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High-energy gamma-ray studying with GAMMA-400 after Fermi-LAT

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Abstract. Fermi-LAT has made a significant contribution to the study of high-energy gamma-ray diffuse emission and the observation of ~3000 discrete sources. However, one third of all gamma-ray sources (both galactic and extragalactic) are unidentified, the data on the diffuse gamma-ray emission should be clarified, and signatures of dark matter particles in the high-energy gamma-ray range are not observed up to now. GAMMA-400, currently developing gamma-ray telescope, will have the angular (~0.01° at 100 GeV) and energy (~1% at 100 GeV) resolutions in the energy range of 10-1000 GeV better than the Fermi-LAT (as well as ground gamma-ray telescopes) by a factor of 5-10 and observe some regions of the Universe (such as Galactic Center, Fermi Bubbles, Crab, Cygnus, etc.) in the highly elliptic orbit (without shading the telescope by the Earth) continuously for a long time. It will permit to identify many discrete sources, to clarify the structure of extended sources, to specify the data on the diffuse emission, and to resolve gamma rays from dark matter particles.



1. Current gamma-ray study challenges

1.1. Analysis of the Fermi-LAT and ground-based telescope gamma-ray results

Since 2008 Fermi-LAT is operating in a near-Earth orbit in the scanning mode and surveying full sky every three hours. Up to now, three catalogs of gamma-ray sources have been published based on the Fermi-LAT observational results: 1FGL [1] and 2FGL [2] for the energy range of 0.1-100 GeV, 3FGL [3] for the energy range of 0.1-300 GeV. Moreover two catalogs of high-energy gamma-ray sources were published: 1FHL [4] for the energy above 10 GeV and 2FHL [5] for the energy range of 50-2000 GeV. From these catalogs, it is seen that 33% of gamma-ray sources are unidentified. The exposition of the source observations presented in [3] shows that during four years of the operation Fermi-LAT observed, e.g., the Galactic center during only ~12% or 1/8 of total operation time.

Based on results of gamma-ray observations at energies above 100 GeV by ground-based facilities VERITAS [6], MAGIC [7], H.E.S.S. [8] and others the TeVCat catalog of discrete gamma-ray sources [9] was created, which contains about 180 sources and mainly matches with 3FGL.

It is important to note that the observational data from Fermi-LAT and ground-based facilities were obtained for the energy ranges, which overlap insufficiently for many gamma-ray sources. Sometimes they don't overlap at all. Hence, the frontier range around 100 GeV is still very interesting for investigations from space. In addition, the angular resolution of Fermi-LAT, existing ground-based telescopes, and even planned CTA [10] in the region of around 10-300 GeV is only ~0.1°. Therefore a much better angular resolution is required in order to identify many gamma-ray sources.

1.2. Indirect searches of dark matter

Another very interesting and important goal in the studies of gamma-ray sky is indirect searches of dark matter (DM). In general, an exact physical nature of DM is a top puzzle in the modern astrophysics. There are many candidates on the DM role being proposed. However, WIMPs with mass between several GeV and several TeV are still considered as the most probable candidate [11]. WIMPs can annihilate or decay with the production of gamma rays. This emission can have both continuum energy spectrum or monoenergetic lines. This depends on which annihilation channel realizes in the nature. The continuum spectrum would come in the case of annihilation into particle pairs like

$$\chi\chi \rightarrow b\bar{b}, \tau^+\tau^-, W^+W^-, \mu^+\mu^-, q\bar{q}, ZZ$$

or others and gamma-ray lines would be produced in the case of direct annihilation into photons $\chi\chi \rightarrow \gamma\gamma, \gamma Z, \gamma H$ [12]).

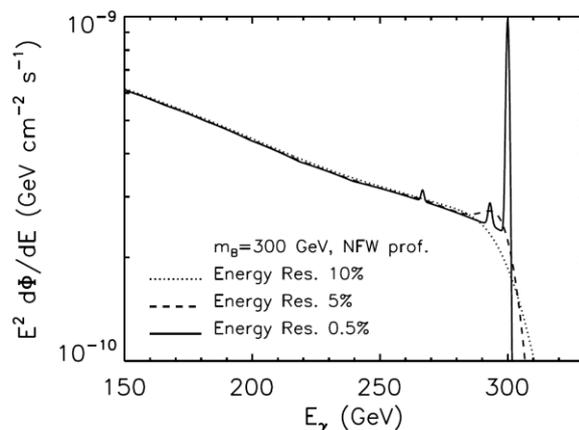


Figure 1. Expected energy spectrum for the annihilation of 300-GeV WIMP producing gamma rays ($\gamma\gamma$, γZ , and γH lines), which can be resolved from background by various telescopes with the energy resolutions of 10%, 5%, and 0.5% [13].

