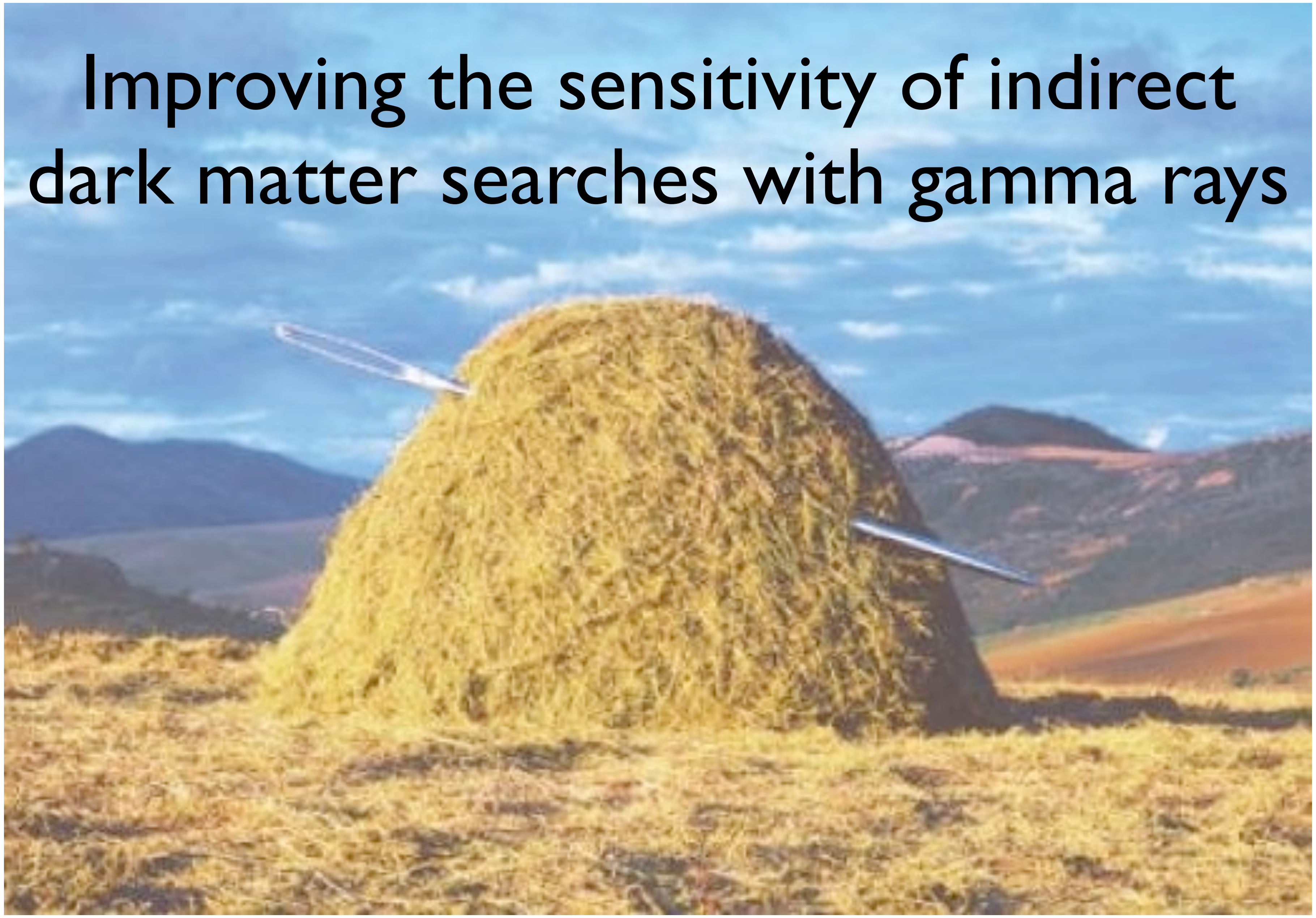
Improving the sensitivity of indirect dark matter searches with gamma rays



Jennifer Siegal-Gaskins

Caltech

The challenge

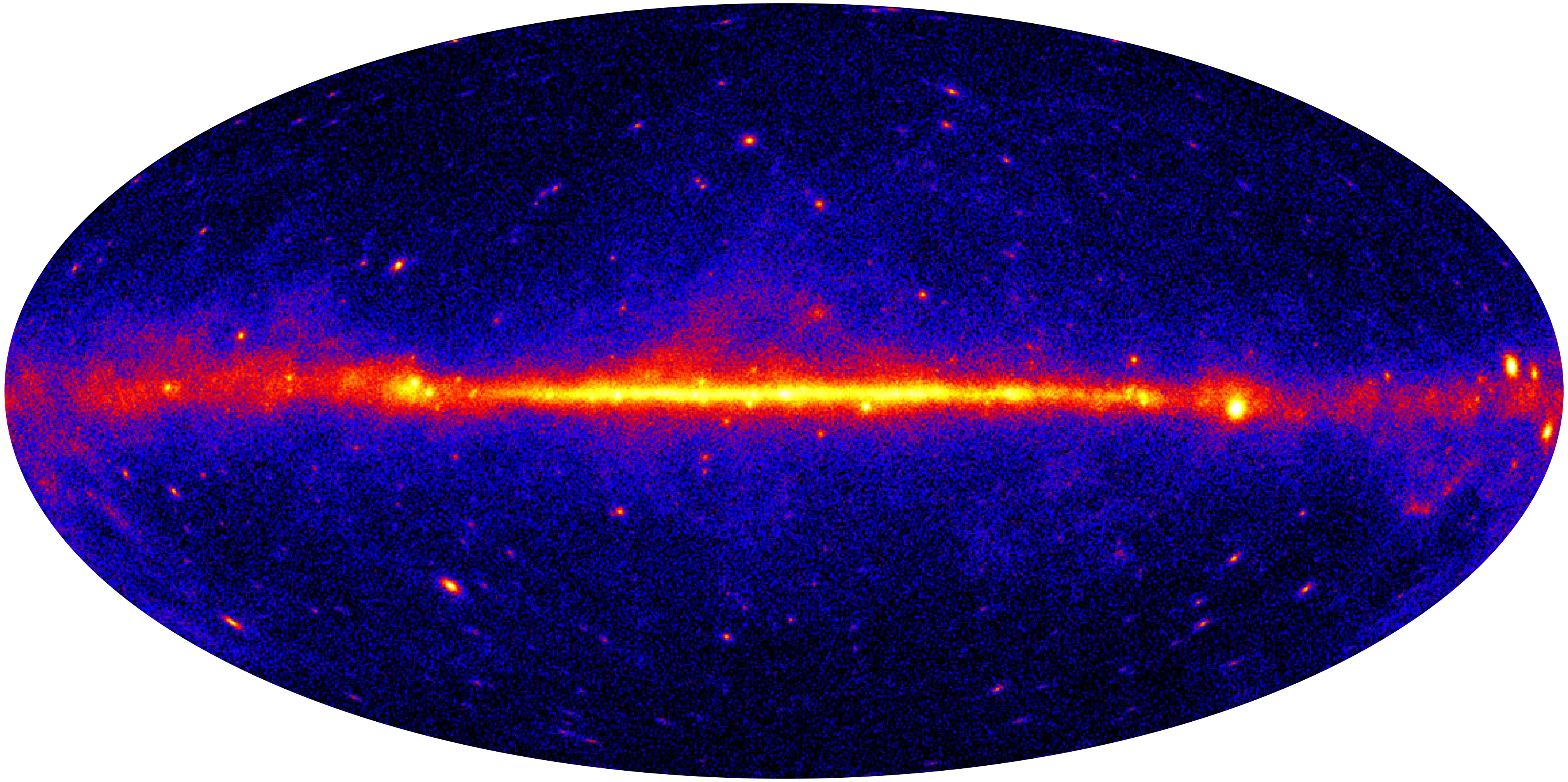
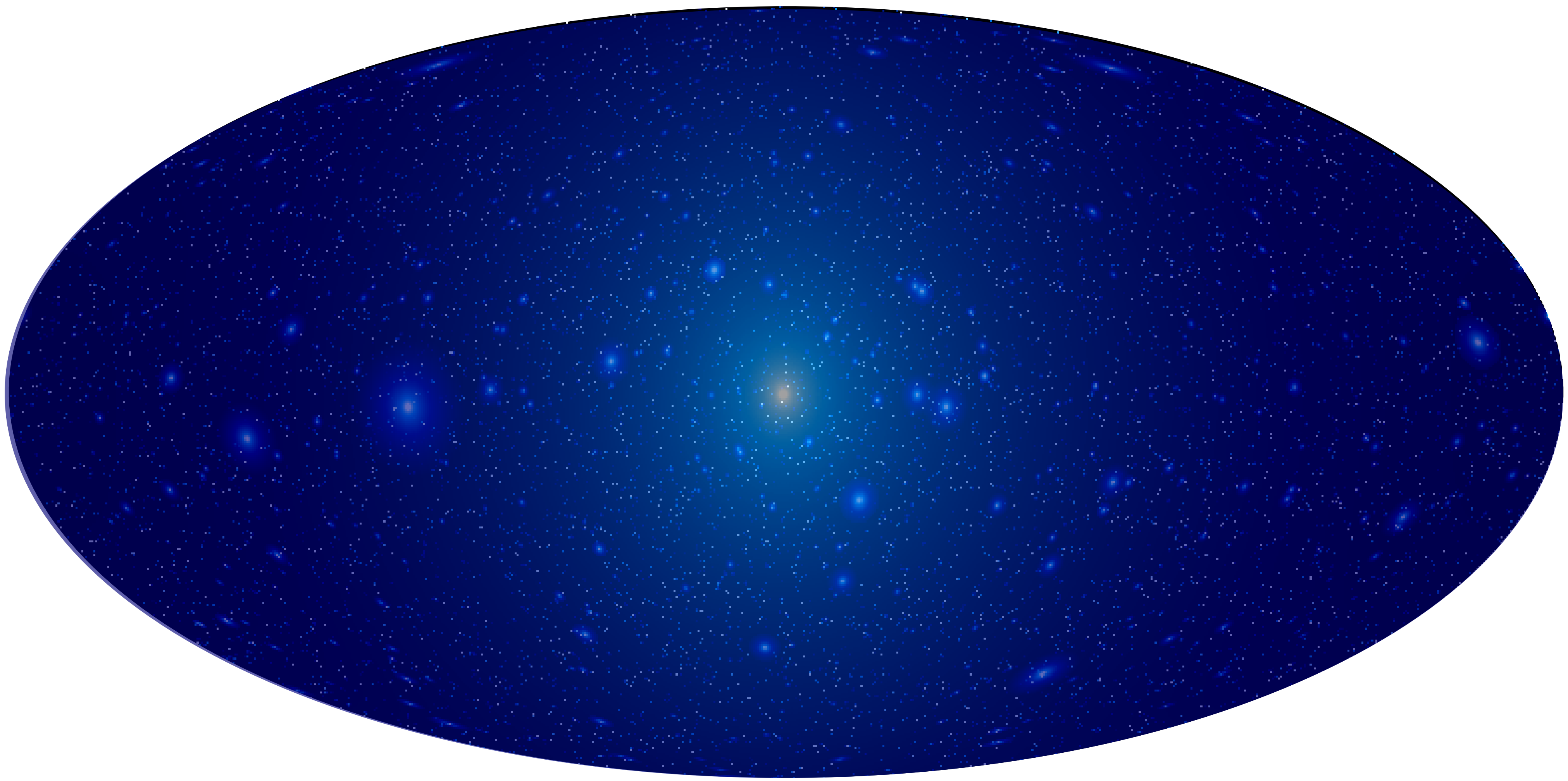


