TAUP
Sep 9, 2015
Turin, Italy

Dark matter indirect searches: Multi-wavelength and anisotropies

Shin'ichiro Ando
University of Amsterdam

GRAPPA
GRavitation AstroParticle Physics Amsterdam

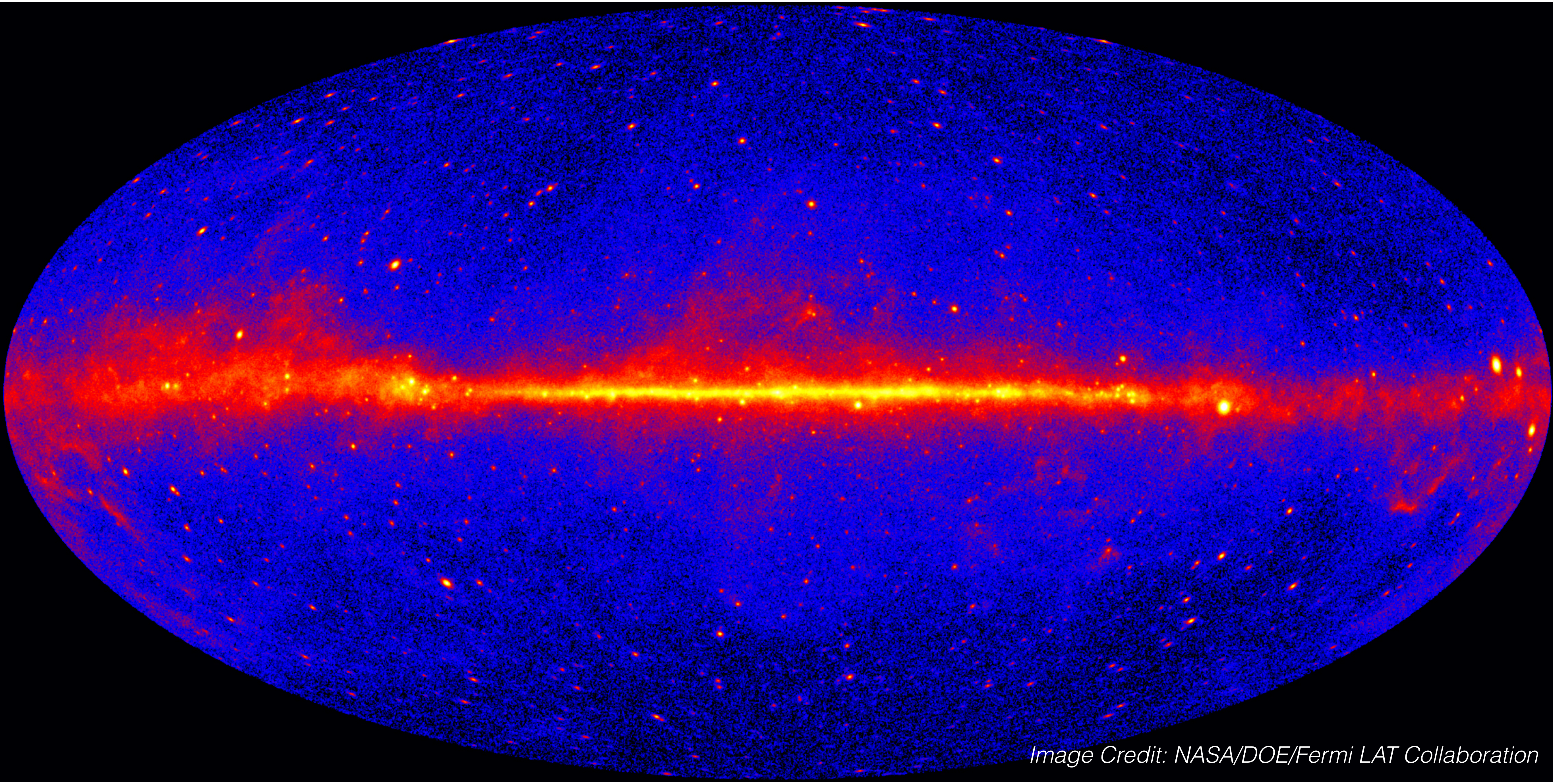
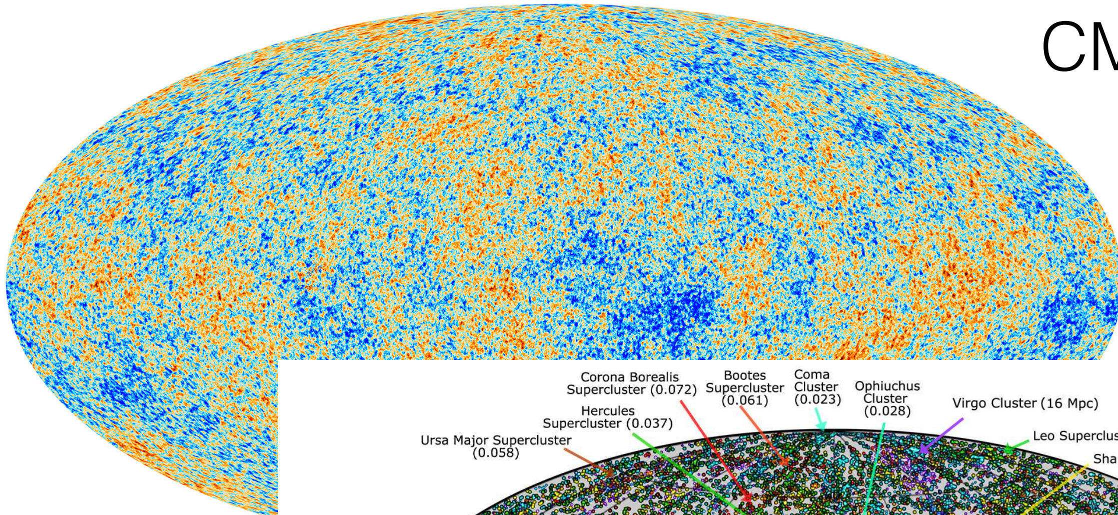
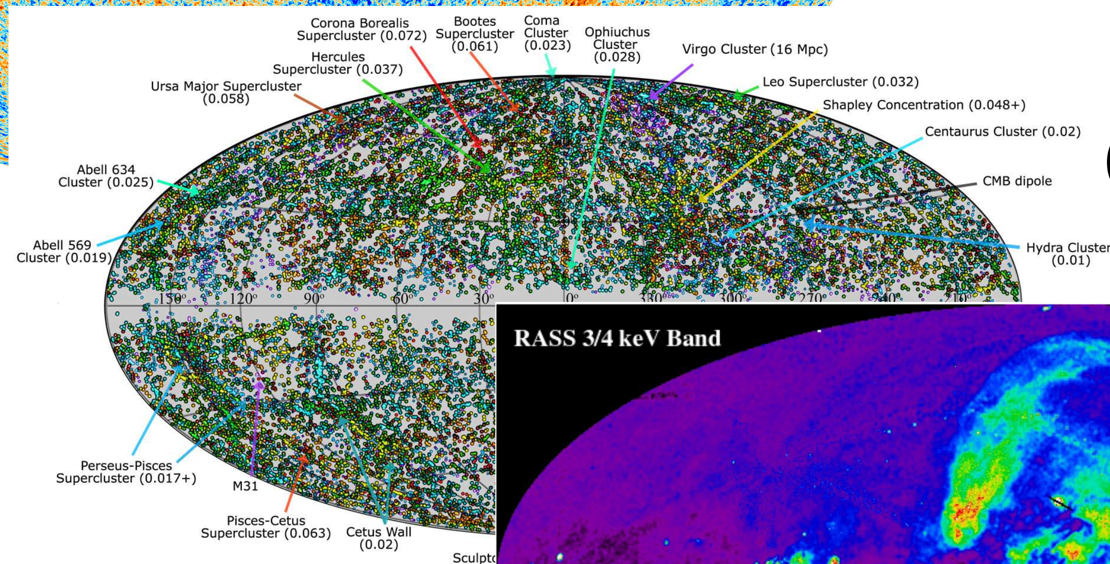


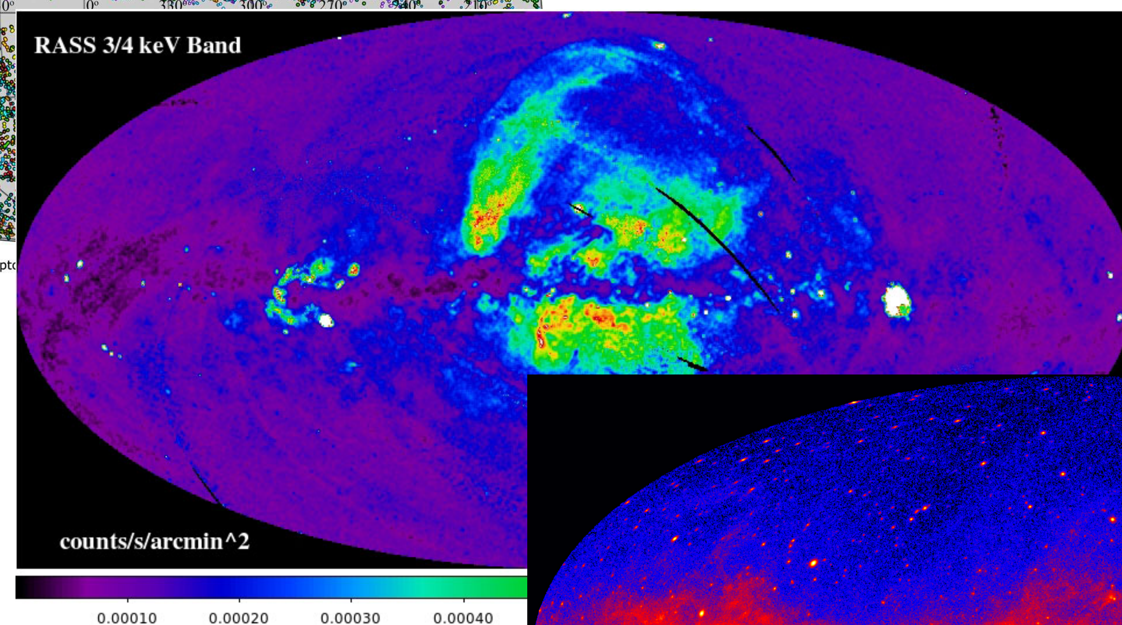
Image Credit: NASA/DOE/Fermi LAT Collaboration



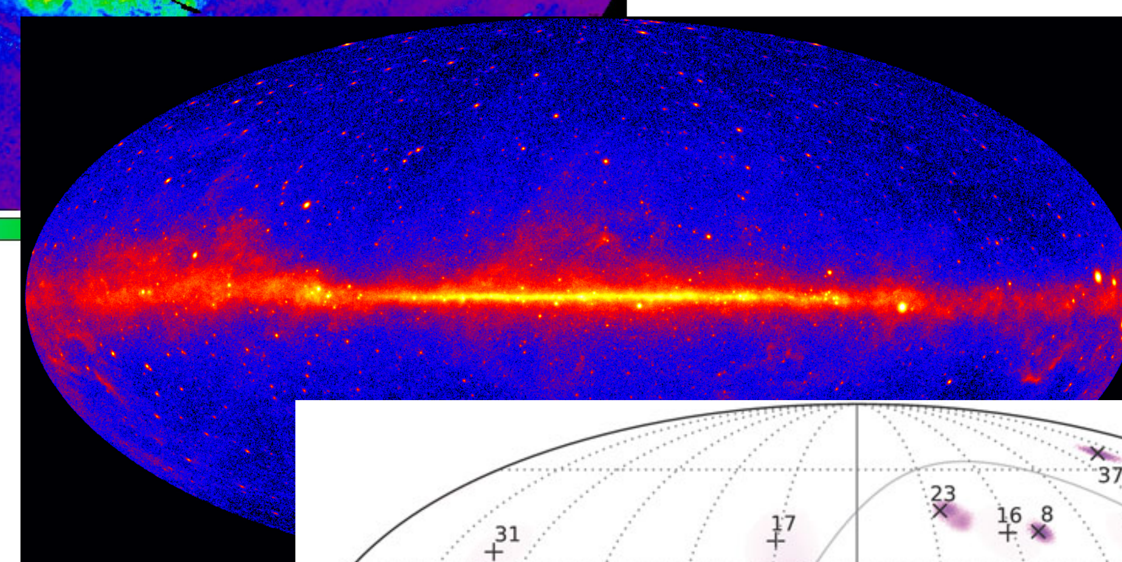
CMB (Planck)



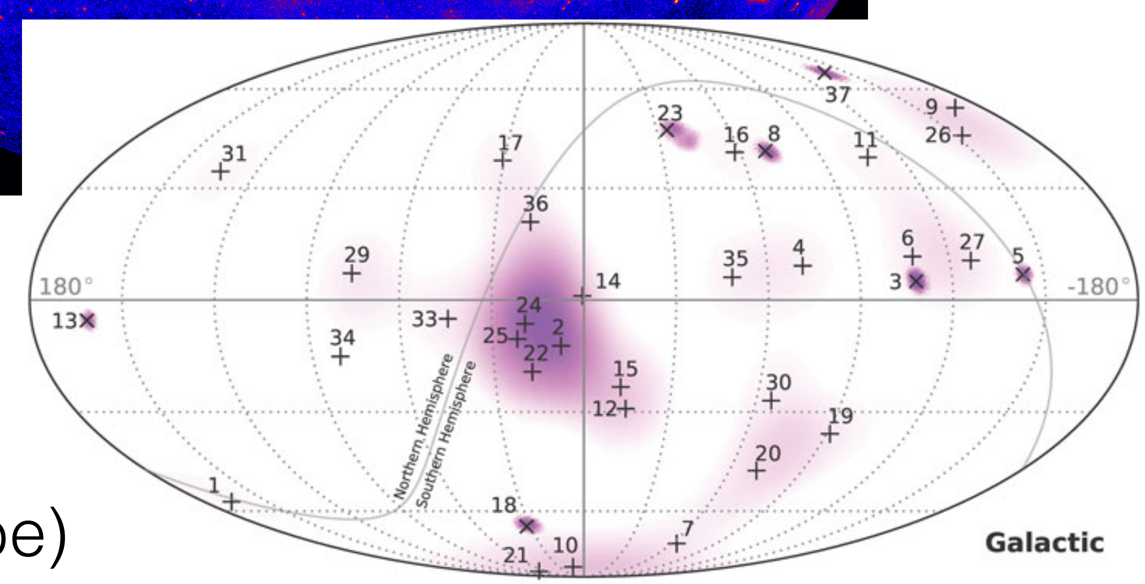
Infrared/optical (galaxy catalogs)



CXB (ROSAT, eROSITA)



CGB (Fermi)



CNB (IceCube)

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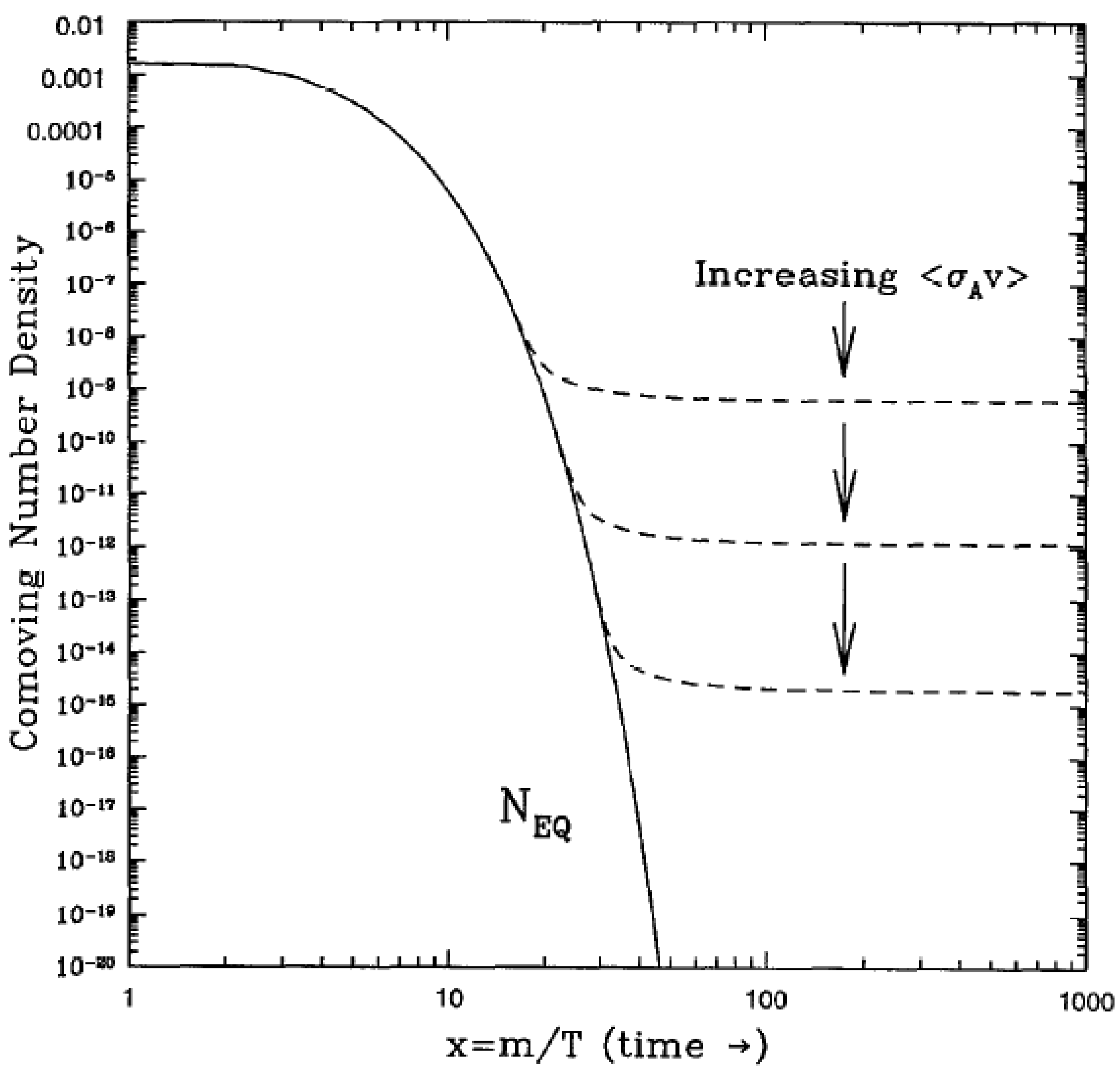
Candidate particle: WIMP

