Status of Dark Matter
Indirect Detection and Future Prospects

Simona Murgia
University of California, Irvine

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Indirect Dark Matter Detection

Collider Searches

DM → SM

Direct Searches

SM → DM

Indirect Searches

IceCube

AMS-02

Fermi-LAT

NB: I’ll focus on WIMPs
EXPERIMENTS

Gamma rays
- VERITAS
- HESS
- MAGIC
- HAWC
- Fermi LAT

Cosmic Rays
- AMS-02
- PAMELA
- Fermi LAT

Neutrinos
- IceCube
Gamma rays from Dark Matter Annihilation

Dark matter substructures

Galactic center

Pieri et al, arXiv:0908.0195
Gamma rays from Dark Matter Annihilation

Predicted signal from galactic center much larger than dark matter substructures (~10-1000x or more, depending on DM profile, region around GC)

Pieri et al, arXiv:0908.0195
The Gamma-Ray Sky

Fermi LAT data

4 years, $E > 1$ GeV
The interstellar gamma-ray emission in the Milky Way is produced by cosmic rays interacting with the interstellar gas and radiation field.
Interaction of cosmic rays and interstellar gas & radiation field = gamma-ray interstellar emission

NB: Details of cosmic-ray propagation are uncertain!
Galactic Center Region

- Complex region: CR intensities, density of radiation fields and gas are highest and most uncertain; significant foreground/background contribution with long integration path over the entire Galactic disc. Large uncertainties modeling the gamma-ray interstellar emission.

- Large density of gamma-ray sources: many energetic sources near to or in the line of sight of the GC, difficult to disentangle from interstellar emission.

A signal of new physics (dark matter annihilation/decay) is predicted to be largest here, where modeling of the interstellar emission + sources is problematic.
**Galactic Center Excess**

An excess in the Fermi LAT GC data consistent with dark matter annihilation was first claimed by Goodenough and Hooper (arXiv:0910.2998.) More recent analyses also find an excess.

Different approaches for the interstellar emission model (IEM):

- IEMs based on the CR propagation code (GALPROP): physically motivated, however do not fully capture complexity of the Galaxy.
- IEM provided by the Fermi LAT collaboration for point source analysis: template based, not fully physically motivated.

Develop a set of specialized IEMs for the inner 15°x15° region to extract the emission from the innermost ~1 kpc. (Fermi LAT Collab.)

4 variants for the fore/background IEM: Pulsars intensity-scaled, Pulsars index-scaled, OB Stars intensity-scaled, OB Stars index-scaled.

Determine point sources self-consistently.
Residual Maps

Structured excesses and deficits point to imperfectly modeled components and/or un-modeled contributions.

Counts in $0.1^\circ \times 0.1^\circ$ pixels, $0.3^\circ$ radius gaussian smoothing.
**Additional Component**

Spatial morphology: 2D gaussians, dark matter annihilation/decay, or a gas-like as proxy for unresolved source. Spectrum: **exponentially cutoff power law** (motivated by some dark matter and pulsar models); fit in **independent energy bins**

- The dark matter annihilation morphology yields the most significant improvements in the data-model agreement for the 4 fore/background IEMs

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Integrated flux in 15°15° ROI

**Power-law with exp cutoff**

**Independent energy bins**

**Improvements over the full energy range**

**Pulsars, index scaled**
Residual Maps

Dark Matter

DATA-MODEL (Pulsars, index scaled)

Without dark matter:

- 1-2 GeV
- 2-10 GeV
- 10-100 GeV

Counts in 0.1°x0.1° pixels, 0.3° radius gaussian smoothing

With dark matter:

- 1-2 GeV
- 2-10 GeV
- 10-100 GeV

Improvements across the region
Dark Matter Component

Morphology

- Cuspidness of the DM profile (whether a standard, $\gamma=1$, or cuspiest, e.g. $\gamma=1.2$, profile is favored) depends on IEM modeling
- Centroid may be offset compared to Sgr A* (disfavored at $\sim90\%$ C.L., C. Karwin et al, in prep), but:
  - ✓ some dependence on IEM (offset $\sim0.5^\circ-1^\circ$)
  - ✓ cannot rule out offset is due to shortcomings in modeling of IEM