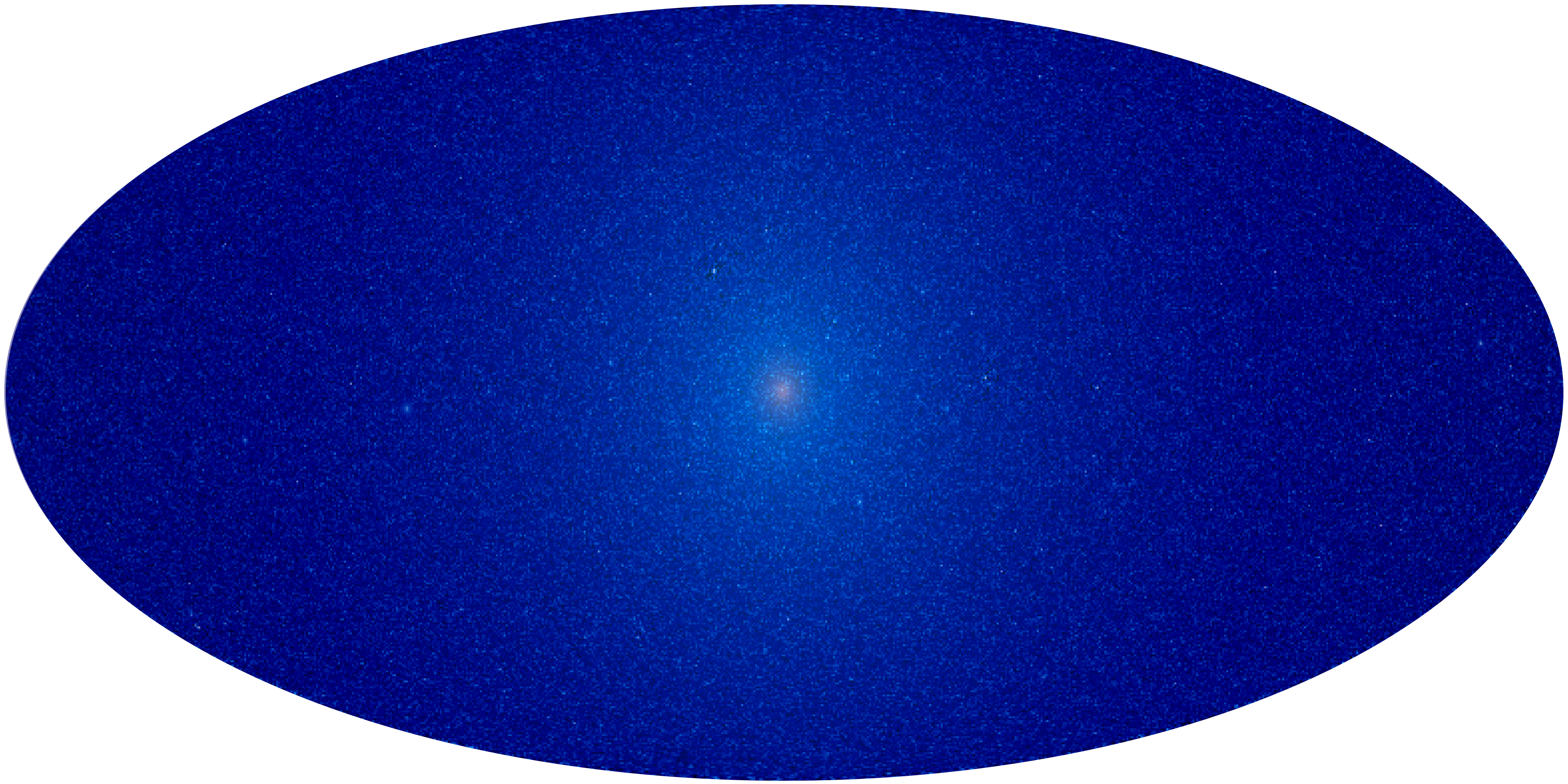
Image Credit: NASA/DOE/International LAT Team