To resolve gamma-ray lines from background it is necessary to have a high-energy resolution. Figure 1 shows expected energy spectrum for the annihilation of 300-GeV WIMP producing gamma rays ($\gamma\gamma$, γZ , and γH lines), which can be resolved from background by various telescopes with the energy resolutions of 10%, 5%, and 0,5% [13]. Note that the energy resolution of Fermi-LAT and ground-based telescopes is only 10-15% for the energy of 10-300 GeV. Thus, as seen from figure 1, the future telescopes need to have 1-2% energy resolution.

2. The GAMMA-400 gamma-ray telescope

Thus, to resolve unidentified gamma-ray sources and search for the potential gamma-ray lines from DM we need in a gamma-ray telescope with the angular resolution of several hundredth degrees and the energy resolution of few percent for the energy of ~ 100 GeV. This is going to be GAMMA-400, which will be installed onboard the Russian space observatory [14-18].

The GAMMA-400 main scientific goals are: dark matter searching by means of gamma-ray astronomy; precise measurements of Galactic Center, Fermi Bubbles, Crab, Vela, Cygnus, Geminga, Sun, and other regions, extended and point gamma-ray sources, diffuse gamma rays with unprecedented angular ($\sim 0.01^\circ$ at $E_\gamma > 100$ GeV) and energy ($\sim 1\%$ at $E_\gamma > 100$ GeV) resolutions.

2.1. The GAMMA-400 physical scheme

The physical scheme of the GAMMA-400 gamma-ray telescope is shown in figure 2. The GAMMA-400 energy range for gamma-ray studies is from ~ 20 MeV to ~ 1000 GeV. The GAMMA-400 field of view (FoV) is $\pm 45^\circ$.

GAMMA-400 consists of plastic scintillation anticoincidence top and lateral detectors (AC top and AC lat), converter-tracker (C), plastic scintillation detectors (S1 and S2) for the time-of-flight system (TOF), calorimeter (CC), plastic scintillation detector (S3).

The anticoincidence detectors surrounding the converter-tracker are used to distinguish gamma rays from significantly larger number of charged particles (e.g., in the region of 10-100 GeV, the flux ratios for gamma rays to electrons and protons are $\sim 1:10^2:10^5$).

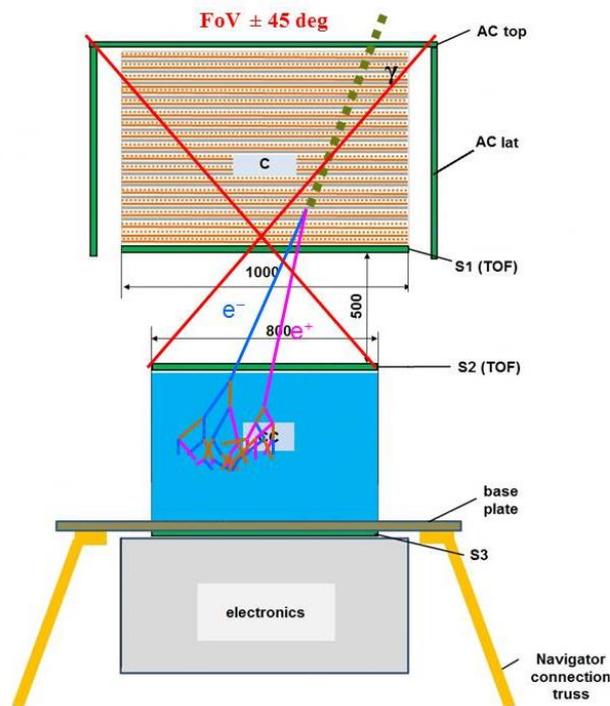


Figure 2. The GAMMA-400 physical scheme.

All scintillation detectors consist from two independent 1-cm layers. The time-of-flight system, where detectors S1 and S2 are separated by approximately 500 mm, determines the top-down direction of arriving particles. The additional scintillation detector S3 improves hadron and electromagnetic shower separation.

The converter-tracker consists of 22 layers of double (x, y) silicon strip coordinate detectors (pitch of 0.08 mm). Twenty layers are interleaved with tungsten conversion foils and final two layers have no tungsten. This configuration allows us to measure gamma rays down to ~ 20 MeV. The total converter-tracker thickness is $\sim 1 X_0$. The converter-tracker information is used to precisely determine the conversion point and the direction of each incident particle.

