



Istituto Nazionale di Fisica Nucleare



European  
Commission



Korea Institute of  
Science and Technology Information

# Frillion

## New Geant4 model of channeling in crystals and its potential applications

**Dr. Alexei Sytov**

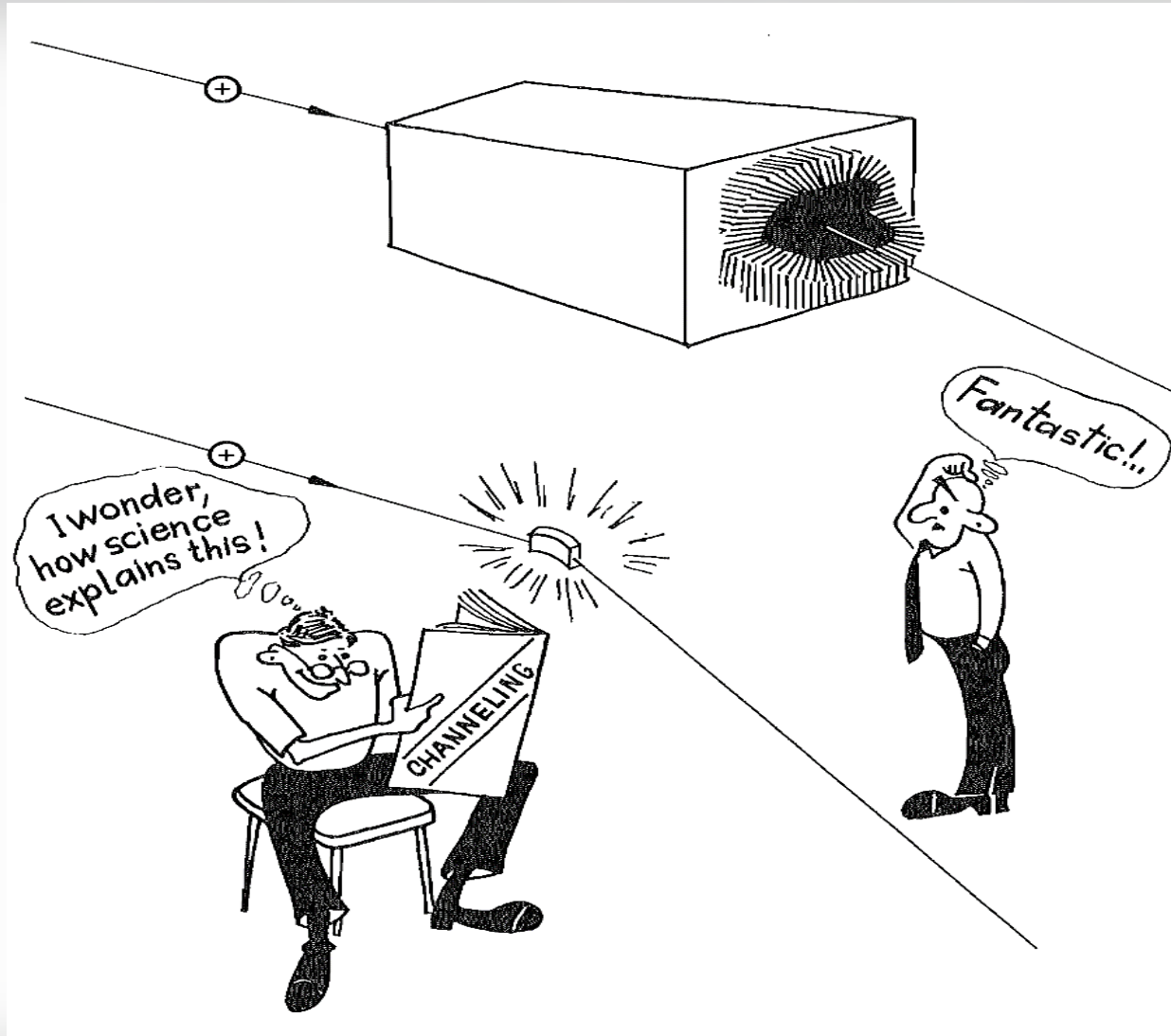
**9th International Geant4 Tutorial in Korea 2022**

**Daejeon, 22/12/05**

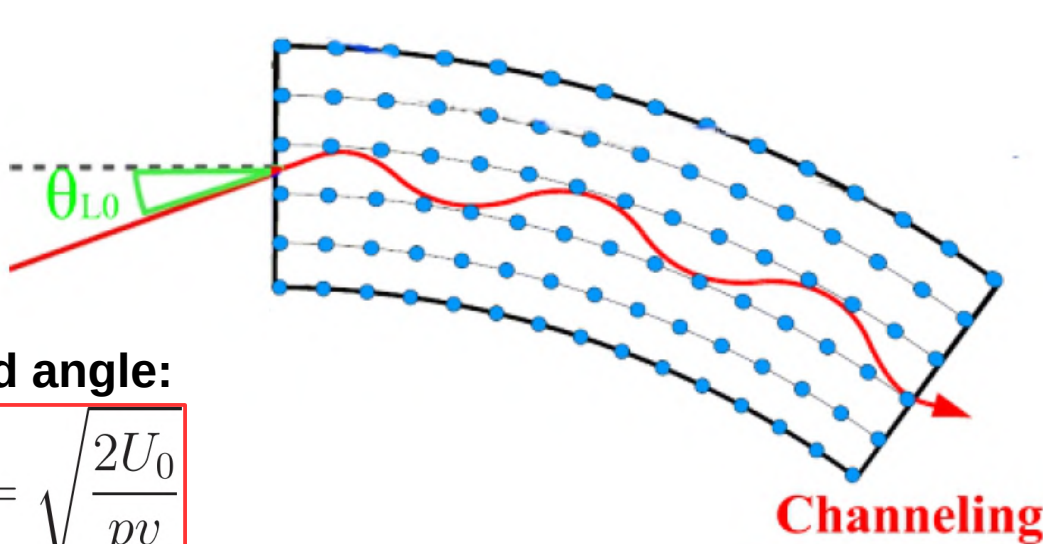
# Outline

- **The world of channeling effect**
  - Channeling, Radiation and pair production
  - Electromagnetic shower acceleration
  - Main applications
- Implementation of the new physics into Geant4
  - What has been done previously in Geant4?
  - Main conception: **FastSim** interface
  - What has been done by now?

