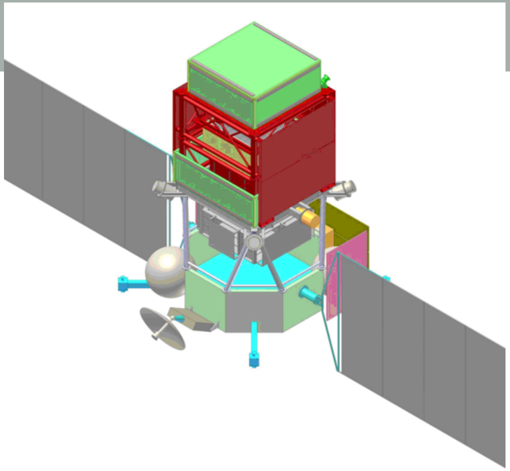


THE GAMMA-400 SPACE EXPERIMENT

Oscar Adriani
University of Florence and INFN Firenze

What Next LNF
Frascati, November 11th , 2014

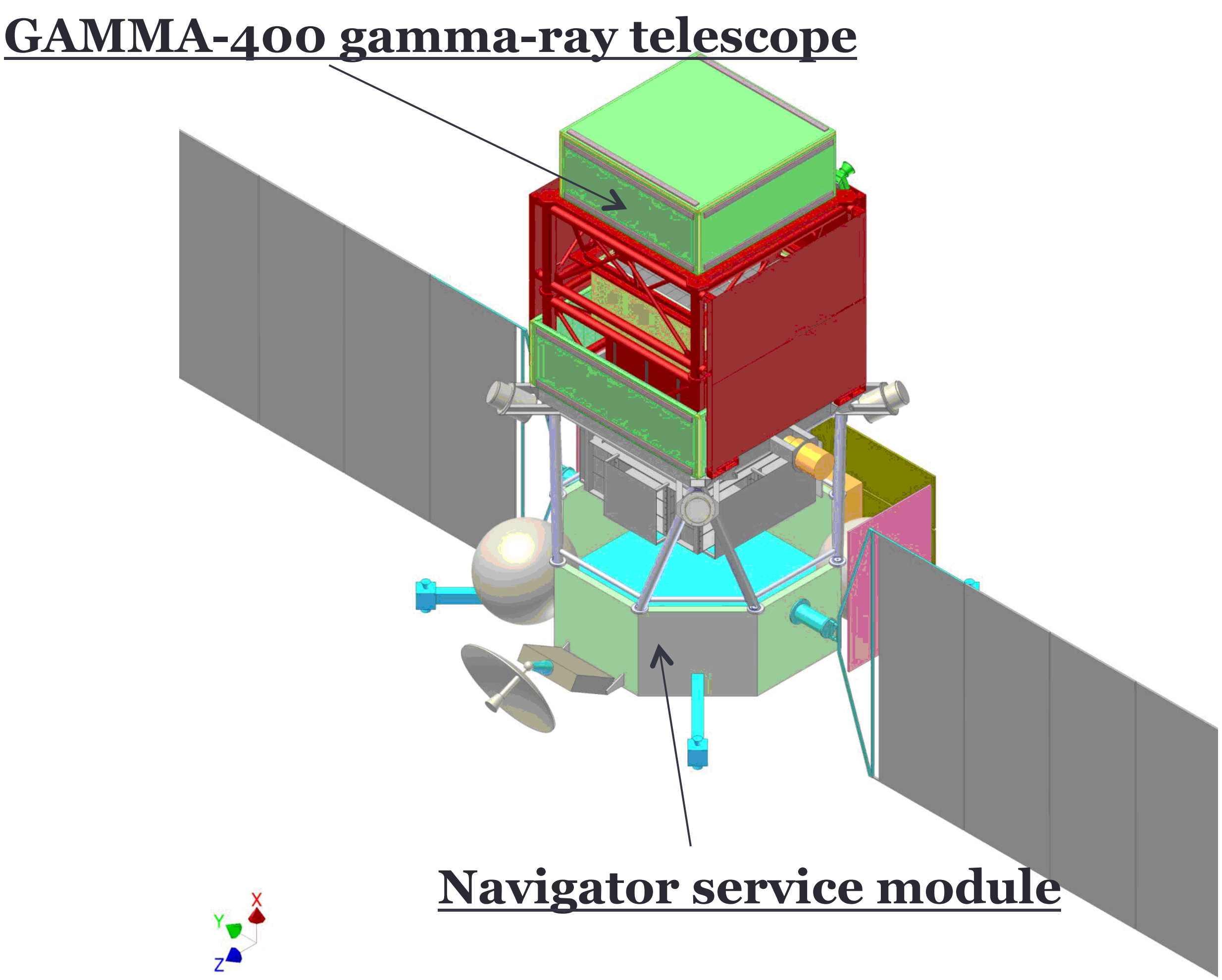
The GAMMA-400 project

- Mission is approved by ROSCOSMOS (launch currently scheduled by beginning of 2020s)
- GAMMA-400:
  - Scientific payload mass: 4100 kg
  - Power budget: 2000 W
  - Telemetry downlink capability: 100 GB/day
  - Lifetime: > 7 years
  - Orbit (initial parameters): apogee 300000 km, perigee 500 km, orb. period 7 days, inclination 51.8 °
  - GAMMA-400 will be installed onboard the platform "Navigator" manufactured by Lavochkin

Cooperation in the design and production of scientific equipment

Russian scientific organizations	Foreign scientific organizations
LPI RAS — main collaborator	INFN (Italy) — stripped detector and calorimeter
NRNU MEPhI — detectors	INAF (Italy) — stripped detector
NIIEM — design, temperature control system	Taras Schevchenko National University (Ukraine) — Ukrainian main collaborator
NIISI RAS — electronics	CrAO (Ukraine) — ground-based observations
Ioffe Institute — Konus-FG burst monitor	IKI (Ukraine) — magnetometer
IKI — star sensor	ISM (Ukraine) — scintillators
IHEP — calorimeters, scintillators	KTH (Sweden) — anticoincidence
TsNIIMASH — space qualification	IFAE (Spain) - Calorimeter

GAMMA-400 SCIENTIFIC COMPLEX ON THE NAVIGATOR



Star sensors (2) with
accuracy of ≈5"
(Space Research Institute)

Gamma-ray burst monitor “Konus-FG” (6)
(Ioffe Physical Technical Institute, St. Petersburg)

4 direction detectors on telescopic booms

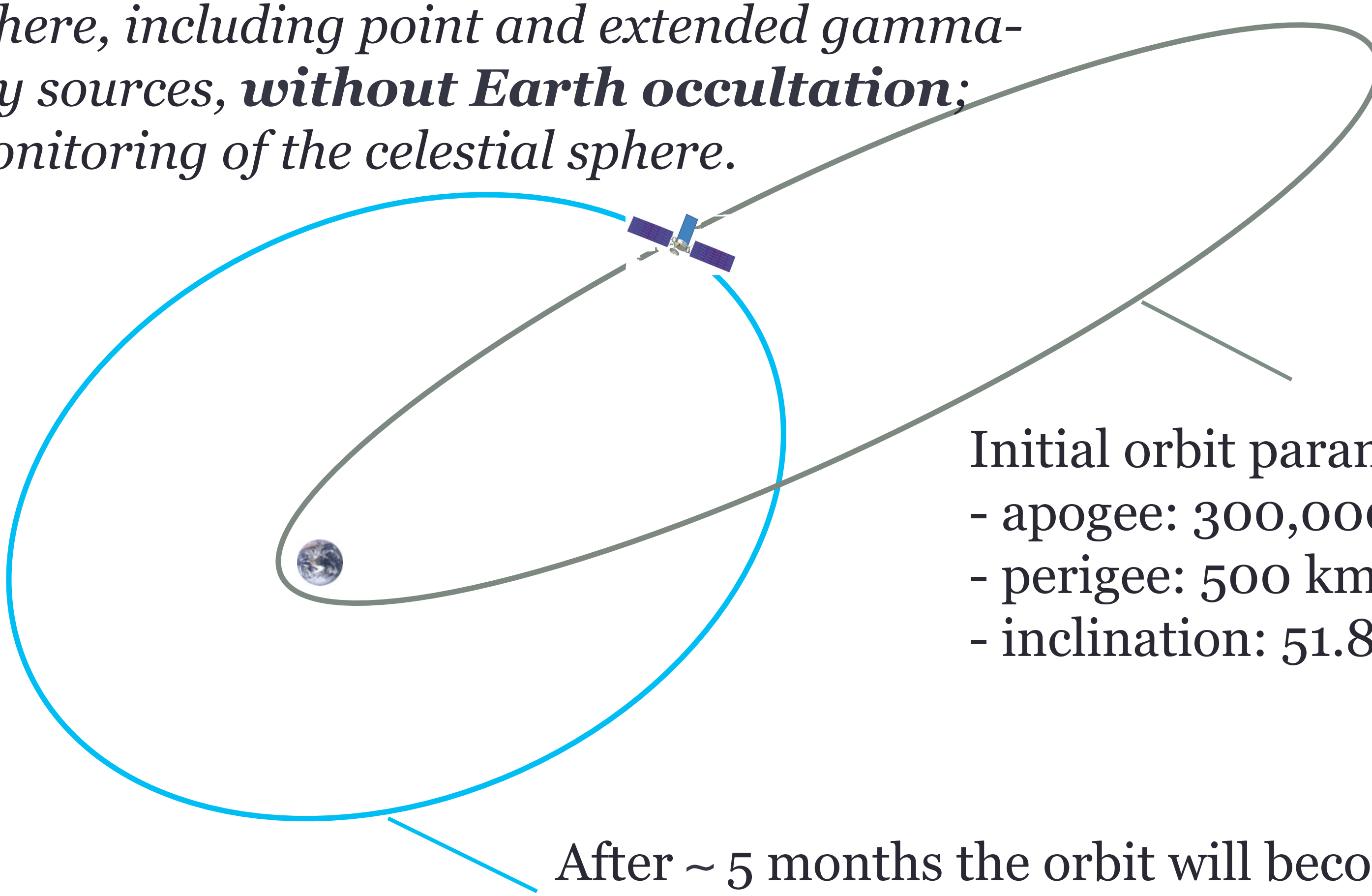
2 spectrometric detectors

Magnetometer (2)
(Ukraine, Lviv)
on telescopic boom

ORBIT EVOLUTION AND OBSERVATION MODES

Observation modes:

- *continuous long-duration (~100 days) observation of specific regions of celestial sphere, including point and extended gamma-ray sources, **without Earth occultation**;*
- *monitoring of the celestial sphere.*



Initial orbit parameters:
- apogee: 300,000 km:
- perigee: 500 km;
- inclination: 51.8°

After ~ 5 months the orbit will become more circular with a radius of ~200,000 km.

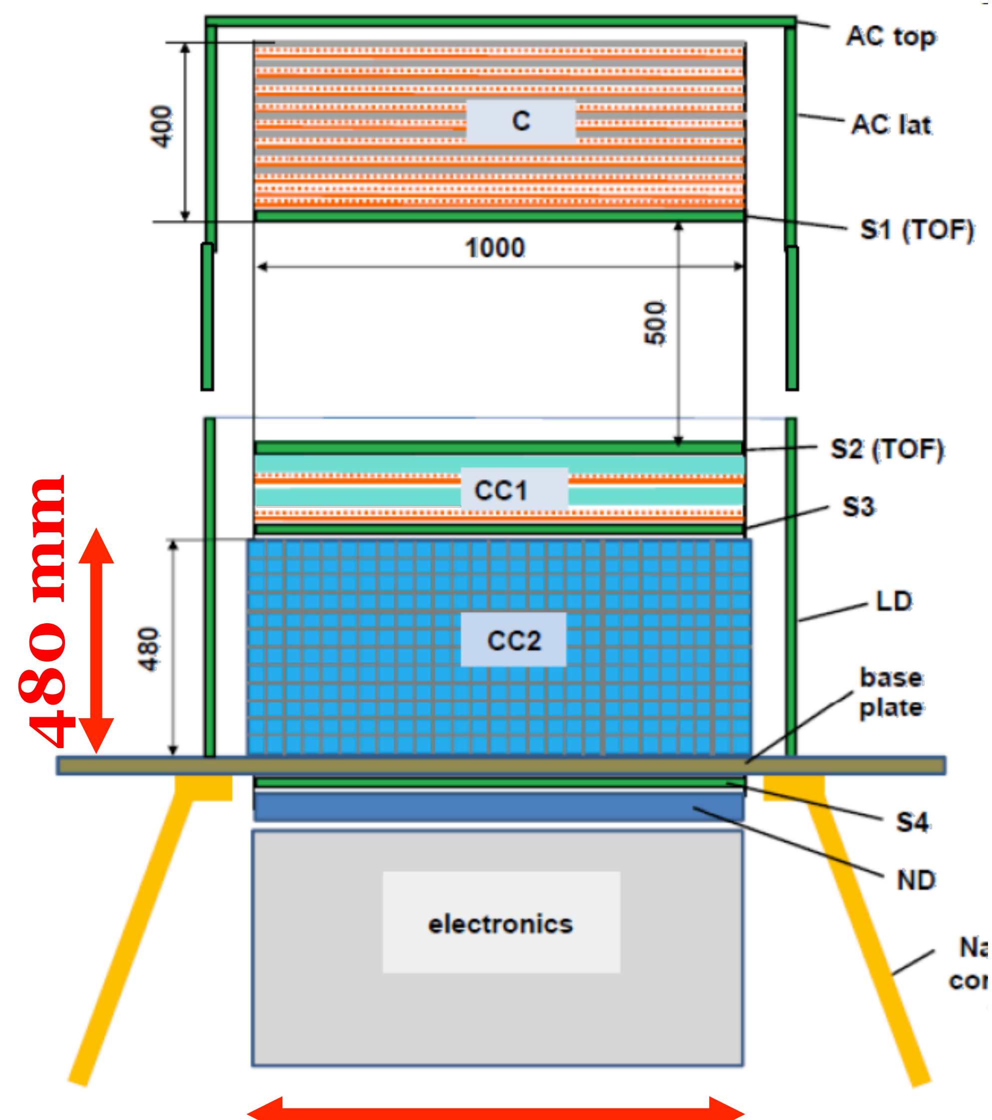
GAMMA-400

- Original Russian design focused on:
  - High Energy Gamma-rays (~ 10 GeV – 3 TeV)
  - High energy electrons (e^+ and e^-) up to TeV
- Scientific objectives (from Russian proposal):
  - "To study the nature and features of weakly interacting massive particles, from which the Dark Matter consists"
  - "To study the nature and features of variable gamma-ray activity of astrophysical objects, from stars to galactic clusters"
  - "To study the mechanisms of generation, acceleration, propagation and interaction of cosmic rays in galactic and intergalactic spaces"

