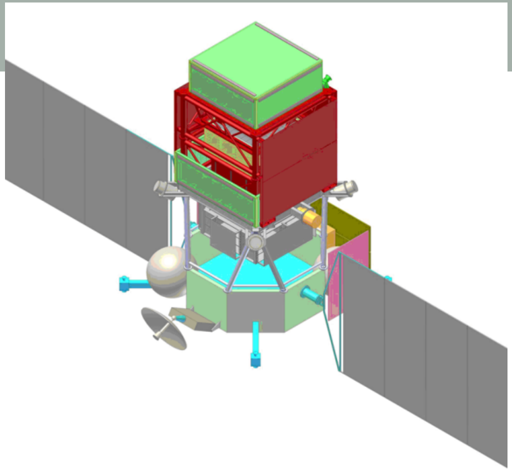


THE GAMMA-400 EXPERIMENT: STATUS AND PERSPECTIVES

Oscar Adriani
University of Florence and INFN Firenze
On behalf of the GAMMA-400 Collaboration

SciNeGHE 2014, Lisbon, June 6th, 2014

Outline

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

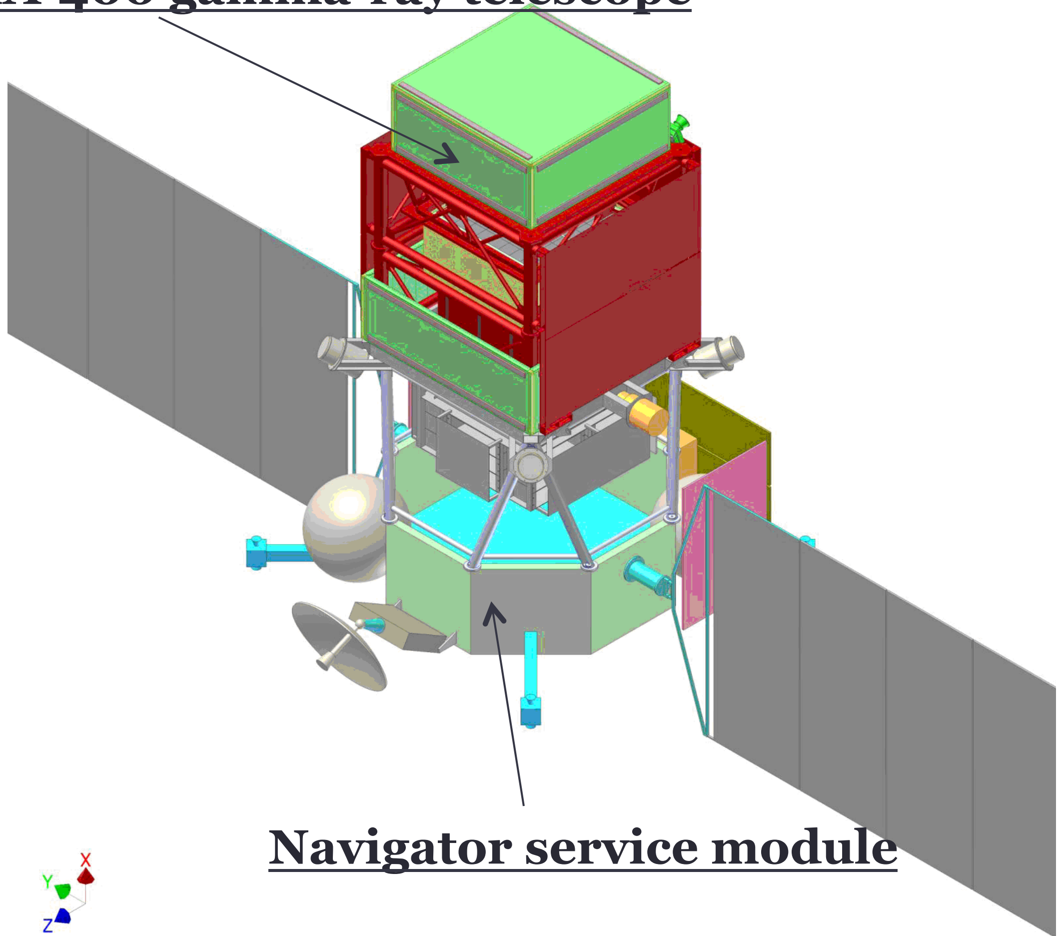
The GAMMA-400 project

- Mission is approved by ROSCOSMOS (launch currently scheduled by 2020)
- 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 – Leading Institute	INFN (Italy) – Converter/Tracker and Calorimeter
NRNU MEPhI – TOF and A/C detectors	INAF (Italy) – Converter/Tracker
NIIEM — design, temperature control system	Taras Schevchenko National University (Ukraine) — Ukrainian main collaborator
NIISI RAS — electronics	CrAO (Ukraine) — ground-based observatio
Ioffe Institute — Konus-FG burst monitor	IKI (Ukraine) — magnetometer
IKI — star sensor	ISM (Ukraine) — scintillators
IHEP — calorimeters, scintillators	KTH (Sweden) — anticoincidence
TsNIIMASH — space qualification	

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

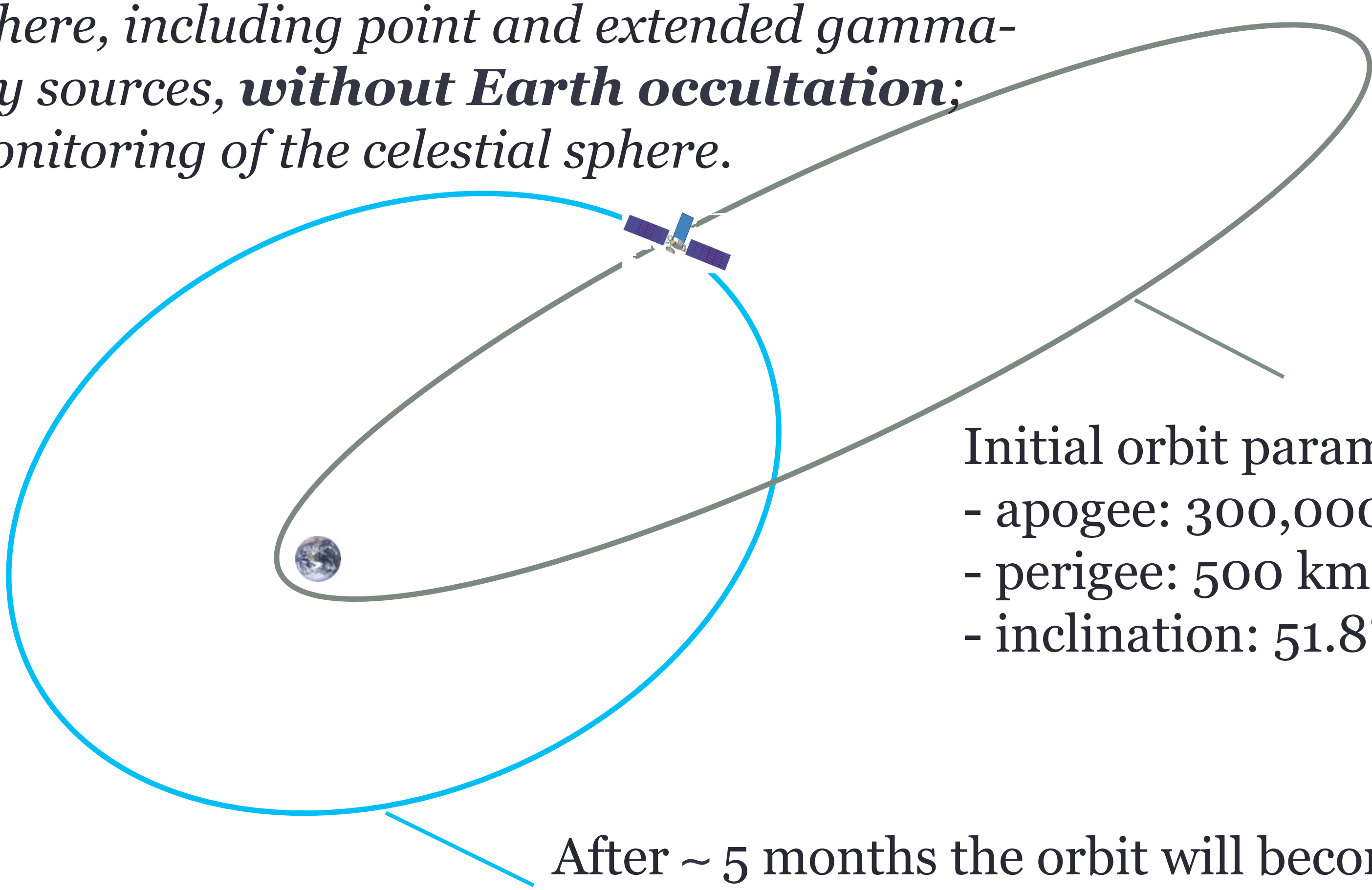
2 spectrometric detectors

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.

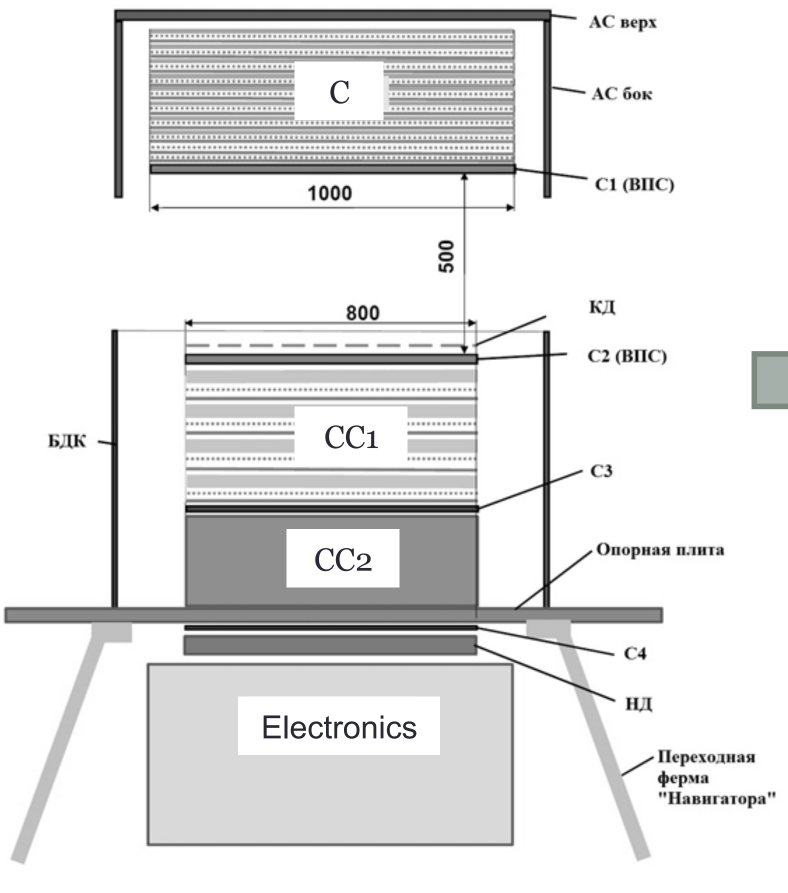
GAMMA-400

- 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"

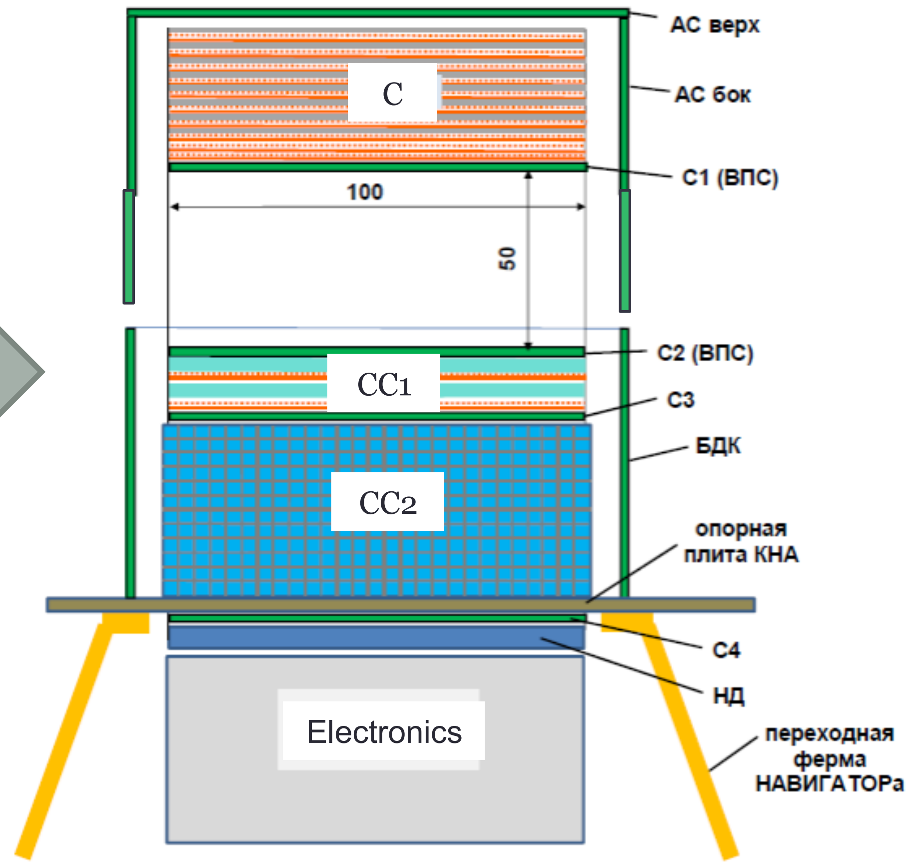
Improvements in the GAMMA-400 design and performance

- 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.**

GAMMA-400 evolution

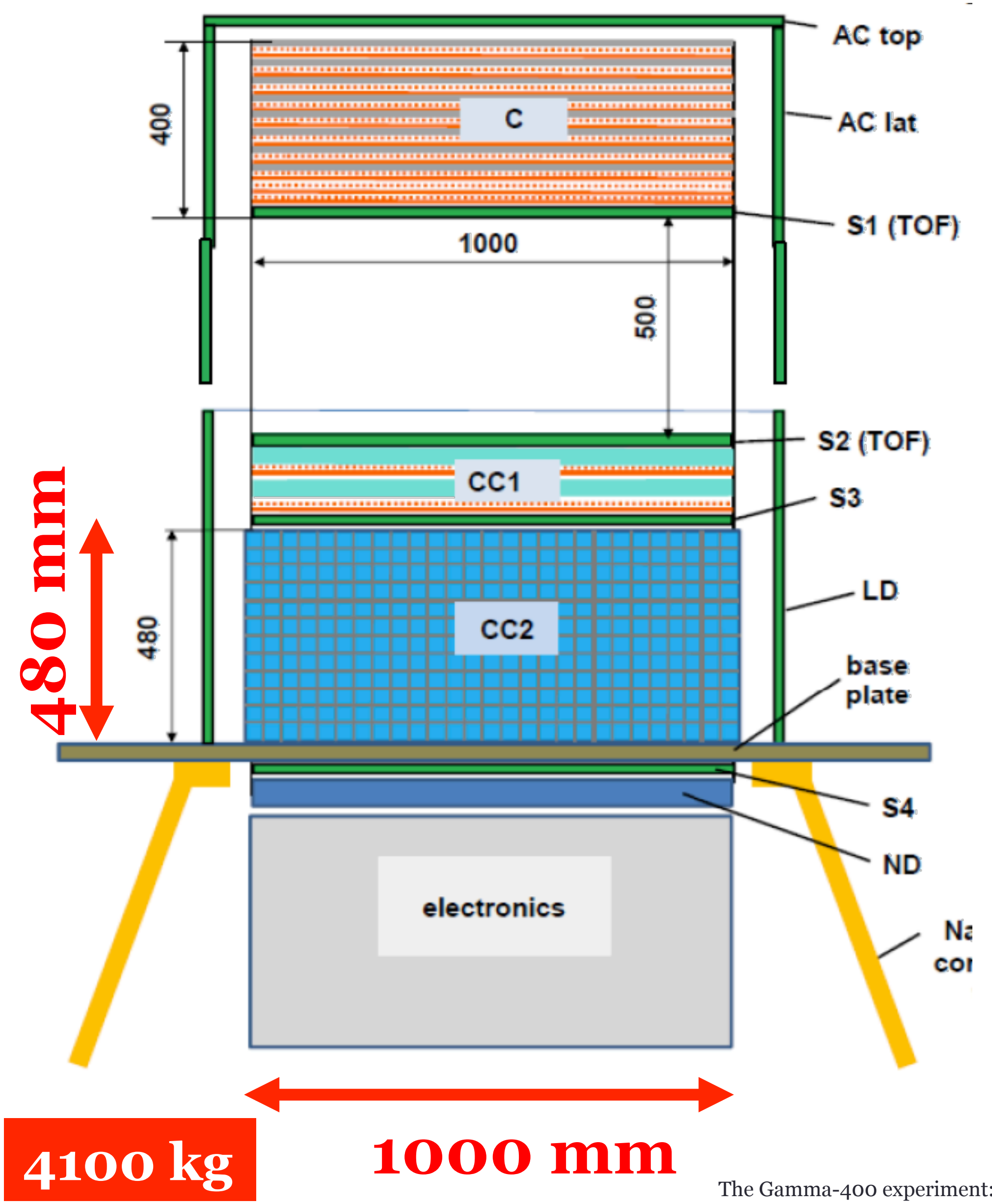


Original Russian proposal (2011)



Jointly agreed Russian-Italian proposal (2013)

The GAMMA-400 apparatus



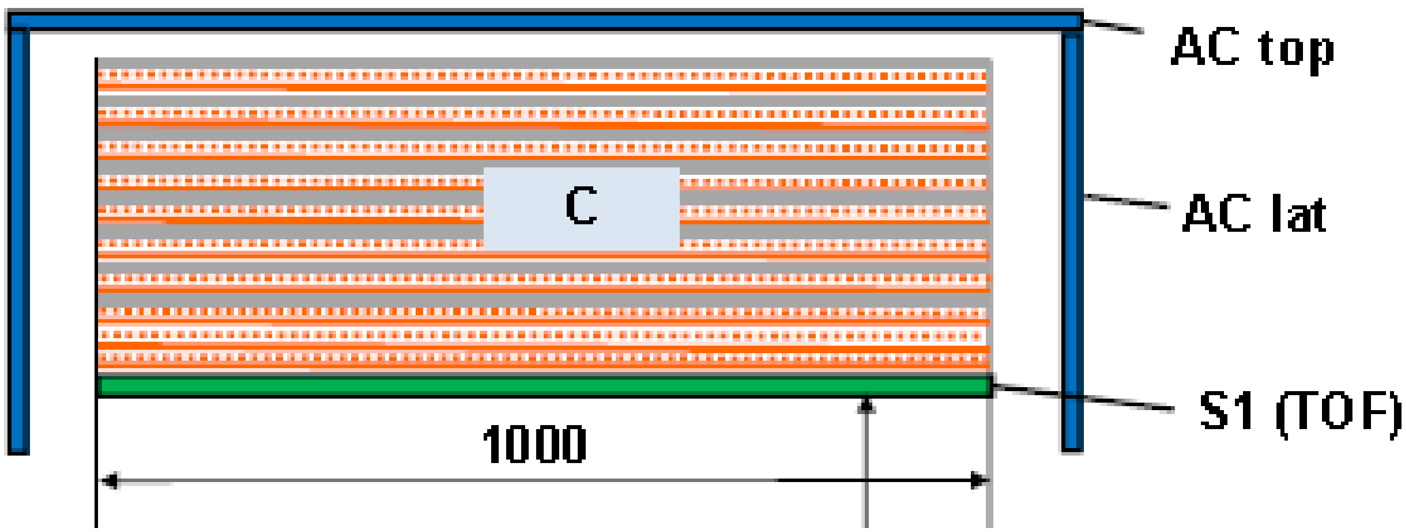
B2 over B1 improvements:

- 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:

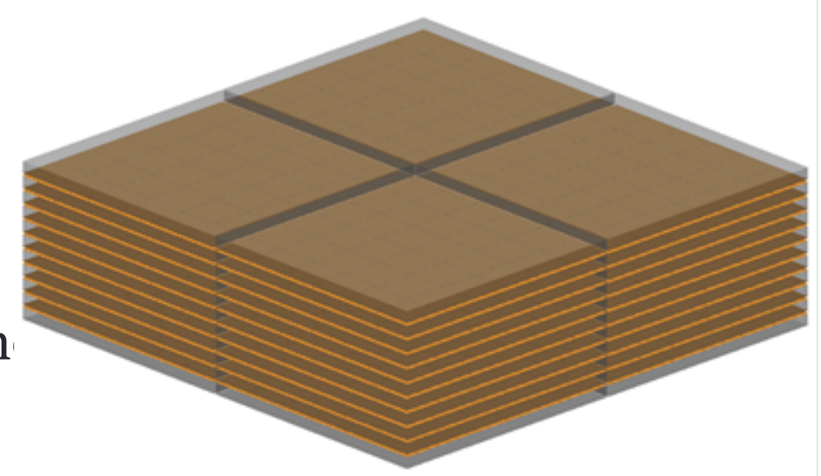
- **a dual instrument** for **photons** (100 MeV ÷ 1 TeV) and **cosmic rays** (electrons ~ 10 TeV and high energy cosmic-ray nuclei, p and He spectra at the "knee" (10^{14} – 10^{15} eV);
- **State of the art Si-W converter/tracker with analogue read-out;**
- **3-D, deep, homogeneous calorimeter with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

Converter/Tracker



- 10 x-y layers (20 views):
  - 8 layers W $0.08X_0$ + 8 planes Si (x,y)
  - 2 layers of Si (x,y), no W

