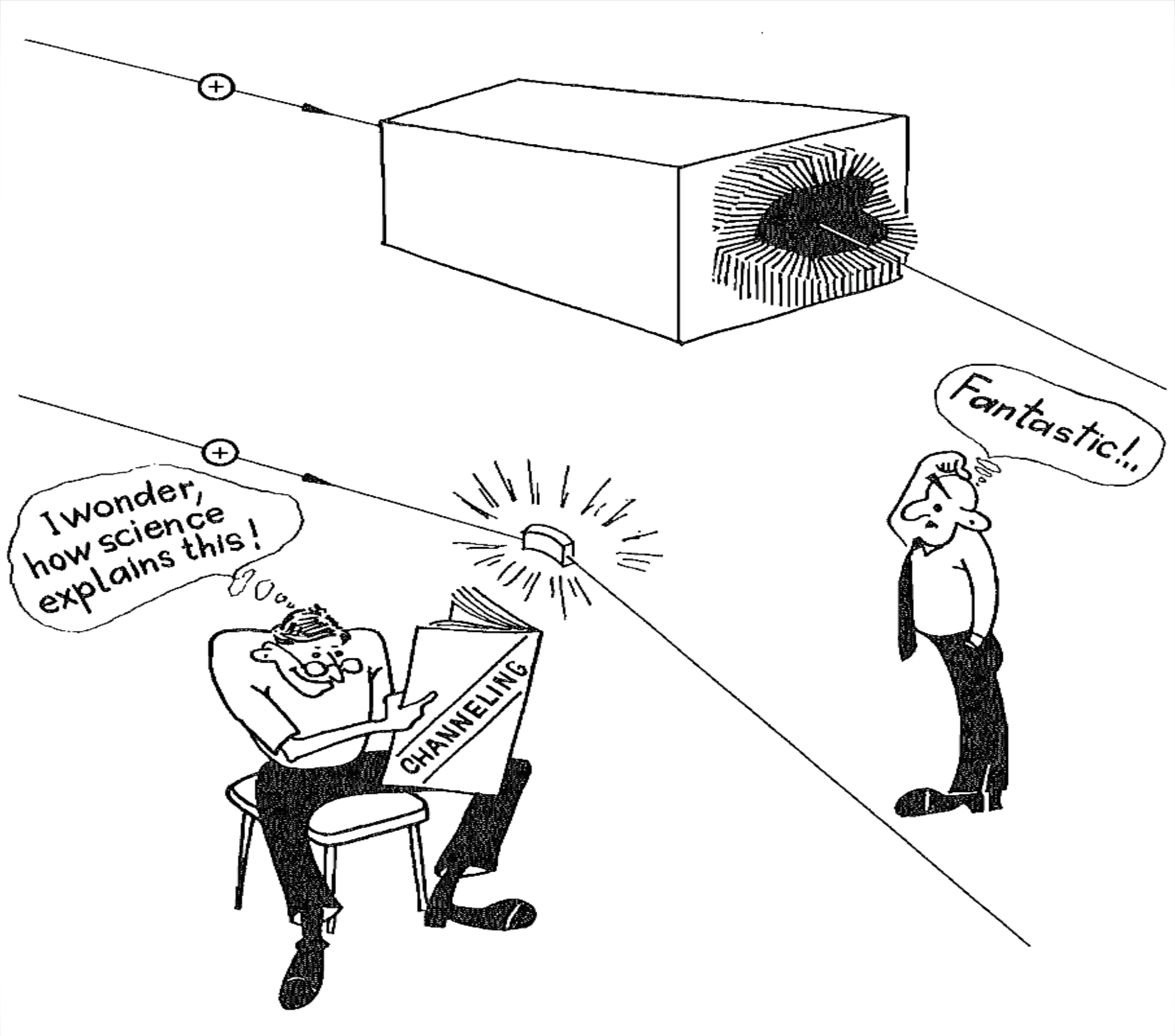
Prof. Vincenzo Guidi

Dr. Laura Bandiera

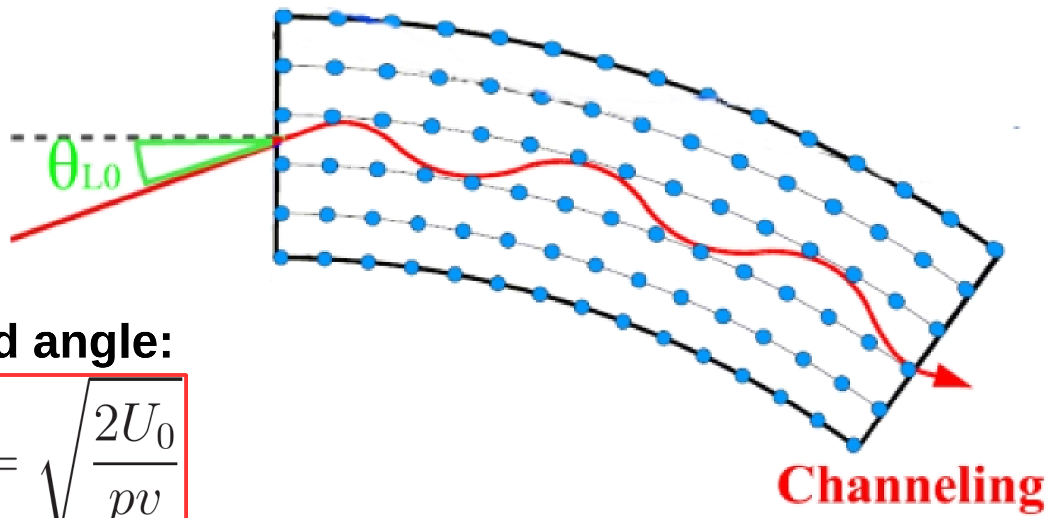
INFN and University of Ferrara
INFN Legnaro Lab and University of Padua
INFN of Milan Bicocca and Insubria University
INFN and University of Milan
INFN and Sapienza University of Rome
INFN Frascati Lab

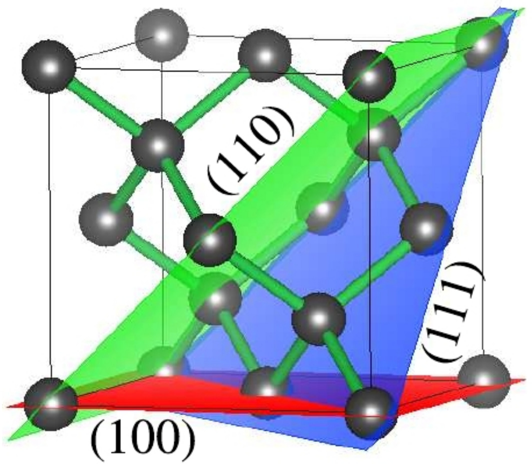
Main external collaborations
CERN, MAMI, DESY, MBN Center,
ESRF, Kharkiv, INP Minsk, IJCL Orsay

The world of the channeling effect



Channeling effect*





Lindhard angle:

$$\theta < \theta_L = \sqrt{\frac{2U_0}{pv}}$$

Channeling* **is the effect of the penetration of charged particles through a monocrystal quasi parallel to its atomic axes or planes.** In dependence on the crystal alignment along either planes or atomic strings channeling can be divided into

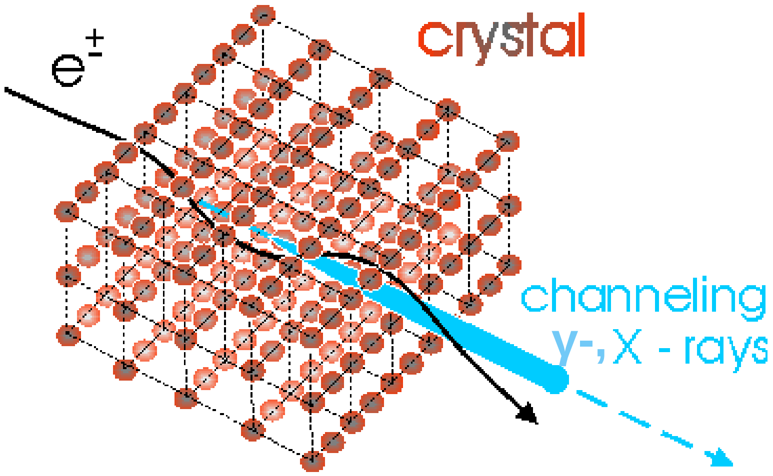
- ***Planar*** **channeling**
- ***Axial*** **channeling**