- Weakly Interacting Massive Particle (**WIMP**)
- Current dark matter density: determined by competition between Hubble expansion and annihilation (e.g., Jungman et al. 1996; Steigman et al. 2012)
  - Later, expansion becomes too fast for WIMPs to annihilate (thermal freeze-out)
- WIMP models can naturally explain the relic abundance
- E.g., neutralino predicted by supersymmetry

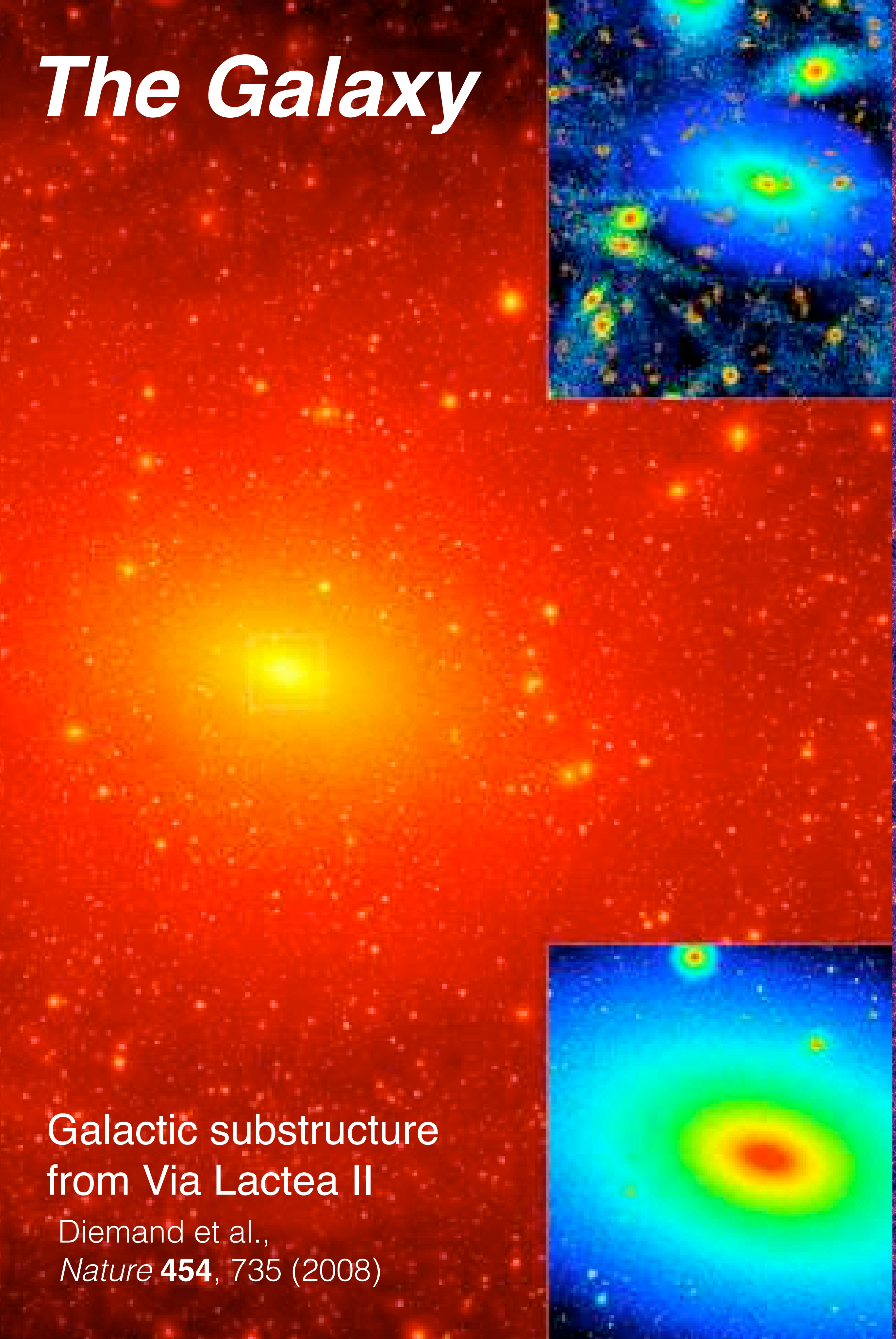


$$\Omega_\chi h^2 \simeq \frac{3 \times 10^{-27}\ \mathrm{cm}^3\ \mathrm{s}^{-1}}{\langle \sigma_{\rm ann} v \rangle}$$

$$\langle \sigma_{\rm ann} v \rangle \sim \alpha^2 (100\ \mathrm{GeV})^{-2}$$

$$\sim 3 \times 10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$$

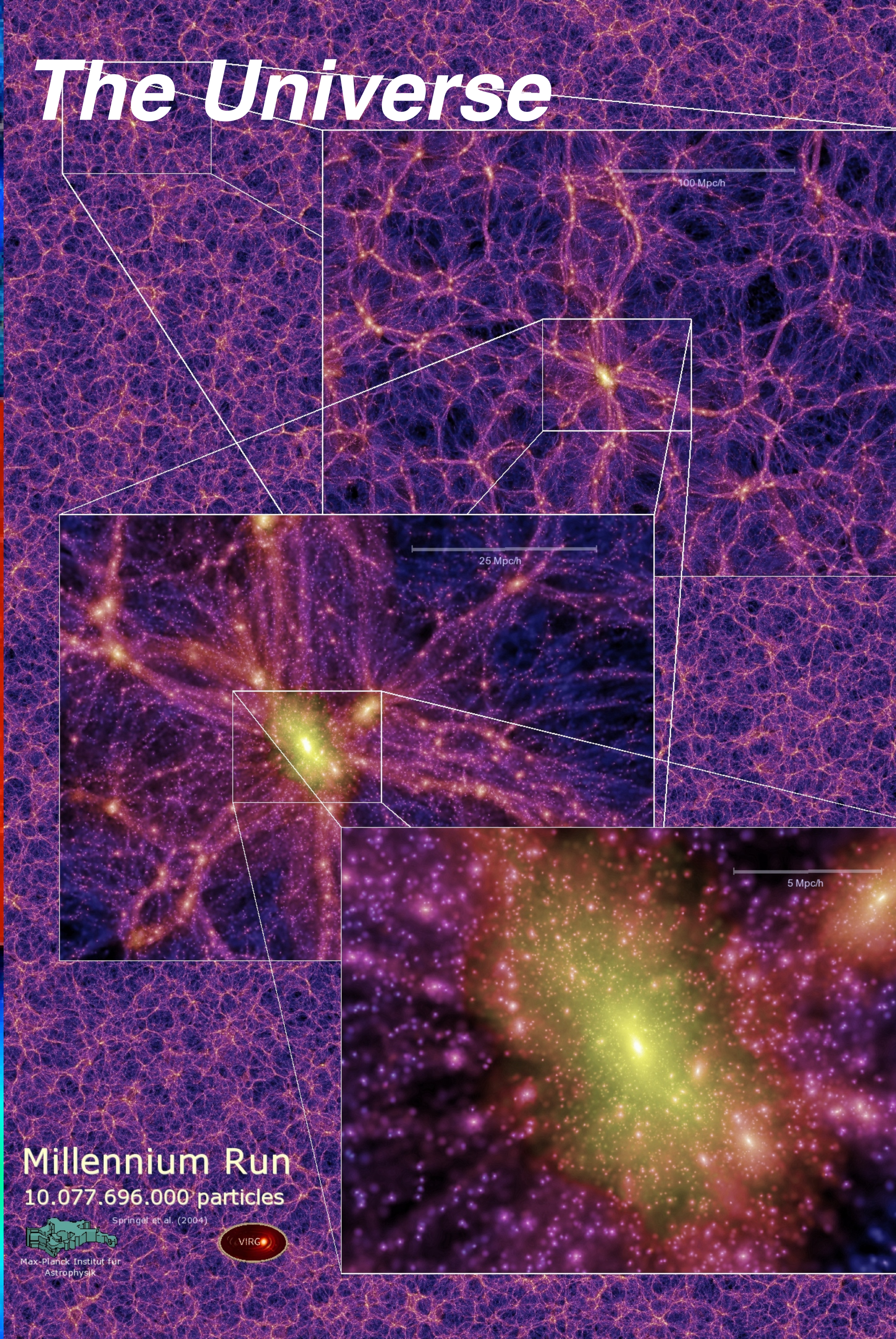
The Galaxy



Galactic substructure from Via Lactea II

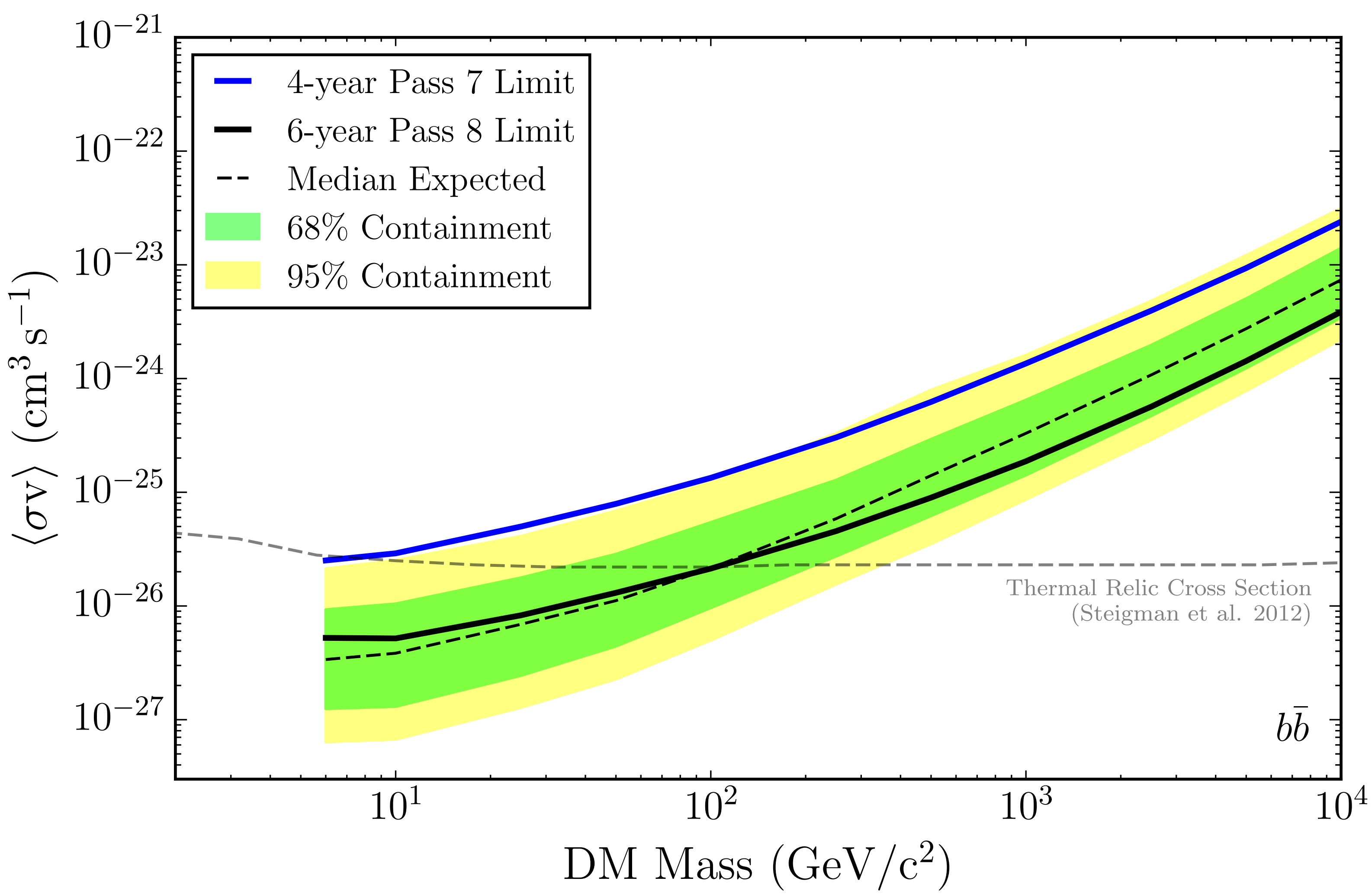
Diemand et al., *Nature* **454**, 735 (2008)

The Universe



Constraints from dwarf spheroidal galaxies

Fermi-LAT, arXiv:1503.02641 [astro-ph.HE]

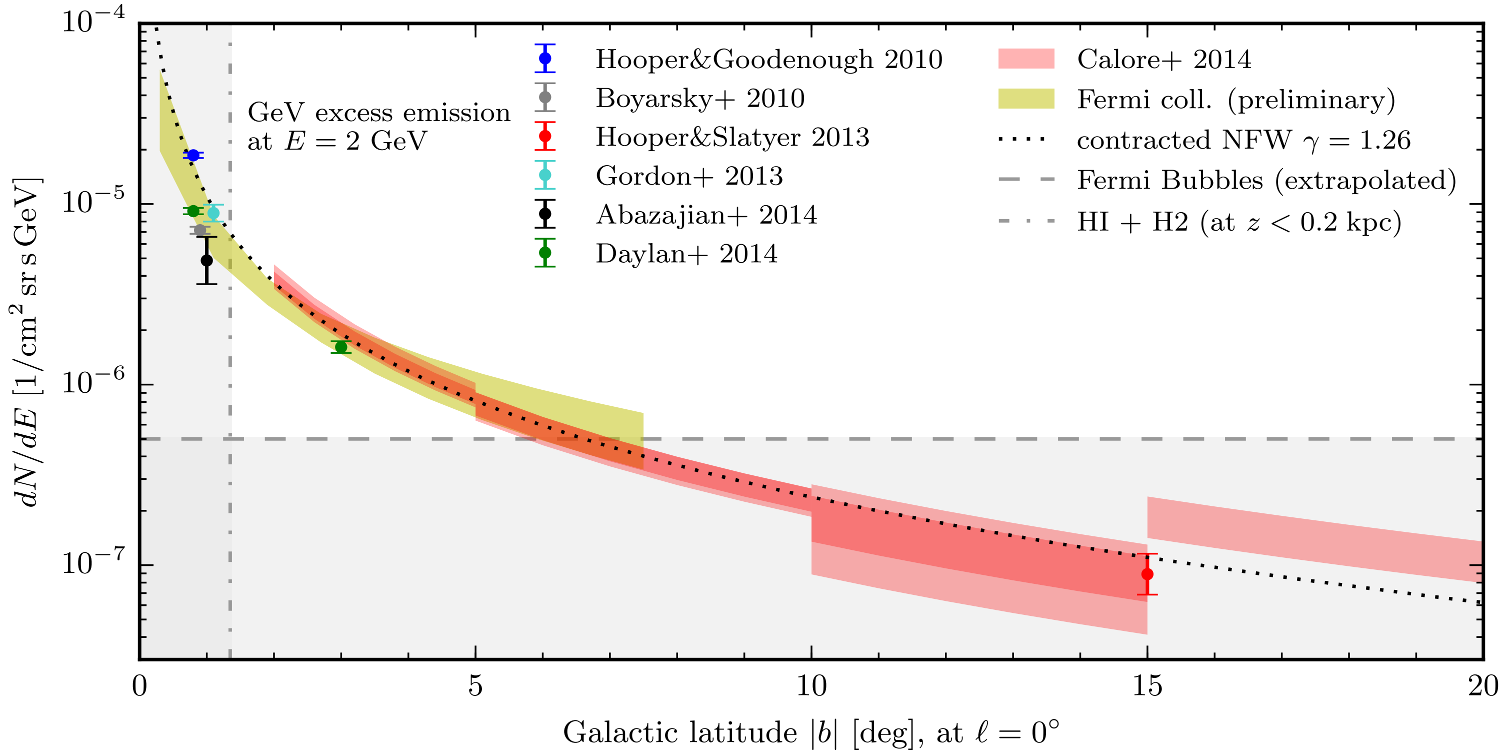


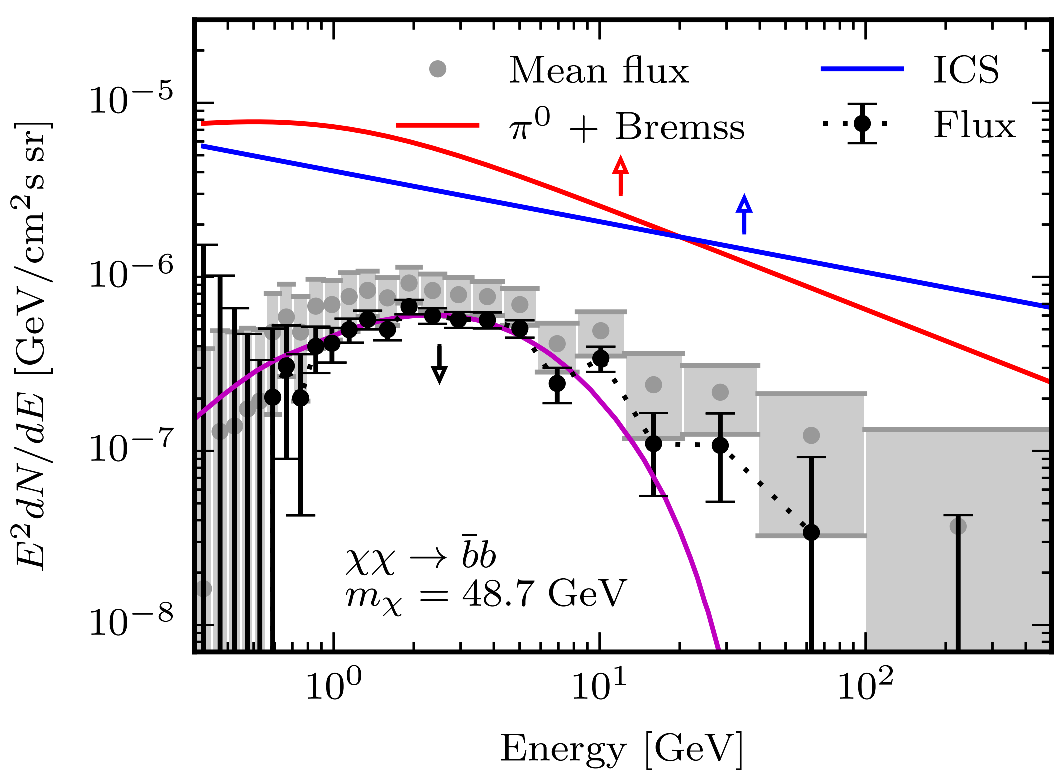
Bonnivard *(Mon)*
Bechtol *(Wed)*
Ichikawa *(Thu)*
Geringer-Sameth *(Thu)*

- Highly DM dominated system → suitable environment to test DM annihilation
  - Most robust constraints
- The latest results with PASS 8 data are pretty stringent
- They exclude the canonical cross section for WIMPs lighter than 100 GeV (15 dwarfs combined)

GeV excess: Signals of dark matter annihilation?

