



# TRILLION

**Geant4 simulations of applications of oriented crystals  
breaking down the challenges in accelerator physics,  
particle physics and space science**  
**Marie Curie Global Fellowships, Project TRILLION GA n. 101032975**

**Dr. Alexei Sytov**

**IJCLab, Orsay, 22/03/2024**

# Where I am from?

I work in  
Italy, Ferrara



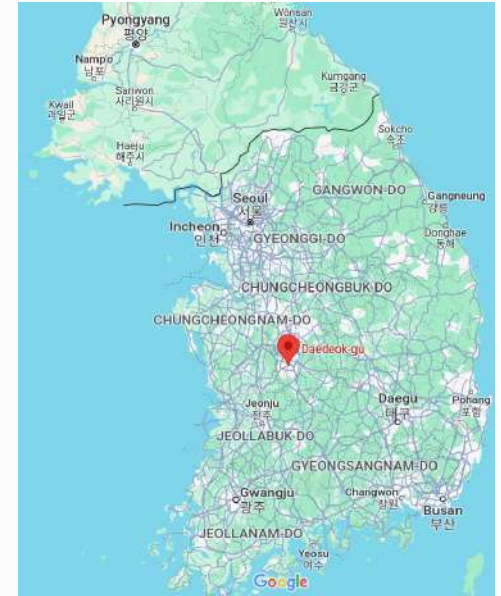
Originally I am from  
Belarus, Minsk



Serey\_Nik\_Minsk



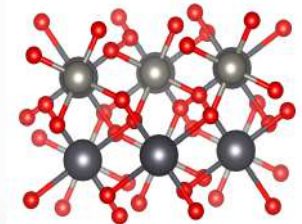
I spent almost 2 years in  
Daejeon, Korea



# Briefly about me

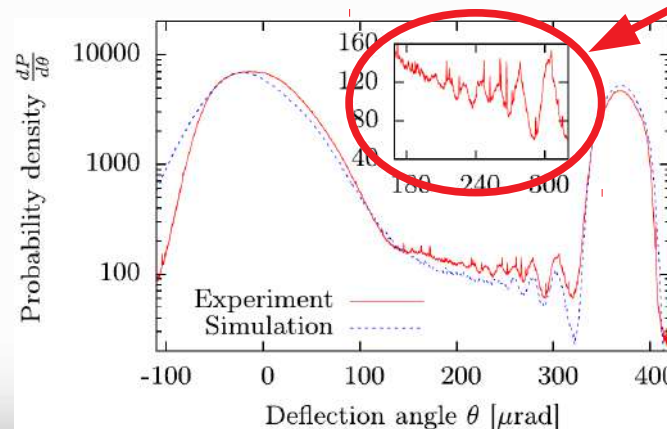
- **2018: 2 PhDs** – in Experimental Physics, University of Ferrara and in Theoretical Physics, Belarusian State University
- **2019-2021: Post-doctoral Fellow** in Experimental Physics at the INFN Division of Ferrara.
- Since **2020** involved in **MC\_INFN** – INFN **Geant4** project
- Since **02/09/2021**: Marie Skłodowska-Curie Action Global Individual Fellowships, GA n. 101032975 – project **FRILLION**
- **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<sup>+</sup>/e<sup>-</sup>/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.
- Since 2022 member of

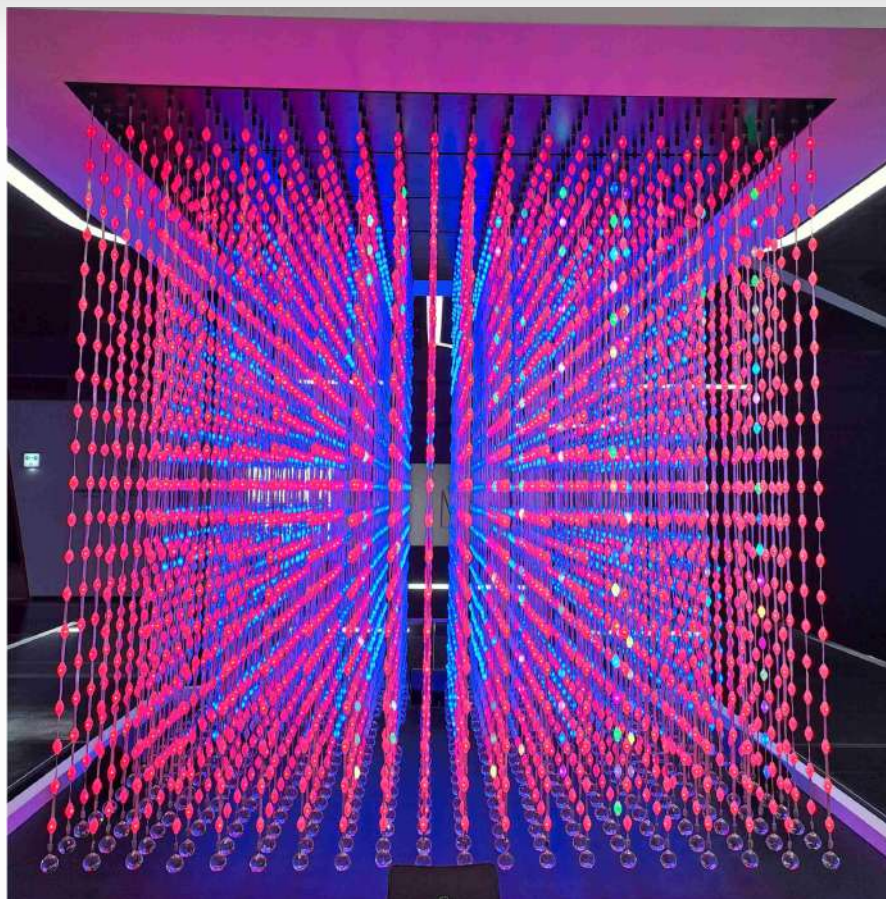


**Quasichanneling  
oscillations**



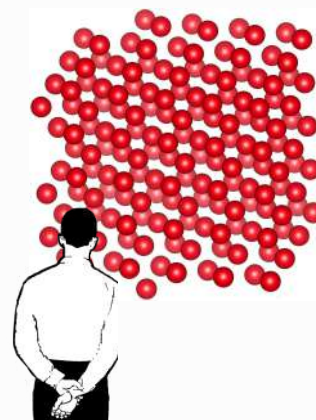
European Commission

# How an oriented crystal looks like

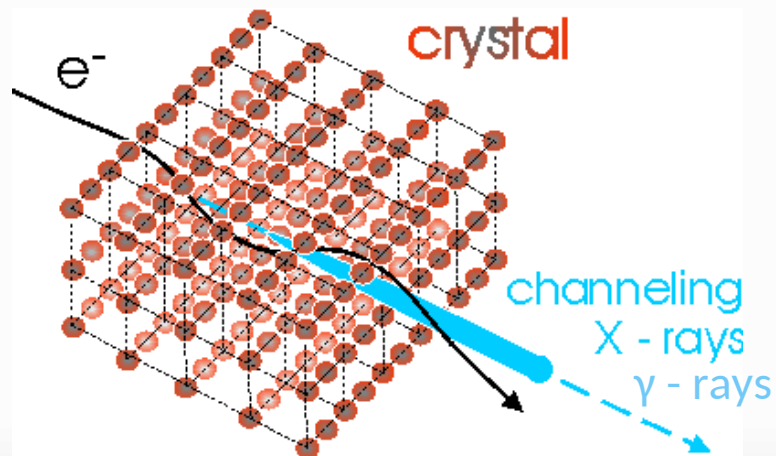
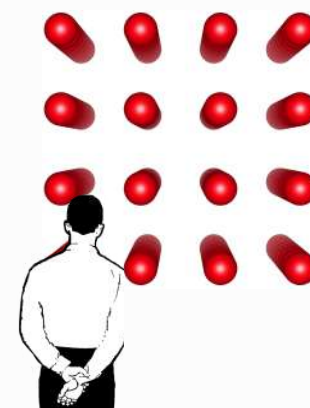


from National Science Museum, Daejeon, Korea

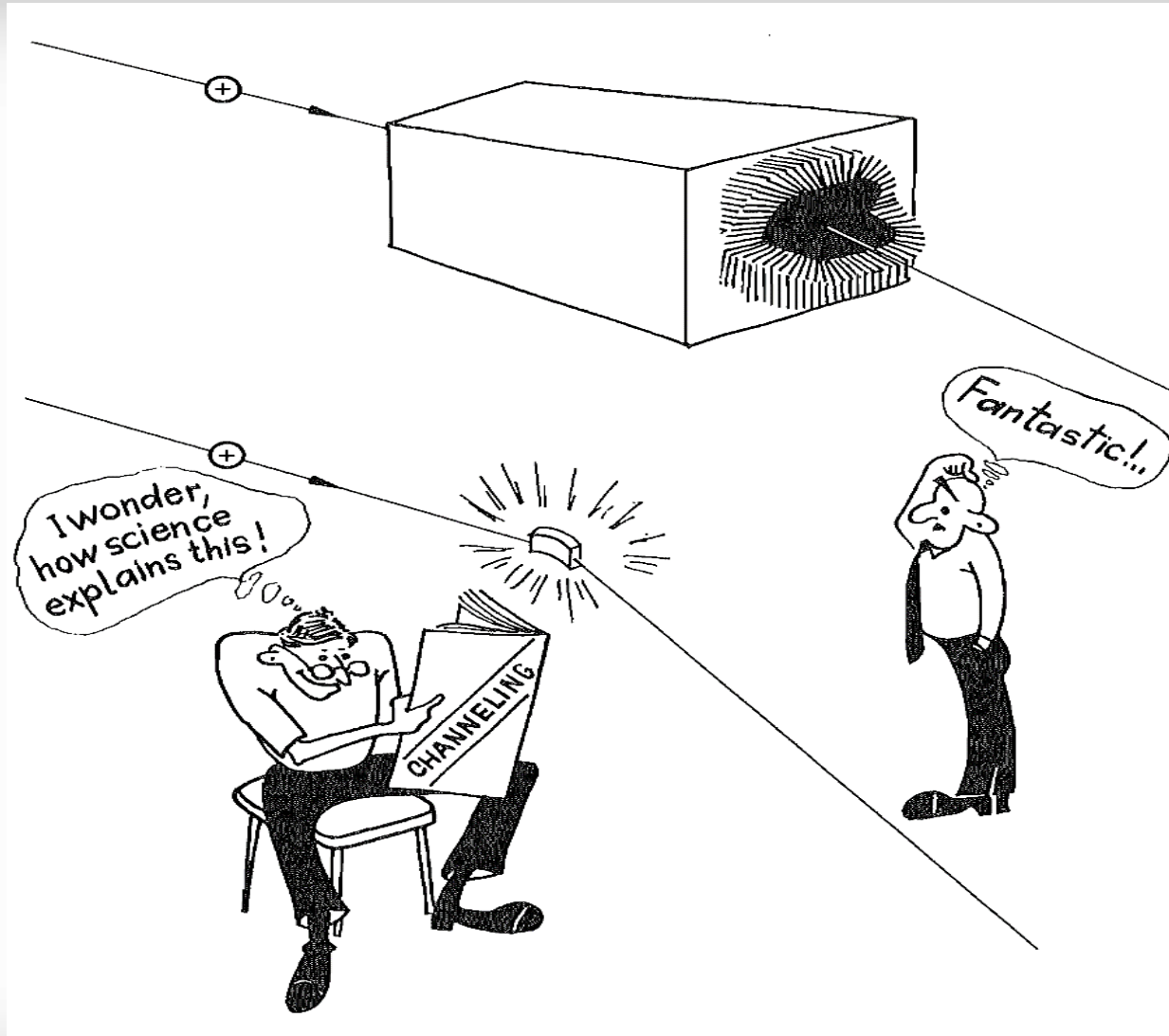
Non-oriented crystal



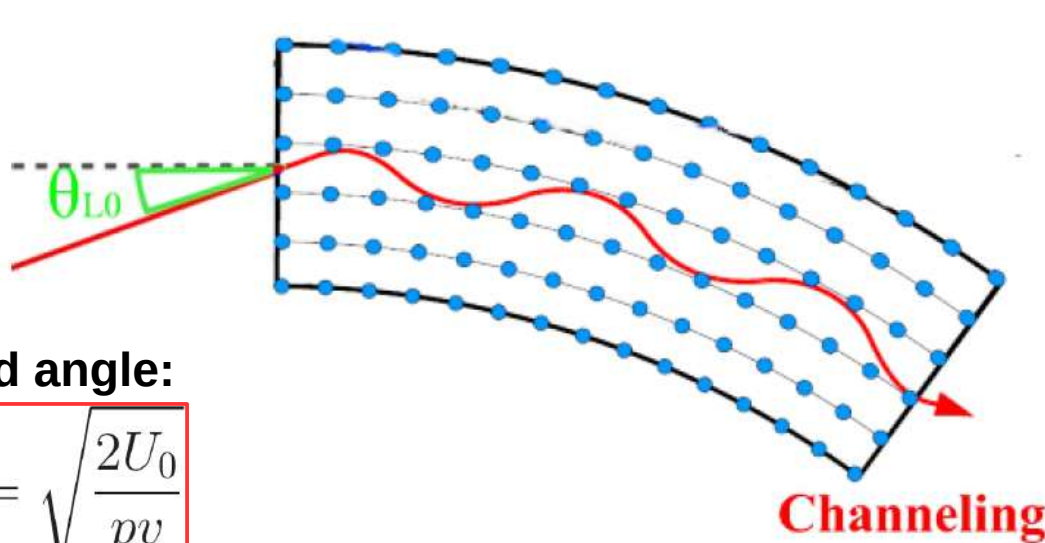
Oriented crystal



# The world of the channeling effect

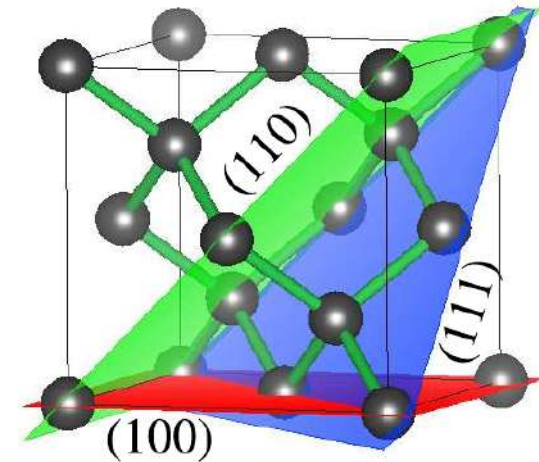


# Channeling effect\*



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

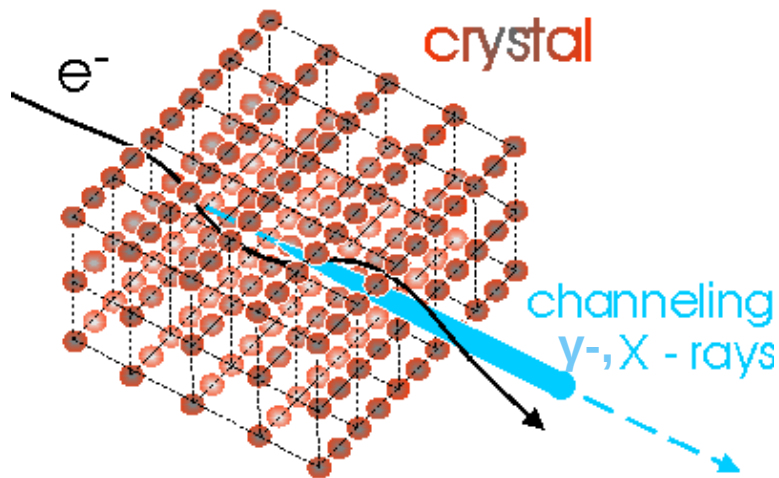
- **Planar channeling**
- **Axial channeling**

**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)

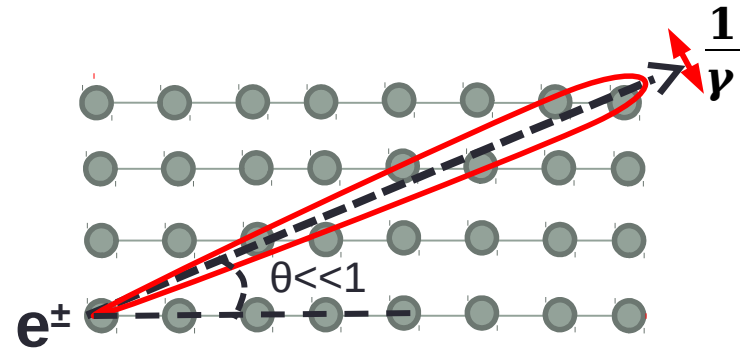
# Coherent effects in a crystal

## Channeling radiation\*

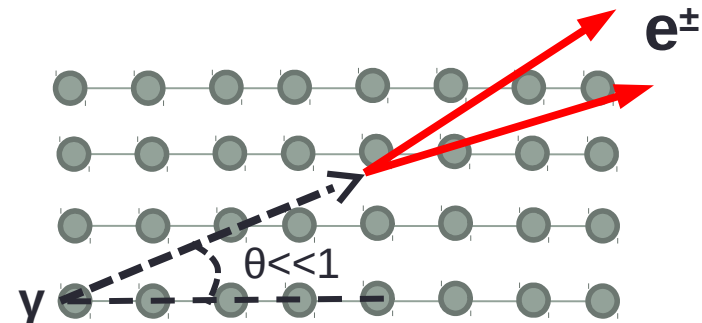


Coherent effects preserve  
**up to few mrad** of particle  
direction vs the crystal axis

## 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).

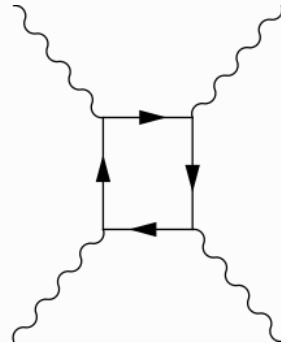
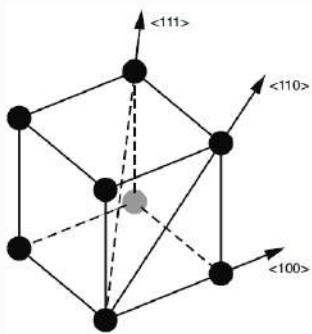