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

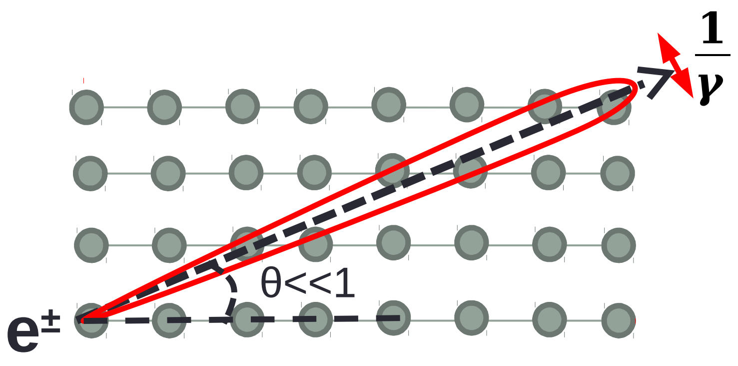
*J. Stark, Zs. Phys. 13, 973–977 (1912)
J. A. Davies, J. Friesen, J. D. McIntyre, Can J. Chem. 38, 1526–1534 (1960)
M. T. Robinson, O. S. Oen, Appl. Phys. Lett. 2, 30–32 (1963)
J. Lindhard, Kgl. Dan. Vid. Selsk. Mat.-Fys. Medd. 34 No 4, 2821–2836 (1965)

Coherent effects in a crystal

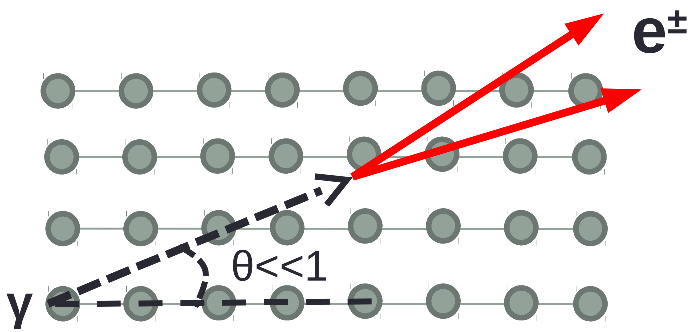
Channeling radiation*



Coherent bremsstrahlung**



Coherent pair production***



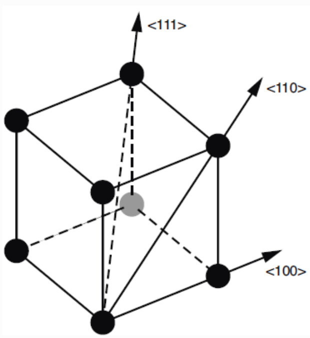
Coherent effects preserve **up to few mrad** of particle direction vs the crystal axis

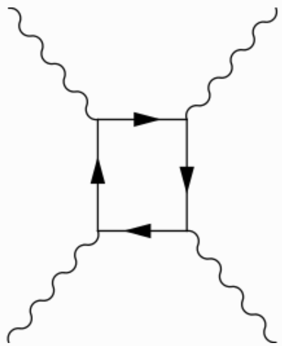
***M.A. Kumakhov, Phys. Lett. A 57(1), 17–18 (1976)**
****B. Ferretti, Nuovo Cimento 7, 118 (1950).**
****M. Ter-Mikaelian, Sov. Phys. JETP 25, 296 (1953).**
***** H. Überall, Phys. Rev. 103, 1055 (1956).**

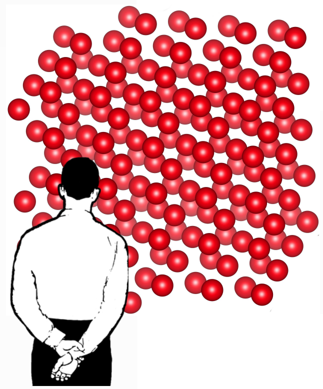
Electromagnetic shower acceleration

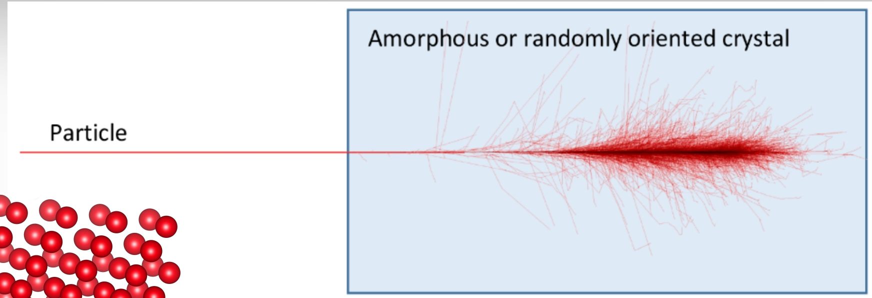
Axial field 10^{11} V/cm

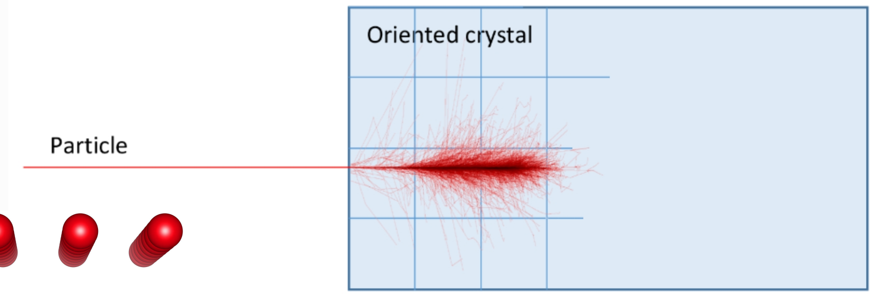
Approaching the **Schwinger limit** starting from few **GeV** for **e+/e-**

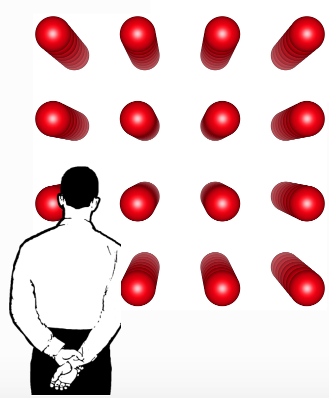










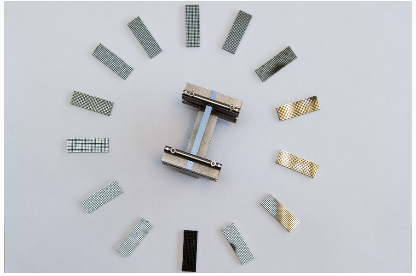


The **radiation** intensity and the **pair production** cross-section **drastically increase** in **oriented crystals!**

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

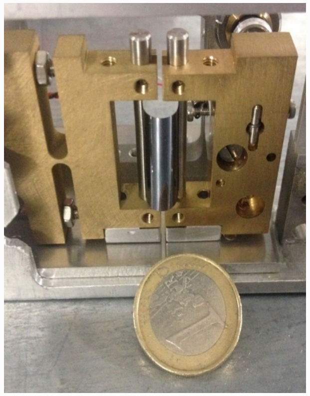
INFN Ferrara expertise

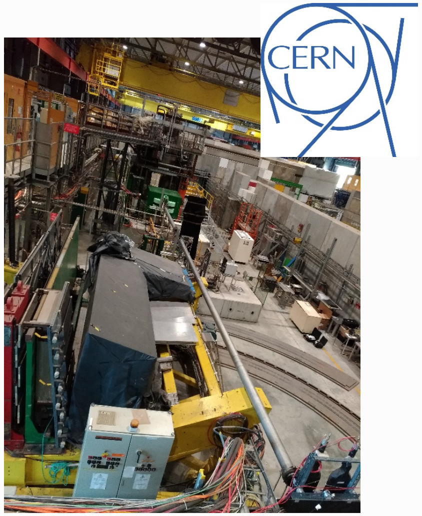
- **Combination of high-energy, accelerator and solid state physics**
  - Development of innovative ideas and research activities
  - Design of setups for channeling experiments
  - Crystals manufacturing and characterization
  - Data analysis
  - Simulations of channeling in crystals



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

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





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

Channeling experiments at INFN

INFN
Istituto Nazionale di Fisica Nucleare

Involved in Channeling activities for about 20 years

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

SLAC
- Innovative radiation sources
- Beam steering

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)

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IJCLab
Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

DESY.

Marie Skłodowska-Curie Actions, Postdoctoral Fellowships

European Commission

Developing talents, advancing research

Objective of Postdoctoral Fellowships:

- To support researchers' **careers** and foster **excellence in research**.
- To help researchers gain **experience** in other countries, disciplines and non-academic sectors.

Global Postdoctoral Fellowships:

- Funding the **mobility** of researchers **outside Europe** (1-2 years).
- Mandatory **return phase** of 1 year to an organization based in an EU Member State or Horizon Europe Associated Country.
- May also include **short-term secondments** anywhere in the world.

