DETECTING PARTICLE DARK MATTER SIGNATURES

by

CROSS-CORRELATING GAMMA-RAY ANISOTROPIES

&

WEAK GRAVITATIONAL LENSING

Stefano Camera

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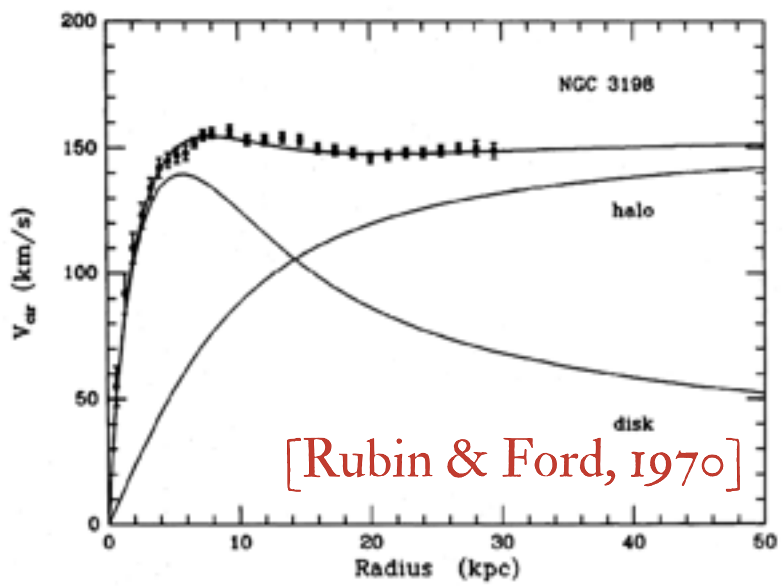
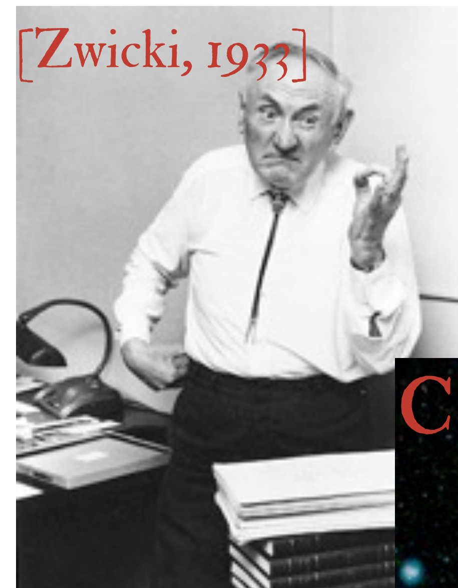
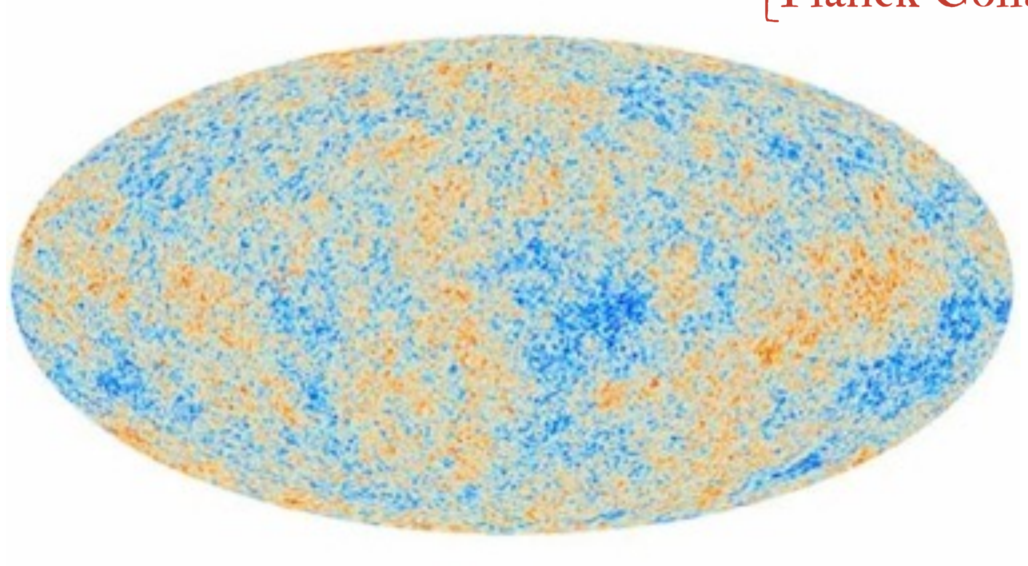
OBSERVATIONAL EVIDENCE OF DARK MATTER

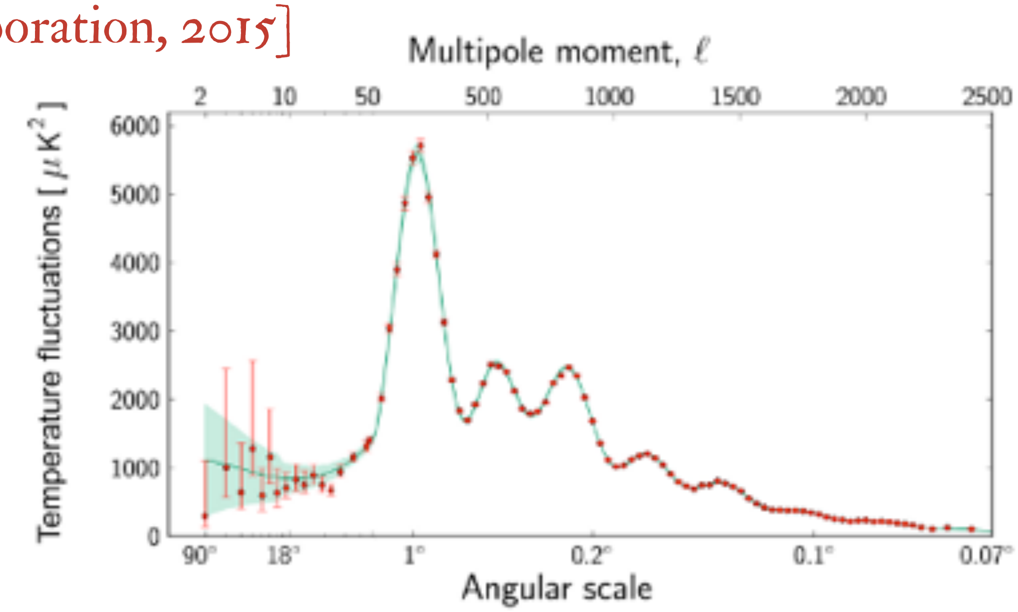
- Signatures of invisible matter in the cosmos at all physical scales





[Planck Collaboration, 2015]





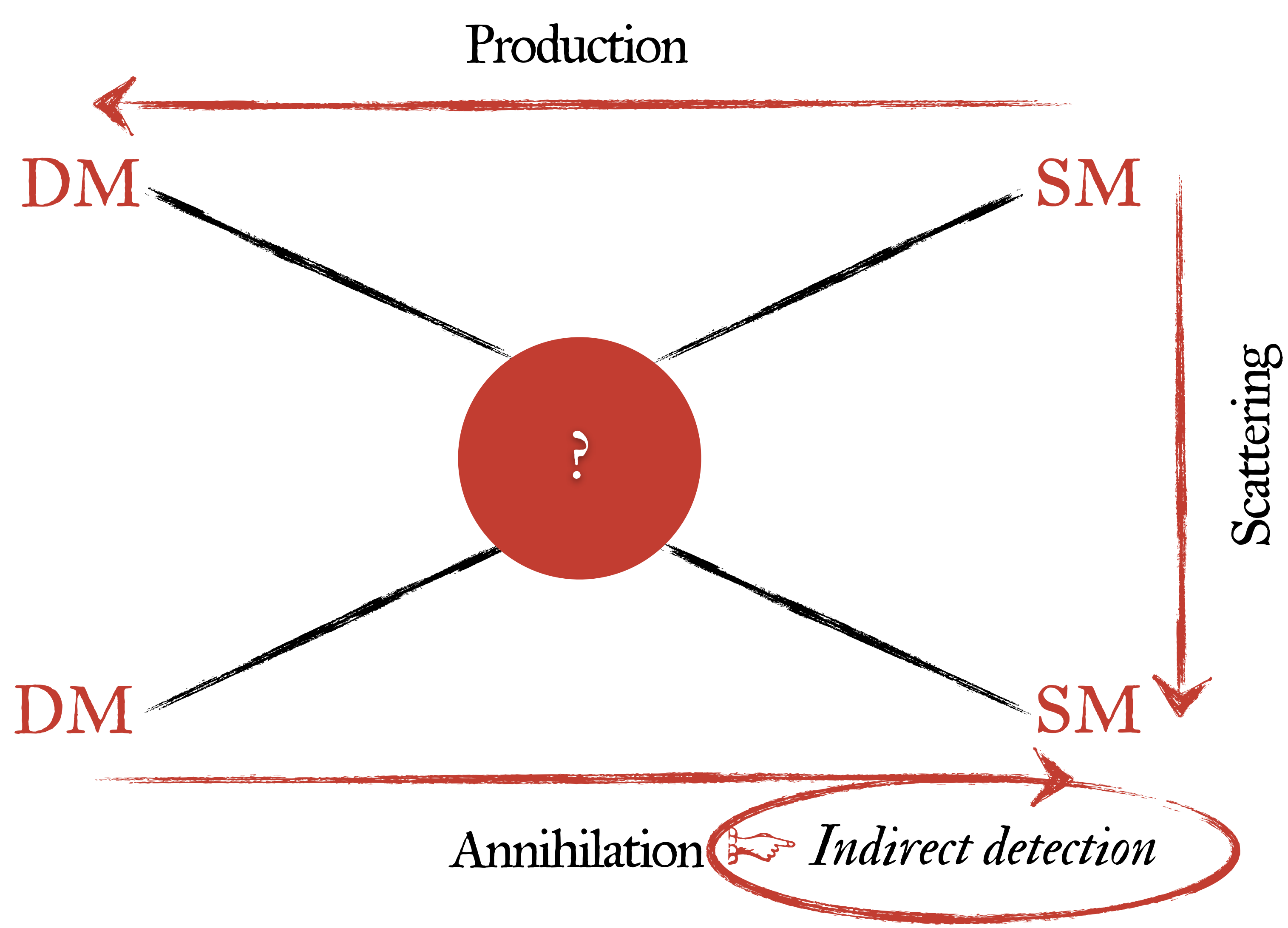
OBSERVATIONAL EVIDENCE OF DARK MATTER

- What do we eventually learn from gravitational pieces of evidence?
  - Galaxies ☞ *Dissipationless (suppressed e.m. and strong interactions)*
  - Galaxy clusters ☞ *Collisionless (very weak self-interactions)*
  - Large-scale structure ☞ *Non-relativistic (bottom-up hierarchy)*
  - Cosmology ☞ *Non-baryonic, stable, thermally produced*

