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)

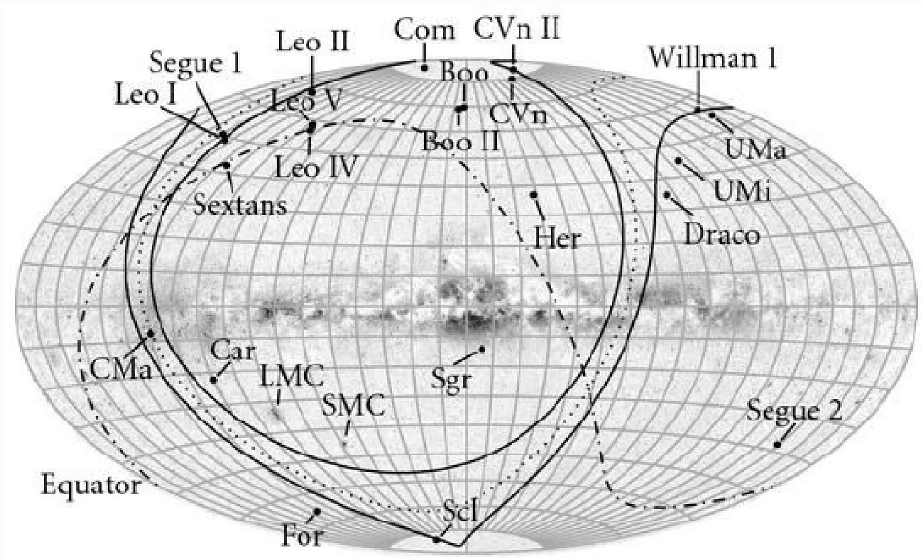
Gyeongju, 2023/07/04

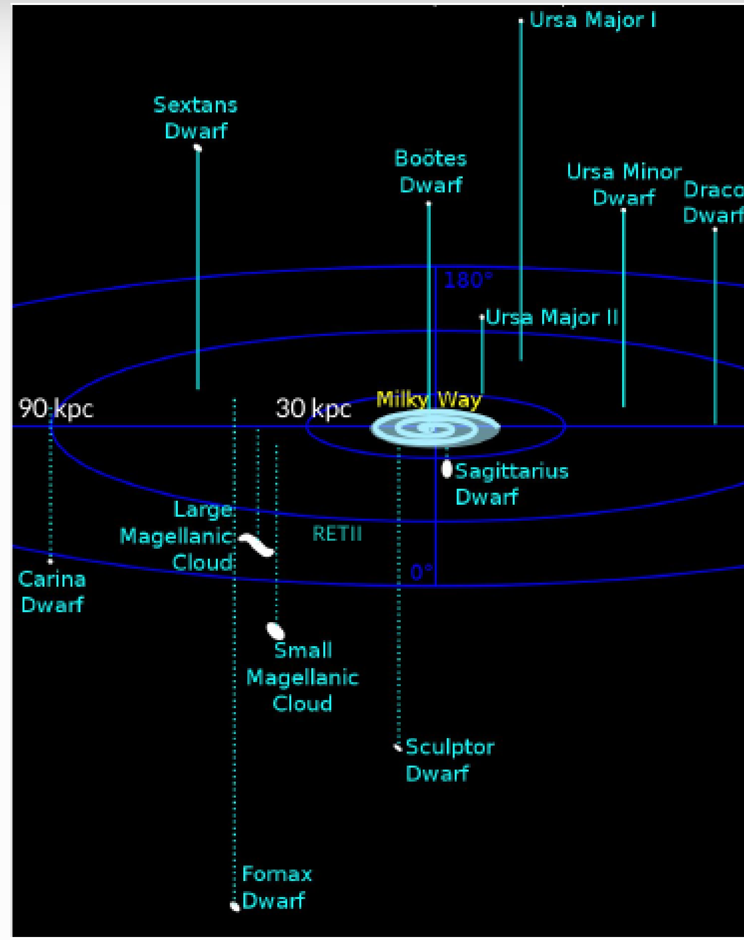
Dwarf spheroidal galaxies (dSph) as dark matter laboratories

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)





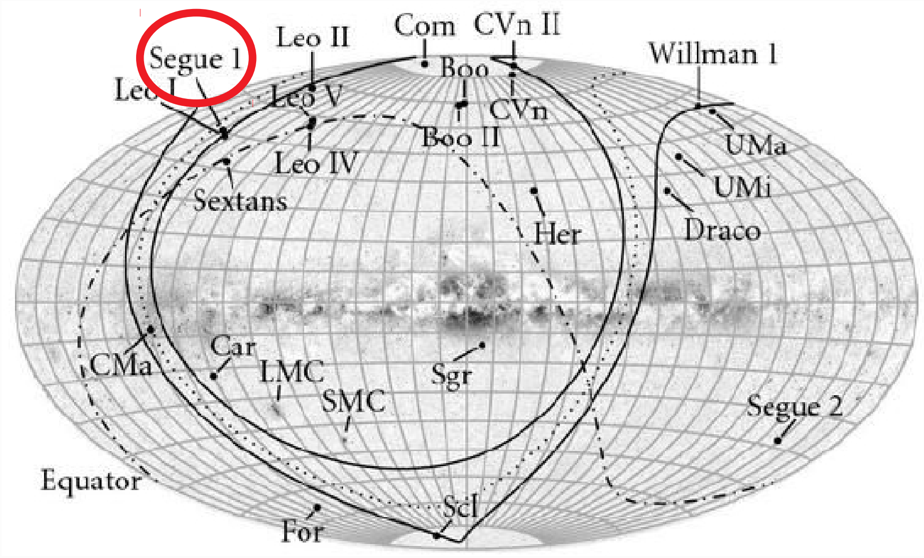
More than **50 dwarf galaxies** are currently **known**, with more to be discovered with upcoming surveys!

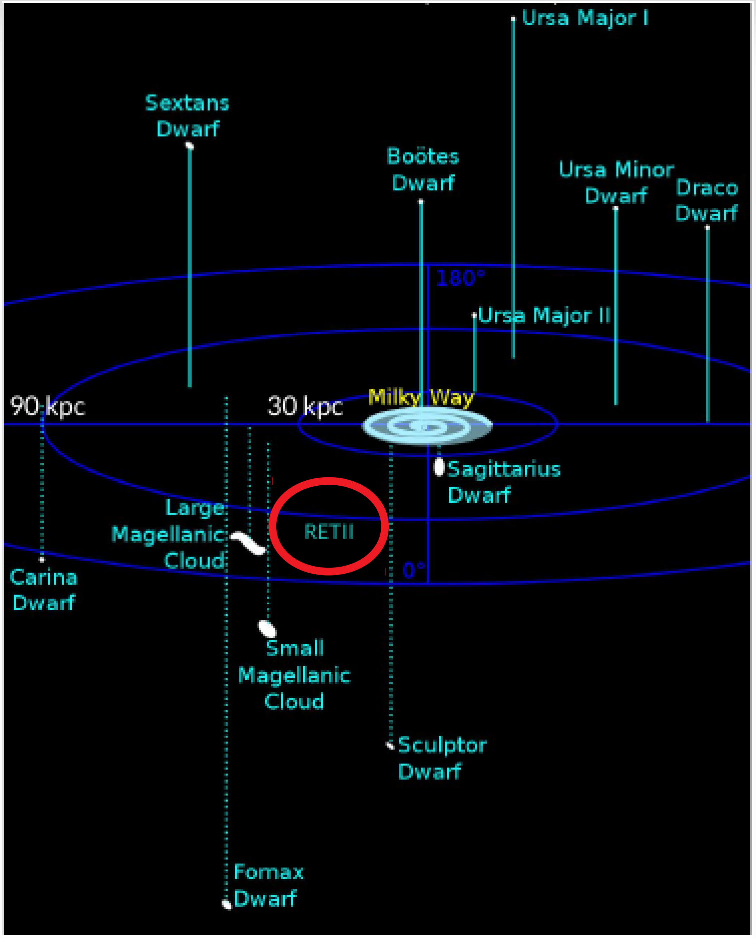
Dwarf spheroidal galaxies (dSph) as dark matter laboratories

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)