The challenge



JSG 2008

The challenge



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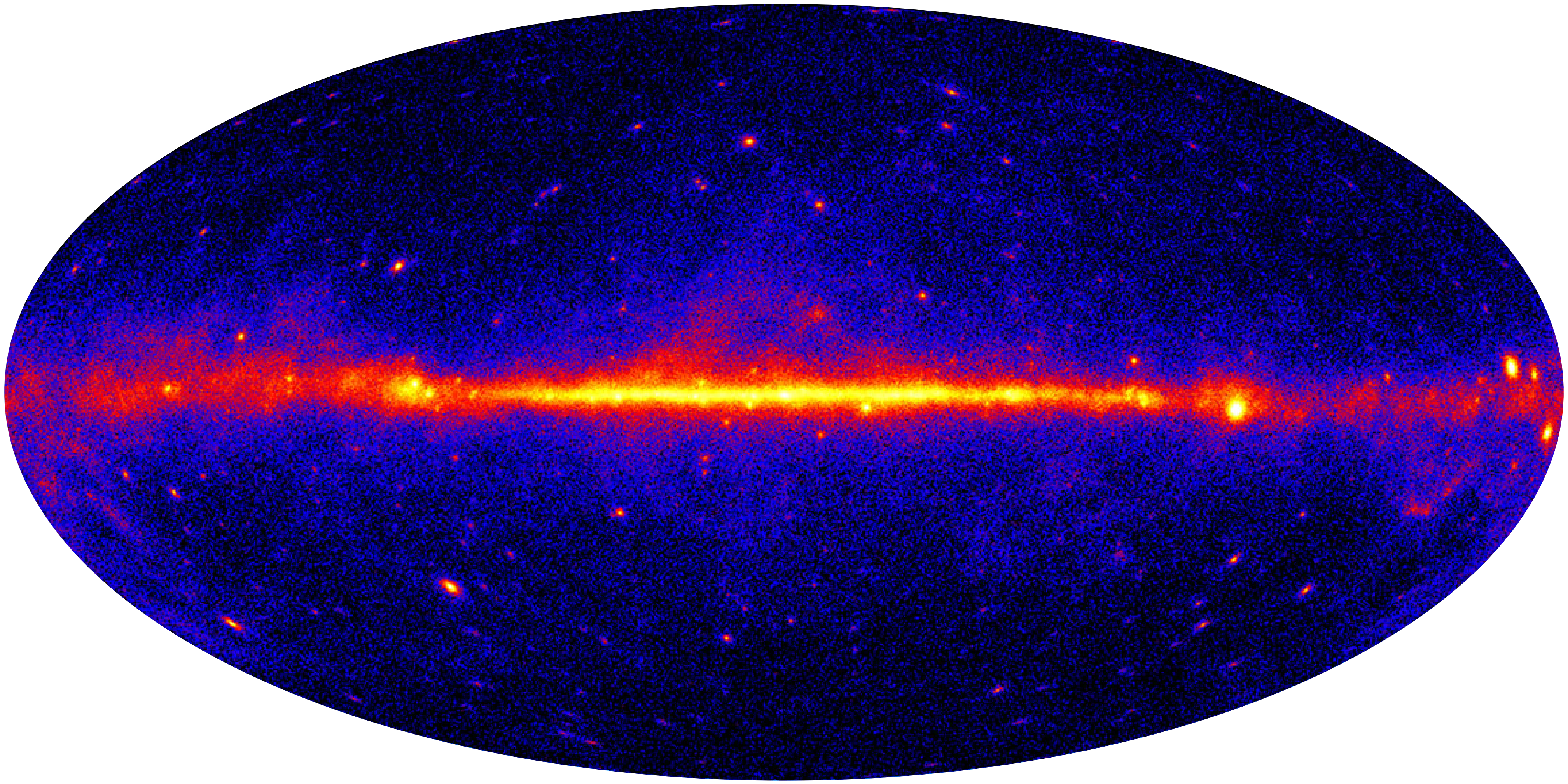

Image Credit: NASA/DOE/International LAT Team

The challenge

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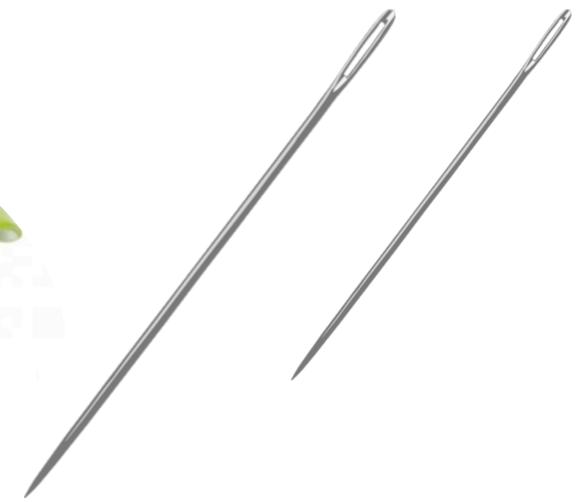

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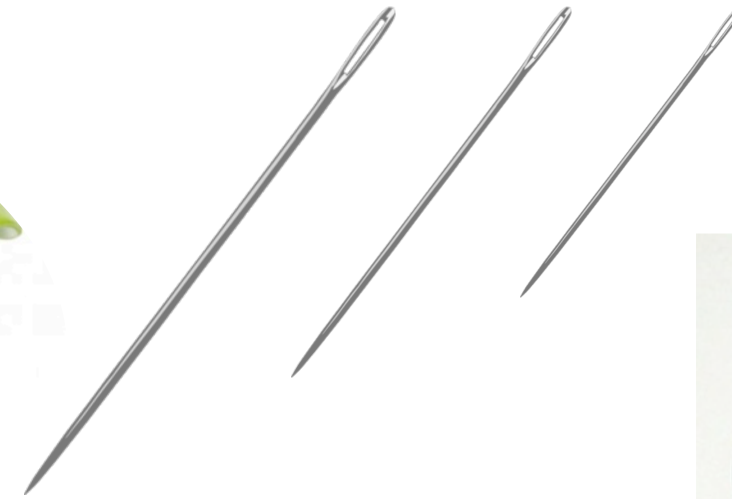


The challenge

The challenge

The challenge

The challenge

The challenge

The challenge

The challenge

The challenge

The challenge

To detect an uncertain (and likely subdominant) signal in the presence of uncertain backgrounds

The challenge

The challenge

Strategy

- the "best" approach depends on both the expected dark matter signal and the target source or emission
- complementarity is key for making the most of the data: info from other dark matter searches (indirect and otherwise) and from studies of astrophysical sources is essential
  - multiwavelength studies can provide new insights about gamma-ray sources and source populations
  - multiwavelength (and multimessenger) studies can leverage searches beyond a single experiment and help alleviate issues with systematics
  - making full use of complementary results will help to efficiently direct future efforts