# Electromagnetic shower acceleration

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

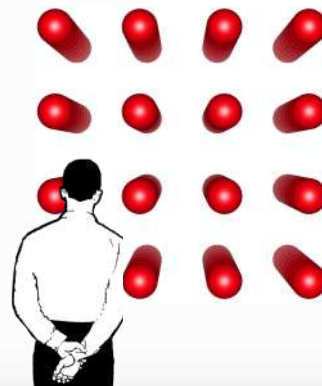
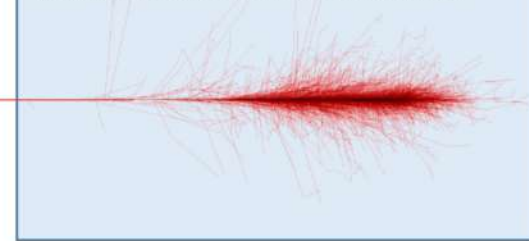


Approaching the  
**Schwinger limit**  
starting from few  
**GeV** for **e<sup>+</sup>/e<sup>-</sup>**



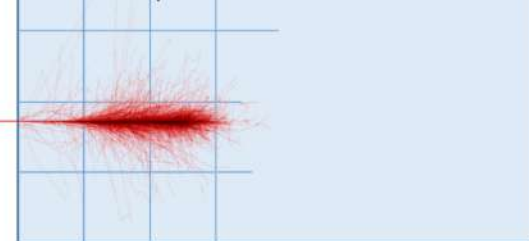
Particle

Amorphous or randomly oriented crystal



Particle

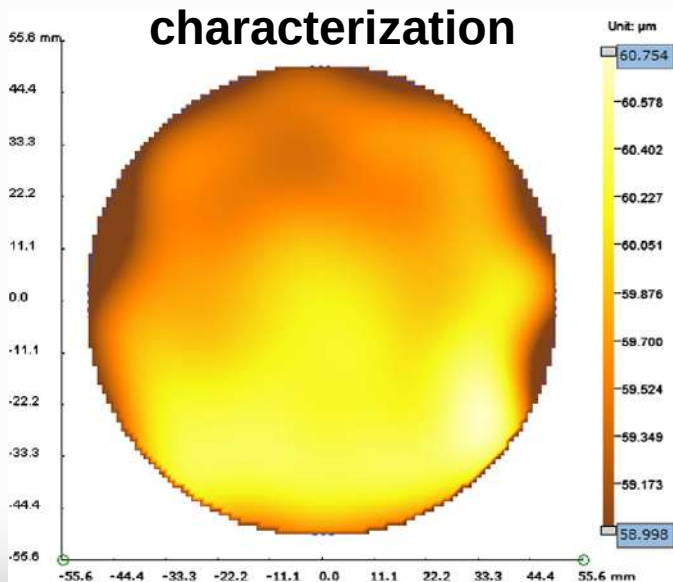
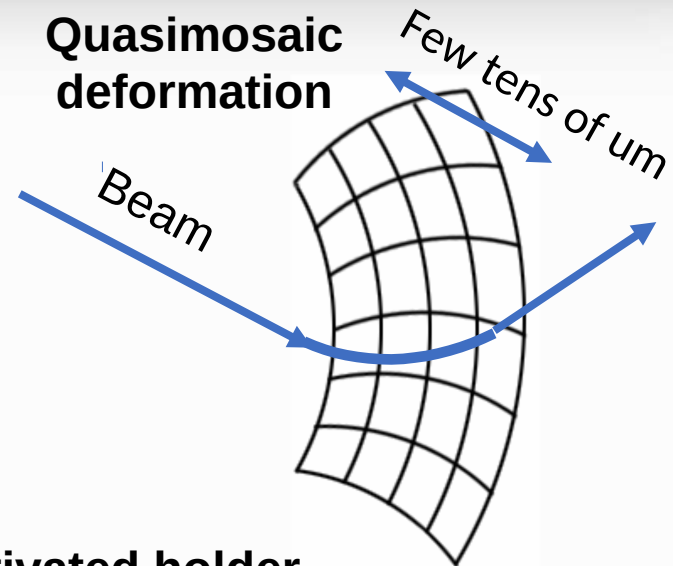
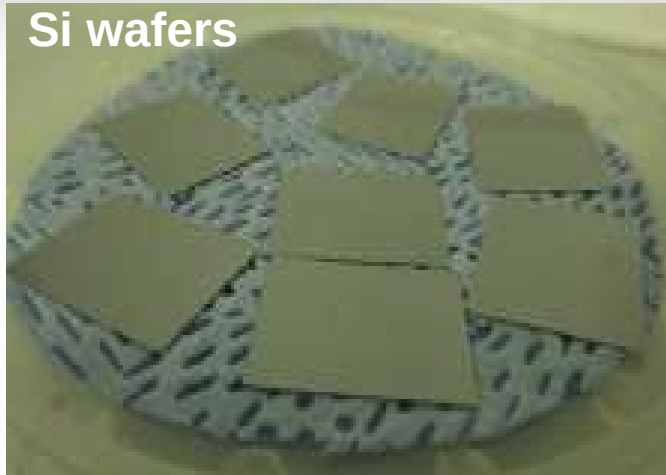
Oriented crystal



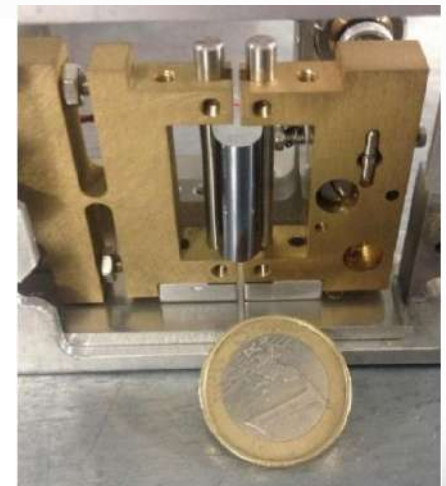
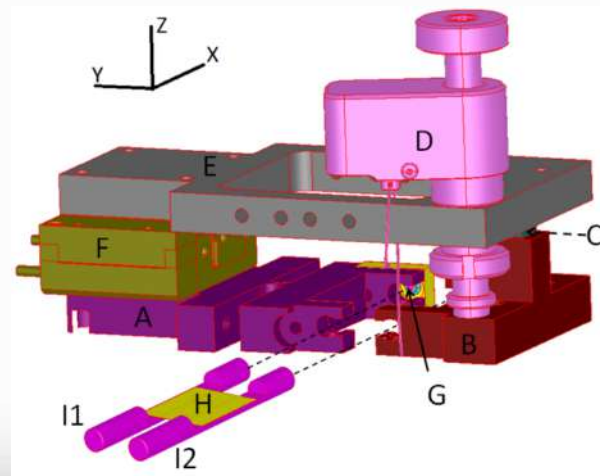
The **radiation** intensity and the **pair production** cross-section **drastically increase** in **oriented crystals!**

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

# Manufacturing and characterization of bent silicon crystals @INFN Ferrara



Piezo-activated holder

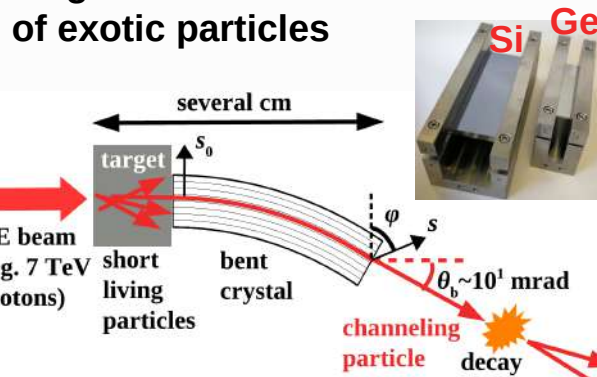


# Applications\*

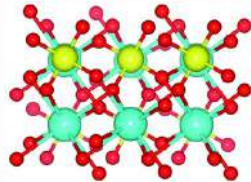
Crystal-based collimation or beam extraction from an accelerator



Measurement of dipole magnetic and electric moments of exotic particles



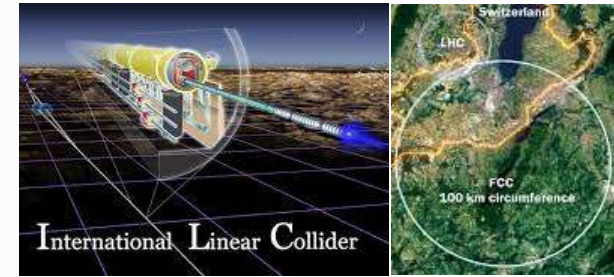
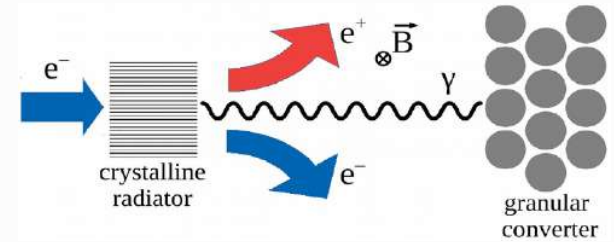
Ultrashort crystalline calorimeter



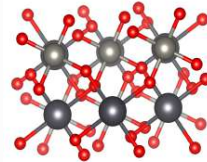
Gamma-ray Space Telescope



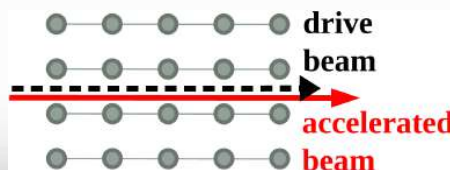
Positron source for future e<sup>+</sup>/e<sup>-</sup> and muon colliders



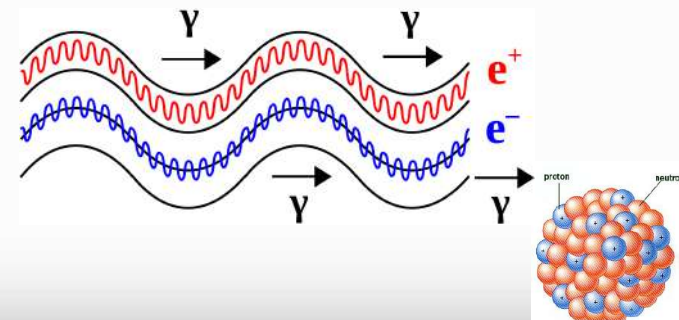
Oriented crystals



Plasma acceleration



X and  $\gamma$ -ray source for nuclear and medical physics



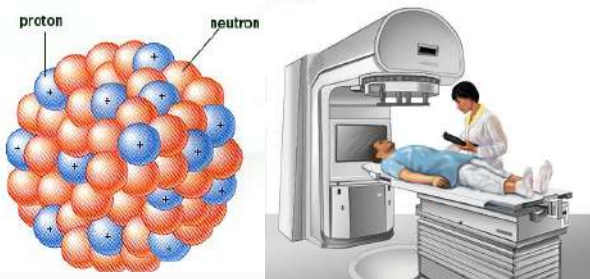


European Commission

# Applications of oriented crystals\*



X and  $\gamma$ -ray source for nuclear physics and cancer radiotherapy



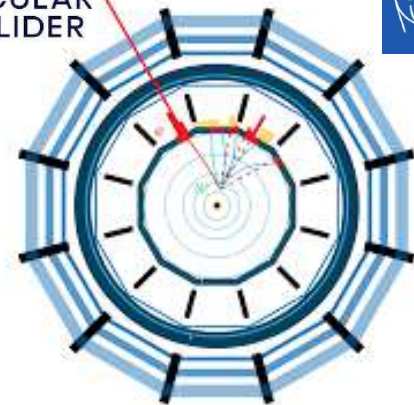
Gamma-ray Space Telescope



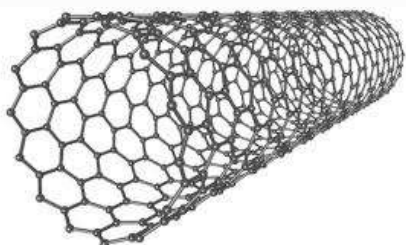
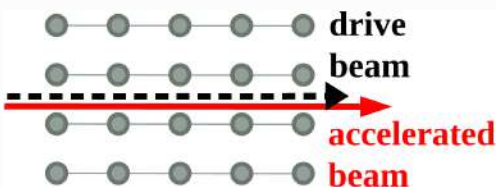
Positron source for future multi-billion € e<sup>+</sup>/e<sup>-</sup> and muon colliders



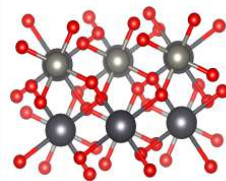
FUTURE CIRCULAR COLLIDER



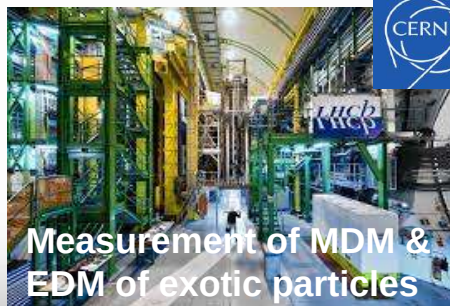
Plasma wakefield acceleration



Oriented crystals



Crystal-based beam extraction from accelerators and colliders



Measurement of MDM & EDM of exotic particles

# Marie Skłodowska-Curie Action Global Individual Fellowships by A. Sytov in 2021-2025, 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

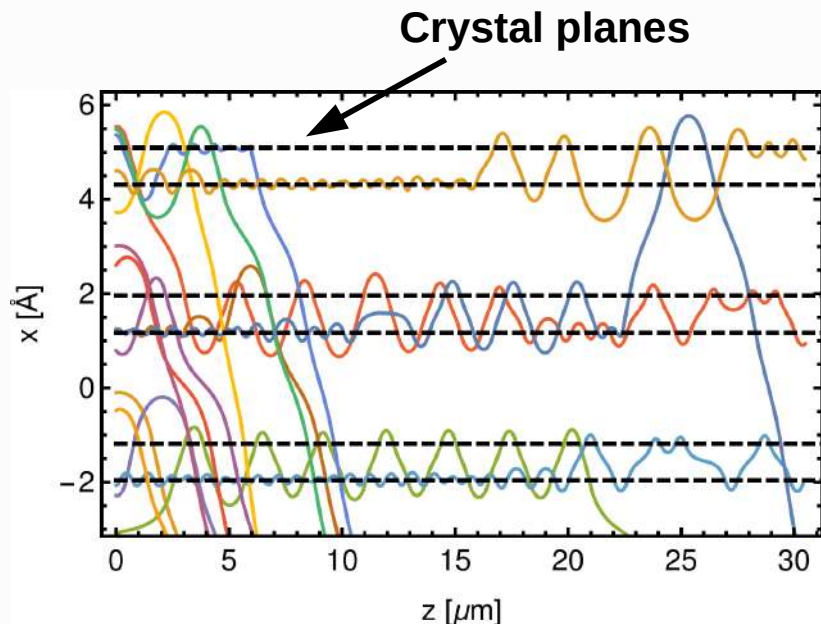
## Location:

- 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)



# Baseline channeling simulation technique: CRYSTALRAD Monte Carlo simulation code

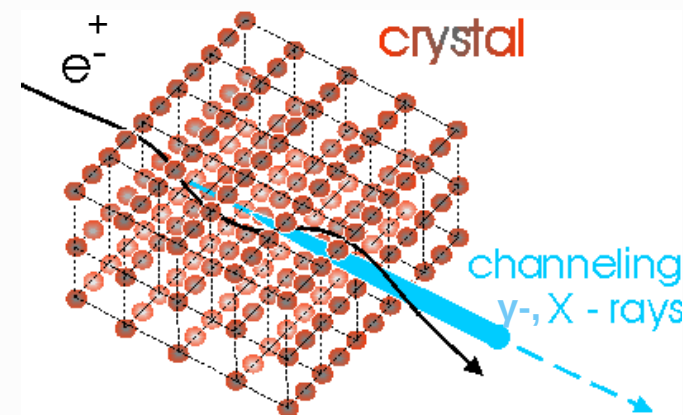
**Main conception** – simulation of classical trajectories of charged particles in a crystal in averaged atomic potential of planes or axes. Multiple and single **scattering simulation** at every step



## Advantages:

- High calculation speed
- MPI parallelization for high performance computing

channeling\*



## Baier-Katkov formula:

integration is made over the classical trajectory

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

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)

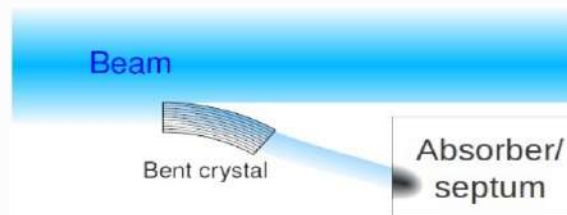
\*A. Sytov et al. Journal of the Korean Physical Society 83, 132–139 (2023)

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

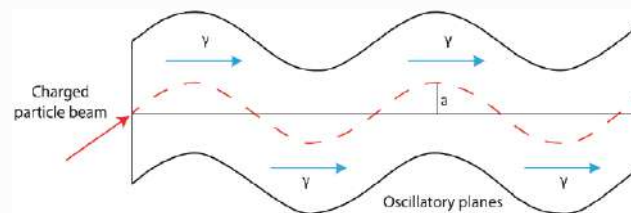
# Marie Sklodowska-Curie Action Global Fellowships by A. Sytov in 2021-2024, Project TRILLION

## Specific applications to implement into Geant4:

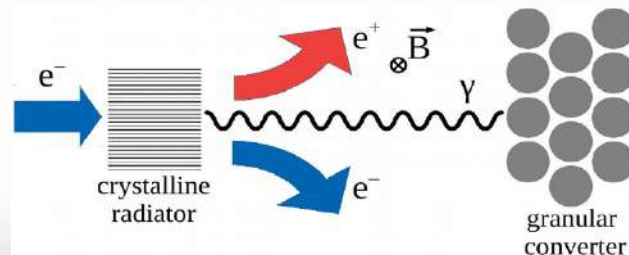
- **Crystalline deflector to extract a charged particle beam from an accelerator** (electron synchrotron, hadron collider) to supply fixed-target experiments by an intense low-emittance beam.



