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The Science of AGILE: Part I

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AGILE is an ASI Small Scientific Mission dedicated to gamma-ray astrophysics, which will detect and image photons in the 30 MeV – 50 GeV and in the 10–40 keV energy ranges. It is planned to be operational in early 2004 and it will be the only Mission entirely dedicated to source detection above 30 MeV during the period 2004-2006. AGILE will be an excellent gamma-ray imager with a spatial resolution of $\sim$ 40 μm and a very large FOV ($\sim$ 1/5 of the sky). It allows simultaneous observations in the hard X-ray and in the γ-ray bands and it is characterized by an optimal temporal resolution (absolute timing of $\sim$ 2 μs and deadtimes of $\sim$ 100 μs for the GRID and of $\sim$ 5 μs for Super-AGILE and the Mini-Calorimeter). AGILE main scientific objectives will be: Active Galactic Nuclei, Gamma-Ray Bursts, Pulsars, unidentified gamma-ray sources and diffuse Galactic and extragalactic gamma-ray emission. In this paper (Part I) we focus on the AGILE scientific goals, the AGILE instrument and the on-board data processing.

1. THE AGILE MISSION

AGILE is a Small Scientific Mission dedicated to high-energy astrophysics supported by the Italian Space Agency. The AGILE instrument is highly innovative and designed to detect and image photons in the 30 MeV–50 GeV and 10–40 keV energy bands [1].

It is planned to be operational in early 2004 and it will be the only Mission entirely dedicated to source detection above 30 MeV during the period 2004-2006.

AGILE is characterized by excellent spatial resolution ($\sim$ 40 μm) and timing capabilities (absolute timing of $\sim$ 2 μs and deadtimes of $\sim$ 100 μs for the GRID and of $\sim$ 5 μs for Super-AGILE and the Mini-Calorimeter), and by an unprecedently large field of view covering $\sim$ 1/5 of the entire sky

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at energies above 30 MeV.

AGILE allows simultaneous observations in the hard X-ray and in the γ-ray bands and AGILE data will be very important for joint studies of high-energy sources in different energy ranges: from radio to optical, X-ray and TeV bands.

The AGILE Science Program will be open to the international scientific community and collaborations with scientists working with other satellites and ground-based facilities will be fundamental to have a coordinated program for multiwavelength studies [2].

In this paper (Part I) we outline the AGILE main scientific goals and we present the AGILE instrument. We focus in particular on the problem of the on-board data processing, aimed at efficiently detecting cosmic gamma-ray photons and rejecting the charged-particle and the Earth albedo-photon background. In another paper (Part II) [3] we discuss the expected scientific performance of the AGILE mission.

2. SCIENTIFIC GOALS

We summarize here the main AGILE's scientific objectives. We base our discussion on refs. [1] and [4].

• **Active Galactic Nuclei.**
EGRET remarkable discovery of strongly variable gamma-ray emission from blazars started a new way of investigating black holes and jets. The understanding of particle acceleration and evolution in the jet is still preliminary, and certainly we need more exposure, photon statistics, and a larger sample of detected AGNs to study in detail the fundamental processes. With AGILE it will be possible to address several outstanding issues concerning the mechanism of AGN gamma-ray production and activity: (1) the study of transient vs. low-level gamma-ray emission and duty-cycles; (2) the relationship between the gamma-ray variability and the radio-optical-X-ray-TeV emission; (3) the correlation between relativistic radio plasmoid ejections and gamma-ray flares; (4) hard X-ray/gamma-ray correlations. A program for joint AGILE and ground-based monitoring observations is being planned. On the average, AGILE will achieve deep exposures of AGNs, substantially improving our knowledge on the low-level emission, and it will be able to detect a large number of flares. We conservatively estimate that for a 3-year program AGILE will detect a number of AGNs 2–3 times larger than that of EGRET. Super-AGILE will monitor, for the first time, simultaneous AGN emission in the gamma-ray and hard X-ray ranges.