Improvements in the GAMMA-400 design and performance

- During the last years, the collaboration between Italian and Russian groups has resulted in a new version of the apparatus. Guideline:
  - to develop a jointly defined **dual instrument** that, taking into account the currently available financial resources, optimizes the scientific performance and improves them with respect to the original version: this new version **has been agreed upon by both (Russian and Italian) sides during a collaboration meeting held in Moscow in February 2013.**

The GAMMA-400 apparatus



4100 kg

B2 over B1 improvements:

- Introduction of a highly segmented homogeneous calorimeter with CsI cubes ⇒ improved energy resolution, extended GF with lateral particle impingement, high energy protons and nuclei capability
- Increase of the planar dimensions of the calorimeter (from 80 cm x 80 cm to 100 cm x 100 cm) ⇒ larger A_{eff}
- Si strip detector pitch of the 2 CC1 layers decreased from 0.5 mm to 0.08 mm

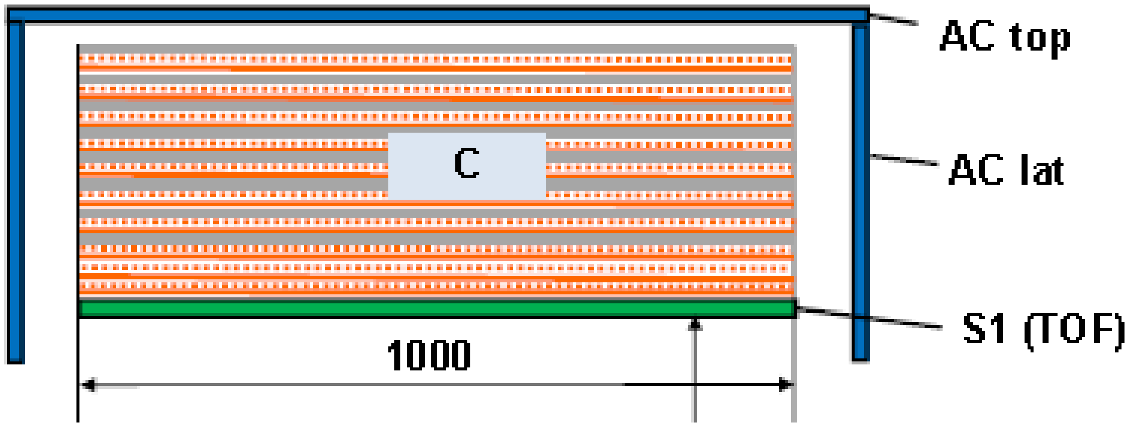
GAMMA-400 characteristics:

- **a dual instrument** for **photons** (100 MeV ÷ 1 TeV) and **cosmic rays** (electrons ~ 10 TeV and high energy cosmic-ray nuclei, p and He spectra at the "knee" (10^{14} – 10^{15} eV);
- **State of the art Si-W converter/tracker with analogue read-out;**
- **3-D, deep, homogeneous calorimeter with excellent resolution and large acceptance.**

Converter/Tracker

INFN Responsibility

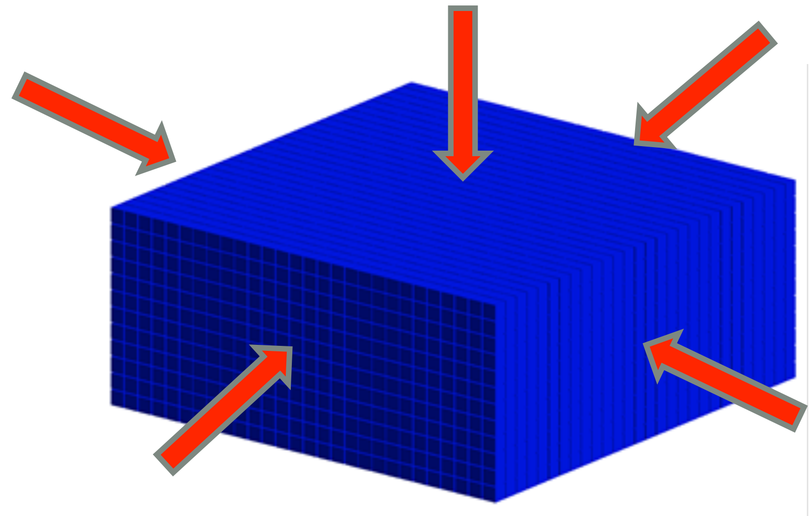
Contract btw Roskosmos/ Lebedev and INFN is being signed for the design and production of the Converter/ Tracker



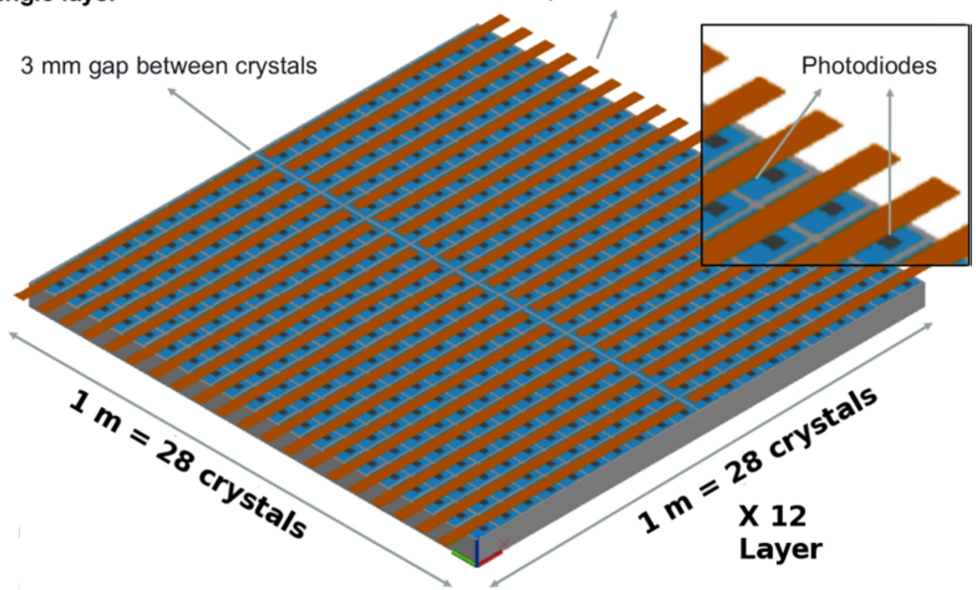
- Si-W Tracker
- 8 W/Si-x/Si-y planes + 2 Si-x/Si-y planes (no W)
- Thickness of each plane 0.1 X_0
- Sensors arranged in ladders (5 detectors/ladder), 1 ladder ~ 50 cm;
- Each sensor ~ 9.7 cm x 9.7 cm from 6" wafers;
- Implant pitch 80 μm, Read-out pitch 240 μm (fine segmentation)
- 2000 silicon detectors;
- 153600 readout channels, 2400 front-end ASICs (64 channels/ASIC)
- Power consumption (FE only): ~ 80 W

CC2 Calorimeter

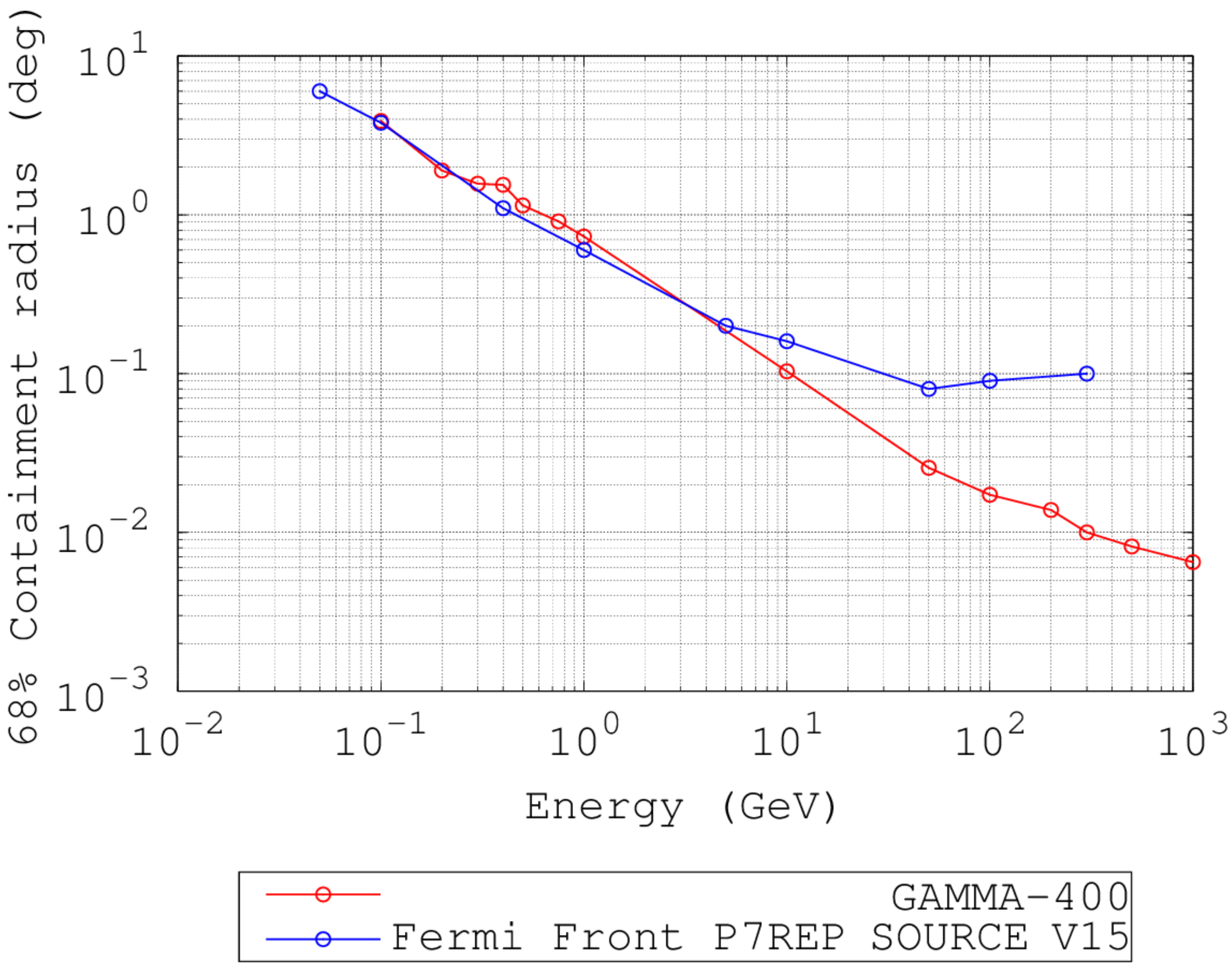
INFN conceptual idea (CaloCube call in CSN5)



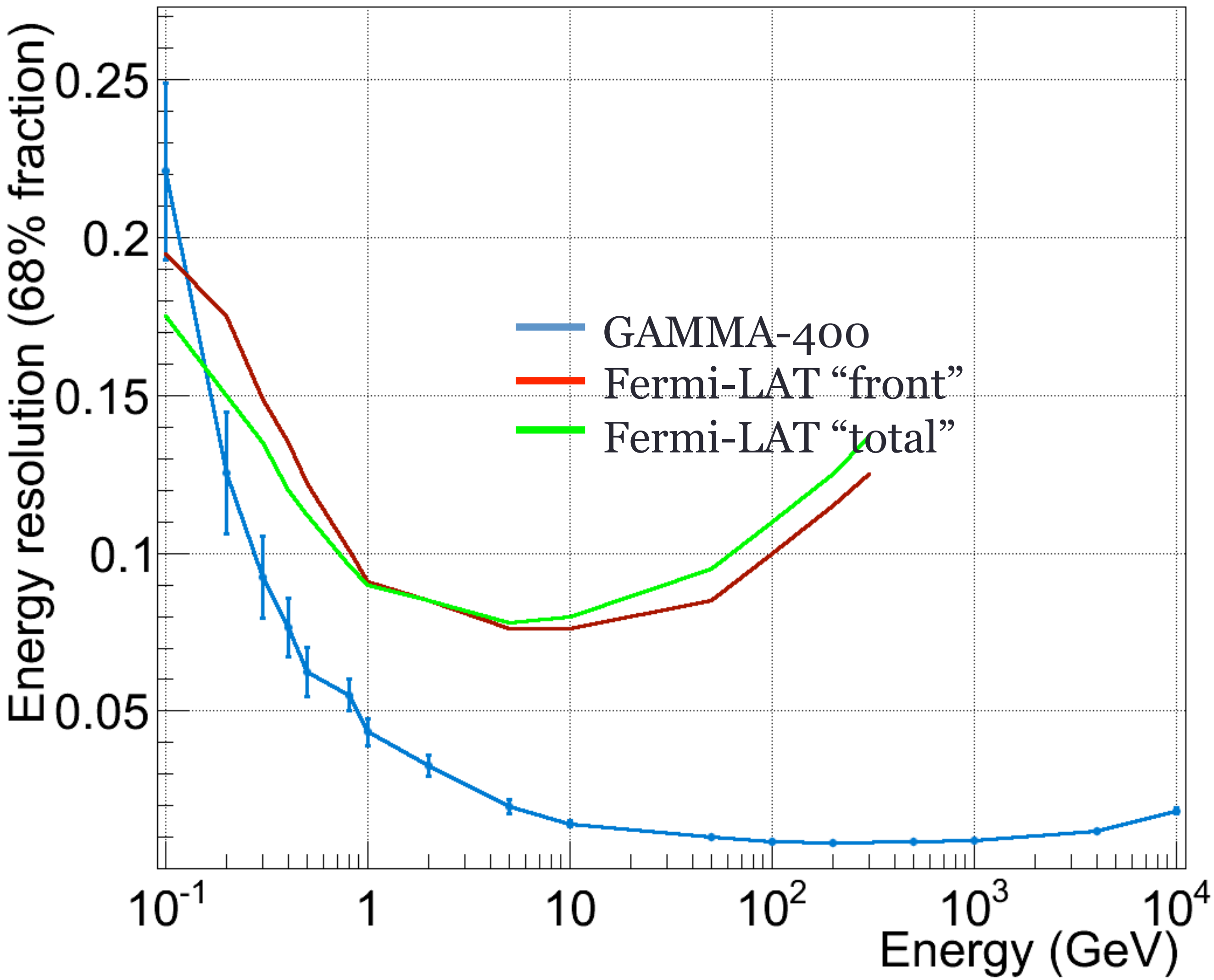
- 28 x 28 x 12 CsI(Tl) cubes
- L_{cubes} = 3.6 cm
- CC2 dimensions: 1 x 1 x 0.47 m^3
- X_0: 54.6 x 54.6 x 23.4
- λ_I: 2.5 x 2.5 x 1.1
- Mass = 1980 kg
- Planar GF: 9.5 m^2sr
- $GF_{eff, el.}^{0.1\text{-}1\ TeV}$ ~ 3.4 m^2sr
- $GF_{eff, prot.}^{1\ TeV}$ ~ 4 m^2sr
- Slightly staggered planes to avoid dead regions