Marie Skłodowska-Curie Actions, Postdoctoral Fellowships

European Commission

Developing talents, advancing research

Global Postdoctoral Fellowships covers:

- a living allowance
- a mobility allowance
- if applicable, family, long-term leave and special needs allowances

- **research**, **training** and **networking** activities
- management and indirect costs

Training, scientific results **dissemination** and **science popularization** are the essential part of the project

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:

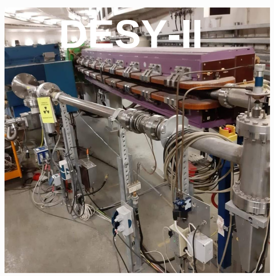
- **A. Sytov** – project coordinator
- **L. Bandiera** – INFN supervisor
- **K. Cho** – KISTI supervisor
- **G. Kube** – DESY supervisor
- **I. Chaikovska** – IJCLab Orsay supervisor

Location:

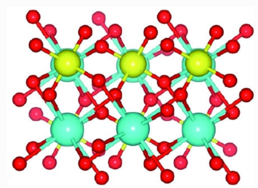
- 2 years at **KISTI** (partner organization)
- 1 year at **INFN Section of Ferrara** (host organization)
- 1 month of secondment at **DESY** (partner organization)
- 1 month of secondment at **IJCLab Orsay** (partner organization)

Applications*

Crystal-based collimation or beam extraction from an accelerator

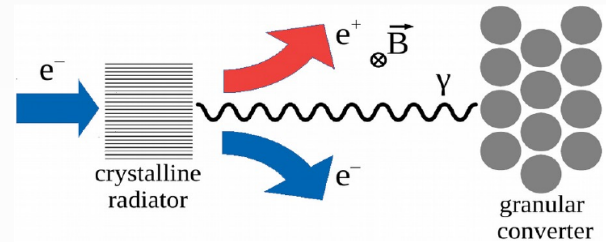


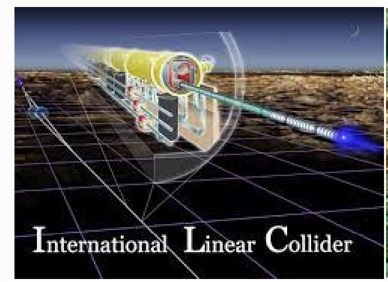
Ultrashort crystalline calorimeter



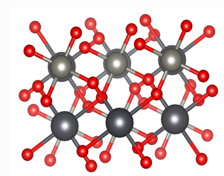
Gamma-ray Space Telescope

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

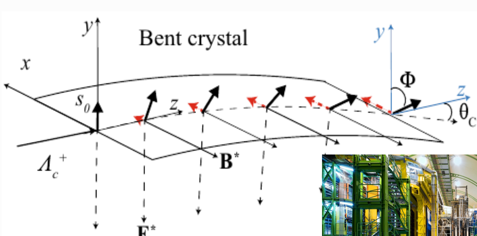




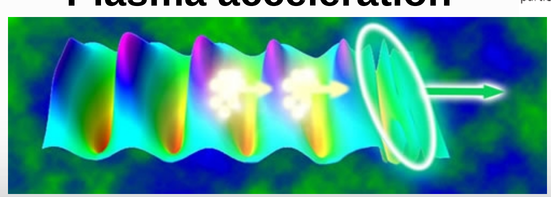
Oriented crystals



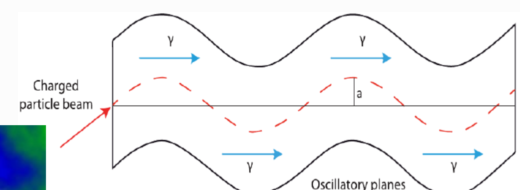
Measurement of dipole magnetic and electric moments of exotic particles

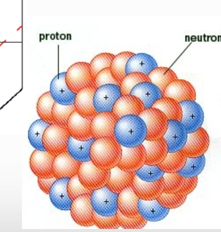


Plasma acceleration



X and γ-ray source for nuclear and medical physics



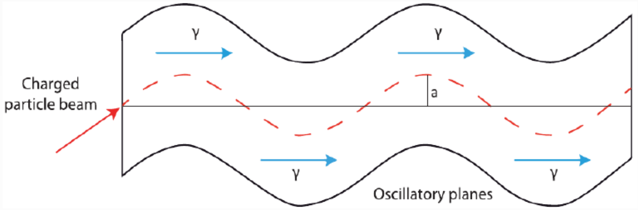


*From A. Sytov presentation at the European Researchers' Night 2021

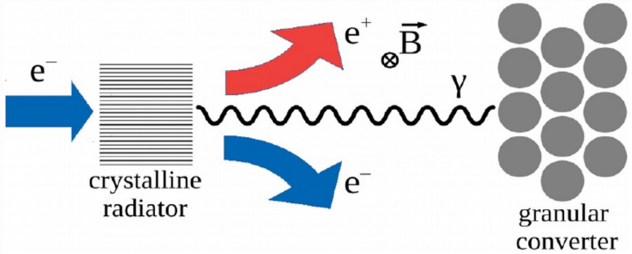
Marie Sklodowska-Curie Action Global Fellowships by A. Sytov in 2021-2024, Project TRILLION

Specific applications to implement into Geant4:

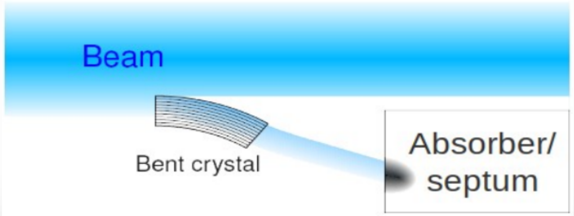
- **Crystalline source of hard X-ray and gamma radiation, crystalline undulator (CU)**.



- **Crystal-based hybrid positron source** for both linear and circular e+e- colliders (**ILC**, **FCC-ee, KEKB* etc.**) as well as for **muon colliders**.



- **Crystalline deflector to extract a charged particle beam from an accelerator** (**electron synchrotron****, hadron collider) to supply fixed-target experiments by an intense low-emittance beam.



*I. Chaikovska et al. Proceedings of the IPAC 17, 2910-2913 (2017).

**A. Sytov et al. Eur. Phys. J. C 82, 197 (2022)

Not only researches and scientific papers!

Training (e.g. **KAIST** and **UST** courses, scientific schools, public seminars)**:**

- **Scientific skills**: **Geant4**, High Performance Computing, C++, Machine Learning, accelerator physics, wake-field acceleration, radiation sources, particle physics etc.
- **Transferable skills**: **Innovation** and **Entrepreneurship** including marketing, management, finance, long-term planning, teamwork, leadership etc. + **한국어** :)

Inter-sectoral and interdisciplinary transfer of knowledge:

- **Secondments** to **DESY** and **IJClab**
- Participation in **high-tech exhibitions** both as an exhibitor and a viewer
- Contacts with other Korean and foreign institutions e.g. **KEK**, **IBS**, **KARI** and **Satrec** (development of compact satellites) etc.
- **Lecturing** - Geant4 courses
- And of course **conferences**!

Science popularization:

- Popularization science events such as **European Researchers' Night*** etc.
- Blogging in social media

Progress of channeling physics implementation into Geant4

GEANT4

A SIMULATION TOOLKIT

Geant4 is a toolkit for the simulation of the **passage** of particles **through matter**. Its areas of application include **high energy**, **nuclear** and **accelerator physics**, as well as studies in **medical** and **space science**.

Status of channeling in Geant4

Currently implemented Channeling physics:

- Only trajectories (**no radiation**)
- Only for hadrons
- Changing cross-sections using **Geant4 Biasing**

To do:

- To resolve the **problems** with modification of **continuous discrete processes**
- To add channeling of **e+/e-**
- To add channeling **radiation**
- To add coherent **pair production**

Problem with modification of the **electromagnetic physics list**:
class G4ChannelingOptrChangeCrossSection

```
        switch (type) {
            case fNotDefined:
                fProcessToDensity[processName] = fDensityRatioNone;
                break;
            case fTransportation:
                fProcessToDensity[processName] = fDensityRatioNone;
                break;
            case fElectromagnetic:
                if(subType == fCoulombScattering ||
                   subType == fMultipleScattering){
                    fProcessToDensity[processName] = fCancelProcess;
                }
                if(subType == fIonisation ||
                   subType == fBremsstrahlung){
                    fProcessToDensity[processName] = fCancelProcess;
                }
                if(subType == fPairProdByCharged ||
                   subType == fAnnihilation ||
                   subType == fAnnihilationToMuMu ||
                   subType == fAnnihilationToHadrons){
```

It is not possible to turn off/to modify **continuous discrete processes** (multiple scattering, ionization losses) in this way but only **discrete processes**

Crucial for e+/e-

Solution: Geant4 FastSim interface

A. Sytov thanks **Prof. Vladimir Ivanchenko** (CERN) for this solution and the group of **Prof. P. Cirrone** (INFN LNS), in particular **Dr. L. Pandola** for fruitful discussions!

