The power of the unresolved

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What Fermi sees

Take the total γ-ray emission

Remove Galactic diffuse emission
What Fermi sees

Take the total γ-ray emission

Remove Galactic diffuse emission

Novae, Super Nova Remnants (SNRs)

Pulsars

Star-forming regions

Pulsar wind nebulae (PWN)

Globular clusters

Binary systems
What Fermi sees

Remove Galactic diffuse emission

Take the total $\gamma$-ray emission

BL-Lacs

Flat Spectrum Radio Quasars (FSRQs)

Radio Galaxies

Star forming galaxies (SFG)

Uncertain type Blazars

Misaligned active galactic nuclei (mAGN)
What Fermi sees

Take the total $\gamma$-ray emission

Remove Galactic diffuse emission

2FGL (2-year catalog)

3FGL (4-year catalog)

FL8Y (8-year list)

>5500 sources

What Fermi sees

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>5500 sources
The UGRB

Take the total $\gamma$-ray emission

Remove Galactic diffuse emission

Remove Resolved sources

1) time-dependent component!

Unresolved $\gamma$-ray Background (UGRB)
What contributes to the UGRB intensity

Estimated contribution to the unresolved emission intensity:

- Star-forming galaxies (SFG)
- Radio galaxies
- Blazars
- Pulsar
- Type Ia supernovae
- Dark Matter (?)
- Gamma-ray Bursts
- Millisecond pulsars
- UGRB Energy Spectrum

Graph showing contributions to UGRB intensity with different energy fluxes and spectral distributions.
Beyond the monopole...

Estimated contribution to the unresolved emission intensity:

- Gamma-ray Bursts
- Millisecond pulsars
- Radio galaxies
- Star-forming galaxies (SFG)
- Blazars
- Pulsar
- Type Ia supernovae
- Dark Matter (?)

UGRB Energy Spectrum

UGRB is not truly isotropic
Beyond the monopole thanks to Fermi-LAT performances*

Gamma-ray Bursts
Millisecond pulsars
Radio galaxies
Star-forming galaxies (SFG)
Blazars
Pulsar
Type Ia supernovae
Dark Matter (?)

UGRB Energy Spectrum

* see poster n.107

Effective Area

PSF 95% containment

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8th International Fermi Symposium
**Autocorrelation**

2-point correlation function (ACF): the excess probability, above the expectation from a random distribution, of finding an object in a volume dV at a separation r.

\[
dP = n \left[ 1 + \xi(r) \right] dV
\]

\[
\xi(r) = \langle \delta(x) \delta(x + r) \rangle_V
\]

For a spherical surface geometry it is convenient to use the Legendre transform: the angular power spectrum (APS), \(C\ell\):

\[
ACF(\theta) = \sum_\ell \frac{2\ell + 1}{4\pi} \tilde{C}_\ell P_\ell[\cos(\theta)]
\]

If the anisotropy field is produced by point-like sources:

\[
\begin{align*}
\text{Physical space} & \quad \text{Harmonic space} \\
\xi(\theta) & \quad C\ell
\end{align*}
\]

\[
\theta \sim 180^\circ \ell \cdot \ell
\]

\[
\text{Signal at 0 separation angle}
\]

\[
\text{Flat APS}
\]

\[
C_P
\]
Past Measurements - Ackermann et al. 2012

APS estimator:

\[ C_{\ell, E}^{\text{sig}} = \frac{C_{\ell, E}^{\text{raw}} - f_{\text{sky}} C_N}{W_{\ell, E}^2} \]

\[ C_N = \frac{\langle N_{\gamma, \text{pix}} \rangle}{\Omega_{\text{pix}} \langle A_{\text{pix}}^2 \rangle} \]

\[ W_{\ell}^{\text{beam}}(E) = 2\pi \int_{\theta_{\min}}^{\theta_{\max}} P_l(\cos\theta) \text{PSF}(\theta; E) \sin\theta d\theta \]

2) Noise-dominated probe!

22 months (Pass 6)
1-50 GeV (4 bins)
Resolved sources from the 1FGL

\[ \alpha = 2.4 \pm 0.07 \]
Past Measurements - Ackermann et al. 2012

Autocorrelation to constrain source populations models:

\[ I = \int_0^{S_t} S \frac{dN}{dS} dS \]

\[ C_P = \int_0^{S_t} S^2 \frac{dN}{dS} dS \]

- The majority of anisotropy signal: blazars
- Blazars contribute to <20% of the UGRB intensity
- The 80% being due to low-intrinsic-anisotropy component

3) UGRB species do not contribute to intensity and to anisotropy at the same extent!
Past Measurements - Fornasa et al. 2016

