Particle dark matter searches in the anisotropic sky

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Based on:

S. Camera, M. Fornasa, NF, M. Regis
“A novel approach in the WIMP quest: Cross-Correlation of Gamma-Ray Anisotropies and Cosmic Shear”

S. Camera, M. Fornasa, NF, M. Regis
“Detecting Dark Matter Signatures via Cosmic-Shear/Gamma-Rays Tomography”
to appear

See also:
NF, M. Regis
“Particle dark matter searches in the anistropic sky”
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
Weak gravitational lensing

**Convergence**: controls modifications in the size of the image

**Shear**: accounts for shape distortions

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<thead>
<tr>
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<th>$&lt; 0$</th>
<th>$&gt; 0$</th>
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<tbody>
<tr>
<td>$\kappa$</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>$\text{Re}[\gamma]$</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
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<tr>
<td>$\text{Im}[\gamma]$</td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
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In the flat-sky approximation, they generate identical angular power spectra.
Cosmic shear auto-correlation

Auto-correlation between gravitational cosmic shear in two different directions can provide information on the clustering of the large scale structures responsible for the lensing effect.

Technique already used with data from COSMOS galaxy survey

Future surveys: Pan-STARRS, Dark Energy Survey, Euclid

Cosmic structures and gamma-rays

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

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

Gamma-rays emitted by DM may exhibit strong correlation with lensing signal
Auto-correlation in the gamma-rays emission has been reported. For \( l > 100 \) galactic foreground can be neglected: EGB contribution. Features of the signal (energy and multipole independent) point toward interpretation in terms of blazars.

DM likely to play a subdominant role (as for EGB intensity).

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Ackerman et al. (Fermi), Phys. Rev. 85 (2012) 083007
Signal

Cross-correlation of

gravitational shear with

extragalactic gamma-ray background (the residual radiation contributed by the cumulative emission of unresolved gamma-ray sources)
**Correlation functions**

**Source Intensity**

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

**Density field of the source**

**Window function**

Cross-correlation angular power spectrum

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

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

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

\[ \hat{f}_g : \text{Fourier transform} \]

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

\[ P_{ij}^{2h}(k) = \left[ \int dm_1 \, \frac{dn}{dm_1} \, b_i(m_1) \hat{f}_{i}^*(k|m_1) \right] \left[ \int dm_2 \, \frac{dn}{dm_2} \, b_j(m_2) \hat{f}_{j}(k|m_2) \right] \, P_{\text{lin}}(k) \]

**Linear matter PS**

**Linear bias**
Window functions

Lensing

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

Gamma-rays from decaying DM

\[ W^{\gamma_d} (E_\gamma, z) = \frac{1}{4\pi} \frac{\Omega_{DM} \rho_c}{m_\chi \tau_d} J_d(E_\gamma, z) \]

\[ J_d = \int_{E_\gamma}^{\infty} dE \frac{dN_d(E(1+z))}{dE} e^{-\tau(E(1+z), z)} \]

Gamma-rays from annihilating DM

\[ W^{\gamma_a} (E_\gamma, z) = \frac{(\Omega_{DM} \rho_c)^2}{4\pi} \frac{(\sigma_a v)}{2m_\chi^2} (1 + z)^3 \Delta^2(z) J_a(E_\gamma, z) \]

Astrophysical sources

\[ W^{\gamma_s} (E_\gamma, z) = \frac{A_S(z) \langle g_S(z) \rangle}{4\pi E_0^2} \int_{E_\gamma}^{\infty} dE \left( \frac{E}{E_0} \right)^{-\alpha} e^{-\tau(E, z)} \]
Window functions

DM peaks at lower z
3D Power spectrum

Cross-correlation 3D Power Spectrum

DM cross-correlation has more power at intermediate scales
Cross-correlation predictions

Fermi-LAT/5-yr with DES

Fermi-LAT/5-yr with Euclid

**Energy slicing and redshift tomography**

![Graphs showing energy spectrum and redshift information.]

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

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

Classes of astro sources:
- blazars
- SFR
- mAGN

Ingredients:
- gamma-rays luminosity function
- energy spectrum
- relation $M(L)$ between GRL and mass of host halo
- bias

Analysis: marginalized over astro

Fermi-LAT/5-yrs with DES

Camera, Fornasa, NF, Regis, to appear
Forecasts: discovery potential

Halo mass functions from [a]
Concentration from [b]
Halos profile: NFW
Min halo-mass: $10^{-6} \, M_{\text{sun}}$ (or $10^7 \, M_{\text{sun}}$)
$c_{\text{vir}}$ extrapolation at low $M$ from [c]


“Virgo C.” substr. : VC1 and VC2
“Via Lactea” substr. : VL [I + 3]
“No” substr. and $10^7 \, M_{\text{sun}}$ : NS

[I + 2]

Sanchez-Conde et al, JCAP 1112 (2011) 011
Modeling

Blazars:
- GLF from [1] with AGN X-ray luminosity function from [2]
- relation halo-mass/X-ray luminosity from [3]
- second model: gamma-rays luminosity related to smBH-mass, related to halo mass as in [3]

mAGN:
- GLF from [4]
- M(L) from BH-mass relation to radio luminosity [5] (then transferred to gamma luminosity) and DM-halo mass [3]
- large scatter in M(L), accounted through a free norm in (0.1 - 2.5)

SFG:
- M(L) from relating gamma-ray luminosity to SFR [9]

Forecasts on parameters reconstruction

Fermi-LAT/5-yr with DES
Effect of energy and redshift information

Fermi-LAT/5-yr with DES
Dependence on clustering model

For each model, cross-correlations with shear allow better reach than intensity or auto-correlation alone.