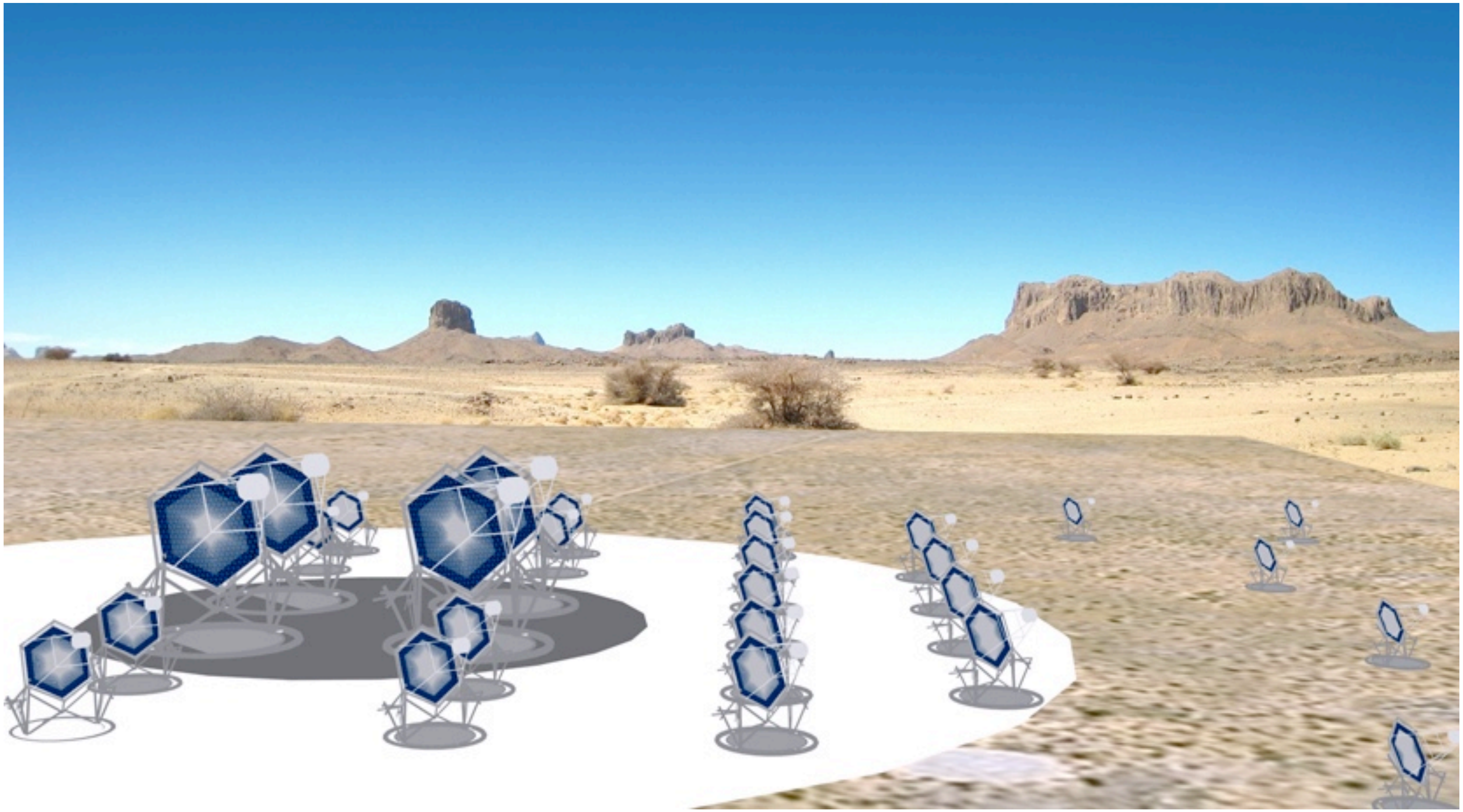
Tools

1. spectral information
2. spatial information
3. know your backgrounds and impostor signals better

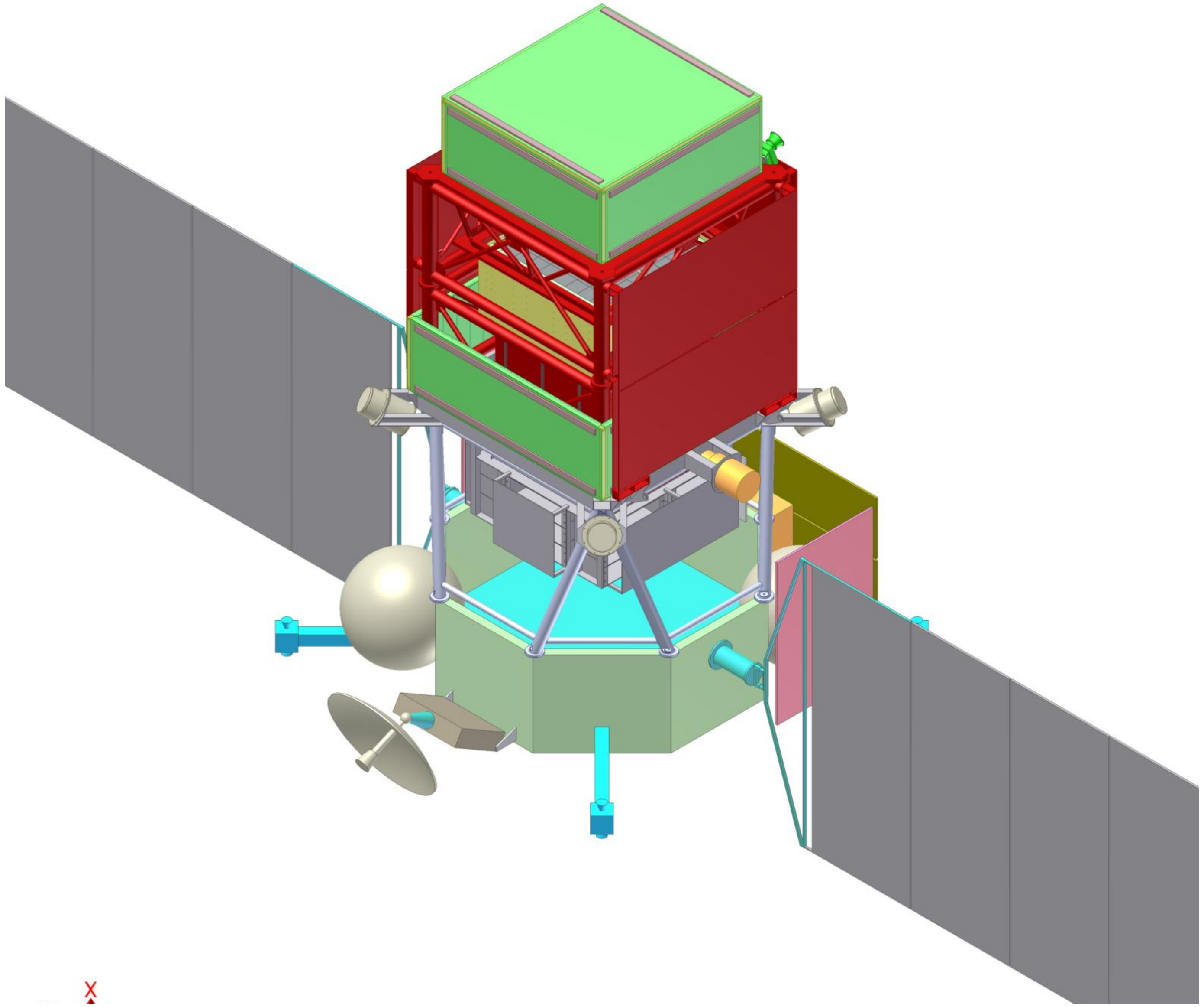
The Fermi Large Area Telescope (LAT)

Credit: NASA/General Dynamics

The Cherenkov Telescope Array (CTA)

