Dark matter through gamma-ray cross-correlations with gravitational tracers

Shunsaku Horiuchi
Center for Neutrino Physics
Virginia Tech
Extragalactic gamma-ray background

Shunsaku Horiuchi (Virginia Tech)

Fermi collaboration (2015)
Unresolved gamma-ray background

Contributors
FSRQ, BL Lacs, galaxies, pulsars, UHECR, ... and dark matter?

![Graph showing energy spectrum and various contributions to the background radiation.](image-url)
Angular cross correlation

Use anisotropy to help probe contributions

We’d like to test the origins of the noise-dominated unresolved gamma-ray data: ...
...we can get help by using signal-dominated datasets that trace source populations

Advantage: will also largely negate concerns for foreground modeling

2PCF: excess probability (of finding a pair of objects i and j at a certain scale) above what is expected from unclustered random distributions

\[
\langle \delta_i(\theta_1) \delta_j(\theta_2) \rangle \rightarrow \text{CCF}^{ij}_l (|\theta_1 - \theta_2|) \rightarrow C_l^{ij}\]

(physical) (harmonic)

Shunsaku Horiuchi (Virginia Tech) Cuoco et al (2008), Ando & Pavlidou (2009), Camera et al (2013), ...
**Angular cross correlation**

**Use anisotropy to help probe contributions**

We’d like to test the origins of the noise-dominated unresolved gamma-ray data: ...we can get help by using signal-dominated datasets that trace source populations

- Fermi unresolved gamma-ray background
- Galaxies
- Galaxy lensing
- CMB lensing
- Cluster of galaxies

Advantage: will also largely negate concerns for foreground modeling

**2PCF:** excess probability (of finding a pair of objects i and j at a certain scale) above what is expected from unclustered random distributions

\[
\langle \delta_i(\theta_1) \delta_j(\theta_2) \rangle \rightarrow \text{CCF}^{ij}_l (|\theta_1 - \theta_2|) \rightarrow C^{ij}_l
\]

*(physical)  (harmonic)*

Shunsaku Horiuchi (Virginia Tech)  
Cuoco et al (2008), Ando & Pavlidou (2009), Camera et al (2013), ...
CORRELATION WITH GALAXIES
Many galaxy catalogs:

- 2MASS & 2MPZ
- WISE × SuperCOSMOS
- SDSS DR12 photometric
- SDSS DR6 QSO
- NVSS

Cuoco et al (2017)
Tomography

Multiple galaxy catalogs will provide tomographic information to help unravel contributors.

e.g., 2MASS overlaps nicely with DM, predicting strong correlation, despite small contribution to total intensity

Ando 2014

Shunsaku Horiuchi (Virginia Tech)
Datasets

**Gamma rays**
- Energies 500 MeV or 1 GeV and above
  - *balance of PSF & statistics*
- Fit & remove Galactic emission
  - *foregrounds not expected to correlate with LSS maps*
- Mask point sources
- Mask large diffuse structures:
  Galactic disk, Fermi bubbles, loop I

(similar procedures for most cross correlation analyses)
First detection of cross correlation

- Use 5 galaxy catalogs, 5 yrs Fermi P7REP from 500 MeV to 100 GeV
- Many sanity checks: estimator, Galactic diffuse, null detection in mock realizations

2MASS, NVSS, SDSS-MG, -LRG, -QSO
- Astrophysical sources modeled under the halo model can explain the correlations (except NVSS which needs additional shot noise term)

\[ C_l^{(ij)} = \int \frac{d\chi}{\chi^2} W_i(\chi) W_j(\chi) P_{ij}(k = l/\chi, \chi) \]

\( i: \) galaxy catalog, \( j: \) astrophysical source

New correlation analyses

• More data (6.5 yrs P8 >0.25 GeV), more galaxies, additional redshift tomography → Higher detection significances (e.g., ~12σ for SDSS-DR12, ~11σ for WIxSC)

• CC varies by catalog, energy range, and redshift → sources with different properties contribute differently to UGRB

Stay tuned...