![Pulsars, index scaled]![Pulsars, intensity scaled]

DM centroid
Sgr A*
The dark matter component spectrum depends strongly on the IEM

- The excess is consistent with a dark matter annihilation signal in spectrum and spatial morphology (details depend on IEM), however:
  - The claimed signal is a small fraction of the observed emission (depending on selected region)
  - The background is brighter and uncertainties in modeling it can significantly affect the characterization of the signal
Other Interpretations

In addition to DM, unresolved pulsar interpretation is found plausible
- Claimed excess is found consistent with O(1000) millisecond pulsars within ~1 kpc of GC (Abazajian et al arXiv:1402.4090), but see also Hooper et al arXiv:1606.09250
- Very young pulsars might also contribute to the excess (O’Leary et al arXiv:1504.02477)
- Also tested with non-poissonian photon statistics template analysis and wavelet decomposition (Lee et al arXiv:1412.6099, 1506.05124; Bartels et al arXiv:1506.05104)

CR proton or electron outbursts interpretations have also been proposed (e.g. Carlson et al arXiv:1405.7685, Petrovic et al 1405.7928, Cholis et al arXiv:1506.05119)
Optically observed dwarf spheroidal galaxies: largest clumps predicted by N-body simulation.

Excellent targets for gamma-ray DM searches

- Very large M/L ratio: 10 to ~ 1000 (M/L ~ 10 for Milky Way)

- DM density inferred from the stellar data! Data so far cannot discriminate, in most cases, between cusped or cored dark matter profiles.

  However, Fermi’s DM constraints with dSph do not have a strong dependence on the inner profile

- Expected to be free from other gamma ray sources and have low dust/gas content, very few stars
Dwarf Spheroidal Galaxies

Before 2015

NEW

DES

DES Collaboration, arXiv:1508.03622
Dwarf Spheroidal Galaxies

- Search for a signal in 25 dwarf spheroidal galaxies, 6 years of Fermi LAT data
- No significant emission is found
- Limits probe DM explanation of the GC excess

Fermi LAT Collaboration, arXiv 1503.02641
DWARF SPHEROIDAL GALAXIES

Search for a signal in 25 dwarf spheroidal galaxies, 6 years of Fermi LAT data

No significant emission is found

Limits probe DM explanation of the GC excess

N.B.:
Dwarf Spheroidal Galaxies

Search for a signal in 25 dwarf spheroidal galaxies, 6 years of Fermi LAT data

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Limits probe DM explanation of the GC excess

N.B.:
Contours do not fully reflect uncertainties in the DM profile (also see Abazajian et al, arXiv:1510.06424)

Uncertainties in the astrophysical background model also allow for a broader range of DM masses and annihilation channels (see e.g. Agrawal et al, arXiv:1411.2592)
Consider general models with DM particles annihilating into two-body (fermionic) final states where the interactions between the dark sector and standard model particles occurs via scalar or vector interactions:

- Scalar interaction proportional to the fermion mass
- Vector interaction independent of fermion mass

Broad range in DM masses and annihilation cross-section is not ruled out by dSphs.
Consider general models with DM particles annihilating into two-body (fermionic) final states where the interactions between the dark sector and standard model particles occurs via scalar or vector interactions

- Scalar interaction proportional to the fermion mass
- Vector interaction independent of fermion mass

Convert GC excess annihilation cross sections into WIMP-nucleon cross sections

Karwin et al, in prep

Direct detection doesn’t rule out scalar interactions as an interpretation of the GC excess, while vector interactions are largely excluded.
VHE Gamma Rays: H.E.S.S., MAGIC, VERITAS