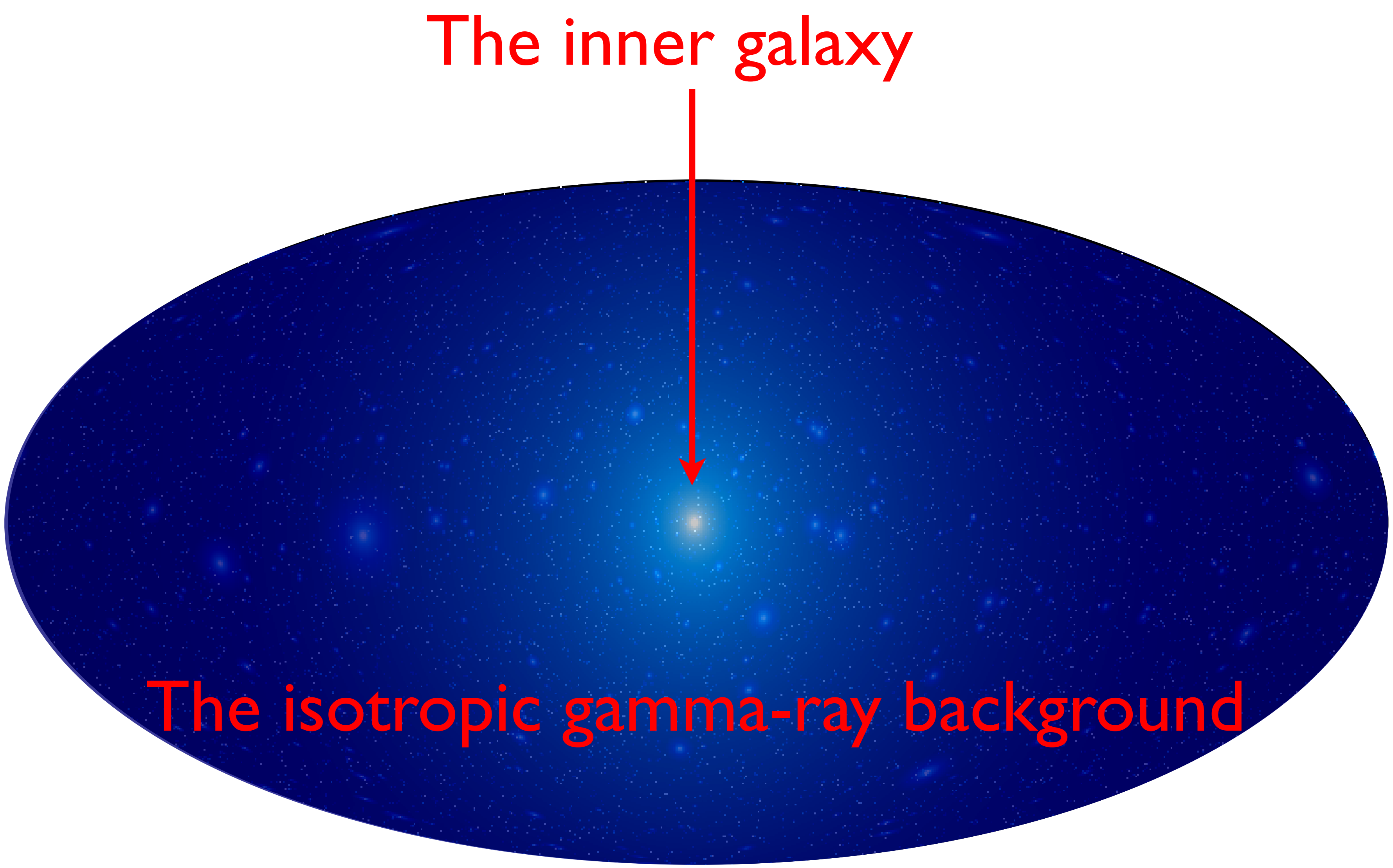


GAMMA-400



launch scheduled for 2018

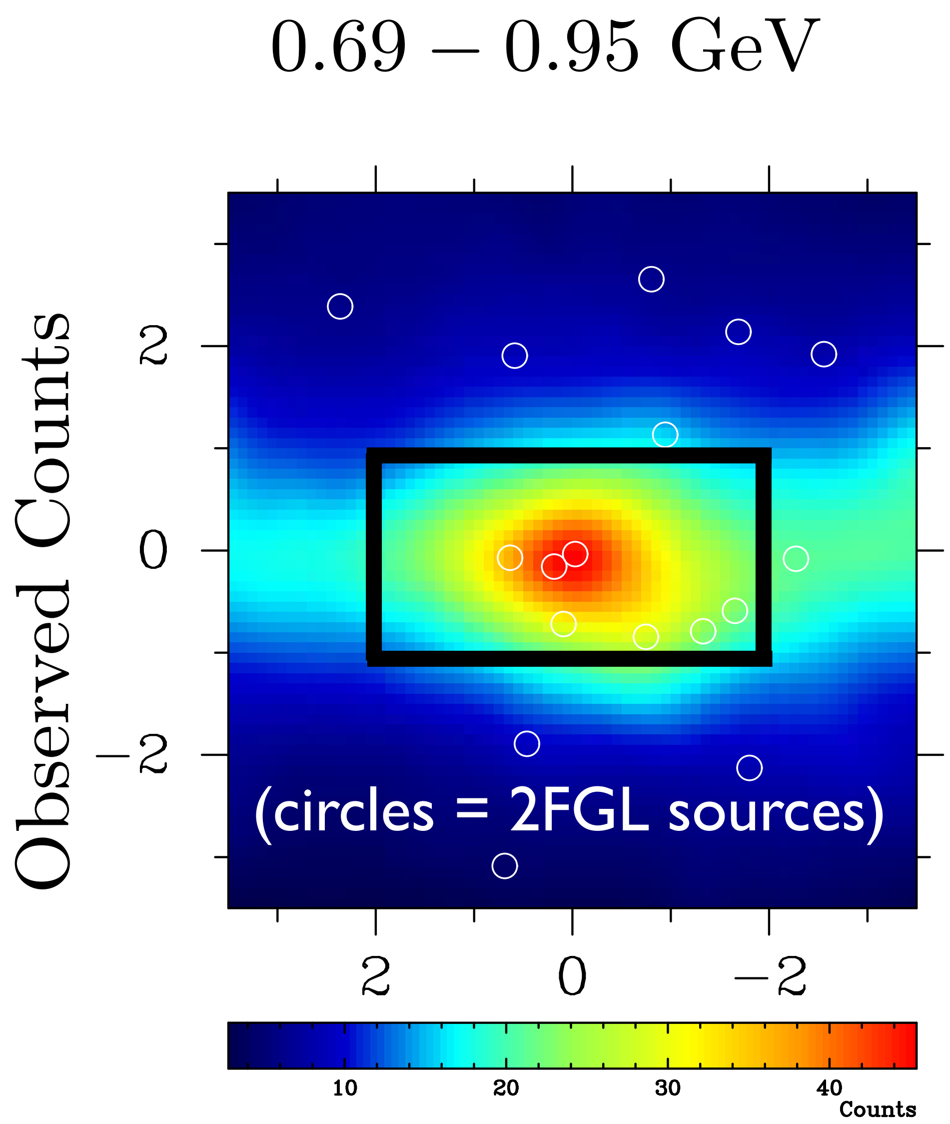
Selected gamma-ray dark matter search targets



