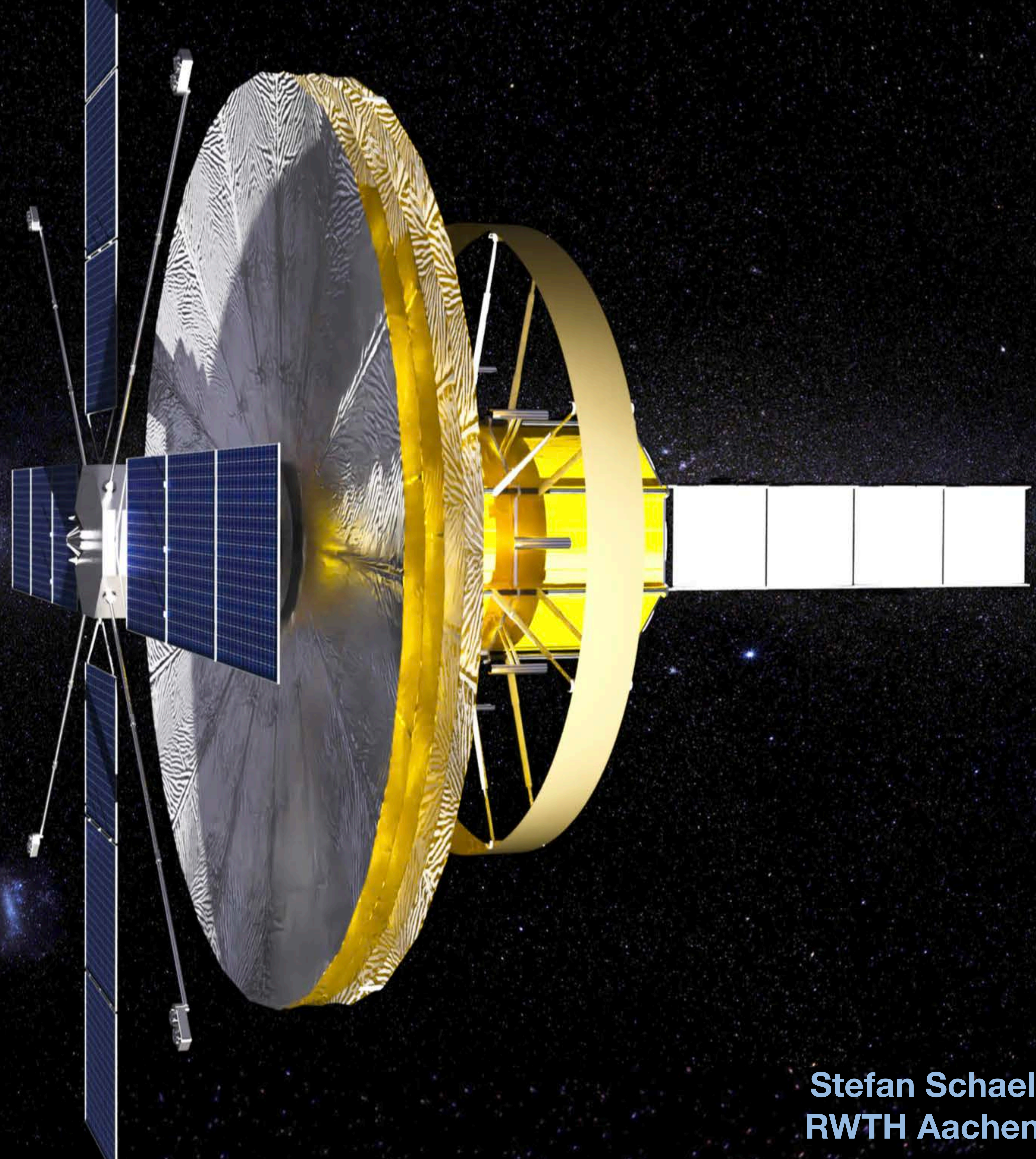
# AMS-100

## A Magnetic Spectrometer with an acceptance of 100 m² sr in Space



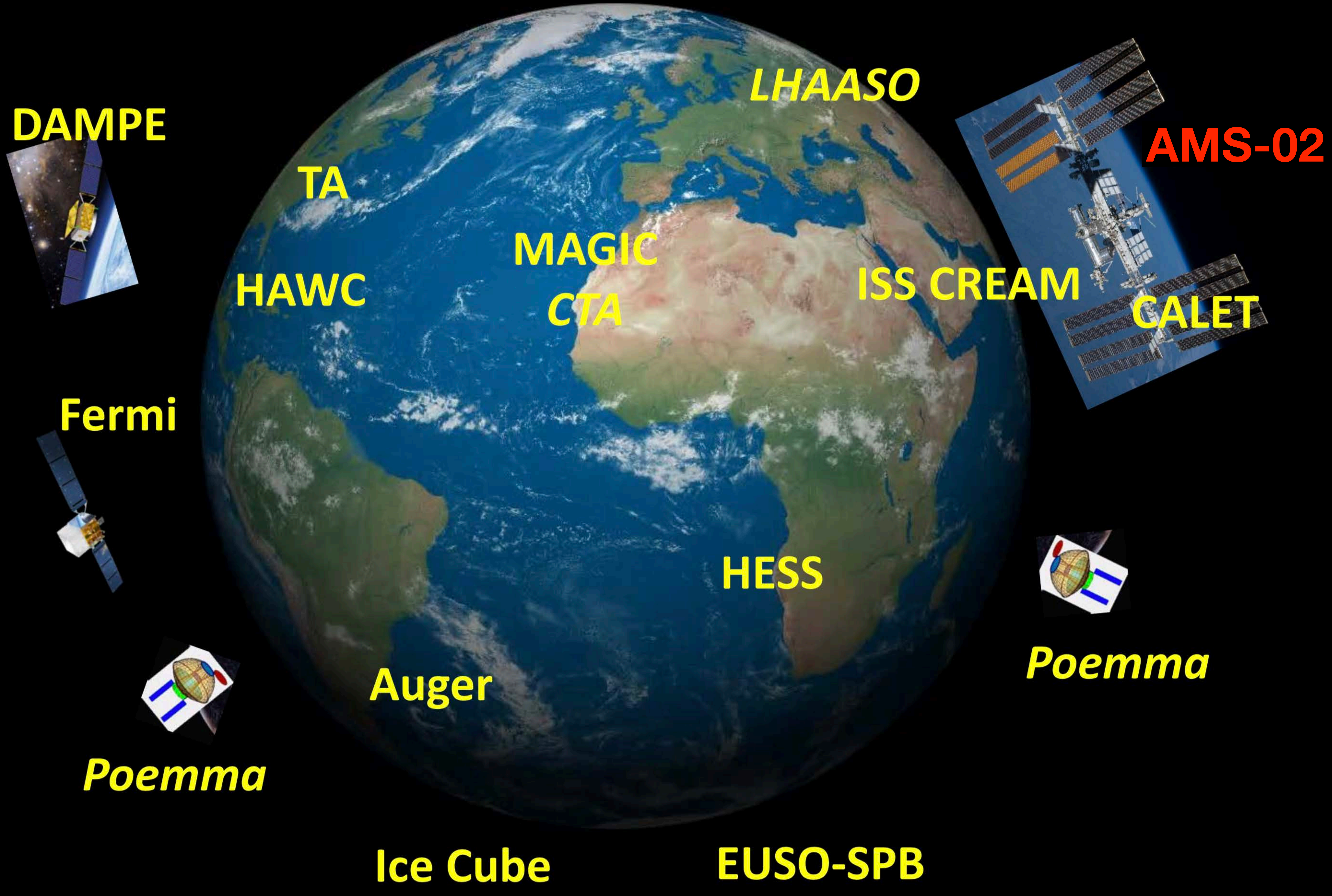
*First Workshop NextGAPES -2019*

*Lomonosov Moscow State University, Physics Department, Skobeltsyn Institute of Nuclear Physics.*

*Moscow - June, 21-22, 2019*

Stefan Schael
RWTH Aachen

# Major Cosmic Ray Experiments



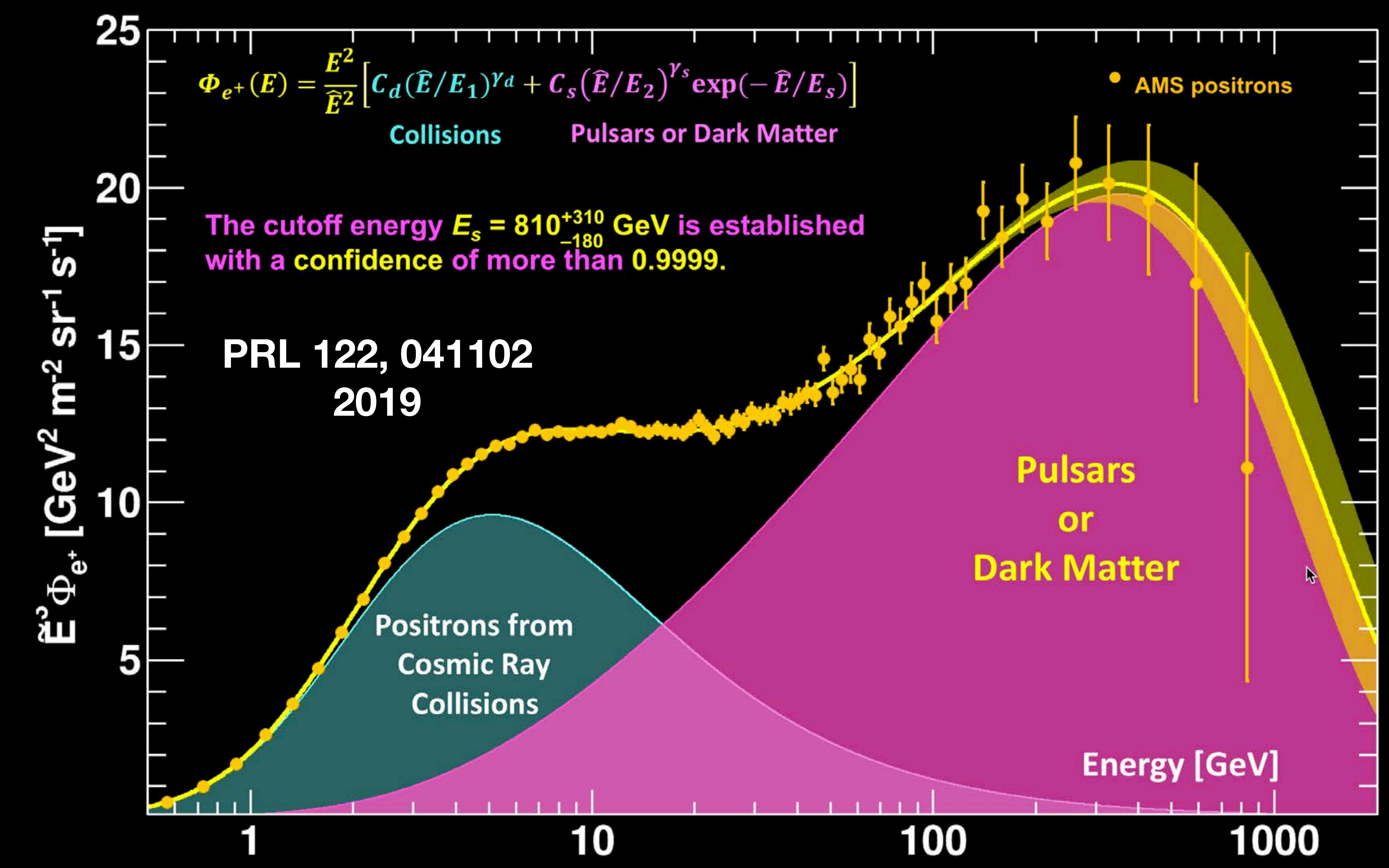

We have only one magnetic spectrometer in space: AMS-02

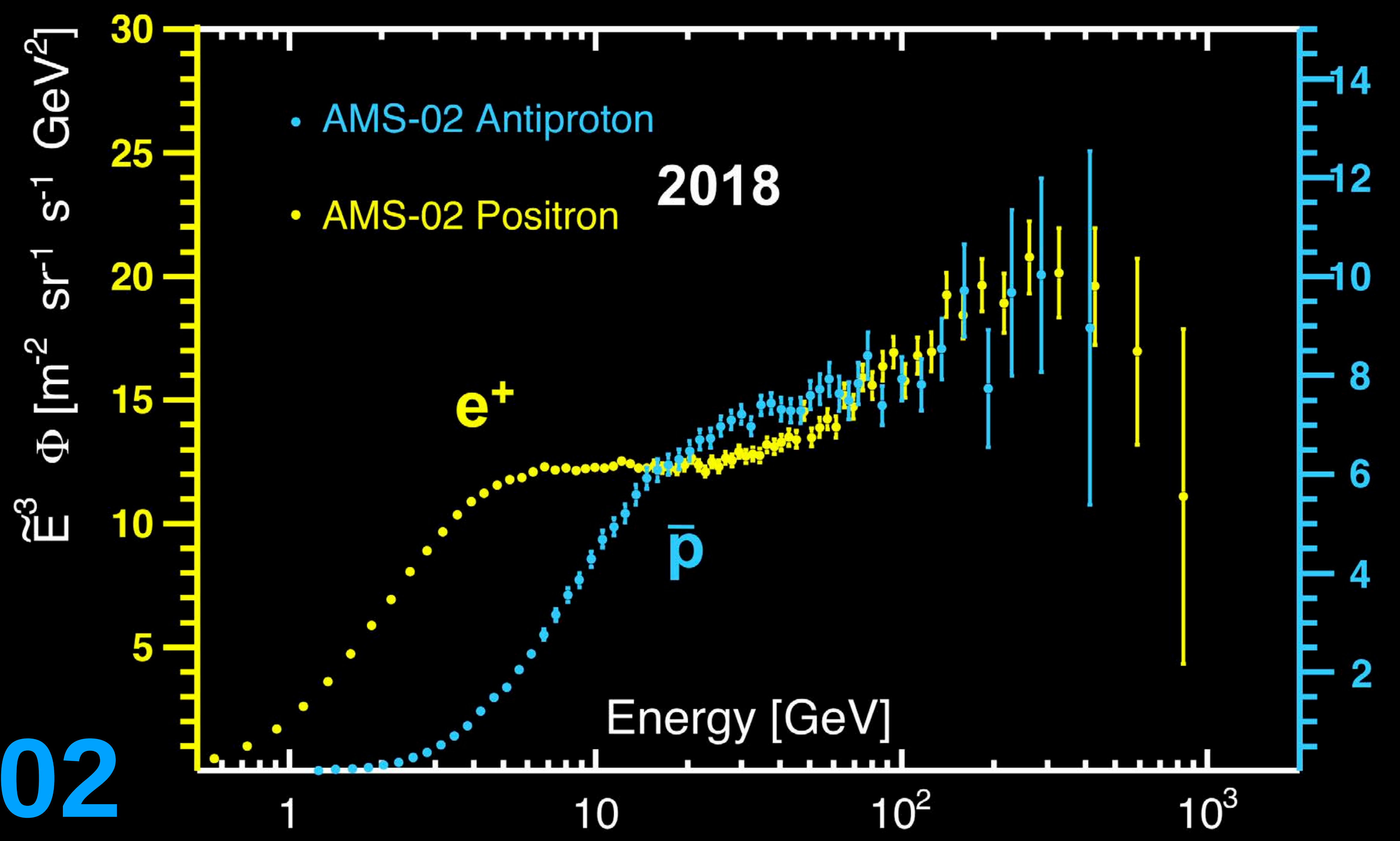

The **A**lpha **M**agnetic **S**pectrometer was installed on the ISS in May 2011.

**AMS-02** has recorded more than 135 Billion cosmic rays and will continue through the lifetime of ISS.

# The AMS-02 Transition Radiation Detector was build at RWTH Aachen
# October 2007

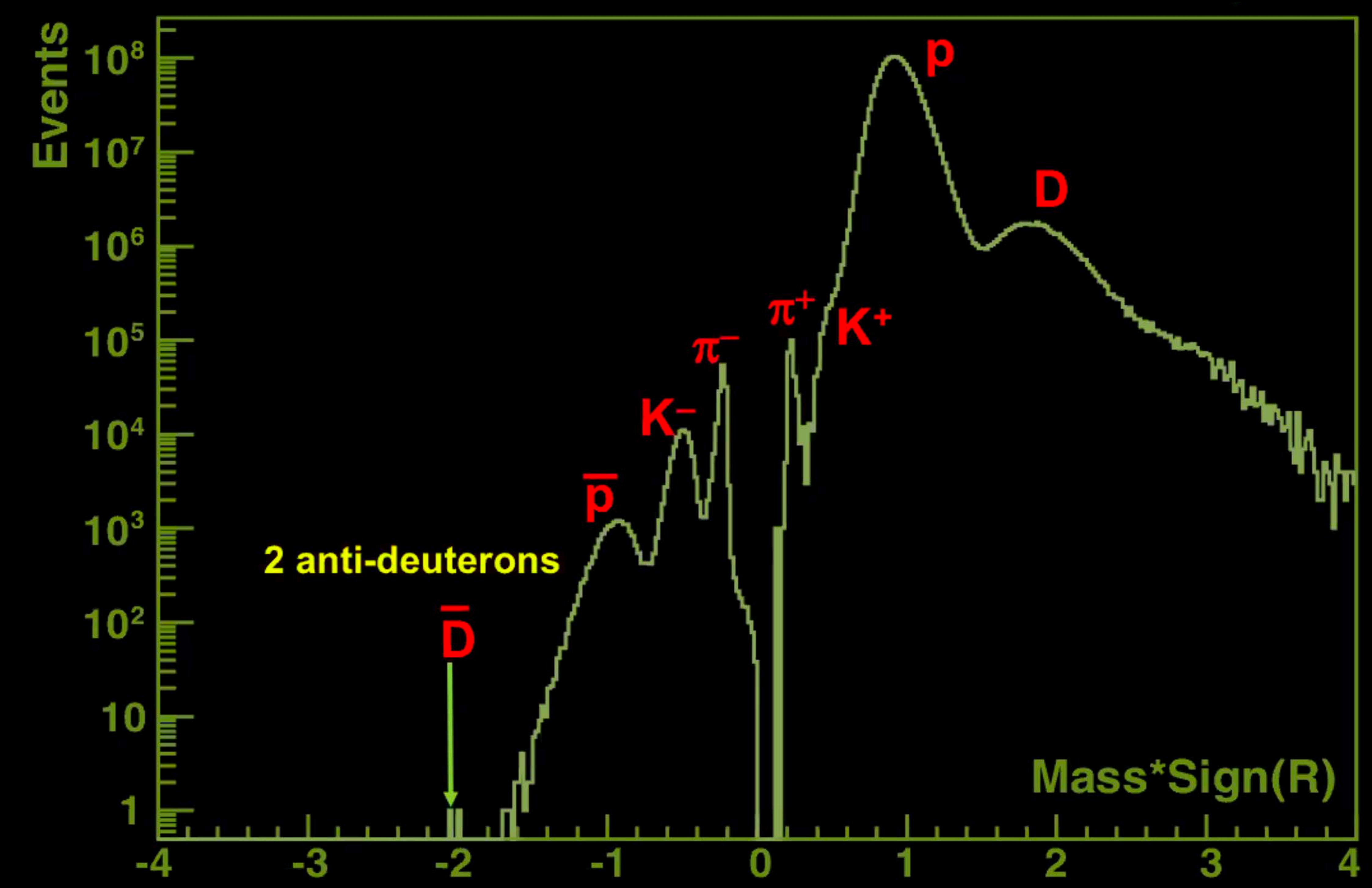
**The 200 kg Upgraded Tracker Thermal Pump System for AMS-02 was build at RWTH Aachen and will be brought to the ISS in October 2019.**

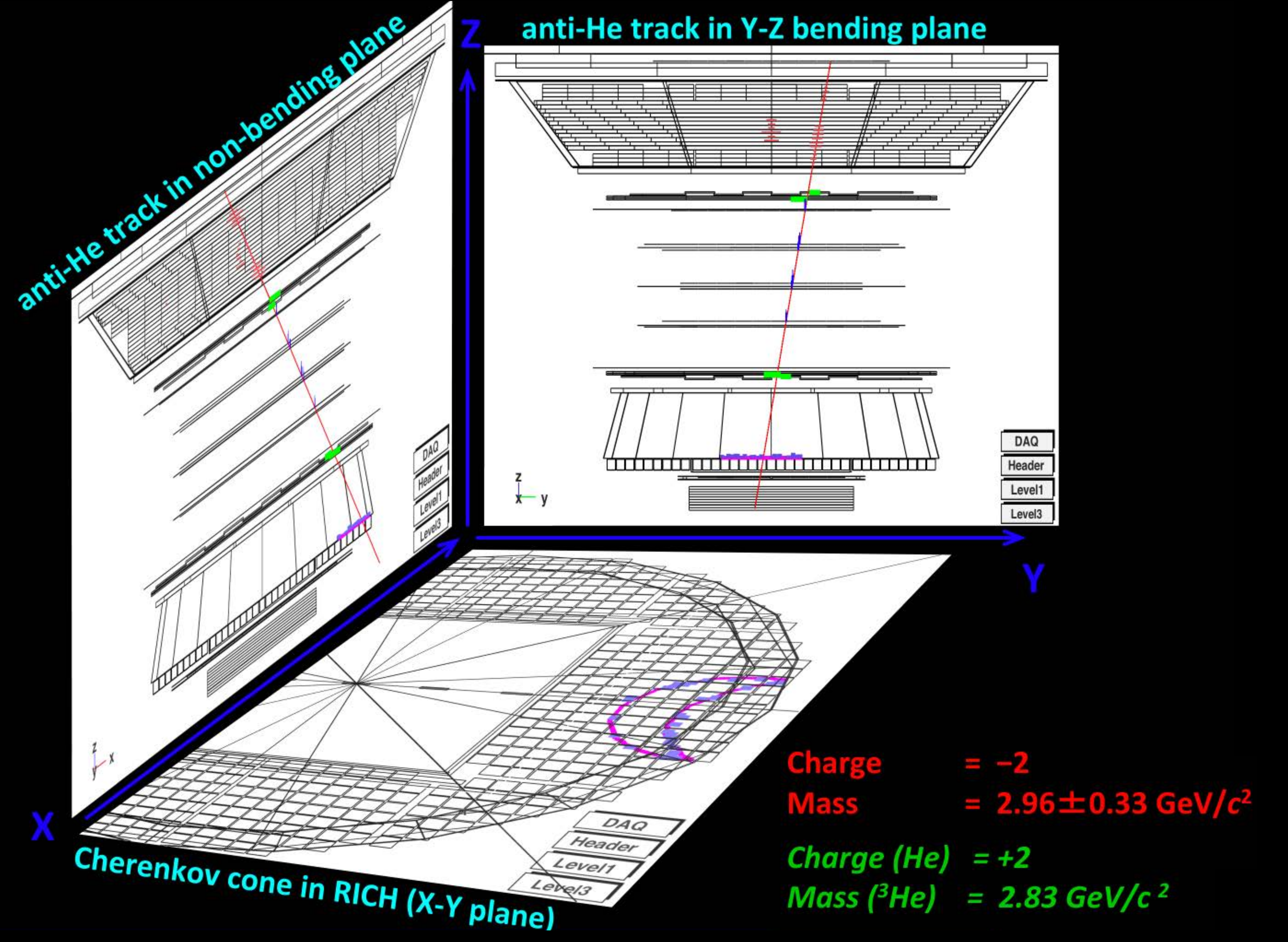


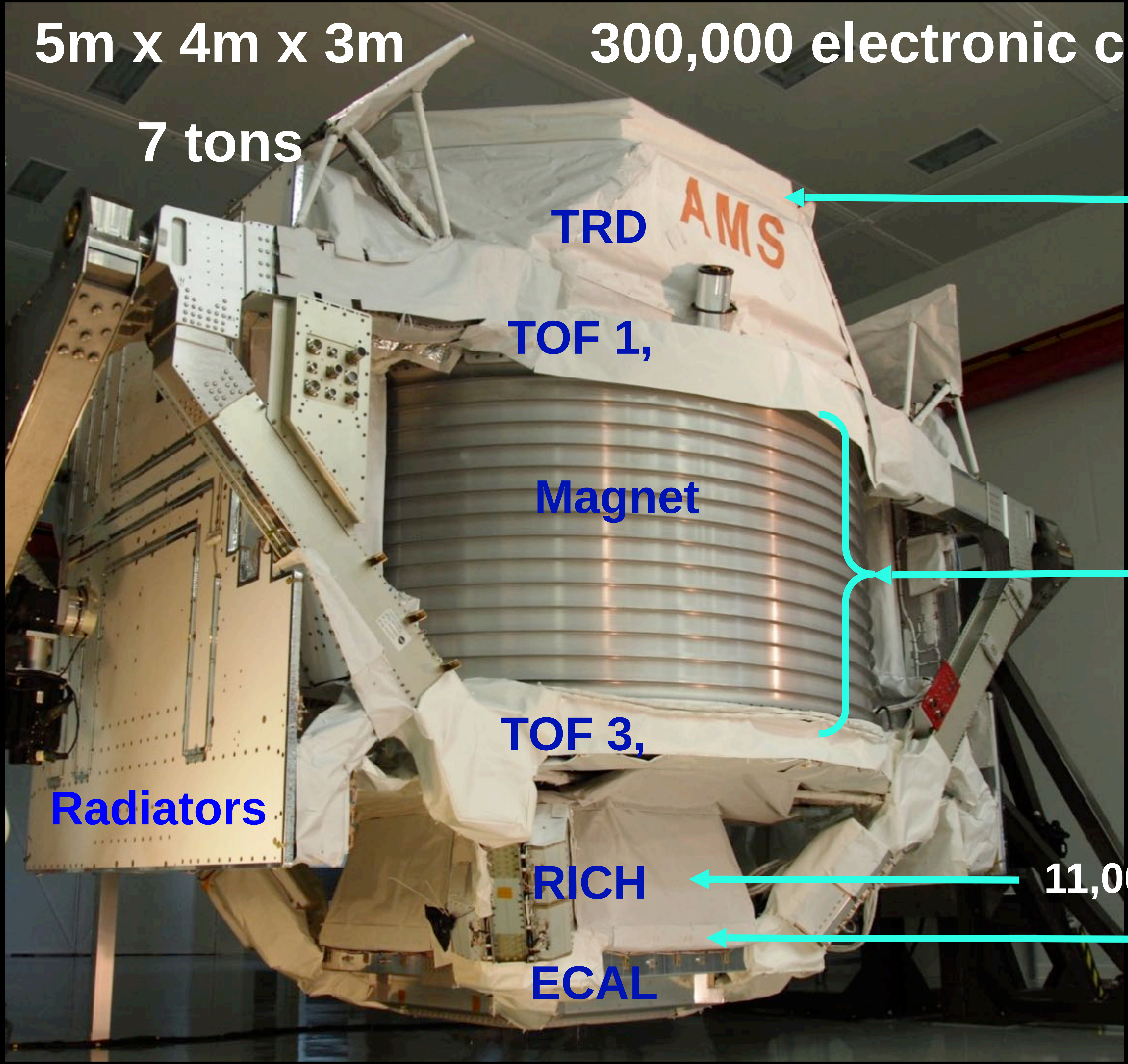

# AMS-02 Results

**A. Kounine, NextGAPES-2019, Moscow**



It took 600 Physicists and Engineers from 16 Countries and 60 Institutes
17 years to construct the Alpha Magnetic Spectrometer.



