From PAMELA to GAMMA-400: search for signatures of hypothetical dark matter particles and primary cosmic radiation study

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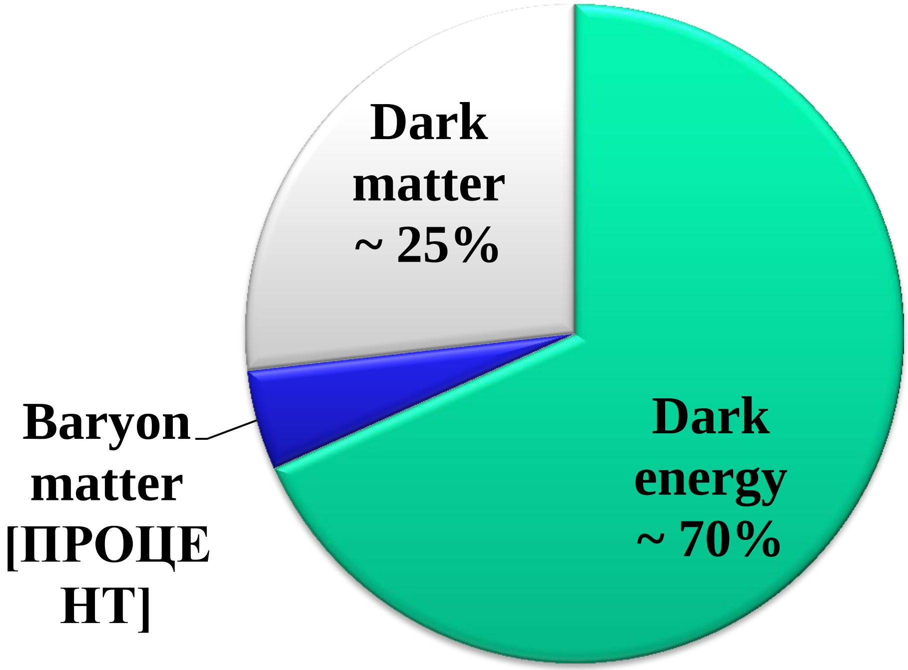
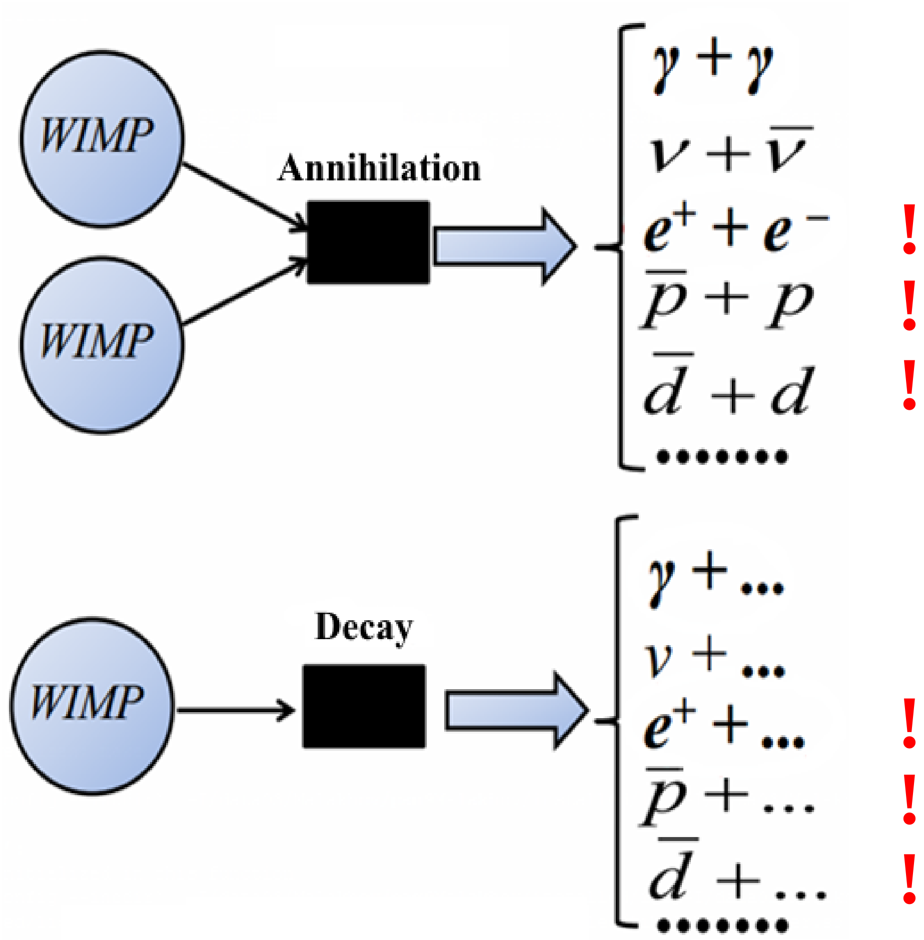
The 19th Lomonosov Conference, August 2019

Energy in the Universe



WIMPs: Weakly Interacting Massive Particles

1. Possess only gravitational interaction
2. Interaction intensity not more than weak interaction
3. Neutral
4. Stable or with large time of decay
5. Have a very low or a very large mass?



Blackbox: $b\bar{b}, t\bar{t}, \tau^+\tau^-, \mu^+\mu^-, e^+e^-, Z^0Z^0, Z^0\gamma, W^+W^-, HH, ...$

PAMELA collaboration

Italy:

Bari Florenc Frascat Naples Rome Triest CNR, Florence

Russia:

Moscow
St. Petersburg

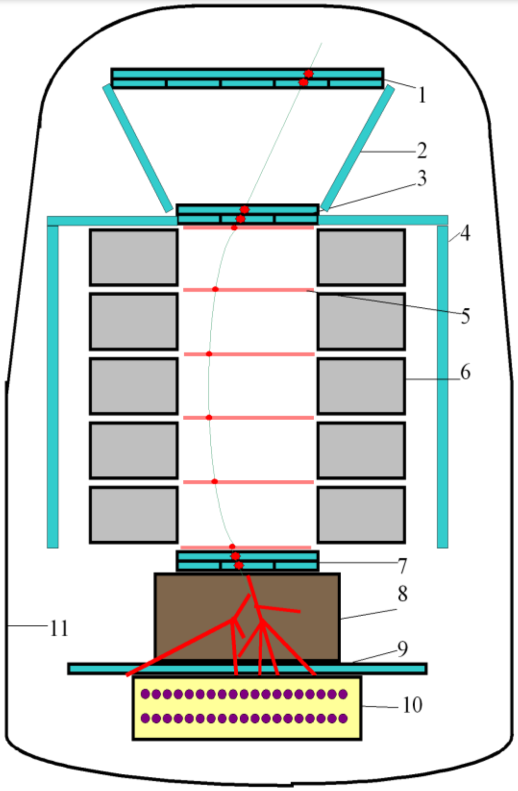
Germany: Siegen

Sweden: KTH, Stockholm

PAMELA science case

1. Search for signatures of exotic processes connected to the Dark Matter problem;
2. Help solving the cosmological problem about the existence of the apparent asymmetry between matter and antimatter;
3. Provide new high precision data about CR primary and secondary fluxes, to constrain on current acceleration and diffusion models of cosmic rays in the Galaxy.
4. Investigating the heliosphere and Earth magnetosphere.

PAMELA scheme



Measurements:

- Velocity (β)
- Deflection & Rigidity
- Energy losses
- Cascades
- Number of neutrons

Determine:

- Lepton/hadron
- Charge and sign of charge (±Z)
- Mass (A, M)
- Momentum and energy
- Particle’s direction

Magnetic spectrometer PAMELA

1, 3, 7	*Time-of-Flight;*
2, 4	*Anticoincidence;*
5	*Coordinate tracking system (6 double-side orthogonal planes);*
6	*Magnet (5 modules);*
8	*Silicon strip coordinate-sensitive detector;*
9	*Cascade tail detector C4;*
10	*Neutron detector;*
11	*Herm container.*

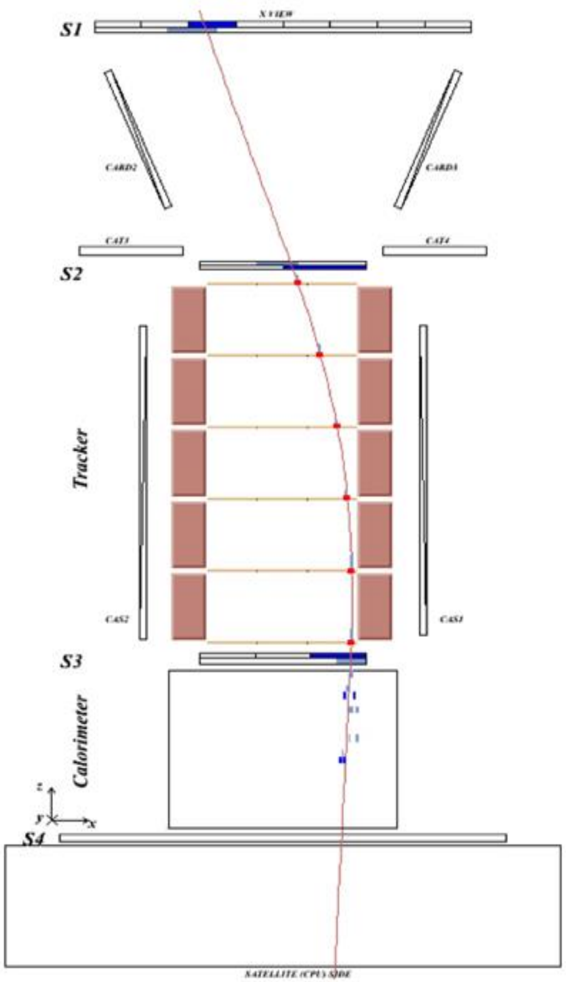
PAMELA

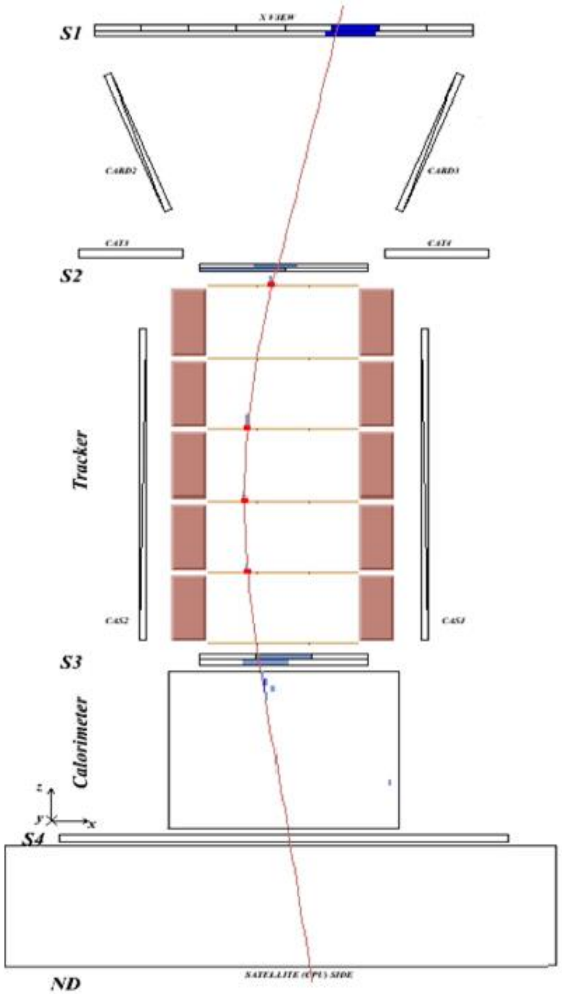
Energies:	
protons	0.08 – 1200 GeV
antiprotons	0.08 – 350 GeV
electrons	0.08 – 700 GeV
positrons	0.08 – 300 GeV
nuclei	0.05 – 100 GeV/nuc.
Mass	450 kg
Dimensions	1 m × 1 m ×1.25 m
Magnetic field	0.48 T
Power	350 W

