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Trillion

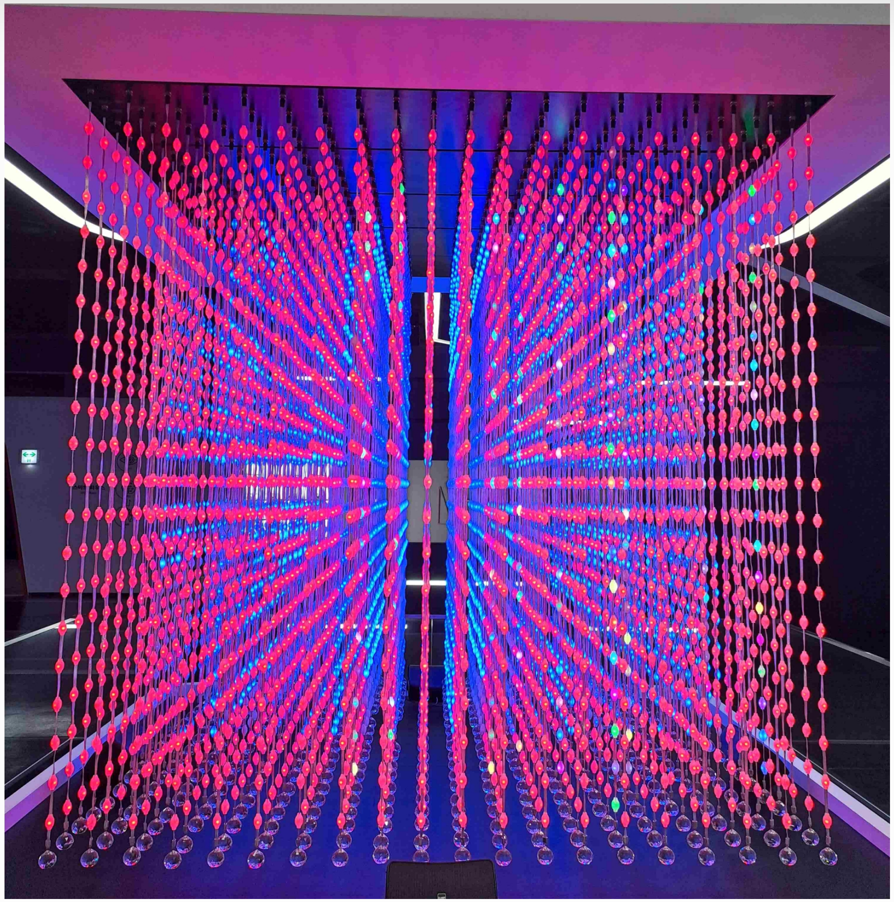
Applications of oriented crystals in accelerator physics, particle physics and space science and their simulations with Geant4

Marie Curie Global Fellowships, Project TRILLION GA n. 101032975

Dr. Alexei Sytov

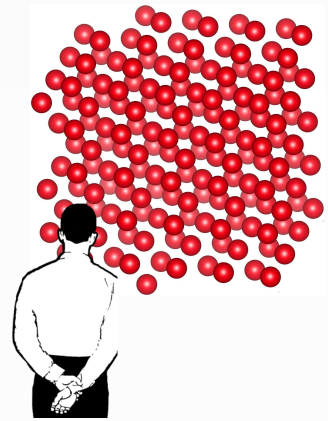
KISTI, Daejeon, 2023/07/26

How an oriented crystal looks like

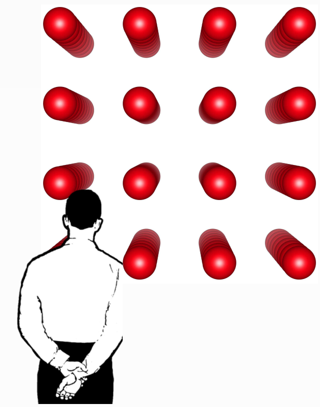


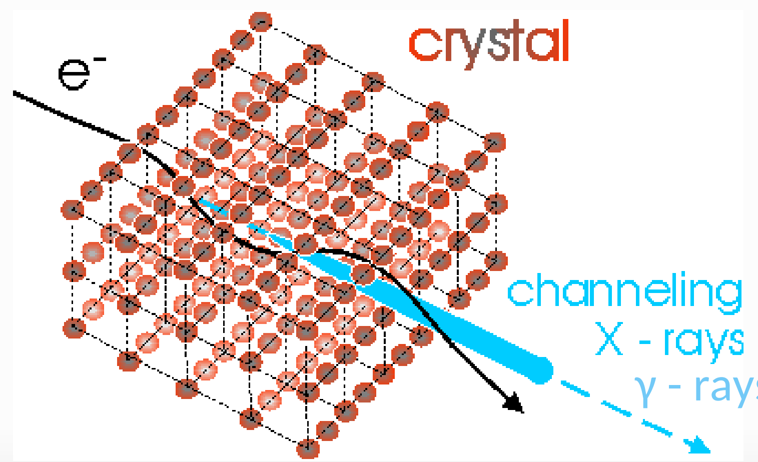
from National Science Museum, Daejeon, Korea

Non-oriented crystal

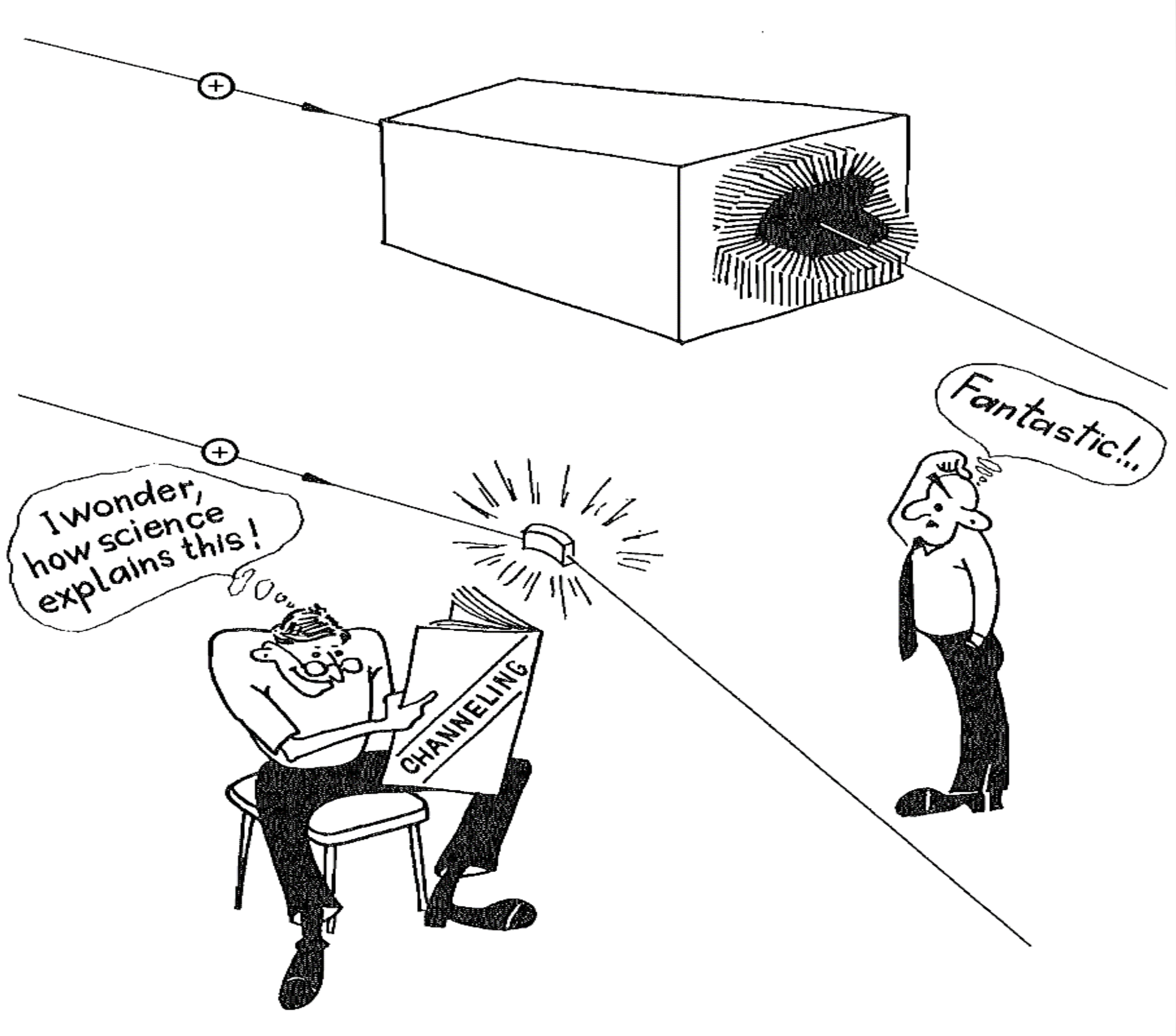


Oriented crystal

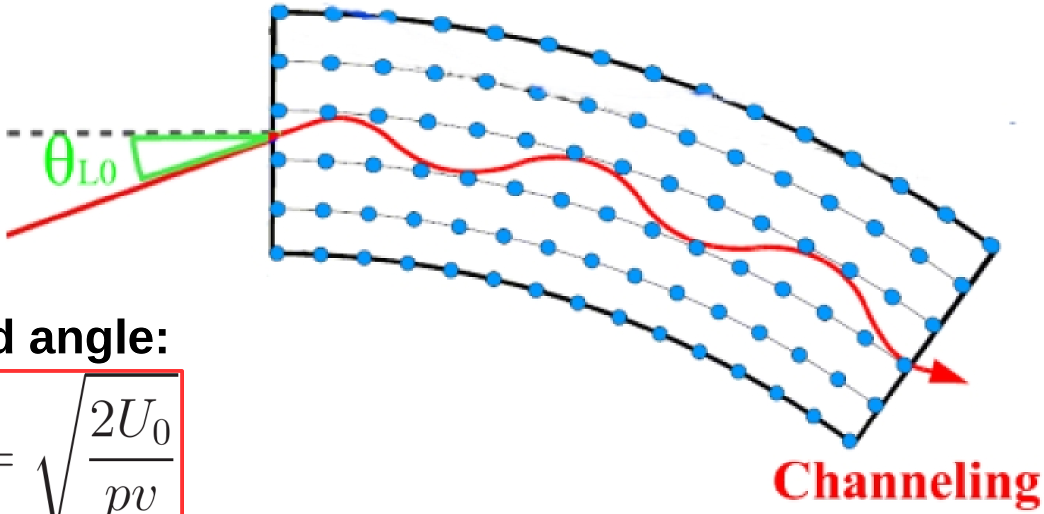


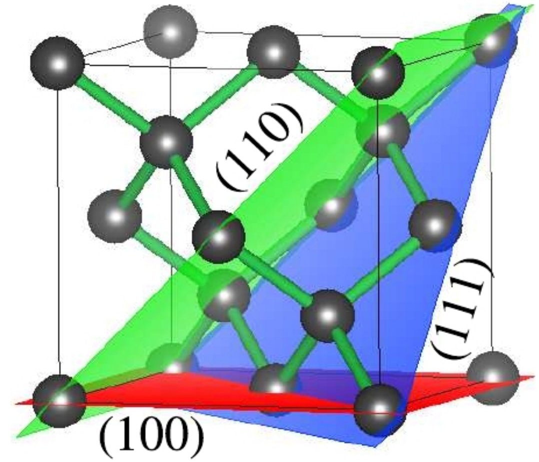


The world of the channeling effect



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

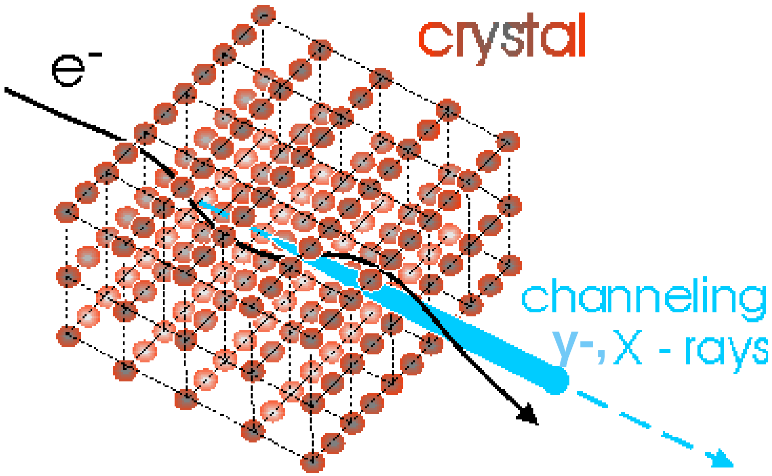
- ***Planar*** **channeling**
- ***Axial*** **channeling**

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)