Calore et al., *Phys. Rev. D* **91**, 063003 (2015)

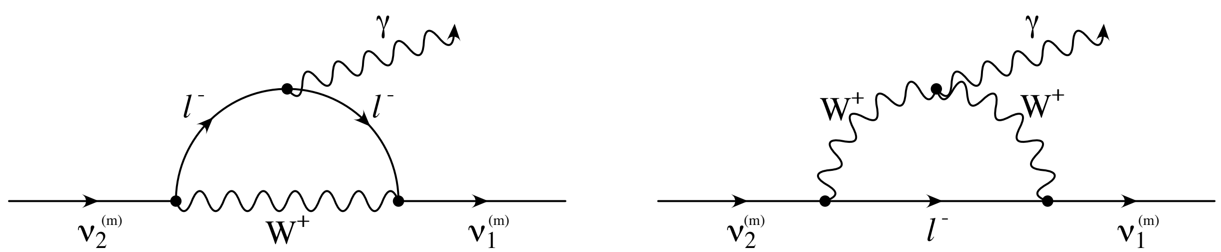


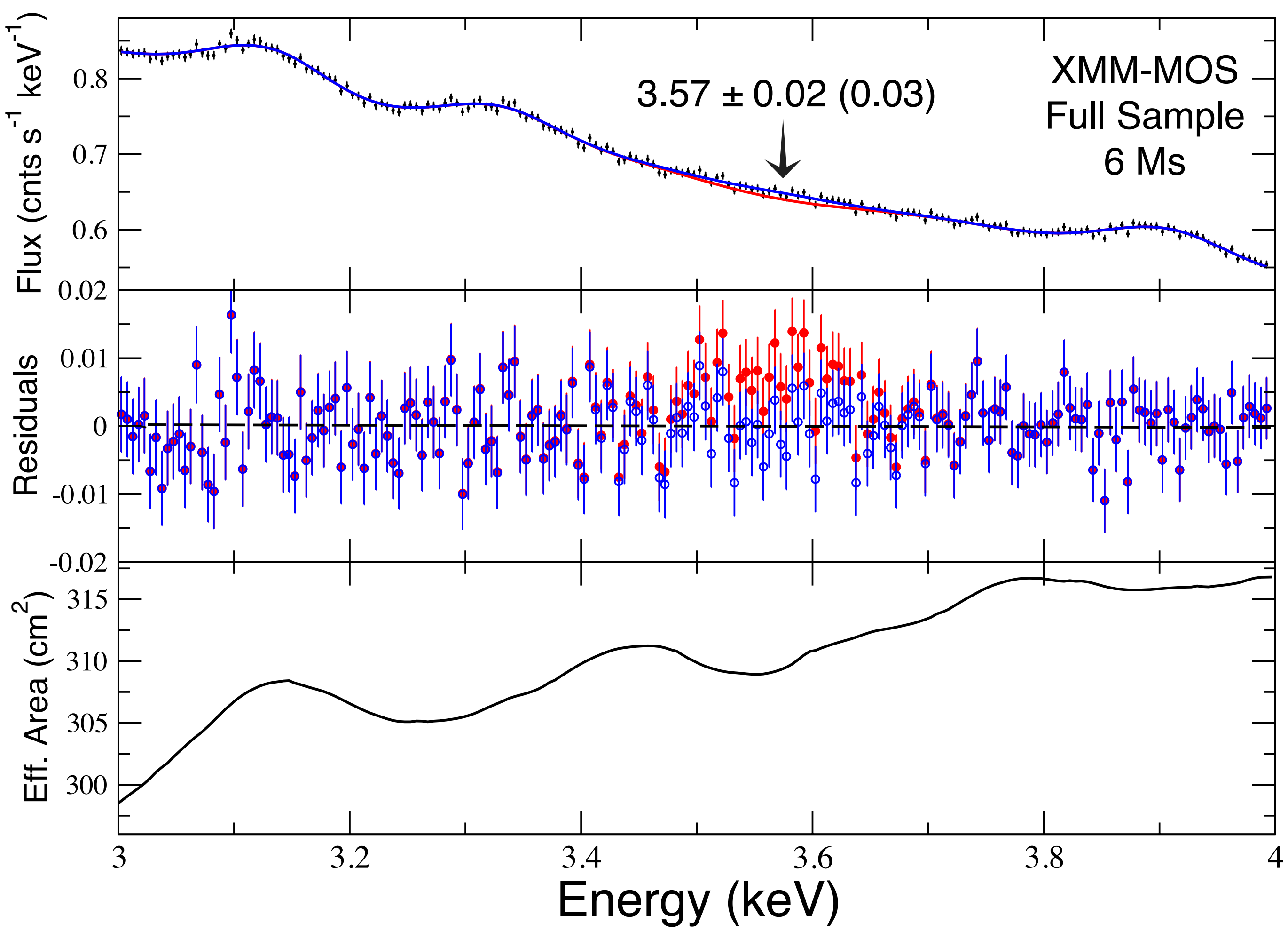


Seto *(Tue)*
Taoso *(Thu)*
Calore *(Thu)*

- Gamma-ray excess in GeV regime from the Galactic center (many sigma) of unknown origin
- Brightness profile is consistent with NFW^2 (with inner slope of 1.26)
- Spectral shape is also consistent with expectation from annihilation
- Inferred parameters
  - mass: ~50 GeV
  - cross section: ~2×10^{-26} cm^3 s^{-1}
- But recent analyses (Bartels et al. 2015; Lee et al. 2015) suggest astrophysical source origin (e.g., millisecond pulsars)

Decays of sterile neutrinos?: 3.5 keV line



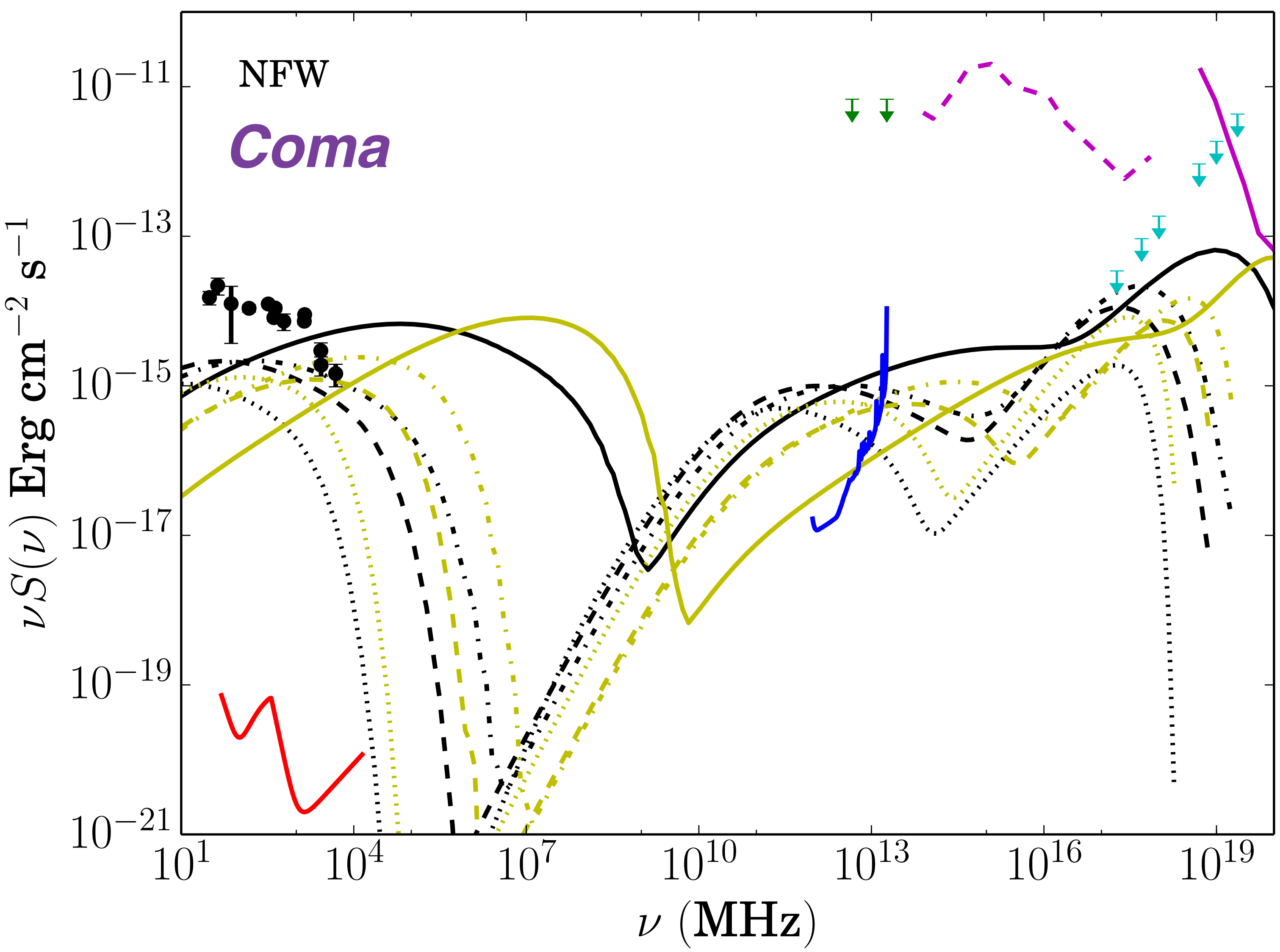


Bulbul et al., *Astrophys. J.* **789**, 13 (2014)

- 3.5 keV line found from galaxies and galaxy clusters (stacked or individual) (Bulbul et al. 2014; Boyarsky et al. 2014)
- Might be a signal of sterile neutrinos with mass of 7 keV
- Still lots of controversy (possibility of atomic line, consistency with different galaxies, instrumental systematics, etc.)

Zandanel *(Tue)*
Franse *(Wed)*

Multi-wavelength test of dark matter models

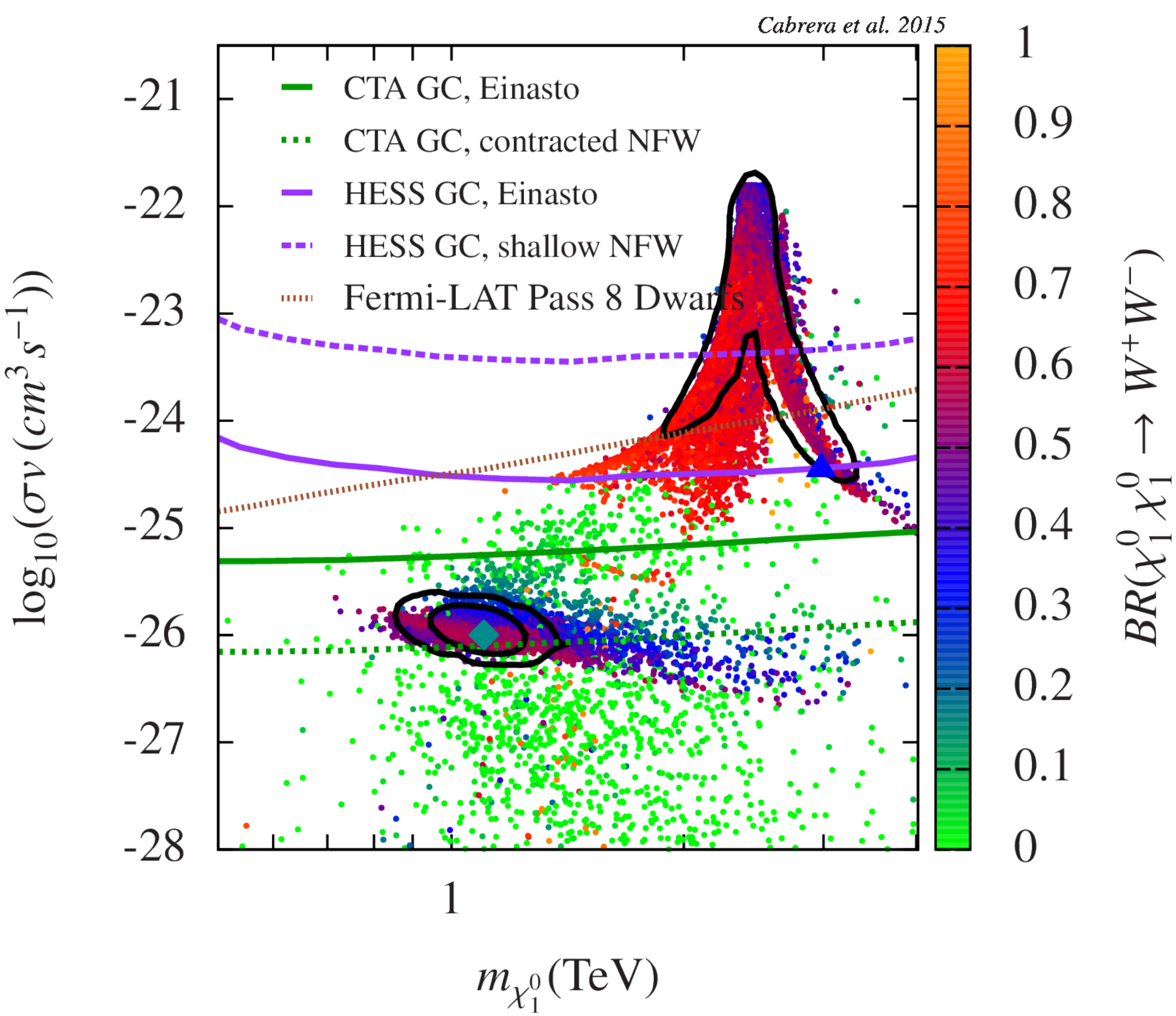


- Annihilation creates hadronic cascade
  - Synchrotron (radio) and inverse-Compton (X rays) emission from charged leptons
- Test of recent models to explain AMS-02 data, GeV excess, possible signal toward Reticulum 2 dwarf galaxy

Beck, Colafrancesco, arXiv:1508.01386 [astro-ph.CO]

Thusday:
Colafrancesco

Prospects for TeV gammas: Heavy dark matter



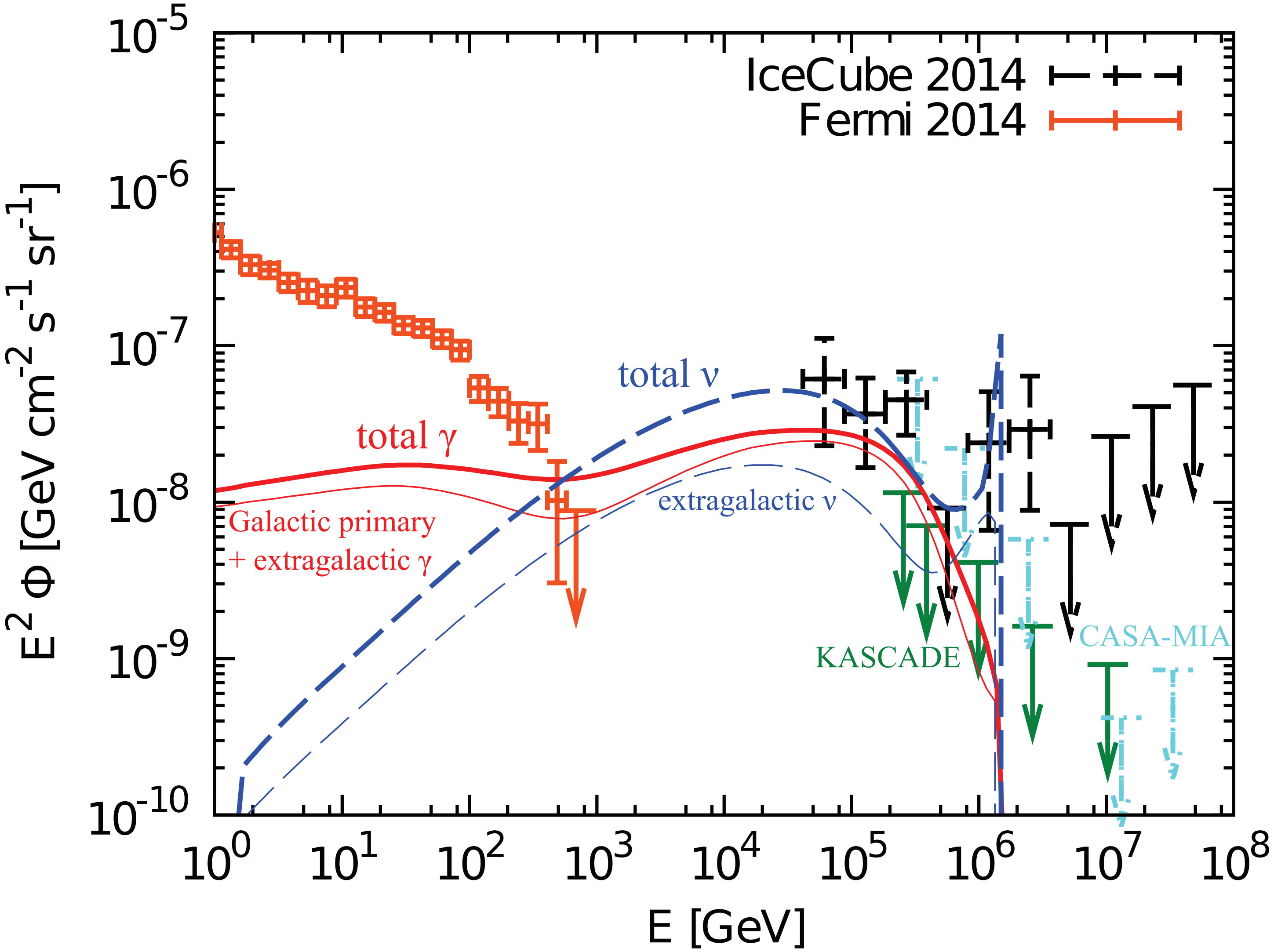
- No signal at LHC and measurements on Higgs mass (126 GeV) started to constrain MSSM models
- Current data imply TeV dark matter as “most probable region” (e.g., 9-parameter MSSM)
- Test with very-high-energy gamma-ray telescopes: CTA, HAWC, etc.

