Indirect dark-matter searches with gamma-rays experiments: status and future plans from 300 KeV to 100 TeV

Aldo Morselli
INFN Roma Tor Vergata

ICNFP2017, 6th International Conference on New Frontiers in Physics
OAC, Creta, 25 Aug. 2017
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, even more evidence:

**Rotation curves of galaxies**

**Gravitational lensing**

**Bullet cluster**

Structure formation as deduced from CMB

Data by Plank imply:

\[ \Omega_{DM} \approx 26.8\% \]

\[ \Omega_{M} \approx 4.9\% \]
Annihilation channels

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

Gamma-rays

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

Neutrinos

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

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 Propogation and Galactic Interaction i.e. GALPROP

Detector Simulation i.e. GEANT4

Analysis Chain

??

Dark Matter Density e.g. N-body Simulation

New Particle Theory e.g. SUSY, Extra-dim

Cosmic Ray Propagation and Galactic Interaction i.e. GALPROP

Detector Simulation i.e. GEANT4
Dark Matter Search: Targets and 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**
  - Little or no astrophysical uncertainties, but low sensitivity because of expected small branching ratio

- **Galaxy Clusters**
  - Low background, but low statistics

- **Isotropic” contributions**
  - Large statistics, but astrophysics, galactic diffuse background

Dark Matter Search: Targets and Strategies

(Another way to see it)

signal strength

GC

GC halo

cumulative extragalactic signal
dwarf satellites

spectral line

clusters of galaxies

robustness
Fermi Gamma-Ray Space Telescope

Multi-Messenger and Multi-Wavelength Astrophysics

Time Domain Astronomy • Searches for Dark Matter • Particle Astrophysics
Happy 9th Birthday Fermi!!

11 June 2008
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 GeV excess

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

Calore et al, arXiv:1409.0042v1
Very similar to the mass range found with the EGRET data in 2004!

mass ~ 50-80 GeV

Lines of constant reduced $\chi^2$ corresponding to best fits of the EGRET GC excess

bbar channel

EGRET, $E > 1$ GeV
Mayer-Hasselwander et al, 1998
Annihilation channel $W^+W^-$
$M_\chi = 80.3$ GeV

Typical $N_\chi$ values:
- NFW: $N_\chi = 10^4$
- Moore: $N_\chi = 9 \times 10^6$
- Isotermal: $N_\chi = 3 \times 10^1$

$N_b = 1.82 \times 10^{21}$
$N_\chi = 8.51 \times 10^4$

the GALACTIC CENTER : any hints of Dark Matter?
the beginning of the history :

The Galactic Center as a Dark Matter Gamma-Ray Source

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

Background model systematics for the Fermi GeV excess

Fermi-LAT observations of high-energy γ-ray emission toward the galactic centre
(using Pass7, Pass8 analysis in progress)
The GeV excess (Pass8 analysis)

- Variation of GALPROP models
- Distribution of gas along the line of sight

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

Se non è vero è ben trovato
(If it is not true, it is well conceived)

Bœhm et al. JCAP05(2014)009
arXiv:1401.6458
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)
- Series of Leptonic Cosmic-Ray Outbursts
  Cholis et al. arXiv:1506.05119
- Stellar population of the X-bulge and the nuclear bulge
  Macias et al. arXiv:1611.06644
- Molecular Clouds in the disk
- Population of pulsars in the Galactic bulge
  e.g., Yuan and Zhang arXiv:1404.2318v1, Lee et al. arXiv:1506.05124, Bartels et al. 1506.05104

How to discriminate between different hypothesis?
Population of pulsars in the Galactic bulge and the GeV excess

M.Ajello et al. [Fermi-LAT Coll.] Apj sub. [arXiv:1705.00009]

A population with about 2.7 $\gamma$-ray pulsars in the Galactic disk for each pulsar in the Galactic bulge is consistent with the population of known $\gamma$-ray pulsars as well as with the spatial profile and energy spectrum of the GC excess.
August 4, 2008, to July 31, 2010

100 MeV to 300 GeV energy range

The Fermi LAT 3FGL Inner Galactic Region

arXiv:1501.02003
Fermi-LAT Instrument Response Functions (Pass 8) Angular Resolution
How to discriminate between different hypothesis?