# The world of the channeling effect

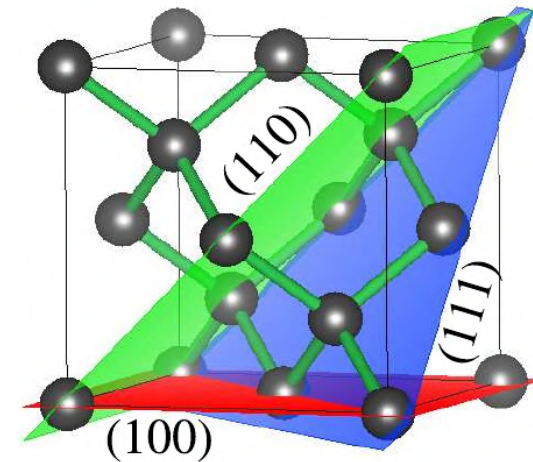


# Channeling effect\*



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)

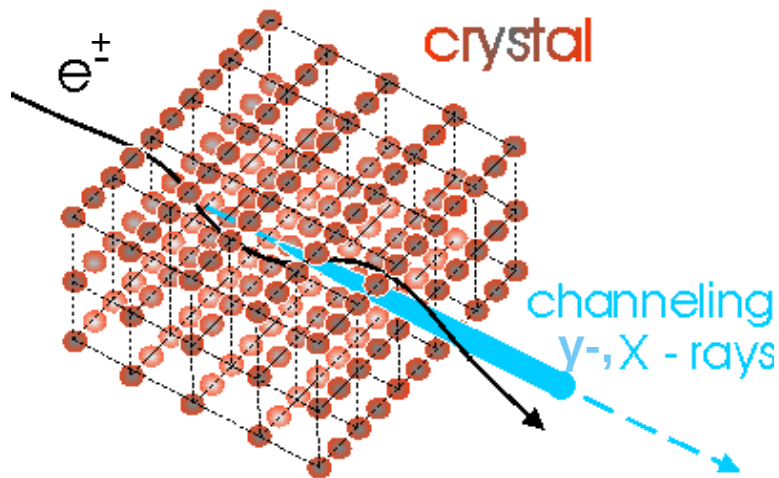
J. A. Davies, J. Friesen, J. D. McIntyre, Can J. Chem. 38, 1526–1534 (1960)

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)

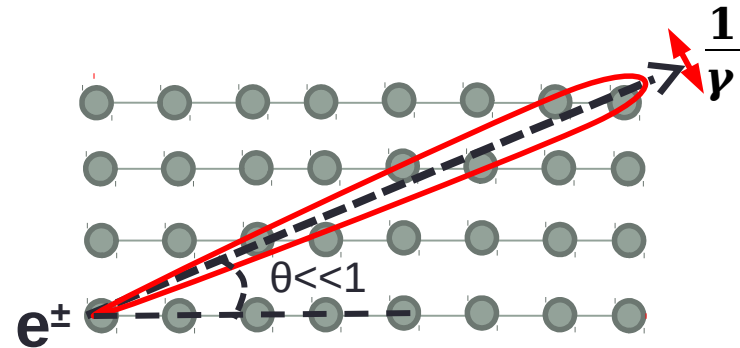
# Coherent effects in a crystal

## Channeling radiation\*

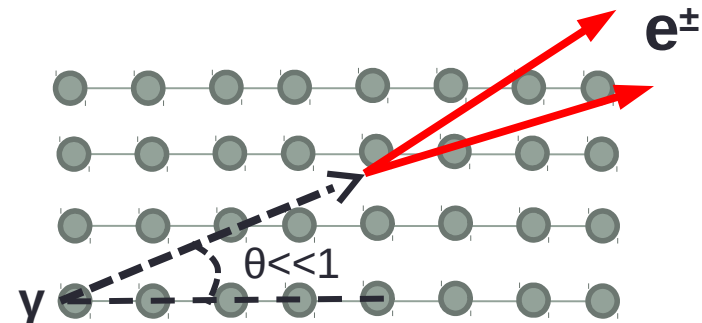


Coherent effects preserve  
**up to few mrad** of particle  
direction vs the crystal axis

## 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).

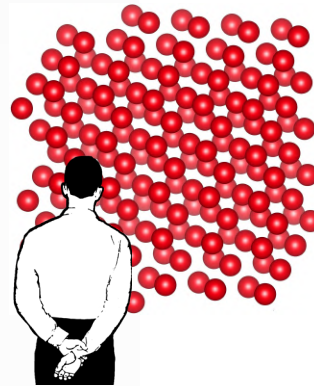
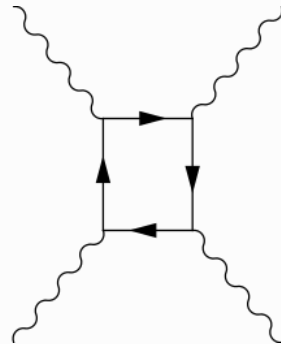
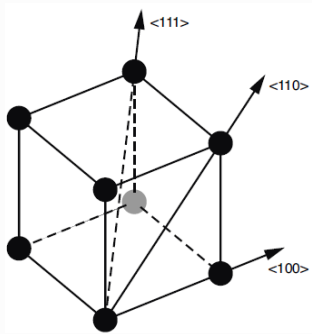
\*\*\* H. Überall, Phys. Rev. 103, 1055 (1956).

# Electromagnetic shower acceleration

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

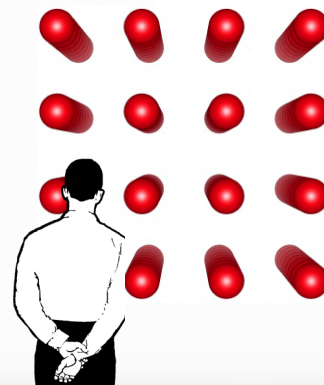
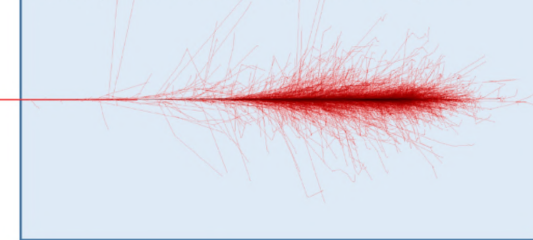


Approaching the  
**Schwinger limit**  
starting from few  
GeV for  $e^+/e^-$



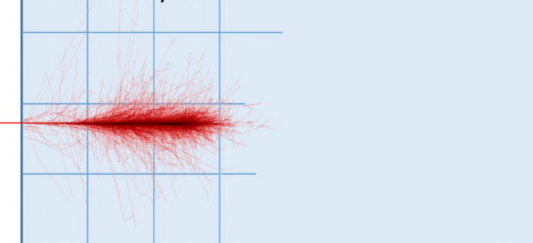
Particle

Amorphous or randomly oriented crystal



Particle

Oriented crystal



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

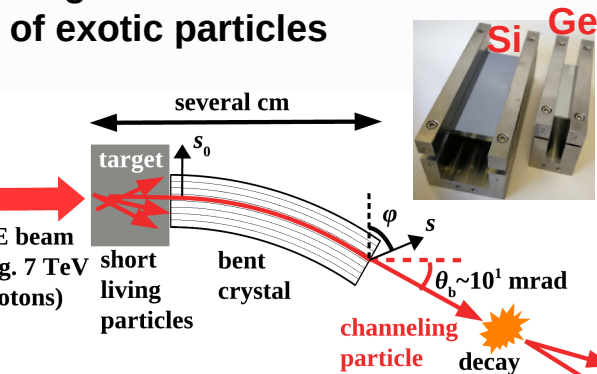
**Shower development** in the  
field of axes is **accelerated**.  
The radiation length is  
considerably reduced\*.