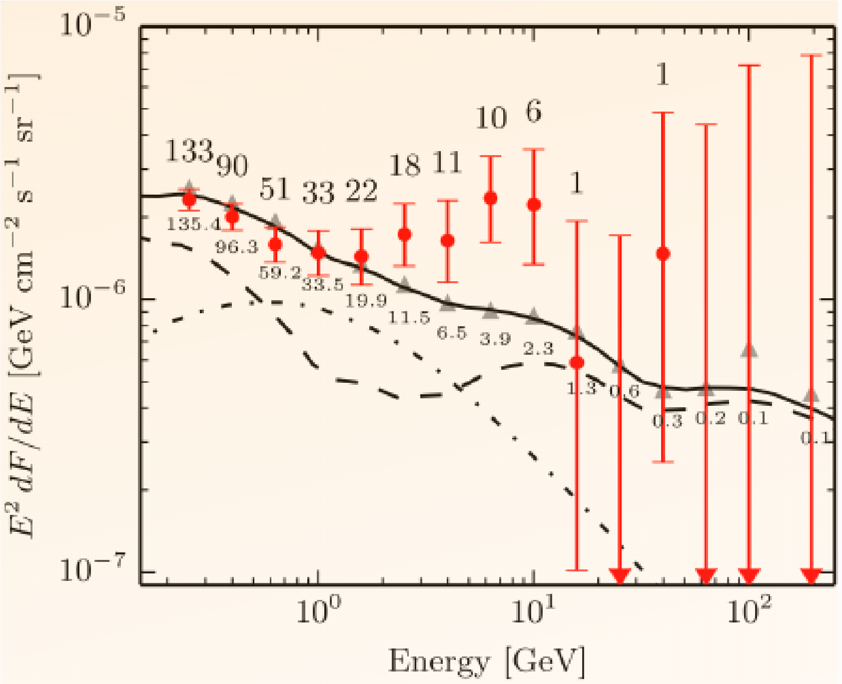


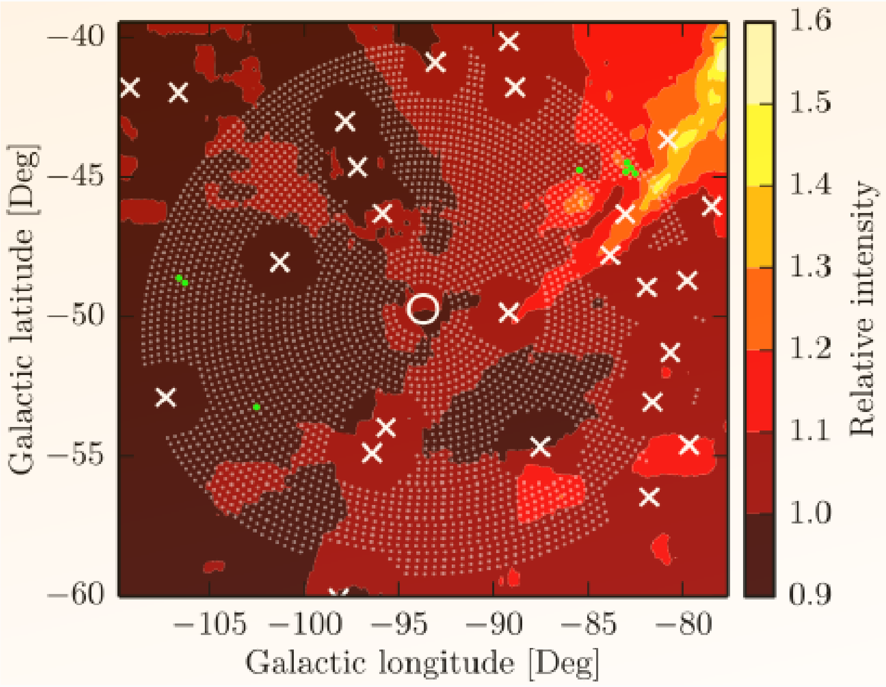
More than **50 dwarf galaxies** are currently **known**, with more to be discovered with upcoming surveys!

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.





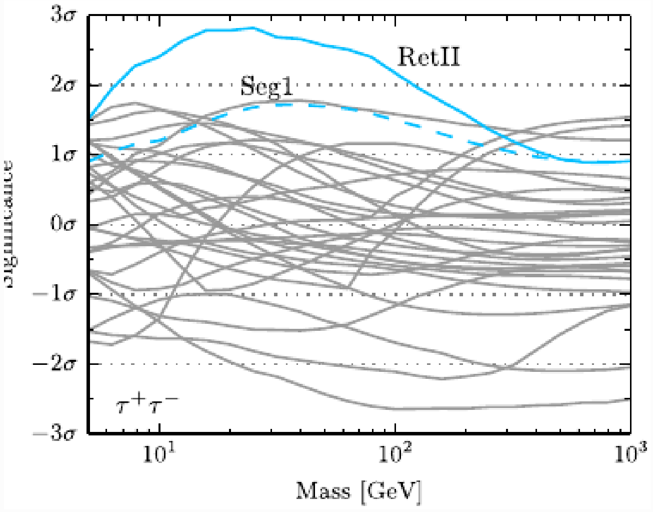
A signal at ~**3σ** that exceeds expected backgrounds between ~**2–10 GeV***

*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***



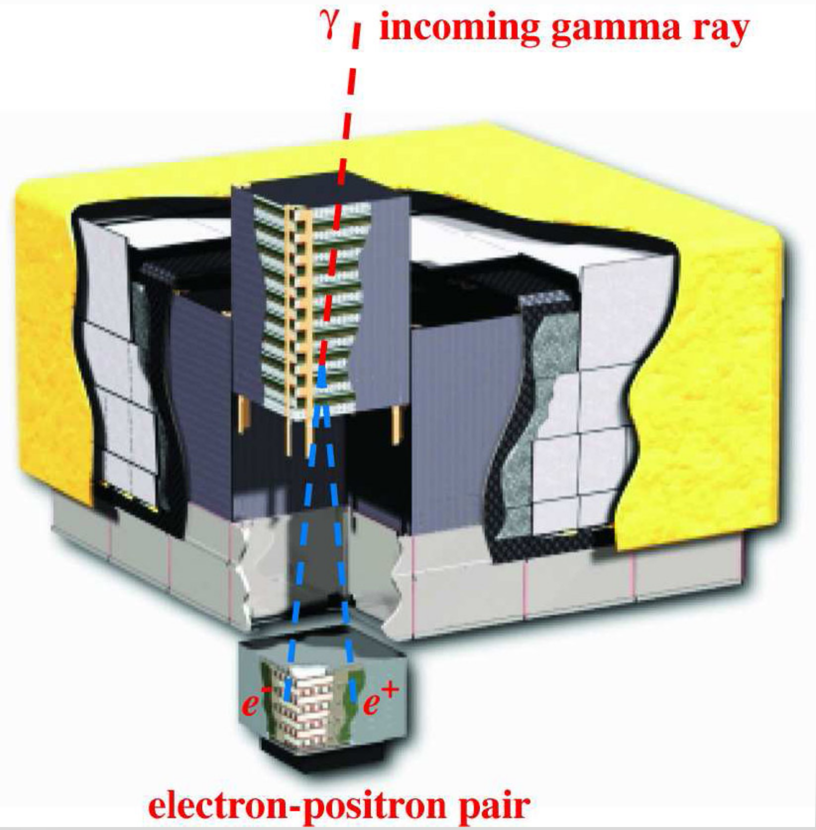
Reticulum II is the **widest** and the **brightest** dSph **source** on the sky => **more statistics**, **mild angular resolution limits**. But other dwarfs galaxies are also interesting!

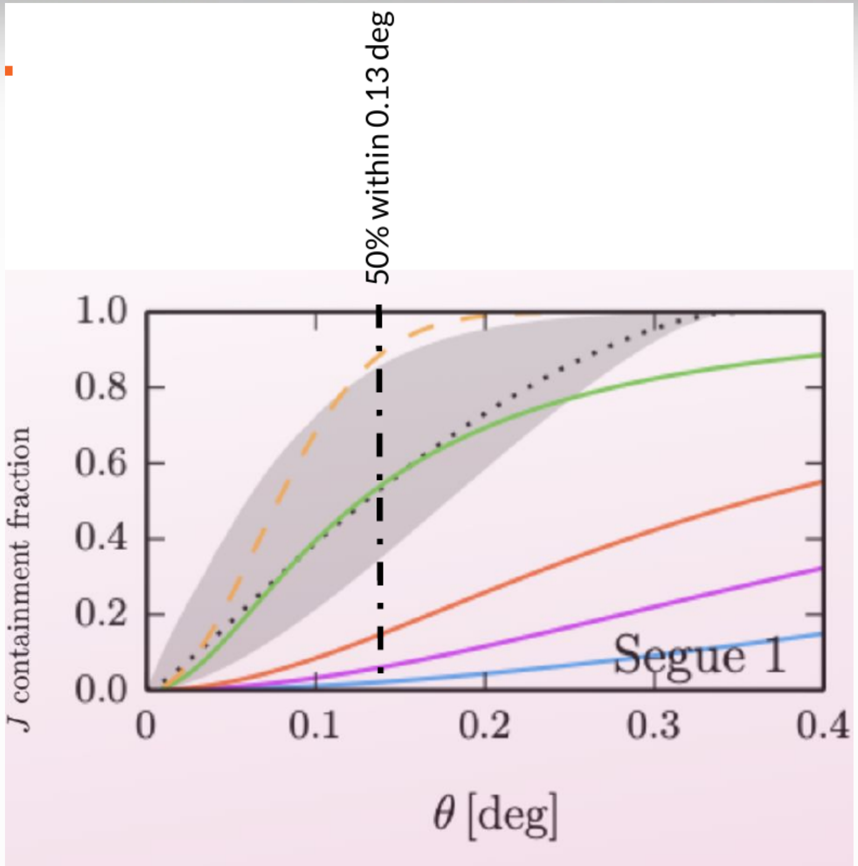
*A. Geringer-Sameth et al. Phys. Rev. Lett. 115, 081101 (2015)

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!

