Istituto Nazionale di Fisica Nucleare

European Commission

Korea Institute of Science and Technology Information

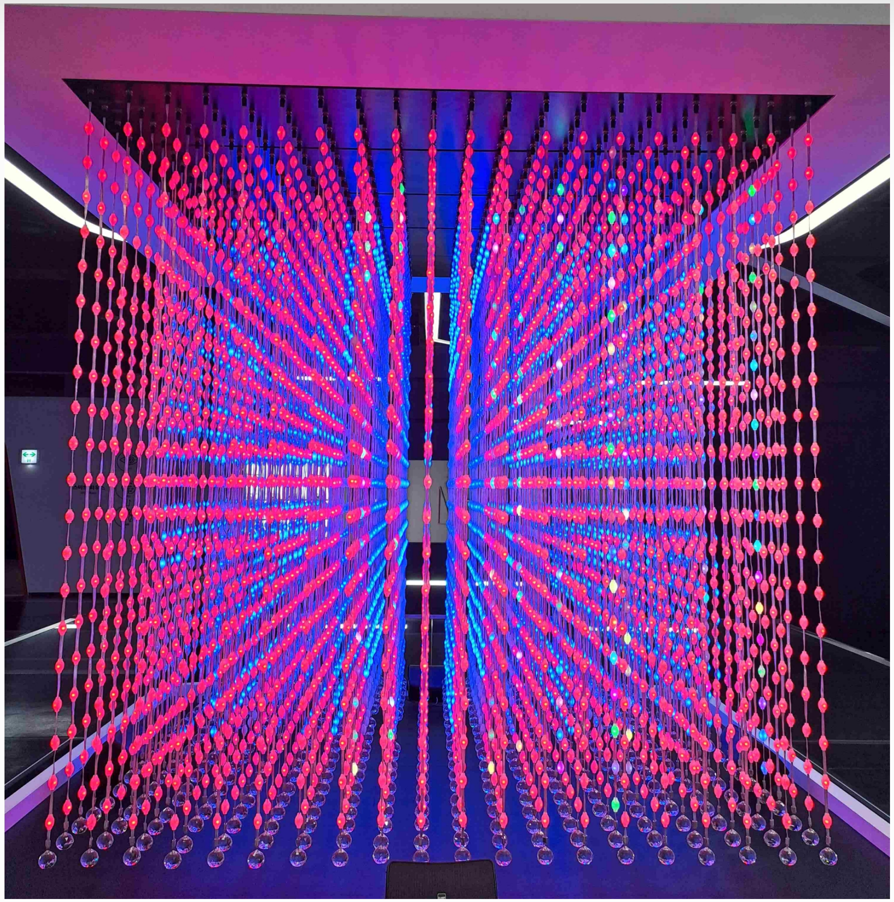
New Geant4 fast simulation model of channeling and radiation in crystals and its potential applications

Dr. Alexei Sytov

10th International Geant4 Tutorial in Korea 2022

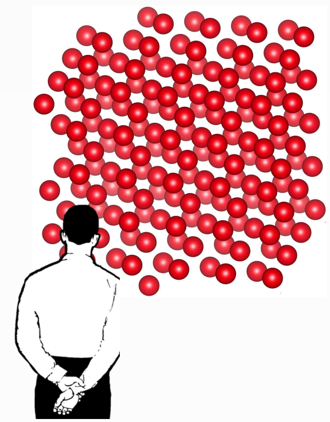
Jeju, 23/11/06

How an oriented crystal looks like

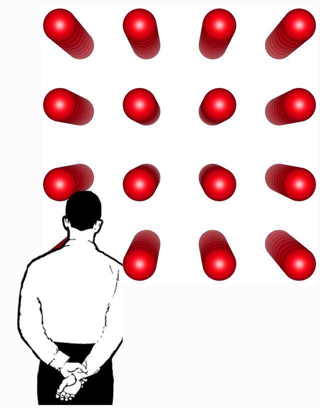


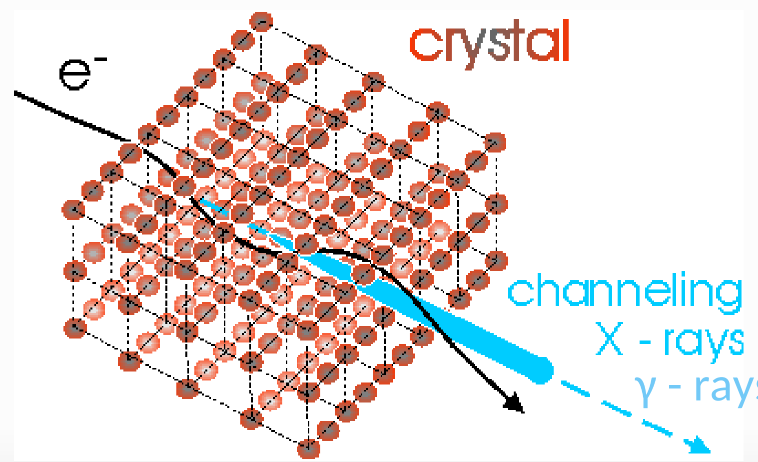
from National Science Museum, Daejeon, Korea