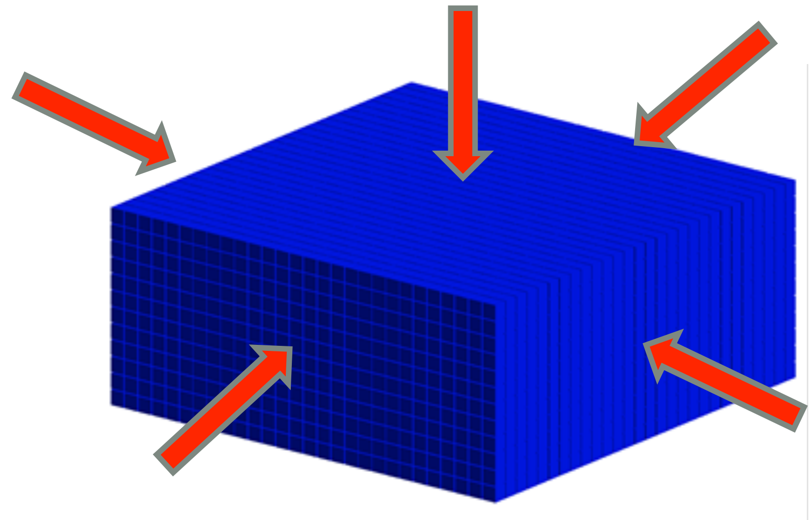
Converter/Tracker

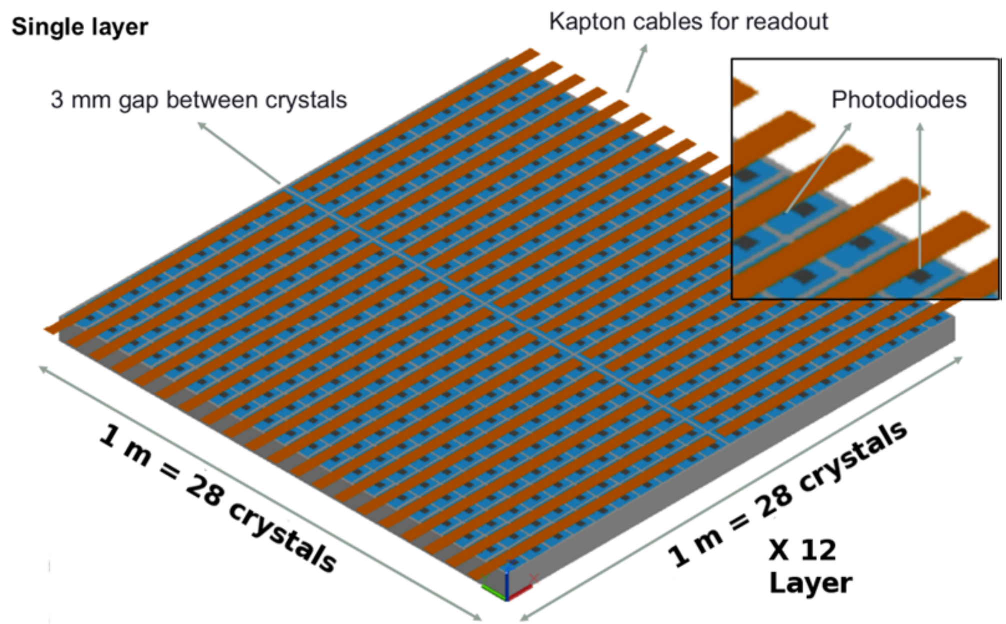


- Homogeneous Si-W Tracker
- 4 towers (~ 50 cm x 50 cm each);
- 8 W/Si-x/Si-y planes + 2 Si-x/Si-y planes (n
- Thickness of each plane 0.1 X_0
- Each sensor ~ 9.7 cm x 9.7 cm from 6" wafers;
- Sensors arranged in ladders (5 detectors/ladder), 1 ladder ~ 50 cm;
- Implant pitch 80 μm (fine segmentation)
- Read-out pitch 240 μm (capacitive charge division, one strip every 3 is read-out), 384 read-out strips/ladder;
- 2000 silicon detectors;
- 153600 readout channels, 2400 front-end ASICs (64 channels/ASIC)
- Power consumption (FE only): ~ 80 W

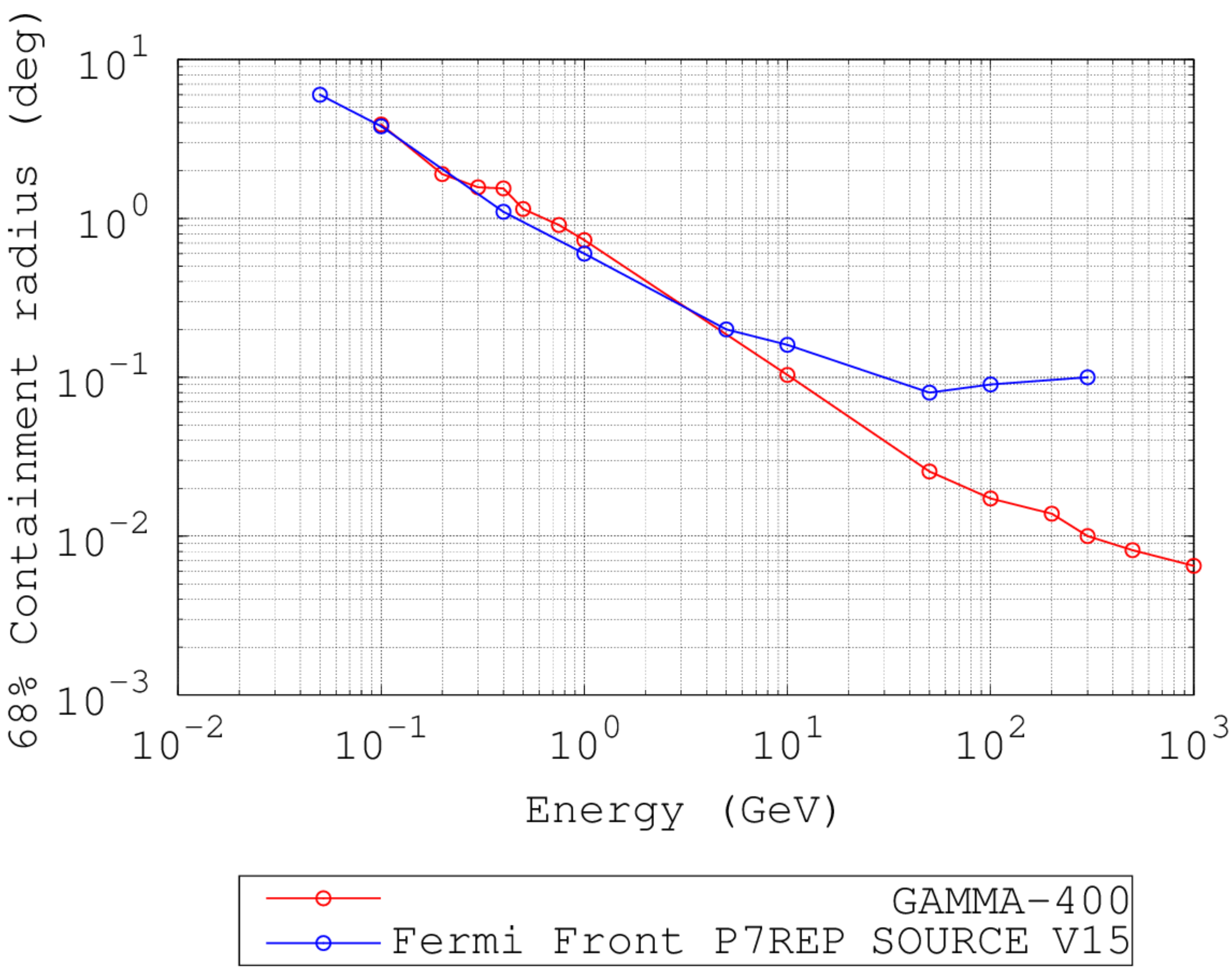
CC2 Calorimeter

- 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
- $GF_{eff,\ el.}^{0.1\text{-}1\ TeV} \sim 3.4\ m^2sr$
- $GF_{eff,\ prot.}^{1\ TeV} \sim 3.9\ m^2sr$
- Slightly staggered planes to avoid dead regions

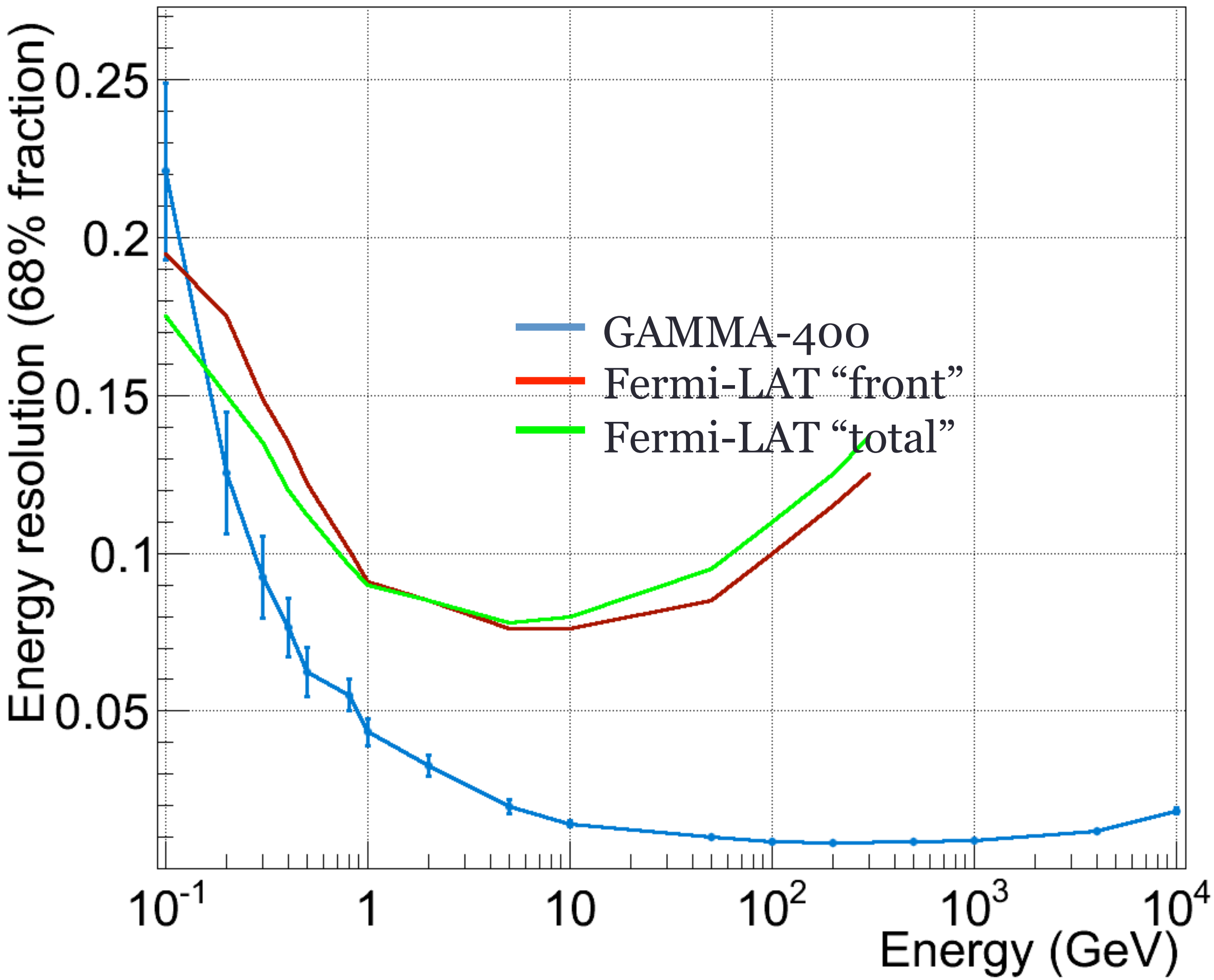




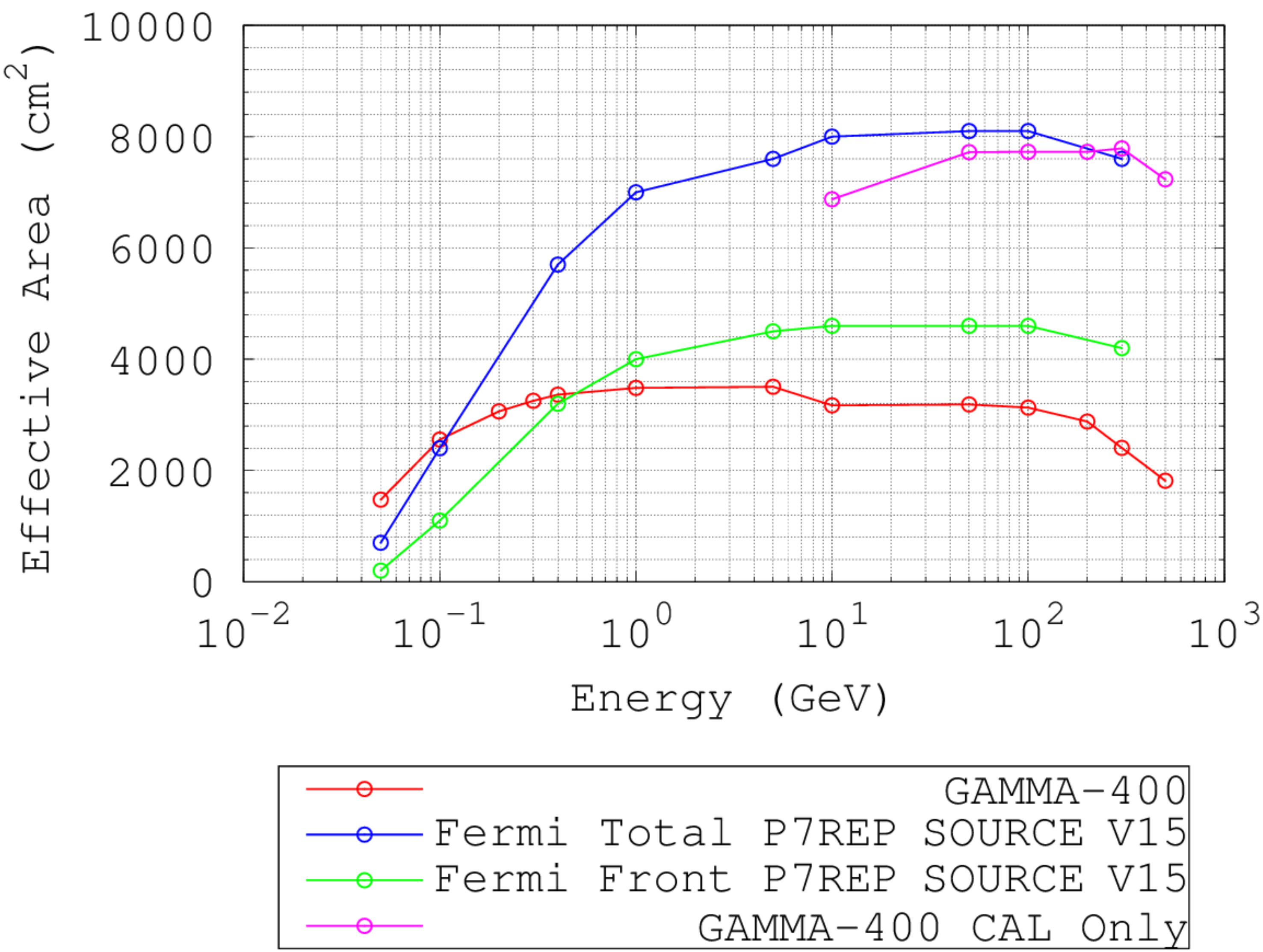
Angular resolution for γ



Energy resolution for γ



Effective area



Expected number of high energy charged cosmic rays events

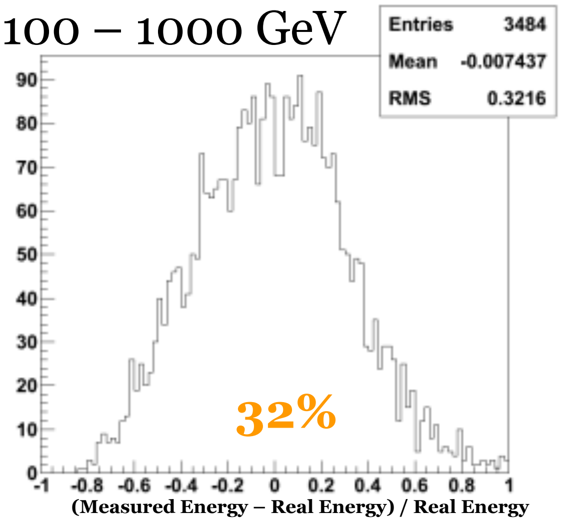
Some assumptions:

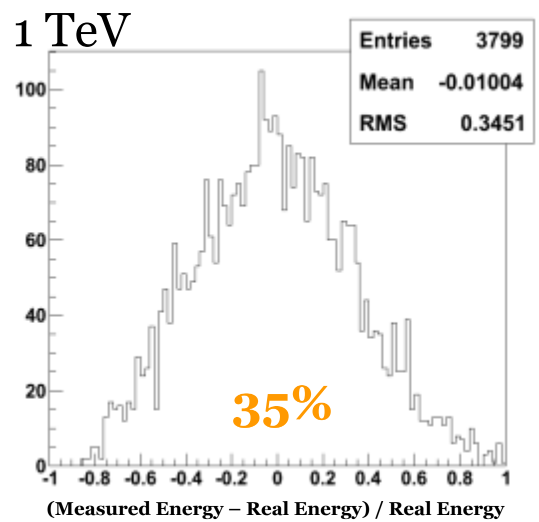
- 10 years exposure
- e/p rejection factor ~ 10^5

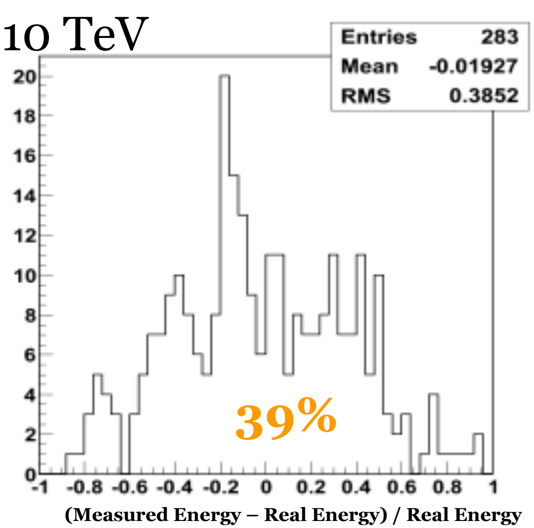
Protons and Helium (Polygonato model)												
Effective GF (m² sr)	σ(E)/E	E>0.1 PeV		E>0.5 PeV		E>1 PeV		E>2 PeV		E>4 PeV	
		p	He	p	He	p	He	p	He	p	He
~4.0	35%	$7.8.10^3$	$7.4.10^3$	$4.6.10^2$	$5.1.10^2$	$1.2.10^2$	$1.5.10^2$	28	43	5	10

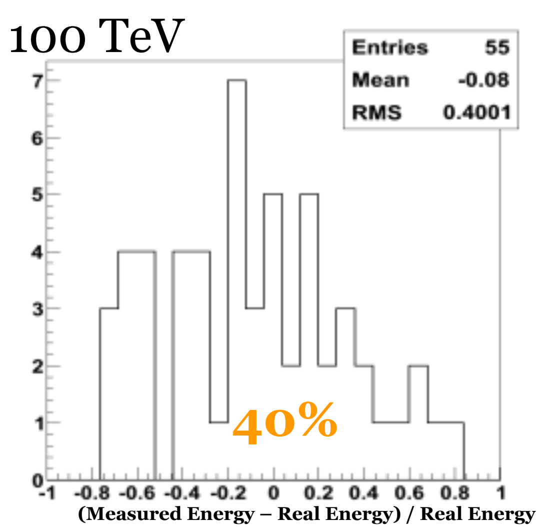
Electrons (no nearby sources)					
Effective GF (m² sr)	σ(E)/E	E>0.5 TeV	E>1 TeV	E>2 TeV	E>4 TeV
3.4	~1%	181.10^3	35.10^3	5.10^3	6.10^2

Protons: energy resolution









Selection efficiencies:

$\varepsilon^{0.1\text{-}1TeV} \sim 35\%$

$\varepsilon^{1TeV} \sim 41\%$

$\varepsilon^{10TeV} \sim 47\%$

- **generally higher values with respect to electrons due to the absence of shower containment criteria**
- **increase due to the requirement on the single-crystal energy deposit**

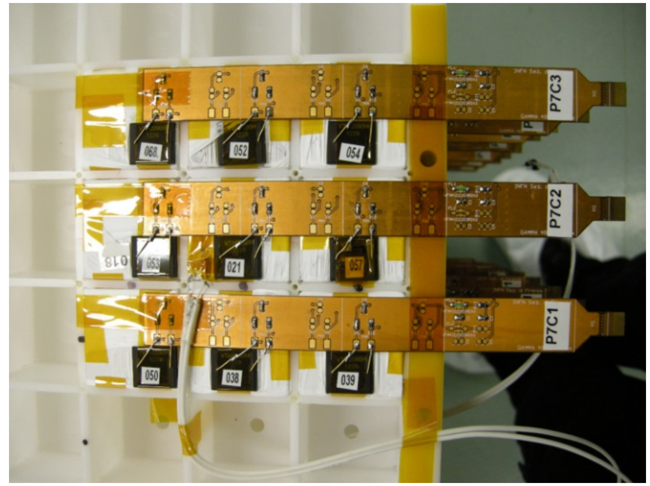
$GF_{eff}^{0.1\text{-}1TeV} \sim 3.3\ m^2sr$

$GF_{eff}^{1TeV} \sim 3.9\ m^2sr$

$GF_{eff}^{10TeV} \sim 4.5\ m^2sr$

Calorimeter prototype

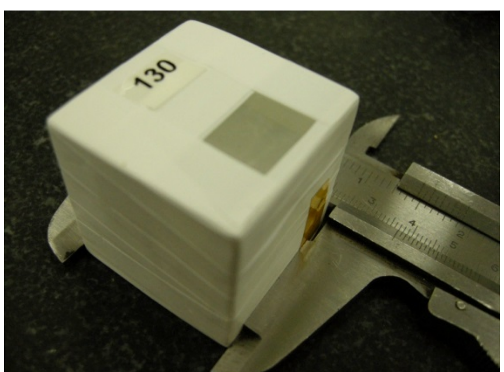
- 14 Layers
- 9 crystals in each layer (crystals 3.6 x 3.6 x 3.6 cm^3)
- 126 Crystals in total
- 126 Photodiodes
- 50.4 cm of CsI(Tl)
- 27 X_0, 1.44 λ_I
- Photodiodes read-out by 9 CASIS1.2A 16-channel ASICs)