Angular resolution for γ



Energy resolution for γ



Expected number of high energy charged cosmic rays events

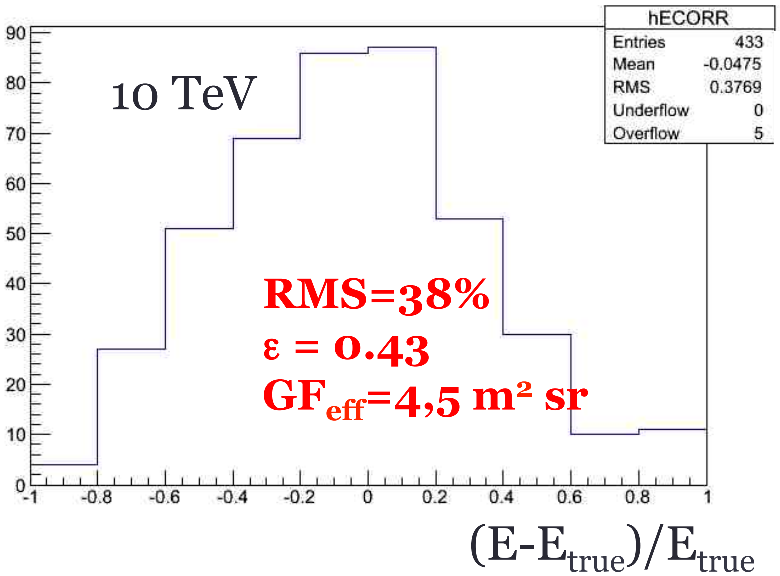
Some assumptions:

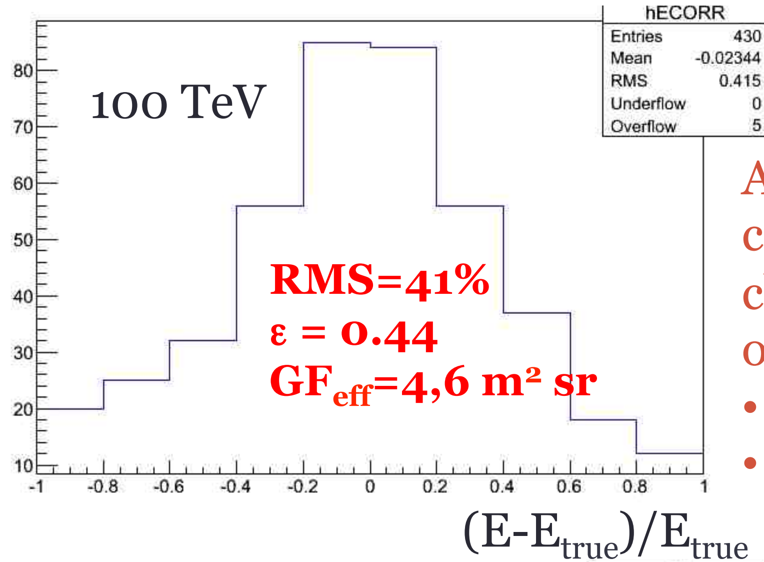
- 10 years exposure
- e/p rejection factor ~ 10^5

Protons and Helium (Polygonato model)											
Effective GF (m^2 sr)	σ(E)/E	E>0.1 PeV		E>0.5 PeV		E>1 PeV		E>2 PeV		E>4 PeV	
		p	He	p	He	p	He	p	He	p	He
~4.0	35%	$7.8 \cdot 10^3$	$7.4 \cdot 10^3$	$4.6 \cdot 10^2$	$5.1 \cdot 10^2$	$1.2 \cdot 10^2$	$1.5 \cdot 10^2$	28	43	5	10

Electrons (no nearby sources)					
Effective GF (m^2 sr)	σ(E)/E	E>0.5 TeV	E>1 TeV	E>2 TeV	E>4 TeV
3.4	~1%	$181 \cdot 10^3$	$35 \cdot 10^3$	$5 \cdot 10^3$	$6 \cdot 10^2$

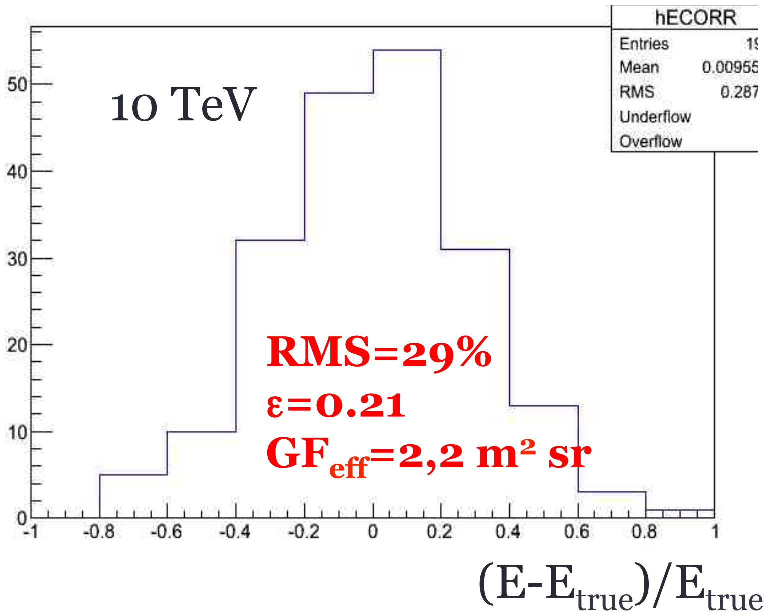
Protons: energy resolution

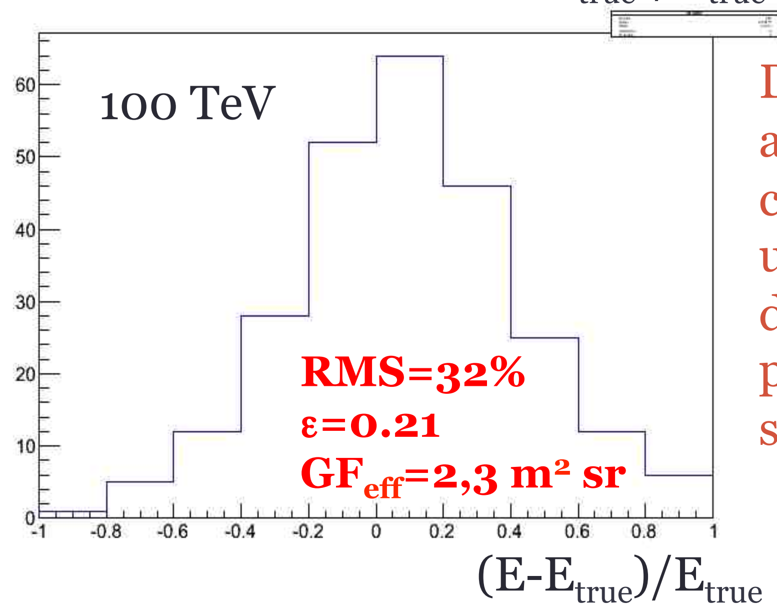




Analysis criteria can be changed to optimize:

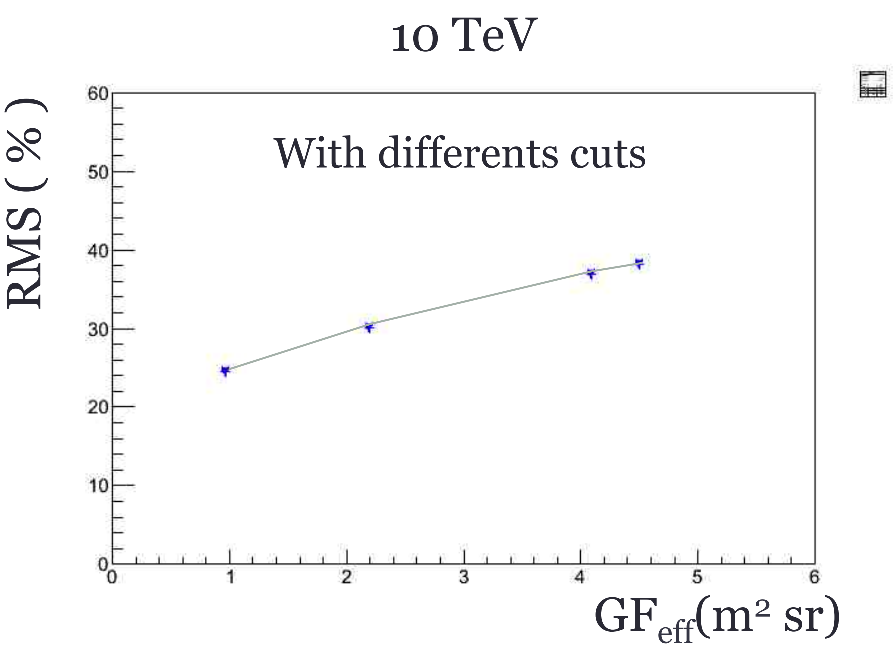
- Acceptance
- Energy resolution

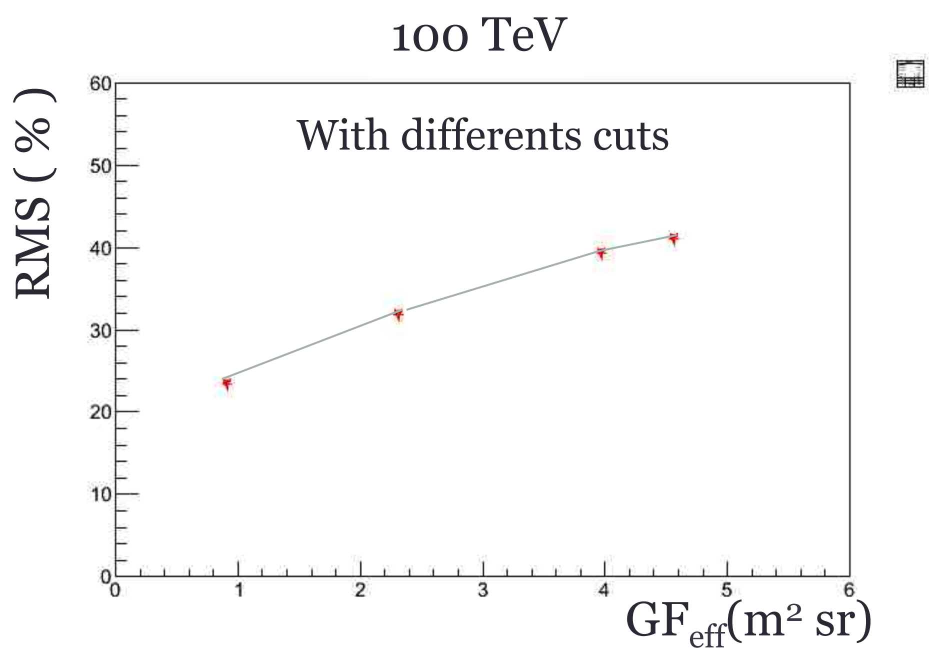




Different analysis criteria can be used for different portions of the spectrum

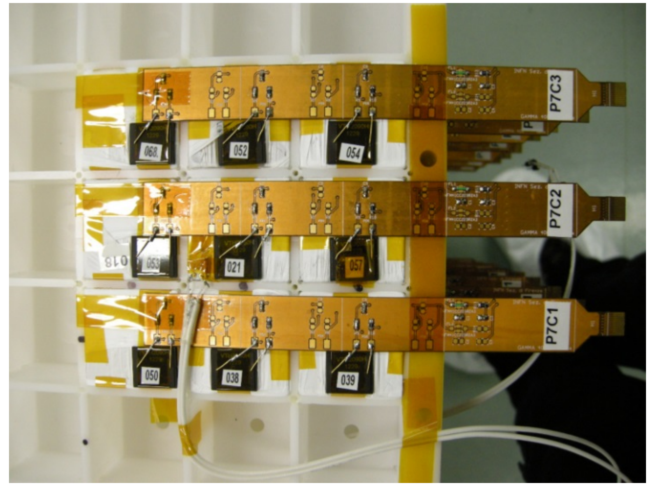
Protons: energy resolution





Calorimeter prototype

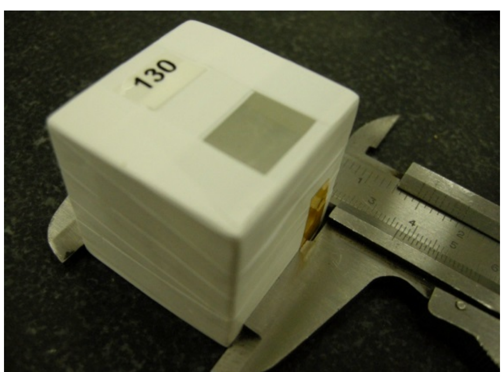
- 14 Layers
- 9 crystals in each layer (crystals 3.6 x 3.6 x 3.6 cm^3)
- 126 Crystals in total
- 126 Photodiodes
- 50.4 cm of CsI(Tl)
- 27 X_0, 1.44 λ_I
- Photodiodes read-out by 9 CASIS1.2A 16-channel ASICs)