☞ ***DM > 80% of the matter in the Universe!***

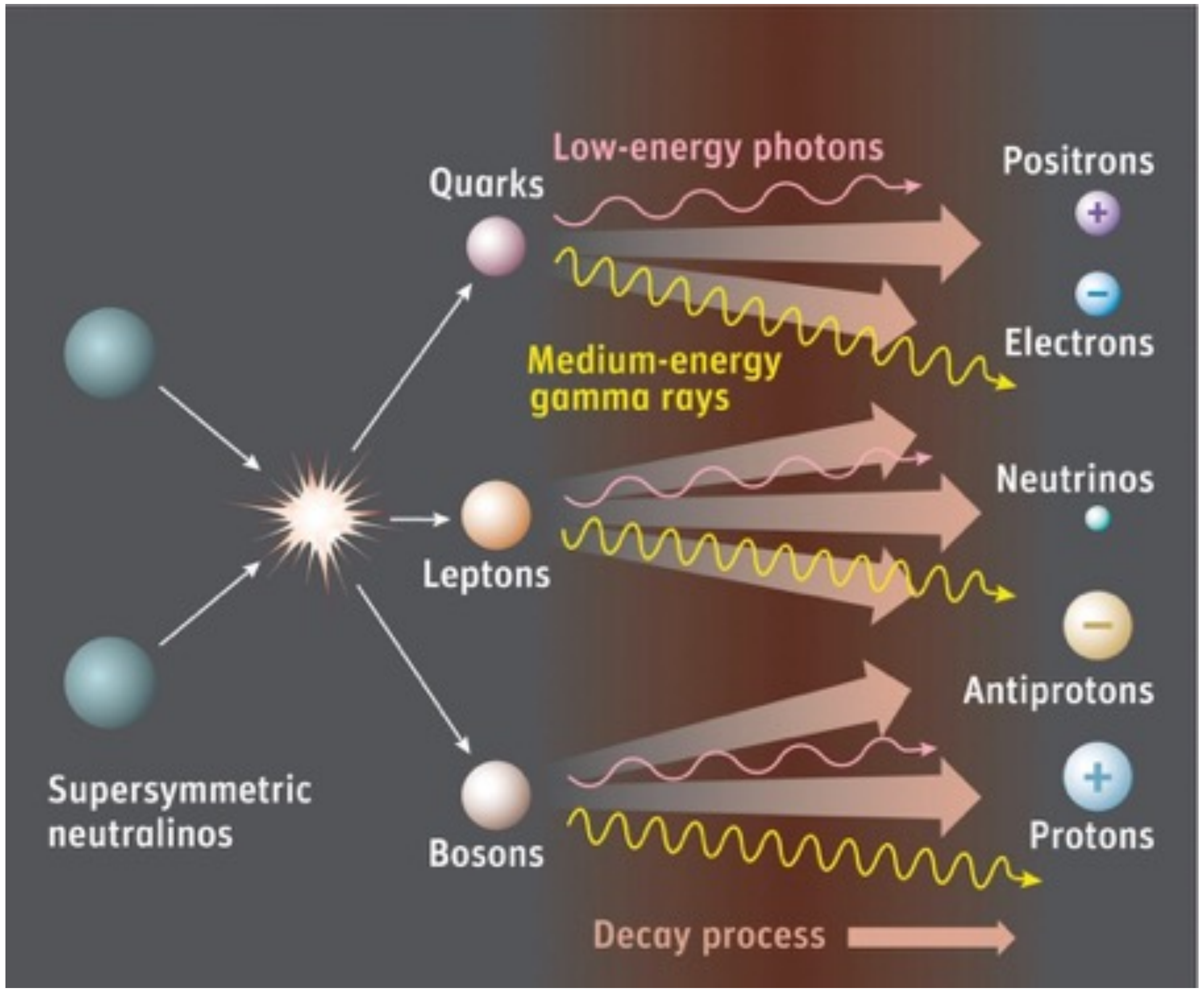
PARTICLE DARK MATTER DETECTION

- Weakly Interacting Massive Particles (WIMPs)
  - WIMPs have weak — but non-negligible! — interactions with ordinary matter
- WIMPs detection strategies



WIMP IMPRINTS IN GAMMA RAYS?

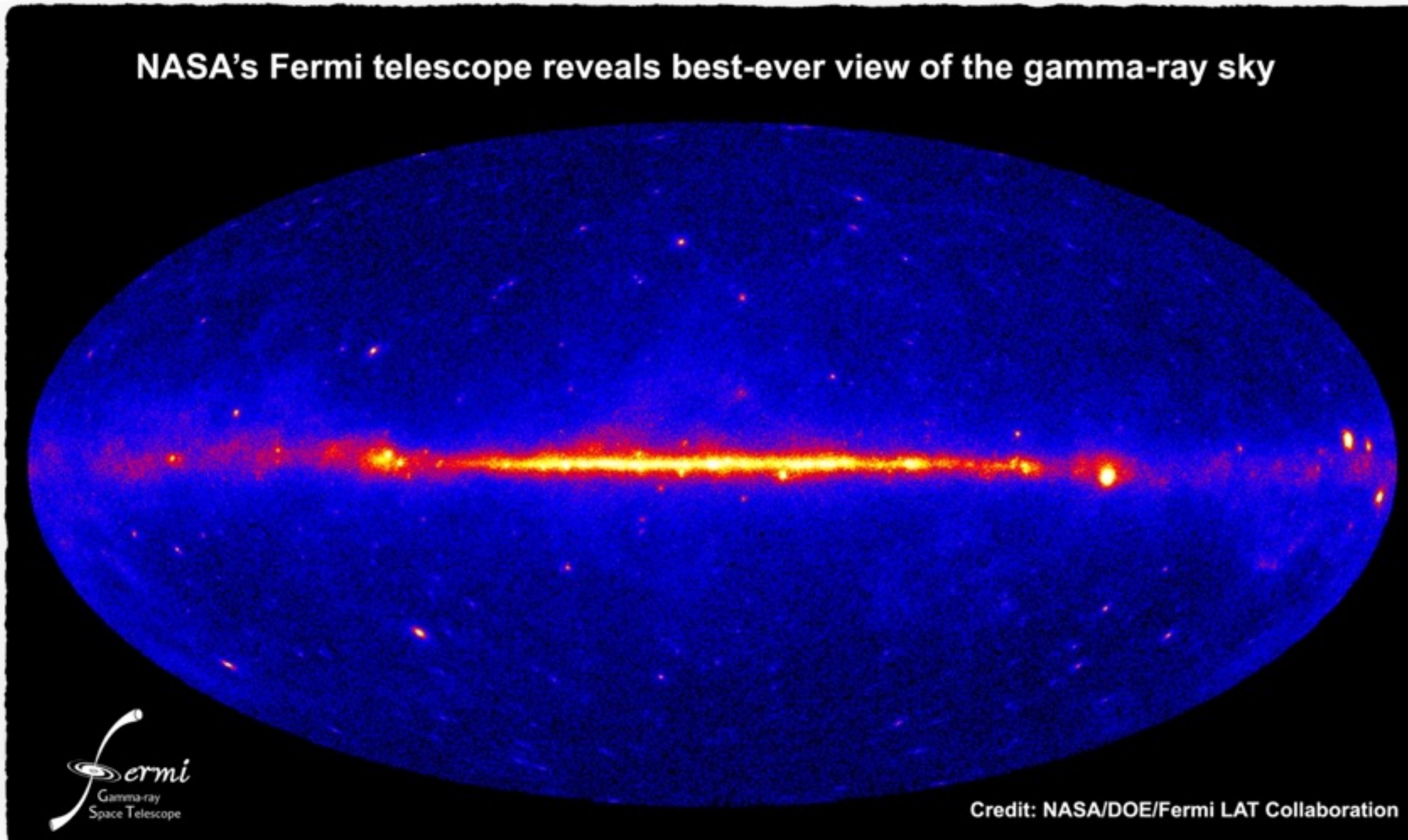
- DM particle annihilations (or decay) can produce SM particles



Extra-galactic, high-energy gamma rays

- Energy of the process set by the DM mass ~ GeV-TeV
- WIMPs are source of high energy cosmic and gamma rays

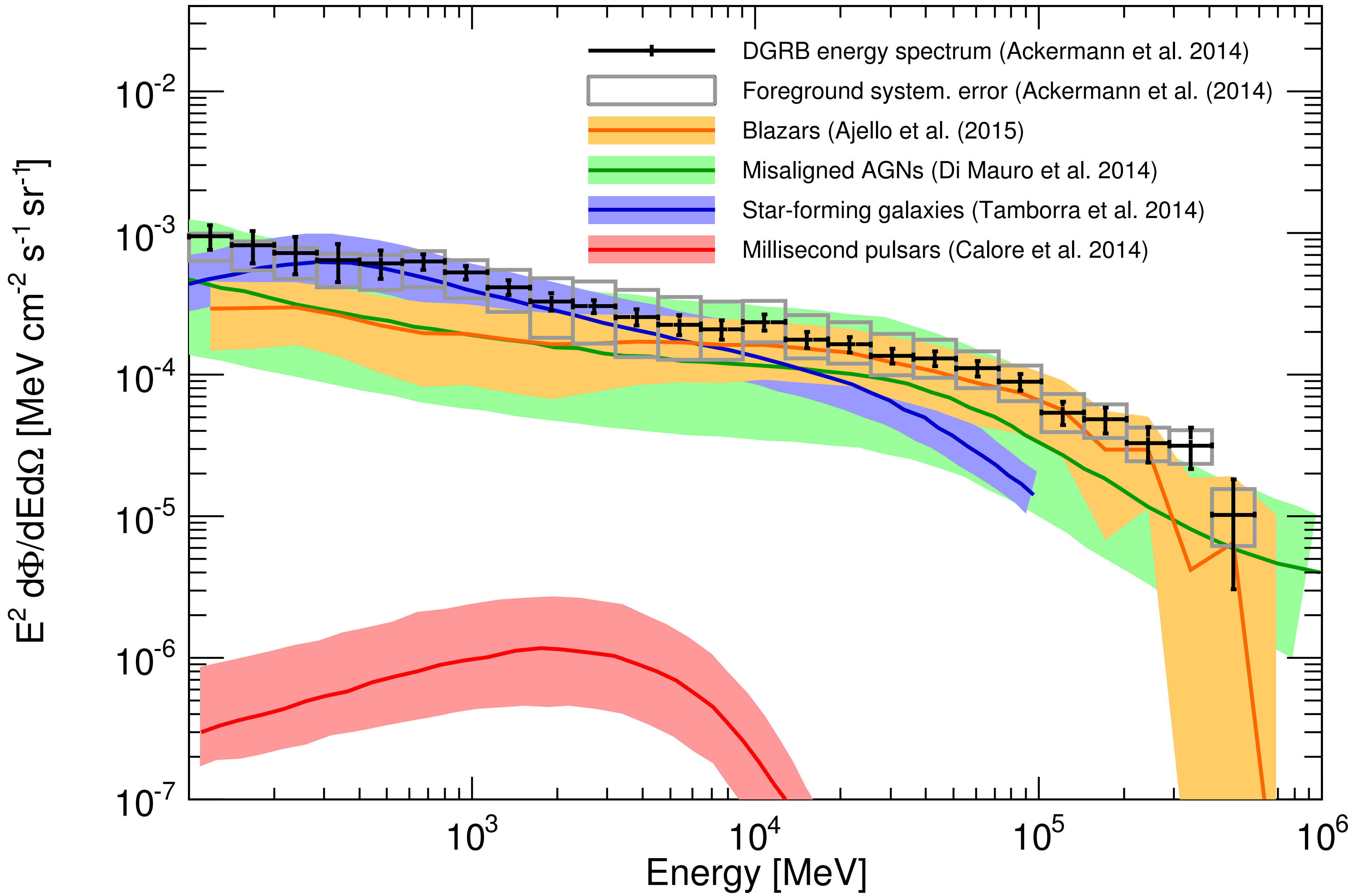
WIMP IMPRINTS IN GAMMA RAYS?



