Indirect dark matter searches with Fermi-LAT

The Aquarius Project: the subhalos of galactic halos

Figure 3. Projected dark matter density in our six different high-resolution halos at $z=0$, at the resolution level. In each panel, all particles within a cubic box of side length $2.5 \times 50$ centred on the halo are shown, and the circles mark the radius $r_{50}$. The image brightness is proportional to the logarithm of the squared dark matter density, and the colour hue encodes the local particle velocity dispersion, with the same colour map as in Figure 2.

To make them feasible on today's supercomputers, we have carried out our most expensive calculation, the Aq-A-1 run, on the Altix 4700 supercomputer of the Leibniz Computing Center (LRZ) in Garching/Germany, using 1024 CPUs and about 3 TB of main memory. The calculation took more than 3.5 million CPU hours to carry out about $10^{1400}$ timesteps that involved $6.72 \times 10^{13}$ force calculations in total. We have stored 128 simulation dumps for this calculation, amounting to a data volume of about 45 TB. The other simulations of the Aquarius Project were in part calculated on the LRZ system, and in part on other supercomputers across Europe. These were the COSMA computer at Durham University/UK, the Bluegene/L system STELLA of the LOFAR consortium in Groningen/Netherlands, and a Bluegene/P system of the Max-Planck Computing Center in Garching. For all these simulations we also stored at least 128 outputs, but for Aq-A-2 and Aq-A-4 we kept 1024 dumps, and for Aq-A-3 half this number. This provides exquisite time resolution for studies of the detailed formation history of halo and the evolution of their substructure. In the present study, however, we focus on an analysis of the objects at $z=0$.

2.4 A first view of the simulations

In Figures 2 and 3, we show images† of the dark matter distribution in our 6 high resolution halos at redshift $z=0$. The brightness of each pixel is proportional to the logarithm of the squared dark matter density projected along the line-of-sight,

$$S(x, y) = \int \rho^2(r) \, dz,$$

while the colour hue encodes the mean dark matter velocity dispersion, weighted as

$$\sigma(x, y) = \frac{1}{S(x, y)} \int \sigma_{\text{loc}}(r) \rho^2(r) \, dz.$$

Here the local dark matter density $\rho(r)$ and the local velocity dispersion $\sigma_{\text{loc}}(r)$ of the particles are estimated with an SPH kernel interpolation scheme based on 64 neighbours. We use a two-dimensional colour-table (see Fig. 2) in which the information about the local dark matter 'temperature' is...
Dark matter not contained within Standard Model of particle physics

Postulate a particle, solve for its abundance

A particle’s annihilation cross section and abundance are related:

\[
\langle \sigma_{\text{ann}} v \rangle \approx \frac{3 \times 10^{-27}}{\Omega_{\text{DM}} h^2} \text{ cm}^3 \text{s}^{-1}
\]

\[
\langle \sigma_{\text{ann}} v \rangle \approx 3 \times 10^{-26} \text{ cm}^3 \text{s}^{-1}
\]

“Thermal relic scale”

Annihilation cross section characteristic of a weakly-interacting particle

Weakly-interacting particles (WIMPs) a leading candidate for dark matter
Macro-physics and microphysics of dark matter

\[
\phi_s(\Delta \Omega) = \frac{1}{4\pi} \frac{\langle \sigma v \rangle}{2m_{\text{DM}}^2} \int_{E_{\text{min}}}^{E_{\text{max}}} \frac{dN_\gamma}{dE_\gamma} dE_\gamma \times \int_{\Delta \Omega} \int_{1\text{o.s.}} \rho_{\text{DM}}^2(r) dl d\Omega'
\]

- LCDM N-body simulations predict NFW-like profile \( \rho_{\text{DM}}(r) = \frac{\rho_0 r_s^3}{r(r_s + r)^2} \)

- Clumping and substructure predicted from N-body simulations

- Measurements of smooth dark matter distributions from astronomical observations

- Significant debate as to how NFW profile describes observations
Indirect dark matter detection: micro-physics

For continuum photon final states:

- Tens to hundreds of photons produced per WIMP annihilation
- 100 GeV mass WIMPs gives photons in the gamma-ray band, 10 MeV-10 GeV
Space and ground-based gamma-ray astronomy