Cuoco et al (2017)
New correlation analyses

- More data (6.5 yrs P8 >0.25 GeV), more galaxies, redshift tomography
  → Higher detection significances (e.g., \( \sim 12\sigma \) for SDSS-DR12, \( \sim 11\sigma \) for WIxSC)

- CC varies by catalog, energy range, and redshift
  → sources with different properties contribute differently to UGRB

Stay tuned...

- Spectrum shows hints of an energy break

\[ \hat{C}_{\ell}^{\gamma C} = C_{\ell}^{1h} + A_{\ell}^{2h} C_{\ell}^{2h} \]

Shunsaku Horiuchi (Virginia Tech)
New correlation analyses

• More data (6.5 yrs P8 >0.25 GeV), more galaxies, redshift tomography

→ Higher detection significances (e.g., ~12σ for SDSS-DR12, ~11σ for WlxSC)

• CC varies by catalog, energy range, and redshift

→ sources with different properties contribute differently to UGRB

Stay tuned...

• Spectrum shows hints of an energy break

LE dominated by softer small-scale term

HE dominated by large-scale term with harder spectra

\[ \hat{C}_\ell^{\gamma C} = C^{1h}_\ell + A^{2h}_\ell C^{2h}_\ell \]

Shunsaku Horiuchi (Virginia Tech)
Focus on the 2MASS (2MPZ)

Focus on 2MPZ

- 2MPZ: 2MASS with 8 multi-wavelength data.
- 2MRS: subset of 2MPZ with spec-z
- Further split into redshift, B-band, and K-band samples
- Correlate with 9 yrs of P8 Fermi-LAT data
Focus on the 2MASS (2MPZ)

Marginalized posterior distributions
- Correlation consistent with arising mostly from mAGN
- SFG and blazars appear subdominant
- 2MPZ probes local 10% of $\gamma$-rays; situation can change at higher redshifts

NB: shot-noise
With 2MPZ, can be estimated more directly:
- Identify mAGN and blazars candidates
- Using scaling relations, estimate the $\gamma$ rays
Implications for dark matter

Dark matter: peaks consistent with expectations
- Small peak in inferred annihilation cross section in 2MPZ
- 2MRS (lower-z) shows more prominent peak than 2MPZ
- Low-B / high-K (low-astro / large-DM) sample shows slightly more prominent peak

![Graph 1](image1)

![Graph 2](image2)

Limits on dark matter

**Fit including astrophysics**

Limits on improve by factor of $\sim 4$ when concurrently modeling astrophysics

Sensitivity from cross-correlation better than other EGB methods

---

**Graphs**

- **Left graph:**
  - Plot of $\sigma_{\text{ann}} > [\text{cm}^3/\text{s}]$ vs. $m_{\text{DM}} [\text{GeV}]$
  - Different lines represent different annihilation channels:
    - $b\bar{b}$ - ALL GeV
    - $\mu^+\mu^-$ - ALL GeV
    - $\tau^{+}\tau^-$ - ALL GeV
    - $W^+W^-$ - ALL GeV
    - $b\bar{b}$ - DM only
  - Thermal WIMP is marked.

- **Right graph:**
  - Ratio wrt CC limit vs. $m_{\text{DM}} [\text{GeV}]$
  - Different lines represent different methods:
    - IGRB
    - $c_1^{\gamma\gamma}$
    - Clusters
  - Different markers indicate different channels:
    - Decaying DM
    - Annihilating DM
  - $b\bar{b}$ 95% C.L.

---


*Shunsaku Horiuchi (Virginia Tech)*
CORRELATION WITH LENSONG MAPS
Correlation with lensing maps

Images of distant galaxies are distorted by matter along the line of sight.

Distortions: convergence ($k$) and shear ($\gamma$)

- The lens object is also a gamma-ray source (astrophysical and potential dark matter physics)
- Probe this connection with cross-correlation
First studies & predictions

Shear probes a broad redshift range that overlaps nicely with major sources.