FastSim model:

- **Physics list** independent
- Declared in the **DetectorConstruction**
- Is activated only in a **certain G4Region** at a **certain condition** and only for **certain particles**
- **Stops Geant processes** until the exit from the model and then resumes them

```
G4bool TestModel::IsApplicable(const G4ParticleDefinition& particleType)
{
  return
    &particleType == G4Proton::ProtonDefinition()||
    &particleType == G4AntiProton::AntiProtonDefinition()||
    &particleType == G4Electron::ElectronDefinition() ||
    &particleType == G4Positron::PositronDefinition();// ||
    //&particleType == G4Gamma::GammaDefinition();
}

//....oooOO0OOooo........oooOO0OOooo........oooOO0OOooo........oooOO0OOooo......

G4bool TestModel::ModelTrigger(const G4FastTrack& fastTrack)
{
}

//....oooOO0OOooo........oooOO0OOooo........oooOO0OOooo........oooOO0OOooo......

void TestModel::DoIt(const G4FastTrack& fastTrack,
                     G4FastStep& fastStep)
{
```

Insert particles for which the model is applicable

Insert the condition to enter the model

Insert what the model does

Baseline simulation code: CRYSTALRAD

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:

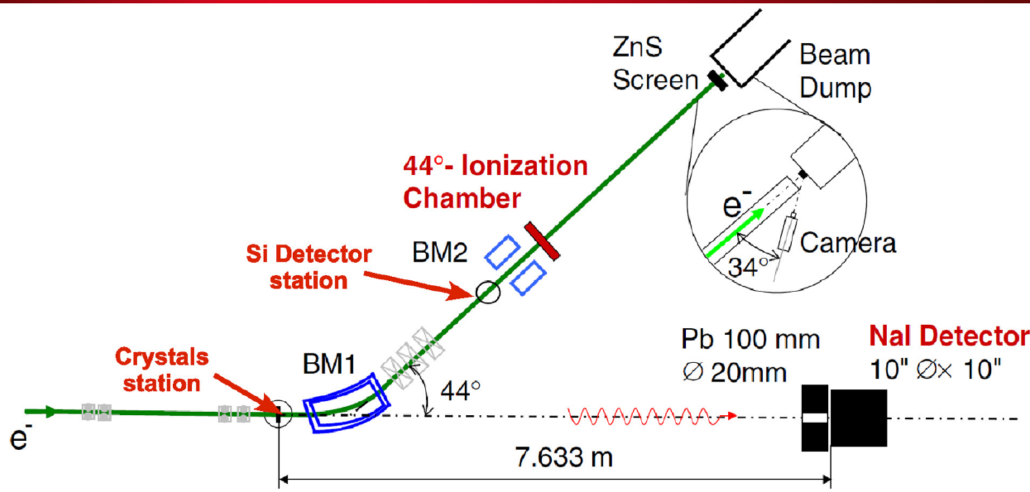
- High calculation speed
- **MPI** parallelization for high performance computing

***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)**

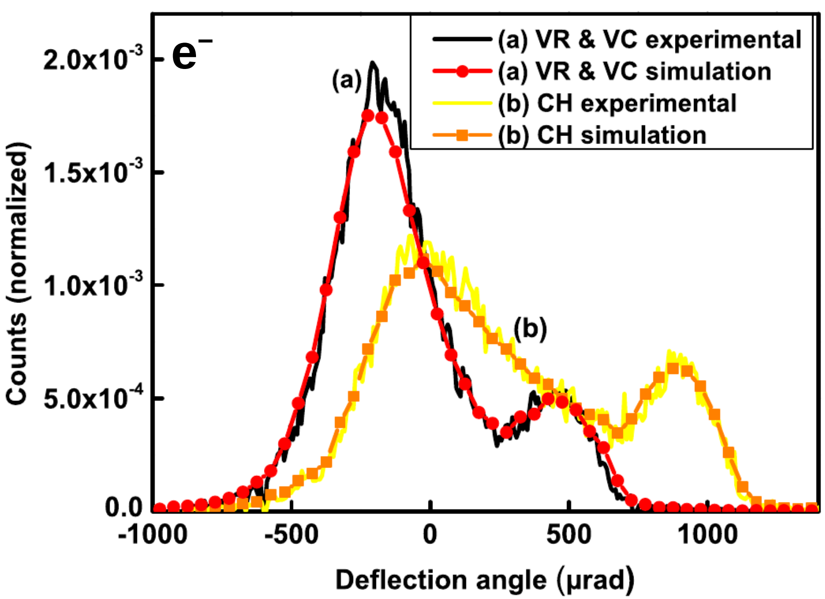
Preliminary results: Geant4 simulation of channeling of 855 MeV electrons at Mainzer Mikrotron MAMI



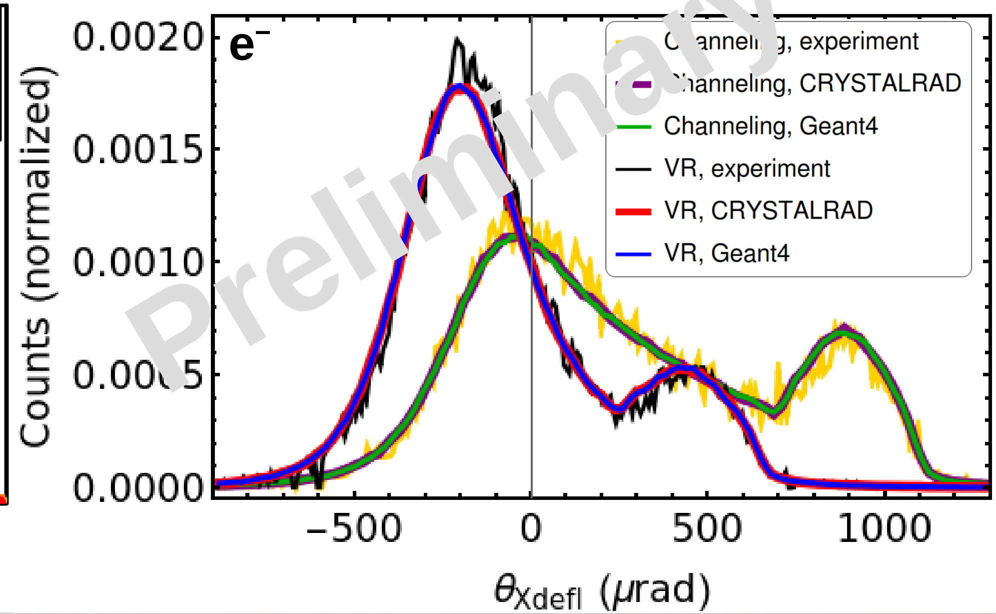
Simulation parameters

- Silicon crystal **30.5 µm** thick
- Planes: **(111)**
- Electron beam **855 MeV**
- Beam divergence **30 µrad**

Results published in 2014*



Geant simulations vs experiment and CRYSTALRAD simulations



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

New channeling 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

High Performance Computing at CINECA

CINECA*

- **Cineca** is a non profit Consortium, made up of **70 Italian universities**, 5 Italian Research Institutions (including INFN) and the Italian Ministry of Education.
- the **largest Italian computing centre**, one of the most important worldwide
- **Supercomputer Marconi 100: 21th** position in the Top500 list (**6th** in **EU**) with a sustained performance of **21.640 Pflops** (peak performance up to ∼**29.354 Pflops**)
- **10^5-10^6** times faster than a personal computer
- **Location**: Cineca, Casalecchio di Reno, Bologna, Italy

*http://www.cineca.it/

Our project MIRACLE, no. HP10BIW7VR
Cineca ISCRA Class B National Italian project

MIRACLE
Medical physIcs and RAdiation in Crystals simuLation with gEant4
Main goal: to supply **Italian Geant4 community** and their international collaborators by CINECA HPC resources necessary to accomplish **MC_INFN** and **TRILLION** projects.
25/10/2021 - 25/10/2022

Marconi 100: 0.992 Mh for 1 year

Galileo 100: 2.4 Mh for 1 year

Italian organizations involved
- INFN Sezione di Catania
- INFN Sezione di Ferrara
- INFN Laboratori Nazionali del Sud
- INFN Napoli
- INFN Roma1
- Istituto Superiore di Sanità
- University of Messina
- University of Napoli

Foreign organizations involved
- ELI-Beamlines, Institute of Physics, (FZU), Czech Academy of Sciences
- Institute for Nuclear Problems, Belarusian State University
- University of Surrey