# Applications\*

Crystal-based collimation or beam extraction from an accelerator

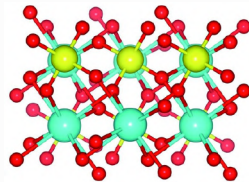


Measurement of dipole magnetic and electric moments of exotic particles

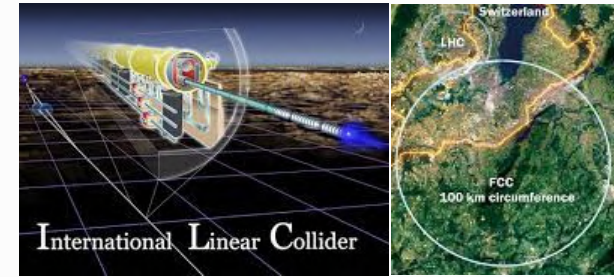
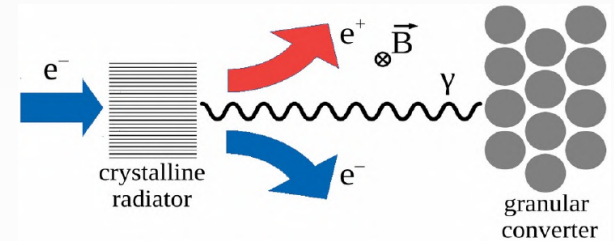


Gamma-ray Space Telescope

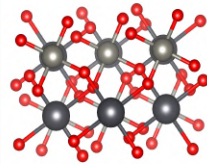
Ultrashort crystalline calorimeter



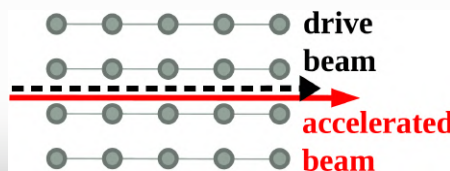
Positron source for future e+/e- and muon colliders



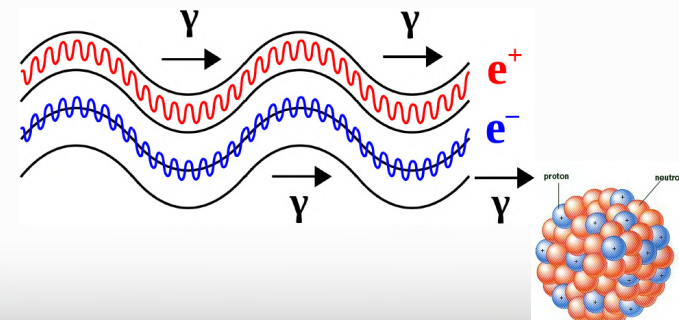
Oriented crystals



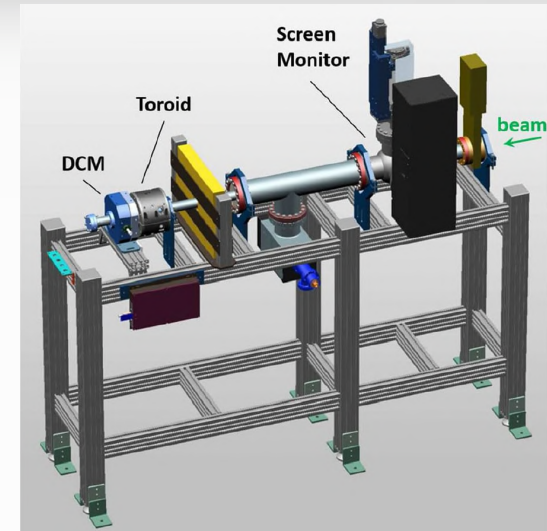
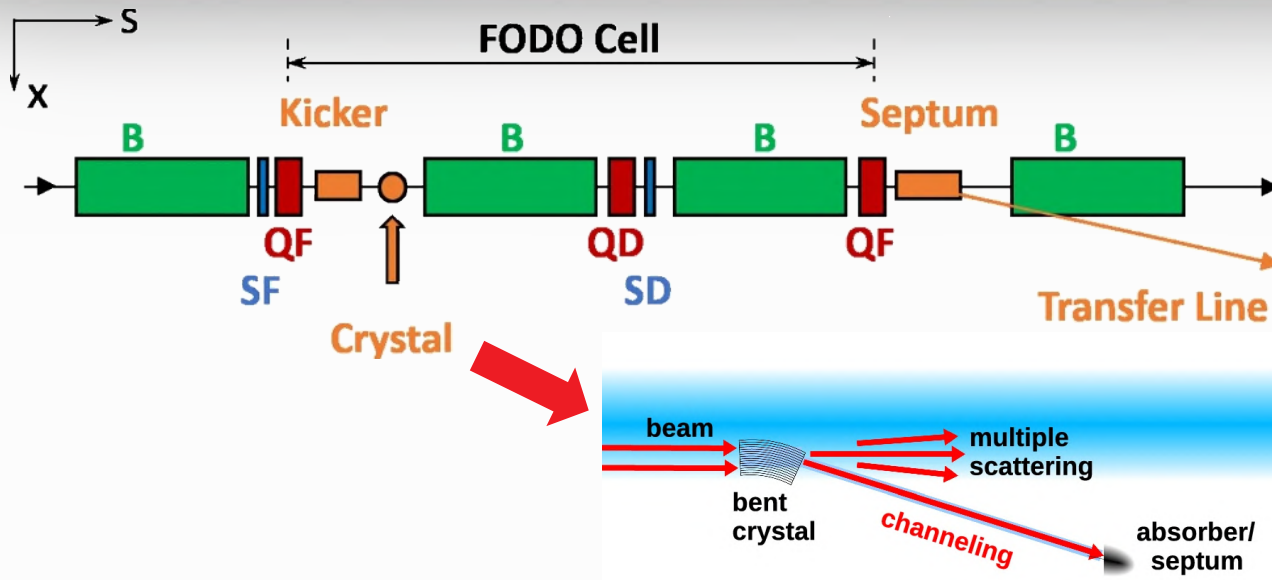
Plasma acceleration



X and gamma-ray source for nuclear and medical physics



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



Crystal-based beam extraction: applied only for protons,  
never applied for 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 electron synchrotrons** existing in the world.