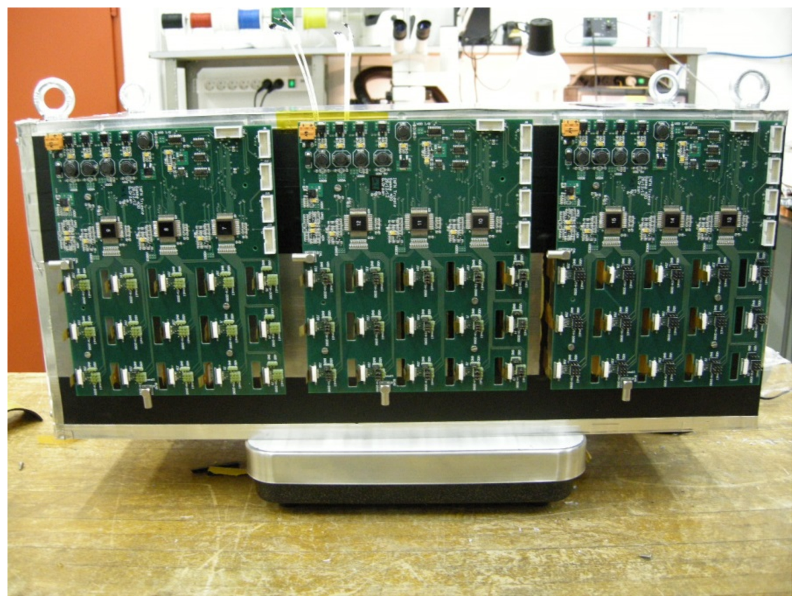


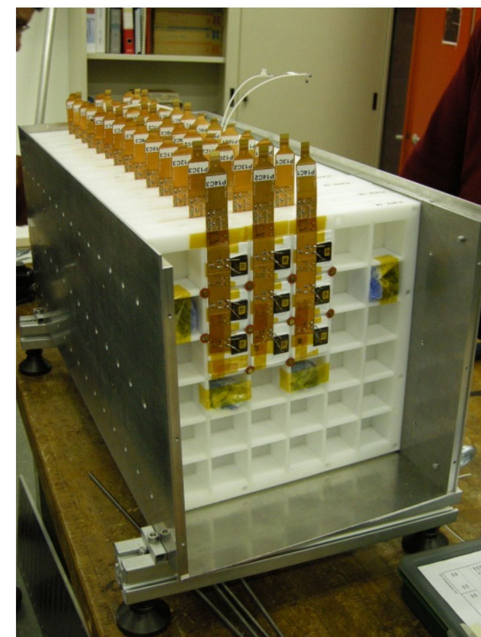
Mechanics:
INFN Pisa

Front-end electronics:
INFN Trieste

Crystals, photodiodes, DAQ, assembly:
INFN Florence



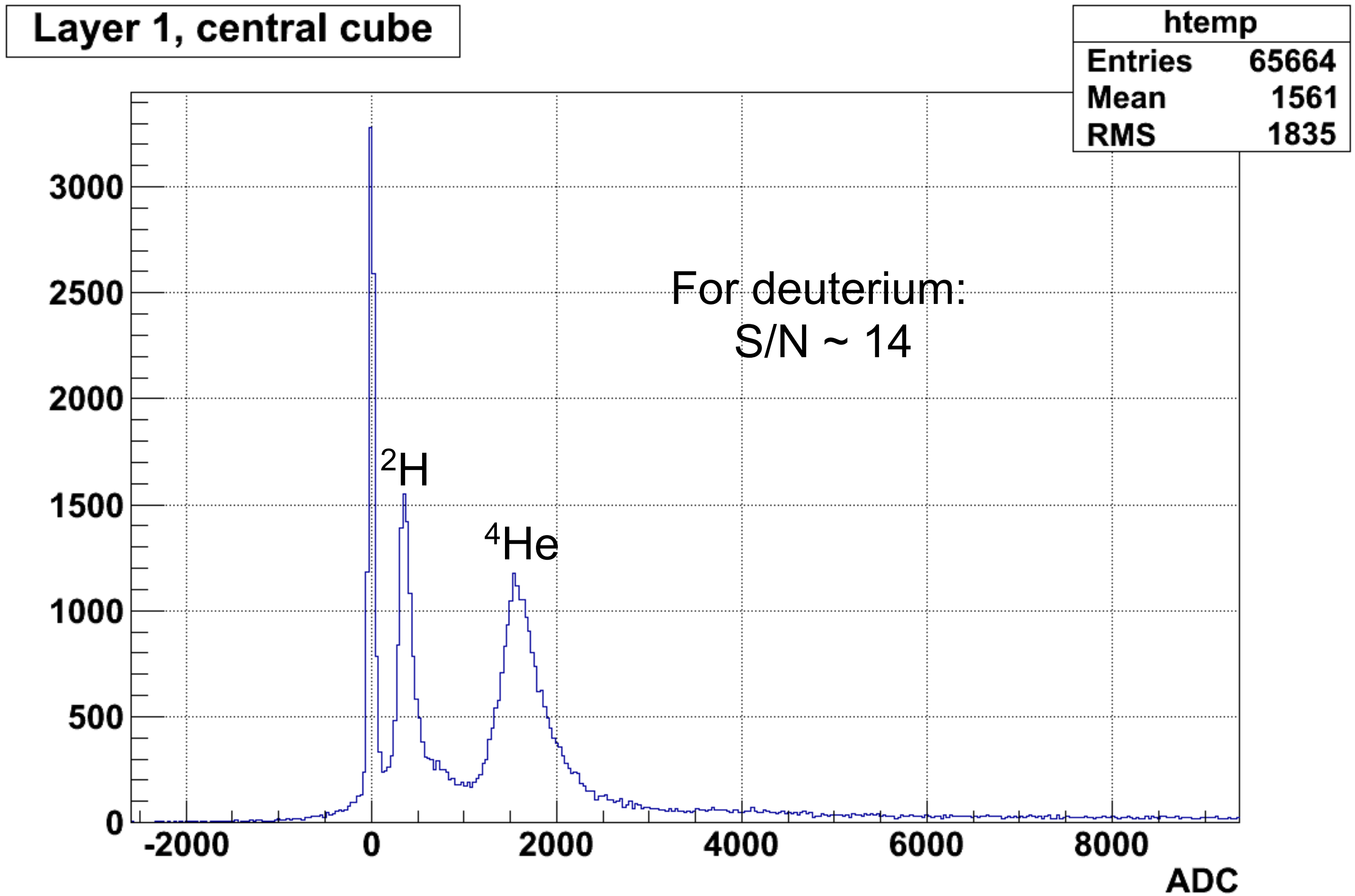




Prototype test beam results

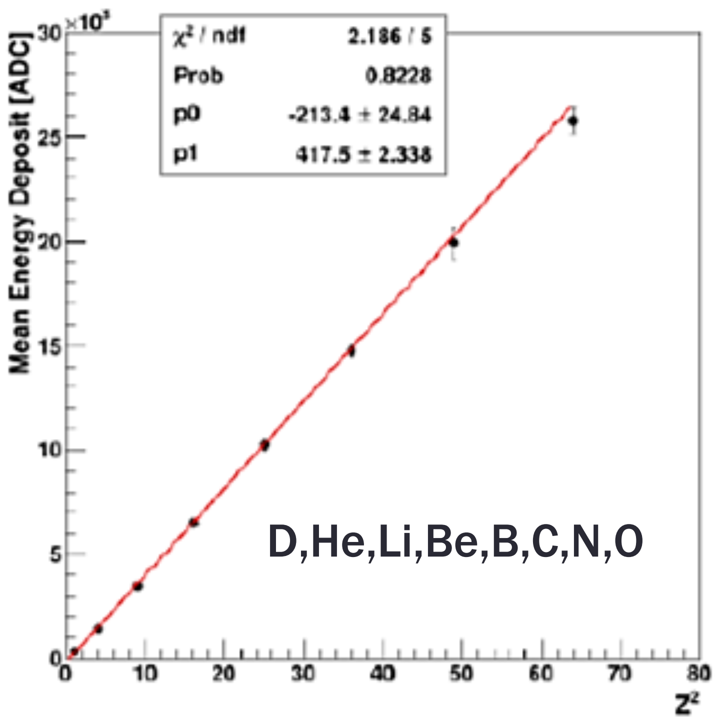
CERN SPS H8 Ion Beam: Z/A = 1/2, 12.8 GV/c and 30 GV/c (February 2013)

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

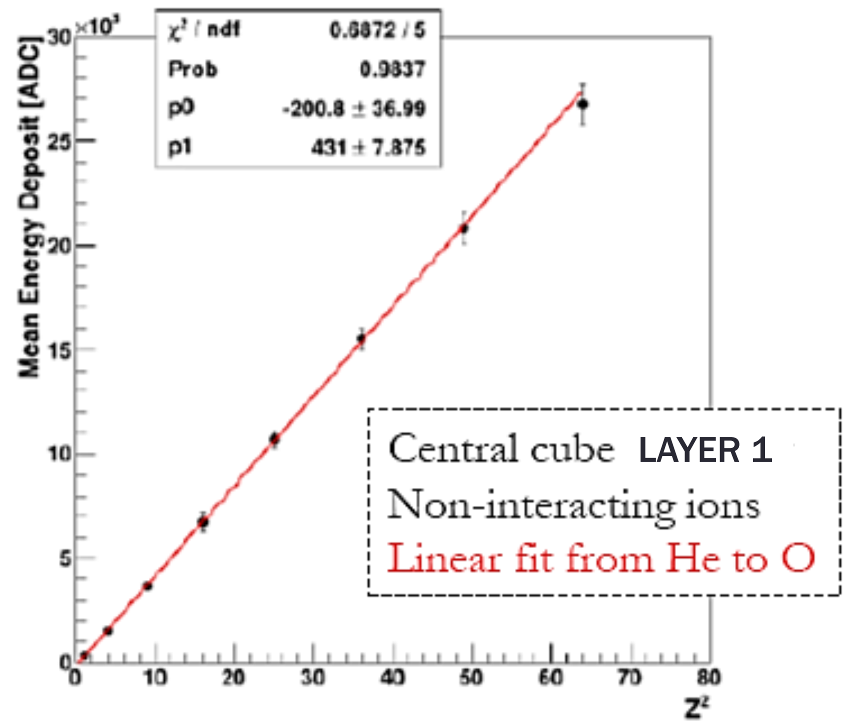


Non interacting ions: charge linearity

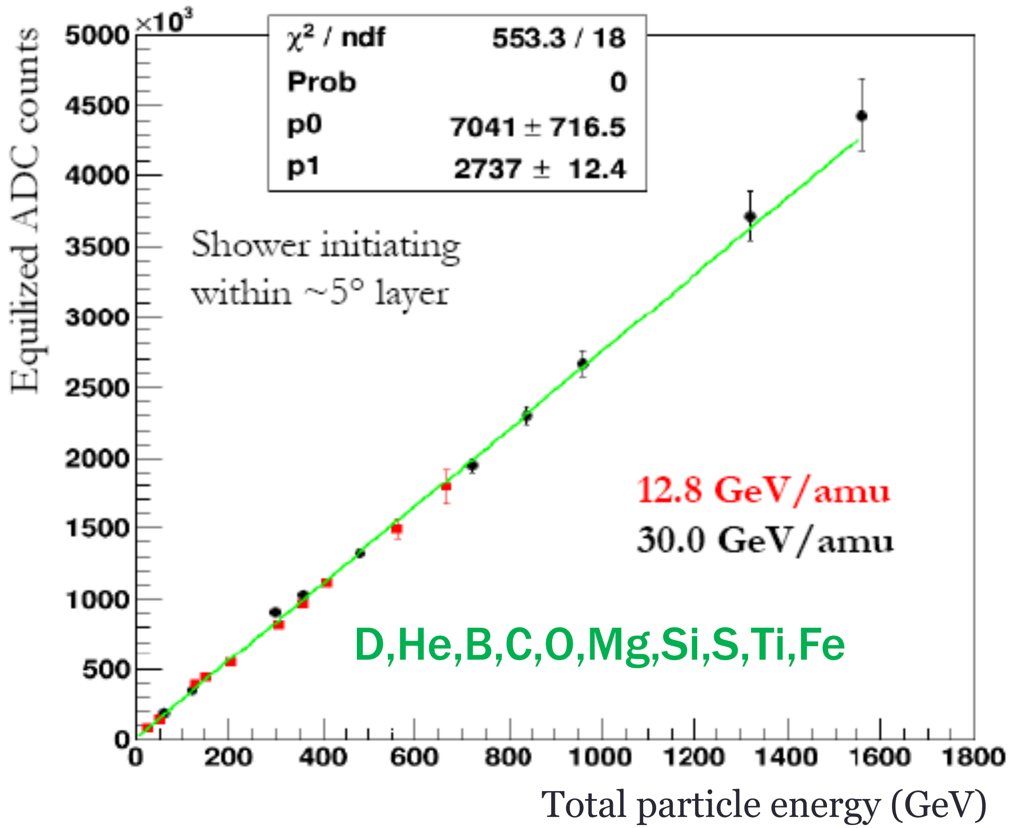
12.8 GeV/amu



30.0 GeV/amu



Interacting ions: charge linearity



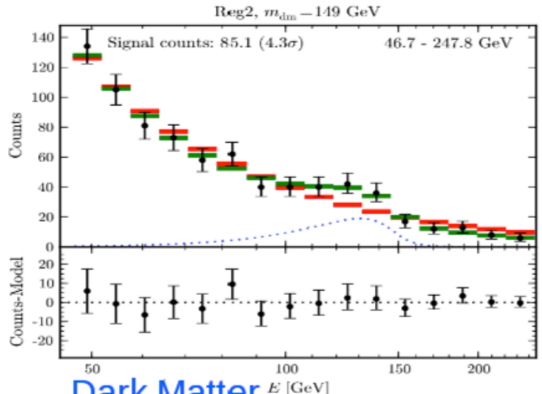
- Charge is selected by Beam Tracker in front of the calorimeter
- Good linearity even with just the large-area photodiode

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

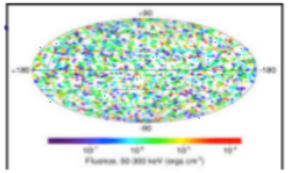
Physics of GAMMA-400

Galactic/ Extragalactic gamma-ray sources

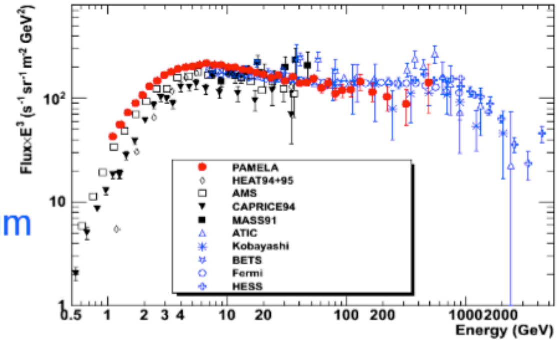


Dark Matter

CR propagation



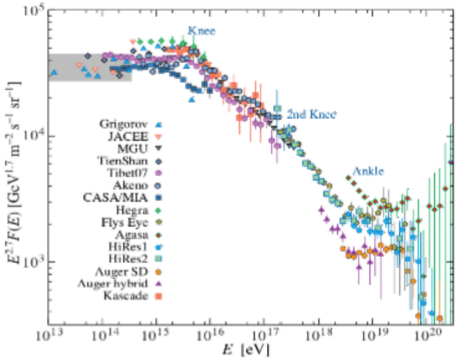
GRBs



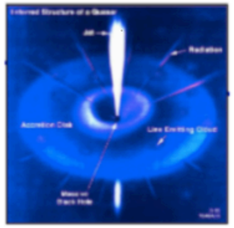
Electron spectrum

Pulsars

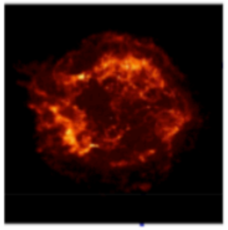
Knee origin



CR origin and acceleration mechanisms



AGNs

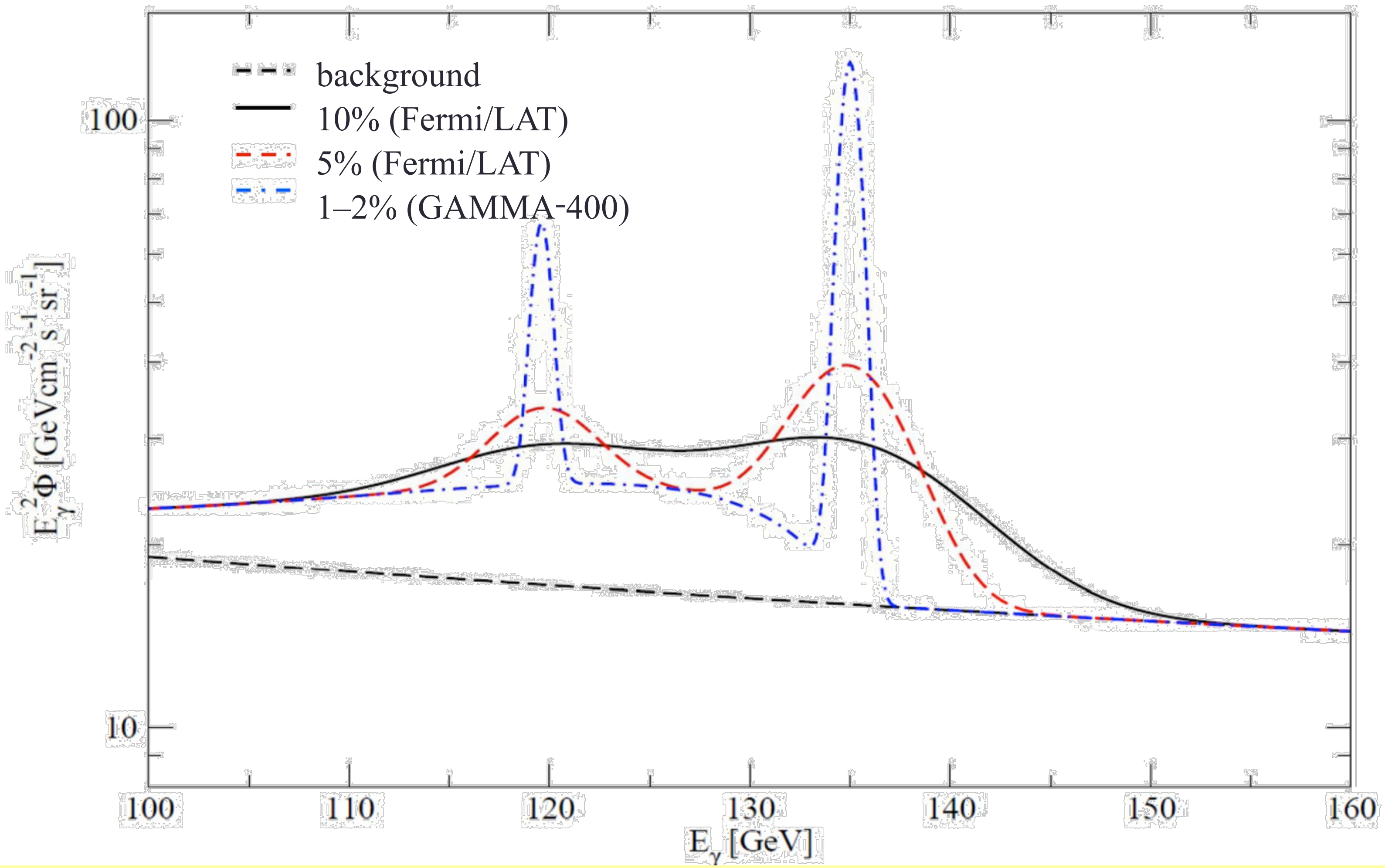


SNRs

Photons

- Detection of possible Dark Matter signal
  - Gamma-ray lines
  - Satellites
  - Dwarf Spheroidal Galaxies
  - Galactic Center
- Measurement of the high-energy γ-ray spectrum
  - SNR
  - Pulsars and PWN
  - Massive star clusters
  - AGN
  - GRB

Increasing the energy resolution



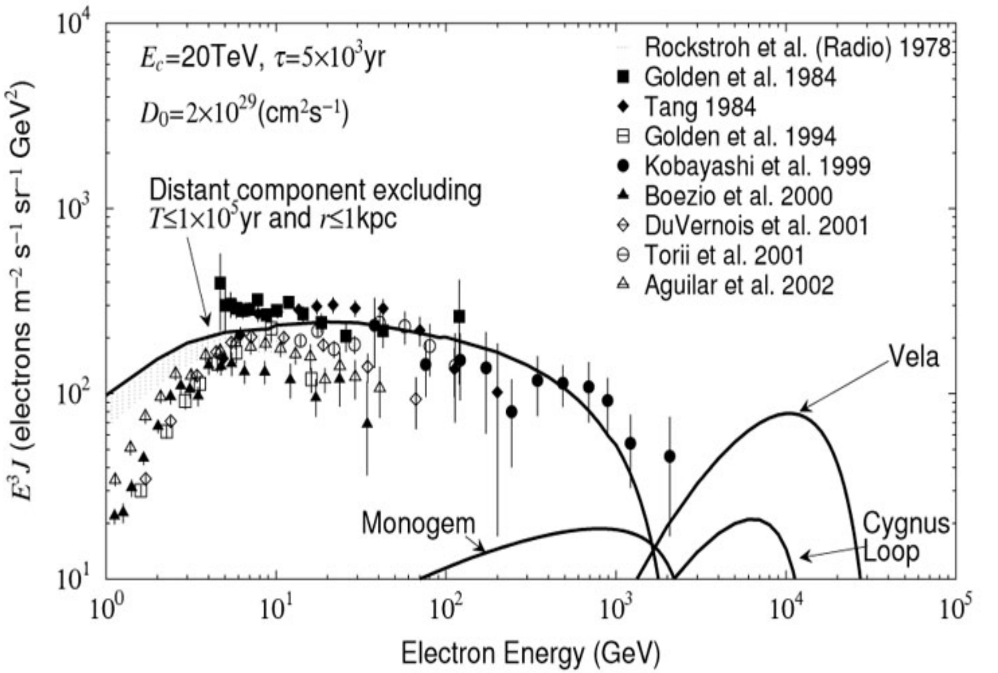
The γ-ray differential energy results for a 135 GeV right-handed neutrino dark matter candidate.

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

Electrons can tell us about local GCR sources

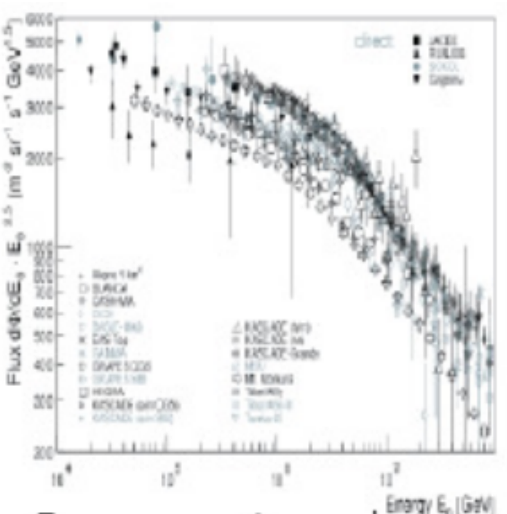
- High energy electrons have a high energy loss rate ∝ E^2
  - Lifetime of ~10^5 years for > 1 TeV electrons
- Transport of GCR through interstellar space is a diffusive process
  - Implies that source of high energy electrons are < 1 kpc away