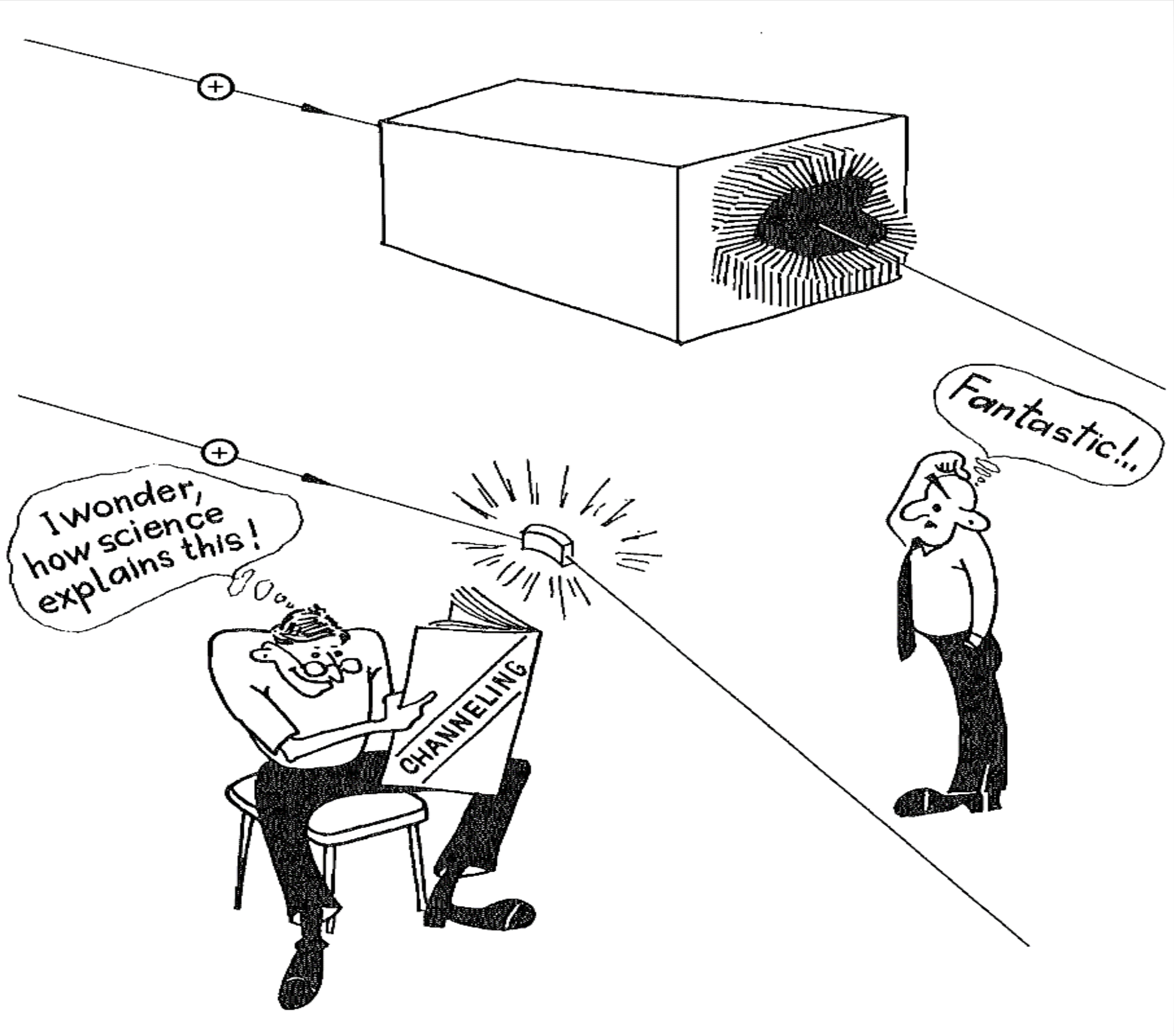




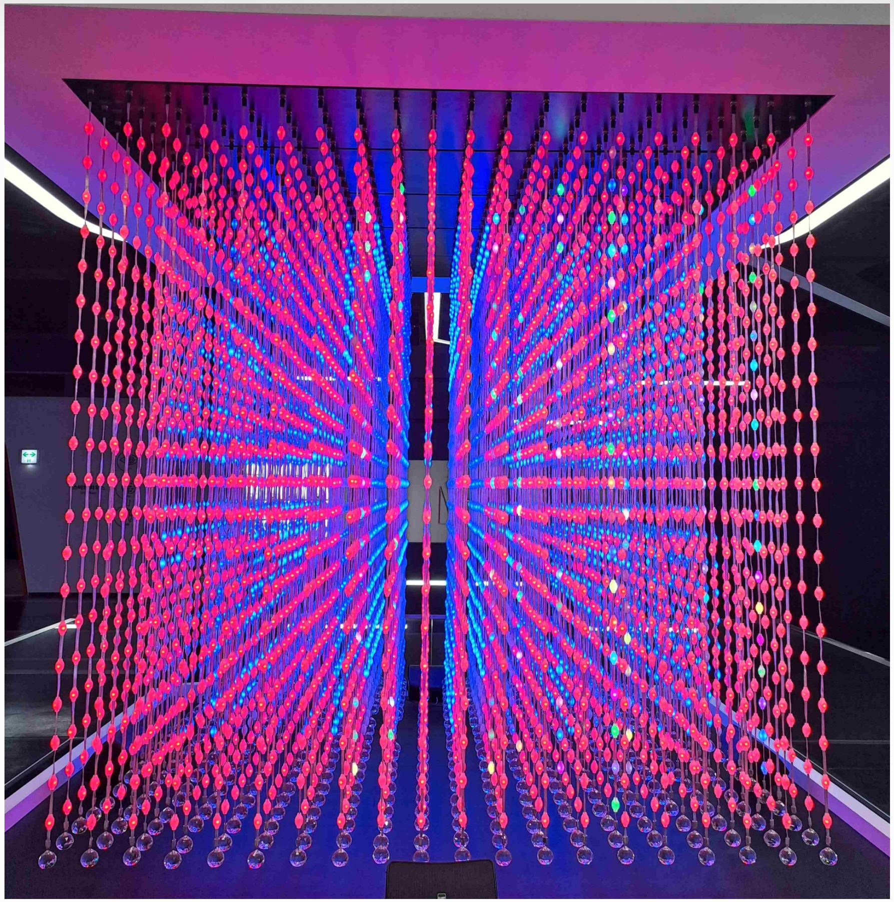
Containment fraction for **DM annihilation** as a function of **angular distance** from the center of **Segue 1***.
The solid colored curves show the PSF of a silicon detector, while the dashed colored line shows the PSF of an Atmospheric Cerenkov telescope.

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

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

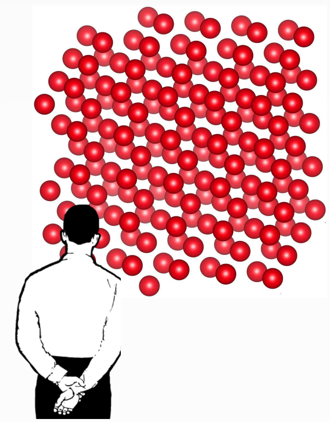


How does an oriented crystal look like?

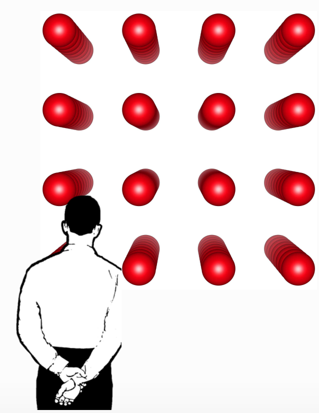


from National Science Museum, Daejeon, Korea

Non-oriented crystal

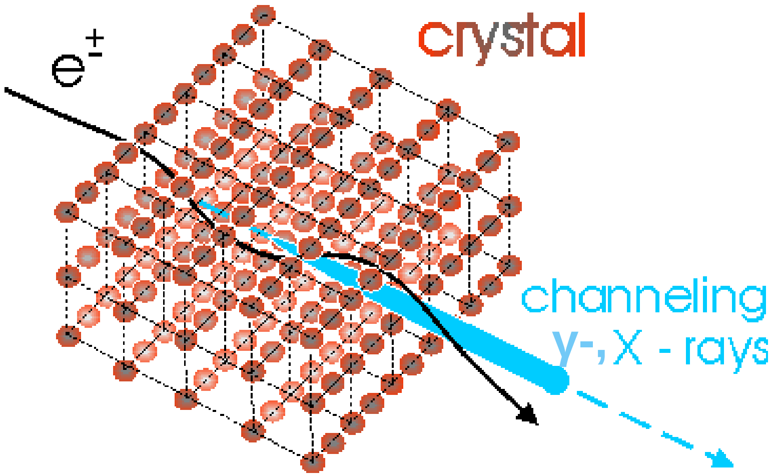


Oriented crystal



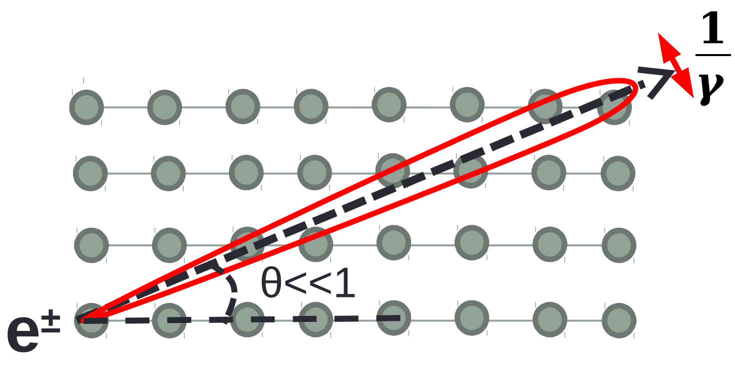
Coherent effects in a crystal

Channeling radiation*

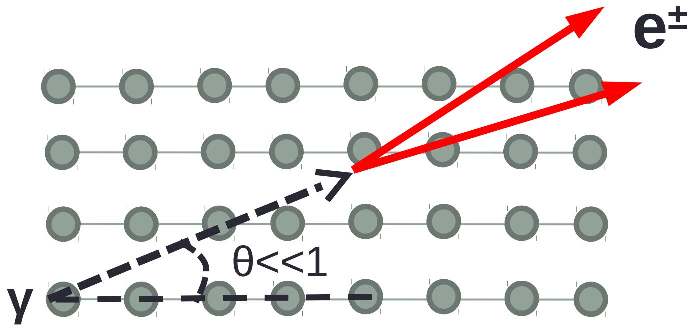


Coherent effects preserve **up to few mrad** of particle direction vs the crystal axis

Coherent bremsstrahlung**



Coherent pair production***

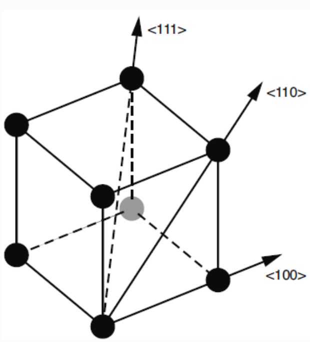


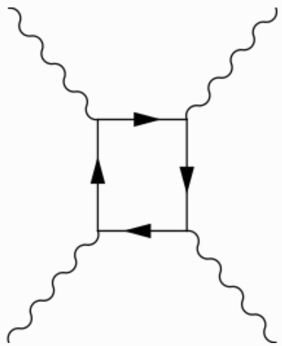
*M.A. Kumakhov, Phys. Lett. A 57(1), 17–18 (1976)
**B. Ferretti, Nuovo Cimento 7, 118 (1950).
**M. Ter-Mikaelian, Sov. Phys. JETP 25, 296 (1953).
*** H. Überall, Phys. Rev. 103, 1055 (1956).

