Particle dark matter signals in the anisotropic sky: A cross correlation approach

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Neutrino and Dark Matter in Nuclear Physics (NDM 2015)
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Based on:

Camera, Fornasa, NF, Regis, arXiv:1411.4651
Regis, Xia, Cuoco, NF, Branchini, Viel, arXiv:1503.05922

Cuoco, Xia, Regis, NF, Branchini, Viel, *to appear*
Dark Matter

• The presence of DM is supported by copious and consistent astrophysical and cosmological probes
  - Horizon-scale: average DM density about 6 times baryon density
  - Smaller scales: DM distribution is quite anisotropic and hierarchical clusters – galaxies – subhalos

• Observations are consistent with a theoretical understanding of cosmic structure formation through gravitational instability, based on the LCDM model
  Although:
  - Some problem on very small scales
  - Role of baryons in galaxy formation just started to be investigated
Dark Matter

- **DM evidence purely gravitational**
  - Galaxy clusters dynamics
  - Rotational curves of spiral galaxies
  - Gravitational lensing
  - Hydrodynamical equilibrium of hot gas in galaxy clusters
  - Energy budget of the Universe
  - The same theory of structure formation

- **This evidence can be ascribed either to:**
  - Modification of the theory of Gravity
  - $DM = \text{elementary particle, relic from the early Universe}$
    - No viable candidate in the SM: **New Physics BSM**
    - However, if $DM$ is a new particle, a **non-gravitational signal**
      (due to it’s particle physics nature) is expected
Where to search for a signal

We can try to exploit every structure where DM is known to be present:

- Our Galaxy
  - Smooth component
  - Subhalos
- Satellite galaxies (dwarfs)
- Galaxy clusters
  - Smooth component
  - Individual galaxies
  - Galaxies subhalos
- “Cosmic web”
Galactic dark matter signals

Halo signals
- Charged CR ($e^\pm, \text{antip}, \text{antiD}$)
- Neutrinos
- Photons
  - Gamma-rays
    - Prompt production
    - IC from $e^\pm$ on ISRF and CMB
  - X-rays
    - IC from $e^\pm$ on ISRF and CMB
  - Radio
    - Synchro from $e^\pm$ on mag. field

Local signals
- Direct detection
- Neutrinos from Earth and Sun
Extragalactic/Cosmological signals

Photons: gamma, X, radio
Neutrinos

Impact on CMB:
  SZ effect in clusters
  Back to recombination
Features of the Extra Galactic DM signal

- Sources of DM signals are:
  - Faint
  - Very numerous

- The DM emission is very likely subdominant in the “IGRB”
Features of the Extra Galactic DM signal

- Sources of DM signals are:
  - Faint
  - Very numerous

- The cumulative emission from these \textit{unresolved} sources produces a nearly “isotropic” component, but ...

- DM sources can affect the statistics of photons across the sky, even though they are too dim to be individually detected

\textbf{Statistical Correlations}
Simulation of extraGalactic $\gamma$ ray emission

Intensity at 4 GeV
$m_{\text{DM}} = 200$ GeV
$\langle \sigma v \rangle$ thermal
bb channel

Fornasa et al., MNRAS 329 (2013) 1529
Statistical correlators

- 1-point correlator: pixel count
  - Useful to constrain the source number count $dN/dS$ below detection threshold

- 2-point correlator: angular power spectrum
  - Auto-correlation
2-point auto-correlation function

APS of the gamma-rays auto-correlation observed by Fermi/LAT

Overall significance: 9σ

Ackerman et al. (Fermi) PRD 85 (2012) 083007
Gamma-rays auto-correlation

Features of the signal point toward interpretation in terms of blazars

DM likely plays a subdominant role (as for total intensity)

Difficult to extract a clear WIMP signature from the EGB alone
Can we do more?

Cross-correlation of EM signal with gravitational tracer of DM

It exploits two distinctive features of particle DM:
- An electromagnetic signal, manifestation of the particle nature of DM
- A gravitational probe of the existence of DM

It can offer a direct evidence that what is measured by means of gravity is indeed due to DM in terms of an elementary particle.
GAMMA RAYS/COSMIC SHEAR
CROSS CORRELATIONS
Weak gravitational lensing

- **Weak lensing**: small distortions of images of distant galaxies, produced by the distribution of matter located between background galaxies and the observer.

- Powerful probe of dark matter distribution in the Universe.