WIMP IMPRINTS IN GAMMA RAYS?

- Besides DM, unresolved astrophysical sources also contribute to the extragalactic diffuse gamma-ray background

[Fornasa & Sánchez-Conde, 2015]



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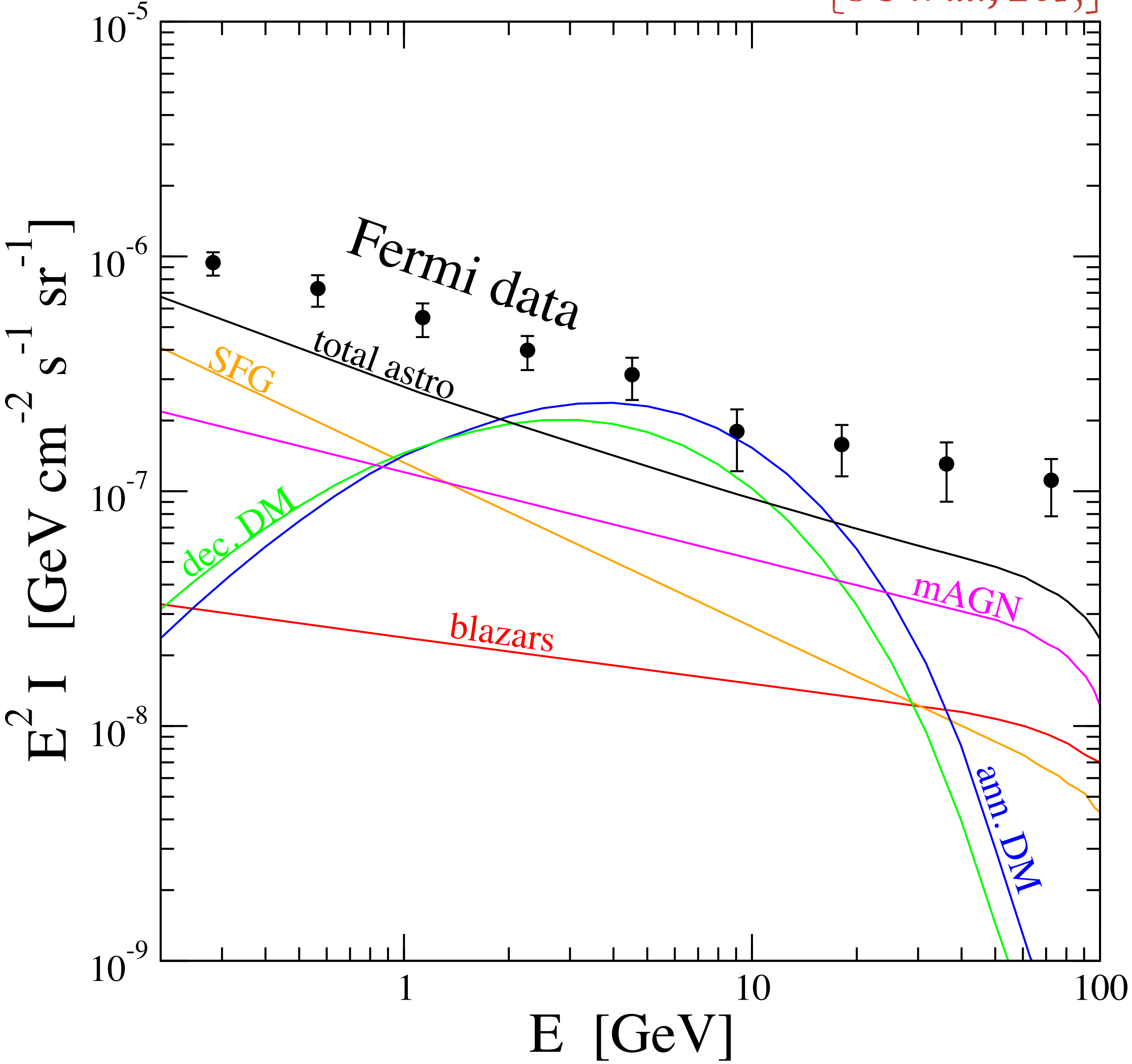
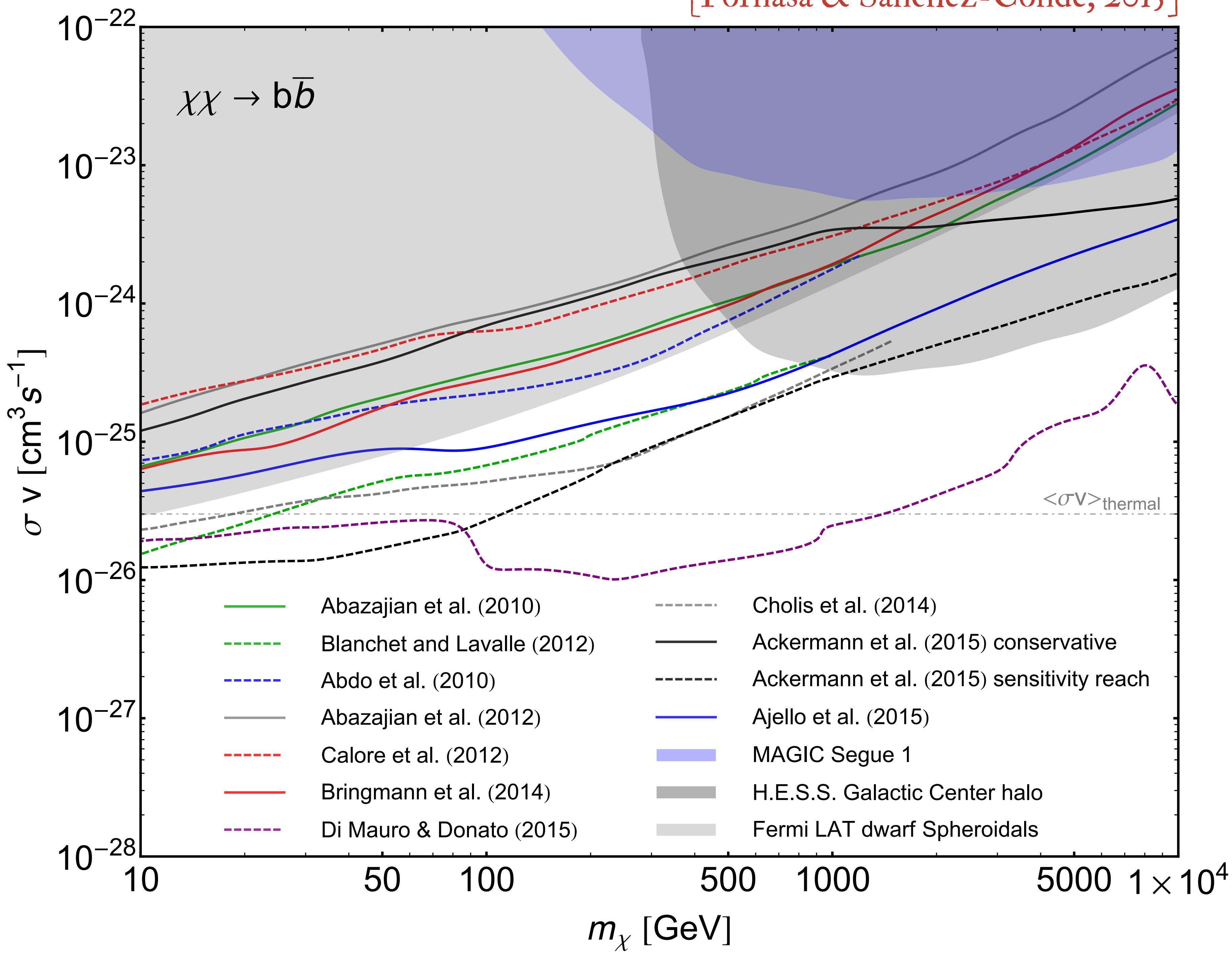
[SC *et al.*, 2013]



WIMP IMPRINTS IN GAMMA RAYS?

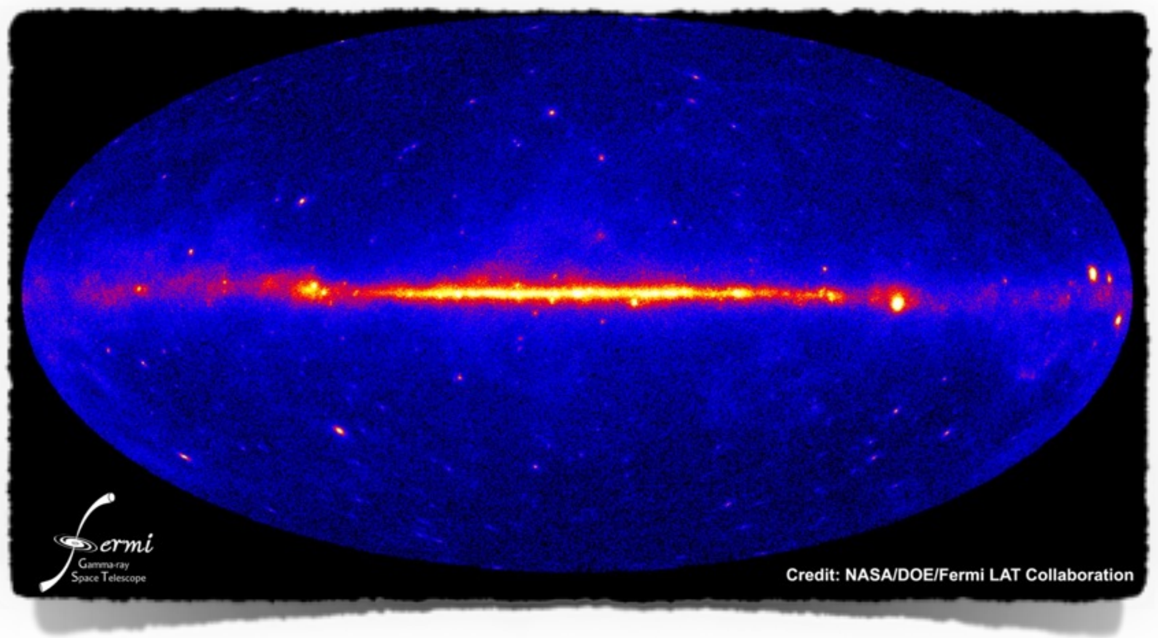
- Constraints on annihilating DM from gamma-ray energy spectrum

[Fornasa & Sánchez-Conde, 2015]

