New Geant4 model to simulate ultra-thin crystalline electromagnetic calorimeters for novel gamma-ray space telescopes

Dr. Alexei Sytov

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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)

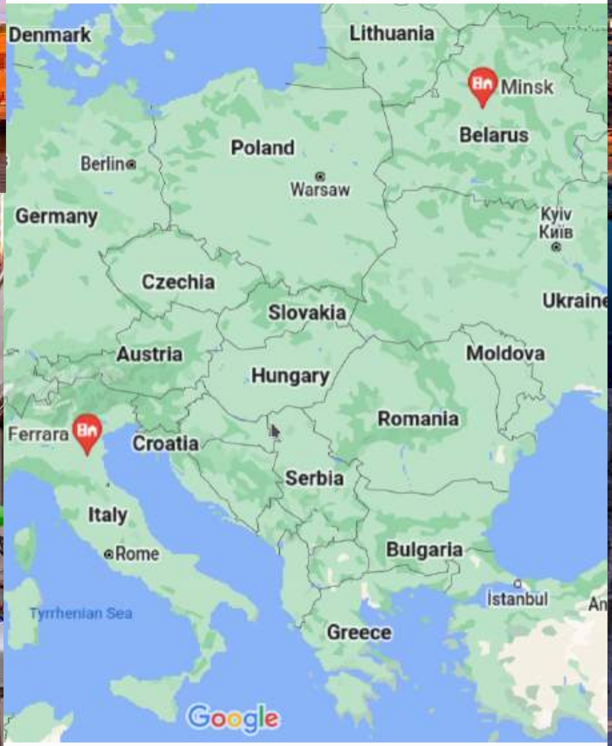
Chungnam National University

Daejeon, 2024/01/15

Where I am from?

I work in Italy, Ferrara

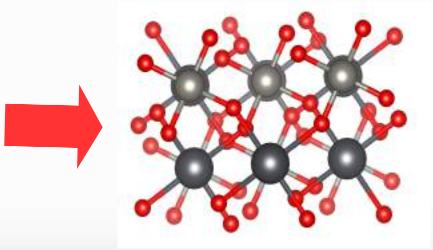
Originally I am from Belarus, Minsk



Briefly about me

- **2018: 2 PhDs –** in Experimental Physics, University of Ferrara and in Theoretical Physics, Belarusian State University
- **2019-2021**: **Post-doctoral Fellow** in Experimental Physics at the INFN Division of Ferrara.
- Since **2020** involved in **MC_INFN** – INFN **Geant4** project
- Since **02/09/2021**: Marie Sklodowska-Curie Action Global Individual Fellowships, GA n. 101032975 – project Trillion
- **My field**: **Electromagnetic effects** of charged particles interaction with **oriented crystals** (deflection, radiation and pair production) and their applications in **accelerator physics**, **detector physics**, **nuclear physics**, **medical physics**.
- **Effects**: **Channeling**, channeling radiation, coherent pair production

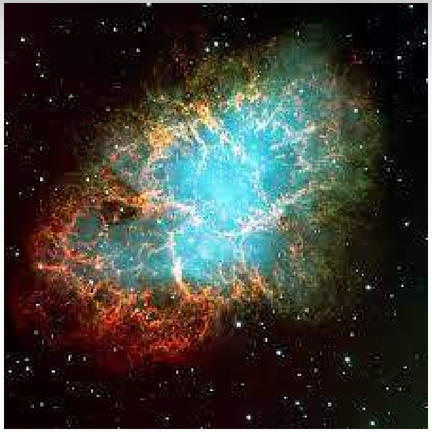
e+/e-/γ; hadrons

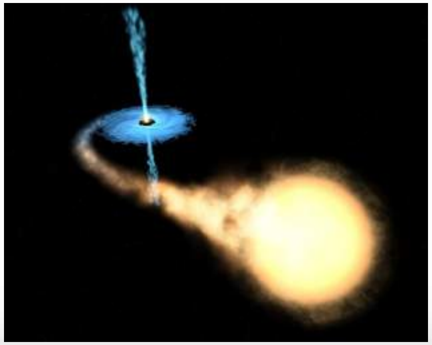


What can be observed with a gamma-ray space telescope?

- **Very High Energy γ-ray sources providing insights into lepton and hadron space acceleration**
- Pulsars and their nebulae
- Blazars
- Supernova remnants
- Gamma-ray binary systems
- Gamma-ray bursts
- Any misidentified sources

Element of multi-messenger astronomy





To understand better mechanisms of γ-rays production in space

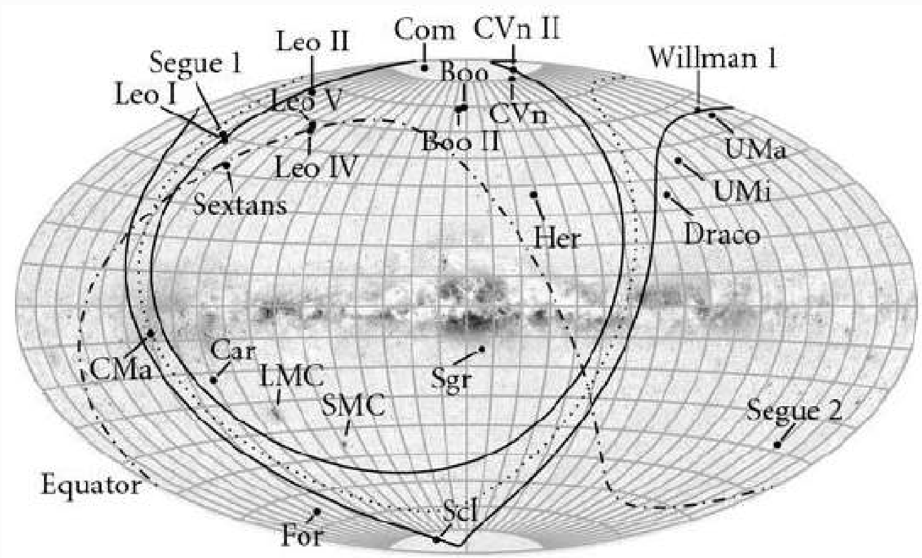
- p+p, p+γ, p+space gas reactions & π decay
- Inverse Compton scattering
- Synchrotron radiation of leptons and protons
- **Dark matter annihilation**

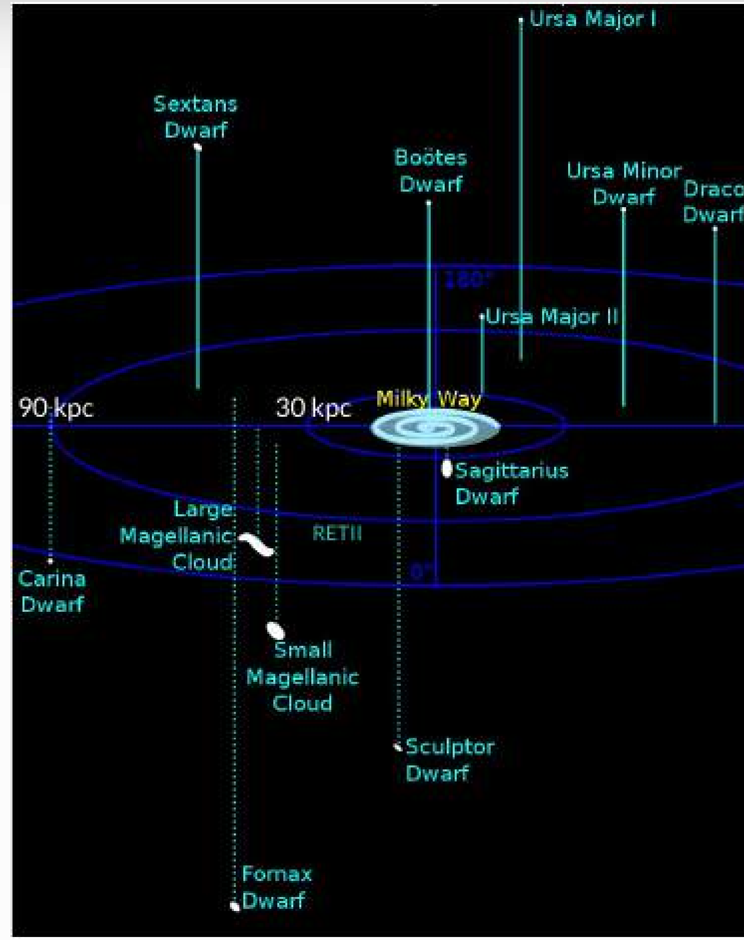
Dwarf spheroidal galaxies (dSph) as dark matter laboratories

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!

Dwarf spheroidal galaxies (dSph) as dark matter laboratories

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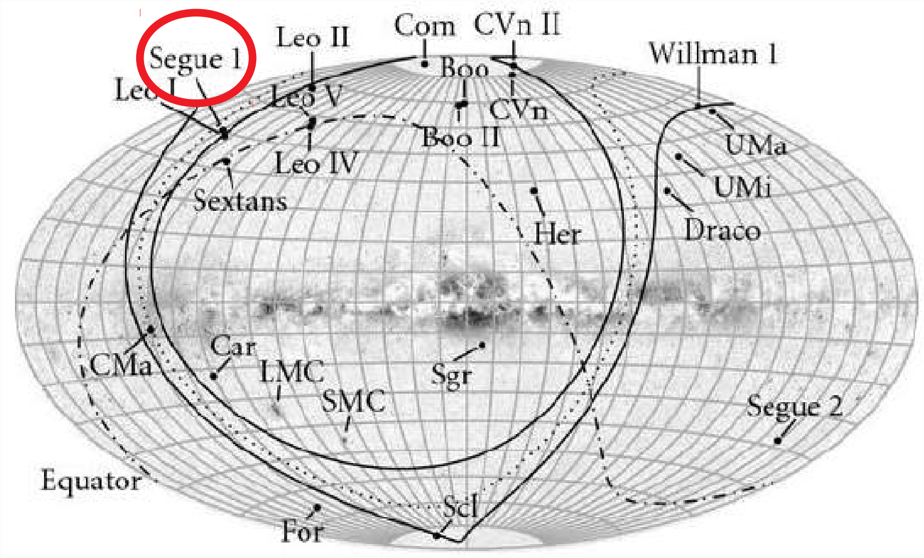