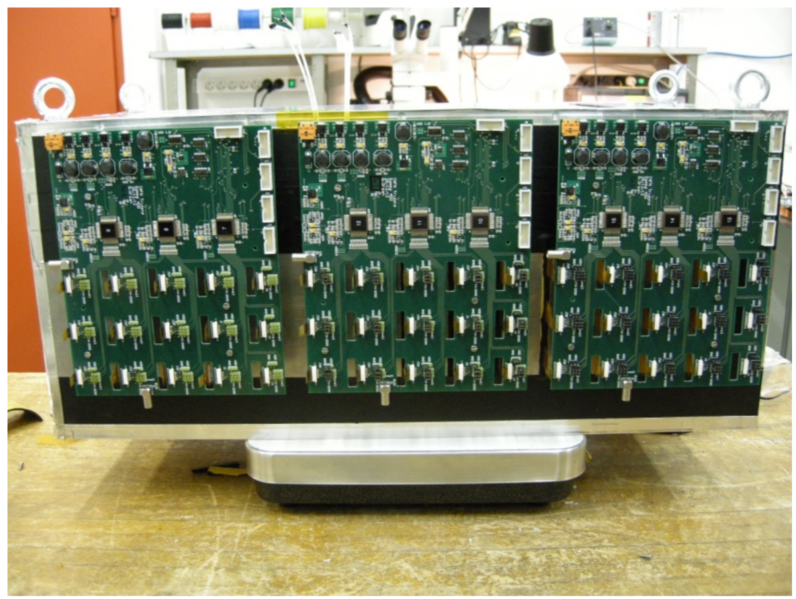


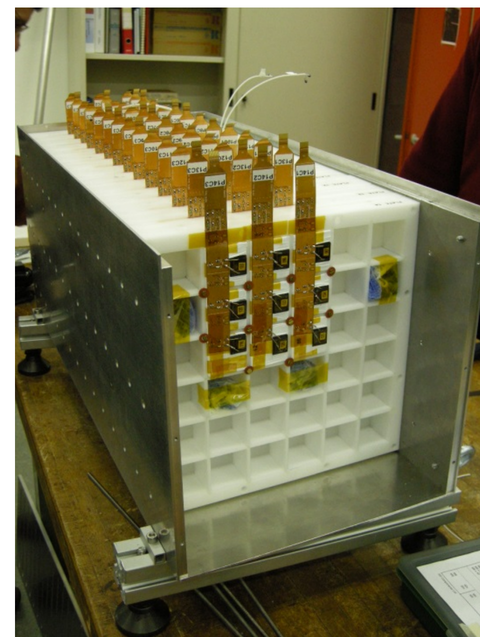
Mechanics:
INFN Pisa

Front-end electronics:
INFN Trieste

Crystals, photodiodes, DAQ, assembly:
INFN Florence







Space qualification

- Proton launcher will be used to put in orbit the instrument
- Expensive and complex space qualification procedures are necessary since the beginning of any space project
  - Radiation tests on single components and at board level
    - Hardware protections against failures
    - Hot/Cold redundancy
    - Software protections in the design of VHDL codes
  - Vibrations tests
    - On single parts in the prototype/design phase
    - On the Mass Model
    - On the Flight models (at reduced levels)
  - Thermo/Vacuum tests
    - Outgassing
    - Thermal model/Cooling
  - EMI/EMC tests
- A possible support from INFN-LNF will be extremely useful to save money and time, and to design a more reliable instrument
  - Expertise and consulting during the design phase
  - Facilities to carry on space qualification tests

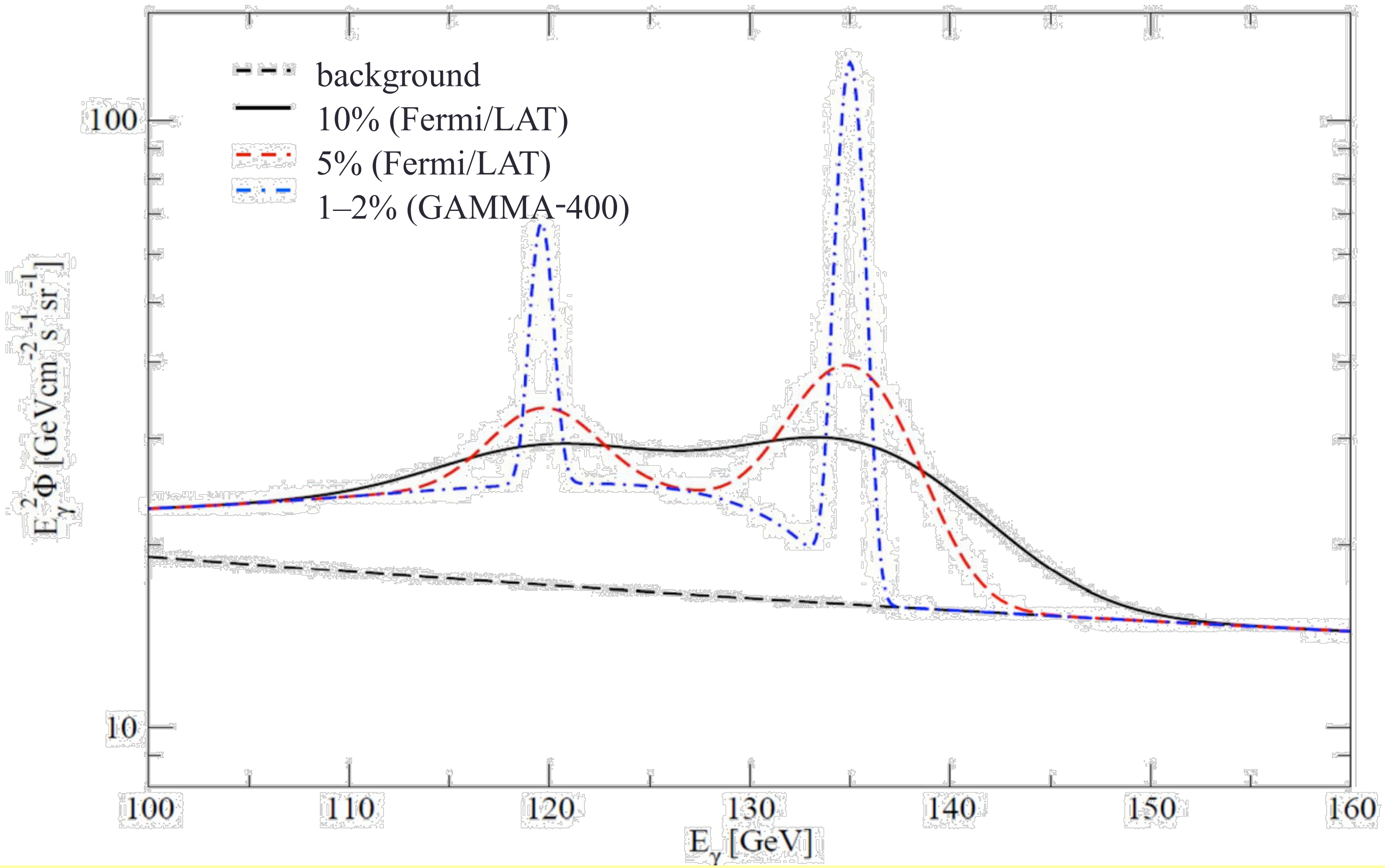
Physics with GAMMA-400

- GAMMA-400 is focused on the detection of the three main component of cosmic radiation:
  - **γ-rays from 100 MeV up to TeV energies**, to be studied with substantial improvements concerning the angular resolution at high energies and the continuous exposure to sources without Earth occultation
  - **electrons/positrons up to ~ 10 TeV**, to be measured with much improved sensitivity compared with current space, balloon-borne, and ground measurements
  - **cosmic-ray nuclei up to the "knee"**, whose spectrum and composition is to be studied with unprecedented detail up to ~ few PeV/nucleon

Photons

- Detection of possible Dark Matter signal
  - Gamma-ray lines
  - Satellite galaxies
  - Dwarf Spheroidal Galaxies
  - Galactic Center
- Measurement of the γ-ray spectrum with excellent angular and energy resolution
  - SNR
  - Pulsars
  - Massive star clusters
  - AGN
  - GRB

Increasing the energy resolution



The γ-ray differential energy results for a 135 GeV right-handed neutrino dark matter candidate.

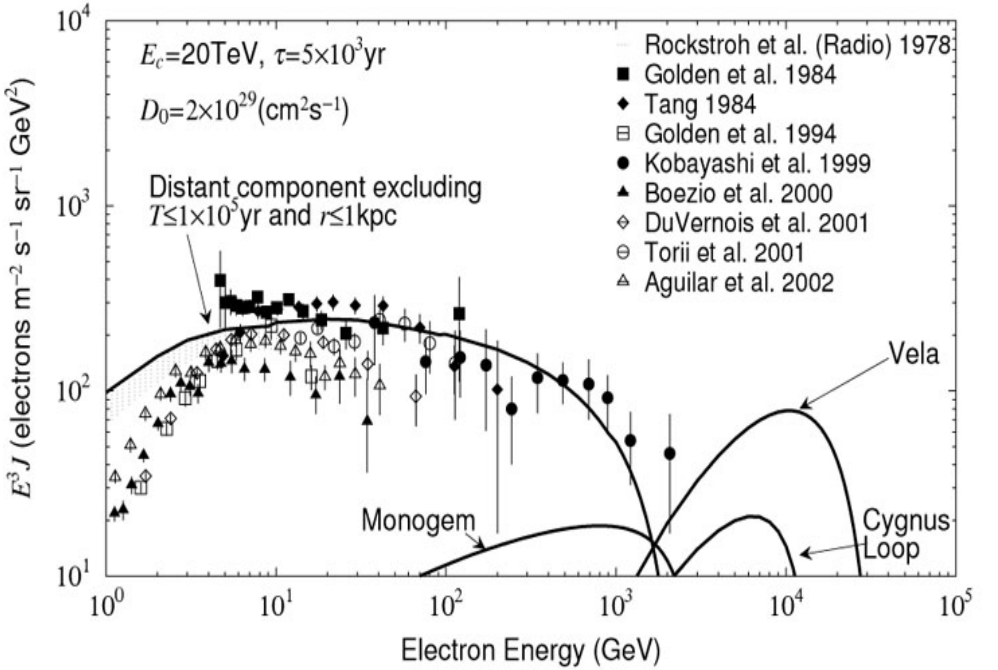
L. Bergström, Phys. Rev. D 86 (2012) 103514, arXiv:1208.6082

Electrons can tell us about local GCR sources

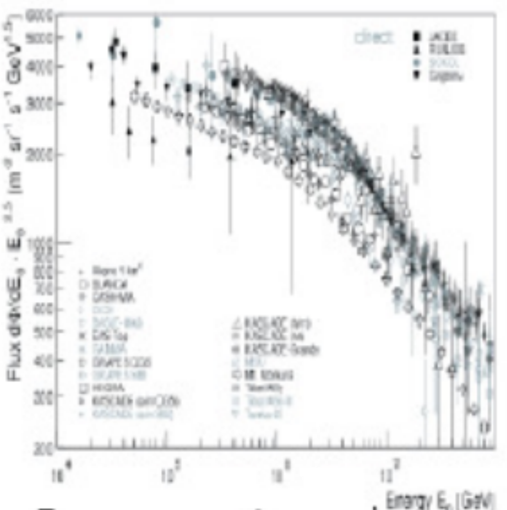
- High energy electrons have a high energy loss rate ∝ E^2
  - Lifetime of ~10^5 years for > 1 TeV electrons
- Transport of GCR through interstellar space is a diffusive process
  - Implies that source of high energy electrons are < 1 kpc away

Only a handful of SNR meet the lifetime & distance criteria
Kobayashi et al., ApJ 601 (2004) 340-351: calculations show structure in electron spectrum at high energy

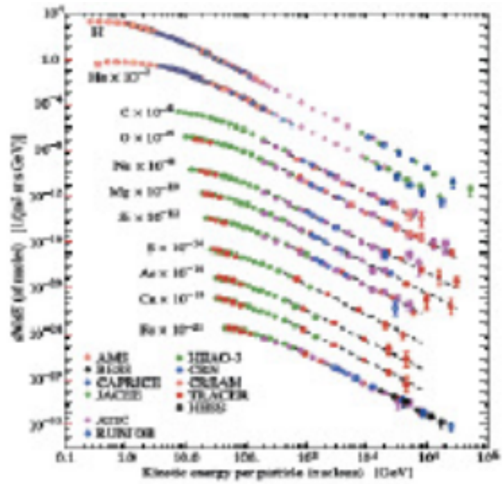
J. P. Wefel, TevPA 2011, Stockholm (2011)



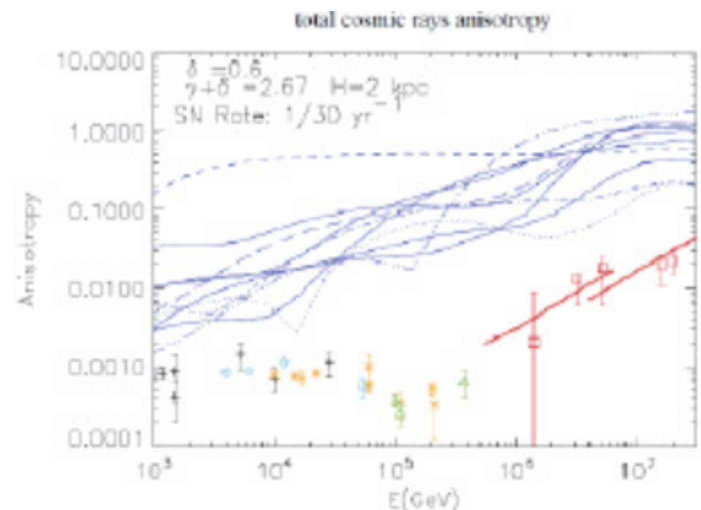
Nuclei up to the Knee



Energy spectrum shape



Composition



Anisotropy

- Study the acceleration mechanism (or mechanisms)
- Study the limit of the acceleration phenomena
- Understand the kind of sources in the Galaxy
- Answer the question: is there the same mechanism (or source) for different nuclei?
- Study the distribution of the sources
- Study the propagation process in the Galaxy

Conclusions

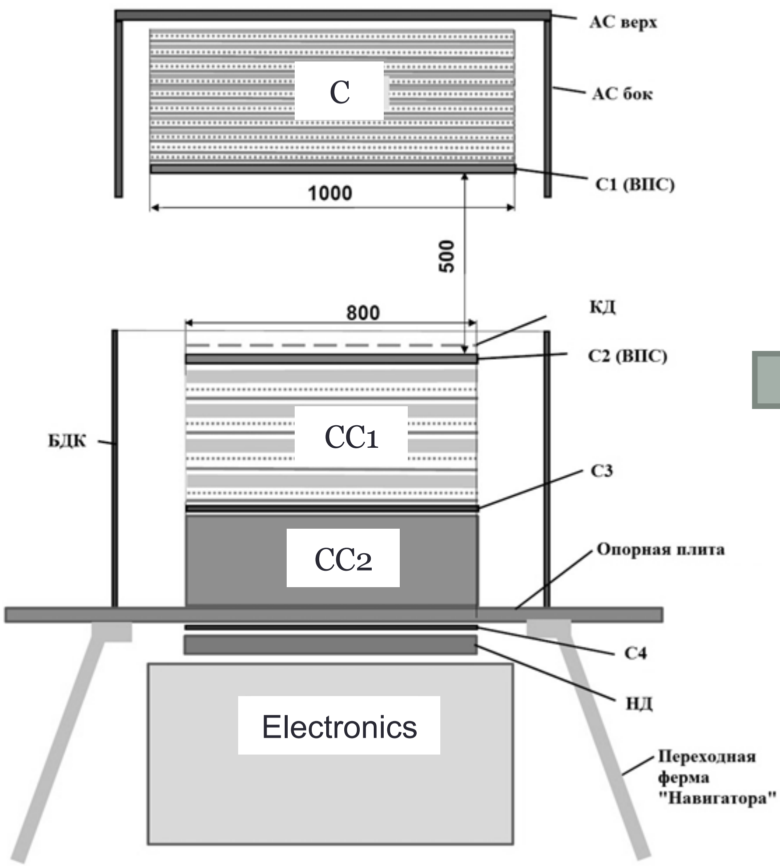
- The GAMMA-400 mission represents a unique opportunity to perform simultaneous measurements of photons, electrons and nuclei with unprecedented accuracy.
- GAMMA-400 will provide in-depth investigations on some of the most challenging physics items, such as:
  - DM search in γ and high-energy electron spectra
  - CR origin, production and acceleration to the highest energies
  - Flux and elemental composition of nuclei at the knee
- Synergy with ground-based Cerenkov arrays (CTA) and other wavelength instruments.
- A possible design and technical support from INFN-LNF will be very appreciated!