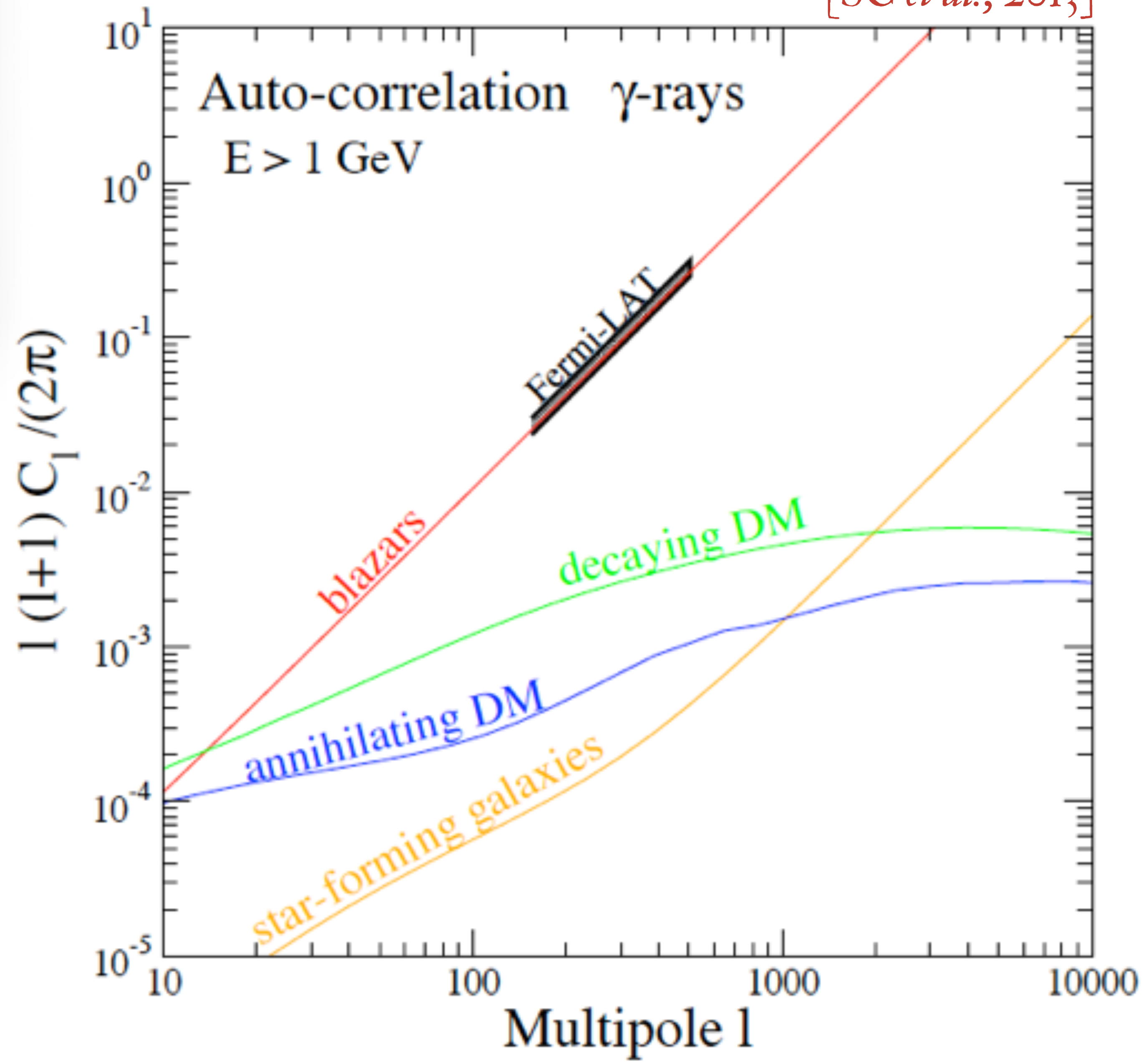


WIMP IMPRINTS IN GAMMA RAYS?

- Gamma-ray anisotropy auto-correlation angular power spectrum



[SC *et al.*, 2013]



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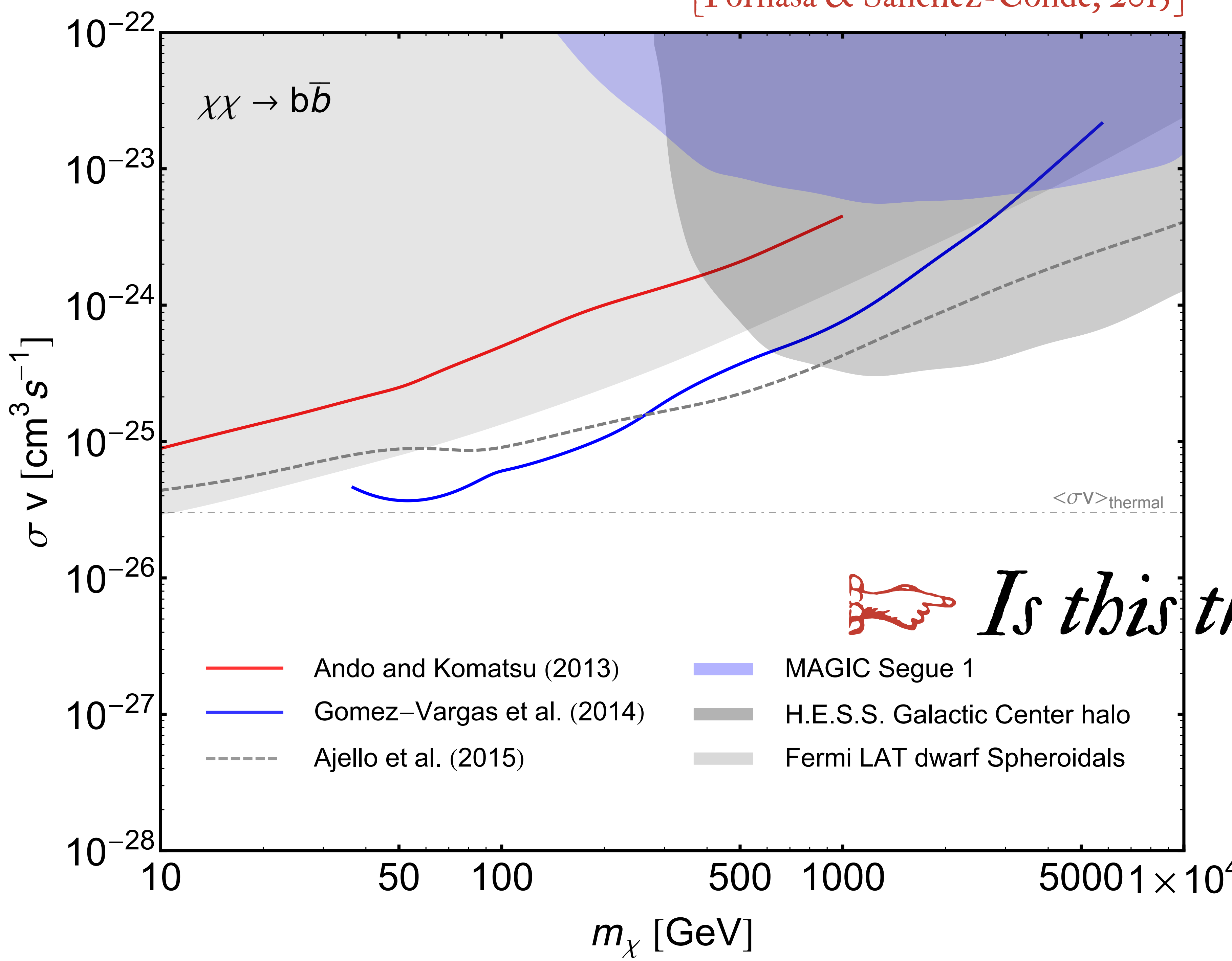

☞ *Is this the end?*

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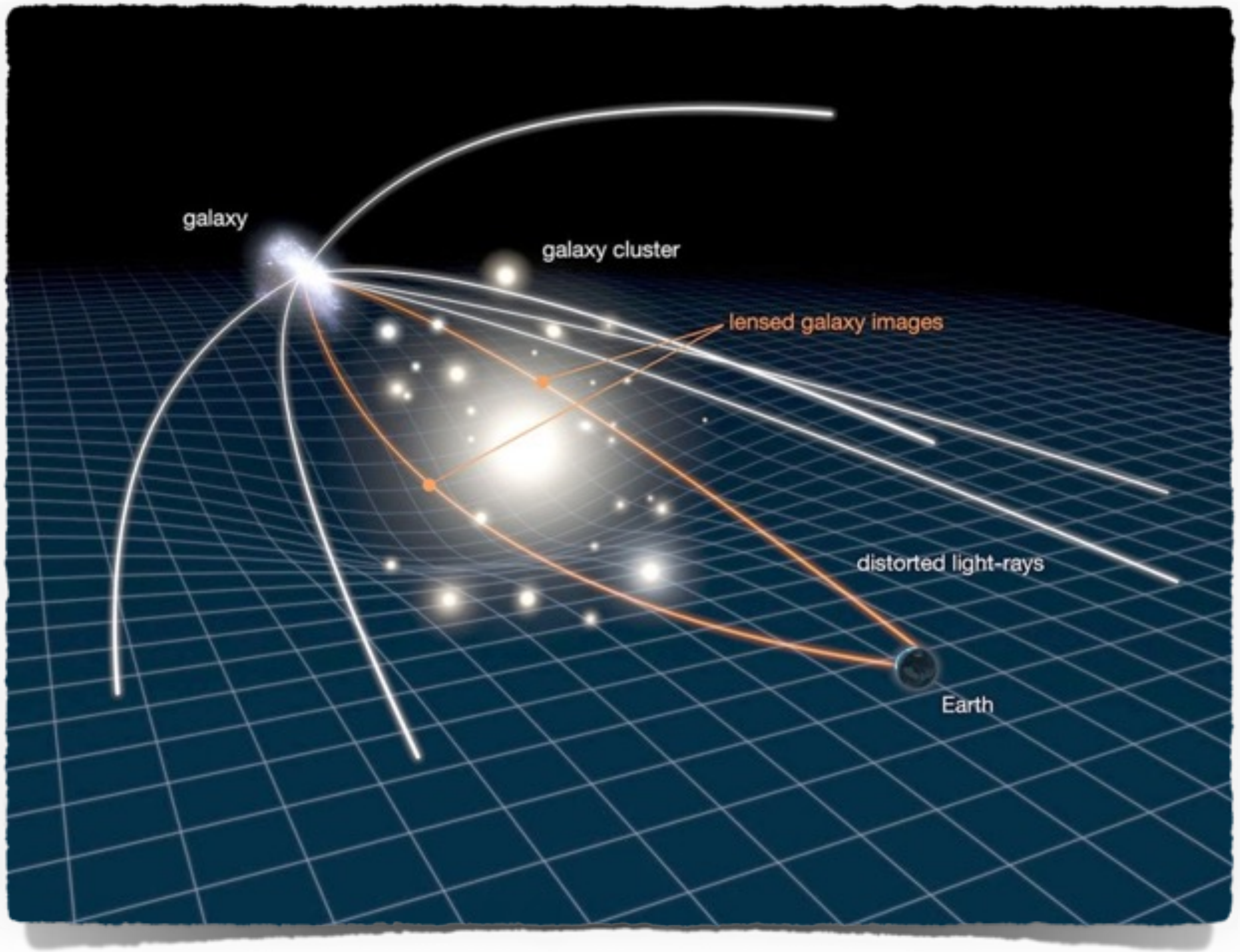
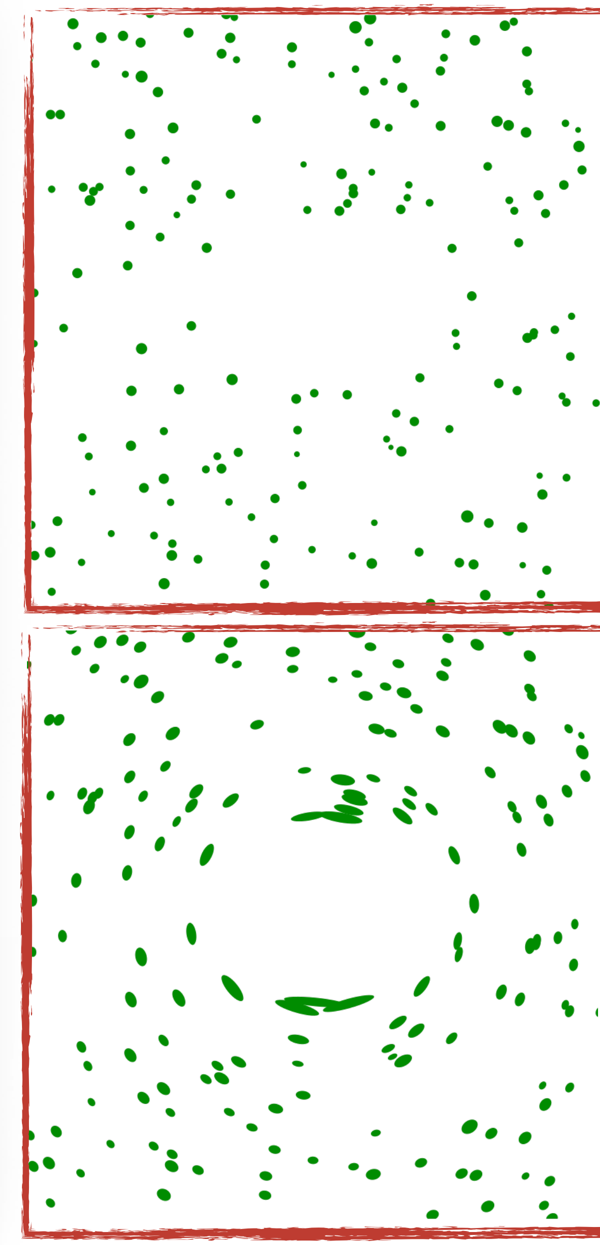
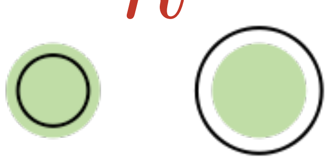
WEAK GRAVITATIONAL LENSING