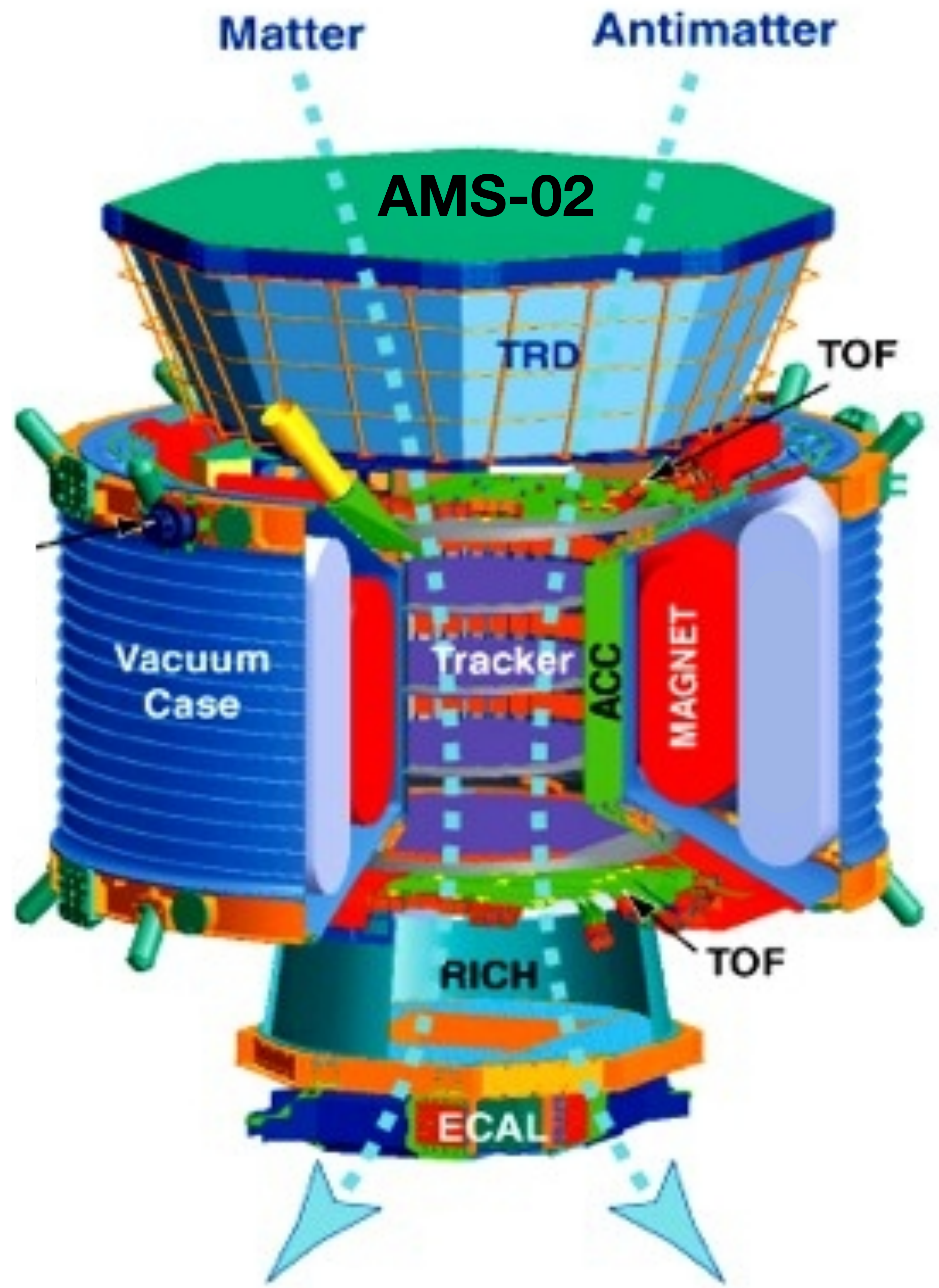

Silicon layer

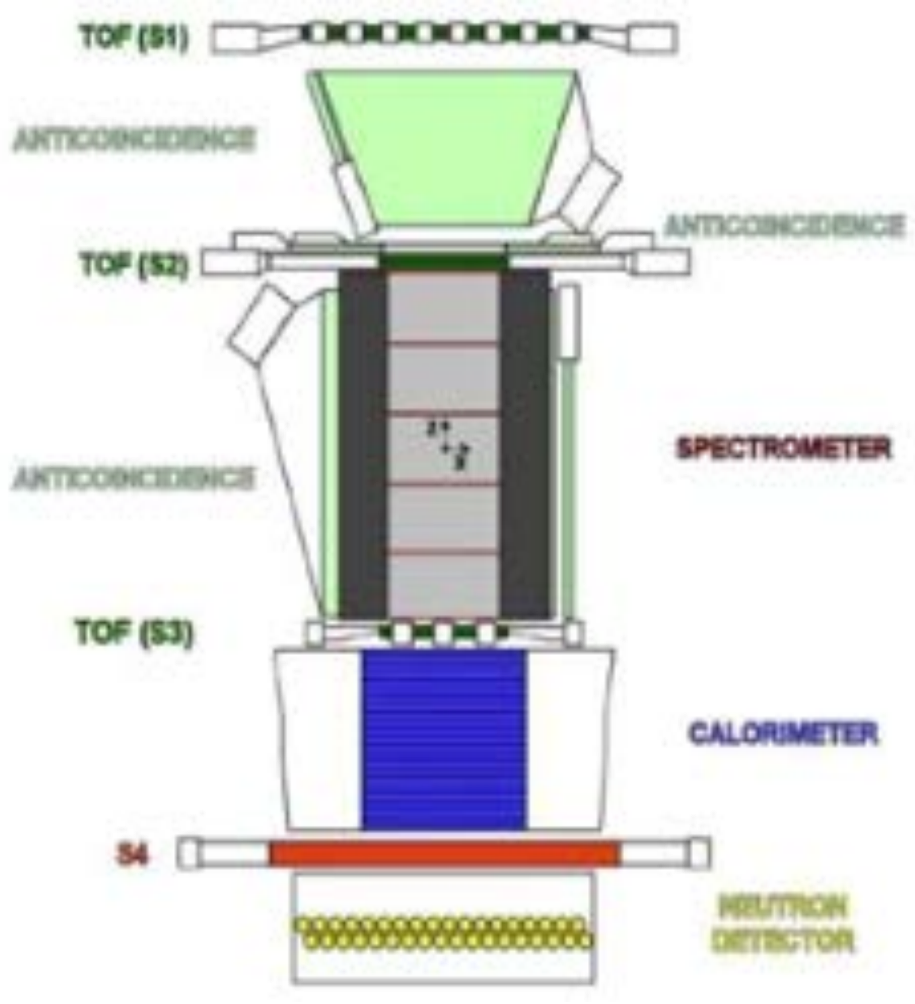
7 Silicon layers

11,000 Photo Sensors

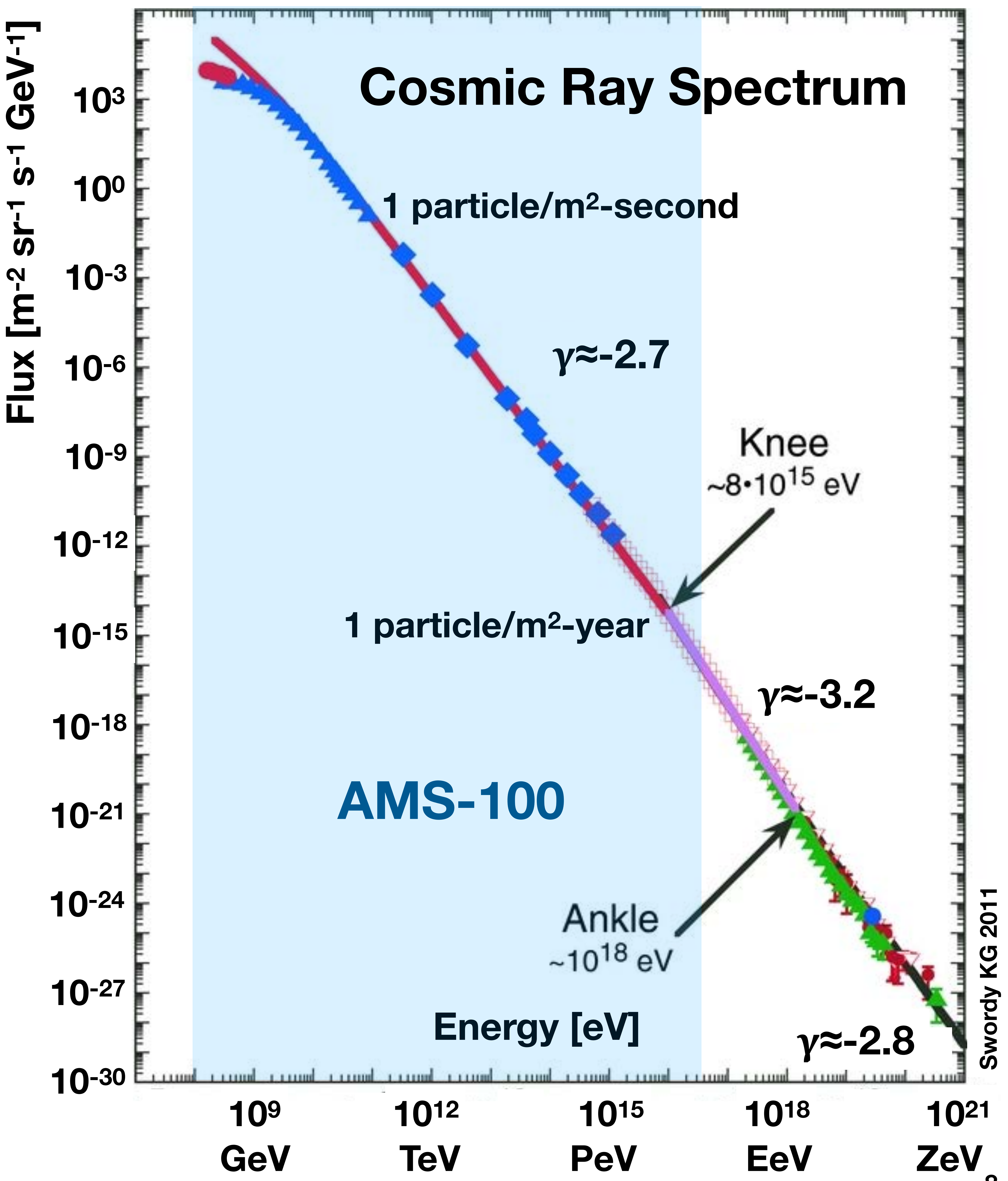
Silicon layer

We have to start now to work on the next generation magnetic spectrometer in space !

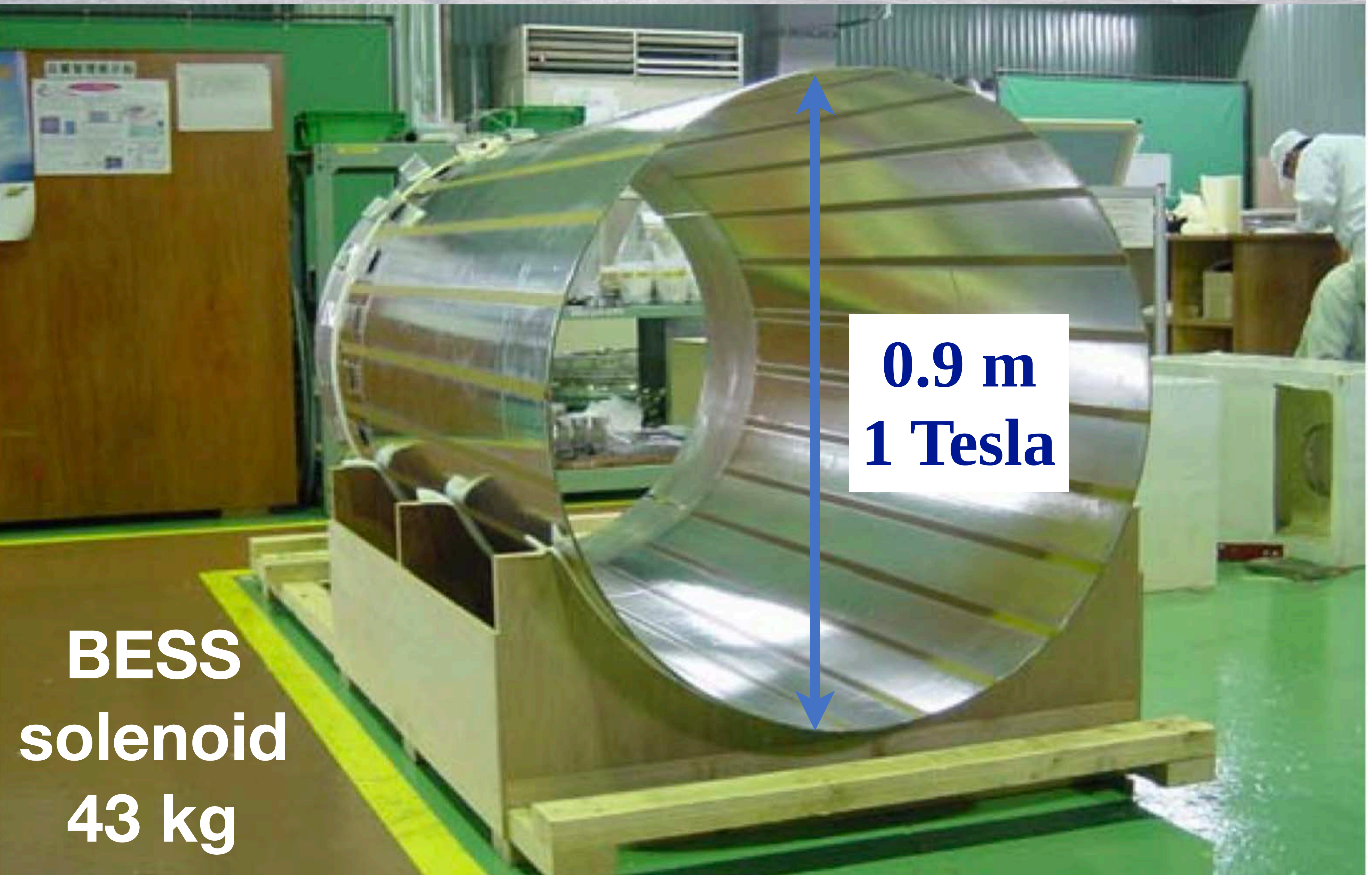


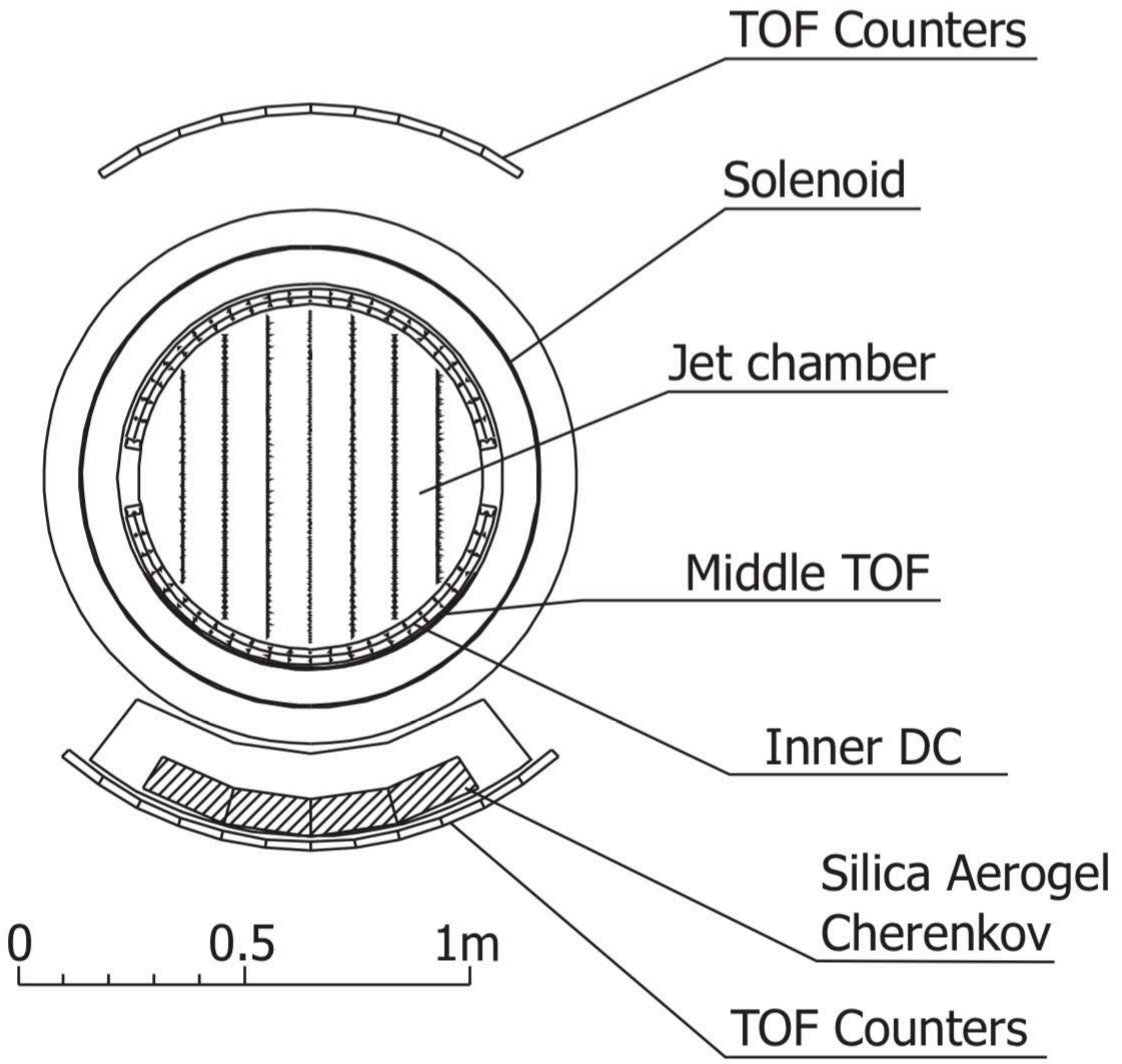

PAMELA



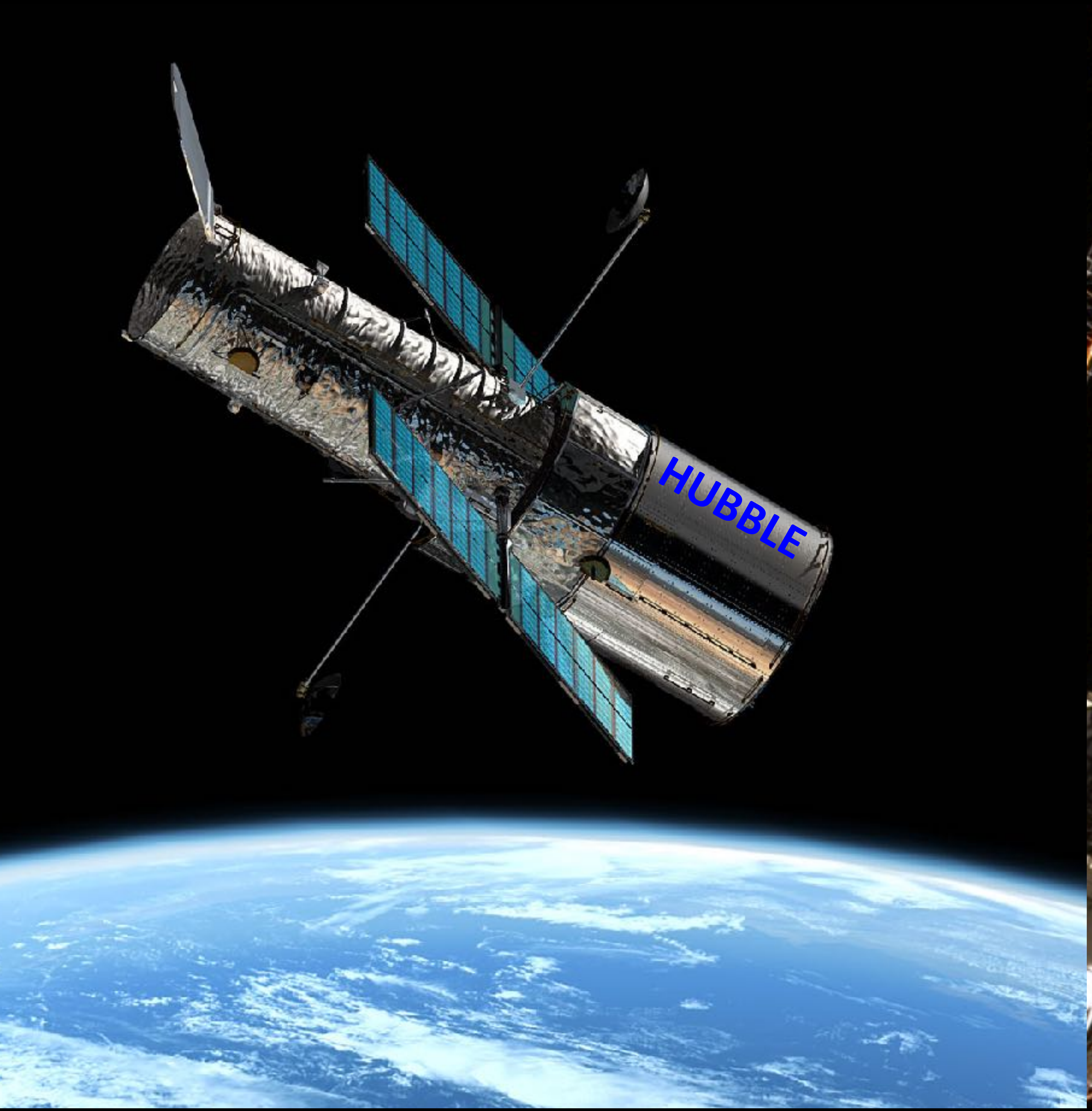

- The cosmic ray flux follows a power law $\Phi \approx C\,E^{-3}$
- An increase in energy by a factor 10 requires an increase in acceptance by 1000. AMS-02 weights 7 tons.
- Both PAMELA and AMS-02 have a telescope like geometry.
- Just scaling such a geometry does not allow to increase the energy reach by a factor 10 and simultaneously the acceptance by a factor 1000.

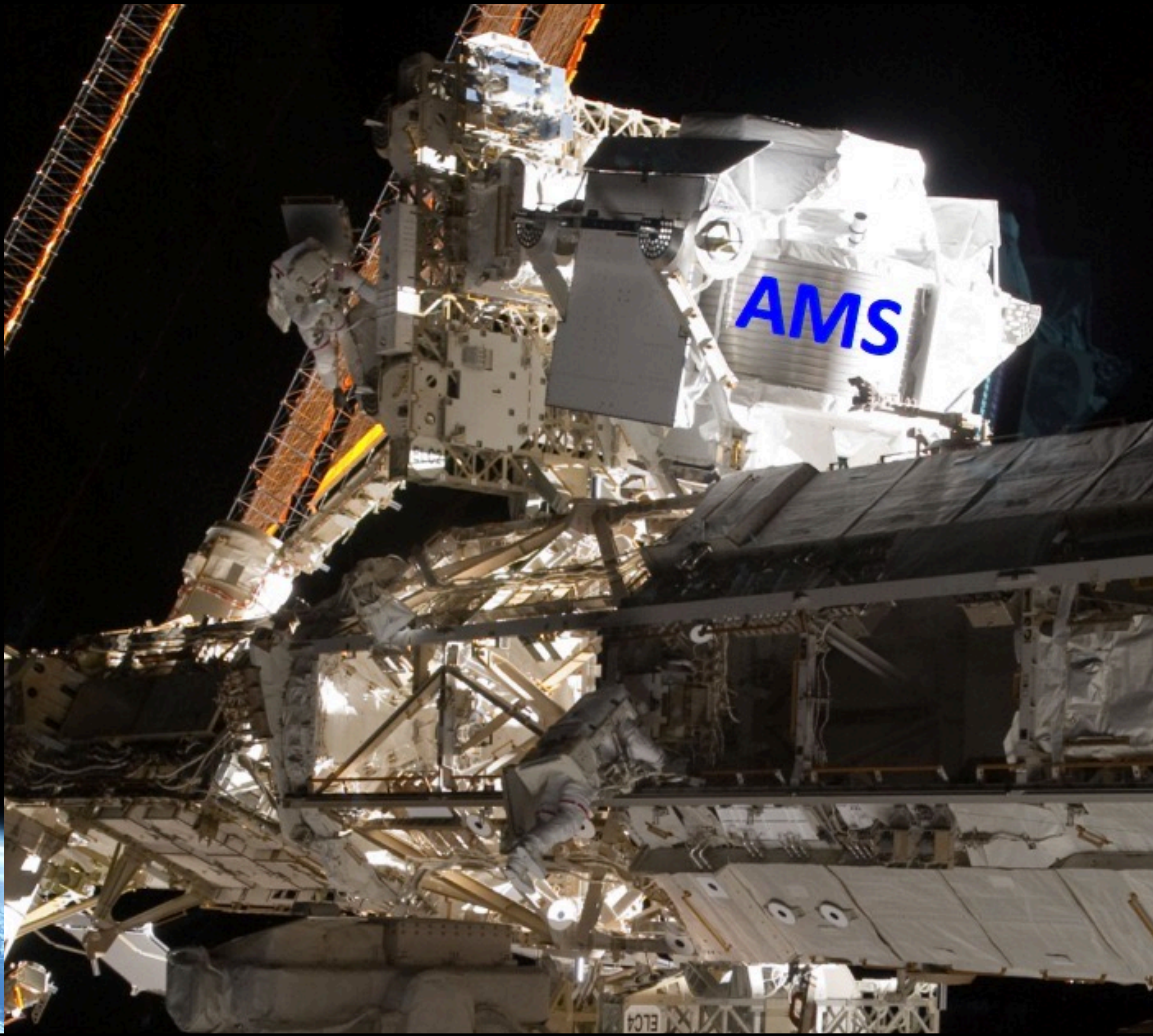




- The design of AMS-100 was inspired by the BESS Ballon Experiment.
- A thin solenoid instrumented on the inside with a tracker like a classical collider experiment has an angular acceptance for cosmic rays of $4\pi$, if operated in space far away from earth, superior to any telescope like geometry.
- The B-Field of a long solenoid depends only on the number of turns, the current and the length, but not on the radius.
- Increasing the radius will therefore quadratically increase both the energy reach and the acceptance of the spectrometer at the same time.



**James Webb, the next generation space telescope will be operated at Lagrange Point 2,**



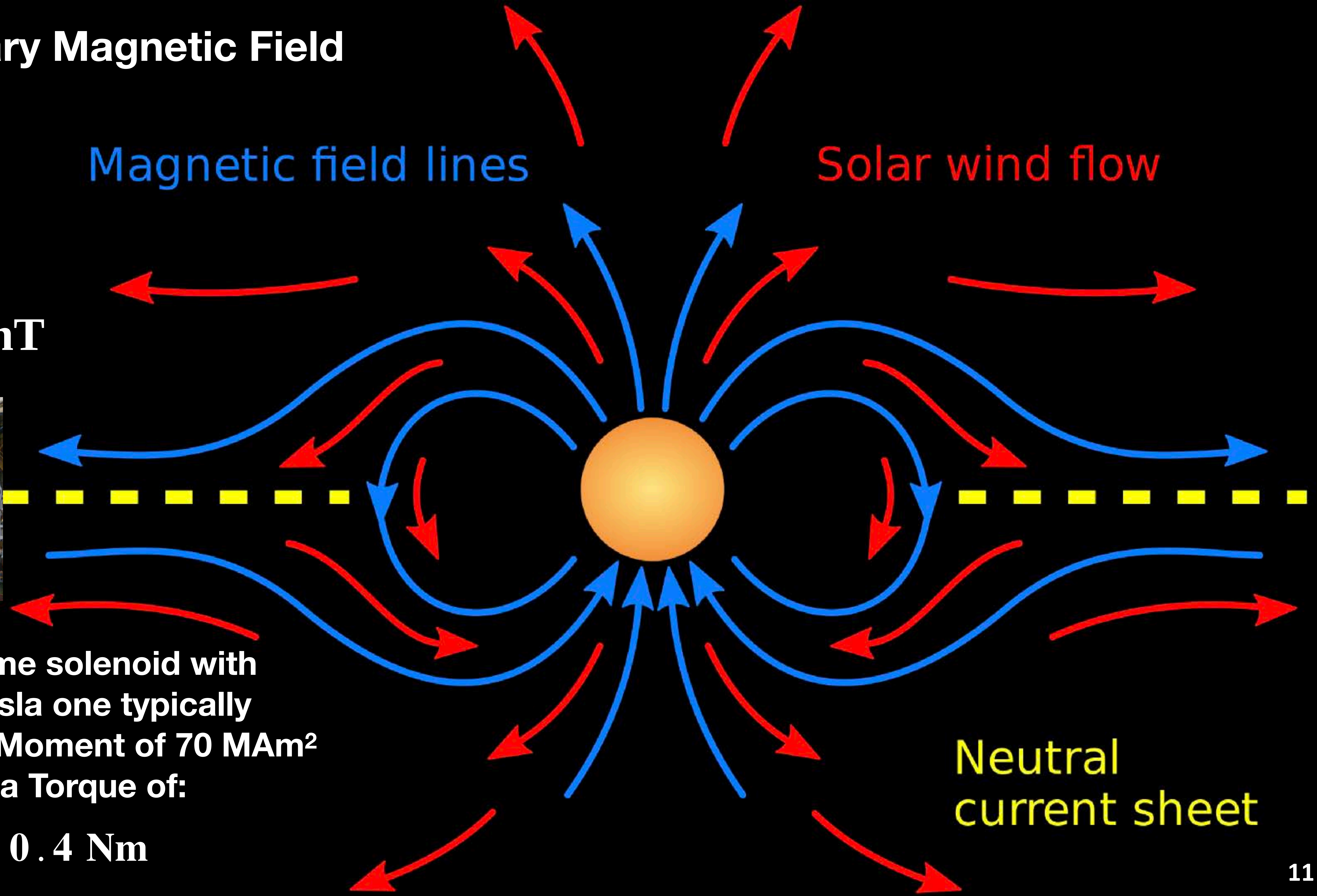




**and this is also the only option to significantly extend the AMS-02 physics program.**

# Interplanetary Magnetic Field

$$\bar{B} = 6\ nT$$

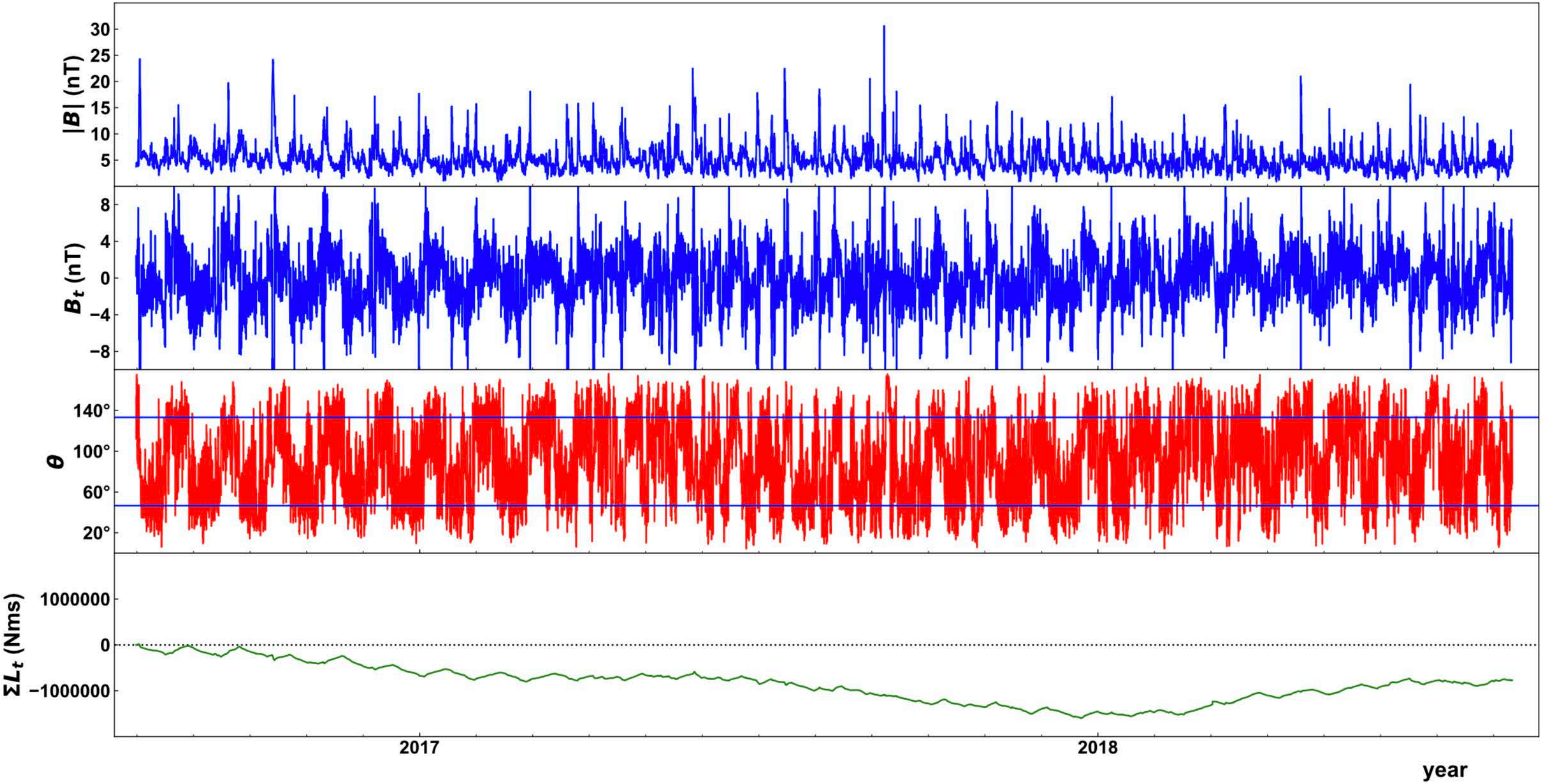
$$B = 0 - 37\ nT$$




**For a large volume solenoid with a B-Field of 1 Tesla one typically has a Magnetic Moment of 70 MAm² which results in a Torque of:**