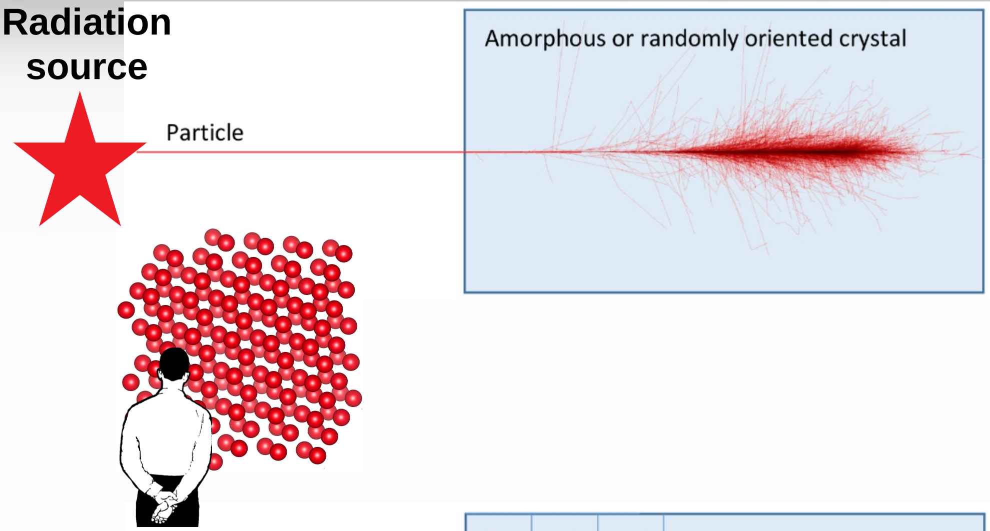
Electromagnetic shower acceleration

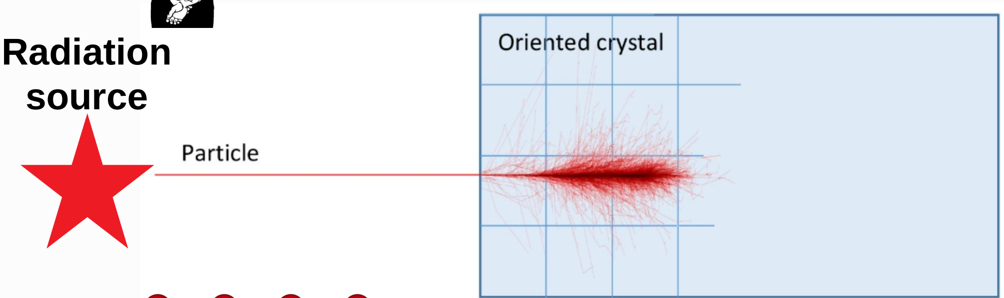
Axial field 10^{11}-10^{12} V/cm

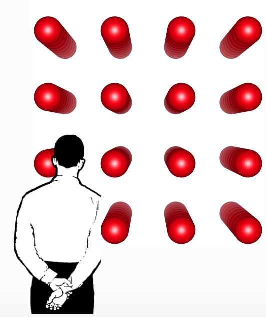
Approaching the **Schwinger limit** starting from few **GeV** for **e+/e-**











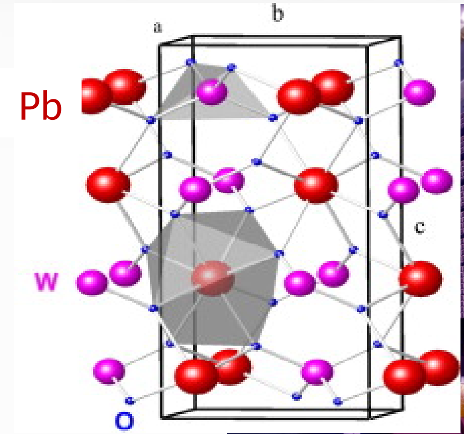
The **radiation** intensity and the **pair production** cross-section **drastically increase** in **oriented crystals!**

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

L. Bandiera et al., Phys. Rev. Lett. 121, 021603 (2018)

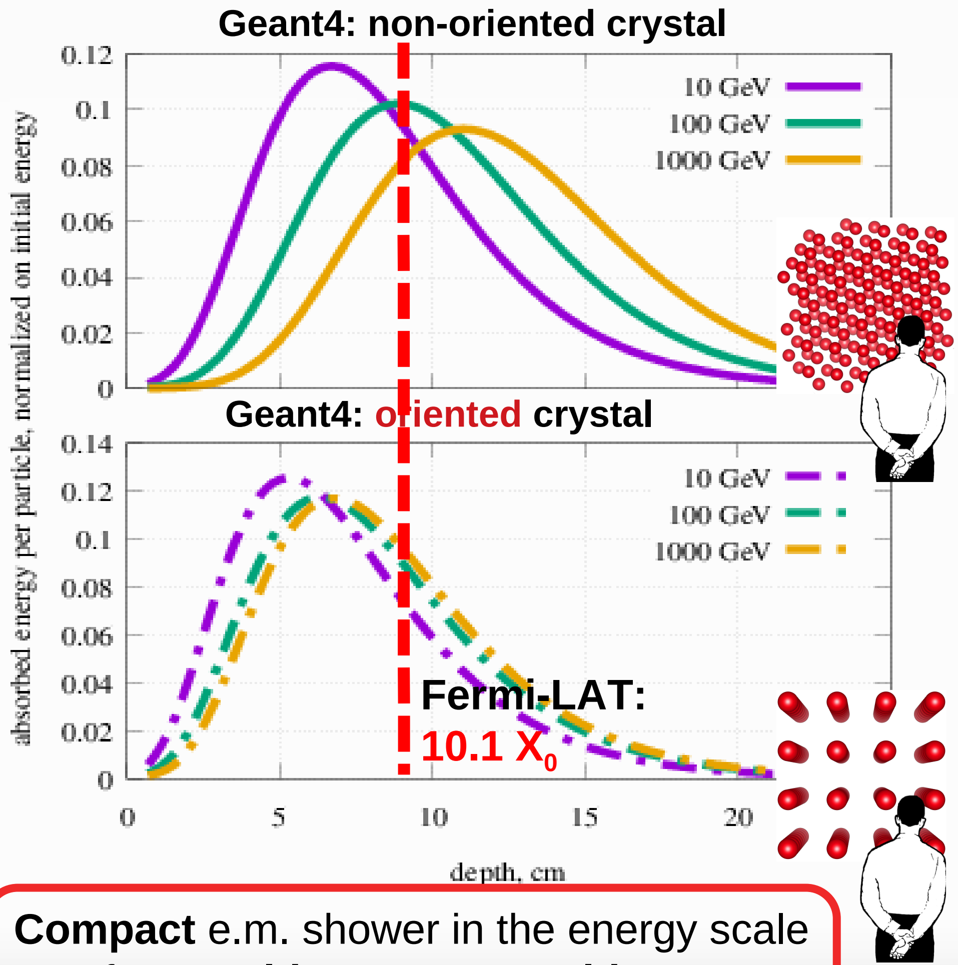
Orienting the electromagnetic calorimeter => making it thinner!

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**!

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:

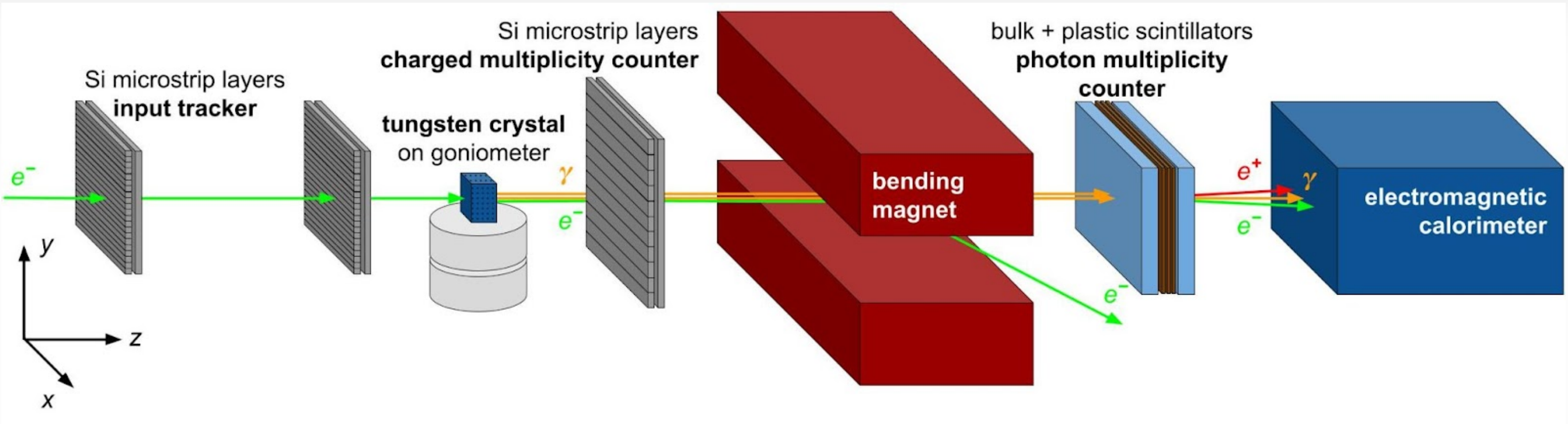
- **A. Sytov** – project coordinator
- **L. Bandiera** – INFN supervisor
- **K. Cho** – KISTI supervisor
- **G. Kube** – DESY supervisor
- **I. Chaikovska** – IJCLab Orsay supervisor

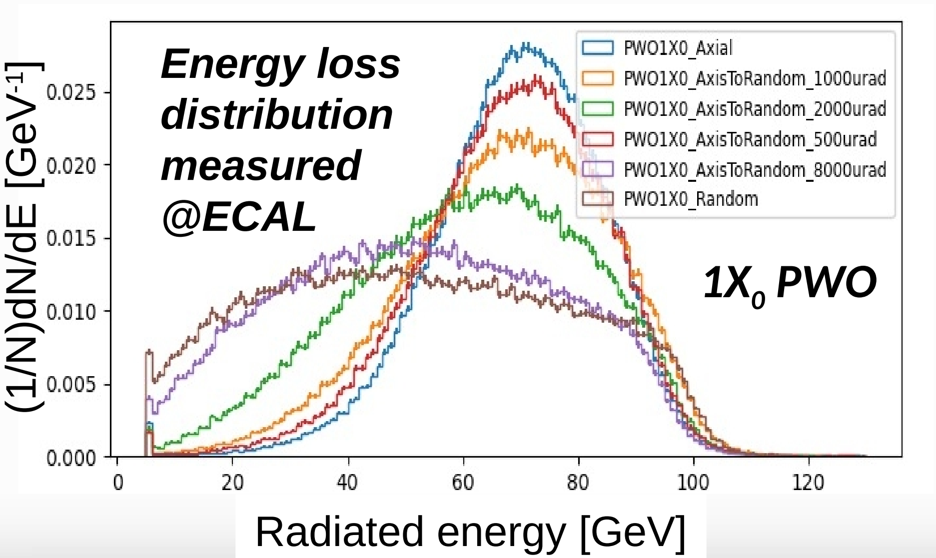
Location:

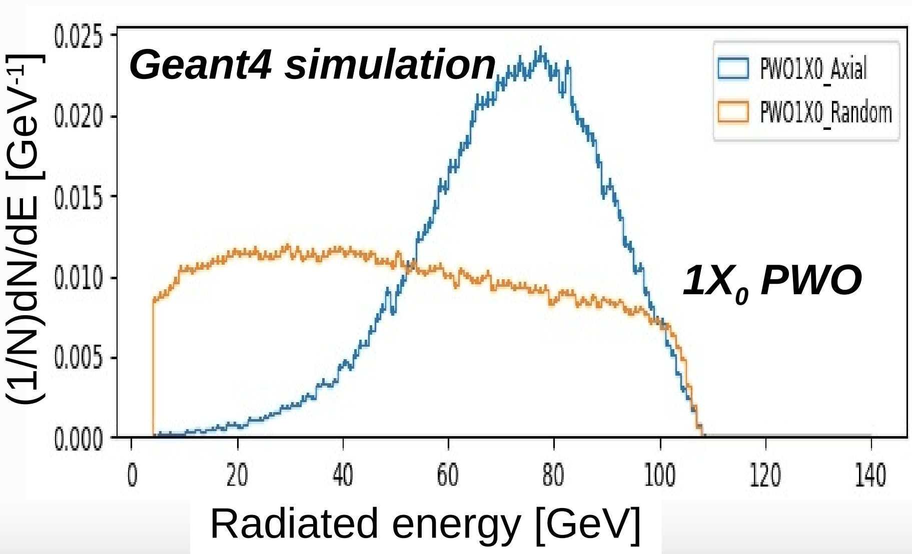
- 2 years at **KISTI** (partner organization)
- 1 year at **INFN Section of Ferrara** (host organization)
- 1 month of secondment at **DESY** (partner organization)
- 1 month of secondment at **IJCLab Orsay** (partner organization)

Experimental data for PWO oriented crystal at CERN SPS H4 line

Beam: e⁻ @120 GeV

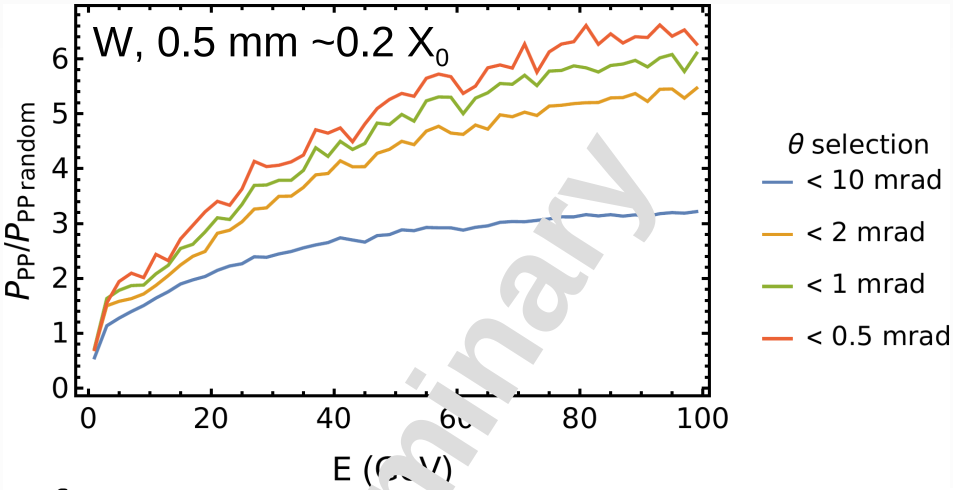


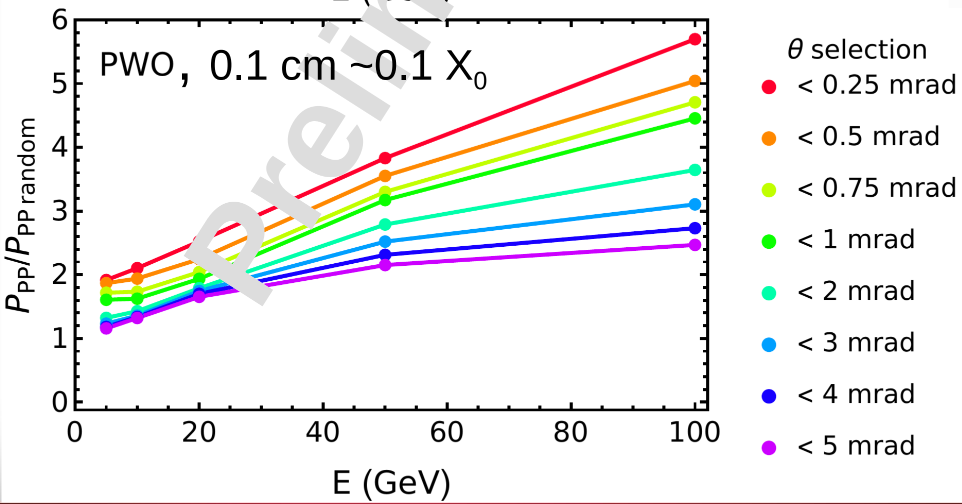




What gamma-ray about angles?

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





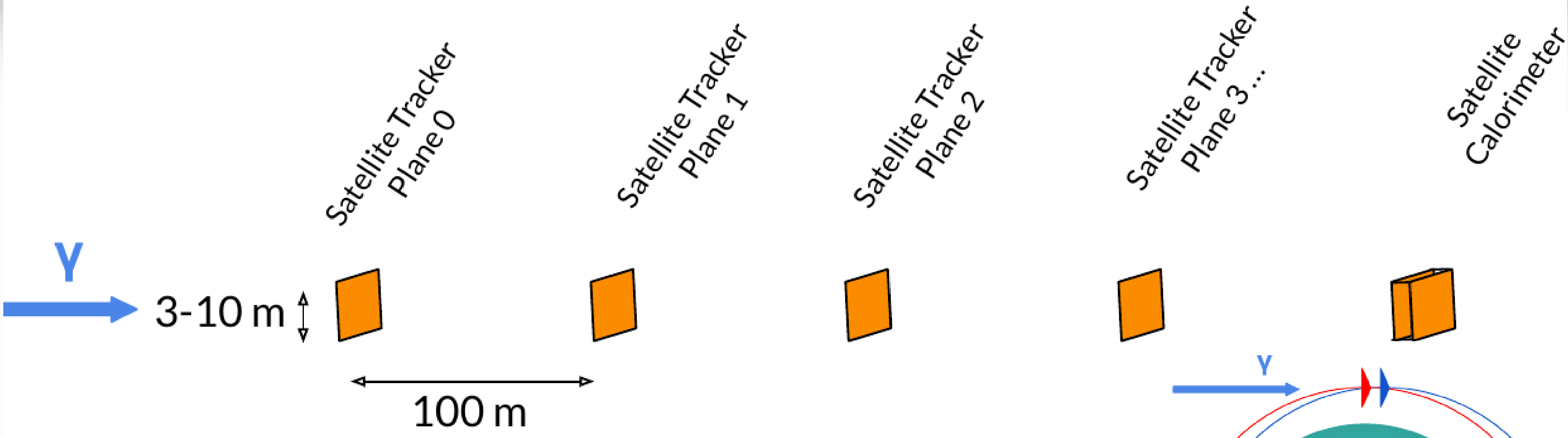
Dwarf Galaxies (Favored in Bold)	Distance [kpc]	Theta_0p5 Median Value for angle estimate [deg]	+Error	J_0p5 / 1e18 J scale in linear units (Arb)
UrsaMinor	66	0.06	0.07	8.51
Segue1	23	0.13	0.05	22.91
LeoII	205	0.04	0.05	0.93
UrsaMajorII	30	0.24	0.06	26.30
Coma	44	0.16	0.02	10.47
Sculptor	92	0.15	0.05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

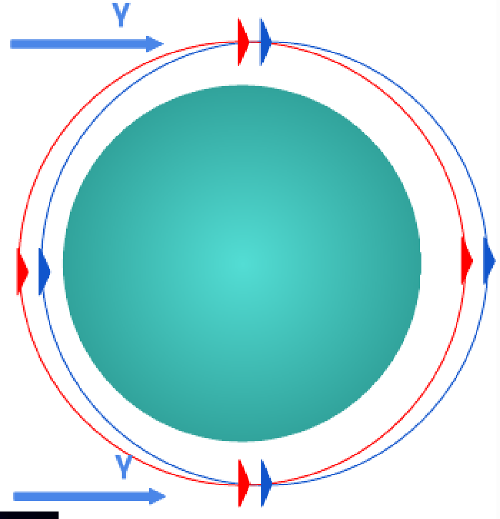
Pair Production Enhancement happens within 2 mrad~**0.1°** for W and 1 mrad~**0.05°** for PWO => optimal for dwarf galaxies

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).

What about multiple satellite for particle tracking?

