Indirect dark-matter searches with gamma-rays: experiments status and future plans from keV to TeV
In 1933, the astronomer Zwicky realized that the mass of the luminous matter in the Coma cluster was much smaller than its total mass implied by the motion of cluster member galaxies:

Since then, many other evidences:

- Rotation curves of galaxies
- Gravitational lensing
- Bullet cluster
- Structure formation as deduced from CMB

Data by WMAP imply:

\[ \Omega_b h^2 \approx 0.02 \]
\[ \Omega_{DM} h^2 \approx 0.1 \]
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.
Annihilation channels

WIMP Dark Matter Particles
$E_{\text{CM}} \sim 100\text{GeV}$

$\chi \rightarrow W^\pm/Z/\bar{q}$
$\chi \rightarrow W^\pm/Z/\bar{q}$

$\chi \rightarrow \gamma, \pi^0, \pi^\pm, \mu^\pm, \nu_\mu, \nu_e$

Neutralino

+ a few $p/\bar{p}, d/\bar{d}$

Anti-matter

Analysis Chain

- Dark Matter Density e.g. N-body Simulation
- New Particle Theory e.g. SUSY, Extra-dim
- Final State Hadronization e.g. PYTHIA Simulation
- Cosmic Ray Propagation and Galactic Interaction i.e. GALPROP
- Detector Simulation i.e. GEANT4

Detected particles:
- Gamma-rays

WIMP Dark Matter Particles
$E_{\text{CM}} \sim 100\text{GeV}$
Differential yield for each annihilation channel

- Quite distinctive spectrum (no power-law)
- Solid lines are the total yields, while the dashed lines are components not due to $\pi^0$ decays

Differential yield for b bar for different neutralino mass

\[ \gamma \text{yield per annihilation} \times (50 \text{ GeV} / \text{Mchi})^2 \]

\[ 10^3 \]

\[ 10^2 \]

\[ 10^1 \]

\[ 10^0 \]

\[ 10^{-1} \]

\[ 10^{-2} \]

\[ 10^{-3} \]

\[ 10^{-4} \]

\[ 10^{-5} \]

\[ 10^{-6} \]

\[ 10^{-7} \]

\[ 10^{-8} \]

\[ 10^{-9} \]

\[ 10^{-10} \]

\[ 10^{-11} \]

\[ 10^{-12} \]

\[ 10^{-13} \]

\[ 10^{-14} \]

\[ 10^{-15} \]

\[ E_\gamma \text{ (GeV)} \]

\[ 10^{-2} \]

\[ 10^{-1} \]

\[ 1 \]

\[ 10 \]

\[ 10^2 \]

\[ 10^3 \]

neutralino mass

secondary \( \pi^0 \) component (arbitrarily rescaled)

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>
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</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></td>
<td></td>
<td>$r_s = 20$ kpc $\rho_s = 0.06$ GeV/cm$^3$</td>
</tr>
</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.
Spectrum (E $>$ 400 MeV, 7°x7° region centered on the Galactic Center analyzed with binned likelihood analysis)

12 Fermi 1 year catalog sources

Data (stat. error)

Best diffuse model and isotropic emission

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: papers published in articles or in proceedings

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

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
The Galactic Center with Fermi-LAT

LAT counts = sum of:

- Galactic Center diffuse emission
  - Interaction of Cosmic Rays (density?) with gas (distribution?) and interstellar radiation fields (intensity?)
- Foreground/background (all-sky analysis)
  - Interaction of Cosmic Rays with gas and interstellar radiation fields
- Individual sources (~catalog analysis)
- Additional components?

Fermi LAT 1-100 GeV

background

foreground

~1 kpc

15x15deg
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: 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 hypotheses?
The Fermi LAT 3FGL Inner Galactic Region

August 4, 2008, to July 31, 2010
100 MeV to 300 GeV energy range

arXiv:1501.02003
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 γ-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

No detection by Fermi with 11 months of data. 95% flux upper limits are placed for several possible annihilation final states.

Flux upper limits are combined with the DM density inferred by the stellar data\(^*\) for a subset of 8 dSph (based on quality of stellar data) to extract constraints on \(\langle \sigma v \rangle\) vs WIMP mass for specific DM models.