• **Gamma-Ray Bursts.**
EGRET spark chamber detected about ten GRBs during $\sim$ 7 years of operations. This number was limited by the EGRET FOV and sensitivity and not by the GRB emission mechanism. The detection of gamma-ray photons within instrumental deadtimes (100 ms), the absence of a spectral cutoff up to 10 GeV, durations substantially longer than those at lower energies indicating the clear existence of "delayed (afterglow) gamma-ray emission", the spectral variability and re-acceleration in multiple pulse events, all demonstrate the complexity of the engine and the realization of remarkable particle acceleration and radiative efficiencies in GRBs.

If we want to make progress in GRB studies, we need larger fields of view and a better timing. AGILE will help very much in the theoretical interpretation of GRBs high-energy emission because of its optimal timing capabilities (a deadtime $\sim$ 1000 times smaller than that of EGRET). GRB detection rate by the AGILE GRID is expected to be at least a factor of $\sim$ 5 larger than that of EGRET (i.e., $\geq$5–10 events/year). AGILE is expected to be highly efficient in detecting photons above 10 GeV because of limited backsplashing. Super-AGILE will be able to locate GRBs within a few arcminutes, and will systematically study the interplay between hard X-ray and gamma-ray emissions.

• **Diffuse Galactic and Extragalactic Emission.**
Diffuse emission from the Galaxy dominate the detected flux in the gamma-ray energy range. These diffuse photons are a manifestation of cosmic-ray propagation and bombardment in gaseous environments, and are also produced by synchrotron and inverse Compton processes. Gamma-rays reflect the geometry of the Galaxy depending on the number density of cosmic-

rays (that may vary across the Galaxy because of source localization) and the gas distribution. Photons above 30 MeV are therefore a crucial diagnostic for cosmic-ray processes.

The AGILE good angular resolution and large average exposure will further improve our knowledge of cosmic ray origin, propagation, interaction and emission processes. We also note that a joint study of gamma-ray emission from MeV to TeV energies is possible by special programs involving AGILE and new-generation TeV observatories of improved angular resolution.

• **Gamma-ray Pulsars.**
Seven isolated pulsars were detected by EGRET providing a remarkable set of data. Precise timing of gamma-rays is difficult because of a limited statistics and pulsar (micro) glitches that limit the phase coherence reconstruction. Searches of pulsed gamma-ray signals in the EGRET database is therefore difficult without hints from other wavelengths (e.g., radio, X-rays).

The future is promising. Radio monitoring together with gamma-ray larger exposures on fields containing unidentified gamma-ray sources, improved spatial resolution, and better gamma-ray timing properties should lead to new pulsar discoveries. The current debate is on competing pulsar emission models (polar cap vs. outer gap), the existence of a radio-less population of Geminga-like gamma-ray pulsars, whether millisecond pulsars are detectable in gamma-rays, and time-resolved spectral and light curve features. New radio data from the multi-beam Parkes survey led to the discovery of about 30 new young pulsars (age less than 10^5 years). Some of them are apparently coincident with unidentified EGRET sources. Clearly, these young pulsars with characteristics similar to known gamma-ray pulsars are ideal candidates for pulsed gamma-ray detection by future instruments.

AGILE will contribute to the study of gamma-ray pulsars in several ways: (1) improving photon statistics for gamma-ray period searches; (2) detecting possible secular fluctuations of the gamma-ray emission from neutron star magnetospheres; (3) studying unpulsed gamma-ray emission from plerions in supernova remnants and searching for time variability of pulsar wind/nebula interactions, e.g., as in the Crab nebula.

• **Unidentified Gamma-ray Sources.**
A large number of gamma-ray sources discovered by EGRET are still unidentified. The majority is placed near the Galactic plane. Thanks to its better point spread function (PSF) and its longer exposure, AGILE will surely contribute to their unveiling.