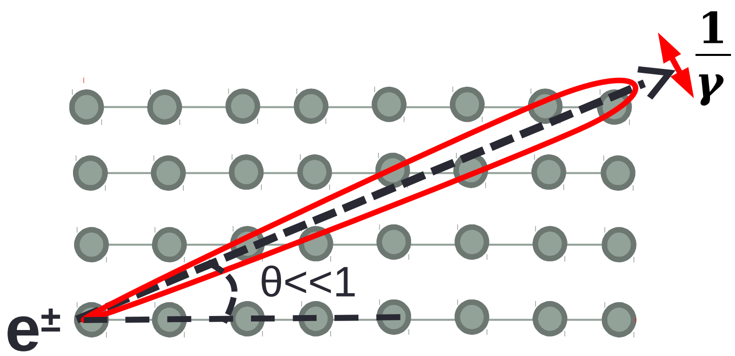
Coherent effects in a crystal

Channeling radiation*

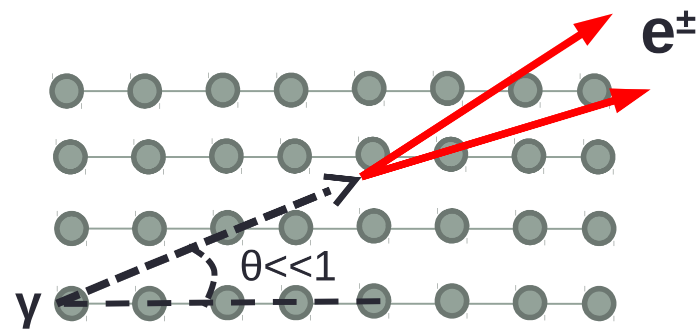


Coherent effects preserve **up to few mrad** of particle direction vs the crystal axis

Coherent bremsstrahlung**



Coherent pair production***

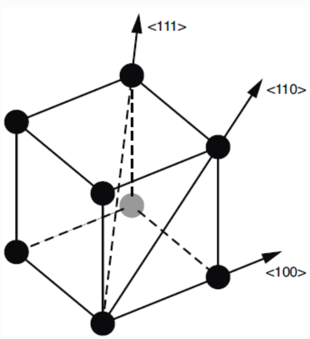


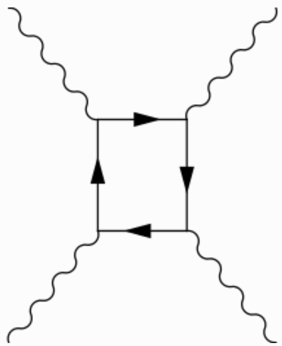
***M.A. Kumakhov, Phys. Lett. A 57(1), 17–18 (1976)**
****B. Ferretti, Nuovo Cimento 7, 118 (1950).**
****M. Ter-Mikaelian, Sov. Phys. JETP 25, 296 (1953).**
***** H. Überall, Phys. Rev. 103, 1055 (1956).**

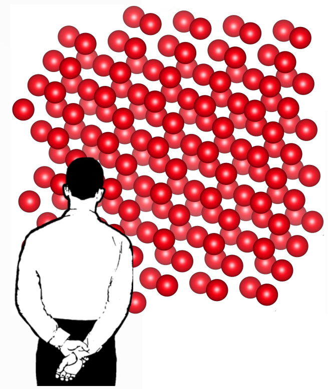
Electromagnetic shower acceleration

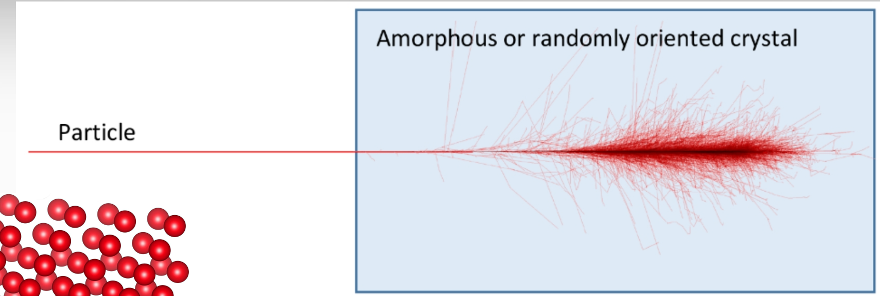
Axial field 10[11] V/cm

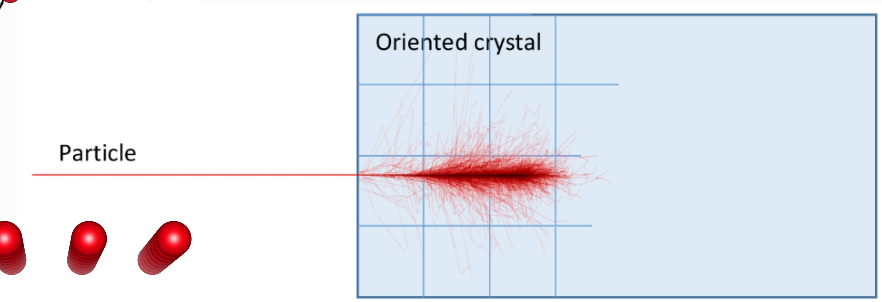
Approaching the **Schwinger limit** starting from few **GeV** for **e+/e-**

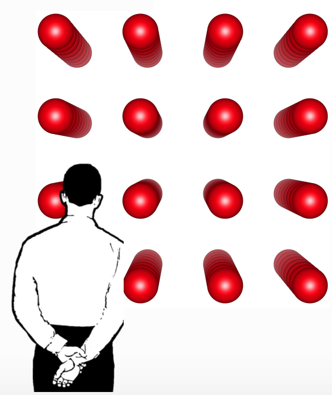










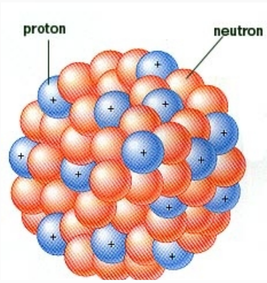


The **radiation** intensity and the **pair production** cross-section **drastically increase** in **oriented crystals!**

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

Applications of oriented crystals*

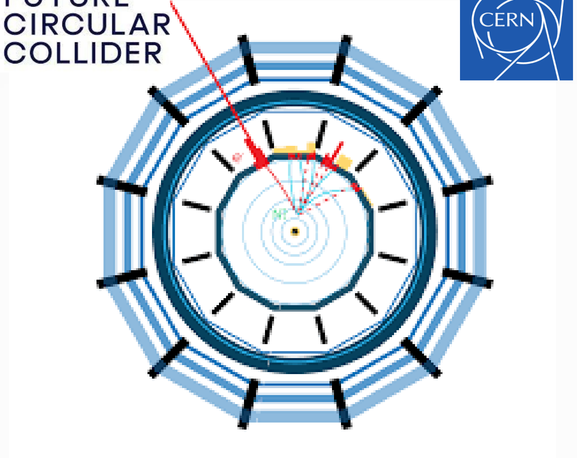
X and γ-ray source for nuclear physics and cancer radiotherapy



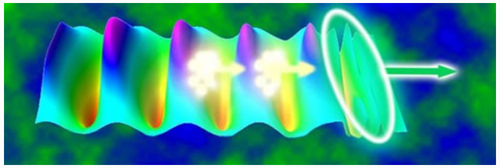
Gamma-ray Space Telescope

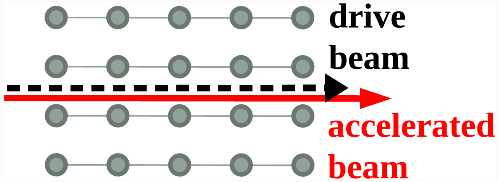
Positron source for future multi-billion € e+/e- and muon colliders

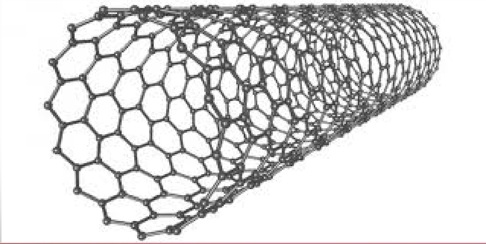
FUTURE CIRCULAR COLLIDER



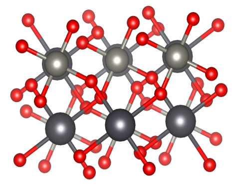
Plasma wakefield acceleration







Oriented crystals



Crystal-based beam extraction from accelerators and colliders

*A. Sytov et al., JKPS 83, 132–139 (2023), https://doi.org/10.1007/s40042-023-00834-6

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

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

Group:

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

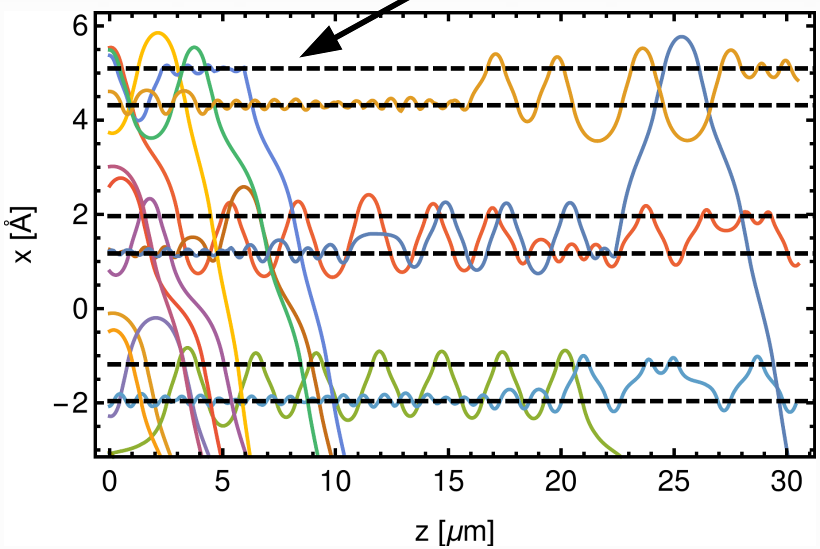
Location:

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

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

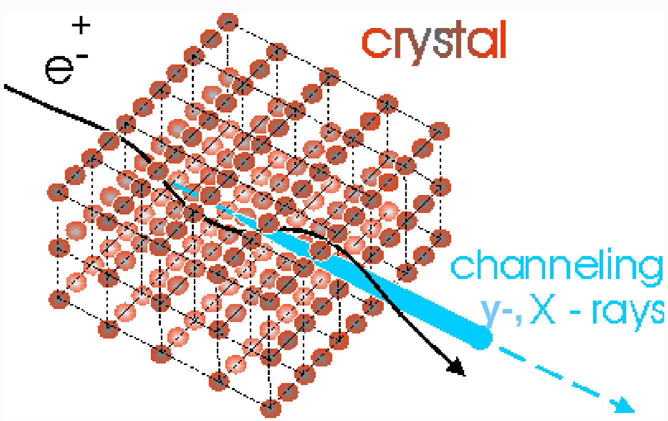
Crystal planes



channeling*

Advantages:

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



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

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

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)