82 months (Pass 7)
0.5-500 GeV (13 bins)
Resolved sources from the 3FGL

Indications (95% CF) of a double population

Cross-correlation between E bins:

\[ E_1 \times E_2 = C_{12}^{12} \leq \sqrt{C_{11}^{11} C_{22}^{22}} \]

\[ E_1 \times E_1 = C_{11}^{11} \]

\[ E_2 \times E_2 = C_{22}^{22} \]

\[ \alpha = 3.3 \pm 0.7 \]

\[ \beta = 2.2 \pm 0.04 \]
Past Measurements - Fornasa et al. 2016

Autocorrelation to constrain WIMP-like DM parameters:

Conservative exclusion limits on annihilating and decaying DM from the new APS measurement by Fornasa et al. 2016

Less stringent than UGRB spectrum limit by factor of 2
**Current measurement**

8 years (Pass 8 P305)  
SOURCEVETO** class  
0.5-1000 GeV (12 bins)  
FL8Y + 3FHL

New APS estimator:

\[ C_{l}^{\text{sig}}(l) = \frac{N}{N-1} \sum_{\alpha, \beta} C_{l}^{\alpha\beta, \text{PolSpice}}(l) \frac{W_{E_{\alpha}}(l)}{W_{E_{\beta}}(l)} \]

Exploits cross-correlations between adjacent micro energy bins: not affected by noise!

**Double population at 99.98% CL**

Off-diagonal values < 1 @ 4σ
Future developments - Autocorrelations: beyond the $C_p$

- Galactic emission
- Resolving 2FGL sources
- Resolving 3FGL sources
- Uncertain Galactic foreground subtraction

Subdominant clustering signal
Future developments - Autocorrelations: beyond the $C_p$

Imperfect knowledge of Galactic foreground and unresolved signal still dominated by shot noise of point-like sources

- Uncertain Galactic foreground subtraction
- Galatic emission
  - Resolving 2FGL sources
  - Resolving 3FGL sources
  - Resolving FL8Y sources
- Subdominant clustering signal
- Multipole
Future developments - Autocorrelations: beyond the $C_p$

Uncertain Galactic foreground subtraction

Galactic emission

Resolving 2FGL sources

Resolving 3FGL sources

Resolving FL8Y sources

Future possible scenario

Powerful to constrain DM parameters

subdominant clustering signal
When CTA will join the effort at TeV energy...

[Hütten & Maier 2018]
Calculation of CTA sensitivity to small-scale anisotropy

Instrumental performance of southern CTA:
- 4 Large-Size Telescopes (LSTs),
- 25 Mid-Size Telescopes (MSTs),
- 70 Small-Size Telescopes (SSTs)

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UGRB anisotropy characterisation through cross-correlations *

* see talk by Horiuchi (diffuse splinter)
UGRB anisotropy characterisation through cross-correlations

Noise-dominated

Signal-dominated

UGRB

Galaxy catalogs
UGRB anisotropy characterisation through cross-correlations

Noise-dominated

Signal-dominated

UGRB

Galaxy catalogs

Investigated surveys with spectral (E) and tomographic (z) approach:

[Cuoco et al. 2017]
- NVSS
- WISE x SuperCOSMOS
- 2MPZ
- SDSS DR12
- SDSS DR6 QSO

Signal varies with redshift:
UGRB produced by different types of sources

Very high significance signal (up to 10σ for NVSS)

E = [10,500] GeV
UGRB anisotropy characterisation through cross-correlations

Beyond the tomographic approach for 2MPZ catalog:

[Ammazzalorso et al. 2018 (Arxiv)]

- redshift slicing (3 bins)
- B-band luminosity slicing: traces the star formation activity
- K-band luminosity slicing: correlates with objects mass
- High K - low B (high masses + low level of star formation): traces DM (WIMP)

Signal dominated by mAGNs emissions + subdominant contribution from blazars and SFGs

z < 0.2
UGRB anisotropy characterisation through cross-correlations

**Noise-dominated**

**Signal-dominated**

**Galaxy catalogs**
- Different types of sources
- Signal evolves with $z$
- AGNs + blazar + SFG (subdominant)

**Clusters**
- Galaxies, hot highly ionized gas, DM, Relativistic CRs
**UGRB anisotropy characterisation through cross-correlations**

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**Clusters**

- WHL12 (158,103 clusters)
- redMaPPer (26,350 clusters)
- PlanckSZ (1,653 clusters)

**1-halo term**
- Small scales: hard component (Blazars?) + soft component (mAGN / SFG / ...)

**2-halo term**
- Large scales: hard power law (Blazars?)

**>3σ signal!**

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Constrain the contribution of **Intra-cluster medium** and **DM**

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UGRB anisotropy characterisation through cross-correlations