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

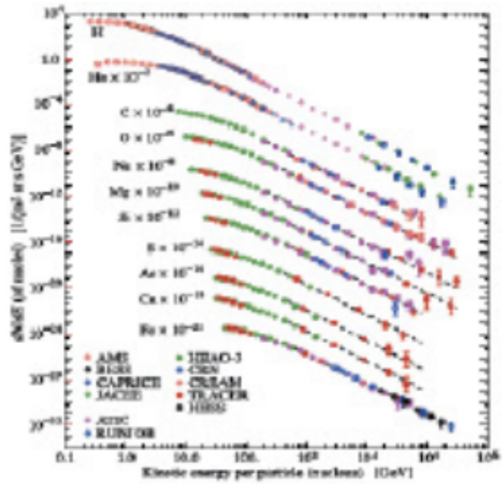


J. P. Wefel, TevPA 2011, Stockholm (2011)

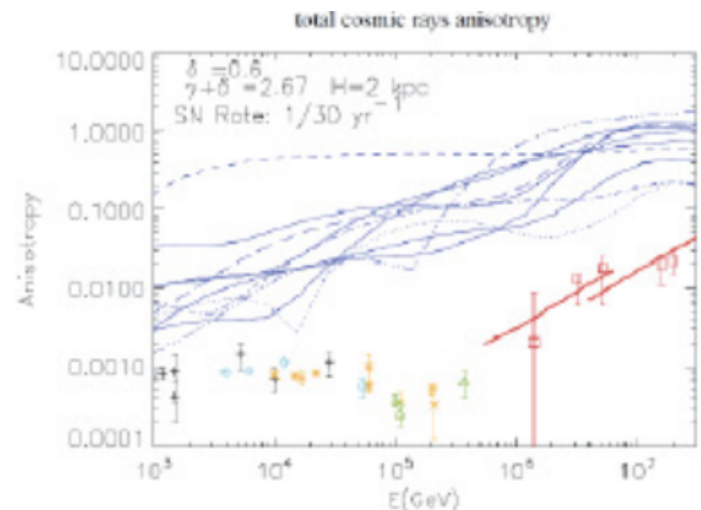
Nuclei



Energy spectrum shape



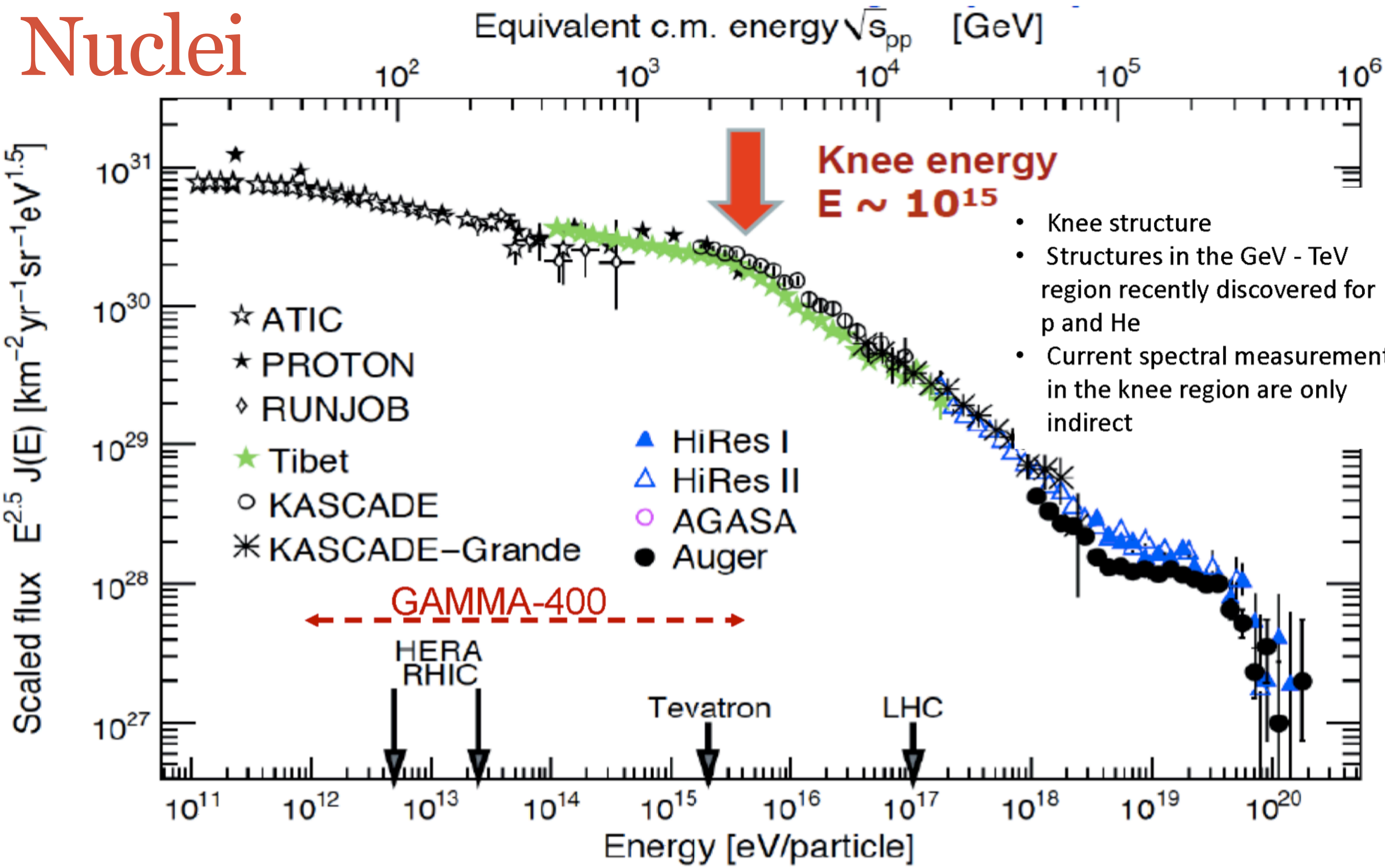
Composition



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

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

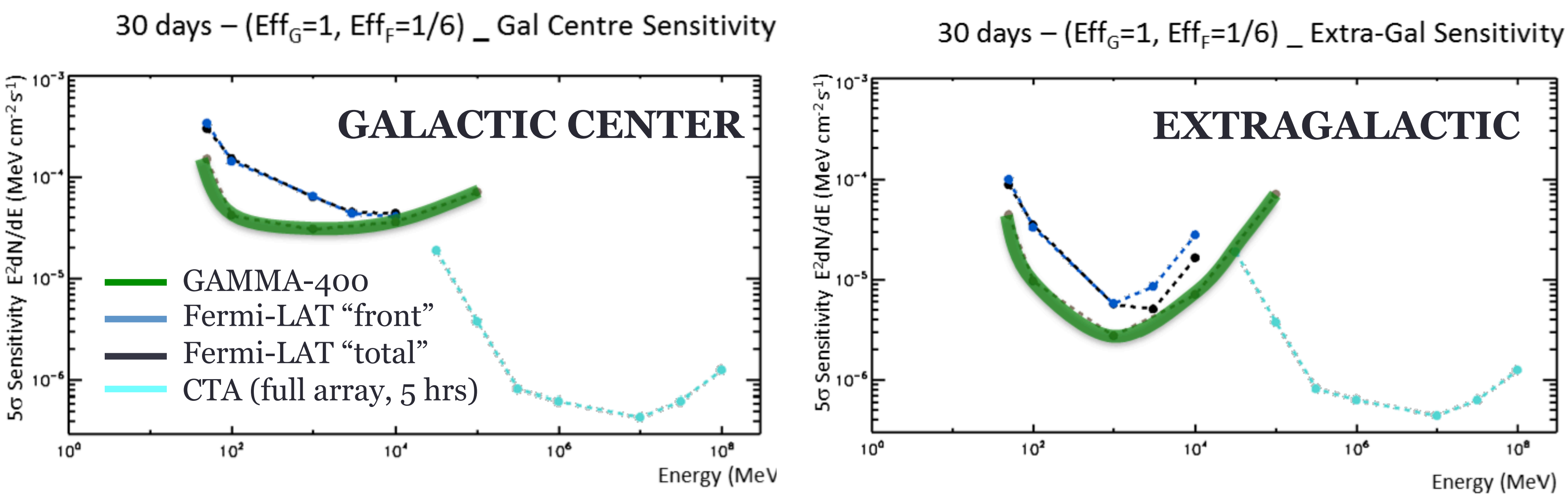
Conclusions

- 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.

Spare slides

GAMMA-400 performances: sensitivity

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



- 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_γ > 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_γ > 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

Basic parameters of the B1 version

Energy range	100 MeV – 3,000 GeV
Field-of-view, sr (Eγ > 1 GeV)	~1.2
Effective area, cm^2 (Eγ > 1 GeV)	~4,000
Energy resolution (Eγ > 10 GeV)	~1%
Angular resolution (Eγ > 100 GeV)	~0.02°
Converter-tracker thickness	~1 X_0
Calorimeter thickness	~25 X_0
Proton rejection factor	~10^5
Telemetry downlink volume, Gbyte/day	100
Total mass, kg	2,600
Maximum dimensions, m^3	2.0x2.0x3.0
Power consumption, W	2,000

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

B2: p and He count estimation

~knee ↓ (E>4 PeV)

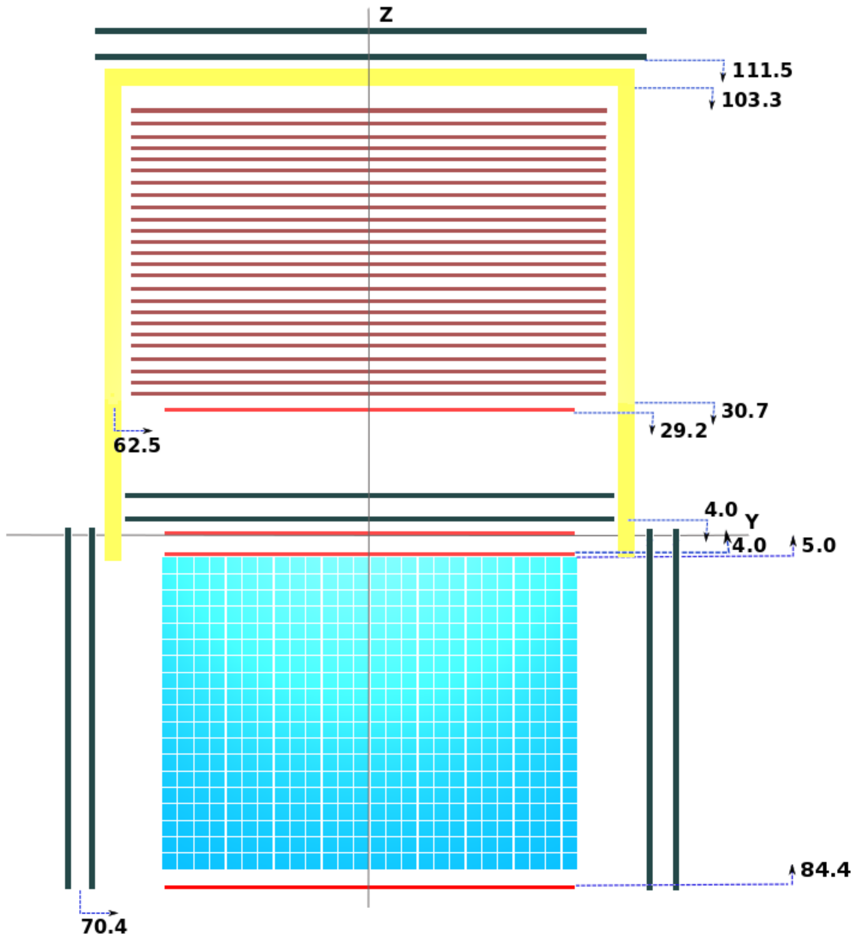
Experiment	Duration	GF (m^2 sr)	Calo $\sigma(E)/E$	Calo depth	ε sel	E>0.1 PeV		E>0.5 PeV		E>1 PeV		E>2 PeV		E>4 PeV	
						p	He	p	He	p	He	p	He	p	He
CALET	5 y	0.12	~40%	30 X_0 1.3 λ_0	0.8	292	276	17	19	5	6	1	2	0	0
CREAM	180 d	0.43	~45%	20 X_0 1.2 λ_0	0.8	103	97	6	7	2	2	0	1	0	0
ATIC	30 d	0.25	~37%	18 X_0 1.6 λ_0	0.8	10	9	1	1	0	0	0	0	0	0
G400	10 y	3.9	~ 35%	25.4 X_0 1.2 λ_0	0.8	18951	17921	1123	1242	300	374	69	106	11	24

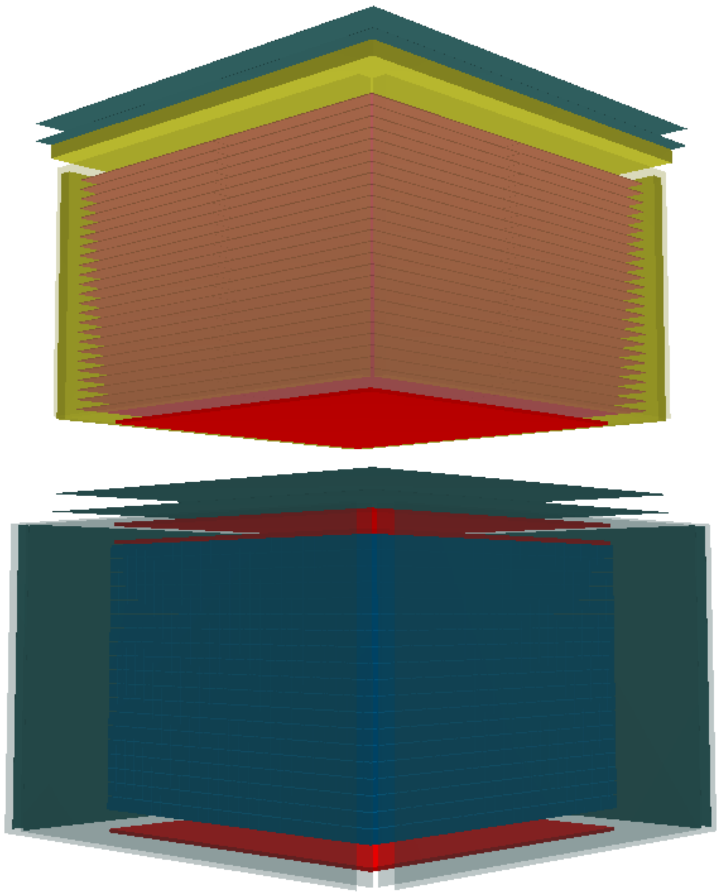
B2: Nuclei count estimation

~knee

Experiment	Duration	GF (m^2 sr)	Calo σ(E)/E	Calo depth	ε sel	E>0.1 PeV		E>0.5 PeV		E>1 PeV		E>2 PeV		E> 4 PeV	
						^{3}Li to ^{9}F	^{10}Ne to ^{24}Cr	^{3}Li to ^{9}F	^{10}Ne to ^{24}Cr	^{3}Li to ^{9}F	^{10}Ne to ^{24}Cr	^{3}Li to ^{9}F	^{10}Ne to ^{24}Cr	^{3}Li to ^{9}F	^{10}Ne to ^{24}Cr
CALET	5 y	0.12	~30%	30 X_0 1.3 λ_0	0.8	136	140	9	10	3	3	1	1	0	0
CREAM	10 y	0.46	~45%	20 X_0 1.2 λ_0	0.8	51	53	4	4	1	1	0	0	0	0
ATIC	30 d	0.25	~37%	18 X_0 1.6 λ_0	0.8	5	5	0	0	0	0	0	0	0	0
TRACER	30 d	5	-	TRD	0.8	93	96	6	7	2	2	1	1	0	0
G400	10 y	3.9	~40%	25.4 X_0 1.2 λ_0	0.8	8830	9073	612	636	193	206	58	69	17	20

GAMMA-400: the enhanced configuration (E2)



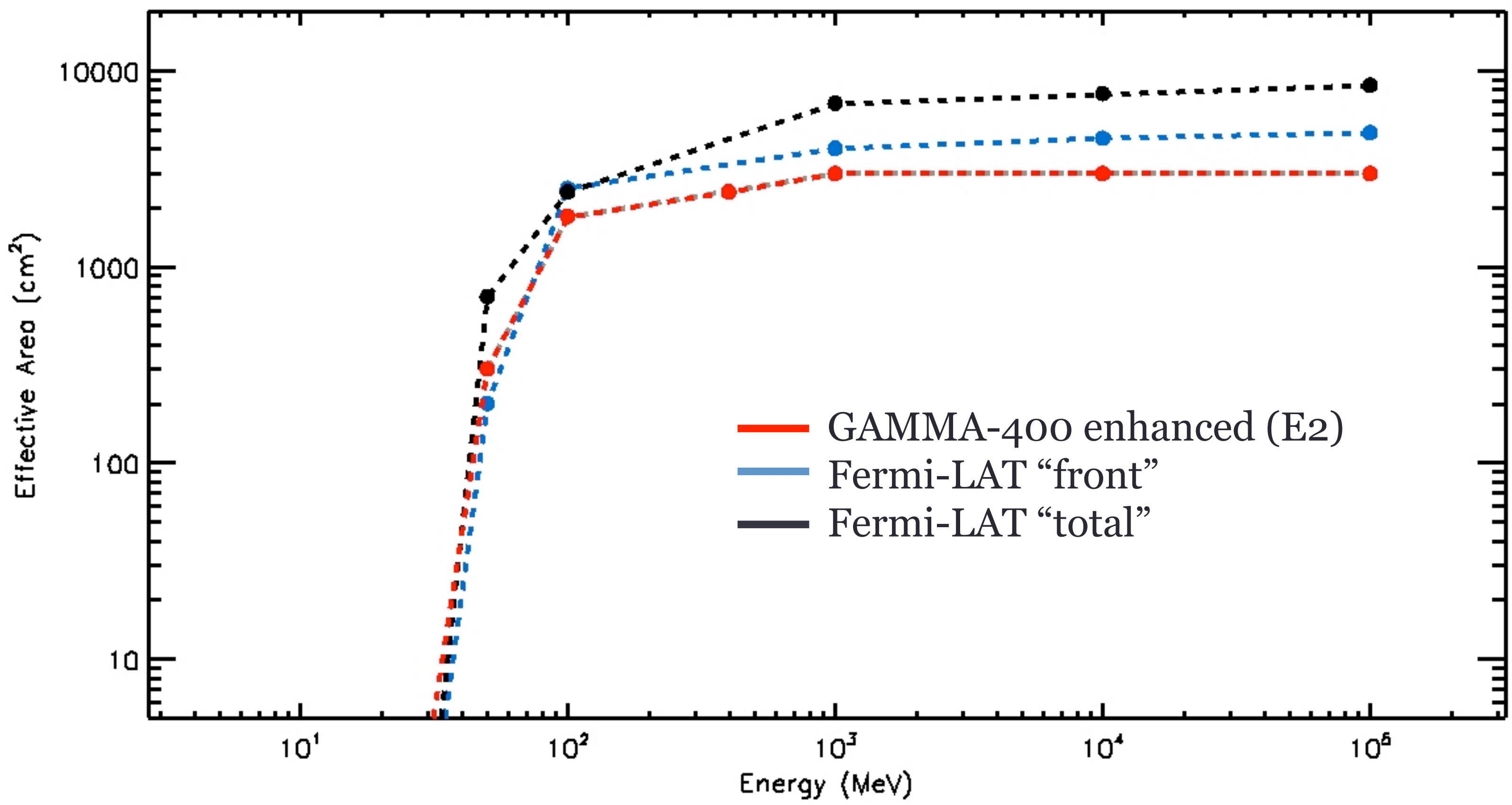


E2 vs. B2 Trackers

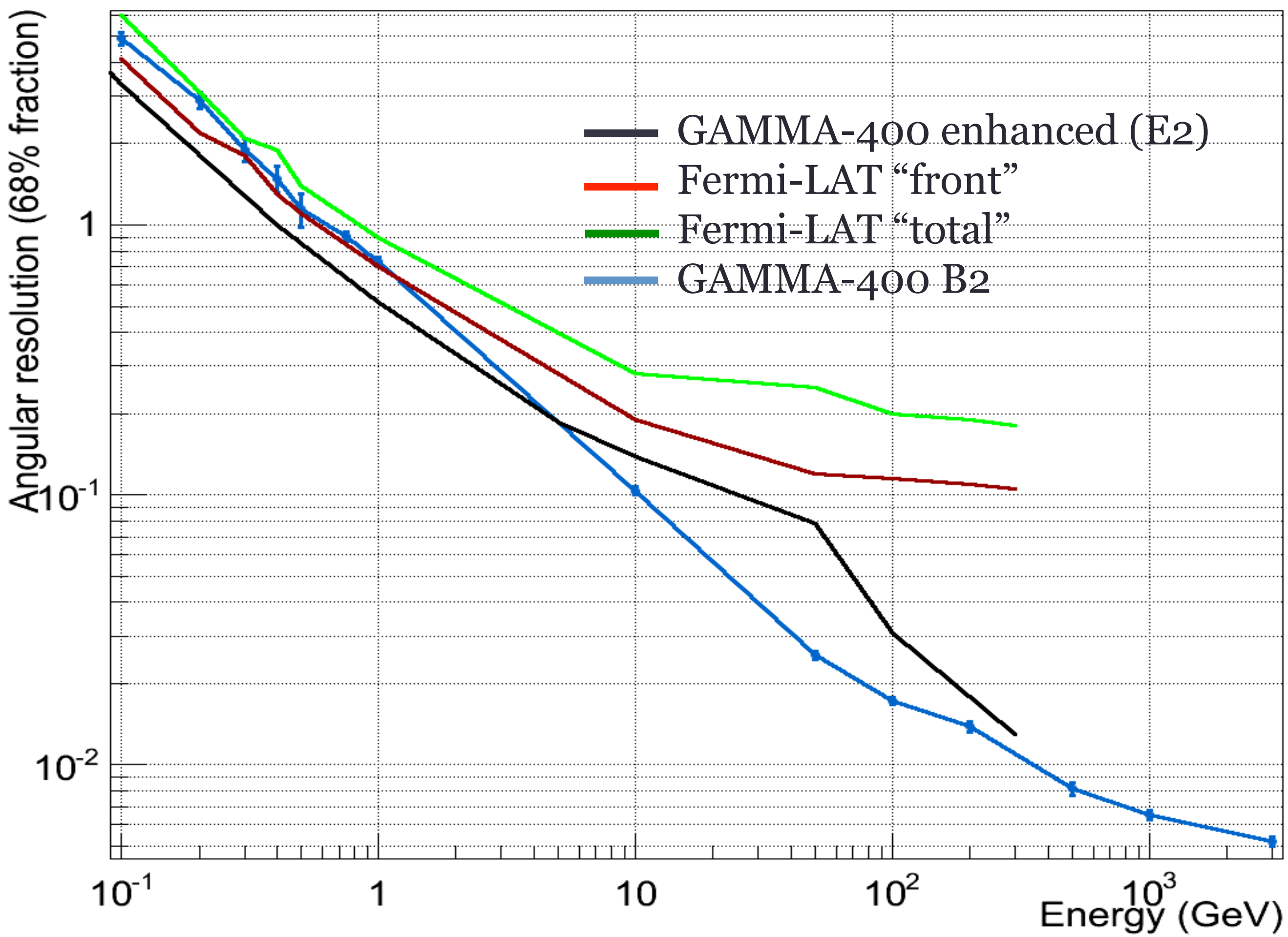
Parameter	B2	E2
N. towers	4	4
N. Planes	10	25
Converter (W) thickness (X_0)	0.1	0.03
Plane spacing (cm)	3.5	2.8-3.0 (TBD)
Si sensor dim. (cm)	9.7x9.7	9.7x9.7
Implant strip pitch (µm)	80 or 120	80 or 120
Readout strip pitch (µm)	240	240
Readout channels/plane	15360	15360
Total readout channels	153600	384000
Total Silicon detector number	2000	5000

- the tungsten converter is very thin, as in the "front/upper" section of Fermi-LAT, to minimize multiple scattering;
- the converter thickness and analog readout are uniform across the tracker, as in AGILE, to optimize the PSF.