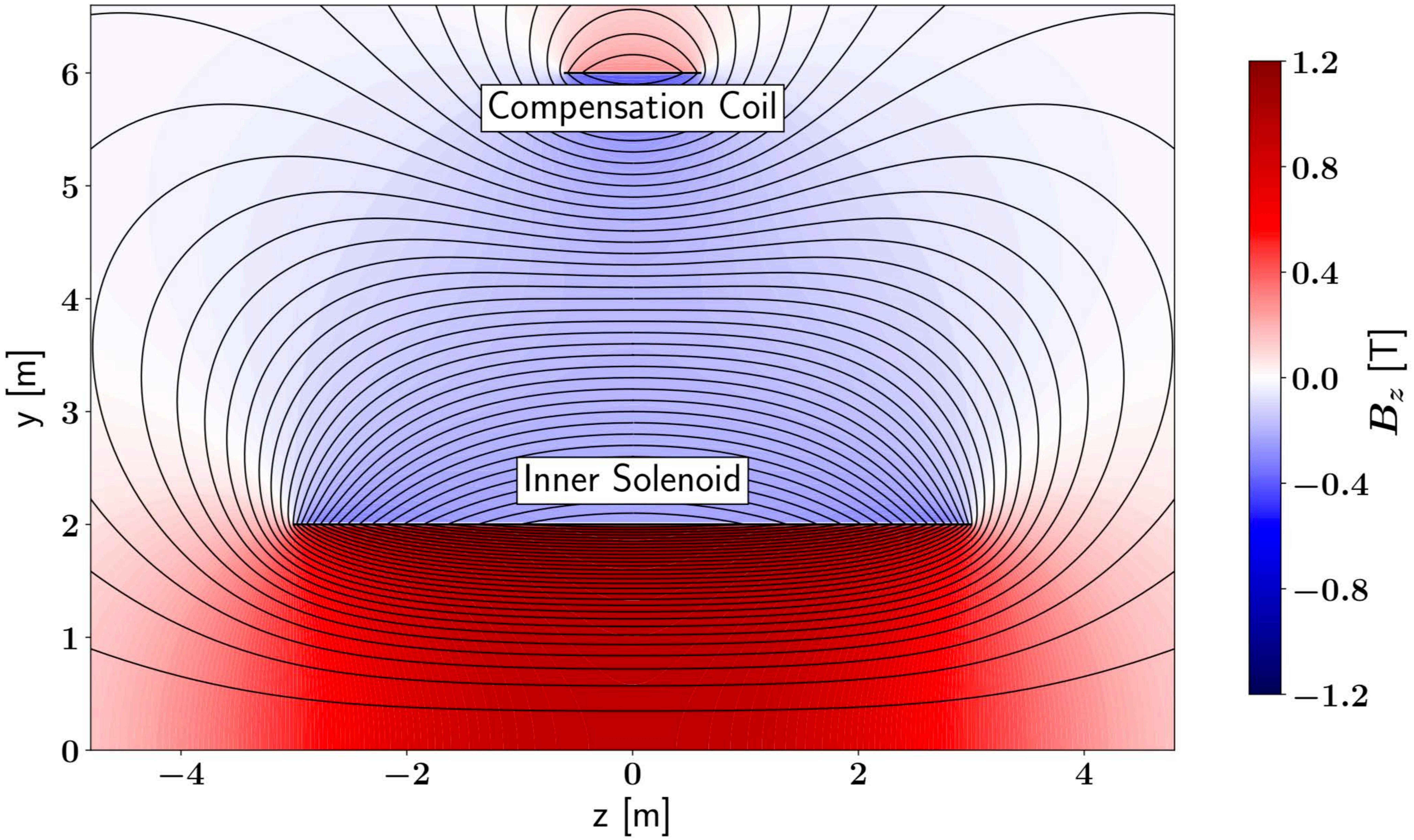
$$\overrightarrow{T} = \overrightarrow{M} \times \overrightarrow{B} \simeq 0.4\ Nm$$

# ACE Measurements at Lagrange Point 1

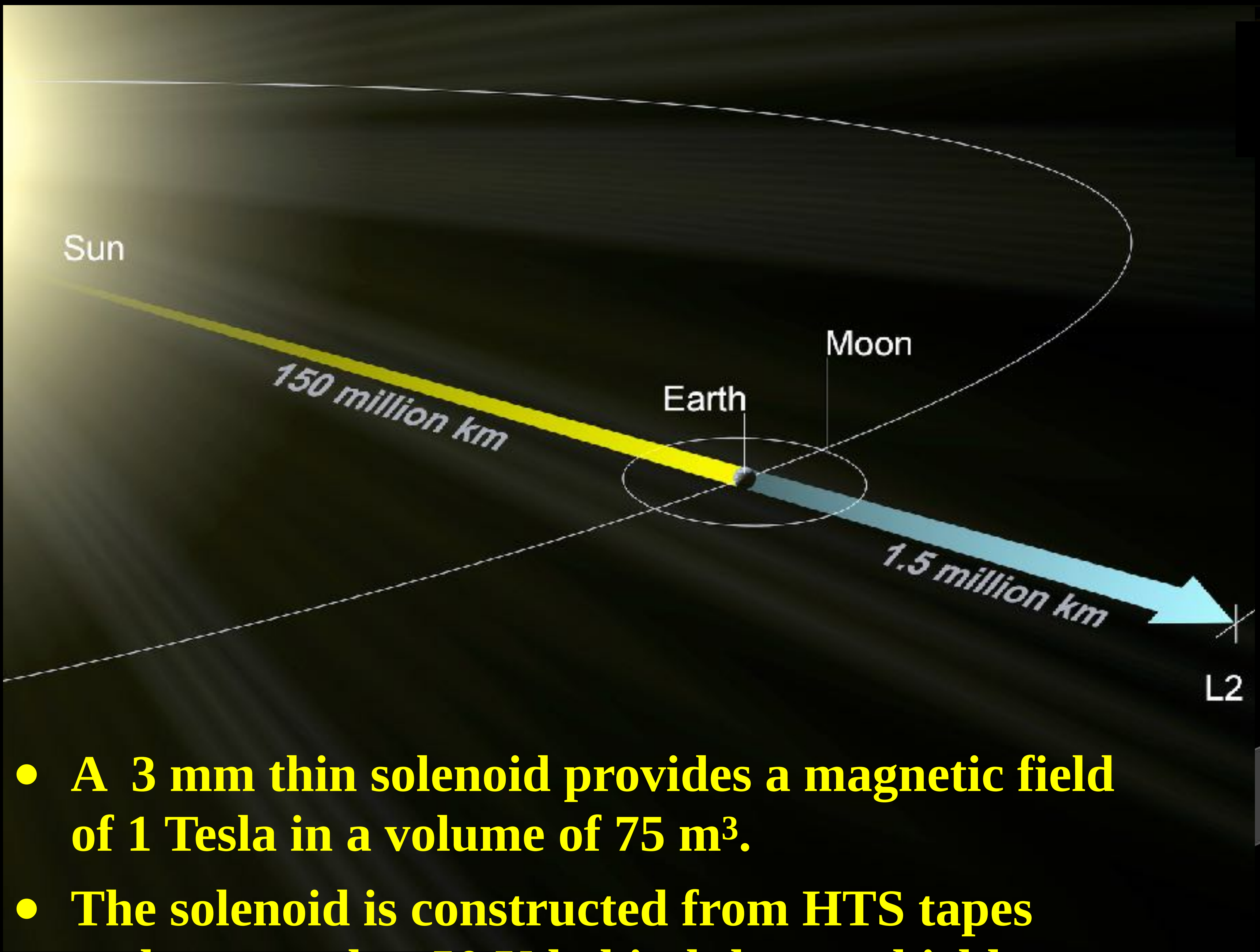


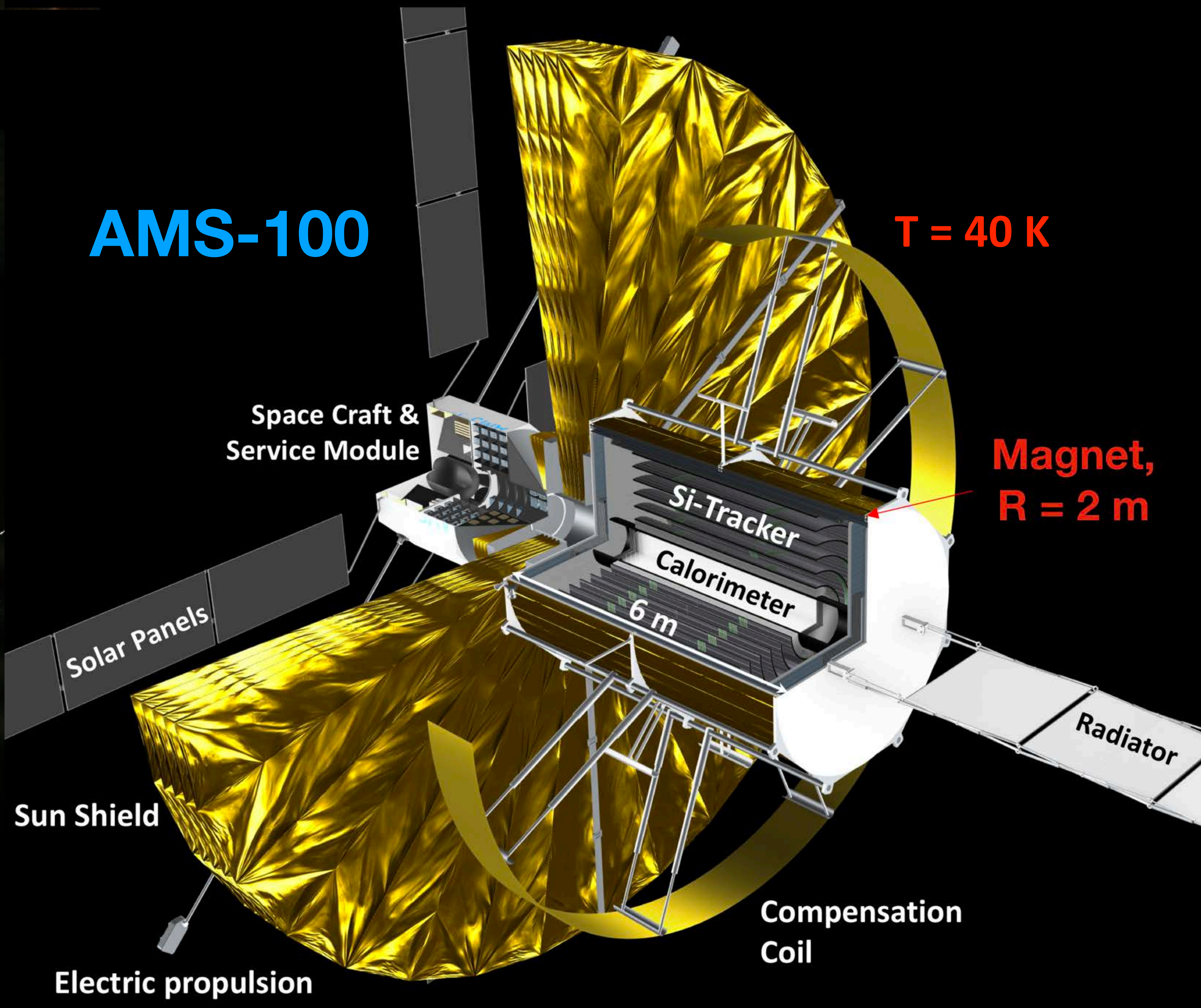

**This large angular momentum can not be balanced by reaction wheels or gyroscopes !**

# The current in the Compensation Coil is adjusted such that the total magnetic dipole moment of the system is zero.



# Physics with cosmic rays at Lagrange Point 2



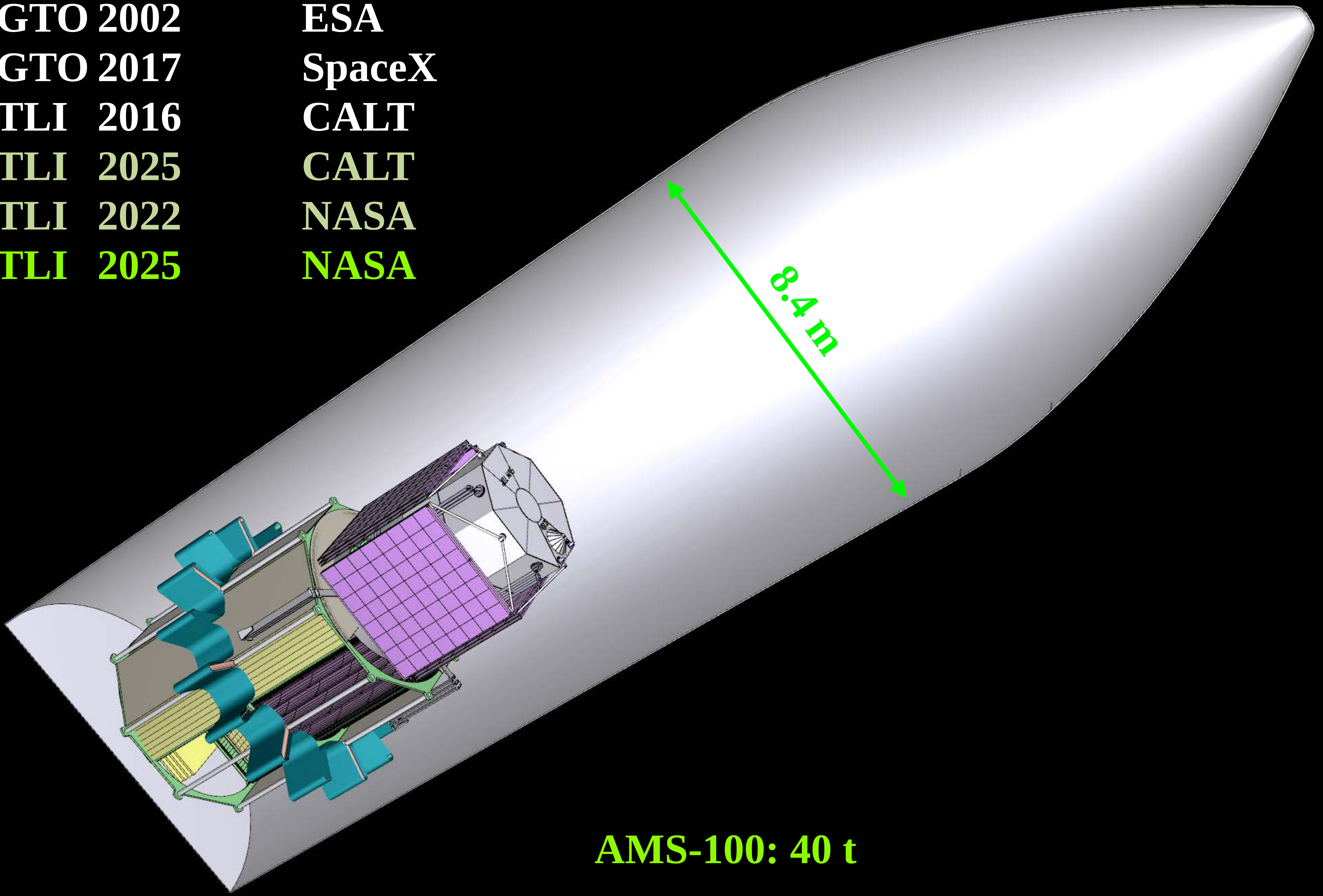

- A 3 mm thin solenoid provides a magnetic field of 1 Tesla in a volume of 75 $m^3$.
- The solenoid is constructed from HTS tapes and operated at 50 K behind the sunshield in thermal equilibrium with the environment.
- An expandable compensation coil with 12 m diameter balances the magnetic dipole moment of the solenoid.
- The solenoid is instrumented on the inside with a silicon tracker and a calorimeter system (70 $X_0$, 4 $\lambda_I$).
- AMS-100 has a geometrical acceptance of 100 $m^2$ sr and a maximum detectable rigidity of 100 TV.

# Current and upcoming rockets

| Name | LEO [kg] | other [kg] | First flight | |
|---|---|---|---|---|
| Ariane 5 | 21,000 | 10,730 GTO | 2002 | ESA |
| Falcon Heavy | 63,800 | 26,700 GTO | 2017 | SpaceX |
| Long March 5 | 25,000 | 8,000 TLI | 2016 | CALT |
| Long March 9 | 130,000 | 50,000 TLI | 2025 | CALT |
| SLS Block 1B | 105,000 | 39,100 TLI | 2022 | NASA |
| SLS Block 2 | 130,000 | 45,000 TLI | 2025 | NASA |

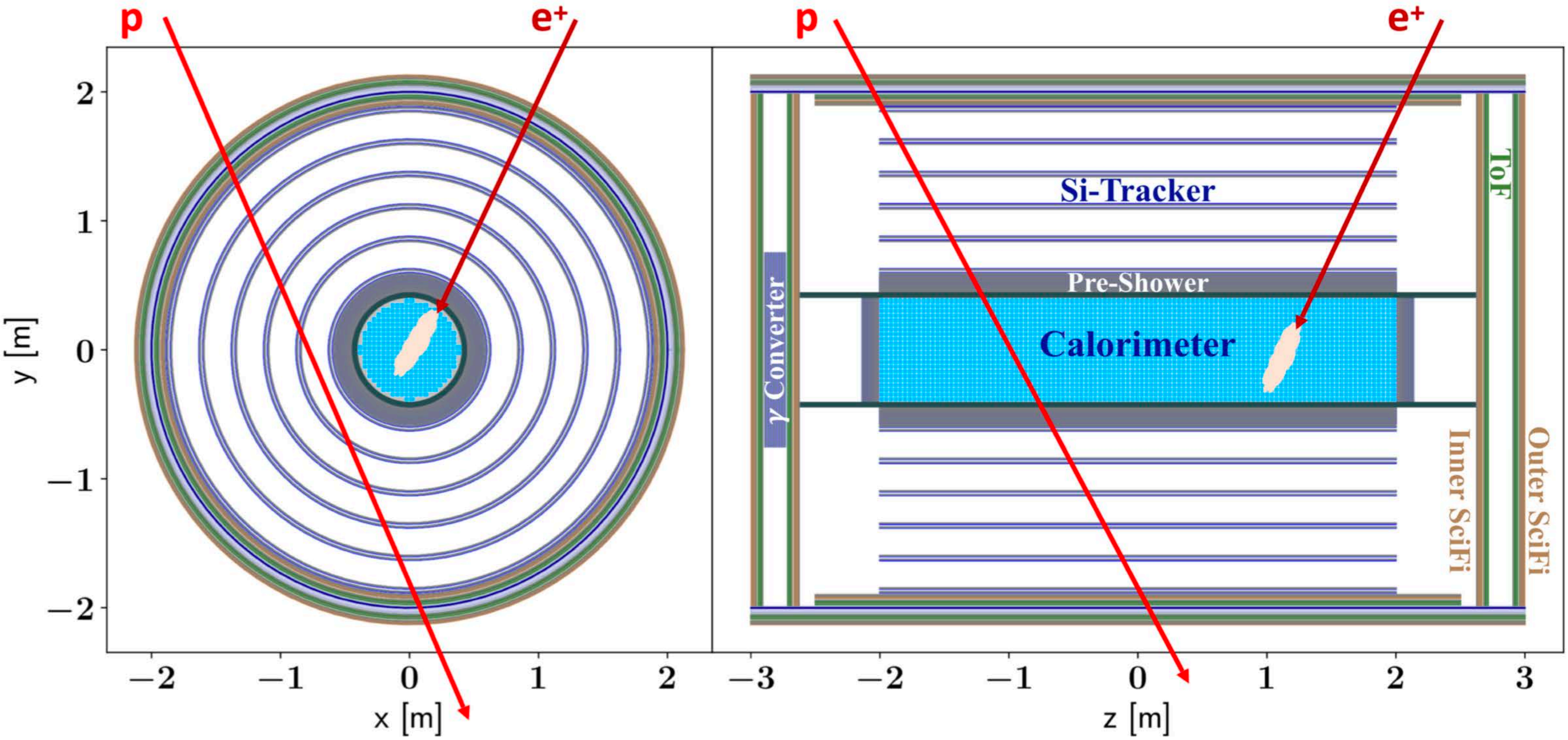
Operational
Under development

LEO: Low Earth orbit
GTO: Geostationary transfer orbit
TLI: Trans-lunar injection




AMS-100: 40 t

# AMS-100 – Detector Concept



Radiator

Outer SciFi, Layer 1 - 3

Outer ToF, Layer 1 & 2

Magnet

Inner ToF, Layer 1 & 2

Inner SciFi, Layer 1 - 3

Si-Tracker, Layer 11 & 12

Si-Tracker, Layer 9 & 10

Si-Tracker, Layer 7 & 8

Si-Tracker, Layer 5 & 6

Si-Tracker, Layer 3 & 4

Si-Tracker, Layer 1 & 2

Pre-Shower

Calorimeter

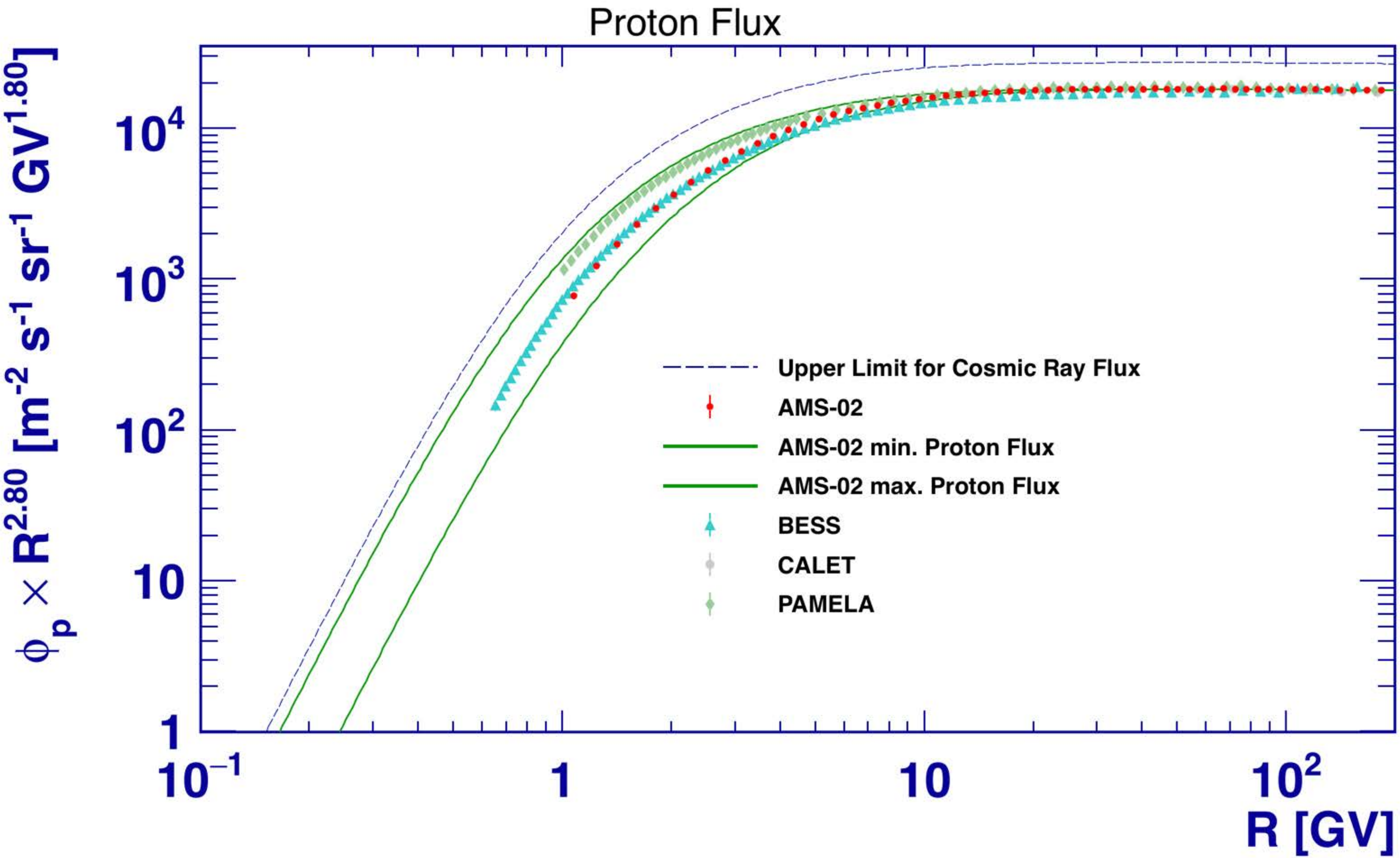
**SciFi-Tracker**
**Measurement of R and Z**
**2 x 6 Measurements,**
**0.040 mm resolution.**

**ToF**
**Measurement of $\beta$=P/E and Z**
**2 x 4 Measurements,**
**<20 ps resolution.**

**Silicon-Tracker**
**Measurement of R and Z**
**2 x 12 Space Points,**
**0.005 mm resolution.**

**Measurement of E and Z**

**Measurement of E and Z**



Proton Flux
$\phi_p \times R^{2.80}$ [$m^{-2}$ $s^{-1}$ $sr^{-1}$ $GV^{1.80}$]
R [GV]
Upper Limit for Cosmic Ray Flux
AMS-02
AMS-02 min. Proton Flux
AMS-02 max. Proton Flux
BESS
CALET
PAMELA