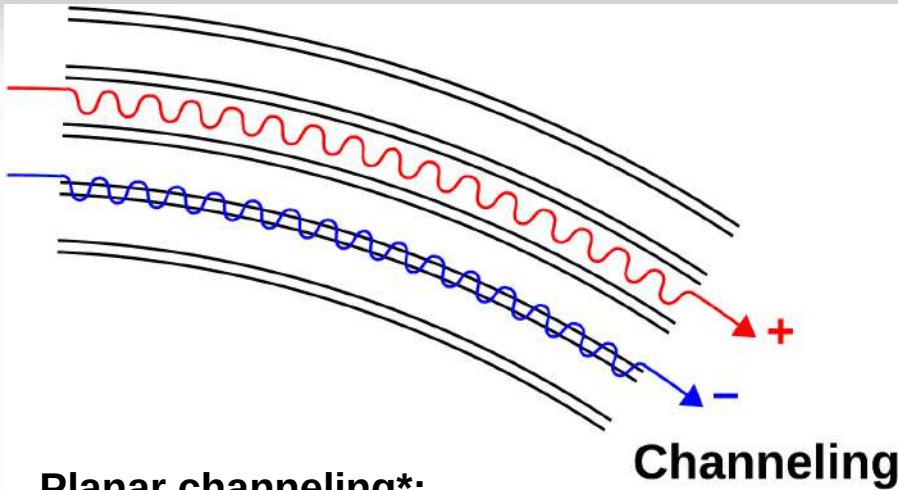
- **Crystalline source of hard X-ray and gamma radiation, crystalline undulator (CU).**



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



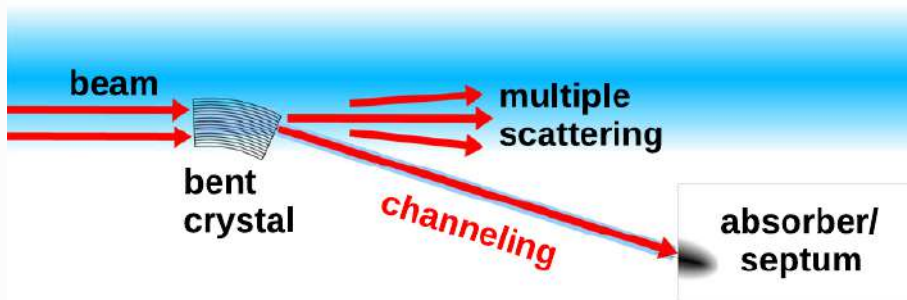
# Crystal-based extraction



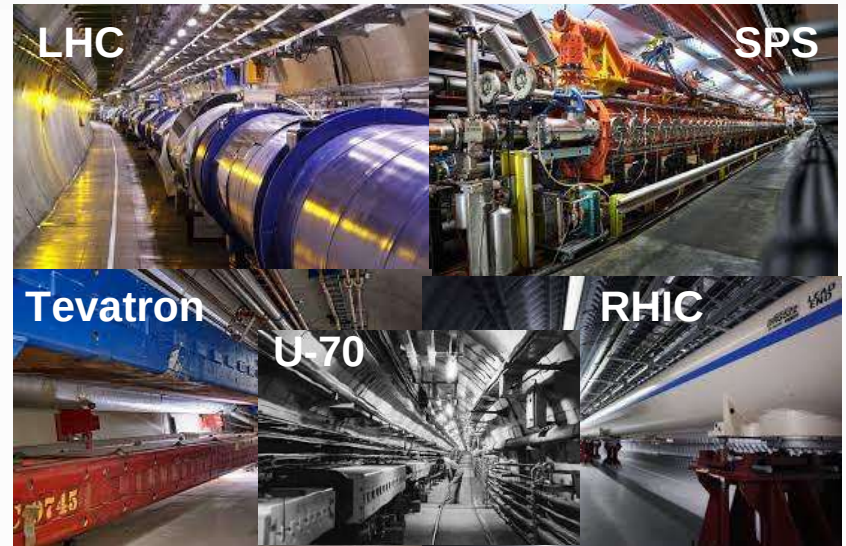
## Planar channeling\*:

- Charge particle penetration through a monocrystal along its atomic planes

## Crystal-based extraction/collimation



Crystal-based collimation and extraction have been used at hadron machines



Crystal-based extraction/collimation: applied only for hadrons, not yet for e-

Interesting for tens of electron synchrotrons



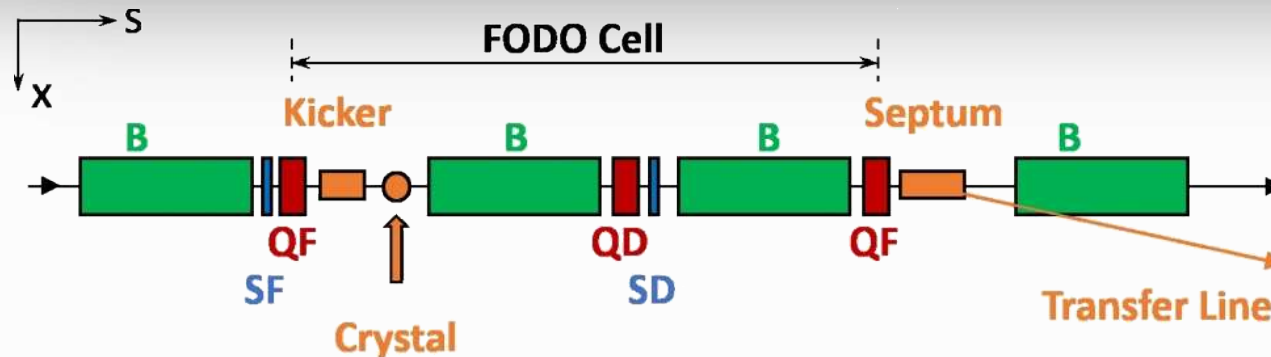
\*J. Lindhard, Kgl. Dan. Vid. Selsk. Mat.-Fys. Medd. 34 No 4, 2821–2836 (1965)

E.N. Tsyganov, Fermilab TM-682 (1976)

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



# Crystal-based extraction: possible setup at DESY-II



B->dipoles  
QF/QD->focusing/  
defocusing quadrupoles

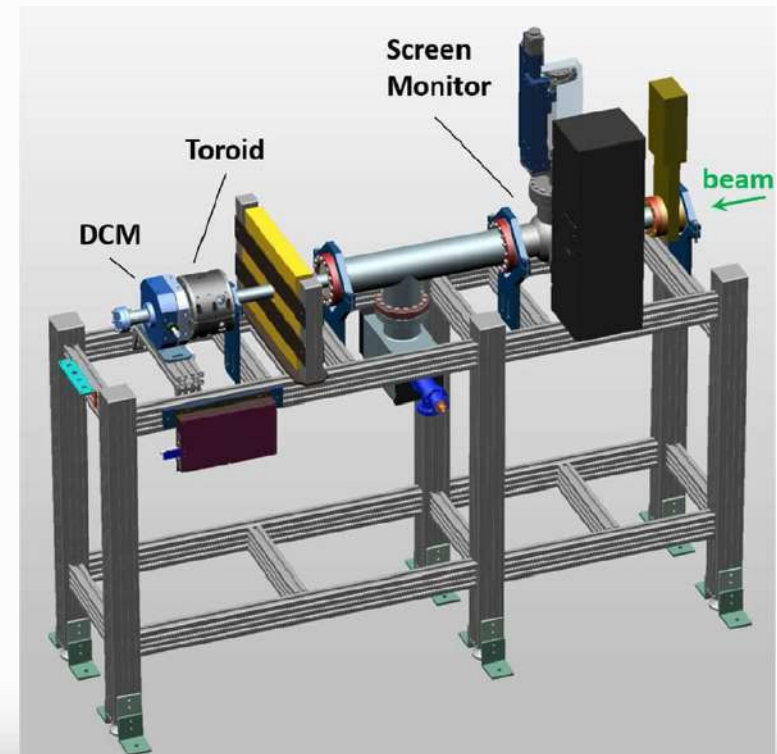
6 GeV electrons

## 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 **synchrotron light sources** existing in the world.

## Applications:

- Nuclear and particle physics detectors and generic **detector R&D**
- Fixed-target experiments in **high-energy physics** including future **lepton colliders**
- Also: **crystal-based collimation** (**synchrotron light sources, colliders**)



# Where the crystal-based extraction of electrons can be applied?

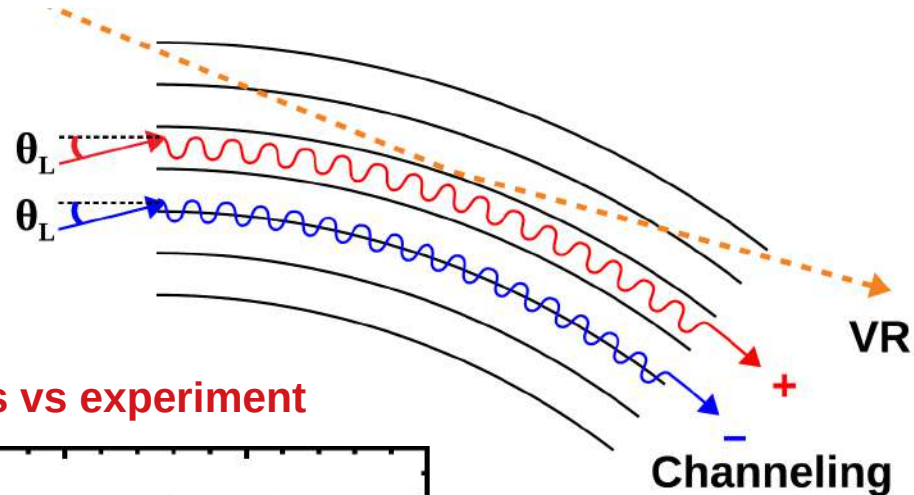




# Geant4 channeling model validation: beam deflection by a bent crystal

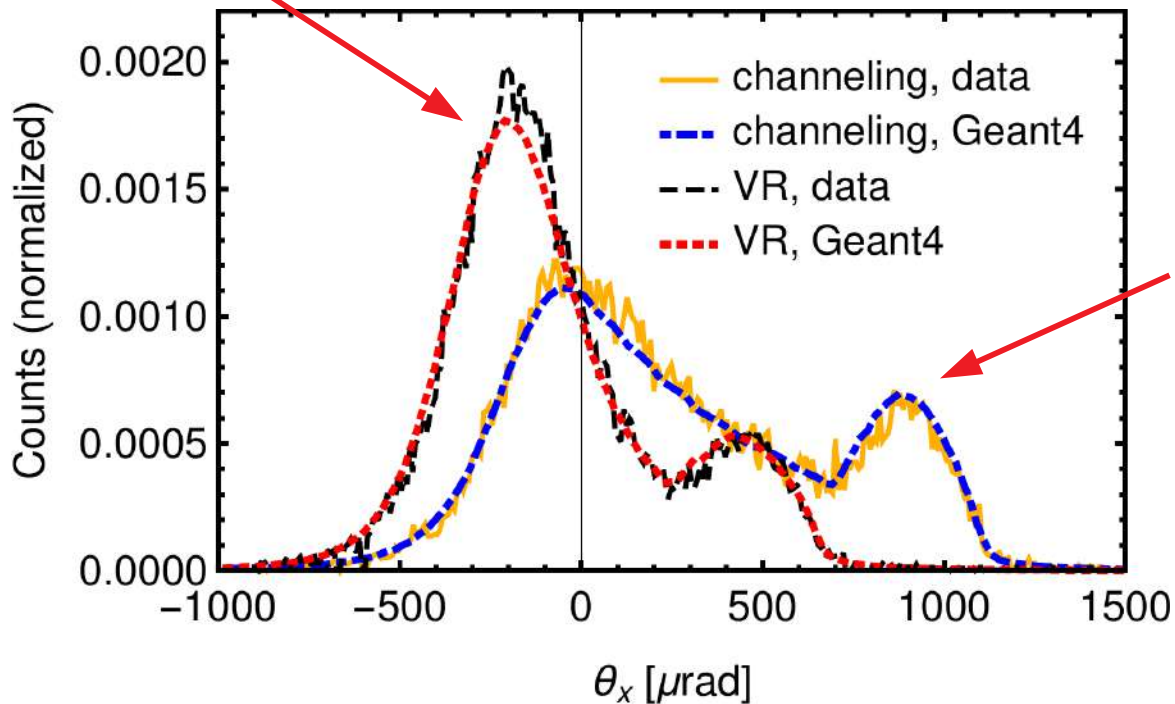
855 MeV  
electrons

15  $\mu\text{m}$  thick  
bent crystal



volume reflection (VR)

Geant4 simulations vs experiment



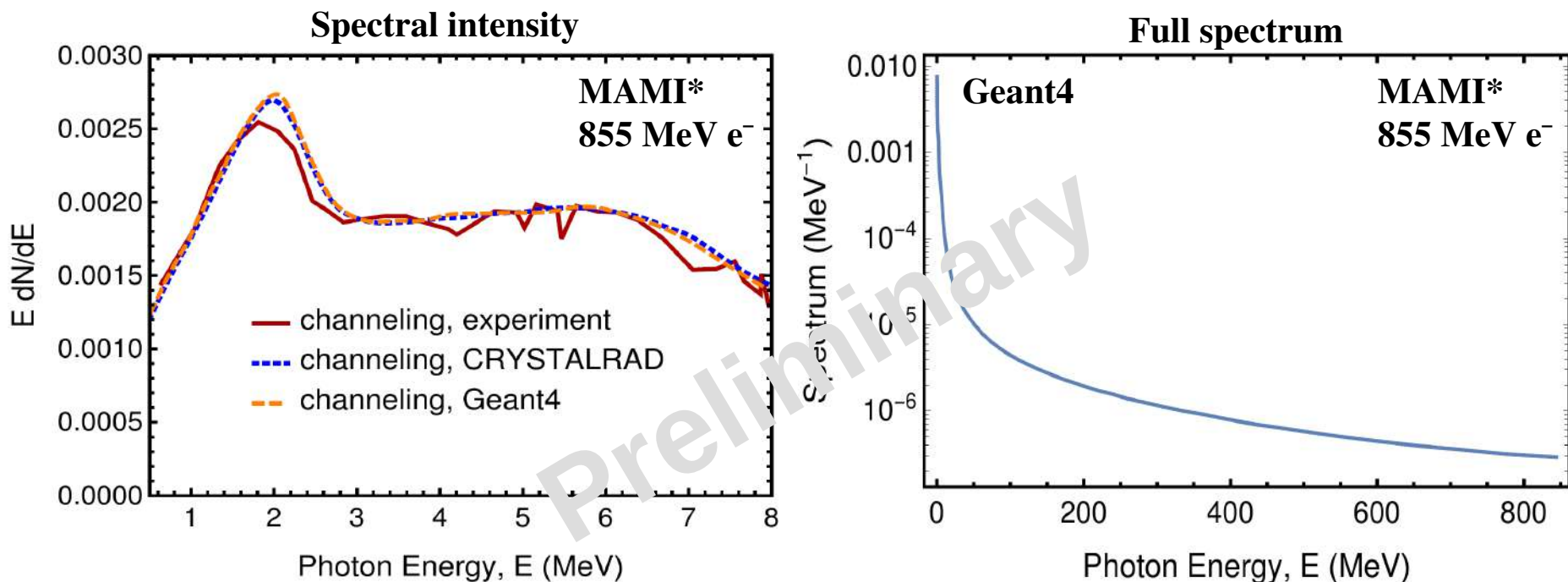
channeling

# First Geant4 Baier-Katkov radiation model: radiation by 855 MeV electrons at Mainz Mikrotron MAMI\*

## G4BaierKatkov:

- Physics list **independent**
- Can be used **outside channeling model** within other FastSim model
- Provides **radiation spectrum** for single-photon radiation mode
- Provides generation of **secondary photons**

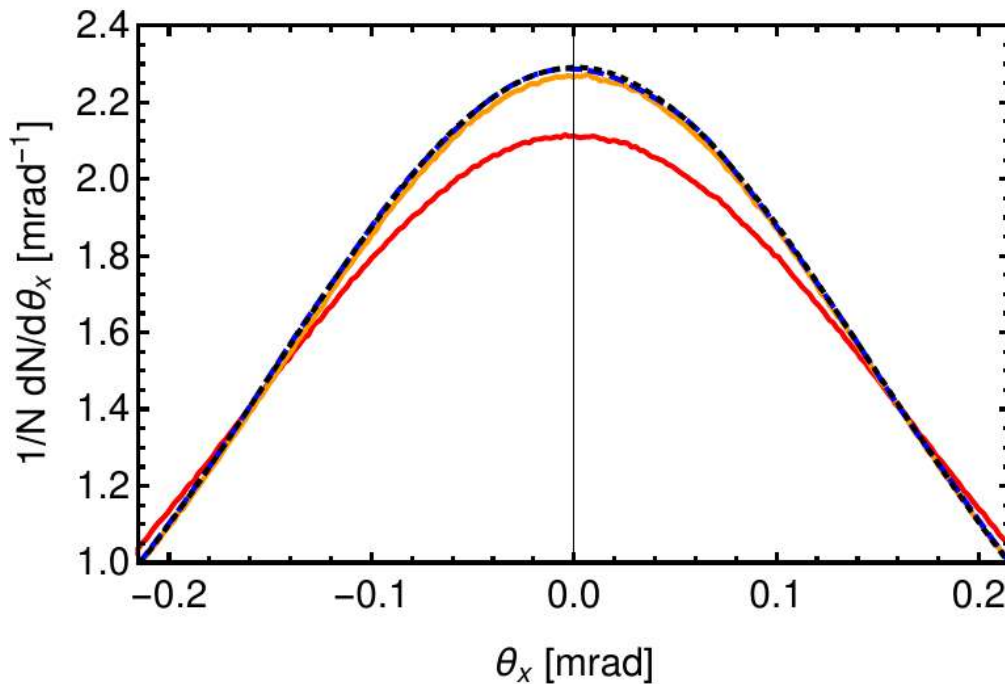
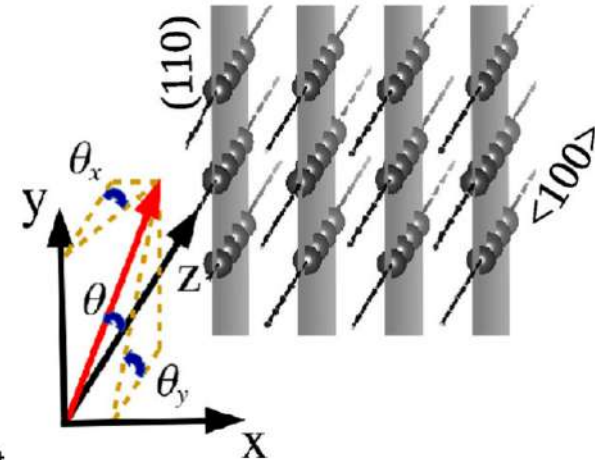
## Geant simulations vs experiment and CRYSTALRAD simulations