PI A. Sytov

Conclusions

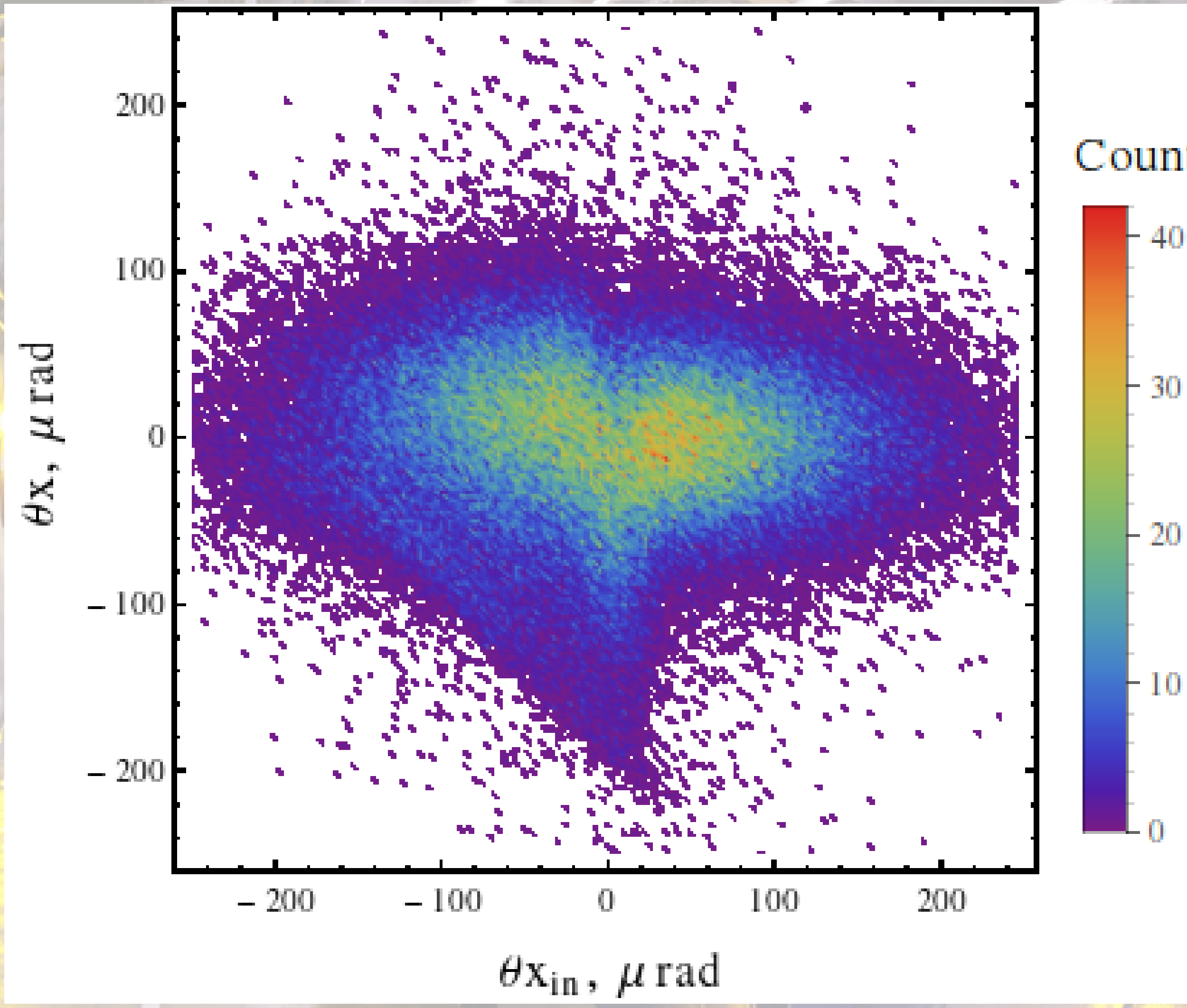
- **Marie Skłodowska-Curie Global Fellowships** give a great impulse to the scientific **career** and **self-development** of the fellow.

- The goal of **TRILLION** is to implement **electromagnetic processes in oriented crystals** into **Geant4** which will bring to a large scientific and industrial community most of possible applications of a crystal.

- The Geant4 examples that will be developed can be **applied** in **nuclear** and **medical physics** (radiation source), at e-/e+ colliders – **ILC**, **FCC-ee** and **muon collider** (positron source) and at all **e-/e+ synchrotrons** existing in the world (crystal-based beam extraction)

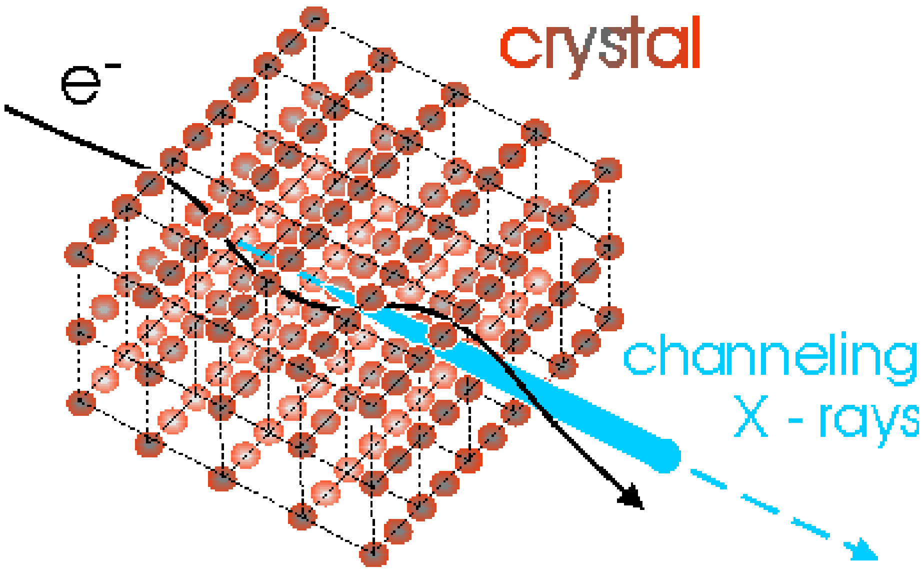
- **TRILLION** includes a lot of activities beyond researches, i.e. **training, inter-sectoral and interdisciplinary transfer of knowledge, science popularization**

- Supercomputing project **MIRACLE** supplies **Geant4 developers** in Italy and their foreign collaborators with supercomputing resources.

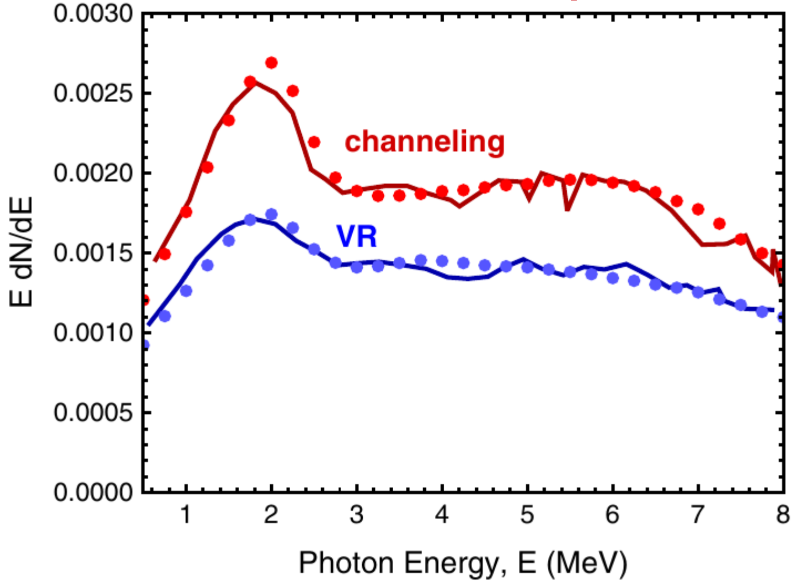


Thank you for attention!

Baier-Katkov algorithm from CRYSTALRAD



CRYSTALRAD *vs* experiment



Baier-Katkov formula:
integration is made over the classical trajectory

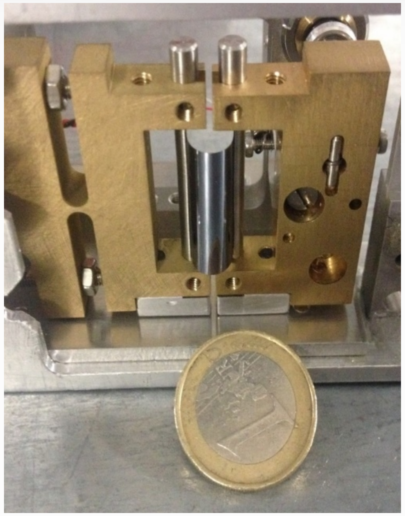
$$\frac{dE}{d^3k} = \omega \frac{dN}{d^3k} \; \frac{\alpha}{4\pi^2} \iint dt_1 dt_2 \; \frac{\left[(E^2+E'^2)(v_1 v_2 - 1) + \omega^2/\gamma^2\right]}{2E'^2} \, e^{-ik'(x_1 - x_2)}$$

The **Baier-Katkov** method permits to simulate the emitted radiation in crystals in a wide energy range, from **sub-GeV** to **hundreds** of **GeV**.