## Can be applied at:

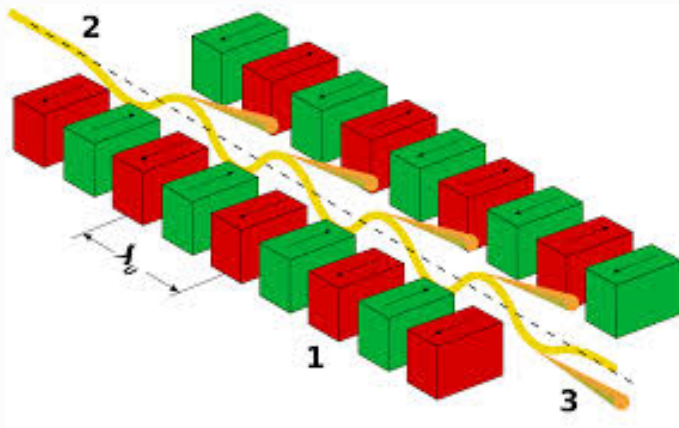
- DESY-II and any e-/e+ synchrotron or a **synchrotron light source**

Have been already applied at:

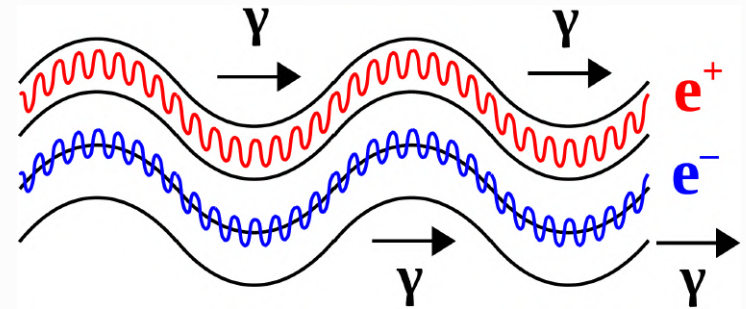
- **LHC, Tevatron, SPS, RHIC, U-70**

# Channeling radiation in a bent crystal: Crystalline undulator

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



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



## Advantage:

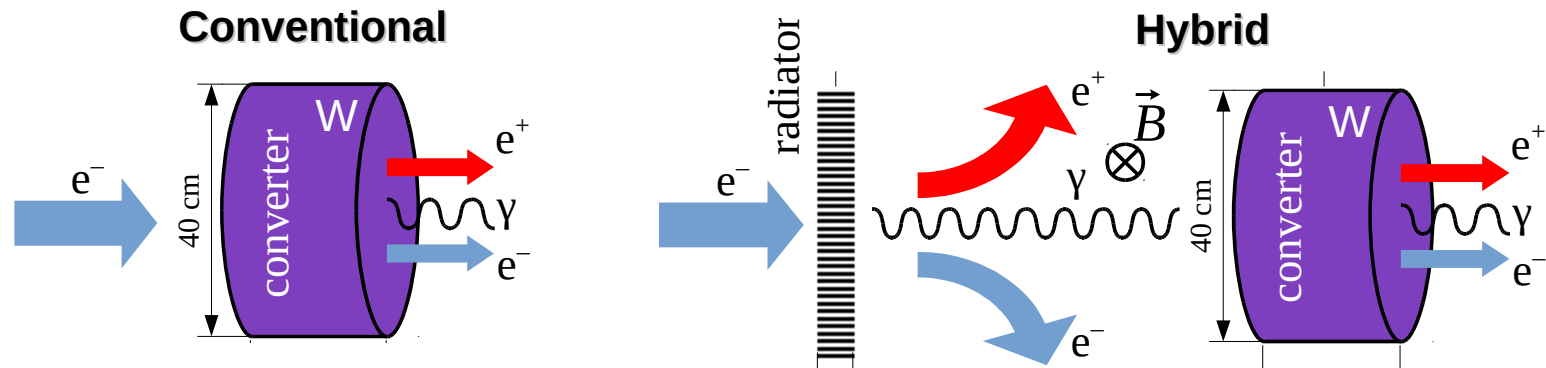
- Intense X- and gamma-rays produced in a crystal, in a compact piece of material