E2 effective area

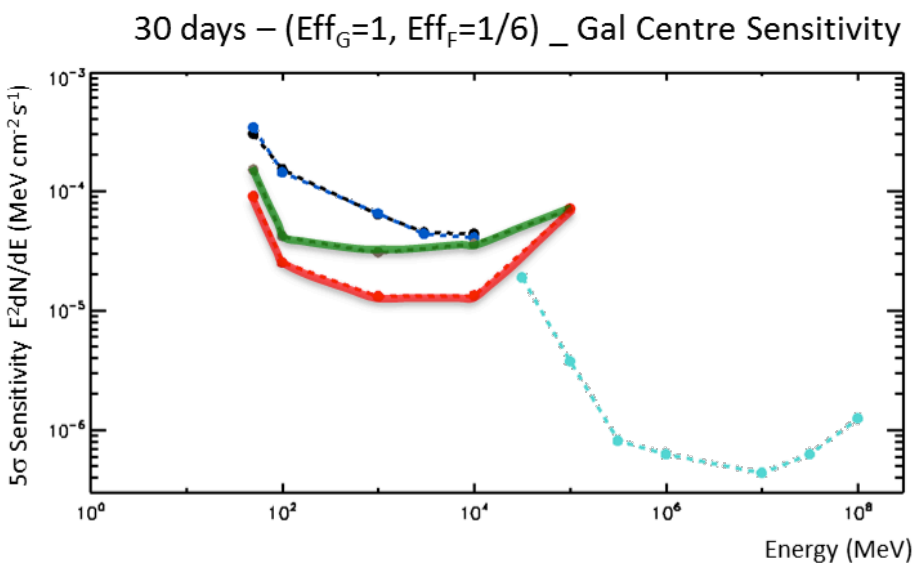


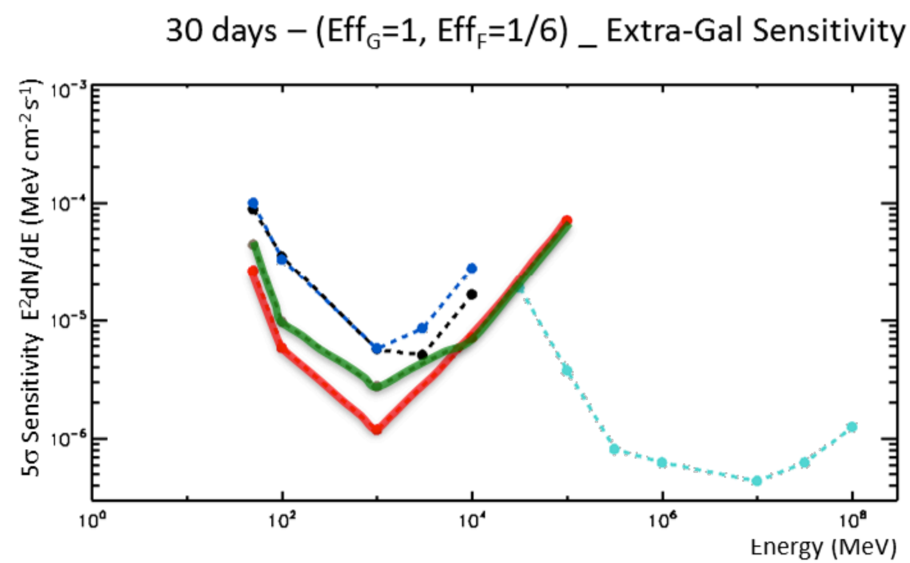
E2 angular resolution



E2 vs. B2: sensitivity

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





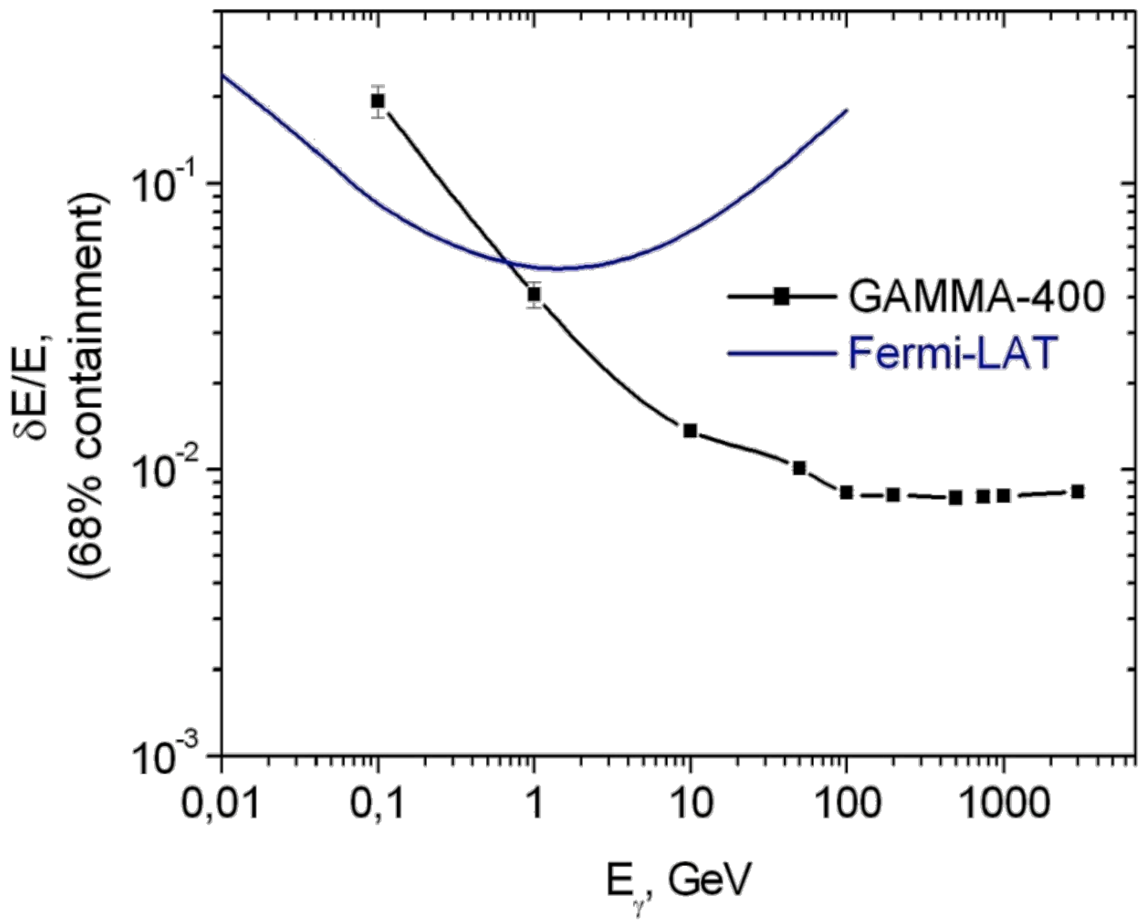
- GAMMA-400 basic (B2)
- GAMMA-400 enhanced (E2)
- Fermi-LAT "front"
- Fermi-LAT "front+back"
- CTA (full array, 5 hrs)

E2 vs. B2 Calorimeters

Parameter	B2	E2
Scintillating medium	CsI(Tl)	CsI(Tl)
NxNxN	28x28x12	20x20x20
L (cm)	3.6	3.6
Crystal Volume (cm^3)	46.7	46.7
Gap (cm)	0.3	0.3
Mass (kg)	1981	1683
N. crystal	9408	8000
Overall size (cm^3)	109.2x109.2x46.8	78.0x78.0x78.0
Depth (R. L.) “ (I. L.)	54x54x23 2.6x2.6x1.1	39x39x39 1.8x1.8x1.8
Planar geometrical acceptance on five surfaces	10.1m^2sr	9.55 m^2sr

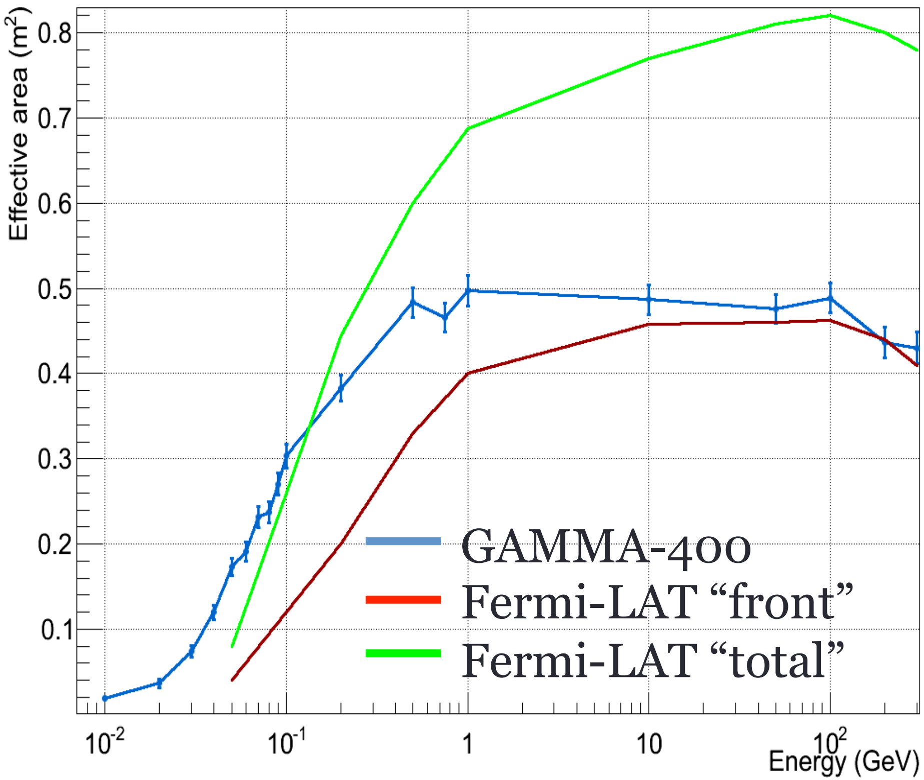
NOTE: the effective geometrical acceptance depends on the selection criteria and typically, for hadrons, $G_{eff}(B2) < G_{eff}(E2)$

Energy resolution for γ

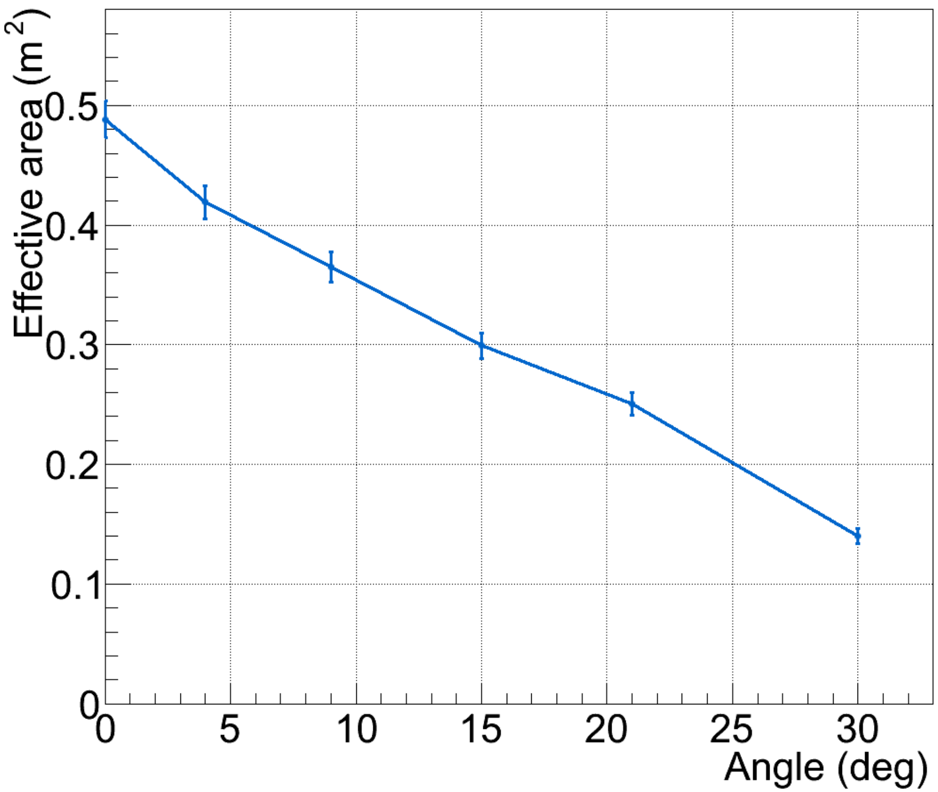


GAMMA-400 performances: effective area

*Simulated gamma-ray **effective area** as a function of photon energy for normal incidence*



*Simulated gamma-ray **effective area** at 100 GeV as a function of the incidence angle*



<u>Gamma-ray effective area:</u>

- ~5000 cm², similar to the upper part of Fermi-LAT in the energy range 1 GeV - 300 GeV

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 x 9.2 mm² for small signals (Excelitas VTH2090)
  - small-area PD 0.5 x 0.5 mm² 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

The starting point

(GAMMA-400 driven idea)

- Exercise made on the assumption that the detector weight is ~ 1600 kg
  - mechanical support is not included in the weight estimation
- The chosen material is CsI(Tl)

Density:	4.51 g/cm^3
X_0:	1.86 cm
λ_I:	38 cm
Moliere radius:	3.5 cm
Light yield:	54.000 ph/MeV
τ_{decay}:	1.3 μs
λ_{max}:	560 nm

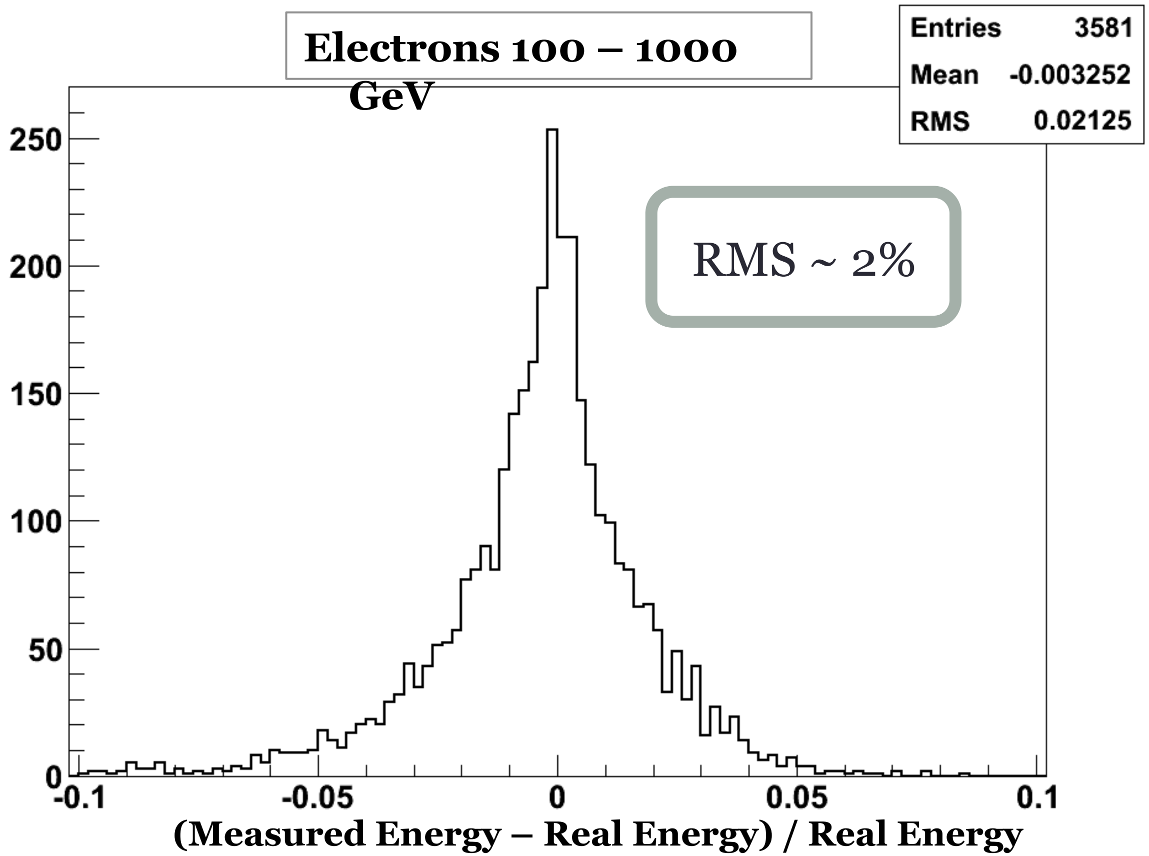
- Simulation and prototype beam tests in order to optimize the detector design

see for example:
N. Mori, et al.,
Homogeneous and isotropic calorimetry for space experiments
NIMA (2013)
http://dx.doi.org/10.1016/j.nima.2013.05.138

N×N×N	20×20×20
crystal side (cm)	3.6
crystal volume (cm^3)	46.7
gap (cm)	0.3
mass (kg)	1685
number of crystals	8000
size (m^3)	0.78×0.78×0.78
depth (R.L.) " (I.L.)	39×39×39 1.8×1.8×1.8
planar GF (m^2sr) *	1.91

(* GF for only one face)

Electrons: ENERGY RESOLUTION



Selection efficiency:
ε ~ 36%

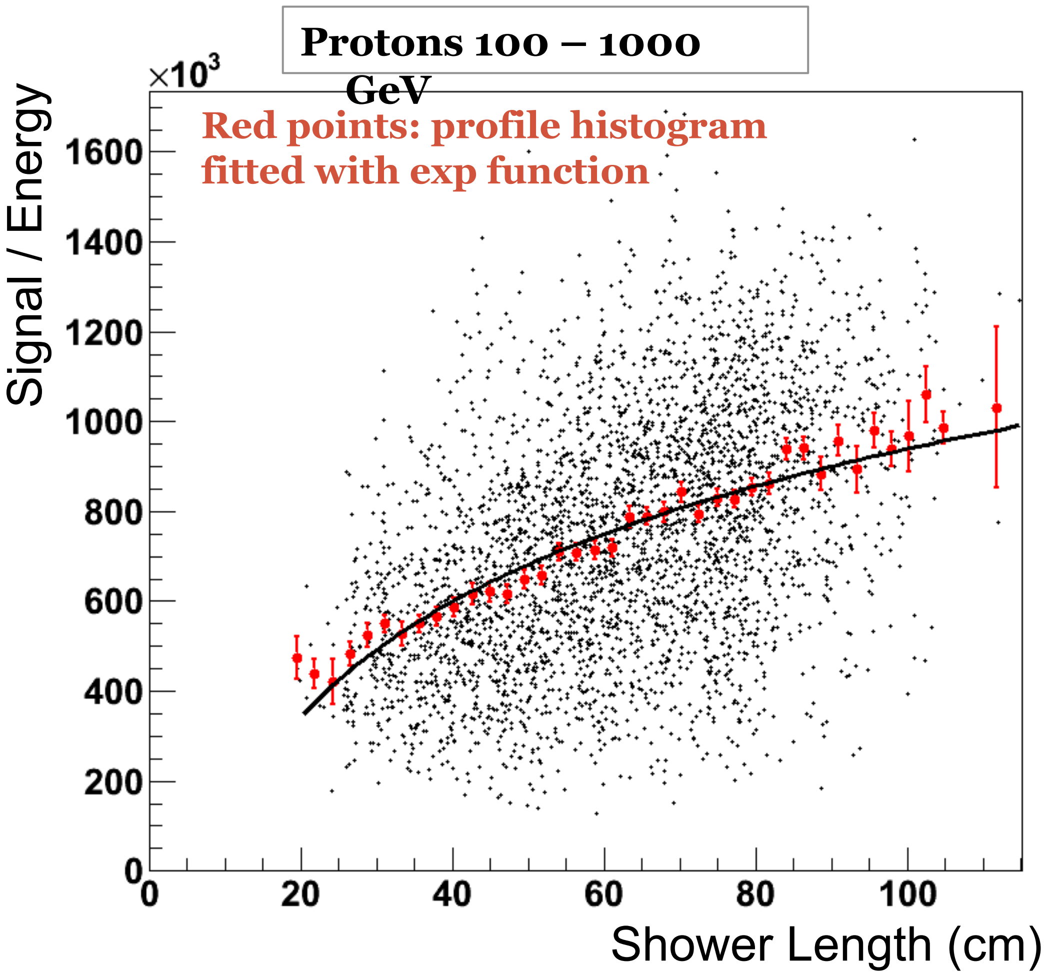
length of the shower
at least 40 cm (~22 X_0)

GF_{eff} ~ 3.4 m^2sr

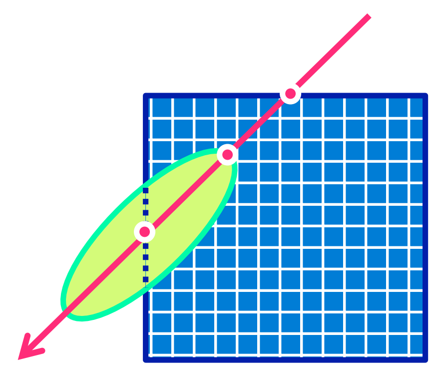
Non-gaussian tails due to leakage and to energy losses in passive material (carbon fiber structure)

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

PROTONS

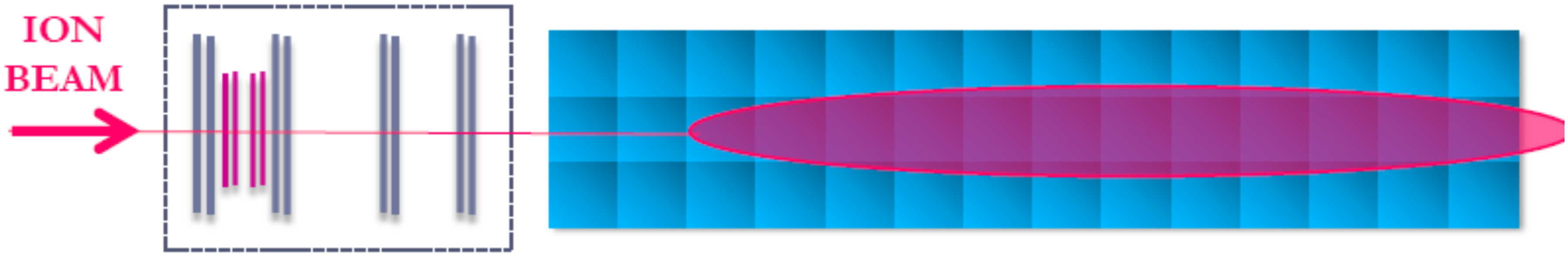


- Shower length can be used to reconstruct energy
- First hadronic interaction is easily accessible due to high granularity of the design



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

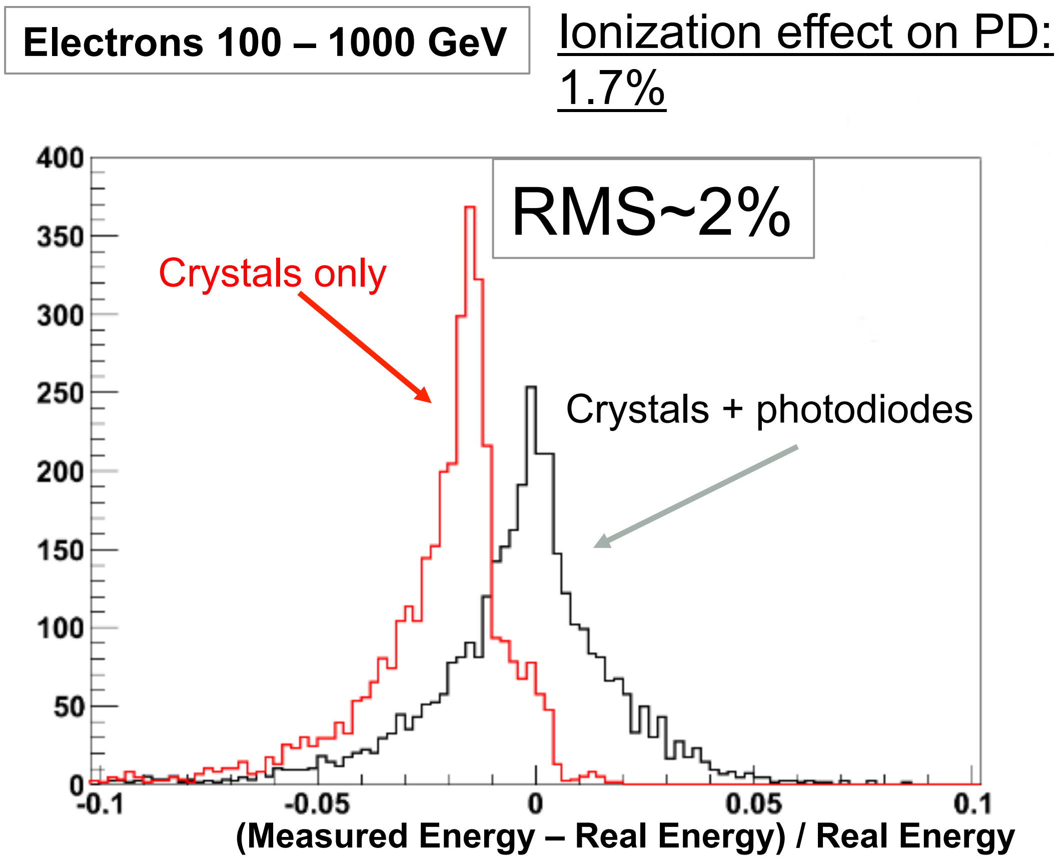
MOVING FORWARD FROM HERE…

Improving the existing CALOCUBE concept:

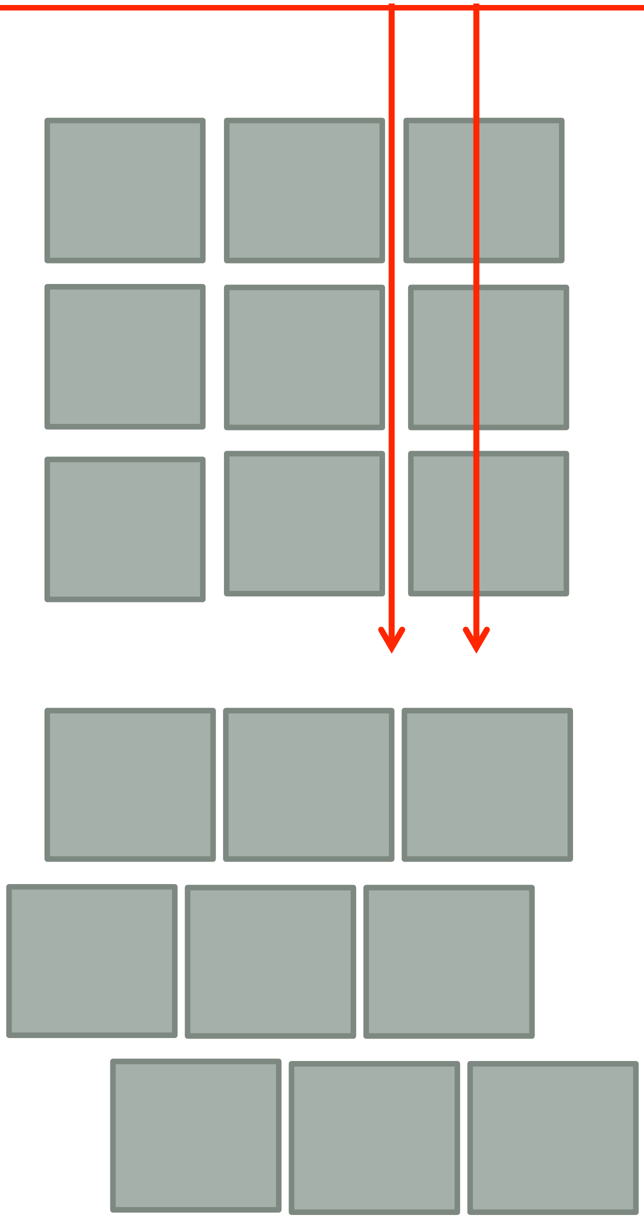
(3-year R&D activity financed by INFN, ~0.8 Meuro)

1. Optimize the overall calorimeter performances, in particular the hadronic energy resolution
   - Calorimeter compensation:
     - Cherenkov light
     - Neutron induced signals
2. Optimize the charge measurement
   - Make use of the excellent results from the SPS test
   - e.g. smaller size cubes on the lateral faces
3. Build up a fully space-qualified prototype
   - Mechanics
   - Thermal aspects

ELECTRONS: PD DIRECT IONIZATION

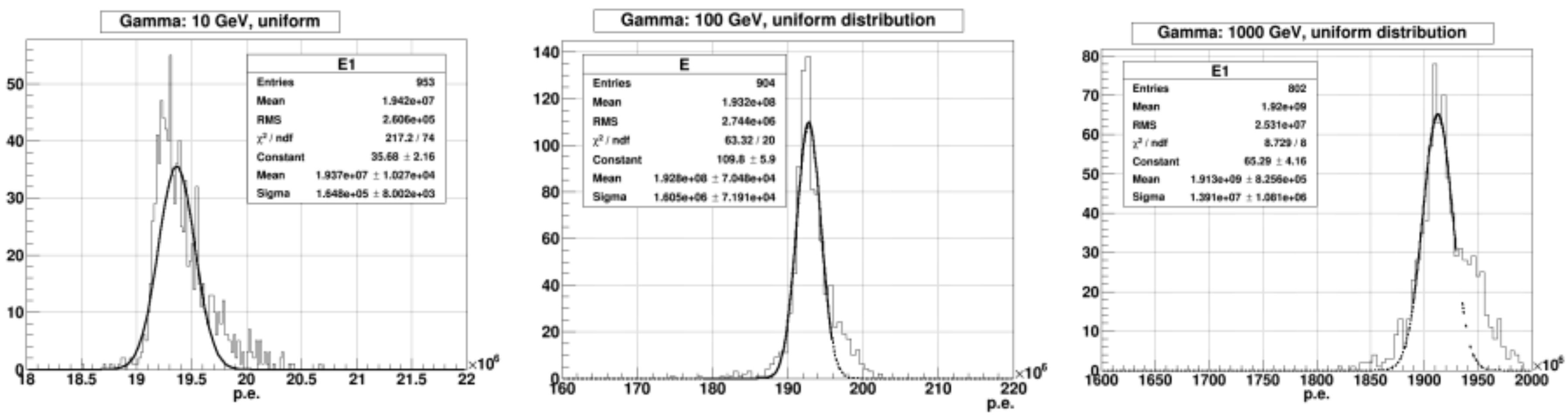


OPTIMIZATION FOR VERTICAL GAMMAS



VERTICAL GAMMA RAYS

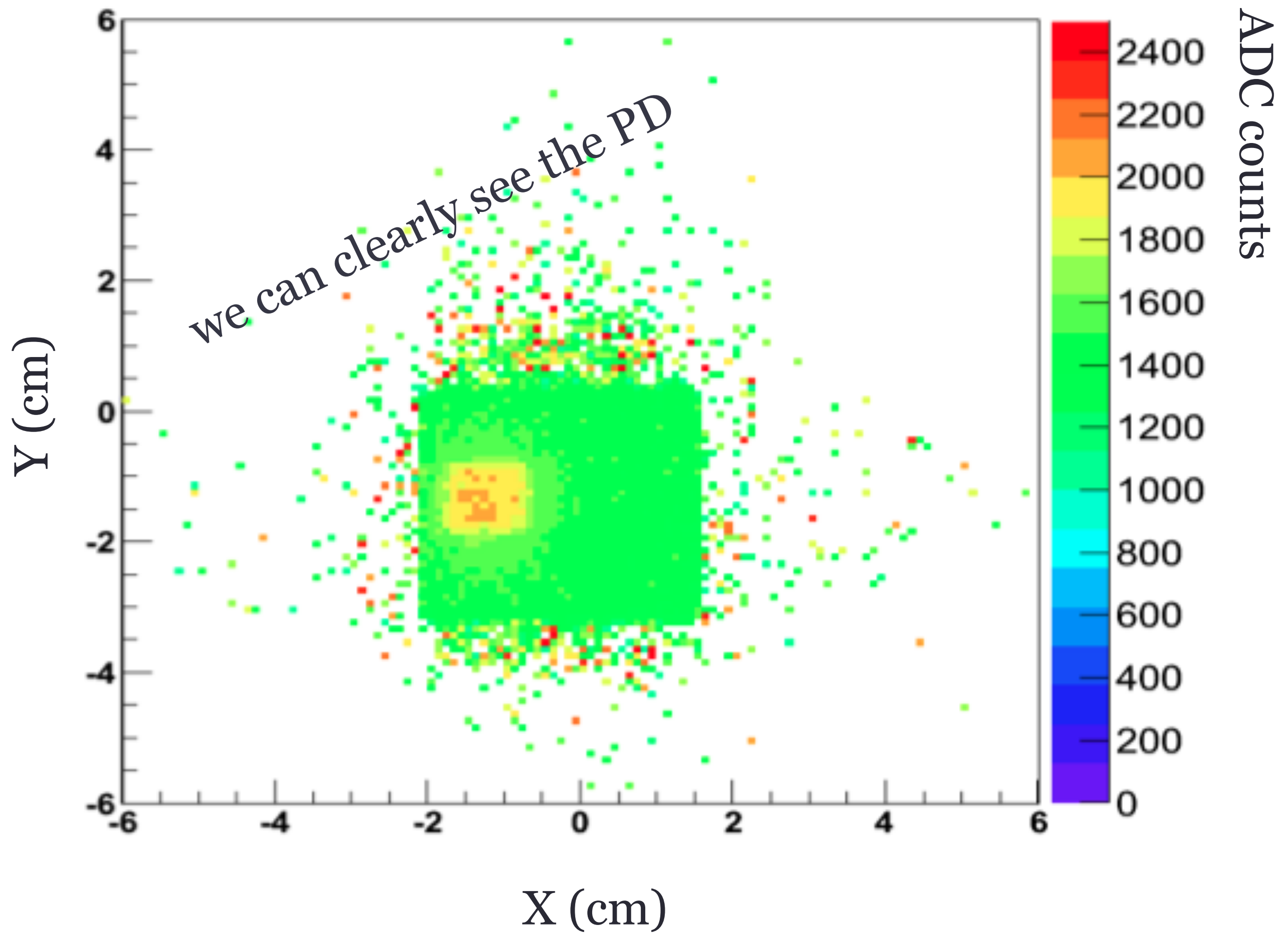
Detector optimized for vertical gammas: 27 X 27 X 14 CRYSTALS;
1 mm vertical gaps; horizontal planes shifted in x-y to avoid alignment



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.

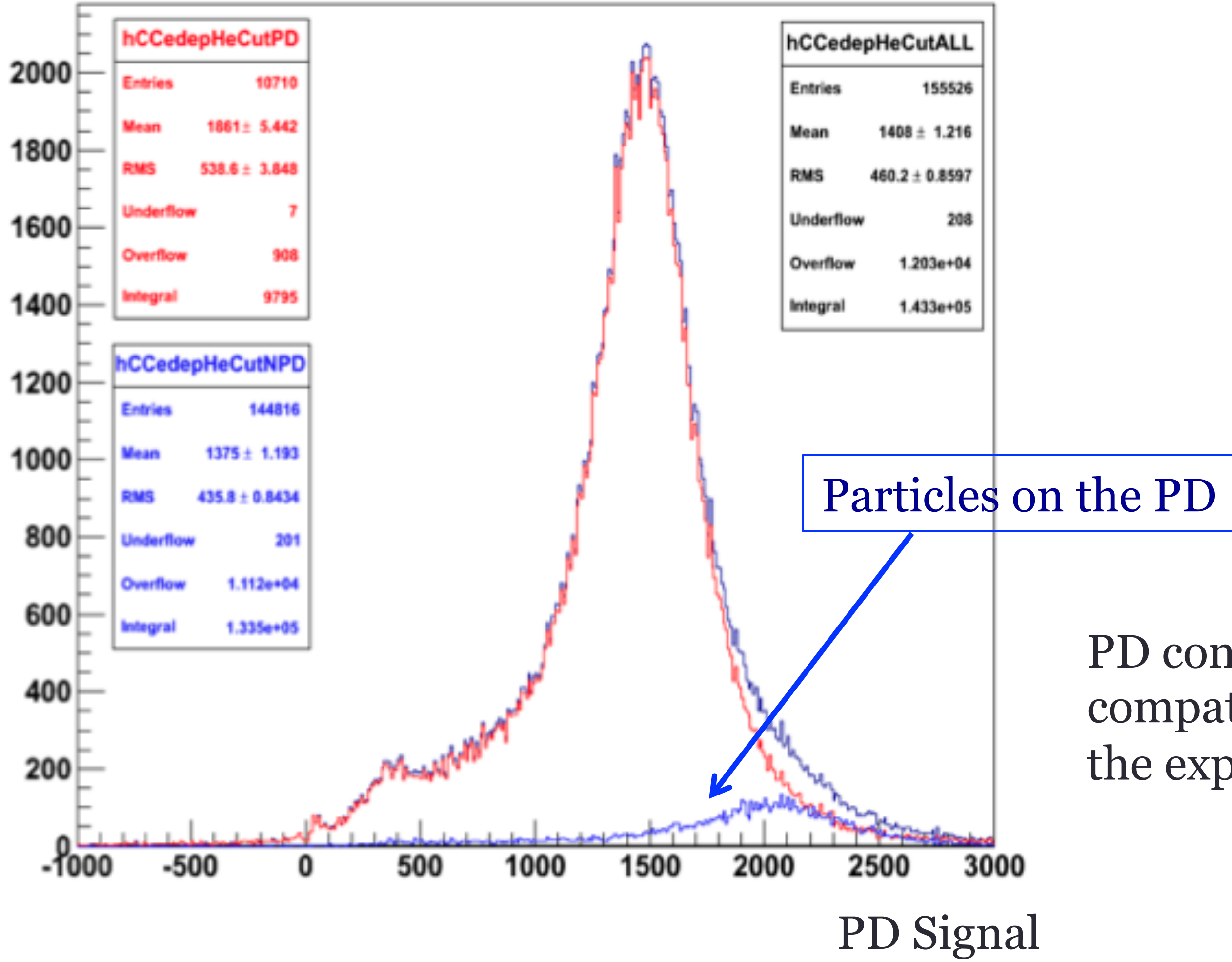
Gamma rays energy	Selection efficiency	Energy resolution
10 GeV	95%	0.86%
100 GeV	90%	0.83%
1 TeV	80%	0.73%

Response as function of impact point



- He ions on the central cube of the first layer, using BT tracking
- PD direct ionization is compatible with MC expectations

Signals for different impact points

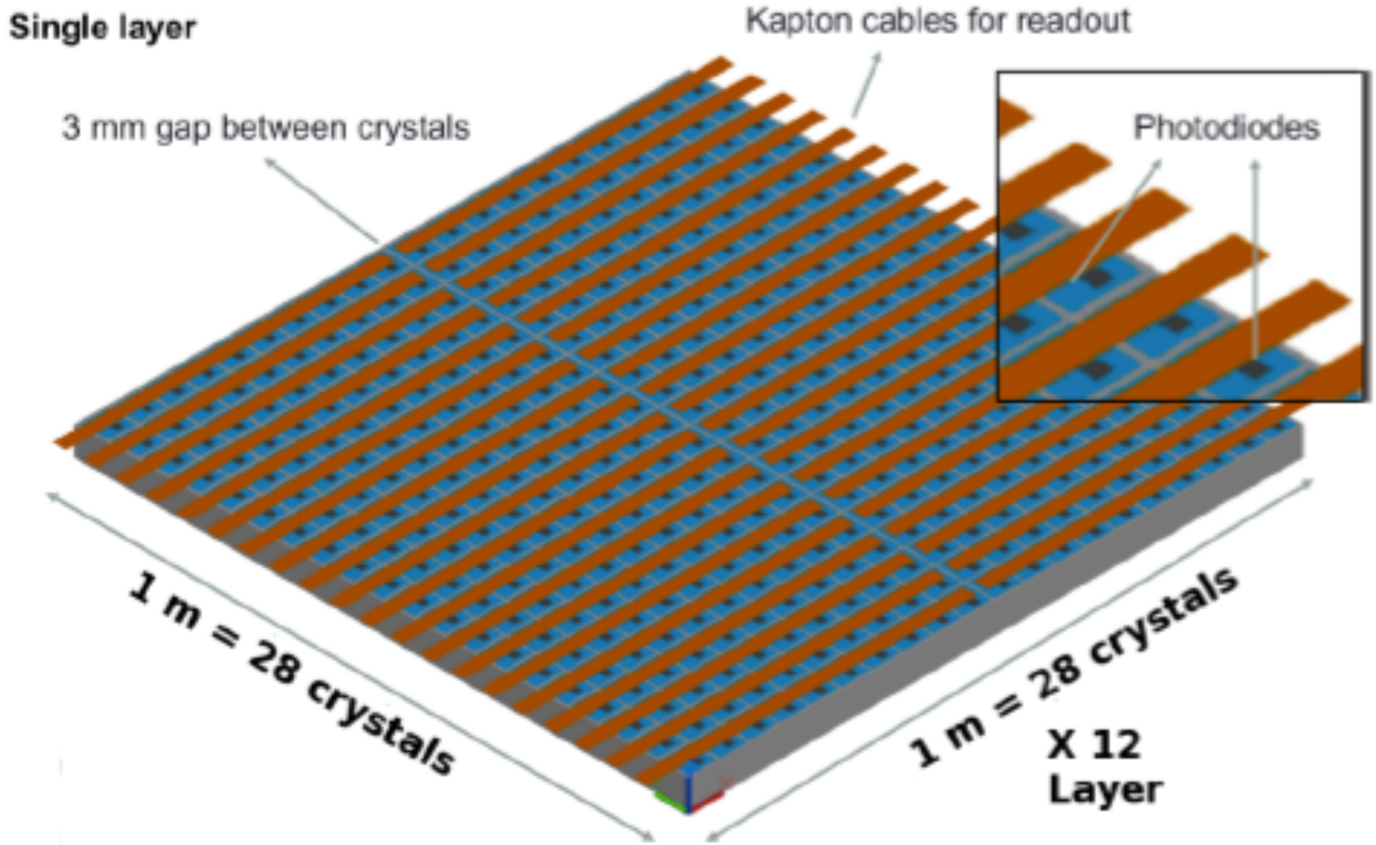


PD contribution is compatible with the expectations!

PH cube energy distributions:

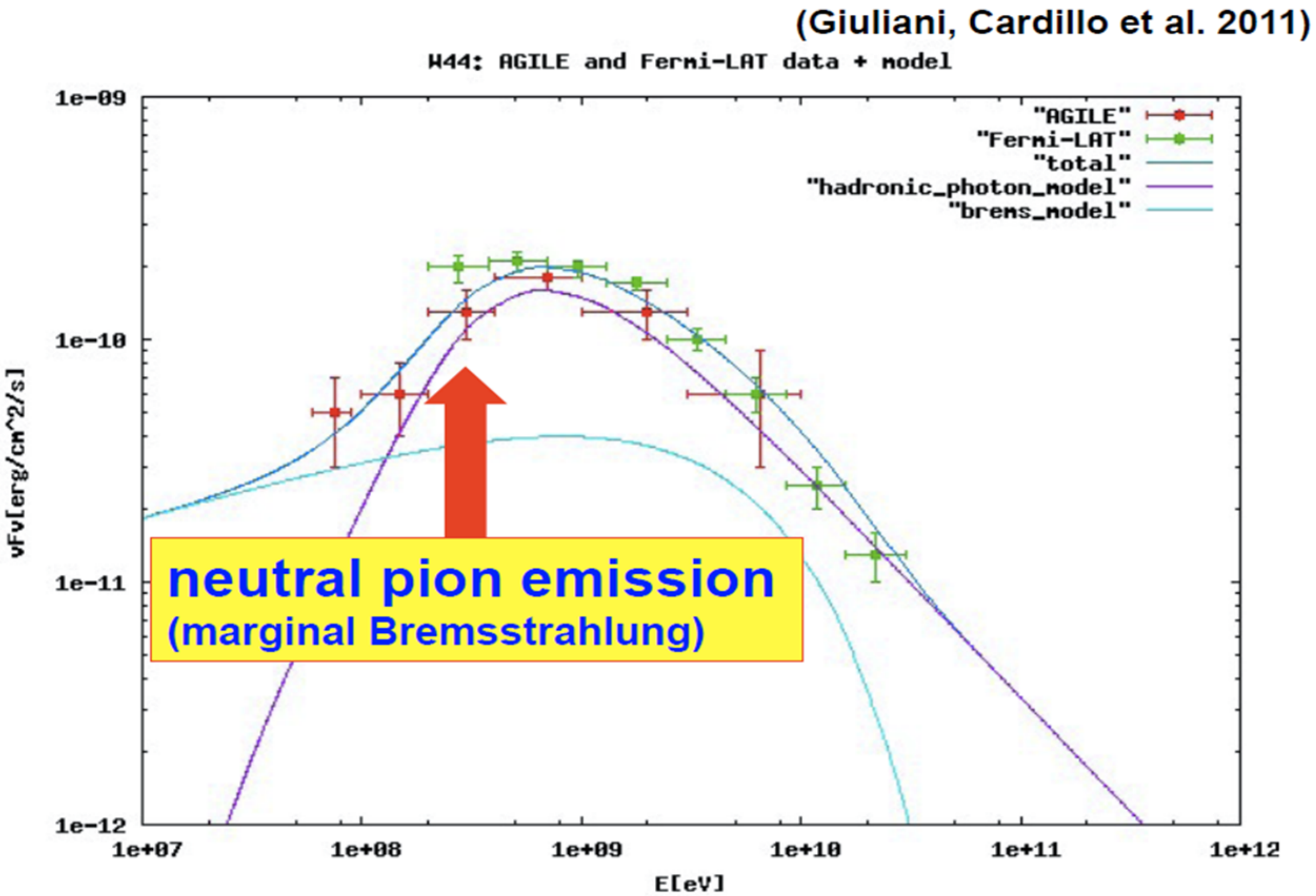
- Black line: all signals
- Red line: tracks not crossing the phodiode
- Blue line: tracks crossing the photodiode

Calorimeter structure



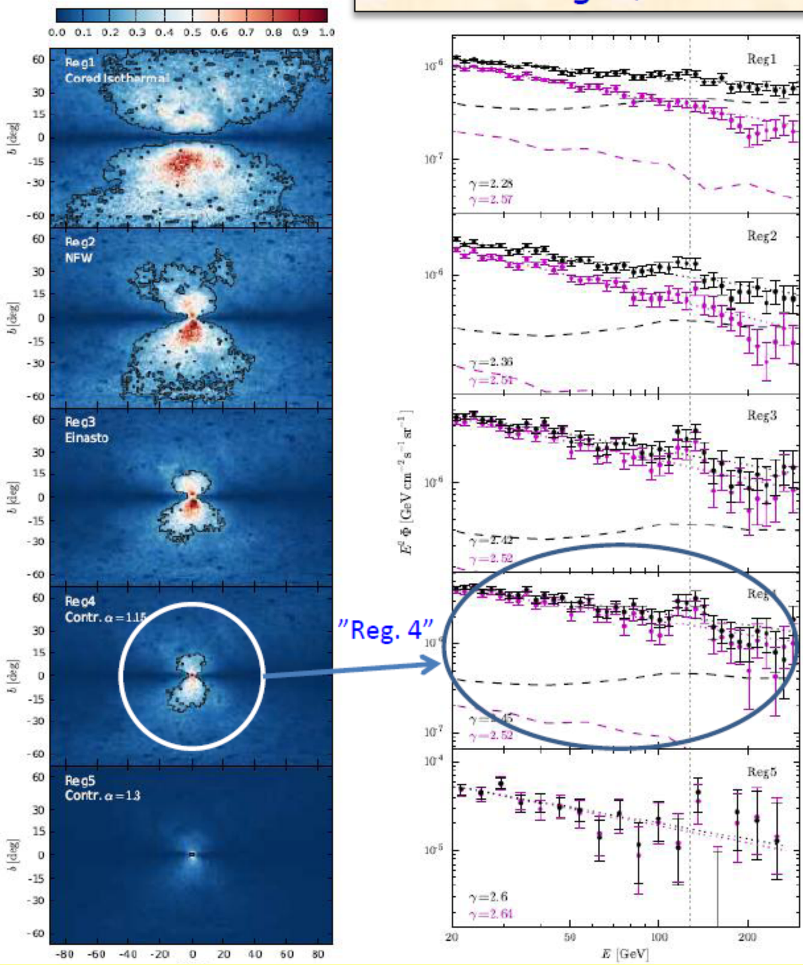
- **Large dynamic range required by a single crystal: 1 - 10^7 MIPs**
- Two double-gain photodiodes coupled to each crystal (4 channels/crystal):
  - large area photodiode (~9.2 x 9.2 mm^2) for small signals
  - small area photodiode (~0.5 x 0.5 mm^2) for large signals
- CASIS 1.2 ASIC (INFN Gr. 5 experiments CASIS and CASIS-2), automatic real-time switching between low- and high- gain modes