MSSM-9: $M_1, M_2, M_3, m_0^{\tilde{q}}, m_0^{\tilde{l}}, m_H, A_0^{\tilde{q}}, A_0^{\tilde{l}}, \tan\beta$

Cabrera, Ando, Weniger, Zandanel, *Phys. Rev. D* **92**, 035018 (2015)

Thusday:
Kelly-Hoskins
Giammaria
Harding
Gaskins
Garcia Cely

Multi-wavelength test of dark matter models Case of IceCube neutrinos

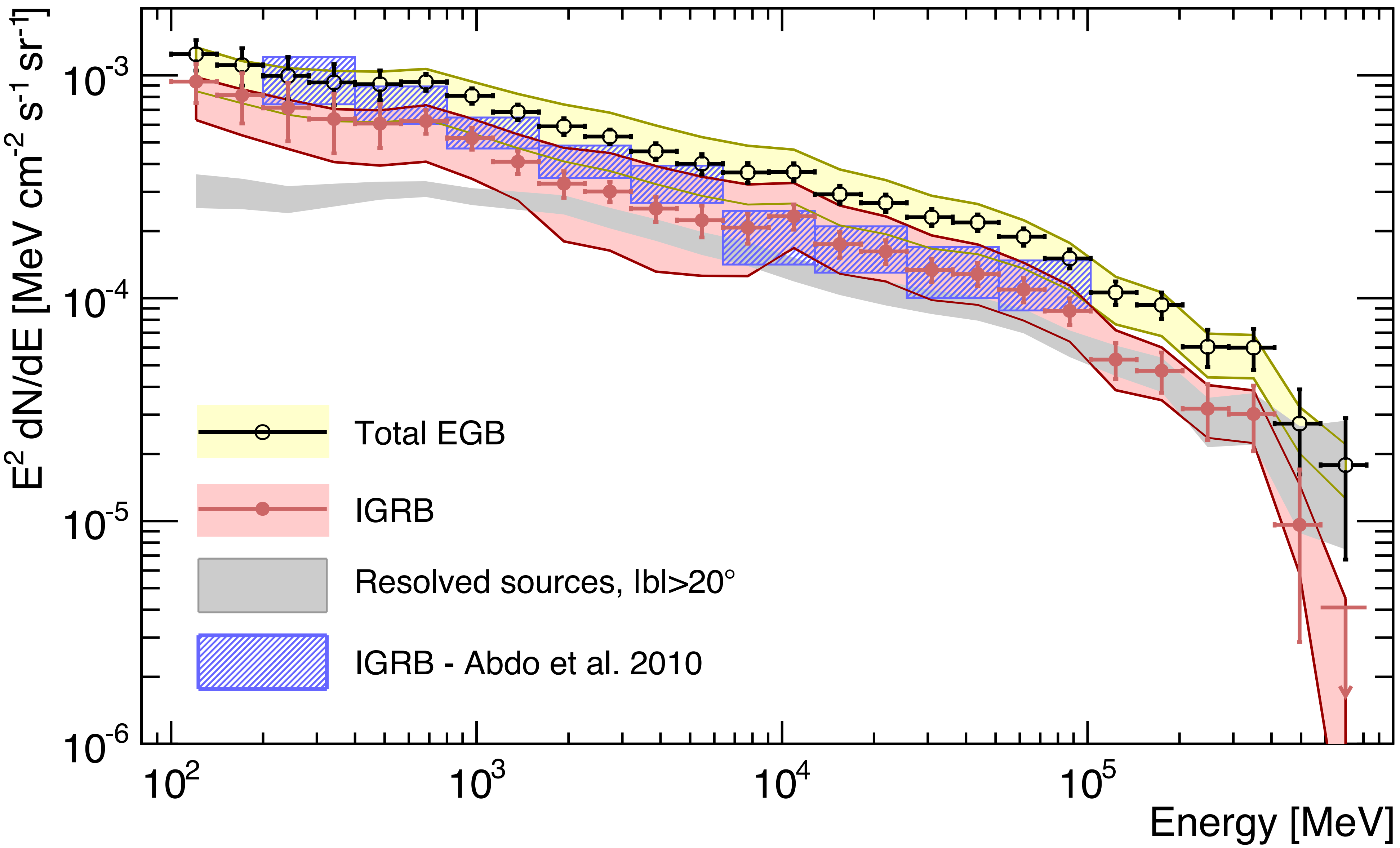


Murase, Laha, Ando, Ahlers, *Phys. Rev. Lett.* **115**, 071301 (2015)

Chianese *(Wed)*
Lin *(Wed)*
Liu *(Thu)*

- High-energy neutrinos might be signals of heavy dark matter decay (e.g., Feldstein et al. 2013; Esmaili & Serpico 2013)
- Hadronic cascades will be produced from the same decay, which produce GeV gamma-ray photons
- This model can be tested with data of the diffuse gamma-ray background measured with Fermi

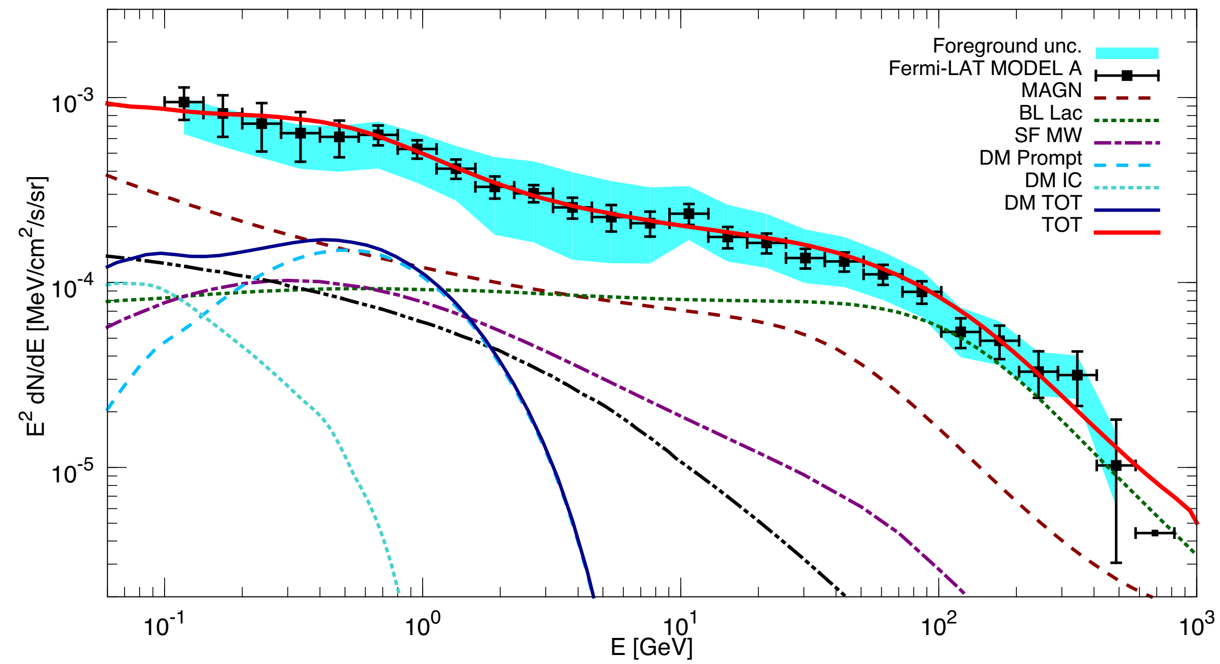
“Isotropic” gamma-ray background (IGRB)

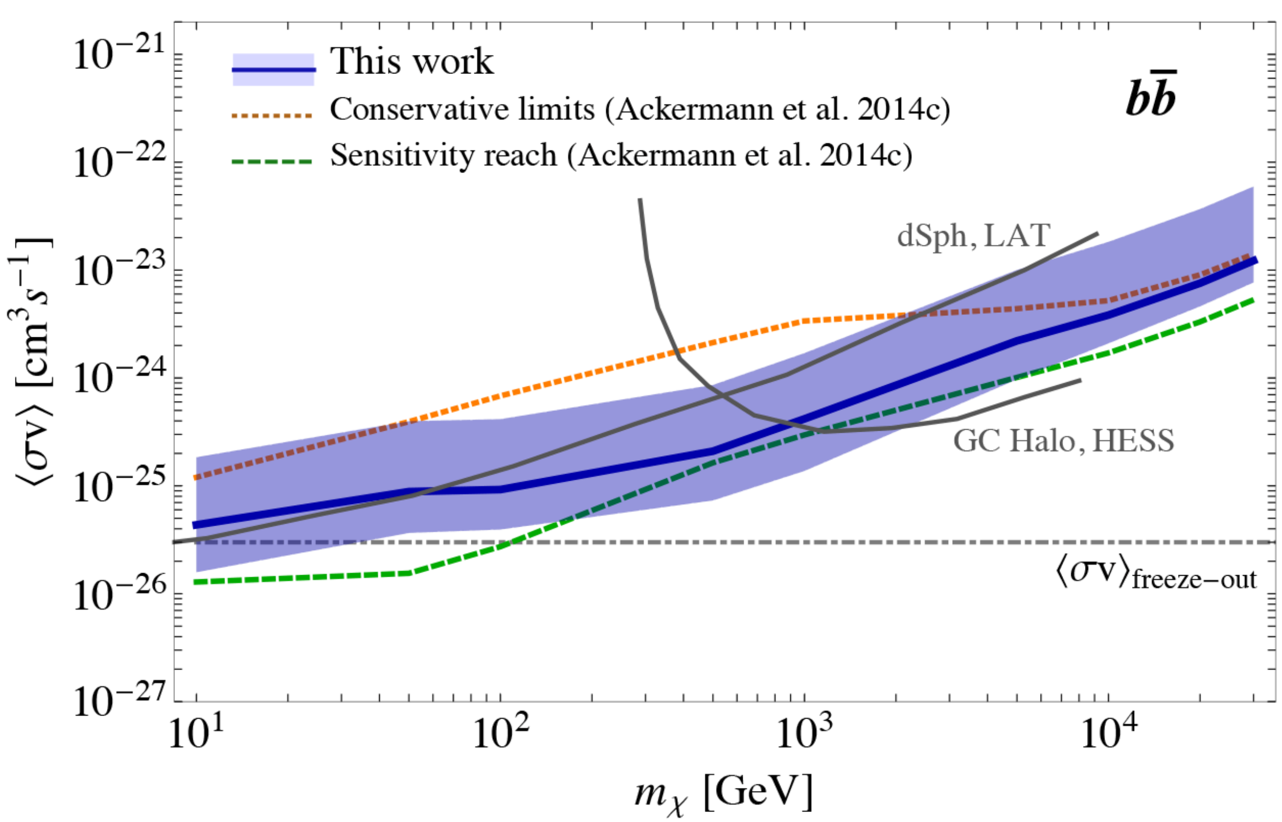


Fermi-LAT, *Astrophys. J.* **799**, 86 (2015)

Constraints from the gamma-ray background spectrum

Di Mauro, Donato, *Phys.Rev. D* **91**, 123001 (2015)





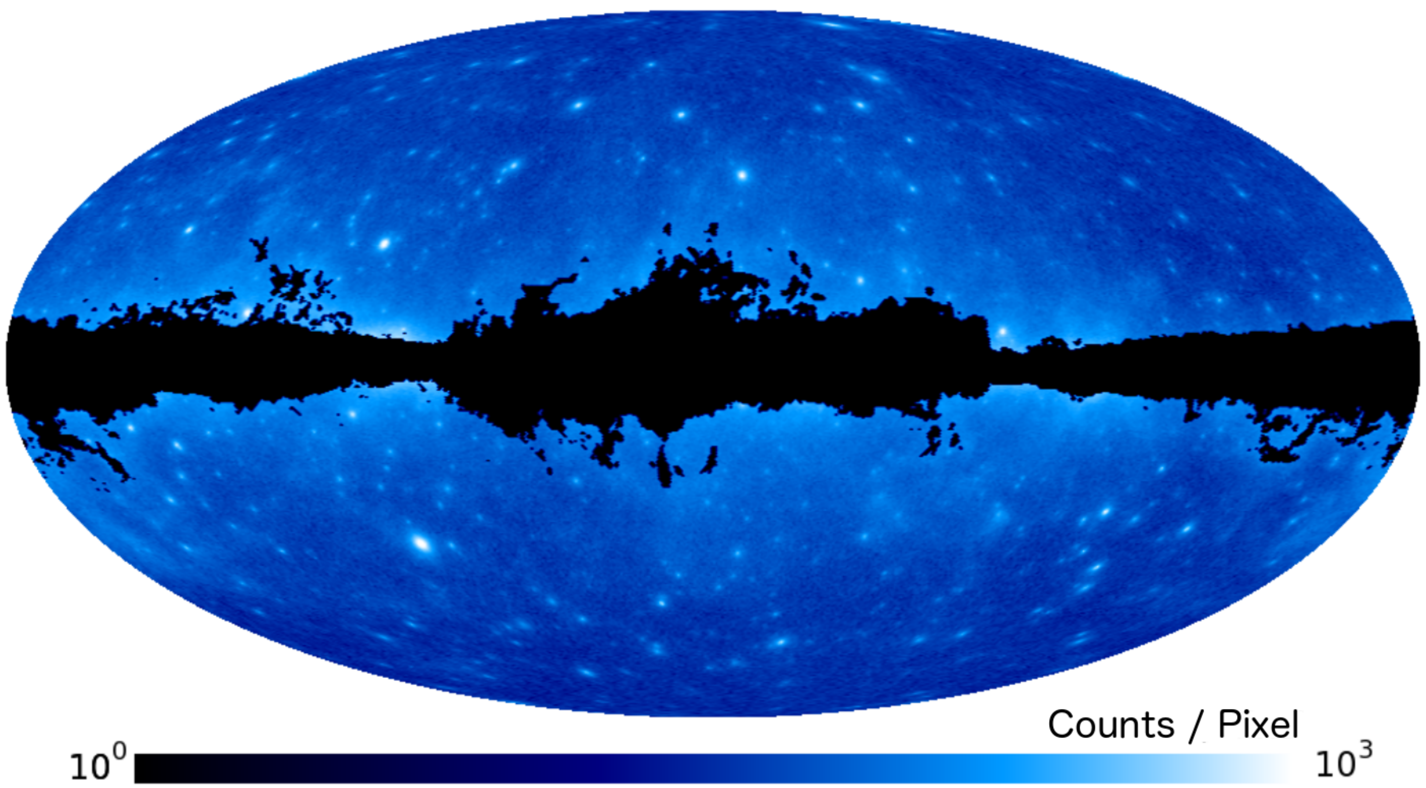
Ajello et al., *Astrophys. J.* **800**, L27 (2015)