Radiator
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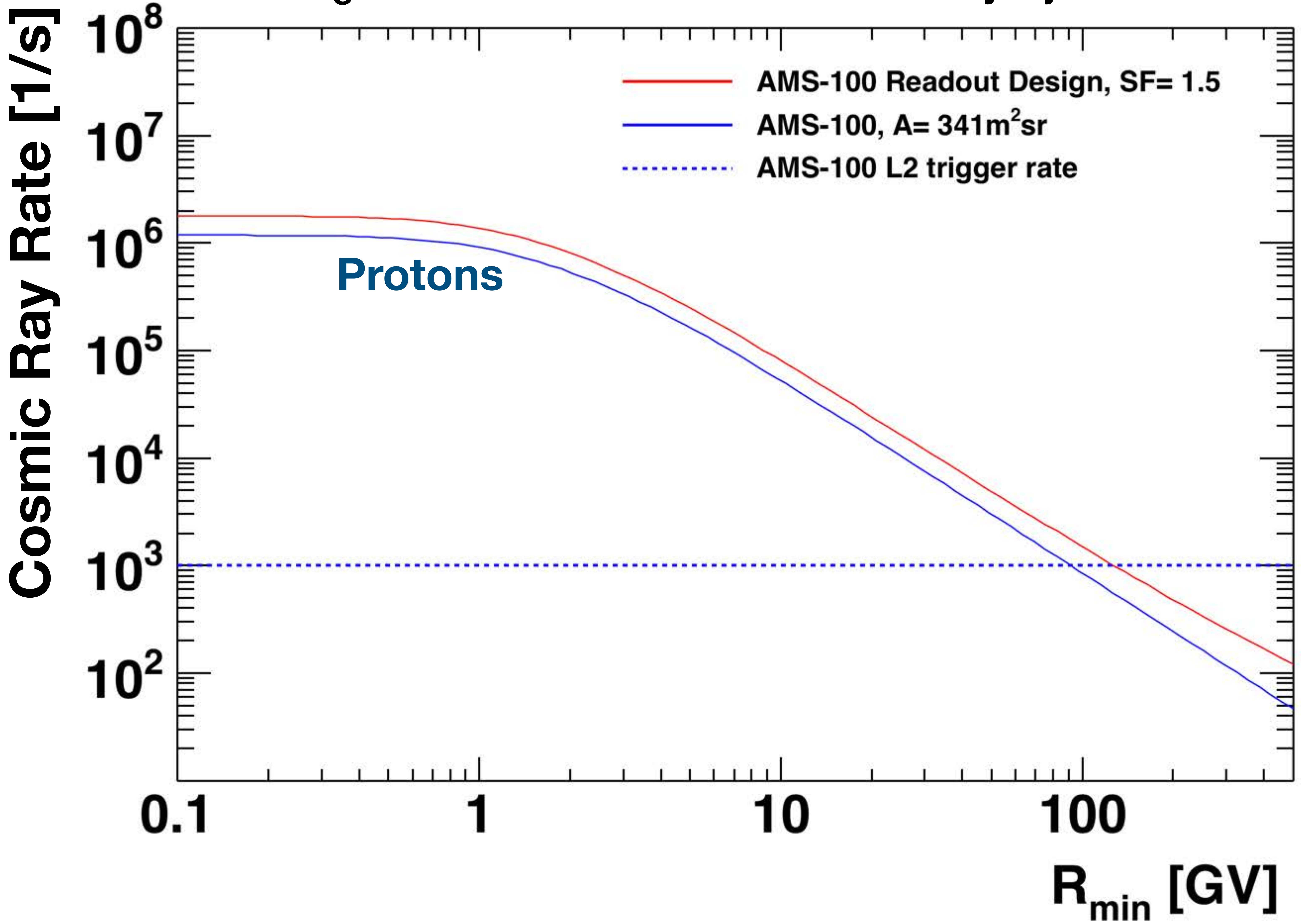
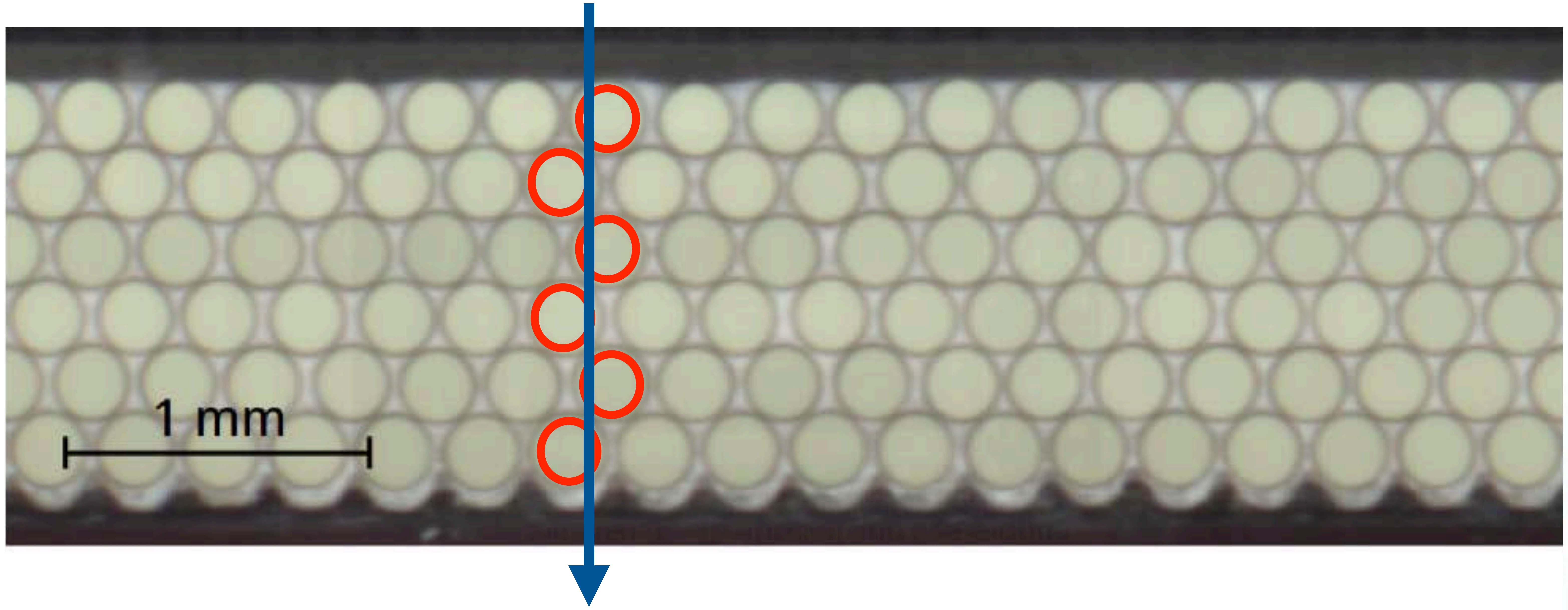
Si-Tracker, Layer 3 & 4
Si-Tracker, Layer 1 & 2
Pre-Shower
Calorimeter

## Scintillating Fiber - Tracker: First & Fast Measurement of R and Z
## Provides 2x6 Measurements with 0.040 mm resolution.
## MDR: 3 TV

**Light nuclei with R<200 GV will be mostly rejected.**



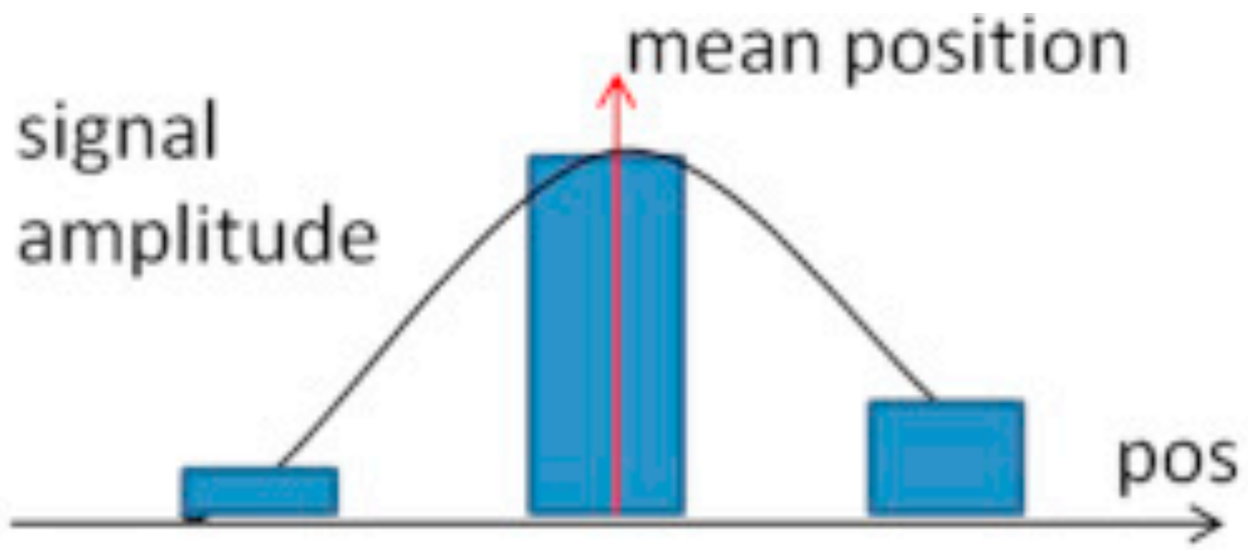
## Scintillating Fiber - Tracker
**R&D started 2005 at RWTH Aachen**



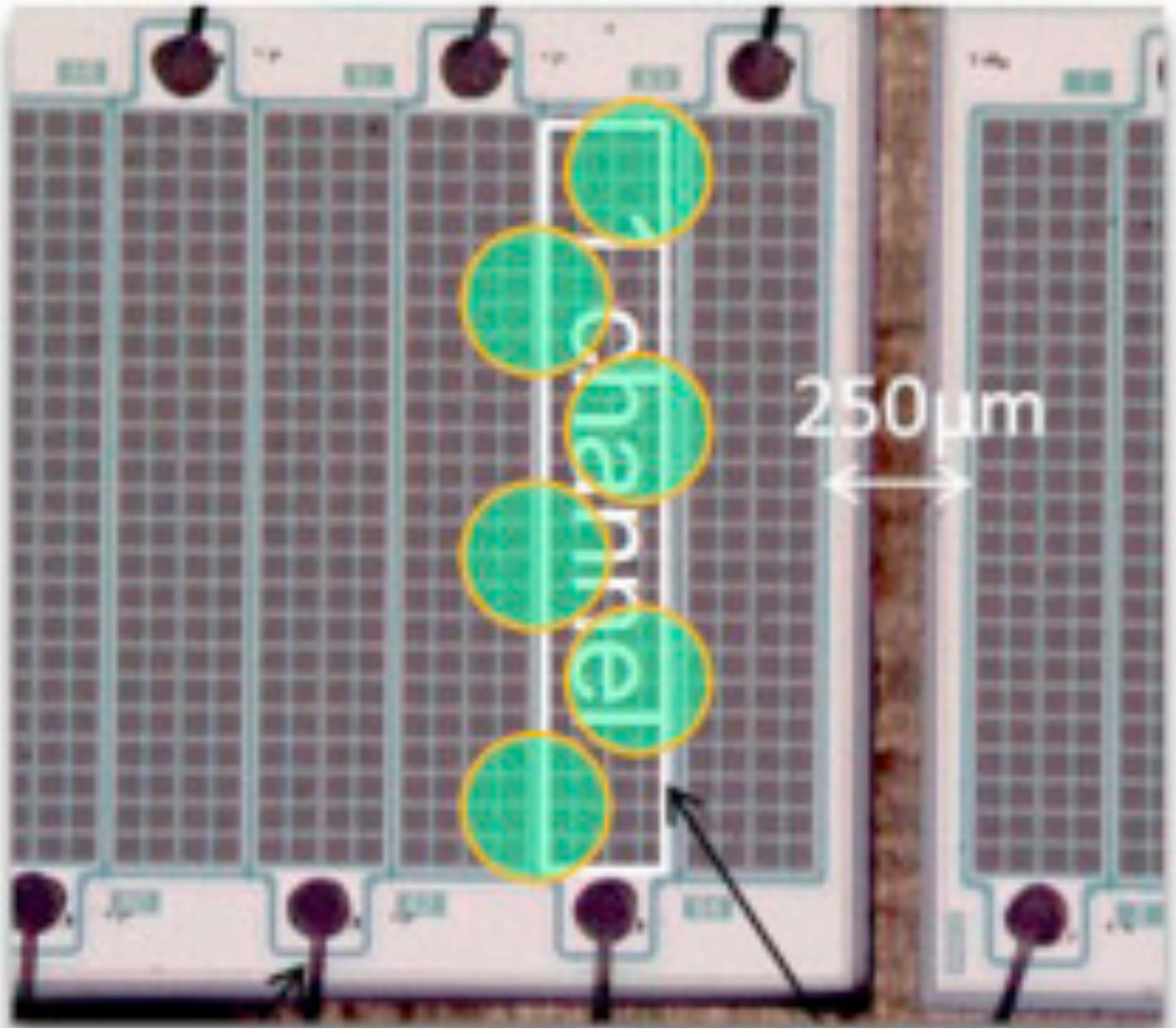

**Coordinate Measurement**

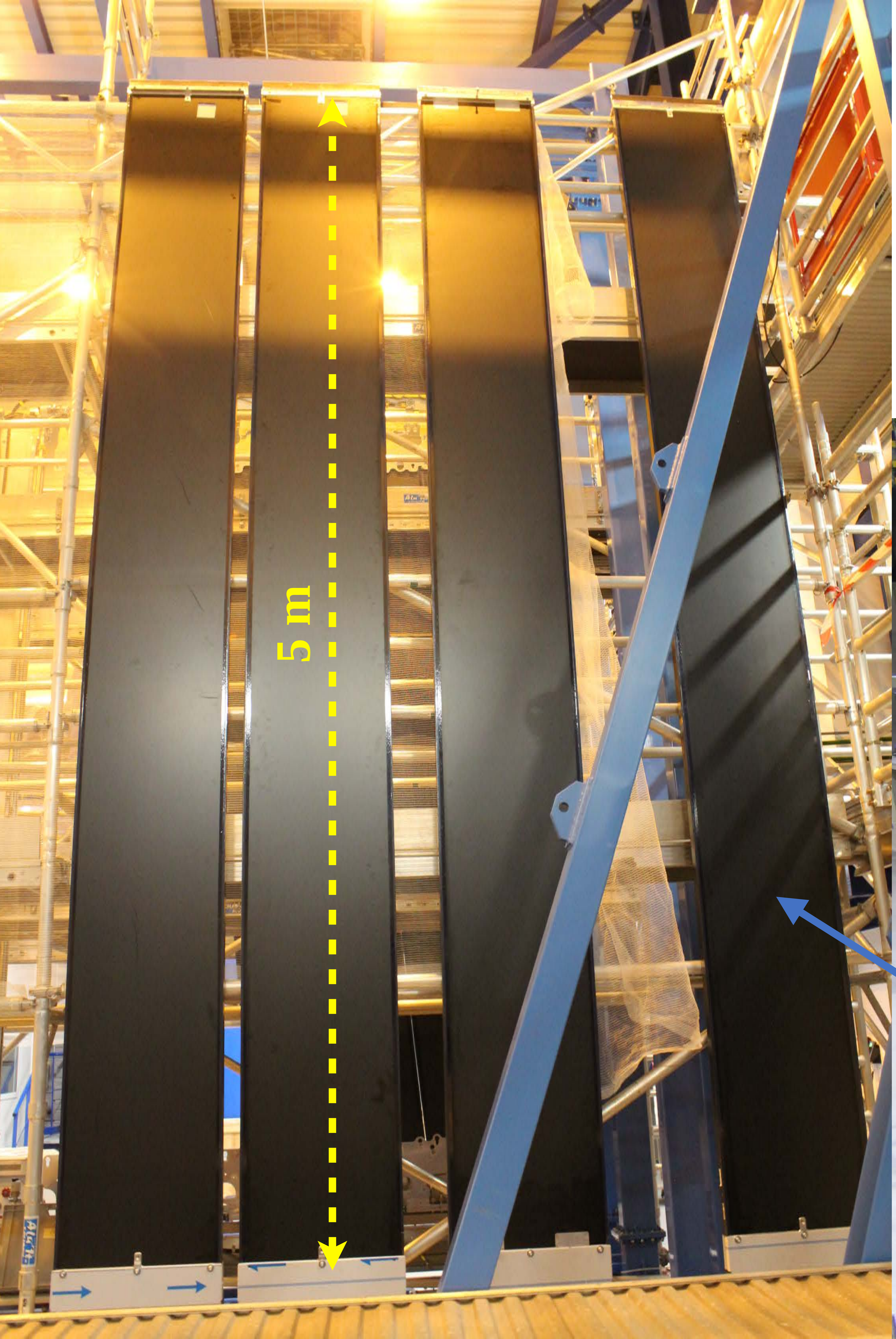
$\sigma_{Cor.}$=0.05 mm

$\varepsilon_{Cor.}$=99%

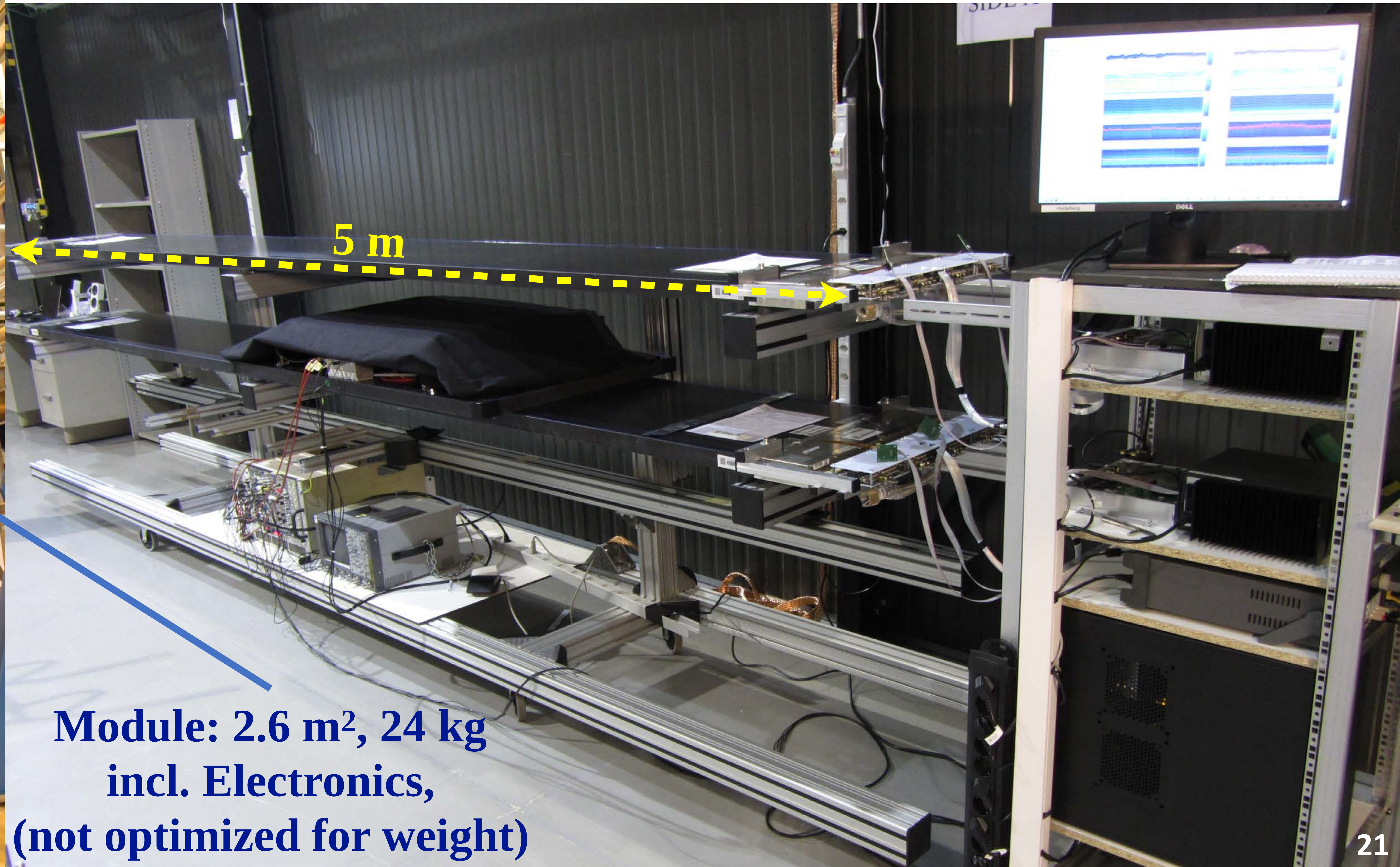



- **Linear Silicon-Photomultiplier Arrays with 0.25 mm readout pitch are attached to the end of the fiber mat.**
- **The other end is covered by a high reflective mirror.**
- **The fiber mats have a width of 13.5 cm and a length of 2.4 m.**






- 350 m² of Scintillating Fiber Tracker Modules have just been produced in the past 2 years by an European Collaboration for the new LHCb Tracker.
- 500 of the 1500 fiber mats were produced at RWTH Aachen.
- The sensor size for a silicon tracker is 10 cm x 10 cm, with $\sigma_{Cor.}$=0.01 mm. For the new SciFi-Tracker of LHCb the sensor size is 13.5 cm x 240 cm, i.e. more than 30 times larger, with $\sigma_{Cor.}$=0.05 mm.

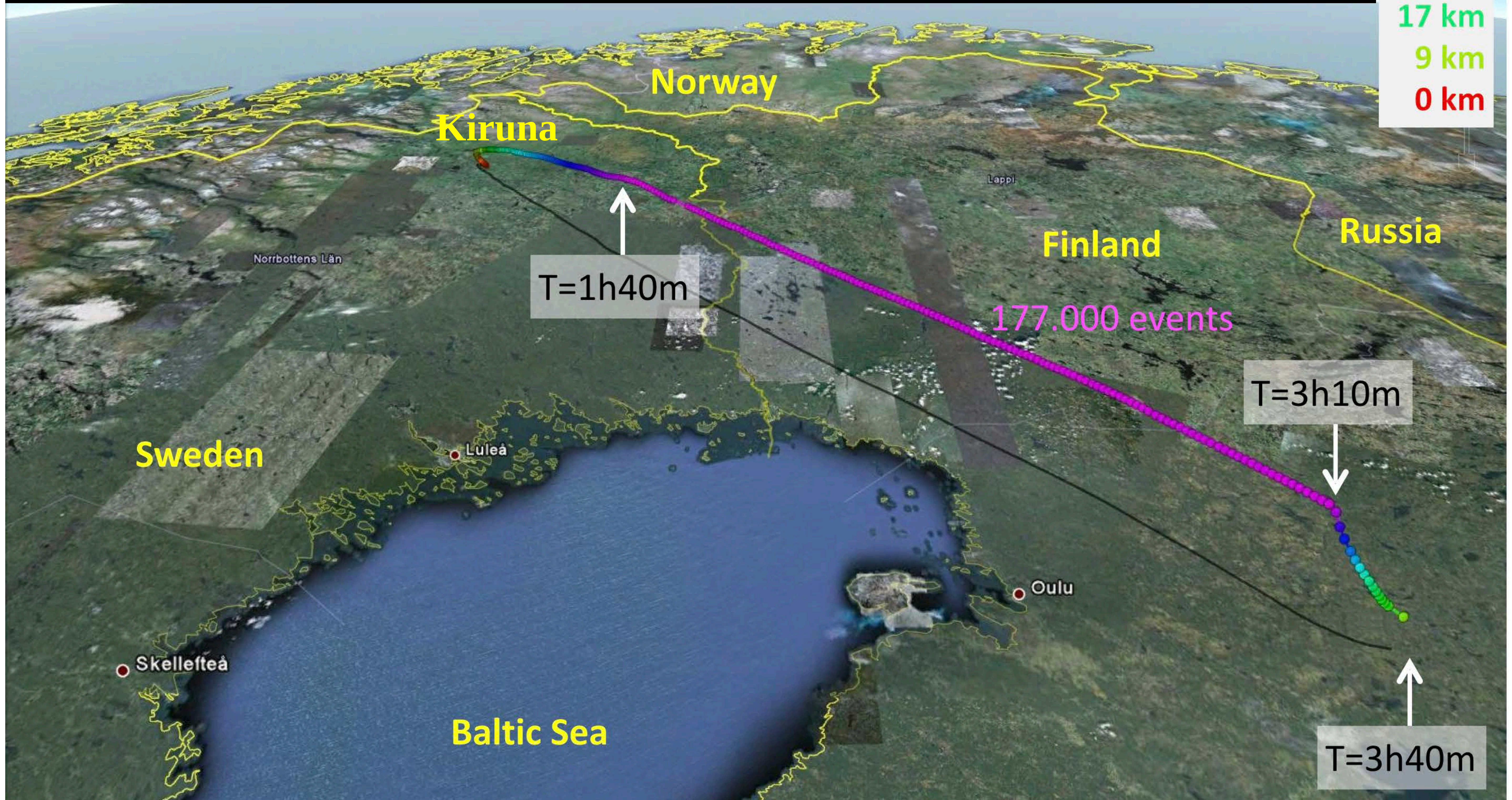



Module: 2.6 m², 24 kg
incl. Electronics,
(not optimized for weight)

Acceptance ~58 cm²sr
weight ~35kg
power ~90W



PERDaix Developed and Constructed at RWTH Aachen



Radiator
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Si-Tracker, Layer 9 & 10
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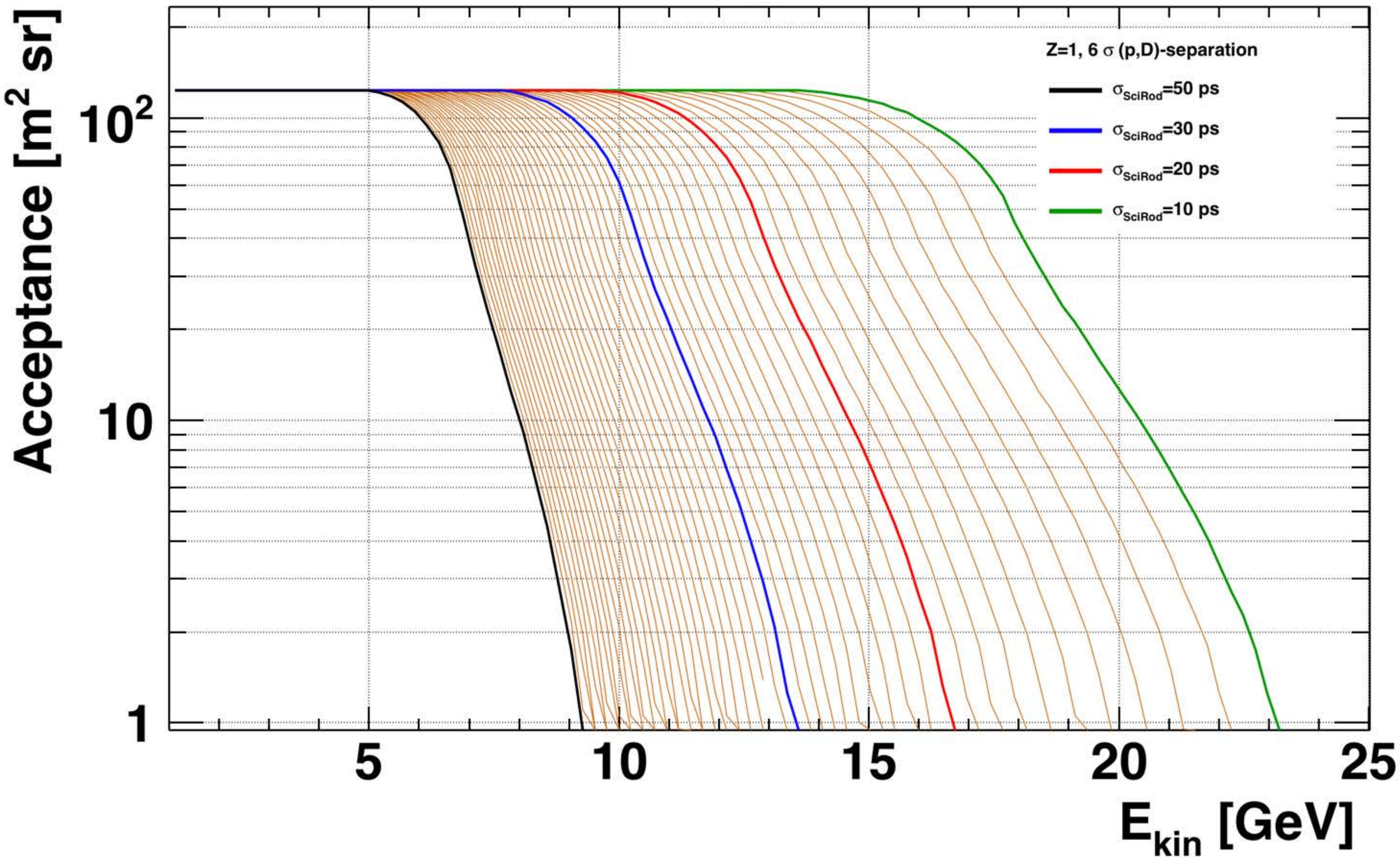
Si-Tracker, Layer 5 & 6
Si-Tracker, Layer 3 & 4
Si-Tracker, Layer 1 & 2
Pre-Shower
Calorimeter

**Time-of-Flight: Provides the Trigger and measures $\beta = v/c$**
**Provides 2x4 time and Z measurements**
**Time Resolution per Scintillator-Rod: < 20 ps**