**Table:**

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Cosmic structures and gamma-rays

The same Dark Matter structures that act as lenses can themselves emit light at various wavelengths, including the gamma-rays range

- From astrophysical sources hosted by DM halos (AGN, SFG, ...)
- From DM itself (annihilation/decay)

Gamma-rays emitted by DM may exhibit strong correlation with lensing signal

The lensing map can act as the filter needed to isolate the signal hidden in a large “noise”
Cross-correlation of:
- Gravitational shear with
- Extragalactic gamma-ray background (the residual radiation contributed by the cumulative emission of unresolved gamma-ray sources)

Looked through the statistical correlations encoded in its cross angular power spectrum \( C_{i}^{\gamma \phi} \)

Camera, Fornasa, NF, Regis, arXiv:1411.4651, to appear in JCAP
NF, Regis, Front. Physics 2 (2014) 6
Correlation functions

Source Intensity

\[ I_g(\vec{n}) = \int d\chi \ g(\chi, \vec{n}) \tilde{W}(\chi) \]

Density field of the source

Cross-correlation angular power spectrum

\[ C^{(ij)}_\ell = \frac{1}{\langle I_i \rangle \langle I_j \rangle} \int \frac{d\chi}{\chi^2} W_i(\chi) W_j(\chi) P_{ij}(k = \ell/\chi, \chi) \]

\[ \langle \hat{f}_g(\chi, \mathbf{k}) \hat{f}^*_g(\chi', \mathbf{k}') \rangle = (2\pi)^3 \delta^3(\mathbf{k} - \mathbf{k}') P_{ij}(k, \chi, \chi') \]

\[ f_g \equiv \left[ g(\mathbf{x}|m, z)/\bar{g}(z) - 1 \right] \]

\( \hat{f}_g \): Fourier transform
Window functions

Lensing

\[ W^\kappa(\chi) = \frac{3}{2} H_0^2 \Omega_m [1 + z(\chi)] \chi \int_\chi^{\infty} d\chi' \frac{\chi' - \chi}{\chi'} \frac{dN_g}{d\chi'}(\chi') \]

Redshift distribution of background galaxies
Window functions

Gamma-rays from annihilating DM

$$W^{\gamma_{\text{DM}}} (\chi) = \frac{\left( \Omega_{\text{DM}} \rho_c \right)^2}{4\pi} \frac{\langle \sigma_v \rangle}{2m_{\text{DM}}^2} \left[ 1 + z(\chi) \right]^3 \Delta^2 (\chi) J_a (E, \chi)$$

Clumping factor

$$\Delta^2 (\chi) \equiv \frac{\langle \rho^2_{\text{DM}} \rangle}{\rho^2_{\text{DM}}} = \int_{M_{\text{min}}}^{M_{\text{max}}} \frac{dM}{dM} \int d^3 x \frac{\rho^2_h (x|M, \chi)}{\rho^2_{\text{DM}}} \left[ 1 + B (M, \chi) \right]$$

Subhalo boost

$$J_{a/d} (E, \chi) = \int_{\Delta E_\gamma} dE_\gamma \frac{dN_{a/d}}{dE_\gamma} [E_\gamma (\chi)] e^{-\tau[\chi, E_\gamma (\chi)]}$$

Gamma-rays are also emitted by astrophysical sources, each of which has a specific window function.
Window functions

\[
H(z)^{-1} \frac{W(z)}{\langle I_{\text{tot}} \rangle} = \begin{cases} 
\text{DE5} & \text{shear} \\
\text{Euclid} & \\
\text{SFG} & \\
\text{ann. DM - HIGH} & \\
\text{ann. DM - LOW} & \\
\text{dec. DM} & \\
\text{blazars} & \\
\text{ann. DM - NS} & 
\end{cases}
\]

Annihilating DM
\[
m_{\text{DM}} = 100 \text{ GeV} \\
\langle \sigma_a v \rangle = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}
\]

Decaying DM
\[
m_{\text{DM}} = 200 \text{ GeV} \\
\Gamma_d = 0.33 \times 10^{-27} \text{ s}^{-1}
\]

Camera, Fornasa, NF, Regis, arXiv:1411.4651, to appear in JCAP
Correlation functions

Source Intensity

\[ I_g(\vec{n}) = \int d\chi \, g(\chi, \vec{n}) \hat{W}(\chi) \]