Non-oriented crystal

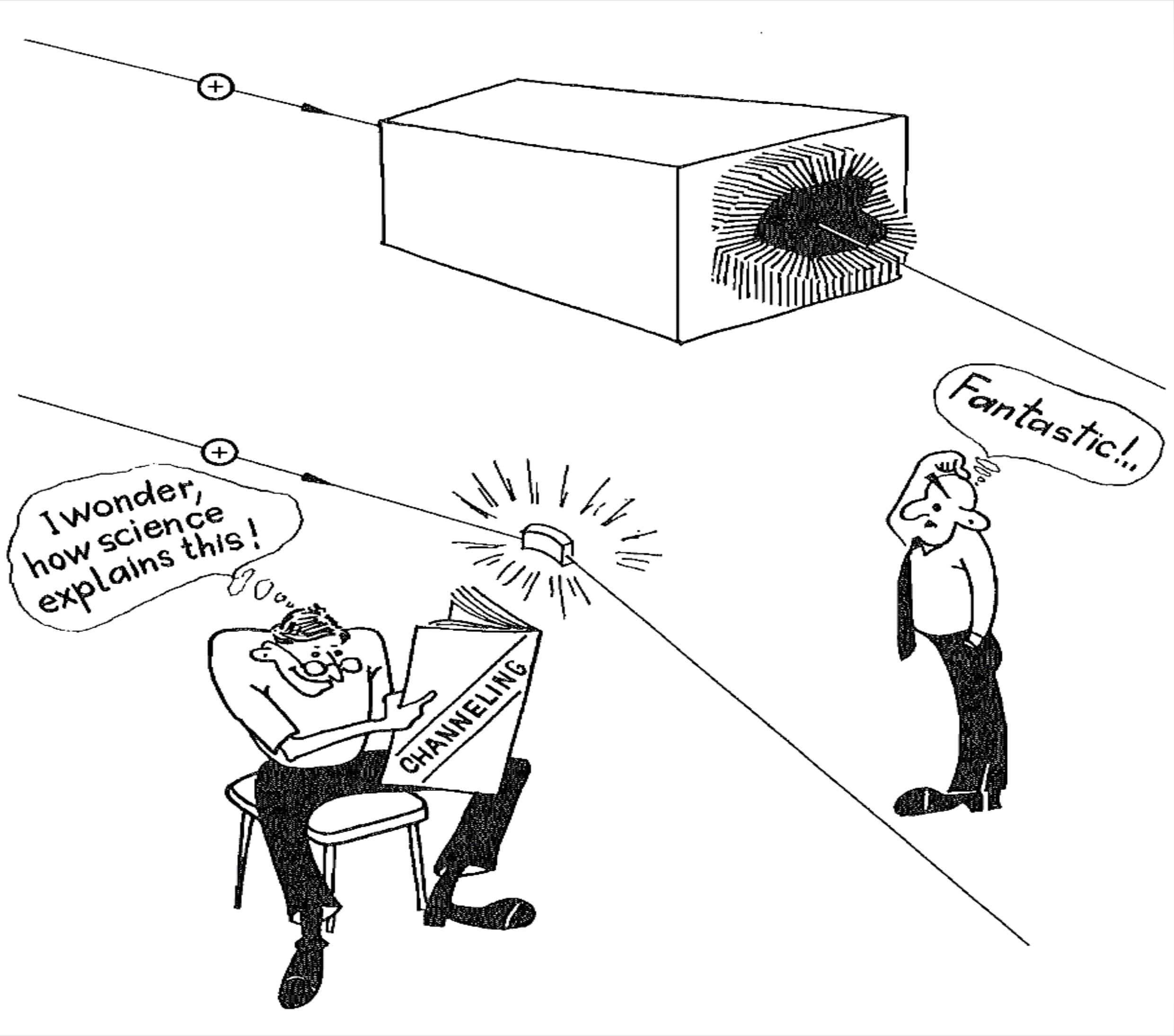


Oriented crystal



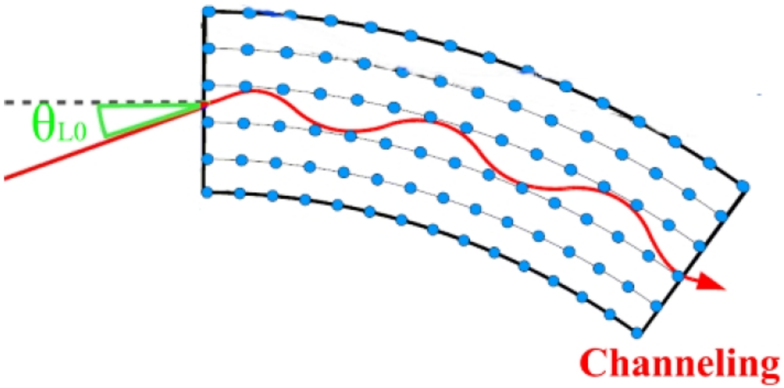


The world of the channeling effect



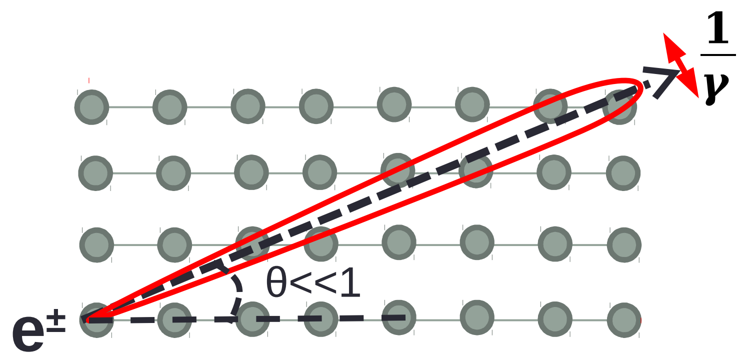
Coherent effects in a crystal

Channeling*



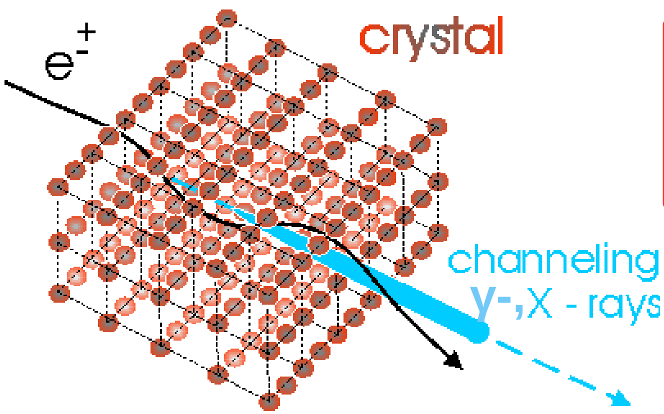
Enegies: MeV - TeV

Coherent bremsstrahlung***



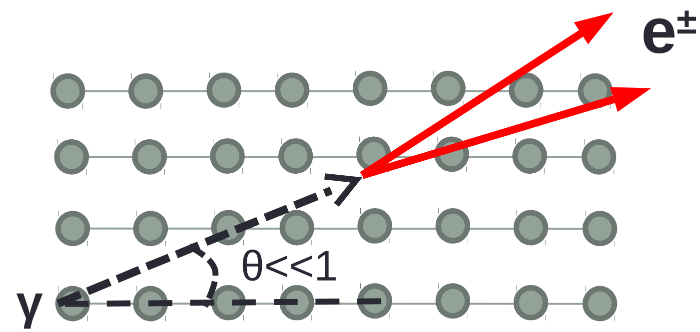
Equivalent magnetic field: more than 100 T

Channeling radiation**



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

Coherent pair production****

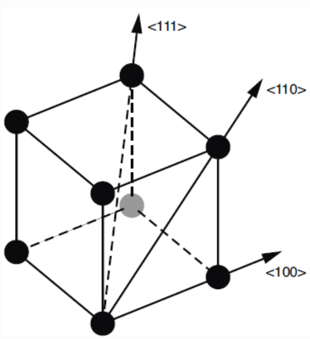


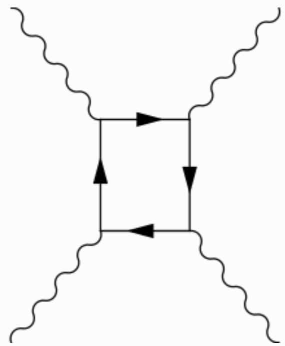
*J. Stark, Zs. Phys. 13, 973–977 (1912); J. A. Davies, J. Friesen, J. D. McIntyre, Can J. Chem. 38, 1526–1534 (1960)
**M.A. Kumakhov, Phys. Lett. A 57(1), 17–18 (1976)
***B. Ferretti, Nuovo Cimento 7, 118 (1950); M. Ter-Mikaelian, Sov. Phys. JETP 25, 296 (1953).
**** H. Überall, Phys. Rev. 103, 1055 (1956).

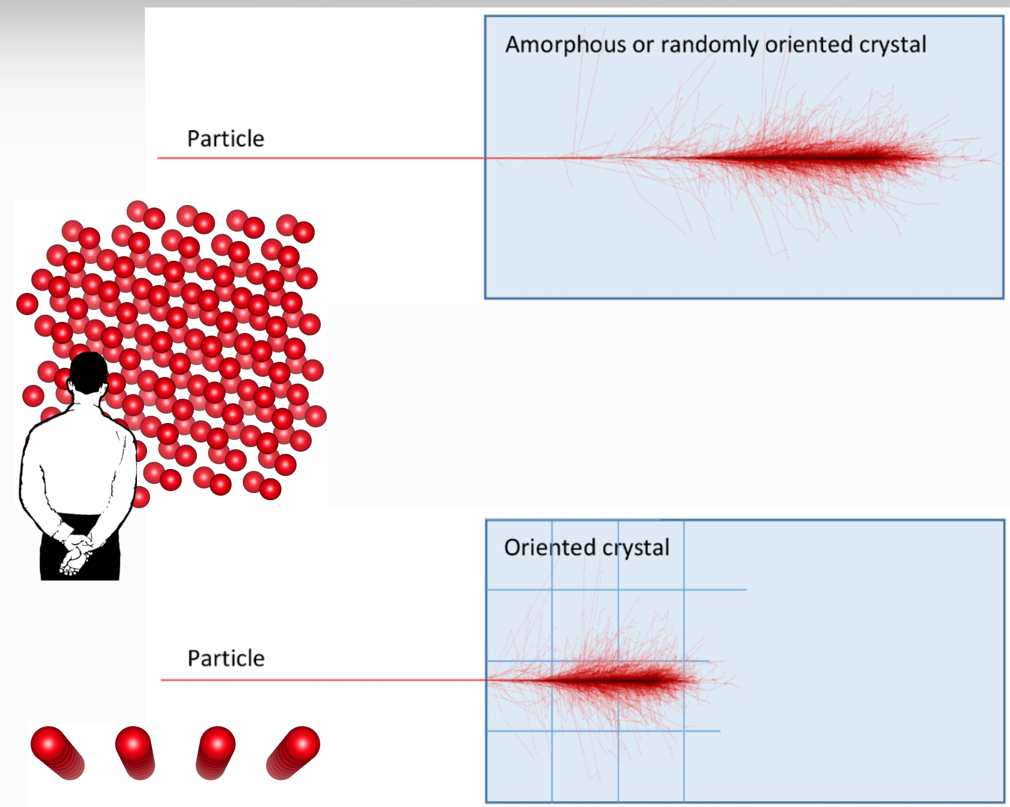
Electromagnetic shower acceleration

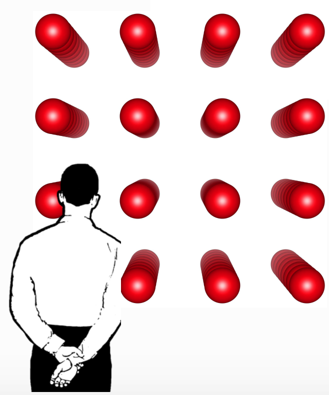
Axial field 10^{11} V/cm

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







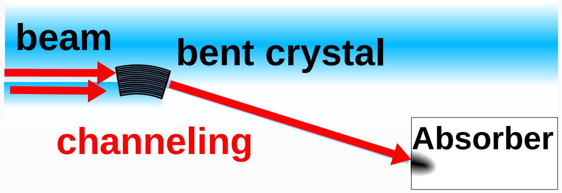


The **radiation** intensity and the **pair production** cross-section **drastically increase** in **oriented crystals!**