With future surveys, dark matter can be disentangled from astrophysics.

Camera et al. (2013, 2014)

(Fermi-LAT & Euclid)
Analysis with real data

Canada-France-Hawaii Lensing Survey (CFHTLenS)
- Four patches, total $\sim 154$ deg$^2$
- 11 resolved galaxies per arcmin$^2$
- Photo-z between $0.2 < z < 1.3$ (median 0.75)
- About 5.7 million galaxies

Fermi-LAT
- Approx 5 yrs of Pass 7REP data
- 1 – 500 GeV ULTRACLEAN photons
- Treat patches independently
Analysis with real data

Canada-France-Hawaii Lensing Survey
- Four patches (total ~154 deg²)
- 11 resolved galaxies per arcmin²
- Photo:z (between 0.2 < z < 1.3 (median 0.75)
- About 5.7 million galaxies

Fermi-LAT
- Approx. (5 – 500) GeV ULTRACLEAN photons
- Treat patches independently

Shirasaki et al (2014)
More attempts

(CFHTLenS + RCSLenS) x 7 yrs Fermi P8

RCSLenS: adds 785 deg2 (~5.8 gal/arcmin2)

⇒ Null detection

(CFHTLenS + RCSLenS + KIDS) x 7 yrs Fermi P8

KIDS: adds 450 deg2 (~8 gal/arcmin2)

⇒ Null detection

Dark matter limits

From null observations

Based on a total of 660 deg$^2$ (about 1.5% of the full sky)

**Boost factor**
Factor of $\sim 10$ between optimistic & conservative subhalo boost factors

Sanchez-Conde & Prada (2013)

Recent calibrated analytic methods providing useful guidance: predicts factor $\sim 2$ more than conservative

e.g., Hiroshima et al (2018)
Ongoing & future developments

1. Significant increase in shear map coverage

Hyper-Suprime Cam: $\sim 1,400$ deg$^2$
Dark Energy Survey: $\sim 5,000$ deg$^2$

Euclid: $\sim 15,000$ deg$^2$ (2021-)
LSST: $\sim 20,000$ deg$^2$ (2023-)

Shirasaki et al (2014)
Camera et al (2014)
Ongoing & future developments

1. Significant increase in shear map coverage

Hyper-Suprime Cam: $\sim 1,400$ deg$^2$
Dark Energy Survey: $\sim 5,000$ deg$^2$

Euclid: $\sim 15,000$ deg$^2$ (2021-)
LSST: $\sim 20,000$ deg$^2$ (2023-)

---

Shirasaki et al (2014)
Shunsaku Horiuchi (Virginia Tech)

Camera et al (2014)
2. Significant increase in catalogs
   e.g., especially in the Southern hemisphere, increasing the use of the $\gamma$-ray data
   e.g., new sources such as cosmic voids

3. Exploit multi-wavelength information
   e.g., tomography in halo mass, SFR
   e.g., improved estimates of shot noise
   e.g., tomography with gravitational lensing

4. Various anisotropy studies
   Complementary; help break degeneracies  ➔ See Michela Negro’s talk!

5. Fermi-LAT will have more data
   e.g., statistics & PSF improvement expected to be impactful.

Together, will be able to make much more detailed studies of the Fermi data!
Concluding remarks

The unresolved gamma-ray background measurement by Fermi contains a wealth of knowledge.

- Guaranteed sources, and potentially new sources like dark matter
- These can be probed by exploiting cross-correlation techniques

Great progress already. Future prospects are high

- **Correlation with galaxies**: highly significant already. Rich prospects with multiple catalogs, subsamples, tomography, etc.
- **Correlation with gravitational lensing**: not significant (so far), but advances guaranteed with upcoming surveys (HSC, DES, LSST, Euclid)
- **Other correlations**: cluster and CMB lensing (significant). More clusters to test/refute ICM origin versus other sources.
- **Synergies**: by combining anisotropy probes

Stay tuned!
First detection of cross correlation

- Use 5 galaxy catalogs and 5 yrs Fermi P7REP from 500 MeV to 100 GeV
- Many sanity checks: estimator, Galactic diffuse, null detection in mock realizations

- NVSS consistent with additional small-scale (1halo-like) term:
  - Correction for inaccuracies in 1h term (due to discrete gamma-ray sources within in the galaxy catalog, causing shot-noise)

- NVSS correlation also shows narrowing with energy

$\sim 8.6\sigma$

**Interpretations of CCF**

Global fit: 5 sources, 5 catalogs, 3 energies

**Marginalized posterior distributions**

Hard to pin-point unique source; mAGN shows hint of a peak.