Launch of Resurs-DK1

15 June 2006

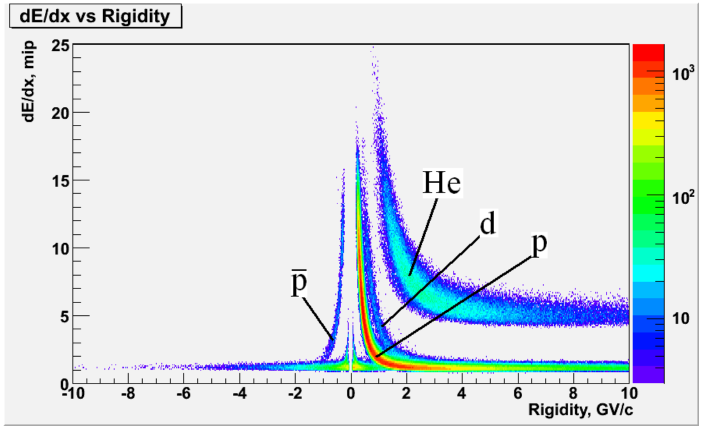
Data processing

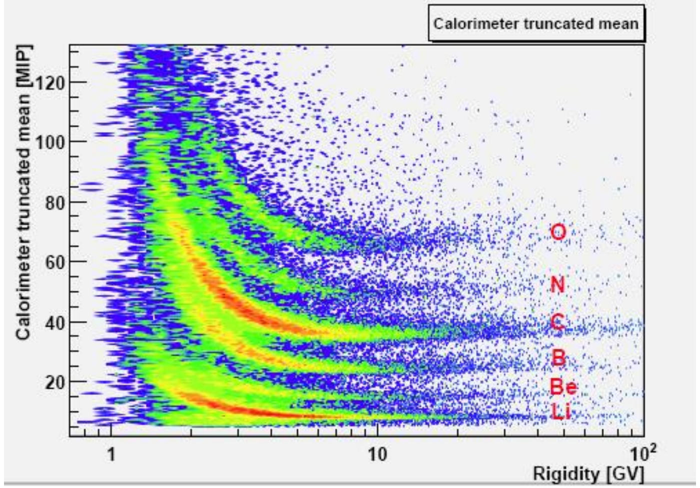




Позитрон e⁺
R=0.171 ГВ

Электрон e⁻
R=0.169 ГВ

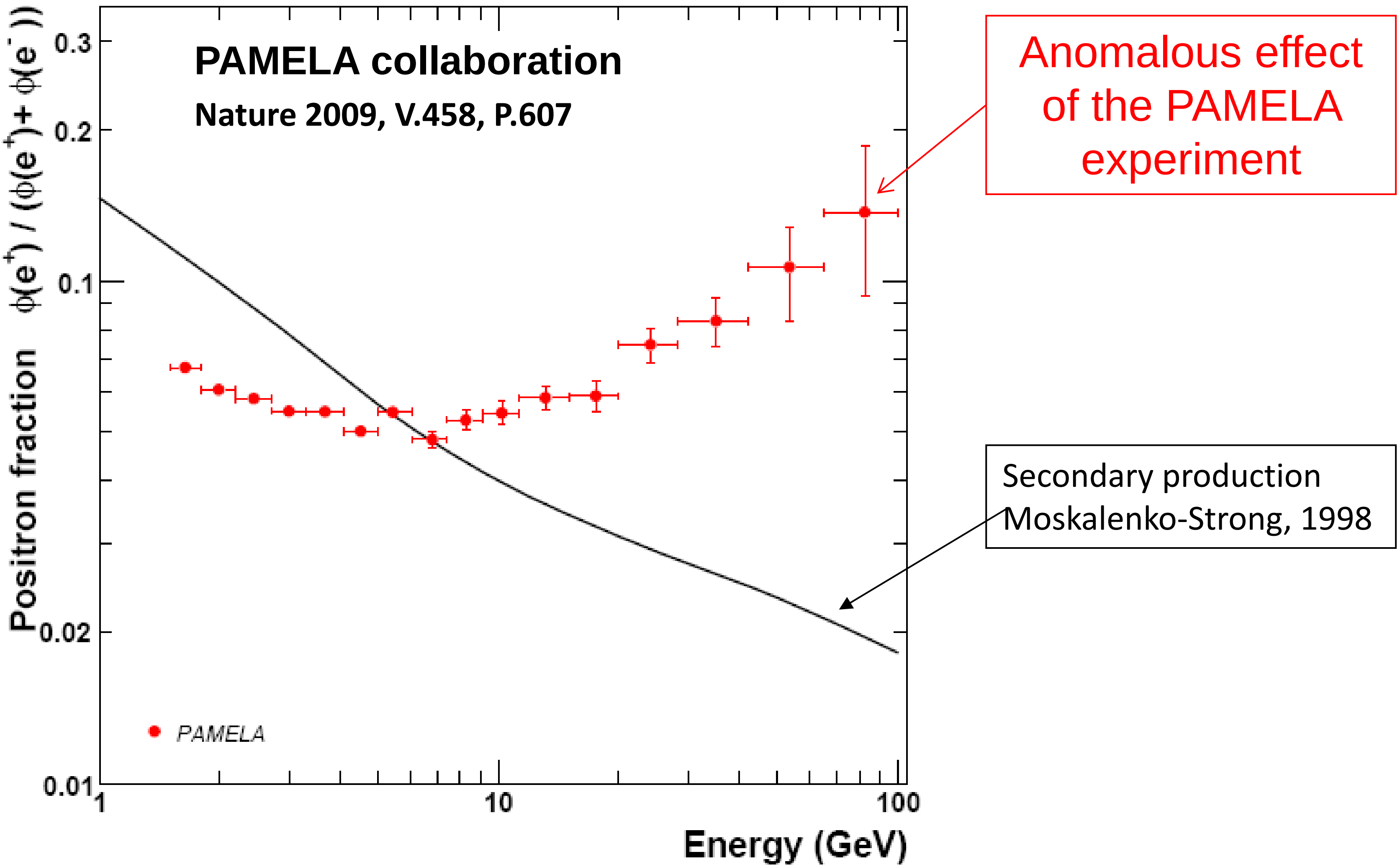




Time of operation
from 21 June 2006 up to 24 January 2016:
2675 days or more than 64 thousands of hours

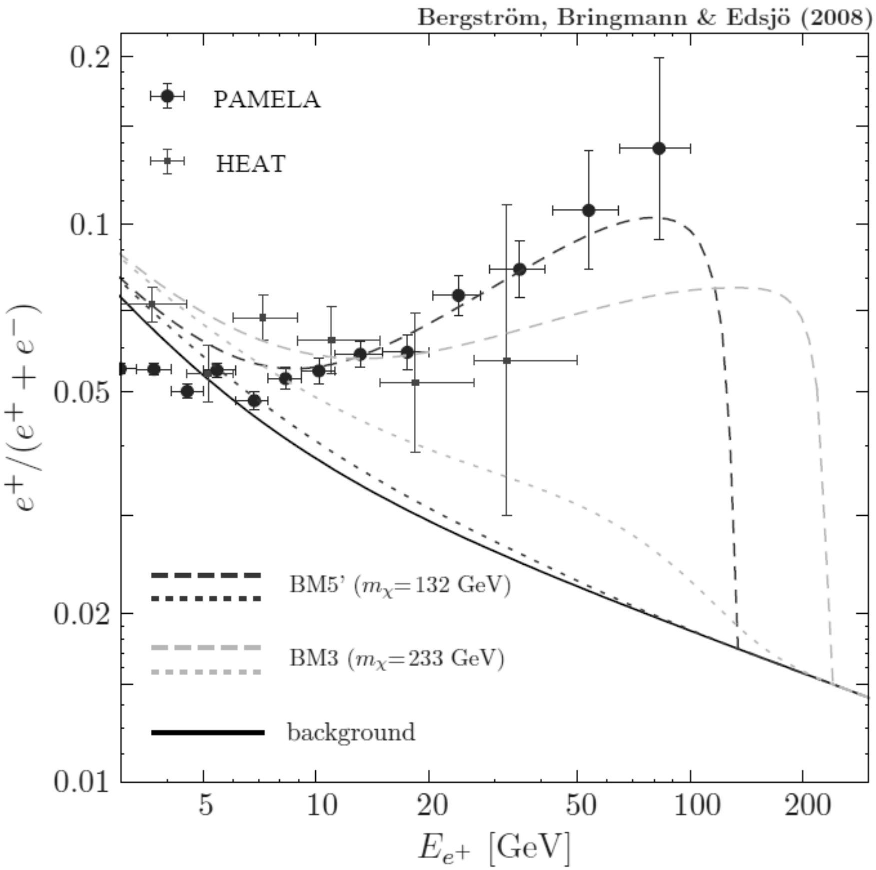
Number of triggers and particles	
Triggers	~ 10 billions
Electrons	~ 500 thousands
Positrons	~ 50 thousands
Protons	~ 750 millions
Antiprotons	~ 5 thousands
Helium	~ 70 millions
Heavier nuclei	~ 150 thousands

Positron to electron + positron ratio



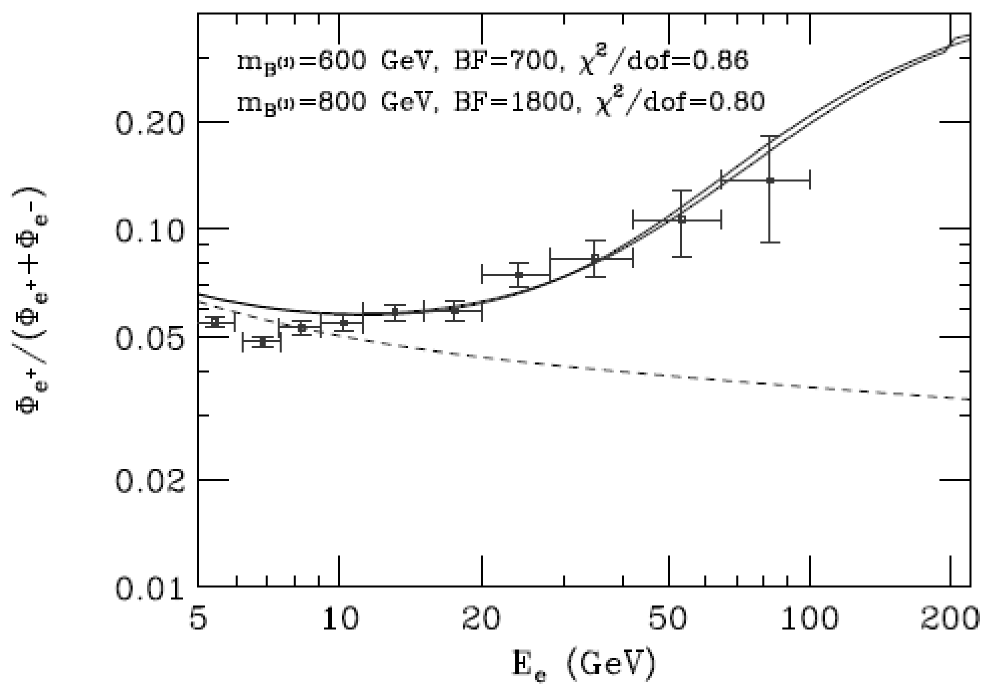
In 2008, the "anomalous effect of the PAMELA experiment" was marked as an outstanding achievement of world science in the field of physics according to the American Institute of Physics.

Positron to electron + positron ratio: nature of dark matter



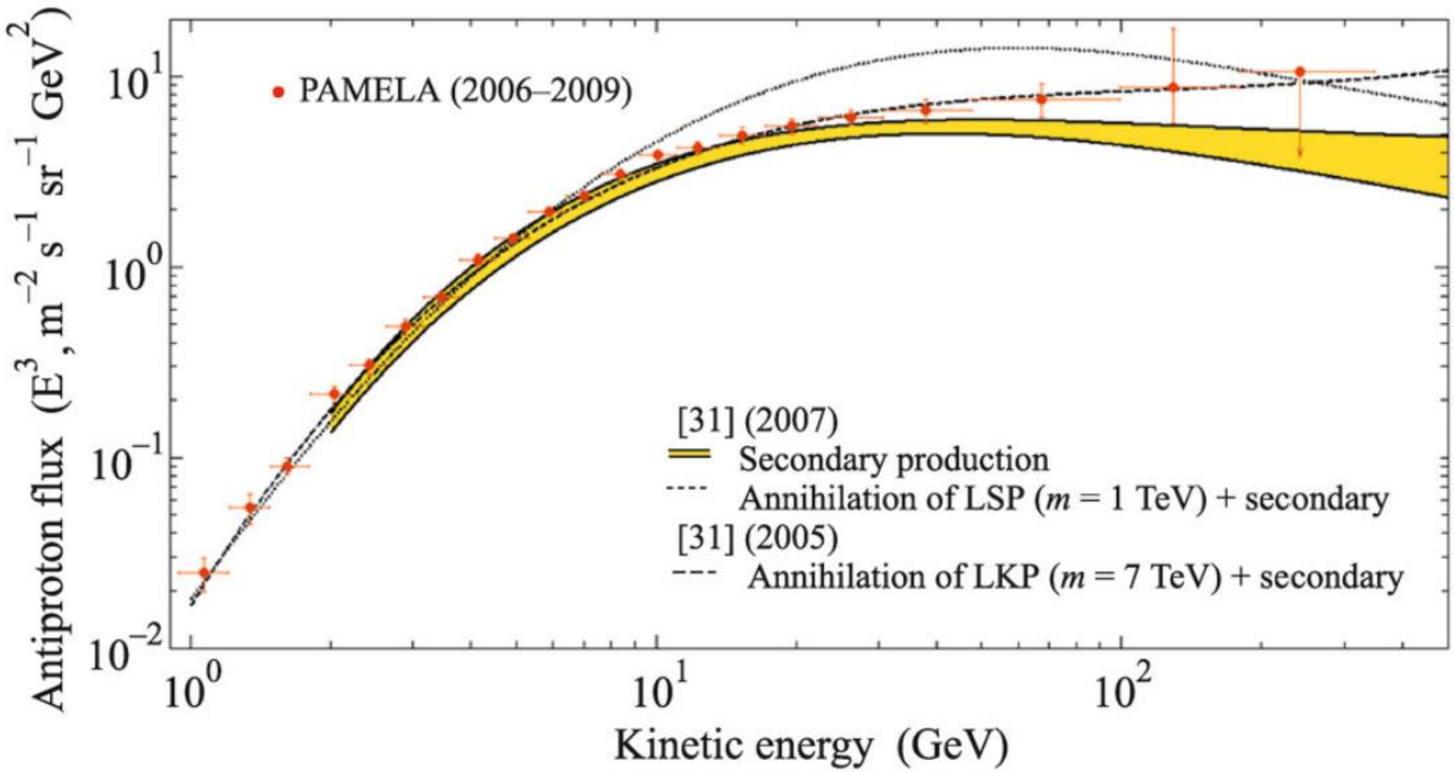
Neutralino annihilation, boost-factor $3 \cdot 10^4$