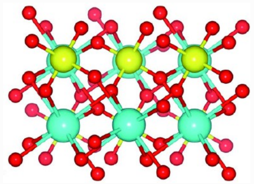
Shower development in the field of axes is **accelerated**. The radiation length is considerably reduced*.

Applications*

Crystal-based collimation or beam extraction from an accelerator

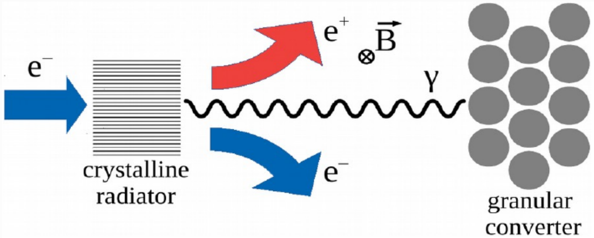


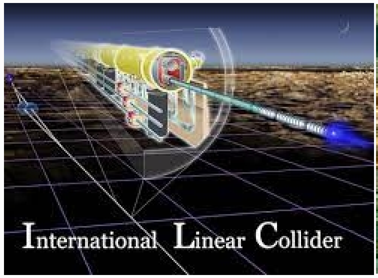
Ultrashort crystalline calorimeter

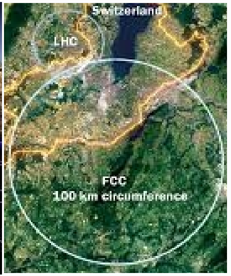


Gamma-ray Space Telescope

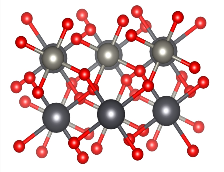
Positron source for future e+/e- and muon colliders



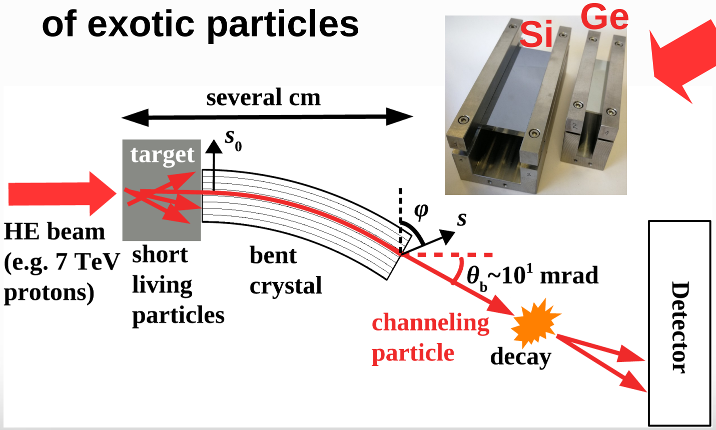




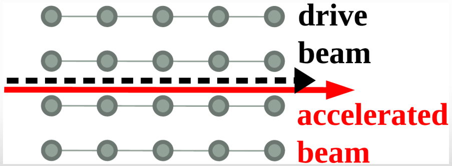
Oriented crystals



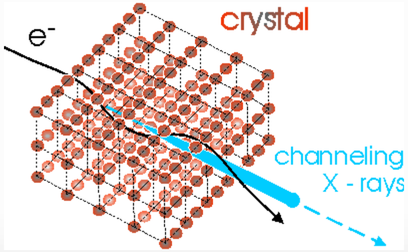
Measurement of dipole magnetic and electric moments of exotic particles

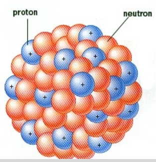


Plasma acceleration



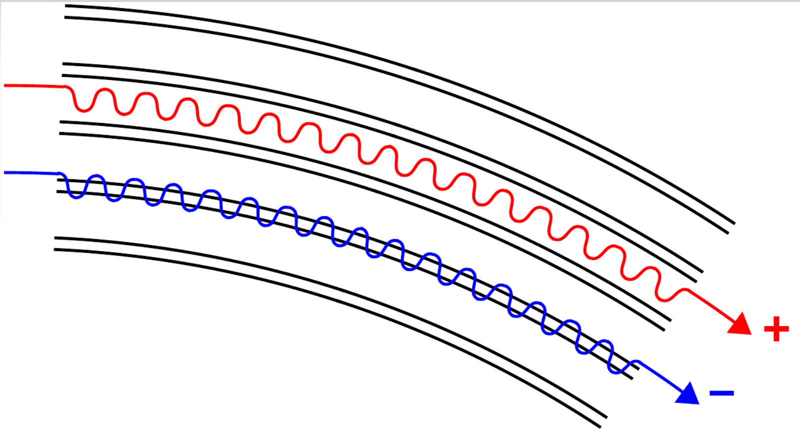
X and γ-ray source for nuclear and medical physics





*A. Sytov et al. JKPS 83, 132–139 (2023)

Crystal-based extraction

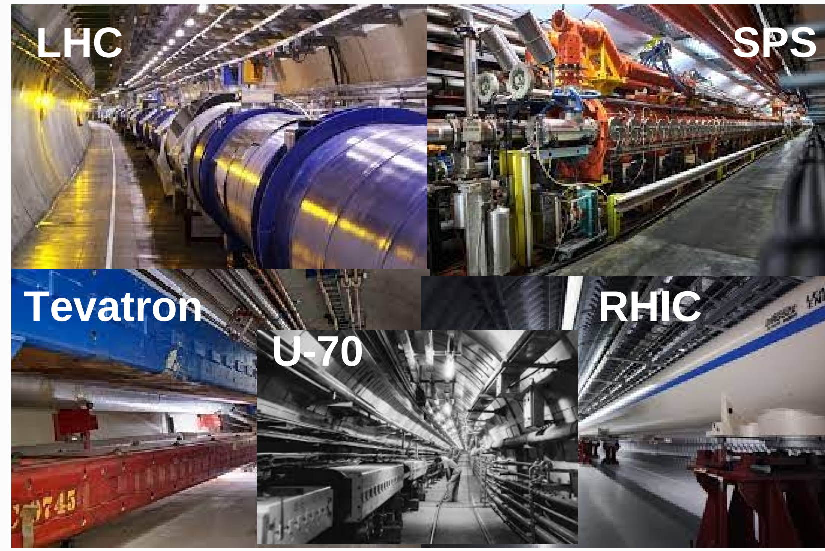


Channeling

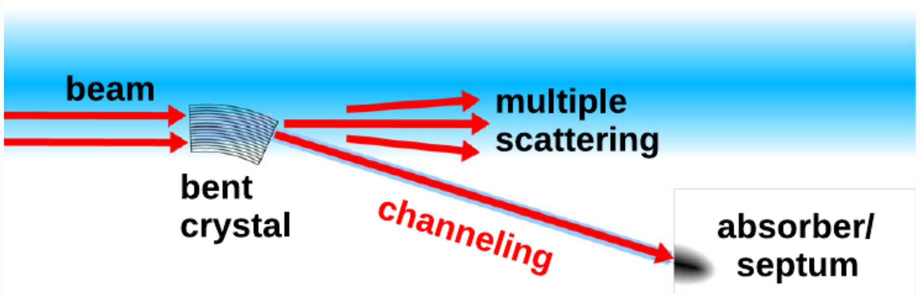
Planar channeling*:

- Charge particle penetration through a monocrystal along its atomic planes

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



Crystal-based extraction/collimation



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

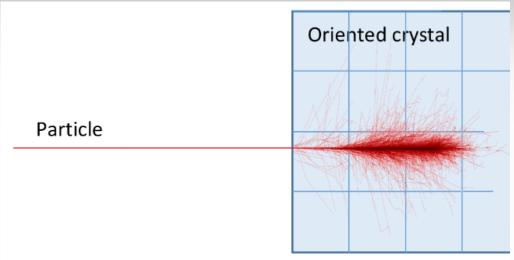
Interesting for tens of electron synchrotrons

***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 ultrashort electromagnetic calorimeter* (The INFN OREO experiment ORiEnted calOrimeter)

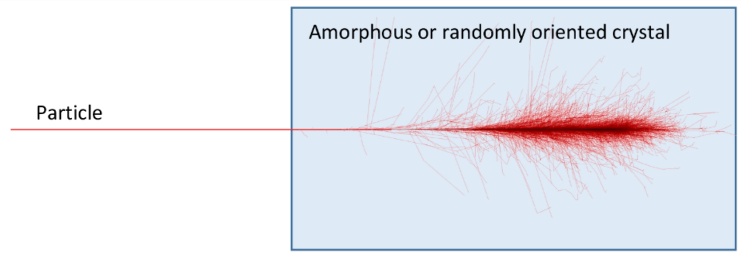
Advantage:

- 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

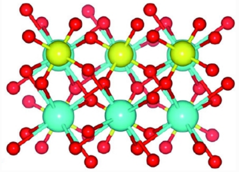
HIKE
High Intensity Kaon Experiments

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

+ dark photon search

Gamma-ray Space Telescope (like Fermi)

PWO



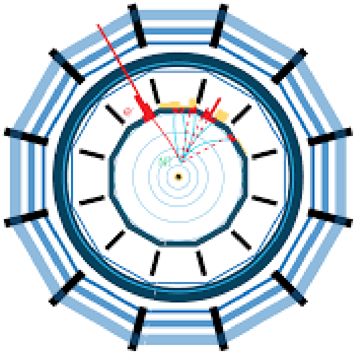
Cristalline calorimeter extends observation **γ energy range** up to **TeV**

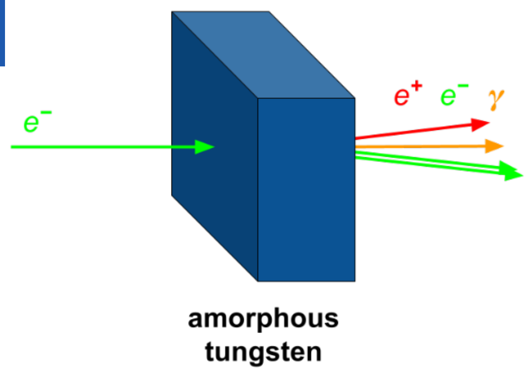
*L. Bandiera, …, A. Sytov et al. Phys. Rev. Lett. 121, 021603 (2018)

Positron source for future lepton colliders

FUTURE CIRCULAR COLLIDER

CERN

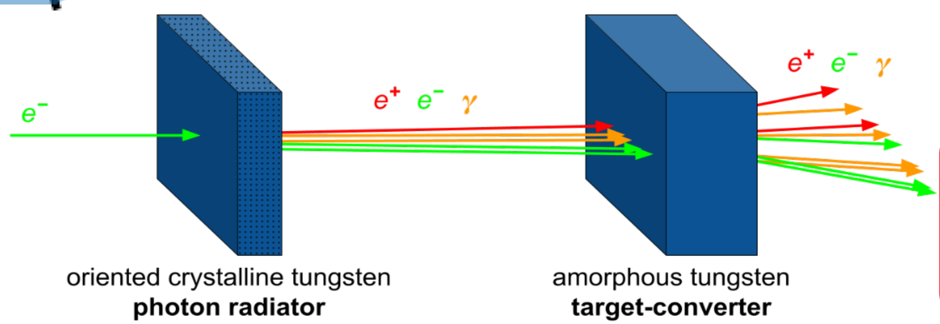


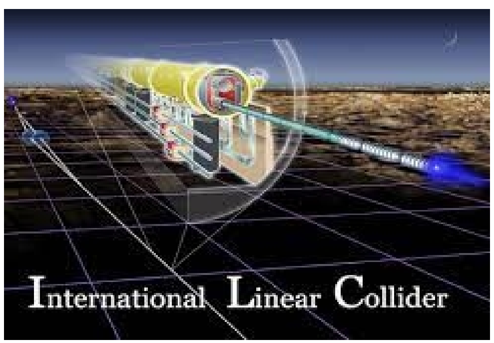


All the future **e+e- colliders** will need an **intense positron source**

Potential challenges:
Target overheating/melting

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



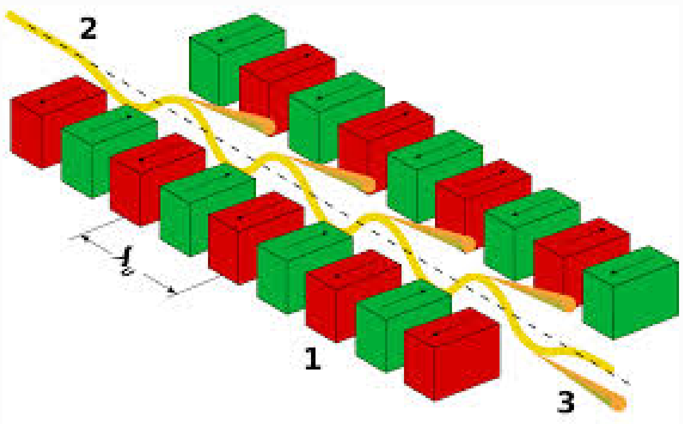


The main **challenge**:
to **increase positron yield**
and to **decrease PEDD**

*S. Maloy et al., Slc target analysis. LANL LA UR-01-1913 72 (2001)

Channeling radiation in a bent crystal: Crystalline undulator

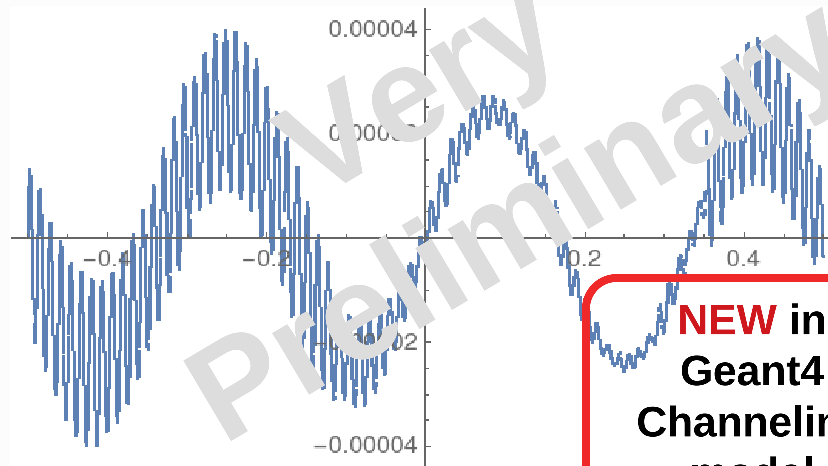
Classical scheme: magnetic undulator in a free electron laser soft X-rays $\lambda_u \sim$ cm



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



NEW in Geant4 Channeling model

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

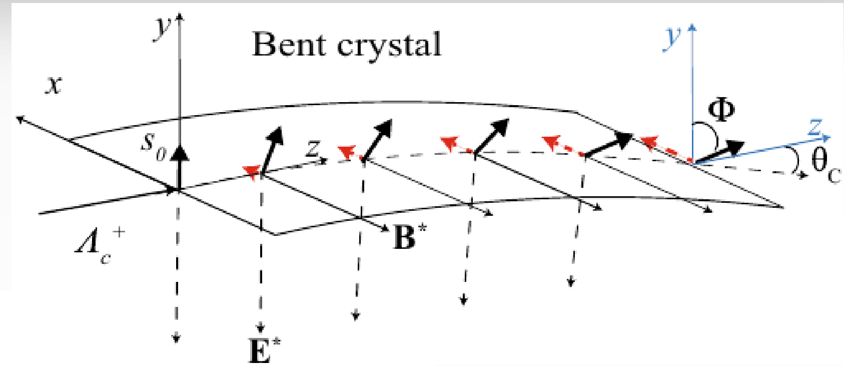
- **Nuclear physics**
- **Medical physics**