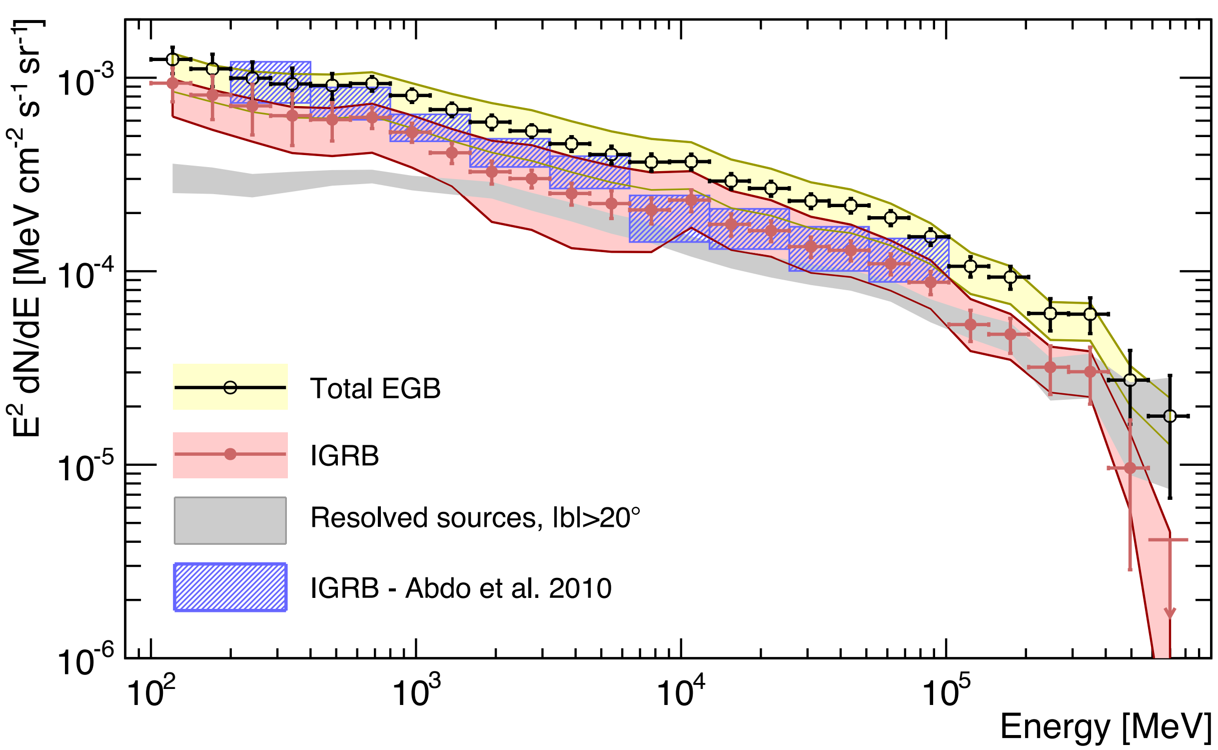
- **Annihilation**
  - Stringent constraints although with relatively large uncertainty (PASS 7)
- **Decay**
  - Stringent constraints (better than dwarf galaxies and galaxy clusters)
- Interesting implications for phenomenological models that address positron excess found with PAMELA and AMS-02

Di Mauro *(Mon)*

Anisotropy of the gamma-ray background

Fermi-LAT, Astrophys. J. **799**, 86 (2015)



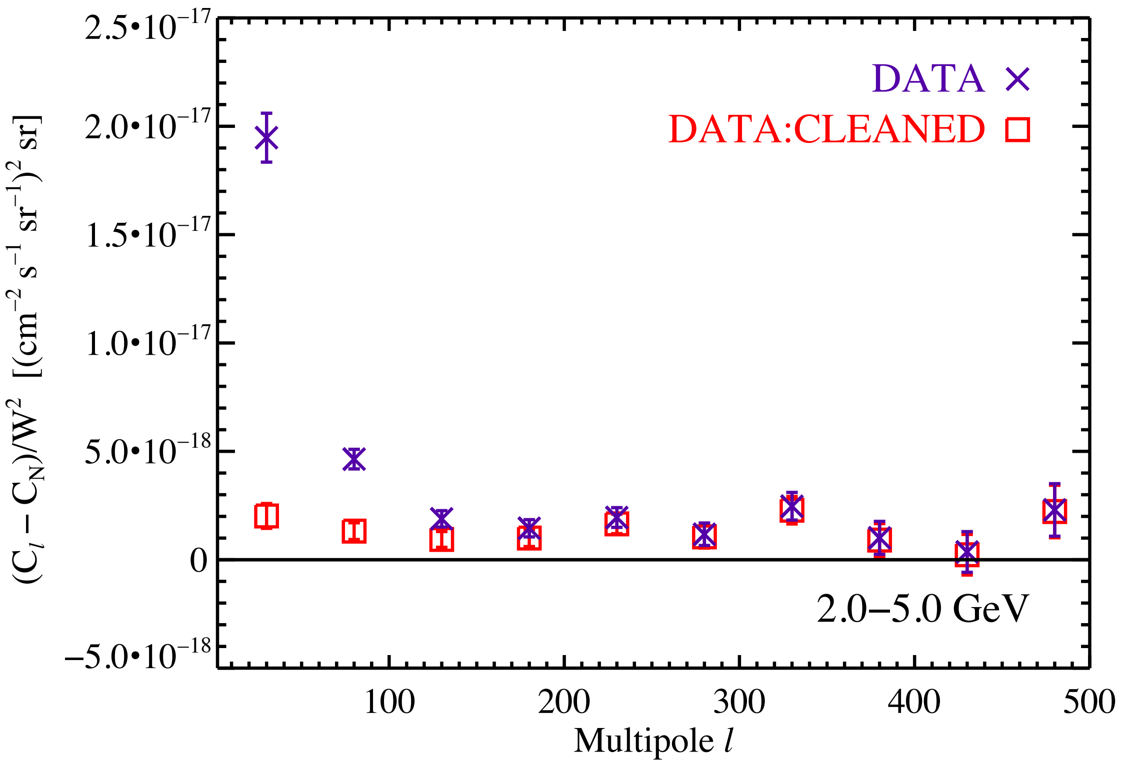


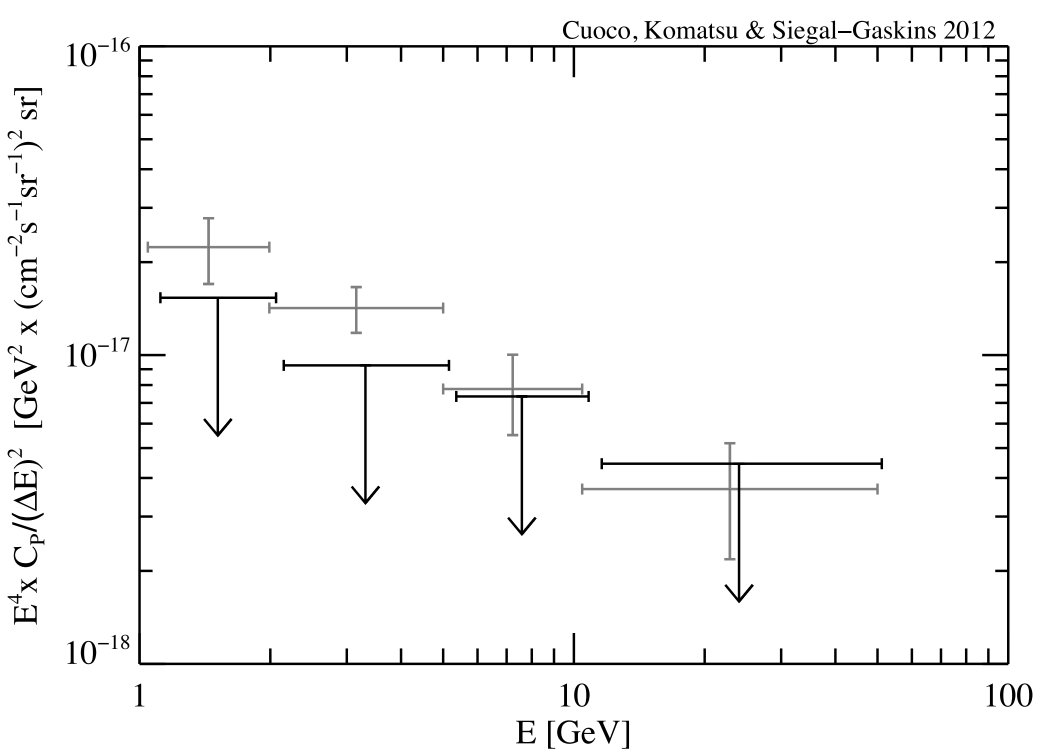
- Number of gamma-ray photons (> 1 GeV) that Fermi collected so far: **> 5,000,000**
- Number of data of the gamma-ray background spectrum: **26**
- Loss of a lot of information → What else can one do?
  - **Anisotropy!**

What can we learn from the gamma-ray background?

- **Energy**
  - Intensity spectrum (Bergstrom et al. 1998)
- **Spatial clustering of sources**
  - Angular power spectrum (Ando & Komatsu 2006)
- **Redshift distribution of sources**
  - Cross correlation with dark matter tracers (Cosmic shear: Camera et al. 2013; Galaxy catalogs: Ando et al. 2014)
- **Luminosity distribution of sources**
  - 1-point PDF of the gamma-ray flux (Lee et al. 2009)

Angular power spectrum: Observations with Fermi



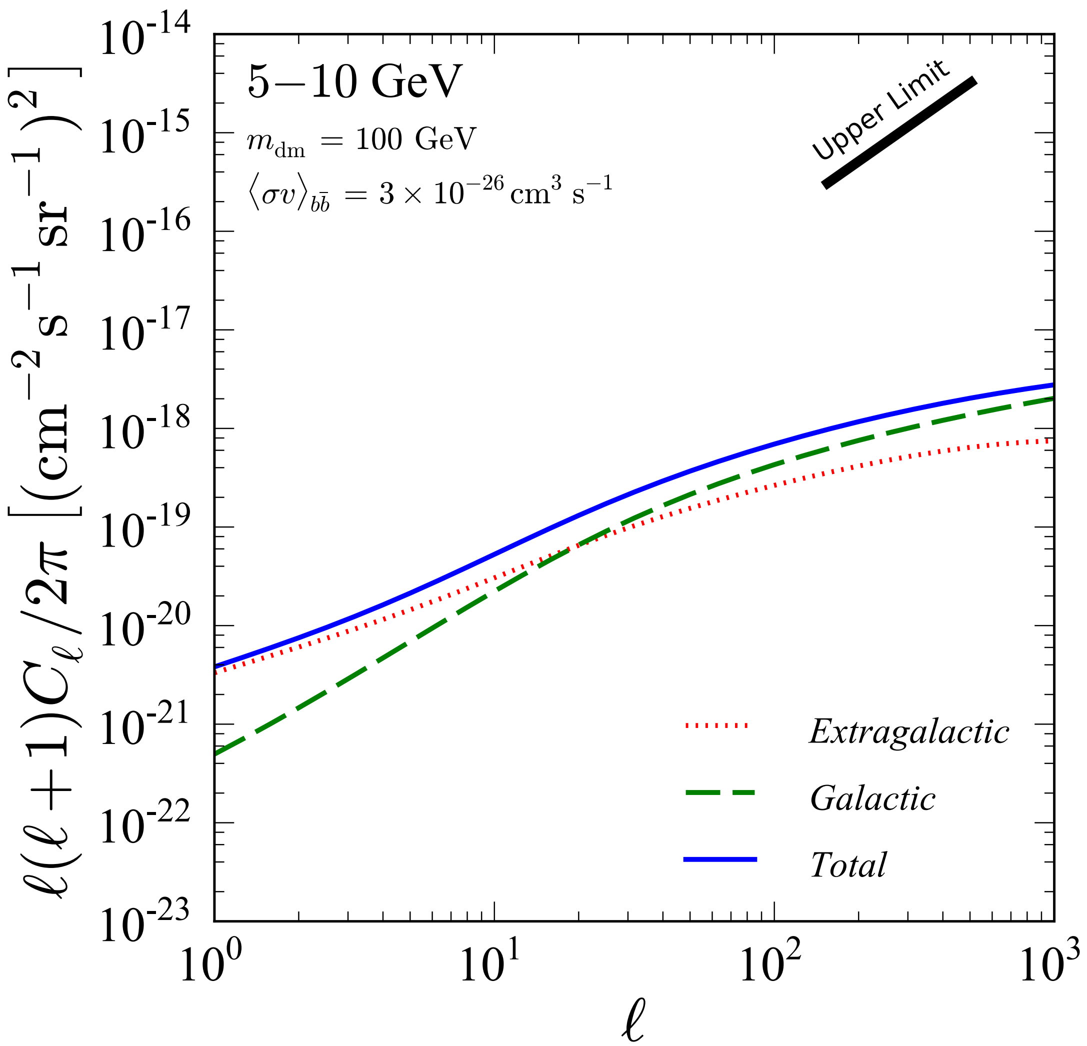


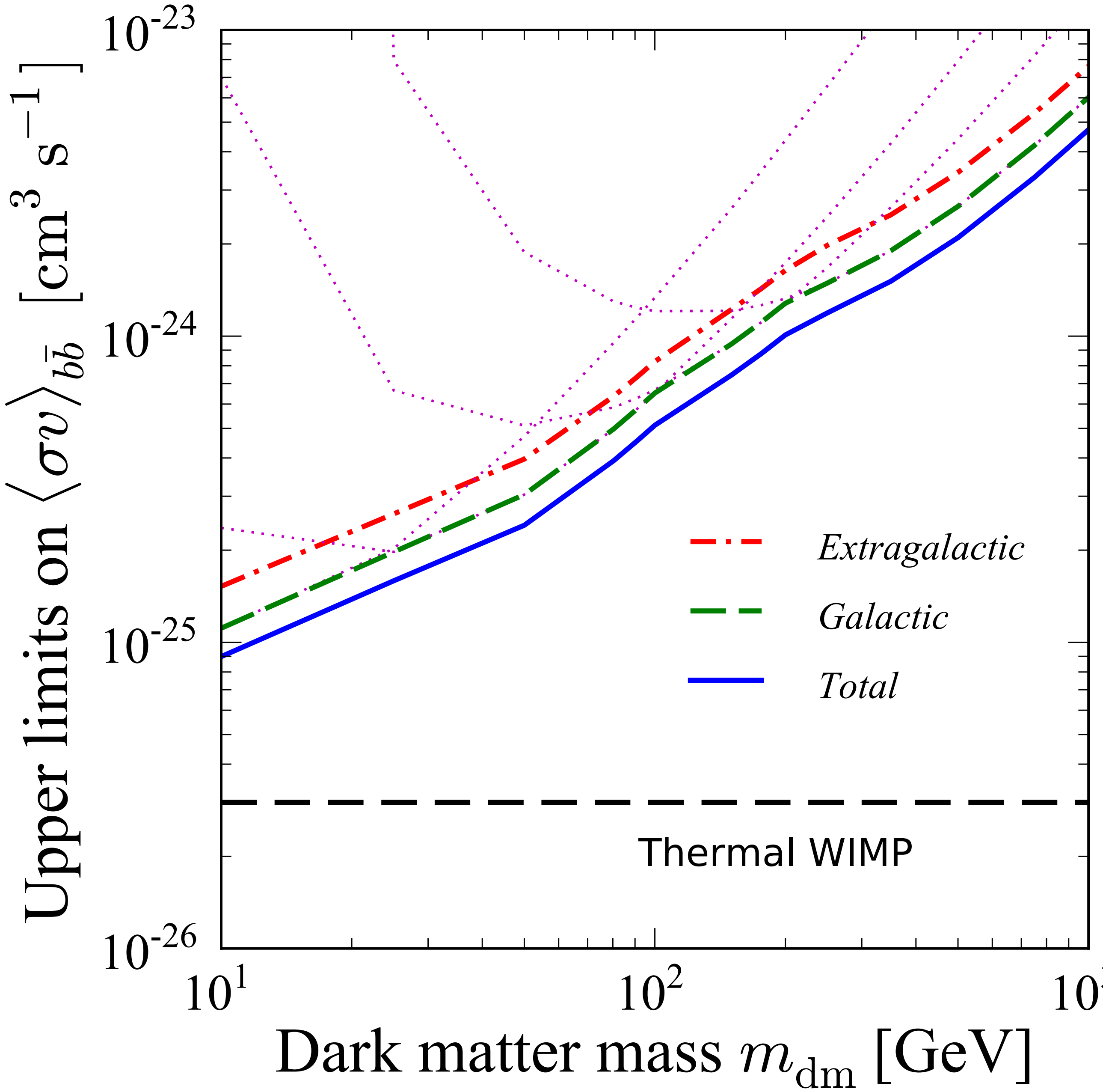
- Analysis of Fermi data for the angular power spectrum of the diffuse gamma-ray background in 2012 → **Discovery of anisotropies**
- Almost constant excess compared with shot noise of the photons at 100 < *l* < 500
- Data are well consistent with astrophysical expectations (blazars; Ando et al. 2007)
- Upper limits on any other components (astrophysics or dark matter)

Fornasa *(Mon)*

Fermi-LAT, *Phys. Rev. D* **85**, 083007 (2012)
Cuoco et al., *Phys. Rev. D* **86**, 063004 (2012)

Upper limits on the annihilation cross section





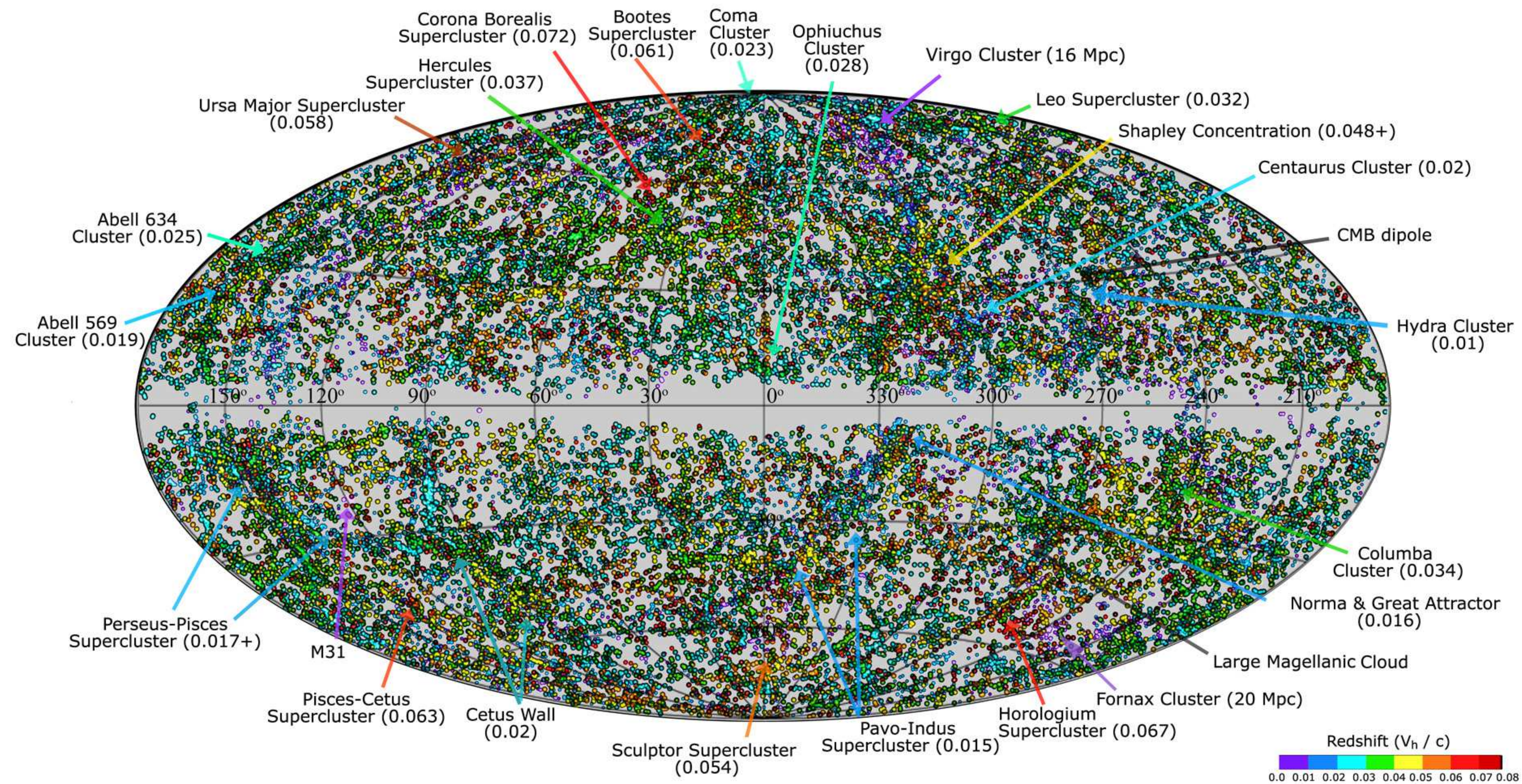
- The current upper limits are still larger than theoretical predictions by more than two orders of magnitude

- Limits on annihilation cross section are still larger by more than a factor of 3, compared with the canonical cross section.