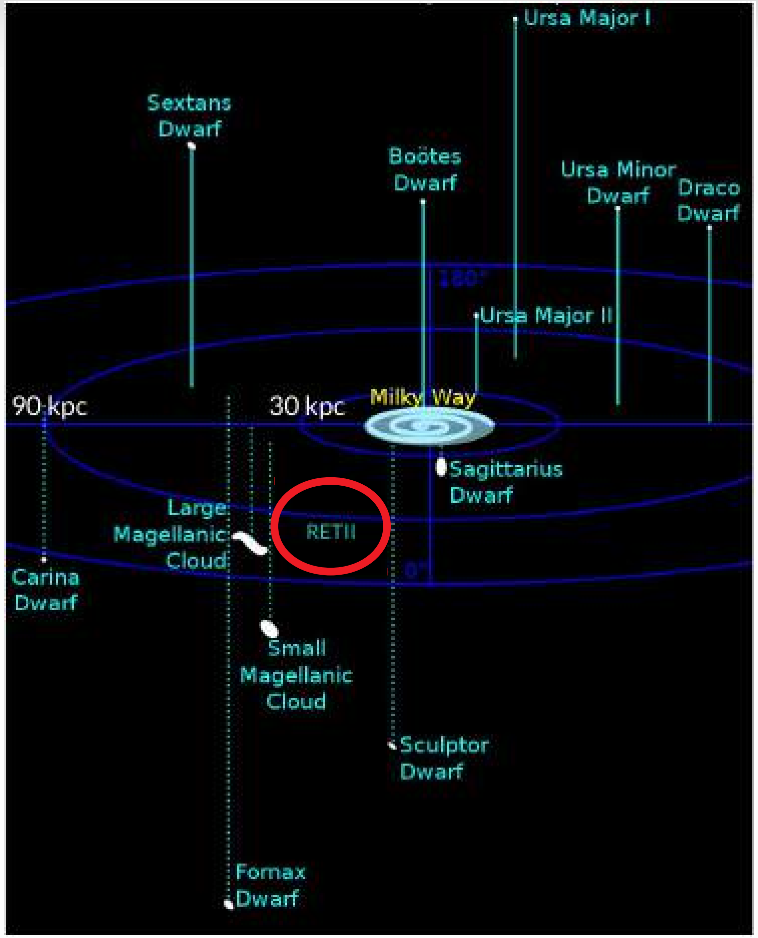

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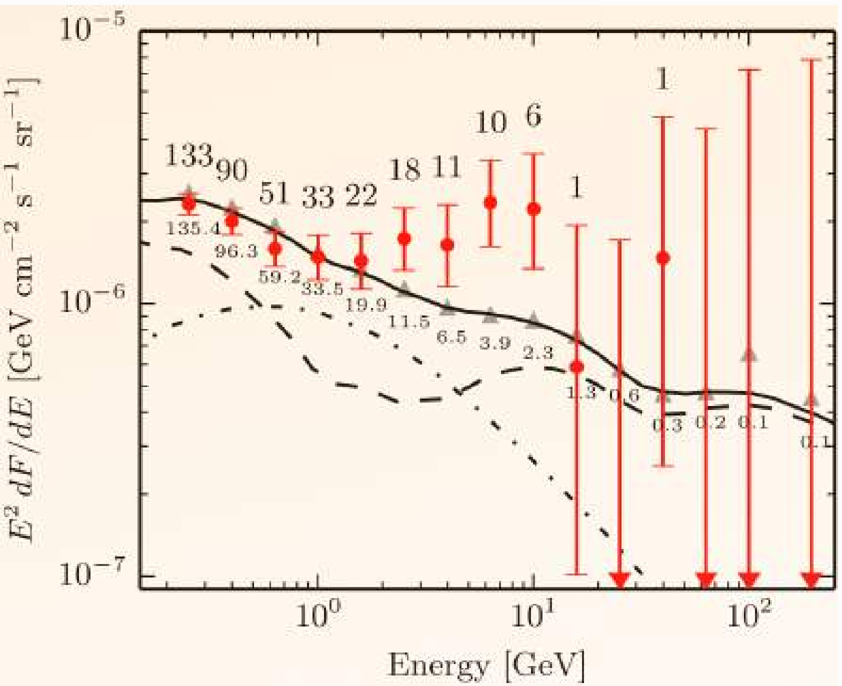
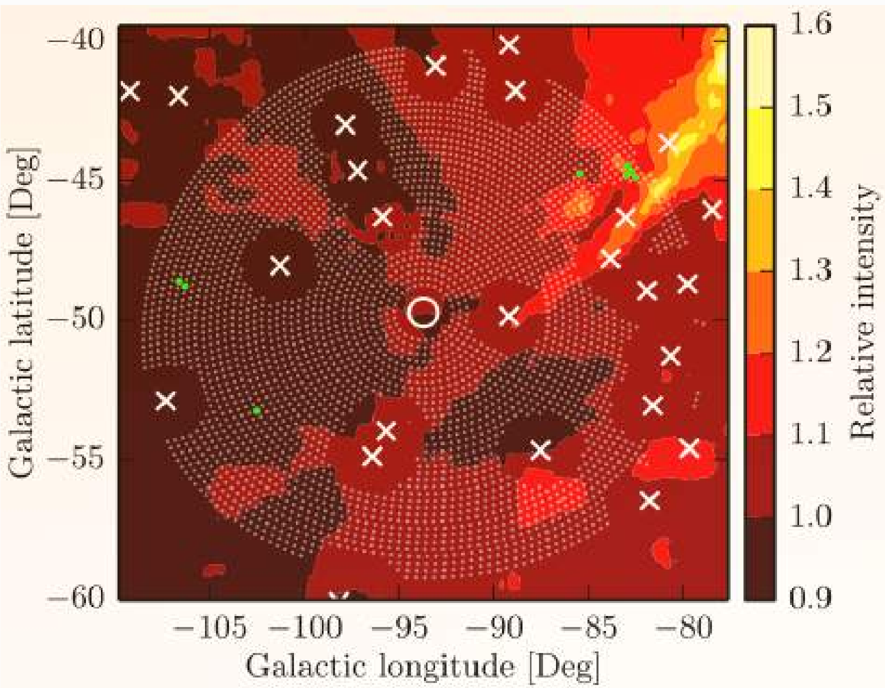
Reticulum II:
Fermi Gamma-ray Space Telescope data*

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.



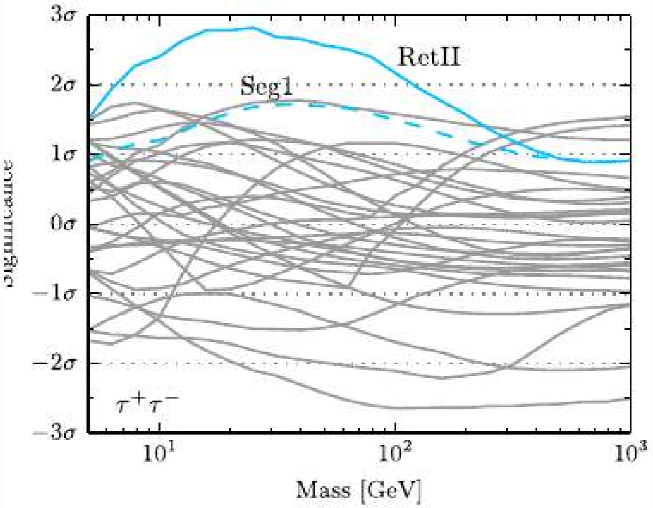
A signal at ~**3σ** that exceeds expected backgrounds between ~**2–10 GeV***

*A. Geringer-Sameth et al. Phys. Rev. Lett. 115, 081101 (2015)

Why Reticulum II? What about other dwarf galaxies?

		Theta for 50% Flux [1]			
	[kpc]	Median Value for angle estimate [deg]		J scale in linear units (Arb)	Concentration of Signal (Relative)
Dwarf Galaxies (Favored in Bold)	Distance	Theta_0p5	+Error	J_0p5 / 1e18	J_0p5 / (Theta_0p5)^2
UrsaMinor	66	0.06	0.07	8.51	2364
Segue1	23	0.13	0.05	22.91	1356
LeoII	205	0.04	0.05	0.93	583
UrsaMajorII	30	0.24	0.06	26.30	457
Coma	44	0.16	0.02	10.47	409
Sculptor	92	0.15	0.05	3.47	154
RET II	30	0.57	0.05	39.81	123

Significance of γ-ray detection for annihilation into τ+τ− for various masses, calculated using the **model-independent procedure***

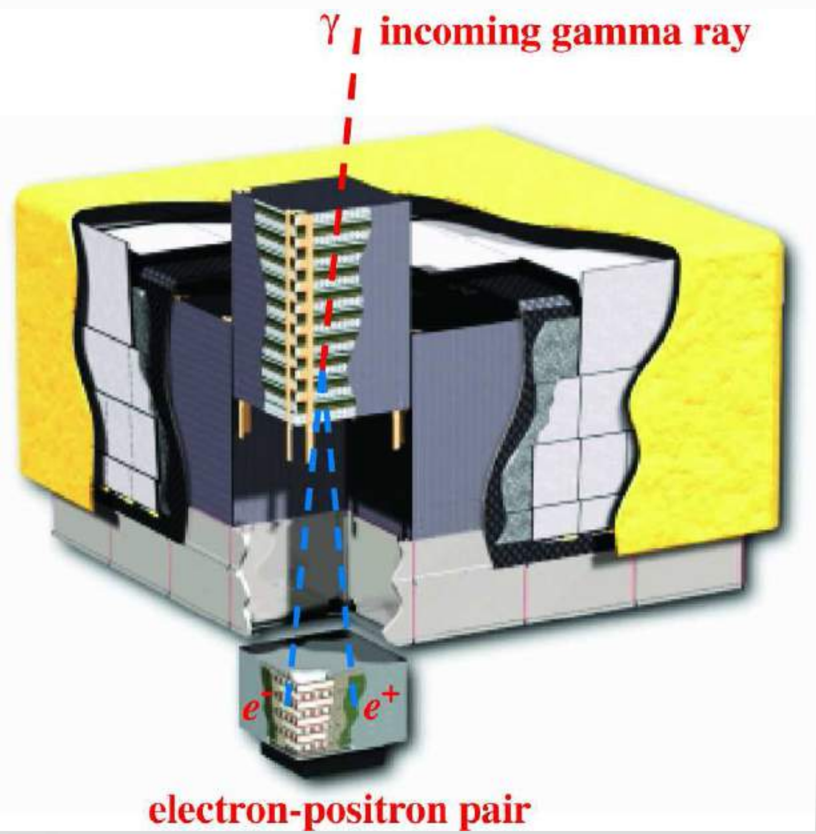


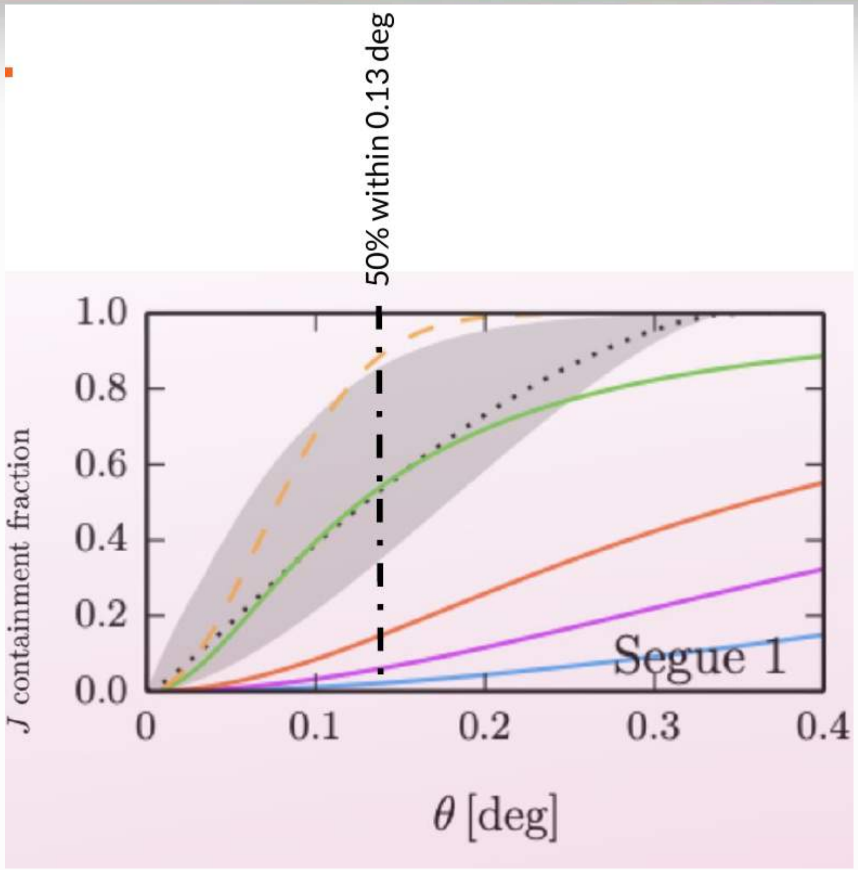
Reticulum II is the **widest** and the **brightest** dSph **source** on the sky => **more statistics**, **mild angular resolution limits**. But other dwarfs galaxies are also interesting!