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

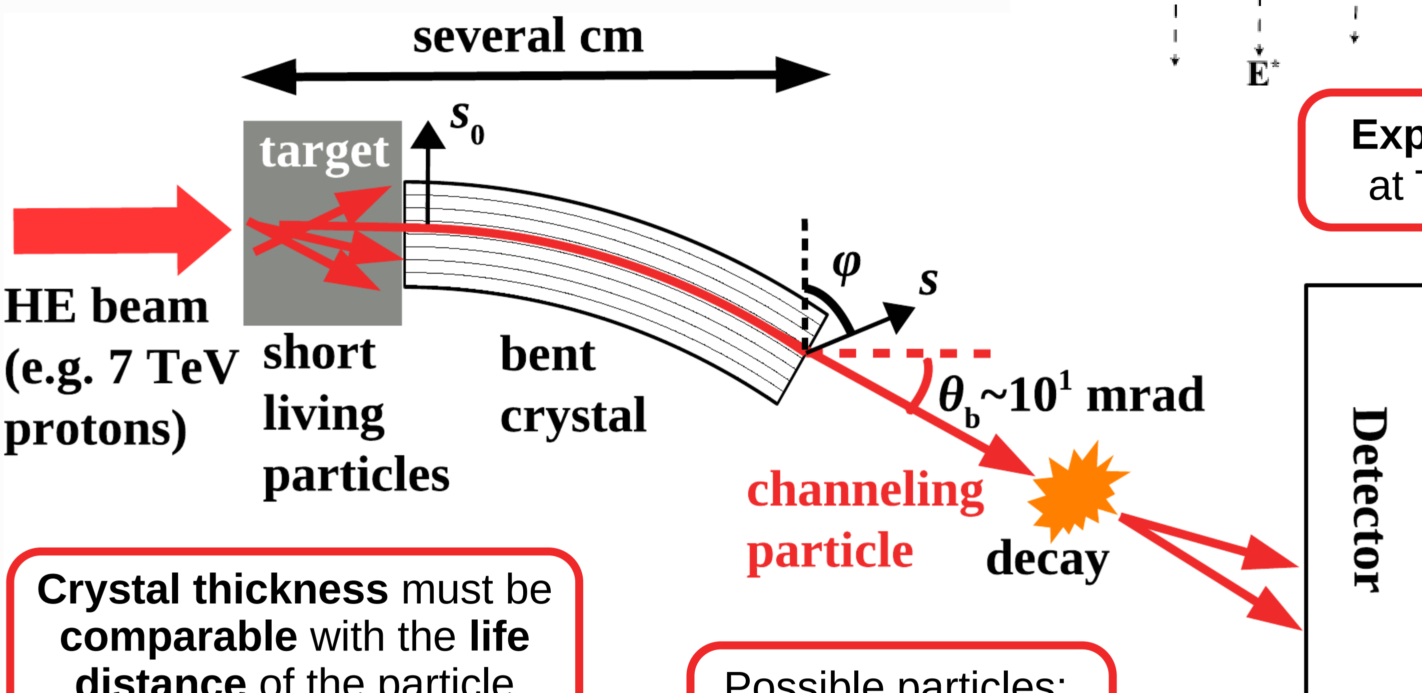
Search of MDM&EDM of short living particles using the effect of spin rotation in oriented crystals*

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)

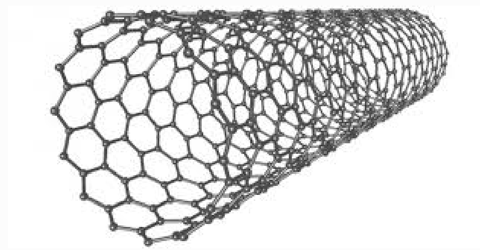
Plasma wake-field acceleration in nanostructures

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

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

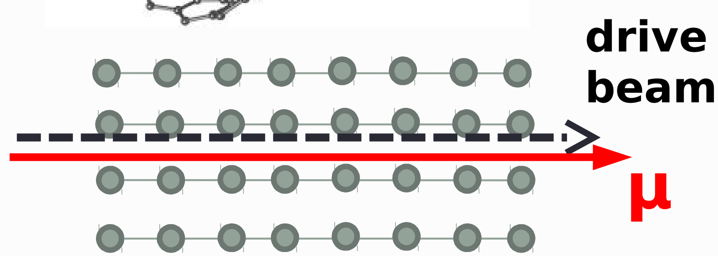
Considerably **higher electron density** in a **solid state** than in a gaseous plasma

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



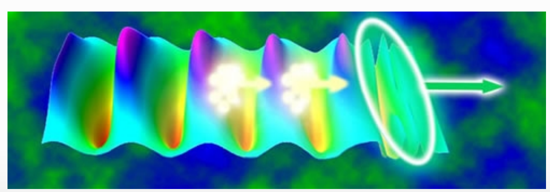
Possible drive beam:

- **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).

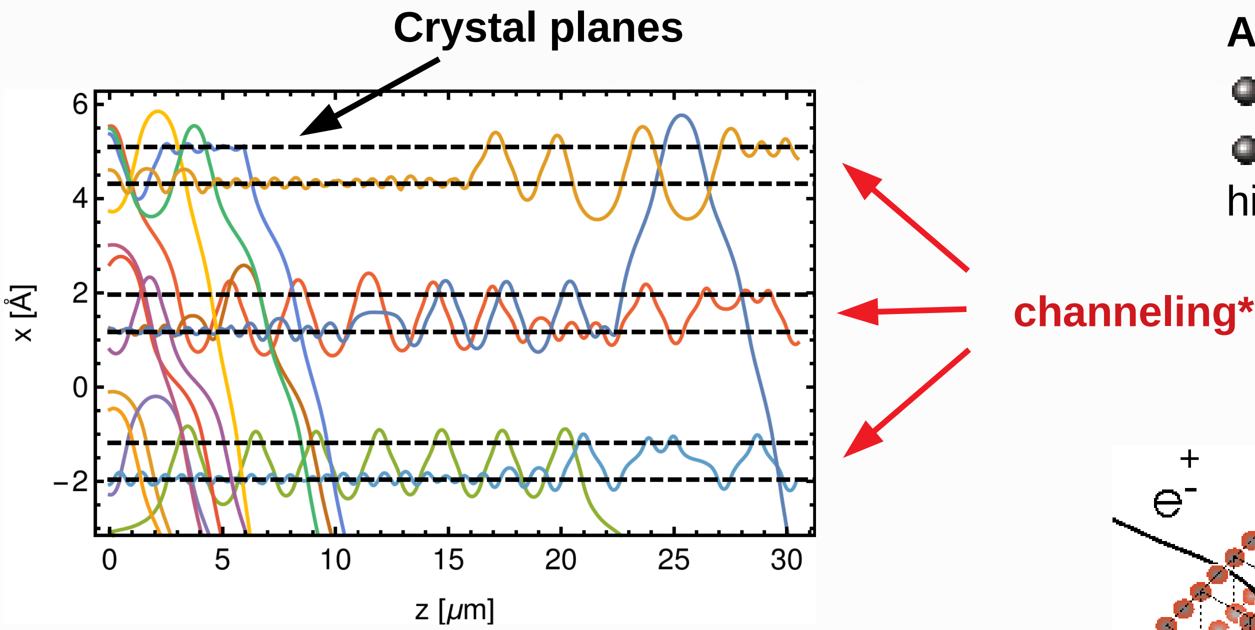
Progress of channeling physics implementation into Geant4

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**.