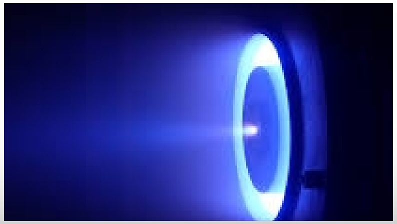




- We can **considerably reduce** amount of read-out electronics => the **mission cost** by using l**arge pixels**
- Angular resolution of ~0.1° requires ~**100 m** of the distance between tracker stations in this case

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

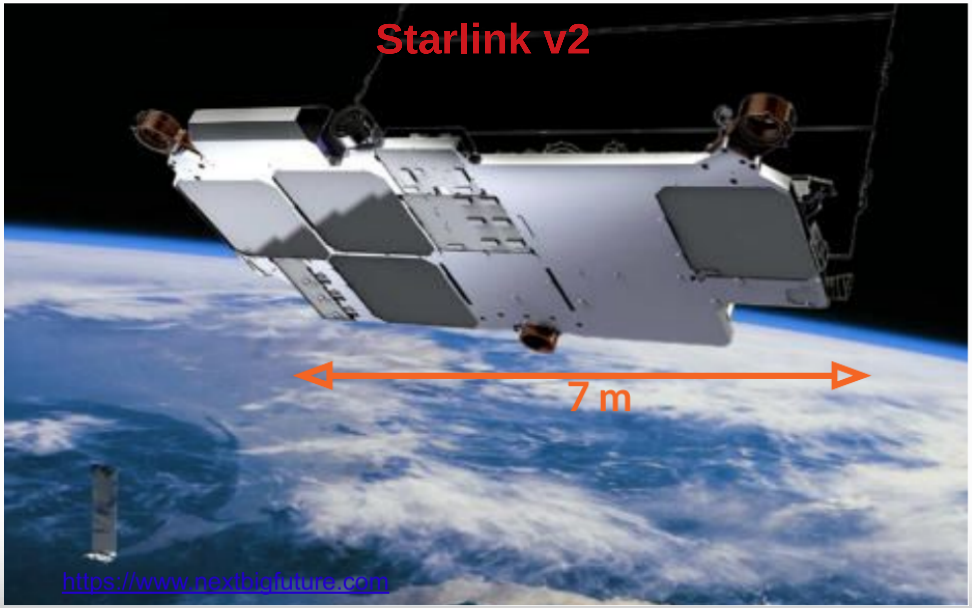
The required thrust magnitudes are consistent with use of **Hall-Effect Thrusters**

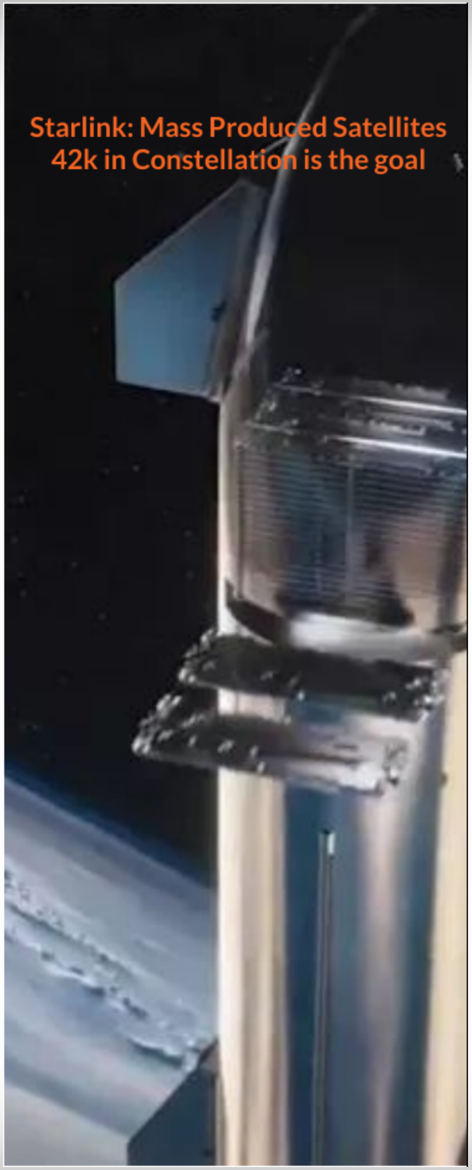


Starlink Satellites v1.5, v2 mini, and v2

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





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!

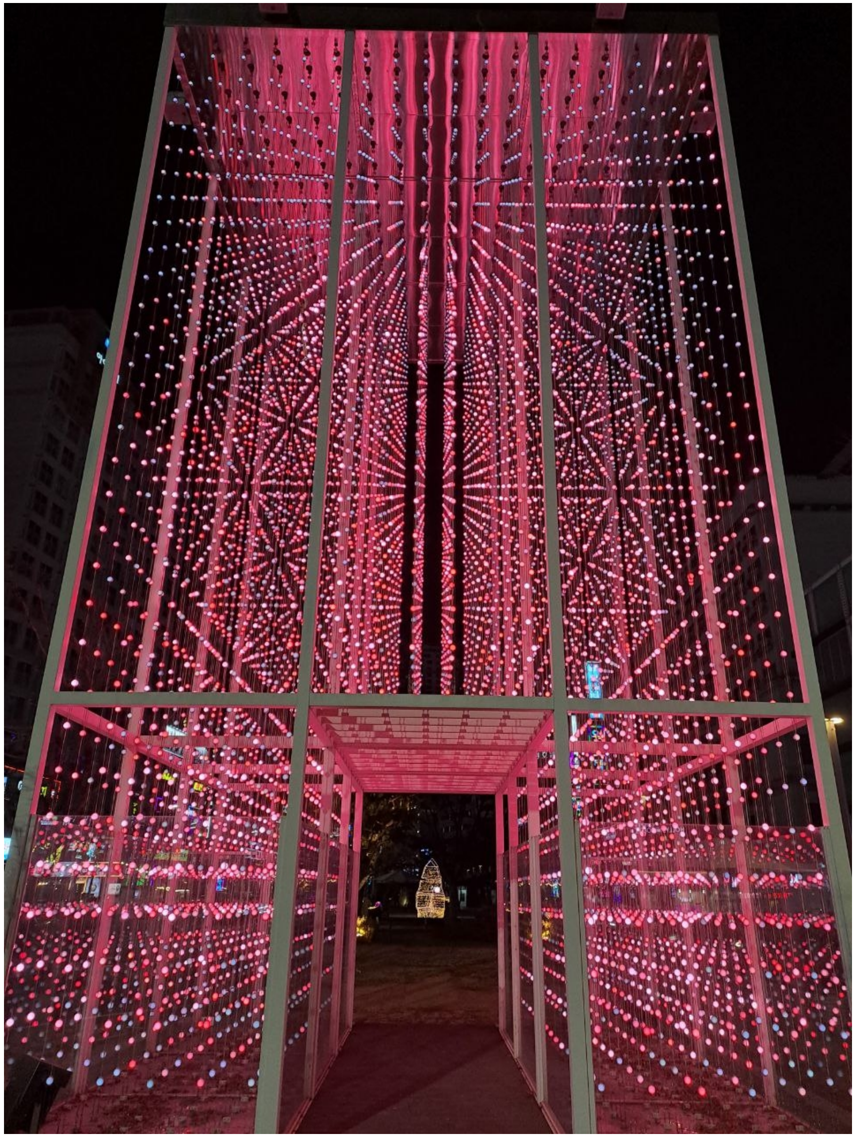
- **Fermi telescope resolution** both energy and angular is **limited** for this purpose. The surface area also needs to be increased to accumulate the statistics faster!

- 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.

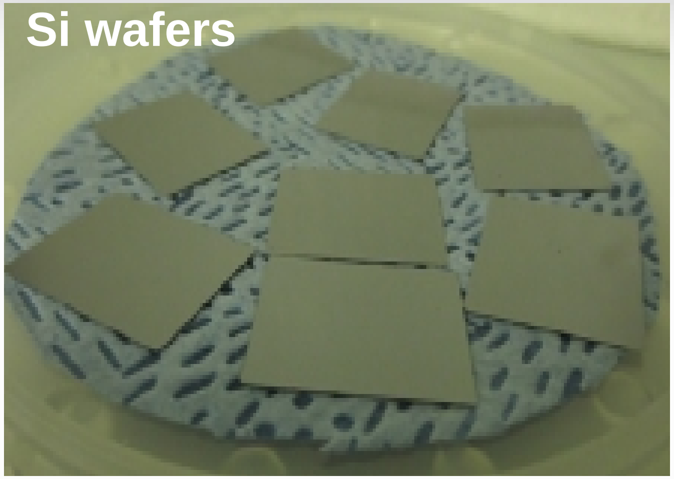
- **Considerable reduction** of the **cost** requires large pixel size. To use the tracker for the measurement of the angles we may need a set of satellites.

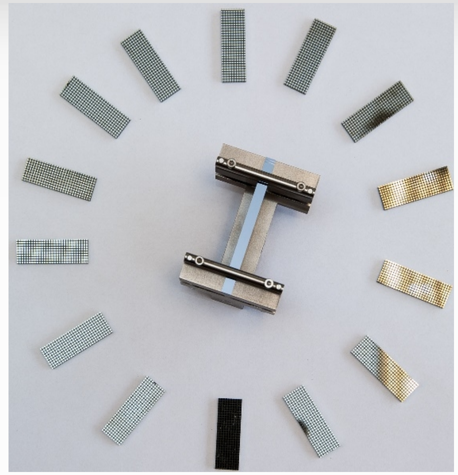
- **The goal of TRILLION** is to implement **electromagnetic processes in oriented crystals** into **Geant4**. This will help to **simulate an entire telescope**.



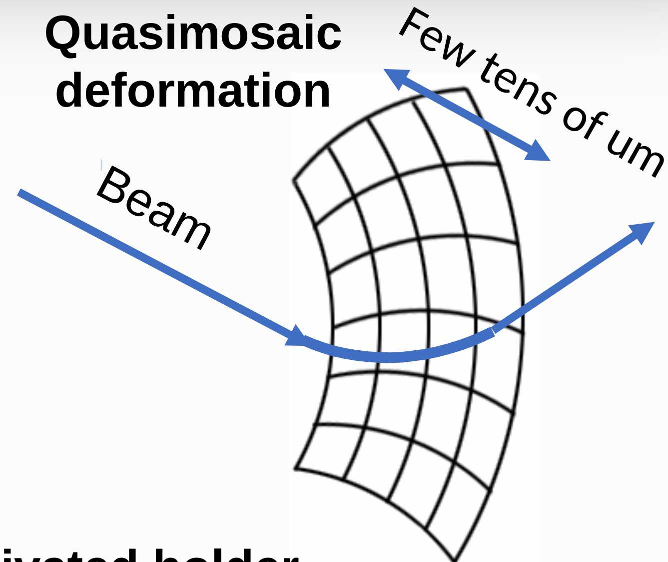
Thank you for attention!

