Current constraints on dark matter and future observational strategies with gamma-rays experiments

Aldo Morselli
INFN Roma Tor Vergata

5Th Workshop On Air Shower Detection At High Altitude
26-28 May, 2014, Paris, France
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:

\[ \Omega_b h^2 \approx 0.02 \]
\[ \Omega_{DM} h^2 \approx 0.1 \]
The anisotropies of the Cosmic microwave background (CMB) as observed by Planck

21 March 2013

Plank Coll. arXiv:1303.5076
An Inventory of Matter in the Universe

So, what is Dark Matter?
Dark Matter Candidates

- Kaluza-Klein DM in UED
- Kaluza-Klein DM in RS
- Axion
- Axino
- Gravitino
- Photino
- SM Neutrino
- Sterile Neutrino
- Sneutrino
- Light DM
- Little Higgs DM
- Wimpzillas
- Q-balls
- Mirror Matter
- Champs (charged DM)
- D-matter
- Cryptons
- Self-interacting
- Superweakly interacting
- Braneworld DM
- Heavy neutrino
- NEUTRALINO
- Messenger States in GMSB
- Branons
- Chaplygin Gas
- Split SUSY
- Primordial Black Holes

L. Roszkowski
Dark Matter Candidates

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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 $E_{CM} \sim 100$ GeV

Gamma-rays

$\gamma$

$\chi$

$\nu_\mu$

$\mu^+$

$\nu_\mu \nu_e$

$\pi^+$

$\nu_\mu$

$\mu^-$

$\nu_\mu \nu_e$

$\pi^-$

$e^+$

$e^-$

Neutrinos

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

$\chi$

$\gamma$

$\gamma$

$\gamma$

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. GEANT4

Detector Simulation i.e. GEANT4

1:2005 0765A1

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1:2006 0765A2

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

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

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

Gamma rays produced per dark matter annihilation

\[ E_\gamma^2 \frac{dN_\gamma}{dE_\gamma} \text{ (GeV)} \]

- \( \bar{b}b \)
- \( \bar{c}c \)
- \( \bar{s}s \)
- \( \bar{u}u, \bar{d}d \)
- \( \tau^+\tau^- \)
- \( e^+e^- \)

\[ m_x = 30 \text{ GeV} \]
Search Strategies

**Satellites:**
Low background and good source id, but low statistics

**Galactic center:**
Good statistics but source confusion/diffuse background

**Milky Way halo:**
Large statistics but diffuse background

And electrons! and Anisotropies

**Spectral lines:**
No astrophysical uncertainties, good source id, but low statistics

**Galaxy clusters:**
Low background but low statistics

**Extra-galactic:**
Large statistics, but astrophysics, galactic diffuse background

The Galactic Center
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>
</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
The angular profile of the gamma-ray signal is shown, as function of the angle $\theta$ to the centre of the galaxy for a Navarro-Frenk-White (NFW) halo distribution for decaying DM, solid (red) line, compared to the case of self-annihilating DM, dashed (blue) line.
The Fermi LAT 2FGL Inner Galactic Region

August 4, 2008, to July 31, 2010

100 MeV to 100 GeV energy range

arXiv:1108.1435
Annihilation channels

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

Gamma-rays

Neutrinos

$\chi$, $W^{-}/Z/q$

$\chi$, $W^{+}/Z/q$

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

Anti-matter

Analysis Chain

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8765A1

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Wimp lines search
A line at ~ 130 GeV?

Reg4 (ULTRACLEAN), $E_\gamma = 129.8$ GeV

Signal counts: 46.1 ($4.36\sigma$)

p-value = 0.37, $\chi^2_{\text{red}} = 23.6/22$

Weniger arXiv:1204.2797
Most of the limits fall within the expected bands.
Near 135 GeV the limits are near the upper edge of the bands.
The huge statistics at low energies mean small uncertainties in the collecting area can produce statistical significant spectral features.
Constraints from the inner Galaxy
3 \sigma upper limits on the annihilation cross-section for different channels and halo profiles
No assumption on background
very robust result

Gomez-Vargas et al.
JCAP 10 (2013) 029
arXiv:1308.3515
New Low Energy Line Search

Purpose:
To perform a spectral search for gamma-ray lines from 100 MeV to 10 GeV with the Fermi-LAT data
This would constrain models of gravitino decay, focus on the $\mu\nu$SSM (Lopez-Fogliani & C. Muñoz PRL 97(2006)041801)

People:
Andrea Albert (SLAC), Elliott Bloom (SLAC), Eric Charles (SLAC),
German Gomez Vargas (PUC-Santiago/INFN-Roma2), Aldo Morselli (INFN Roma2) Carlos Muñoz (UAM/IFT Madrid), Michael Grefe (Hamburg), & Christoph Weniger (GRAPPA Amsterdam).

