Indirect dark-matter searches with gamma-rays: experiments status and future plans from keV to TeV

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IBS-MultiDark Joint Workshop on Dark Matter
23-28 November 2015
Neutralino WIMPs

Assume $\chi$ present in the Galactic halo

- $\chi$ is its own antiparticle $\Rightarrow$ can annihilate in galactic halo producing gamma-rays, antiprotons, positrons….
- Antimatter not produced in large quantities through standard processes (secondary production through $p + p \rightarrow$ anti $p + X$)
- So, any extra contribution from exotic sources ($\chi \chi$ annihilation) is an interesting signature
  - ie: $\chi \chi \rightarrow$ anti $p + X$
  - Produced from (e. g.) $\chi \chi \rightarrow q / g /$ gauge boson / Higgs boson and subsequent decay and/ or hadronisation.
High DM density at the Galactic center
Annihilation radiation from the GC
Milky Way Dark Matter Profiles

\[ \rho(r) = \rho_\odot \left[ \frac{r_\odot}{r} \right]^\gamma \left[ \frac{1 + (r_\odot/r_s)^\alpha}{1 + (r/r_s)^\alpha} \right]^{(\beta - \gamma)/\alpha} \]

<table>
<thead>
<tr>
<th>Halo model</th>
<th>( \alpha )</th>
<th>( \beta )</th>
<th>( \gamma )</th>
<th>( r_s ) in kpc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cored isothermal</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>Navarro, Frenk, White</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>Moore</td>
<td>1</td>
<td>3</td>
<td>1.16</td>
<td>30</td>
</tr>
<tr>
<td>Einasto</td>
<td>( \alpha = 0.17 )</td>
<td>( r_s = 20 ) kpc</td>
<td>( \rho_s = 0.06 ) GeV/cm(^3)</td>
<td></td>
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</tbody>
</table>

All profiles are normalized to the local density 0.3 GeV cm\(^{-3}\) at the Sun’s location \( r \approx 8.5 \) kpc.
The GeV excess 7°x7° region centered on the Galactic Center
11 months of data, E >400 MeV, front-converting events
analyzed with binned likelihood analysis 

- The systematic uncertainty of the effective area (blue area) of the LAT is ~10% at 100 MeV, decreasing to 5% at 560 MeV and increasing to 20% at 10 GeV
the GALACTIC CENTER: any hints of Dark Matter?

the beginning of the history:

Possible Evidence For Dark Matter Annihilation In The Inner Milky Way From The Fermi Gamma Ray Space Telescope
Lisa Goodenough, Dan Hooper  arXiv:0910.2998

Indirect Search for Dark Matter from the center of the Milky Way with the Fermi-Large Area Telescope
Vincenzo Vitale, Aldo Morselli, the Fermi/LAT Collaboration

Search for Dark Matter with Fermi Large Area Telescope: the Galactic Center
V. Vitale, A. Morselli, the Fermi-LAT Collaboration NIM A 630 (2011) 147-150 (Available online 23 June 2010)

Dark Matter Annihilation in The Galactic Center As Seen by the Fermi Gamma Ray Space Telescope

On The Origin Of The Gamma Rays From The Galactic Center

Detection of a Gamma-Ray Source in the Galactic Center Consistent with Extended Emission from Dark Matter Annihilation and Concentrated Astrophysical Emission

Dark Matter and Pulsar Model Constraints from Galactic Center Fermi-LAT Gamma Ray Observations

The Characterization of the Gamma-Ray Signal from the Central Milky Way: A Compelling Case for Annihilating Dark Matter

Background model systematics for the Fermi GeV excess
F. Calore, I. Cholis, C. Weniger  arXiv:1409.0042v1

Fermi-LAT observations of high-energy γ-ray emission toward the galactic centre
The GeV excess

A lot of activity outside the Fermi collaboration with claims of evidence for dark matter in the Galactic Center

i.e. Calore et al, arXiv:1409.0042v1
The GeV excess (Pass8 analysis)

Following uncertainties have relatively small effect on the excess spectrum:
- Variation of GALPROP models
- Distribution of gas along the line of sight

*Most significant sources of uncertainty are:*
- Fermi bubbles morphology
- Sources of CR electrons near the GC

Pass 7 analysis:
M. Ajello et al. [Fermi-LAT Coll.]
arXiv:1511.02938

The GeV excess: Other explanations exist

- past activity of the Galactic center
  (e.g. Petrovic et al., arXiv:1405.7928, Carlson & Profumo arXiv:1405.7685)

- Population of millisecond Pulsars around the Galactic Center
  (e.g., Yuan and Zhang arXiv:1404.2318v1, Lee et al. arXiv:1506.05124)

- Series of Leptonic Cosmic-Ray Outbursts
  Cholis et al. arXiv:1506.05119

- Different diffusion coefficient in the GC region

How to discriminate between different hypotesis?
The Fermi LAT 3FGL Inner Galactic Region

August 4, 2008, to July 31, 2010

100 MeV to 300 GeV energy range

arXiv:1501.02003
Fermi-LAT Instrument Response Functions (Pass 8) Angular Resolution

P8R2_SOURCE_V6 acc. weighted PSF

- Front 68%
- Back 68%
- Total 68%
- Front 95%
- Back 95%
- Total 95%
\[ \theta_0 = \theta_{plane}^{rms} = \frac{1}{\sqrt{2}} \theta_{space}^{rms} \]

\[ \theta_0 = \frac{13.6 \text{MeV}}{\beta c p} z \sqrt{\frac{x}{X_0}} \left[ 1 + 0.038 \ln \left( \frac{x}{X_0} \right) \right] \]
ARE WE SEEING DARK MATTER WITH THE FERMI-LAT IN A REGION AROUND THE MILKY WAY CENTER?