D. Hooper, K.M. Zurek, arXiv:0902.0593v1



KK annihilation, boost-factors 700 & 1800

Adriani O., et al. JETP Lett. 96 (2013) 621-627

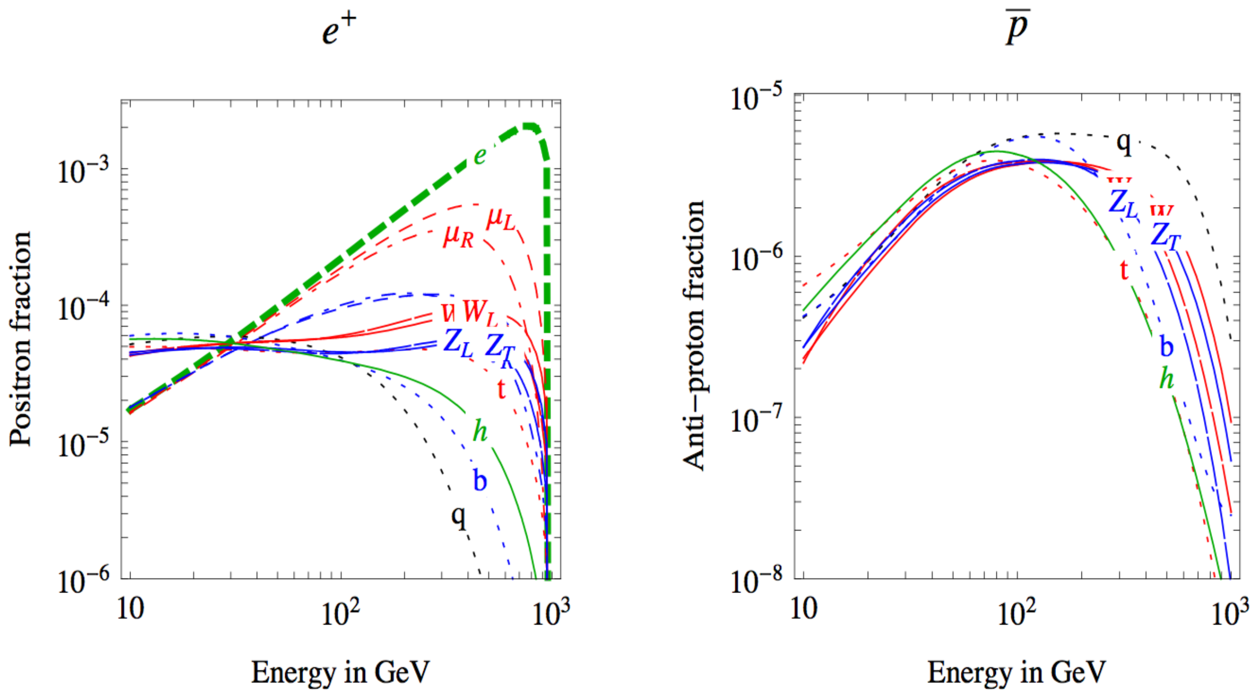


A possible excess of antiprotons was also found. It may be caused by WIMP's decay or annihilation through the hadronic modes.

The shape of spectrum is depends on

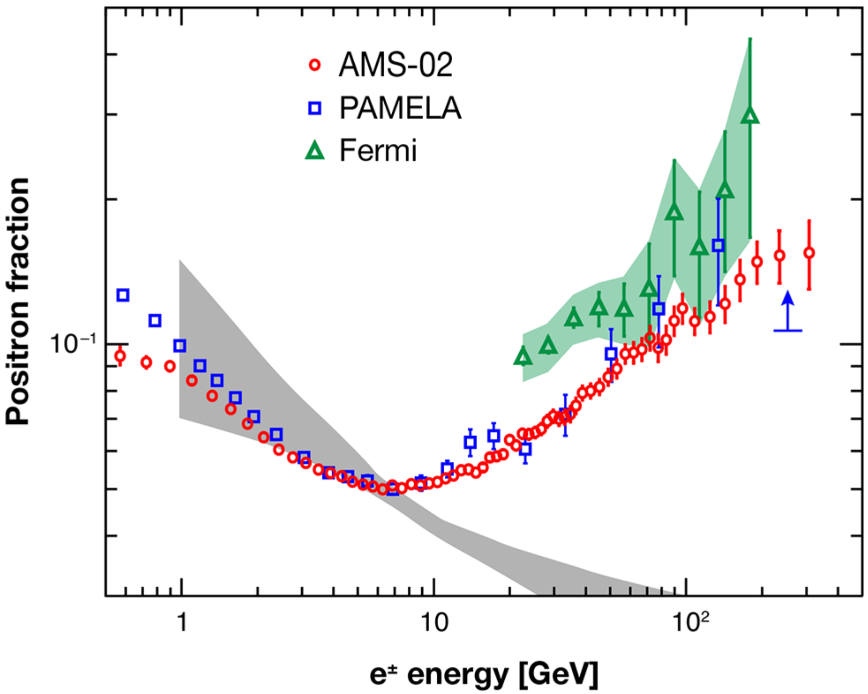
1) Mass of WIMP
2) Channels of annihilation

M_{WIMP}= 1 TeV

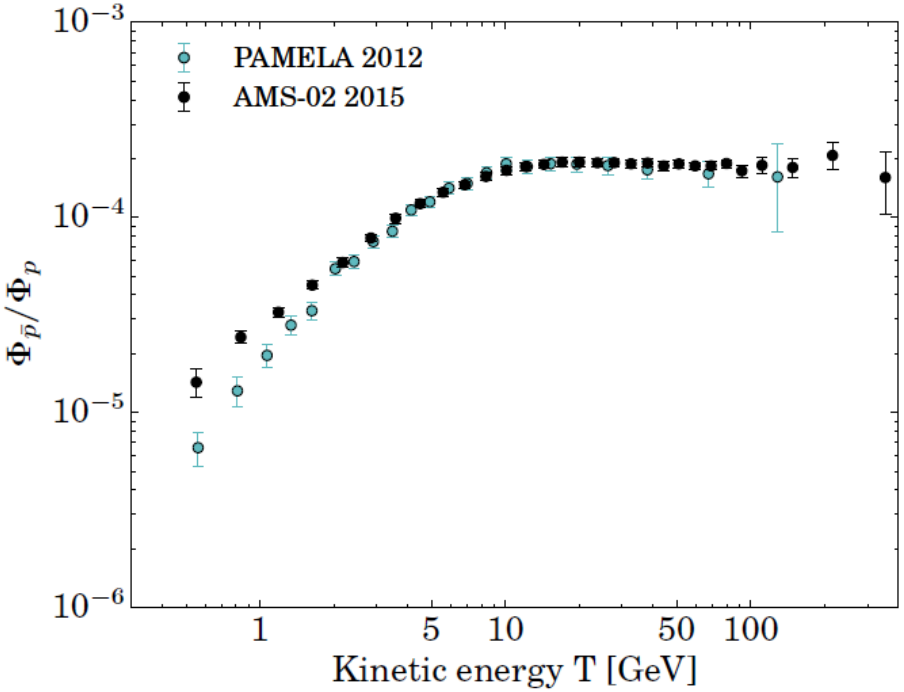


PAMELA vs AMS-02

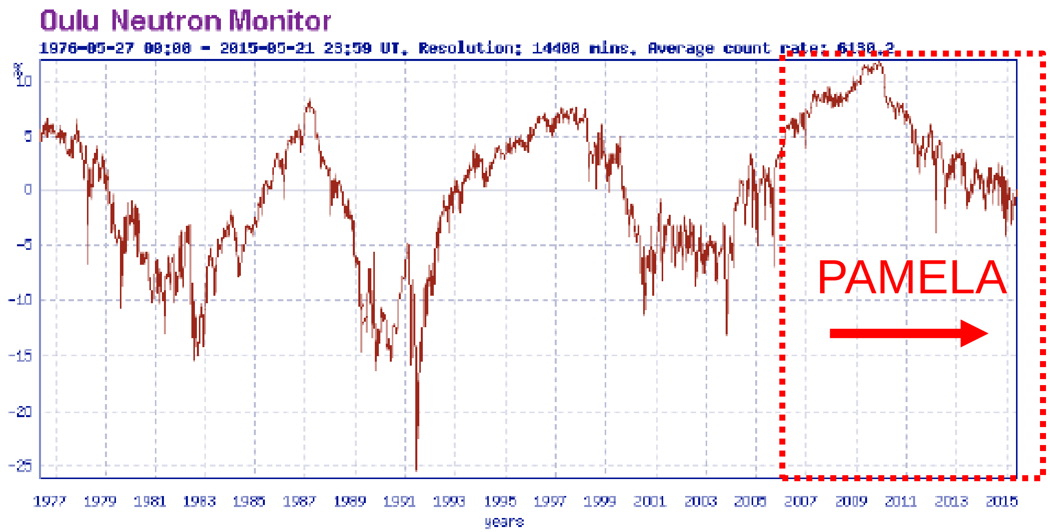
electron to positron ratio



antiproton to proton ratio



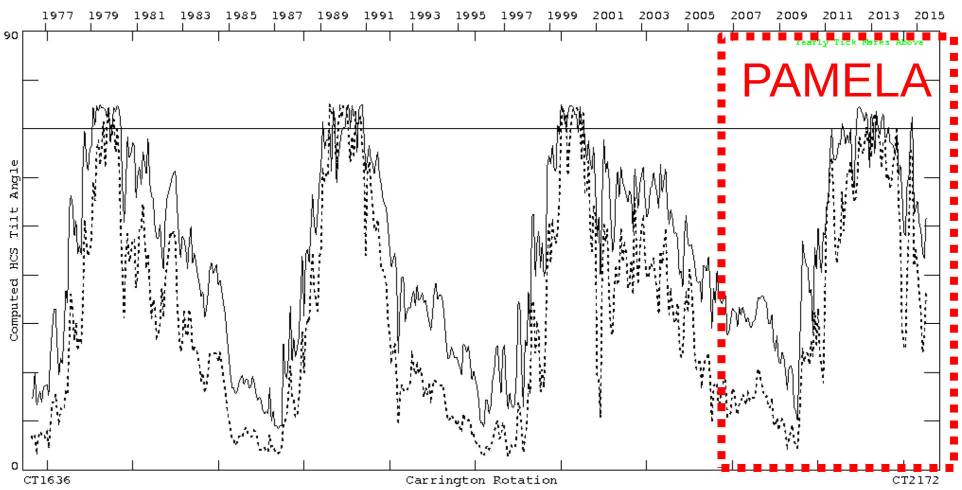
PAMELA and solar conditions



Oulu neutron monitor count rate
http://cosmicrays.oulu.fi/

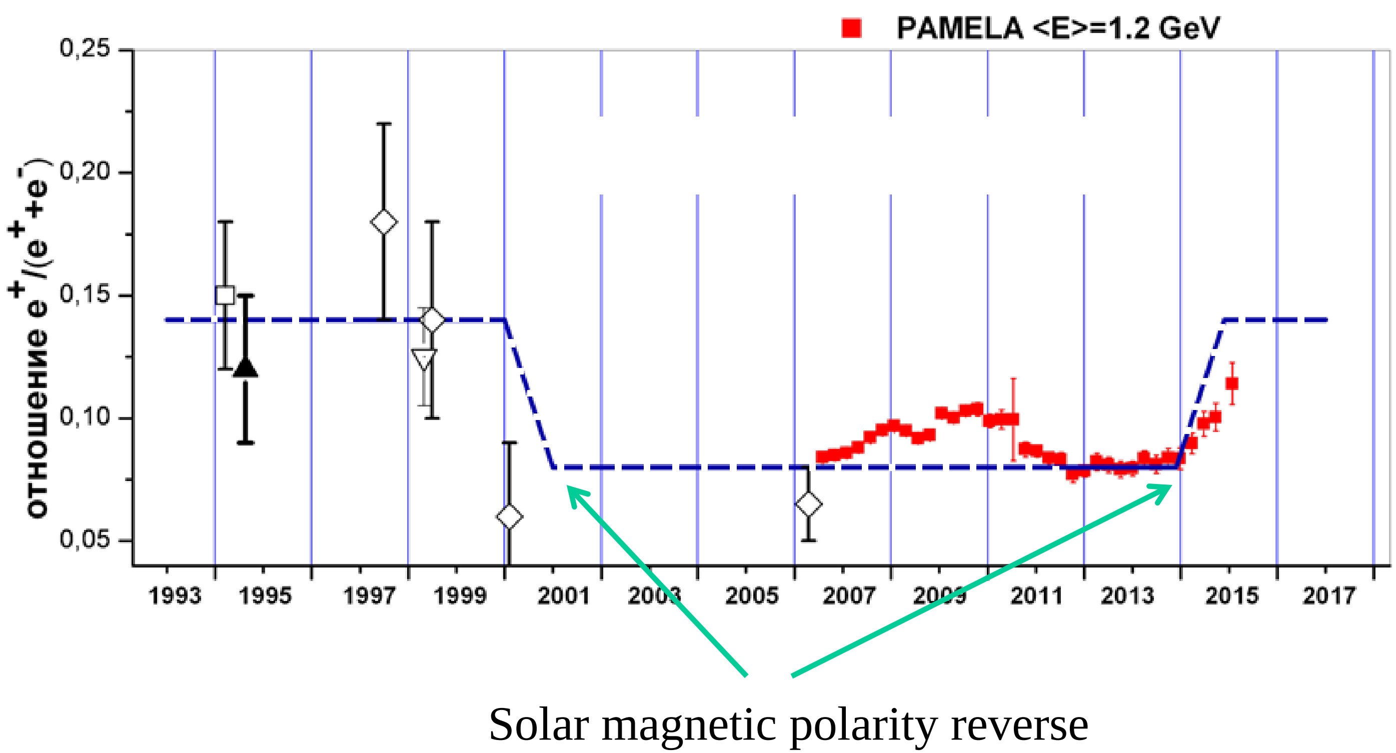
Cycles
23 | 24

Tilt angle of the heliospheric current sheet
http://wso.stanford.edu/



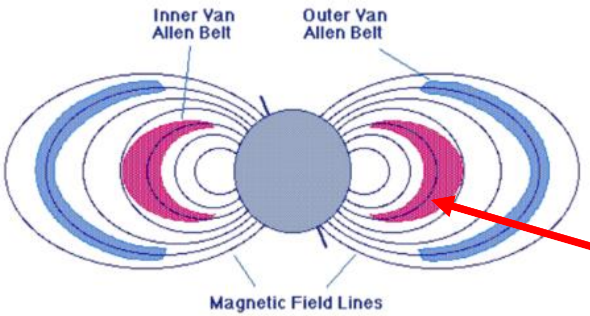
The duration of the PAMELA mission cover almost full 11-th solar cycle