3. THE AGILE INSTRUMENT

The philosophy we adopted is to have one integrated instrument made of three detectors with broad-band detection capabilities: **(1)** the **Gamma-Ray Imaging Detector** (GRID) sensitive in the 30 MeV–50 GeV energy range, which consists of a Silicon Tracker (ST), a Cesium Iodide Mini-Calorimeter (MCAL) and a segmented Anticoincidence System (AC); **(2) Super-AGILE** with detection and imaging capabilities in the hard X-ray range (10–40 keV); **(3)** the **Mini-Calorimeter** able to detect and collect events independently of the GRID in the 0.25-200 MeV range, very useful to provide spectral and accurate timing information on transient sources. See Fig. 1 for a schematic view of the AGILE active detectors.

The **Silicon Tracker** is a gamma-ray pair-converter and imager made of 12 planes, with two Si-layers per plane providing the X and Y coordinates of interacting charged particles. The fundamental Silicon detector unit is a tile of area 9.5×9.5 cm^2, microstrip pitch equal to 121 μm and thickness of 410 μm. The first 10 planes contain also a Tungsten layer 250 μm thick (0.07 X_0). The adopted "floating strip readout" allows to reach an excellent spatial resolution of ~ 40 μm for a variety of incidence angles, and fast low-power electronics allows to reach very short gamma-ray detection deadtimes of order of 100 μs. The AGILE Silicon Tracker will make a crucial use of the analog signal from the Si microstrips, which will be fundamental for on-board background rejection (see sect.4).

Super-AGILE consists of an additional plane of Si detectors placed on top of the Silicon Tracker, and of an ultra-light coded mask system supporting a Tungsten mask placed at a distance of 14 cm from the Si-detectors. SA is aimed at detecting hard X-rays in the energy range between 10 and 40 keV. The Super-AGILE FOV is planned to be ~ 0.8 sr. Super-AGILE will have an excellent timing with absolute time tagging uncertainty and deadtime near 5 μs for each of the 16 independent readout units and it will allow an accurate localization ($\sim$1-2 arcmins) of GRBs and other transient events (for typical transient fluxes above $\sim$1 Crab). Super-AGILE imaging capabilities will be quite good (pixel size of $\sim$ 6 arcmin) for an on-axis ($5-\sigma$) sensitivity of $\sim$ 5 mCrab (50 ksec integration time).

The **Mini-Calorimeter** is made of two planes of 15 Cesium Iodide bars each, for a total (on-axis) radiation length of 1.5 X_0. The MC tasks are: (i) obtaining additional information to support the ST particle energy reconstruction (as part of GRID); (ii) independently detecting photons in the energy range $\sim 0.3-100$ MeV (important for GRBs and other impulsive events detection).

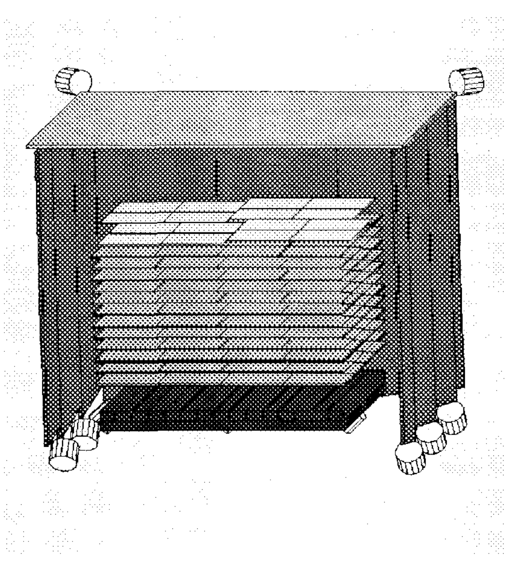

Figure 1. Schematic view of the AGILE istrument, showing the segmented AC system, the 12 Si-Tracker planes, the 4 detecting units of SA and the MCAL positioned at the bottom.