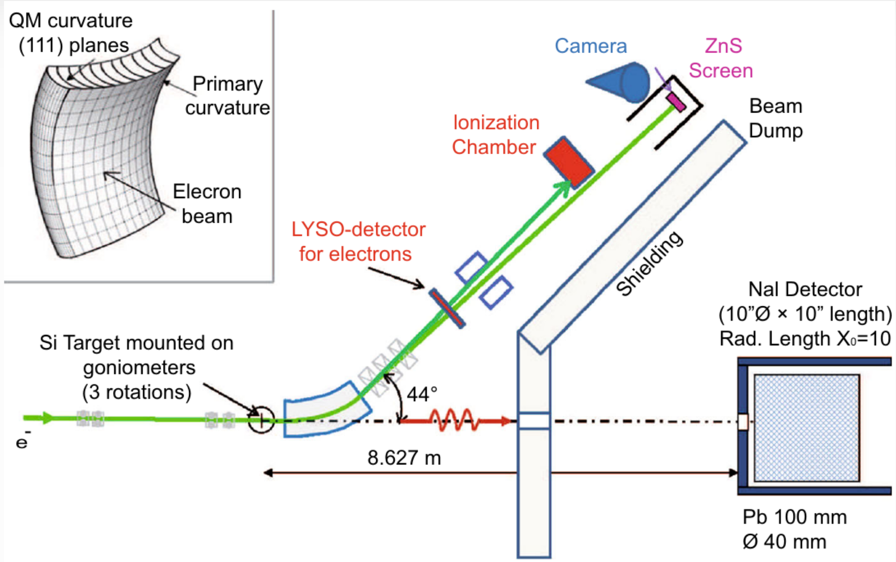
***L. Bandiera, et al., Nucl. Instrum. Methods Phys. Res., Sect. B 355, 44 (2015)**
****V.N. Baier, V.M. Katkov, V.M. Strakhovenko World Scientific, Singapore (1998)**
*****V. Guidi, L. Bandiera, V. Tikhomirov, Phys. Rev. A 86 (2012) 042903**
******A. I. Sytov, V. V. Tikhomirov, and L. Bandiera. PRAB 22, 064601 (2019)**

Channeling radiation in a bent crystal: Mainz Mikrotron MAMI, e- 855 MeV*

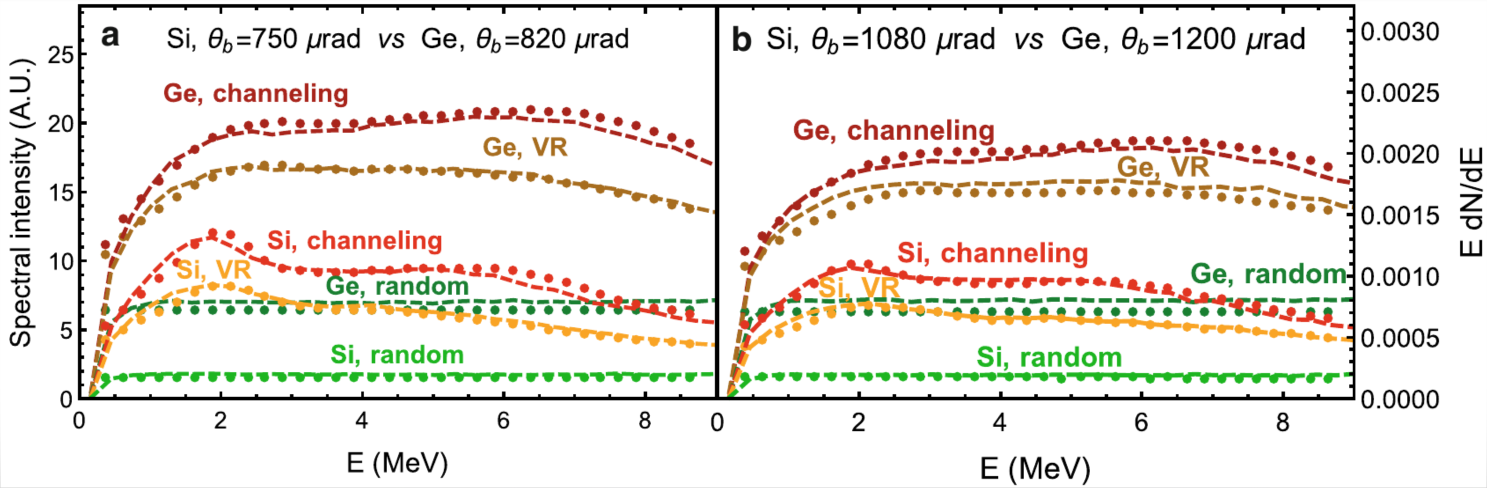
Bent crystal (Si o Ge)



Experimental setup

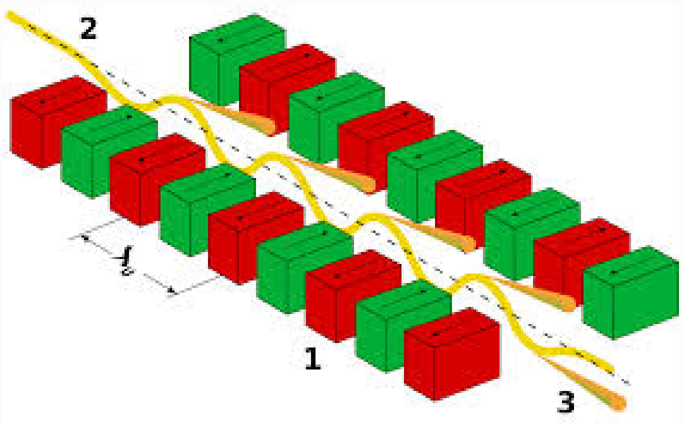


CRYSTALRAD simulation results vs experimental data



Channeling radiation in a bent crystal: Crystalline undulator

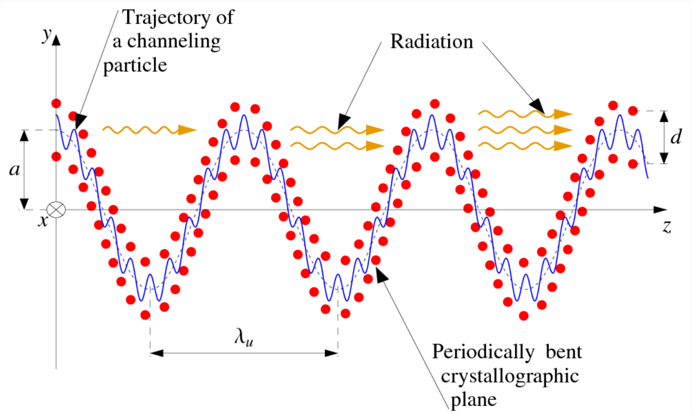
Classical scheme: magnetic undulator in a free electron laser soft X-rays $\lambda_u \sim$ cm



Advantage:

- Intense X- and gamma-rays produced in a crystal, in a compact piece of material

Innovative scheme: Crystalline undulator-> Hard X-rays and gamma rays $\lambda_u <$ mm

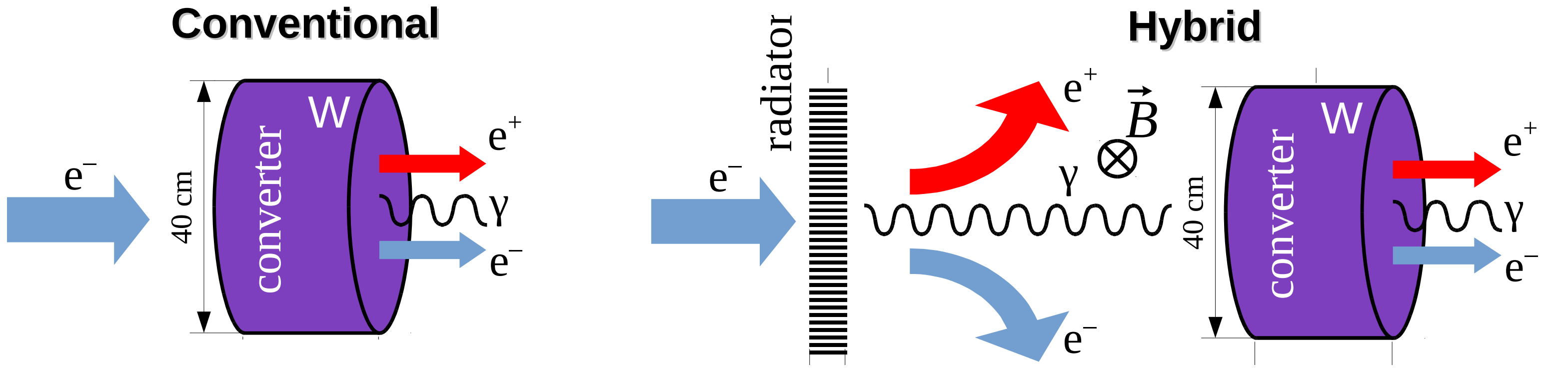


Crystalline X and gamma-ray source **can be applied** in:

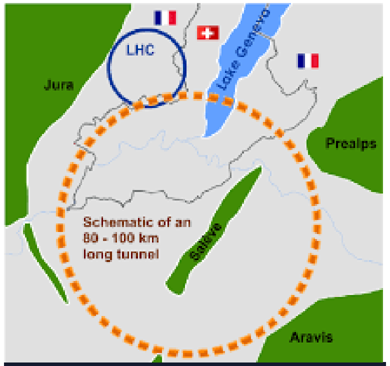
- **Nuclear physics**
- **Medical physics**

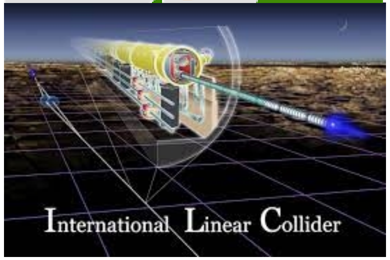
EU project MSCA RISE N-LIGHT G. A. 872196
Coordinator MBN RESEARCH CENTER (Germany)