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

Main limitations of Fermi:

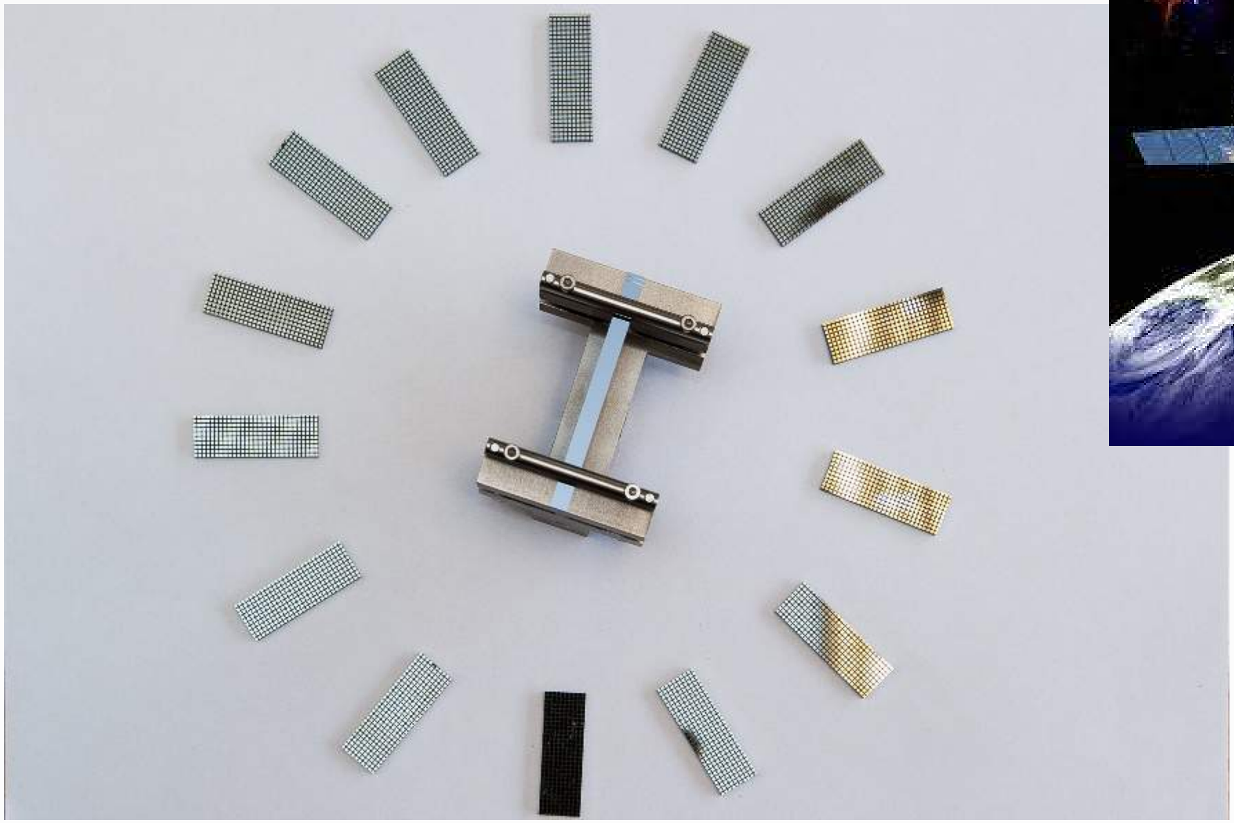
- **angular resolution** => problem to distinguish the **signal vs background** at small angles,
- **Not so large**, we need large surface to accumulate more statistics!



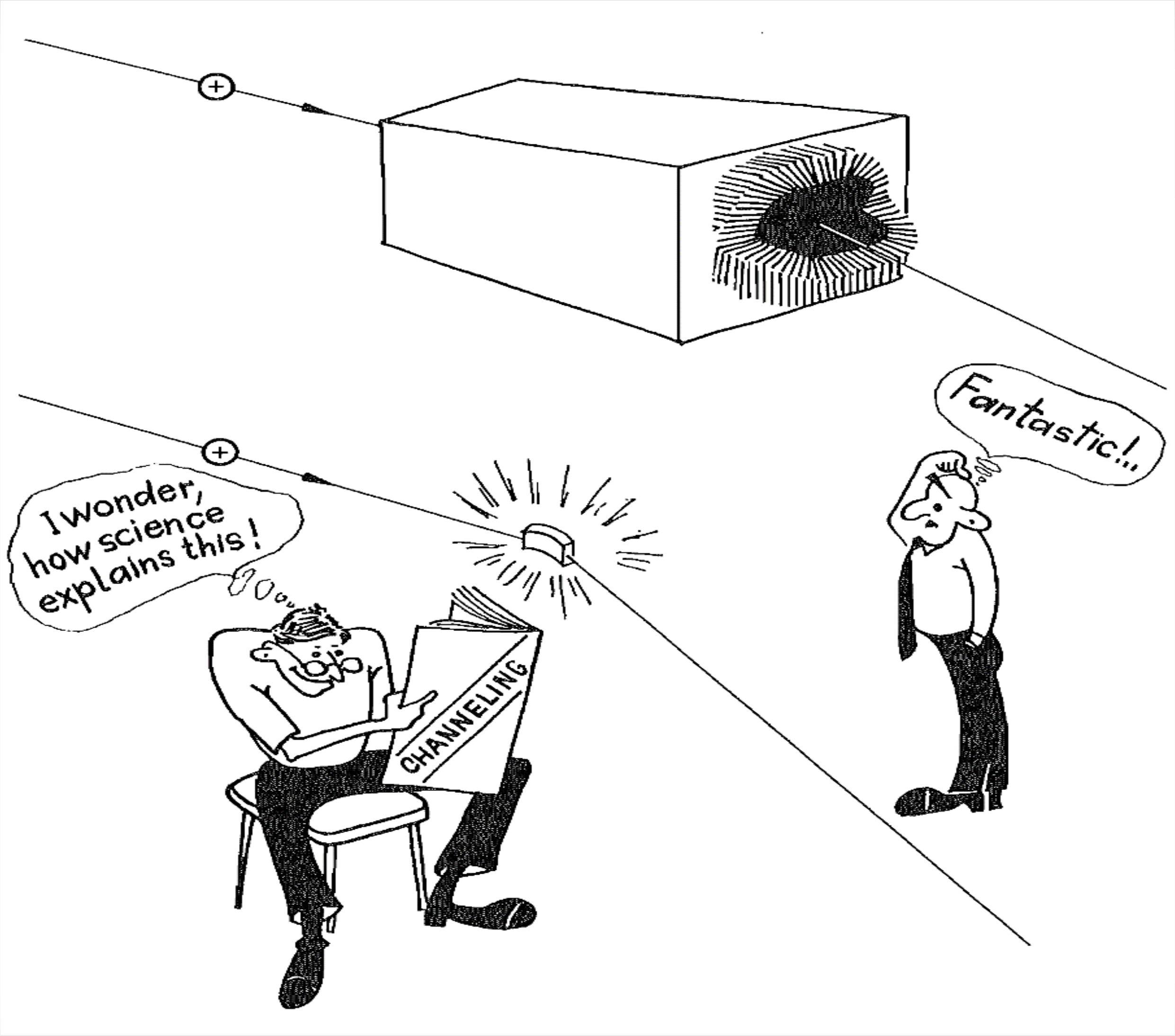


Containment fraction for **DM annihilation** as a function of **angular distance** from the center of **Segue 1***.
The solid colored curves show the PSF of a silicon detector, while the dashed colored line shows the PSF of an Atmospheric Cerenkov telescope.

The idea of oriented crystals for γ-ray astronomy



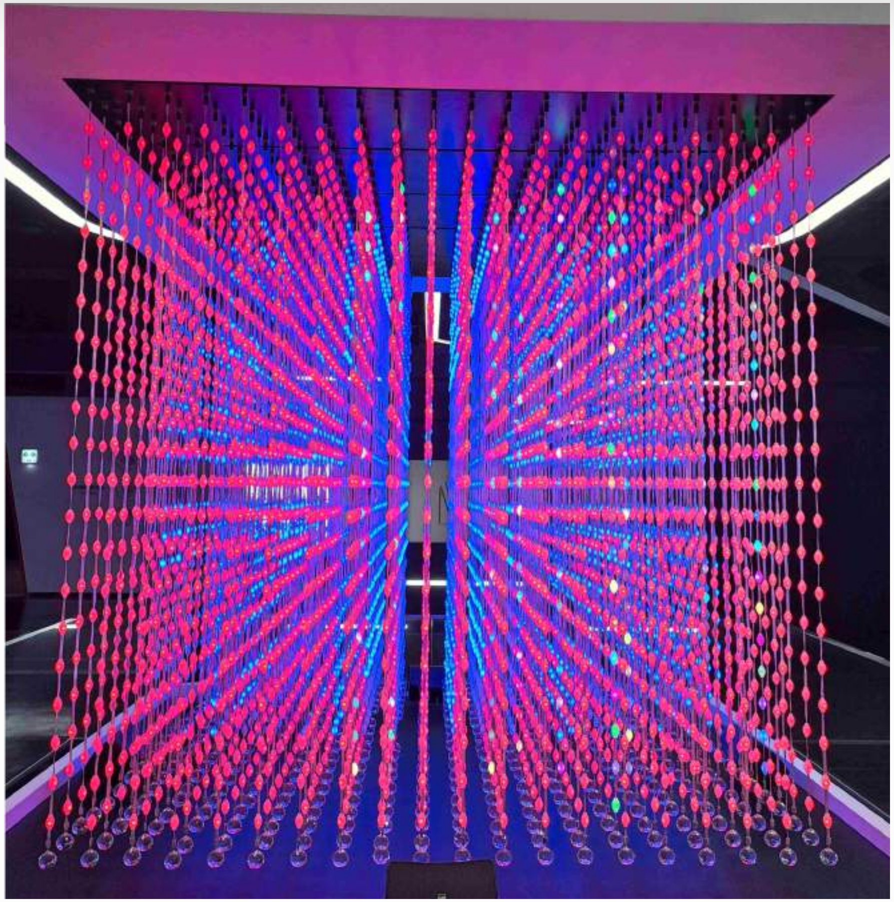
How to do a low-cost large area dedicated space mission? Oriented crystals!