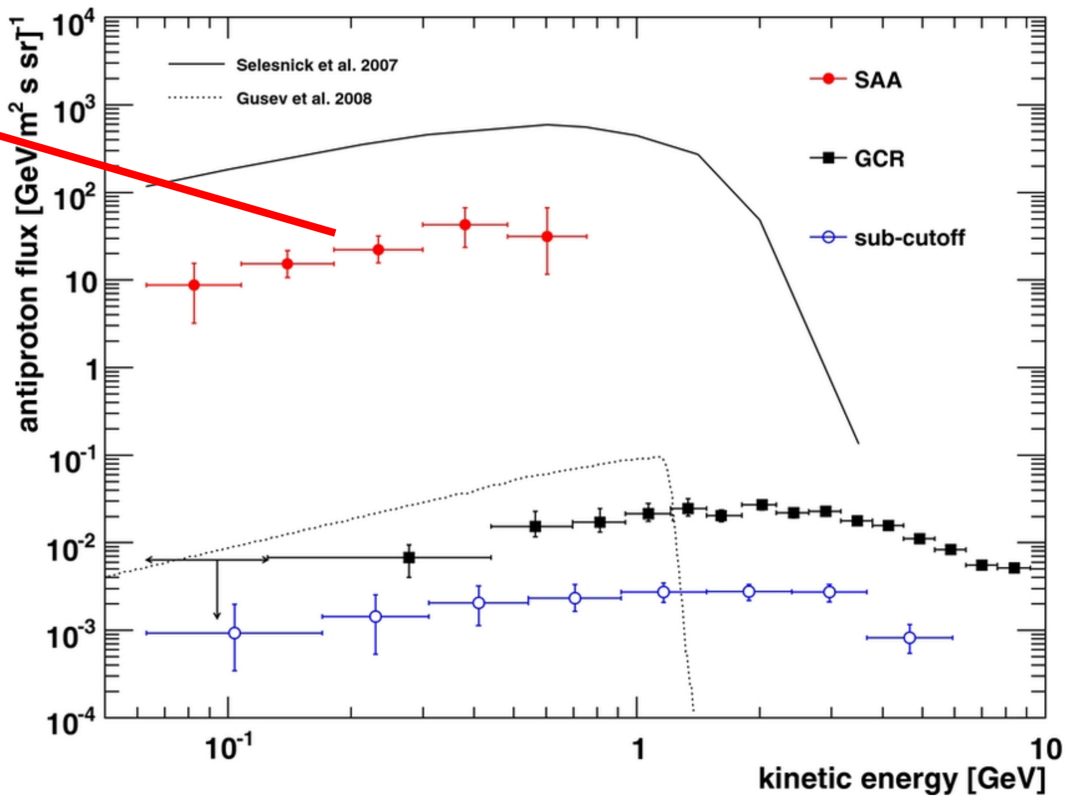
The influence of the polarity of the magnetic field of the Sun on the propagation of particles with different signs of charge in the interplanetary medium



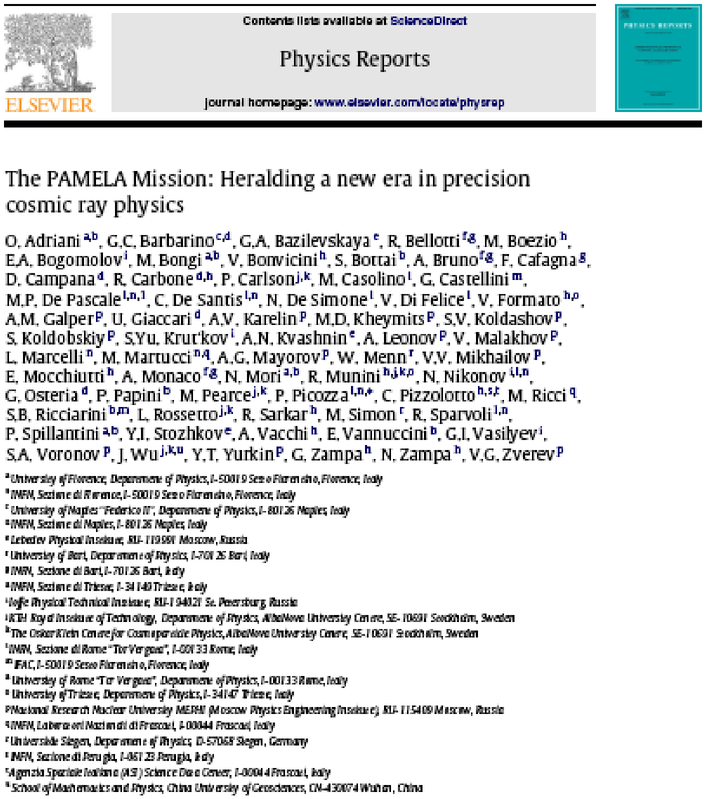
The existence of antiprotons in near-Earth outer space, including in the radiation belt, was firstly discovered

The Astrophysical Journal Letters, 737:L29, 2011





The main PAMELA results



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The PAMELA Mission: Heralding a new era in precision cosmic ray physics

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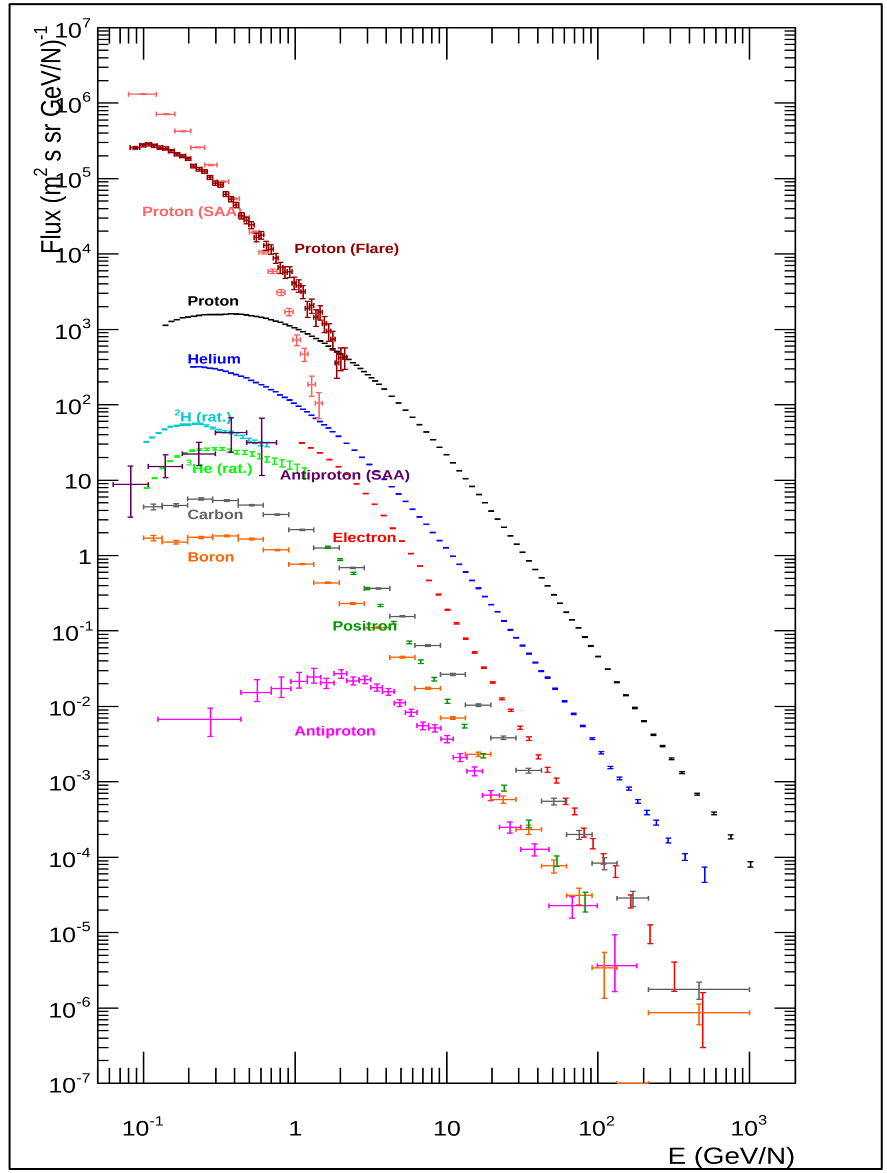


The main PAMELA results

The following results were obtained for the first time with unique accuracy and are important for the development of modern fundamental science in the field of studying the Universe and high-energy physics.

1. Properties of the hypothetical dark matter particles.

1) the ratio of the fluxes of galactic positrons to the total flux of electrons and positrons was measured in the energy range 1.5-300 GeV (anomalous effect of the PAMELA experiment);
2) the ratio of the fluxes of galactic antiprotons and protons was measured in the energy range from 0.08 to 350 GeV;
3) measured energy spectra of galactic positrons and antiprotons in the above energy ranges.

2. Galactic cosmic rays and the problem of the baryon asymmetry of the Universe:

1) the energy spectra of electrons and positron were measured;
2) the energy spectra of protons and light nuclei (up to carbon) were measured;
3) an upper limit has been established for antinuclear fluxes heavier than antiprotons in GCR.

3. Radiation belts of the Earth:

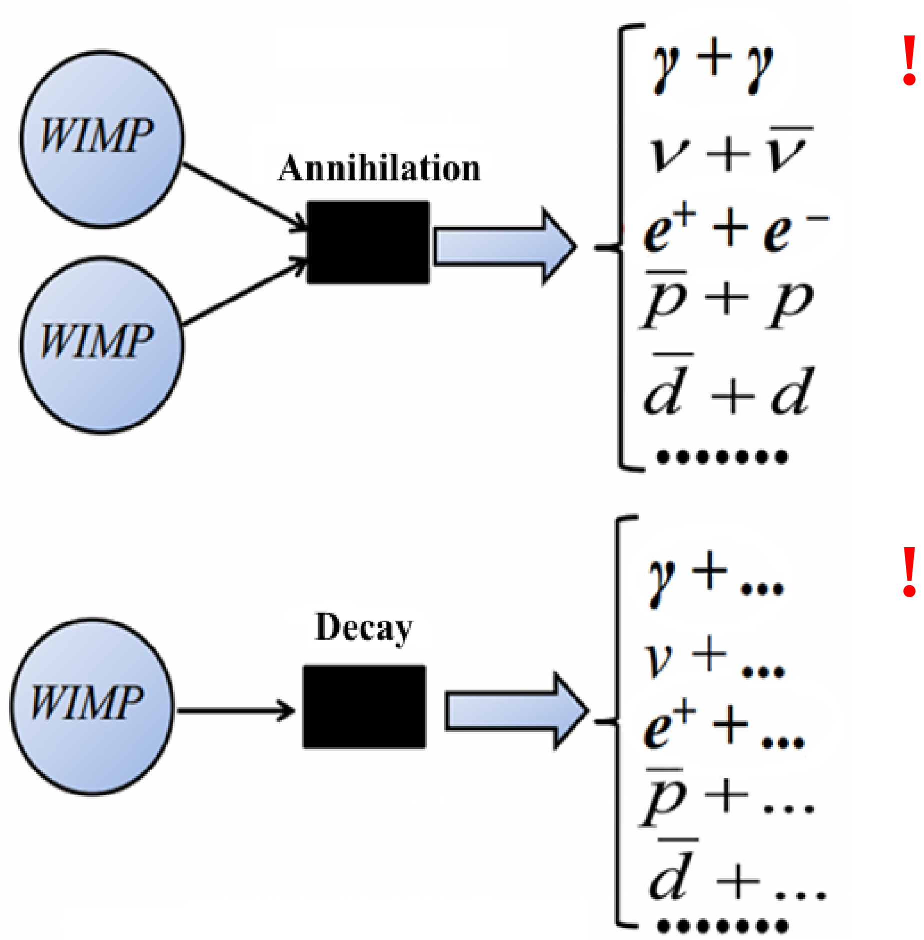
1) trapped antiprotons in the inner radiation belt was discovered and the differential energy spectrum from 80 MeV up to 1 GeV were measured;
2) the energy spectra of protons in the Earth’s radiation belt were measured in a wide range of geomagnetic latitudes in the energy range from 0.1 to 5 GeV.