Data:
5.2 years of Pass 7 Reprocessed data
Fit for lines from 100 MeV to 10 GeV
Preliminary Limits for $|b| > 60^\circ$ RoI

Excluded region

**preliminary**

All limits at 95% CL
New Low Energy Line Search

But this Analysis is Systematics Limited

- Modeling effective area
- background emission
- not masking known point sources: because the broad PSF of the LAT at low energies.

To improve the search a better energy and angular resolution at low energies is needed
Annihilation channels

Continuum emission

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

$\chi$ $W^-/Z/q$ $\gamma$

$\pi^0$ $\nu_\mu$ $\mu^+$ $\nu_\mu\nu_e$

$\pi^-$ $\nu_\mu$ $\mu^-$ $\nu_\mu\nu_e$

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

Neutrinos

Anti-matter

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1-2006 0765A1

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1-2008 0765A2

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**GC Residuals**  $7^\circ \times 7^\circ$ 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 $\sim 10\%$ at 100 MeV, decreasing to 5% at 560 MeV and increasing to 20% at 10 GeV

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*V.Vitale, A.Morselli for the Fermi Coll. NIM A630 (2011) 147, arXiv:0912.3828*
Galactic Center and Dark Matter

- Spatially extended excess of 1-3 GeV $\gamma$ rays with a spectrum, angular distribution, and overall normalization that is in good agreement with that predicted by simple annihilating dark matter models
- Well fit by a 31-40 GeV WIMP with $<\sigma v> = (1.4 - 2.0) \times 10^{-26}$ cm$^3$/s
- Approximately spherically symmetric and centered around the dynamical center of the Milky Way

A Compelling Case for Annihilating Dark Matter arXiv:1402.6703
A comparison of the dark matter mass determination using the spectrum derived from our Inner Galaxy analysis (solid line) and using the spectrum derived from our Galactic Center analysis (dashed and dotted lines)

A Compelling Case for Annihilating Dark Matter
A comparison of the spectral shape of the gamma-ray excess from the sum of all millisecond pulsars detected as individual point sources by Fermi. The gamma-ray spectrum measured from millisecond pulsars and from globular clusters (whose emission is believed to be dominated by millisecond pulsars) is consistently softer than that of the observed excess at energies below \( \sim 1 \) GeV.

**A Compelling Case for Annihilating Dark Matter**  

arXiv:1402.6703
Galactic Center and Dark Matter

arXiv:1306.5725

Se non è vero è ben trovato

arXiv:1401.6458
New gamma projects in space

• **Gamma-light**  (Proposed to ESA but not approved)

  http://agenda.infn.it/getFile.py/access?contribId=67&resId=0&materialId=slides&confId=4267

• **Gamma-400**  launch foreseen by end 2018

  100 MeV – 3 TeV, an approved Russian $\gamma$-ray satellite. Energy resolution (100 GeV) $\sim$ 1 %. Effective area $\sim$ 0.4 m$^2$. Angular resolution (100 GeV) $\sim$ 0.01°.

  Science with Gamma-400 Workshop  http://cdsagenda5.ictp.it/full_display.php?ida=a1311

• **DAMPE**: Satellite of similar performance as Gamma-400. An approved Chinese $\gamma$-ray satellite. Planned launch 2015-16.

• **HERD**: Instrument on the planned Chinese Space Station. Energy resolution (100 GeV) $\sim$ 1 %. Effective area $\sim$ 1 - 2 m$^2$. Angular resolution (100 GeV) $\sim$ 0.01°. Planned launch around 2020.
AMS-02 Acceptance for gamma-rays

BDT selection gamma acceptance

\[ \chi^2 / \text{ndf} \]

\[ p_0 \]

\[ p_1 \]

\[ p_2 \]

\[ p_3 \]

\[ p_4 \]

To be compared with Fermi-LAT 20000 sr cm3 @ 100 GeV
Gamma-400 Angular resolution

68% Containment radius (deg)

10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}

Energy (GeV)

10^{1} 10^{0} 10^{-1} 10^{-2} 10^{-3}

Fermi Front P7REP SOURCE V15

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Gamma-400 Energy resolution for $\gamma$
DAMPE Gamma-ray Sensitivity

Wang YiFang last week
HERD Gamma-ray Sensitivity

Integral flux (Photon\textit{n}s/cm\textsuperscript{2}/s)

Energy (GeV)

FERMI
CALET
DAMPE
HERD
CTA
LHASSO

Crab
P7REP SOURCE V15 PSF Front 68% cont. at normal incidence

Containment angle (deg)

Energy (MeV)

Fermi-PSF

0.25xFermi-PSF

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Galactic Center Region 1-5 GeV

Fermi PSF Pass7 rep v15 *0.25

Fermi PSF Pass7 rep v15 source

Sources from two years Fermi catalog, template ring model for diffuse

Galactic Center Region 0.2-1 GeV

Sources from two years Fermi catalog, template ring model for diffuse,

Gamma-Light Point Spread Function (angular resolution)