European Commission

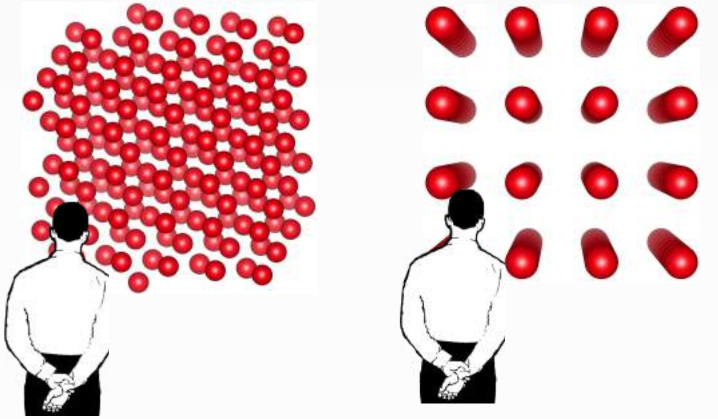
How an oriented crystal looks like

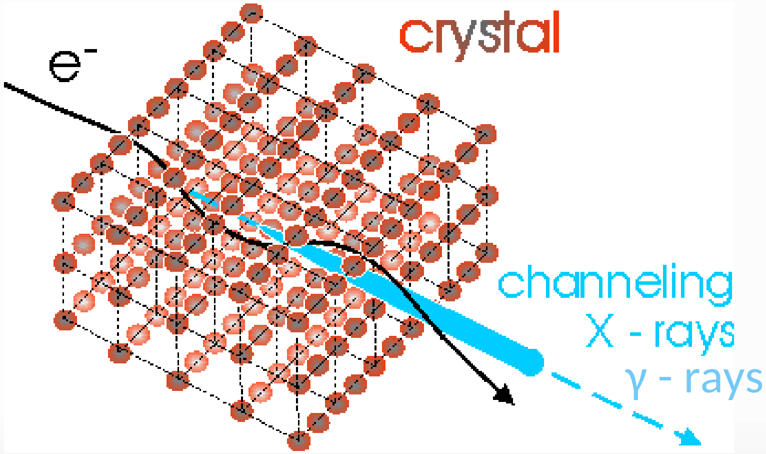
Trillion



from National Science Museum, Daejeon, Korea

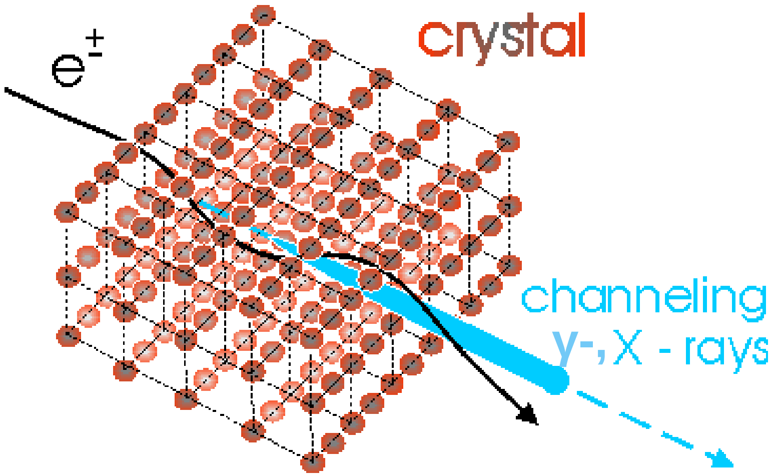
Non-oriented crystal | **Oriented crystal**





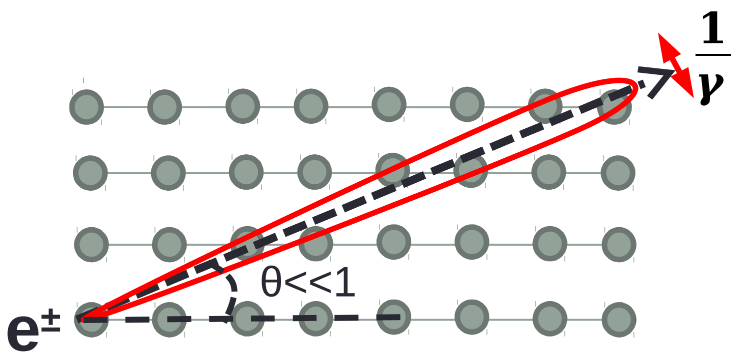
Coherent effects in a crystal

Channeling radiation*

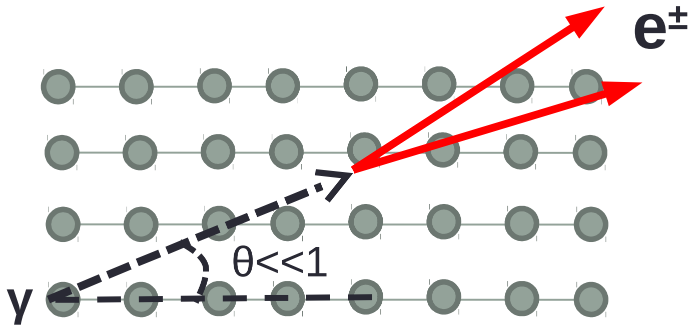


Coherent effects preserve **up to few mrad** of particle direction vs the crystal axis

Coherent bremsstrahlung**



Coherent pair production***

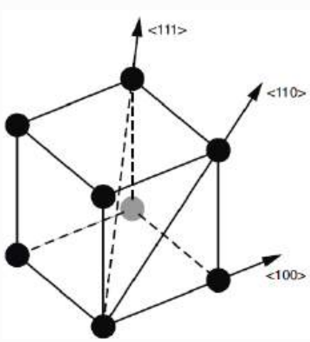


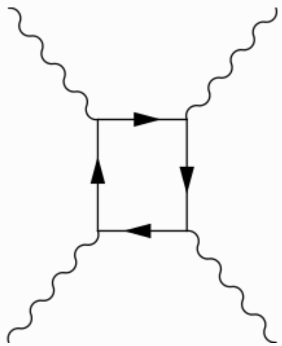
***M.A. Kumakhov, Phys. Lett. A 57(1), 17–18 (1976)**
****B. Ferretti, Nuovo Cimento 7, 118 (1950).**
****M. Ter-Mikaelian, Sov. Phys. JETP 25, 296 (1953).**
***** H. Überall, Phys. Rev. 103, 1055 (1956).**

Electromagnetic shower acceleration

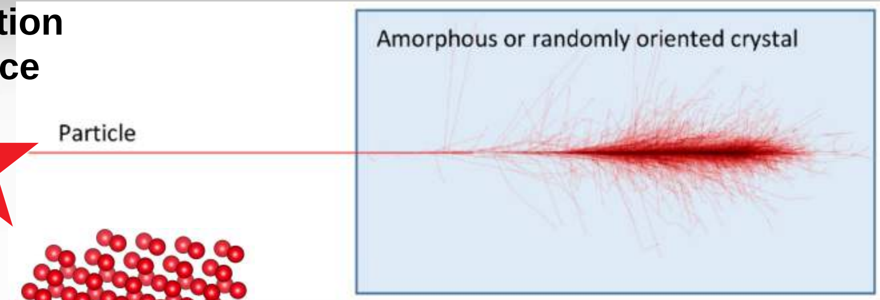
Axial field 10^{11}-10^{12} V/cm

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

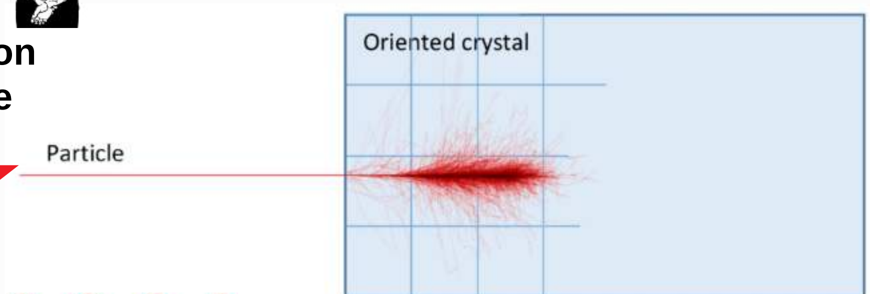




Radiation source



Radiation source



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*.

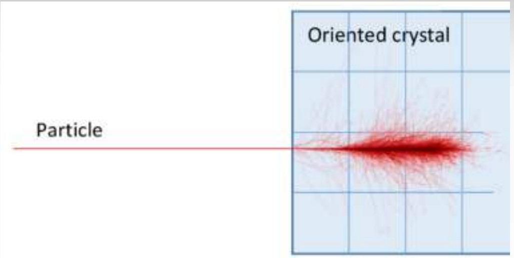
Crystal-based ultrashort electromagnetic calorimeter* (The INFN OREO experiment ORiEnted calOrimeter)

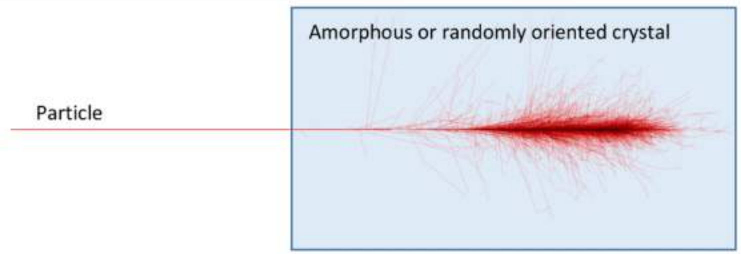
Advantage:

- 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





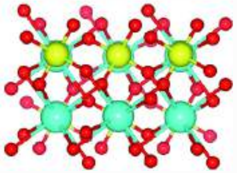
CERN North Area

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

+ dark photon search

Gamma-ray Space Telescope (like Fermi)

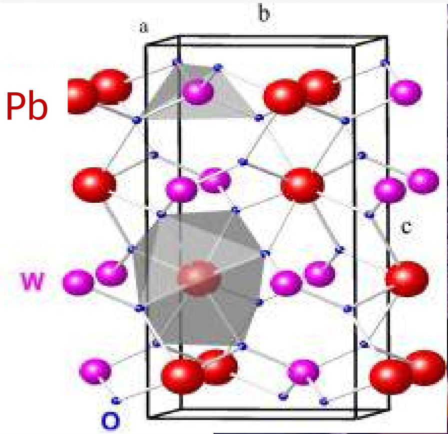
PWO



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

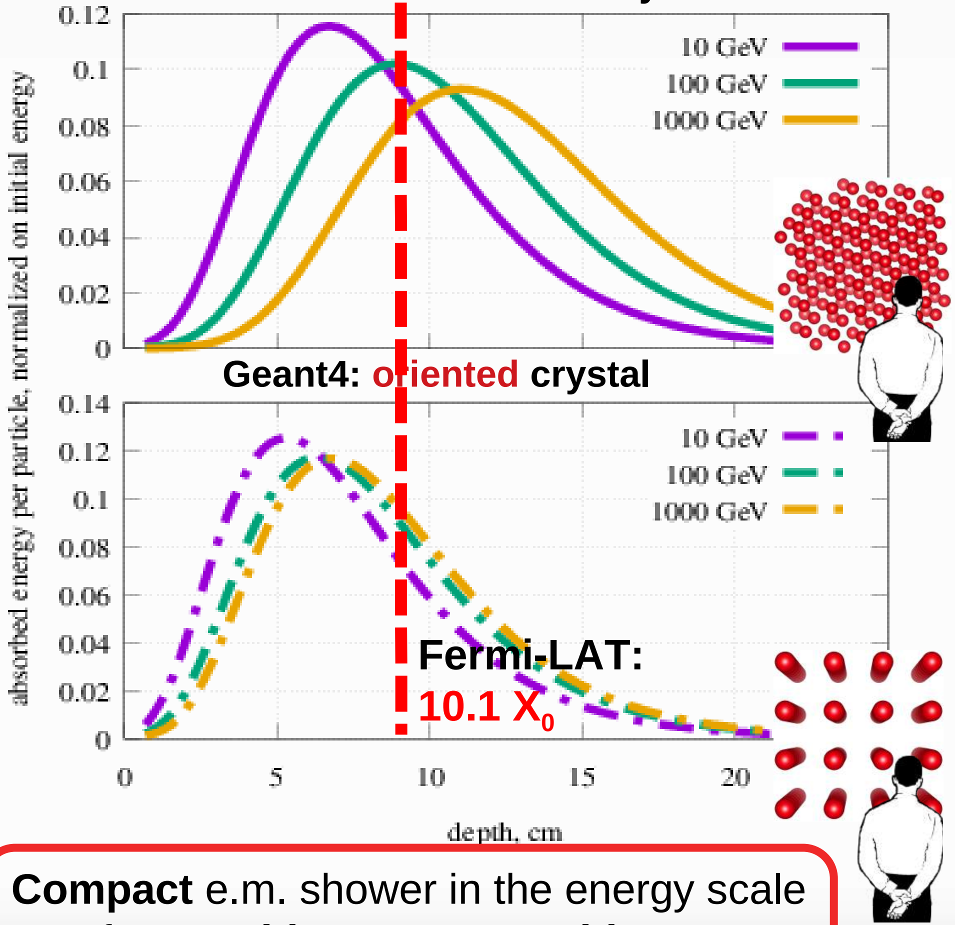
Orienting the electromagnetic calorimeter => making it thinner!