Density field of the source

Cross-correlation angular power spectrum

\[ C_{\ell}^{(ij)} = \frac{1}{\langle I_i \rangle \langle I_j \rangle} \int \frac{d\chi}{\chi^2} W_i(\chi) W_j(\chi) P_{ij}(k = \ell/\chi, \chi) \]

\[ \langle \hat{f}_{g_i}(\chi, k) \hat{f}_{g_j}^*(\chi', k') \rangle = (2\pi)^3 \delta^3(k - k') P_{ij}(k, \chi, \chi') \]

\[ f_g \equiv [g(\chi|m, z)/\overline{g}(z) - 1] \quad \hat{f}_g : \text{Fourier transform} \]

1-halo term \[ P_{ij}^{1h}(k) = \int dm \, \frac{dn}{dm} \hat{f}_i^*(k|m) \hat{f}_j(k|m) \]

2-halo term \[ P_{ij}^{2h}(k) = \left[ \int dm_1 \, \frac{dn}{dm_1} b_i(m_1) \hat{f}_i^*(k|m_1) \right] \left[ \int dm_2 \, \frac{dn}{dm_2} b_j(m_2) \hat{f}_j(k|m_2) \right] P^{\text{lin}}(k) \]
Annihilating DM

\[ P_{1h}^{\delta^2}(k, z) = \int_{M_{\text{min}}}^{M_{\text{max}}} dM \frac{dn}{dM} \tilde{v}(k|M) \frac{\tilde{u}(k|M)}{\Delta^2} \]

\[ P_{2h}^{\delta^2}(k, z) = \left[ \int_{M_{\text{min}}}^{M_{\text{max}}} dM \frac{dn}{dM} b_h(M) \tilde{v}(k|M) \right] \left[ \int_{M_{\text{min}}}^{M_{\text{max}}} dM \frac{dn}{dM} b_h(M) \frac{\tilde{u}(k|M)}{\Delta^2} \right] P_{\text{lin}}(k, z) \]

- \( dn/dM \): Halo mass function
- \( \tilde{v}(k|M) \): Fourier transform of \( \rho_{\text{DM}}(x|M)/\bar{\rho}_{\text{DM}} \)
- \( \tilde{u}(k|M) \): Fourier transform of \( \rho_{\text{DM}}^2(x|M)[1 + b(M, z)]/\bar{\rho}_{\text{DM}}^2 \)
- \( b_h(M) \): Bias between halo and matter
3D Power spectra: dark matter

Cross-correlation 3D Power Spectrum

1-halo cross-correlation 3D PS

(z = 0)

1-halo only)
Cross-correlation predictions

Decaying DM

\[ C_l^{(i,j)} \leftarrow W_i(\chi) W_j(z) P_{ij}(k = l/\chi, \chi) \]

Tomographic-Spectral approach

Reshift information in shear: can help in “filtering” signal sources

Energy spectrum of gamma-rays: can help in DM-mass reconstruction

Camera, Fornasa, NF, Regis, arXiv:1411.4651, to appear in JCAP
**Bayesian Forecasts**

- Discovery potential ($5 \sigma$) in the $(m_{DM}, <\sigma v>)$ plane

- Bounds in the $(m_{DM}, <\sigma v>)$ plane in case the DM contribution is strongly suppressed

- Strength in parameter reconstruction (on specific benchmark models)

- In all cases, the astrophysical components in the gamma emission (AGN, Blazars, SFG) are allowed to vary and are marginalized over

\[ A_{AGN} : (0.2 - 2) \quad A_{SFG} : (0.1 - 10) \quad A_{BLA} : (0.05 - 50) \]
## Detectors and configurations

### Parameter | Description | DES | Euclid
--- | --- | --- | ---
$f_{\text{sky}}$ | Surveyed sky fraction | 0.12 | 0.36
$ar{N}_g$ [arcmin$^{-2}$] | Galaxy density | 13.3 | 30
$z_{\text{min}} - z_{\text{max}}$ | Redshift range | 0.3 – 1.5 | 0 – 2.5
$N_z$ | Number of bins | 3 | 10
$\Delta_z$ | Bin width | 0.4 | 0.25
$\frac{\sigma_z}{1 + z}$ | Redshift uncertainty | – | 0.03
$\sigma_e$ | Intrinsic ellipticity | 0.3 | 0.3

### Parameter | Description | Fermi-10yr | Fermissimo
--- | --- | --- | ---
$f_{\text{sky}}$ | Surveyed sky fraction | 1 | 1
$E_{\text{min}} - E_{\text{max}}$ [GeV] | Energy range | 1 – 300 | 0.3 – 1000
$N_E$ | Number of bins | 6 | 8
$\varepsilon$ [cm$^2$ s] | Exposure | $3.2 \times 10^{12}$ | $4.2 \times 10^{12}$
$\langle \sigma_b \rangle$ [deg] | Average beam size | 0.18 | 0.027

