Astrophysics in the MeV range

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17th Lomonosov Conference on Elementary Particle Physics
Moscow State University, Moscow, 19 - 26 August, 2015
Cosmic rays: about 10 Myears in the Galaxy (6-7 g/cm²)

Source

Creation, acceleration, injection

Propagation

Modulation

Further acceleration?

Direct detection

Extensive Air Shower Detectors

High Montain Detectors

Cherencov Detectors

Particle Accelerators

Cosmic Rays

Space experiments ~ 400 km

Balloons ~ 40 km ~3 g/cm² residual atmosphere

NEMO

ANTARES

IceCube Km3

ARGO-JBJ

Milagro

HAWC

LHAASO

MAGIC

HESS

Veritas

CTA

KASCADE Grande

DECOR

AUGER

Fermi

PAMELA

AGILE

AMS

Cream

Dampe

Gamma-400

HERD

AstroGam

Pangu

Particle Astrophysics Experiments (future in red)
The Low Energy frontier
coverage of the electromagnetic spectrum

- Compton scattering
- x-rays
- gamma-rays
- UV
- total external reflection
- coded apertures
- grazing incidence
- mirror telescopes
- sub-mm/IR
- Cerenkov scattering
- pair tracking
- air
- water
• the 1-100 MeV energy range: the last frontier

• mostly unexplored

• crucial energy range: transition from quasi-thermal (Comptonized) to non-thermal processes.
• 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
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 $p + p \rightarrow \text{anti } p + X$)
- So, any extra contribution from exotic sources ($\chi \chi$ annihilation) is an interesting signature
  - ie: $\chi \chi \rightarrow \text{anti } p + X$
  - Produced from (e. g.) $\chi \chi \rightarrow q / g / \text{gauge boson} / \text{Higgs boson}$ and subsequent decay and/ or hadronisation.
Annihilation channels

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

$\chi \rightarrow W^+/Z/q$

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

Gamma-rays

$\gamma \rightarrow \pi^0$

$\pi^+ \rightarrow \nu_\mu, \nu_\tau$

$\pi^- \rightarrow \mu^-$

$e^+ \rightarrow e^+$

Neutrinos

$\nu_\mu, \nu_\tau$

$\mu^+$

$e^+$

$\nu_\mu, \nu_\tau$

$\nu_\tau$

Neutrinos

+ 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. GEANT4

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
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 $b\bar{b}$ for different neutralino mass.

$\gamma$ yield per annihilation $\times (50 \text{ GeV}/\text{Mchi})^2$ vs. $E_\gamma$ (GeV)

- $b\rightarrow b\bar{b}$
- Neutralino mass
- Secondary $\pi^0$ component (arbitrarily rescaled)
Differential yield for $b\bar{b}$ for different neutralino mass

Low energy range is very important also for high mass neutralino search

High DM density at the Galactic center
Annihilation radiation from the GC
Milky Way Dark Matter Profiles

\[ \rho(r) = \rho_0 \left[ \frac{r_0}{r} \right]^\gamma \left[ \frac{1 + (r_0/r_s)^\alpha}{1 + (r/r_s)^\alpha} \right]^{(\beta - \gamma)/\alpha} \]

<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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<td>Cored isothermal</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>5</td>
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<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.

Different spatial behaviour for decaying or annihilating dark matter

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 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

5.2 years

15x15deg
Spectrum (E > 400 MeV, 7°x7° region centered on the Galactic Center analyzed with binned likelihood analysis)

The GeV excess 7°×7° 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

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
Published in Phys. Rev. D88 (2013) 083521

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

arXiv:1306.5725

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

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)

- Population of millisecond Pulsars around the Galactic Center
  (e.g. Hooper et al. arXiv:1305.0830, 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 2FGL Inner Galactic Region

August 4, 2008, to July 31, 2010

100 MeV to 100 GeV energy range

arXiv:1108.1435
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.
Constraints from the inner Galaxy

Optimized ROI for each profile

Einasto

NFW

NFWc

Burkert

JCAP 10 (2013) 029
[arXiv:1308.3515]

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Constraints from the inner Galaxy

3σ upper limits on the annihilation cross-section for different channels and halo profiles

No assumption on background

very robust result

\( \sigma \)

JCAP 10 (2013) 029
arXiv:1308.3515
Low energy lines limits and implications for gravitino dark matter in the $\mu\nu$SSM

Gravitino Lifetime $\tau_{3/2}$ (s)

Gravitino Mass $m_{3/2}$ (GeV)

This Work (stat. + syst.)