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

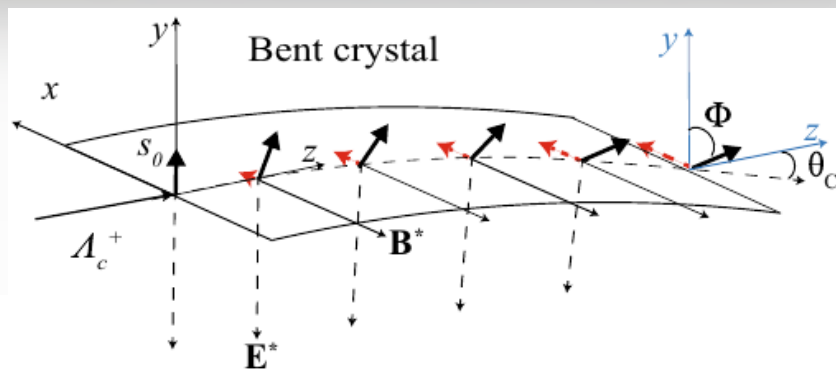


**Simulation model can be also applied for ultrashort crystalline calorimeter**

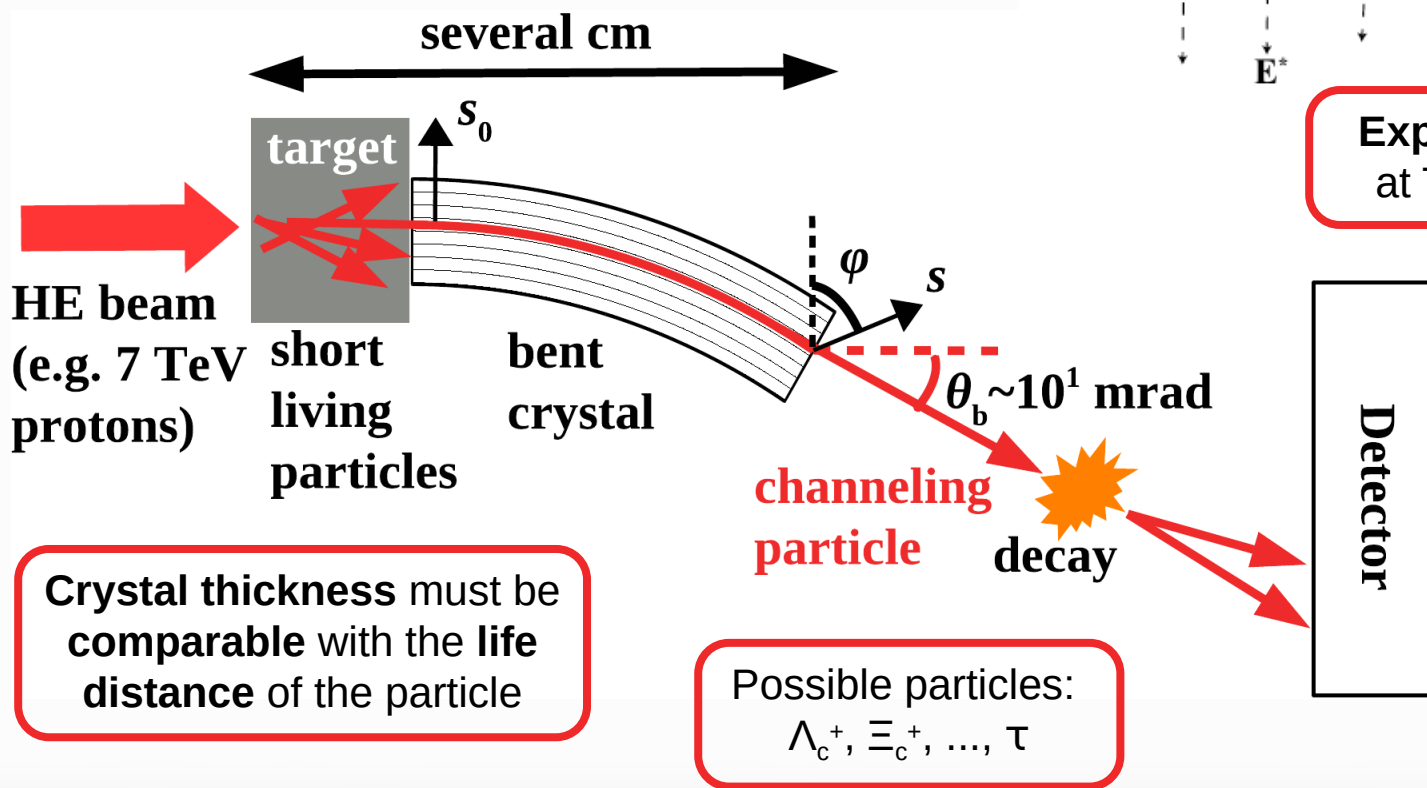
# Search of MDM&EDM of short living particles using the effect of spin rotation in oriented crystals\*

What we want:

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



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



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

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

\* 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\*

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

**Acceleration  
gradient:**

1-10 TeV/m

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

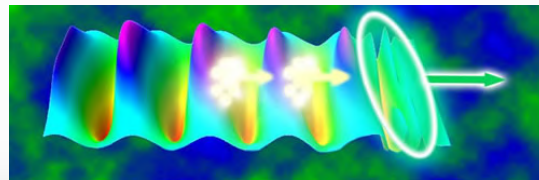
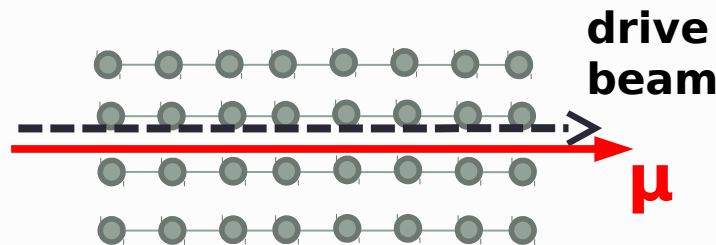
**Channeling** makes crystal almost **transparent** both to accelerated and to drive beam

**Possible drive beam:**

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

**Possible accelerated beam:**

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



**Compact muon collider?**

\* 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).