Crystal-based hybrid positron source*



Coherent effects in a crystal **accelerate electromagnetic shower** development





Coherent effects of e.m. shower in a crystal:

- Channeling radiation/coherent bremsstrahlung
- Coherent pair production

Advantages of the hybrid positron source:

- **Higher** positron yield
- Considerably lower peak deposited energy inside the target => **higher beam intensities**, **longer target lifetime**

Hybrid positron source can be applied at:

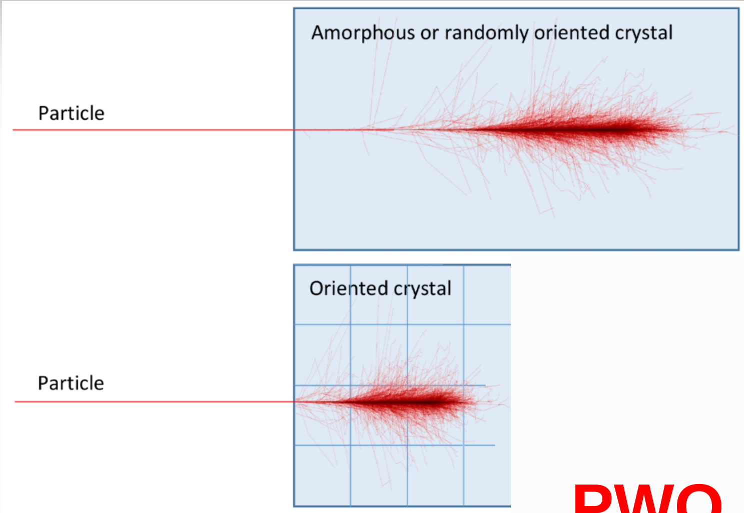
- **FCC-ee**
- **ILC**
- **Muon collider**

Simulation model can be also applied for **ultrashort crystalline calorimeter**

Crystal-based ultrashort electromagnetic calorimeter*

Advantage:

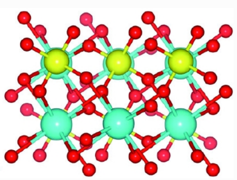
- Considerably shorter thickness
- More transparent for other particles (hadrons)
- Potentially lower time resolution



Crystalline calorimeter can be applied at:

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

PWO



CERN North Area

K_LEVER

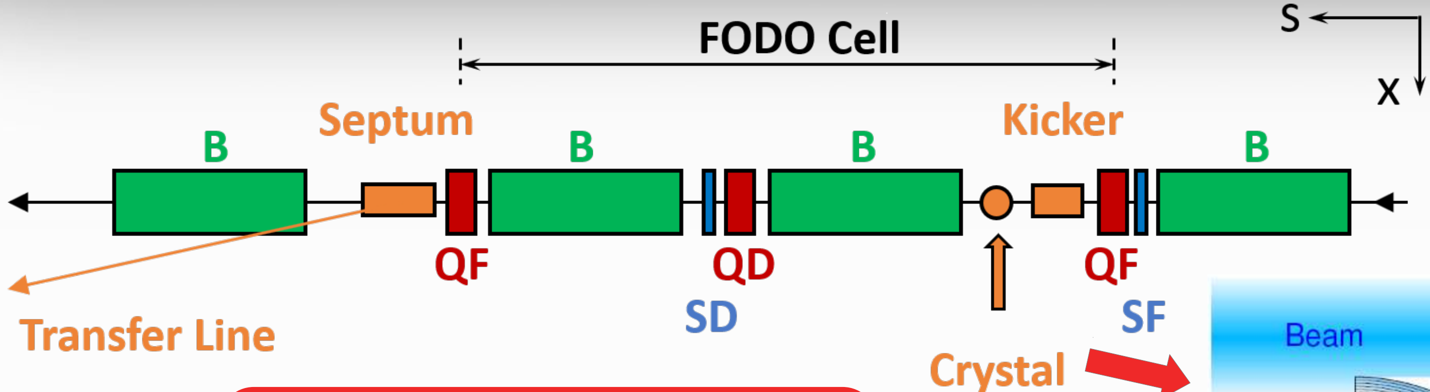
$$K_L \to \pi^0 \nu\nu$$

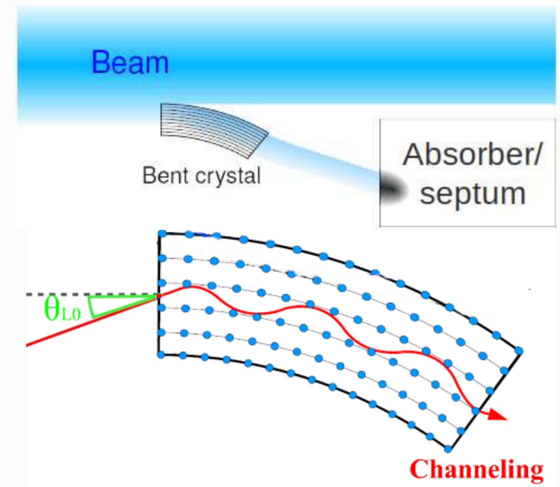
+ dark photon search

Gamma-ray Space Telescope (like Fermi)

Cristalline calorimeter extends observation γ **energy range** up to **TeV**

Crystal-based extraction: possible setup at DESY-II





Channeling of GeV electrons: experimentally observed*

Advantages:

- Extraction of **primary** low-emittance and very **intense electron beam** in a **parasitic mode**.
- The **extraction line** including septum magnets already **exists => ideal for prove-of-principle**
- Few GeV electron beam, **typical for electron synchrotrons** existing in the world.

Crystal-based beam extraction: applied only for protons, not yet for electrons

Can be applied at:

- **DESY-II and any e-/e+ synchrotron**

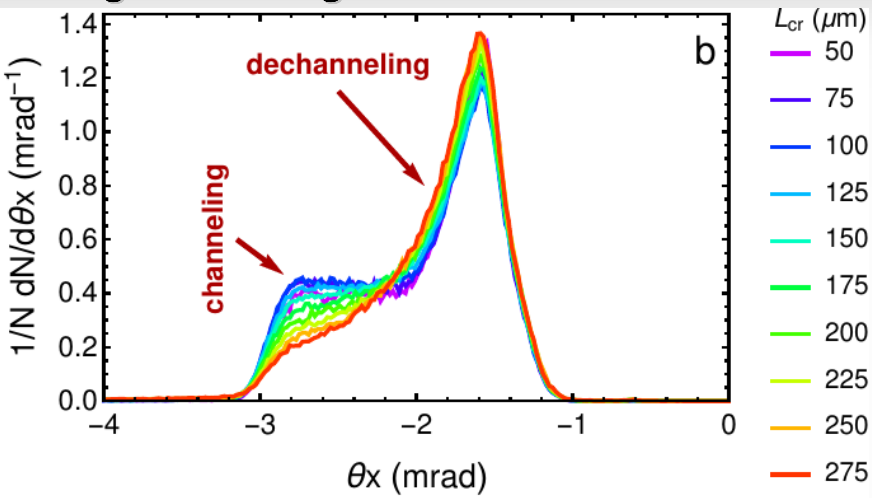
Have been already applied at:

- **LHC, Tevatron, SPS, RHIC, U-70**

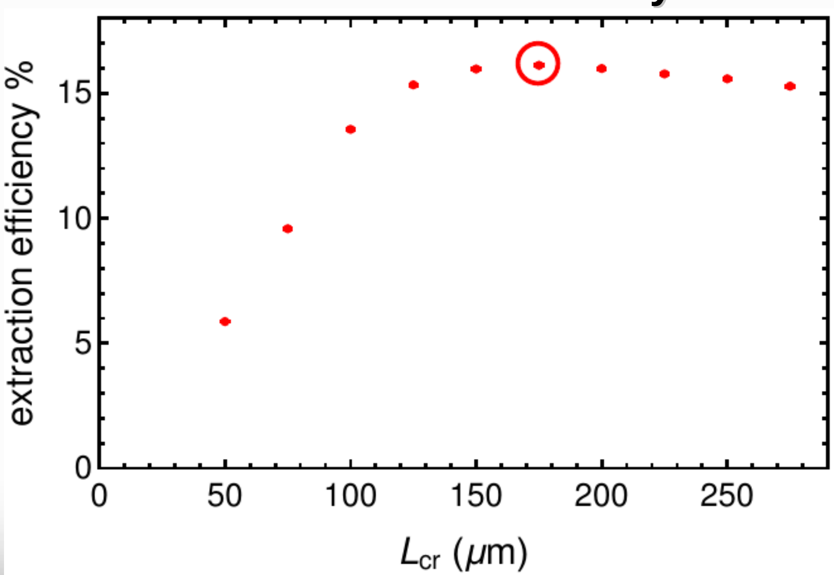
***A. Mazzolari et al. Phys. Rev. Lett. 112, 135503 (2014)**
A.I. Sytov, L. Bandiera et al. Eur. Phys. J. C 76, 77 (2016)
T. N. Wistisen, ..., and A. Sytov. Phys. Rev. Lett. 119, 024801 (2017)