This Work (stat. only)

Fermi–LAT 3.7 yr (stat. only)

Vertongen, Weniger (stat. only)

EGRET Galactic centre (stat. only)

all limits at 95% CL

excluded

Excluded region

New Low Energy Line Search

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

This Analysis is Systematics Limited

To improve this search better energy and angular resolutions at energies below 100 MeV are needed

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 $<\sigma v>$ 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
NFW. 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

Combined 15 Dwarfs
4-year data
500 MeV to 500 GeV

Dwarf Spheroidal Galaxies upper-limits (6 years)

6-year data
500 MeV to 500 GeV

15 Dwarfs

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

\[ \begin{array}{c}
4\text{-year Pass 7 Limit} \\
6\text{-year Pass 8 Limit} \\
\text{Median Expected} \\
68\% \text{ Containment} \\
95\% \text{ Containment}
\end{array} \]

Thermal Relic Cross Section
(Steigman et al. 2012)

M. Ackermann et al., [Fermi Coll.] PRL Accepted [arXiv:1503.02641]

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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

M. Ackermann et al., [Fermi Coll.] PRL Accepted [arXiv:1503.02641]
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

![Graph showing upper limits from various observatories.

Antares Col. arXiv:1505.04866
IceCube Col. arXiv:1505.07259

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ATLAS-Fermi Results

Annihilation rate $<\sigma v>$ for $\chi\chi \rightarrow q\bar{q}$ [cm$^3$/s]

- $2 \times$ (Fermi-LAT dSphs $(\chi\chi)_{\text{Majorana}} \rightarrow b\bar{b}$)
- $D5$: $q\bar{q} \rightarrow (\chi\chi)_{\text{Dirac}}$
- $D8$: $q\bar{q} \rightarrow (\chi\chi)_{\text{Dirac}}$

-1$\sigma_{\text{theory}}$

WIMP mass $m_\chi$ [GeV]

Complementarity and Searches for Dark Matter in the pMSSM

Cahill-Rowley et al. arXiv: 1305.6921
Dwarf Spheroidal Galaxies upper-limits (6 years)

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

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

**Astrogam range**

Thermal Relic Cross Section
(Steigman et al. 2012)

\[ \tau^+ \tau^- \]

M.Ackermann et al., [Fermi Coll.] PRL Accepted [arXiv:1503.02641]
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”
  arXiv:1503.02632

- 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:1503.02079
# 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>
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<td>DES J0222.7−5217</td>
<td>(275.0, −59.6)</td>
<td>95</td>
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<tr>
<td>DES J0255.4−5406</td>
<td>(271.4, −54.7)</td>
<td>87</td>
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<td>DES J0335.6−5403</td>
<td>(266.3, −49.7)</td>
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<td>DES J0344.3−4331</td>
<td>(249.8, −51.6)</td>
<td>330</td>
<td>17.3</td>
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<td>DES J0443.8−5017</td>
<td>(257.3, −40.6)</td>
<td>126</td>
<td>18.1</td>
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<td>DES J2108.8−5109</td>
<td>(347.2, −42.1)</td>
<td>69</td>
<td>18.3</td>
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<tr>
<td>DES J2251.2−5836</td>
<td>(328.0, −52.4)</td>
<td>58</td>
<td>18.8</td>
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<tr>
<td>DES J2339.9−5424</td>
<td>(323.7, −59.7)</td>
<td>95</td>
<td>18.4</td>
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</table>

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Gamma Rays May Be Clue on Dark Matter

By DENNIS OVERBYE  MARCH 10, 2015

A small, newly discovered galaxy orbiting the Milky Way is emitting gamma rays in the form of electromagnetic radiation. The finding may be the latest in a long series of such reported Tuesday. The finding may be the latest in a long series of such findings. They are a hint at the presence of the mysterious material in nearby dwarf galaxy. Dark matter is the missing material making up 80% of the universe's mass.

Have we finally found DARK MATTER?

Gamma rays from a dwarf galaxy are considered a sign of dark matter. They were spotted in direction of the Reticulum 2 (96,000 light-years away).

Scientists say this is the most convincing signal of dark matter yet.


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New DES Dwarf Spheroidal Galaxy Candidates

New DES Dwarf Spheroidal Galaxy Candidates

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.
ESA M-4 Call

• idea of “marriage” with a Compton telescope sensitive in the range 200 keV – 10 MeV.

• possible merging with the Astro-MeV group.

• Science, Instrument, Community.
the ‘‘MeV-GeV’’ concept

• range 200 KeV – 100 MeV: new window.

• sensitivity (continuum and lines) better than INTEGRAL, COMPTEL, AGILE and FERMI by a factor 10-20.

