Space-based GAMMA-400 mission for direct gamma- and cosmic-ray observations
High-energy gamma-ray studying
Space-based Fermi-LAT data

Distribution of 3033 discrete sources
(3FGL, $E_{\gamma} = 100$ MeV – 300 GeV)

- Normal Galaxies
- Other AGN
- Globular Clusters
- Pulsar Wind Nebulae
- Supernova Remnants
- High Mass Binaries
- Novae
- Galactic Associations

Unclassified Blazars 19%
BL Lacs 21%
Flat Spectrum Radio Quasars 16%
Pulsars 6%
Unassociated (low latitude) 11%
Unassociated (high latitude) 22%

~33% sources are unidentified

Fermi-LAT angular resolution is
~0.1° ($E_{\gamma} > 10$ GeV)

Distribution of 1556 discrete sources
(3FHL, $E_{\gamma} = 10$ – 2000 GeV)

SNRs and PWNe
BL Lacs
Unc. Blazars
Other EGAL
Unknown
Unassociated
Pulsars
FSRQs
Other GAL

arXiv :1509.00012
Composition of discrete sources recorded by H.E.S.S.

Distribution of 210 discrete sources
(\texttt{TeVCat}, $E_\gamma > 100$ GeV)

\textbf{Ground-based telescope angular resolution is}$ \sim 0.1^\circ$ ($E_\gamma \sim 100$ GeV)
Fermi-LAT ($\sim 0.1^\circ$, $E_\gamma > 10$ GeV) and ground-based telescope ($\sim 0.1^\circ$, $E_\gamma \sim 100$ GeV) angular resolutions are insufficient to identify many gamma-ray sources.

The percentage of the different types of gamma-ray sources according to the 3FGL Fermi-LAT catalogue

Composition of discrete sources recorded by H.E.S.S.

arXiv:1509.00012

arXiv:1804.02432
One of the leading candidates for the DM particle are weakly interacting massive particles (WIMPs) producing gamma rays after annihilation or decay.
Capabilities of different gamma-ray telescopes to resolve DM lines

Energy resolution for Fermi-LAT is \( \sim 10\% \) \((E_\gamma > 10 \text{ GeV})\) and ground-based gamma-ray telescopes is \( \sim 15\% \) \((E_\gamma \sim 100 \text{ GeV})\)

The gamma ray flux as a function of the photon’s energy for a WIMP of mass 300 GeV. Shown are three different experimental energy resolutions.
Capabilities of different gamma-ray telescopes to resolve DM lines

Energy resolution for Fermi-LAT is \(~10\%\) (\(E_\gamma > 10\text{ GeV}\)) and ground-based telescope \(~15\%\) (\(E_\gamma \sim 100\text{ GeV}\)) energy resolutions are insufficient to resolve gamma-ray lines from DM.

The gamma ray flux as a function of the photon’s energy for a WIMP of mass 300 GeV. Shown are three different experimental energy resolutions.
Future gamma-ray telescopes should have the significantly improved angular and energy resolutions
Such a new generation telescope will be **GAMMA-400**
GAMMA-400

MAIN SCIENTIFIC GOALS

The GAMMA-400 main scientific goals are: dark matter searching by means of gamma-ray astronomy; precise and detailed observations of Galactic plane, especially, 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 resolutions ($\sim 1\%$ at $E_\gamma = 100$ GeV), as well as detecting electron + positron fluxes with energies up to 10 TeV.
The GAMMA-400 physical scheme (gamma-ray detection)

$e^- e^+ \gamma$

- **FoV** = ± 45 deg
- $\Delta E = \sim 20 \text{ MeV} - \sim 10 \text{ TeV}$
- $\Delta \theta = \sim 2^\circ$ (E$_\gamma$ = 100 MeV)
- $\Delta \theta = \sim 0.01^\circ$ (E$_\gamma$ = 100 GeV)
- $\Delta E/E = \sim 10\%$ (E$_\gamma$ = 100 MeV)
- $\Delta E/E = \sim 1\%$ (E$_\gamma$ = 100 GeV)

**AC** – anticoincidence system
**C** - converter-tracker ~1 $X_0$
**S1, S2** – TOF detectors
**CC1, CC2** – calorimeter
  vertical thickness ~22 $X_0$
**S3, S4** – scintillator detectors

$M = \overline{A C} \times S1 \times S2$
The GAMMA-400 physical scheme
(electron + positron detection)