Scientific goals: low-energy γs



Scientific goals: high-energy γs

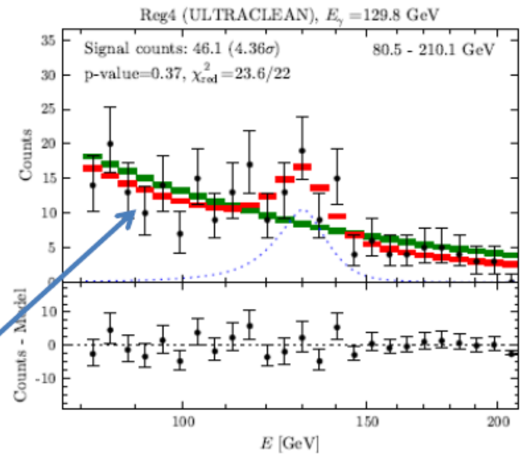
C. Weniger, arXiv:1204.2797



43 months of (public) Fermi data

arXiv:1205.1045
arXiv:1206.1616

γ-ray line fit:



Mass = 130 GeV
Significance 4.6σ (3.3σ if "look elsewhere" effect included)

Gamma-400 ideal for looking for spectral DM-induced features, like searching for γ–ray lines! If Weniger is right, the 130 GeV line should be seen with ~10 σ significance (L. Bergström et al., arXiv:1207.6773v1 [hep-ph])

Physics with GAMMA-400

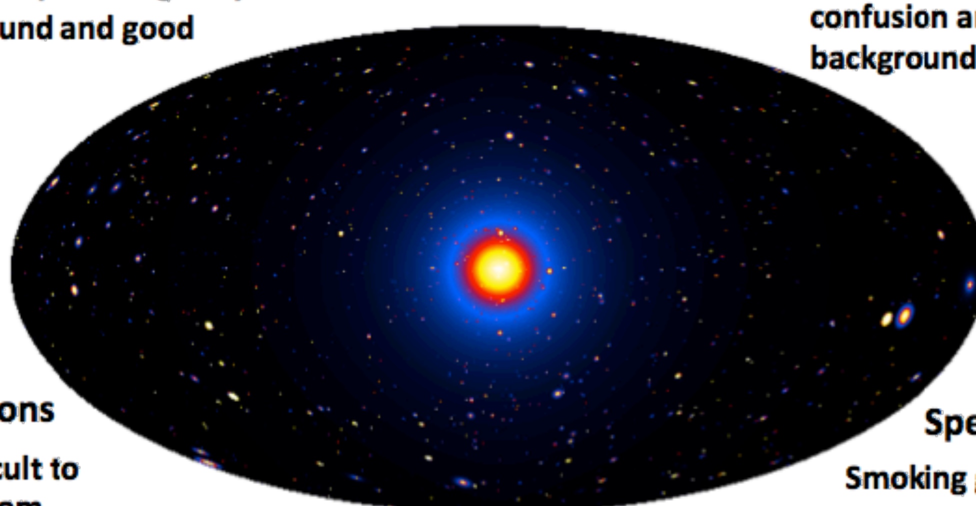
- Possible scenarios in indirect Dark Matter search in γ-rays

Satellites

Unidentified sources, dSphs and galaxy clusters: Low background and good source id

Galactic Center

Good Statistics, but source confusion and extensive diffuse background



Isotropic contributions

Large statistics, but difficult to disentangle DM signal from astrophysical origin

Electron spectrum

If spectral feature is found, would be complementary to γ-ray results

Spectral Lines

Smoking gun: no astrophysical uncertainties, good source id, but low statistics

γ-ray lines in diffuse radiation : Perspectives for GAMMA-400

Back-on-envelope estimate:

Sensitivity to the γ-ray line (flux) in the diffuse radiation can be expressed in simplified form as: $I_\gamma = \frac{n_\sigma}{0.68}\sqrt{\frac{2F_{bck}\eta E_\gamma}{GT}}$

where n is a number of σ , F_{bck} is a (diffuse) background, ηEγ is an energy bin width, which depends on η (energy resolution), G is a geometric factor, T is an observation time

Comparison of Fermi LAT and GAMMA-400 sensitivity:

- ηEγ for GAMMA-400 is 10X less than that for Fermi LAT at E>100 GeV,
- G for GAMMA-400 is ~ 0.5 of that for Fermi LAT,
- the sensitivity for GAMMA-400 for the same observation time is expected to be ~ 2 better than for Fermi LAT.

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γ-ray line from source : Perspectives for GAMMA-400

Assumption: the line is a δ-function in energy spectrrum

Confidence estimate: Confidence of the line detection can be taken similarly to the confidence in detection of point source (probability for the background to fluctuate to create a "feature")

$$C = \frac{N_{sig}}{\sqrt{N_{bkg}}}$$

where N_{sig} is a number of events from the "line" (source), and N_{bkg} is a number of background (diffuse) events

With 10X better PSF for Gamma-400:

- N_{bkg} can be 100X less,
- detection confidence C will be ~5X larger, assuming twice less events from the "line" N_{sig} detected (due to smaller A_{eff})
- **All this works only for the point source!**

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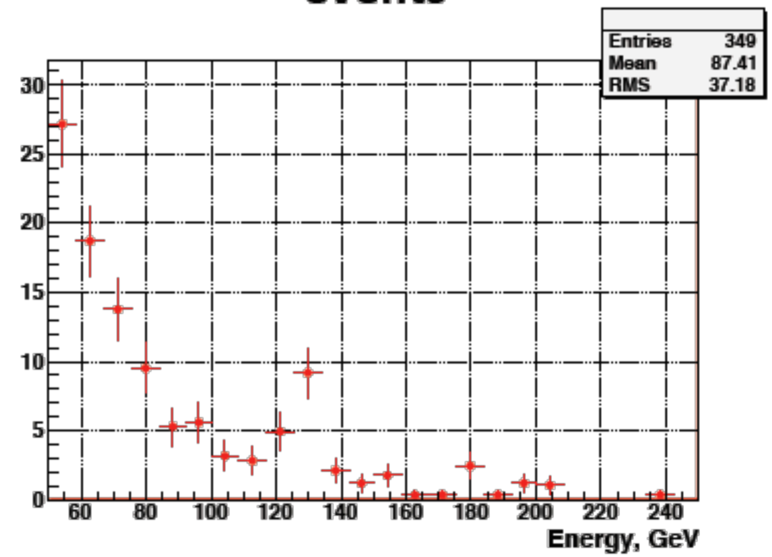
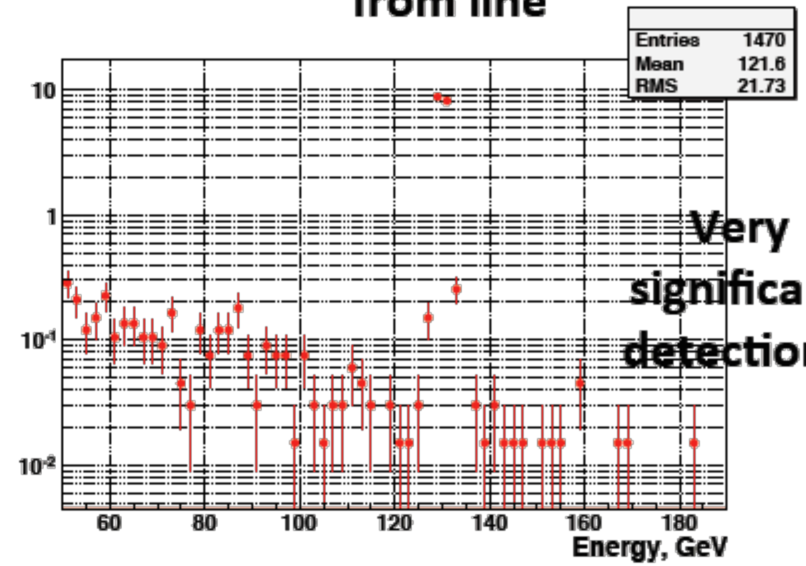
Increasing the energy resolution

LAT-like instrument, 300 events



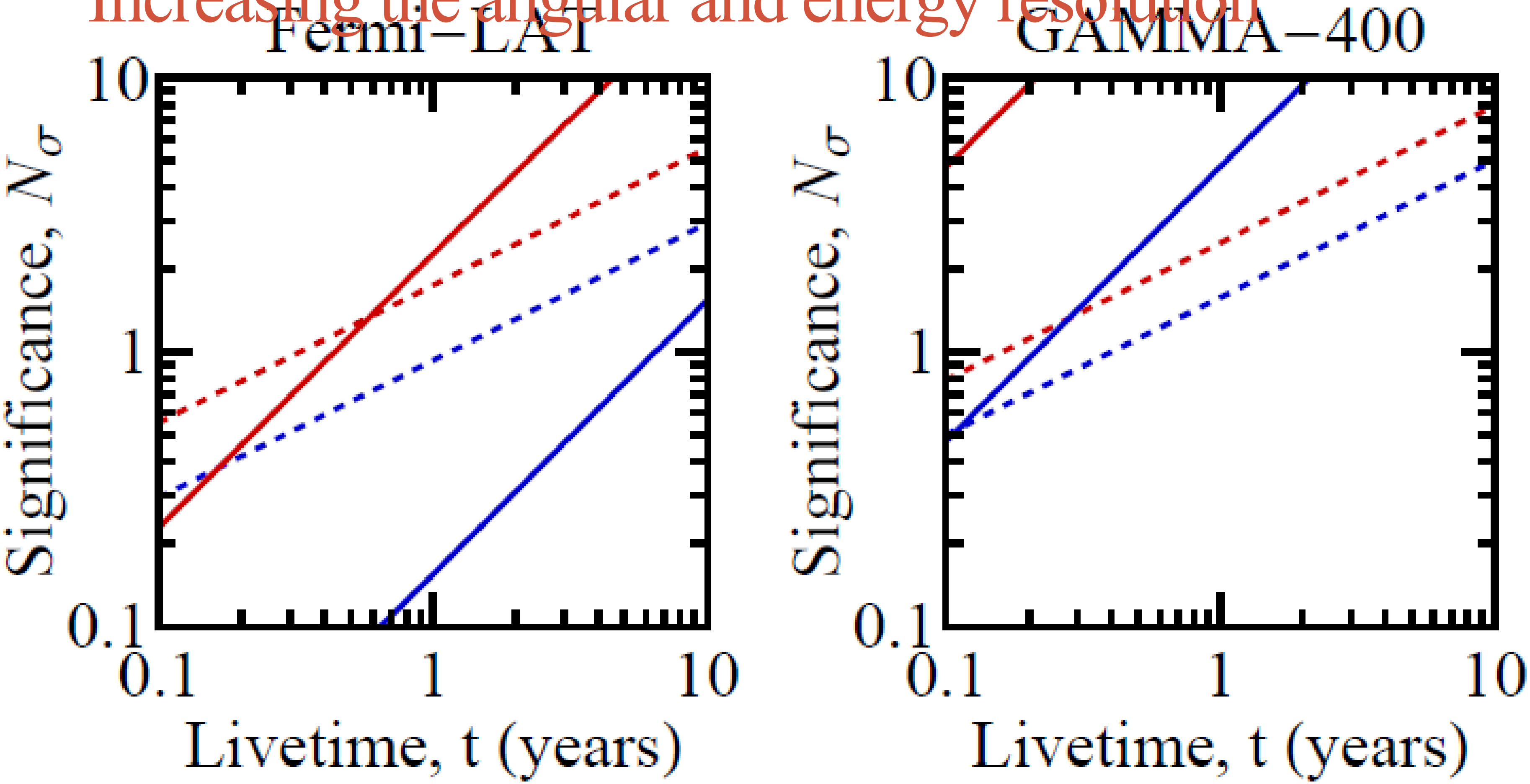
Gamma-400, 10X better dE/E, 10X better PSF (100X less background), same # of events from line



Very significant detection !

Alexander Moiseev Aspen 2013 Closing in on Dark Matter

Increasing the angular and energy resolution



The expected significance of 135 GeV line in the flux spectrum (dashed lines) or the fluctuation angular power spectrum (solid lines) analysis of the diffuse γ-ray background with the Fermi-LAT or GAMMA-400 experiments.
S. S. Campbell and J.F. Beacom (2013) arXiv:1312.3945

Galactic Center

- Expected to be the strongest source of γ-rays from DM annihilation. "EGRET GeV excess" has been in the center of DM discussion for years, until it was closed by Fermi LAT results
- Intense background from unresolved sources remains the main problem, assuming that the part of background created by CR interactions with the matter, is much better known and can be accounted for
- Potential perspectives for GAMMA-400: having >10 times better angular resolution at high energy, faint sources in dense GC area can be localized and their radiation can be removed as a background, and better model of diffuse radiation can be built. Concern: smaller effective area can make this analysis more difficult and not efficient

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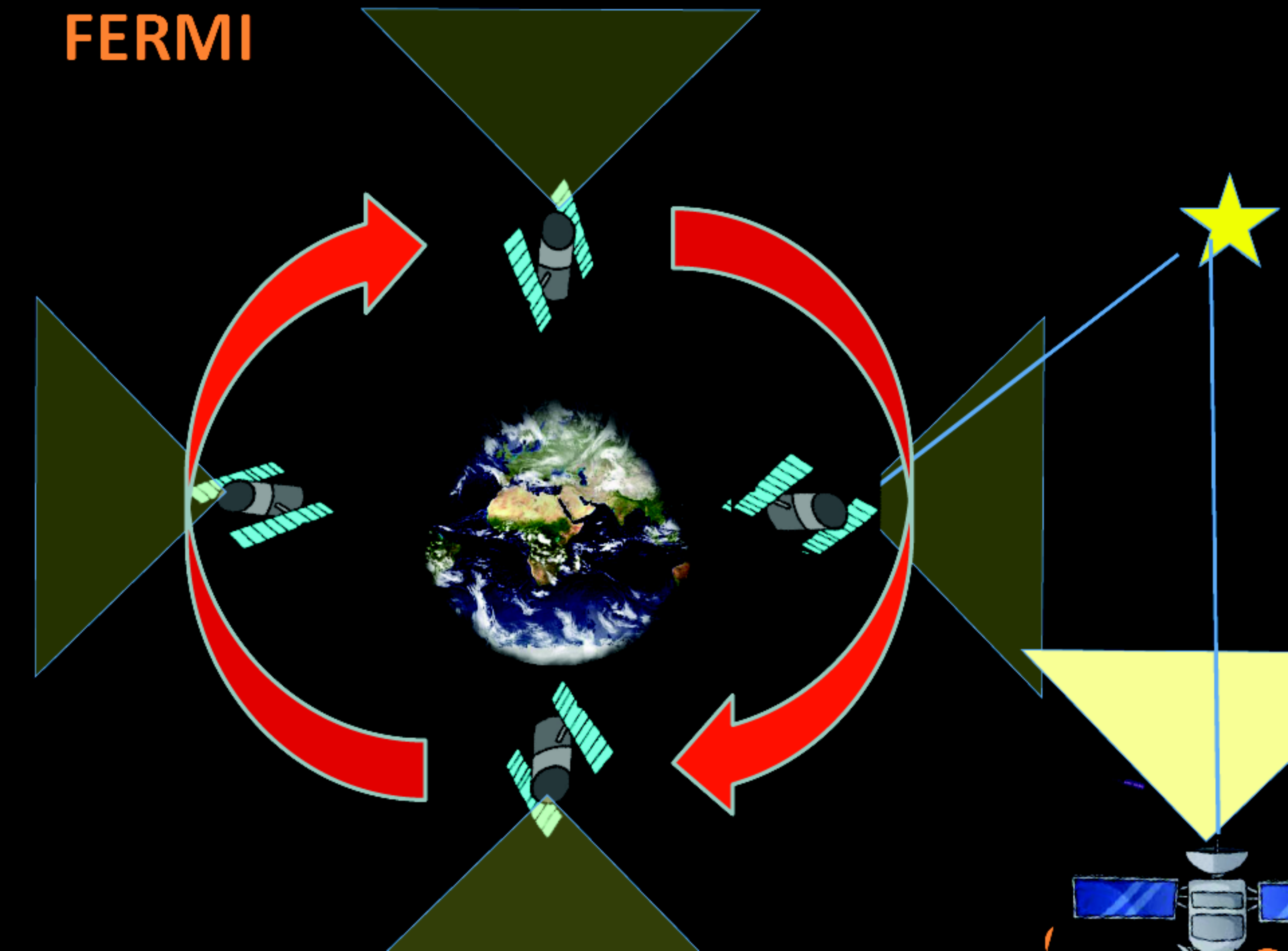
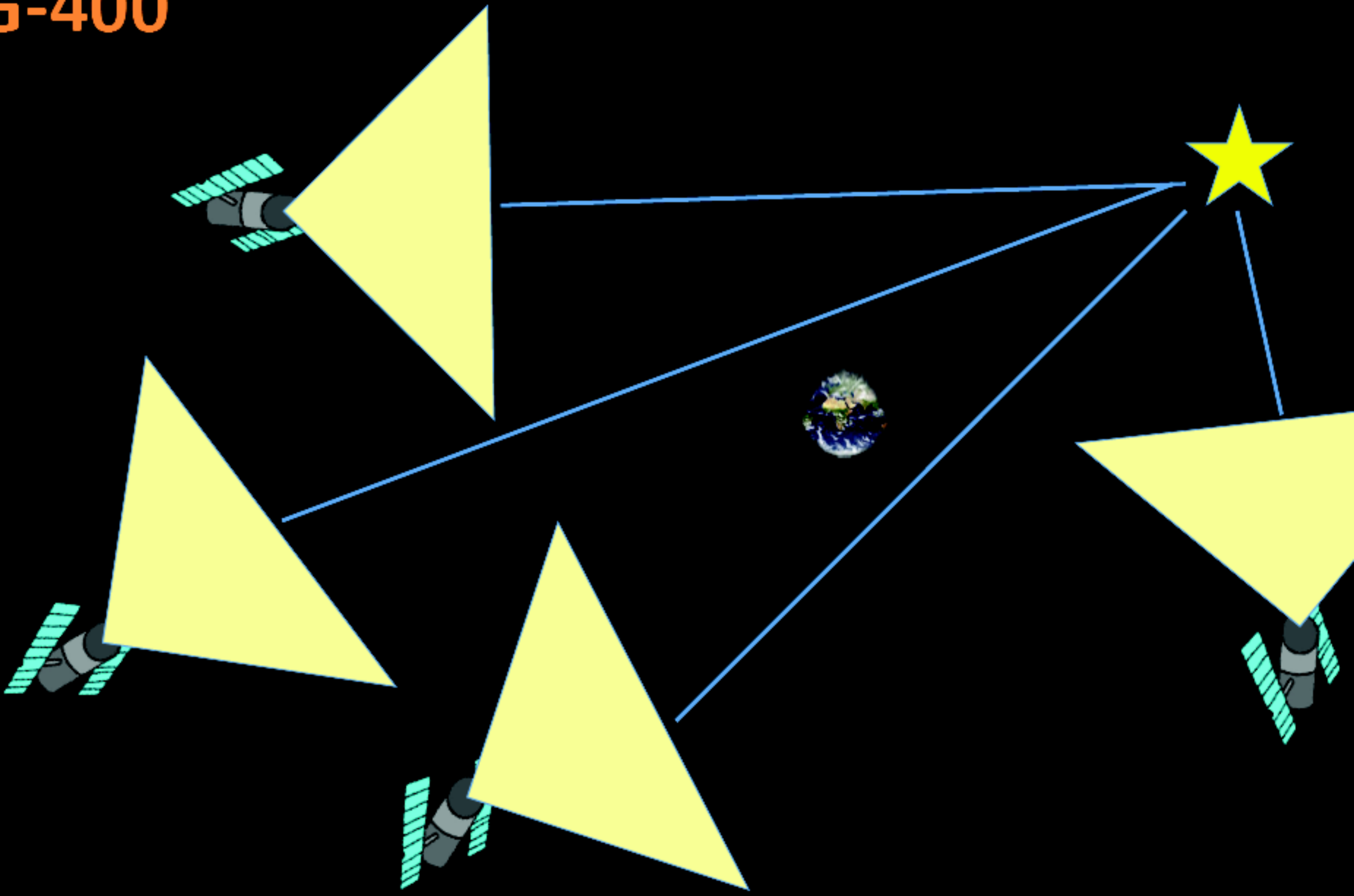
FERMI



G-400



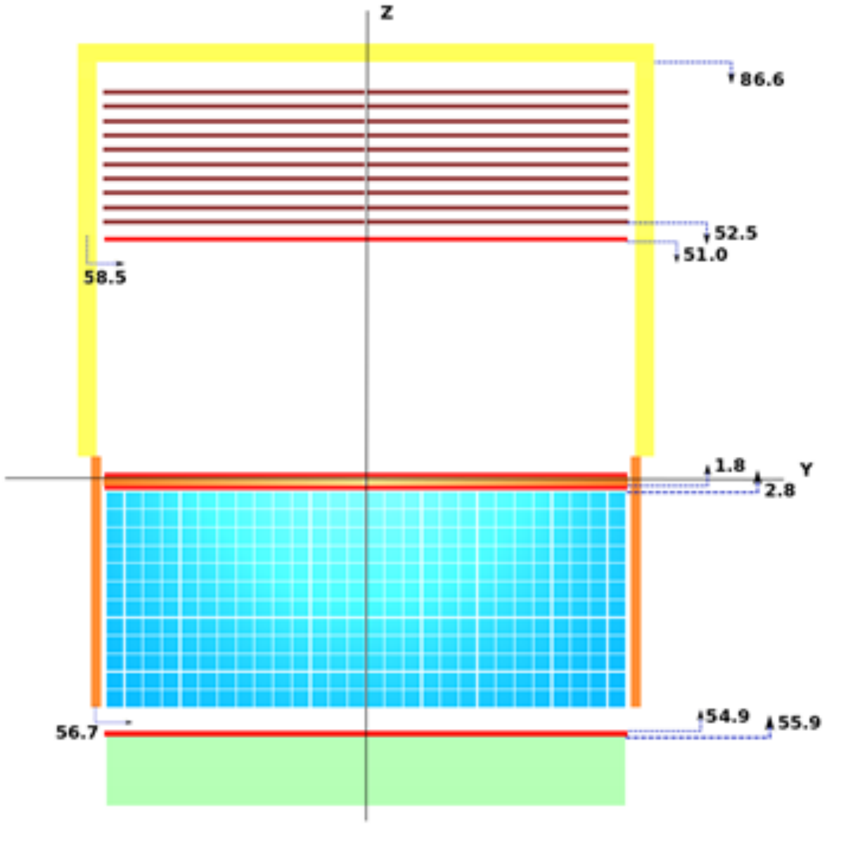
Using the data from the TeV Gamma-Ray Source Catalogue (from the ground-based facilities), we can calculate expected number of gammas, which GAMMA-400 will detect during 100 days of observation (the GAMMA-400 effective area is 5000 cm^2).