Lead tungstate: $PbWO_4$



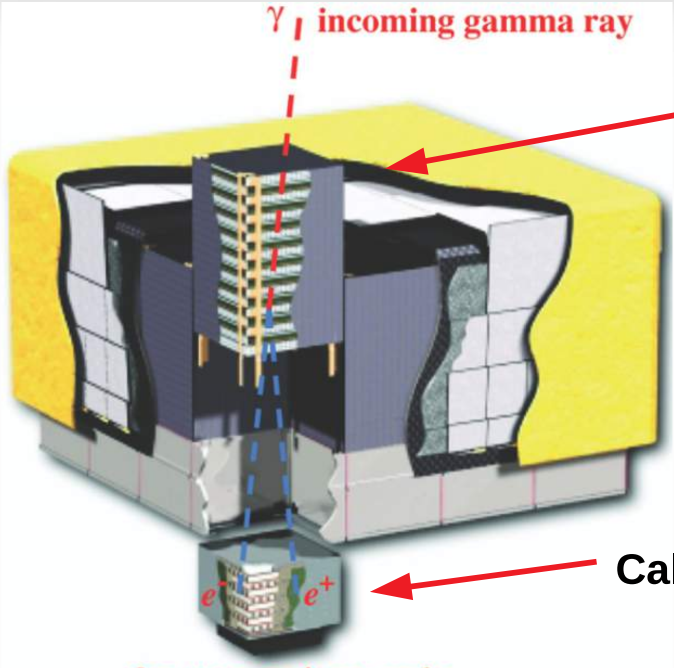
INFN OREO by L. Bandiera et al.

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

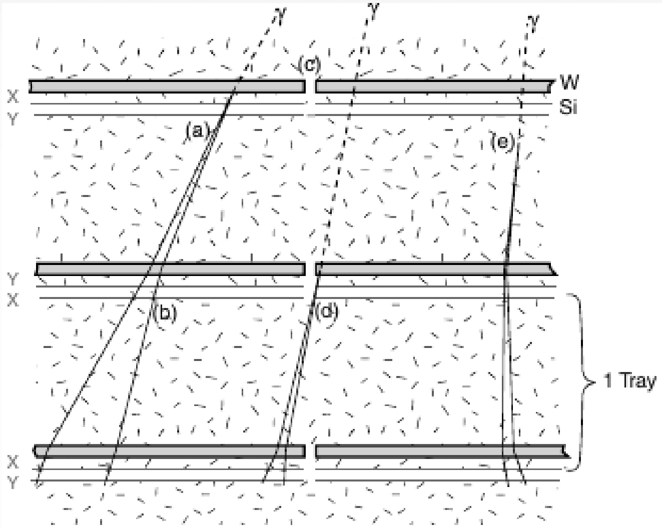


Compact e.m. shower in the energy scale from **multi-GeV** up to **multi-TeV**!

How a gamma-ray space telescope looks like? (Fermi-LAT example*)



Tracker



New γ-ray space telescopes reaching TeV scale

- DAMPE, Chang J. et al., (The DAMPE Collaboration), Astropart. Phys. 95, 6-24 (2017)
- CALET (ISS). S. Torii et al. (The CALET Collaboration), Adv. in Space Res. 64, Iss. 12, 2531-2537 (2019)

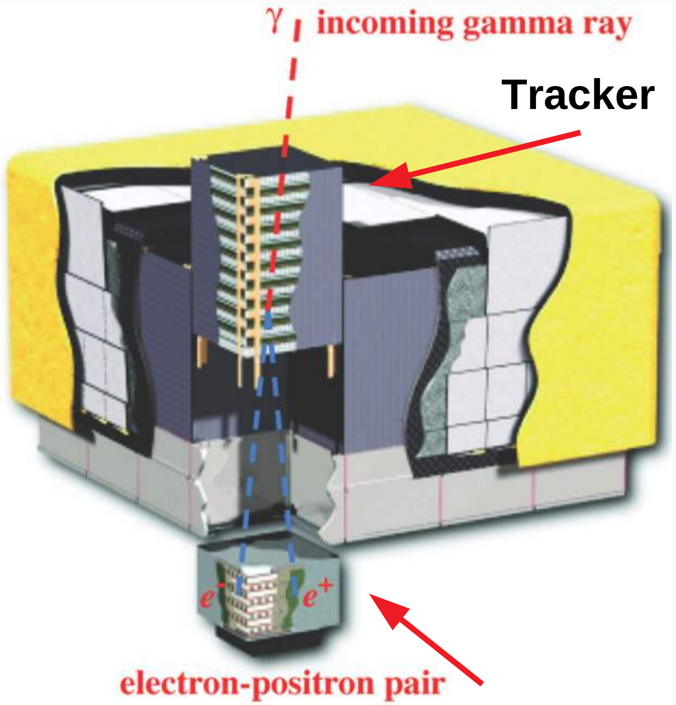
Calorimeter parameters

- 96 CsI(Tl) crystals * 16 modules
  2.7 cm×2.0 cm×32.6 cm each crystal
- 8.6 radiation lengths (segmentation helps)
- **Energy range 20 MeV–300 GeV**
- **Total weight > 1 tonne**

***W.B. Atwood et al. The Astrophysical Journal, 697, 1071–1102 (2009)**

How a gamma-ray space telescope with a crystalline calorimeter will look like?

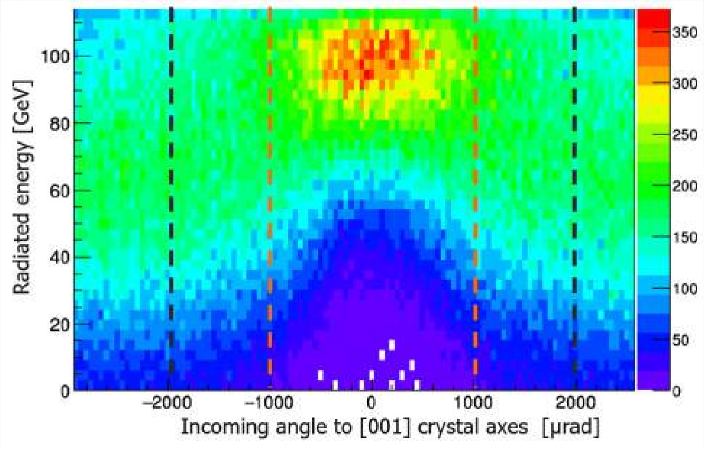
Similar to Fermi-LAT but with **specific parameters** and **features**

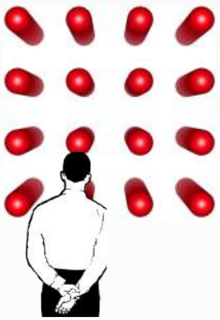


Calorimeter

$$t_{max} = \frac{x_{max}}{X_0} = \ln\frac{E_0}{\varepsilon} \pm 0.5$$

Experimental* radiated energy distribution by 120 GeV e⁻





Main features

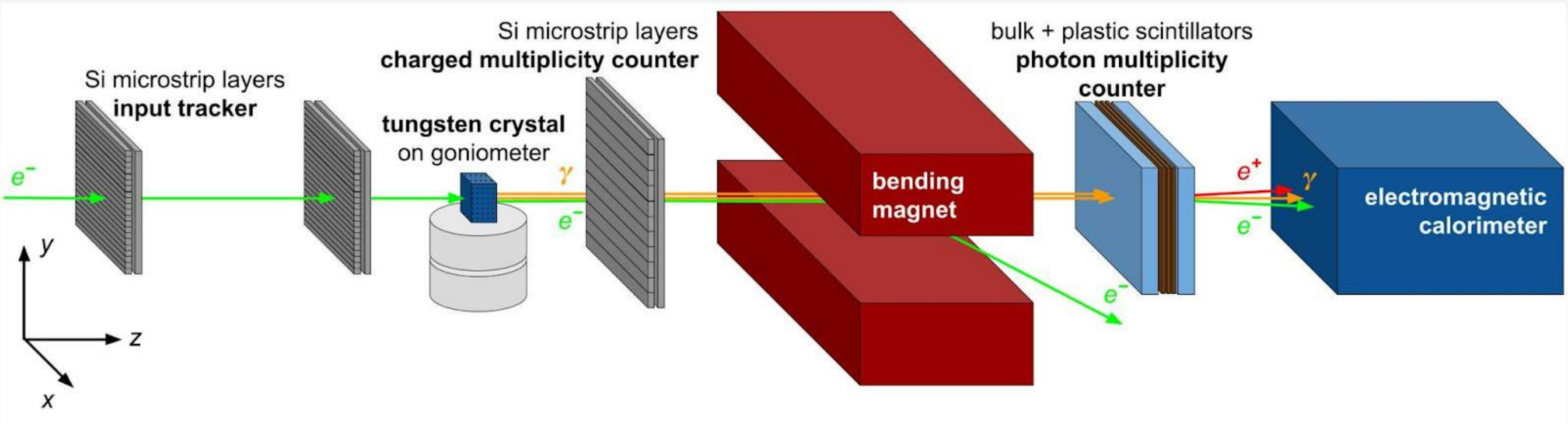
- **Pointing calorimeter**: must be **oriented** towards cosmic object within **few mrad** => tracker is necessary
- Still works as a **conventional calorimeter outside** this **angular region**
- **Drastic reduction** of a crystal **thickness** in the pointing mode => **minus ~1 tonne** of Fermi-LAT weight

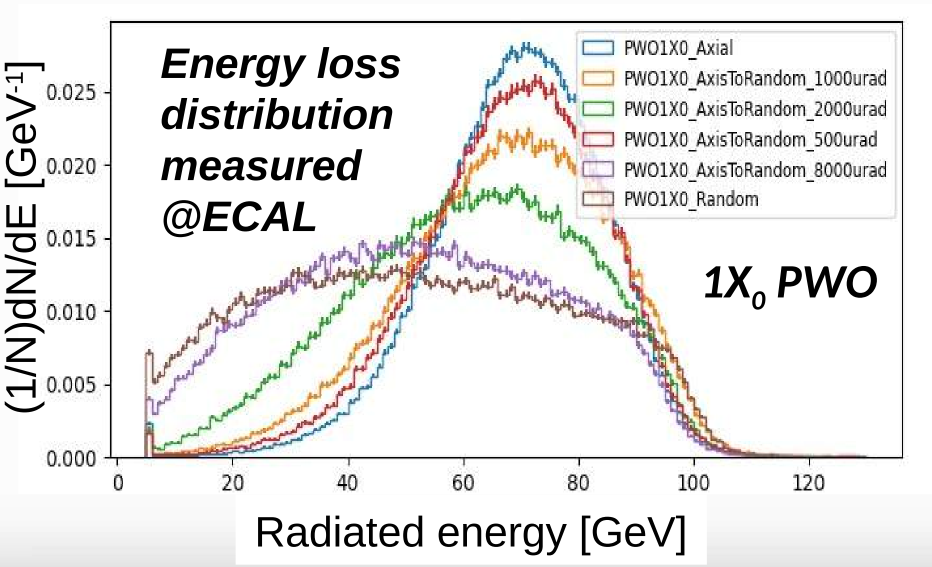
  AND/OR
- Exponential increase of the **maximal energy limit** => **multi-TeV** energy scale with a drastic **reduction** of **costs**