To be submitted for publication soon

# 2D Geant4 channeling model validation: coherent scattering suppression effect\*

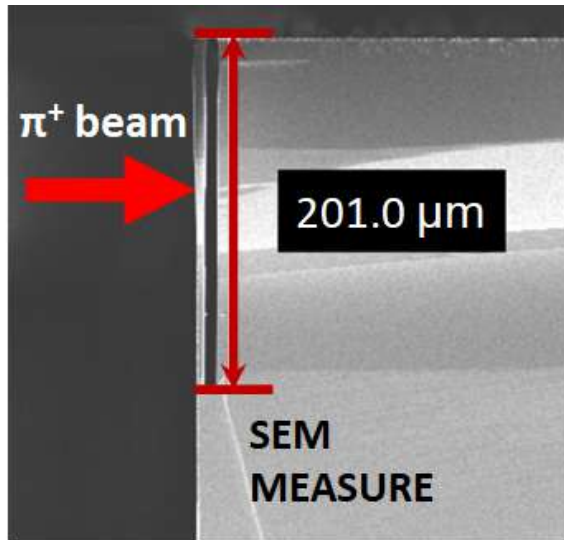
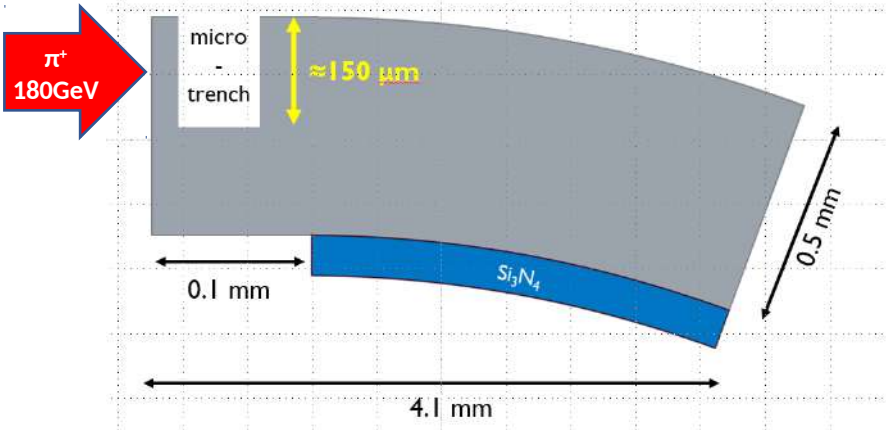
**Multiple scattering in crystal and multiple scattering in amorphous material are different!**



- Experiment amorphous Si
- Experiment Si  $\langle 100 \rangle$  (0.172°, 2°)
- - - Geant4 Si  $\langle 100 \rangle$  (0.172°, 2°)
- - - CRYSTALRAD Si  $\langle 100 \rangle$  (0.172°, 2°)

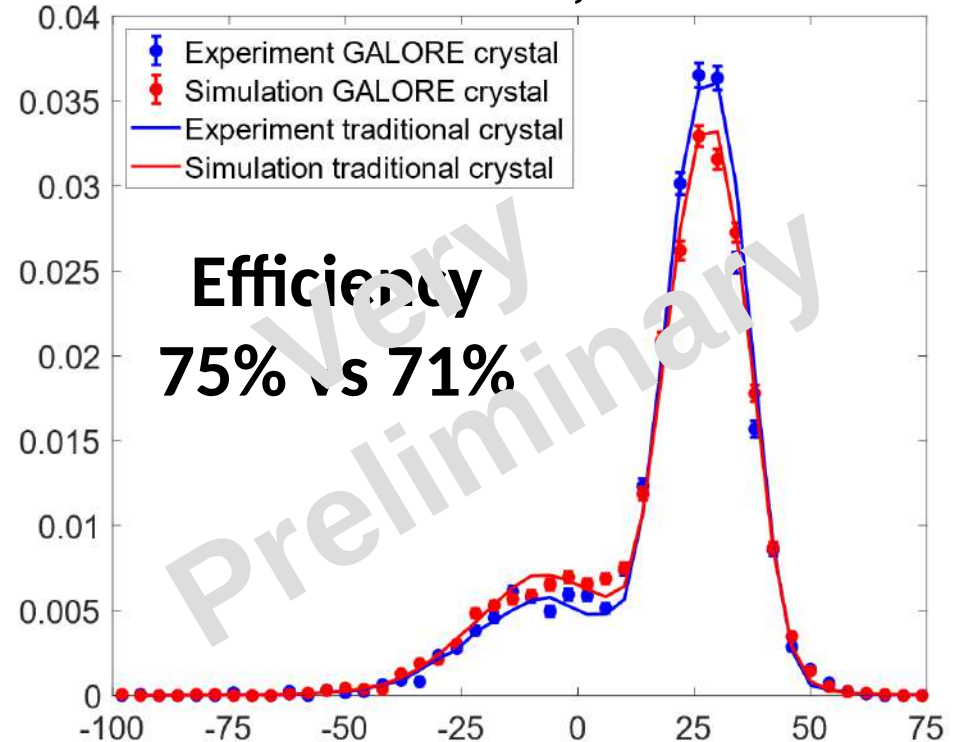
**To be submitted for publication soon**

# Geant4 simulations of the experiment GALORE: Crystalline cut to drastically increase the channeling efficiency



**Geant4 simulations vs  
experimental data**

**GALORE results, 180 GeV  $\pi^+$**

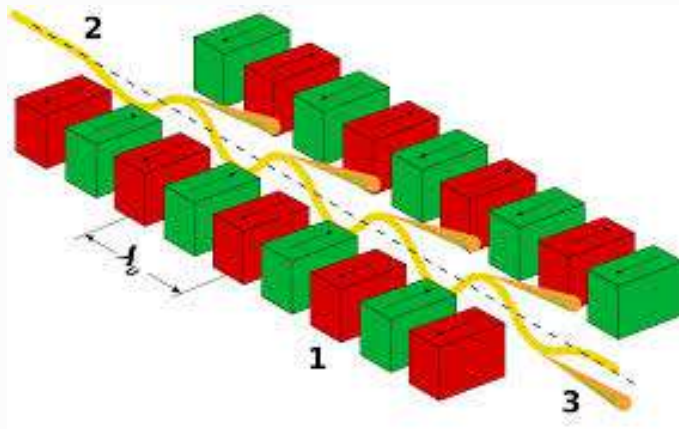


M. Romagnoni, ..., A. Sytov et al. Crystals 12 (9), 1263 (2022)  
M. Romagnoni, ..., A. Sytov et al. Eur. Phys. J. D 76, 135 (2022).

\*V.V. Tikhomirov JINST 2 P08006 (2007)

# Channeling radiation in a bent crystal: Crystalline undulator

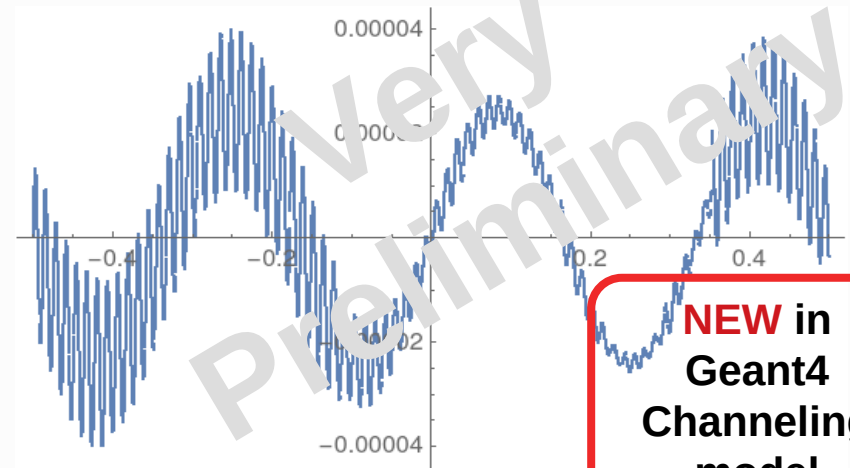
Classical scheme: magnetic undulator in a free electron laser **soft X-rays**  $\lambda_u \sim \text{cm}$



## Advantage:

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

Innovative scheme: Crystalline undulator  $\rightarrow$  **Hard X-rays and gamma rays**  $\lambda_u < \text{mm}$



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

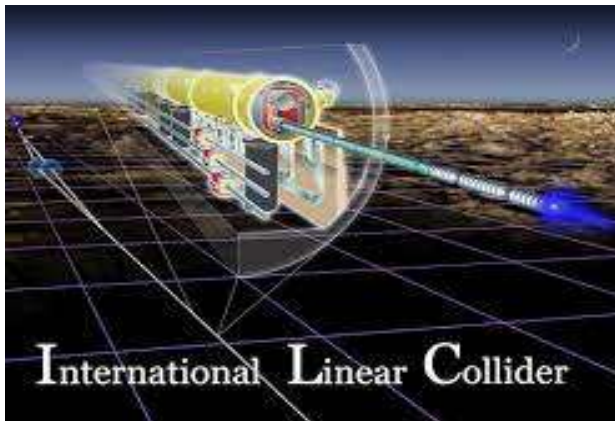
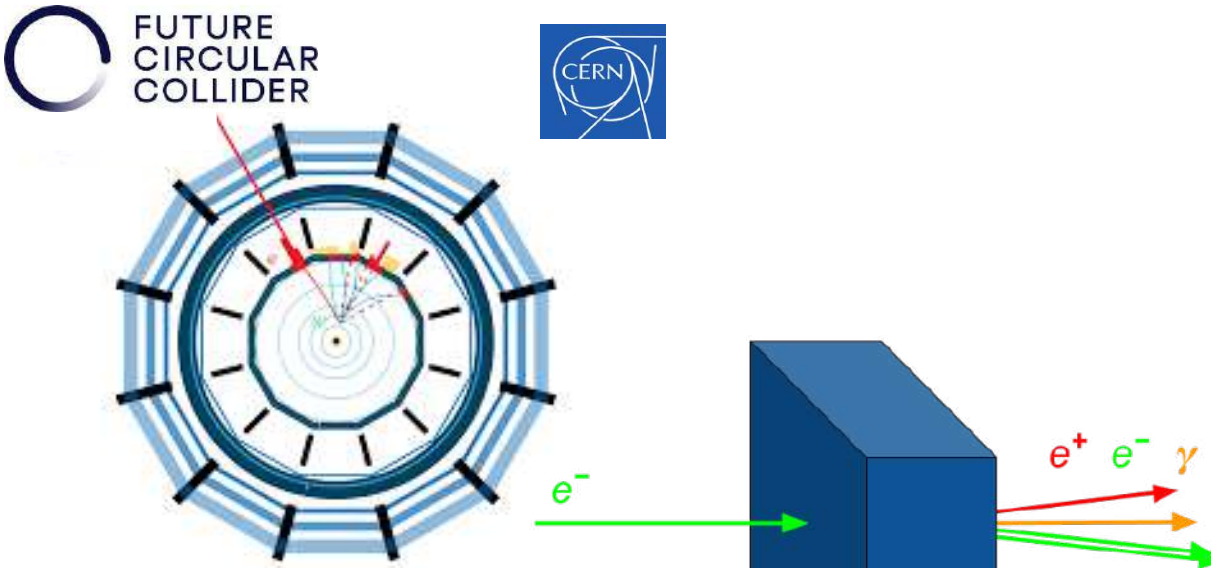
- Nuclear physics
- Medical physics



**H2020-MSCA-RISE N-LIGHT** (G.A. 872196) and  
**EIC-PATHFINDER-OPEN TECHNO-CLS** (G.A. 101046458)  
*Coordinator MBN RESEARCH CENTER (Germany)*



# Positron source for future lepton colliders



International Linear Collider

All the future **e<sup>+</sup>e<sup>-</sup>** colliders will need an **intense positron source**

**Potential challenges:**  
Target overheating/melting

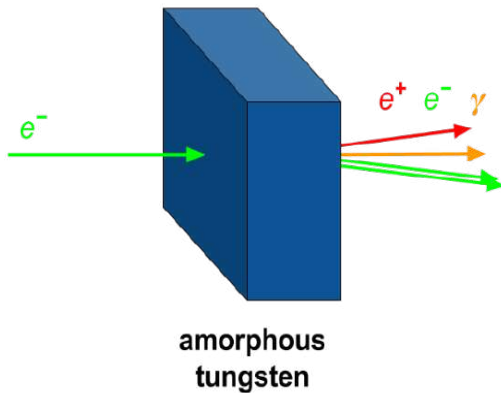


Peak Energy Deposition Density (**PEDD**) limit:  
**35 J/g** for **W\***

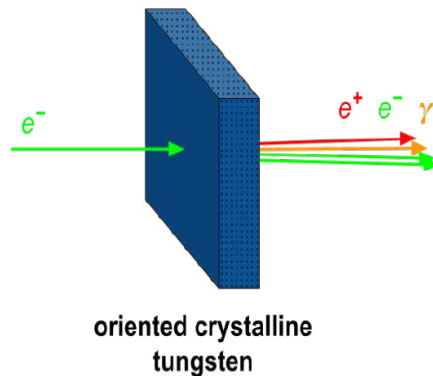
The main **challenge:**  
to **increase positron yield**  
and to **decrease PEDD**

# Different types of crystal-based positron source\*

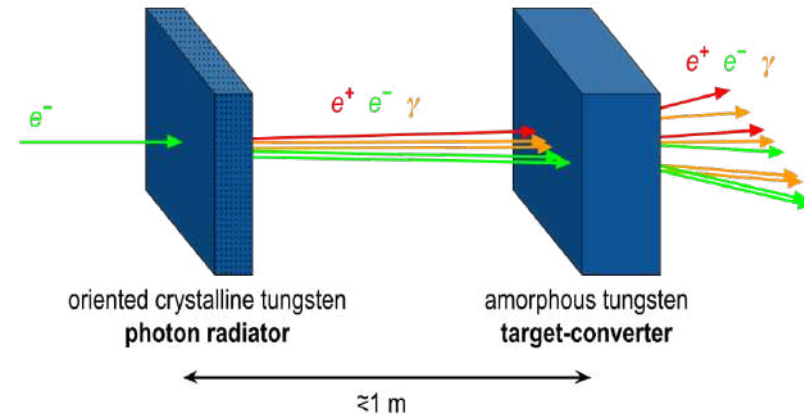
## Conventional target



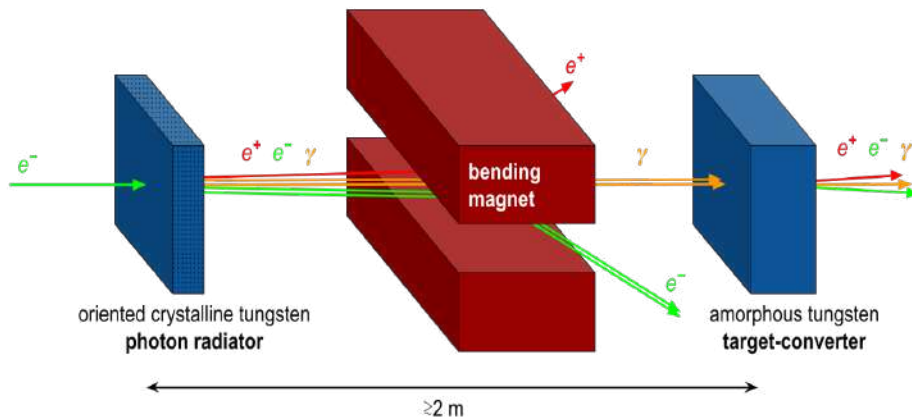
## Crystal target



## Hybrid scheme



## Hybrid scheme with magnetic field

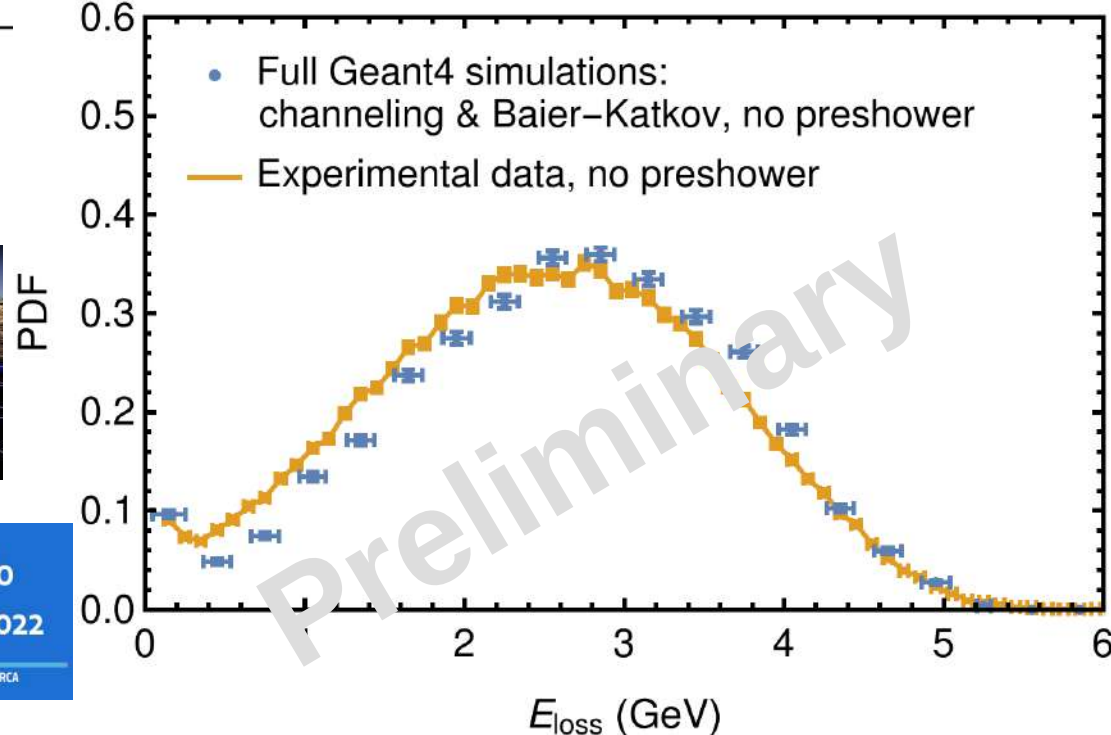
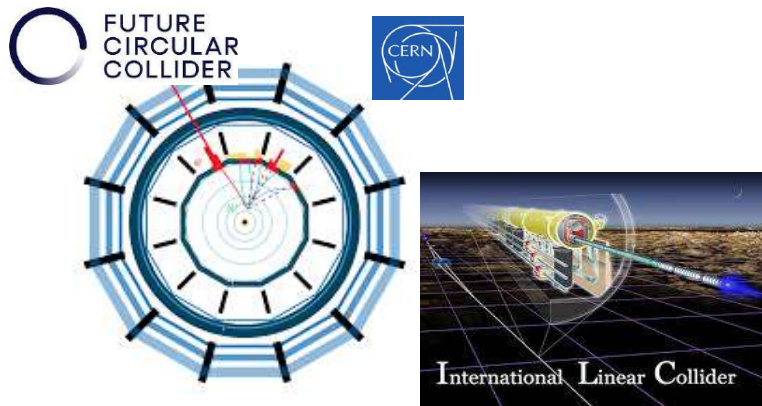
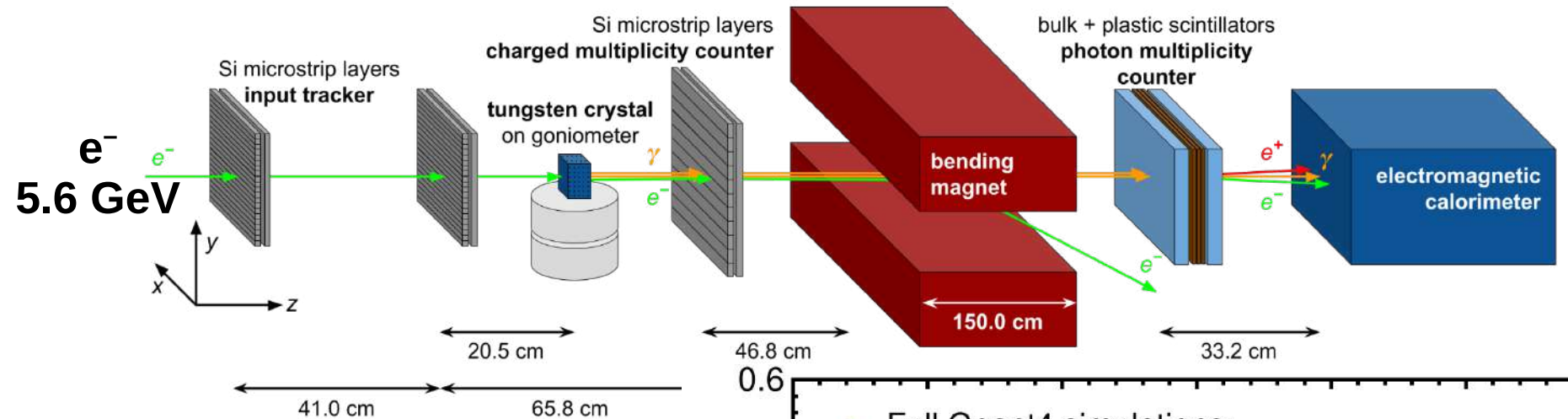