Spare slides

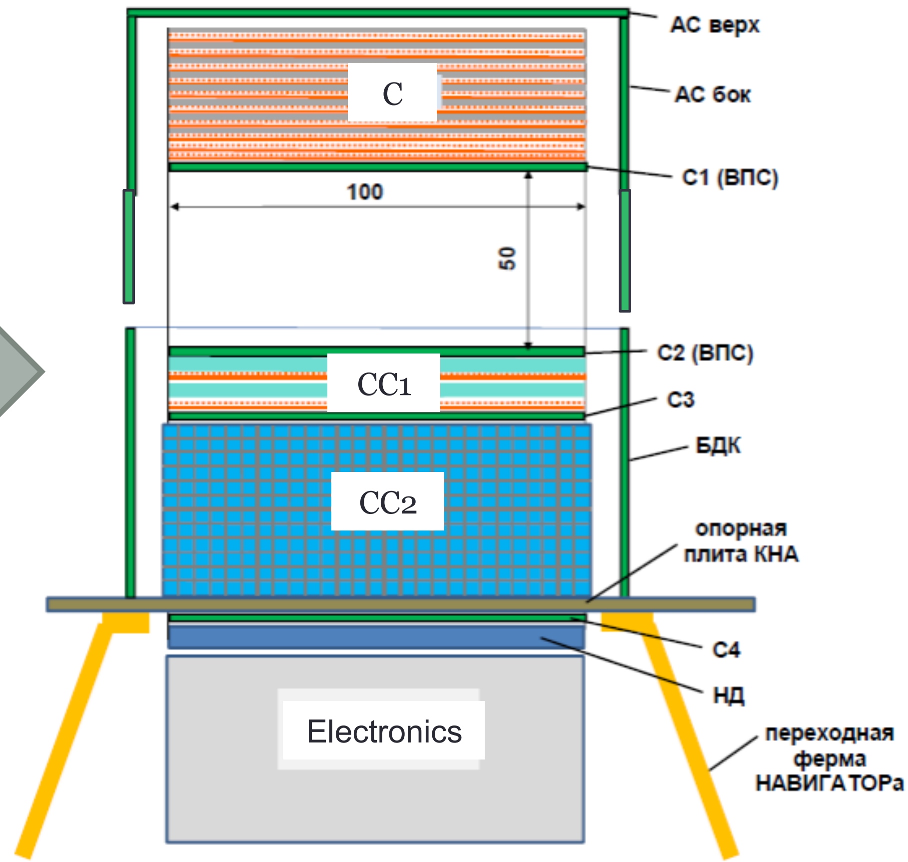
Outline

- Origin and evolution of the project
- The apparatus
  - The converter/tracker
  - The calorimeter
- Space Requirements
- Physics with GAMMA-400
  - Photons
  - Electrons
  - Nuclei
- Conclusions

GAMMA-400 evolution

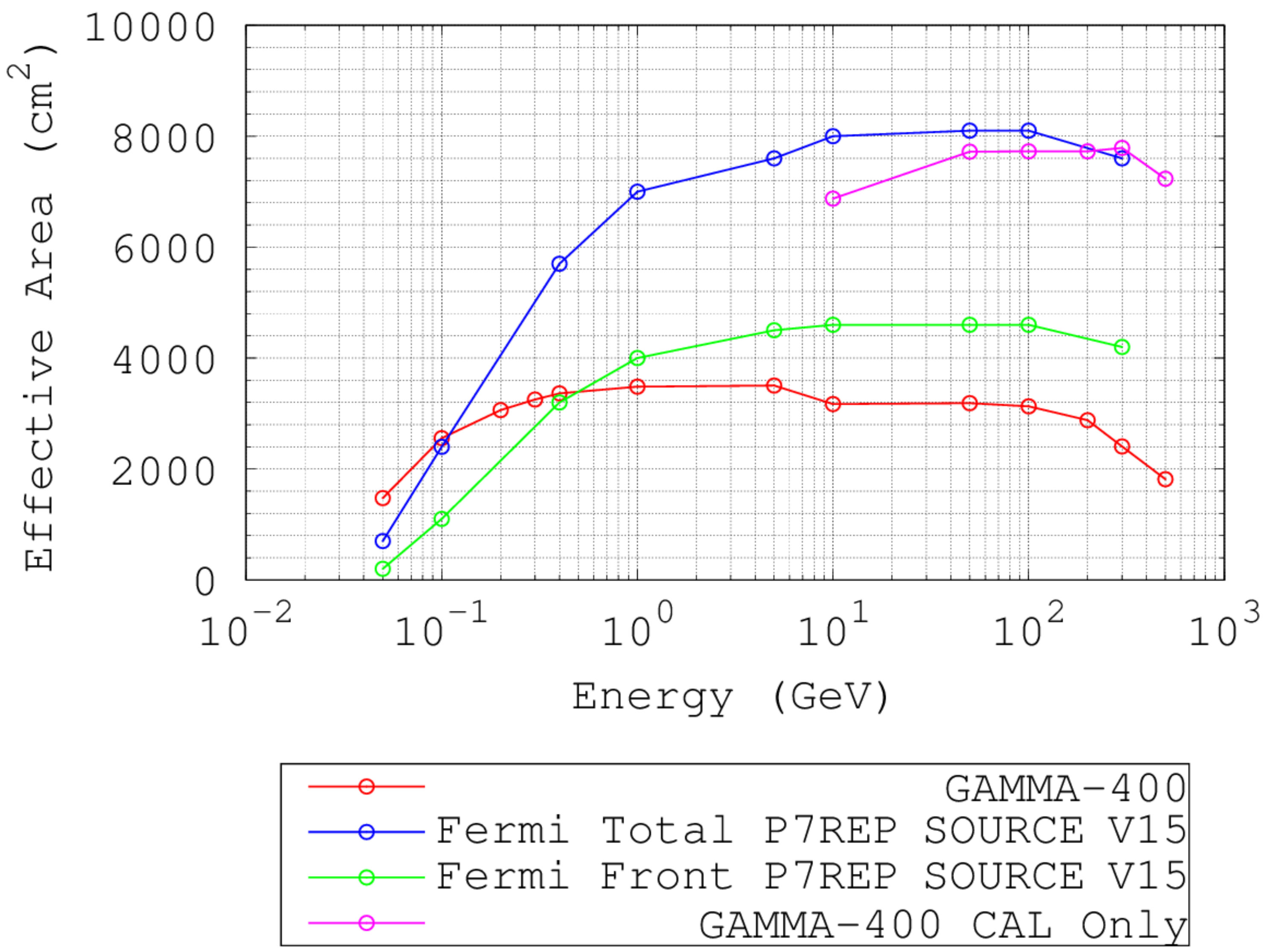


Original Russian proposal (2011)



Jointly agreed Russian-Italian proposal (2013)

Effective area



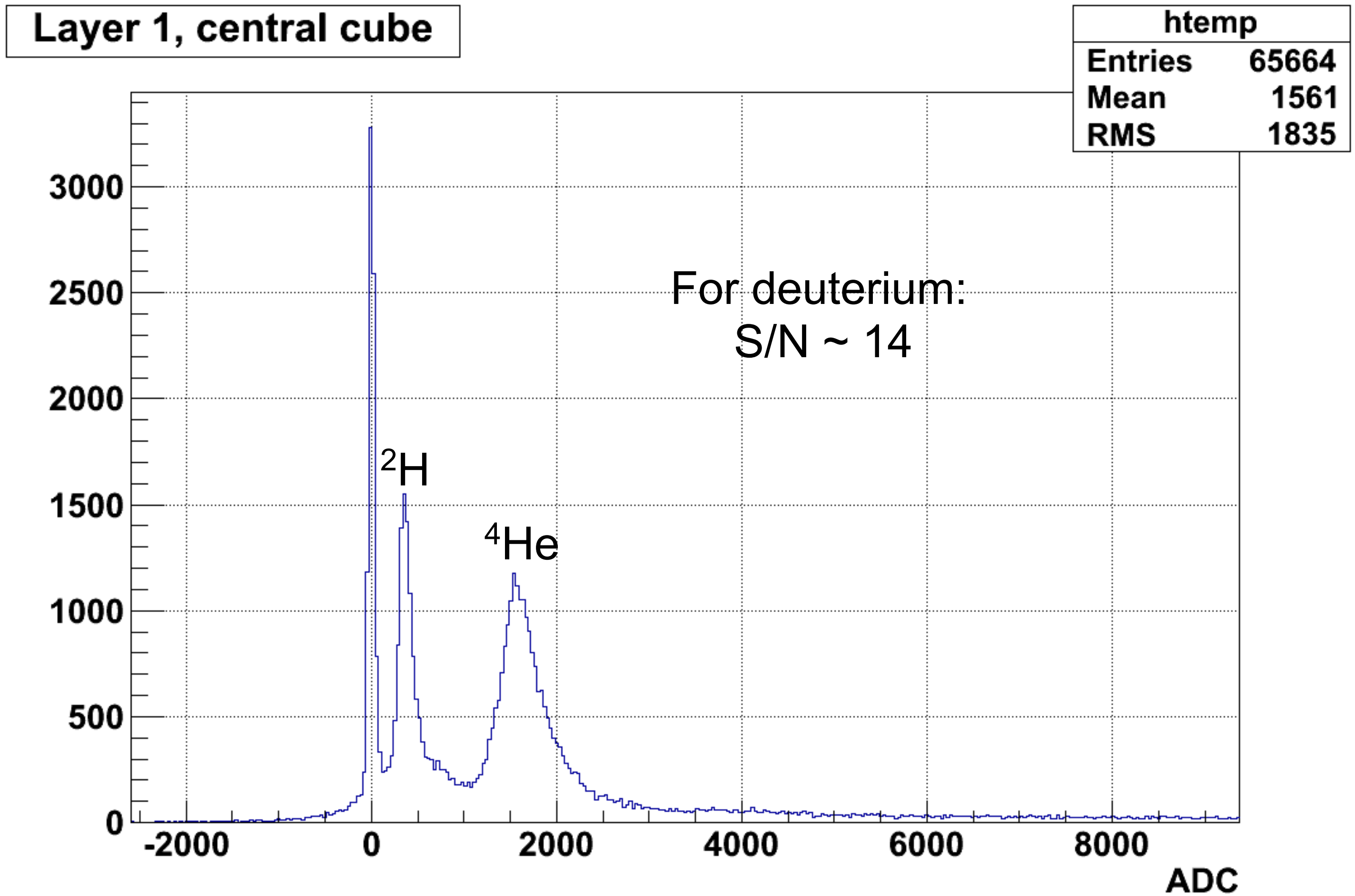
Fermi LAT

- Starting from the front of the instrument, the LAT tracker (TKR) has 12 layers of 3% radiation length tungsten converters (THIN or FRONT section), followed by 4 layers of 18% r.l. tungsten converters (THICK or BACK section). These sections have intrinsically different PSF due to multiple scattering, and the performance plots are presented for both of these sections.