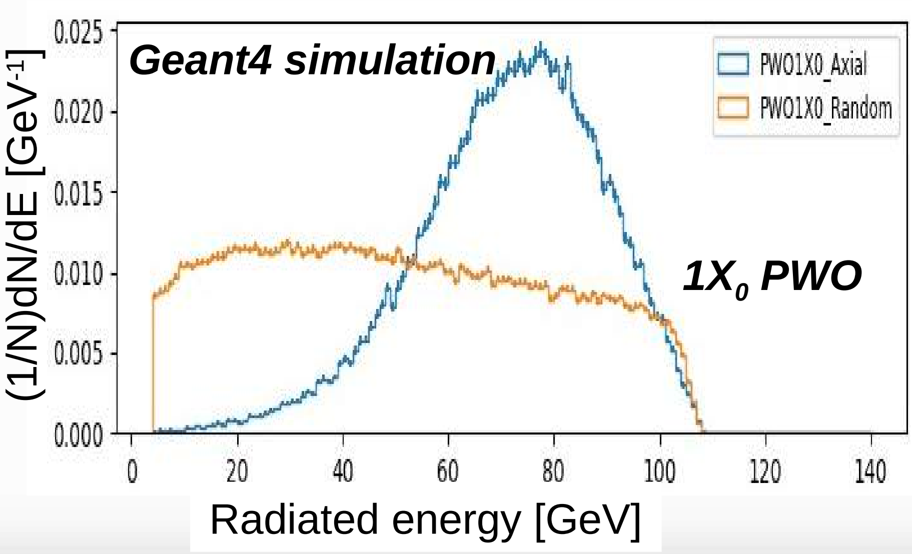
*L. Bandiera, …, A. Sytov et al. Phys. Rev. Lett. 121, 021603 (2018)

Experimental data for PWO oriented crystal at CERN SPS H4 line

Beam: e⁻ @120 GeV

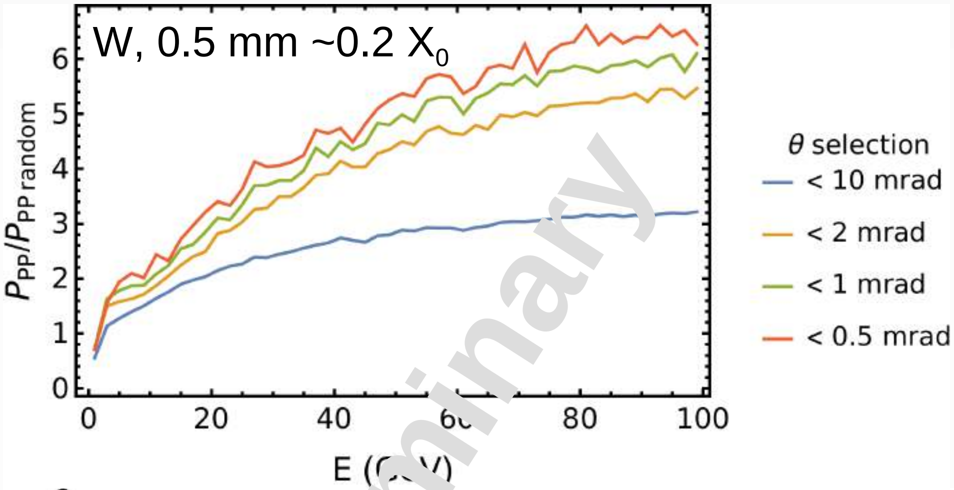


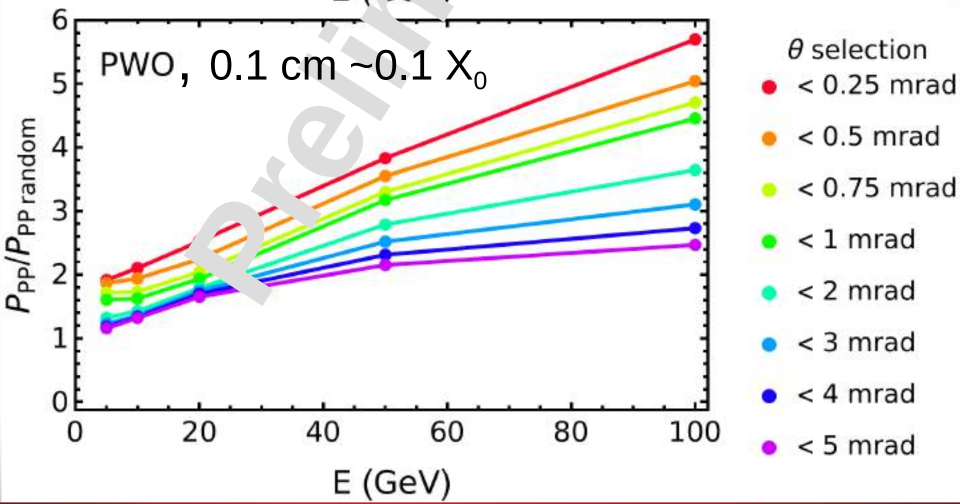




What gamma-ray about angles?

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





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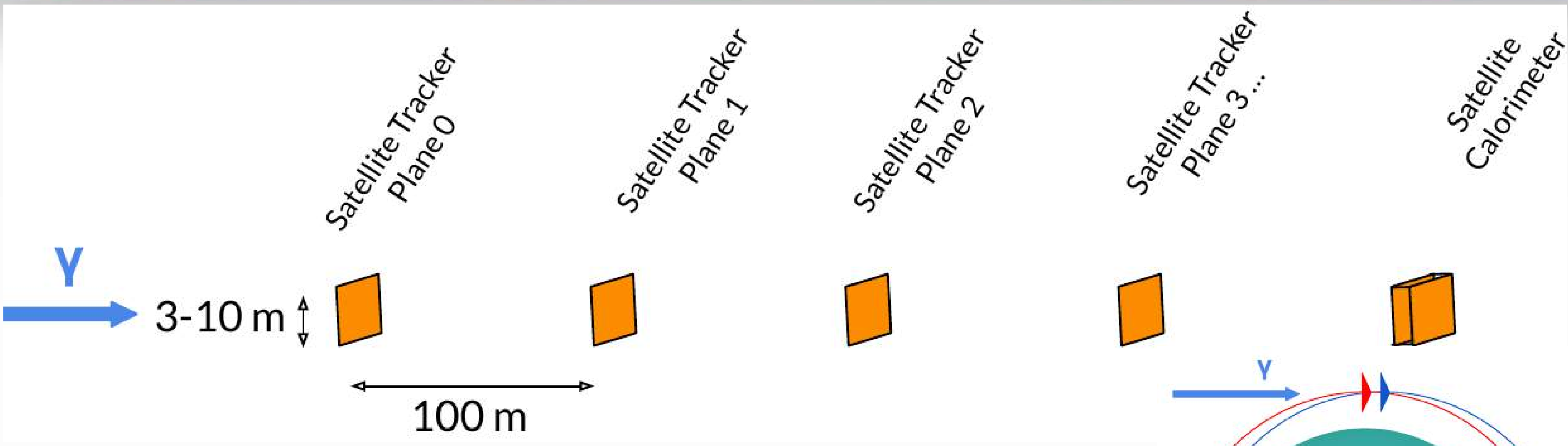
Coma	44	0.16	0.02	10.47
Sculptor	92	0.15	0.05	3.47
RET II	30	0.57	0.05	39.81

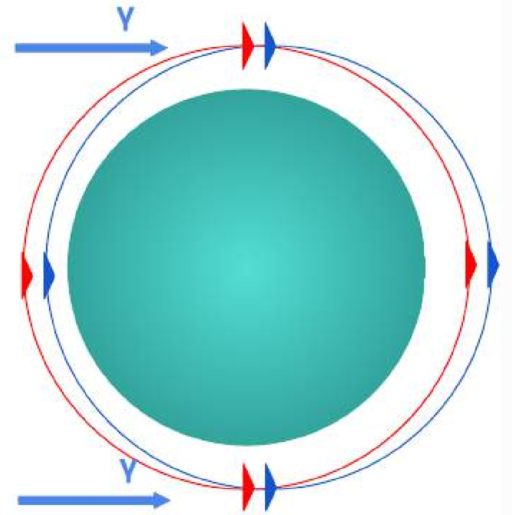
Pair Production Enhancement happens within 2 mrad~**0.1°** for W and 1 mrad~**0.05°** for PWO => optimal for dwarf galaxies

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).

What about multiple satellite for particle tracking?





- We can **considerably reduce** amount of read-out electronics => the **mission cost** by using **large pixels**
- Angular resolution of ~0.1° requires ~**100 m** of the distance between tracker stations in this case

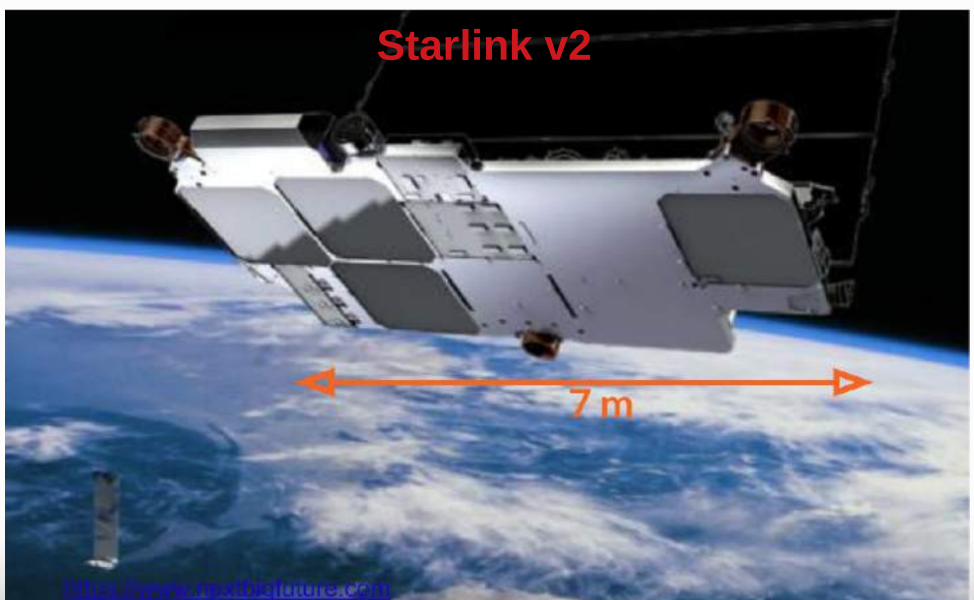
Requires **Δv~1 m/s** per orbit to keep 1 satellite 100 m from a 2nd with a fixed absolute alignment

The required thrust magnitudes are consistent with use of **Hall-Effect Thrusters**

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



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**.