AC – anticoincidence system
C - converter-tracker ~1 \(X_0\)
S1, S2 – TOF detectors
CC1, CC2 – calorimeter
  vertical thickness ~22 \(X_0\)
  lateral thickness ~54 \(X_0\)
S3, S4 – scintillator detectors
C_{LAT} – lateral calorimeter detectors

\[GF_{CR} > 3 \text{ m}^2\text{sr (all sides)}\]
\[\Delta E = \sim 1 \text{ GeV} - \sim 10 \text{ TeV}\]
\[\Delta \theta = \sim 0.01^\circ \text{ (E = 100 GeV)}\]
\[\Delta E/E = \sim 1\% \text{ (E = 100 GeV)}\]
<table>
<thead>
<tr>
<th></th>
<th>Fermi-LAT</th>
<th>GAMMA-400</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Orbit</strong></td>
<td>Circular, 565 km</td>
<td>Highly elliptical, 500-300000 km (without the Earth’s occultation)</td>
</tr>
<tr>
<td><strong>Operation mode</strong></td>
<td>Sky-survey (3 hours)</td>
<td>Point observation (up to 100 days)</td>
</tr>
<tr>
<td><strong>Source exposition</strong></td>
<td>1/8</td>
<td>1</td>
</tr>
<tr>
<td><strong>Energy range</strong></td>
<td>~100 MeV - ~300 GeV</td>
<td>~20 MeV – ~10 TeV</td>
</tr>
<tr>
<td><strong>Effective area ((E_\gamma &gt; 1) GeV)</strong></td>
<td>~5000 cm(^2) (front)</td>
<td>~4000 cm(^2)</td>
</tr>
<tr>
<td><strong>Coordinate detectors - readout</strong></td>
<td>Si strips (pitch 0.23 mm) digital</td>
<td>Si strips (pitch 0.08 mm analog)</td>
</tr>
<tr>
<td><strong>Angular resolution</strong></td>
<td>~3° ((E_\gamma = 100) MeV)</td>
<td>~2° ((E_\gamma = 100) MeV)</td>
</tr>
<tr>
<td></td>
<td>~0.2° ((E_\gamma = 10) GeV)</td>
<td>~0.1° ((E_\gamma = 10) GeV)</td>
</tr>
<tr>
<td></td>
<td>~0.1° ((E_\gamma &gt; 100) GeV)</td>
<td>~0.01° ((E_\gamma = 100) GeV)</td>
</tr>
<tr>
<td><strong>Calorimeter - thickness</strong></td>
<td>CsI(Tl)</td>
<td>CsI(Tl)+Si</td>
</tr>
<tr>
<td></td>
<td>~8.5(X_0)</td>
<td>~22(X_0)</td>
</tr>
<tr>
<td><strong>Energy resolution</strong></td>
<td>~18% ((E_\gamma = 100) MeV)</td>
<td>~10% ((E_\gamma = 100) MeV)</td>
</tr>
<tr>
<td></td>
<td>~10% ((E_\gamma = 10) GeV)</td>
<td>~3% ((E_\gamma = 10) GeV)</td>
</tr>
<tr>
<td></td>
<td>~10% ((E_\gamma &gt; 100) GeV)</td>
<td>~1% ((E_\gamma = 100) GeV)</td>
</tr>
<tr>
<td><strong>Proton rejection factor</strong></td>
<td>~10(^3)</td>
<td>~5x10(^5)</td>
</tr>
<tr>
<td><strong>Mass</strong></td>
<td>2800 kg</td>
<td>~4000 kg</td>
</tr>
<tr>
<td><strong>Telemetry downlink volume, Gbytes/day</strong></td>
<td>15 Gbytes/day</td>
<td>100 Gbytes/day</td>
</tr>
</tbody>
</table>
Comparison of main parameters of operated, current, and planned space-based and ground-based instruments

<table>
<thead>
<tr>
<th></th>
<th>SPACE-BASED INSTRUMENTS</th>
<th>GROUND-BASED GAMMA-RAY FACILITIES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AGILE</td>
<td>Fermi-LAT</td>
</tr>
<tr>
<td>Particles</td>
<td>γ</td>
<td>γ</td>
</tr>
<tr>
<td>Energy range, GeV</td>
<td>0.03-50</td>
<td>0.02-300</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>0.1° (E_γ~1 GeV)</td>
<td>0.1°</td>
</tr>
<tr>
<td></td>
<td>50% (E_γ~1 GeV)</td>
<td>10%</td>
</tr>
<tr>
<td>Sensitive area, m²</td>
<td>0.36</td>
<td>1.8</td>
</tr>
</tbody>
</table>

The table compares the main parameters of space-based and ground-based instruments. The parameters include the types of particles detected, operation periods, energy ranges, angular resolutions, energy resolutions, and sensitive areas. The table highlights the differences and similarities between the two types of instruments.
Comparison of the energy and angular resolutions for GAMMA-400, Fermi-LAT, HAWC, and CTA
Comparison of the capabilities to study Galactic Center by Fermi-LAT with the angular resolution of ~0.1° for $E_\gamma = 100$ GeV (yellow circle) and GAMMA-400 with the angular resolution of ~0.01° for $E_\gamma = 100$ GeV (red circle), using Chandra X-ray observation. The Sgr A* position is marked by cross.
Comparison of the Fermi-LAT and GAMMA-400 capabilities to resolve gamma-ray lines from dark matter particles

FIG. 3. The $\gamma$-ray differential energy results (multiplied by $E^2$) for a 135 GeV right-handed neutrino dark matter candidate are shown, with the present Fermi-LAT energy resolution $\Delta E/E = 10\%$ FWHM (solid line) and with a future $\gamma$-ray instrument, such as GAMMA-400 [38] (dash-dotted line) with resolution at the one percent level. The extrapolated power-law $\sim E^{-2.6}$ of the presently measured continuous $\gamma$-ray background is also shown.