The inner galaxy

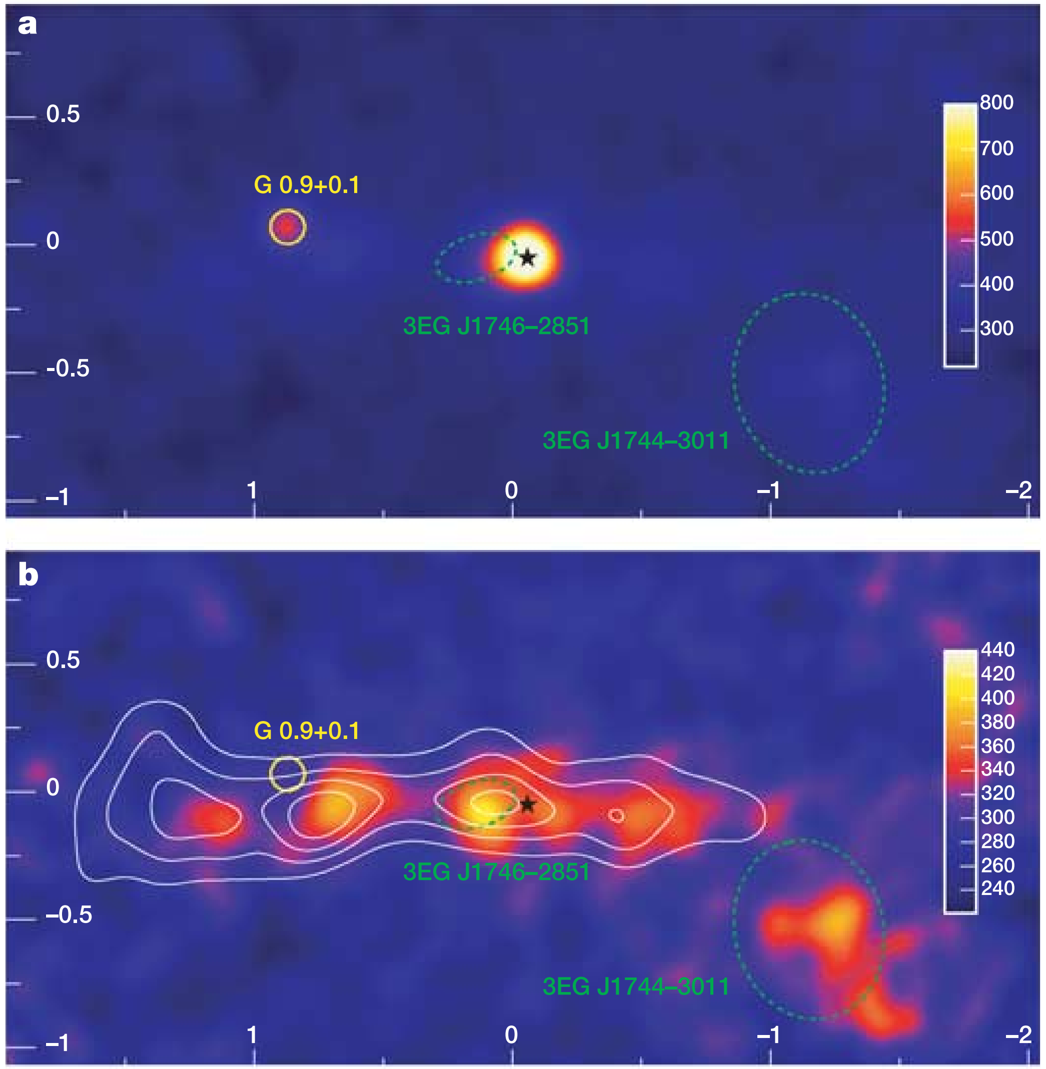
The high-energy inner galaxy

Fermi LAT ~ 1 GeV



Abazajian & Kaplinghat 2012

HESS > 380 GeV



Aharonian et al. 2006

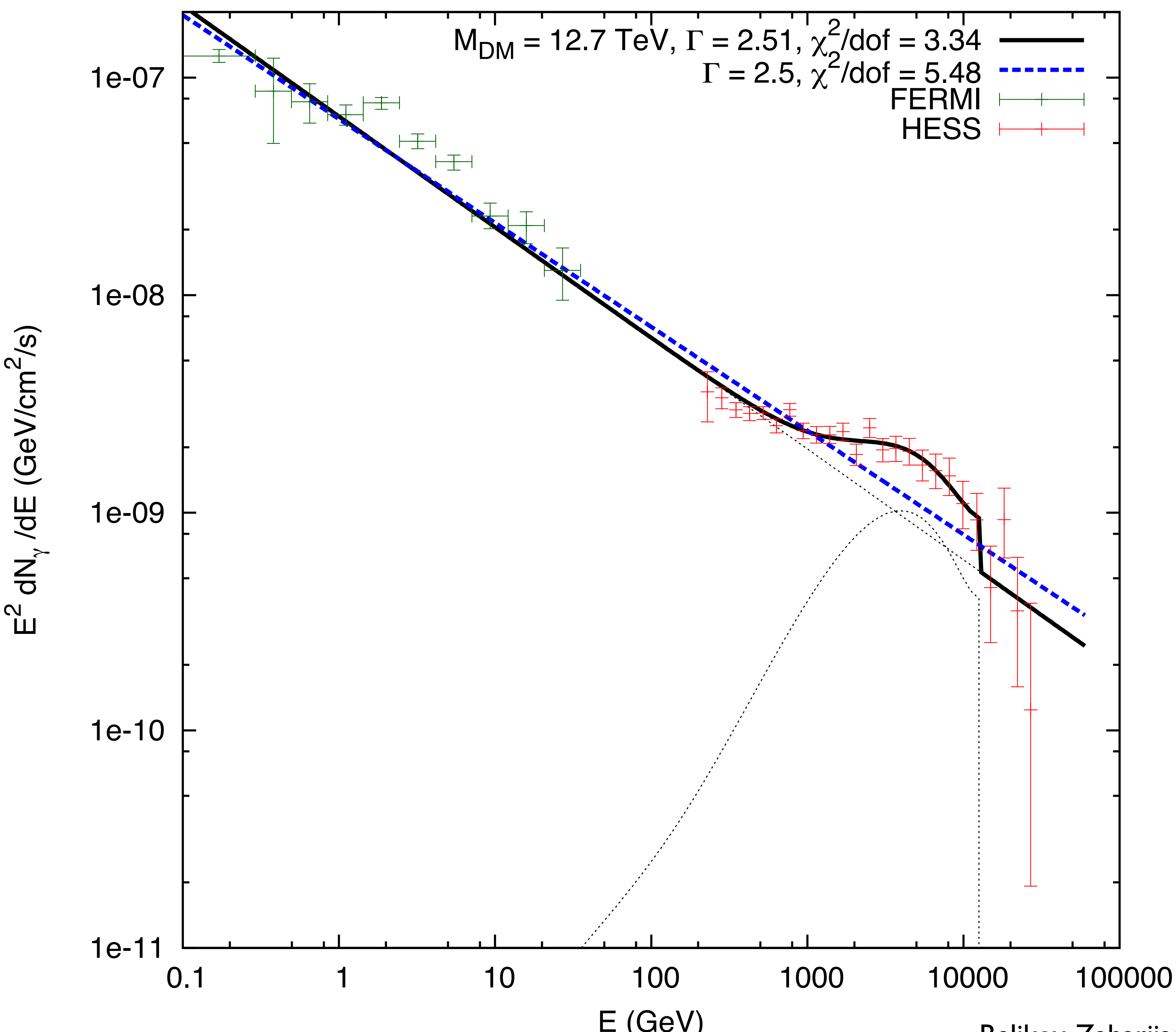
spatially extended emission

consistent with point source

see also: Hooper & Goodenough (2011); Abazajian (2011)

Fermi + HESS GC energy spectrum

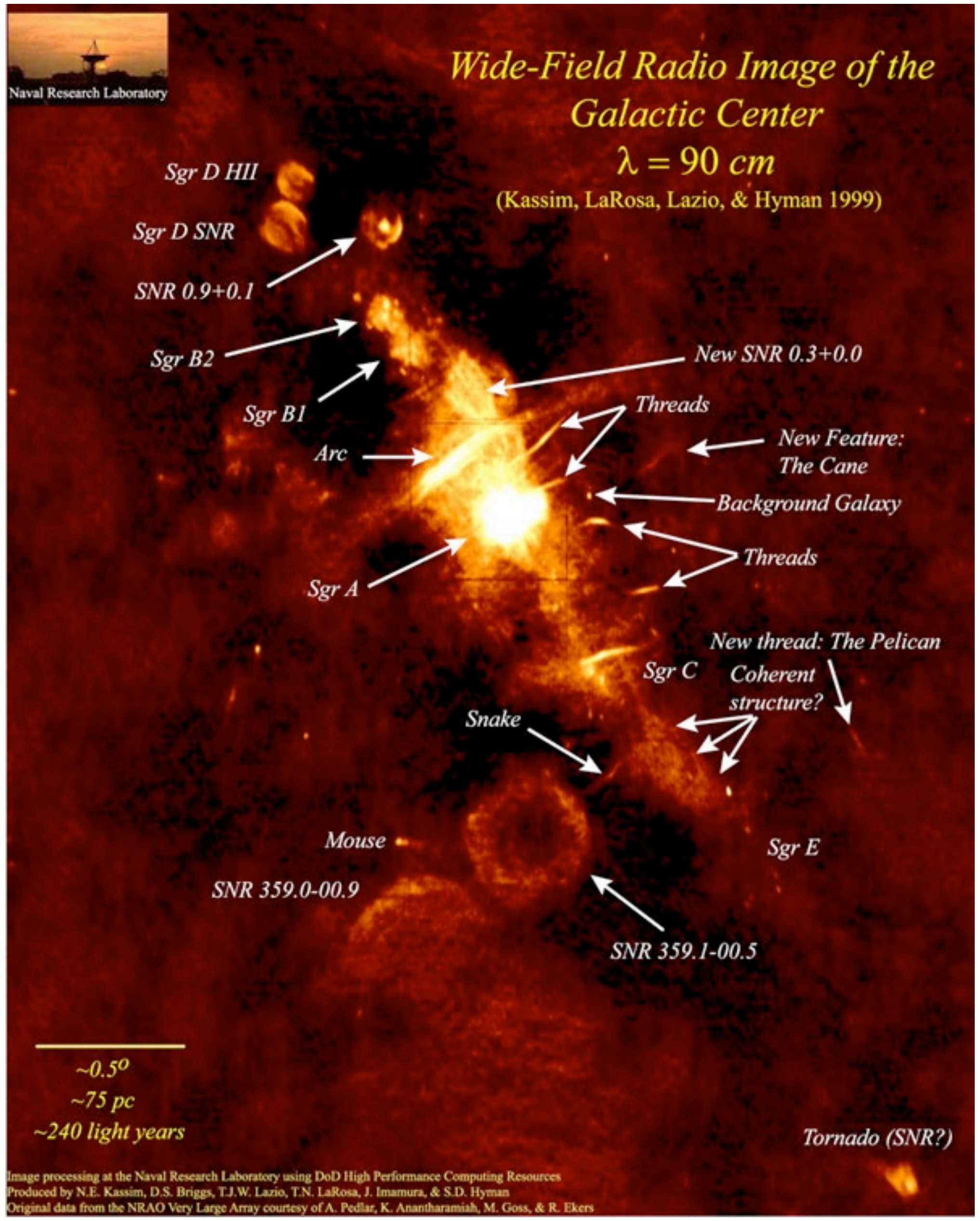
Cases G.1 and G.2 (data set A)