Manufacturing and characterization of bent silicon crystals @INFN Ferrara

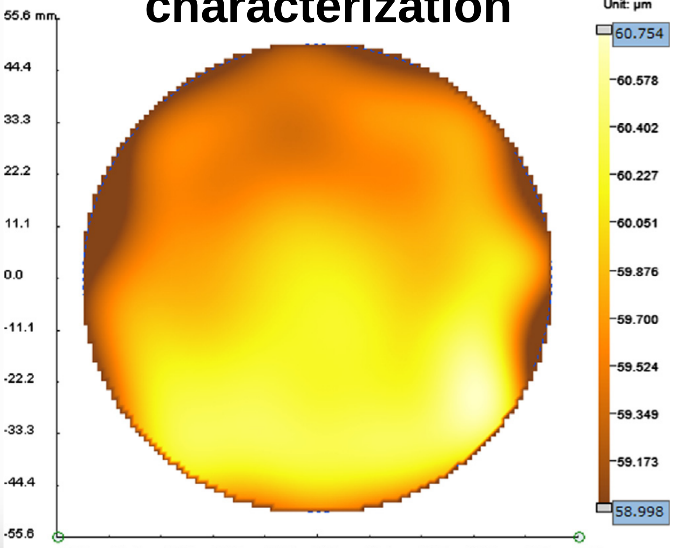




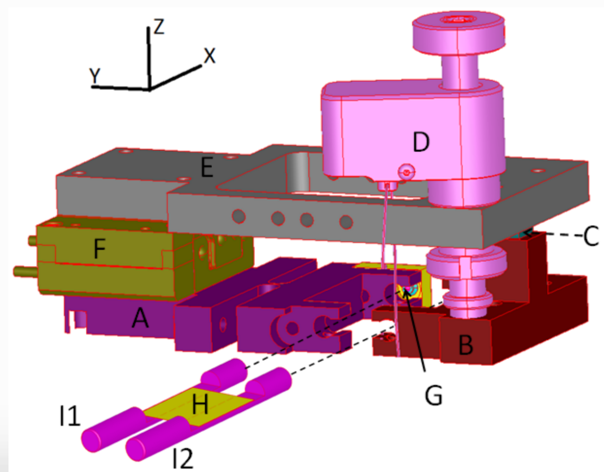
Quasimosaic deformation

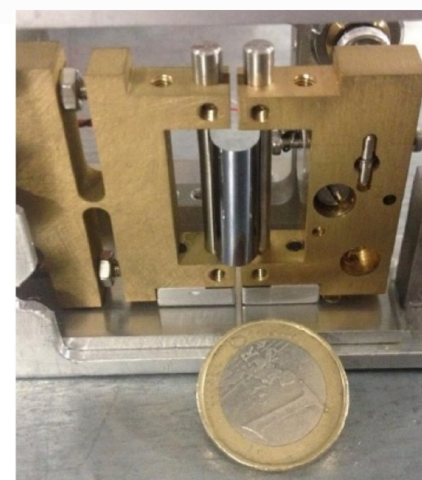


characterization



Piezo-activated holder

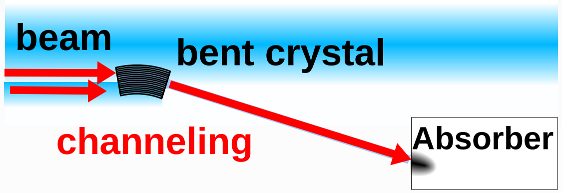


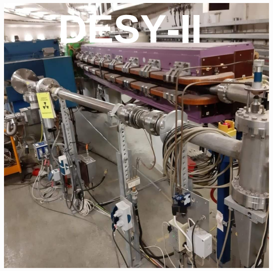


G. Germogli et al. NIM B 355 (2015) 81–85

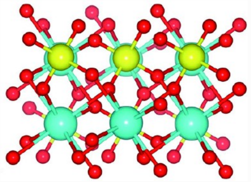
Applications*

Crystal-based collimation or beam extraction from an accelerator



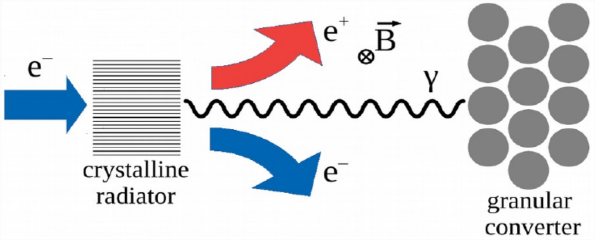


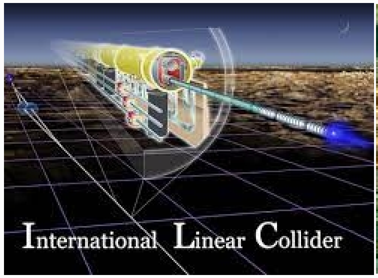
Ultrashort crystalline calorimeter

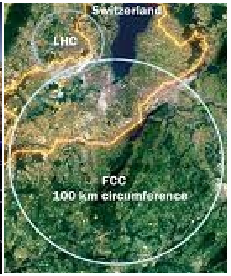


Gamma-ray Space Telescope

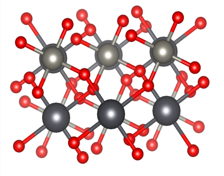
Positron source for future e+/e- and muon colliders



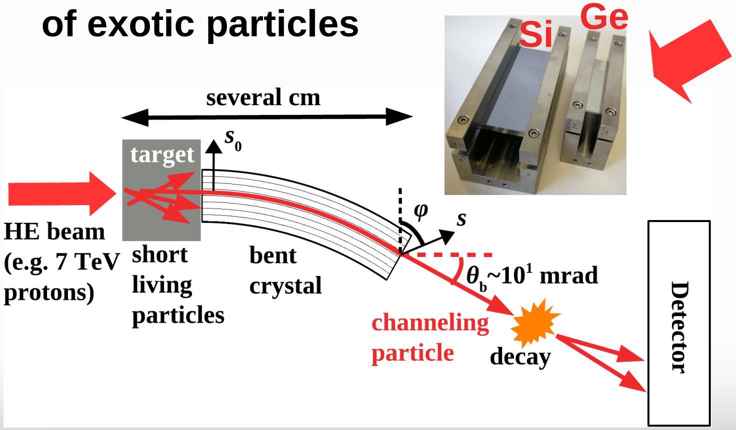




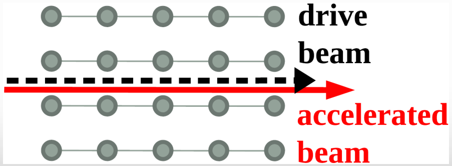
Oriented crystals



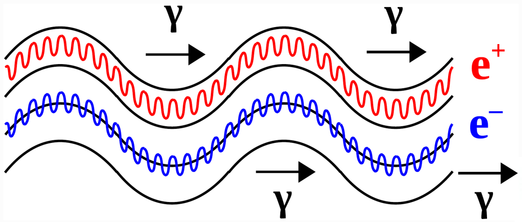
Measurement of dipole magnetic and electric moments of exotic particles

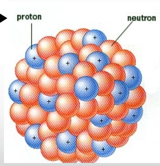


Plasma acceleration



X and γ-ray source for nuclear and medical physics





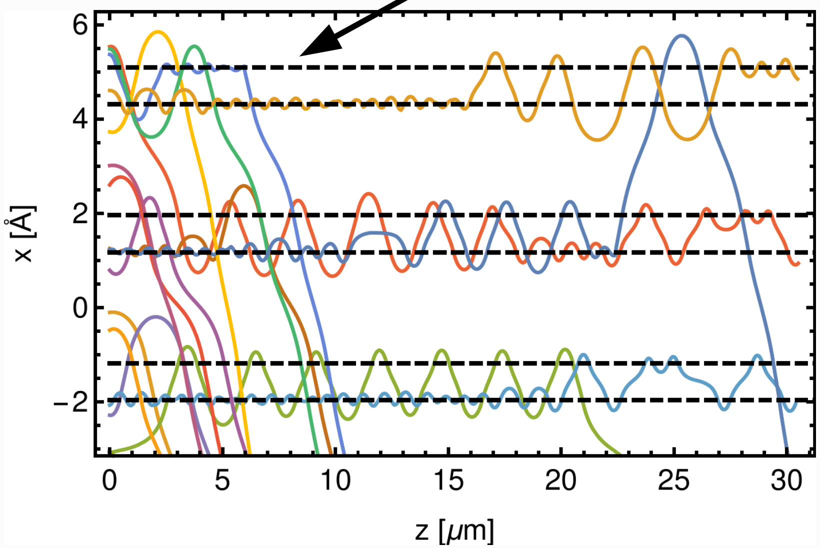
*A. Sytov et al. arXiv: 2303.04385, Accepted for publication in JKPS

Channeling simulation technique: CRYSTALRAD Monte Carlo simulation code

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

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

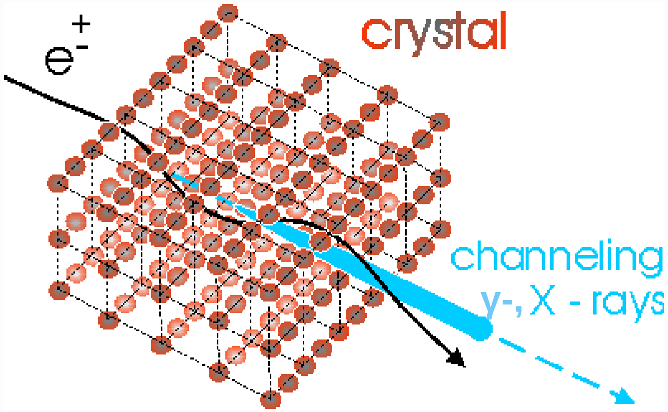
Crystal planes



channeling*

Advantages:

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



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

$$\frac{dE}{d^3k} = \omega \frac{dN}{d^3k} \frac{\alpha}{4\pi^2} \iint dt_1 dt_2 \frac{[(E^2+E'^2)(v_1v_2-1)+\omega^2/\gamma^2]}{2E'^2} e^{-ik'(x_1-x_2)}$$

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. arXiv: 2303.04385, Accepted for publication in JKPS**
A. I. Sytov, V. V. Tikhomirov, and L. Bandiera. PRAB 22, 064601 (2019)

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");
            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(crystalLogic,lattice);
    //setting bending angle of the crystal planes (default is 0)
    BendingAngle = 0.905*mrad;
    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