Crystal-based extraction: CRYSTALRAD simulation results

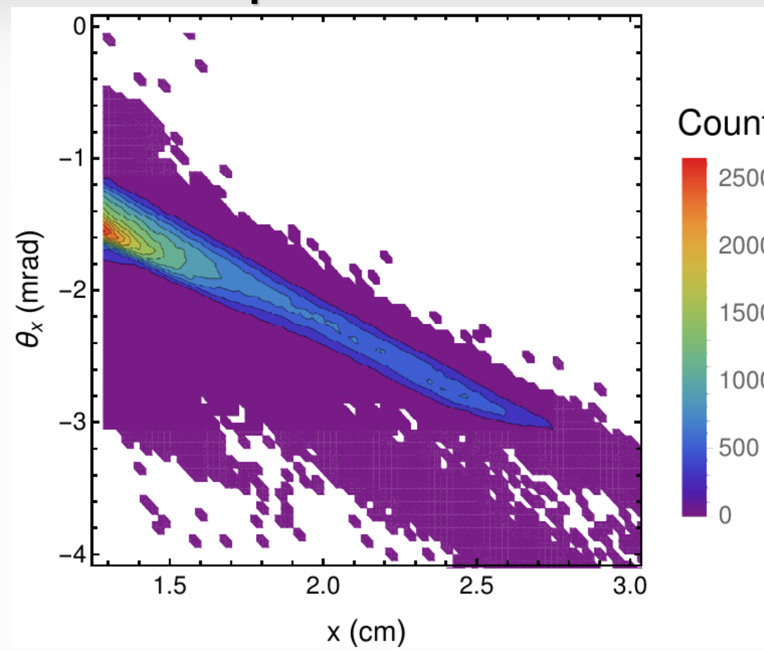
Angular divergence of extracted beam



Extraction efficiency



Phase space of extracted beam



Crystal parameters:

- **Si (111)**
- bending angle **1.75 mrad**
- Crystal length **0.175 mm**
- Crystal transverse thickness **1 cm**

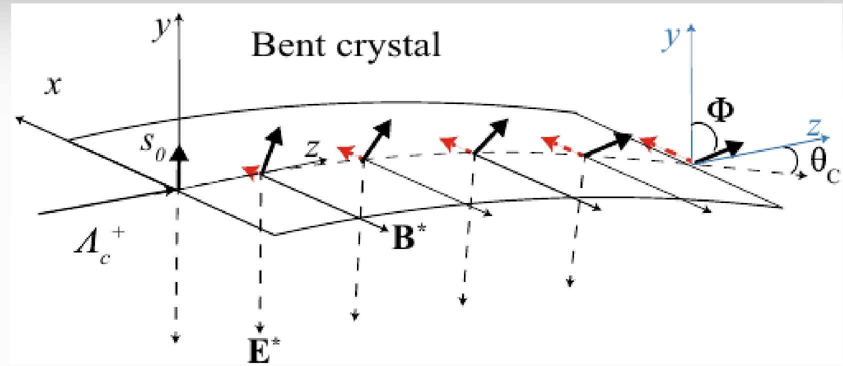
Maximal extraction efficiency: 16.1 %

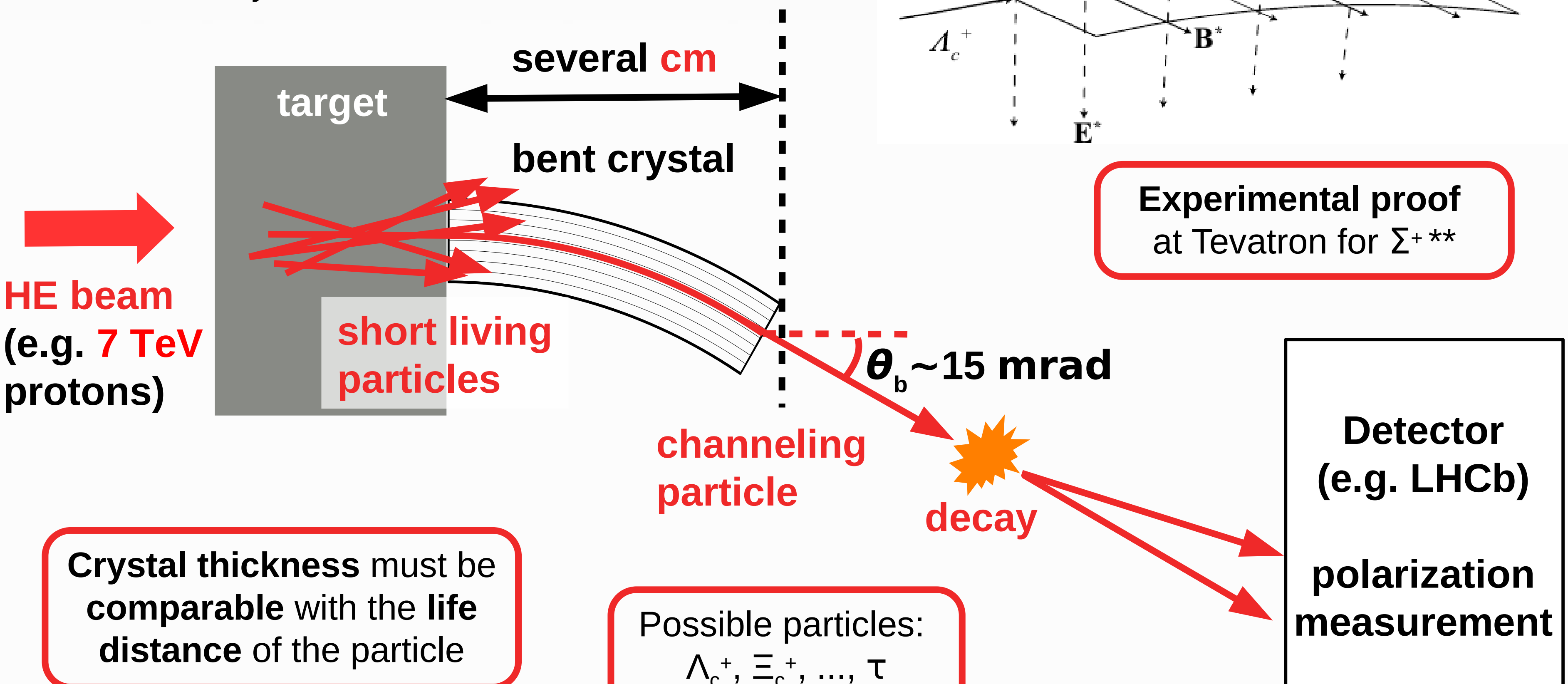
Additional applications of oriented crystals

Search of MDM&EDM of short living particles using the effect of spin rotation in oriented crystals*

What we want:

- To measure **MDM** and **EDM** of exotic baryons





Experimental proof at Tevatron for Σ^+**

Crystal thickness must be **comparable** with the **life distance** of the particle

Possible particles: Λ_c^+, Ξ_c^+, ..., τ

* V. G. Baryshevskii, Pis'ma Zh. Tekh. Fiz. 5, 182 (1979)

**D. Chen et al. (E761 Collaboration) Phys. Rev. Lett. 69, 23 (1992)

Plasma wake-field acceleration in oriented crystals*

$$E[\mathrm{GV/m}] = m_e \omega_p c/e \approx 100\sqrt{n_0[10^{18}\mathrm{cm}^{-3}]}$$

Acceleration gradient: $1\text{-}10\ \mathrm{TeV/m}$

Considerably **higher electron density** in a **solid state** than in a gaseous plasma

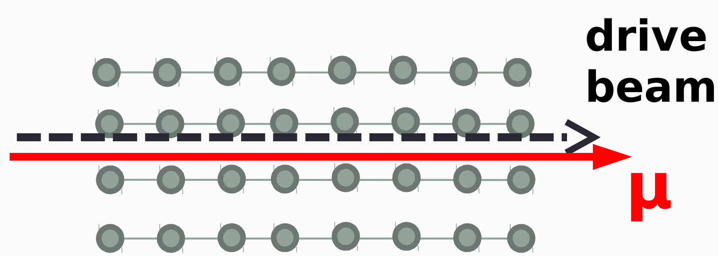
Channeling makes **crystal** almost **transparent** both to accelerated and to drive beam

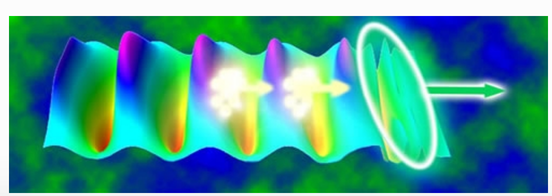
Possible drive beam:

- **X-rays**
- **electrons**
- **heavy high-Z beams**

Possible accelerated beam:

- **muons**
- **e+/e-**
- **protons**





Compact muon collider?

*** R. Ariniello, …, and T. Tajima, Snowmass'2021 AF6: Advanced Acceleration Concepts, arXiv: 2203.07459**

T.Tajima, M.Cavenago, Crystal X-ray accelerator, Phys. Rev. Lett., 59(13), 1440 (1987).