Belikov, Zaharijas, & Silk 2012

The multiwavelength inner galaxy

VLA @ 330 MHz



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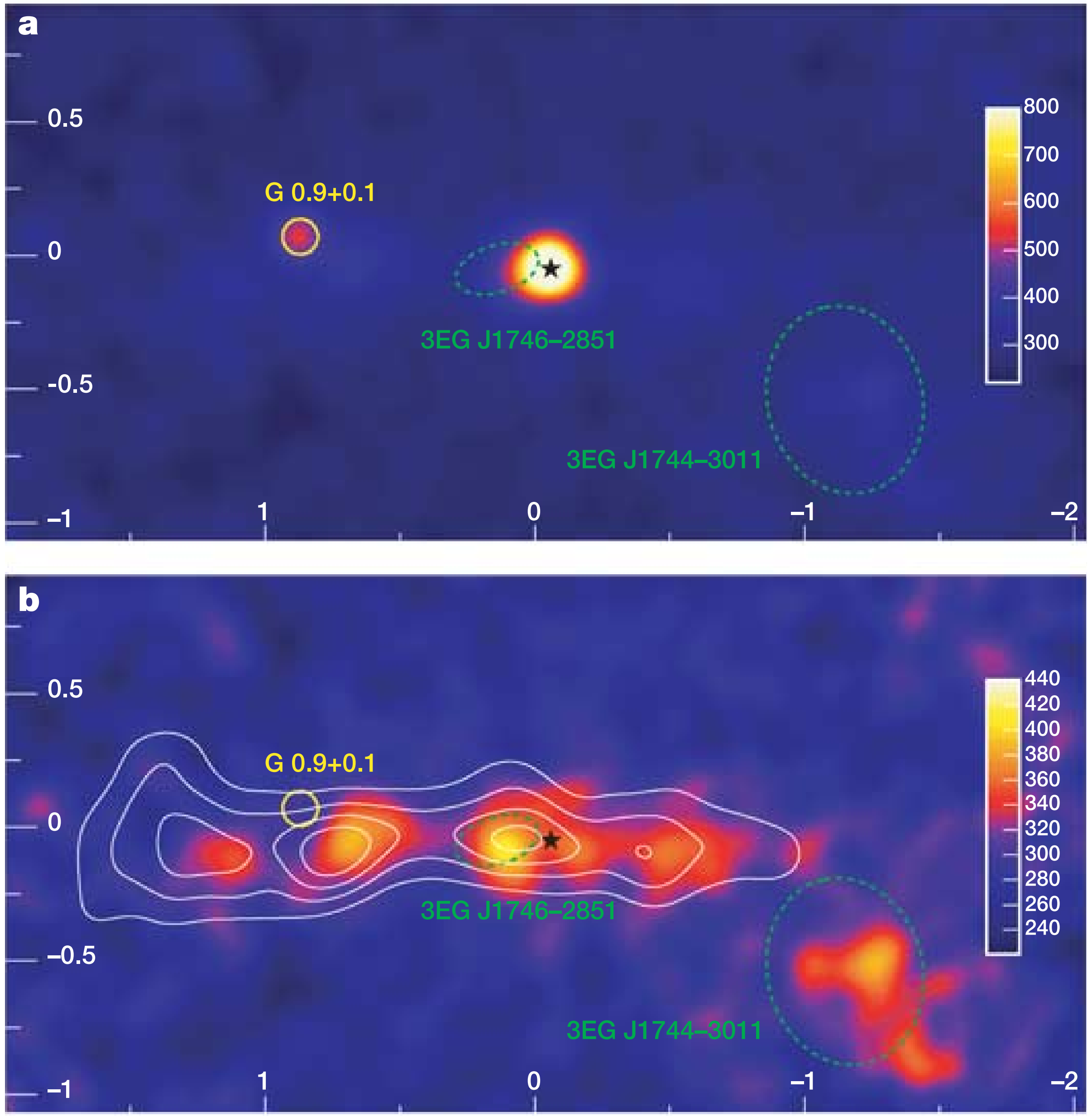
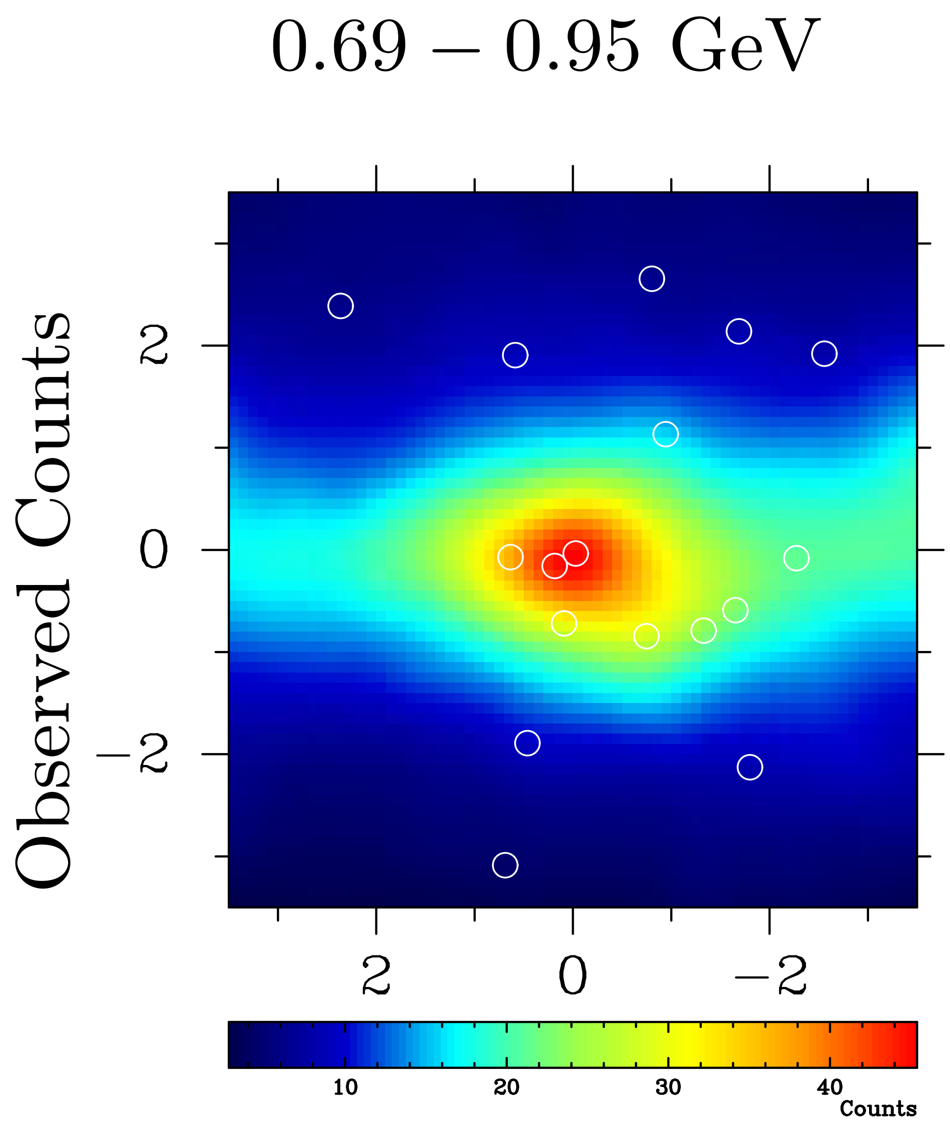


Aharonian et al. 2006

Dark matter in the inner galaxy

- likely the brightest dark matter source in the gamma-ray sky, but...
- embedded in large and complicated backgrounds:
  - resolved sources
  - unresolved sources
  - diffuse emission



Abazajian & Kaplinghat 2012

The inner galaxy

1. spectrally: DM signal may be subdominant, making a spectral signature difficult to identify
2. spatially: strong spatial signatures may be present (source of uncertainty), but not accessible with current data
3. know your backgrounds and impostor signals better: pulsars and other astrophysical sources, cosmic-ray interactions with interstellar gas and radiation...