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130 GeV fingerprint of right-handed neutrino dark matter

Lars Bergström*
The GAMMA-400 orbit evolution and observation modes

The orbit of the GAMMA-400 space observatory will have the following initial parameters:
- an apogee of 300 000 km;
- a perigee of 500 km;
- an inclination of 51.4º

Under the action of gravitational disturbances of the Sun, Moon, and the Earth after ~6 months the orbit will transform to about circular with a radius of ~200 000 km and will be without the Earth’s occultation and out of radiation belts.

The main observation mode will be continuous long-duration (~100 days) observations of the Galactic Center, extended gamma-ray sources, etc.

Time of operation will be 7-10 years
Galactic Center, Fermi Bubbles, Crab, Cygnus, Vela, Geminga, and other regions will be observed with the GAMMA-400 aperture of $\pm 45^\circ$. 
Number of simultaneously and uninterruptedly observed sources (at $N_\gamma > 10$ for each source) and number of gammas, when observing Galactic center, Crab + Geminga, Vela, and Cygnus regions by GAMMA-400 (effective area = 4000 cm$^2$, $T_{\text{obs}} = 100$ days, aperture ±45°), using the data from 3FGL for different energy ranges

<table>
<thead>
<tr>
<th>Direction</th>
<th>Energy range</th>
<th>100 MeV-100 GeV</th>
<th>1 GeV-100 GeV</th>
<th>10 GeV-100 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$N_{\text{sources}}$</td>
<td>$N_\gamma$</td>
<td>$N_{\text{sources}}$</td>
<td>$N_\gamma$</td>
</tr>
<tr>
<td>Galactic center</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$b=0^\circ$, $l=0^\circ$</td>
<td>723</td>
<td>523146</td>
<td>422</td>
<td>47505</td>
</tr>
<tr>
<td>Crab + Geminga</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$b=0^\circ$, $l=190^\circ$</td>
<td>495</td>
<td>310384</td>
<td>175</td>
<td>39163</td>
</tr>
<tr>
<td>Vela</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$b=0^\circ$, $l=265^\circ$</td>
<td>649</td>
<td>523077</td>
<td>280</td>
<td>63253</td>
</tr>
<tr>
<td>Cygnus</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$b=0^\circ$, $l=75^\circ$</td>
<td>604</td>
<td>318788</td>
<td>269</td>
<td>30941</td>
</tr>
</tbody>
</table>
On-axis exposure of GAMMA-400 in seconds

Telescope axis orientation: $b=0^\circ$, $l=0^\circ$ (100 days), $b=0^\circ$, $l=190^\circ$ (100 days), $b=0^\circ$, $l=265^\circ$ (100 days), $b=0^\circ$, $l=75^\circ$ (100 days)

Galactic Center

-180 -120 -60 0 60 120 180
-90
-60
-30
0
30
60
90

Vela
Cygnus
Crab

Galactic longitude, deg.

Galactic latitude, deg.

• $N_\gamma > 10$

• $N_\gamma > 100$

• $N_\gamma > 1000$

• $N_\gamma > 10000$

1.0E4
5.7E5
1.1E6
1.7E6
2.3E6
2.8E6
3.4E6
3.9E6
4.5E6
5.1E6
5.6E6
6.2E6
6.8E6
7.3E6
7.9E6
8.4E6
9.0E6
Electron + positron spectrum

$E^{3.0} \text{ flux}[m^{-2}\cdot s^{-1}\cdot GeV^{-2.0}]$

Energy [GeV]

CALET 2018
uncertainty band (stat. + syst.)
DAMPE 2017
PAMELA $e^-+e^+$ 2017
Fermi-LAT 2017 (HE+LE)
AMS-02 2014
HESS 2008+2009

arXiv:1806.09728
GAMMA-400 laboratory prototypes of detector systems
Calibration of prototypes on electron beam (100-300 MeV) at LPI accelerator.
Conclusions

• After Fermi-LAT the GAMMA-400 mission represents a unique opportunity to significantly improve the direct data of LE+HE gamma rays and electron + positron fluxes due to unprecedented angular and energy resolutions, large area, and continuous long-term observations.

• GAMMA-400 is funded by the Russian Space Agency and according to the Russian Federal Space Program 2016-2025 the GAMMA-400 space observatory is scheduled to launch in ~2025.

• We are open to the participation of foreign scientists in the manufacture of some detector systems.

GAMMA-400 site - [http://gamma400.lebedev.ru/](http://gamma400.lebedev.ru/)