Ando, Komatsu, *Phys. Rev. D* **87**, 123539 (2013)

Gomez-Vargaz et al. *Nucl. Instrum. Meth.* **A742**, 149 (2014)

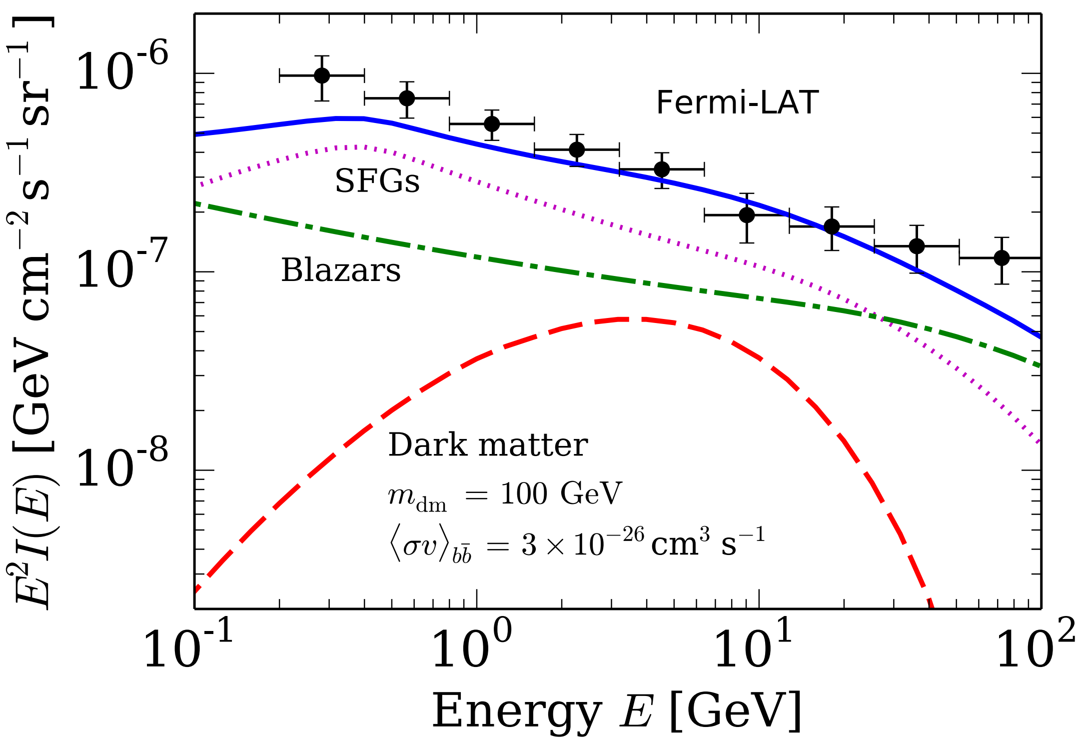
Cross correlation with galaxy catalogs

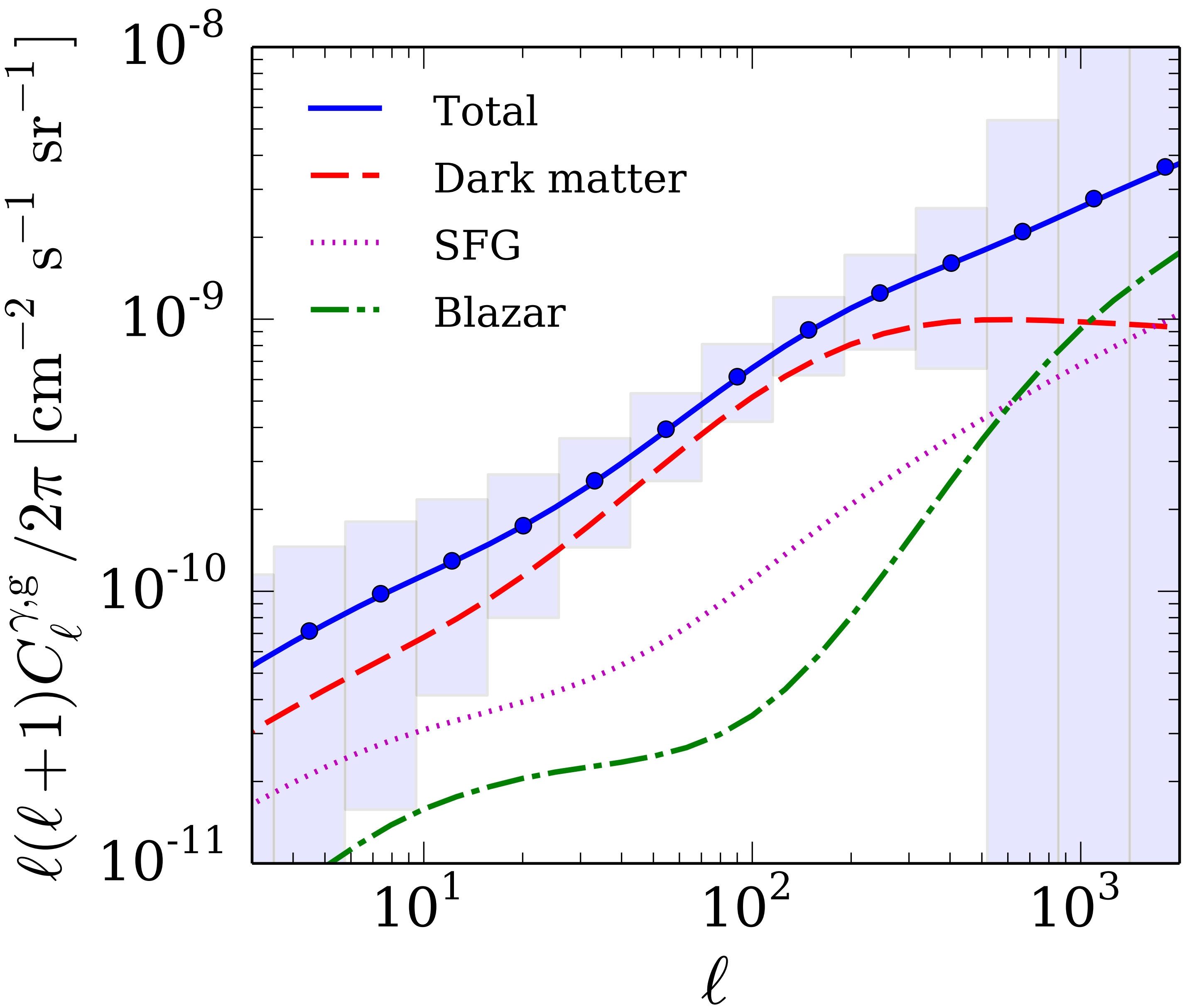


Huchra et al., *Astrophys. J. Suppl. Ser.* **199**, 26 (2011)

2MASS Redshift Survey; ***43000 galaxies up to z ~ 0.1***

2MRS-γ correlation



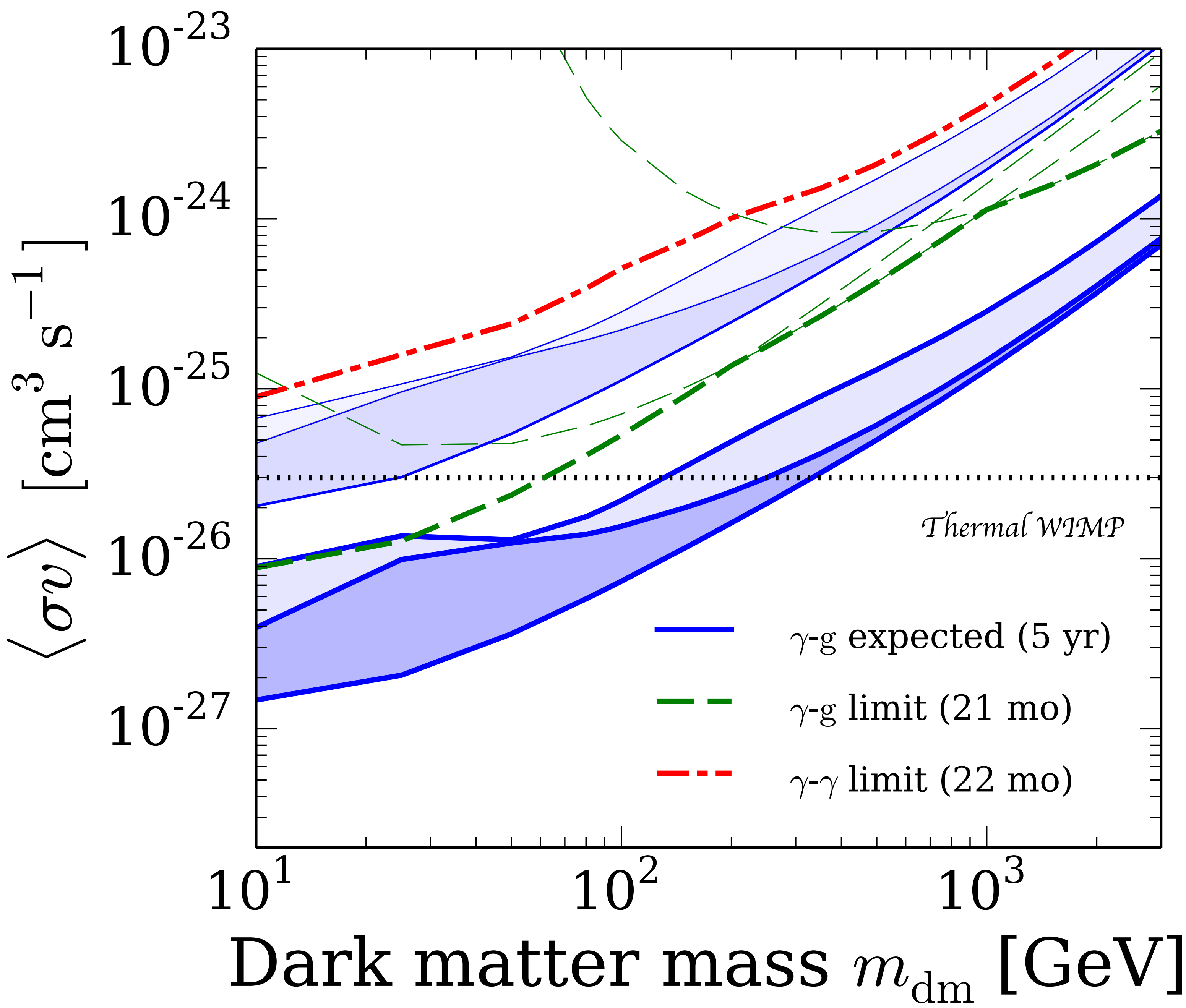


- **DM annihilation** shows **the largest correlation** with 2MRS galaxies
- **Great way of suppressing astrophysical "background"**
- Sensitivity is very good in order to exclude canonical cross section for thermal freeze-out mechanism

Ando, Benoit-Lévy, Komatsu, *Phys. Rev. D* **90**, 023514 (2014)

Fornengo, Regis, *Front. Phys.* **2**, 6 (2014)

Cross correlation: 5-year sensitivity

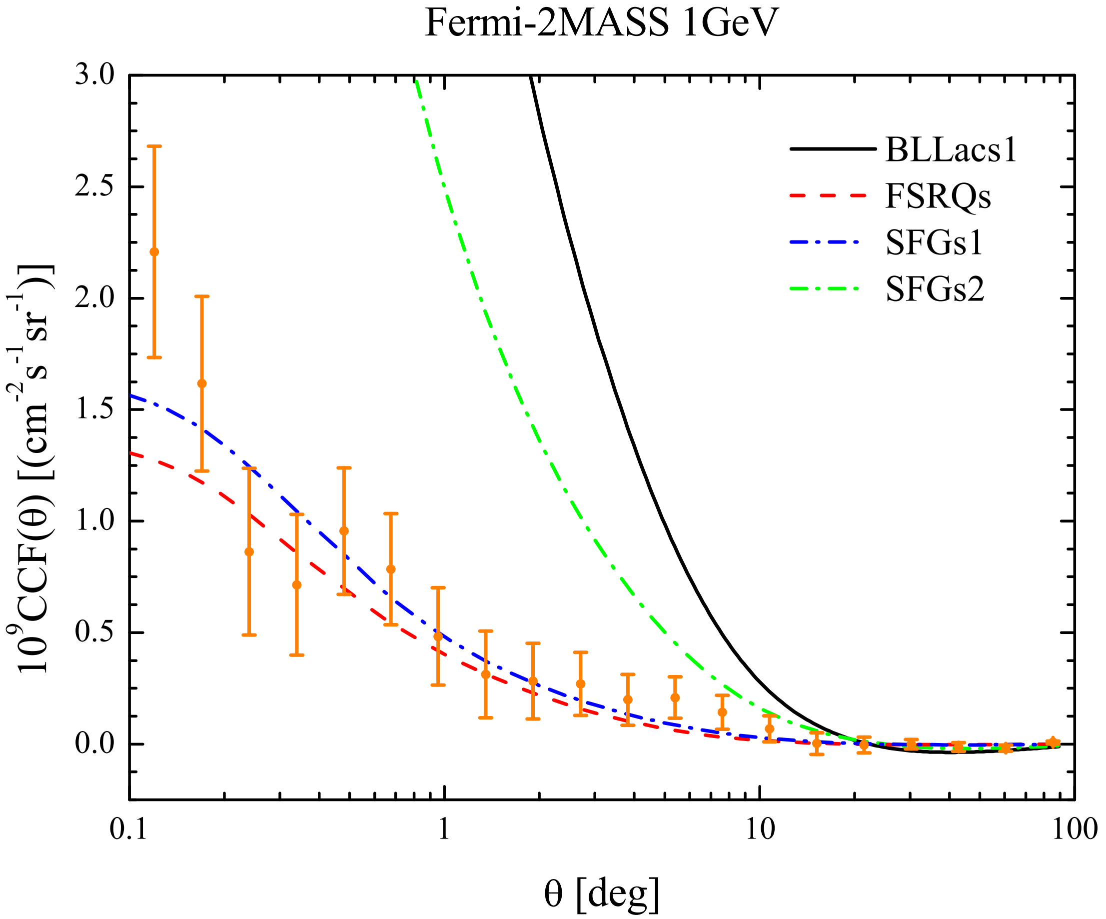


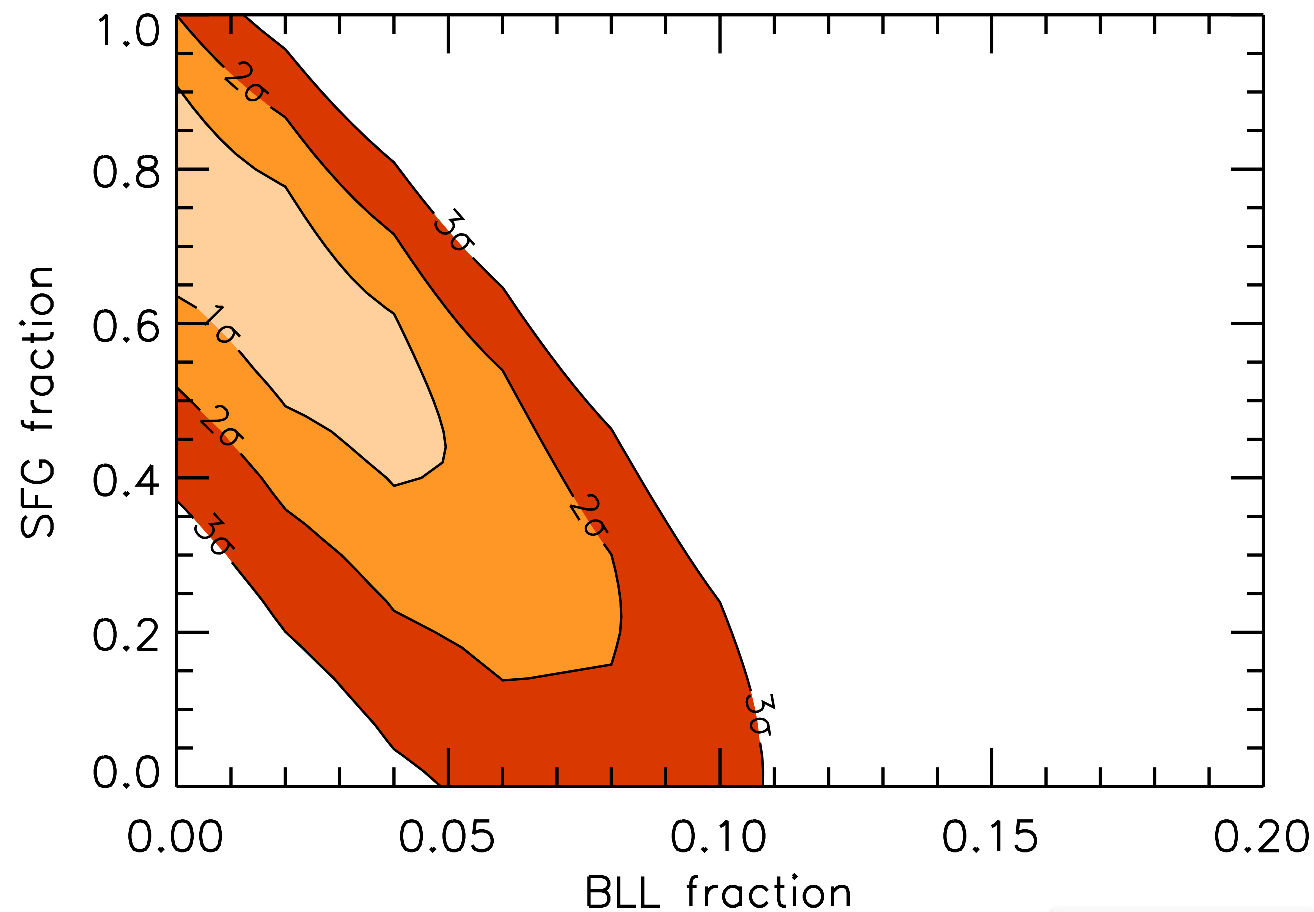
- Very powerful probe of DM
- Uncertainty regarding substructure boost is about one order of magnitude (Sanchez-Conde & Prada 2014 vs Gao et al. 2012)