Logical volume

Model activation

Additional options

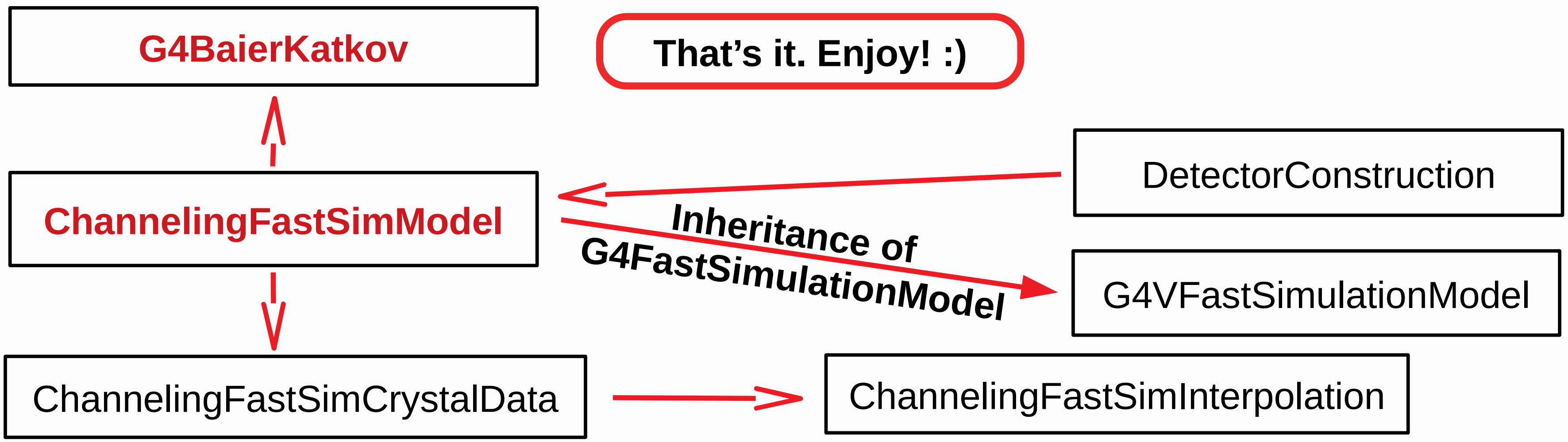
Radiation model activation

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 );
```

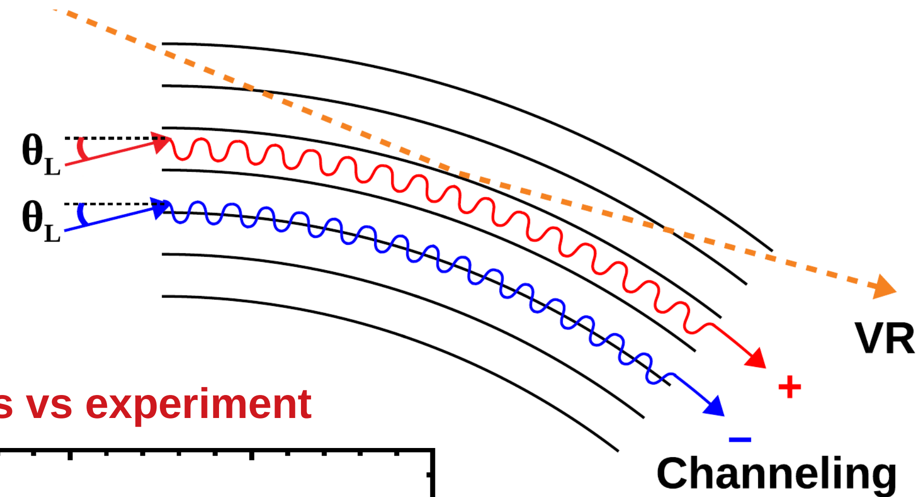


Physics list independent

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

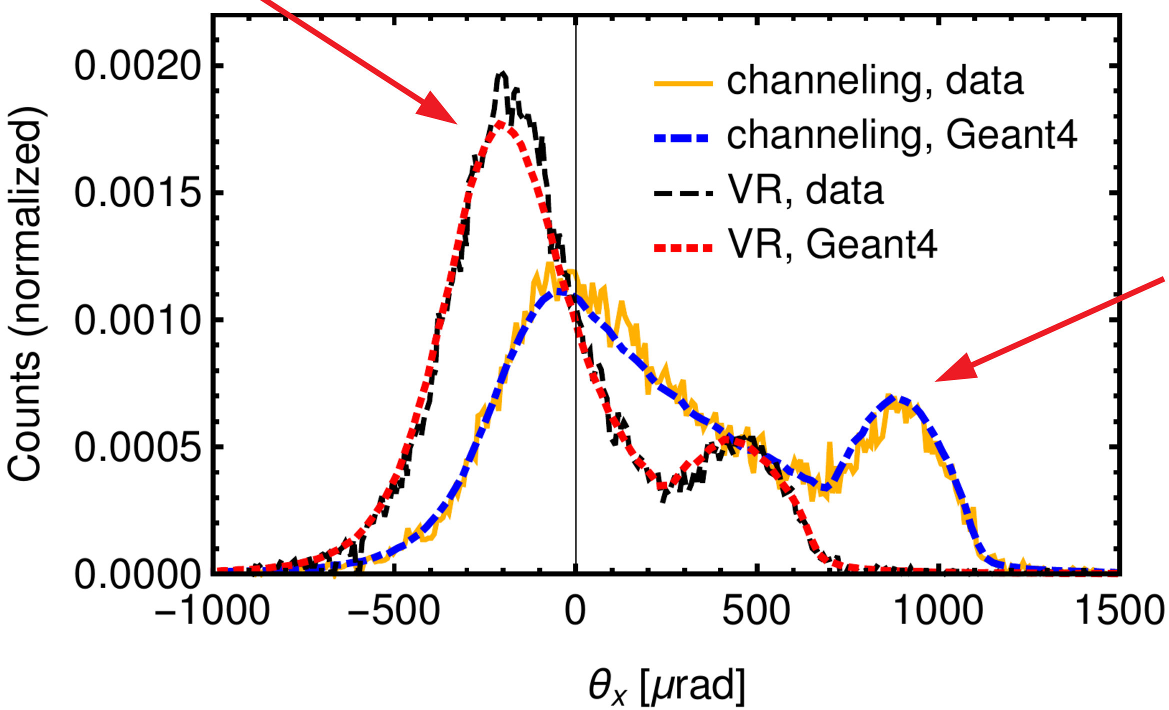
855 MeV electrons

15 µm thick bent crystal



volume reflection (VR)

Geant simulations vs experiment



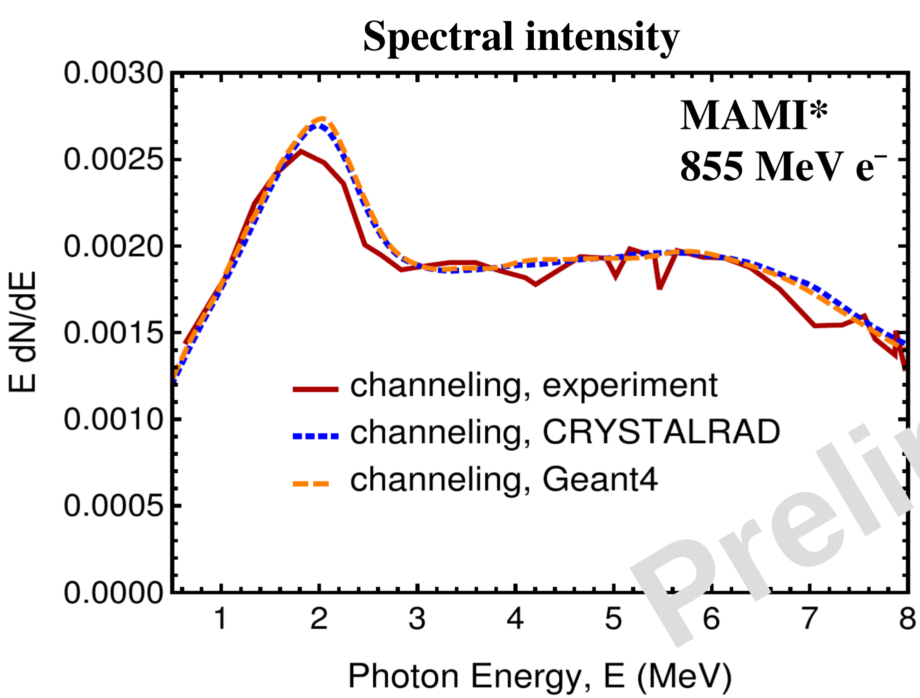
channeling

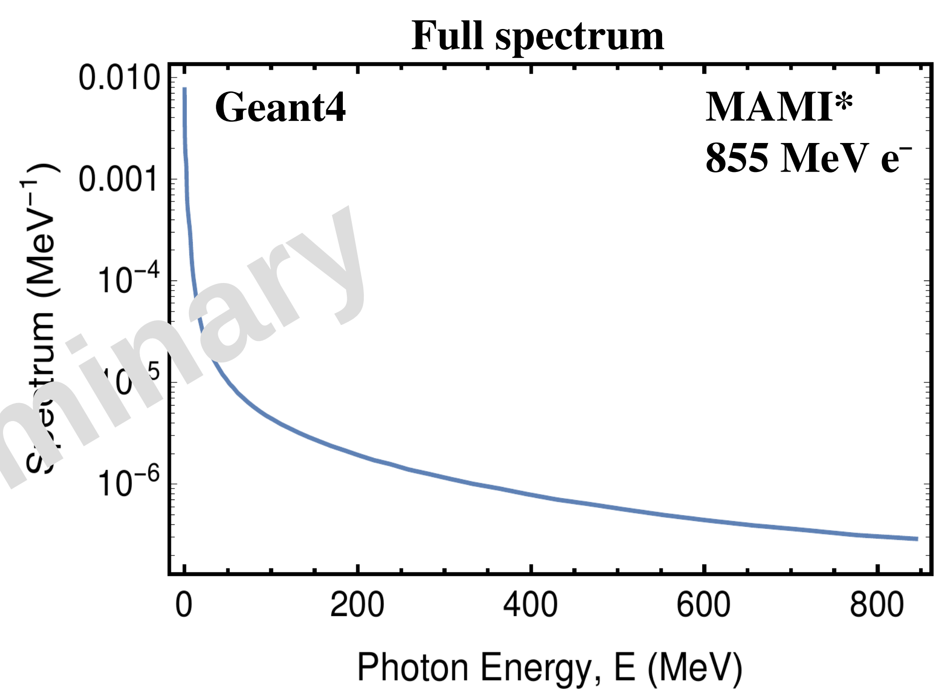
First Geant4 Baier-Katkov radiation model: radiation by 855 MeV electrons at Mainz Mikrotron MAMI*

G4BaierKatkov:

- **Physics list independent**
- Activated in the **DetectorConstruction** and used in **ChannelingFastSimModel**
- Can be used **outside channeling model** (e.g. in **SteppingAction**)
- 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)