- Noise-dominated
  - UGRB
  - Galaxy catalogs
    - Different types of sources
    - Signal evolves with $z$
    - AGNs + blazar + SFG (subdominant)
- Signal-dominated
  - LSS tracers
  - Cosmic shear: statistical measurement of the distortion of images due to the weak lensing
  - Clusters
    - Large-scale: Blazars-like
    - Small-scales: double-component
      - high-energy: Blazars
      - low-energy: SFG/mAGN/...
    - Subdominant ICM and annihilating DM
UGRB anisotropy characterisation through cross-correlations

**Noise-dominated**
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Investigated surveys with **spectral** and **tomographic** approach (proposed by Camera et al. 2013/2015):

- CFHTLenS + RCSLenS + KiDs
  [Troster et al. 2017]
- Subaru Hyper Suprime-Cam
  [Shirasaki et al. 2018]

no signal detected!
UGRB anisotropy characterisation through cross-correlations

**Galaxy catalogs**
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**Signal-dominated**
- LSS tracers

**No signal**

**Cosmic shear**

**Noise-dominated**
- UGRB

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[Xia et al. 2011]: Searched for signature of ISW in cross-correlation between WMAP7-CMB and 21-mo γ-ray data

[CMB lensing] Lensed CMB map as LSS tracer
[Forrenigo et al. 2015]: Cross-correlation of Lensing potential of the CMB and γ-ray field to investigate the LSS

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[Xia et al. 2011]: arXiv:1103.4861v2
[Fornengo et al. 2015]: arXiv:1410.4997v2
UGRB anisotropy characterisation through cross-correlations

- **Noise-dominated**
  - UGRB

- **Signal-dominated**
  - LSS tracers

**Galaxy catalogs**
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**Cosmic shear**
- No signal

**CMB**
- No signal

**CMB lensing**
- Weak signal (~2 sigma)
UGRB anisotropy characterisation through cross-correlations

Most recent results of Cross-correlations between UGRB and LSS tracers

- NVSS Radio srcs (Cuoco et al. 2017)
- SDSS QSO DR6 (Cuoco et al. 2017)
- Wi x CO (Cuoco et al. 2017)
- 2MASS (Cuoco et al. 2017)
- SDSS Main Galaxy (Cuoco et al. 2017)
- 2MPZ (Ammazzalorso et al. 2018)
- CMB lensing (Fornengo et al. 2015)
- Weak lensing (Troster et al. 2017)
- HSC clusters (Hashimoto et al. 2018)
- redMaPPer clusters (Branchini et al. 2017)
- WHL12 clusters (Branchini et al. 2017)
- PSZ2 clusters (Branchini et al. 2017)
Future developments of Cross-correlations

- More with DES, LSST and Euclid
- More with updated data samples

- Galaxy catalogs
- Clusters
- Cosmic shear
- CMB
- CMB lensing

- Cosmic Voids?
  - Null or anti-correlation? (Voids = no clusters)
  - Positive correlation? (less EBL-attenuated objects)
Future developments - Cross-correlations and multi-messanger

Diffuse neutrino flux

More with IceCube Upgrade*
Even more with IceCube-Gen2 *

Cosmic Voids ?
- Null or anti-correlation? (Voids = no clusters)
- positive correlation? (less EBL-attenuated objects)

UGRB
LSS tracers

Galaxy catalogs
Clusters
Cosmic shear
CMB
CMB lensing

More with DES, LSST and Euclid
More with updated data samples

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## Summary

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<th><strong>Future prospects</strong></th>
<th><strong>Link to other (future) experiments</strong></th>
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<td>Direct contribution: provides the measurement</td>
<td>• Unveiling the origin of low-energy component</td>
<td>Čerenkov telescopes (e.g. CTA)</td>
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<td><strong>spin-off:</strong></td>
<td>• Detection of subdominant clustering signal in gamma-rays</td>
<td></td>
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<td>• to exclude/constrain source populations models</td>
<td>• Understand the nature of the high-energy exponential cut-off</td>
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<td>• set DM limits</td>
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<tr>
<td>• unveil unresolved origin</td>
<td></td>
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<tr>
<td>Direct contribution: provides the measurement of the UGRB</td>
<td>• Update UGRB-CMB cross-correlation: ISW effect</td>
<td>Plank</td>
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<td><strong>spin-off:</strong></td>
<td>• Cross-correlation with cosmic voids</td>
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<td>• to constrain subdominant ICM and annihilating DM signal</td>
<td>• Update UGRB-weak lensing cross-correlation: constrain DM limits</td>
<td>DES, LSST, Euclid</td>
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<td>• to characterise the γ-ray unresolved emission</td>
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<td>• high-energy cosmology</td>
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<td></td>
<td>Multimessenger Astrophysics: UGRB/EGB-Neutrinos</td>
<td>IceCube (Upgrade)</td>
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</table>