https://geant4.web.cern.ch/

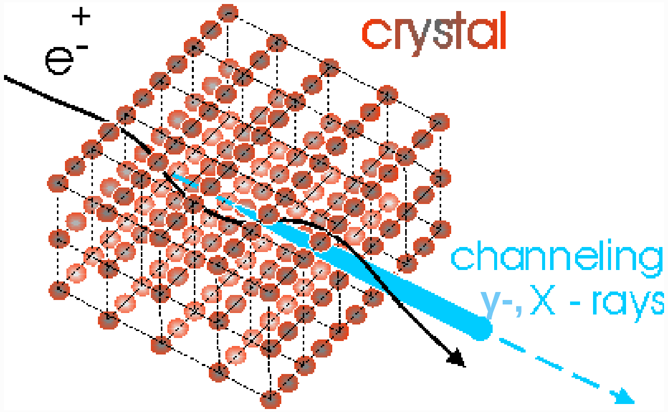
Baseline channeling simulation technique: CRYSTALRAD Monte Carlo simulation code

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



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

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

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. JKPS 83, 132–139 (2023)**
A. I. Sytov, V. V. Tikhomirov, and L. Bandiera. PRAB 22, 064601 (2019)

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

```
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)
{
```

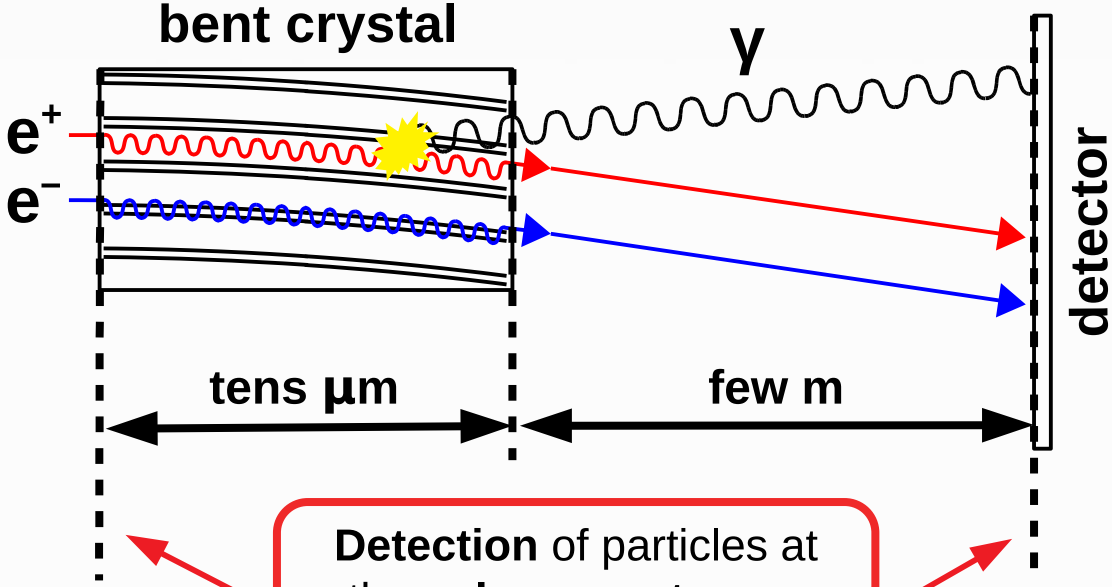
Insert particles for which the model is applicable

Insert the condition to enter the model

Insert what the model does

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 **Galileo100@CINECA** (Italy) **NURION@KISTI** (Korea)

Detection of particles at the **volumes entrance** using **SteppingAction**

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

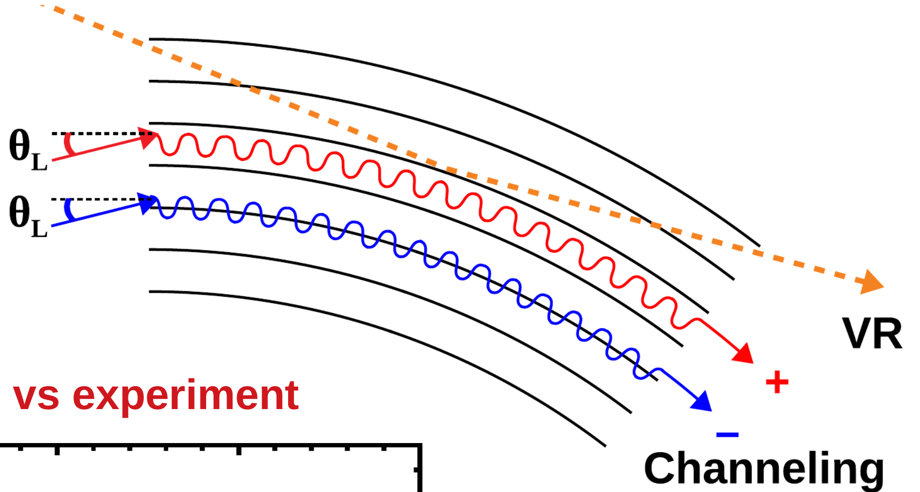
***A. Mazzolari et al. Phys. Rev. Lett. 112, 135503 (2014)**

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

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

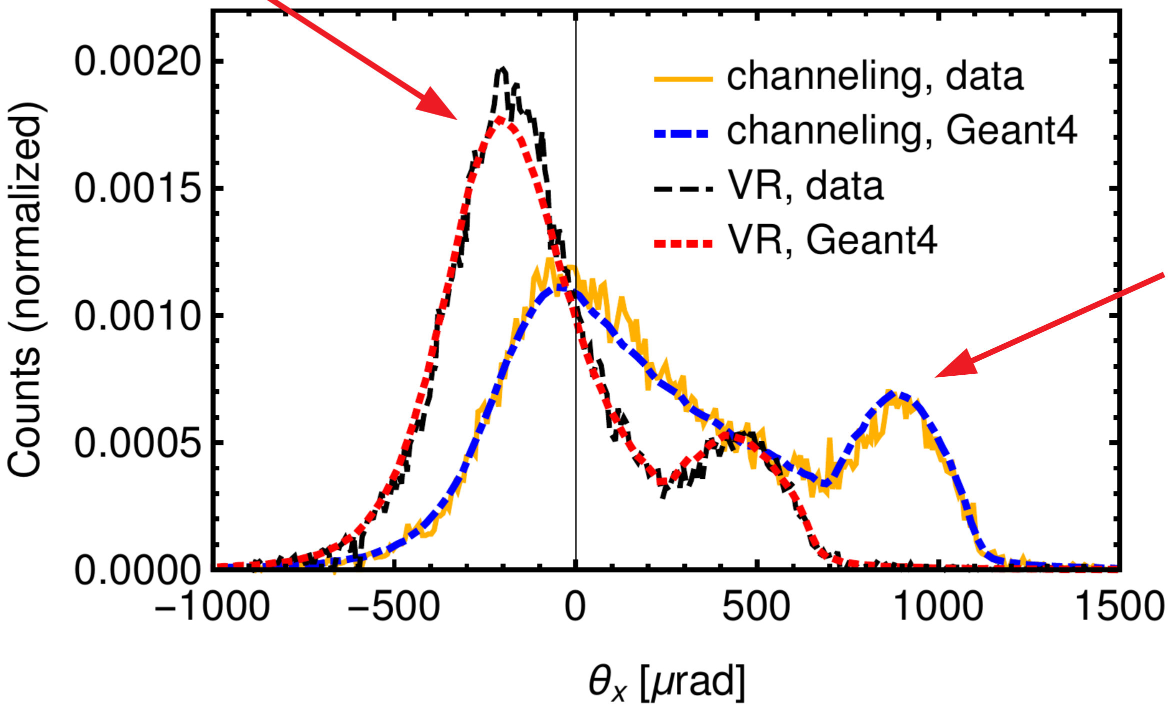
855 MeV electrons

15 μm thick bent crystal



volume reflection (VR)

Geant simulations vs experiment



channeling

*A. Sytov et al. JKPS 83, 132–139 (2023)