Higher energy threshold compared to Fermi LAT

- Sensitive to higher dark matter masses

No dark matter-like emission is observed

Dark matter constraints are competitive with Fermi LAT for dark matter particle masses above ~1 TeV
Higher energy threshold compared to Fermi LAT

Sensitive to higher dark matter masses

No dark matter-like emission is observed

Dark matter constraints are competitive with Fermi LAT for dark matter particle masses above ~1 TeV

HAWC sets constraints up to 100 TeV DM masses
Cosmic rays
Positrons

- Positron fraction measured up to 500 GeV (AMS-02). Rises at high energy, up to \(\sim 250\) GeV
Positrons

- Positron fraction measured up to 500 GeV (AMS-02). Rises at high energy, up to ~250 GeV
- Dark matter can reproduce the rise, but it is disfavored by other searches (gamma rays, CMB, …)
- Other plausible interpretations (nearby single source, population of sources, production of secondaries at source, …)

➡ Anisotropy in the e+e- data could confirm the nearby source hypothesis. Predicted anisotropy is consistent with current bounds (Fermi LAT, AMS-02)

Linden et al, arXiv:1304.1791
Antiprotons

- Measurement of the antiproton fraction up to 450 GeV
- In agreement with secondary production predictions (based on B/C measurements and antiprotons produced by CR interactions in the interstellar medium); consistent with primary source to explain positron fraction

Giesen et al, arXiv:1504.04276
Antiprotons

- Measurement of the antiproton fraction up to 450 GeV
- In agreement with secondary production predictions (based on B/C measurements and antiprotons produced by CR interactions in the interstellar medium); consistent with primary source to explain positron fraction
- However, if a dark matter signal is fitted concurrently, a signal is observed which is consistent with GC excess (assuming B/C is not representative of propagation for light nuclei, Johannesson et al, arXiv:1602.02243)

Cuoco et al, arXiv:1610.03071
Better understanding of the astrophysical background is crucial for most indirect dark matter searches.
GC Excess

Improvements across the region when dark matter is included, but some discrepancies between data and model remain.

DATA-MODEL (Pulsars, index scaled - with dark matter)
The density of cosmic-ray sources and interstellar medium is associated with spiral arms, Galactic bar/bulge, and therefore radially and azimuthally dependent.

Currently there are no detailed 3D models for the interstellar gas, radiation field, and cosmic-ray sources.

Not surprising... there are limitations in all interstellar emission models employed so far, e.g., cylindrical symmetry, the gas distribution, as well as interplay between the interstellar emission and point sources.

Understanding these issues and addressing these limitations is crucial to confirm the presence and properties of additional components, dark matter or otherwise!

Work is underway in addressing these limitations.
The Way Forward

- Better understanding of the astrophysical background is crucial for most indirect dark matter searches
- Improvements in modeling alone won’t be enough to significantly improve prospects for discovery or setting stringent constraints
- Need new and improved experiments!
## Current and Future Experiments