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)
{
```

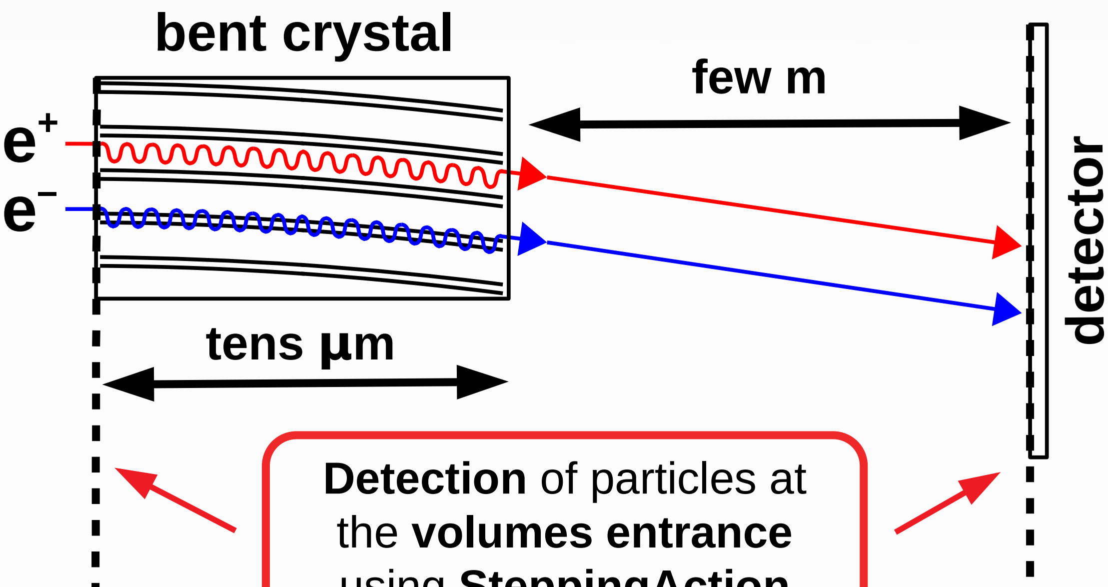
Insert particles for which the model is applicable

Insert the condition to enter the model

Insert what the model does

First Geant4 channeling example for electrons/positrons

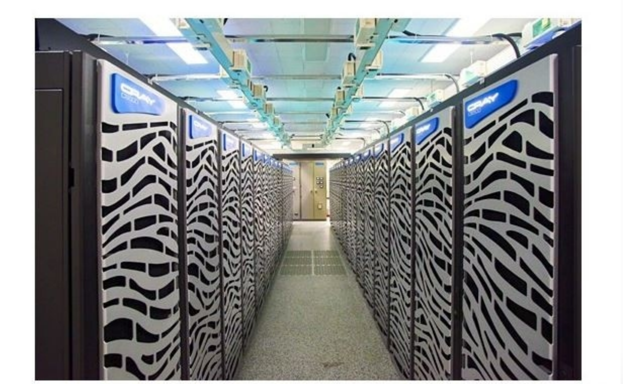
- **Inspired by** our experiments* of **855 MeV electron** beam deflection by an ultrashort **bent crystal** at **Mainz Mikrotron MAMI**



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

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)



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

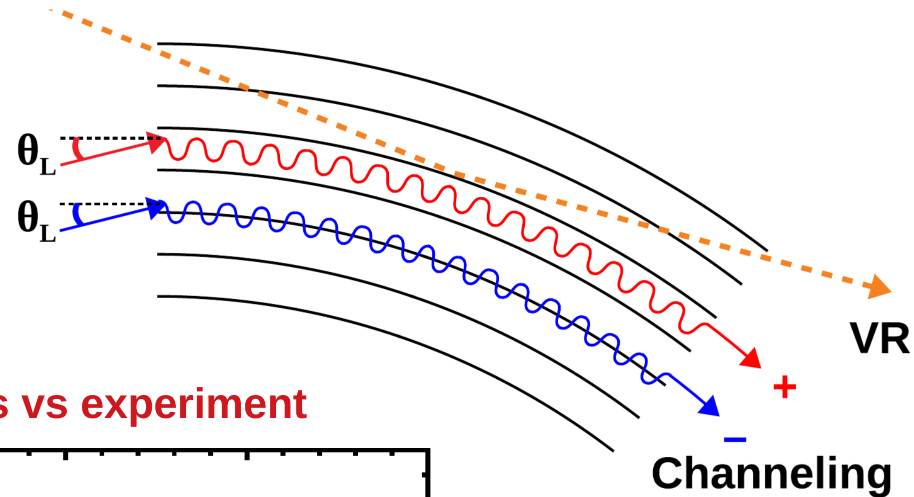
***A. Mazzolari et al. Phys. Rev. Lett. 112, 135503 (2014)**

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

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

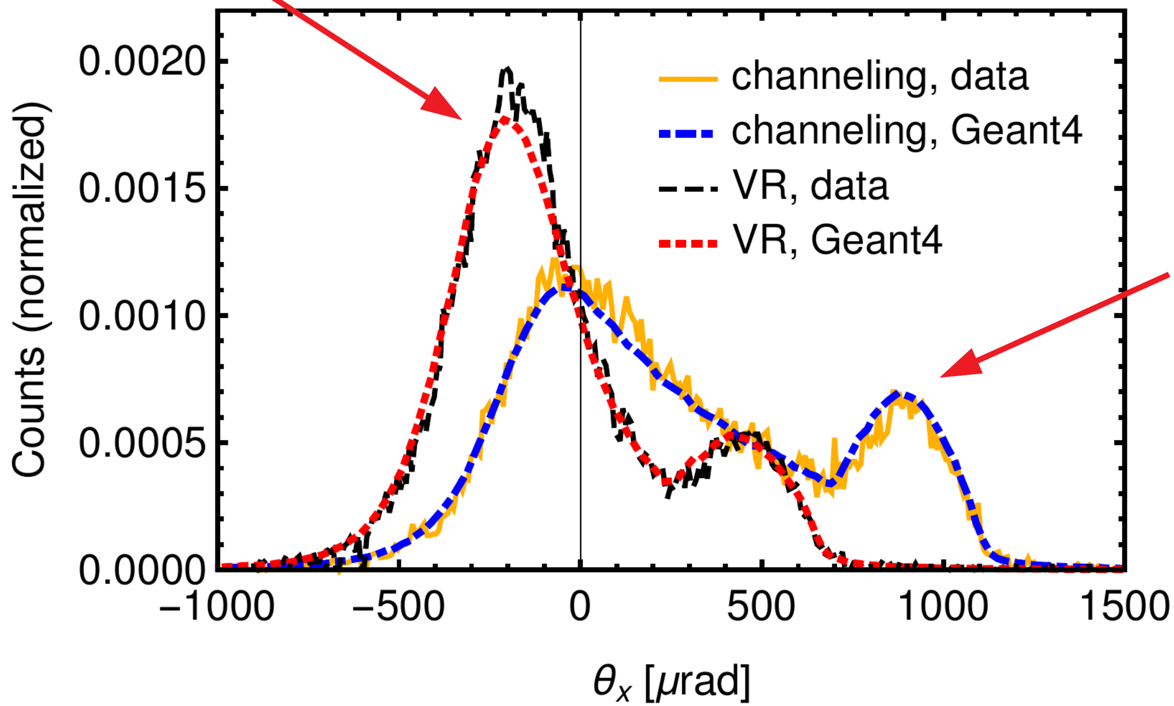
855 MeV electrons

15 µm thick bent crystal



volume reflection (VR)

Geant simulations vs experiment



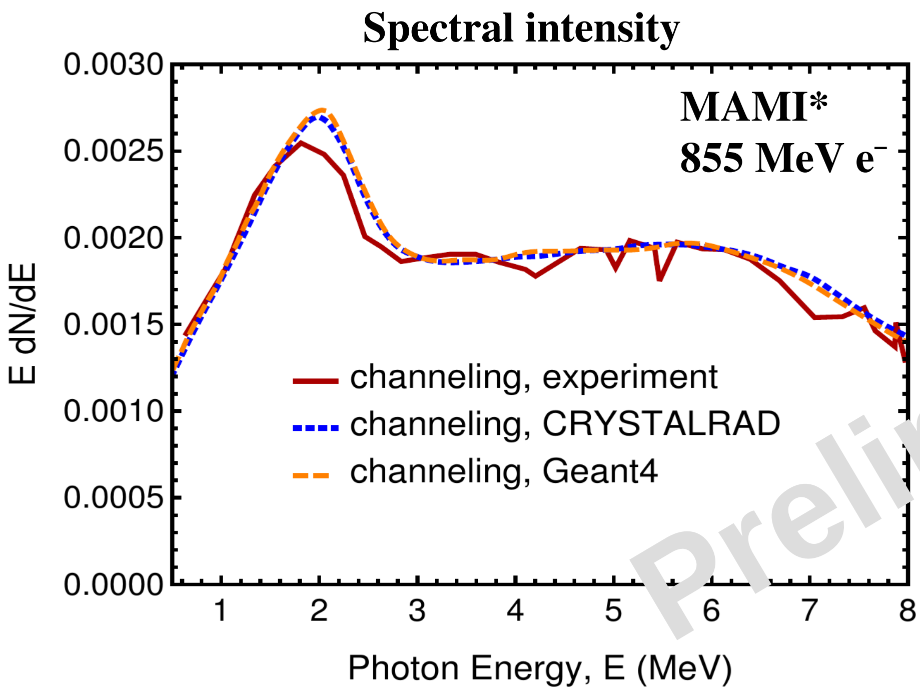
channeling

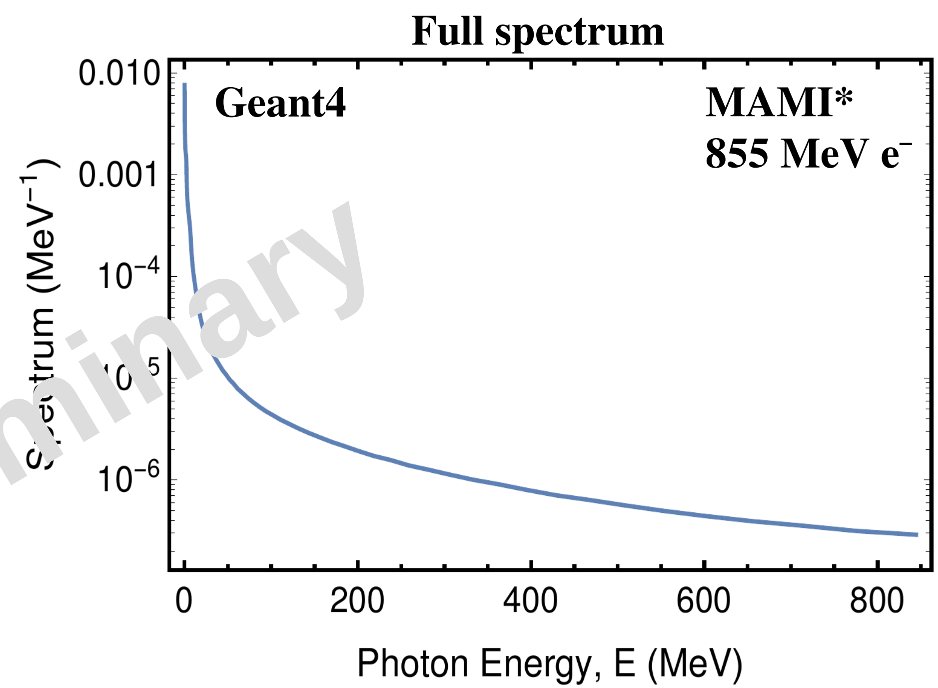
First Geant4 Baier-Katkov radiation model: radiation by 855 MeV electrons at Mainz Mikrotron MAMI*

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





*L. Bandiera et al. Phys. Rev. Lett. 115, 025504 (2015)

Current status

Already in geant4-v11.2.0.beta !

geant4-v11.2.0.beta/source/parameterisations/channeling/

Please use it!

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

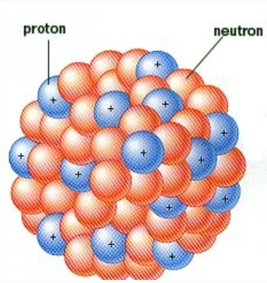
sytov@fe.infn.it

Please cite our papers if you use our model:

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

Applications of oriented crystals*

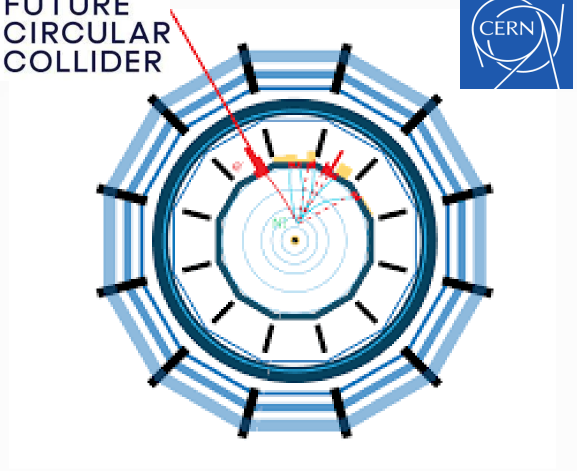
X and γ-ray source for nuclear physics and cancer radiotherapy



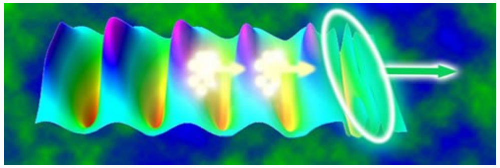
Gamma-ray Space Telescope

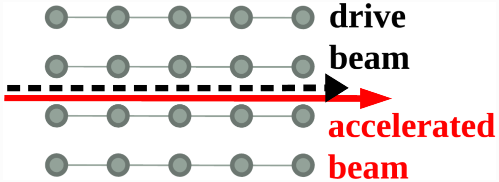
Positron source for future multi-billion € e+/e- and muon colliders

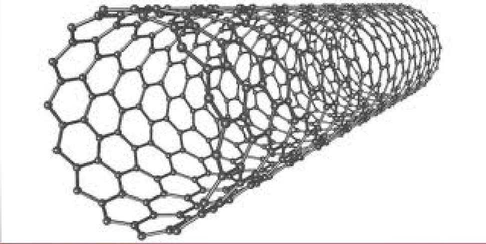
FUTURE CIRCULAR COLLIDER



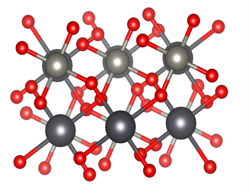
Plasma wakefield acceleration







Oriented crystals

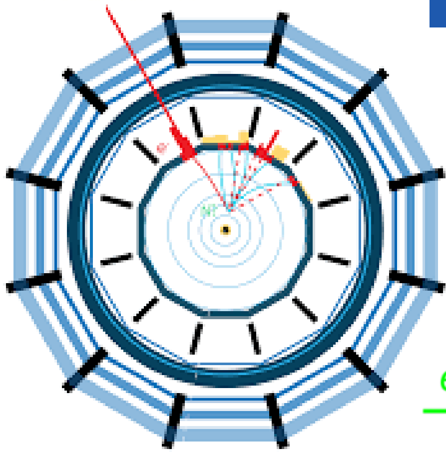


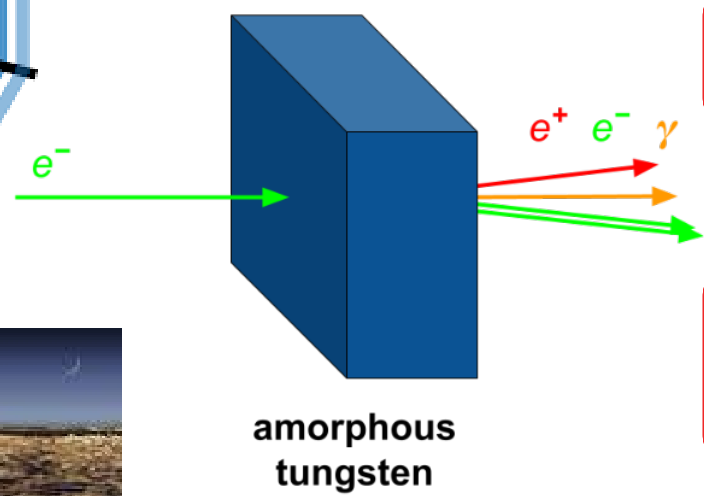
Crystal-based beam extraction from accelerators and colliders

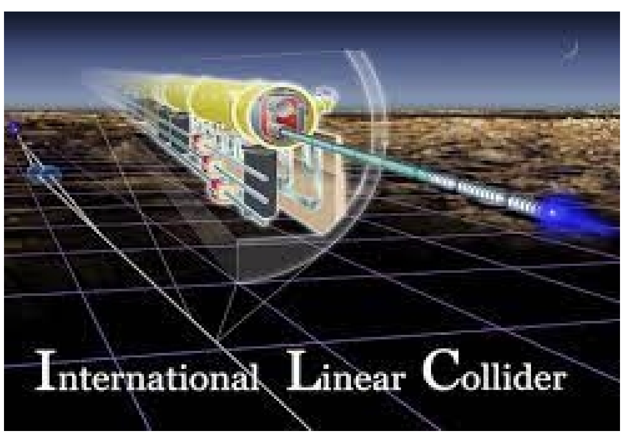