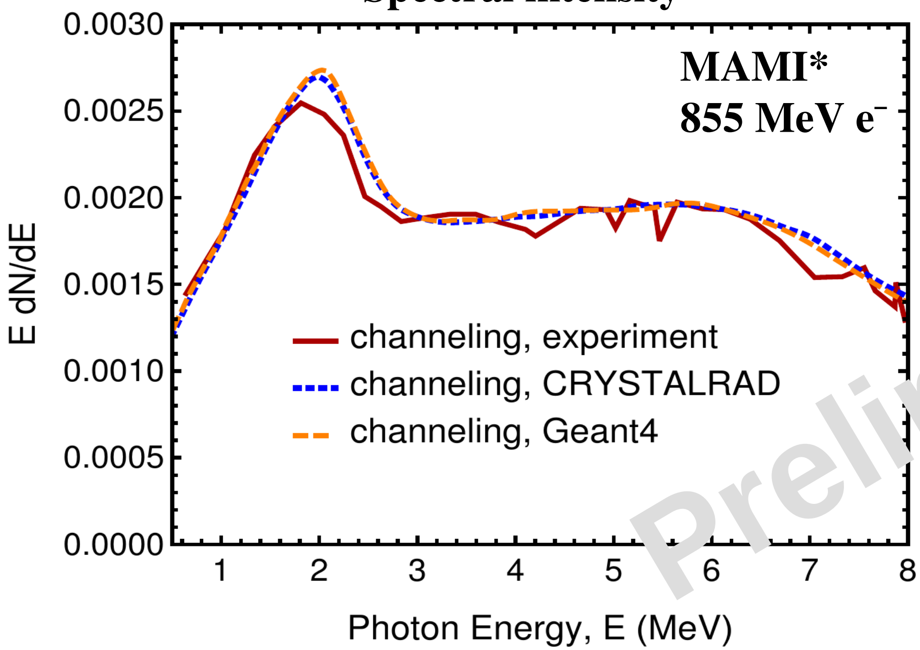
First Geant4 Baier-Katkov radiation model: radiation by 855 MeV electrons at Mainz Mikrotron MAMI*

G4BaierKatkov:

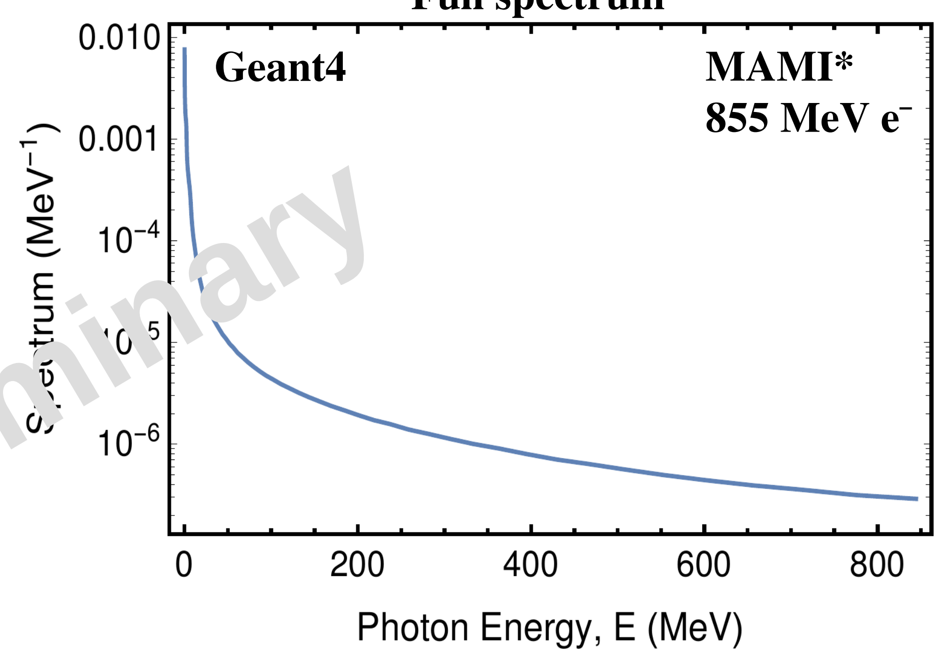
- **Physics list independent**
- Activated in the **DetectorConstruction** and used in **ChannelingFastSimModel**
- Can be used **outside channeling model** within other FastSim model
- Provides **radiation spectrum** for single-photon radiation mode
- Provides generation of **secondary photons**

Geant simulations vs experiment and CRYSTALRAD simulations

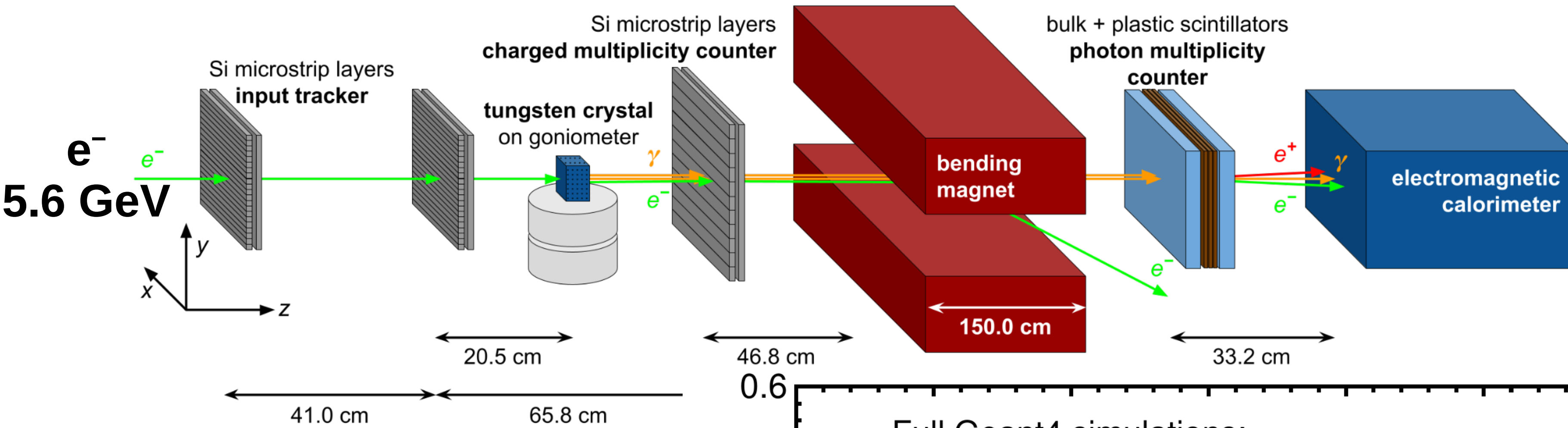
Spectral intensity



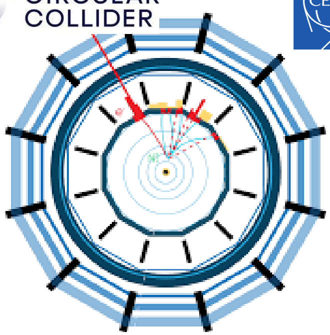
Full spectrum

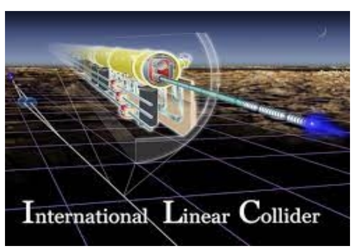


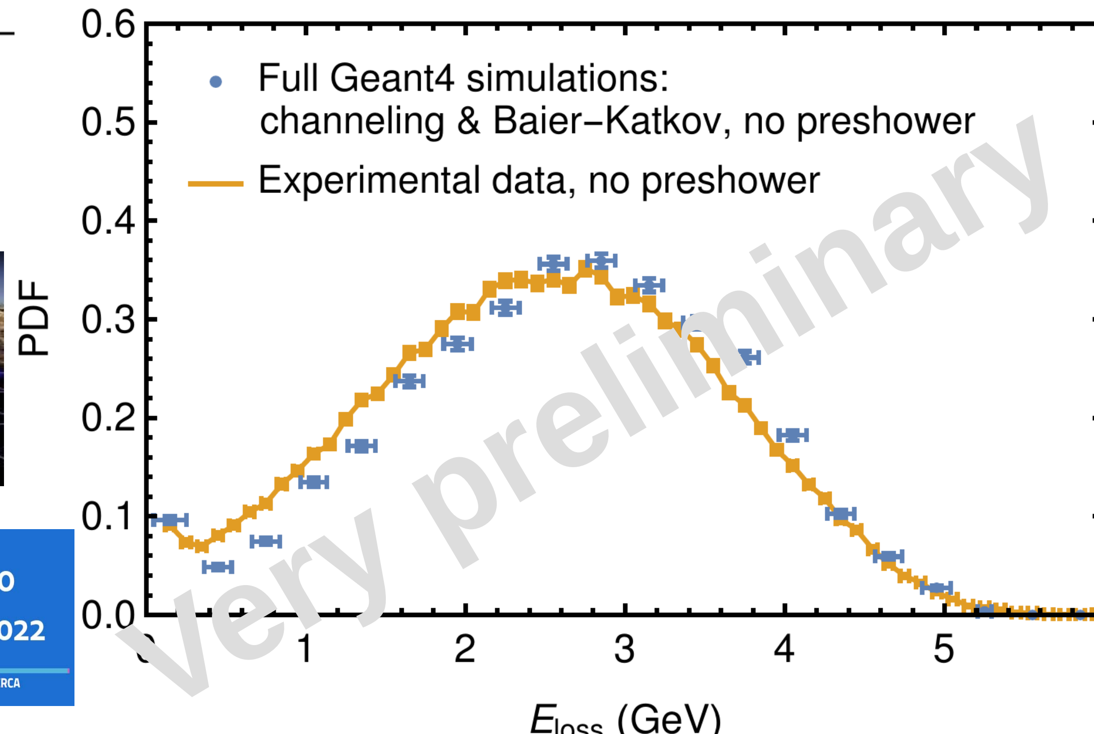
Full Geant4 simulations of the DESY experiment* for the FCC-ee positron source project