## Hybrid positron source: two stages

- 1. Radiation production and beam scattering at the first target
- 2. pair production in the second target
- Optional magnetic field between 2 targets to reduce PEDD at the second target

**positron yield increase**  
**PEDD reduction**

# Full Geant4 simulations of the DESY experiment\* for the FCC-ee positron source project

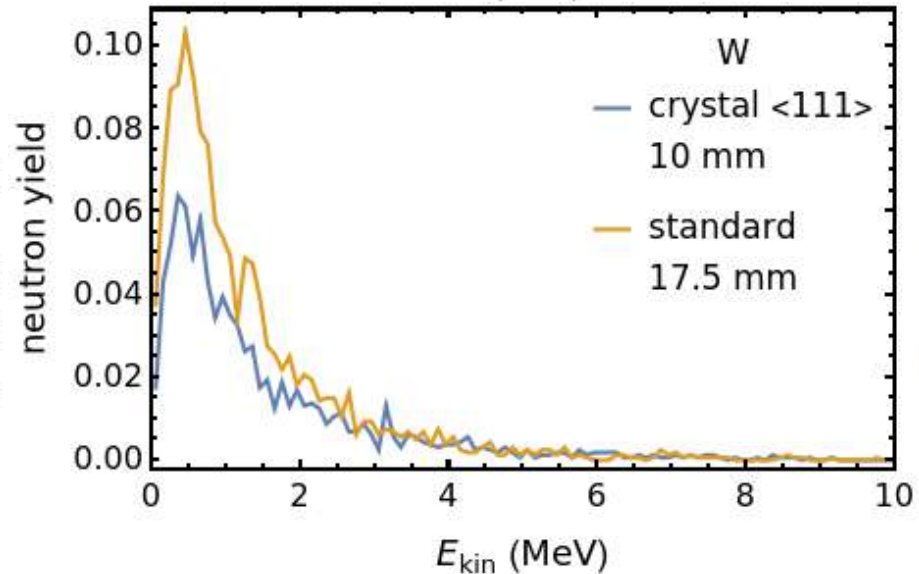
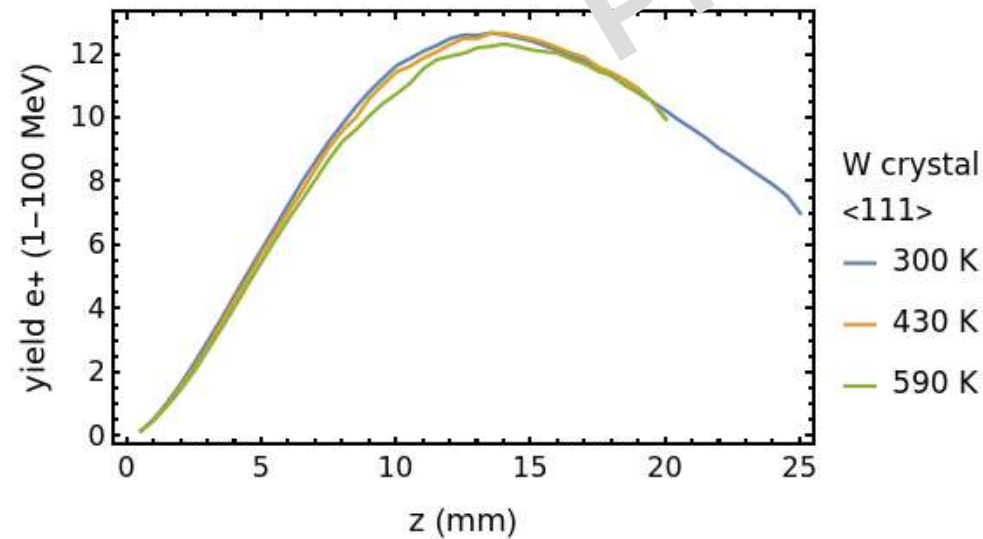
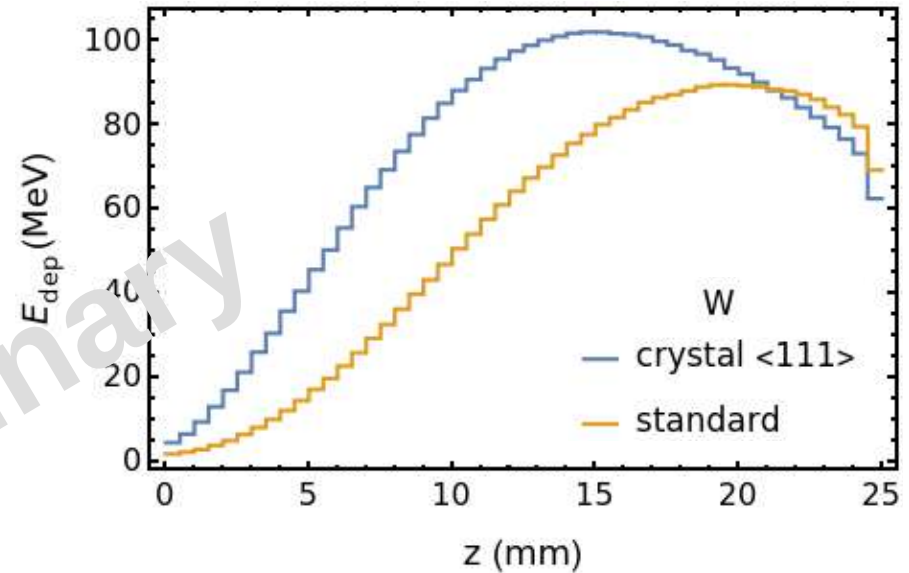
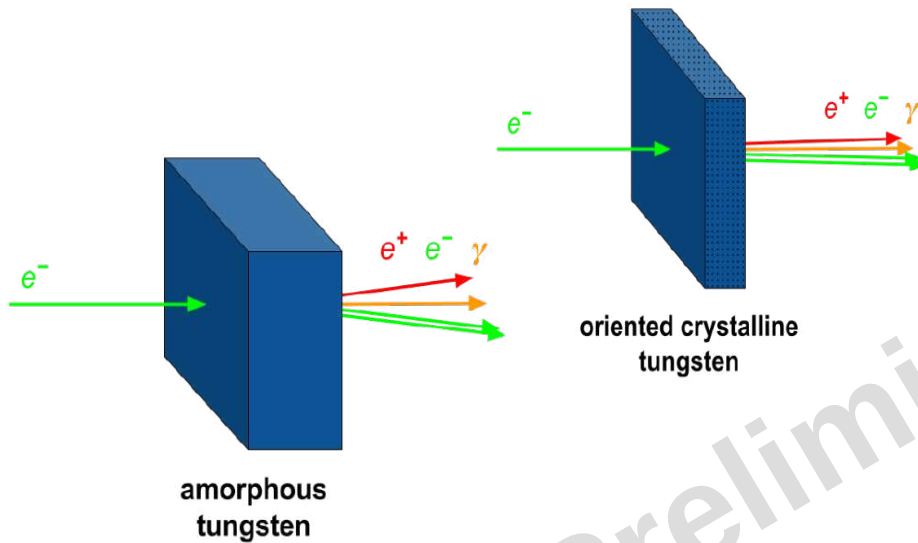


**Intense positron source Based On  
Oriented crySTals - e+BOOST**  
(PI L. Bandiera)  
PRIN2022-2022Y87K7X  
Financed by Italian Ministry of  
University and Research - PRIN project

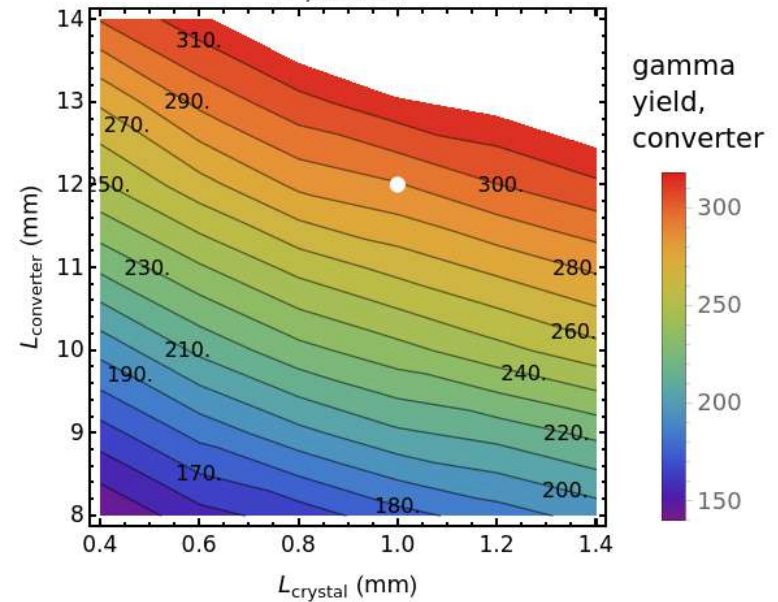
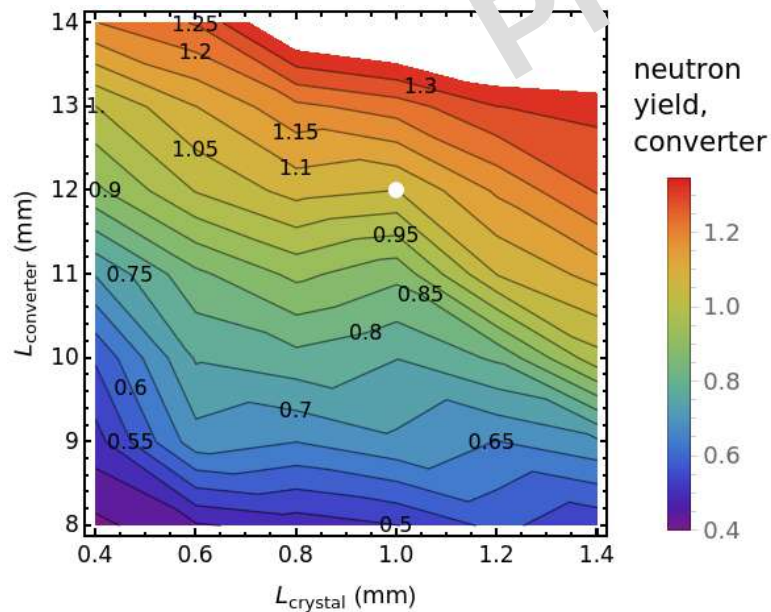
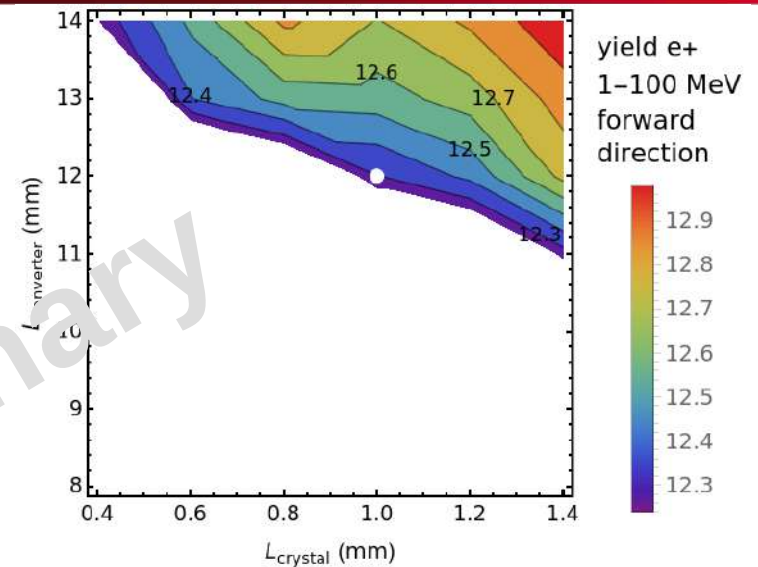
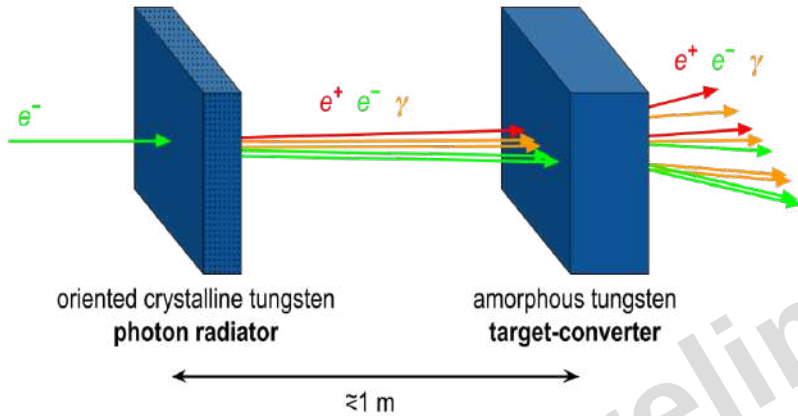


\*L. Bandiera et al. Eur. Phys. J. C 82, 699 (2022)

# FCC-ee positron source project: new simulations



# FCC-ee positron source project: new simulations





# **GEANT4**

**A SIMULATION TOOLKIT**

# How to implement an external code into Geant4?

## Geant4 FastSim interface, a solution of most of challenges

### FastSim model:

- Physics list **independent**
- Declared in the **DetectorConstruction** (just **few lines of code**)
- Is activated **only** in a **certain G4Region** at a **certain condition** and only for **certain particles**
- **Stops Geant processes** at the step of FastSim model and then resumes them

```
71  G4bool TestModel::IsApplicable(const G4ParticleDefinition& particleType)
72  {
73      return
74      &particleType == G4Proton::ProtonDefinition() ||
75      &particleType == G4AntiProton::AntiProtonDefinition() ||
76      &particleType == G4Electron::ElectronDefinition() ||
77      &particleType == G4Positron::PositronDefinition(); // ||
78      //&particleType == G4Gamma::GammaDefinition();
79  }
80
81  //.....ooo0000ooo.....ooo0000ooo.....ooo0000ooo.....ooo0000ooo.....
82
83  G4bool TestModel::ModelTrigger(const G4FastTrack& fastTrack)
84  {
102 }
103
104 //.....ooo0000ooo.....ooo0000ooo.....ooo0000ooo.....ooo0000ooo.....
105
106 void TestModel::DoIt(const G4FastTrack& fastTrack,
107                    G4FastStep& fastStep)
108 {
```

Insert particles for which the model is applicable

Insert the condition to enter the model

Insert what the model does

# How to use the Geant4 channeling model in your example?

## ● Add to DetectorConstruction::Construct()

```
//crystal volume
G4Box* crystalSolid = new G4Box("Crystal",CrystalSizeX/2,CrystalSizeY/2,CrystalSizeZ/2.);
crystalLogic = new G4LogicalVolume(crystalSolid,crystalMaterial,"Crystal");
    new G4PVPlacement(xRot,posCrystal,crystalLogic,"Crystal",logicWorld,false,0);
//crystal region (necessary for the FastSim model)
fRegion = new G4Region("Crystal");
fRegion->AddRootLogicalVolume(crystalLogic);
```

Volume declaration  
(completely standard)

G4Region declaration

## ● Add to DetectorConstruction::ConstructSDandField()

```
void DetectorConstruction::ConstructSDandField()
{
    // ----- fast simulation -----
    //extract the region of the crystal from the store
    G4RegionStore* regionStore = G4RegionStore::GetInstance();
    G4Region* RegionCh = regionStore->GetRegion("Crystal");

    //create the channeling model for this region
    G4ChannelingFastSimModel* ChannelingModel =
        new G4ChannelingFastSimModel("ChannelingModel", RegionCh);
    //activate the channeling model
    ChannelingModel->Input(crystalMaterial, Lattice);
    //setting bending angle of the crystal planes (default is 0)
    ChannelingModel->GetCrystalData()->
        SetBendingAngle(BendingAngle,crystalLogic);

    //activate radiation model
    if (ActivateRadiationModel) ChannelingModel->RadiationModelActivate();
}
```