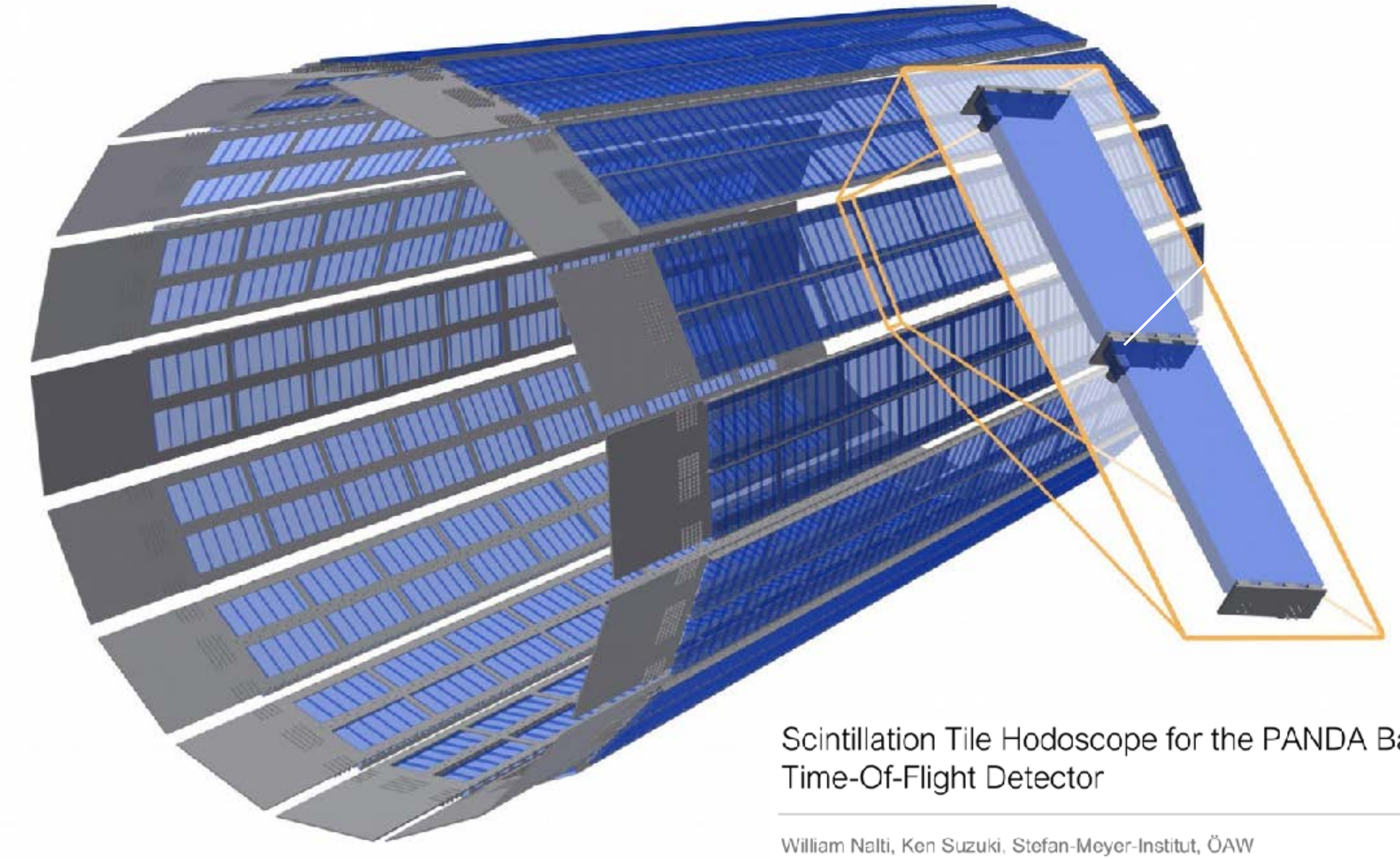
**Separate Anti-Protons from Deuterium**



# AMS-100 ToF based on the PANDA Barrel ToF Design

- Two scintillating rods read out on two sides each.
- Scintillator dimensions 87 x 29.4 x 5 mm³

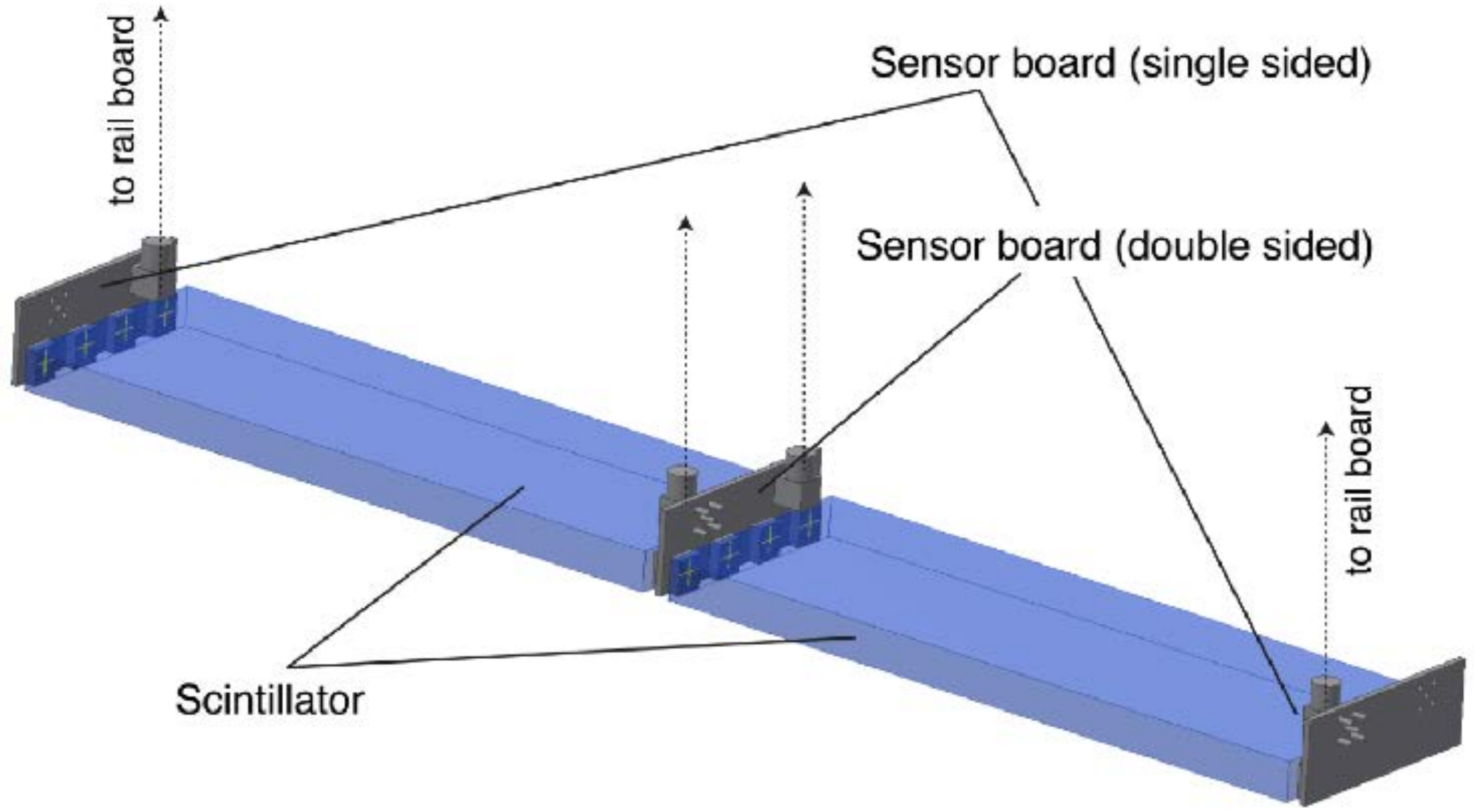
## PANDA Barrel ToF



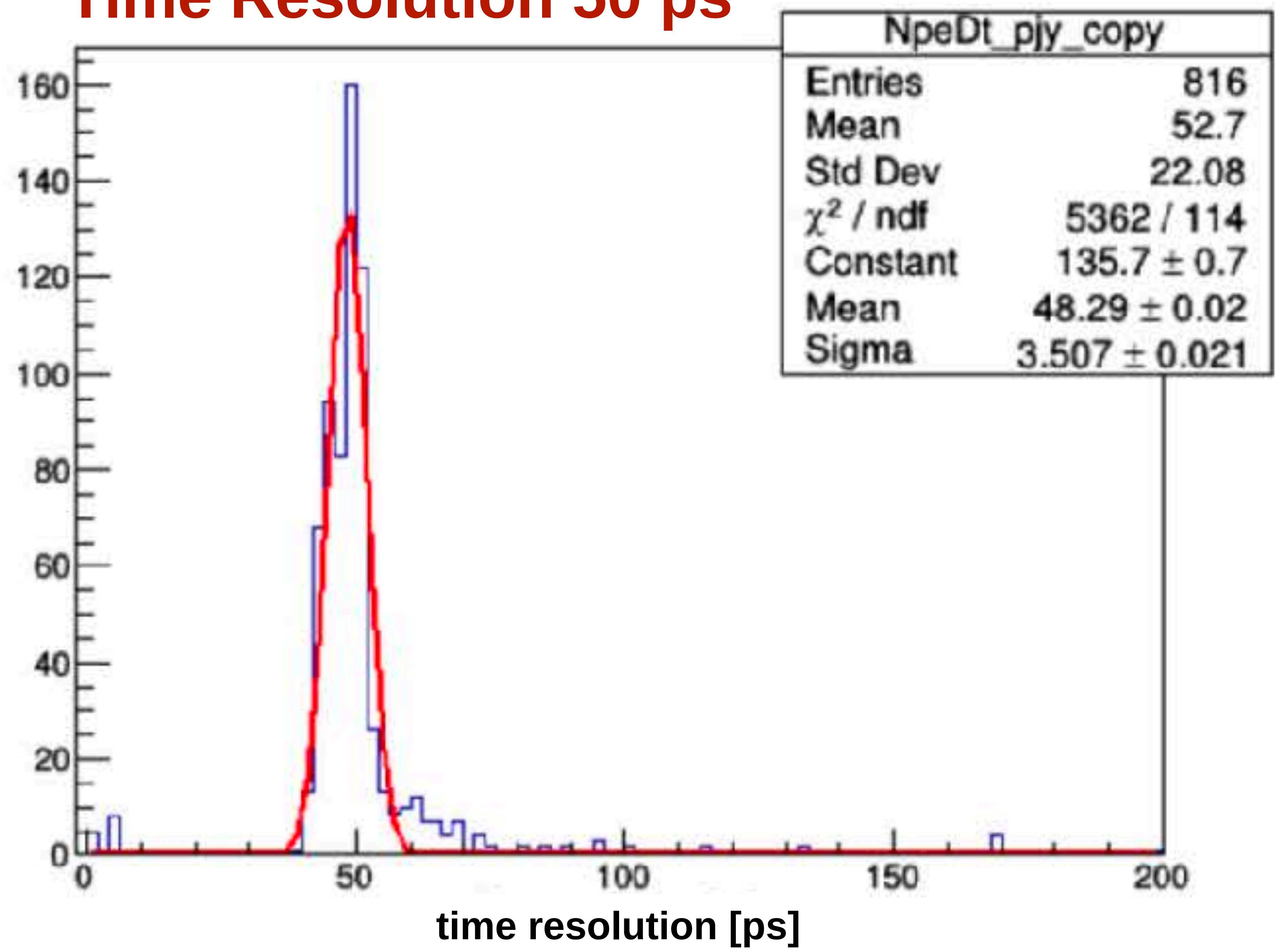
Scintillation Tile Hodoscope for the PANDA Barrel Time-Of-Flight Detector

William Nalti, Ken Suzuki. Stefan-Meyer-Institut, ÖAW
on behalf of the PANDA/Barrel-TOF(SciTil) group

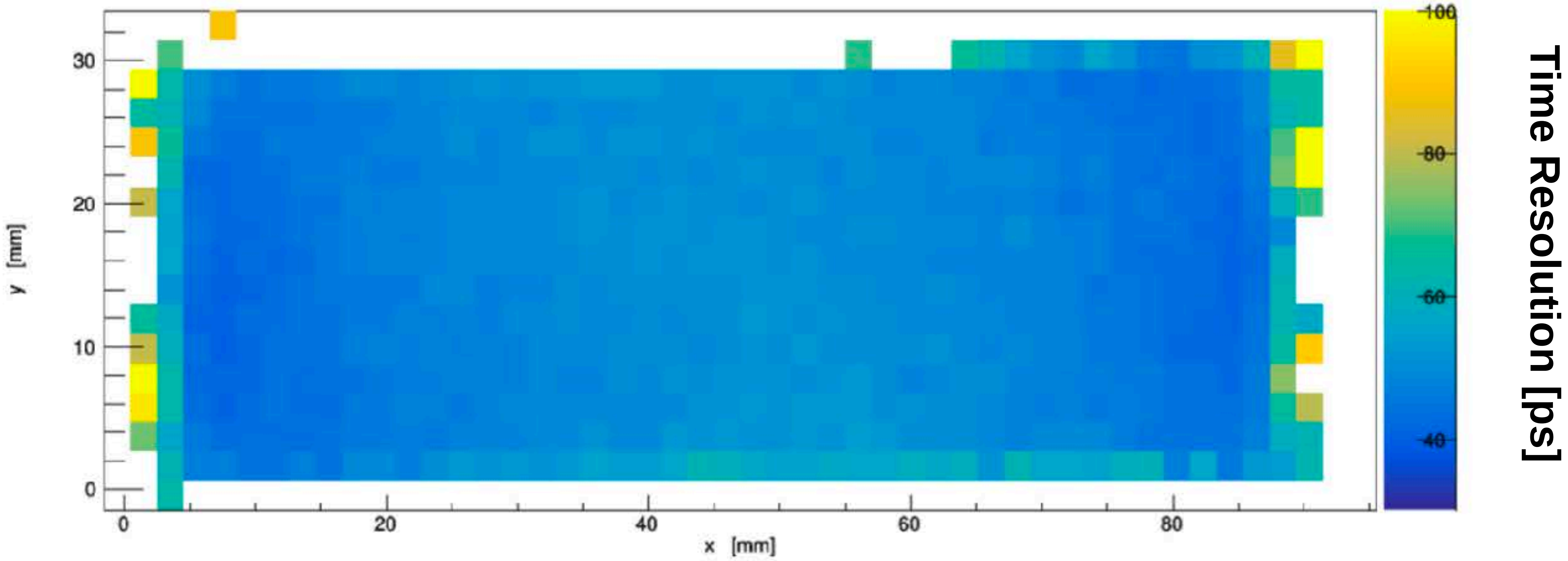
12.06.2018, ICASiPM2018




## Time Resolution 50 ps



# PANDA ToF - SciRod Time Resolution

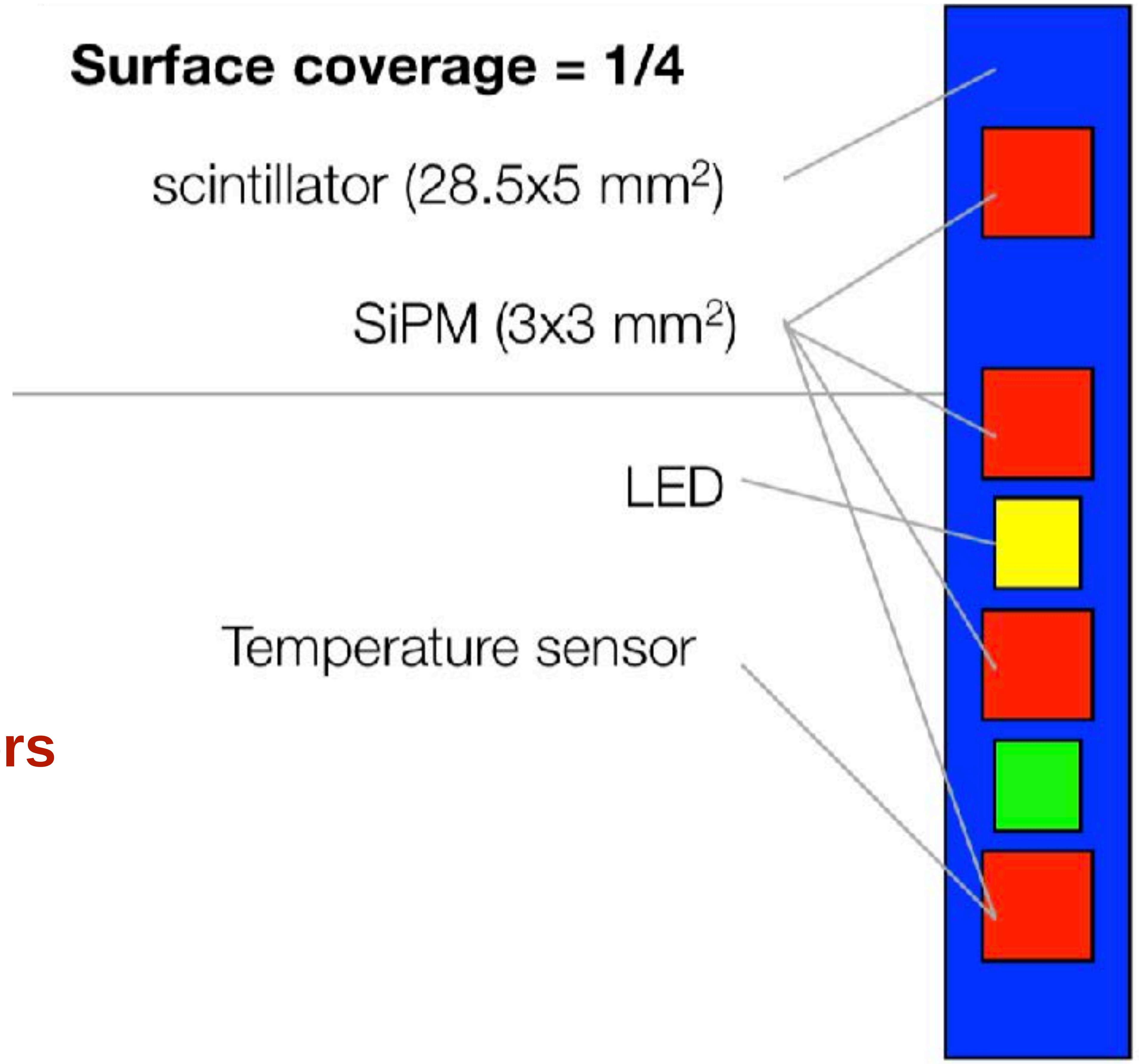



$$\sigma_T \propto 1/\sqrt{Npe}$$

- **Larger SiPM's could increase the Surface coverage and hence improve the time resolution.**
- **Further improvements can be expected from faster scintillators and new SiPM's with higher photon detection efficiency.**

| thickness | | Npe1 | Npe2 | time-resolution (ps) |
|---|---|---|---|---|
| | | | | |
| 3mm | | 72.37 | 46.84 | 60.34 |
| 4mm | | 85.64 | 55.14 | 68.09 |
| 5mm | | 139.94 | 128.69 | 50.14 |
| 5mm polished | | 111.87 | 78.1 | 48.29 |
| 6mm | | 101.7 | 70.7 | 48.7 |

## Side view of the SciRod

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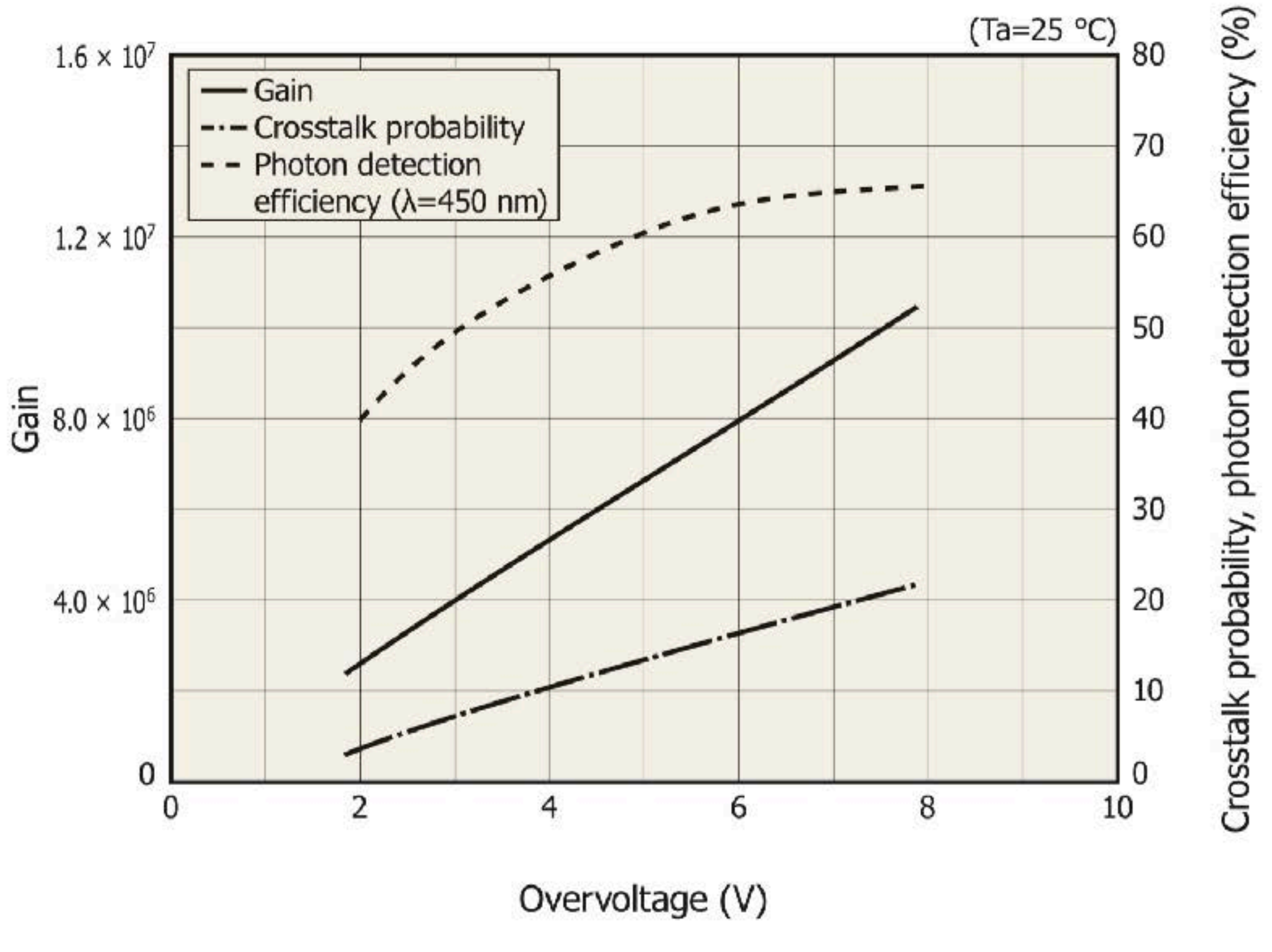
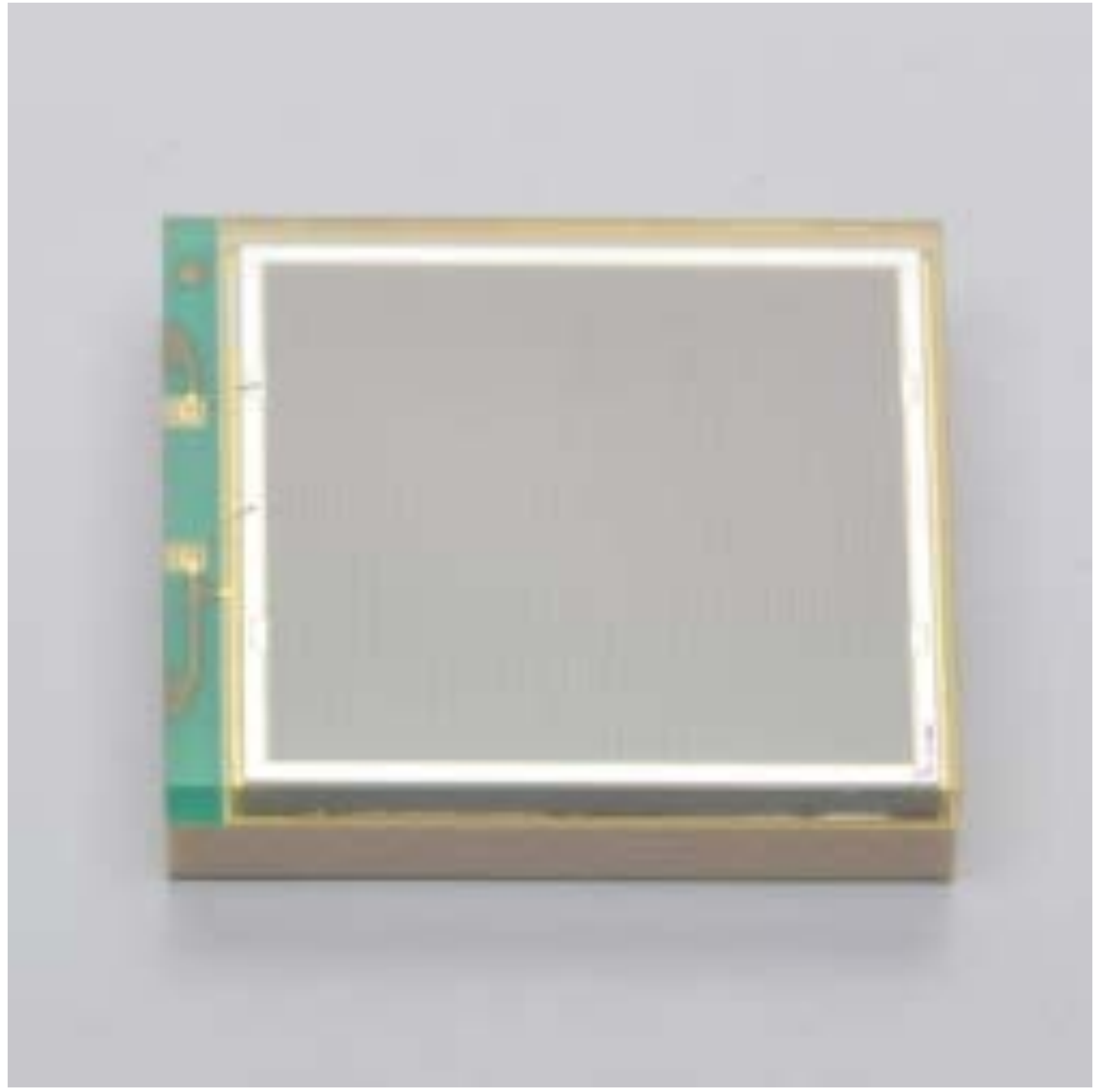
12.06.2018, ICASiPM2018

# S13360-6075PE

Pixel pitch: 75 µm



Photosensitive area: 6.0 x 6.0 mm²
Pixel pitch: 75 µm
Fill Factor: 82%

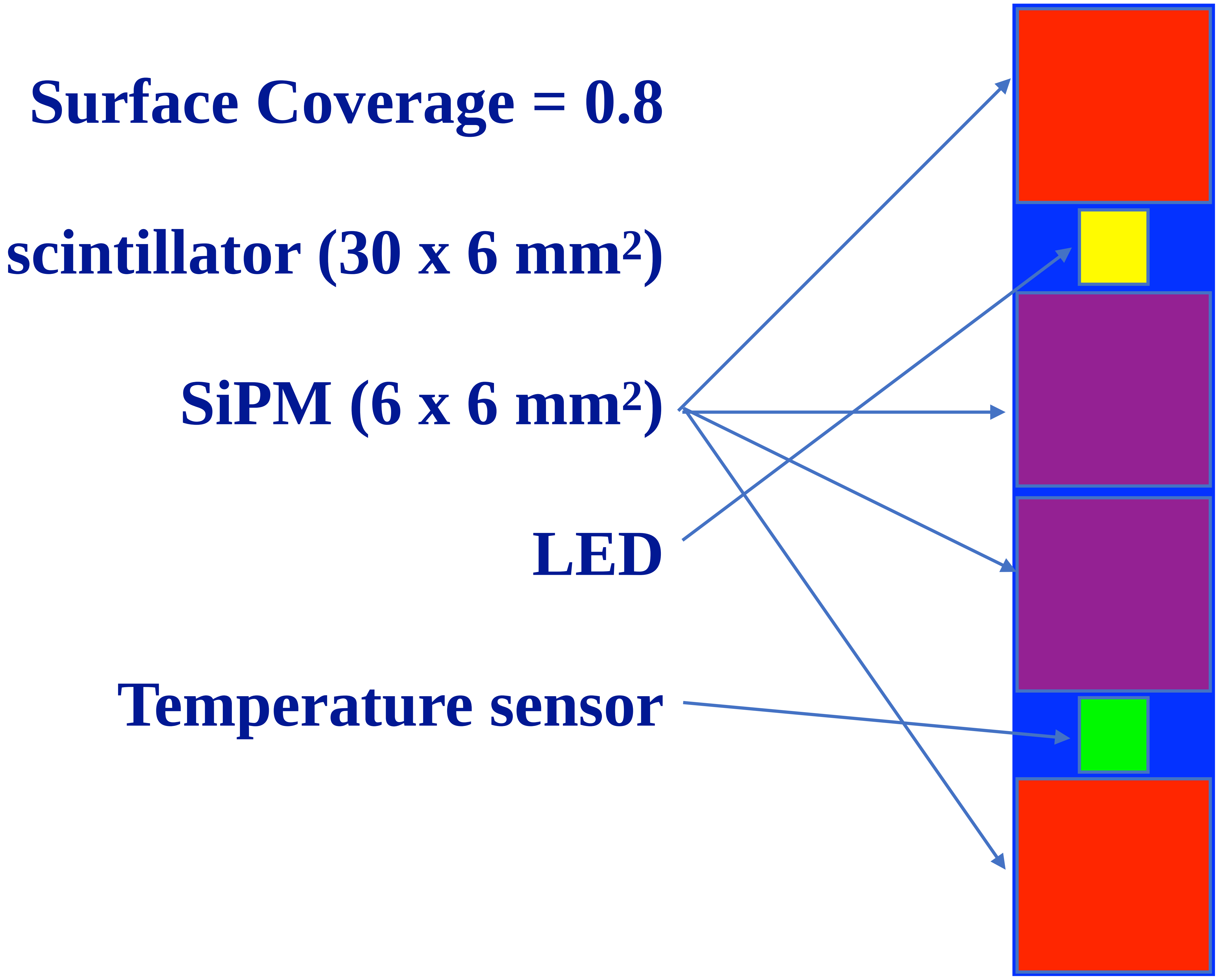
MPPC characteristics vary with the operating voltage. Although increasing the operating voltage improves the photon detection efficiency and time resolution, it also increases the dark count and crosstalk at the same time, so an optimum operating voltage must be selected to match the application.