• Two options under considerations:
  – One single instrument for Compton and pair
  – Two instruments on board the same spacecraft
ASTROGAM: a unified proposal from the entire gamma-ray community

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

M4

ASTROGAM

AstroMeV
An instrument that combine two detection techniques
• 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)

Gamma-ray energy (MeV)

- COMPTEL
- Fermi/LAT
- ASTROGAM
- Compton
- Pair
ASTROGAM view of the Galactic Center Region

100-500 MeV

Fermi PSF Pass7 rep v15 source

2 years, Sources from 3 years Fermi catalog, template ring model for diffuse

with Gomez Vargas
ASTROGAM view of the Galactic Center Region

100-500 MeV

Fermi PSF Pass7 rep v15 source

100 MeV - 500 MeV
Log scale

with Gomez Vargas
Galactic Center Region 0.5-2 GeV

Fermi PSF Pass7 rep v15 source

with Gomez Vargas
Galactic Center Region 0.5-2 GeV

Fermi PSF Pass7 rep v15 source

with Gomez Vargas

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ASTROGAM

positron annihilation

10^{-2}

balloons

HEAO

SMM

OSSE

SPI

ASTROGAM

10^{-3}

total galactic 511 keV flux

10^{-4}

10^{-5}

10^{-6}


sensitivity [ph/cm^2 s]

GRO / OSSE
SNRs and the Origin and Propagation of CRs

- gamma-ray spectrum of SNRs W44. The red curve shows the expected Astrogam sensitivity for a 1-year effective time integration.
The SEDs of many blazars (FSRQs) and non-blazar AGNs detected in γ-rays peak in the “MeV range”

**Total energy output ⇒ feedback**

Observations below 100 MeV are useful to distinguish leptonic and hadronic models

AstroGam will detect more than 1000 AGNs (mostly FSRQs)

- Evolution (“Blazar sequence”)
- Origin of UHECRs and HE neutrinos
- MeV gamma-ray background

Multi-epoch SEDs of the Flat Spectrum Radio Quasar 3C454.3. ASTROGAM will allow us to investigate daily (or sub-daily) SEDs during gamma-ray superflares. 5-σ differential sensitivity for an integration time of 48 hours.
SN 2014J

Type Ia supernova exploded on 2014 Jan 14 in the starburst galaxy M82 at \( D \approx 3.5 \) Mpc \( \Rightarrow \) nearest SN Ia in more than 40 years

Detection with INTEGRAL of gamma-ray lines from \(^{56}\text{Co}\) decay (\( T_{1/2} = 77 \text{ d} \)) \( \Rightarrow \) synthesis of 0.6 \( \pm \) 0.1 \( M_\odot \) of \(^{56}\text{Ni}\) (Churazov et al. 2014, *Nature*, 28 Aug) and from \(^{56}\text{Ni}\) decay (\( T_{1/2} = 6.1 \text{ d} \)) \( \sim \) 20 d after explosion (Diehl et al. 2014, *Science*, 5 Sep); \(^{56}\text{Ni}\) lines are broad and redshifted (!) (Isern et al., in prep.)

INTEGRAL and NuSTAR observations can not be explained by current SN Ia explosion models (Burrows et al., in prep.)
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.
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.
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

CTA GC Halo 500 h

Fermi 15 years, 3x dwarfs  Preliminary

Here we need a new experiment
- 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
ASTROGAM

Complementary to CTA and SKA!
New gamma projects in space

- **AstroGam** 300 KeV- GeV (Proposal to ESA for M4)

- **Gamma-light** (Proposed to ESA but not approved)
  
  [http://agenda.infn.it/getFile.py/access?contribId=67&resId=0&materialId=slides&confId=4267](http://agenda.infn.it/getFile.py/access?contribId=67&resId=0&materialId=slides&confId=4267)

- **Gamma-400** launch foreseen by 2020
  
  100 MeV - 3 TeV, an approved Russian γ-ray satellite. Energy resolution (100 GeV) ~ 1 %. Effective area ~ 0.4 m². Angular resolution (100 GeV) ~ 0.01°.

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


  - **HERD**: Instrument on the planned Chinese Space Station.
    
    Energy resolution (100 GeV) ~ 1 %. Effective area ~ 1 - 2 m². Angular resolution (100 GeV) ~ 0.01°. Planned launch around 2020.  
    
    **Shuang-Nan ZHANG** Saturday

  - **PANGU**: suggested as a candidate for the joint small mission between the European Space Agency (ESA) and the Chinese Academy of Science (CAS)
An instrument to complete the coverage of the electromagnetic spectrum

**Total External Reflection**
- Mirror telescopes
- Coded apertures

**Cerenkov**
- Grazing incidence
- Compton scattering
- Pair tracking

**Sub-mm/IR**

**UV**
- X-rays

**Gamma-ray**
- ASTROGAM
- Water
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, Gamma-400, CTA, LHAASO).

Thank you!