Positron source for future lepton colliders

FUTURE CIRCULAR COLLIDER

CERN







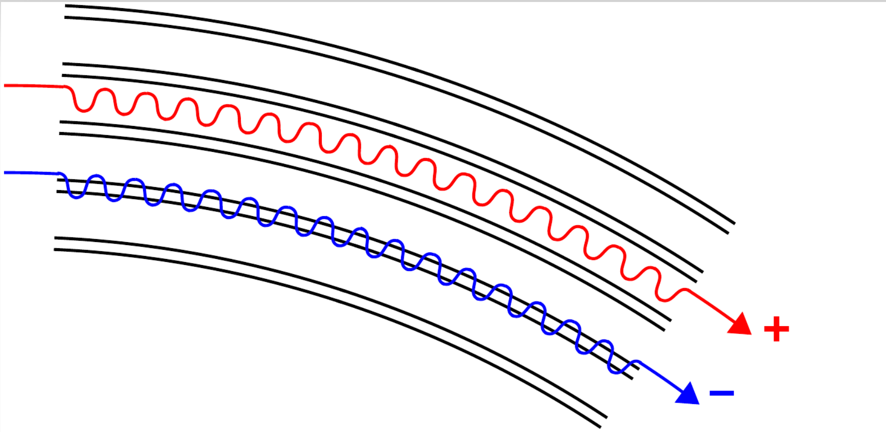
All the future **e+e- colliders** will need an **intense positron source**

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**

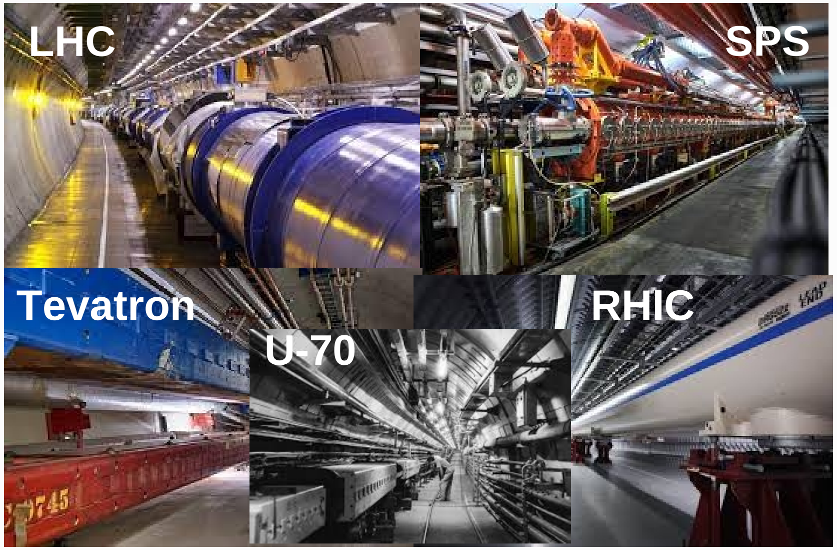
Crystal-based extraction



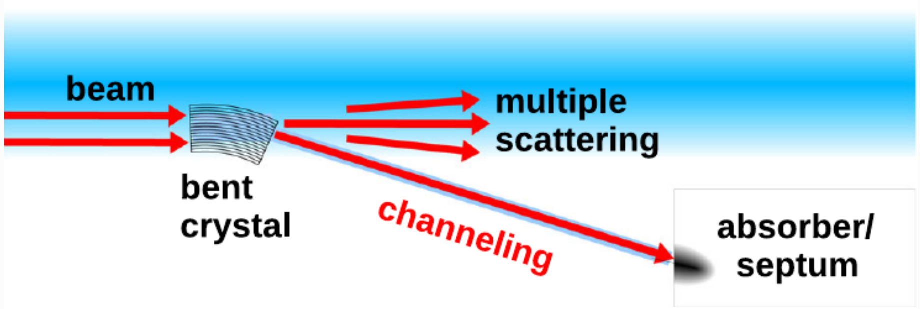
Planar channeling*:

- 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

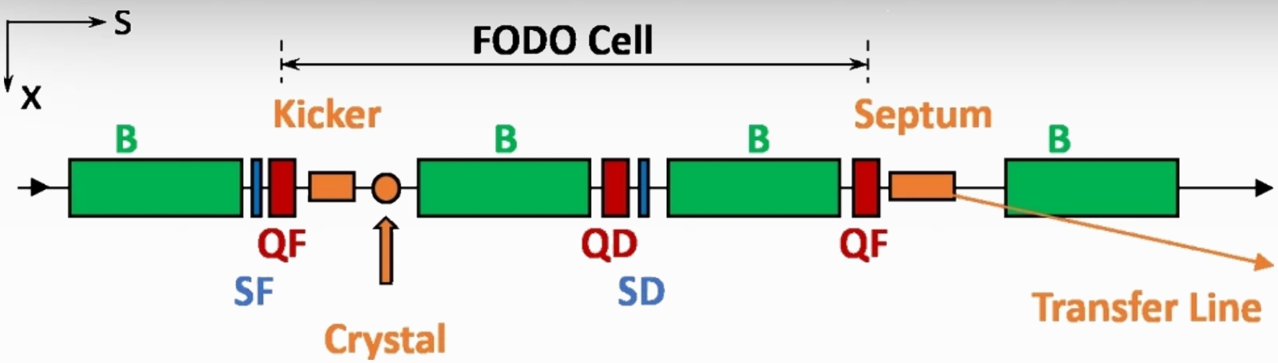


Crystal-based extraction/collimation: applied only for hadrons, not yet for e-

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 extraction: possible setup at DESY-II

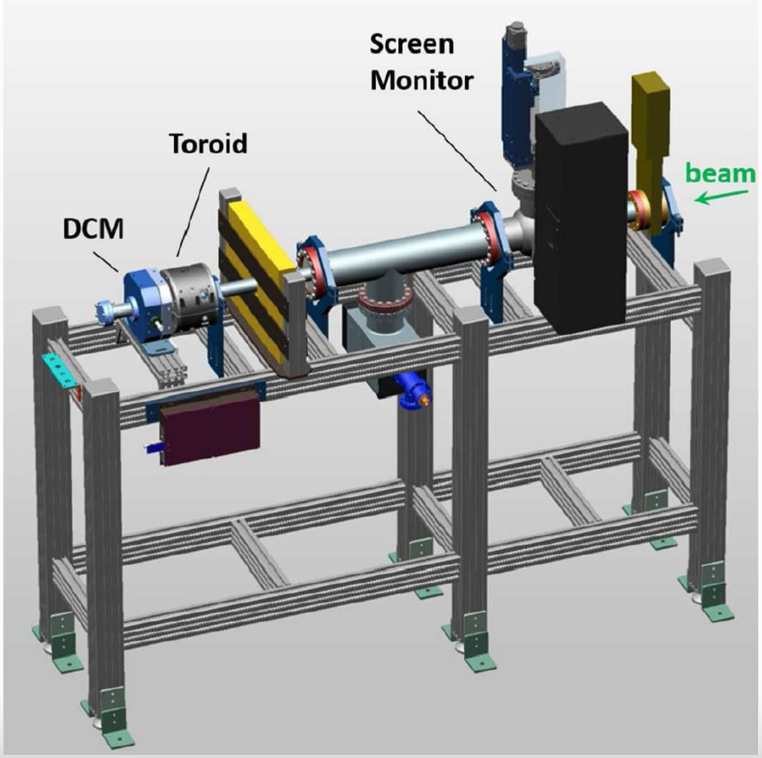


B->dipoles
QF/QD->focusing/ defocusing quadrupoles

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**)

Additional applications of oriented crystals

SLAC NATIONAL ACCELERATOR LABORATORY

FACET-II Facility for Advanced Accelerator Experimental Tests

loa

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INFN Istituto Nazionale di Fisica Nucleare

Fermilab

KiSTi www.kisti.re.kr Korea Institute of Science and Technology Information

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TÉCNICO LISBOA

UCI

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Status and prospects of E336 Experiment at SLAC FACET-II on channeling plasma wakefield acceleration in structured solids

Dr. Alexei Sytov

on behalf of E336 collaboration

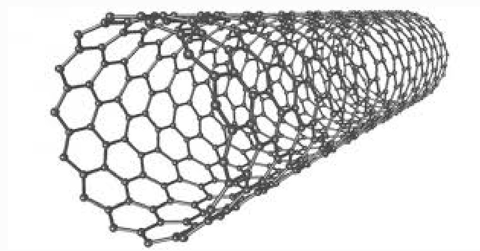
Channeling 2023, Riccione, 06/06/23

Plasma wake-field acceleration in nanostructures

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

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

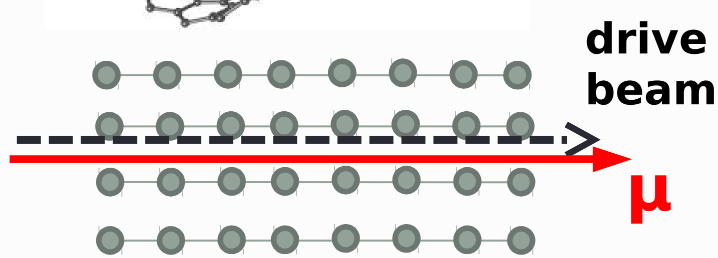
Acceleration gradient: $1\text{-}10\ \mathrm{TeV/m}$



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

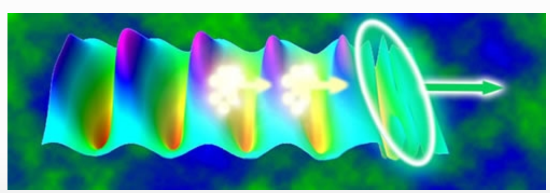
Possible drive beam:

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



Possible accelerated beam:

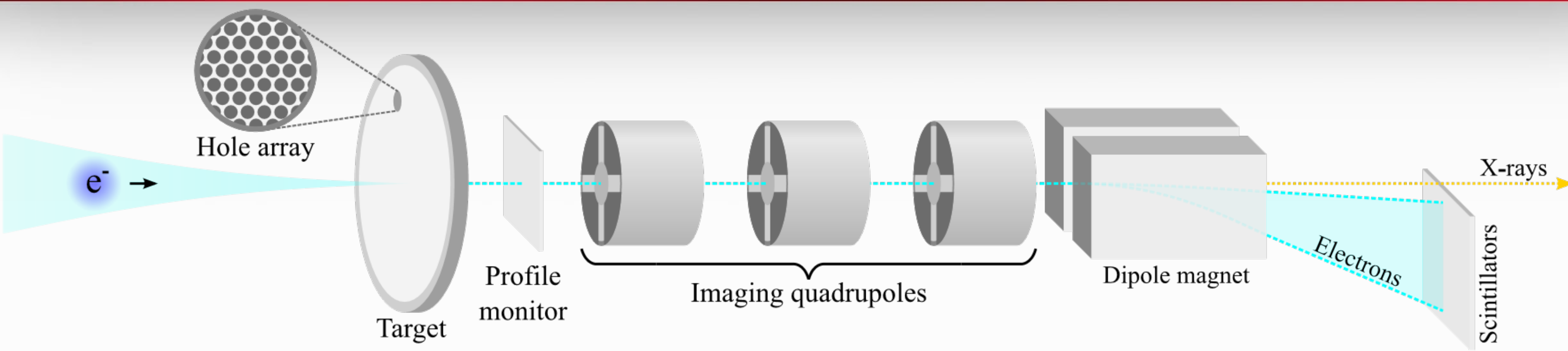
- **muons**
- **e+/e-**
- **protons**



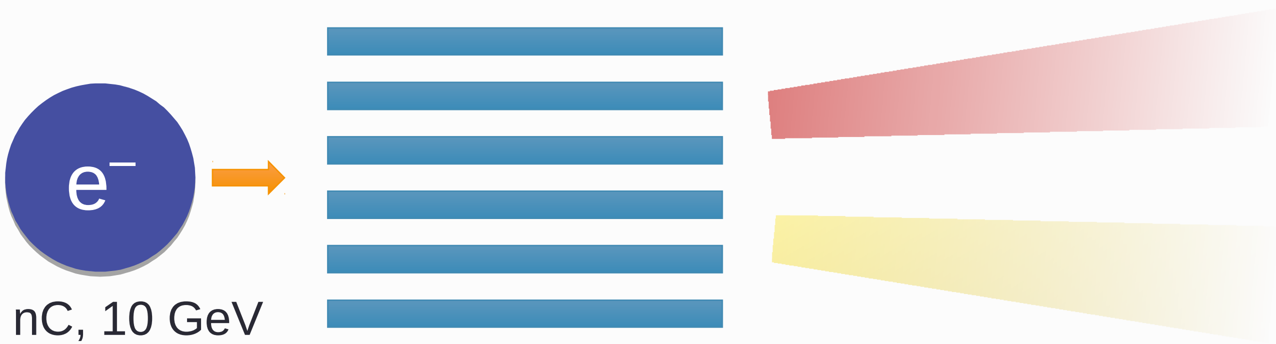
Compact muon collider?

*** 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).

E336 SLAC FACET-II experimental setup



To measure:



2 nC, 10 GeV
1-10 µm