Ando, Benoit-Lévy, Komatsu, *Phys. Rev. D* **90**, 023514 (2014)

Observations: Cross correlation with 2MASS galaxies

Xia et al., *Astrophys. J. Suppl. Ser.* **217**, 15 (2015)





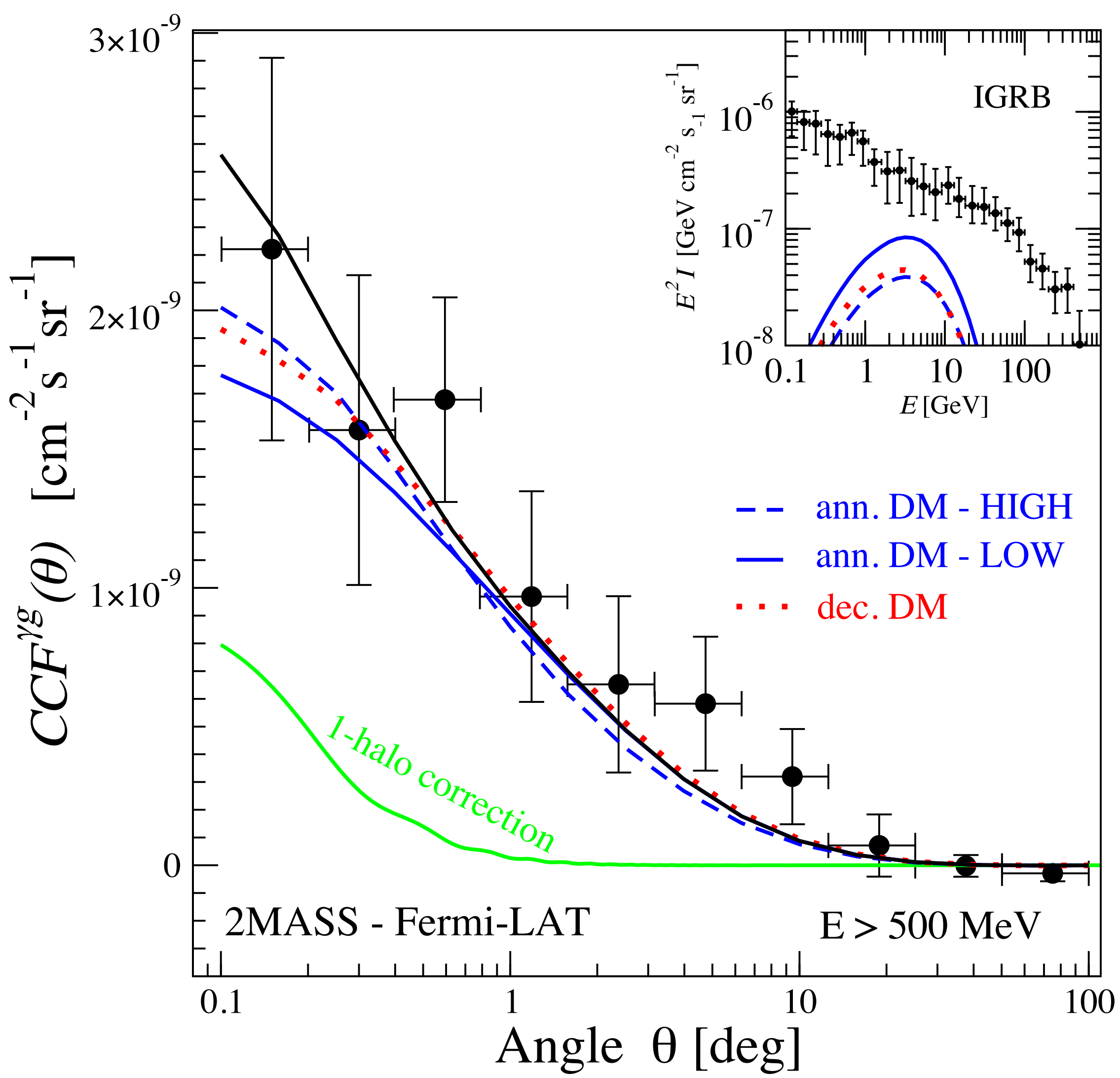
Xia *(Mon)*

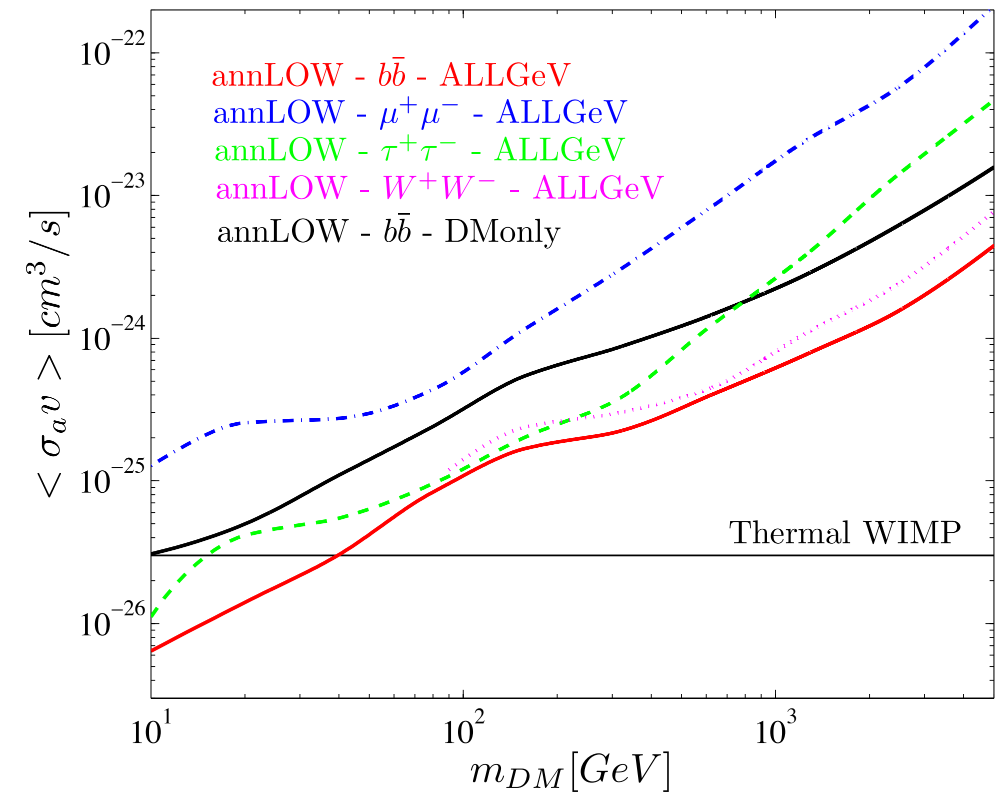
- Positive correlations with several catalogs (>3.5σ for 2MASS, NVSS, SDSS-QSO; >3σ for SDSS galaxies)
- Constraints on astrophysical components to the diffuse background (70% star-forming galaxies; blazars are subdominant)
- Implications for *pp* sources of IceCube neutrinos (Ando, Tamborra, Zandanel, to appear on arXiv today)

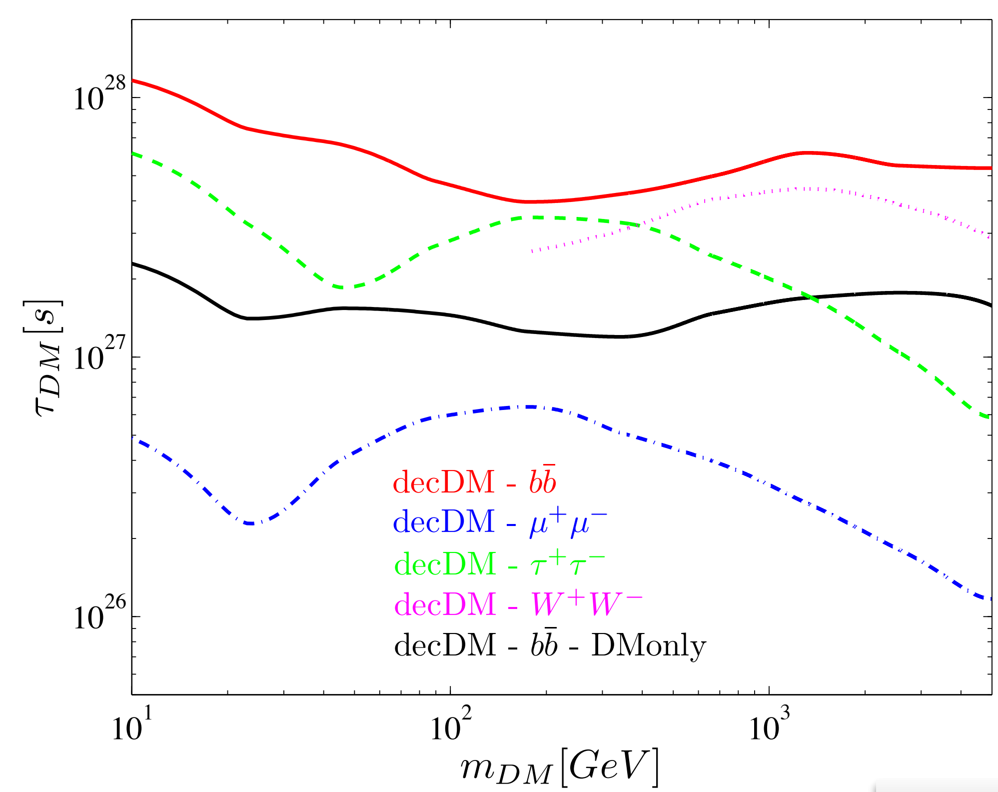
Cross correlation with 2MASS: DM constraints

Regis et al., *Phys. Rev. Lett.* **113**, 241301 (2015)

Cuoco et al., arXiv:1506.01030 [astro-ph.HE]







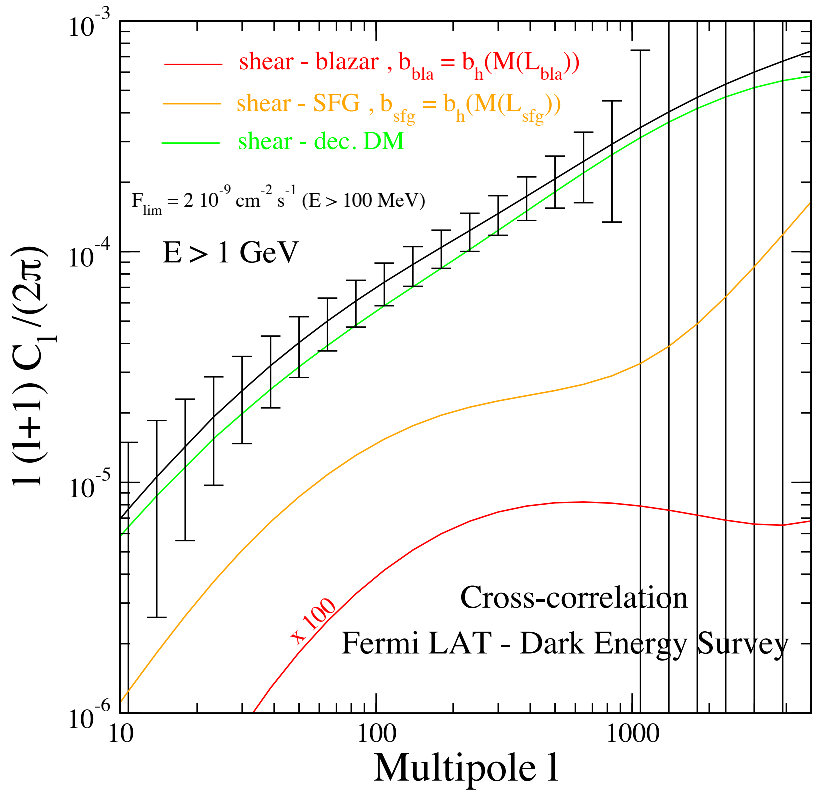
- Very competitive bounds even in the DM only case

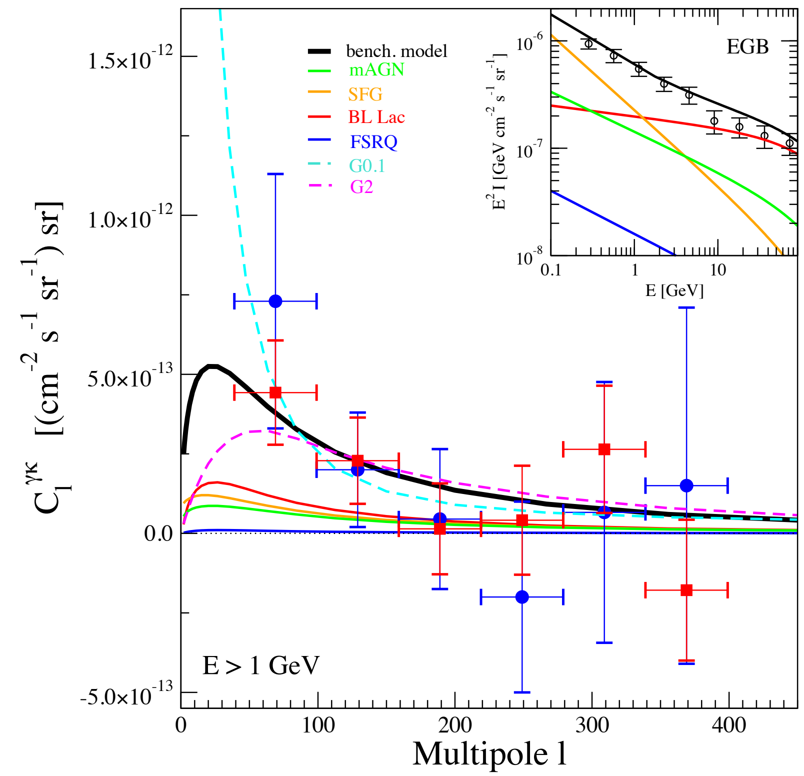
Cuoco *(Tue)*

Cross-correlation analyses: Lensing

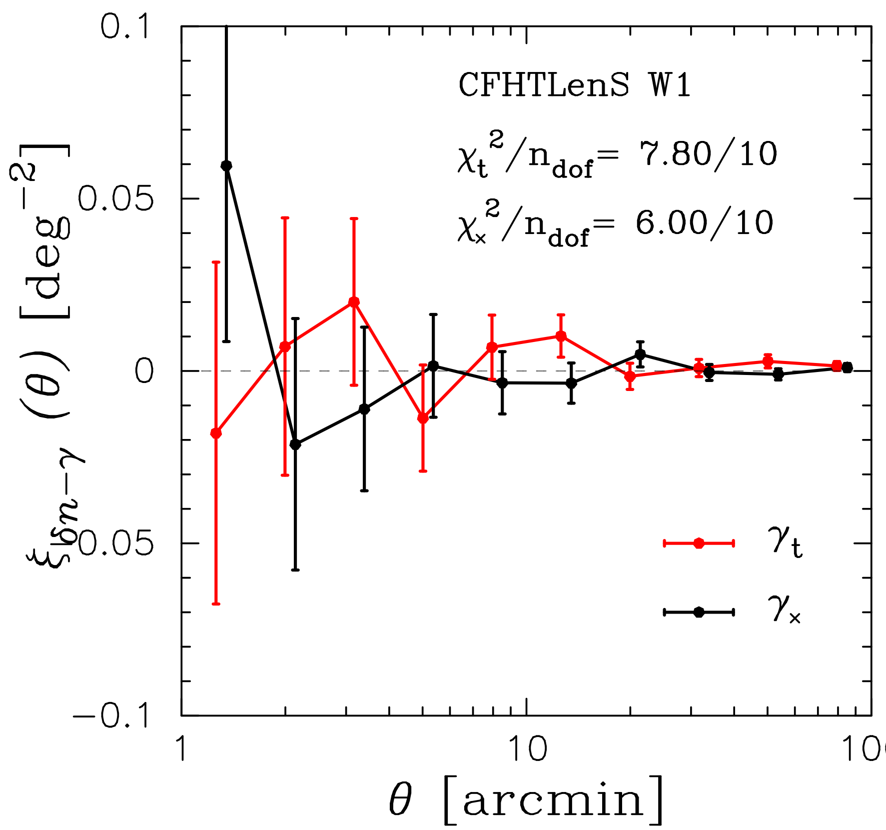
Planck
(CMB lensing)