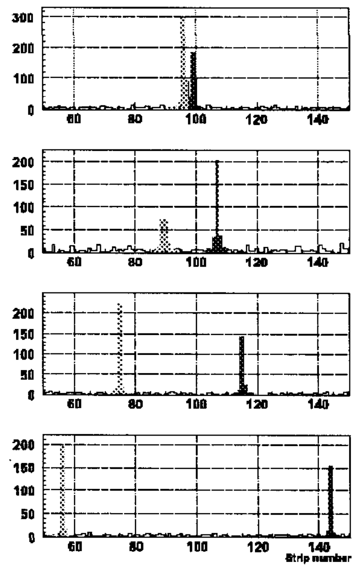

Figure 2. Example of a real typical gamma-ray photon event detected during an AGILE test-beam (August 2000 - CERN T11 beamline). The histograms represent the charge collected on the readout strips configured with the baseline AGILE tracker layout (Silicon microstrip pitch of 121 μm, for a floating strip readout system of 242 μm pitch). The spatial resolution achieved by this readout configuration is excellent (below 40 μm for a wide range of photon incidence angles). Figure and data from ref. [5].

The **Anticoincidence System**, consisting of a top plastic scintillator plane and of 12 lateral panels, surrounds all AGILE active detectors. It is aimed at both charged particle background rejection and preliminary direction reconstruction for photon events.

The **AGILE Data Handling System (DH)** provides the on-board data processing for the GRID, SA and MCAL events. A DH essential task is the implementation of a GRB Search Procedure to be carried out for a large variety of trigger timescales (from $\leq$ 1ms to tens of seconds).

4. GRID ON-BOARD DATA PROCESSING

4.1. Expected background

A quasi-equatorial orbit is preferred for the AGILE mission and will provide a relatively low-background environment. Taking into account data from SAS-2 [6] and Beppo-SAX [7] missions, we expect an average rate of charged particle background above $\sim$ 1 MeV of $\sim$ 0.3 particles cm^{-2} s^{-1} for a quasi-equatorial orbit near 550 km. The charged particle background for this orbit is known to be relatively stable, with an increase by a factor 10-100 near the South Atlantic Anomaly. The charged particle energy spectra assumed in our simulations are shown in Fig. 3. They are based on data from the 1998 AMS Shuttle flight [8] [9], and from the MARYA experiment on board of the MIR space station [10]. These data were selected for events detected near the geomagnetic equator, and their low-energy extrapolations are consistent with the total rates detected by SAS-2 and Beppo-SAX. We used the correct angle distributions for different particle components: an isotropic distribution for electrons, positrons and trapped protons, and an upper-hemispheric distribution for primary protons (for a zenithal AGILE pointing).

Another relevant component of the background is constituted by the Earth albedo photons.

The interaction of the charged cosmic-rays with the upper atmosphere induces a relatively strong and non-isotropic gamma-ray background. It peaks near the Earth horizon (corresponding to a zenith angle $\theta = 112°$ for an orbit of 550 km altitude), and has a characteristic East-West asymmetry (by a factor of $\sim$ 4 in intensity near 40 MeV) [11]. The event rate generated by the albedo photons will depend on the relative orientation of the detector and the Earth. Given the large AGILE-GRID field of view, the Earth will be inside the field of view for a large fraction of the time; however albedo photons will be a source of background also when the field of view is unocculted by the Earth, since they will interact with

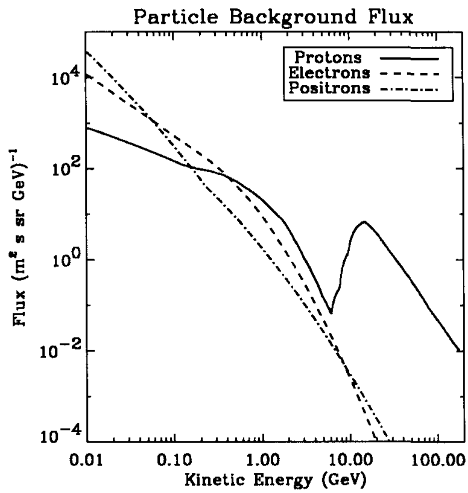

Figure 3. Expected charged particle background energy spectra for a quasi-equatorial orbit near 550 km of altitude [8] [9] [10].

the satellite "from below" producing secondaries able to trigger the GRID.