\(^*\) stellar data from the Keck observatory (by Martinez, Bullock, Kaplinghat)

robust constraints including J-factor uncertainties from the stellar data statistical analysis

For cored dark matter profile, the J-factors for most of the dSphs would either increase or not change much.

Fermi Lat Coll., PRL 107, 241302 (2011) [arXiv:1108.3546]
Dwarf Spheroidal Galaxies upper-limits

15 Dwarfs
4-year data
500 MeV to 500GeV

Dwarf Spheroidal Galaxies upper-limits (6 years)

\[ \langle \sigma v \rangle \text{ (cm}^3\text{s}^{-1}) \]

- 4-year Pass 7 Limit
- 6-year Pass 8 Limit
- Median Expected
- 68% Containment
- 95% Containment

15 Dwarfs
6-year data
500 MeV to 500GeV

\( b\bar{b} \)

DM Mass (GeV/c^2)

M. Ackermann et al., [Fermi Coll.] PRL accepted [arXiv:1503.02641]
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 (1\sigma)
- Gordon & Macias 2013 (2\sigma)
- Daylan et al. 2014 (2\sigma)
- Calore et al. 2014 (2\sigma)

\[ \langle \sigma v \rangle \text{ (cm}^3 \text{s}^{-1}) \]

\[ 10^{-27} \quad 10^{-26} \quad 10^{-25} \quad 10^{-24} \quad 10^{-23} \quad 10^{-22} \]

DM Mass (GeV/c^2) 

\[ 10^1 \quad 10^2 \quad 10^3 \quad 10^4 \]

Thermal Relic Cross Section
(Steigman et al. 2012)
Dwarf Spheroidal Galaxies upper-limits (6 years)

- Pass 8 Combined dSphs
- Fermi-LAT MW Halo
- MAGIC Segue 1
- Abazajian et al. 2014 (1σ)
- Daylan et al. 2014 (2σ)
- Calore et al. 2014 (2σ)

Astrogam range

- Thermal Relic Cross Section
  (Steigman et al. 2012)
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

\[ \langle \phi A v \rangle \text{ (cm}^3\text{s}^{-1} \rangle \]

\[ 10^{-20} \]

\[ 10^{-21} \]

\[ 10^{-22} \]

\[ 10^{-23} \]

\[ 10^{-24} \]

\[ 10^{-25} \]

\[ 10^{-26} \]

\[ M_{\text{WIMP}} \text{ (GeV)} \]

NFW
\[ \chi \chi \rightarrow \tau^+ \tau^- \]

IceCube-DeepCore 79 2010-2011

IceCube 59 2009-2010

ANTARES 2007-2012

Pamela/Fermi/AMS positron excess

MAGIC 2011-2013

Fermi-LAT 2008-2014

natural scale

Antares Coll. arXiv:1505.04866

IceCube Coll. arXiv:1505.07259

Aldo Morselli, INFN Roma Tor Vergata

AAPCOS 15

Kolkata 13 October 2015
2015: An interesting start

LAT Collaboration – DES Collaboration agreement – Feb 2015
- first joint paper “Search for Gamma-Ray Emission from DES Dwarf Spheroidal Galaxy Candidates with Fermi-LAT Data”

• analysis of observations of 8 new Dwarf Spheroidal Galaxies found by DES:
  Bechtol, et al.
  arXiv:1503.02584
  also found by Koposov, et al.
  arXiv:150302079
# New DES Dwarf Spheroidal Galaxy Candidates

<table>
<thead>
<tr>
<th>Name</th>
<th>$(\ell, b)^a$</th>
<th>Distance$^b$</th>
<th>$\log_{10}(\text{Est.J})^c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DES J0222.7−5217</td>
<td>(275.0, −59.6)</td>
<td>95</td>
<td>18.3</td>
</tr>
<tr>
<td>DES J0255.4−5406</td>
<td>(271.4, −54.7)</td>
<td>87</td>
<td>18.4</td>
</tr>
<tr>
<td>DES J0335.6−5403</td>
<td>(266.3, −49.7)</td>
<td>32 (Reticulum II)</td>
<td>19.3</td>
</tr>
<tr>
<td>DES J0344.3−4331</td>
<td>(249.8, −51.6)</td>
<td>330</td>
<td>17.3</td>
</tr>
<tr>
<td>DES J0443.8−5017</td>
<td>(257.3, −40.6)</td>
<td>126</td>
<td>18.1</td>
</tr>
<tr>
<td>DES J2108.8−5109</td>
<td>(347.2, −42.1)</td>
<td>69</td>
<td>18.3</td>
</tr>
<tr>
<td>DES J2251.2−5836</td>
<td>(328.0, −52.4)</td>
<td>58</td>
<td>18.8</td>
</tr>
<tr>
<td>DES J2339.9−5424</td>
<td>(323.7, −59.7)</td>
<td>95</td>
<td>18.4</td>
</tr>
</tbody>
</table>