**Combinations:**

- **DES + Fermi 10 yr**
- **Euclid + “Fermissimo”**
Forecasts

$\langle \sigma v \rangle$ [cm$^3$/s]

$b\bar{b}$ channel
- Red: DMa Low
- Blue: DMa High
- Green: DMa NS

DES+Fermi10yr
5σ detection for $C_i^\kappa$

$2σ$ bounds for $C_i^\kappa$

$\langle \sigma v \rangle$ [cm$^3$/s]

$5\sigma$ detection

sensitivity limit

Camera, Fornasa, NF, Regis, arXiv:1411.4651, to appear in JCAP
Forecasts: detection reach

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**DES+Fermi10yr**
5σ detection for $C_i^{\gamma\nu}$

**Euclid+"Fermissimo"**
5σ detection for $C_i^{\gamma\nu}$

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Camera, Fornasa, NF, Regis, arXiv:1411.4651, to appear in JCAP
Forecasts: reconstruction capabilities

Camera, Fornasa, NF, Regis, arXiv:1411.4651, to appear in JCAP
The cross-correlation between gamma-rays + cosmic-shear looks promising

Fermi has already accumulated 6+ yr of data

DES will likely release its first data in a few years

For the future:

- Fermi will likely double its statistics
- Successors of Fermi are under discussion/preparation
- Euclid will largely improve over DES
Attempt on data with a small survey

Patch W1: 72 sq. deg

CFHTLenS W1
\( \chi_t^2 / n_{\text{dof}} = 10.34 / 10 \)
\( \chi_x^2 / n_{\text{dof}} = 7.89 / 10 \)

\( \xi \delta \eta - \gamma \) (deg\(^{-2}\))

\( \theta \) [arcmin]

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

DM mass [GeV]

CFHTLenS + Fermi/5yr

Shirasaki, Horiuchi, Yoshida, PRD 90 (2014) 063502
CROSS CORRELATIONS
EXTENSION OF THE APPROACH
Extension of the cross-correlation approach

- Gravitational tracers:
  - Weak lensing surveys (cosmic shear) traces the whole DM
  - CMB lensing
  - LSS surveys traces light -> bias

- Electromagnetic signals:
  - Radio
  - X
  - Gamma

\[ \langle G_i \times E_b \rangle \quad \langle E_a \times E_b \rangle \]
Additional cross correlations channels

Window functions

Multiwavelength signals with LSS tracers and gravitational probes

2MASS
shear
CMB lensing
LSS
NVSS

Cross-correlation annihilating DM
$E_\gamma = 1$ GeV

NF, Regis, Front. Physics 2 (2014) 6
Fermi/gamma + Planck/CMB lensing
Cross-correlation: 3.0σ evidence
Compatible with AGN + SFG + BLA gamma-rays emission
Points toward a direct evidence of extragalactic origin of the IGRB

Fermi/gamma + Galaxy catalogs
• 2MASS, SDSS-QSO and NVSS: >3.5 σ
• SDSS galaxies: 3.0 σ
• Signal is stronger in two energy bands: E > 0.5 GeV and E > 1 GeV
• Also seen at E > 10 GeV
• Results robust against the choice of statistical estimator, estimate of errors, map cleaning procedure and instrumental effects
Fermi + 2MASS: DM interpretation

The DM kernel peaks at low redshift, as well as the 2MASS one.

Best option for DM studies: cross-correlate with 2MASS.

The different behaviour of kernels can help to discriminate the sources.

The observed cross-correlation is perfectly reproduced (both in shape and size) by a DM contribution.

While the DM emission is largely subdominant in the total intensity.

Analysis includes spectral information (3 energy bins)

Fermi + 2MASS: DM analysis

Bound from cross correlation

Bounds ratios
Correlation technique stronger

Fermi + all LSS catalogs: DM + astro sources

2MASS (>500MeV)

SDSSmain (>500MeV)

SDSSlr (500MeV)

NVSS (>500MeV)

Cuoco, Xia, Regis, Branchini, NF, Viel, to appear
Fermi + LSS catalogs: DM + astro sources

LOW
degeneracy between DM and mAGN

Cuoco, Xia, Regis, Branchini, NF, Viel, to appear
• DM signal:
  - peaks at low redshift
  - mostly contributed by massive halos

• To mimic this, an astrophysical source must be hosted in large halos at low z:
  - mAGN likely hosted in large halos
  - SFG typically populate galaxy-size halos
Data show power at the sub-degree scale