In our Montecarlo simulations, we assumed a model for the Earth albedo photon based on the SAS-2 observations of the Earth photon albedo above 35 MeV [11]. In this model, for a fixed detector position, the flux is a complicated function $\phi_\gamma(\theta, \varphi, E_\gamma)$ of the zenith angle θ, the azimuth angle φ and the the photon energy E_γ. The energy distribution is generated according to a simple power law: $dN/dE \propto E^{-\alpha(\theta)}$ with an esponent α that depends on the zenith angle. The spectrum is softest ($\alpha = \alpha_{max} = 2.4$) for the vertical direction and it is hardest ($\alpha = \alpha_{min} = 2.1$) at the horizon.

4.2. Trigger strategies and on-board background rejection

The number ratio of charged particle events (penetrating the AC) to cosmic gamma-ray photon events is typically of order $10^3 - 10^4$ for photons of energy 20-100 MeV, and $10^4 - 10^5$ for photons above 100 MeV. Albedo photon rates are

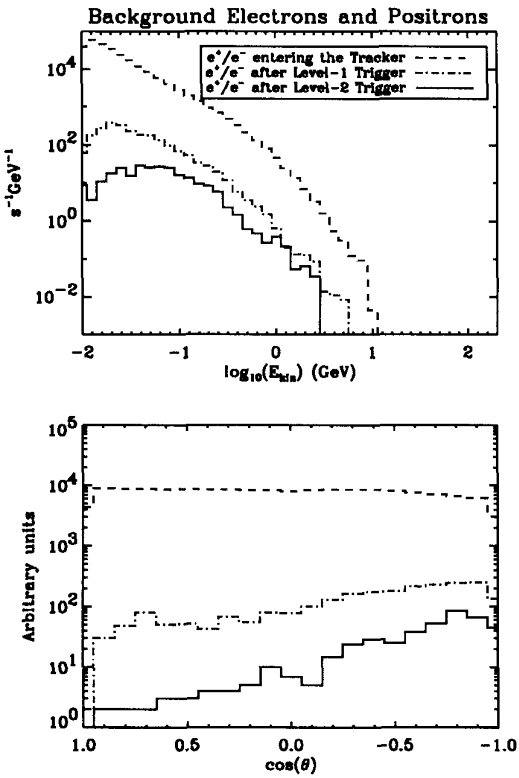

Figure 4. Simulated differential energy (upper panel) and angle (lower panel) distributions resulting from the on-board processing of the background electrons and positrons by the AGILE-GRID. The dashed curve represents the electrons and positrons of kinetic energies above 10 MeV penetrating into the Tracker volume. The dash-dotted and the solid line curves represent the e^+ and e^- flux passing respectively the Level-1 and Level-2 on-board trigger cuts. ($\theta = 0°$ corresponds to on-axis particles entering the GRID from above, $\theta = 180°$ is for particles entering the GRID from below.)