Prototype test beam results

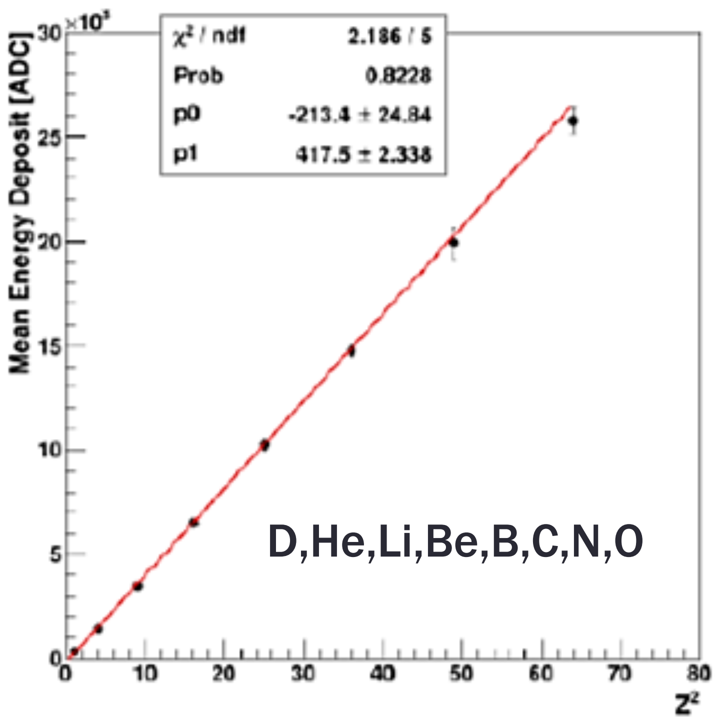
CERN SPS H8 Ion Beam: Z/A = 1/2, 12.8 GV/c and 30 GV/c (February 2013)

Notice: charge information from a precise silicon Z-measuring system located in front of the prototype

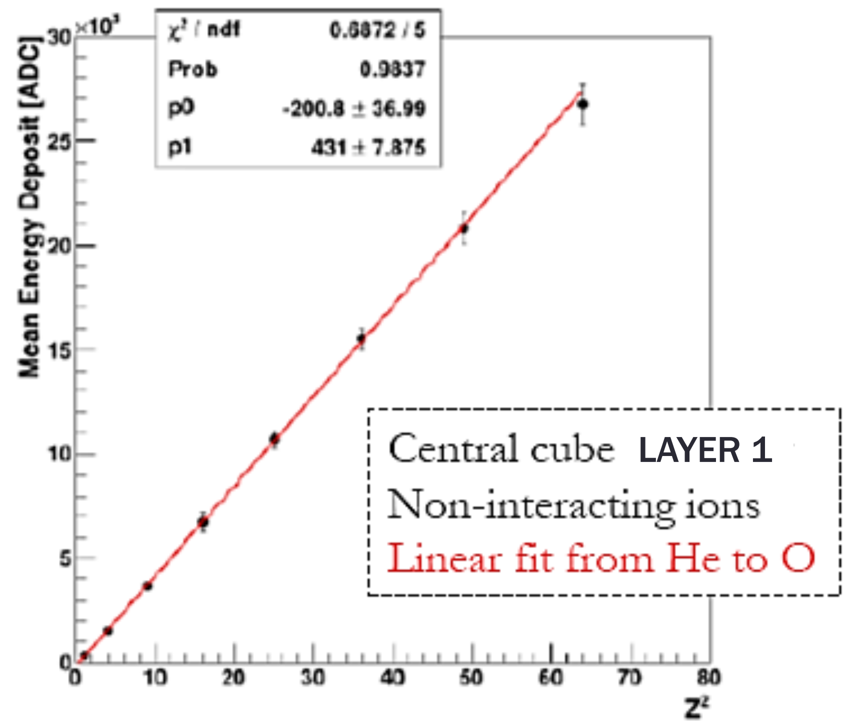


Non interacting ions: charge linearity

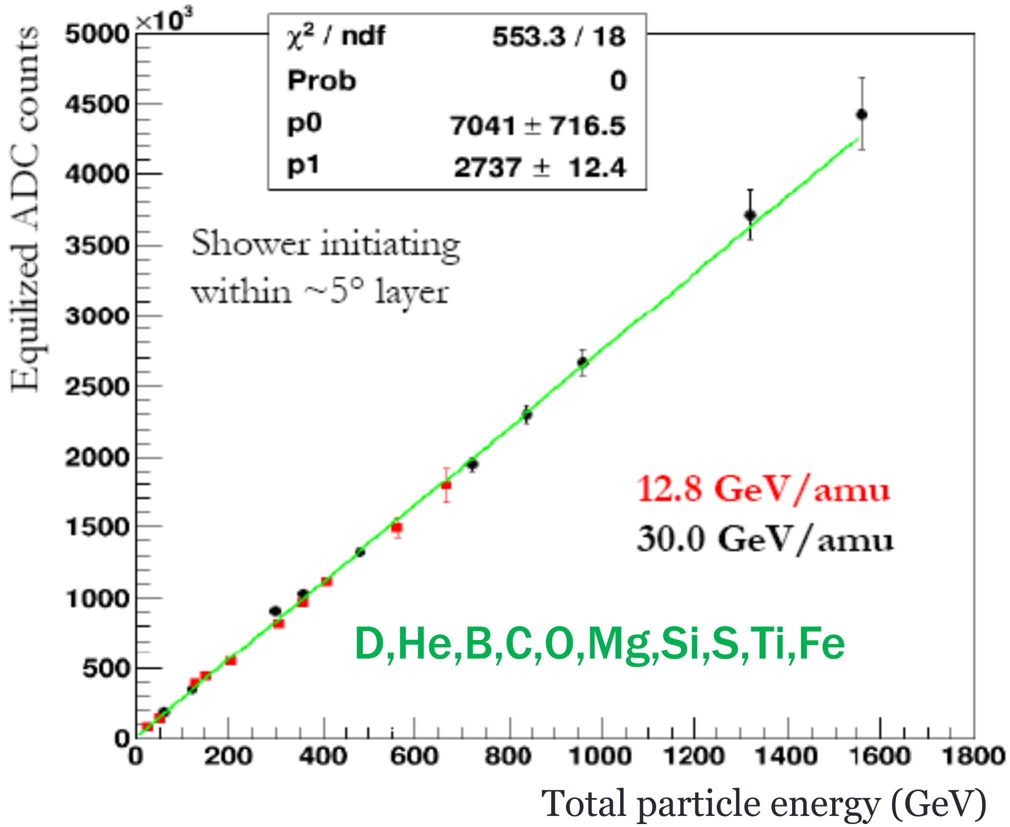
12.8 GeV/amu



30.0 GeV/amu



Interacting ions: charge linearity



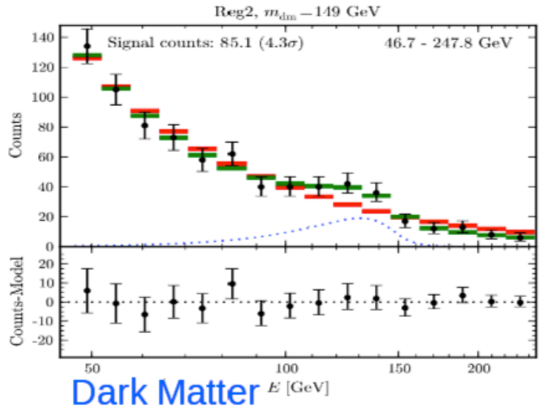
- Charge is selected by Beam Tracker in front of the calorimeter
- Good linearity even with just the large-area photodiode

Space qualification (I)

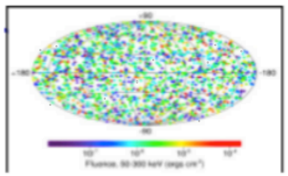
- Proton launcher will be used to put in orbit the instrument
- Space qualification requirements:
  - Radiation resistance
    - Total dose
    - Single Event Effects
  - Mechanical stresses
    - Static linear acceleration
    - Resonance frequencies/Sinusoidal vibrations
    - Random vibration with Spectral Power Density
    - Shocks
  - Thermal environment
  - Electromagnetic compatibility
    - EMC
    - EMI

Physics of GAMMA-400

Galactic/ Extragalactic gamma-ray sources

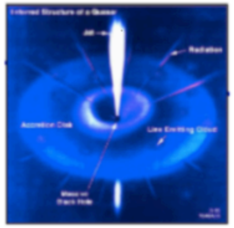


Dark Matter

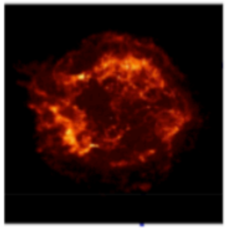


GRBs

Pulsars

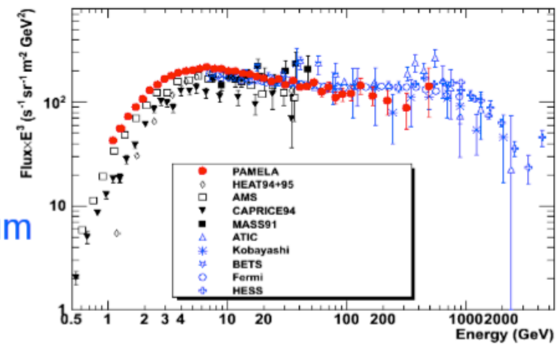


AGNs



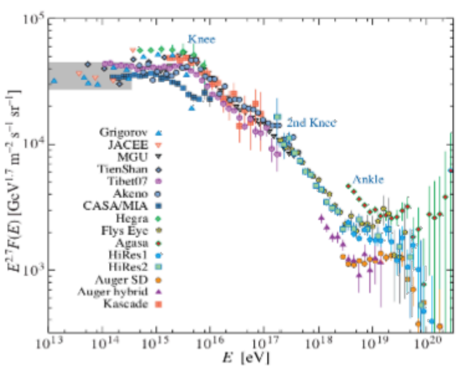
SNRs

CR propagation



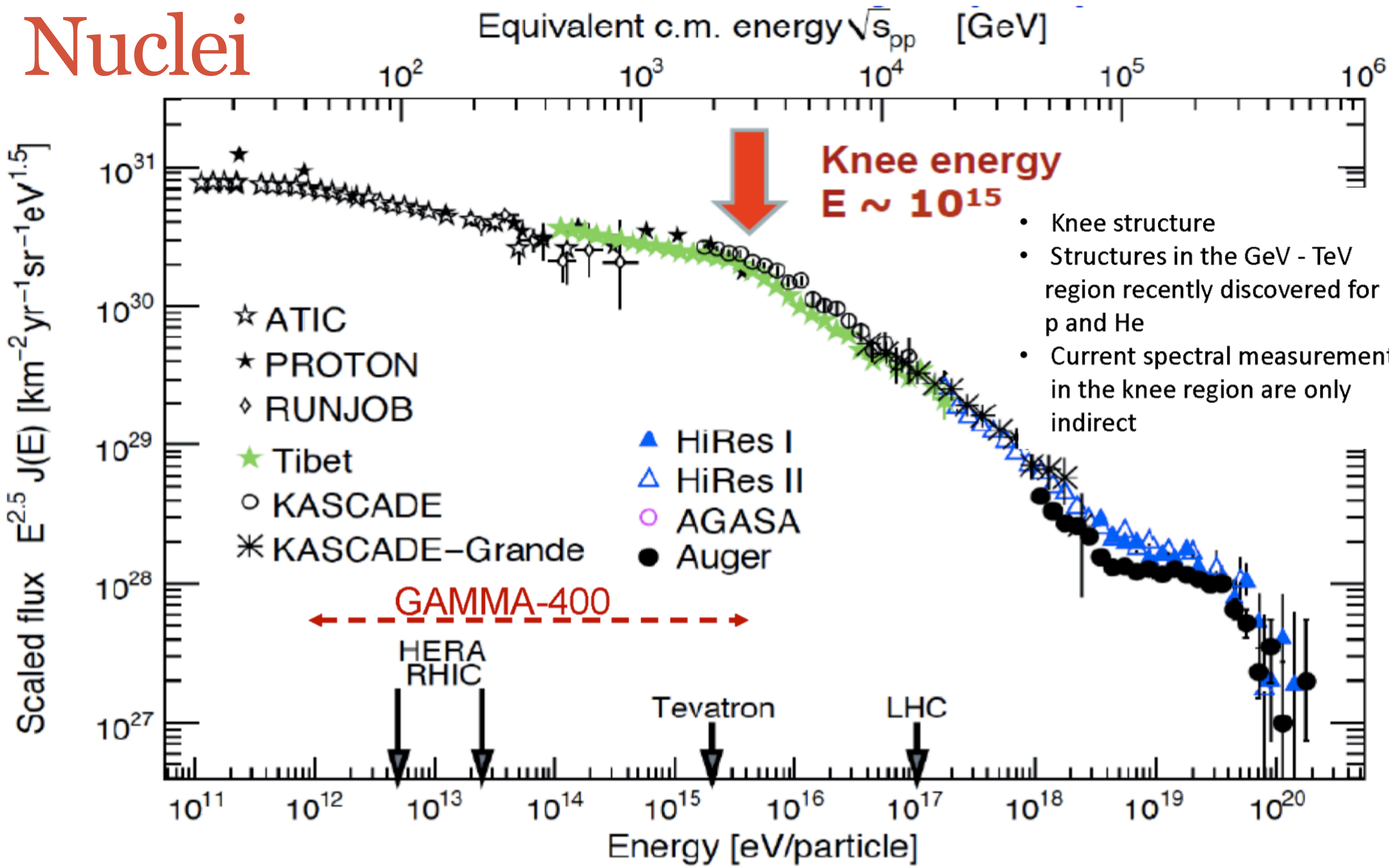
Electron spectrum

Knee origin



CR origin and acceleration mechanisms

Nuclei



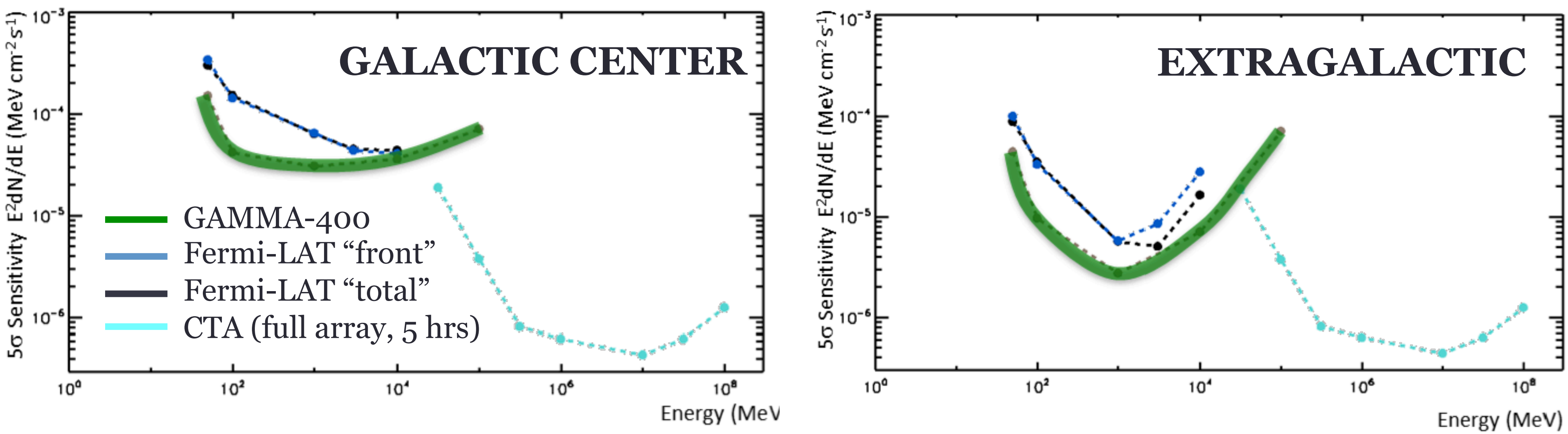
- Knee structure
- Structures in the GeV - TeV region recently discovered for p and He
- Current spectral measurements in the knee region are only indirect

GAMMA-400 performances: sensitivity

*Simulated point source **sensitivity** (5 σ) for different background conditions (30 days integration time, 30 degrees off-axis)*

30 days – (Eff_G=1, Eff_F=1/6) _ Gal Centre Sensitivity

30 days – (Eff_G=1, Eff_F=1/6) _ Extra-Gal Sensitivity



- Gamma-ray sensitivity better than Fermi-LAT for point sources (pointing w/o Earth occultation)
- Space instrument complementary to next generation TeV ground detectors (CTA, HAWC) for the next decade