**Autocorrelation**

**Cross-correlation**

**UGRB Anisotropy**
Fermi’s future is bright!

(but we could even deal with a less-bright one very well :) )
Conclusion
Intensity and anisotropy energy spectra

... as complementary observables of the UGRB:

Cumulative contribution of blazar to the Intensity and to anisotropy as a function of source intensity

The anisotropy from unresolved sources is more strongly dependent on the sensitivity limit: improved point source sensitivity have a more notable impact on the measured IGRB anisotropy.
Autocorrelation to investigate the UGRB composition:

Blazars VS Blazars+new-population:

[Abdo et al. 2017]

Preferred @ 5 σ !

Very steep!!

2.8

3.3

Past Measurements - Fornasa et al. 2016
Fenomenological models

\[ N_1 \times (E_i E_j)^{-\alpha} e^{-\frac{E_i + E_j}{E_{\text{cut}}}} \]

\[ [N_1 \times (E_i E_j)^{-\alpha} + N_2 \times (E_i E_j)^{-\beta}] e^{-\frac{E_i + E_j}{E_{\text{cut}}}} \]

sPLE is excluded at 99.8% CL

(estimation from \( \Delta \chi^2 \) distribution evaluated with MC)
Two populations

Observations:
- the less luminous the harder
- less luminous are usually BL-Lacs
- Observed BL-Lacs and FSRQs have different z distributions

Unresolved blazars:
- harder spectra than resolved ones
- likely BL-Lac type
UGRB anisotropy characterisation through cross-correlations *

Population a: $n_a$, $dV_1$
Population b: $n_b$, $dV_2$

2-point cross-correlation function (CCF):

$$dP = n_a n_b \left[ 1 + \xi_{ab}(r) \right] dV_1 dV_2$$

$$\xi_{ab}(r) = \left\langle \delta_a(x) \, \delta_b(x + r) \right\rangle$$

Cross-correlation angular power spectrum:

$$\text{CCF}^{(ab)}(\theta) = \sum_{\ell} \frac{2\ell + 1}{4\pi} \tilde{C}_\ell^{(ab)} P_\ell[\cos(\theta)]$$
How to choose a good probe

Window functions

\[ W(z) = \frac{I(z)}{<I>} \]

- gamma
- X-rays
- radio
- ann. DM
- dec. DM

Window functions

\[ W(z) = \frac{I(z)}{<I>} \]

- MASS
- shear
- LSS
- NVSS
- DES
- CMB lensing
- Field
UGRB anisotropy characterisation through cross-correlations: CMB / CMB lensing

[Forengo et al. 2015]:
Cross-correlation of Lensing potential of the CMB and γ-ray field to investigate the LSS

\[ \psi_0 \leq \psi(t) \leq \psi_0 \]

Gravitational lensed CMB map
(as Traces the LSS)

Planck Collaboration

\[ \sim 2\sigma \text{ limit} \]

[Xia et al. 2011]:
Searched for signature of ISW in cross-correlation between WMAP7-CMB and 21-mo γ-ray data

Sachs-Wolfe effect:
contributes to Cosmic Microwave Background (CMB) anisotropy:
photons from the CMB are gravitationally redshifted

\[
\text{INTEGRATED SACHS-WOLFE EFFECT (ISW)}
\]
(between last scattering surface and Earth)

When the Universe is dark energy dominated potential wells or hills evolve significantly

No signal detected
UGRB anisotropy characterisation through cross-correlations

- Noise-dominated
- Signal-dominated

Galaxy catalogs
- Different types of sources
- Signal evolves with $z$
- AGNs + blazar + SFG (subdominant)

Clusters
- Galaxies, hot highly ionized gas, DM, Relativistic CRs

[Hashimoto et al. 2018]
- Subaru Hyper Suprime-Cam (HSC) (4,948 clusters)

- Stacked maps
- Compatible with emission from the AGNs along the LSS:
  Constrain the contribution of Intra-cluster medium and DM annihilation

- Low redshift ~2.3σ signal
- High redshift ~1.6σ signal
UGRB anisotropy characterisation through cross-correlations: weak lensing

It is possible to produce cosmic shear maps to cross-correlate with gamma-ray maps

1) Hp: galaxies are intrinsically randomly oriented
2) Measure the net ellipticity exceeding the Poisson Noise
3) Infer the strength of the tidal gravitational field

Investigated surveys with spectral and tomographic approach (proposed by Camera et al. 2013/2015):

- CFHTLenS + RCSLenS + KiDs [Troster et al. 2017]
- Subaru Hyper Suprime-Cam [Shirasaki et al. 2018]

no signal detected!