Get crystal region

Channeling FastSim  
model declaration

Model activation  
and input

Optional

Radiation model  
activation

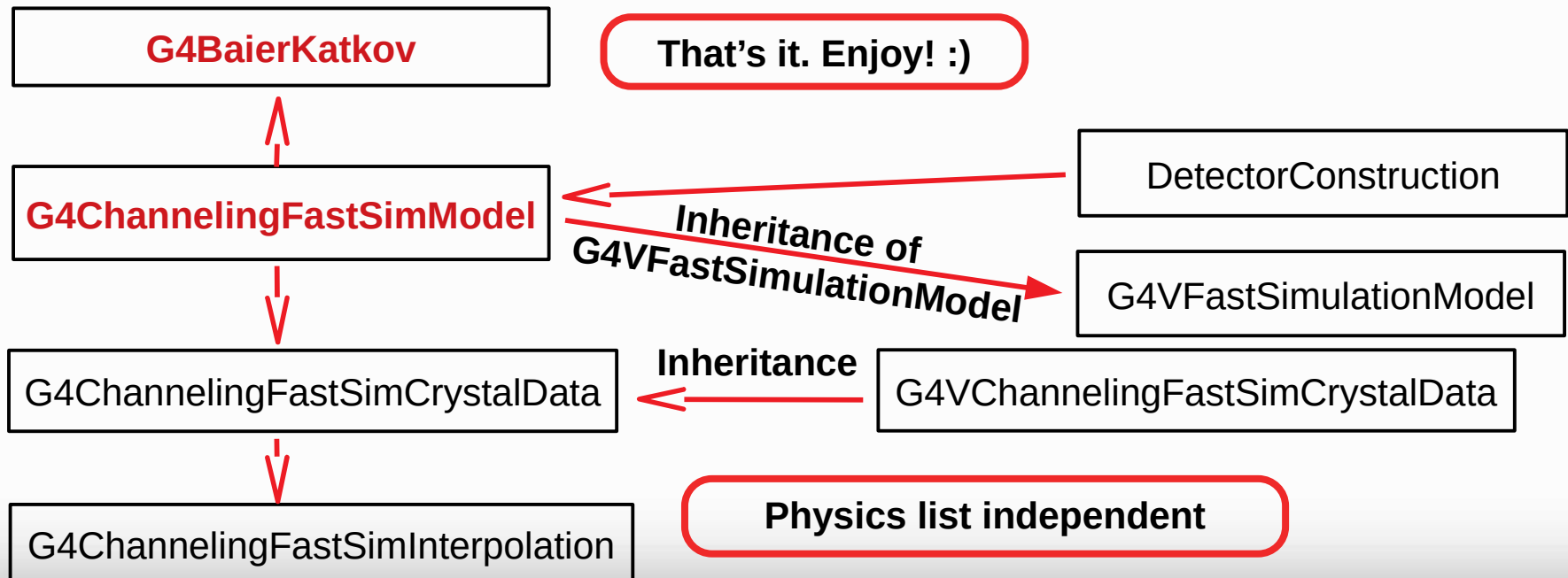


# How to use the Geant4 channeling model in your example?

## ● Add to main:

### Register FastSimulationPhysics

```
G4FastSimulationPhysics* fastSimulationPhysics = new G4FastSimulationPhysics();
fastSimulationPhysics->BeVerbose();
// -- activation of fast simulation for particles having fast simulation models
// -- attached in the mass geometry:
fastSimulationPhysics->ActivateFastSimulation("e-");
fastSimulationPhysics->ActivateFastSimulation("e+");
// -- Attach the fast simulation physics constructor to the physics list:
physicsList->RegisterPhysics( fastSimulationPhysics );
```



# Current status

**Already in geant4-11.2.0 !**

[geant4-v11.2.0/source/parameterisations/channeling/](https://geant4-v11.2.0/source/parameterisations/channeling/)

**Please use it!**

**Release December 8, 2023** <https://geant4.web.cern.ch/download/11.2.0.html>

**Don't hesitate to contact me in the case of  
any problems/issues/suggestions**

**[sytov@fe.infn.it](mailto:sytov@fe.infn.it)**

**Geant4 Physics Reference Manual:**

[https://geant4-userdoc.web.cern.ch/UsersGuides/PhysicsReferenceManual/html/solidstate/channeling/channeling\\_fastsim.html](https://geant4-userdoc.web.cern.ch/UsersGuides/PhysicsReferenceManual/html/solidstate/channeling/channeling_fastsim.html)

**Please cite our papers if you use our model:**

1. A. Sytov et al. Journal of the Korean Physical Society 83, 132–139 (2023)
2. A. I. Sytov, V. V. Tikhomirov, and L. Bandiera. PRAB 22, 064601 (2019)

# 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 - 25/01/2023**

**Marconi 100: 0.992 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

**Galileo 100: 2.4 Mh for 1 year**

### 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**



# Korea National Supercomputing Center, KISTI KSC-2022-CHA-0003

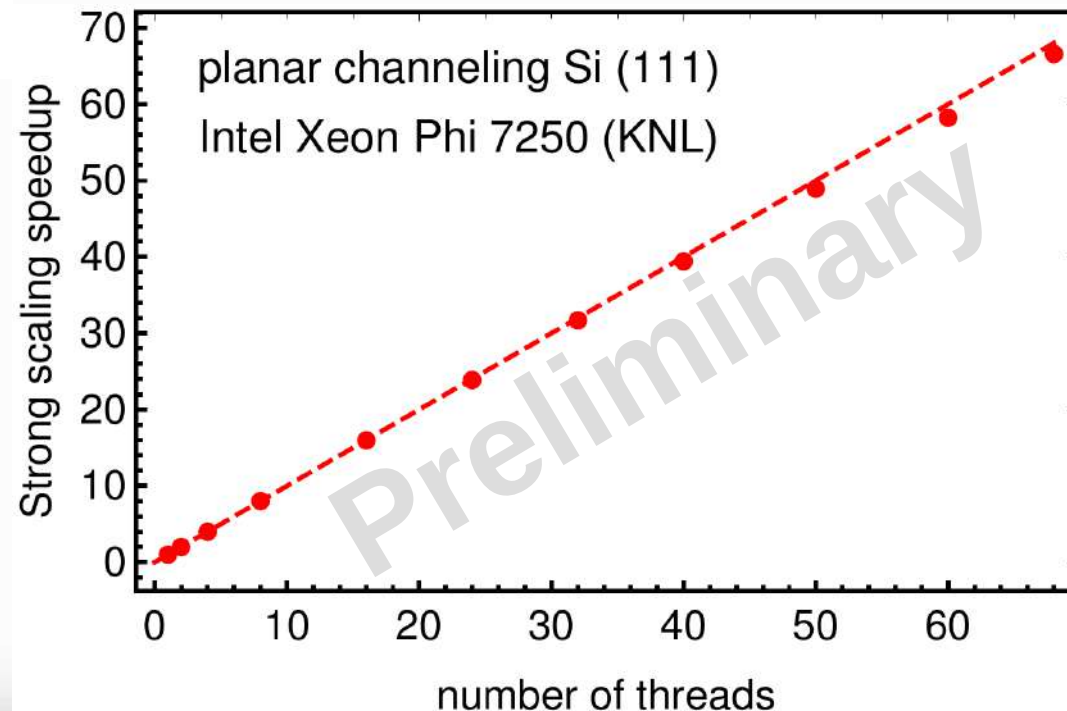


Korea Institute of  
Science and Technology Information

**supercomputer**  
**NURION@KISTI (Korea)**

**Multithreading works!**  
Checked at the supercomputer  
**Galileo100@CINECA (Italy)**  
**NURION@KISTI (Korea)**

## Geant4 channeling model scaling on Nurion

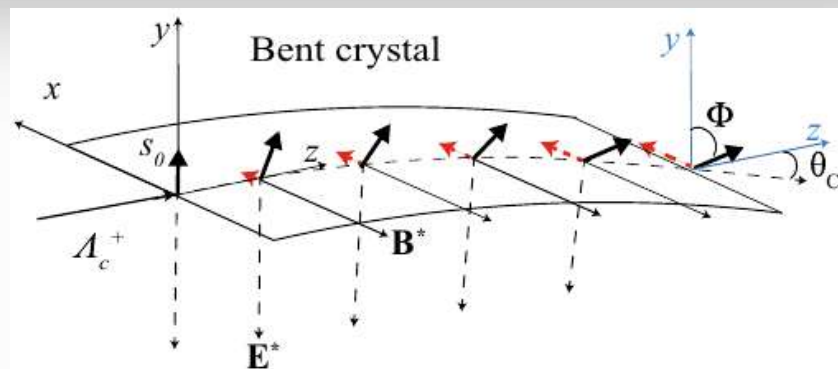


# Additional applications of oriented crystals

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

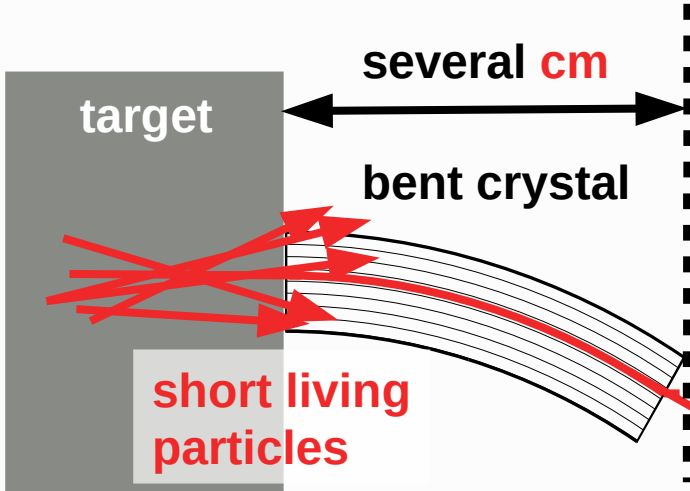
What we want:

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



Experimental proof at Tevatron for  $\Sigma^{+**}$

HE beam (e.g. 7 TeV protons)



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

Possible particles:  
 $\Lambda_c^+, \Xi_c^+, \dots, \tau$

Detector (e.g. LHCb)  
polarization measurement

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

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

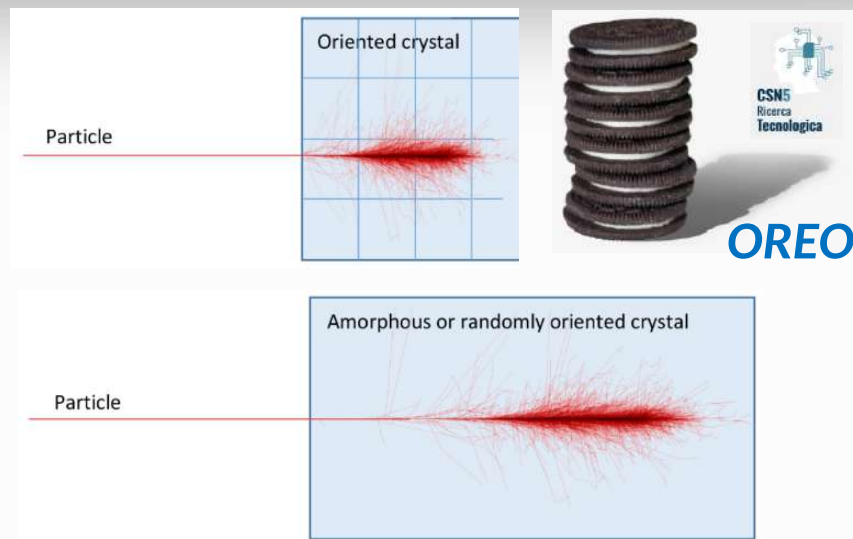
# Crystal-based ultrashort electromagnetic calorimeter\* (The INFN OREO experiment ORiEnted calOrimeter)

## 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**



## CERN North Area



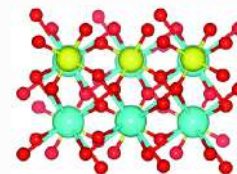
$$K_L \rightarrow \pi^0 \nu \nu$$

**+ dark photon search**

## Gamma-ray Space Telescope (like Fermi)



## PWO



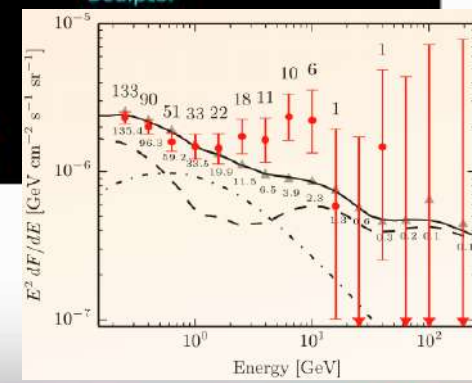
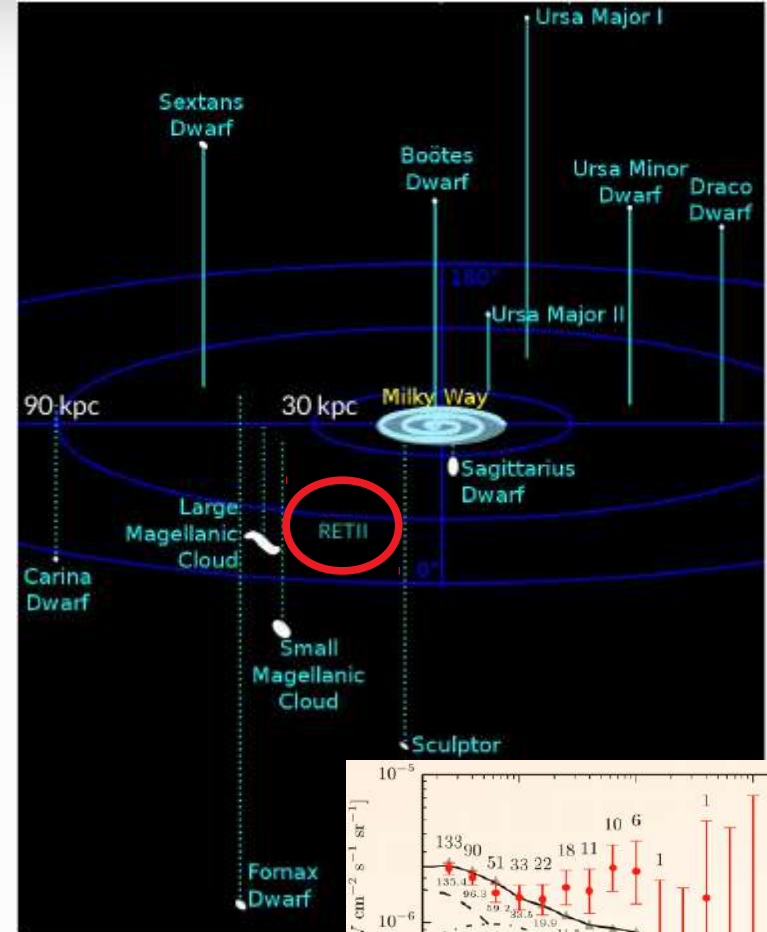
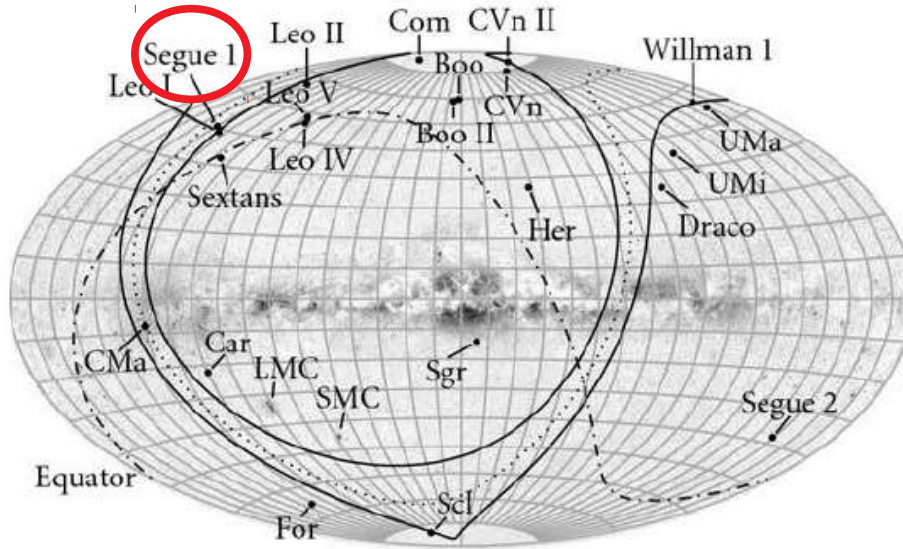
Cristalline calorimeter  
extends observation  $\gamma$   
energy range up to **TeV**

# Dwarf spheroidal galaxies (dSph) as dark matter laboratories

## Why dwarf galaxies for the dark matter search?

Dwarf galaxies are:

- nearby,
- dark matter-dominated,
- contain **no conventional sources** of astrophysical **backgrounds** (e.g., cosmic ray generation and propagation through interstellar gas)

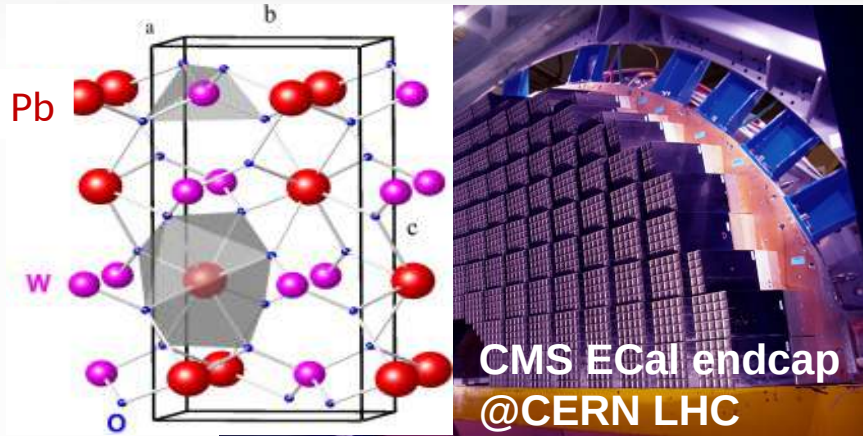


More than **50 dwarf galaxies** are currently **known**, with more to be discovered with upcoming surveys!