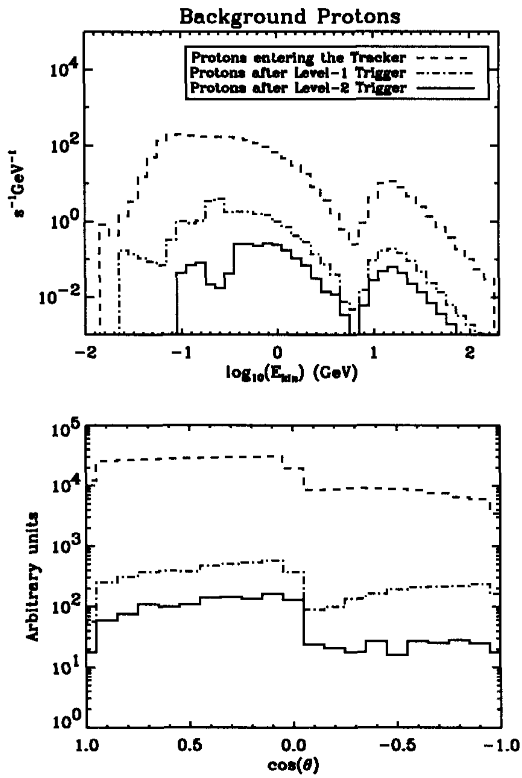

Figure 5. Simulated differential energy (upper panel) and angle (lower panel) distributions resulting from the on-board processing of the background protons by the AGILE-GRID. The dashed curve represents the protons of kinetic energies above 10 MeV penetrating into the Tracker volume. The dash-dotted and the solid line curves represent the proton flux passing respectively the Level-1 and Level-2 on-board trigger cuts.

larger than those of cosmic gamma-ray photons by factors between 10 and 100 (depending on the pointing geometry and energy range).

Clearly, is necessary to 'filter' the GRID events in order to obtain a very efficient on-board background rejection, without affecting too much the detection of cosmic gamma-rays. This task is carried out by a hardware-implemented fast logic ("Level-1 trigger"), and by a set of asynchronous software algorithms and CPU processing ("Level-2 processing"). The adopted requirements for the DH processing depend on the downlink teleme-

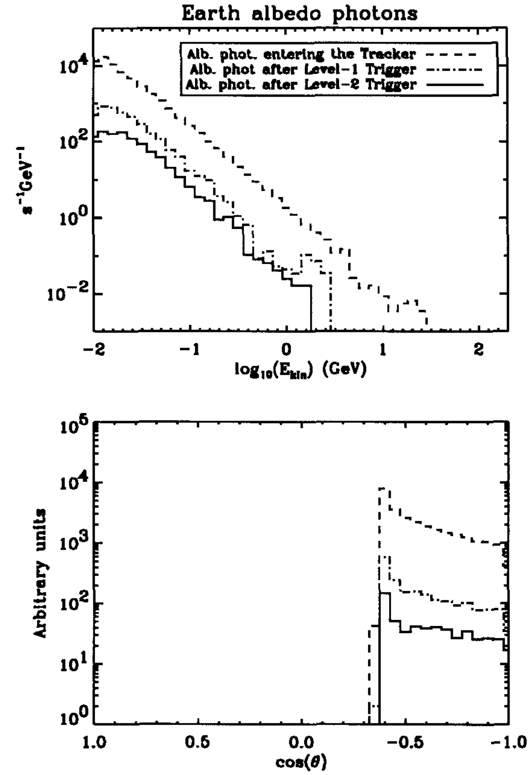

Figure 6. Simulated differential energy (upper panel) and angle (lower panel) distributions resulting from the on-board processing of the Earth albedo photons by the AGILE-GRID (in the case of "unocculted FOV", when the AGILE GRID points to the opposite direction with respect to the Earth center). The dashed curve represents the albedo-photons of energies above 10 MeV penetrating into the Tracker volume. The dash-dotted and the solid line curves represent the albedo-photon flux passing respectively the Level-1 and Level-2 on-board trigger cuts.

try rate, assumed to be 512 kbit/s during the 10 minute duration of satellite visibility from the ASI ground station in Malindi (Kenya).

The charged particle and the albedo-photon background models described in the previous section were used in Montecarlo simulations in order to optimize the DH processing [12] [13] [14].