The calorimeter CC measures particle energy and consists of CsI(Tl) crystals. The total calorimeter thickness is $\sim 21 X_0$ or $\sim 1.0 \lambda_0$ when detecting vertical incident particles and $\sim 43 X_0$ or $\sim 2.0 \lambda_0$ when detecting laterally incident particles. Using the deep calorimeter allows us to extend the energy range up to several TeV for gamma rays, and to reach the energy resolution of $\sim 1\%$ above 100 GeV.

2.2. *The GAMMA-400 gamma-ray observatory*

The GAMMA-400 gamma-ray observatory will be installed onboard of the Navigator space platform, which is designed and manufactured by the Lavochkin Association.

Using the Navigator space platform gives the GAMMA-400 experiment a highly unique opportunity for the near future gamma- and cosmic-ray science, since it allows us to install a scientific payload (mass of 2500 kg, power consumption of 2000 W, and telemetry downlink of 100 GB/day, with lifetime more than 7 years), which will provide GAMMA-400 with the means to significantly contribute as the next generation instrument for gamma-ray astronomy and cosmic-ray physics.

The GAMMA-400 experiment will be initially launched into a highly elliptical orbit (with an apogee of 300,000 km and a perigee of 500 km, with an inclination of 51.4°), with 7 days orbital period. Under the action of gravitational disturbances of the Sun, Moon, and the Earth after ~ 6 months the orbit will transform to about an approximately circular one with a radius of $\sim 200\,000$ km and will not suffer from the Earth's occultation and shielding by the radiation belts. The launch of the GAMMA-400 space observatory is planned for the middle of the 2020s.

2.3. *Comparison of GAMMA-400 with Fermi-LAT and ground-based telescopes*

GAMMA-400 has numerous advantages in comparison with the Fermi-LAT:

- highly elliptical orbit (without the Earth's occultation and away from the radiation belts) allows us to observe with the full aperture of $\pm 45^\circ$ different gamma-ray sources continuously over a long period of time with the exposition greater by a factor of 8 than for Fermi-LAT operating in the sky-survey mode;
- thanks to a smaller pitch (by a factor of 3) and analog readout in the coordinate silicon strip detectors, GAMMA-400 has an excellent angular resolution above ~ 20 MeV;
- due to the deep ($\sim 21 X_0$) calorimeter, GAMMA-400 has an excellent energy resolution and can more reliably detect gamma rays up to several TeV for vertically incident events;
- owing to the better gamma-ray separation from cosmic rays (in contrast to Fermi-LAT, the presence of a special trigger with event timing, time-of-flight system, two-layer scintillation detectors), GAMMA-400 is significantly well equipped to separate gamma rays from the background of cosmic rays and backscattering events.

GAMMA-400 will have also the better angular and energy resolutions in the energy region 10-1000 GeV in comparison with current and future ground-based instruments: VERITAS [6], MAGIC [7], H.E.S.S. [8], CTA [10], and HAWC [19] (figure 3) and it allows us to fill the gap at the energy of ~ 100 GeV between the space- and ground-based instruments.

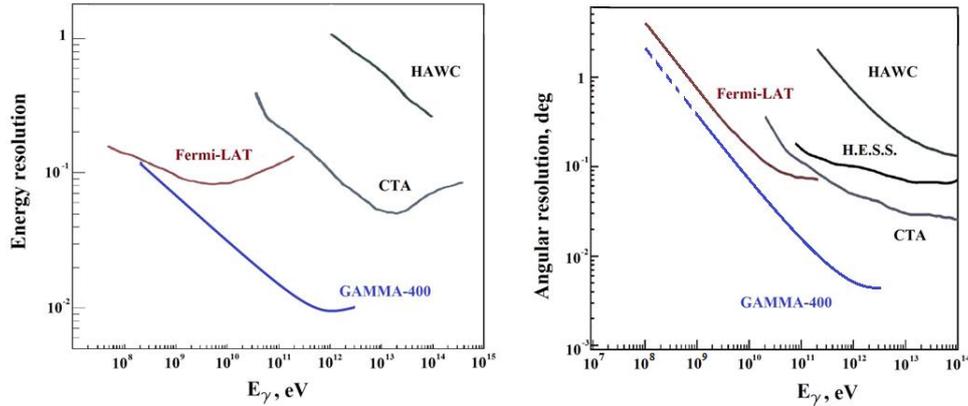


Figure 3. Comparison of energy and angular resolutions for GAMMA-400, Fermi-LAT, H.E.S.S., HAWC, and CTA.