Halo mass functions from [a]
Concentration from [b]
Halos profile: NFW
Min halo-mass: $10^{-6} \, M_\odot$ (or $10^7 \, M_\odot$)
$c_{\text{vir}}$ extrapolation at low $M$ from [c]


“Virgo C.” substr.: VC1 and VC2
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Experiments

- **Gamma-rays**
  - **Fermi-LAT**
    - space based
    - $0.3 < E < 300$ GeV
    - sensitivity: $10^{-9}$ cm$^{-2}$ s$^{-1}$
    - angular resolution: 0.1 deg at high-energy
    - sky coverage: 66%
    - until 2018
  - **DAMPE, Gamma400, HERD?**

- **CTA**
  - ground based
  - "10 GeV" $< E < "10$ TeV"
  - few square degrees, but allows to explore higher multipoles

- **Cosmic-shear**
  - **DES**
    - $0.3 < z < 1.5$
    - 13.3 gal / arcmin$^2$
    - 5000 squared degrees
    - 2012-2017
  - **Euclid**
    - $0 < z < 2.5$
    - 30 gal / arcmin$^2$
    - 20000 squared degrees
    - 2020-2026
Enhanced experimental sensitivities

DES: 3 redshift bins
Euclid: 10 redshift bins

Fermi: 5 years

"Fermissimo": gamma rays detector with 2.5x Fermi exposure
Forecasts on parameters reconstruction

- **DES**: 3 redshift bins
- **Euclid**: 10 redshift bins
- **Fermi**: 5 years
- “Fermissimo”: gamma rays detector with 2.5x Fermi exposure
Attempt on data with a small survey

Patch W1: 72 sq. deg

CFHTLenS W1
\[ \chi_\tau^2/n_{\text{dof}} = 10.34/10 \]
\[ \chi_\gamma^2/n_{\text{dof}} = 7.89/10 \]

\[ \xi_{\delta\eta-\gamma} \, (\theta) \, [\text{deg}^{-2}] \]

\[ \theta \, [\text{arcmin}] \]

CFHTLenS + Fermi/5yr

\[ 0.2 < z_{\text{source}} < 1.3 \]

\[ \tau^+\tau^- \text{ channel} \]

\[ b\bar{b} \text{ channel} \]

Conclusions

- DM structures in the Universe are the sources of weak lensing observables.

- The same structures can themselves emit light at various wavelengths, including the gamma-ray range:
  - From astrophysical sources hosted by DM halos
  - From DM itself (annihilation/decay)

- Cross-correlation of gravitational shear with extragalactic gamma-ray background offers an interesting possibility for signal detection:
  - Redshift information in shear: can help in “filtering” signal sources
  - Energy spectrum of gamma-rays: can help in DM-mass reconstruction
Backup Slides
Cross-correlation: shear/DM

3D power spectrum

Angular power spectrum
Cross-correlation: shear/blazars

3D power spectrum

Angular power spectrum
Cross-correlation: shear/SFG

3D power spectrum

Angular power spectrum

Matter-SFG

Cross-correlation $\gamma$-rays - Shear
E > 1 GeV

Star-forming galaxies

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

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Gamma-rays auto-correlation

For $l > 100$ galactic foreground can be neglected: EGB contribution
Features of the signal point toward interpretation in terms of blazars

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

Very difficult to extract a clear WIMP signature from the EGB alone

For the gamma autocorrelation signal:
Ando, Komatsu, PRD 73 (2006) 023521
Ando, Komatsu, Narumoto, Tótani, PRD D75 (2007) 063519
Siegal-Gaskins, JCAP 0810 (2008) 040
Cuoco, Brandbyge, Hannestad, Haugboelle, Miele, PRD 77 (2008) 123518
Fornasa, Pieri, Bertone, Branchini, PRD 80 (2009) 023518
Taoso, Ando, Bertone, Profumo, PRD 79 (2009) 043521
Ibarra, Tran, Weniger, PRD 81 (2010) 023529
Cuoco, Komatsu, Siegal-Gaskins, PRD 86 (2012) 063004
Harding, Abazajian, JCAP 11 (2012) 26
Extension of the cross-correlation approach

- Cross-correlation of an electromagnetic signal with gravitational probes:
  - LSS surveys
  - Weak lensing surveys (cosmic shear)

- Cross-correlation among signals at different wavelengths

Auto and Cross Correlations

Window functions

\[ H(z)^{-1} \frac{W(z)}{<I>} \]

\( z \)

redshift

\( H(z) \)

\( W(z) / <I> \)

dec. DM

ann. DM

gamma

X-rays

radio

Annihilating DM

\[ 1 (1+1) C_l / (2\pi) \]

Multipole \( l \)

radio: \( v = 1 \) GHz

X-rays: \( E = 10 \) keV

\( \gamma \)-rays: \( E = 1 \) GeV

among multiwavelength signals
Auto and Cross Correlations

multiwavelength signals with gravitational probes