Comparison of the main parameters for GAMMA-400 and Fermi-LAT

	Fermi-LAT	GAMMA-400
Orbit	circular, 565 km	1. Elliptical, 500-300,000 km 2.Semi-circular, 200,000 km
Energy range	20 MeV - 300 GeV	100 MeV – 3 TeV
Effective area ($E_\gamma > 1$ GeV)	~ 8000 cm^2 (Fermi total) ~ 4300 cm^2 (Fermi front)	~ 3800 cm^2
Coordinate detectors	Digital Si strips (pitch 0.23 mm)	Analog Si strips (pitch 0.08 mm)
Angular resolution ($E_\gamma \geq 100$ GeV)	~ 0.1°	~ 0.01°
Calorimeter - thickness	CsI ~ $8.5X_0$	CsI(Tl)+Si strips ~ $25X_0$
Energy resolution ($E_\gamma \geq 100$ GeV)	~ 10%	~ 1%
Proton rejection coefficient	~ 10^4	~ 10^5
Mass	2800 kg	4100 kg
Downlink capability	15 GB/day	100 GB/day

COMPARISON OF BASIC PARAMETERS OF OPERATED, EXISTING, AND PLANNED SPACE-BASED AND GROUND-BASED INSTRUMENTS

	SPACE-BASED INSTRUMENTS					GROUND-BASED GAMMA-RAY FACILITIES			
	EGRET	**AGILE**	**Fermi-LAT**	**CALET**	**GAMMA-400**	**H.E.S.S.-II**	**MAGIC**	**VERITAS**	**CTA**
Operation period	1991-2000	2007-	2008-	2014	2019	2012-	2009-	2007-	2018
Energy range, GeV	0.03-30	0.03-50	0.02-300	10-10000	**0.1-10000**	> 30	> 50	> 100	> 20
Angular resolution ($E_\gamma > 100$ GeV)	0.2° (E_γ~0.5 GeV)	0.1° (E_γ~1 GeV)	0.1°	0.1°	**~0.01°**	0.07°	0.07° (E_γ = 300 GeV)	0.1°	0.1° (E_γ = 100 GeV) 0.03° (E_γ = 10 TeV)
Energy resolution ($E_\gamma > 100$ GeV)	15% (E_γ~0.5 GeV)	50% (E_γ~1 GeV)	10%	2%	**~1%**	15%	20% (E_γ = 100 GeV) 15% (E_γ = 1 TeV)	15%	20% (E_γ = 100 GeV) 5% (E_γ = 10 TeV)

A. Galper, Workshop on the Future of Dark Matter Astroparticle Physics 2013, Trieste, Italy

B2: Electron count estimation

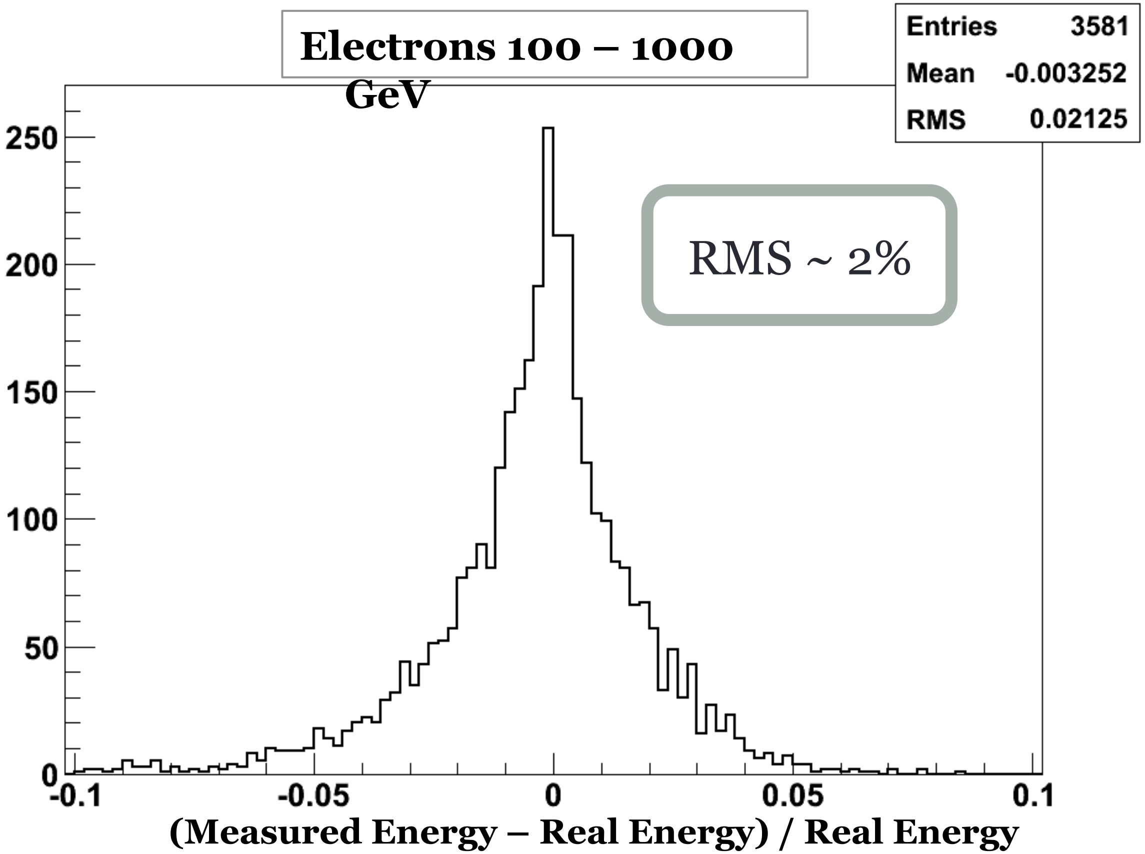
Experiment	Duration	GF (m^2 sr)	Calo σ(E)/E	Calo depth	e/p rejection factor	E>0.5 TeV	E>1 TeV	E>2 TeV	E>4 TeV
CALET	5 y	0.12	~2%	30 X_0	10^5	7982	1527	238	25
AMS02	10 y	0.5	~2%	16 X_0	10^3	66515	12726	1986	211
ATIC	30 d	0.25	~2%	18 X_0	10^4	273	52	8	1
FERMI	10 y	1.6 @ 300 GeV 0.6@ 800 GeV	~15%	8.6 X_0	10^4	59864	6362	NA	NA
G400	10 y	3.9	~ 1%	25.4 X_0	10^5	518819	99266	15488	1647

Readout sensors and front-end chip

- At least 2 Photo Diodes are necessary on each crystal to cover the whole huge dynamic range from 1 MIP to 10^7 MIP (in a single crystal $E_{max} \sim 0.1\ E_{tot}$):
  - large-area PD $9.2 \times 9.2\ mm^2$ for small signals (Excelitas VTH2090)
  - small-area PD $0.5 \times 0.5\ mm^2$ for large signals

- Front-End electronics: a big challenge
- The CASIS chip, developed in Italy by INFN-Trieste, is very well suited for this purpose
  - IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 57, NO. 5, OCTOBER 2010
- 16 channels, Charge Sensitive Amplifier + Correlated Double Sampling filter and shaper
- Automatic real-time switching between low- and high-gain mode
- 2.8 mW/channel
- $3.10^3\ e^-$ noise for 100 pF input capacitance
- 53 pC maximum input charge

Electrons: ENERGY RESOLUTION



Selection efficiency:
ε ~ 36%

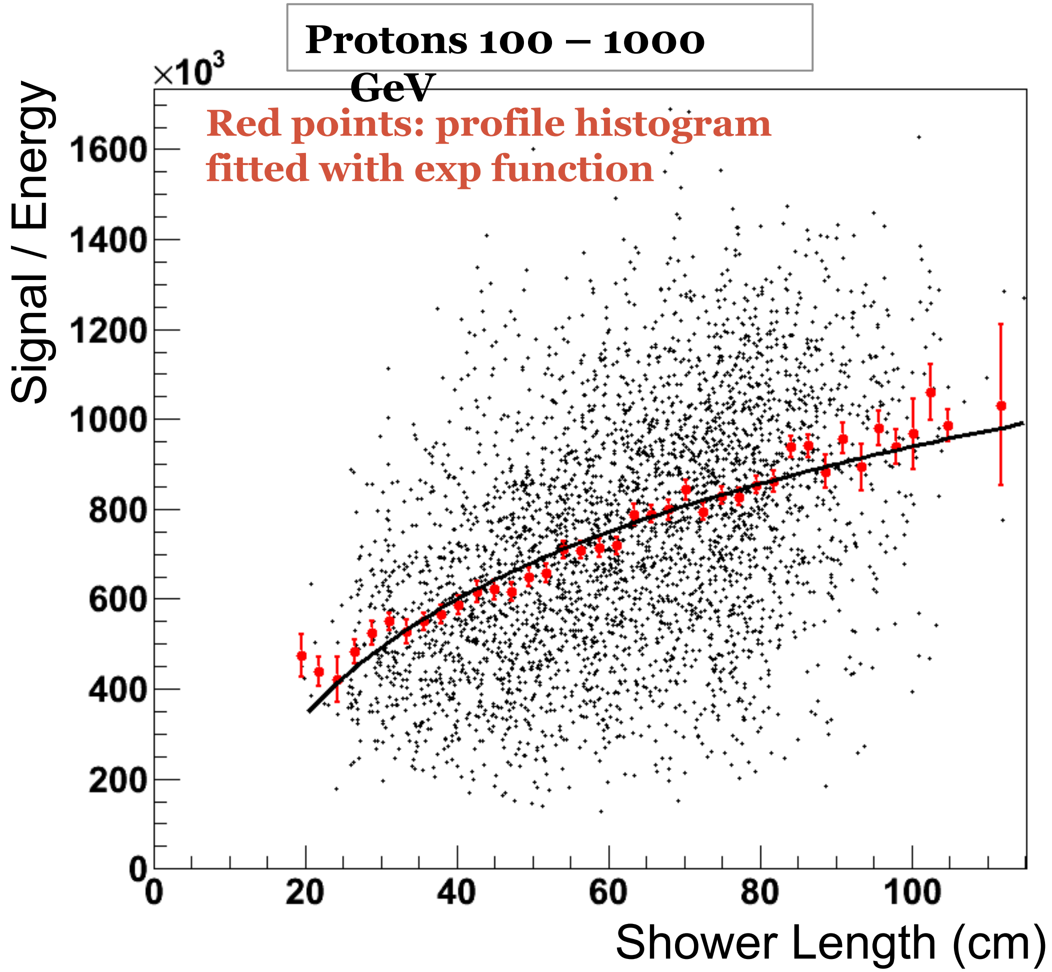
length of the shower
at least 40 cm (~22 X_0)

GF_{eff} ~ 3.4 m^2sr

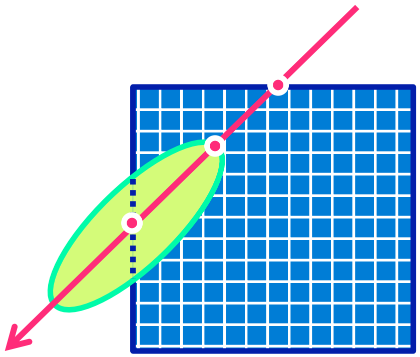
Non-gaussian tails due to leakage and to energy losses in passive material (carbon fiber structure)

Effect of direct ionization on PD: ~1.7% on the average value, negligible on the RMS

PROTONS

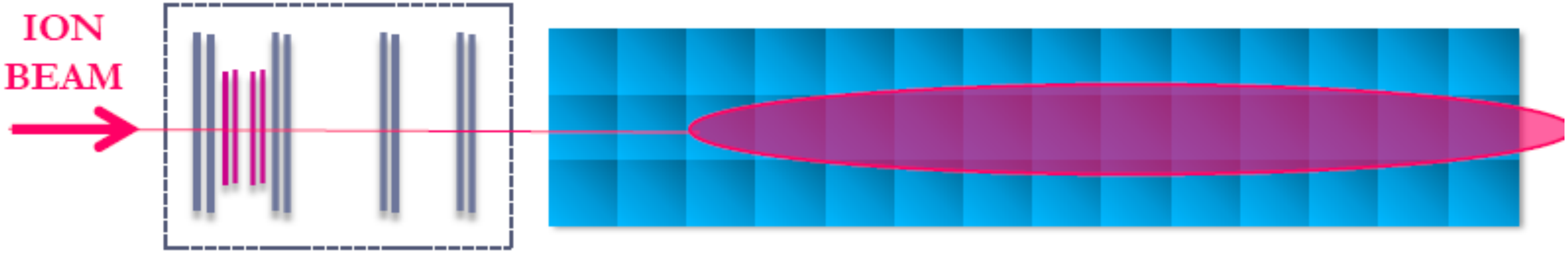


- Shower length can be used to reconstruct energy
- First hadronic interaction is easily accessible due to high granularity of the design



SETUP of the test beam, Feb. 2013

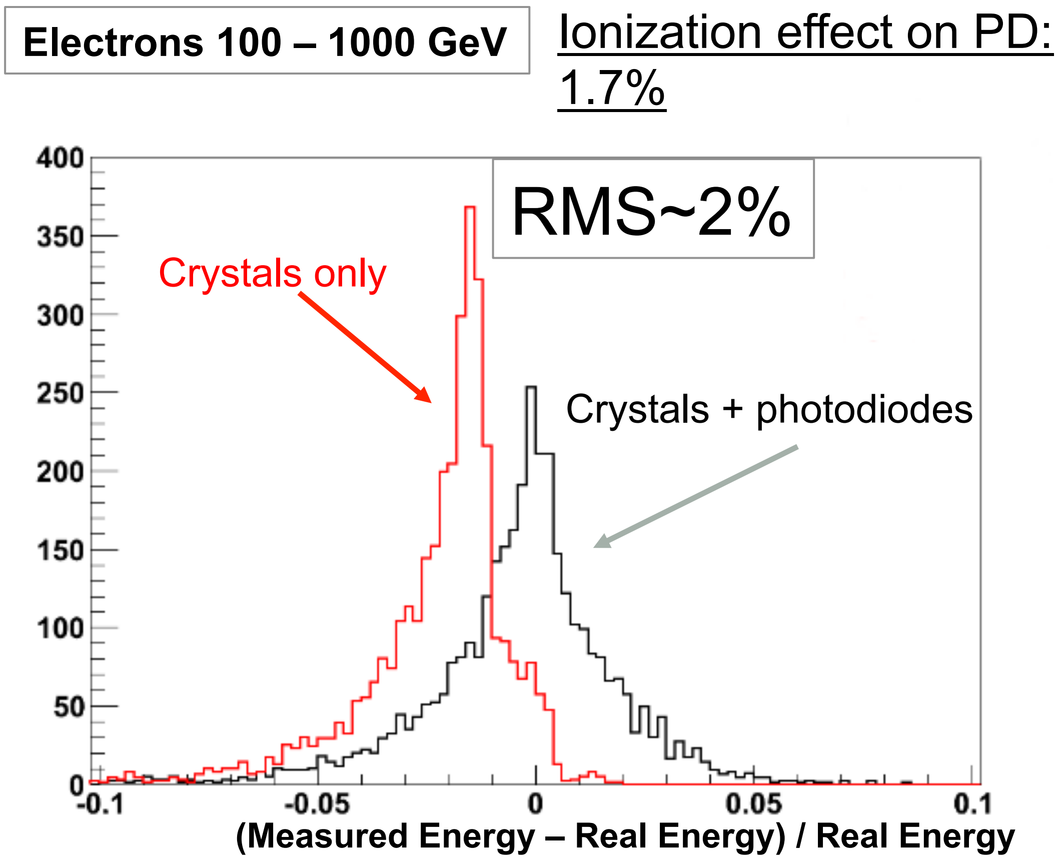
- Ion beam extracted from CERN SPS H8 line
- Primary Pb beam on Be target
- Nuclear fragments A/Z=2, from Deuterium to Iron
- Energy: **12.8** and **30.0 GeV/amu**