Structured target

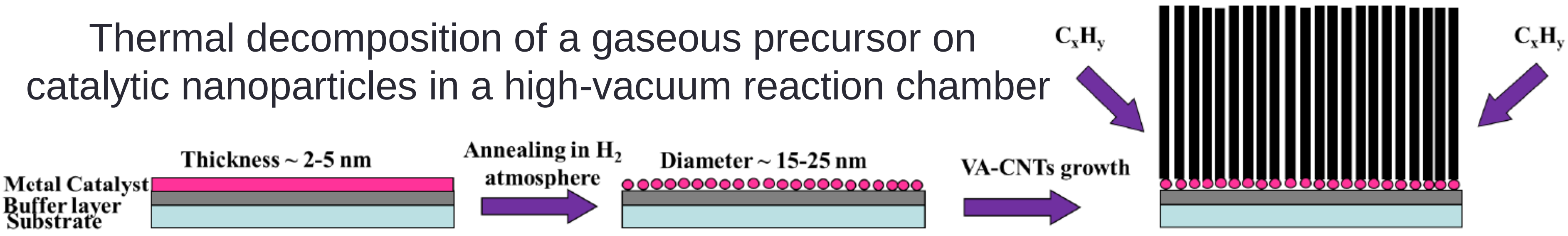
Transverse momentum distribution & other beam parameters

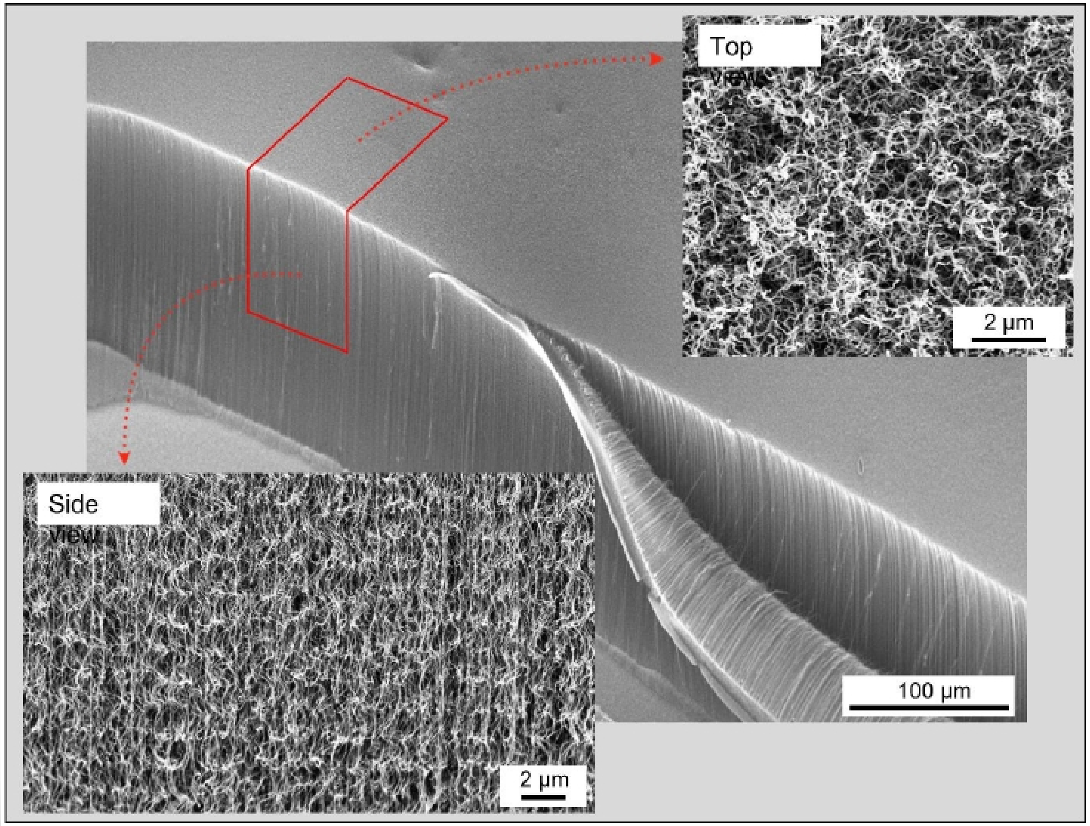
X-rays
Gamma-rays

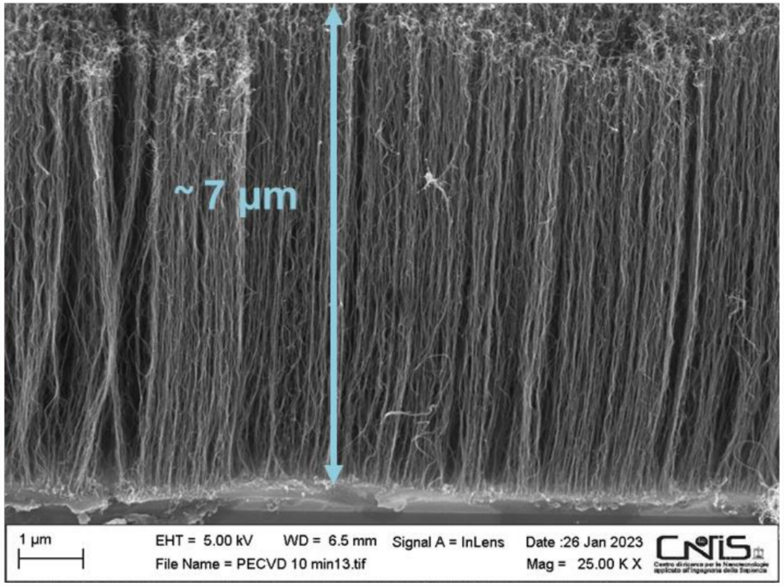
Observation of transverse plasma waves

Future target: carbon nanotubes

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





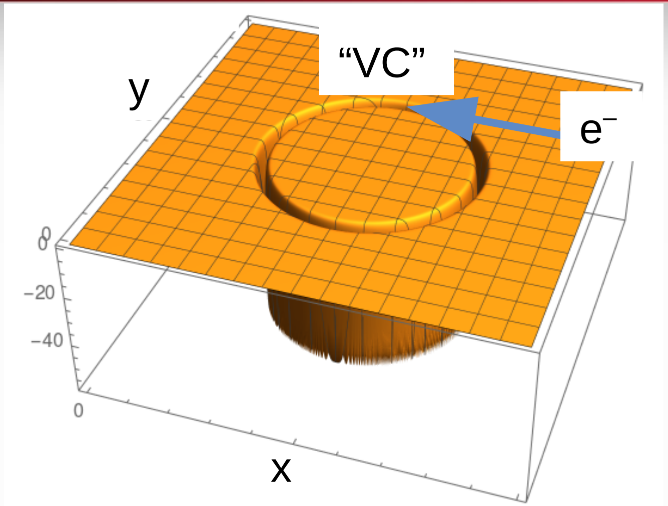


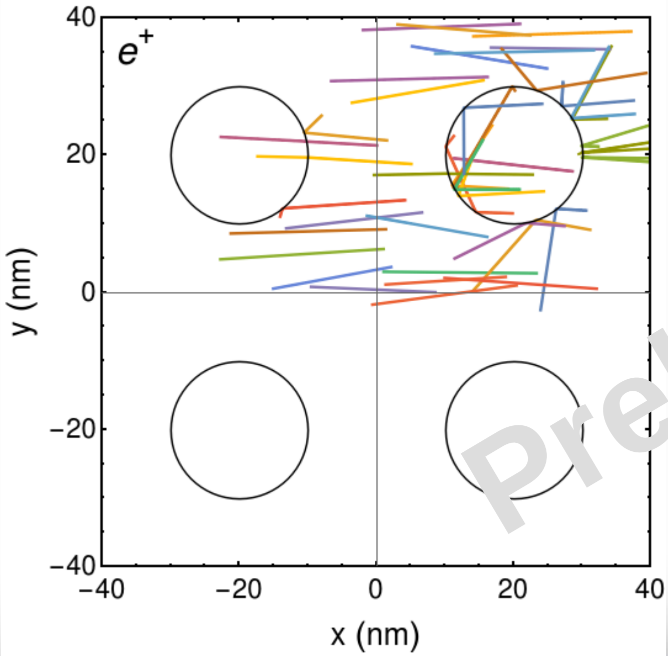
Courtesy of
Prof. Gianluca Cavoto,
Dr. Ilaria Rago

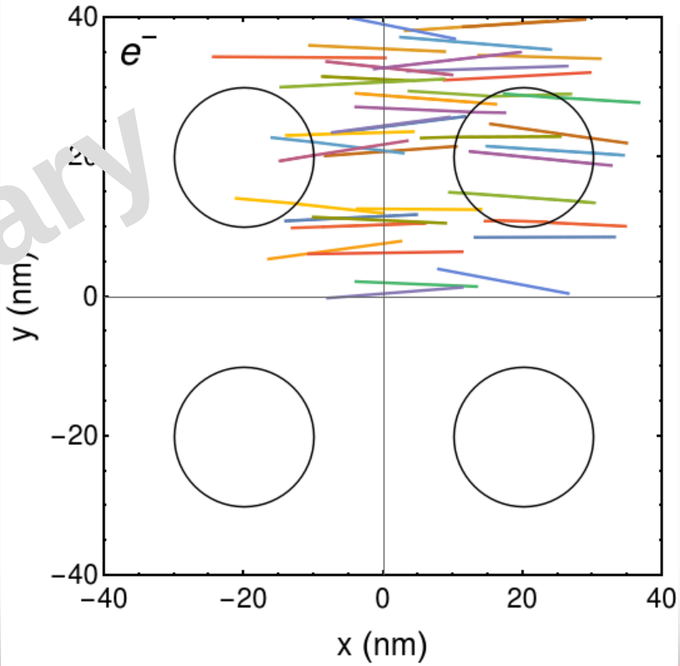
Channeling simulations in CNT: trajectories, ideal case

Simulations with **CRYSTALRAD** simulation code*

Simulation parameters:
Beam: e^-/e^+
Divergence: 10 μrad
CNT diameter: 20 nm
CNT length: 0.2 mm







Preliminary

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

Laser-driven plasma wakefield acceleration with the University of Valencia group

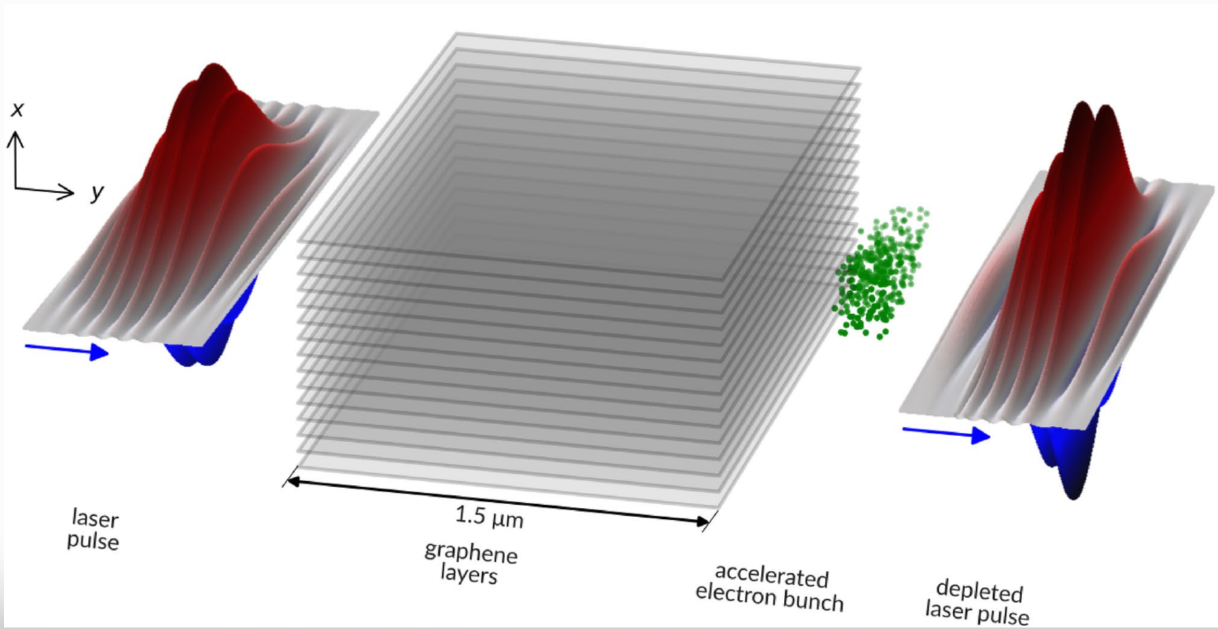
scientific reports

Check for updates

OPEN

TeV/m catapult acceleration of electrons in graphene layers

Cristian Bonțoiu[1,2]✉, Öznur Apsimon[2,5], Egidijus Kukstas[1,2], Volodymyr Rodin[1,2], Monika Yadav[1,2], Carsten Welsch[1,2], Javier Resta-López[3], Alexandre Bonatto[4] & Guoxing Xia[2,5]



Dr. Alexei Sytov

sytov@fe.infn.it

on behalf of

L. Bandiera (INFN, **PI** of INFN **OREO** project), R. Gaitskell (Brown University), S.M. Koushiappas (Brown University), A. Sytov (INFN, KISTI), K. Cho (KISTI), V. Haurylavets (INP, BSU), G. Paternò (INFN), M. Soldani (INFN, University of Ferrara), V. Tikhomirov (INP, BSU)

New ideas for dark matter search in dwarf galaxies through direct gamma-ray detection exploiting the acceleration of electromagnetic shower development in oriented crystals

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

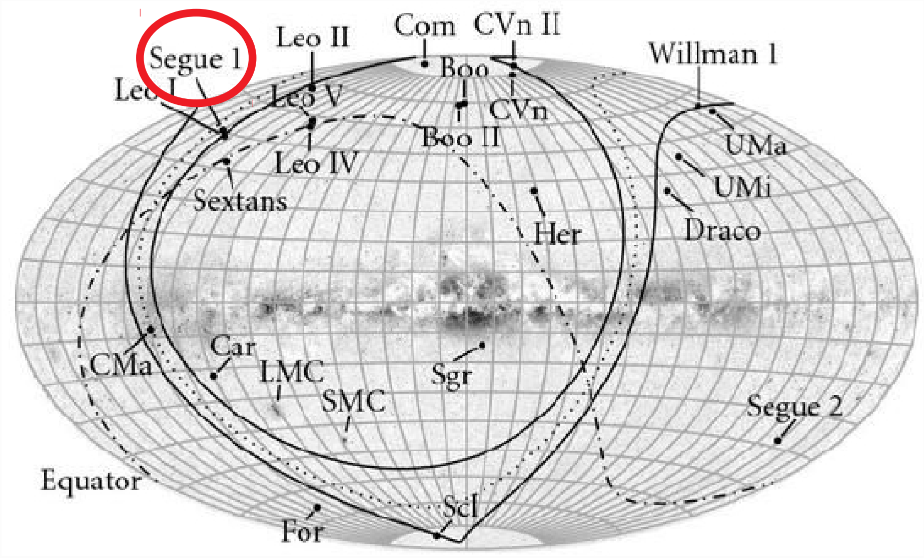
Gyeongju, 2023/07/04

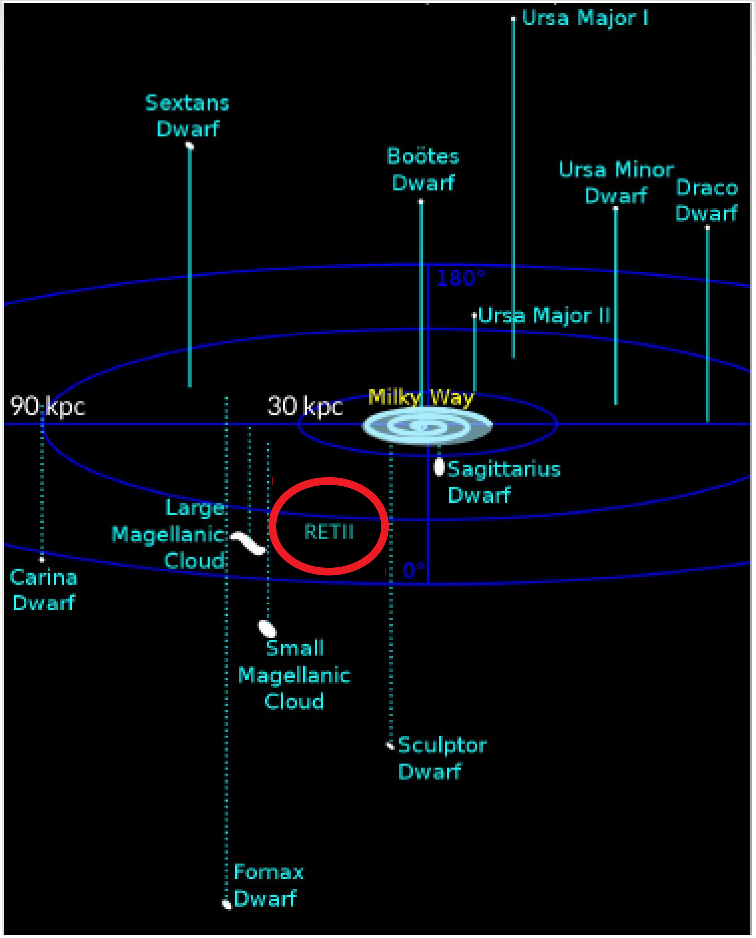
Dwarf spheroidal galaxies (dSph) as dark matter laboratories

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)



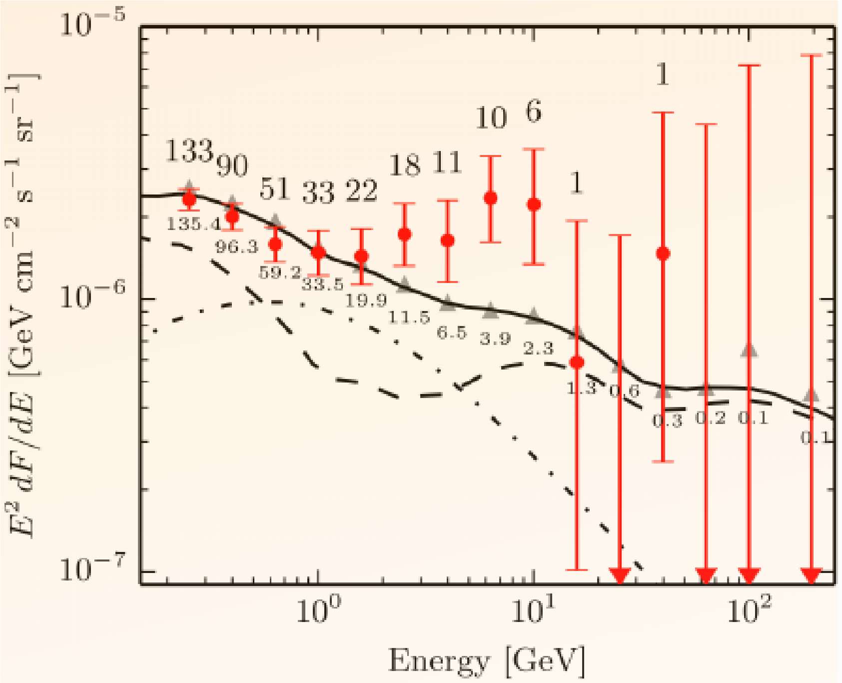


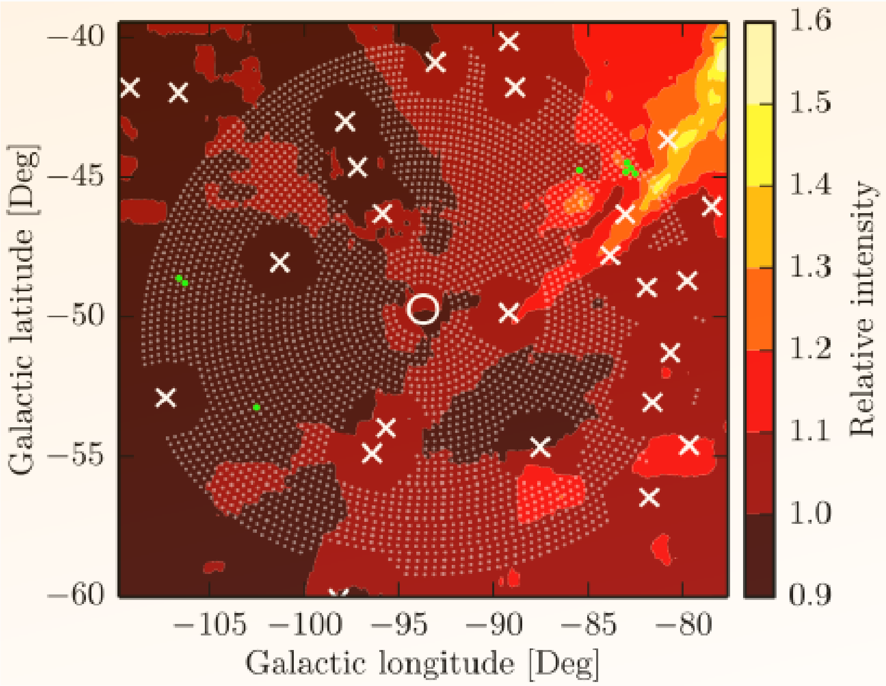
More than **50 dwarf galaxies** are currently **known**, with more to be discovered with upcoming surveys!

Reticulum II: Fermi Gamma-ray Space Telescope data*