κ

$\Re[\gamma]$

$\Im[\gamma]$

INTERLUDE: GALAXY SURVEYS

PRL **114,** 241301 (2015) PHYSICAL REVIEW LETTERS week ending 19 JUNE 2015

Particle Dark Matter Searches Outside the Local Group

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(Received 20 March 2015; published 16 June 2015)

If dark matter (DM) is composed by particles which are nongravitationally coupled to ordinary matter, their annihilations or decays in cosmic structures can result in detectable radiation. We show that the most powerful technique to detect a particle DM signal outside the Local Group is to study the angular cross-correlation of nongravitational signals with low-redshift gravitational probes. This method allows us to enhance the signal to noise from the regions of the Universe where the DM-induced emission is preferentially generated. We demonstrate the power of this approach by focusing on GeV-TeV DM and on the recent cross-correlation analysis between the 2MASS galaxy catalogue and the Fermi-LAT γ-ray maps. We show that this technique is more sensitive than other extragalactic γ-ray probes, such as the energy spectrum and angular autocorrelation of the extragalactic background, and emission from clusters of galaxies. Intriguingly, we find that the measured cross-correlation can be well fitted by a DM component, with a thermal annihilation cross section and mass between 10 and 100 GeV, depending on the small-scale DM properties and γ-ray production mechanism. This solicits further data collection and dedicated analyses.

CORRELATIONS AND POWER SPECTRA

- Cosmological (scalar) perturbation—e.g. density fluctuations, temperature anisotropies &c.

$$f(t,\mathbf{x})$$

- 3D correlation function

$$\xi^{fg}(t,|\mathbf{x}-\mathbf{y}|)=\langle f(t,\mathbf{x})g(t,\mathbf{y})\rangle$$

- 3D power spectrum

$$\langle f_k(z)g^*_{k'}(z)\rangle=\delta_D(\mathbf{k}-\mathbf{k}')P^{fg}(k,z)$$

- Angular power spectrum—e.g. of observable X sourced by perturbation f

$$C^{XY}(\ell)=\int\mathrm{d}\chi\,\frac{W^X(\chi)W^Y(\chi)}{\chi^2}P^{fg}\left(\frac{\ell}{\chi},\chi\right)$$

GAMMA RAYS AND COSMIC SHEAR

- Gamma-ray – weak-lensing cross-correlation angular power spectrum

$$C_\ell^{\gamma\kappa} = \int \frac{\mathrm{d}z}{H(z)} \frac{W^\gamma(z) W^\kappa(z)}{\chi^2(z)} P^s\left[k = \frac{\ell}{\chi(z)}, z\right]$$

  - The window functions, $W^X(z)$, encode the relative magnitude of the signals and the overlap in the observed redshift range

  - The source power spectrum, $P^s(k, z)$, represents the three-dimensional correlation between the large-scale gravitational potential—the lensing source field—and the processes at the origin of astrophysical and WIMP-sourced gamma rays

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GAMMA RAYS AND COSMIC SHEAR

- Photometric redshift surveys
  - redshift range
    $0.3 < z < 1.5$ and $0 < z < 2.5$
  - sky coverage
    5,000 and 15,000 sq. deg.
  - ~13.3 and 30 galaxies arcmin^{-2}

- Gamma-ray telescope
  - energy range
    $1 < E/\mathrm{GeV} < 300$
  - sky coverage
    all sky
  - ~0.27° beam size

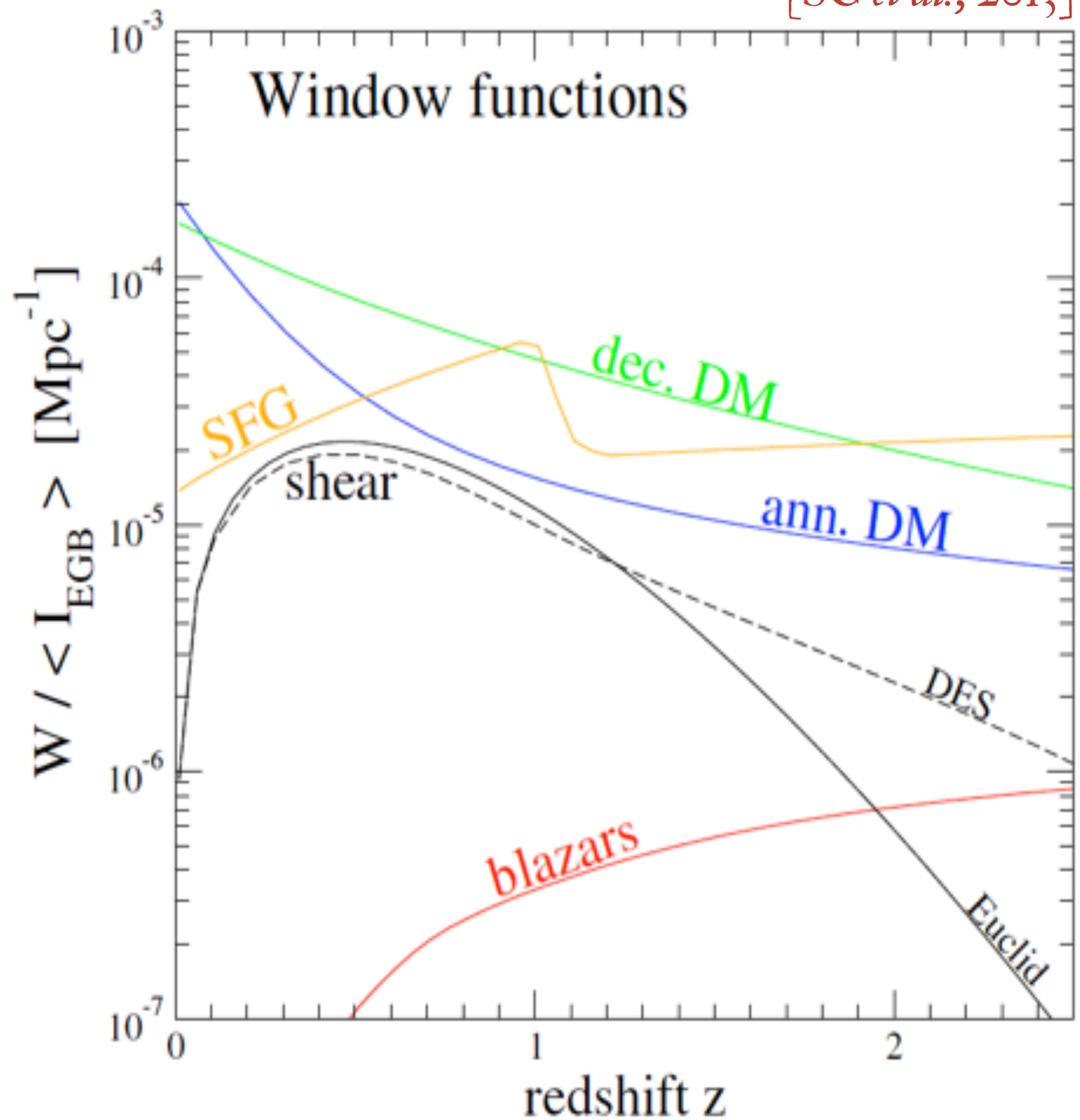
GAMMA RAYS AND COSMIC SHEAR

- Benchmark DM model (dominant final state $b\bar{b}$):
  - Decaying DM: mass 200 GeV, decay rate $3.3 \times 10^{-27}\ \mathrm{s}^{-1}$
  - Annihilating DM: mass 100 GeV, annihilation rate $3 \times 10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$
- Astrophysical sources: SFGs and blazars
- 3D source power spectra $P^s(k, z)$
  - Weak lensing: large-scale gravitational potential
  - Decaying DM: DM density
  - Annihilating DM: DM density squared
  - Astrophysical sources: gamma-ray luminosity functions

GAMMA RAYS AND COSMIC SHEAR

- Window functions $W^X(z)$
  - Weak lensing:
    Universe's background geometry
    Poisson's equation
    galaxy redshift distribution
    (depending upon DES/Euclid)
  - DM:
    DM dec./ann. properties
  - Astrophysical sources:
    bulk of unresolved sources
    (depending upon Fermi
    gamma-ray threshold)