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

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

Group:

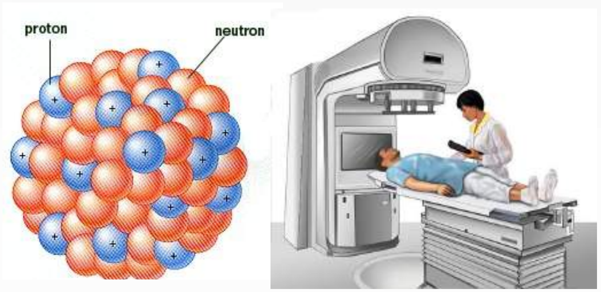
- **A. Sytov** – project coordinator
- **L. Bandiera** – INFN supervisor
- **K. Cho** – KISTI supervisor
- **G. Kube** – DESY supervisor
- **I. Chaikovska** – IJCLab Orsay supervisor

Location:

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

Applications of oriented crystals*

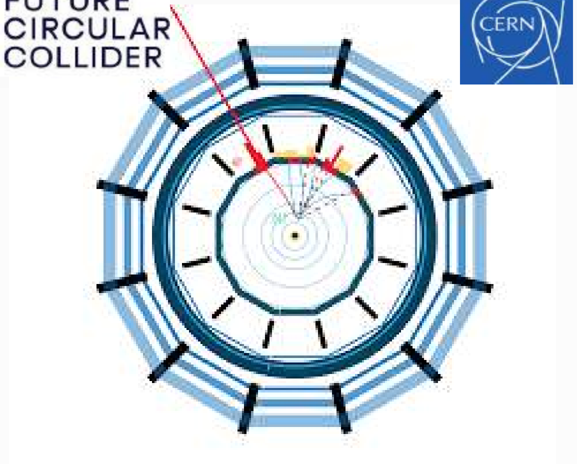
X and γ-ray source for nuclear physics and cancer radiotherapy



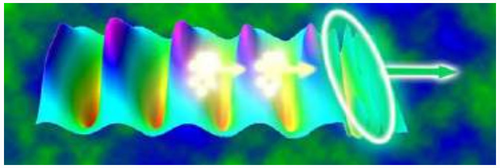
Gamma-ray Space Telescope

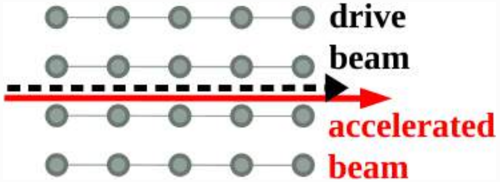
Positron source for future multi-billion € e+/e- and muon colliders

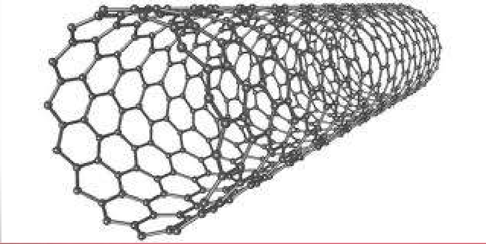
FUTURE CIRCULAR COLLIDER



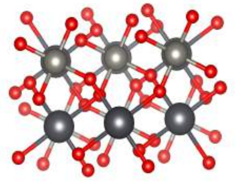
Plasma wakefield acceleration







Oriented crystals



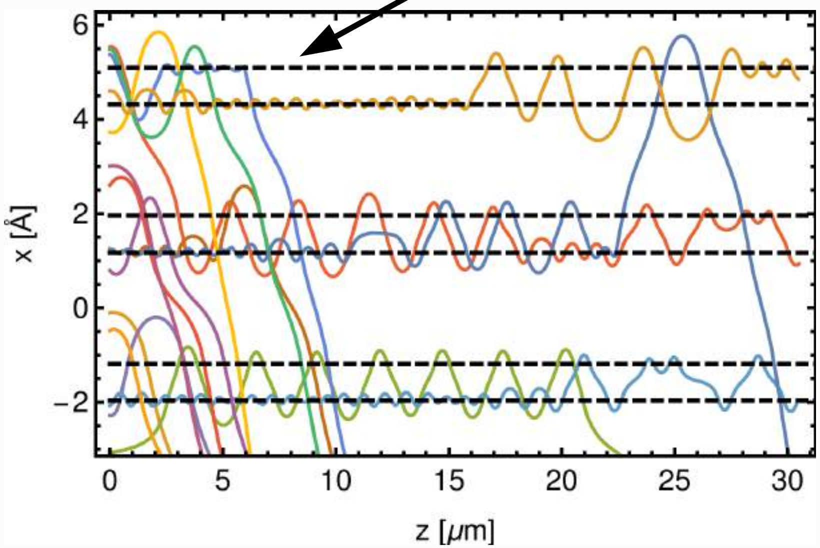
Crystal-based beam extraction from accelerators and colliders

Channeling simulation technique: Geant4 ChannelingFastSimModel

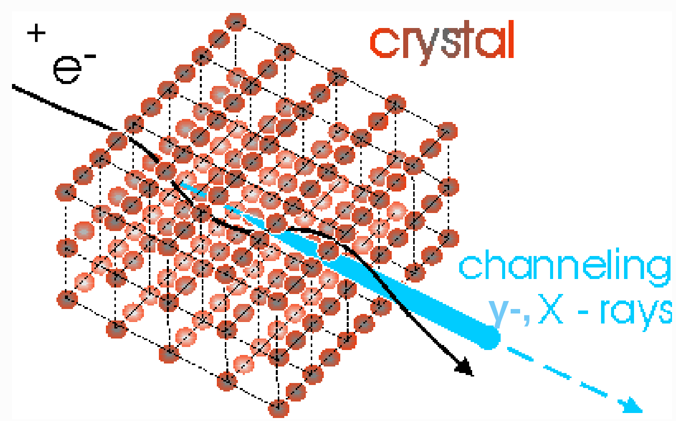
Main conception – simulation of classical trajectories of charged particles in a crystal

Multiple and single **scattering simulation** at every step

Crystal planes



channeling*



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

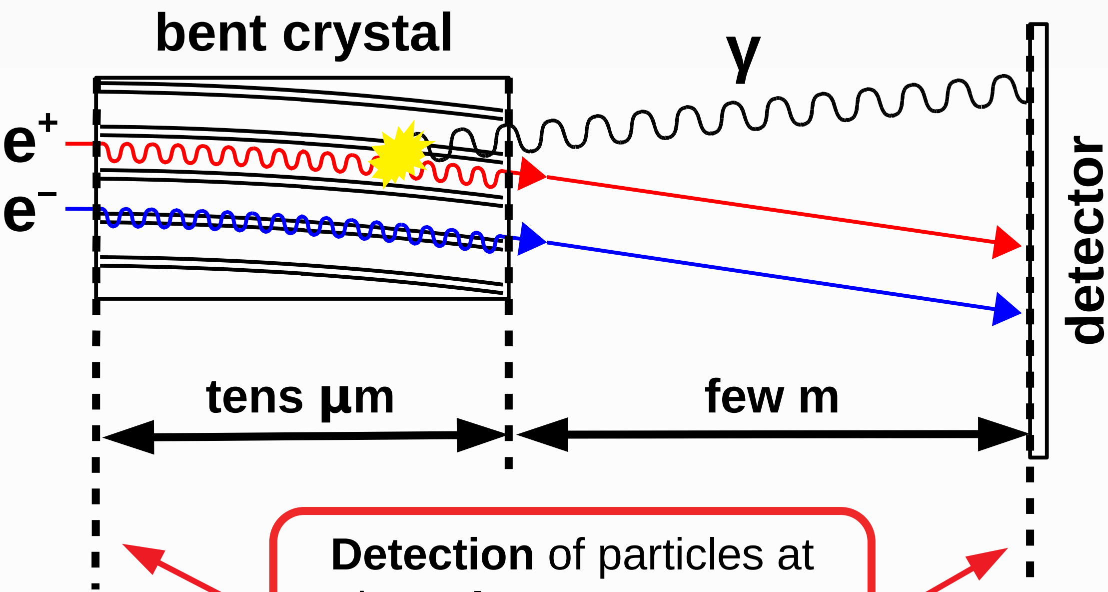
$$\frac{dE}{d^3k} = \omega \frac{dN}{d^3k} \frac{\alpha}{4\pi^2} \iint dt_1 dt_2 \frac{\left[(E^2+E'^2)(v_1 v_2 - 1) + \omega^2/\gamma^2\right]}{2E'^2} e^{-ik'(x_1-x_2)}$$

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)

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

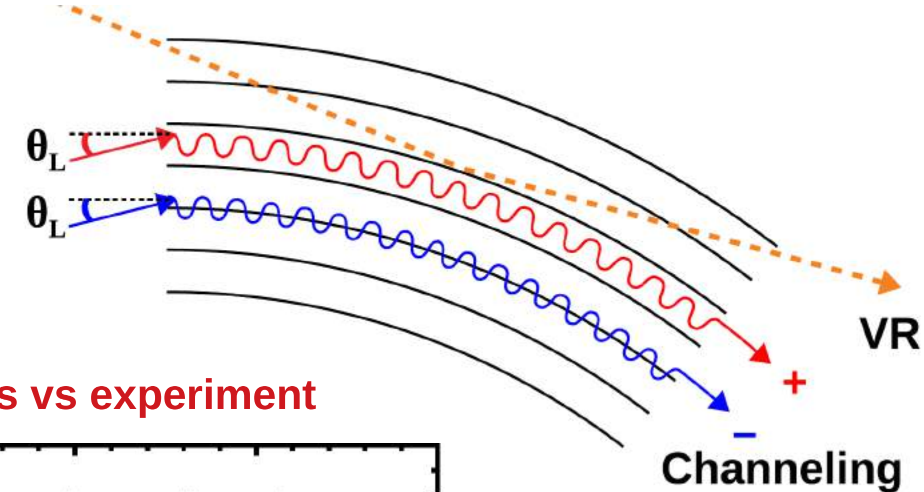
***A. Mazzolari et al. Phys. Rev. Lett. 112, 135503 (2014)**