### Table 2. Comparison of parameters for the current, future space- and ground-based instruments.

<table>
<thead>
<tr>
<th></th>
<th>SPACE-BASED GAMMA-RAY INSTRUMENTS</th>
<th>GROUND-BASED GAMMA-RAY INSTRUMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fermi-LAT</td>
<td>DAMPE</td>
</tr>
<tr>
<td>Particles</td>
<td>$\gamma, e$</td>
<td>$e, \text{nuclei, } \gamma$</td>
</tr>
<tr>
<td></td>
<td>$e, \text{nuclei, } \gamma$</td>
<td>$\gamma, e, \text{nuclei}$</td>
</tr>
<tr>
<td>Operation period</td>
<td>2008-2015</td>
<td>2015</td>
</tr>
<tr>
<td>Energy range, GeV</td>
<td>0.02-300</td>
<td>5-10000</td>
</tr>
<tr>
<td></td>
<td>0.02-100000</td>
<td>10-10000</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>$0.1^\circ$</td>
<td>$0.1^\circ$</td>
</tr>
<tr>
<td>(E$_\gamma$ &gt; 100 GeV)</td>
<td>$\sim0.01^\circ$</td>
<td>$0.07^\circ$ (E$_\gamma$ = 300 GeV)</td>
</tr>
<tr>
<td>Energy resolution</td>
<td>10%</td>
<td>1.5%</td>
</tr>
<tr>
<td>(E$_\gamma$ &gt; 100 GeV)</td>
<td>$\sim1%$</td>
<td>2%</td>
</tr>
<tr>
<td></td>
<td>15%</td>
<td>15%</td>
</tr>
<tr>
<td></td>
<td>$15%$</td>
<td>$20%$</td>
</tr>
<tr>
<td></td>
<td>(E$_\gamma$ = 100 GeV)</td>
<td>(E$_\gamma$ = 100 GeV)</td>
</tr>
<tr>
<td></td>
<td>15%</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>(E$_\gamma$ = 1 TeV)</td>
<td>(E$_\gamma$ = 10 TeV)</td>
</tr>
<tr>
<td></td>
<td>CTA</td>
<td></td>
</tr>
</tbody>
</table>
CALET, DAMPE

Some overlap in energy with Fermi LAT

CALET: on ISS since Aug 2015. $10^1$ GeV - $10^{20}$ TeV $\gamma$ (e), $10'$s GeV - 1000 TeV nuclei. Thick calorimeter, excellent energy resolution. Test dark matter scenarios and interpretation via spectral features in $e^+e^-$ and $\gamma$ spectra, e.g. lines, LKP. Detection of nearby astrophysical sources of electrons

DAMPE: launched in Dec 2015. 1 GeV - 10 TeV $e/\gamma$, 100 GeV - 100 TeV cosmic rays. Tracker+thick imaging calorimeter, excellent energy resolution

High precision measurement of the electron spectrum at high energy with excellent energy resolution might reveal evidence of a nearby source (e.g. SNR)
The GAMMA-400 γ-ray telescope, ~20 MeV to TeV for γ-rays, and up to 10 (1000) TeV for electrons (nuclei)

- Very similar in design to Fermi LAT, but with some significant improvements
  - Deep calorimeter for improved energy resolution, and to extend to high energies
  - Tracker with small pitch between Si layers, and no converter for top layers, for improved angular resolution

Planned for mid 2020 (Russian Federal Space Program)

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**Table 1. Comparison of the Fermi-LAT and GAMMA-400 parameters.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fermi-LAT</th>
<th>GAMMA-400</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit</td>
<td>Circular, 565 km</td>
<td>Highly elliptical, 500-300000 km (without the Earth’s occultation)</td>
</tr>
<tr>
<td>Operation mode</td>
<td>Sky-survey (3 hours)</td>
<td>Point observation (up to 100 days)</td>
</tr>
<tr>
<td>Source exposition</td>
<td>1/7</td>
<td>1</td>
</tr>
<tr>
<td>Energy range (Eγ, Ee)</td>
<td>20 MeV - 300 GeV (γ), 1 GeV - 10 TeV (e)</td>
<td>~20 MeV - 1 TeV (γ)</td>
</tr>
<tr>
<td>Effective area</td>
<td>~6500 cm² (total), ~4000 cm² (front)</td>
<td>~4000 cm²</td>
</tr>
<tr>
<td>Coordinate detectors</td>
<td>Si strips (pitch 0.23 mm), digital</td>
<td>Si strips (pitch 0.08 mm), analog</td>
</tr>
<tr>
<td>- readout</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angular resolution</td>
<td>~4° (Eγ = 100 MeV)</td>
<td>~2° (Eγ = 100 MeV)</td>
</tr>
<tr>
<td></td>
<td>~0.2° (Eγ = 10 GeV)</td>
<td>~0.1° (Eγ &gt; 100 GeV)</td>
</tr>
<tr>
<td></td>
<td>~0.1° (Ee &gt; 100 GeV)</td>
<td>~0.01° (Ee &gt; 100 GeV)</td>
</tr>
<tr>
<td>Calorimeter</td>
<td>CsI(Tl)</td>
<td>CsI(Tl) + Si</td>
</tr>
<tr>
<td>- thickness</td>
<td>~8.5 X0</td>
<td>~25 X0</td>
</tr>
<tr>
<td>Energy resolution</td>
<td>~10% (Eγ = 10 GeV)</td>
<td>~3% (Eγ = 10 GeV)</td>
</tr>
<tr>
<td></td>
<td>~10% (Eγ &gt; 100 GeV)</td>
<td>~1% (Ee &gt; 100 GeV)</td>
</tr>
<tr>
<td>Proton rejection factor</td>
<td>~10²</td>
<td>~5x10⁷</td>
</tr>
<tr>
<td>Mass, kg</td>
<td>2800</td>
<td>4100</td>
</tr>
<tr>
<td>Telemetry downlink volume</td>
<td>15 Gbytes/day</td>
<td>100 Gbytes/day</td>
</tr>
</tbody>
</table>