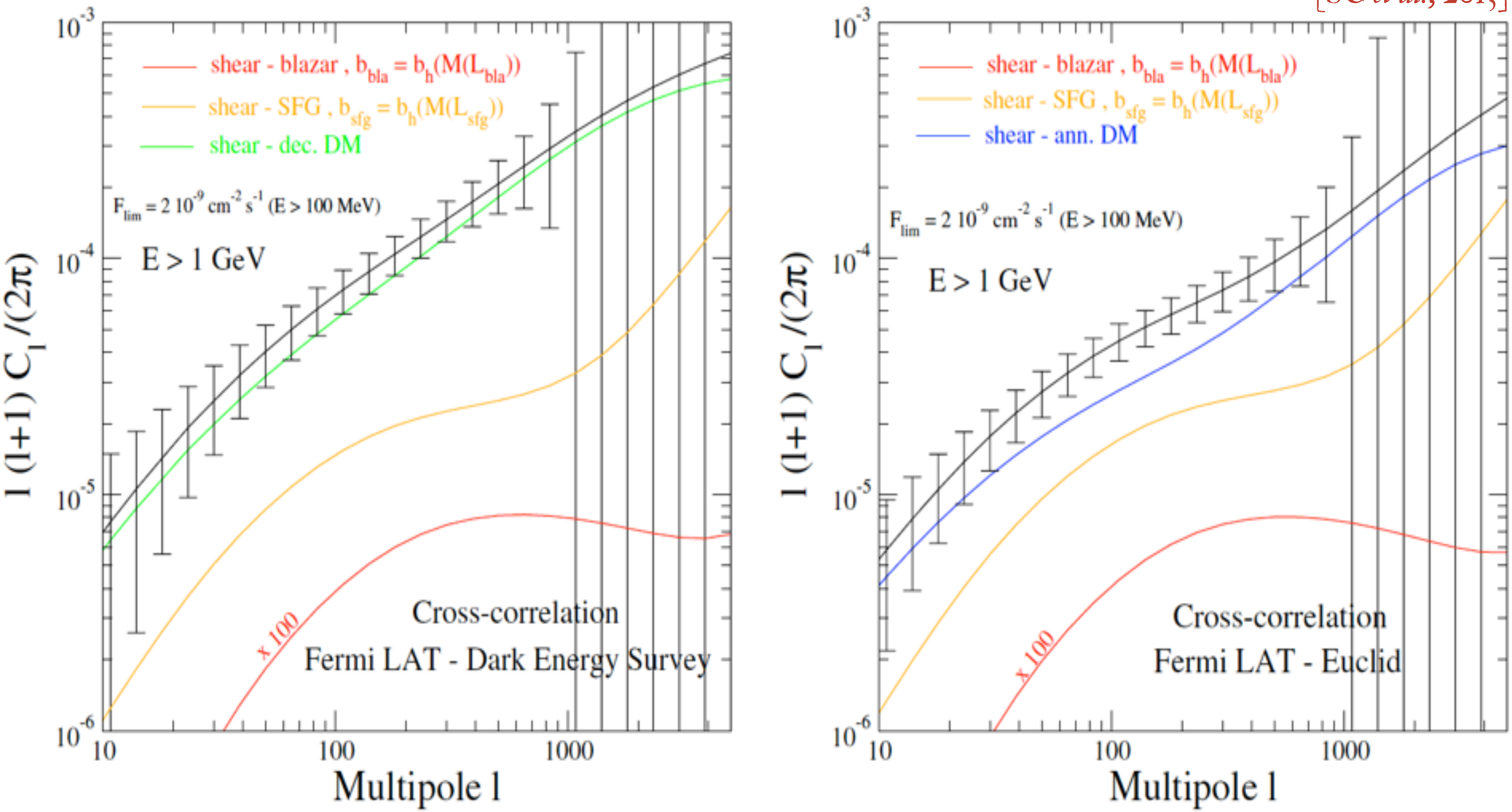
[SC *et al.*, 2013]



GAMMA RAYS AND COSMIC SHEAR

- Gamma-ray – cosmic-shear cross-corr. angular power spectrum

[SC *et al.*, 2013]



INTERLUDE:CFHTLenS

PHYSICAL REVIEW D **90,** 063502 (2014)

Cross correlation of cosmic shear and extragalactic gamma-ray background: Constraints on the dark matter annihilation cross section

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(Received 22 April 2014; published 3 September 2014)

We present the first measurement of the cross correlation of weak gravitational lensing and the extragalactic γ-ray background emission using data from the Canada-France-Hawaii Lensing Survey and the *Fermi* Large Area Telescope. The cross correlation is a powerful probe of signatures of dark matter annihilation, because both cosmic shear and gamma-ray emission originate directly from the same dark matter distribution in the Universe, and it can be used to derive constraints on the dark matter annihilation cross section. We show that the measured lensing-γ correlation is consistent with a null signal. Comparing the result to theoretical predictions, we exclude dark matter annihilation cross sections of $\langle \sigma v \rangle = 10^{-24}$–$10^{-25}$ cm^3 s^{-1} for a 100 GeV dark matter. If dark matter halos exist down to the mass scale of $10^{-6} M_\odot$, we are able to place constraints on the thermal cross sections $\langle \sigma v \rangle \sim 5 \times 10^{-26}$ cm^3 s^{-1} for a 10 GeV dark matter annihilation into $\tau^+\tau^-$. Future gravitational lensing surveys will increase sensitivity to probe annihilation cross sections of $\langle \sigma v \rangle \sim 3 \times 10^{-26}$ cm^3 s^{-1} even for a 100 GeV dark matter. Detailed modeling of the contributions from astrophysical sources to the cross correlation signal could further improve the constraints by ~40%–70%.

GAMMA RAYS AND COSMIC SHEAR

- Photometric redshift surveys
  - redshift range
    $0.3 < z < 1.5$ and $0 < z < 2.5$
  - sky coverage
    5,000 and 15,000 sq. deg.
  - ~13.3 and 30 galaxies arcmin^{-2}
  - 3 and 10 redshift bins

- Gamma-ray telescope
  - energy range
    $1 < E/\mathrm{GeV} < 300$
  - sky coverage
    all sky
  - ~0.27° beam size
  - 6 energy bins

TOMOGRAPHY

FORECASTS FROM TOMOGRAPHY

- In the Bayesian approach, and under the assumption of Gaussian likelihoods, the Fisher information matrix approximates the inverse of the covariance matrix of a given model parameters

[Fisher (1935), J. R. Stat. Soc. 98, 39;
Tegmark, Taylor & Heavens (2007), Astrophys. J. 480, 22]

$$\mathbf{F} = \left\langle -\frac{\partial^2 \ln \mathcal{L}}{\partial \boldsymbol{\vartheta}^2} \right\rangle$$

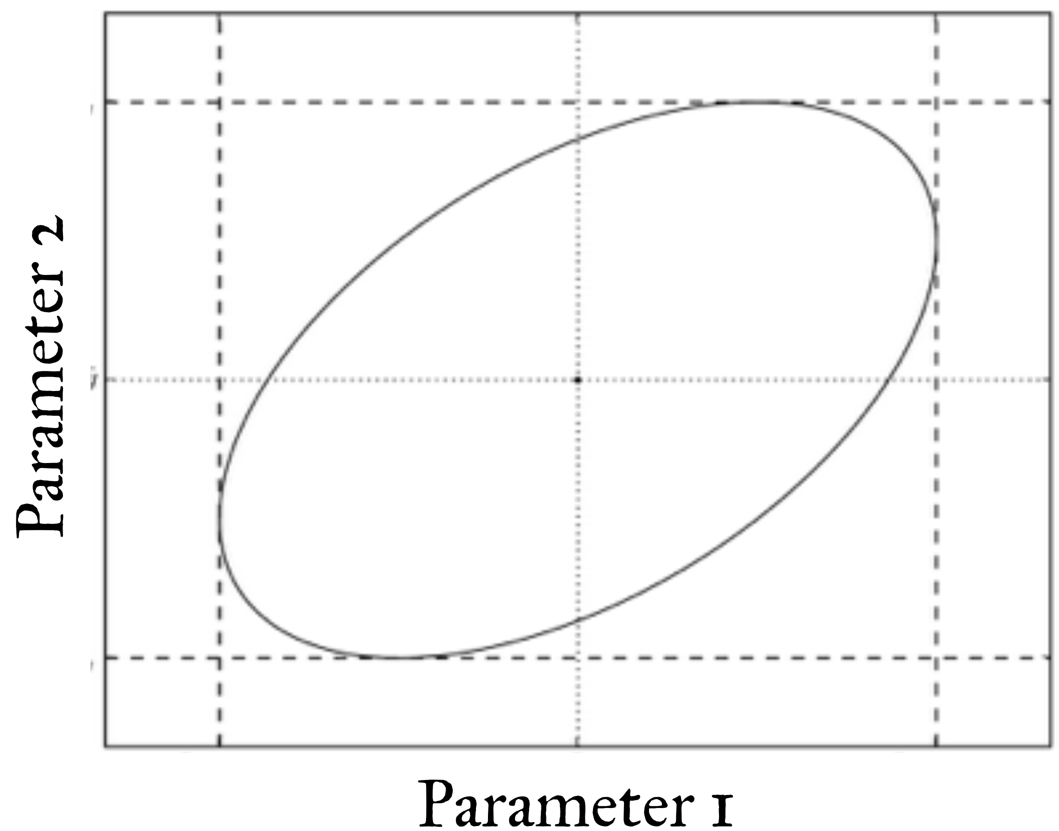
$$\mathbf{F}^{\gamma\kappa}_{\alpha\beta} = \sum_\ell (2\ell+1) f_{\rm sky} \frac{\partial C^{\gamma\kappa}_\ell}{\partial \vartheta_\alpha} \left(\Gamma^{\gamma\kappa}_\ell\right)^{-1} \frac{\partial C^{\gamma\kappa}_\ell}{\partial \vartheta_\beta}$$

FORECASTS FROM TOMOGRAPHY

- Given a future experiment, via its Fisher matrix we can
  - Infer accuracy on parameters measurements

$$\sigma\left(\vartheta_\alpha\right)=\sqrt{\left(\mathbf{F}^{-1}\right)_{\alpha\alpha}}$$

  - Forecast error confidence regions



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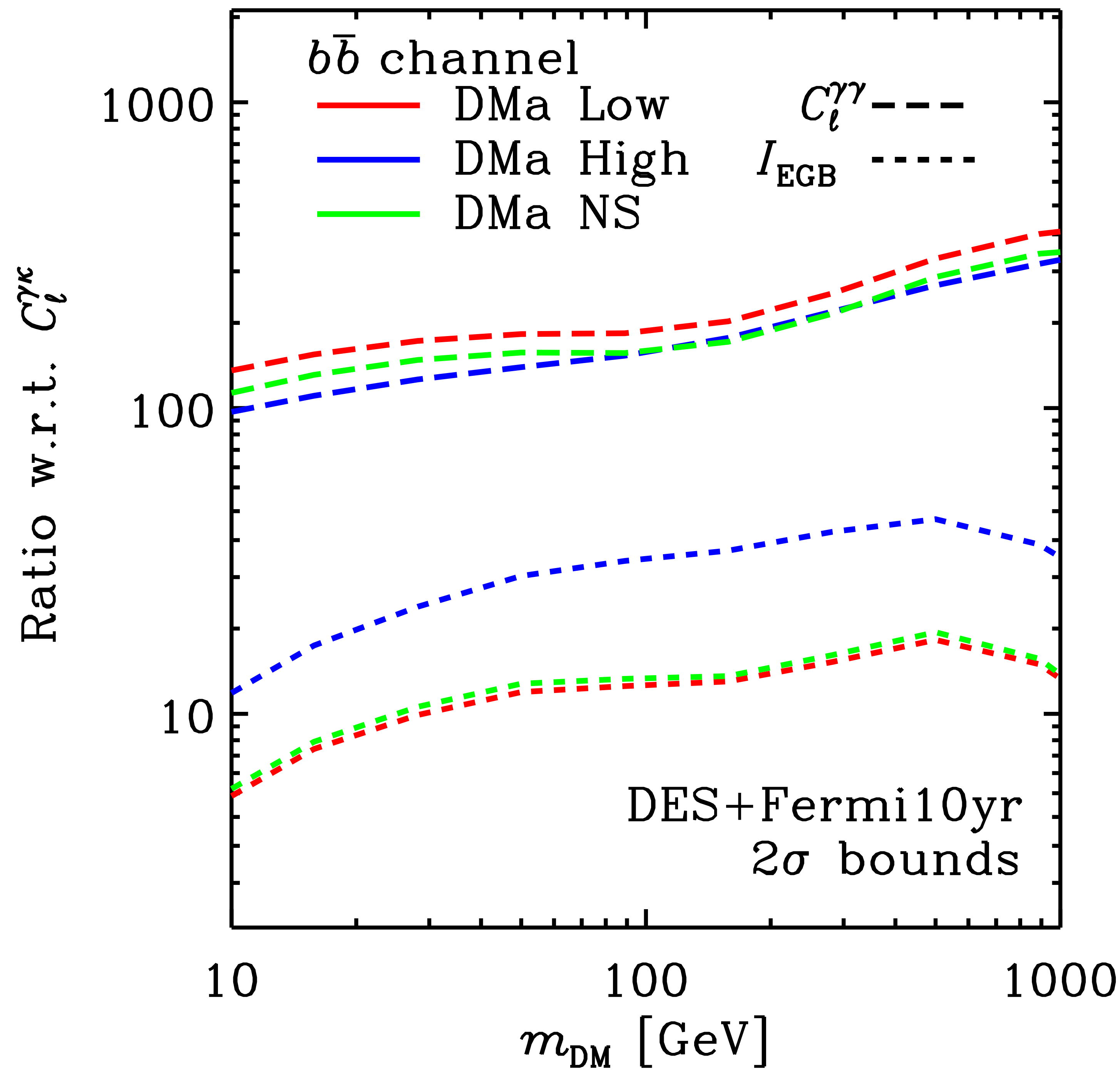
- Astrophysical sources:
  SFGs, blazars
  and misaligned AGNs