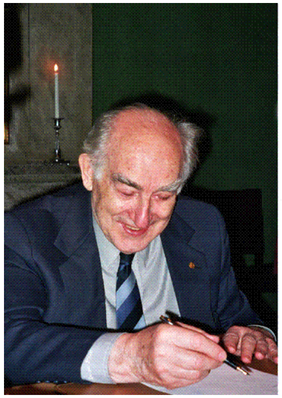
4. Solar-Earth connections:

1) the energy spectra of protons, helium nuclei, electrons, and low-energy positrons were measured (solar modulation);
2) the energy spectra of protons accelerated during the active processes on the Sun solar were measured.

Experiments which shows signatures on dark matter

Experiment	Comments
DAMA/LIBRA: yearly modulation	No confirmation from other experiments
CoGeNT: some DM scattering events	In contradiction with some other data
EGRET excess of gamma with E ~ГэВ	Not confirm by FERMI
INTEGRAL 511 keV line from the center of Galaxy	Not a spherical symmetry
PAMELA: anomalous positron to electron ratio Confirmed by AMS-02	The effect may be caused by dark matter or pulsar - does not point unequivocally to the dark matter
FERMI: bump on electron + positron flux	
PAMELA: antiproton to proton ratio Confirmed by AMS-02	The effect may be associated with the annihilation of dark matter or the interaction of cosmic rays
FERMI: an excess of gamma rays in the direction of the galactic center	There is no explanation; maybe it astrophysical effect
WMAP radio "haze"	Meets "FERMI bubbles" - perhaps caused by the flow emanating from the galactic center
IceCube: solar neutrino fluxes	In progress


WIMP
WIMP
Annihilation
$\gamma + \gamma$
$\nu + \bar{\nu}$
$e^+ + e^-$
$\bar{p} + p$
$\bar{d} + d$
!
WIMP
Decay
$\gamma + ...$
$\nu + ...$
$e^+ + ...$
$\bar{p} + ...$
$\bar{d} + ...$
!



УТВЕРЖДАЮ
Директор
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Физического института
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академик
Месяц Г.А.
2009 г.

ПРОЕКТ ГАММА-400

ИССЛЕДОВАНИЕ КОСМИЧЕСКОГО ГАММА-ИЗЛУЧЕНИЯ И ПОТОКОВ ЭЛЕКТРОНОВ И ПОЗИТРОНОВ В ДИАПАЗОНЕ ЭНЕРГИЙ 1-3000 ГэВ

От ФИАН

Руководитель научного направления
академик
Гинзбург В.Л.
2009 г.

Научный руководитель проекта
ГАММА-400
профессор, г.н.с.
Гальпер А.М.
21 мая 2009 г.

Москва, 2009 г.

APPROVE
Director of
Lebedev Physical Institute
Academician G.A. Mesyats
June 2, 2009

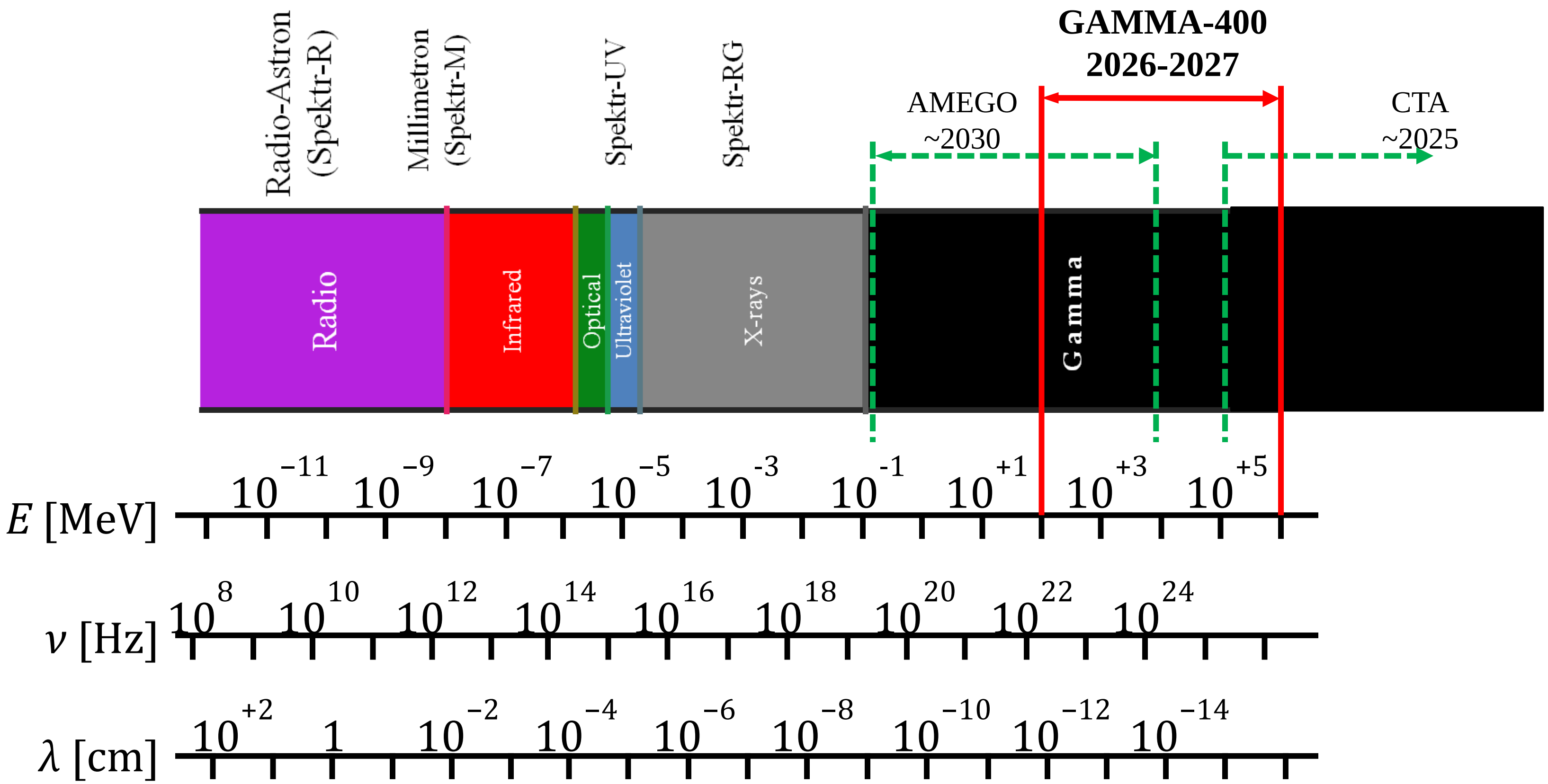
GAMMA-400 Project
Study of cosmic gamma rays and electron/positron fluxes in the energy range of 1-3000 GeV

Academician V.L. Ginzburg

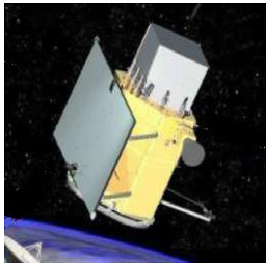
PI GAMMA-400 Project A.M. Galper

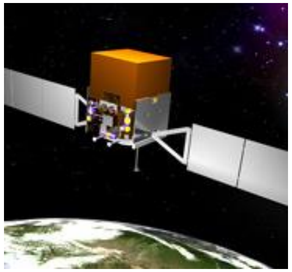
Moscow, 2009

Russian space observatories for various EM spectrum researches

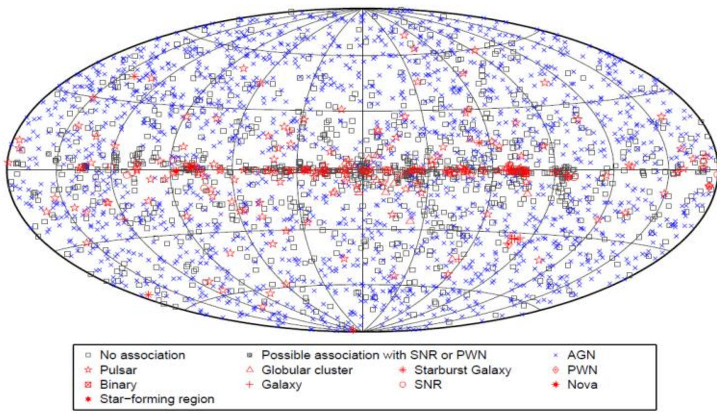


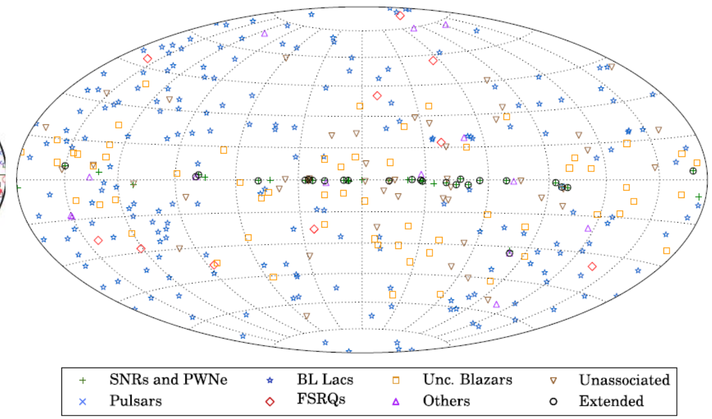
Gamma-ray study of discrete sources on current spacecraft





AGILE	Fermi-LAT	CALET	DAMPE
Italy	USA	Japan	China
2007	2008	2015	2015
100 MeV – 50 GeV	100 MeV – 300 GeV	1 GeV – 10 TeV	5 GeV – 10 TeV

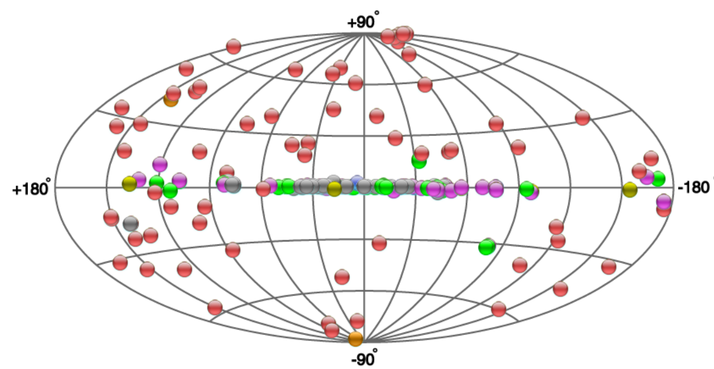




~33% sources are unidentified

Fermi-LAT angular resolution is ~0.1° (E_γ > 10 GeV)

Ground-based telescope angular resolution is ~0.1° (E_γ ~ 100 GeV)

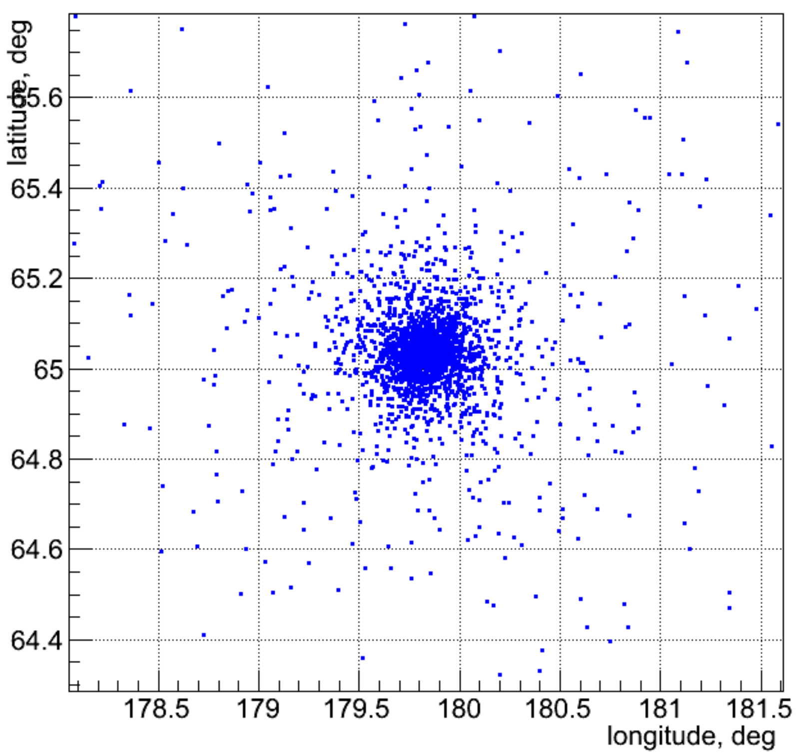


Distribution of 210 discrete sources
(**TeVCat**, E_γ > 100 GeV)

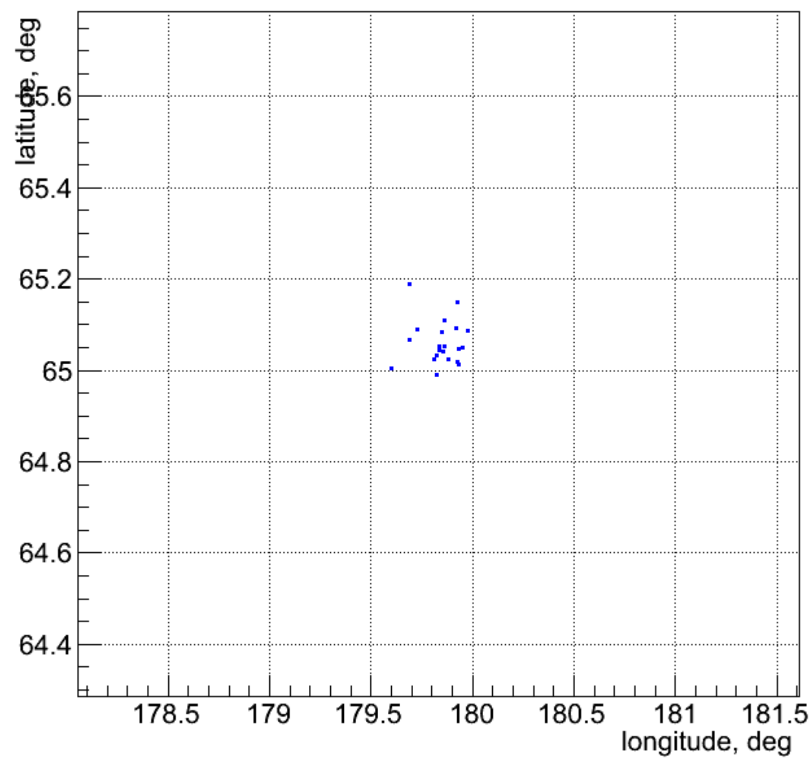
GAMMA-400 main scientific goals

- 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 **(~0.01° at E_γ > 100 GeV)** and energy resolutions **(~2% at E_γ > 100 GeV)**.