Fermi gamma-ray space telescope
20 MeV-300 GeV

Air Cherenkov telescopes:
H.E.S.S., Magic, Veritas
30 GeV-100 TeV

Water Cherenkov telescopes:
HAWC
50 GeV-100 TeV
Fermi gamma-ray space telescope

Fermi two-year all-sky map

Credit: NASA/DOE/Fermi/LAT Collaboration
Fermi-LAT all-sky search strategies

Dwarf Galaxies:
- Known location and dark matter content
- Low statistics

Pieri et al. (2011)

Milky Way halo:
- Large statistics
- Diffuse background

Low-Mass Satellites:
- Start with known gamma-ray emission
- Unknown origin

Galactic Center:
- Large statistics
- Lots of astrophysics

Spectral lines:
- "Clean" from astrophysics

Galaxy clusters:
- Possibly large statistics
- Astrophysical signal expected

Electrons and Positrons!

Galactic Center:
- Large statistics
- Lots of astrophysics

Extragalactic background:
- Large statistics
- Lots of astrophysics
Galactic center (GC)

- Significant uncertainty in dark matter mass profile in Galactic center (bulge, nuclear star cluster dominate dynamics)

- Several Fermi-LAT point sources within 1 sq. deg. of Galactic center

- At higher energies: H.E.S.S. and MAGIC source coincident with Sgr A* (HESS 1745-290)

- H.E.S.S. diffuse emission correlated with Giant Molecular Clouds
H.E.S.S. Gamma ray data from the Galactic Center

- No statistically-significant excess in gamma-rays
- DM cross section limits assume a core in density profile of constant density
Gamma ray data from the Inner Galaxy

- Spherically-symmetric emission from the Galactic center not explained by standard cosmic ray propagation models

- Non-DM interpretations include pulsars, leptonic outbursts from GC (Cholis et al. 1506.05119)

- DM interpretation: 50 GeV WIMP annihilation to b quarks
  Hooper & Goodenough 0910.2998; Abazajian & Kaplinghat 1207.6047; Gordon & Macias 1306.5725; Dylan et al. 1402.6703; Calore et al 1409.0042

- Statistical evidence for a point source population?
  Bartels et al. 1506.05104; Lee et al. 1506.05124
Milky Way satellite galaxies (dwarf spheroidals)

- Dark matter masses from motions of individual stars
- Most dark matter-dominated galaxies known
- Luminosities from hundreds to millions Solar luminosities
- No high energy gamma-rays from astrophysical sources

M. Walker et al 2007
Satellite galaxies in visible light and gamma-rays

Segue 1

Visible Light

Draco

Gamma-rays
• Determine the total mass of dark matter from velocities of stars in each satellite

• Combine measured gamma-ray flux upper bound with total dark matter mass in each satellite to get upper bound on annihilation cross section

Fermi-LAT collaboration
PRL, 1108.3546
PRD, 1310.0828
PRL, 1503.02641
Implications for Galactic center searches

- Some interpretations of Galactic center gamma-ray emission are constrained
- Uncertainty in Galactic center dark matter distribution prevents more definitive statement

Fermi-LAT collaboration PRL, 1503.02641
New dwarf spheroidal discoveries

Found 8 new dwarf candidates!

figure in DES discovery paper

Bechtol et al. DES Collaboration 1503.02584, Koposov et al. 1503.02079
Fermi/DES analysis of satellite candidates

Drlica-Wagner et al. DES/Fermi-LAT collaborations 1503.02632
Evidence for Gamma-ray Emission from the Newly Discovered Dwarf Galaxy Reticulum 2

• Geringer-Sameth et al. 1503.02320 identify 2-3 sigma excess from Reticulum II

• No similar excess reported in DES/Fermi-LAT analysis 1503.02682

Measurements of DM distribution needed to shed further light....
Reticulum II is a dark matter-dominated satellite galaxy

- Dark matter mass most likely too low to allow for a dark matter interpretation of the Reticulum II gamma ray observations
  Simon et al. DES collaboration 1504.02889

- Some parameter space available for DM interpretation of Ret II gamma-rays
  Walker et al. 1504.03060
Summary: Gamma-ray limits from dSphs

Also searches for subhalos with no associated stars that emit gamma-rays (Fermi-LAT collaboration 1201.2691, Bertoni et al. 1504.02087)

J. Conrad, J. Cohen-Tanugi, L. Strigari
1503.06348 JTEP

Also searches for subhalos with no associated stars that emit gamma-rays (Fermi-LAT collaboration 1201.2691, Bertoni et al. 1504.02087)
Weniger 1204.2797 identified a line-like feature ~ 130 GeV in global Fermi-LAT data at ~ 2-5 sigma (also Su & Finkbeiner 1206.1616)

Systematic or DM annihilation signal?