The Level-1 trigger logic uses the information from the Silicon detectors and AC panels, and considers also a simplified view of the event topology obtained by the front-end chips. Level-1 trigger is expected to reduce the background from a rate of $\sim$ 2000 Hz to a rate of $\sim$ 60 Hz. A (software) Level-2 on-board data processing makes a crucial use of the analog (charge) information in the Si-microstrips for a refined view of the event topology at the "cluster" level. Level-2 on-board processing also selects events based on a simplified photon direction reconstruction, especially useful to reject Earth albedo photons. After the on-board Level-2 processing, we are able to reduce the total (charged particle and albedo-photon) background rate to $\sim 20 - 30$ Hz.

We also studied how the different trigger cuts modify the energy spectra and the angular distributions of the different background components. Figs. 4, 5 and 6 show the modifications of the charged particle and Earth albedo-photon background spectra and angular distributions due to Level-1 and Level-2 on-board data processing.

4.3. Effective area

Using the trigger logic outlined in the previous section, we studied the AGILE-GRID efficiency to detect gamma-rays at different incidence angles and energies (after the on-board trigger cuts). The effective area is, by definition: $A_{eff} = \epsilon A_{\perp}$, where $A_{\perp}$ is the detector "geometrical area" (equivalent area perpendicular to the incident flux direction) and ϵ is the detector efficiency, given by the product $\epsilon = \epsilon_i \cdot \epsilon_t$, with ϵ_i the photon interaction probability, ϵ_t and the trigger efficiency.

Fig. 7 shows the comparison among AGILE, EGRET and COMPTEL effective areas, for fixed directions, as a function of photon energy. Note that the AGILE-GRID is characterized by an excellent performance off-axis, and by an effective area smaller by only a factor of 2 than that of EGRET for on-axis events, despite of the fact that AGILE is a very small mission compared to EGRET. Note also that EGRET has a cut-off at 100 MeV, while AGILE cut-off is between

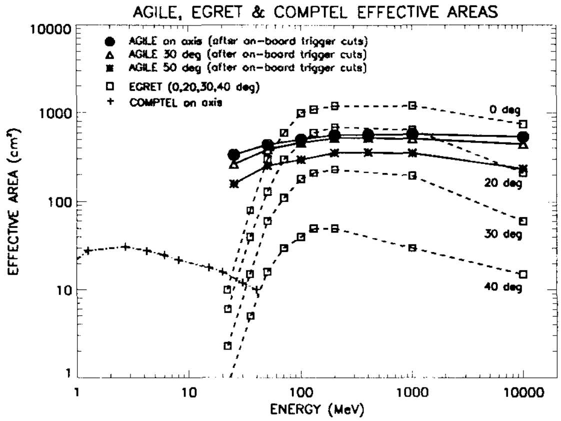

Figure 7. AGILE effective area (after the on-board trigger cuts) as a function of photon energy compared to EGRET and COMPTEL effective areas [15] [16].

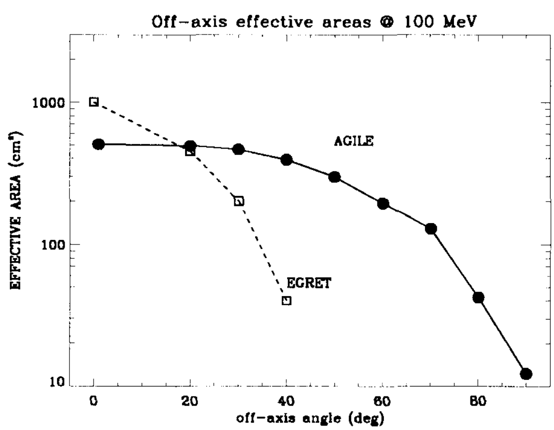

Figure 8. AGILE effective area (after the on-board trigger cuts) at 100 MeV as a function of photon incidence direction compared to that of EGRET [15].

10 and 20 MeV, meaning that we will be able to do science also in a new window of the gamma-ray range between 20 and 100 MeV. Fig. 8 show AGILE and EGRET effective areas at 100 MeV as a function of photon incidence angle; it is evident that the AGILE Field of View is really larger than the EGRET one, allowing to monitor a large fraction of the entire sky ($\sim 1/5$) for each pointing.

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