• Maybe yes, but we can’t be sure as far as we don’t understand the background at the level needed for disentangle a DM-induced $\gamma$-ray flux in this interesting region.

It would be really very nice to have a new experiment with better angular resolution at energies below 100 MeV
Dwarf spheroidal galaxies (dSph) : promising targets for DM detection
Dwarf Spheroidal Galaxies upper-limits (6 years)

- Pass 8 Combined dSphs
- Fermi-LAT MW Halo
- H.E.S.S. GC Halo
- MAGIC Segue 1
- Abazajian et al. 2014 (1σ)
- Gordon & Macias 2013 (2σ)
- Daylan et al. 2014 (2σ)
- Calore et al. 2014 (2σ)

M.Ackermann et al., [Fermi Coll.] PRL accepted [arXiv:1503.02641]
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Upper limits from AMS antiprotons and Fermi LAT for different halo profiles

Jin et al., arXiv:1504.04604

Fermi data from M.Ackermann et al., [Fermi Coll.] PRL accepted [arXiv:1503.02641]
Upper limits from Fermi LAT, Antares, IceCube, Magic

New DES Dwarf Spheroidal Galaxy Candidates

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DM limit improvement estimate in 15 years with the composite likelihood approach (2008-2023)

15 years, 3x dwarfs  Preliminary
DM limit improvement estimate in 15 years with the composite likelihood approach (2008-2023)

Together Fermi and CTA will probe most of the space of WIMP models with thermal relic annihilation cross section.
Dwarf Spheroidal Galaxy: Growing number of known targets
DM limit improvement estimate in 15 years with the composite likelihood approach (2008-2023)

Together Fermi and CTA will probe most of the space of WIMP models with thermal relic annihilation cross section.
Sensitivity of present and future experiments

![Graph showing sensitivity of experiments](image)
LHAASO advantage:
combined analysis of different dwarf galaxies observed at the same time
• 1-100 MeV unexplored domain for
  - Dark Matter searches
  - Galactic compact stars and nucleosynthesis
  - Cosmic rays
  - Relativistic jets, microquasars
  - Blazars
  - Gamma-Ray Bursts
  - Solar physics

• and...
  - Terrestrial Gamma-Ray Flashes
Gamma-light project

Power ~ 400 W
Weight Tracker ~ 110 Kg
Weight Calorimeter ~ 60 Kg
Total weight ~ 600 Kg
• First proposed in 2012 for the ESA Call of Small Scientific Missions.
• Focused on gamma-ray detection with much improved sensitivity in the range $10$-$100$ MeV.
• Very high level of readiness (AGILE, Fermi heritage).
• New astrophysics in the range below 100 MeV for both Galactic and extragalactic sources.
GAMMA-LIGHT: the instrument (total weight: 260 kg)

- Silicon Tracker with **analog readout** and **no heavy absorber** (10 MeV – 1 GeV)
- CsI Calorimeter (200 keV – 200 MeV)
- Anticoincidence
- Data Handling
Gamma-light Simulation

100 MeV

1 GeV
ESA M-4 Call

• quite different from previous Medium-sized Mission Calls (Solar Orbiter, EUCLID, PLATO);
• total ESA budget: 450 Meuro.
• guidelines for an ‘‘ESA-only’’ mission:
  – Payload mass: 300 kg;
  – total spacecraft mass: 800 kg.
ASTROGAM  a unified proposal from the entire gamma-ray community

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<tr>
<td>CLAIRE</td>
<td>NCT</td>
<td>GRI</td>
<td>DUAL</td>
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<tr>
<td>NCT</td>
<td>COMPTEL</td>
<td>GRIPS I</td>
<td></td>
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<tr>
<td>COMPTEL</td>
<td>CAPSITT</td>
<td>GRIPS II</td>
<td></td>
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<tr>
<td>AGILE 2007</td>
<td>FERMI 2008</td>
<td>Gamma-Light</td>
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</tbody>
</table>
An instrument that combine two detection techniques

- Tracker
- Calorimeter

Tracked Compton event

AC system

Pair event

Tracker

Calorimeter
ASTROGAM Angular Resolution

Angular resolution (degree) vs. Gamma-ray energy (MeV)