Camera et al., *Astrophys. J.* **771**, L5 (2015)





Shirasaki et al., *Phys. Rev. D* **90**, 063502 (2014)



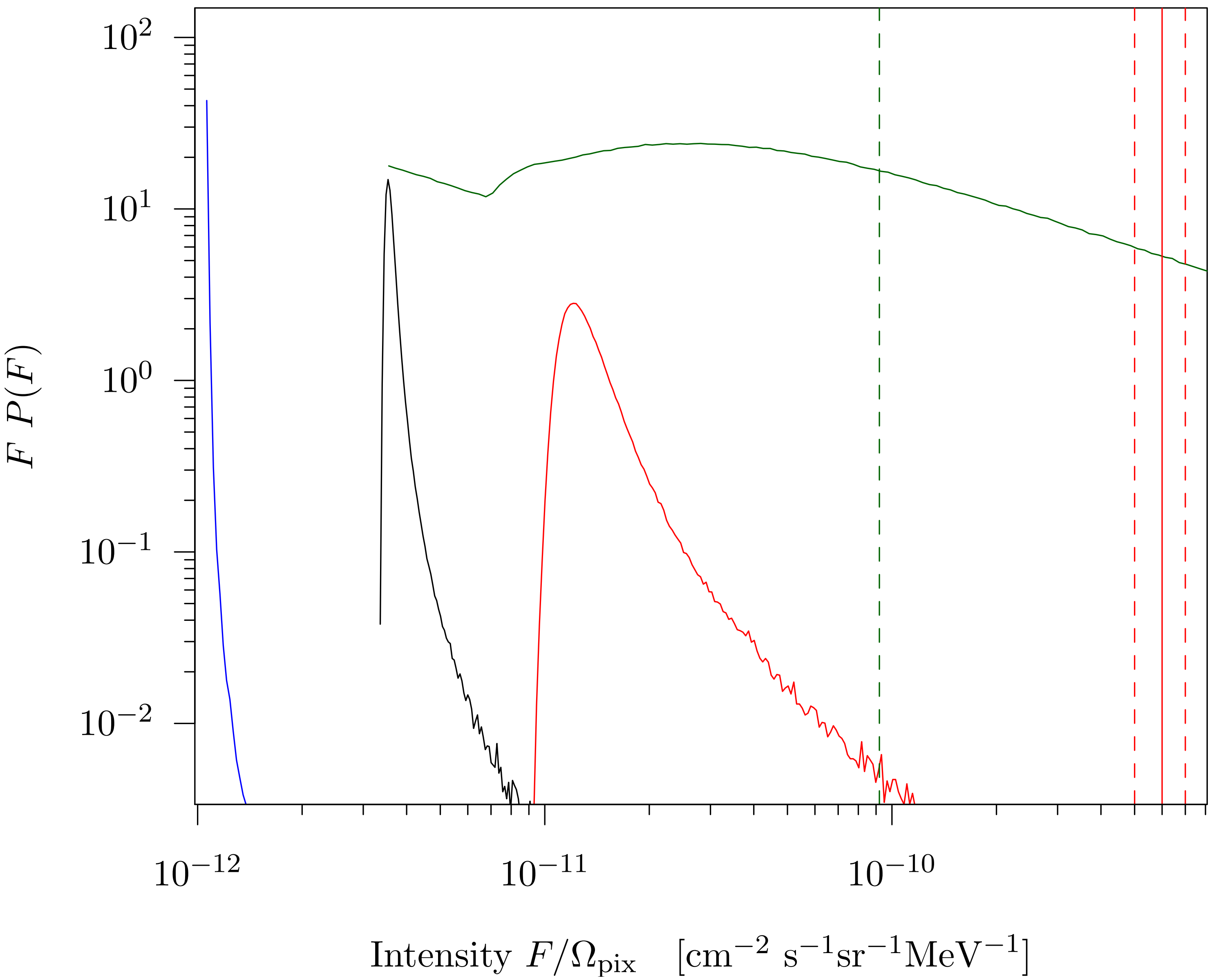
Fornengo et al., *Astrophys. J.* **802**, L1 (2015)

Theory (DES)

CFHTLenS

Camera *(Mon)*

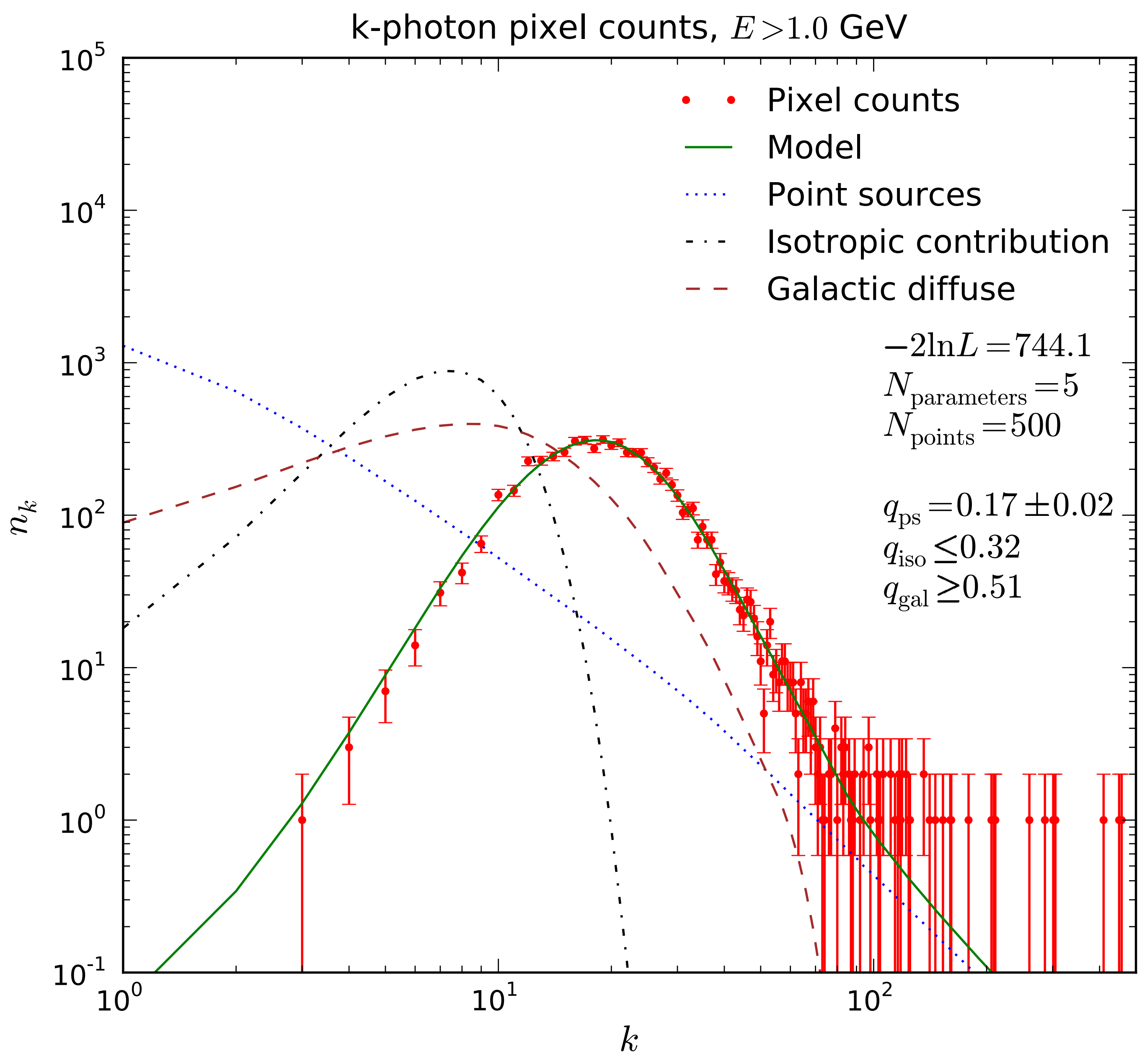
Flux PDF: Probe of luminosity distribution



Feyereisen, Ando, Lee, arXiv:1506.05118 [astro-ph.CO]

- Probability distribution function (PDF) of gamma-ray flux is a probe of luminosity function
- If the source is truly diffuse, then it is a delta function
- PDF for most astrophysical sources is power-law like
- Dark matter PDF is a Gaussian plus power-law tail
- Another diagnosis for dark matter

Flux PDF: Photon count distribution in Fermi data



Malyshev, Hogg, *Astrophys. J.* **738**, 181 (2011)

- Analysis of 11-month of Fermi data
- So far, the flux PDF can be well explained with all known sources (Galactic diffuse emission, isotropic background emission, and point sources)
- Further analysis has to be carried out

What can we learn from the gamma-ray background?

✓ **Energy**

- Intensity spectrum (Bergstrom et al. 1998)

✓ **Spatial clustering of sources**

- Angular power spectrum (Ando & Komatsu 2006)

✓ **Redshift distribution of sources**

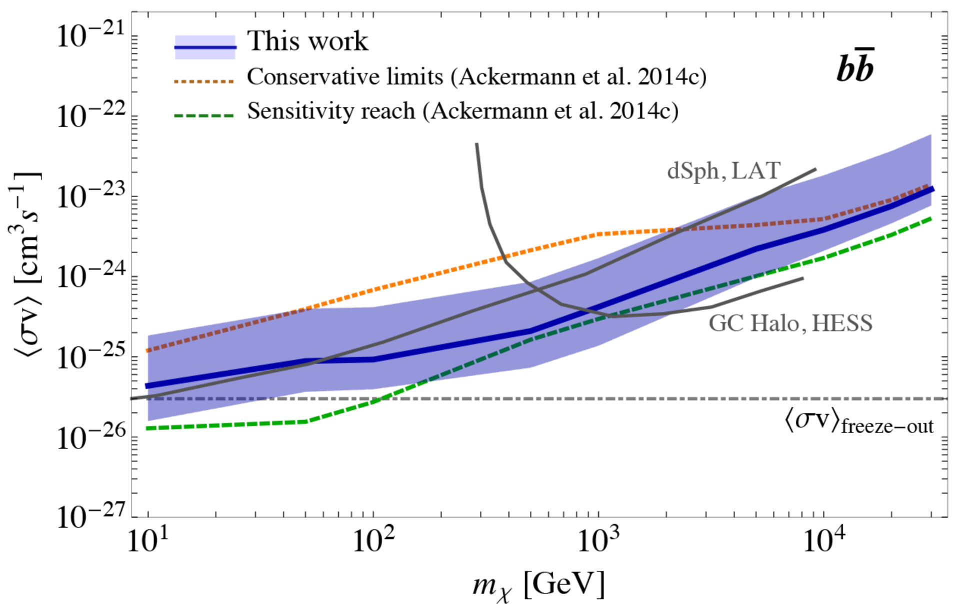
- Cross correlation with dark matter tracers (Cosmic shear: Camera et al. 2013; Galaxy catalogs: Ando et al. 2014)

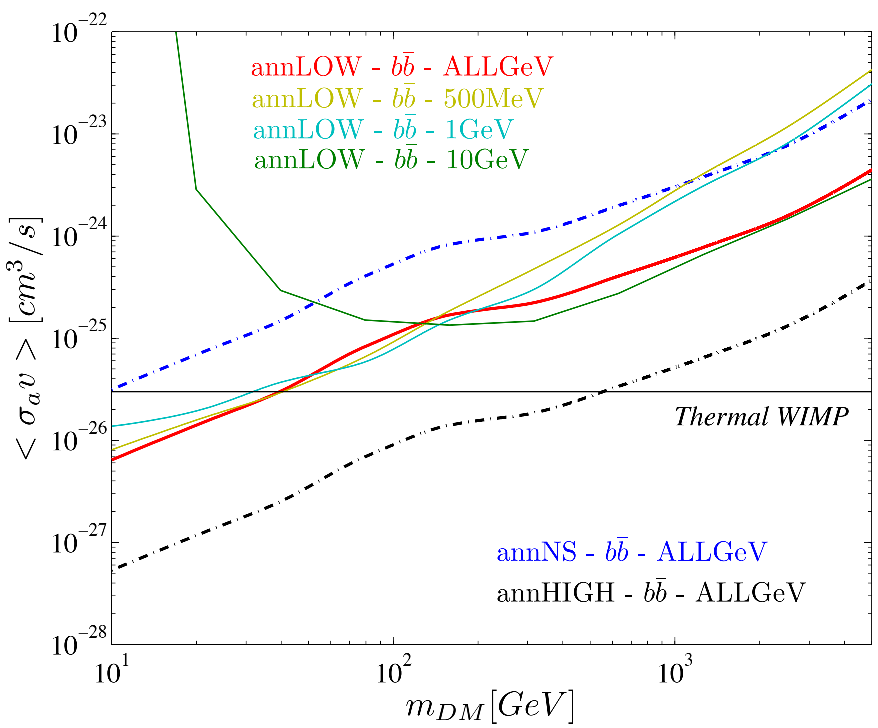
✓ **Luminosity distribution of sources**

- 1-point PDF of the gamma-ray flux (Lee et al. 2009)

Interpretation: Annihilation boost

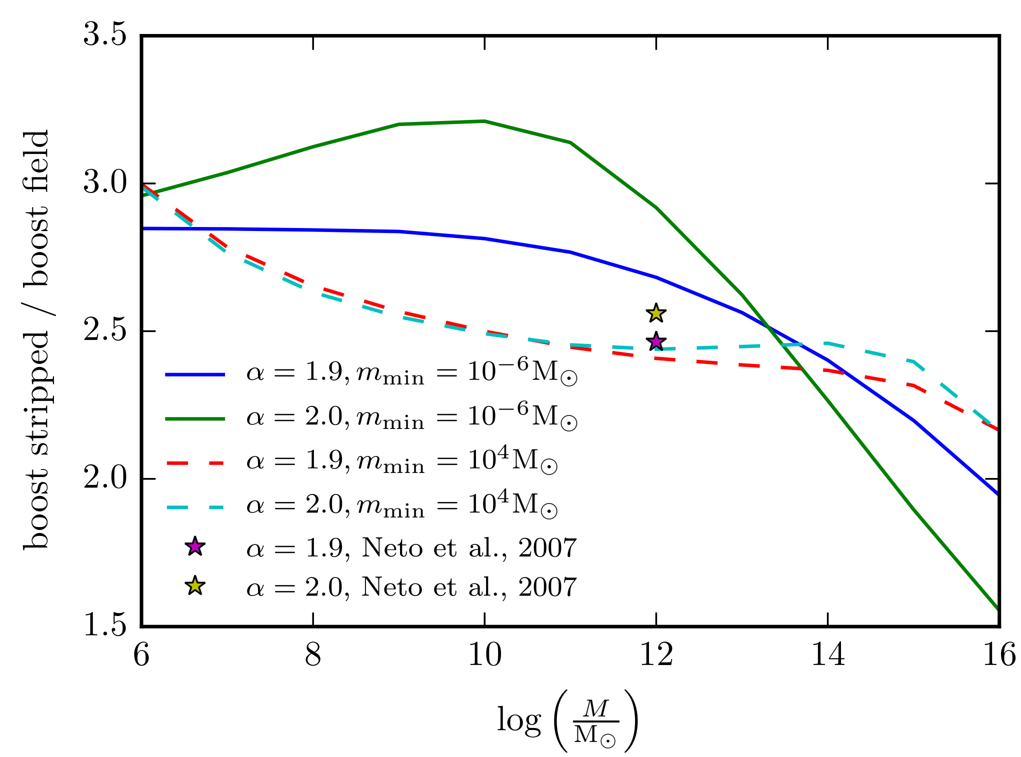
Ajello et al., *Astrophys. J.* **800**, L27 (2015)





Cuoco et al., arXiv:1506.01030 [astro-ph.HE]

- About one order of magnitude uncertainty on subhalo boost
  - Optimistic: extrapolation of luminosity-mass relation found in simulations, down to smallest subhalo mass
  - Conservative: use of *field halo* concentration to calculation subhalo luminosity
- Tidal stripping of subhalos will make them denser (hence brighter) than field halos of equal mass, by a factor of ~3



Bartels, Ando, arXiv:1507.08656 [astro-ph.CO]

Conclusions

- Plenty of data of high-energy gamma rays and other wavelength enable
  - ***Multi-wavelength*** study from radio to TeV gamma rays
  - Beyond spectral analysis of IGRB: ***Anisotropies***
- Interesting claims (GeV excess, 3.5 keV lines, AMS-02 excess, IceCube neutrinos) should be tested with multi-wavelength approach
- IGRB Anisotropy has started to be probed extensively and already shown some promise for the future
  - Angular power spectrum
  - PDF of gamma-ray flux
  - Cross correlation with nearby galaxy distribution