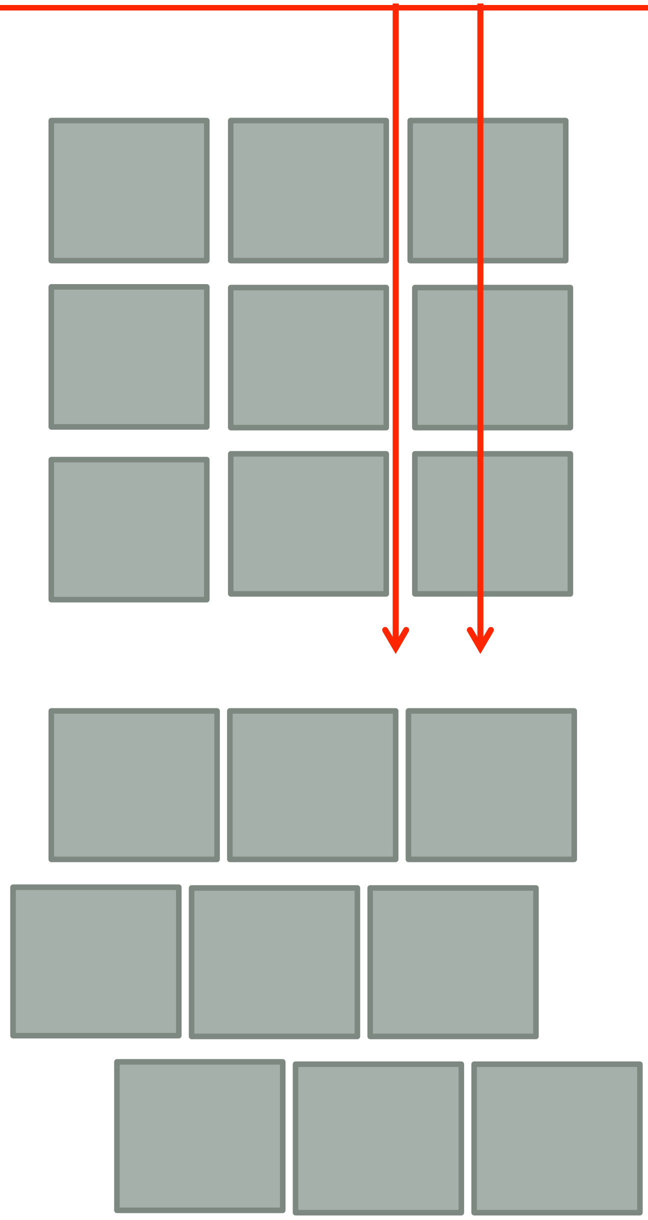
BEAM TRACKER (BT)
4 Si-pixel matrixes + 8 Si-strip layers
- Z tagging
- particle tracking (<200μm spatial resolution)

CALORIMETER
3×3×14 CsI crystals

ELECTRONS: PD DIRECT IONIZATION

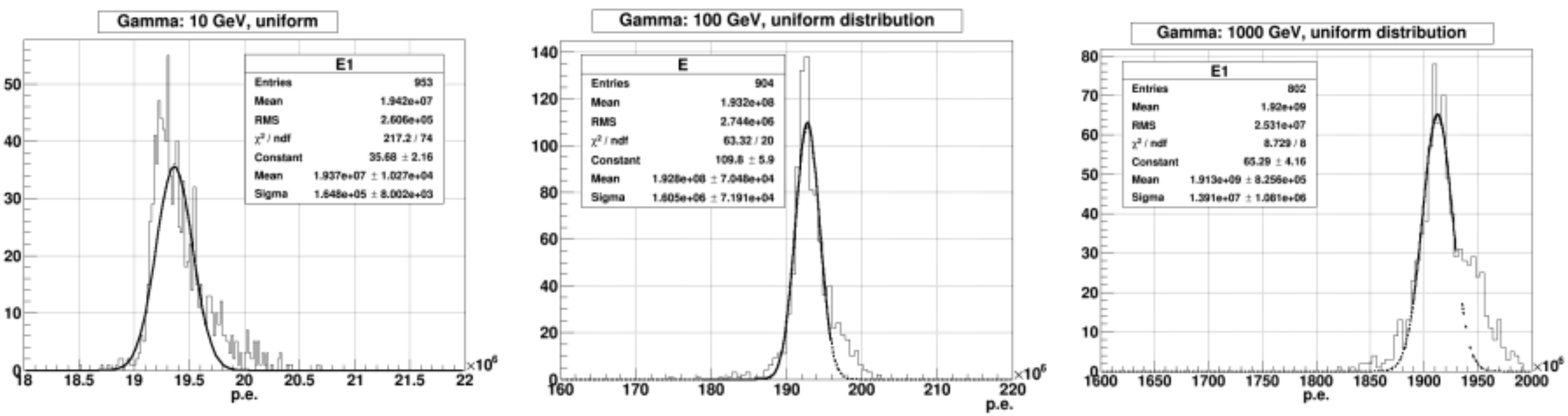


OPTIMIZATION FOR VERTICAL GAMMAS



VERTICAL GAMMA RAYS

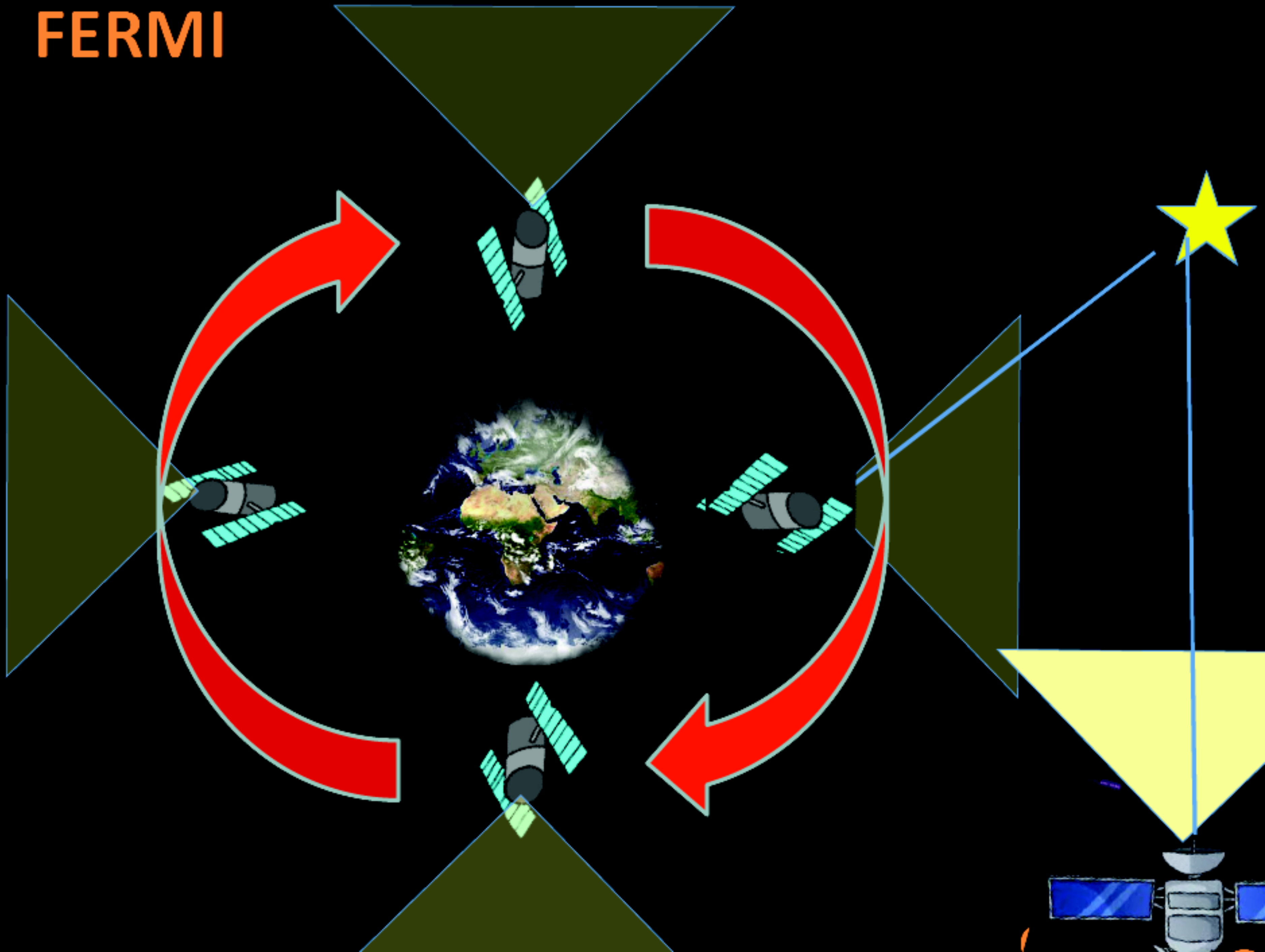
Detector optimized for vertical gammas: 27 X 27 X 14 CRYSTALS;
1 mm vertical gaps; horizontal planes shifted in x-y to avoid alignment

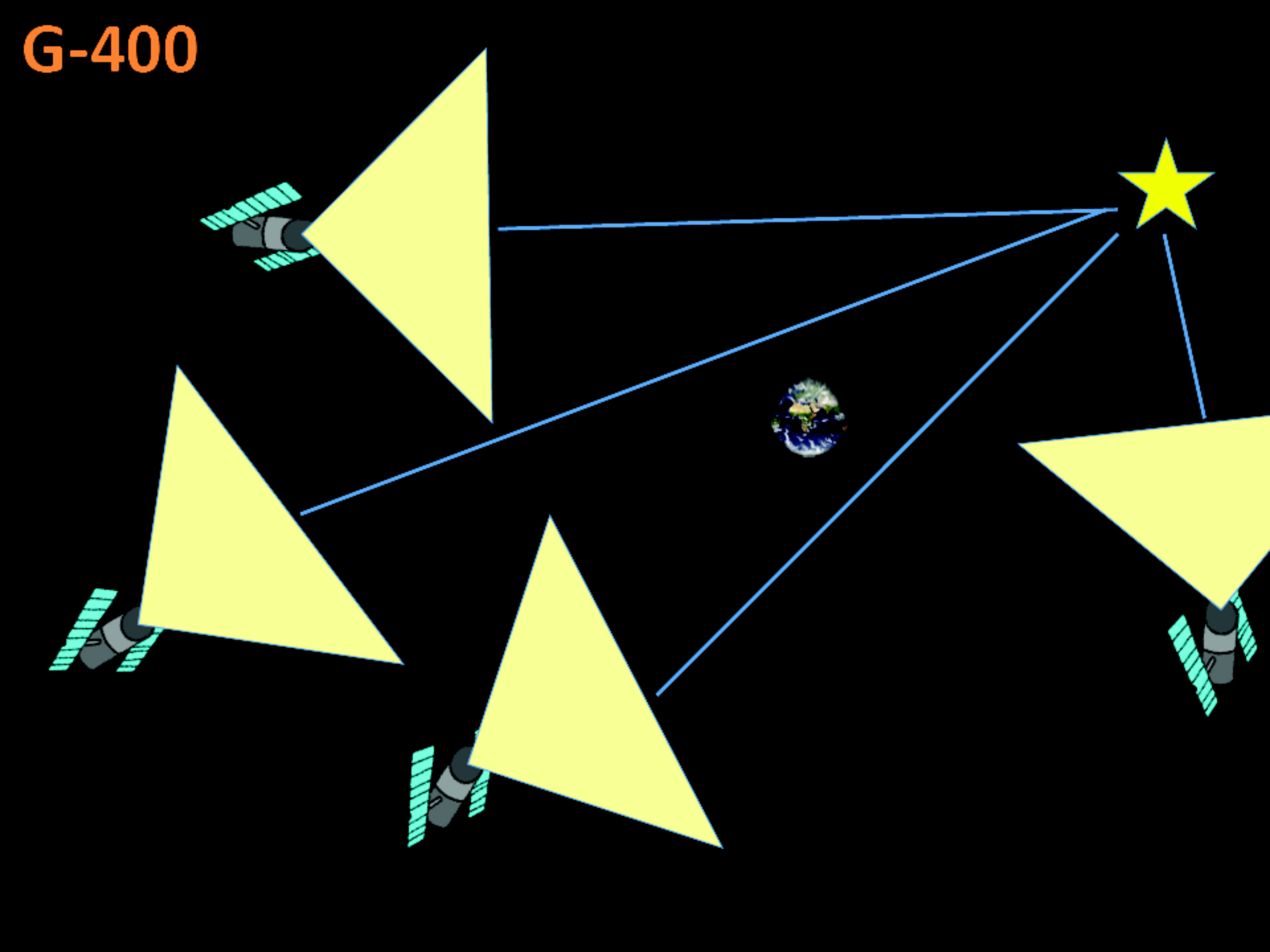


Gamma rays total signal distribution for energies: 10 GeV, 100 GeV and 1 TeV. The incident position is uniform on the top of the calorimeter.

Gamma rays energy	Selection efficiency	Energy resolution
10 GeV	95%	0.86%
100 GeV	90%	0.83%
1 TeV	80%	0.73%

FERMI




G-400