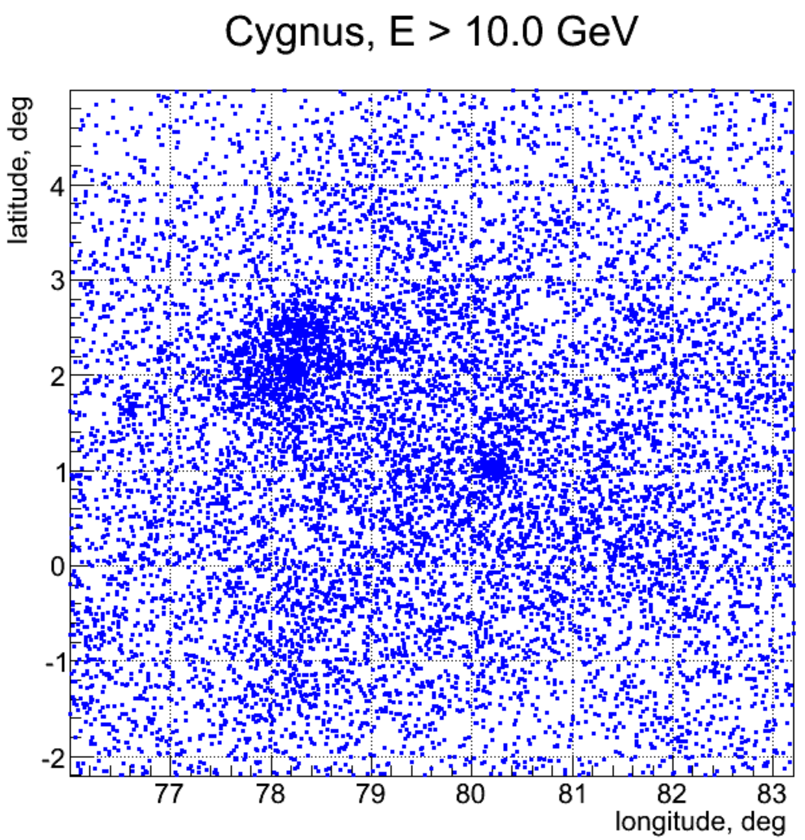
Mkn 421, E > 10.0 GeV

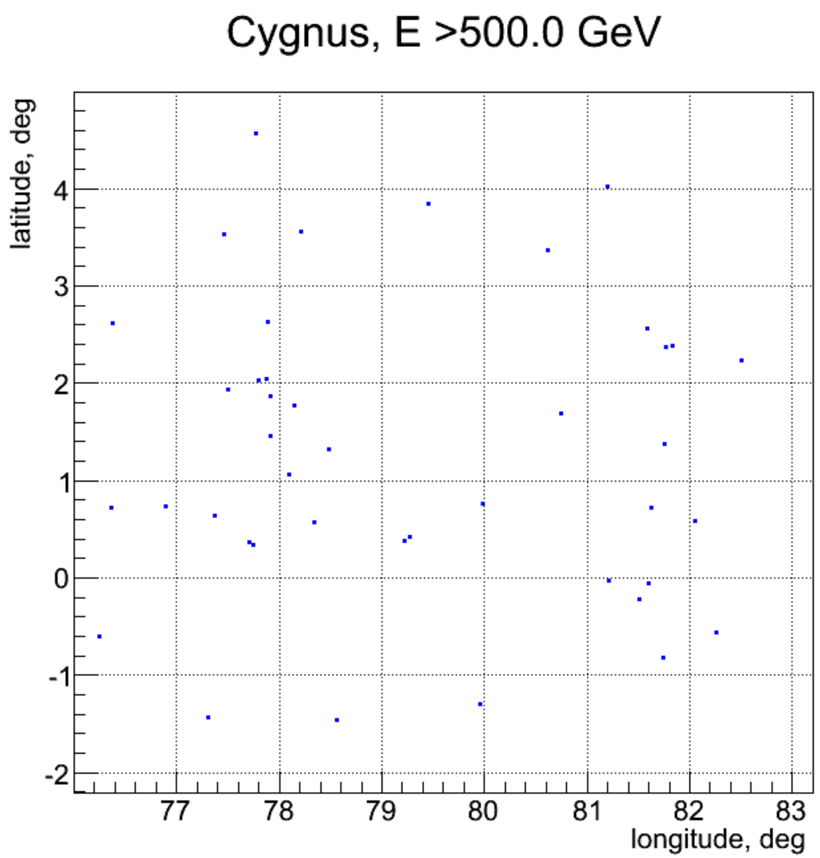


Mkn 421, E >500.0 GeV

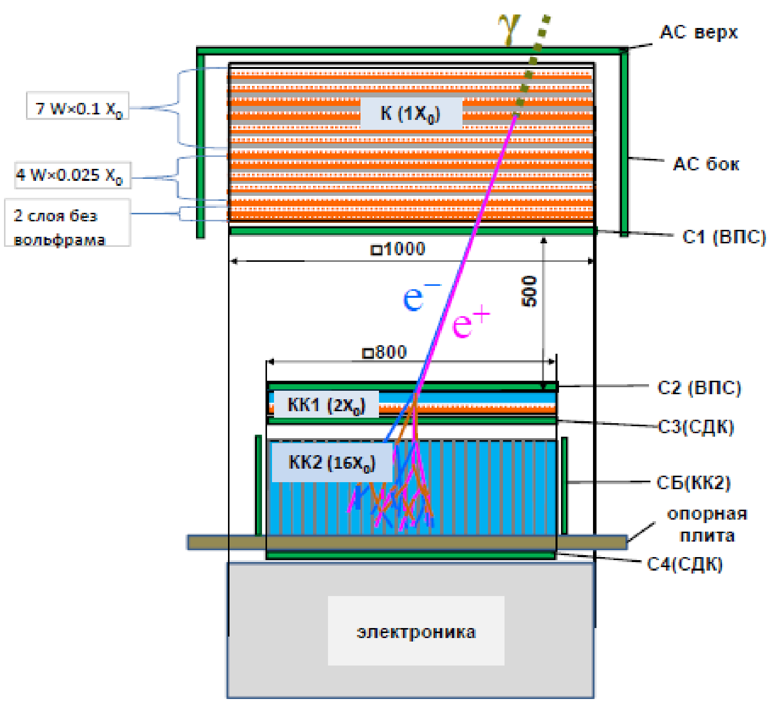


Complex source as seen by Fermi/LAT

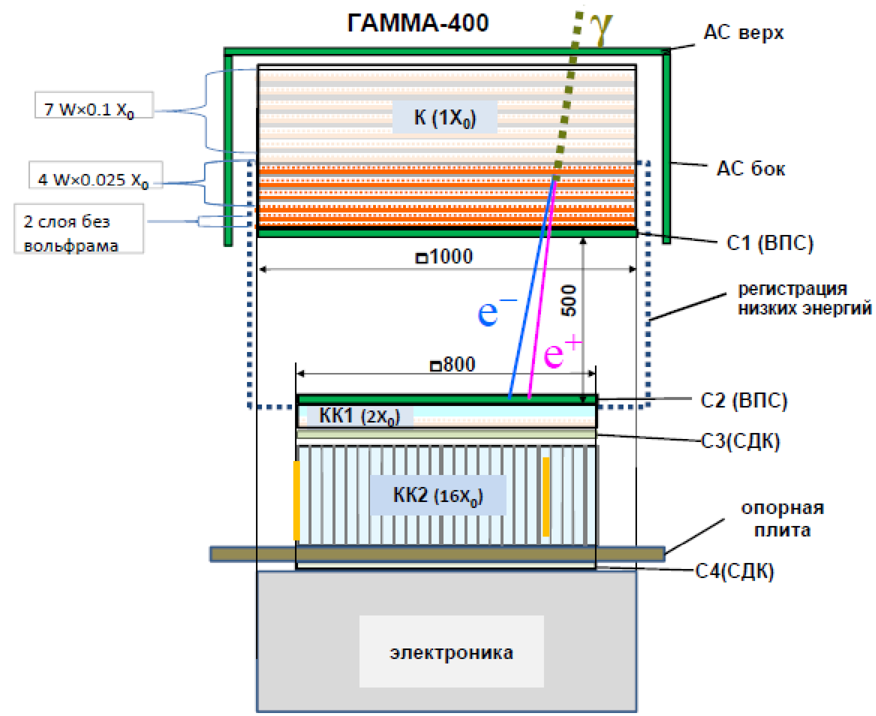




High energy (> 100 MeV)

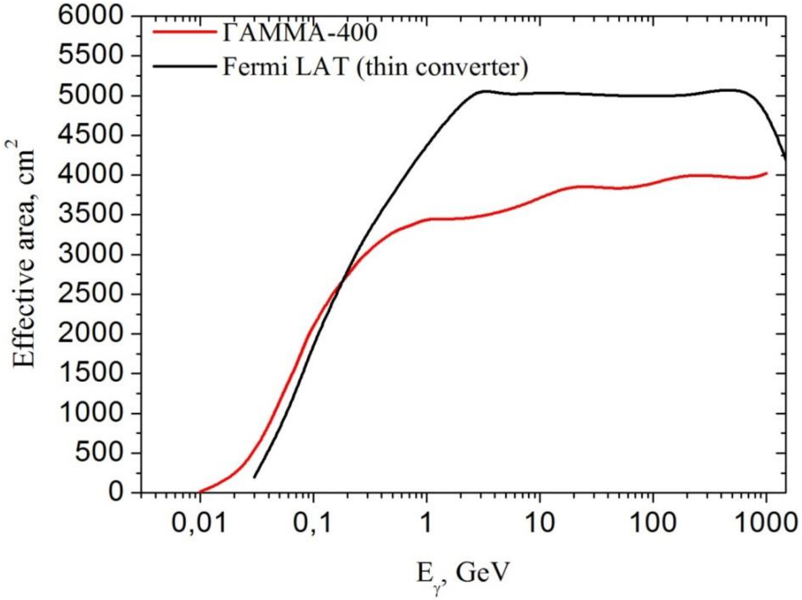


Low energy (> 20 – 100 MeV)

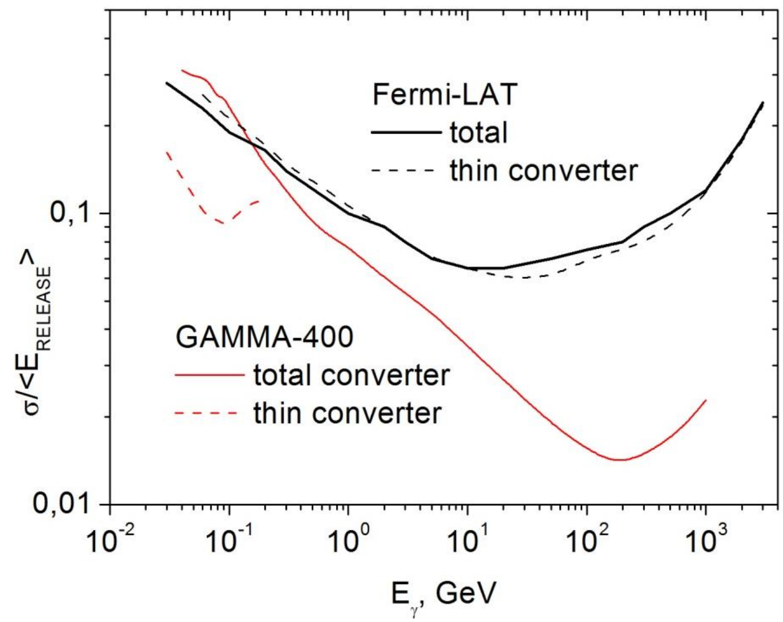


GAMMA-400 characteristics (from simulation)