3. The anticipated GAMMA-400 scientific output

3.1. Galactic plane

GAMMA-400 will study continuously over a long period of time different regions of Galactic plane (figure 4), for example, Galactic center, Fermi Bubbles, Crab, Vela, Cygnus, Geminga with FoV of $\pm 45^\circ$. In particular, using the gamma-ray fluxes obtained by Fermi-LAT, we can expect that GAMMA-400 when observing the Galactic center with aperture of $\pm 45^\circ$ during 1 year will detect: 57400 photons for $E_\gamma > 10$ GeV; 5240 photons for $E_\gamma > 50$ GeV; 1280 photons for $E_\gamma > 100$ GeV; 535 photons for $E_\gamma > 200$ GeV.

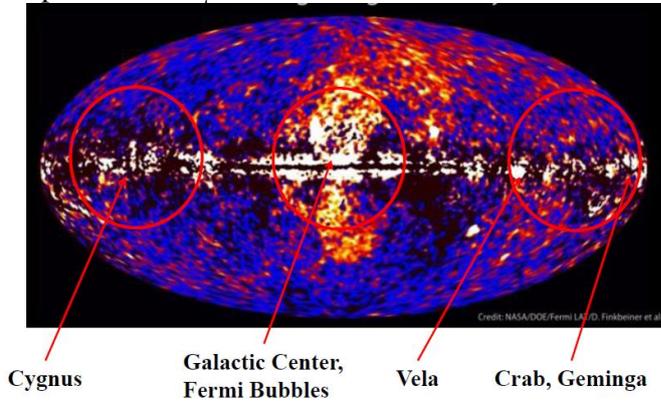


Figure 4. Galactic center, Fermi Bubbles, Crab, Cygnus, Vela, Geminga, and other regions will be observed with the GAMMA-400 FoV of $\pm 45^\circ$.

3.2. Dark matter searching

When detecting gamma rays from DM, the intensity from gamma rays is calculated by

$$\frac{d\Phi}{d\Omega dE} = \frac{1}{2} \frac{\langle \sigma v \rangle}{m_\chi^2} \frac{dN_\gamma}{dE} \times \frac{J}{4\pi} [\text{erg s}^{-1} \text{cm}^2 \text{GeV}^{-1} \text{sr}^{-1}], J = \int_{l.o.s.} \rho^2(\vec{r}) dl.$$

Here, $\langle \sigma v \rangle$ is particle annihilation cross section, m_χ is particle mass, dN_γ/dE is the spectrum of gamma rays from annihilation, $\rho(\vec{r})$ is the DM density of investigated object [20].

The Galactic center is, apparently, the best potential source of DM emission possessing the largest J -factor [11]. Moreover, recently, the anomaly excess of gamma-ray emission in the GeV energy range was revealed near the Galactic center (the region of about one degree) [21], which can be well described by DM with mass of several tens of GeV and annihilation cross section of about standard thermal $10^{-26} \text{ cm}^3/\text{s}$. However, this observed excess can have another interpretation - the presence a population of millisecond pulsars [22]. Therefore, the new GAMMA-400 observational data can help to solve this problem.

Dwarf galaxies are considered for a long time as the strongest sources of constraints for DM, because they have sufficiently large J -factors and at the same time have considerably less gamma-ray background in comparison with the Galactic center. Current and predicted constraints for DM parameters according to observations of 15 known dwarf galaxies are shown in figure 5 (for the typical quark-antiquark channel [23]). GAMMA-400 will able to specify the constrain area.

Potentially interesting objects are other galaxies and their clusters, where DM presents and can emit gamma rays. GAMMA-400 with the highest energy resolution of $\sim 1\%$ will have unique sensitivity for detecting DM.

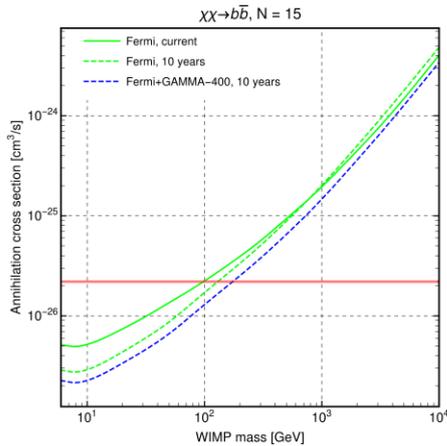


Figure 5. Current and predicted constraints for DM parameters according to observations of 15 known dwarf galaxies.

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