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Aldo Morselli, INFN Roma Tor Vergata

New DES Dwarf Spheroidal Galaxy Candidates


The New York Times

SCIENCE

Gamma Rays May Be Clue on Dark Matter

By DENNIS OVERBYE MARCH 19, 2015

A small, newly discovered galaxy orbiting the Milky Way is emitting a large amount of electromagnetic radiation in the form of gamma rays, a discovery reported Tuesday. The finding may be the latest in a long line of similar findings, or it might be that the mysterious missing mass of the universe is finally showing its face.

Have we finally found DARK MATTER?

Gamma rays hint at the presence of the mysterious material in nearby dwarf galaxy

• Dark matter is the missing material making up 80% of universe’s mass
• Gamma rays from a dwarf galaxy are considered a sign of dark matter
• They were spotted in direction of Reticulum 2 98,000 light-years away

Scientists say this is the most convincing signal of dark matter yet!
Gamma-ray Emission from Reticulum 2


Total background
isotropic background
galactic diffuse background

~ 2.3σ evidence
New DES Dwarf Spheroidal Galaxy Candidates

New DES Dwarf Spheroidal Galaxy Candidates

New DES Dwarf Spheroidal Galaxy Candidates

New DES Dwarf Spheroidal Galaxy Candidates

if the excess in Reticulum II is real, we have already a theory that explain it together with the 3.5 KeV line

Anirban Biswas, Debasish Majumdar, Probir Roy arXiv:1507.04543
DM limit improvement estimate in 15 years with the composite likelihood approach (2008-2023)

15 years, 3x dwarfs Preliminary

$\langle \sigma v \rangle$ (cm$^3$s$^{-1}$)

DM Mass (GeV/c$^2$)

Pass 8 Combined dSphs (15 dSphs, 6 Years)
H.E.S.S. GC Halo
Abazajian et al. 2014 (1$\sigma$)
Gordon & Macias 2013 (2$\sigma$)
Daylan et al. 2014 (2$\sigma$)
Calore et al. 2015 (2$\sigma$)

$\bar{b}b$
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
talk tomorrow by Prof. B. S. ACHARYA
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.
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
GAMMA-LIGHT

- 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
Gamma-Light Point Spread Function (angular resolution)

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

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>CLAIRE</td>
<td>NCT</td>
<td>GRI</td>
<td>DUAL</td>
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<tr>
<td>COMPTEL</td>
<td>CAPSITT</td>
<td>GRIPS I</td>
<td>GRIPS II</td>
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<tr>
<td>AGILE 2007</td>
<td>FERMI 2008</td>
<td>Gamma-Light</td>
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</tr>
</tbody>
</table>

M4

ASTROGAM
An instrument that combine two detection techniques

Tracked Compton event

Pair event

Tracker

AC system

Calorimeter
• 70 layers of 6×6 double sided Si strip detectors = 2520 DSSDs
• Each DSSD has a total area of 9.5×9.5 cm², a thickness of 400 μm, a strip width of 100 μm and pitch of 240 μm (384 strips per side), and a guard ring of 1.5 mm
• Spacing of the Si layers: 7.5 mm
• The DSSDs are wire bonded strip to strip to form 2-D ladders
⇒ 322 560 electronic channels
• DSSD strips connected to ASICs (32 channels each) through a pitch adapter (DC coupling)
• 144 ASICs (IDeF-X HD) per layer (72 per DSSD side)
⇒ 10 080 ASICs total
ASTROGAM Angular Resolution

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

- COMPTEL
- Fermi/LAT
- ASTROGAM

Angular resolution:
- Compton
- Pair

-10^1 to 10^4 MeV
-10^0 to 10^1 degree
• 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
A wide-field γ-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 γ-ray sky at lower energies to trigger Target-of-Opportunity observations.
e-ASTROGAM

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

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
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.
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!