FUTURE CIRCULAR COLLIDER







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

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

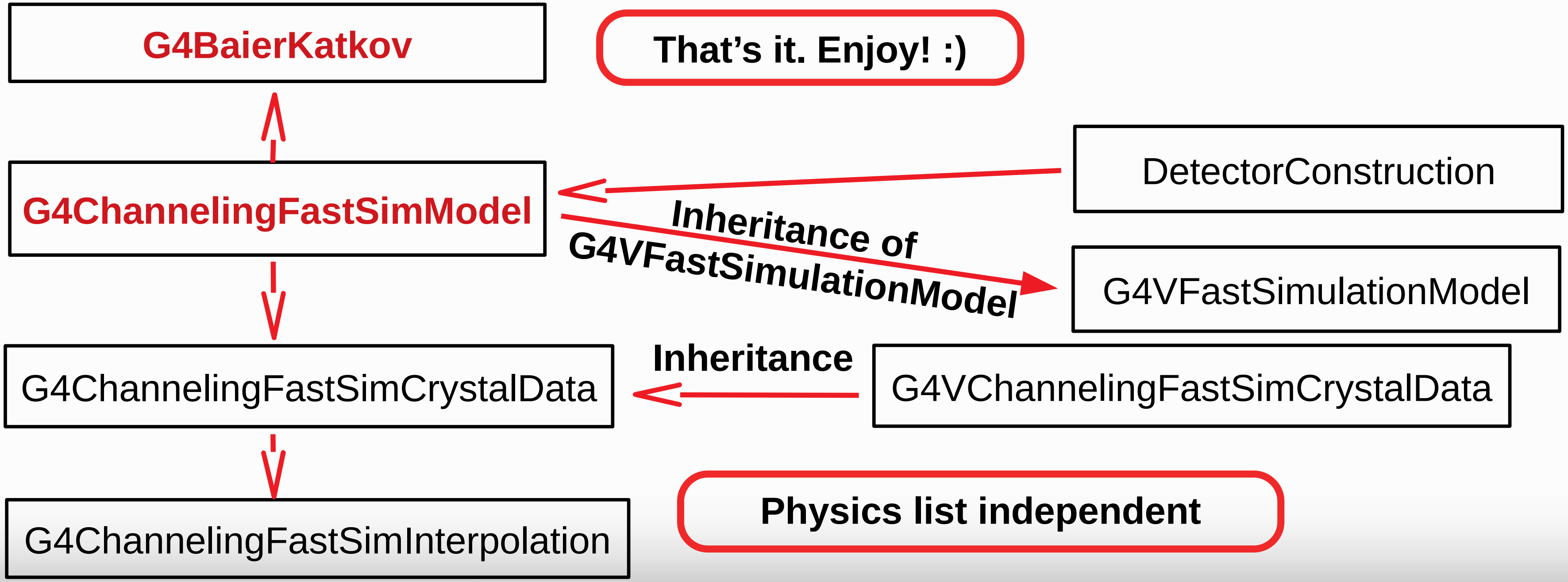
Radiation model activation

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 kernel!

Geant4-11.2.0.beta
Please use it!

Don't hesitate to contact me in the case of any problems/issues/suggestions
sytov@fe.infn.it

Please cite our papers if you use our model:

1. A. Sytov et al. JKPS 83, 132–139 (2023)
2. A. I. Sytov, V. V. Tikhomirov, and L. Bandiera. PRAB 22, 064601 (2019)

Conclusions

- **Oriented crystals** can be **applied**:
- at **e-/e+/hadron synchrotrons** (crystal-based beam extraction/ collimation)
- in **nuclear** and **medical physics** (radiation source)
- at e-/e+ colliders – **ILC**, **FCC-ee** and **muon collider** (positron source)
- as **ultrashort electromagnetic calorimeters**
- for **MDM** and **EDM** measurement
- ultrahigh gradient (more than 1 **TeV/m**) **plasma wakefield acceleration**

- 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.

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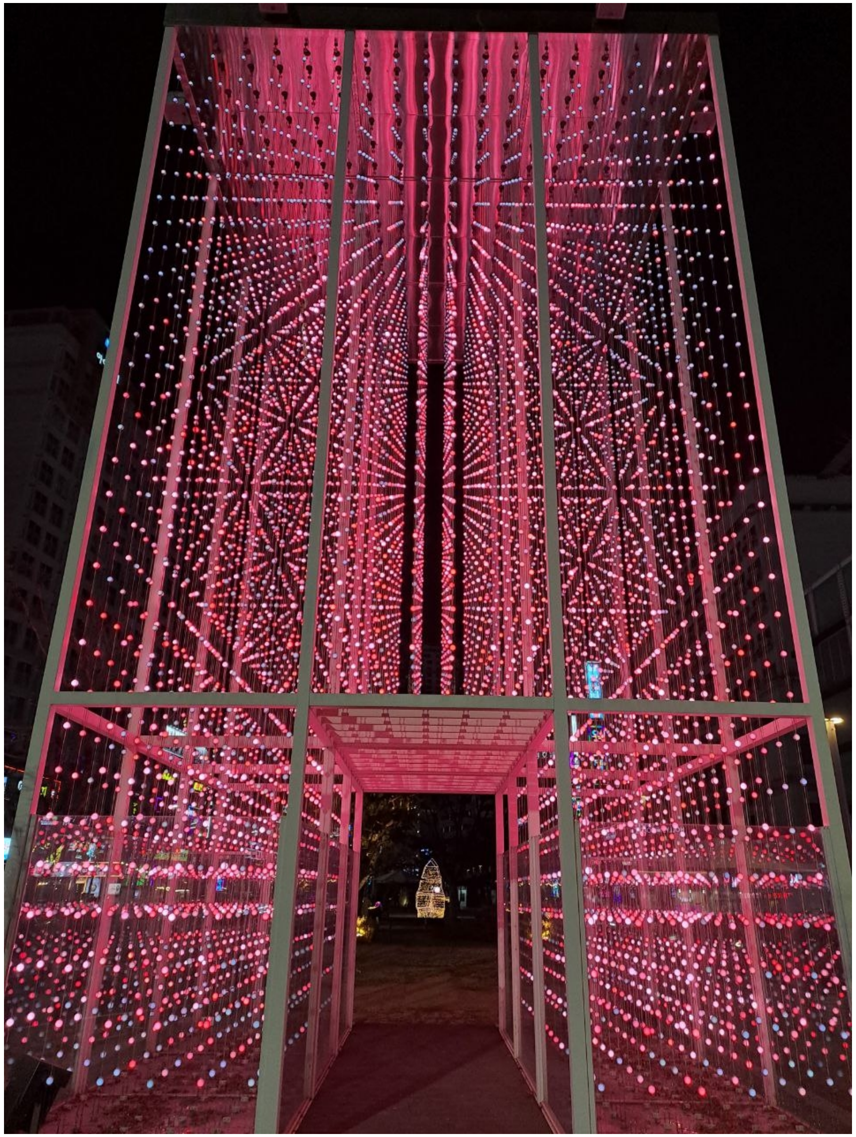

Thank you for attention!