Considerable degeneracy exist between sources

\[
M_{\theta_i}^{(p,n)} = \sum_{\alpha=1}^{5} A_\alpha c_{\alpha}^{(p,n)}(\theta_i) + A_{1h}^{(p)} c_{1h}^{(n)}(\theta_i)
\]

- \(\alpha\): source
- \(p\): catalog
- \(n\): energy

*Cuoco et al (2015)*
**Shot-noise term**

With 2MPZ, shot-noise can be estimated more directly:

- Based on IR colors, can identify mAGN and blazars candidates
- Using scaling relations, can estimate the $\gamma$ rays

*Massaro & Abrusco (2016)*  
*Mingo et al (2016)*

**NB: free shot-noise term**

- mAGN remains non-zero
- Blazar goes from subdominant to weakly constrained

*Ammazzalorso et al (2018)*
Pure dark matter interpretation

Fit with only dark matter
Both the shape and intensity can be satisfied by dark matter. Not excluded since high 2MASS—DM correlation does not much affect high $z$'s

(Fermi–2MASS cross-correlation)
Correlation functions

Source intensity

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

Source density field

Window function

DM particle properties

W(z): e.g., for annihilation

\[ W^a_{\gamma}(z) = \frac{(\Omega_{DM}\rho_c)^2}{8\pi m_{DM}} \frac{\langle \sigma_a v \rangle}{2} (1 + z)^3 \Delta^2(z) \frac{dN_a}{dE_{\gamma}} e^{-\tau[z,E_{\gamma}(z)]} \]

DM distribution

Gamma-ray optical depth

Cross correlation APS:

\[ C_{i}^{(ij)} = \int \frac{d\chi}{\chi^2} W_i(\chi) W_j(\chi) P_{ij}(k = l/\chi, \chi) \]

Cross 3D power spectrum

Decompose: \( P(k) = P^{1h}(k) + P^{2h}(k) \)

Halo mass function

FT of source density field

Halo model: gamma-ray emitters confined to DM halos.

Linear bias

Linear matter power spectrum

See e.g., Fornengo & Regis (2014)
Boost factor uncertainties

Analytic subhalo model

- Complementary to simulations
- Tested against simulations at resolved scales
- Physics-based extrapolation (extended Press-Schechter formalism + prescriptions for tidal stripping and mass loss) beyond simulations

CAPS measurements & interpretations

- Positive CAPS: > 5σ for redMaPPer and WHL12, > 3σ for PlanckSZ
- Can be explained by either blazars, mAGN, or SFG, providing 100% of the UGRB

\[ C_l^{(ij)} = \int \frac{d\chi}{\chi^2} W_i(\chi) W_j(\chi) P_{ij}(k = l/\chi, \chi) \]

- Small-scale correlation needs additional power
  - ICM? Constrained by nearby clusters
  - Correction for inaccuracies in 1h term? (due to discrete gamma-ray sources)

Decompose: \( P(k) = P^{1h}(k) + P^{2h}(k) \)

Branchini et al (2017)

Shunsaku Horiuchi (Virginia Tech)
Hints from energy spectrum

- Fit to CAPS derived in 8 energy bins
- Large scales: single power-law (hard) → BL Lacs?
- Small scales: two power-laws preferred over a single power-law
  - High-energy spectrum consistent with large scale → BL Lacs?
  - Spectrum is softer at low energies → SFG? ICM? Others?

Branchini et al (2017)