Gamma ray spectrum of photons within 0.5 degrees along the line of sight to the **Reticulum II** dwarf galaxy

Background amplitude in a broad area **around Reticulum II**. The spectrum shows a mild excess around few GeV.



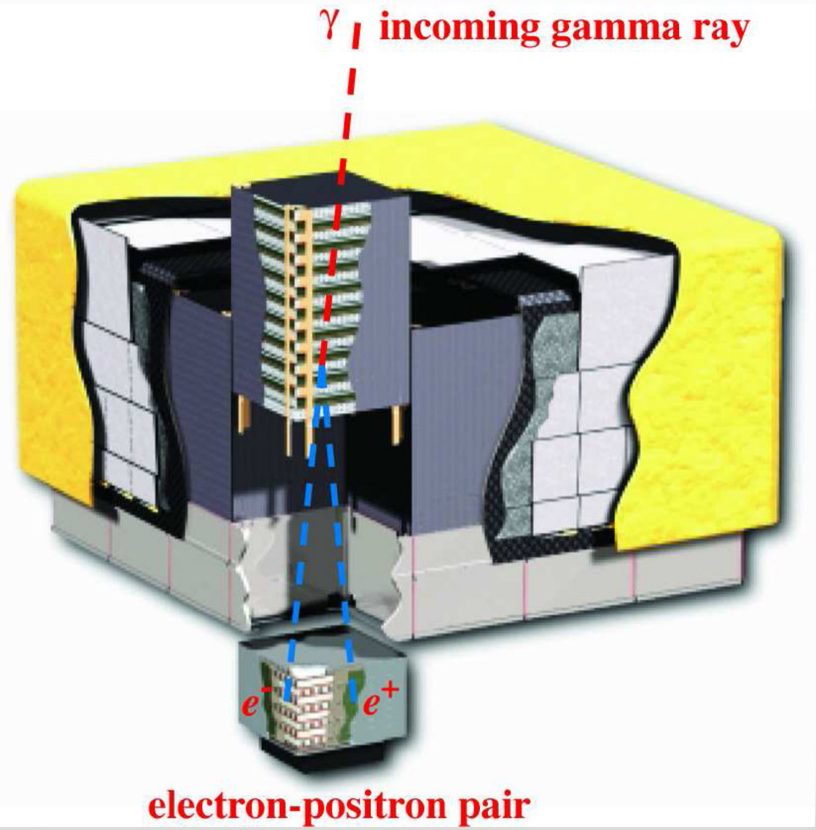


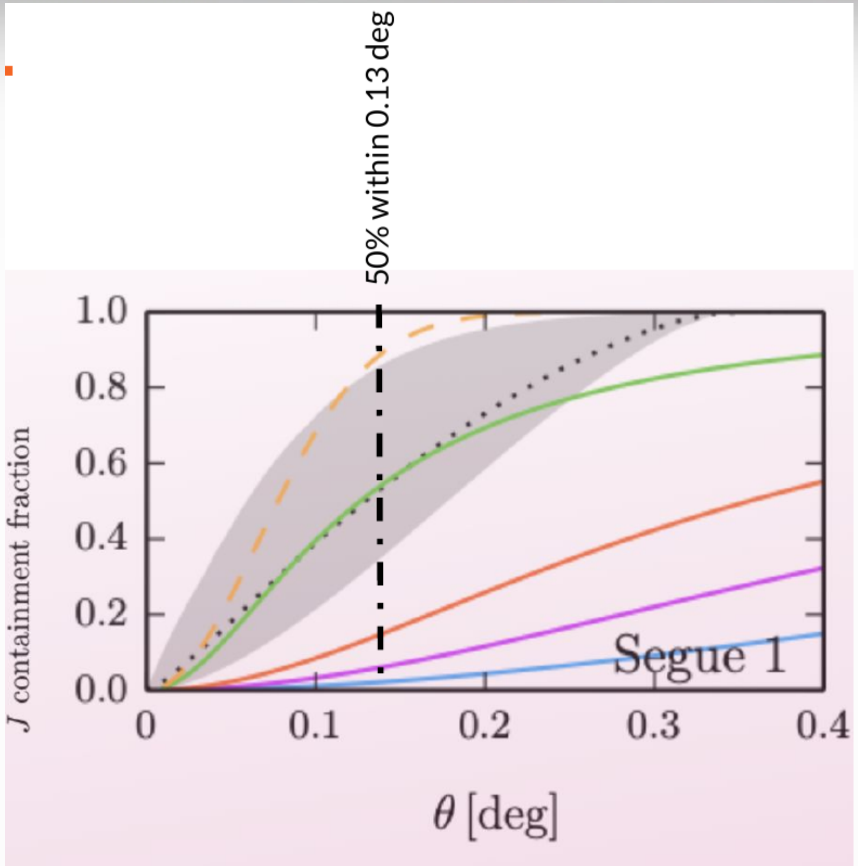
A signal at ~**3σ** that exceeds expected backgrounds between ~**2–10 GeV***

Fermi Gamma-ray Space Telescope limits for dark matter search in dwarf galaxies

Main limitations of Fermi:

- **angular resolution** => problem to distinguish the **signal vs background** at small angles,
- **Not so large**, we need large surface to accumulate more statistics!



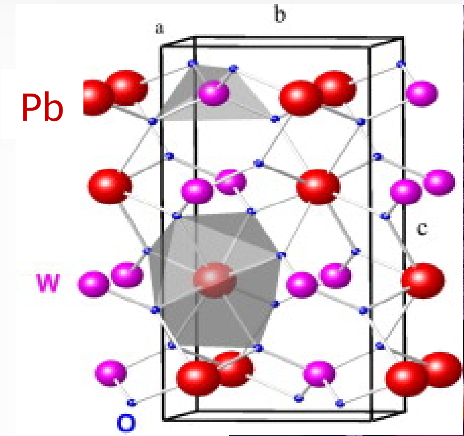


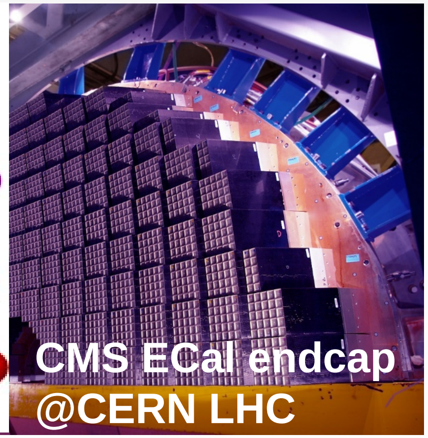
Containment fraction for **DM annihilation** as a function of **angular distance** from the center of **Segue 1***.
The solid colored curves show the PSF of a silicon detector, while the dashed colored line shows the PSF of an Atmospheric Cerenkov telescope.

*A. Geringer-Sameth et al. ApJ 801, 74 (2015)

Orienting the electromagnetic calorimeter => making it thinner!

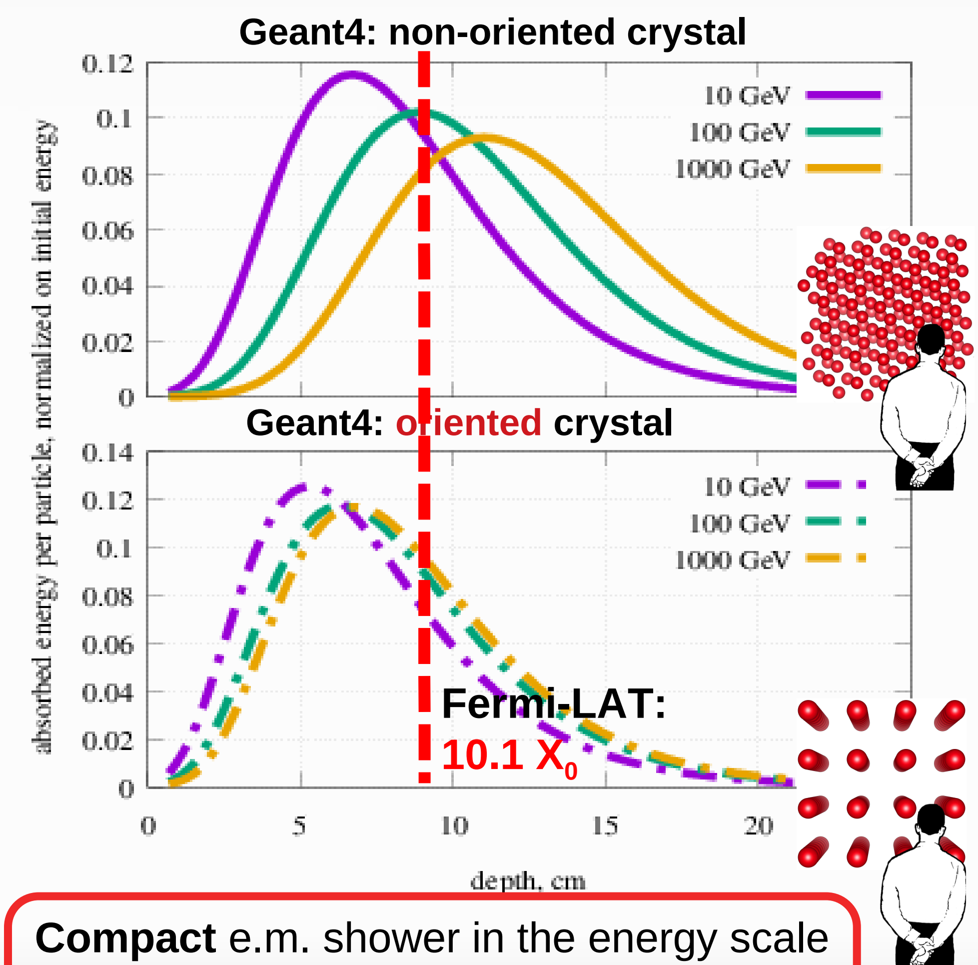
Lead tungstate: $PbWO_4$





INFN OREO by L. Bandiera et al.

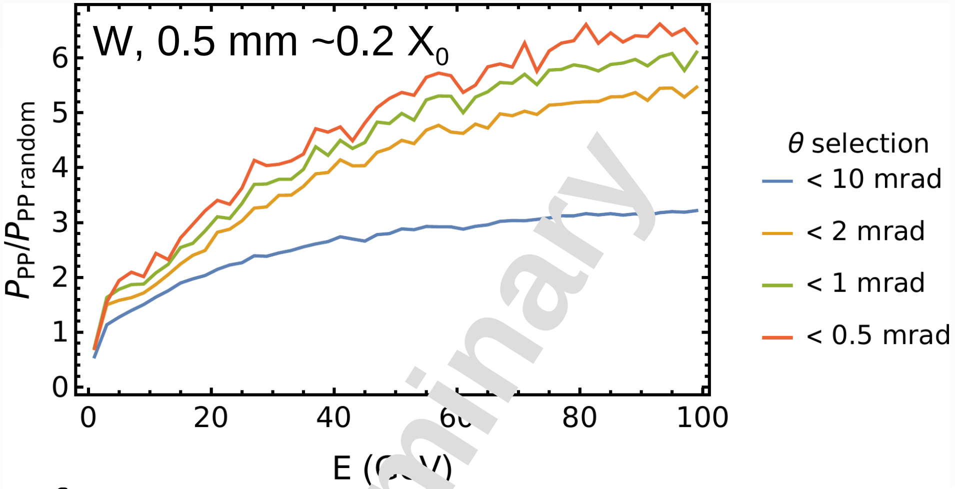
Simulation of the e.m. shower of HE electrons in a PWO crystal

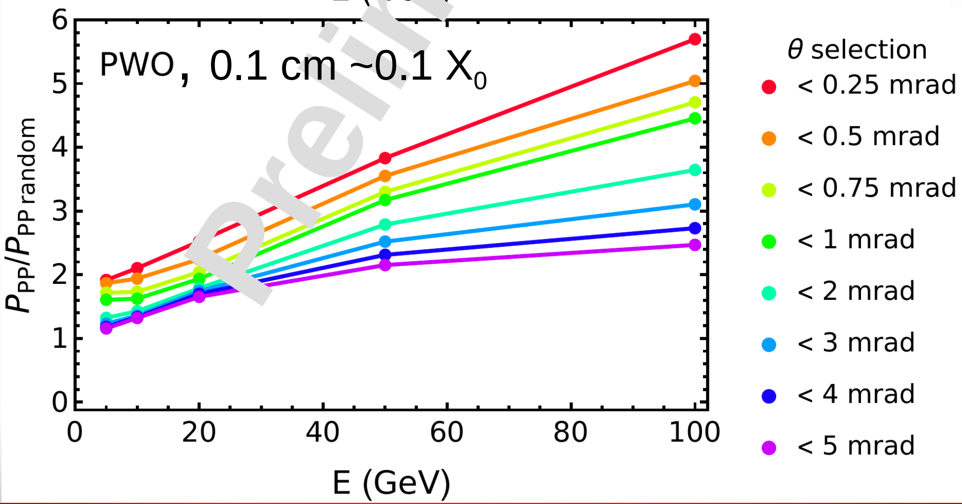


Compact e.m. shower in the energy scale from **multi-GeV** up to **multi-TeV**!

What gamma-ray about angles?

Enhancement of **Pair Production probability** in Oriented Crystals Calculations in **Tungsten** (W) and **$PbWO_4$** (PWO) at axial orientation*





Dwarf Galaxies (Favored in Bold)	[kpc] Distance	Median Value for angle estimate [deg] Theta_0p5	+Error	J scale in linear units (Arb) J_0p5 / 1e18
UrsaMinor	66	0.06	0.07	8.51
Segue1	23	0.13	0.05	22.91
LeoII	205	0.04	0.05	0.93
UrsaMajorII	30	0.24	0.06	26.30
Coma	44	0.16	0.02	10.47
Sculptor	92	0.15	0.05	3.47
RET II	30	0.57	0.05	39.81

Pair Production Enhancement happens within 2 mrad~**0.1°** for W and 1 mrad~**0.05°** for PWO => optimal for dwarf galaxies

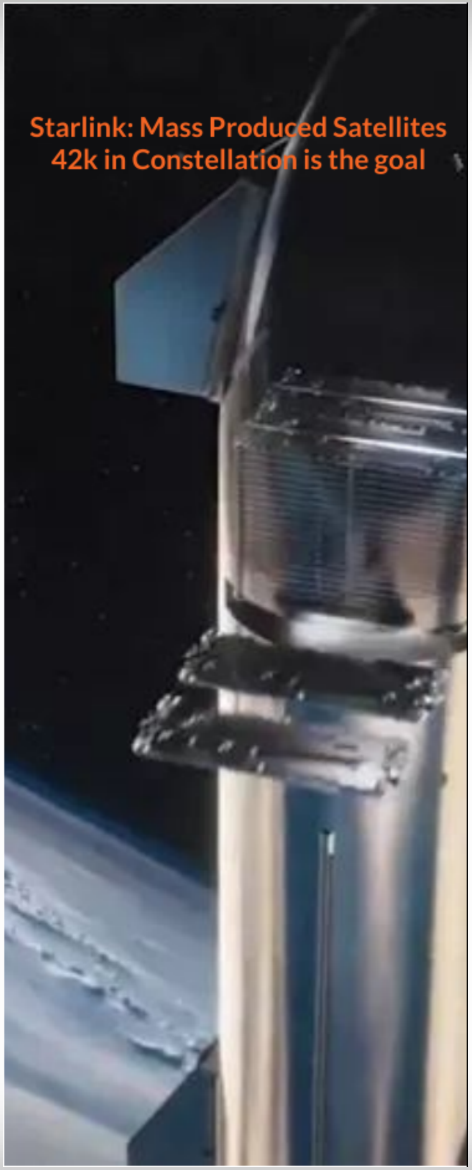
Electromagnetic shower depends on the **angle** => some information **can be extracted**

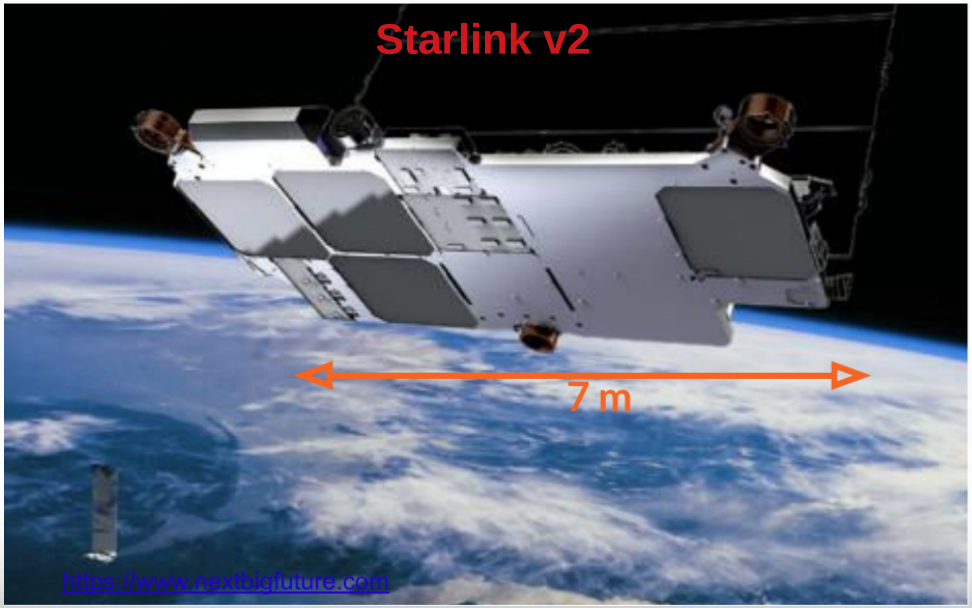
Simulations using V. Tikhomirov's code: L. Bandiera,..., A. Sytov, …, V. Tikhomirov et al. EPJC 82, 699 (2022).