**eROSITA**
- Modeling of the Fermi bubbles
- Look for correlated features near the Galactic center

**HESS, MAGIC, CTA**
- Fermi bubbles near the GC are much brighter
- Possible to see with Cherenkov telescopes?

**Radio observations, MeerKAT, SKA**
- Search for individual pulsars in the halo around the GC

**Radio surveys, Planck**
- Look for correlated synchrotron emission near the GC

**More Fermi LAT analysis**
- Diffuse emission modeling
- Analysis of point sources near the GC

But ultimately We need a new experiment with better angular resolution below 100 MeV
Classical Dwarf spheroidal galaxies: promising targets for DM detection
Dark Matter in the Milky Way (from simulations)

Springel et al. (Nature, 2005)
Dwarf Spheroidal Galaxies: Growing number of known targets
Dwarf Spheroidal Galaxies upper-limits (6 years)

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

- 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)

```
```
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)

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

\[ \text{DM Mass (GeV/c}^2\text{)} \]

CTA
CTA PERFORMANCE

Southern Site:
4 Large-size telescopes
25 Medium-size telescopes
70 Small-size telescopes

Northern Site:
4 Large-size telescopes
15 Medium-size telescopes

$E^2 \times \text{Flux Sensitivity (erg cm}^2 \text{s}^{-1})$

$E_R \text{ (TeV)}$

Angular Resolution ($^\circ$)

Energy $E_R (\text{TeV})$
There are several of the newly discovered dSph that have a better case for being a promising target,
Will choose most promising targets before observations with the latest knowledge.
Which channel to choose?
Example: The dominant annihilation modes in the pMSSM scan
Annihilation spectra for the continuum signals from the quark, lepton and gauge boson primary channels

The line-like feature expected from the virtual internal Bremsstrahlung process contribution is particularly prominent for the $W^+W^-$ channel

$m_\chi = 2$ TeV
note: the “thermal” cross section is only a reference value. The real cross section can be higher or lower

Example:
Annihilation cross-section points from a 19 dimensional pMSSM fit


Note that a strong enhancement of the annihilation cross section occurs for winos around 2-3 TeV due to Sommerfeld enhancement.
Complementarity and Searches for Dark Matter in the pMSSM

Cahill-Rowley et al. arXiv:1305.6921
Dwarf Spheroidal Galaxies: CTA Sensitivity

for different Dwarfs.

Dashed lines correspond to ±1σ on the J-factors

N.B. recent doubts on Segue 1 J-factor due to interlopers in stellar-kinematic samples. V. Bonnivard et al., arXiv:1506.08209
The predictions shown here can be considered optimistic, even when systematics errors are included, as we do not consider the effect of the Galactic diffuse emission as background for DM searches that can affect the results by ~ 50%. This will be investigated in detail in a forthcoming publication by the CTA Consortium.
CTA Galactic Halo DM upper-limits

Effect of the different Halo profiles
Together Fermi and CTA will probe most of the space of WIMP models with thermal relic annihilation cross section.

The expectation for CTA for the Galactic Halo is for the Einasto profile and is optimistic as includes only statistical errors.

The effect of the Galactic diffuse emission can affect the results by ~ 50%.

As we saw in the previous slides the limits from dwarfs are much less dependent from the systematic uncertainties.
Together Fermi and CTA will probe most of the space of WIMP models with thermal relic annihilation cross section. The expectation for CTA is for the Einasto profile and is optimistic as it includes only statistical errors. The effect of the Galactic diffuse emission can affect the results by ~50%.
HESS, FERMI, Ice Cube, ANTARES Dark Matter upper-limits