**SiPM's will be operated in AMS-100 at 200 K.**
**This will allow for a larger Overvoltage and hence increase the photon detection efficiency.**

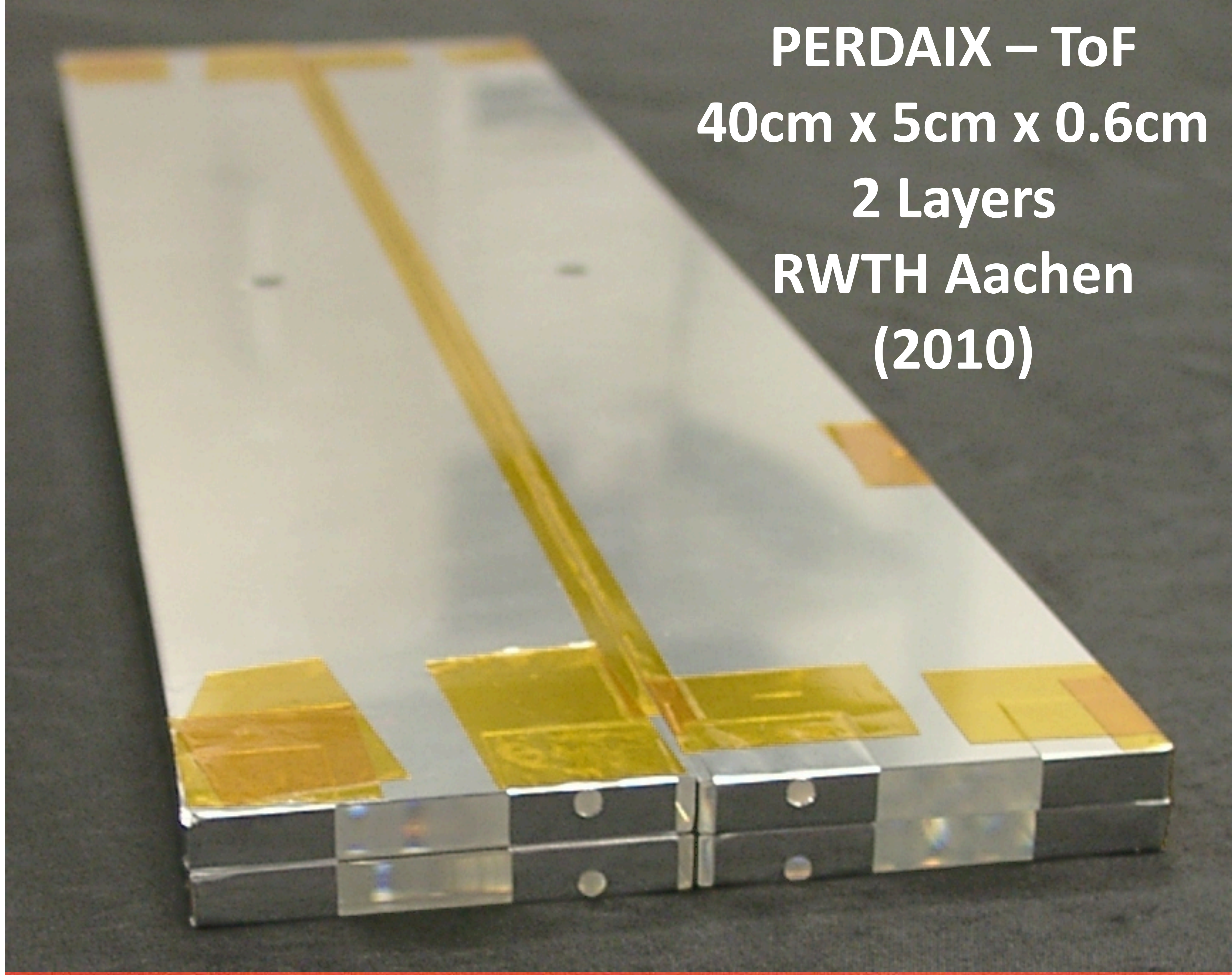
# AMS-100 ToF

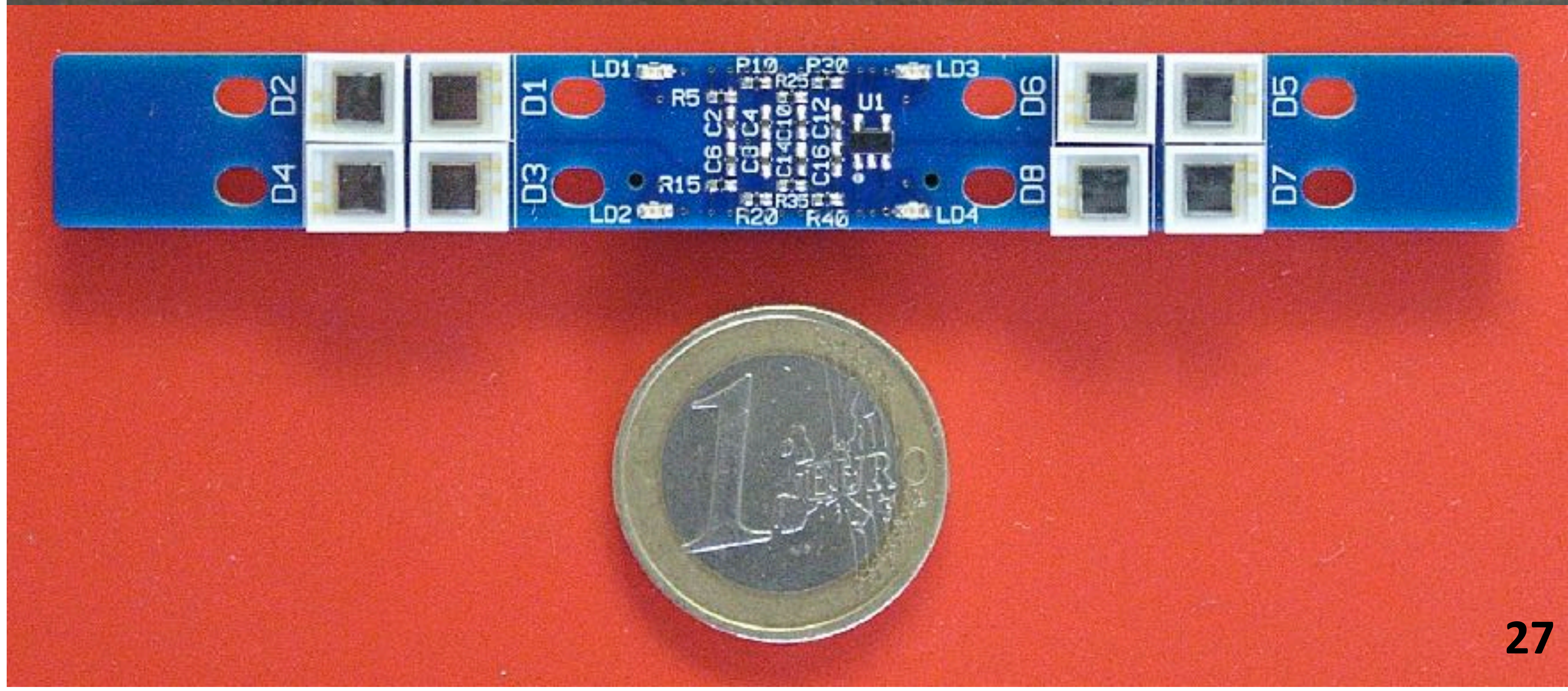
**Scintillator rods (90mm x 30mm x 6mm) with high-gain and low-gain SiPM readout arranged in 4 overlapping layers.**

## Side view of the SciRod




- **Time Resolution per SciRod: <20 ps**
- **Defines the region of interest for the SciFi-Tracker readout.**



Radiator
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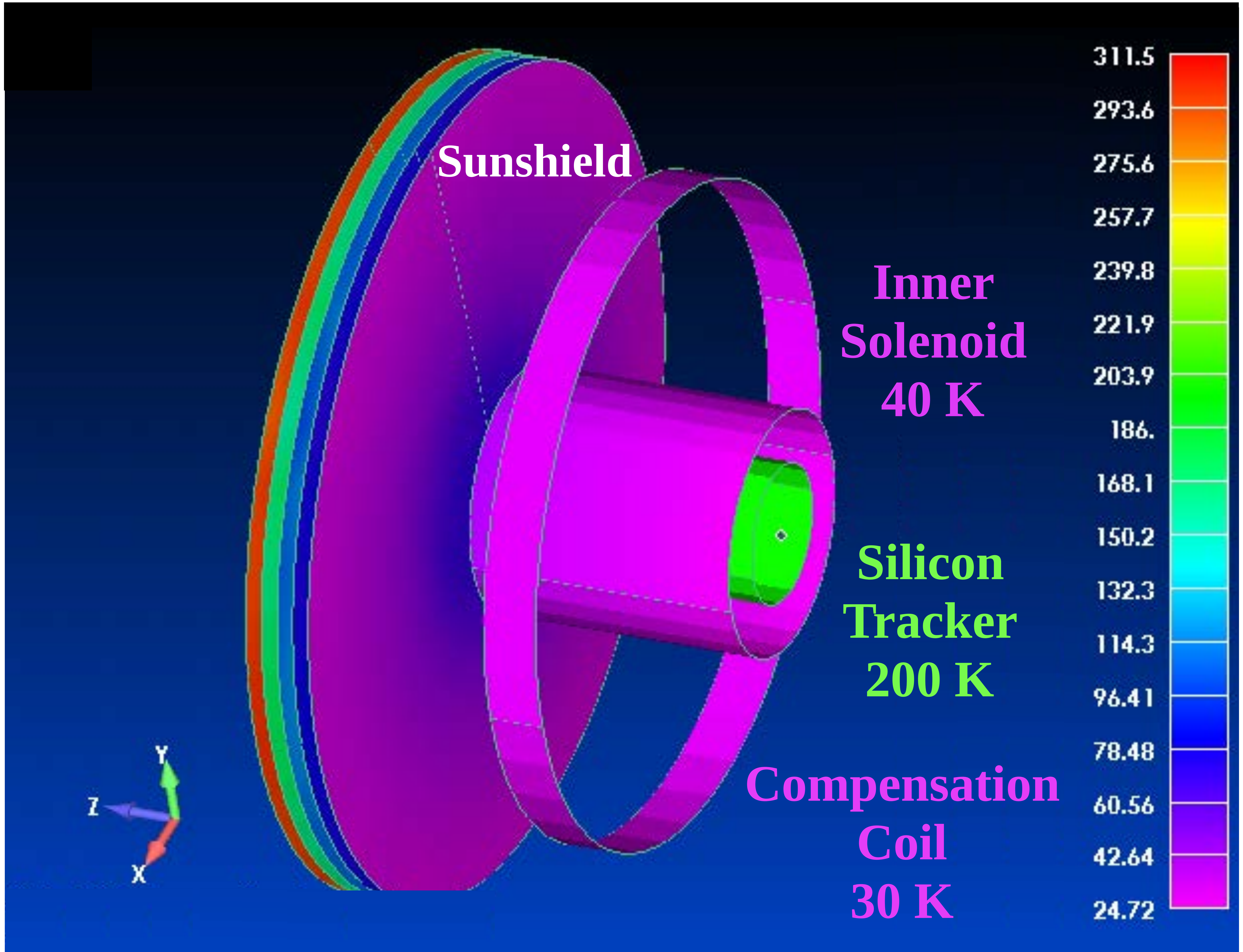
Si-Tracker, Layer 5 & 6
Si-Tracker, Layer 3 & 4
Si-Tracker, Layer 1 & 2
Pre-Shower
Calorimeter

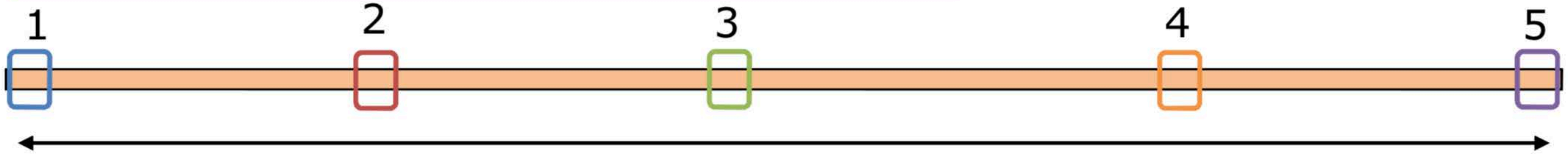
# High Temperature Superconducting Magnet

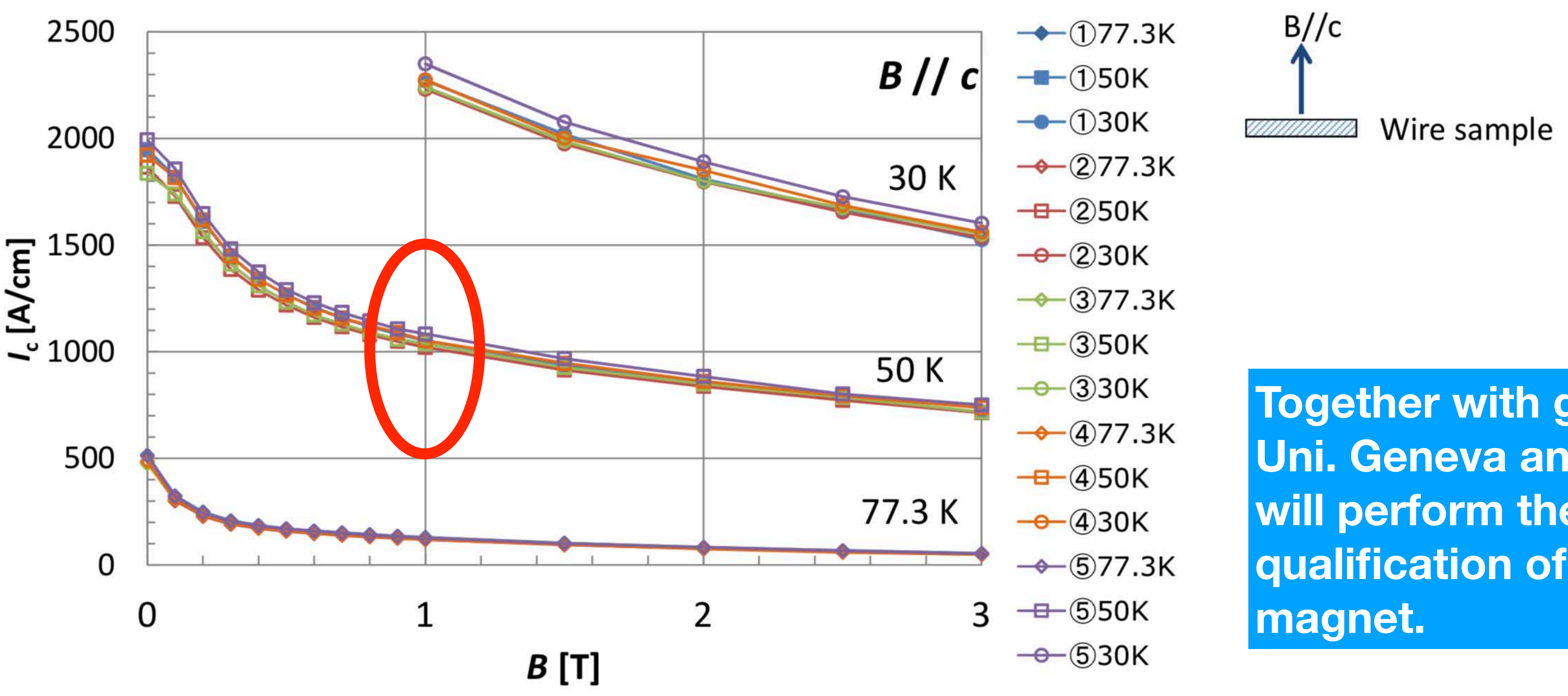
**Provides a homogenous magnetic field of 1 Tesla in a Volume of 75 m³**

**Operated at 50 Kelvin in thermal equilibrium with the environment**



# In-field $I_c$ distribution in a 450m long sample (30, 50, 77 K, 3 T)



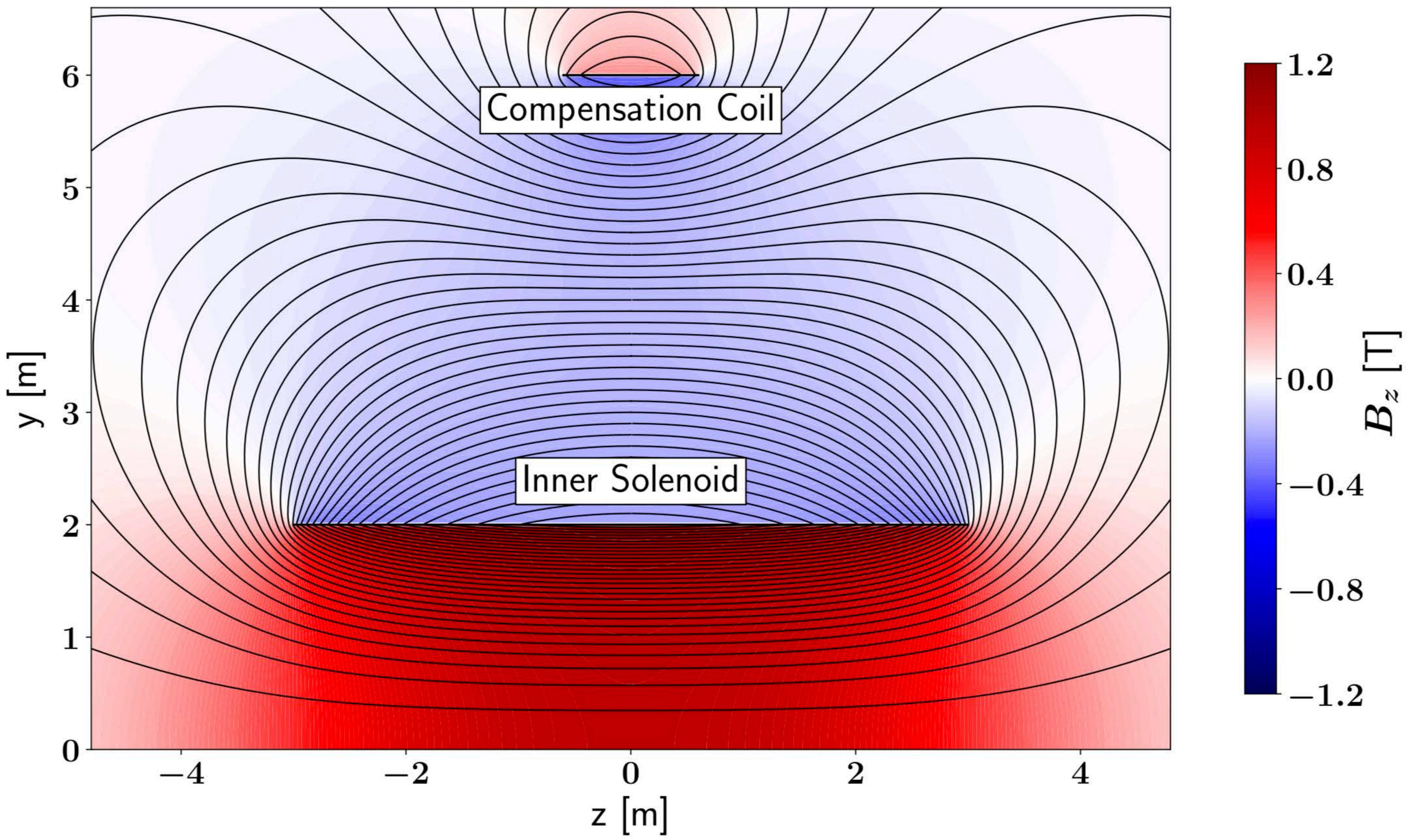




difference of Max. and Min. in-field Ic at 30K 1T ≦ 5%

**Together with groups from Uni. Geneva and EPFL we will perform the first space qualification of a HTS magnet.**

# AMS-100 Magnet Parameters

| | Inner Solenoid | Compensation Coil |
|---|---|---|
| Inner Radius | 2.0 m | 6.0 m |
| Length | 6.0 m | 1.2 m |
| Current | 500 A | 1500 A |
| Temperature | 50 – 60 K | 30 – 40 K |
| HTS Tape Width | 12 mm | 12 mm |
| HTS Tape Layers | 22 | 4 |
| $B_z$ at Center | 1.0 T | −0.06 T |
| Stored Energy | 37 MJ | 4.5 MJ |
| Magnetic Moment | $70\,\mathrm{MA\,m^2}$ | $-70\,\mathrm{MA\,m^2}$ |
| Coil Thickness | 3.0 mm | 0.5 mm |
| Mass | 1.2 t | 0.13 t |
| Volume | $75\,\mathrm{m^3}$ | $136\,\mathrm{m^3}$ |
| Material budget | $0.12\,X_0$<br>$0.012\,\lambda_I$ | $0.02\,X_0$<br>$0.002\,\lambda_I$ |
| Wire Length | 150 km | 15 km |
| $\sigma_R$ | −130 kPa | −40 kPa |
| $\sigma_\theta$ | 270 MPa | 250 kPa |
| $\sigma_Z$ | −140 MPa | −79 kPa |



Radiator

Outer SciFi, Layer 1 - 3

Outer ToF, Layer 1 & 2

Magnet

Inner ToF, Layer 1 & 2

Inner SciFi, Layer 1 - 3

Si-Tracker, Layer 11 & 12

Si-Tracker, Layer 9 & 10

Si-Tracker, Layer 7 & 8

Si-Tracker, Layer 5 & 6

Si-Tracker, Layer 3 & 4

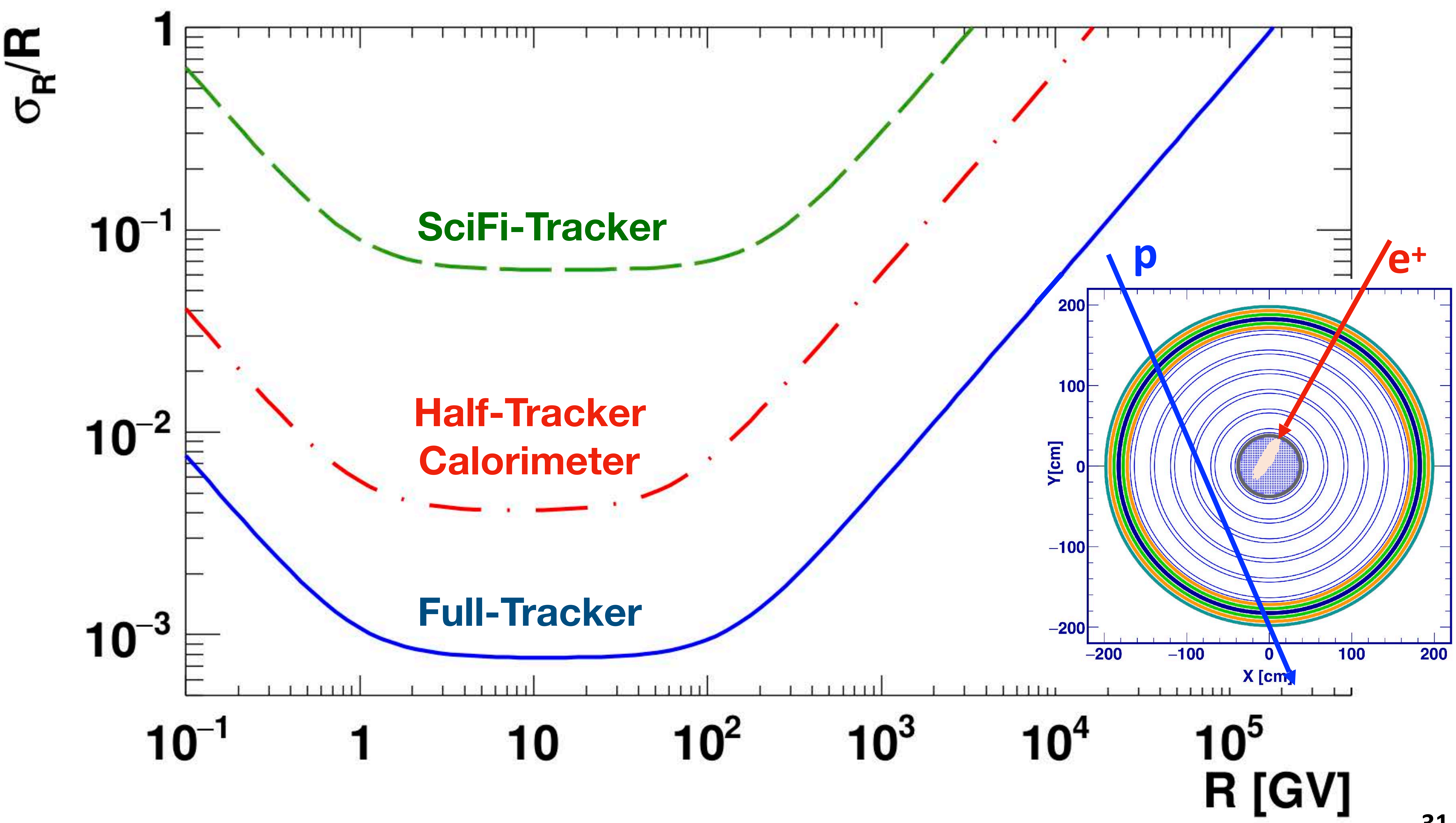
Si-Tracker, Layer 1 & 2

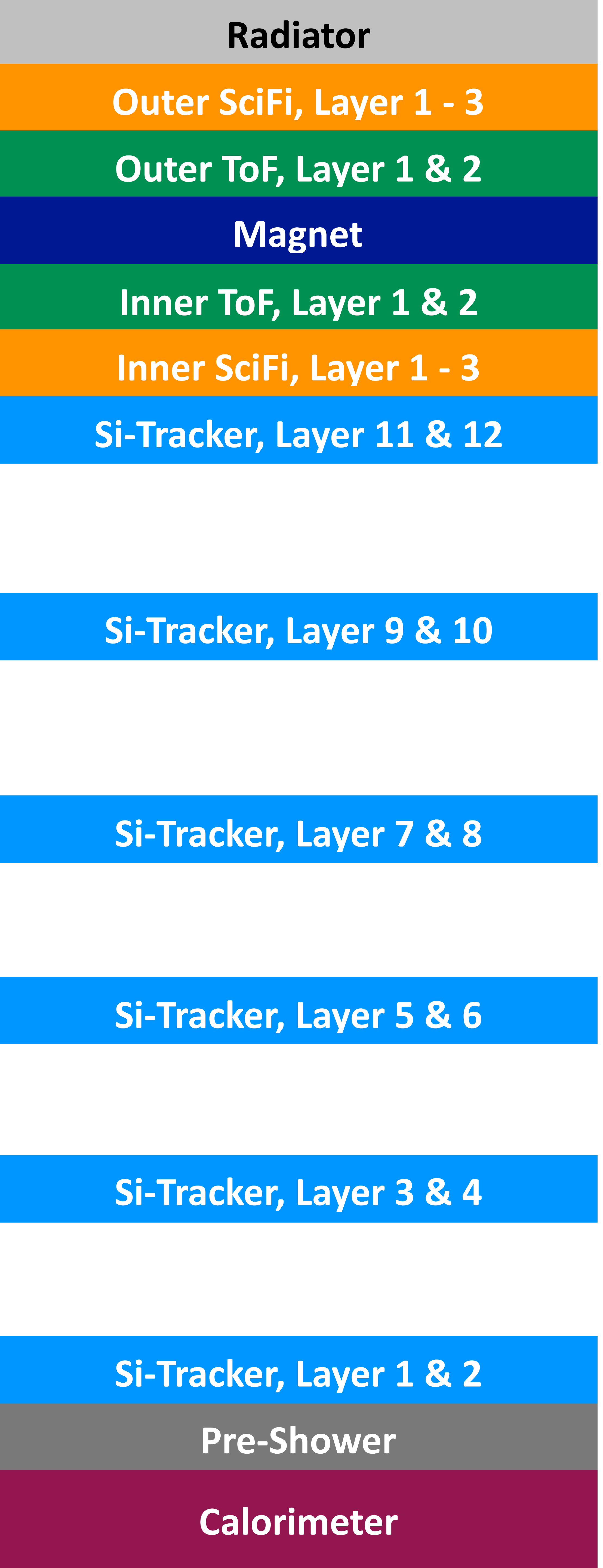
Pre-Shower

Calorimeter

# Performance of the Tracking System

## The concentric 6 double layers of the Silicon Tracker provide up to 2x12 Space Points with 0.005 mm resolution and measurements of Z