- COMPTEL
- ASTROGAM
- Fermi/LAT
- Compton
- Pair

Log-log scale for both axes.
Galactic Center Region 0.5-2 GeV

Fermi PSF Pass7 rep v15 source

with Gomez Vargas
Together Fermi and CTA will probe most of the space of WIMP models with thermal relic annihilation cross section, improving the DM limit in the next 15 years with the composite likelihood approach (2008-2023).
The next gamma-ray MeV-GeV mission: the e-Astrogam project

Proposed for the ESA M4 call; currently under study for enhancement and reconfiguration for the ESA M5 call. ASTROGAM is focused on gamma-ray astrophysics in the range 0.3-100 MeV with excellent capability also at GeV energies.
e-ASTROGAM

- 4 towers
- 50 layers of 5*5 double sides Si strip detectors
- Read-out pitch 240 $\mu$m
- Spacing of Si layers 7.5 mm
- Si thickness 400 $\mu$m

e-ASTROGAM core science

1. The Galactic Center and inner galaxy the central black hole, compact stars, the beginning of Fermi bubbles, DM search
2. Nucleosynthesis throughout the Galaxy and beyond
3. The extragalactic and cosmic gamma-ray background
ASTROGAM sensitivity $[\text{ph/cm}^2\text{s}]$

- total galactic 511 keV flux

sensitivity $[\text{ph/cm}^2\text{s}]$ vs. time (1970-2020)

- balloons
- HEAO
- SMM
- OSSE
- GRO / OSSE
- SPI
- ASTROGAM

Aldo Morselli, INFN Roma Tor Vergata

IBS-Multidark 15

Madrid 24 November 2015
• ASTRO-H/SGD – 3σ sensitivity for 100 ks exposure of an isolated point source
• COMPTEL and EGRET – sensitivities accumulated during the whole duration of the CGRO mission (9 years)
• Fermi/LAT – 5σ sensitivity for a high Galactic latitude source and after 1 year observation in survey mode
• ASTROGAM – 5σ sensitivity for a high Galactic latitude source after 3.5 years in survey mode
The extragalactic gamma-ray background (EGB)

- Extragalactic X-ray and gamma-ray background now measured over 9 orders of magnitude in energy.
- Largest uncertainties in the 1 MeV - 100 MeV range.
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Extragalactic X-ray and gamma-ray background now measured over 9 orders of magnitude in energy.

Largest uncertainties in the 1 MeV - 100 MeV range.
An instrument to complete the coverage of the electromagnetic spectrum

<table>
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<tr>
<th>Frequency Range</th>
<th>Equipment</th>
</tr>
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<tbody>
<tr>
<td>Radiofrequencies</td>
<td>Mirror telescopes</td>
</tr>
<tr>
<td>Infrarouge</td>
<td>Total external reflection</td>
</tr>
<tr>
<td>Ultraviolet</td>
<td>Cerenkov</td>
</tr>
<tr>
<td>Visible</td>
<td>Grazing incidence</td>
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<tr>
<td>Rayons X</td>
<td>Coded apertures</td>
</tr>
<tr>
<td>Rayons gamma</td>
<td>Compton scattering</td>
</tr>
<tr>
<td>UV</td>
<td>Gamma-ray</td>
</tr>
<tr>
<td>X-rays</td>
<td>Pair tracking</td>
</tr>
<tr>
<td>Sub-mm/IR</td>
<td>Air</td>
</tr>
<tr>
<td>Gamma-ray</td>
<td>Water</td>
</tr>
</tbody>
</table>
A wide-field $\gamma$-ray observatory operating at the same time as facilities like LSST and SKA will give a more coherent picture of the transient sky.

CTA science related to variable sources will need a coverage of the $\gamma$-ray sky at lower energies to trigger Target-of-Opportunity observations.
New gamma projects in space

• **AstroGam** 300 KeV- GeV (Proposal to ESA for M4 and now M5)

• **Gamma-light** (Proposed to ESA for S1)

  A.Morselli et al. arXiv:1406.1071

• **Gamma-400** launch foreseen by 2020


  Performance are under revision

• **DAMPE**: Chinese $\gamma$-ray satellite with INFN participation

  Planned launch 18/12/2015. 5 GeV- TeV G.F. 0.3 m$^2$ sr (Fermi ~1)

• **HERD**: Instrument on the planned Chinese Space Station.

  Energy resolution (100 GeV) ~ 1 %. Effective area ~ 1 - 2 m$^2$.

  Angular resolution (100 GeV) ~ 0.01°. Planned launch around 2020.

• **PANGU**: suggested as a candidate for the joint small mission between the European Space Agency (ESA) and the Chinese Academy of Science (CAS)
Conclusions

Detection of gamma rays from the annihilation or decay of dark matter particles is a promising method for identifying dark matter, understanding its intrinsic properties, and mapping its distribution in the universe (in synergy with the experiments at the LHC and in the underground laboratories).

In the future it would be extremely important to extend the energy range of experiments at lower energies (compared to the Fermi energies) (AstroGAM) and higher energies (HAWC, Dampe, HERD, CTA, LHAASO).

Thank you!
All of you are invited to the sixth edition of RICAP 2016 that will be hosted by INFN & Roma Tor Vergata University.