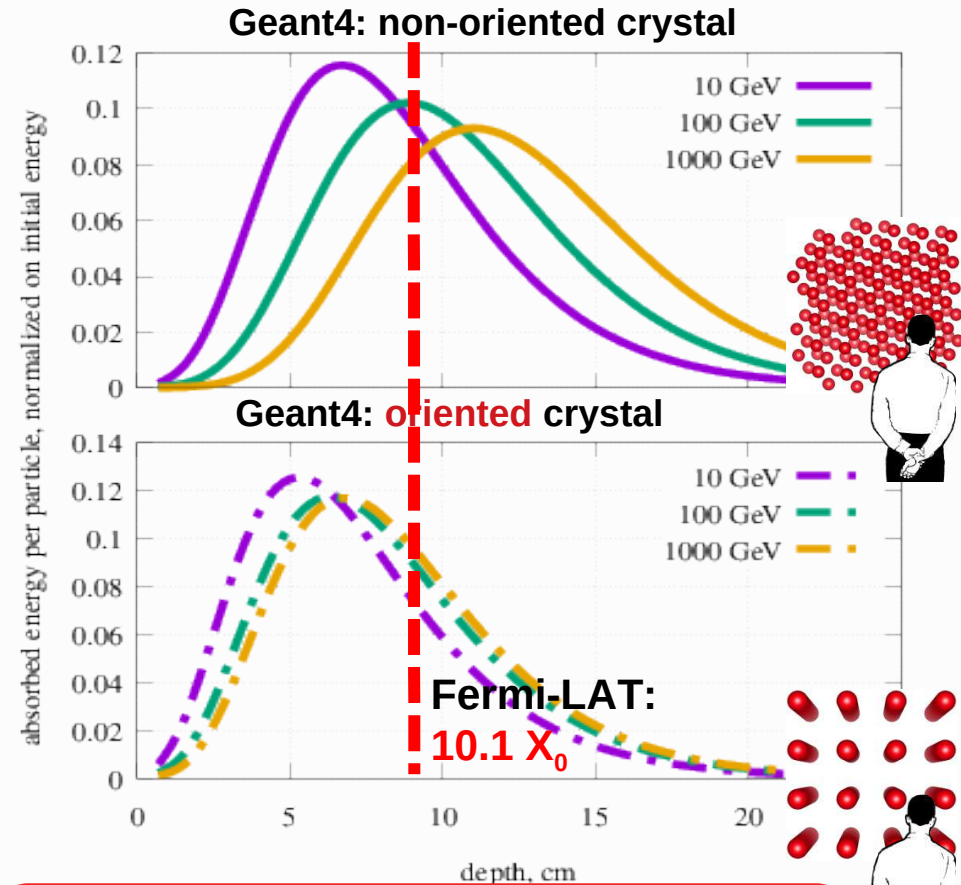
# Orienting the electromagnetic calorimeter => making it thinner!

Lead tungstate:  $\text{PbWO}_4$



INFN OREO by L. Bandiera et al.

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



Compact e.m. shower in the energy scale from multi-GeV up to multi-TeV!

# Starlink Satellites v1.5, v2 mini, and v2

## Starlink

- **Starlink v1.5** (270 kg, launched in SpaceX Falcon 9, 51 per launch)
- **Starlink v2 Mini** (800 kg, 21 launched at a time in SpaceX Falcon 9),  
**Body 11 m<sup>2</sup>**, Panels 105 m<sup>2</sup> (May 2023) 4,400 sat. already launched  
>90% fully operational
- **Starlink v2** (~50 per launch in future SpaceX Starship)  
**Body 25 m<sup>2</sup>**, 1200 kg

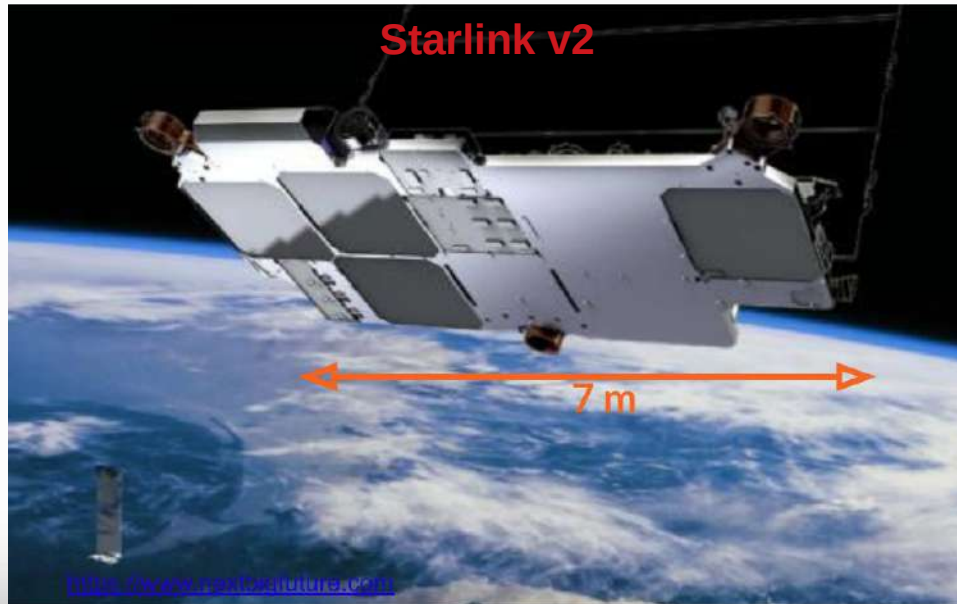
Starlink: Mass Produced Satellites  
42k in Constellation is the goal

Starlink V2 Mini



4 m

Starlink v2



7 m

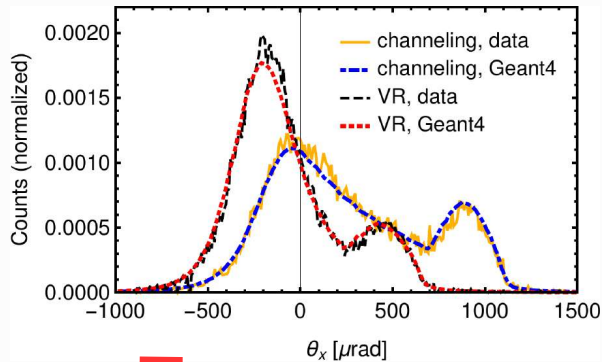
<https://www.spacex.com>



# What about Neural Nets? My proposal

**Geant4 simulations can produce datasets for neural nets training.**  
**Neural nets are less precise but much faster!**

**Step 1:  
beam  
deflection**



Layer (type)	Output Shape	Param #
dense (Dense)	(None, 200)	800
dense_1 (Dense)	(None, 500)	100500
dense_2 (Dense)	(None, 1000)	501000
dense_3 (Dense)	(None, 500)	500500
dense_4 (Dense)	(None, 200)	100200
dense_5 (Dense)	(None, 100)	20100

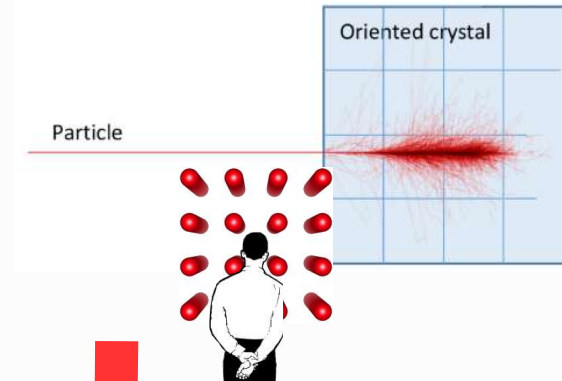
Total params: 1,223,100  
 Trainable params: 1,223,100  
 Non-trainable params: 0

**My first attempt**

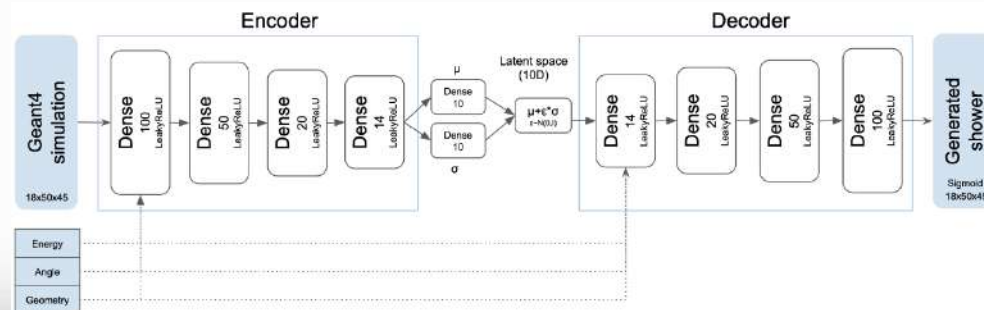
**Step 2:  
electro  
magnetic  
shower**



Korea Institute of  
Science and Technology Information



To use the **variational autoencoder** model  
 already existing in **Geant4**  
**Anna Zaborowska & Marc Verderi**



# Plasma wake-field acceleration in nanostructures

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

**Acceleration  
gradient:**

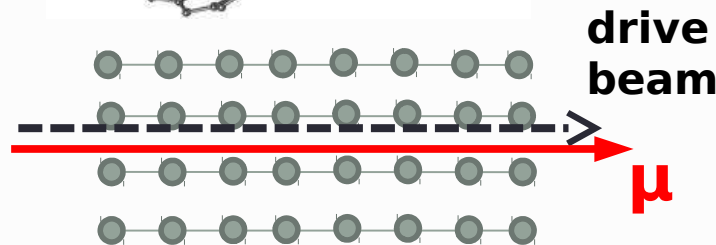
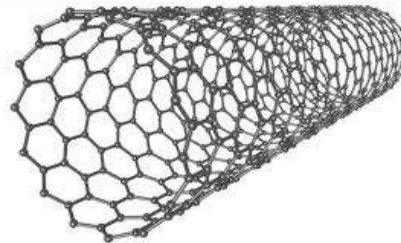
1-10 TeV/m

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

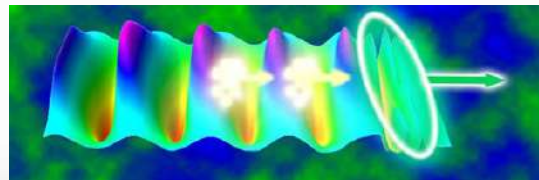
**Possible drive beam:**

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



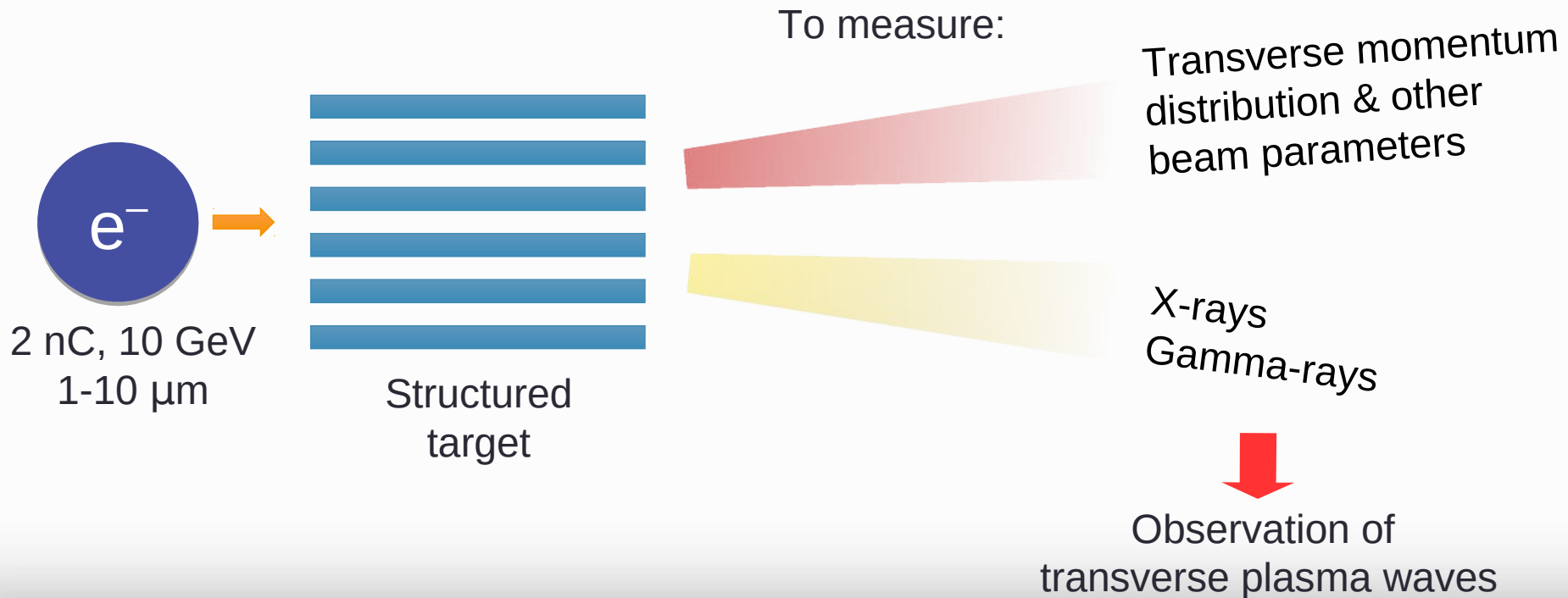
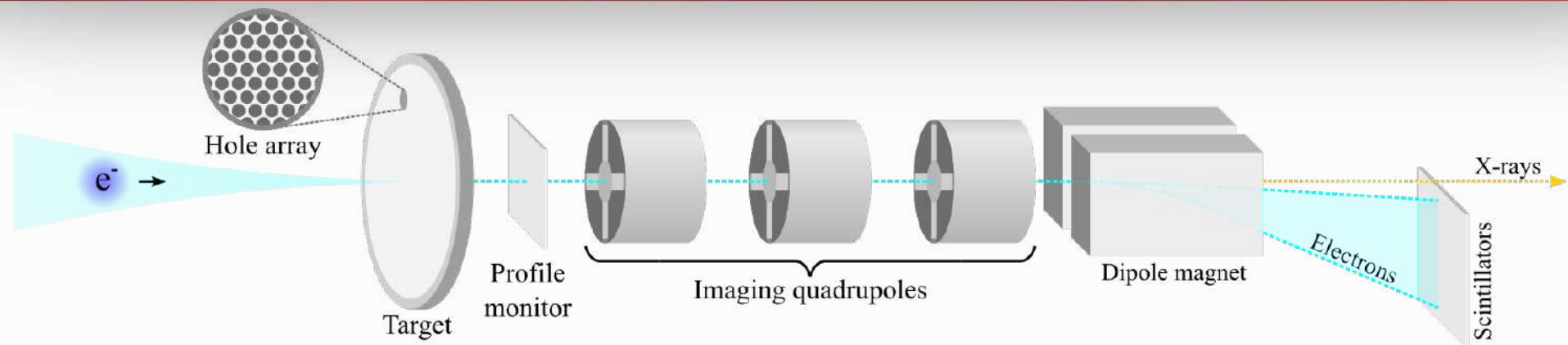
**Possible accelerated beam:**

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



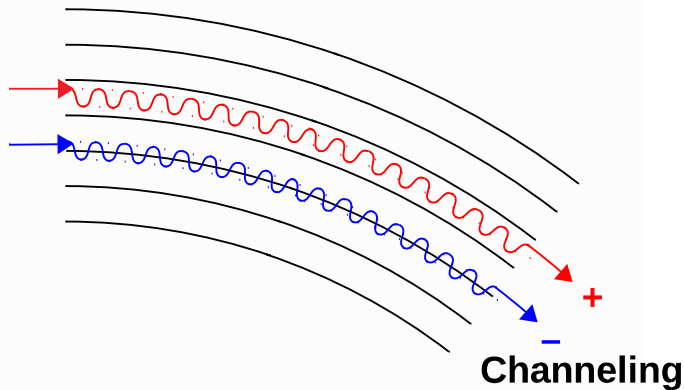
**Compact muon collider?**

# E336 SLAC FACET-II experimental setup

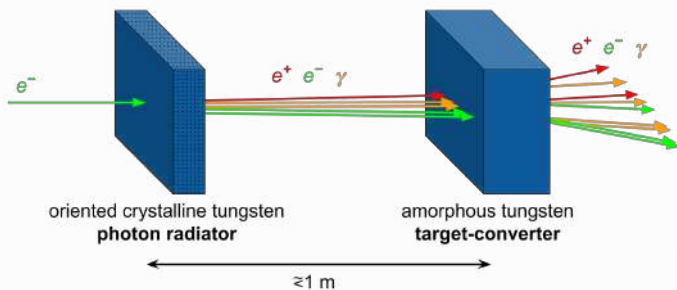


# Let's dream about future lepton colliders!

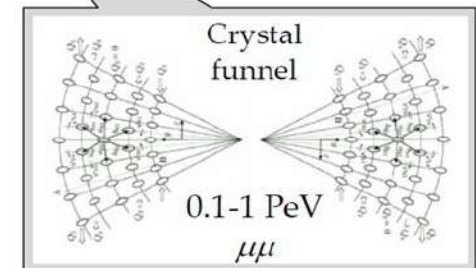
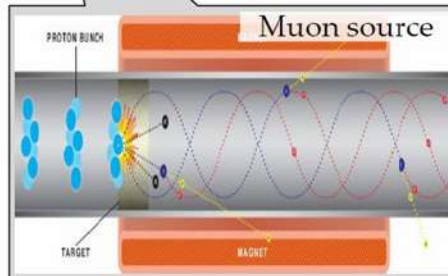
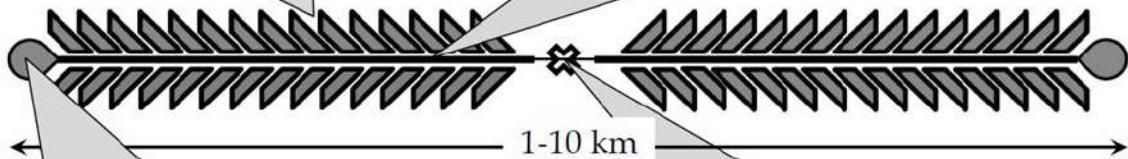
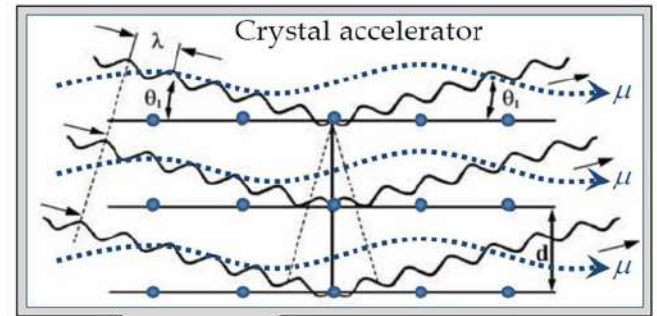
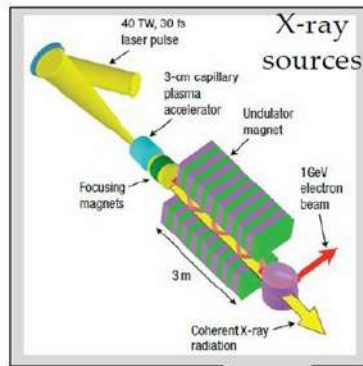
## Channeling in a bent crystal