# 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

```
93
94
95
96
97
98
99
100
101
102
103
104
105
106
107
108
109
110
111
112
113
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-** though not so important for high energy protons

# Solution: Geant4 FastSim interface

A. Sytov thanks **Prof. Vladimir Ivanchenko (CERN)** for this solution and the group of **Prof. Pablo Cirrone (INFN LNS)**, in particular **Dr. Luciano Pandola** as well as **Prof. Kihyeon Cho** and **Dr. Kyungho Kim (KISTI)**, **Prof. Susanna Guatelli** and **Prof. Anatoly Rosenfeld (University of Wollongong)** for fruitful discussions!

## 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 //.....ooo00000ooo.....ooo00000ooo.....ooo00000ooo.....ooo00000ooo.....
82
83 G4bool TestModel::ModelTrigger(const G4FastTrack& fastTrack)
84 {
102 }
103
104 //.....ooo00000ooo.....ooo00000ooo.....ooo00000ooo.....ooo00000ooo.....
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

# 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**

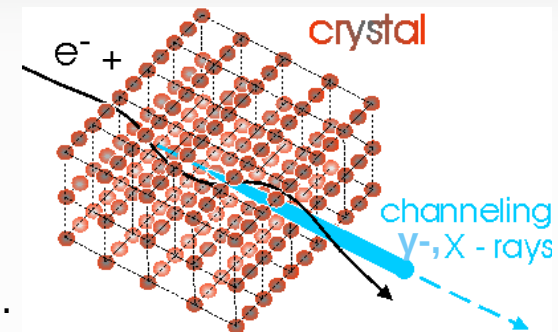
**Baier-Katkov formula:**

integration is made over the classical trajectory

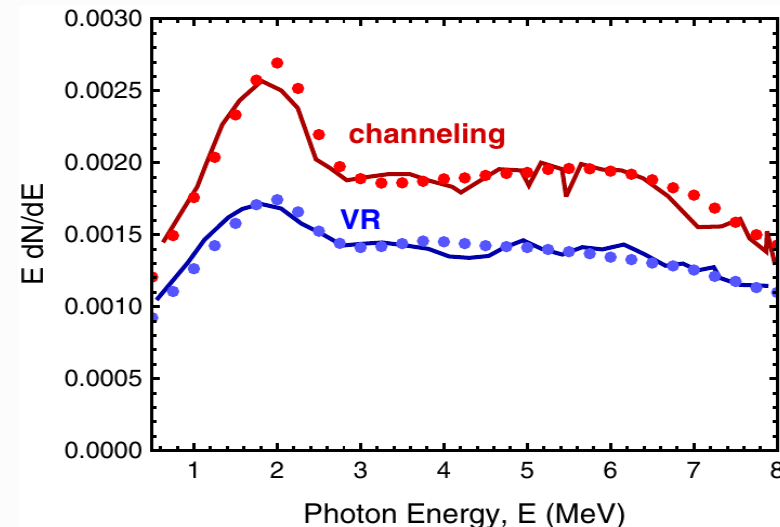
$$\frac{dE}{d^3k} = \omega \frac{dN}{d^3k} \frac{\alpha}{4\pi^2} \iint dt_1 dt_2 \frac{[(E^2 + E'^2)(v_1 v_2 - 1) + \omega^2 / \gamma^2]}{2E'^2} e^{-ik'(x_1 - x_2)}$$

**Advantages:**

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



**CRYSTALRAD vs experiment**



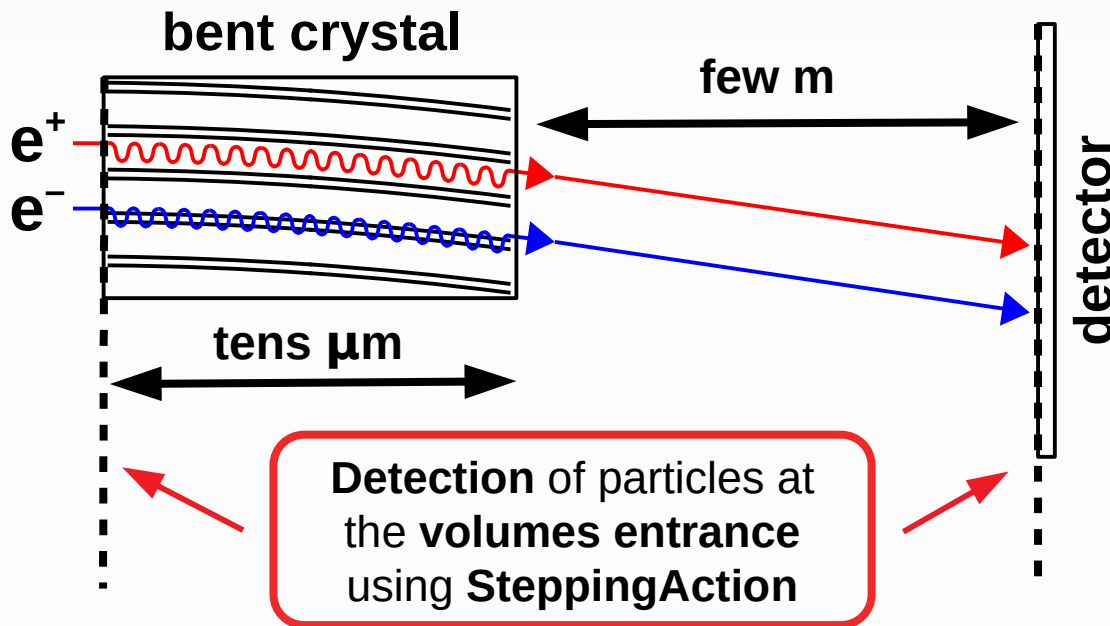
A.I. Sytov, V.V. Tikhomirov. NIM B 355 (2015) 383–386.

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)

# First Geant4 channeling example for electrons/positrons

- Inspired by our experiments\* of 855 MeV electron beam deflection by an ultrashort bent crystal at Mainz Mikrotron MAMI



Beam setup in **run.mac** using **GPS** commands; all the **geometry** in **DetectorConstruction**

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