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 m2**, Panels 105 m2 (May 2023) 4,400 sat. already launched >90% fully operational
- **Starlink v2** (~50 per launch in future SpaceX Starship) Body 25 m2, 1200 kg



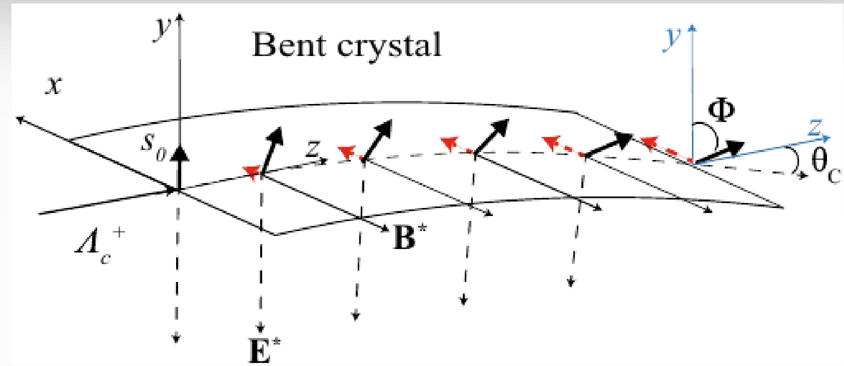


Probable applications of oriented crystals in particle physics

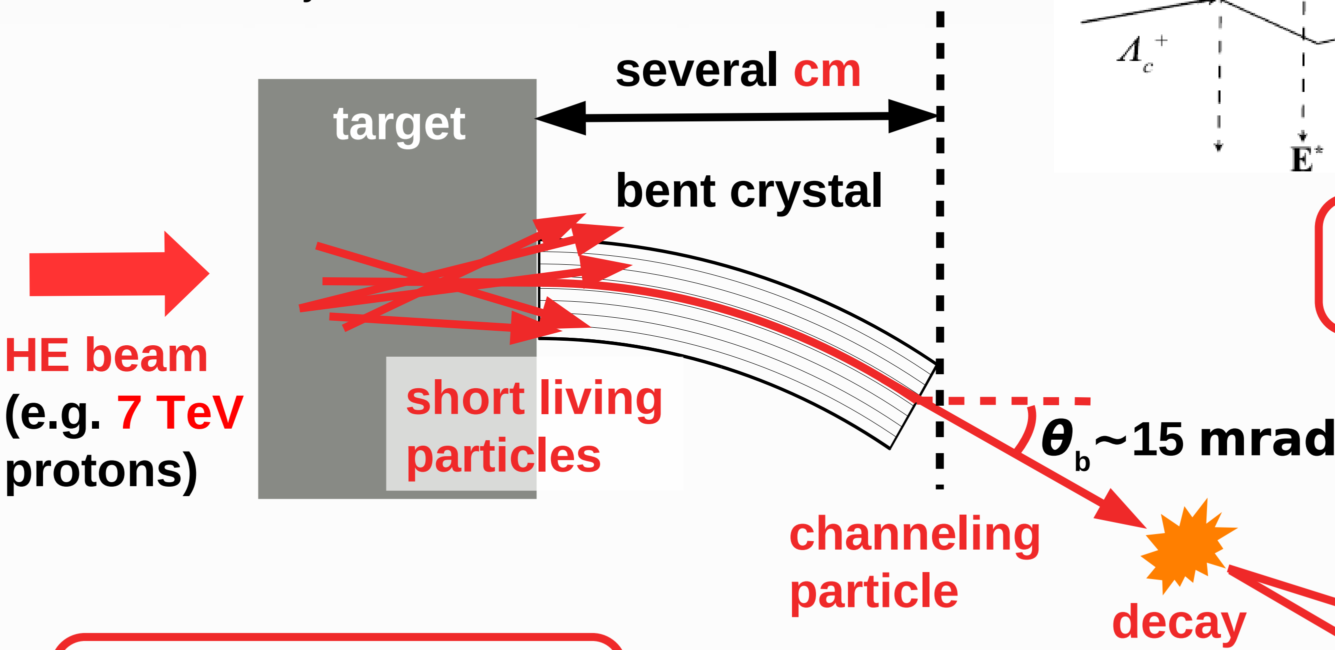
Search of MDM&EDM of short living particles using the effect of spin rotation in oriented crystals*

What we want:

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



Experimental proof at Tevatron for Σ^+**



Detector (e.g. LHCb)

polarization measurement

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)

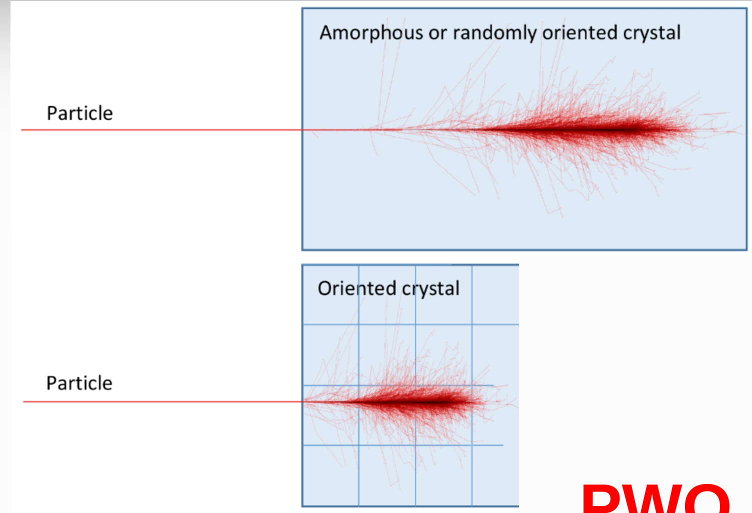
Crystal-based ultrashort electromagnetic calorimeter*

Advantage:

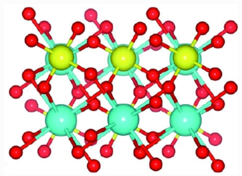
- Considerably shorter thickness
- More transparent for other particles (hadrons)
- Potentially lower time resolution

Crystalline calorimeter can be applied at:

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



PWO



CERN North Area

K_LEVER

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

+ dark photon search

Gamma-ray Space Telescope (like Fermi)

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

List of collaborations

TRILLION initially:

Host: INFN – Istituto Nazionale di Fisica Nucleare

Geant4 collaboration: Geant4 – A simulation toolkit

Planned secondments: DESY, IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

Partner for outgoing phase: KISTI – Korea Institute of Science and Technology Information (www.kisti.re.kr)

My Project MIRACLE (supercomputing time): CINECA

Laser-driven plasma wakefield acceleration in nanostructures: Universitat de València, University of Liverpool, The University of Manchester (1824), UFRGS – Universidade Federal do Rio Grande do Sul

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: Fermilab, SLAC National Accelerator Laboratory, Stanford, FACET-II Facility for Advanced Accelerator Experimental Tests, École Polytechnique Université Paris-Saclay, loa, cea, Técnico Lisboa, UCI

Experiments for code validation: CERN, JGU Johannes Gutenberg Universität Mainz

NA62: CERN

MU2E: Fermilab

Geant4& medical physics: University of Wollongong Australia