## Hybrid crystal-based positron source\*\*



## Concept of a linear X-ray crystal muon collider\*,\*\*

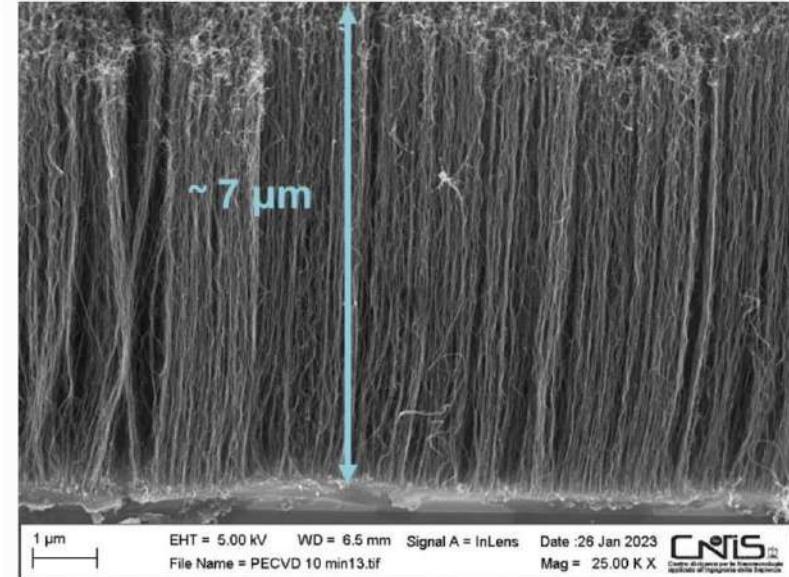
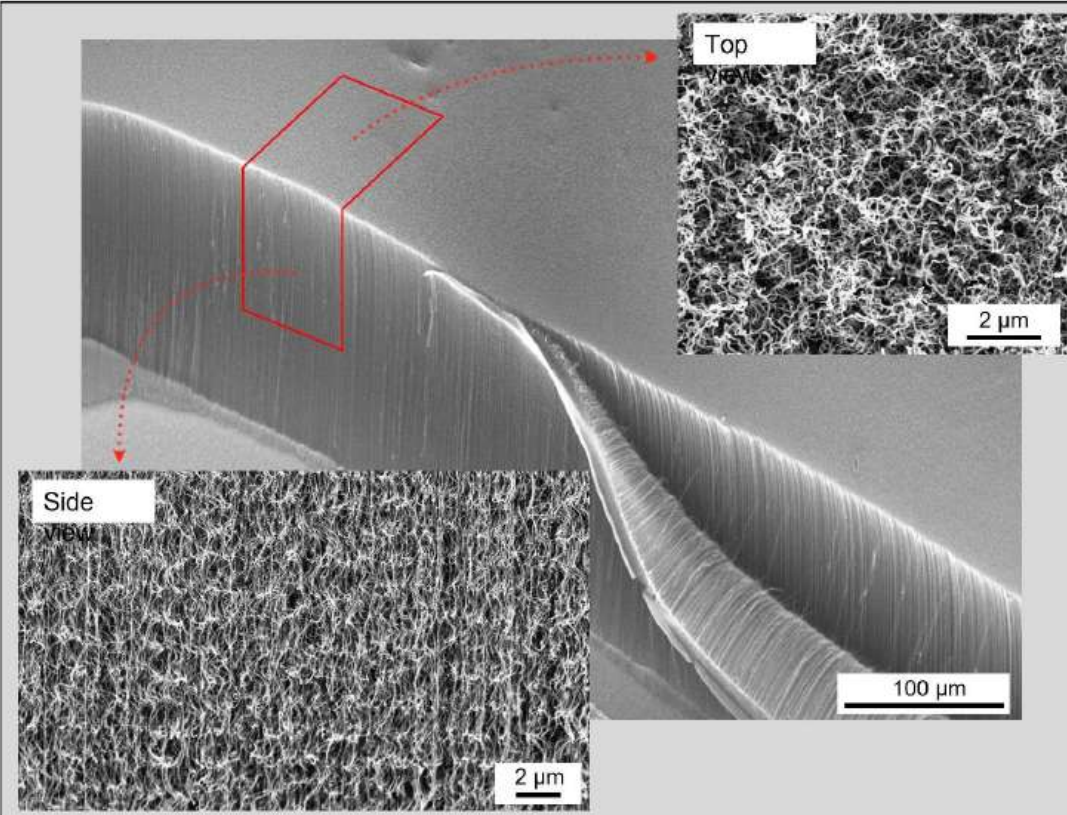
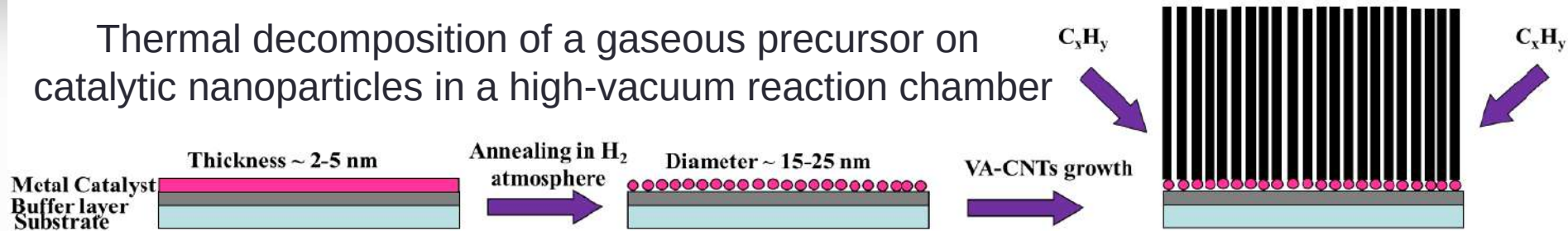


\*\*\*L. Bandiera et al. Eur. Phys. J. C 82, 699 (2022)

\*\*V. Shiltsev, Physics-Uspekhi 55, (10), 965 (2012)

# Future target: carbon nanotubes

Thermal decomposition of a gaseous precursor on catalytic nanoparticles in a high-vacuum reaction chamber



Courtesy of  
Prof. Gianluca Cavoto,  
Dr. Ilaria Rago

# Channeling simulations in CNT: trajectories, ideal case

Simulations with **CRYSTALRAD** simulation code\*

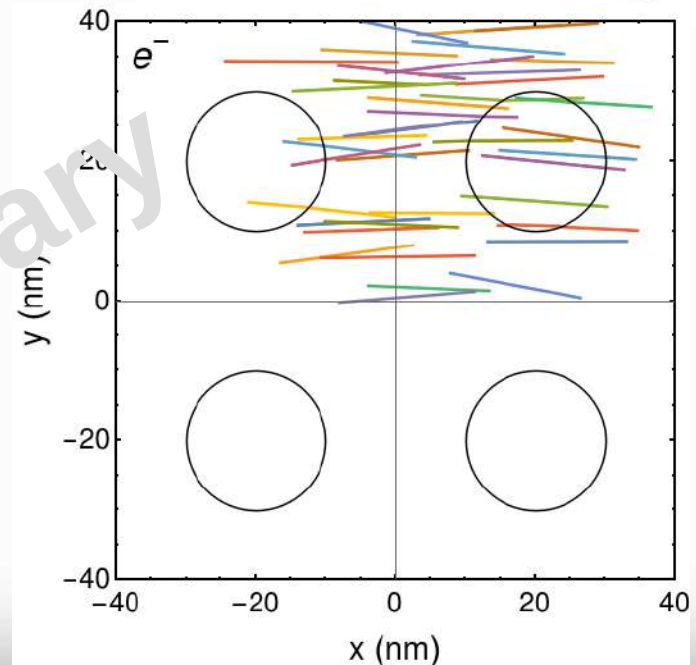
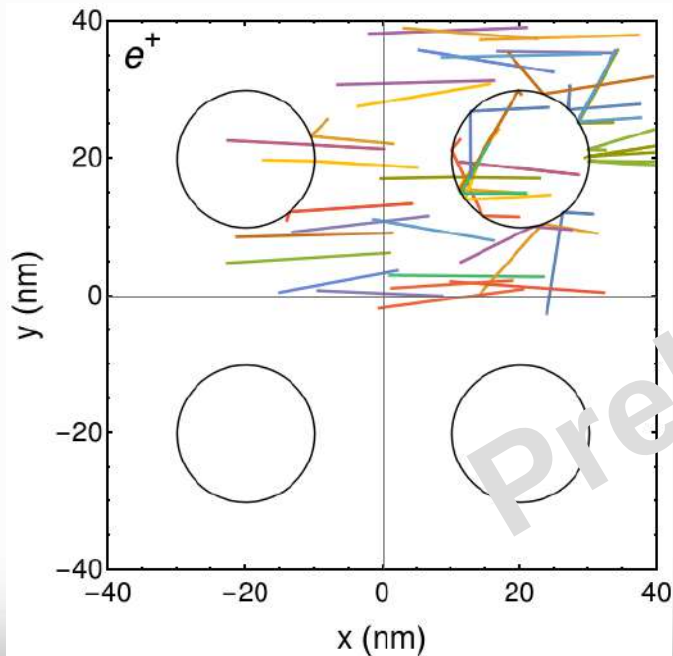
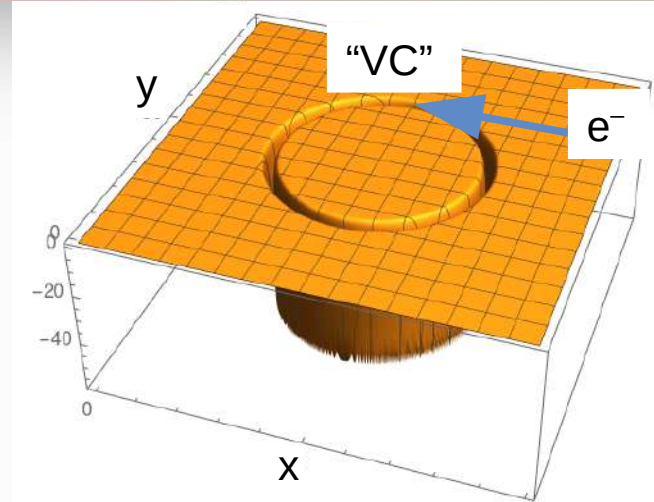
## Simulation parameters:

Beam:  $e^-/e^+$

Divergence:  $10 \mu\text{rad}$

CNT diameter: 20 nm

CNT length: 0.2 mm

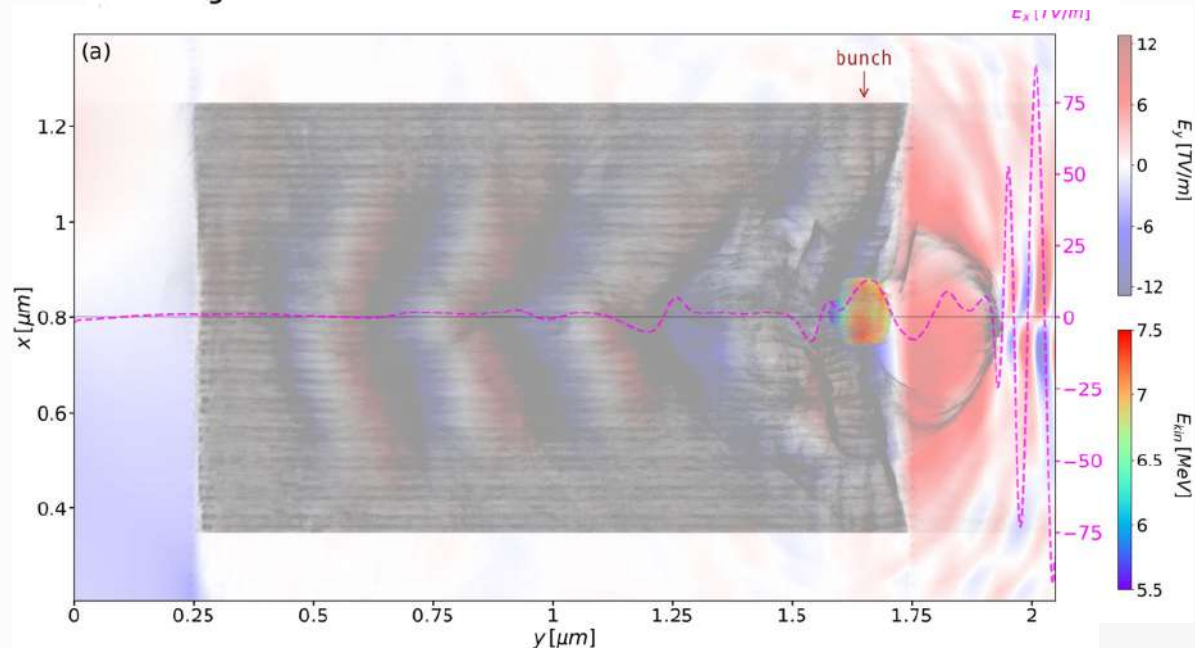




# Laser plasma acceleration in carbon nanotubes

## TeV/m catapult acceleration of electrons in graphene layers

Cristian Bonțoiu<sup>1,2</sup>, Öznur Apsimon<sup>2,5</sup>, Egidijus Kukstas<sup>1,2</sup>, Volodymyr Rodin<sup>1,2</sup>, Monika Yadav<sup>1,2</sup>, Carsten Welsch<sup>1,2</sup>, Javier Resta-López<sup>3</sup>, Alexandre Bonatto<sup>4</sup> & Guoxing Xia<sup>2,5</sup>



VNIVERSITAT  
D VALÈNCIA



UNIVERSITY OF  
LIVERPOOL

MANCHESTER  
1824

The University of Manchester



# Collaboration with Pohang Acceleration Laboratory



POHANG ACCELERATOR LABORATORY

10 GeV electrons in beam dump

## Our collaboration topics

- laser/X-ray plasma acceleration
- positron source
- beam deflection/X-FEL diagnostics



# TRILLION synergy with different fields

- Beam manipulation: **e-/e+/proton/... synchrotrons/colliders**
- Positron source: **FCC-ee**
- Radiation source: **crystalline undulator**
- Detector physics: **electromagnetic calorimeter**
- **MDM and EDM measurement**
- **Space gamma-telescopes for dark matter search**
- **Machine Learning**
- **Beam-driven plasma acceleration in nanostructures**
- **Laser-driven plasma acceleration in nanostructures**



European Commission

# List of collaborations



Host:



Istituto Nazionale di Fisica Nucleare

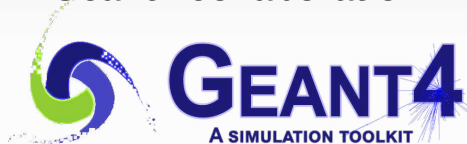
Partner for outgoing phase:



Korea Institute of Science and Technology Information

TRILLION initially:

Geant4 collaboration:



Planned secondments:



My Project MIRACLE (supercomputing time):



POHANG ACCELERATOR LABORATORY

Laser-driven plasma wakefield acceleration in nanostructures:



VNIVERSITAT ID VALÈNCIA



UNIVERSITY OF LIVERPOOL



UFRGS

UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL

MANCHESTER 1824

The University of Manchester

TRILLION synergy with: H2020-MSCA-RISE N-LIGHT, EIC-PATHFINDER-OPEN TECHNO-CLS:



MBN Research Center

Gamma-ray space telescope for dark matter search:



BROWN UNIVERSITY

E-336 experiment at SLAC FACET-II:



FACET-II Facility for Advanced Accelerator Experimental Tests



ÉCOLE POLYTECHNIQUE UNIVERSITÉ PARIS-SACLAY



Experiments for code validation:



JOHANNES GUTENBERG UNIVERSITÄT MAINZ

NA62:



Geant4& medical physics:



MU2E:



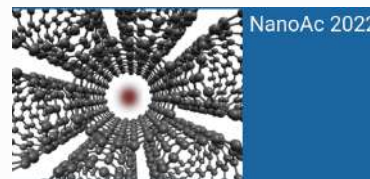
SLAC NATIONAL ACCELERATOR LABORATORY

Stanford



European Commission

Missions, conferences



International Symposium on Grids & Clouds (ISGC) 2023

High1 Workshop on Particle, String and Cosmology

Jan. 29 - Feb. 4, 2023 High1 Resort

9th International Geant4 Tutorial in Korea 2022

59th Geant4 Technical Forum



XV International Conference on Gravitation, Astrophysics and Cosmology (ICGAC15)

28th Geant4 Collaboration Meeting  
Geant4 Training Course in Medicine 2023  
2023 Korea Supercomputing Conference  
2023 KPS Fall Meeting



10th International Geant4 Tutorial in Korea 2023

Date: 2023.11.6~10  
Place: Jeju National University, Jeju, Korea



A. Sytov TRILLION short internships to the INFN group of the Geant4 collaboration (Laboratori Nazionali del Sud, Catania, Italy):

- 13/09/2021-17/09/2021
- 27/10/2022-28/10/2022
- 14/05/2022-19/05/2022



A. Sytov TRILLION research expeditions to CERN:

- 03/08/2022 – 18/08/2022
- 07/06/2023 – 13/06/2023



## TRILLION publications:

- A. Sytov et al. Journal of the Korean Physical Society 83, 132-139, (2023). DOI: <https://doi.org/10.1007/s40042-023-00834-6> arXiv:2303.04385
- L. Bandiera, ..., A. Sytov, et al. Eur. Phys. J. C 82, 699 (2022). DOI: <https://doi.org/10.1140/epjc/s10052-022-10666-6>
- A. Sytov et al. Eur. Phys. J. C 82, 197 (2022). DOI: <https://doi.org/10.1140/epjc/s10052-022-10115-4>
- M. Romagnoni, ..., A. Sytov et al. Crystals 12 (9), 1263 (2022). DOI: <https://doi.org/10.3390/cryst12091263>
- M. Romagnoni, ..., A. Sytov et al. Eur. Phys. J. D 76, 135 (2022). DOI: <https://doi.org/10.1140/epjd/s10053-022-00439-x>
- M. Soldani, ..., A. Sytov et al. Eur. Phys. J. C 83, 101 (2023). DOI: <https://doi.org/10.1140/epjc/s10052-023-11247-x>
- L. Bandiera, ..., A. Sytov et al. Frontiers in Physics 11 Pages: 1254020 (1-11) (2023). DOI: <https://doi.org/10.3389/fphy.2023.1254020>
- Max F. Gilljohann, ..., A. Sytov et al. JINST 18, P11008 (2023) DOI: 10.1088/1748-0221/18/11/P11008 arXiv:2203.07459
- K. Park, K. Kim, A. Sytov, K. Cho. J. Astron. Space Sci. 40 (4), 259-266 (2023). DOI: <https://doi.org/10.5140/JASS.2023.40.4.259>
- M. Soldani, ..., A. Sytov et al. Nuclear Instruments and Methods in Physics Research, Section A 1058, 168828 (1-6) (2024) DOI: <https://doi.org/10.1016/j.nima.2023.168828>
- L. Bandiera, ..., A. Sytov et al. Nuclear Instruments and Methods in Physics Research, Section A 1060, 169022 (2024). DOI: <https://doi.org/10.1016/j.nima.2023.169022>
- K. Park, K. Kim, A. Sytov, K. Cho. Journal of the Korean Physical Society, 84, 403–426, (2024). DOI: <https://doi.org/10.1007/s40042-024-01005-x>



Thank you! 감사합니다!