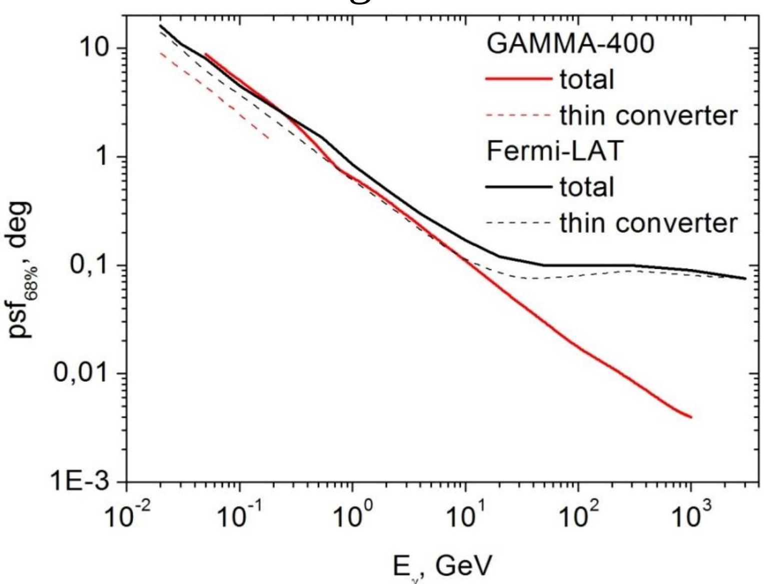
Effective area (on-axis)



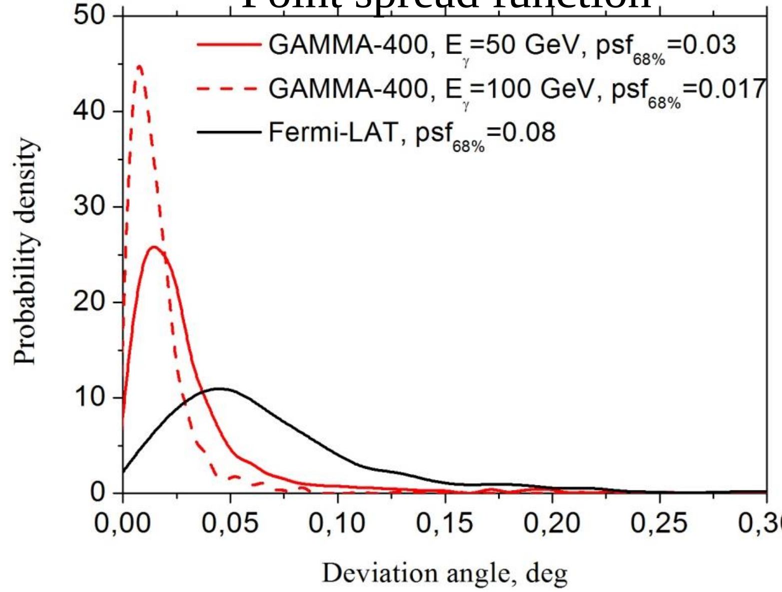
Energy resolution



Angular resolution



Point spread function



GAMMA-400 and other experiments

	SPACE-BORN EXPERIMENTS					GROUND STATIONS			
	AGILE	**Fermi-LAT**	**DAMPE**	**CALET**	**GAMMA-400**	**H.E.S.S.-II**	**MAGIC**	**VERITAS**	**CTA**
Particles	γ	γ	e, nuclei, γ	e, nuclei, γ	γ, e	γ	γ	γ	γ
Operation period	2007-	2008-	2015	2015	~2026	2012-	2009-	2007-	~2020
Regime of operation	Sky scan				Continuous observation up to 100 days	Observation for hours			
Energy range, GeV	0.03-50	0.02-300	5-10000	10-10000	**0.02-~400**	> 30	> 50	> 100	> 20
Angular resolution (E_γ = 100 geV)	0.1° (E_γ~1 GeV)	0.1°	0.1°	0.1°	**0.01-0.02°**	0.07°	0.07° (E_γ = 300 GeV)	0.1°	0.1° (E_γ = 100 GeV) 0.05° (E_γ > 1 TeV)
Energy resolution (E_γ = 100 GeV)	50% (E_γ~1 GeV)	10%	1.5%	2%	**2-3%**	15%	20% (E_γ = 100 GeV) 15% (E_γ = 1 TeV)	15%	20% (E_γ = 100 GeV) 5% (E_γ = 10 TeV)
Sensitive area, m^2	0,36	1,8	0,36	0,1	**0,64**				

- **Program I:** galactic disk scan

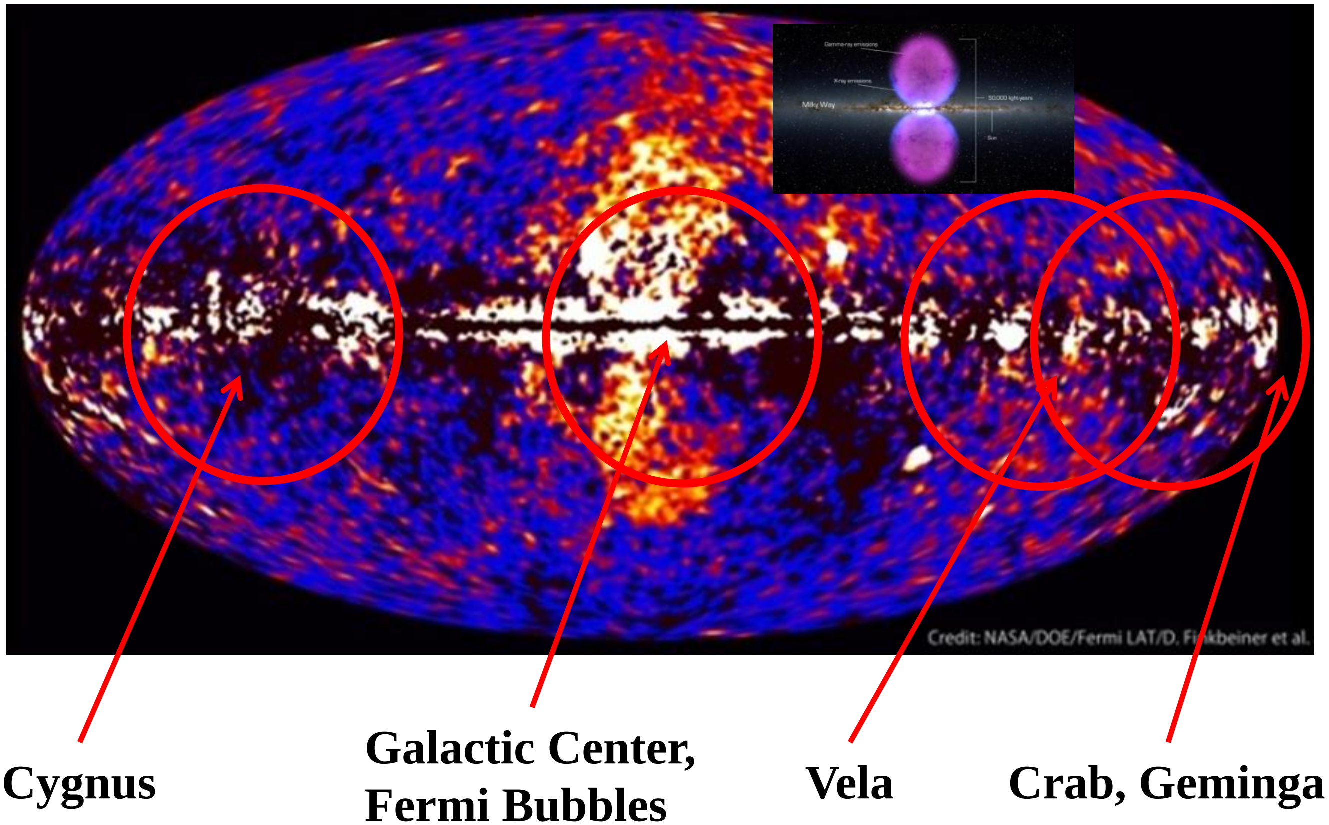
Telescope axis orientation: b=0°, 0° < l < 360°
Exposure: 1440 days

- **Program II:** center of Galaxy observation

Telescope axis orientation: b=0°, l= 0°
Exposure: 1440 days

Note: most of the observations will be carried out simultaneously in the gamma and x-ray ranges.

Sky regions observed by GAMMA-400 with the aperture of ±45°



Expected number of sources (with $N_\gamma > 30$) observed by GAMMA-400

Catalog	Energy interval $E_{min} \div E_{max}$	Number of sources with $N_\gamma > 30$	
		Observation program I	Observation program II
3FGL	100 MeV – 100 GeV	**2331**	**848**
3FGL	300 MeV – 100 GeV	**2039**	**775**
3FGL	1 GeV – 100 GeV	**1293**	**642**
3FGL	3 GeV – 100 GeV	**432**	**425**
3FHL	10 GeV – 2 TeV	**83**	**106**
3FHL	20 GeV – 2 TeV	**34**	**46**
3FHL	50 GeV – 2 TeV	**8**	**18**

According to modern Fermi/LAT observations

Number of expected gamma (according to Fermi/LAT)

Program I:

100 MeV - 2 TeV – 10.3 millions of events

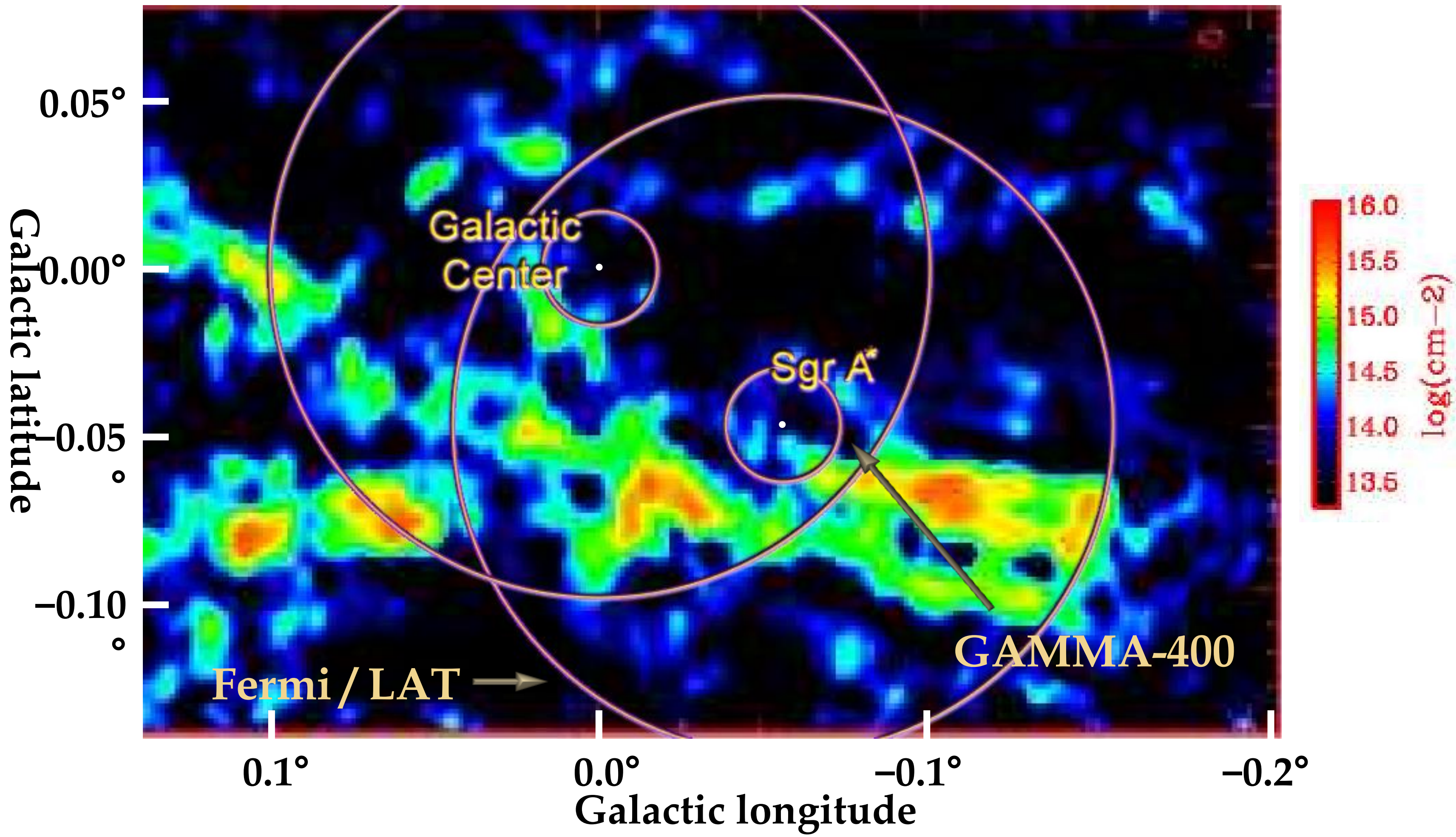
10 GeV - 2 TeV – 28.7 thousands of events

Program II:

100 МэВ - 2 ТэВ – 15.1 millions of events

10 ГэВ - 2 ТэВ – 38.7 thousands of events

Galactic center observations: GAMMA-400 vs Fermi-LAT



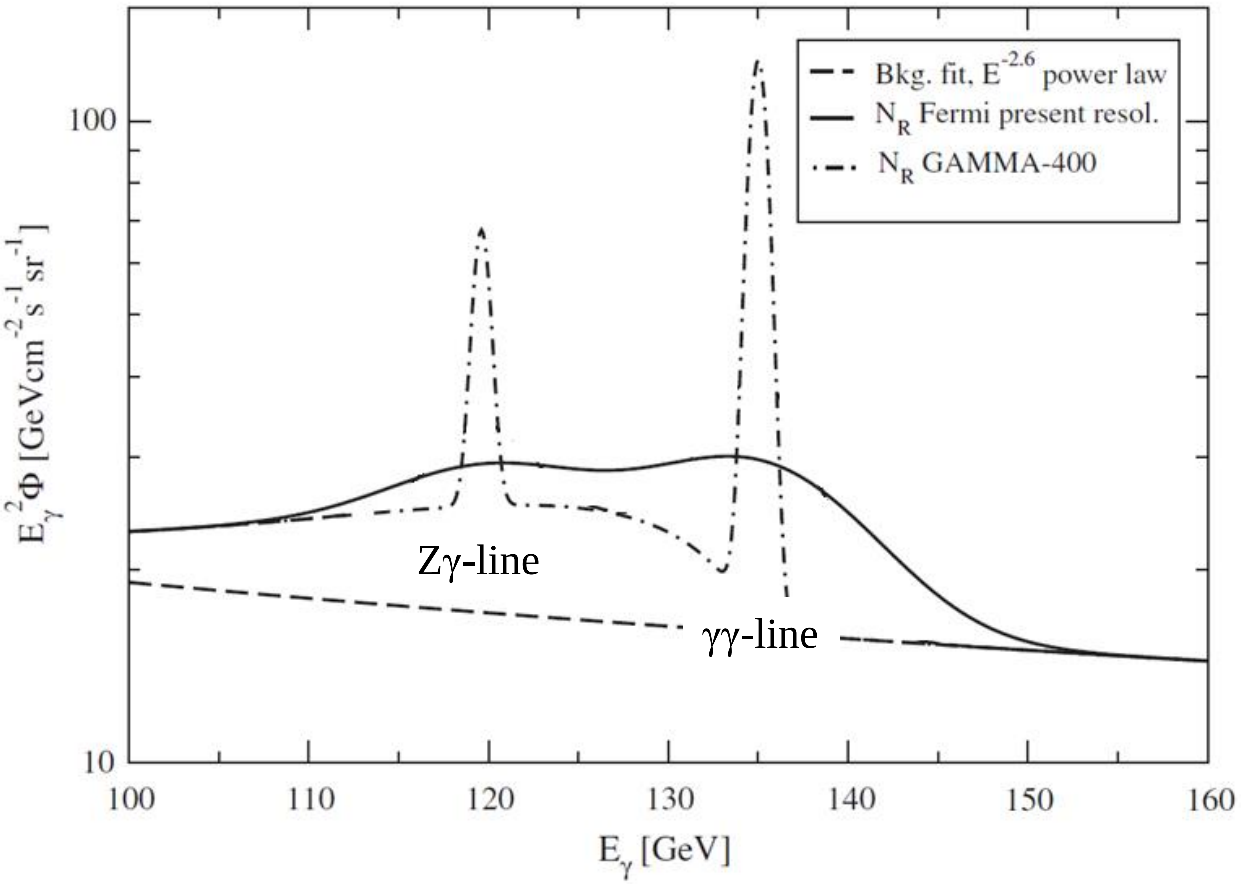
Background:

Integrated intensity map of the NH_3 (1,1) emission (1.2652 cm wavelength) from [arXiv:1402.4531].

Circles:

point spread functions for Fermi/LAT (outer: ~0.1°) and GAMMA-400 (inner: ~0.015°) at $E_\gamma \sim 100$ GeV

GAMMA-400 vs Fermi/LAT in searching for gamma-lines from DM



ΔE/E
10%
1%

FIG. 3. The γ-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 γ-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 γ-ray background is also shown.

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130 GeV fingerprint of right-handed neutrino dark matter

Lars Bergström*

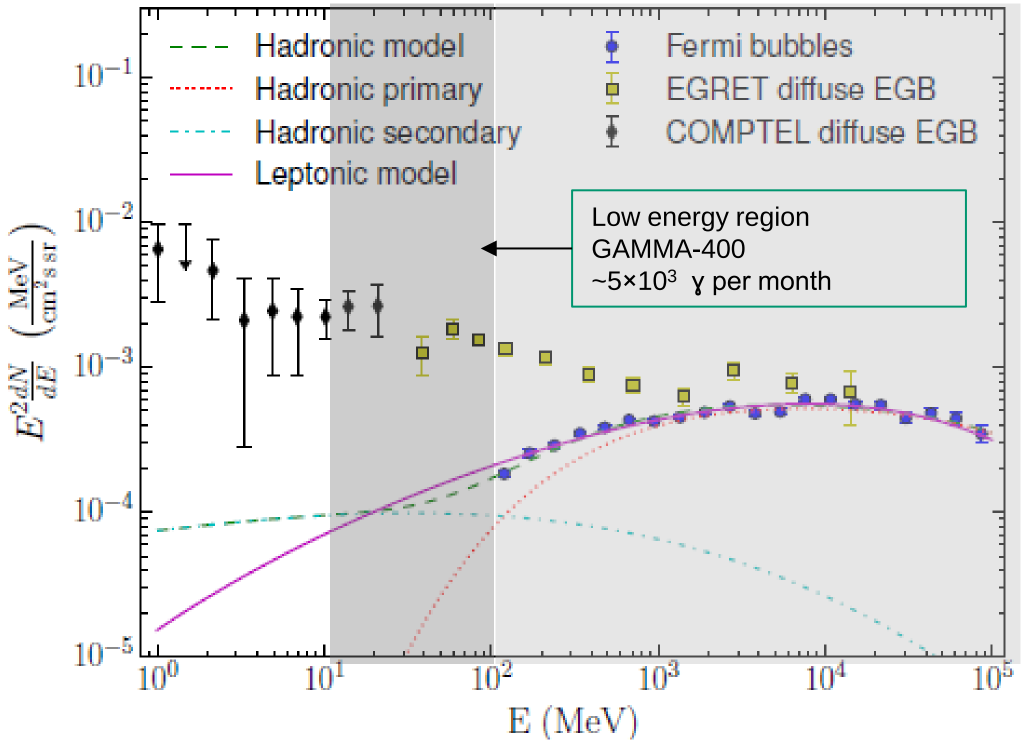
Observation exposure of different areas on the sky: GAMMA400 vs Fermi

The Fermi collaboration achieved angular resolution (PSF3) **3 times worse than GAMMA-400**, and energy resolution (EDISP3) **2 times worse than GAMMA-400**. However, an improvement in these characteristics was achieved by **significantly reducing the effective area of Fermi/LAT**.

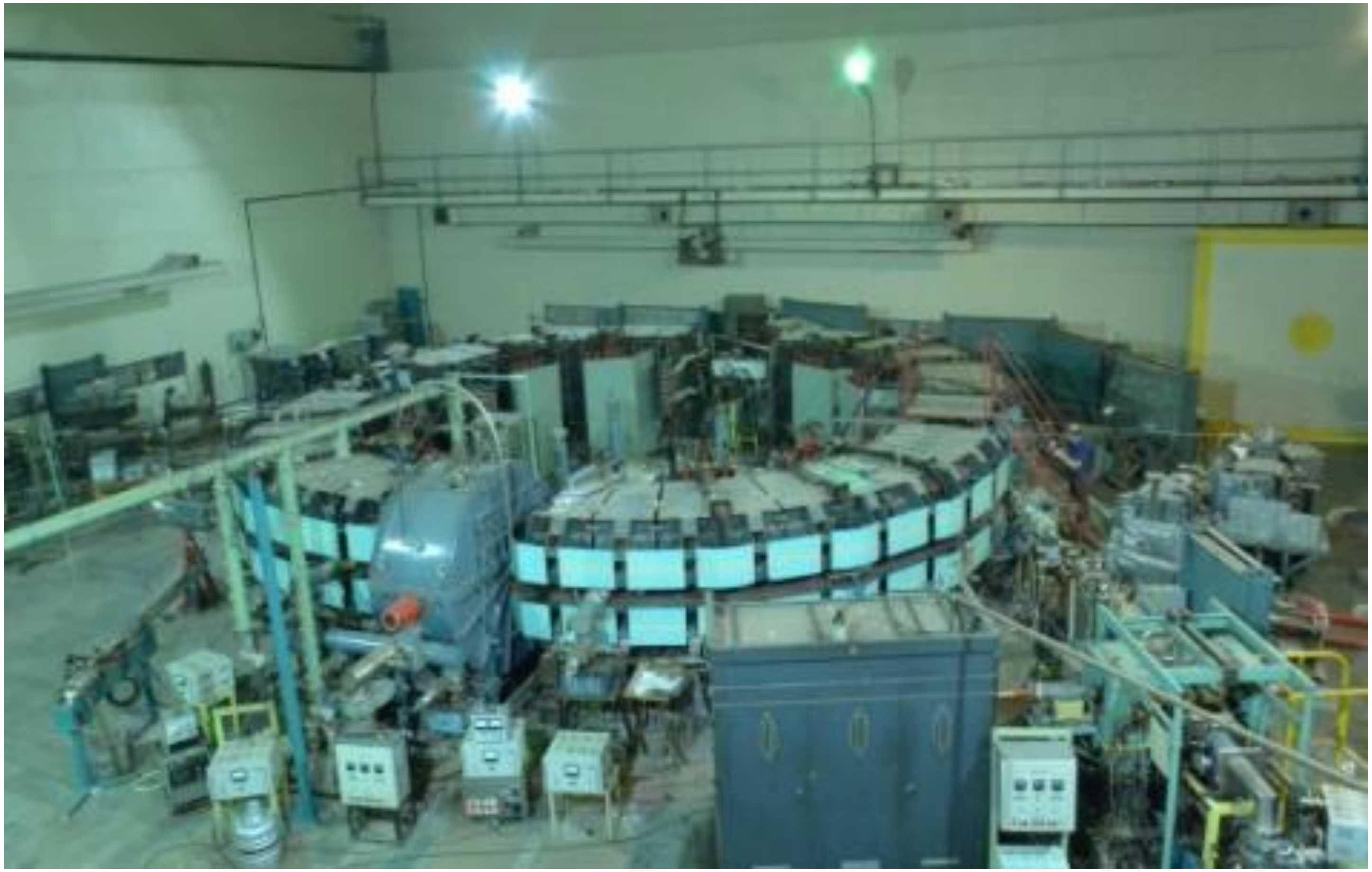
Fermi regime	Total Fermi acceptance (7.5 years), см^2 с	Equivalent GAMMA-400 exposure, months
Total	1.8×10^{11}	17
PSF3	0.47×10^{11}	4.5
EDISP3	0.26×10^{11}	2.4
PSF3 + EDISP3	0.12×10^{11}	1.1

The first physical result will be received in 3 months.

Understanding the nature of gamma-ray emission from the Fermi bubbles



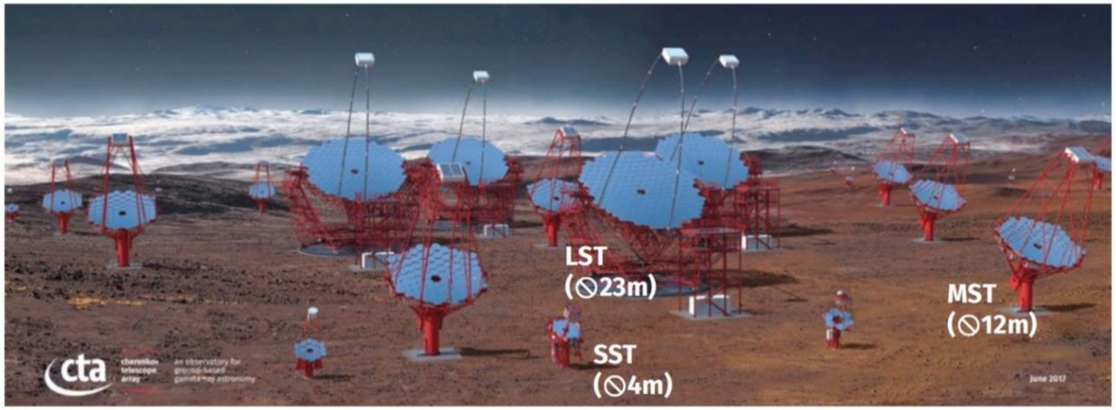
Calibration of GAMMA-400 detectors on synchrotron C-25R (LPI, Pakhra)



Calibration of GAMMA-400 ToF detectors on positron beam

Possible collaborations

Cherenkov Telescope Array



“One of our worries in terms of maximising the science output of **CTA** is the coverage of the GeV domain - that is crucial for interpretation of sources - after the termination of Fermi. Obviously, **GAMMA-400** is very well suited to fill that gap, and **joint observations or joint projects seem very natural**.
We are currently slightly reorganising our science groups, and one essential element of CTA science planning in the next years will be to set up relations with other instruments aiming to coordinate multiwavelength observations, ultimately with the goal to aim for MoUs where appropriate. **We are certainly be very happy to interact with your team on this** (our yet-to-be appointed new science coordinator would be the prime contact).”

Professor Werner Hofmann

Conclusion

Extra-atmospheric and terrestrial astrophysical studies on high and ultra-high energy gamma astronomy provide extremely important information:

on physical conditions in discrete astrophysical objects,

on the properties of interstellar and intergalactic space,

on the nature of dark matter.

After the Fermi-LAT, the launch of the GAMMA-400 gamma telescope presents a unique opportunity to significantly improve data on gamma radiation of high and ultrahigh energies, on the fluxes of high-energy electrons and positrons due to significantly better angular and energy resolutions, large area, and long-term continuous observations.

At present, the Lebedev Physical Institute, in collaboration with MEPhI, IKI, NIISI, SIC KI, NPOL and IFBRAN, is successfully carrying out the GAMMA-400 program.

GAMMA-400 is funded by Roscosmos and, according to the Federal Space Program of the Russian Federation for 2016-2025, the launch is planned in ~ 2026.

GAMMA-400 web-page http://gamma400.lebedev.ru/

Thank you for your attention!

Your are welcome for cooperation!