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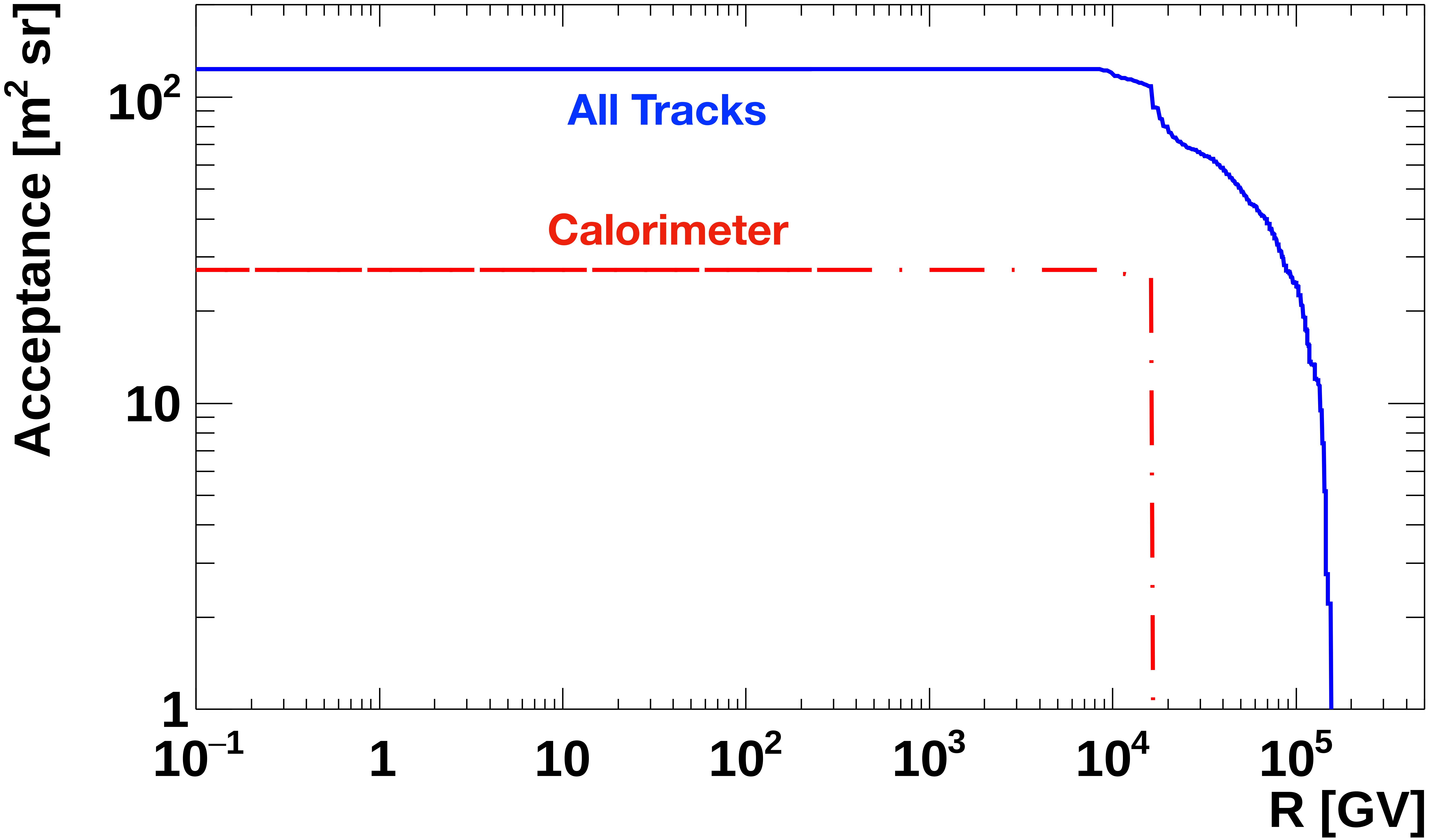
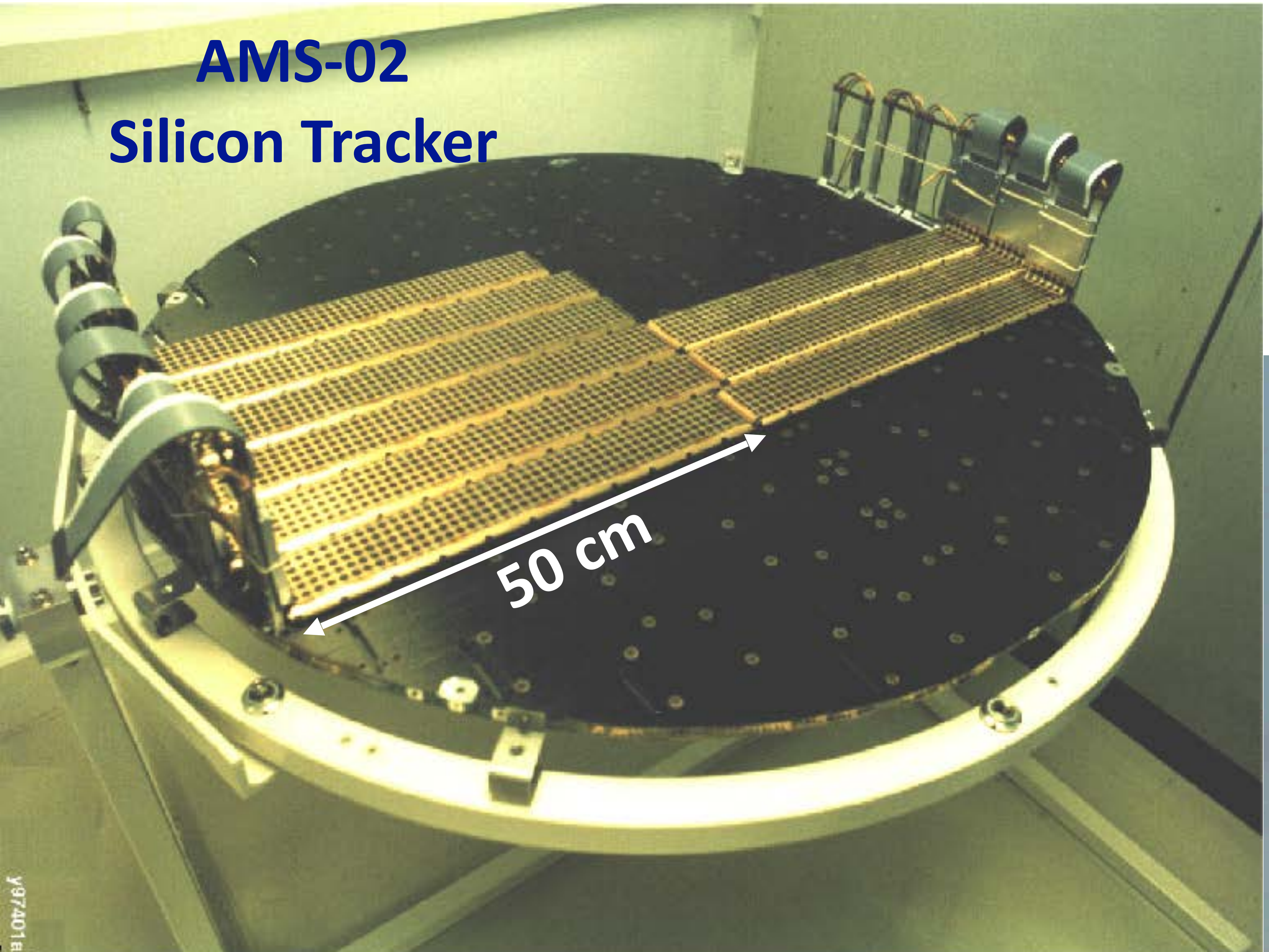
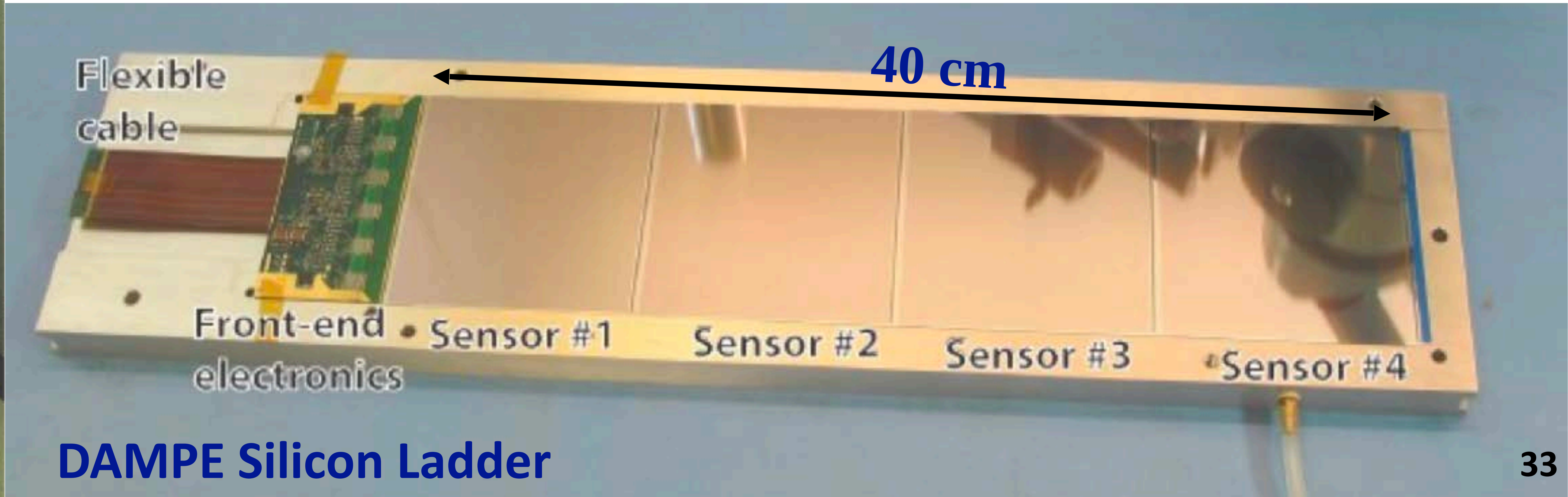



- 6 Cylinders, 12 Layers
- Double-Sided Silicon Detectors, 380 m$^2$ (similar to CMS)
- Readout: VA-140 Chip, 0.35 μm CMOS, 0.3 mWatt/Channel
- 5.2 $10^6$ Channels



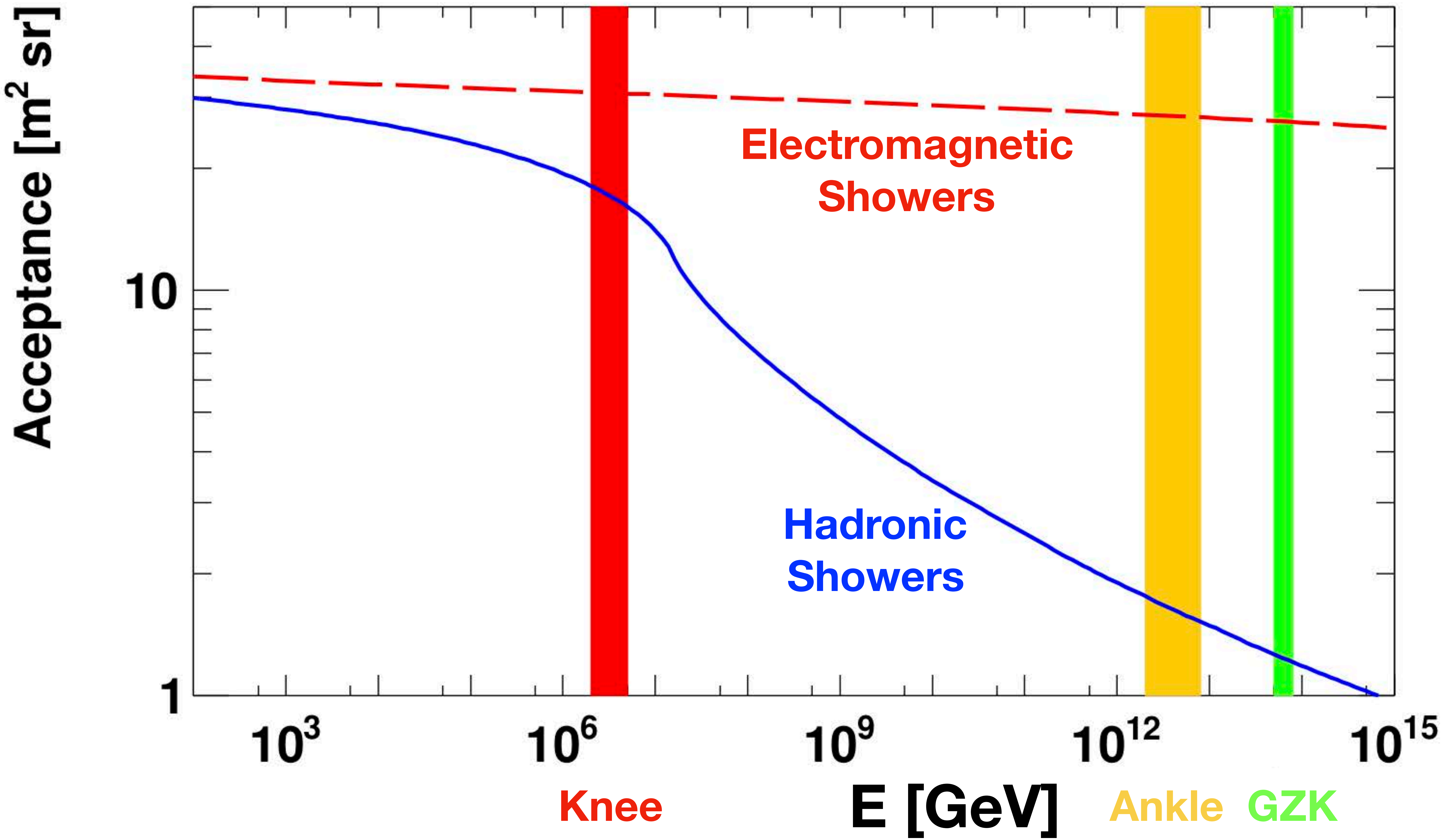
Radiator
Outer SciFi, Layer 1 - 3
Outer ToF, Layer 1 & 2
Magnet
Inner ToF, Layer 1 & 2
Inner SciFi, Layer 1 - 3
Si-Tracker, Layer 11 & 12
Si-Tracker, Layer 9 & 10
Si-Tracker, Layer 7 & 8
Si-Tracker, Layer 5 & 6
Si-Tracker, Layer 3 & 4
Si-Tracker, Layer 1 & 2
Pre-Shower
Calorimeter

# Pre-Shower & Calorimeter: 70 $X_0$ and 4 $\lambda_I$

**Energy and Direction Measurements for Photons, Positrons and Hadrons**

**3D Shower Reconstruction for Particle Identification**

**Energy up to which the shower maximum is contained in the calorimeter.**



# Calorimeter

## inspired by the HERD Detector Concept

**LYSO Crystal**
**3 cm x 3 cm x 3 cm**

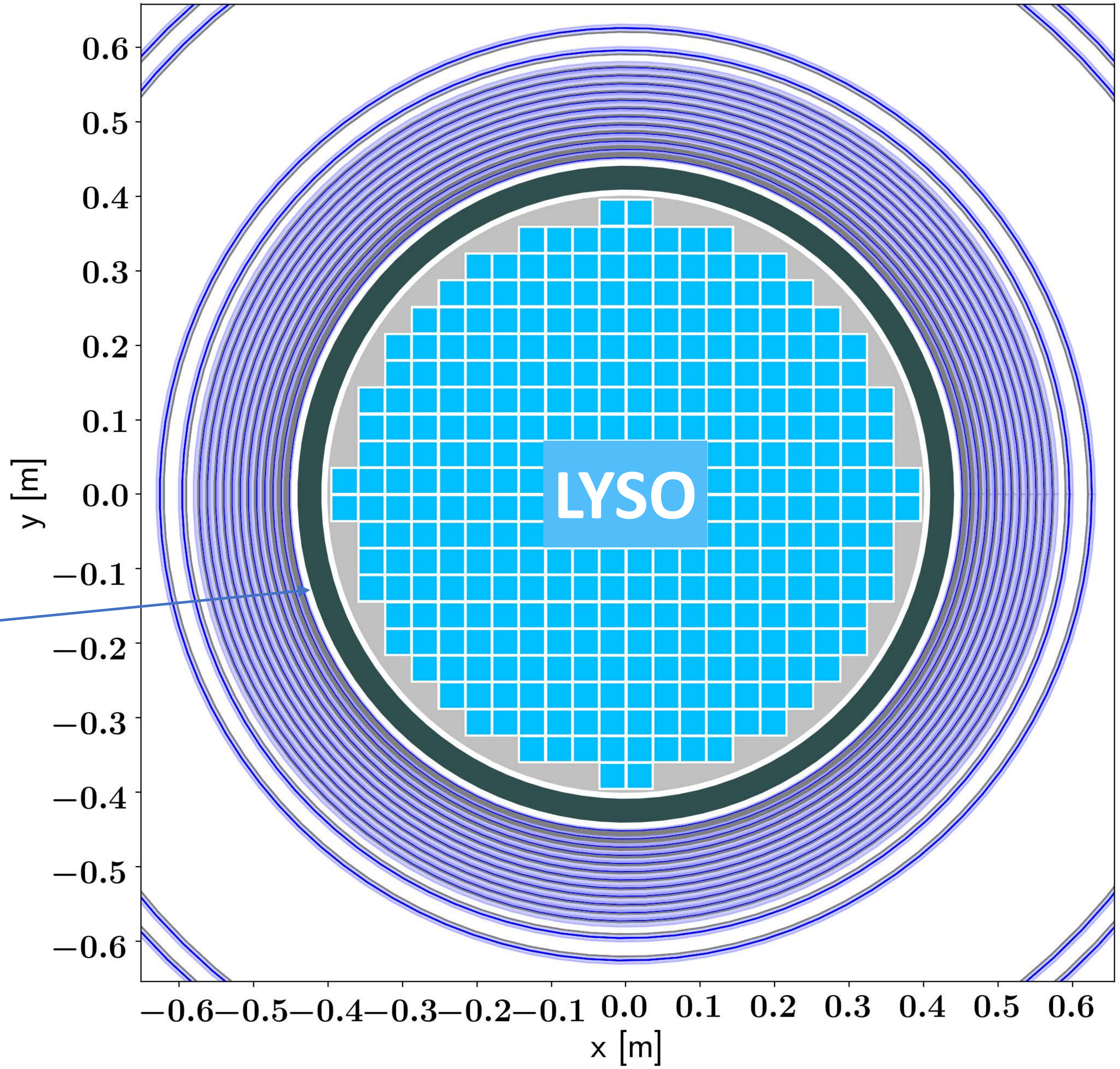
- **LYSO is a Cerium doped Lutetium based scintillation crystal with a density of 7.1 g/cm³.**
- **The $X_0$ of LYSO is 1.14 cm, so each crystal is ~ 2.6 $X_0$**

**LYSO crystal with large and small area photodiodes glued to one face of the cube.**

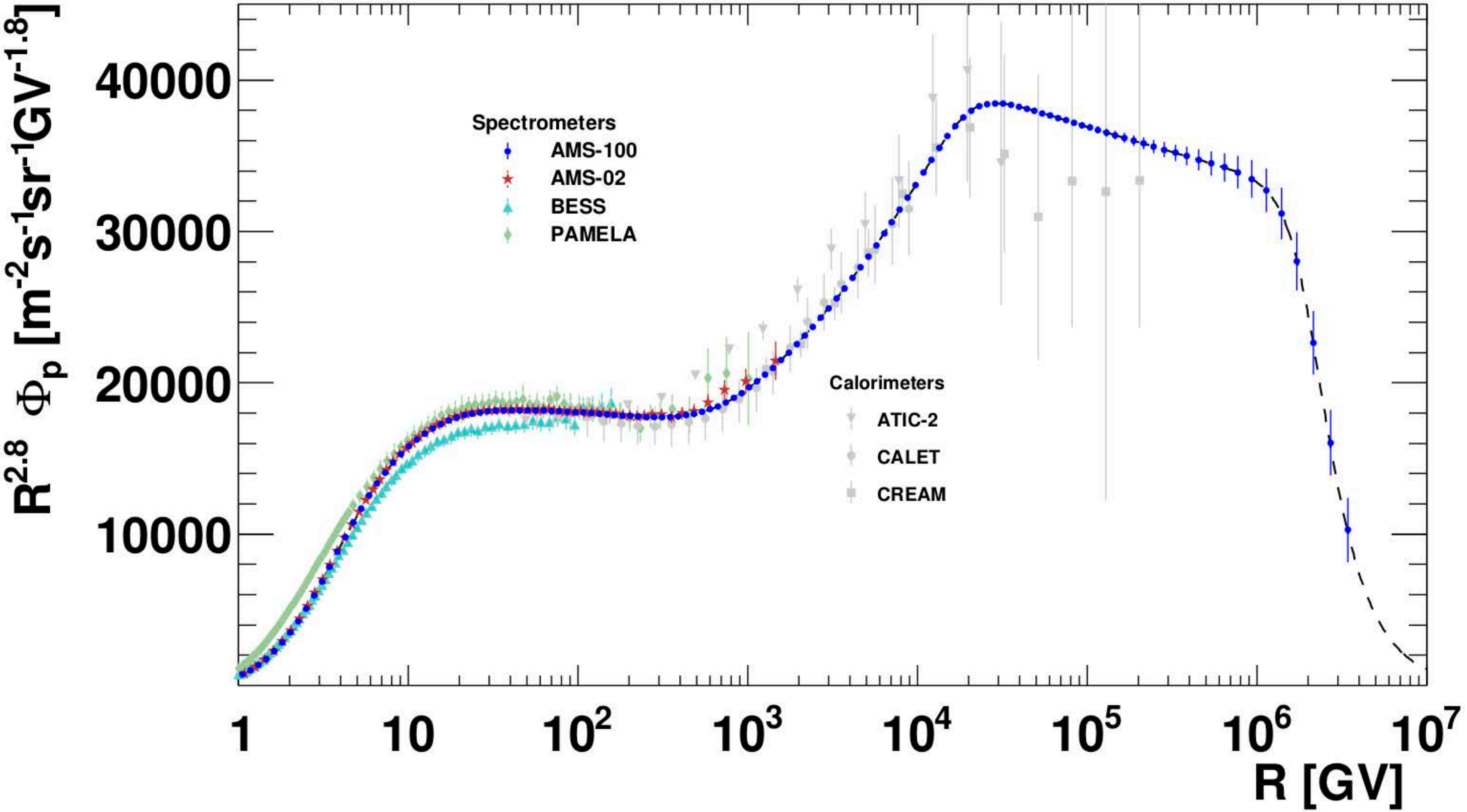
## R=40 cm, L= 400 cm, Weight 8.2 t
## 37 740 LYSO Crystals

**Pre-shower: L=400 cm, Weight 4 t,**
**Tungsten (5 $X_0$) instrumented with Si-Detectors**

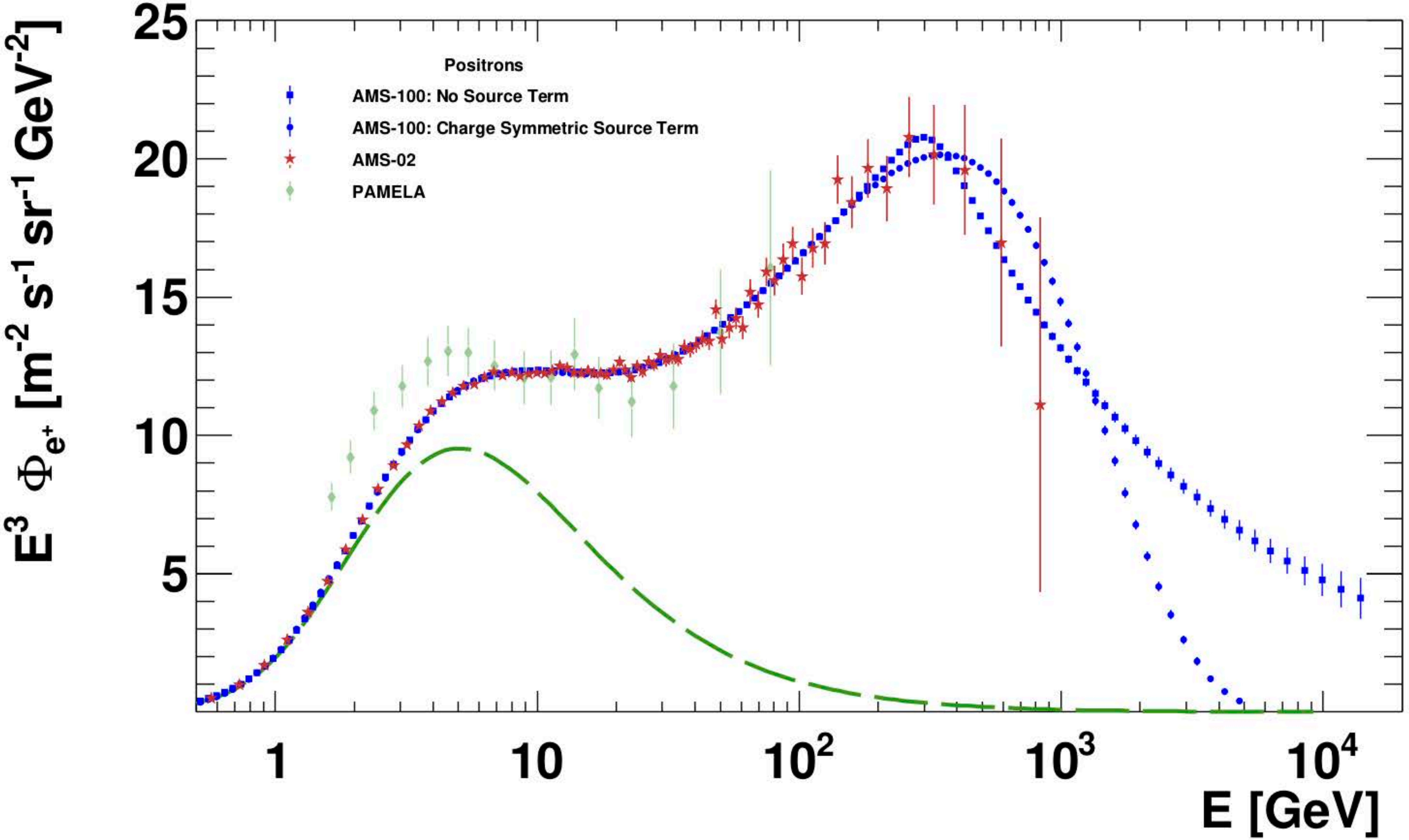
Central
Support Tube
3 cm CF



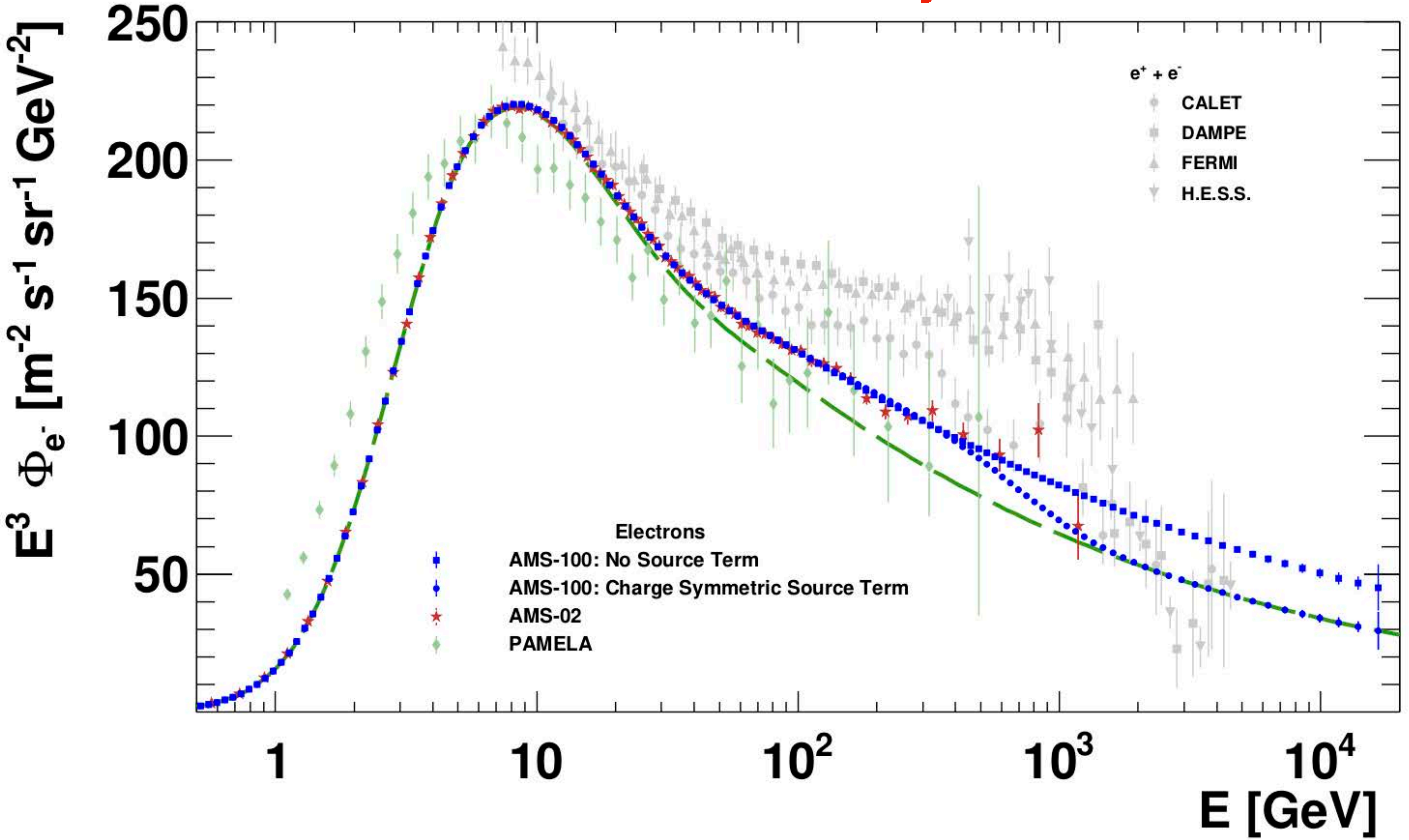
# AMS-100 will measure light Nuclei in Cosmic Rays up to the maximum energy that can be reached by cosmic ray accelerators in our galaxy.