Missions, conferences and publications

European Commission

Trillion

IPAC22

ICHEP 2022 BOLOGNA

ICABU 2022

IPAC23

KPS 70th Anniversary and 2022 Fall Meeting
Oct. 18(Tue) – 21(Fri), 2022
BEXCO Convention Hall, Busan

2022 KOREA SUPERCOMPUTING CONFERENCE
HPC makes the future!

NanoAc 2022

2023 KPS Spring Meeting
April 19(Wed) ~ 21(Fri), 2023
Daejeon Convention Center (DCC) & IBS Science Culture Center (IBS SCC)

GEANT4 — 27th Geant4 Collaboration Meeting

International Symposium on Grids & Clouds (ISGC) 2023

High1 Workshop on Particle, String and Cosmology
Jan. 29 - Feb. 4, 2023 High1 Resort

The 1st Yemilab Workshop

9th International Geant4 Tutorial in Korea 2022

59th Geant4 Technical Forum

ASAP 2023

Channeling 2023

GEANT4 — IV Geant4 International User Conference at the physics-medicine-biology frontier

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

TRILLION publications:

- **A. Sytov** et al. *Eur. Phys. J. C* **82**, 197 (2022).
- L. Bandiera, ..., **A. Sytov** et al. *Eur. Phys. J. C* **82**, 699 (2022).
- M. Romagnoni, ..., **A. Sytov** et al. *Crystals* **12**, Issue 9, 1263 (2022).
- M. Romagnoni, ..., **A. Sytov** et al. *Eur. Phys. J. D* **76**, 135 (2022).
- M.F. Gilljohann, …, **A. Sytov** et al. (**E336**) submitted to JINST
- **A. Sytov** et al. *Journal of the Korean Physical Society*, 83, 132–139 (2023) https://doi.org/10.1007/s40042-023-00834-6 arXiv:2303.04385

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

INFN LNS

A. Sytov TRILLION research expeditions to CERN:

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

CERN

Conclusions

- The goal of **TRILLION** is to implement **channeling**, **channeling radiation** and **coherent pair production** 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** (positron source) and at all **e-/e+ synchrotrons** existing in the world (crystal-based beam extraction)

- Additional applications are ultrashort crystalline **calorimeter** for particle physics and gamma-ray space telescope, exotic particles **MDM** and **EDM measurement**, and **plasma wakefield acceleration**.

- My **additional ideas** are about **exotic particles production in strong field** and using the Geant4 channeling model to **train neural nets**.


GANGNAM STYLE
Thank you! 감사합니다 !