Fermi-LAT analysis of 5.8 yrs of data find no significant detection of line-like feature:1506.00013

\[
\begin{align*}
\text{DM} & \quad \gamma \\
\text{DM} & \quad \gamma
\end{align*}
\]

\[
\text{Gamma-ray Line searches}
\]

\[
\begin{align*}
\text{P8 \_CLEAN R3 5.8 yr} & \quad E_\gamma = 133.0 \text{ GeV} \\
\Gamma_{\text{bkg}} & = 2.47 \\
n_{\text{sig}} & = 7.3 \text{ evts (0.7 } \sigma) \\
n_{\text{bkg}} & = 700 \pm 30 \text{ evts}
\end{align*}
\]

\[
\begin{align*}
\text{Residual}(\sigma) & \quad \text{Events / (5.0 GeV)}
\end{align*}
\]

\[
\begin{align*}
\text{Energy (GeV)} & \quad 40 \quad 60 \quad 80 \quad 100 \quad 120 \quad 140 \quad 160 \quad 180 \quad 200 \quad 220
\end{align*}
\]
Galaxy clusters

- Masses of galaxy clusters determined from temperature profile of x-ray spectra, and electron gas density profile from the X-ray luminosity

- Assumption of hydrostatic equilibrium gives the mass within a fixed physics radius, $M(r)$

- Nearby clusters Fornax, Coma, and Virgo are some of the most interesting sources (Pinzke et al 1105.3240; Ando & Nagai 1201.0753)

- Significant contribution to the flux expected from substructure in the clusters (e.g. Gao et al. 1107.1916)
Extragalactic gamma-ray background

Fermi-LAT collaboration PRD 1410.3696
Fermi-LAT collaboration JCAP 1501.05464

- Extragalactic gamma-ray background = isotropic gamma-ray background + resolved sources

- Sources include Blazars, star-forming galaxies, radio galaxies
Anti-matter searches ($e^{+/−}$, $p^{+/−}$)

• AMS-02 confirmed and extended previous indications of rising positron fraction

• Diffuse flux falls steeply as a function of energy. Indicative of source term at high energies

• Source candidates are pulsars (DiMauro et al 1402.0321), SN remnants (Mertsch & Sarkar 1402.0855), or DM annihilation (e.g. Cirelli et al 0809.2409)

• Recent AMS-02 results for anti-protons
• DM annihilation injects energy into CMB at $z \sim 1000$.

• Annihilation products lose energy due to interactions with plasma.

• Widens the surface of last scattering and alters CMB peaks.

• Results are relatively insensitive to annihilation channels. Everything except directly annihilation to just neutrinos strongly constrained.

• Also information from polarization.

**Planck** fraction in the freeze-out tail following recombination. As a result, the expression of the amplitude of the peaks both in temperature and polarization likelihood and there is little enhancement in polarization caused by the increased ionization. Constraints on DM annihilation from CMB experiments with angular resolution comparable to that of WMAP9. The dashed green line delineates a forecast for a cosmic variance limited experiment with angular resolution comparable to that of WMAP9, however, dark matter annihilation can produce an enhancement in polarization caused by the increased ionization.

The constraints on $\sigma_{\text{ann}}$ are about 3 times weaker than the 95% limit of $10^{-28}$ cm$^3$/s (green), and also information from polarization.

**Planck T E + lowP (blue) data combinations.**

Widens the surface of last scattering and alters CMB peaks. As a result, the enhancement in polarization caused by the increased ionization. Constraints on DM annihilation from CMB experiments with angular resolution comparable to that of WMAP9, however, dark matter annihilation can produce an enhancement in polarization caused by the increased ionization.

**Planck T E + lowP (red), E E + lowP.** Possible interpretations for: AMS-02/Fermi/Pamela, Fermi GC. Planck collaboration 1502.01589.
Indirect searches with neutrinos

- Ice cube observations of the Galactic center probe direct WIMP annihilation to neutrinos
Summary/interpretations/future progress

• Fermi-LAT gamma-ray searches have reached the thermal relic scale

• Planck constraints also reaching thermal relic scale. Strongly constrain AMS-02, Pamela DM interpretations

• Strongly constraining thermal relic WIMP dark matter with velocity independent annihilation cross sections

• Future progress:
  • More Fermi-LAT, Cherenkov telescope data
  • Discovery of more dSphs of the Milky Way
  • Neutrino constraints