[SC *et al.*, 2015]



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[SC *et al.*, 2015]

$m_{\rm DM}$ [GeV]	$\Gamma_d\,[10^{-27}\,{\rm s}^{-1}]$
$20 \pm 4.2\ (6.7)$	$0.33 \pm 6.2\ (9.1) \times 10^{-3}$
$200 \pm 17\ (31)$	$0.33 \pm 3.3\ (6.4) \times 10^{-3}$
$2000 \pm 110\ (230)$	$0.33 \pm 2.0\ (4.3) \times 10^{-3}$

$m_{\rm DM}$ [GeV]	$\langle\sigma_a v\rangle\,[10^{-26}\ {\rm cm}^3\,{\rm s}^{-1}]$
$10 \pm 0.52\ (0.78)$	$3 \pm 0.22\ (0.32)$
$100 \pm 18\ (34)$	$3 \pm 0.72\ (1.6)$
$1000 \pm 1000\ (2500)$	$3 \pm 3.9\ (10.1)$

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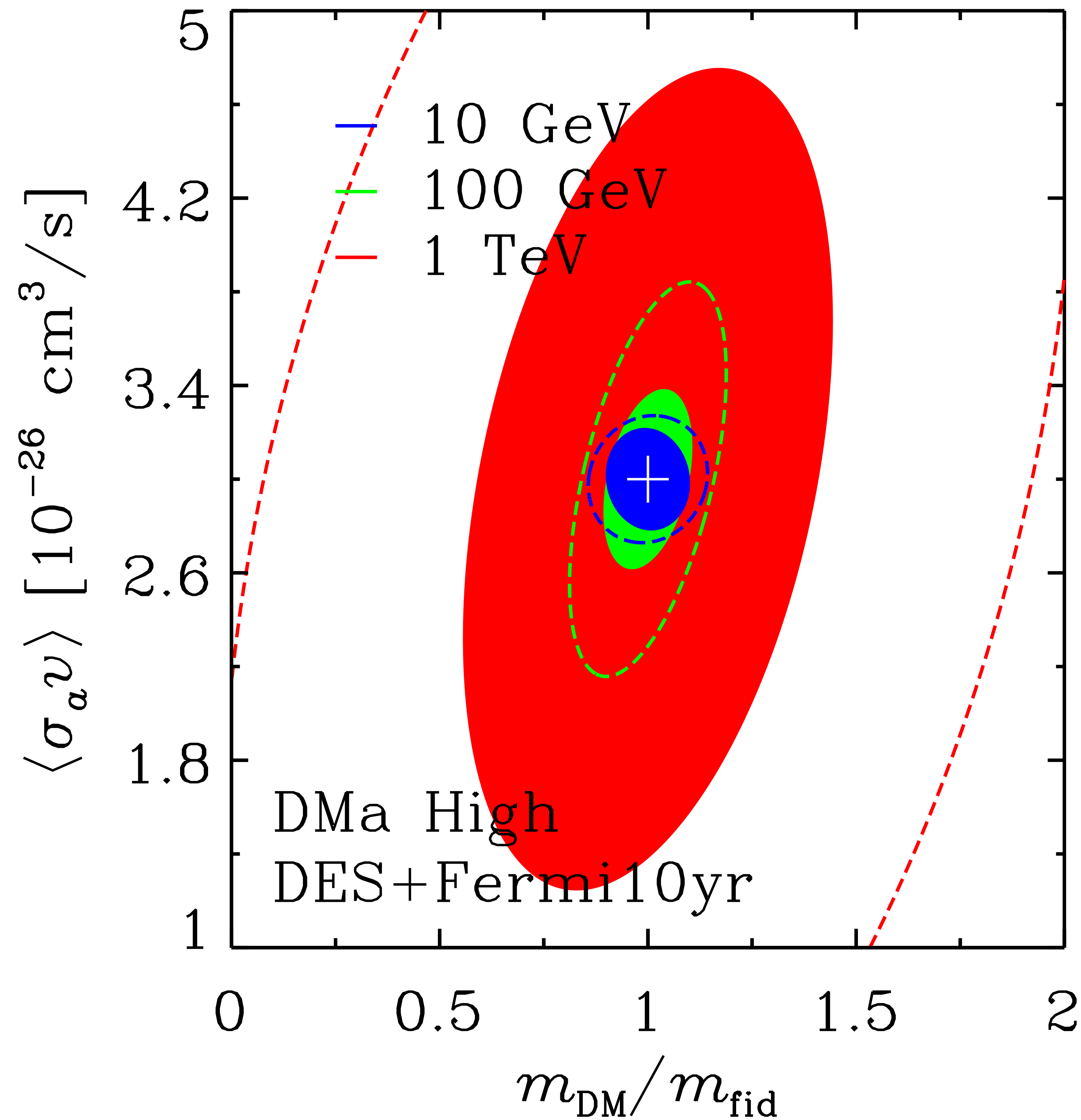

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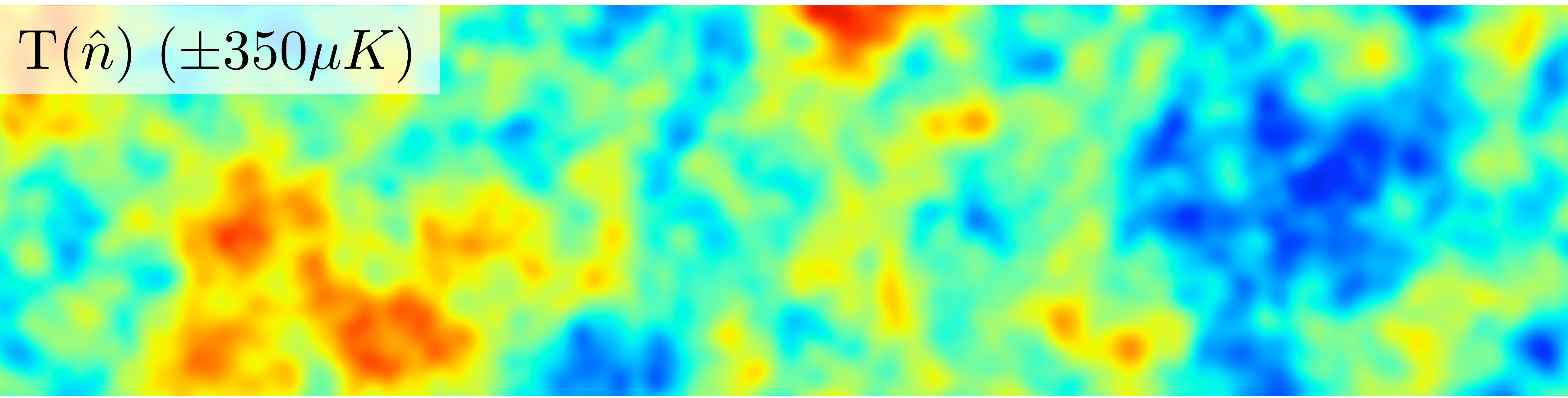

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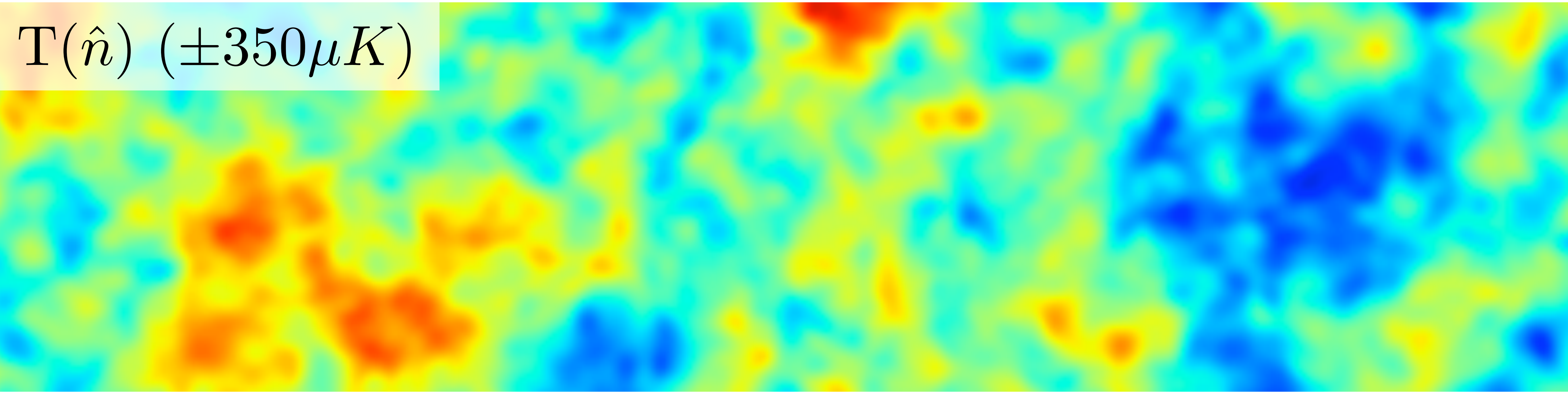
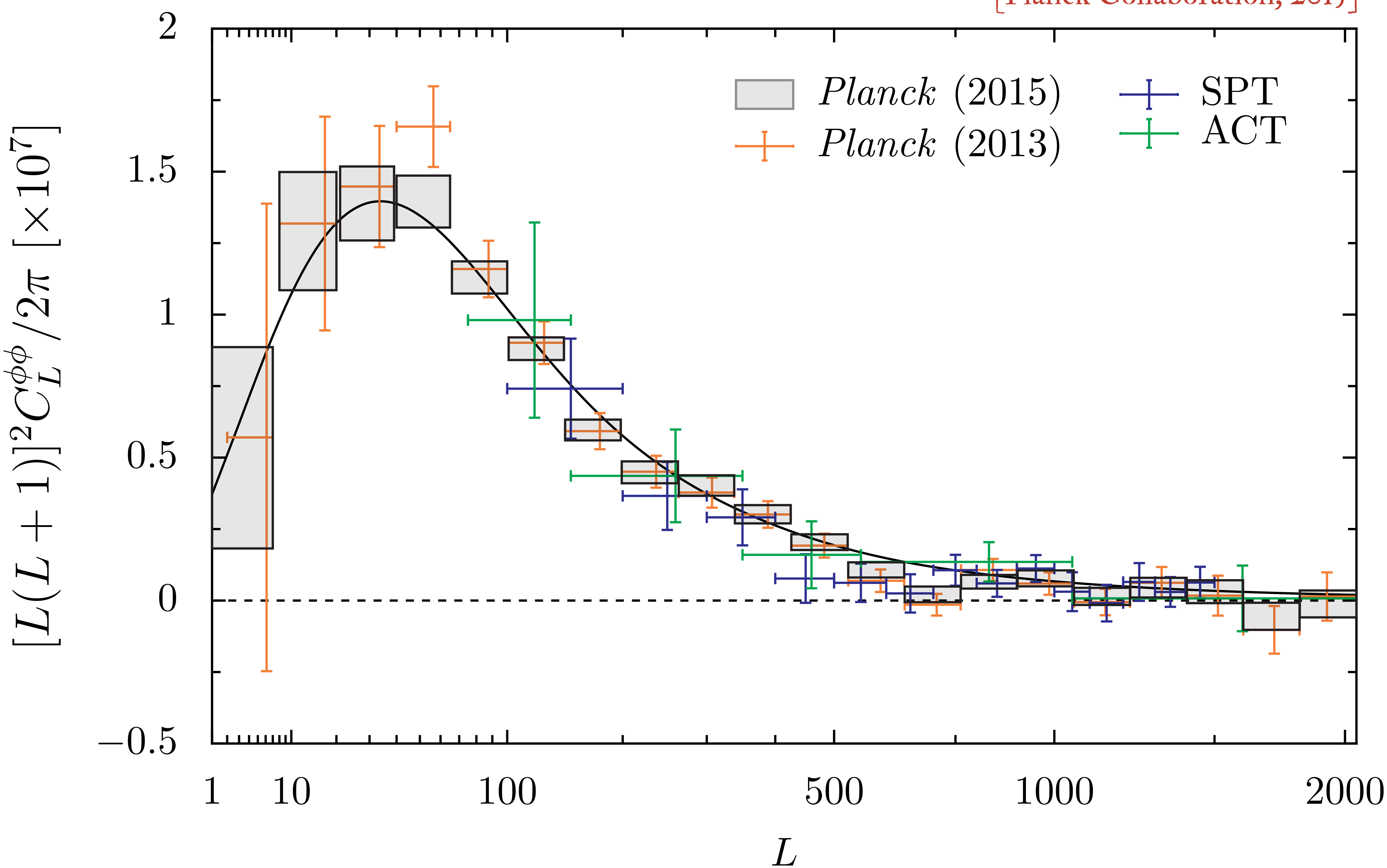