Mission proposed to ESA

AGILE
30°

GAMMA-LIGHT
30°

Fermi LAT
(Front + Back)

Fermi LAT
front P7v6

Effective area

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Energy (MeV)</th>
<th>Effective Area (cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fermi LAT (Front + Back)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fermi LAT (Front)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GAMMA-LIGHT 30⁰</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AGILE 30⁰</td>
<td></td>
<td></td>
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<tr>
<td>COMPTEL</td>
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</tr>
</tbody>
</table>

Kalman reconstruction, assumed bkg rejection eff. 10⁻⁴

Flux Sensitivity

48 hours - Galactic Centre Region Sensitivity

Energy (MeV)

Fermi LAT (Front)
Fermi LAT (Front+Back)
AGILE
GAMMA-LIGHT

$5\sigma$ Sensitivity $E^2 dN/dE$ (MeV cm$^{-2}$ s$^{-1}$)

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Search Strategies

Satellites:
Low background and good source id, but low statistics

Galactic center:
Good statistics but source confusion/diffuse background

Milky Way halo:
Large statistics but diffuse background

Spectral lines:
No astrophysical uncertainties, good source id, but low statistics

Galaxy clusters:
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Large statistics, but astrophysics, galactic diffuse background

And electrons!

Dwarf spheroidal galaxies (dSph): promising targets for DM detection
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
Dwarf Spheroidal Galaxies combined analysis

Upper limits, Joint Likelihood of 10 dSphs

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

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

Dwarf Spheroidal Galaxies upper-limits

15 Dwarfs
4-year data
500 MeV to 500GeV

M. Ackermann et al., [Fermi Coll.]
[arXiv:1310.0828]
25 Dwarf Spheroidal Galaxies upper-limits

DM limit improvement estimate in 10 years with the composite likelihood approach (2008-2018)

- 10 years of data instead of 2(5x)
- 30 dSphs (3x) (supposing that the new optical surveys will find new dSph)
- -10% from spatial extension (source extension increases the signal region at high energy \( E > 10 \text{ GeV}, M > 200 \text{ GeV} \))

- There are many assumptions in this prediction
- Doesn’t deal with a possible detections.
ATLAS-Fermi Results

Dwarf Spheroidal Galaxies upper-limits

Update of Doro et al. arXiv:1208.5356
HAWC and Dark Matter Search

![Graph of Dark Matter Limits from Segue1](image)

- **HAWC-300**: 1 yr $b\bar{b}$$\bar{b}$
- **VERITAS**: $b\bar{b}$
- **FERMI**: $\tau\tau$ and $b\bar{b}$

**Thermal Cross Section**

- $\langle \sigma v \rangle$ [cm$^3$ s$^{-1}$]
- $M_{\chi}$ [TeV]
HAWC and Dark Matter Search

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

\[ M_\chi \left[ \text{TeV} \right] \]

\[ \chi \chi \rightarrow b \bar{b} \]

Draco
Coma Berenices
Segue 1
VERITAS Segue 1
Thermal DM

HAWC Coll. arXiv:1405.1730
Sensitivity of present and future experiments
LHAASO and Dark Matter Search

A.Morselli 2014

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

- Draco
- Coma Berenices
- Hawc Segue 1
- VERITAS Segue 1
- LHASSO Segue 1
- Thermal DM

\[ \chi \chi \rightarrow b \bar{b} \]

update of arXiv:1405.1730
LHAASO CTA and HAWC and Dark Matter Search

A. Morselli 2014

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

\[ 10^{-26} \quad 10^{-25} \quad 10^{-24} \quad 10^{-23} \quad 10^{-22} \quad 10^{-21} \quad 10^{-20} \quad 10^{-19} \]

\[ M_\chi \quad [\text{TeV}] \]

\[ 1 \quad 10 \quad 100 \quad 1000 \]

\( \chi \chi \rightarrow b \bar{b} \)

Draco

Coma Berenices

VERITAS Segue 1 47.8 hr

LHASSO Segue 1 5 yr

HAWC Segue 1 5 yr

CTA Segue 1 Array B 100 h

Thermal DM

Past decades saw precision studies of 5% of our Universe -> Discovery of the Standard Model

The LHC is delivering data

We are just at the beginning of exploring 95% of the Universe.

Exciting prospects

R.-D. Heuer, CERN General Director 36th International Conference on High Energy Physics ICHEP2012, Closing Talk
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) (e.g. Gamma-Light) and higher energies (HAWC, CTA, LHAASO)
For long time we saw the sky tranquil and calm
During the 20th century the quest to broaden our view of the universe has shown us the vastness of the Universe and revealed violent cosmic phenomena and mysteries.
The future?