**Output** both in **root** (only primary particles) and in **textfile** (all the particles) format



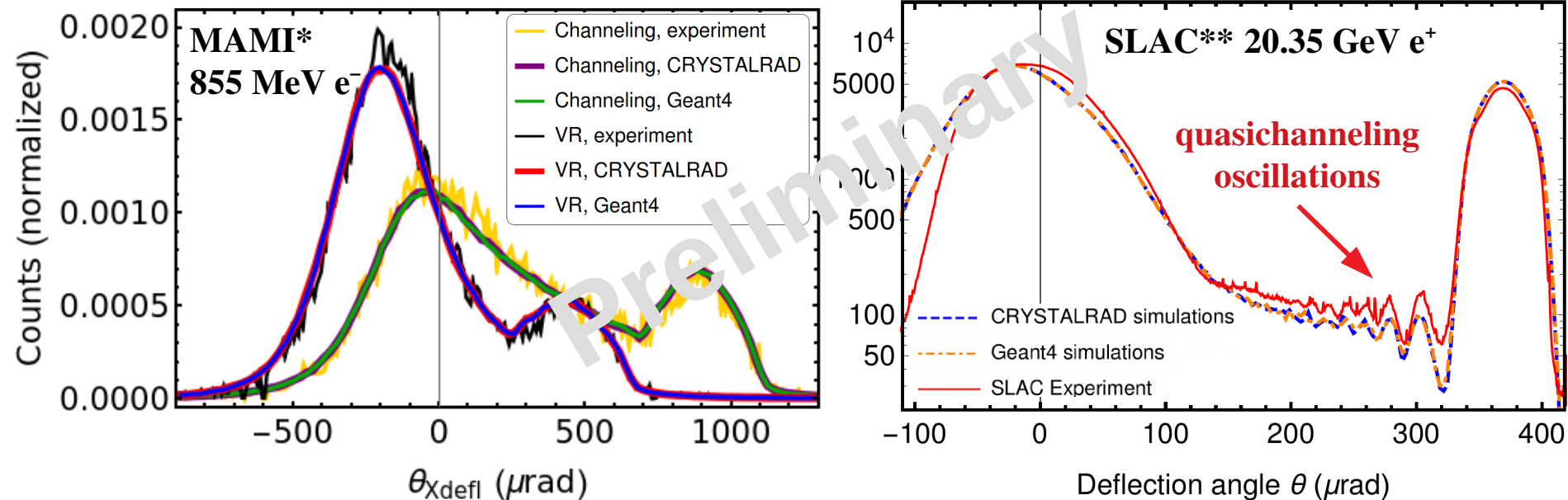
\*A. Mazzolari et al. Phys. Rev. Lett. 112, 135503 (2014)

A. Sytov et al. Eur. Phys. J. C 77, 901 (2017)

# First simulations with Geant4 channeling model: beam deflection by a bent crystal



## Geant simulations vs experiment and CRYSTALRAD simulations



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

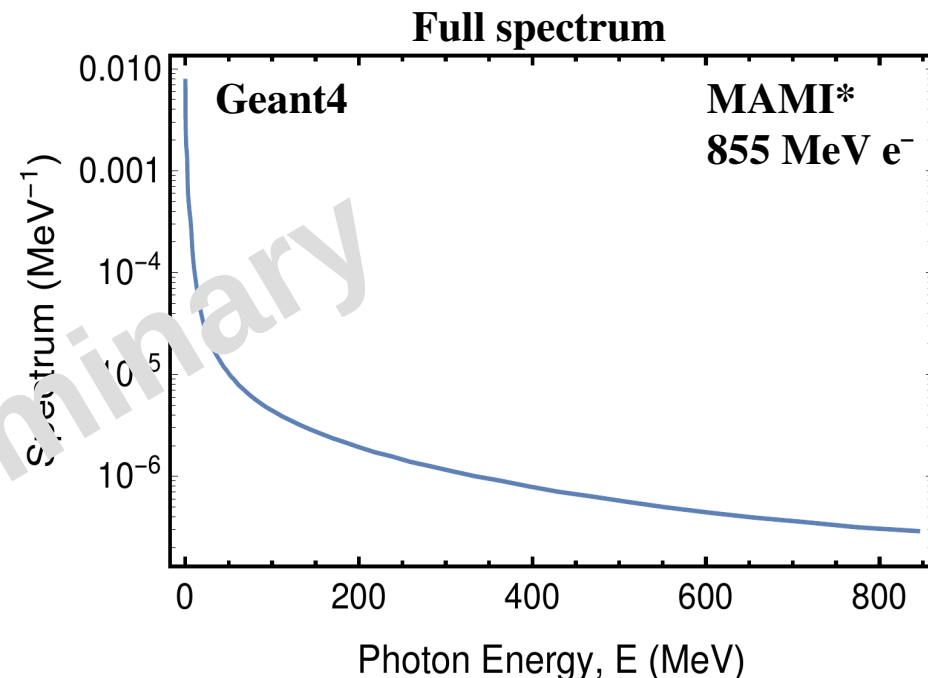
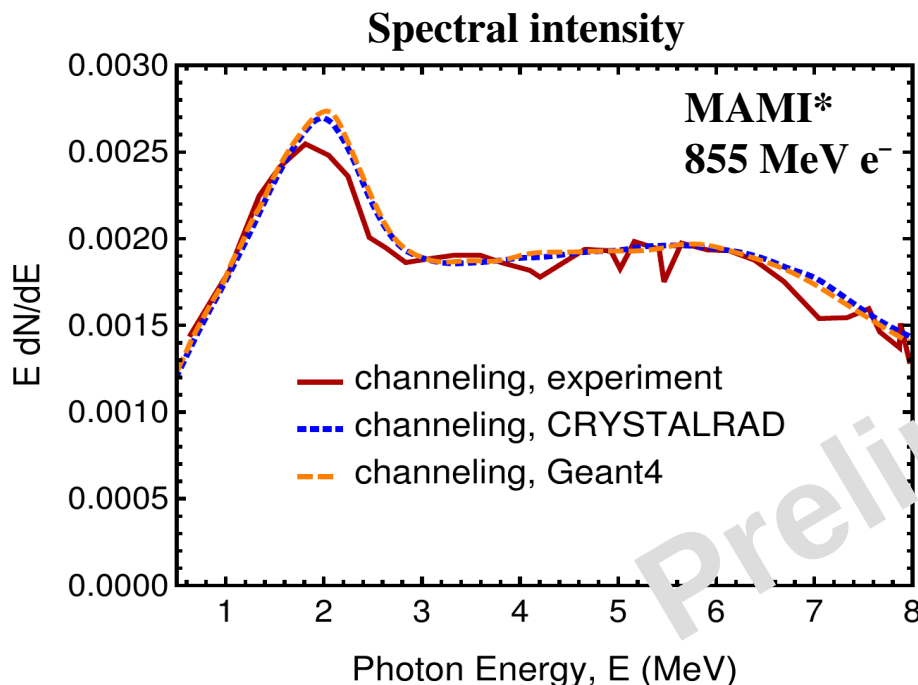
\*\*T. N. Wistisen, ..., and A. Sytov. Phys. Rev. Lett. 119, 024801 (2017)

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

## G4BaierKatkov:

- **Physics list independent**
- Activated in the **DetectorConstruction** and used in **ChannelingFastSimModel**
- Can be used **outside channeling model** (e.g. in **SteppingAction**)
- Provides **radiation spectrum** for single-photon radiation mode
- Provides generation of **secondary photons**

## Geant simulations vs experiment and CRYSTALRAD simulations



# 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.);
G4LogicalVolume* crystalLogic = new G4LogicalVolume(crystalSolid,Silicon,"Crystal");
CrystalN1 = 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
    ChannelingFastSimModel* ChannelingModel = new ChannelingFastSimModel("ChannelingModel",RegionCh);
    //set the type of crystal planes
    G4String lattice = "(111)";
    //activate the channeling model
    ChannelingModel->Input(CrystalN1,lattice);
    //setting bending angle of the crystal planes (default is 0)
    BendingAngle = 0.905*mrاد;
    ChannelingModel->GetCrystalData()->SetBendingAngle(BendingAngle);

    //activate radiation model (do it only when you want to take into account
    //radiation production in an oriented crystal; it takes a lot of computational power)
    ChannelingModel->RadiationModelActivate();
}
```