GAMMA RAYS AND CMB LENSING

- CMB lensing angular power spectrum

[Planck Collaboration, 2015]



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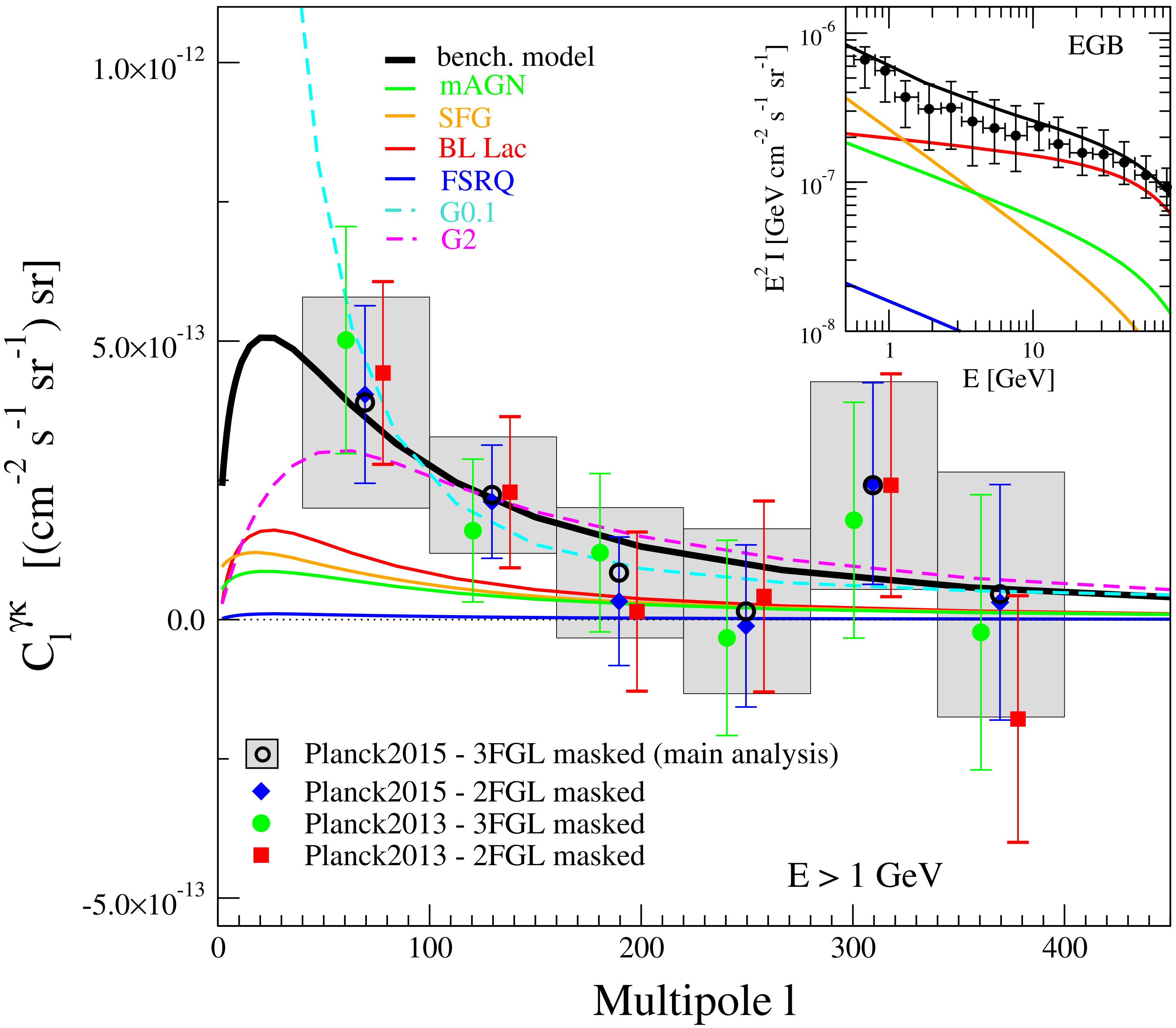
- Gamma-ray – CMB lensing cross-corr. angular power spectrum

[Fornengo, Perotto, Regis & SC, 2015]



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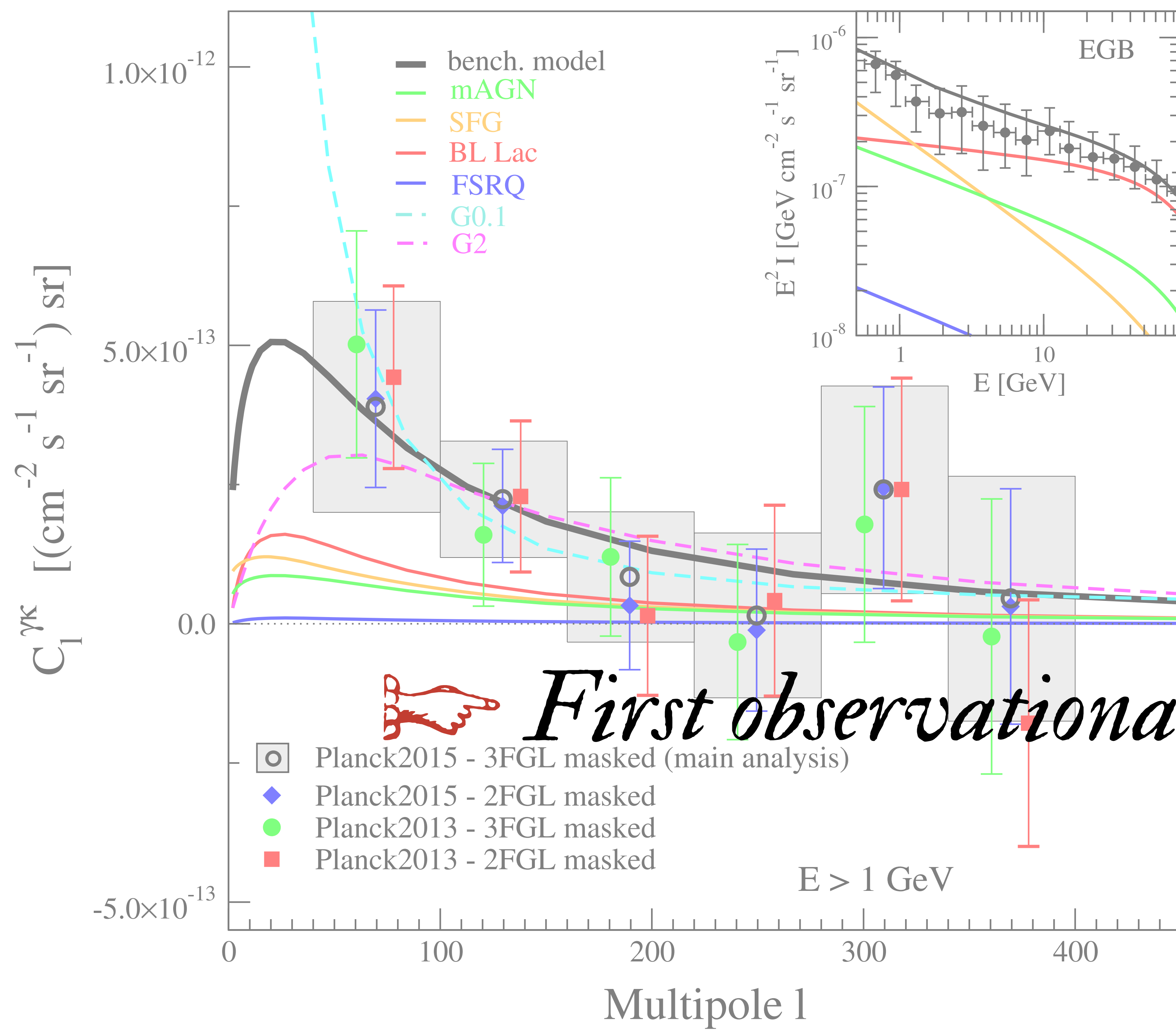

☛ *First observational evidence!*

TAKE HOME MESSAGE

- Albeit particle DM is currently an established ingredient of our understanding of the Universe, we have hitherto failed to detect it
- The diffuse gamma-ray background does not, in itself, provide an exploitable tool for probing WIMP DM through its annihilating/decaying processes, because astrophysical emission is far dominant
- Contrarily, the cross-correlation of extragalactic gamma-ray background anisotropies with weak lensing appears promising!

TAKEHOMEMESSAGE

- Contrarily, the cross-correlation of extragalactic gamma-ray background anisotropies with weak lensing appears promising!
    - First measurement of the cross-correlation between gamma-ray anisotropies and CMB lensing!
    - Weak lensing window function nicely overlaps with that of ann./dec. DM, whilst this happens only at intermediate or high redshift for astrophysical sources
    - Since both gravitational lensing and WIMP-induced gamma rays are stronger for larger haloes, their cross-correlation is more effective compared to that of astrophysical sources
    - The combination of Fermi with weak lensing surveys like DES or Euclid, and the exploitation of energy and redshift tomography, can thus potentially provide evidence for WIMPs

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