S. Flis for the Ice Cube Coll. ICRC17

HESS, FERMI, Ice Cube, ANTARES Dark Matter upper-limits update

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

\[ 10^{-22} \]

\[ 10^{-24} \]

\[ m_\chi [\text{GeV}] \]

\[ 10^1 \]

\[ 10^2 \]

\[ 10^3 \]

\[ 10^4 \]

\[ 10^5 \]

IceCube Preliminary

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

IC 3yr halo cascades

IC 2yr cascades

IC 3yr GC tracks

ANTARES GC

IC 4yr PS+ 3yr MESE

HESS, FERMI, Ice Cube, ANTARES Dark Matter upper-limits update
Together Fermi and CTA will probe most of the space of WIMP models with thermal relic annihilation cross section.
CTA sensitivity curve from Carr et al. 2015 500 hr, statistical only, NFW, 30 GeV threshold arXiv:1508.06128

Together Fermi and CTA will probe most of the space of WIMP models with thermal relic annihilation cross section

Here we need a new experiment

DM limit improvement estimate in 15 years (2008-2023)
• 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

ESA S1 Call
Power ~ 400 W
Weight Tracker ~ 110 Kg
Weight Calorimeter ~ 60 Kg
Total weight ~ 600 Kg
Gamma-Light Point Spread Function (angular resolution)


AGILE

30°

GAMMA-LIGHT

30°

Fermi LAT (Front + Back)

Fermi LAT

front P7v6

Energy (MeV)
ASTROGAM a unified proposal from the entire gamma-ray community

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CLAIRE</td>
<td>GRI</td>
<td>DUAL</td>
<td></td>
</tr>
<tr>
<td>NCT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COMPTEL</td>
<td>GRIPS I</td>
<td>CAPSITT</td>
<td>Gamma-Light</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GRIPS II</td>
<td></td>
</tr>
<tr>
<td>AGILE 2007</td>
<td>FERMI 2008</td>
<td></td>
<td>M4 ASTROGAM</td>
</tr>
</tbody>
</table>

AstroMeV
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.
An instrument that combine two detection techniques

Tracked Compton event

AC system

Tracker

Calorimeter

Pair event
ASTROGAM Angular Resolution

Angular resolution (degree)

Gamma-ray energy (MeV)

COMPTEL
Fermi/LAT

ASTROGAM

Compton Pair
- e-ASTROGAM performance evaluated with MEGAlib and both tools based on Geant4 – and a detailed numerical mass model of the gamma-ray instrument.

*e-Astrogam: arXiv:1611.02232*
Galactic Center Region 0.5-2 GeV

Fermi PSF Pass7 rep v15 source

Morselli, Gomez Vargas, preliminary
An instrument to complete the coverage of the electromagnetic spectrum

- Compton scattering
- X-rays
- Gamma-rays
- UV
- Sub-mm/IR

**Total external reflection**
- Mirror telescopes
- Grazing incidence
- Coded apertures

**Cerenkov**
- Compton scattering
- Pair tracking
- Air
- Water
Particle Astrophysics Experiments

**Source**

Creation acceleration injection

Further acceleration?

**Propagation**

**Modulation**

Cosmic rays: about 10 Myears in the Galaxy (6-7 g/cm²)

Atmosphere

40 km

23 Xo

High Montain Detectors

Cherencov Detectors

Particle Accelerators

**Extensive Air Shower Detectors**

**Fermi**

**PAMELA**

**AGILE**

**AMS**

**Calet**

**Gamma-400**

**Jem-EUSO**

**KASCADE Grande**

**DECOR**

**AUGER**

**LOFAR**

**CODALEMA**

**ARGO-JBJ**

**Milagro**

**HAWC**

**LHAASO**

**NEMO**

**ANTS**

**ANTARES**

**IceCube**

**KM3NeT**

**Baikal-GVD**

**DAMA/LIBRA**

**CoGeNT**

**CRESST-II**

**CDMS**

**Xenon1T**

**LUX**

**PandaX**

**DarkSide**

...
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-AstroGAM, AMEGO) and higher energies (CTA, HAWC).

Thank you!
Through most of history, the cosmos has been viewed as eternally tranquil.
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?

Thank you!