Get crystal region

Channeling FastSim  
model declaration

Physical volume

Model activation

Additional options

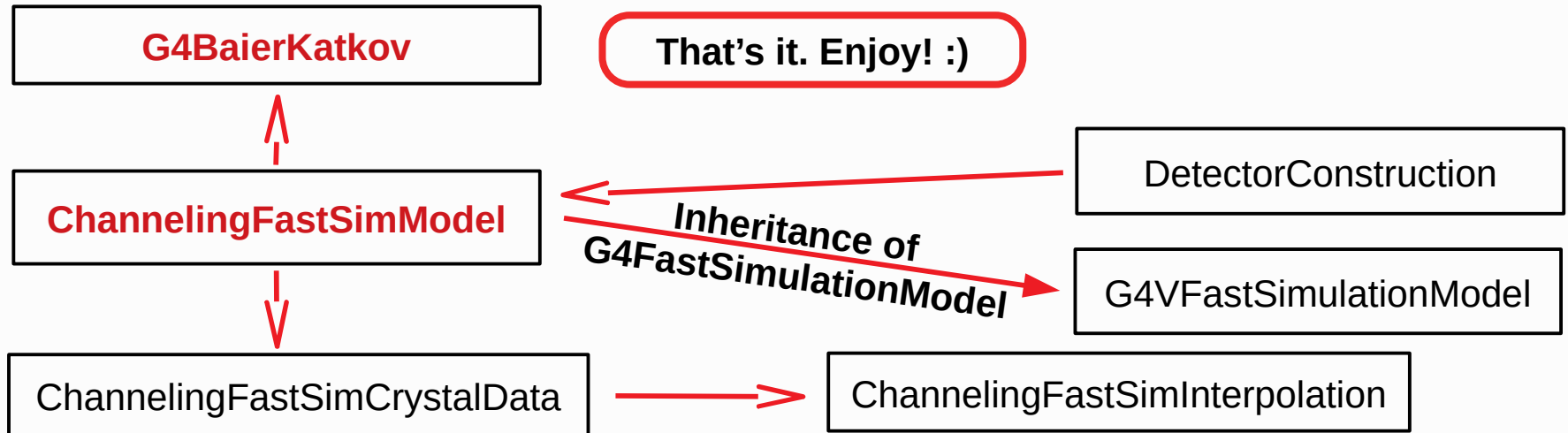
Radiation model  
activation

# 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 );
```

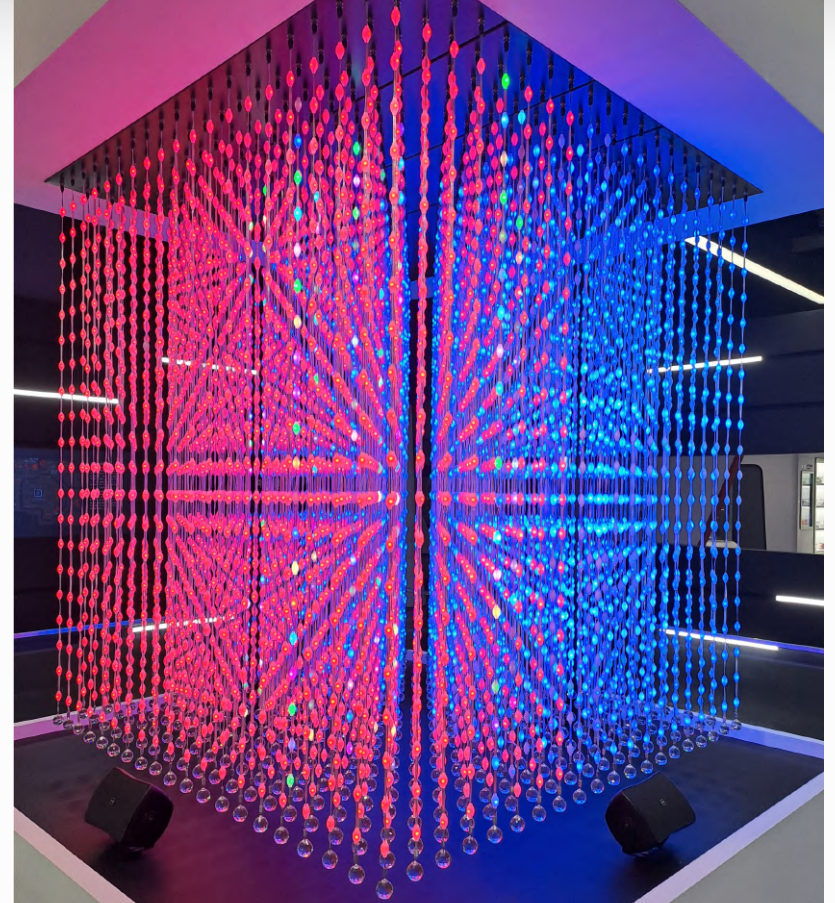
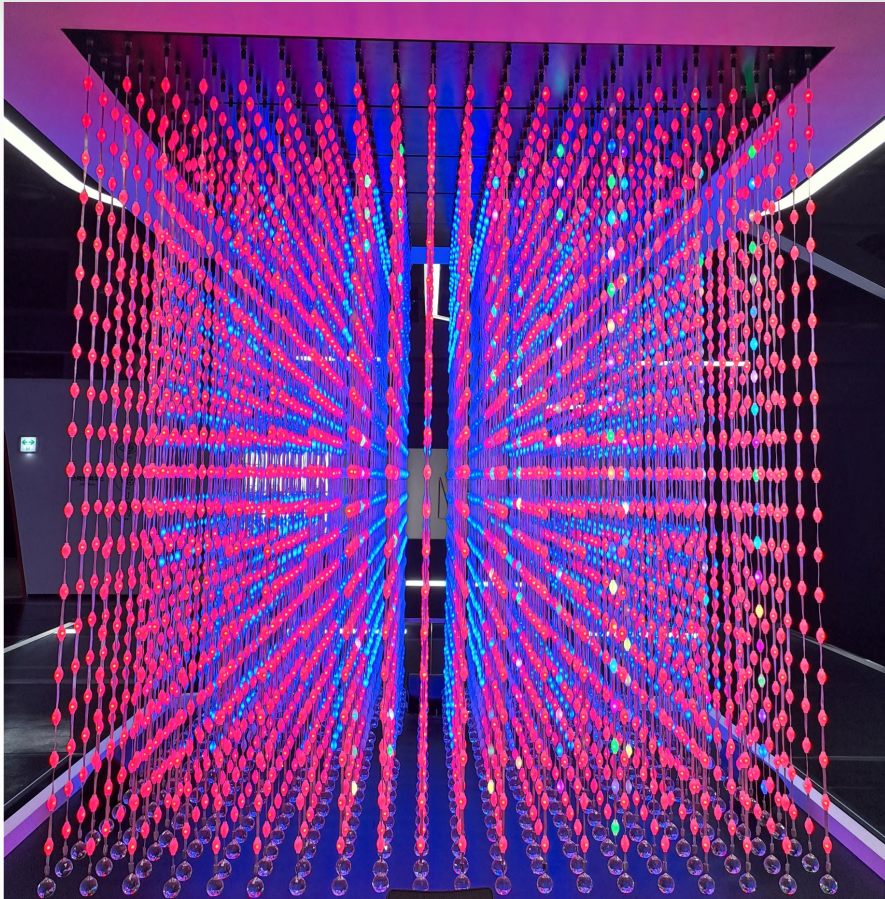


Physics list independent

# Conclusions

- The goal 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).
- Additional applications are ultrashort crystalline **calorimeter**, exotic particles **MDM** and **EDM measurement**, and **plasma wakefield acceleration**.

# Crystal lattice model in the National Science Museum (Daejeon)



**Thank you for attention!**