# Positrons in Cosmic Rays

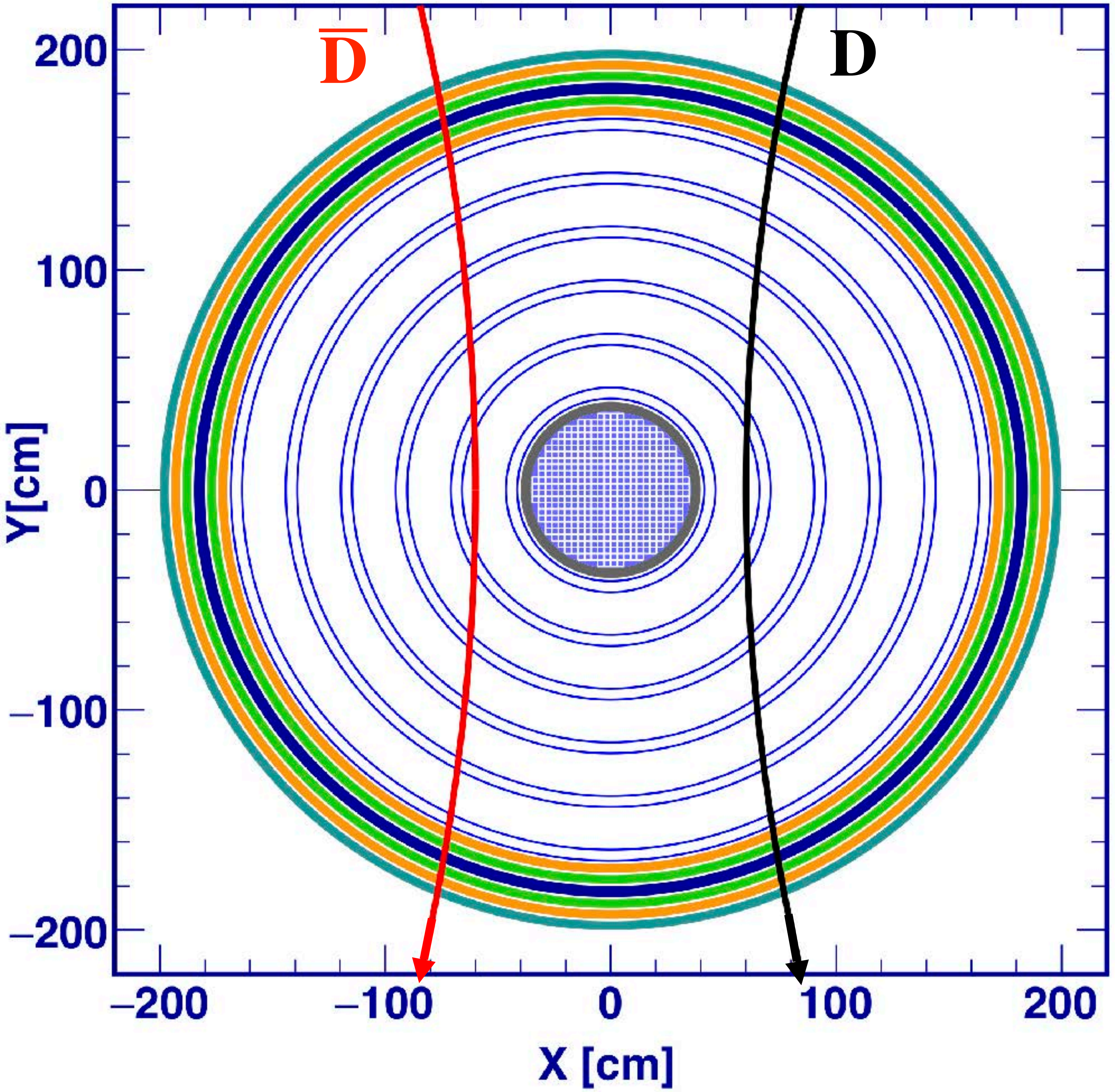


# Electrons in Cosmic Rays



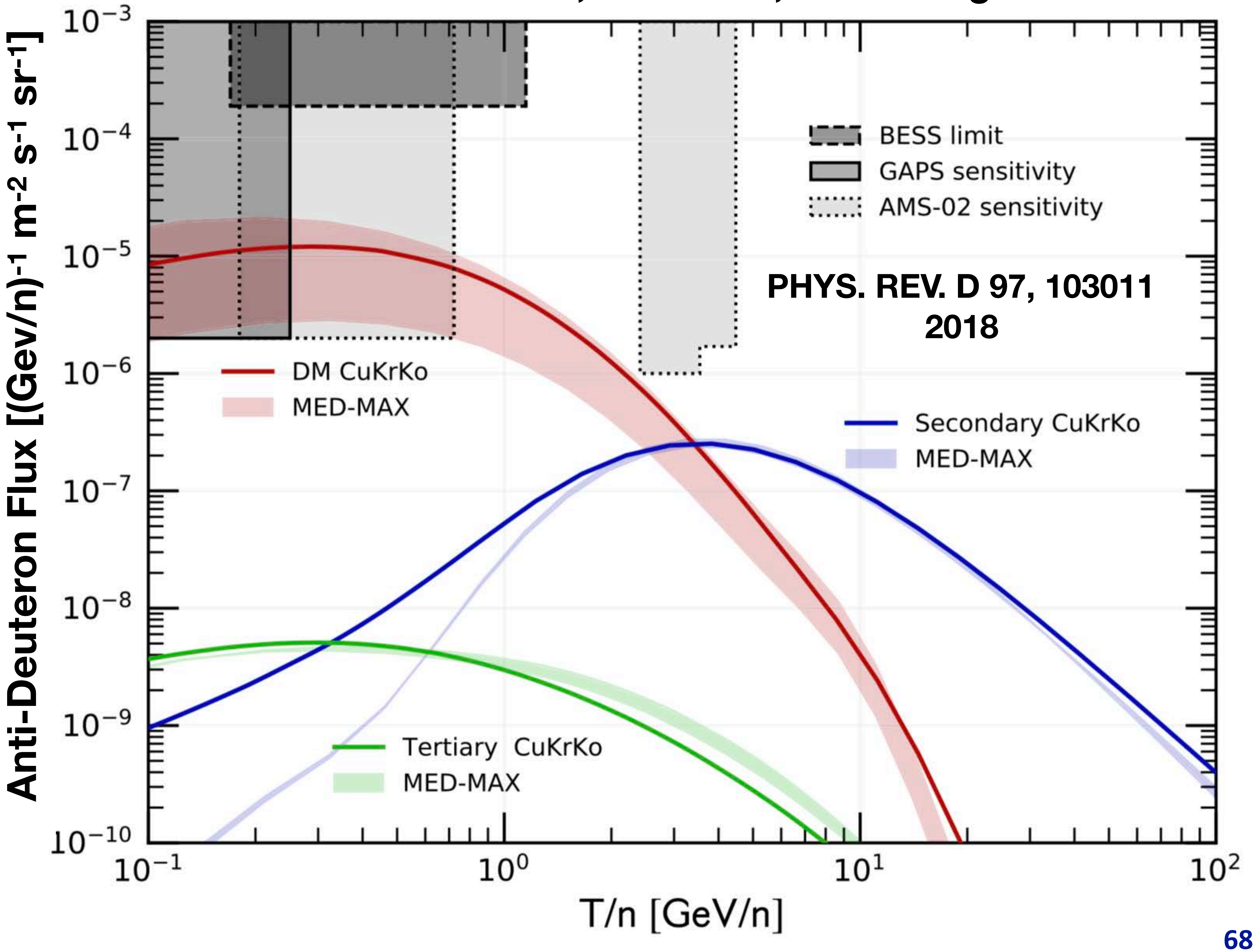
# Anti-Deuterons are the most sensitive probe for New Physics in Cosmic Rays

## As a Magnetic Spectrometer AMS-100 can separate Anti-Matter from Matter.

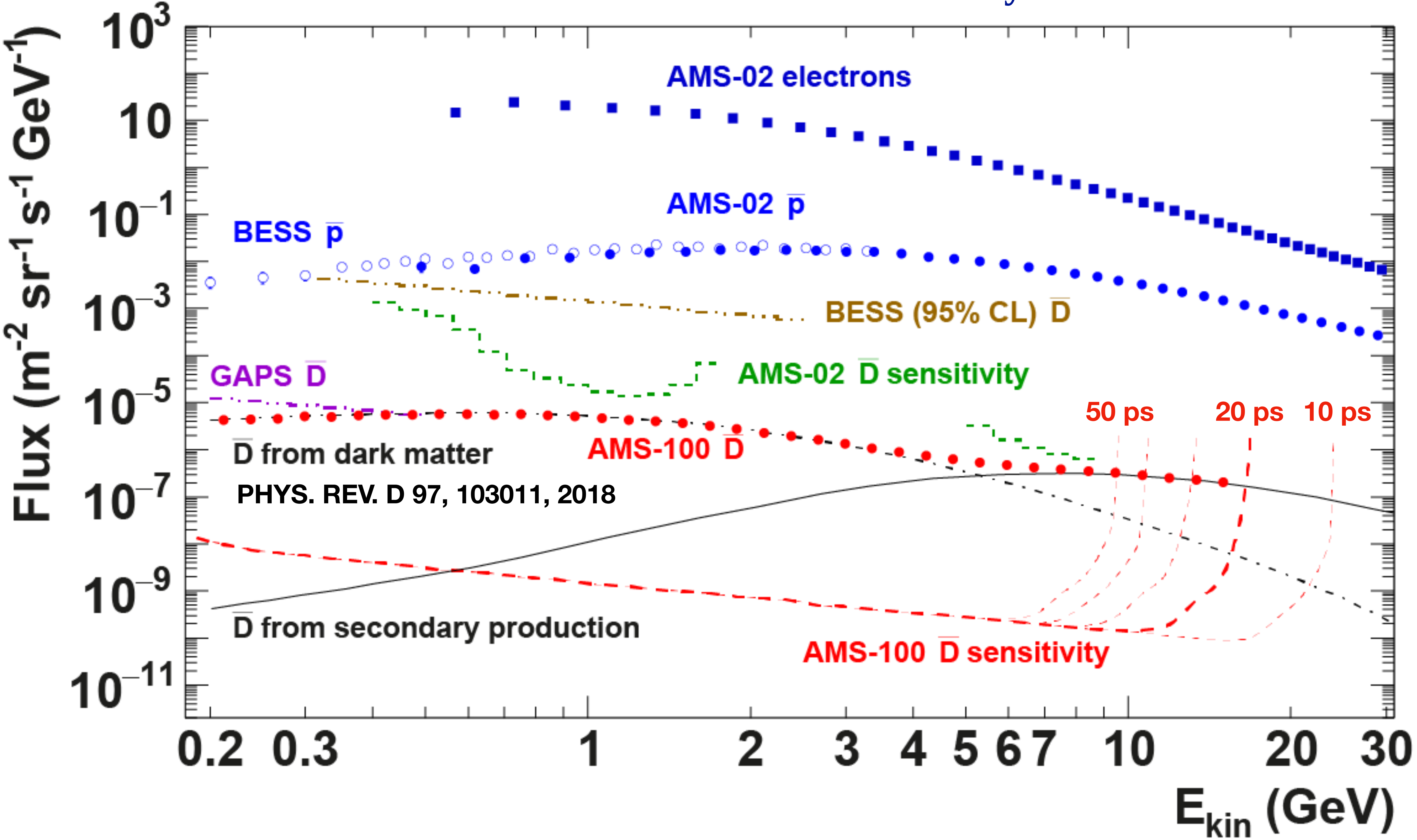



## AMS-100 would observe thousands of Anti-Deuterons in cosmic rays. Integral sensitivities are not useful.

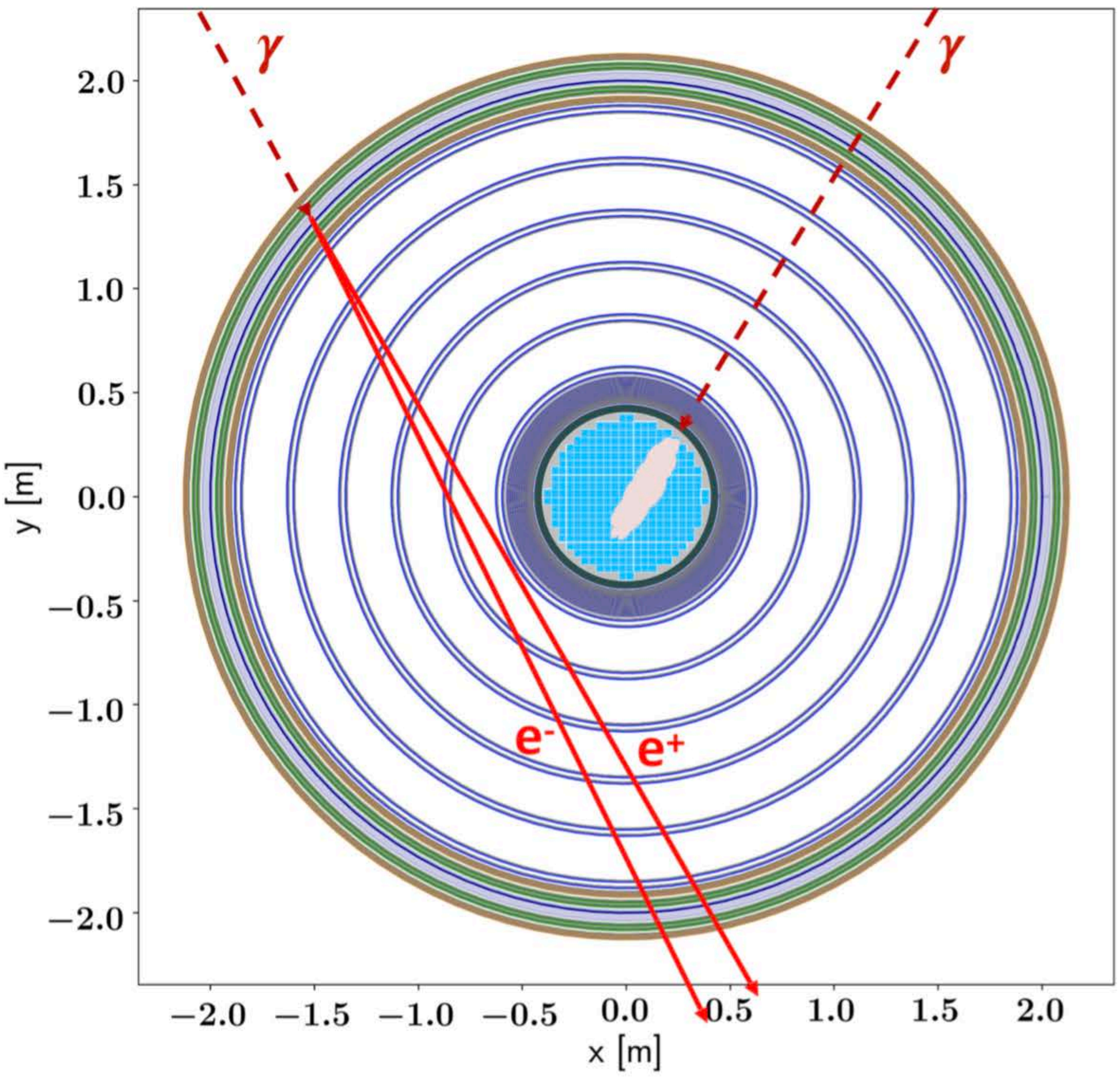
**M. Korsmeier, F. Donato, N.Fornengo**



# Z = – 1 Particles in Cosmic Rays



# Measurement of cosmic gamma rays with AMS-100

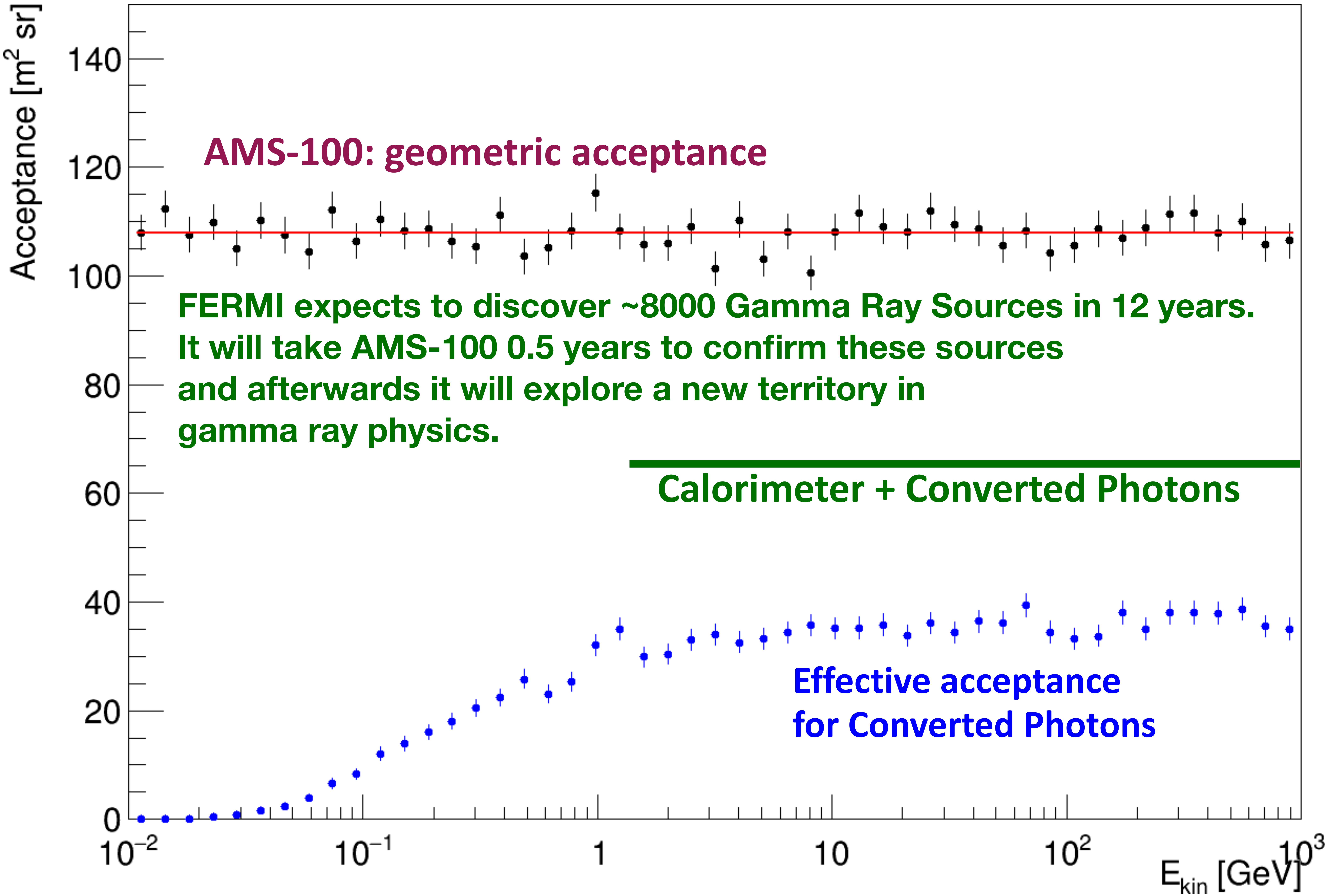



Gamma rays are measured in three ways:

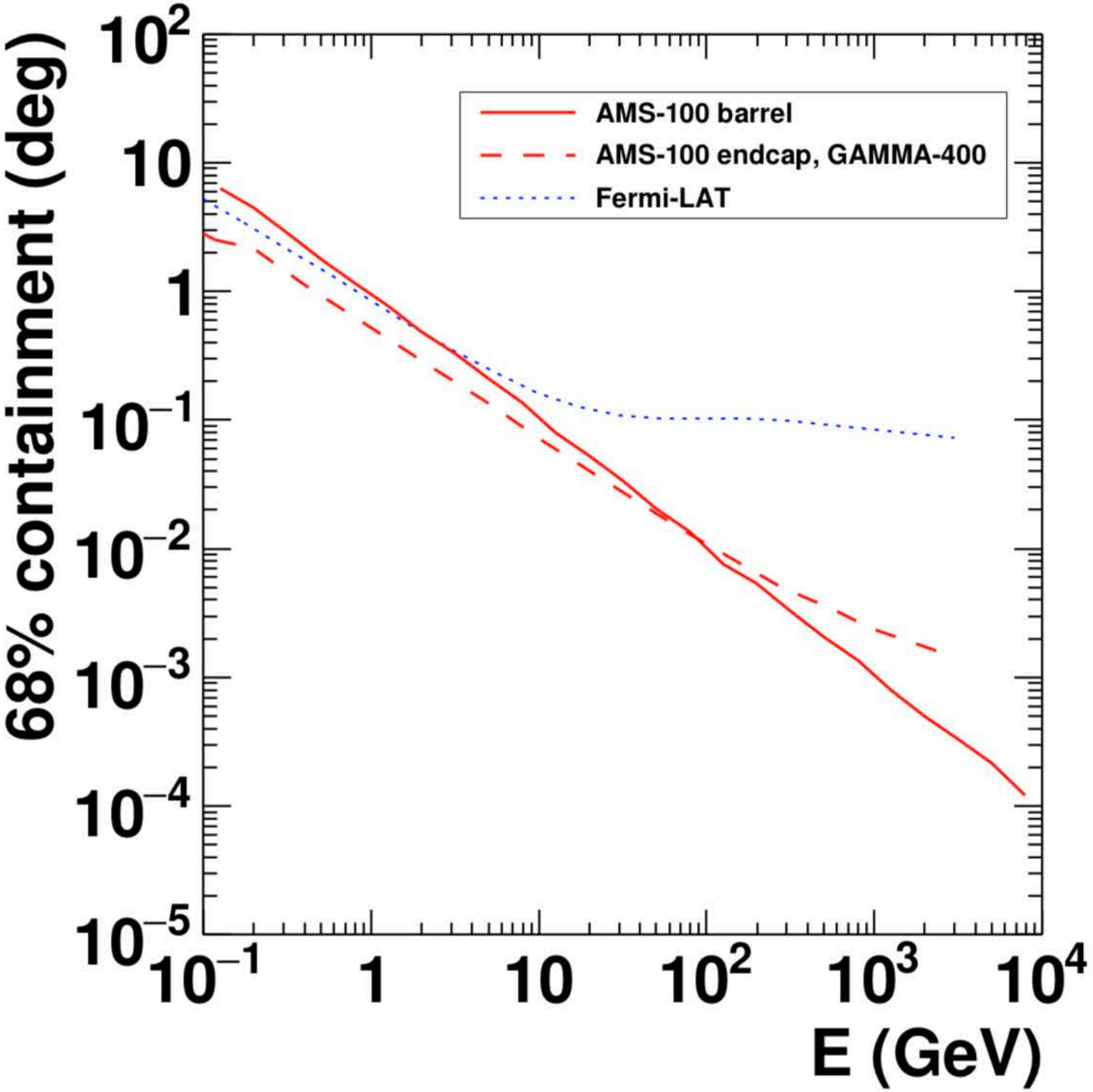
1. Using the calorimeter the acceptance is 30 m² sr. The energy reach is limited by the flux, not by the depth of the calorimeter. For energies above ~1 GeV the whole sky is covered continuously.

2. The 3 mm thin magnet coil (12% $X_0$) is a well localized converter for photons. The angular resolution at high energies is excellent, geometrically 0.005 mm/4000 mm, covering most of the sky continuously.

3. The endcap opposite to the service module is instrumented with a dedicated photon detector inspired by the GAMMA-400 design to optimize the angular resolution at low energies.


Acceptance [m2 sr]
AMS-100: geometric acceptance
FERMI expects to discover ~8000 Gamma Ray Sources in 12 years.
It will take AMS-100 0.5 years to confirm these sources
and afterwards it will explore a new territory in
gamma ray physics.
Calorimeter + Converted Photons
Effective acceptance
for Converted Photons
Ekin [GeV]

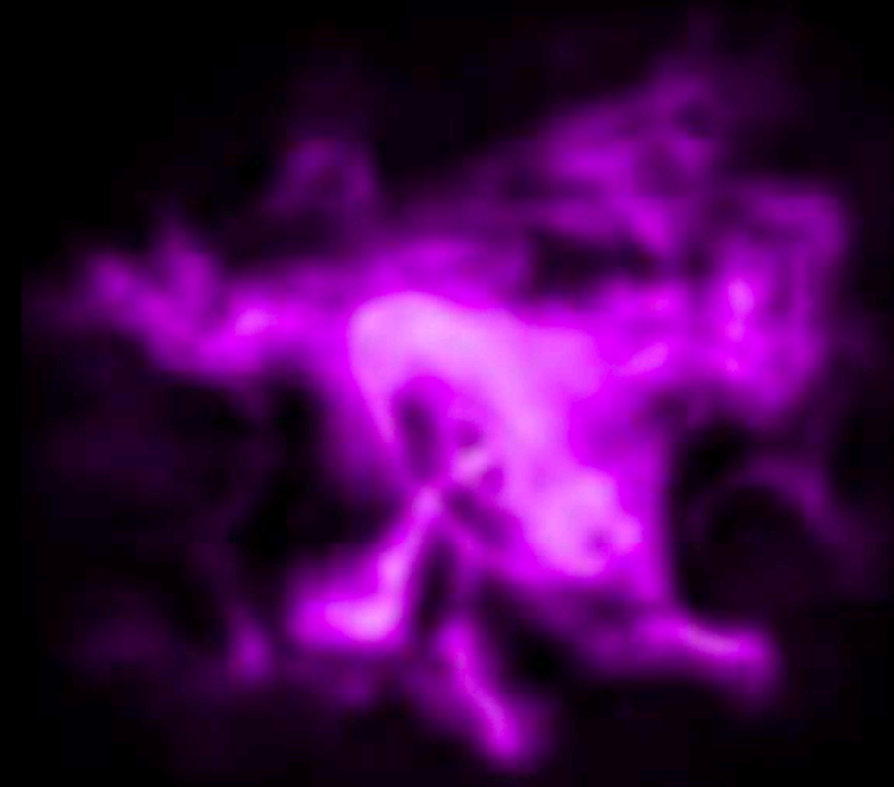
# Angular Resolution for Converted Photons




Crab Nebula with Chandra (blue and white), Hubble (purple), and Spitzer (pink) data.

FERMI, CTA

AMS-100

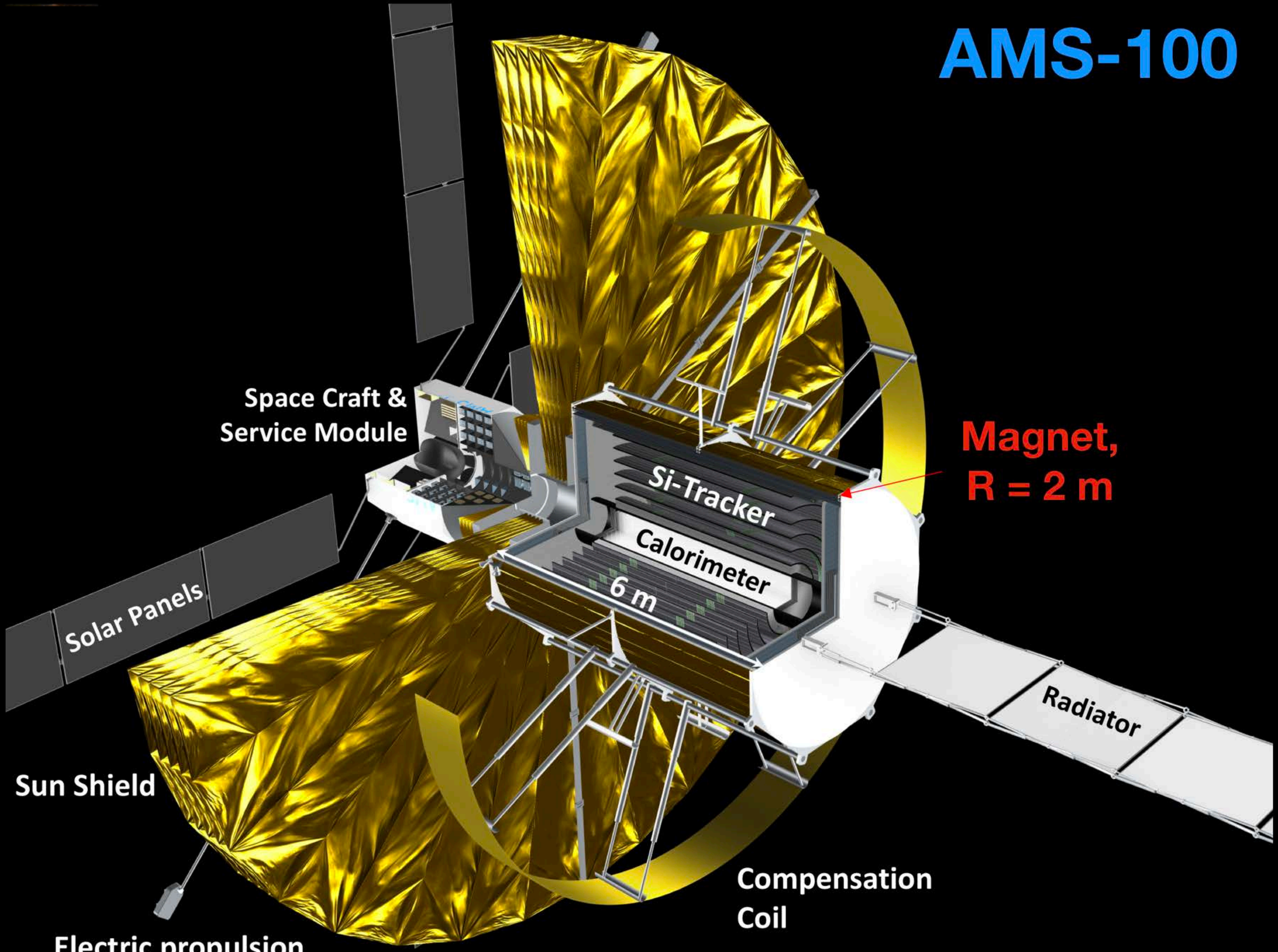


CRAB Nebula TeV - Photons

Weight: 40 t | Readout-Channels: 8 $10^6$ | Power: 10 kW | Measurement Time: 10 years

MDR: 100 TV | Acceptance: 100 $m^2$ sr | B-Field: 1 Tesla | Calorimeter: 70 $X_0$, 4λ

# AMS-100




**New groups who are interested to work on AMS-100 are very welcome !**