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(Translated by Topchiev et al., J.Phys.Conf.Ser. 675 (2016) no.3, 032009)
Cosmic Rays and Dark Matter

- CR data difficult to interpret in the context of DM signals because of large astrophysical uncertainties
- Upcoming experiments such as GAPS searching for anti-deuterons from DM are predicted to be less sensitive to the astrophysical uncertainties and thus might provide less controversial results

Balloon, planned (~2020)
**Cherenkov Telescope Array (CTA)**

- Next generation gamma ray observatory
- Improve sensitivity of current ATCs (~10x), extend to lower and higher energies (~ 10s GeV to >300 TeV), two sites (northern and southern hemisphere)
- Basic design: small core of large telescopes, surrounded by mid size telescopes and an outer ring of small telescopes (southern site)
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- Basic design: small core of large telescopes, surrounded by mid size telescopes and an outer ring of small telescopes (southern site)
- Sensitivity for dark matter masses above 200 GeV is below thermal relic

Ground based, planned (~2020)
Covering the MeV Energy Range

- Improve coverage between hard X-rays and ~ GeV, so far poorly explored. Improvements in source sensitivity, source localization, energy resolution. Include polarization measurements

- Mission concepts: e-Astrogam (0.3 MeV to 3 GeV), ComPair.
Covering the MeV Energy Range

Rich science program: ultra-relativistic jets, Galactic chemical evolution, origin and propagation of CRs.

Also dark matter: low mass WIMPs (better than Fermi for ~GeV masses; also cover 1-100 MeV mass). Much improved sensitivity compared to INTEGRAL to investigate 511 keV $e^+e^-$ annihilation line.

Improved understanding of astrophysical process will benefit DM searches. Discovery of many new sources: observation of nearby pulsars will provide clues in the interpretation of the rise in the positron fraction, better source characterization (relevant to dark matter subhalo searches).

Much better angular resolution below ~ 1 GeV compared to current state of the art (Fermi LAT).
Concluding Remarks

All planned improvements are going to significantly improve the prospects for indirect dark matter WIMP searches in the next 5-10 years.

A more targeted approach should also be considered, i.e. develop and build instrument with the desired capabilities to find dark matter, e.g. an instrument with much improved angular resolution in the Fermi LAT energy range to improve sensitivity in the GC region, where signal is expected to be brightest (and also improve energy resolution and flux sensitivity).

Aim for big and targeted improvements for dark matter searches, not only incremental or indirect.

Such an instrument will most certainly greatly improve the prospects for other astrophysics studies (while the reverse is not necessarily true).
Central Region of the Milky Way

Image (width~0.5°) combines a near-infrared view from the Hubble Space Telescope (yellow), an infrared view from the Spitzer Space Telescope (red) and an X-ray view from the Chandra X-ray Observatory (blue and violet) into one multi-wavelength picture.
Thank You!