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

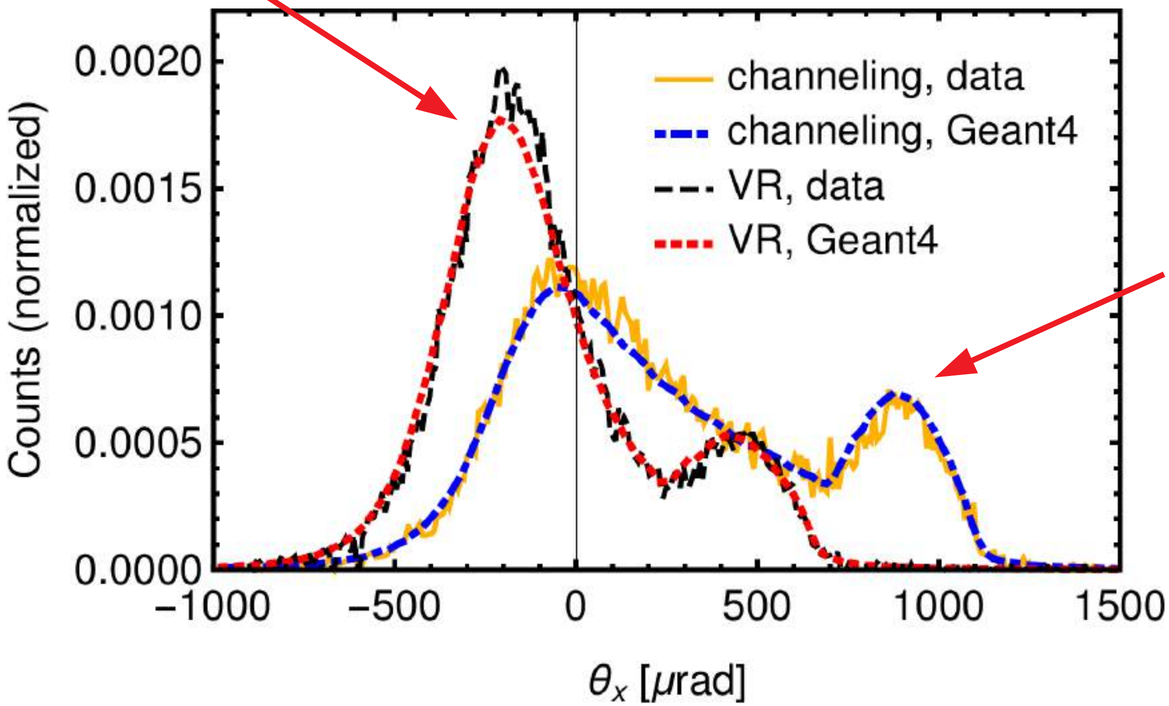
15 µm thick bent crystal



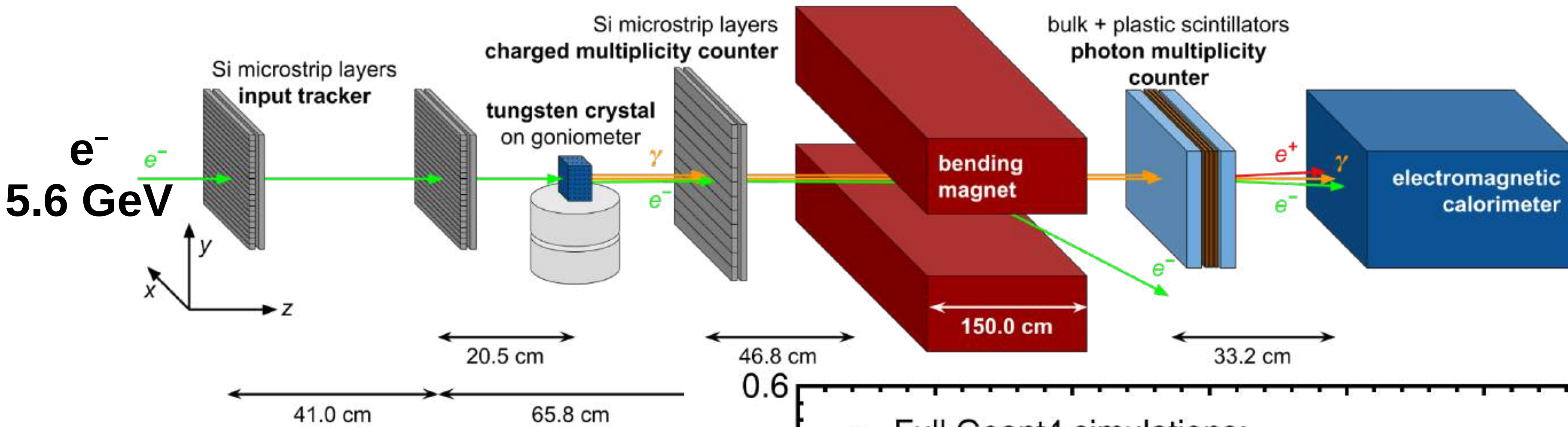
volume reflection (VR)

Geant simulations vs experiment

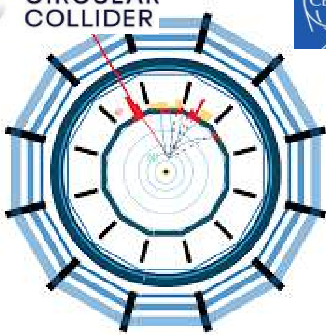
channeling

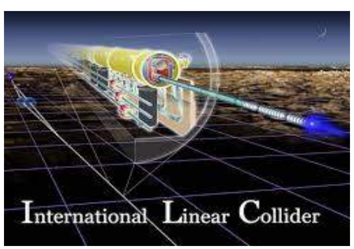


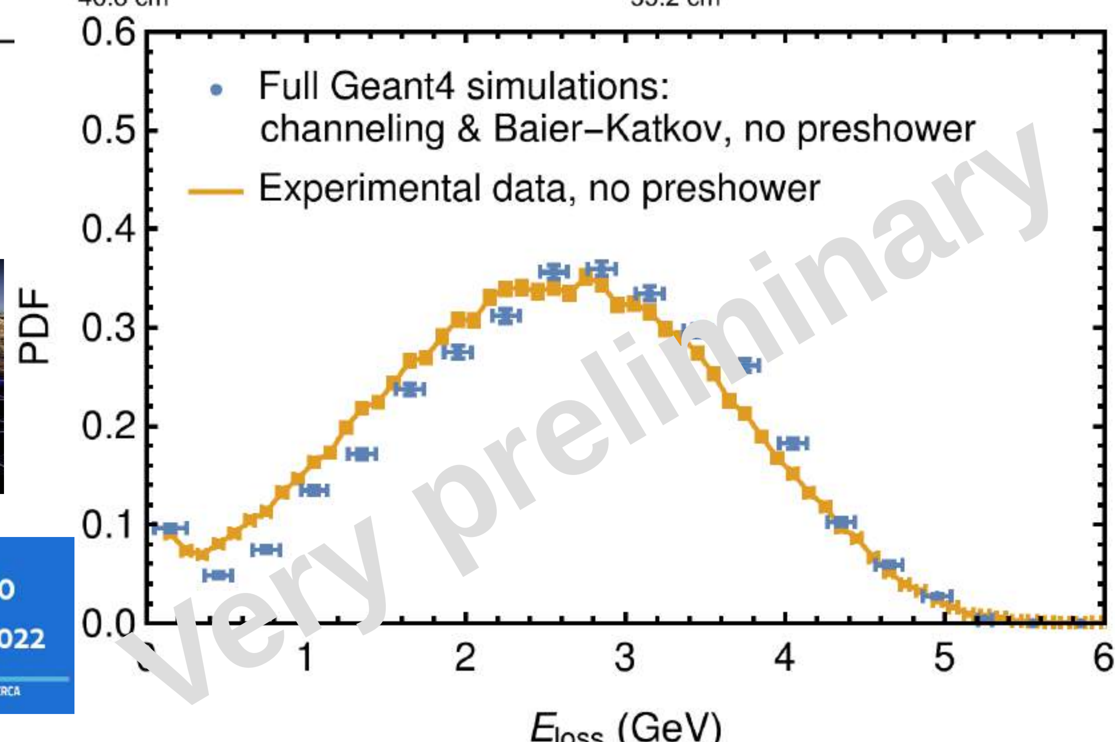
Full Geant4 simulations of the DESY experiment* for the FCC-ee positron source project



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

Current status

Already in Geant4 kernel!

Geant4-11.2.0
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

- The **dwarf galaxies** are interesting for **dark matter annihilation** search! Fermi data demonstrate a **signal** for the **Reticulum II** galaxy between 2 an 10 GeV!

- **Fermi telescope resolution** both energy and angular is **limited** for this purpose. The surface area also needs to be increased to accumulate the statistics faster!

- A probable solution for a dedicated cheap mission can **oriented crystals**. They allow one to contain electromagnetic shower at shorter distances drastically **reducing** the **electromagnetic calorimeter thickness** and enhancing the energy range up to **TeV scale**!

- The information about **photon angles** can be extracted using the angular dependence of the electromagnetic shower.

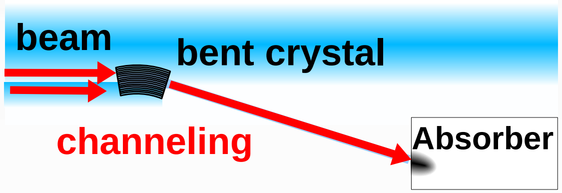
- **Considerable reduction** of the **cost** requires large pixel size. To use the tracker for the measurement of the angles we may need a set of satellites.

- **The goal of TRILLION** is to implement **electromagnetic processes in oriented crystals** into **Geant4**. This will help to **simulate an entire telescope**.

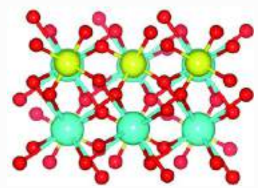
Thank you for attention!

Applications*

Crystal-based collimation or beam extraction from an accelerator

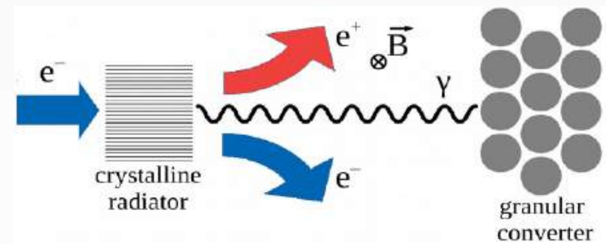


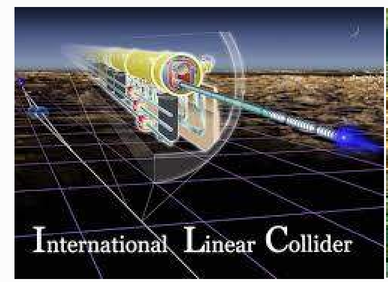
Ultrashort crystalline calorimeter

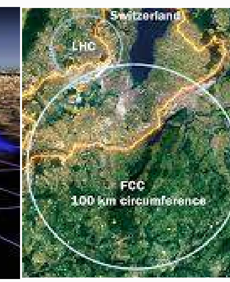


Gamma-ray Space Telescope

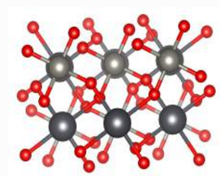
Positron source for future e+/e- and muon colliders



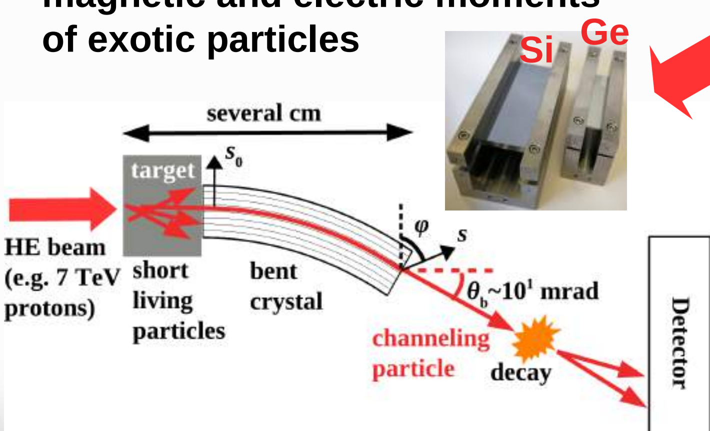




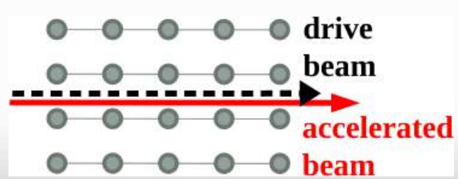
Oriented crystals



Measurement of dipole magnetic and electric moments of exotic particles



Plasma acceleration



X and γ-ray source for nuclear and medical physics