At the 2MASS redshift, sub-deg corresponds to Mpc scales, which are more compatible with DM or mAGN, rather than SFG

Clear separation requires improved γ rays angular resolution

Cuoco, Xia, Regis, Branchini, NF, Viel, to appear
Model uncertainty on mAGN is large (only few detected in γ rays so far)

Key quantity: γ-rays -luminosity vs host-halo-mass relation
**Fermi + LSS catalogs: DM + astro sources**

LOW results when mAGN contribution is suppressed

Cuoco, Xia, Regis, Branchini, NF, Viel, to appear
Fermi + all LSS catalogs: DM bounds

Cuoco, Xia, Regis, Branchini, NF, Viel, to appear
Conclusions

- In order to separate a DM non-gravitational signal from other astrophysical emissions, a filter based on the DM properties (i.e. the associated gravitational potential) appears to be very promising.

- Cross-correlations offer an emerging opportunity:
  - DM particle signal: multiwavelength emission (radio, X, gamma)
  - DM gravitational signal: cosmic-shear, LSS surveys, CMB lensing

- Gamma rays + cosmic shear is the cleanest possibility and it appears to be quite powerful.

- First relevant observational opportunity hopefully in a few years with DES.

- High-sensitivity will require Euclid (or LSST), together with the total accumulated Fermi statistics (plus possible novel gamma-ray detectors).
Conclusions

- In the meanwhile, two gamma-rays/gravity-tracers correlations have been measured:
  - Cross-correlation with galaxy catalogues and LSS objects ($3.5\sigma$)
  - Cross-correlation with CMB-lensing ($3.0\sigma$)

- Implications for DM starts to be intriguing

- Cross-correlations represent the strongest technique to investigate DM and its clustering properties outside the local neighbourhood, setting a critical bridge between the CMB and the local enviromnent (galactic center, dwarf galaxies) scales
Angular power spectra

Dark Matter APS

Cross-correlation $\gamma$-rays - shear
Dark Matter

$C_l^{(i,j)} \leftarrow W_i(\chi) W_j(z) P_{ij}(k = l/\chi, \chi)$

Astrophysical sources APS

Cross-correlation $\gamma$-rays - shear
Astrophysical sources

$E > 1$ GeV

$F_{\text{lim}} = 2 \times 10^{-9}$ cm$^{-2}$ s$^{-1}$ ($E > 100$ MeV)

Camera, Fornasa, NF, Regis, arXiv:1411.4651, to appear in JCAP
# Detectors and configurations

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<th>Euclid</th>
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**DES + Fermi 5 yr** (expected to be available this year)

**Euclid + Fermi 10 yr**

**Euclid + “Fermissimo”**
- CMB-lensing autocorrelation is measured: $40\sigma$ significance
- CMB-lensing: integrated measure of DM distribution up to last scattering
- It might exhibit correlation with gamma-rays emitted in DM structures
Analysis:

- Fermi-LAT 68 months
- Planck 2013 and 2015 lensing releases
- Galactic emission subtracted
- Masks for CMB lensing:
  - Planck official masks (available sky fraction 70%)
  - 5 deg apodized
- Masks for gamma rays:
  - Planck masks + |b| < 25 deg cut
  - 1 deg cut around 2FGL (3FGL) Fermi source catalogs apodized 3 deg/2 deg sky fraction 24% (23%)

Results stable for different sets of apodization and galactic masks, including Fermi bubble mask.
$\langle \sigma v \rangle$ [cm$^3$/s] vs. WIMP mass $M_\chi$ [GeV]

- this work
- dSph - Fermi LAT
- MW halo - Fermi LAT
- GC - Ref.[5]

Additional notes:

- Cross section $<\sigma v>$
- WIMP mass $M_\chi$
Galactic center

Galactic center

$\langle \sigma v \rangle / A [cm^3s^{-1}]$

$10^{-27}$

$10^{-26}$

$10^{-25}$

$10^2$

$10^1$

$\tau^+ \tau^-$

$W^+ W^-$

$qq$

$ZZ$

$c\bar{c}$

$hh$

$\bar{b}b$

$t\bar{t}$

$gg$

Calore, Cholis, McCabe, Weniger, PRD 91 (2015) 063003
Dwarf galaxies

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

- 4-year Pass 7 Limit
- 6-year Pass 8 Limit
- Median Expected
- 68% Containment
- 95% Containment

Thermal Relic Cross Section (Steigman et al. 2012)

Ackermann et al. (Fermi Collab.), arXiv:1503.02641