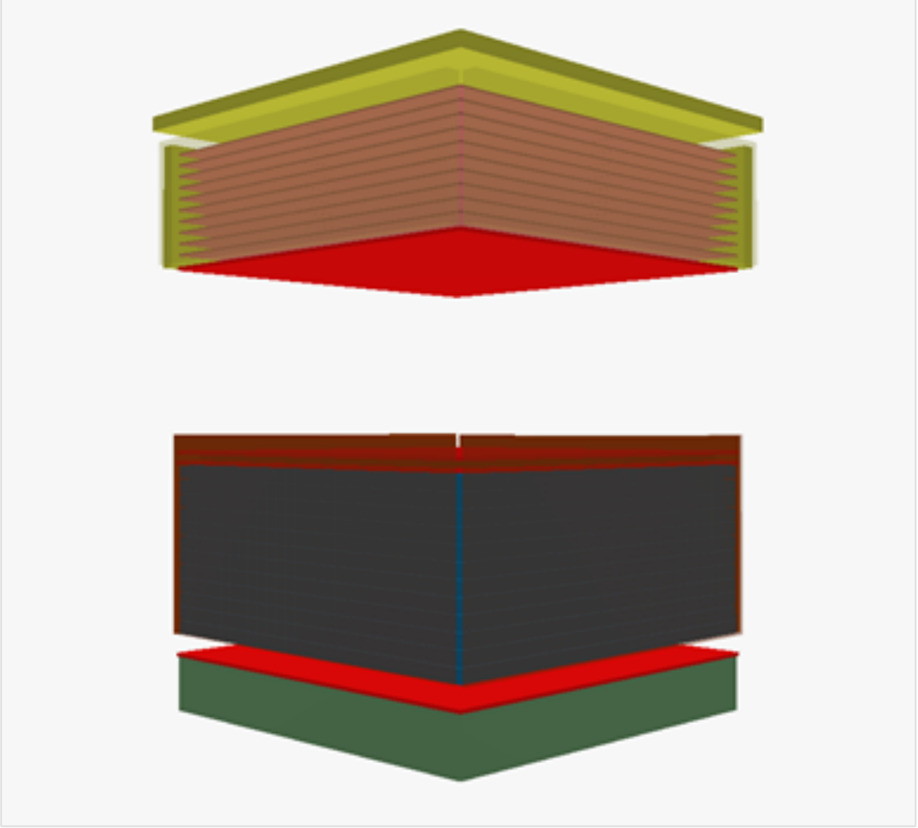
Name	Facility	Spectr. index	Integr. flux F(> 100 GeV), 10^{-9} $cm^{-2}s^{-1}$	Expected gammas N(> 100 GeV) per 100 days
1ES 1011+496	MAGIC	4.0	67.7	2921
1ES 1218+304	MAGIC	3.0	4.09	177
1ES 1959+650	MAGIC	2.78	5.805	251
1ES 2344+514	MAGIC	3.3	1.67	72
3C 279	MAGIC	4.11	219.0	9458
BL Lac	MAGIC	3.64	3.18	138
Crab	H.E.S.S., MAGIC	2.48	11.7	504
MAGIC J0616+225	MAGIC, VERITAS	3.1	0.605	26
Mkn 180	MAGIC	3.25	3.60	155
Mkn 421	H.E.S.S., MAGIC	3.2	6.05	261
Mkn 501	MAGIC	2.28	10.7	463
PG 1553+113	H.E.S.S., MAGIC	4.01	204.0	8833
PKS 2155-304	H.E.S.S., MAGIC	3.53	69.0	2983
RX J0852.0-4622	H.E.S.S.	2.2	0.331	14
RX J1713.7-3946	H.E.S.S.	2.84	0.618	27
W Com	VERITAS	3.8	4.570	198

GAMMA-400

- Mission approved by ROSCOSMOS (launch currently scheduled by 2019)
- GAMMA-400 will be installed onboard the platform "Navigator" manufactured by Lavochkin
  - Scientific payload mass 4100 kg (rocket changed from Zenith to Proton-M)
  - Power budget 2000 W
  - Telemetry downlink capability 100 GB/day
  - Lifetime ~ 10 yrs

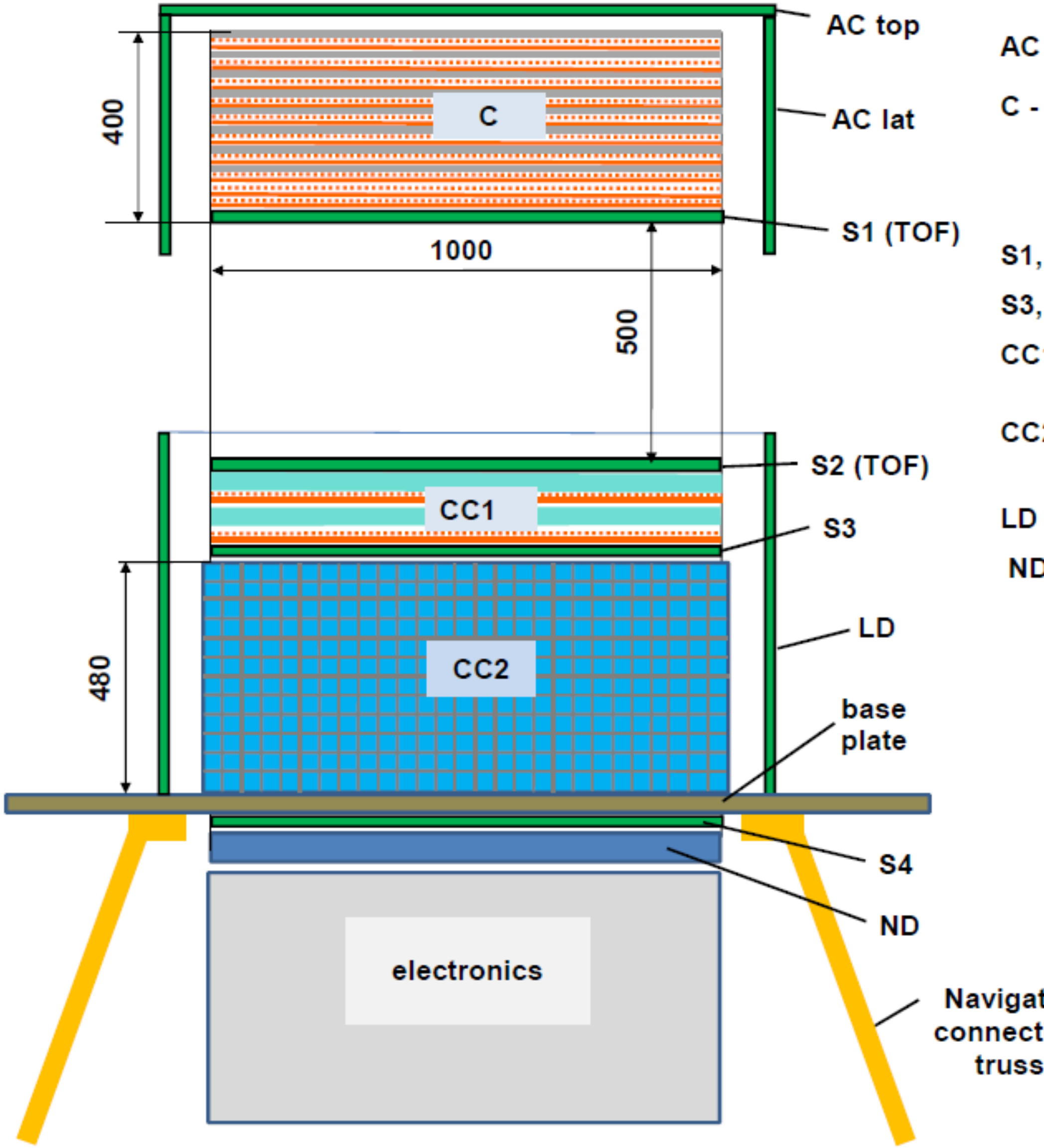
The GAMMA-400 apparatus





Schematic views of the GAMMA-400 apparatus

The new B2 baseline



AC - anticoincidence detectors (AC top , AC lat)

C - Converter-Tracker - total 1 Xo
8 layers W 0.1 Xo +Si (x,y) (pitch 0.1mm)
2 Si(x,y) no W

S1, S2 - TOF detectors

S3, S4 calorimeter scintillator detectors

CC1 - imaging calorimeter (2Xo)
2 layers: CsI(Tl) 1Xo + Si(x,y) (pitch 0.1 mm)

CC2 - electromagnetic calorimeter
CsI(Tl) 23 Xo 3.6x3.6x3.6 cm^3 - 28x28x12=9408 crystals

LD - 4 lateral calorimeter detectors

ND - neutron detector

B2 over B1 improvements:

- Introduction of the highly segmented homogeneous calorimeter with CsI cubes ⇒ improved energy resolution, extended GF with lateral particle impingement, 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 0.1 mm

B2: Converter/Tracker

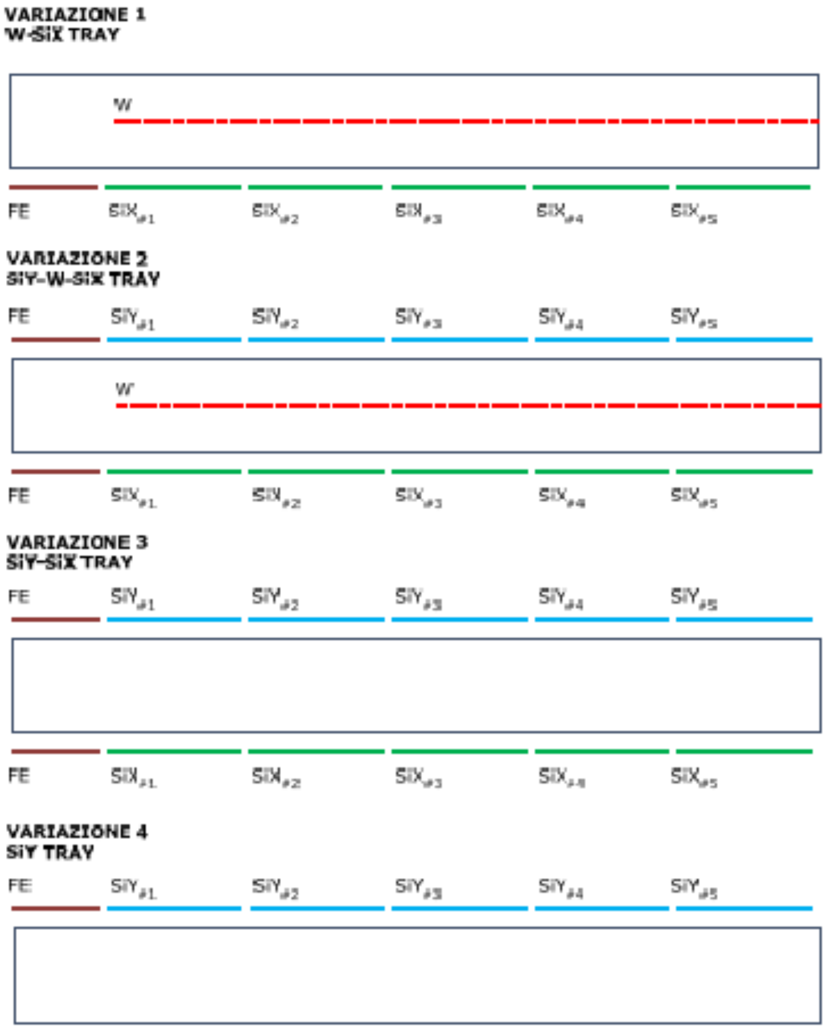


Figura 1 – Tray Type

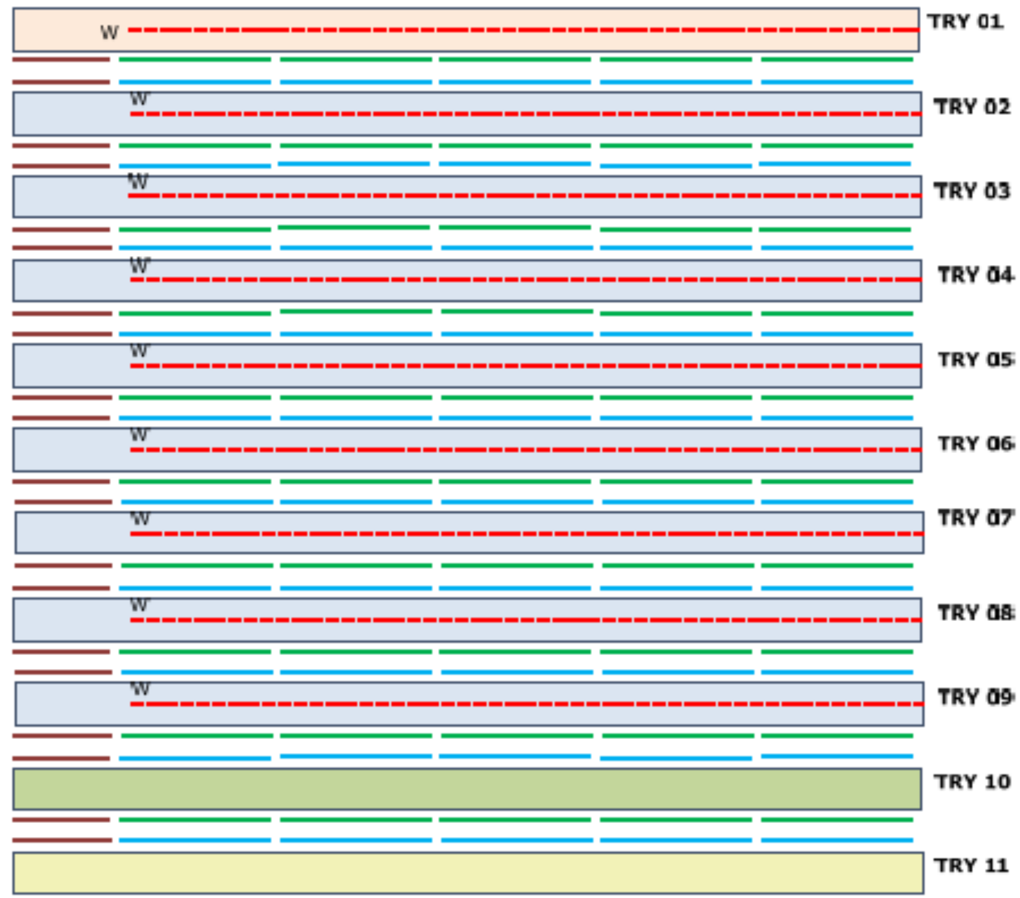
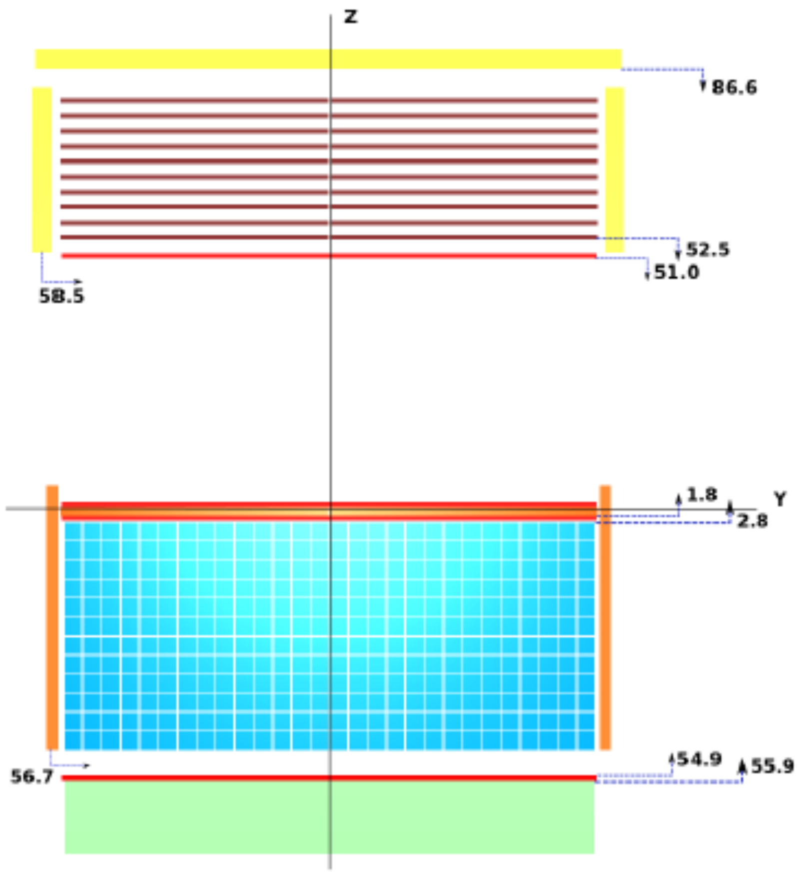


Figura 2 – Tower Assembly

B2: Calorimeter

GAMMA-400: Calorimeter

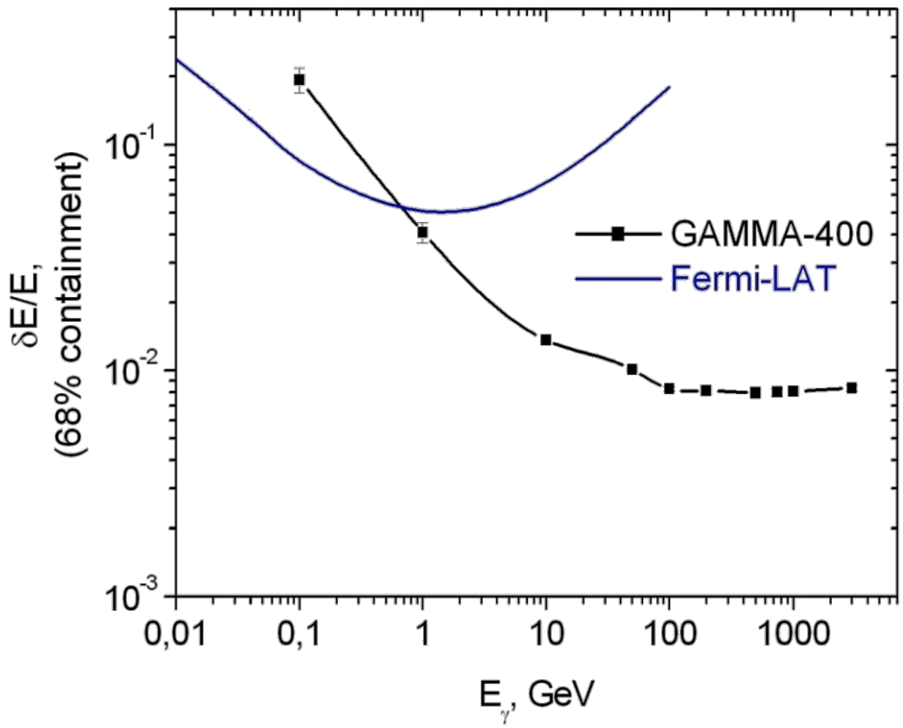


Calorimeter CC1 (Si-CsI(Tl))

N layers	2
Si pitch	0.1 mm
Size	1x1x0.04 m^3
X_0	2
λ_I	0.1

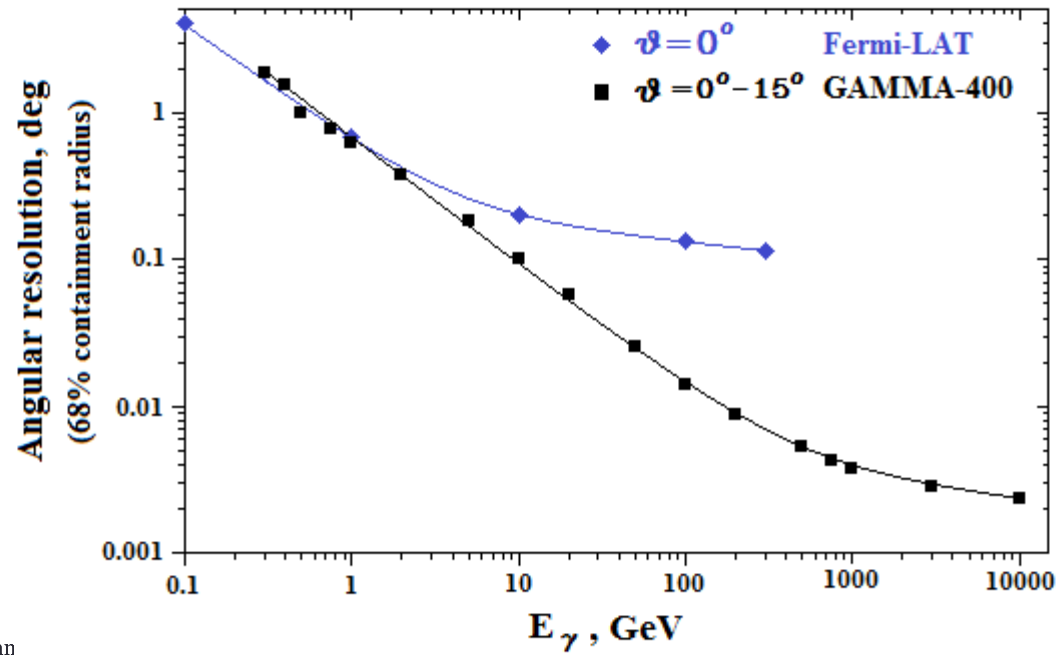
Calorimeter CC2 (CsI(Tl))

NxNxN	28x28x12
L	3.6 cm
Size	1x1x0.47 m^3
X_0	54.6x54.6x23.4
λ_I	2.5x2.5x1.1
Mass	1683 kg



Energy resolution vs. energy for normal incidence for Fermi-LAT P7 V6 and GAMMA-400

Angular resolution vs. energy for Fermi-LAT P7 V6 (for normal incidence) and GAMMA-400 (for θ=0°-15°)

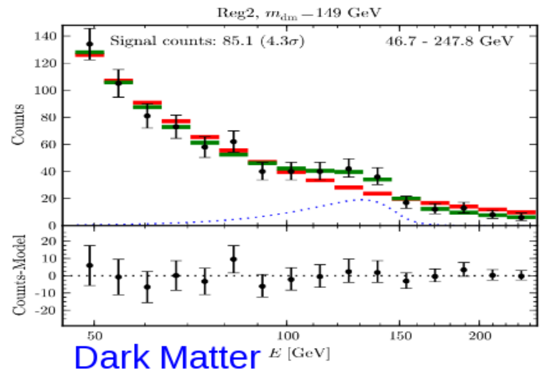


A. Galper, Workshop on the Future of Dark Matter Astroparticle Physics 2013, Trieste, Italy

Gamn

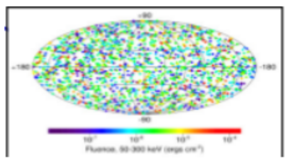
Physics with GAMMA-400

Galactic/ Extragalactic gamma-ray sources

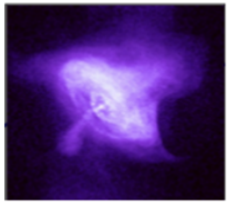


Dark Matter

CR propagation

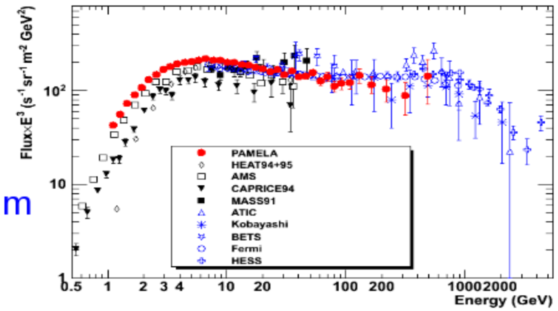


GRBs

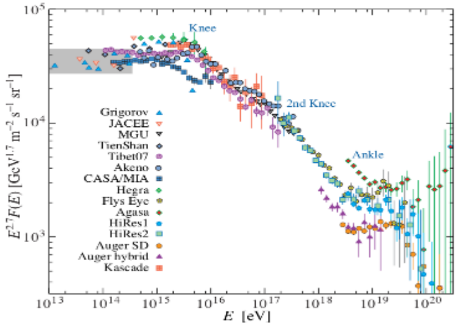


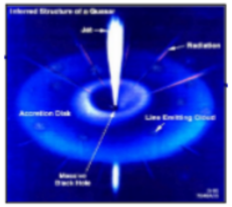
Pulsars

Electron spectrum

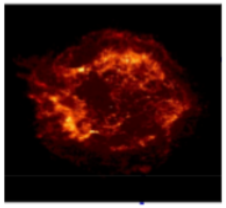


Knee origin





AGNs



SNRs

CR origin and acceleration mechanisms