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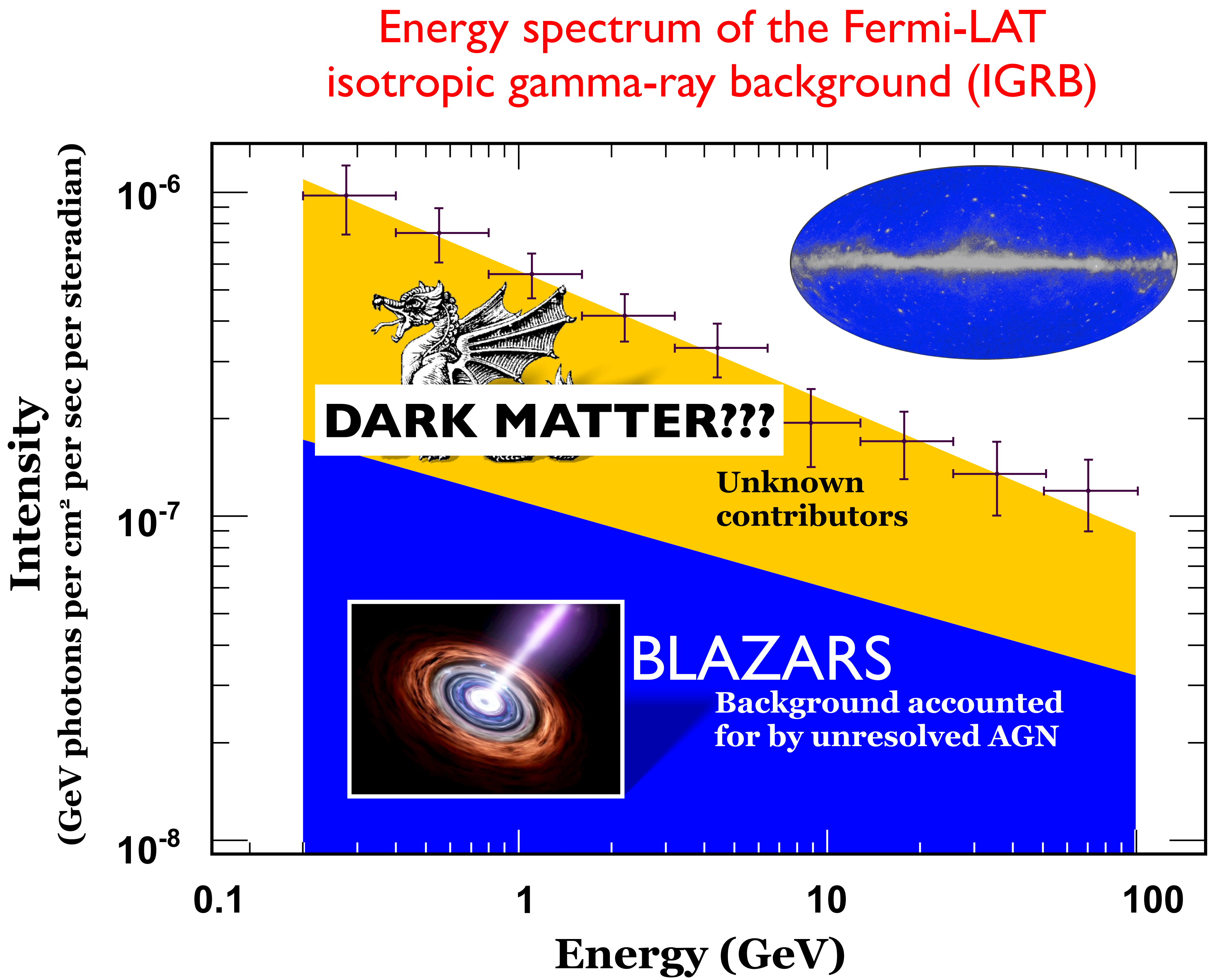
1+2 = improved angular resolution could help to determine morphology of emission and address differences between GeV and TeV results

2+3 = multiwavelength studies can access smaller angular scales and could pin down origin and spatial distribution of some components

The isotropic gamma-ray background

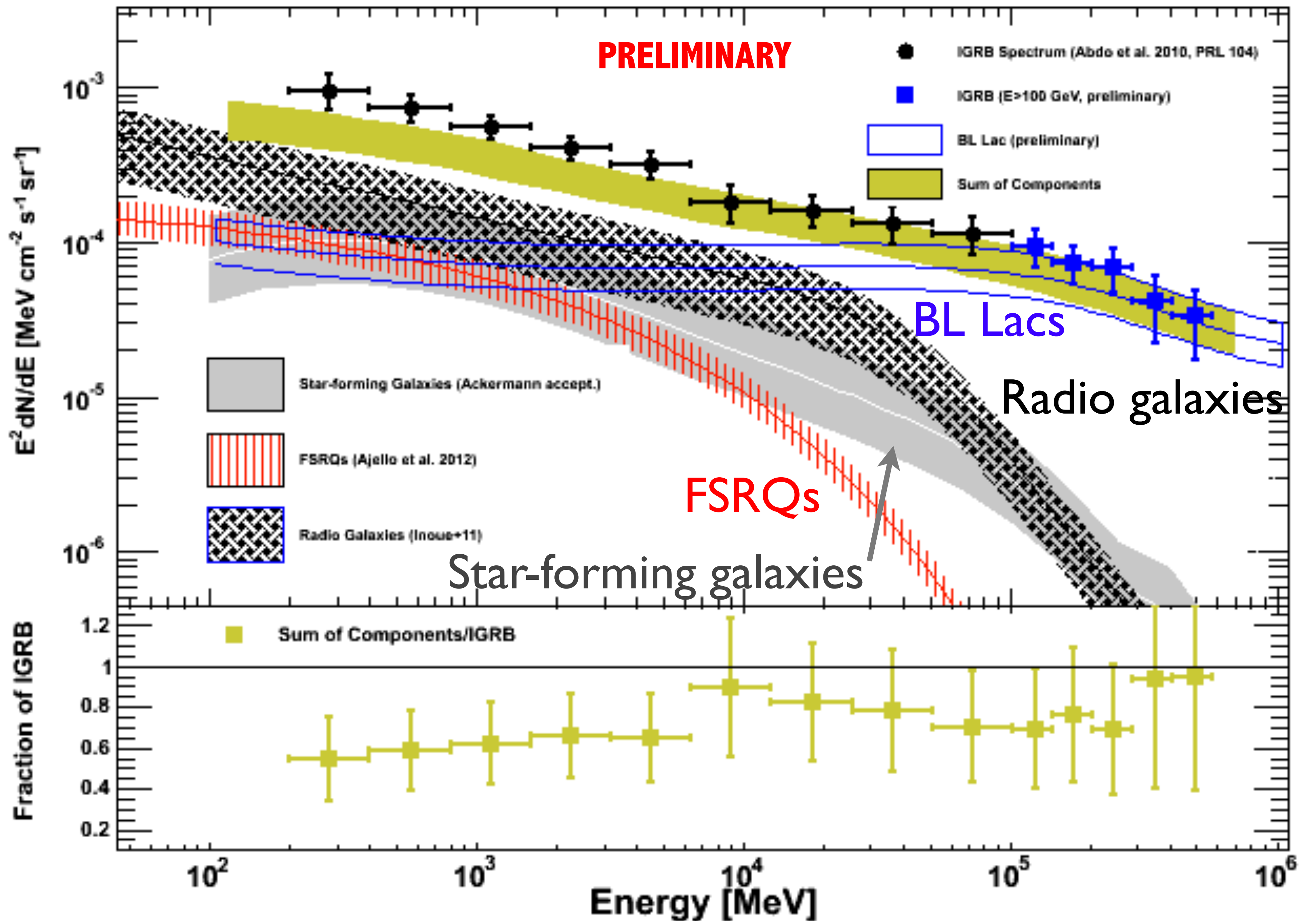
What is making the diffuse gamma-ray background?



Credit: NASA/DOE/Fermi LAT Collaboration

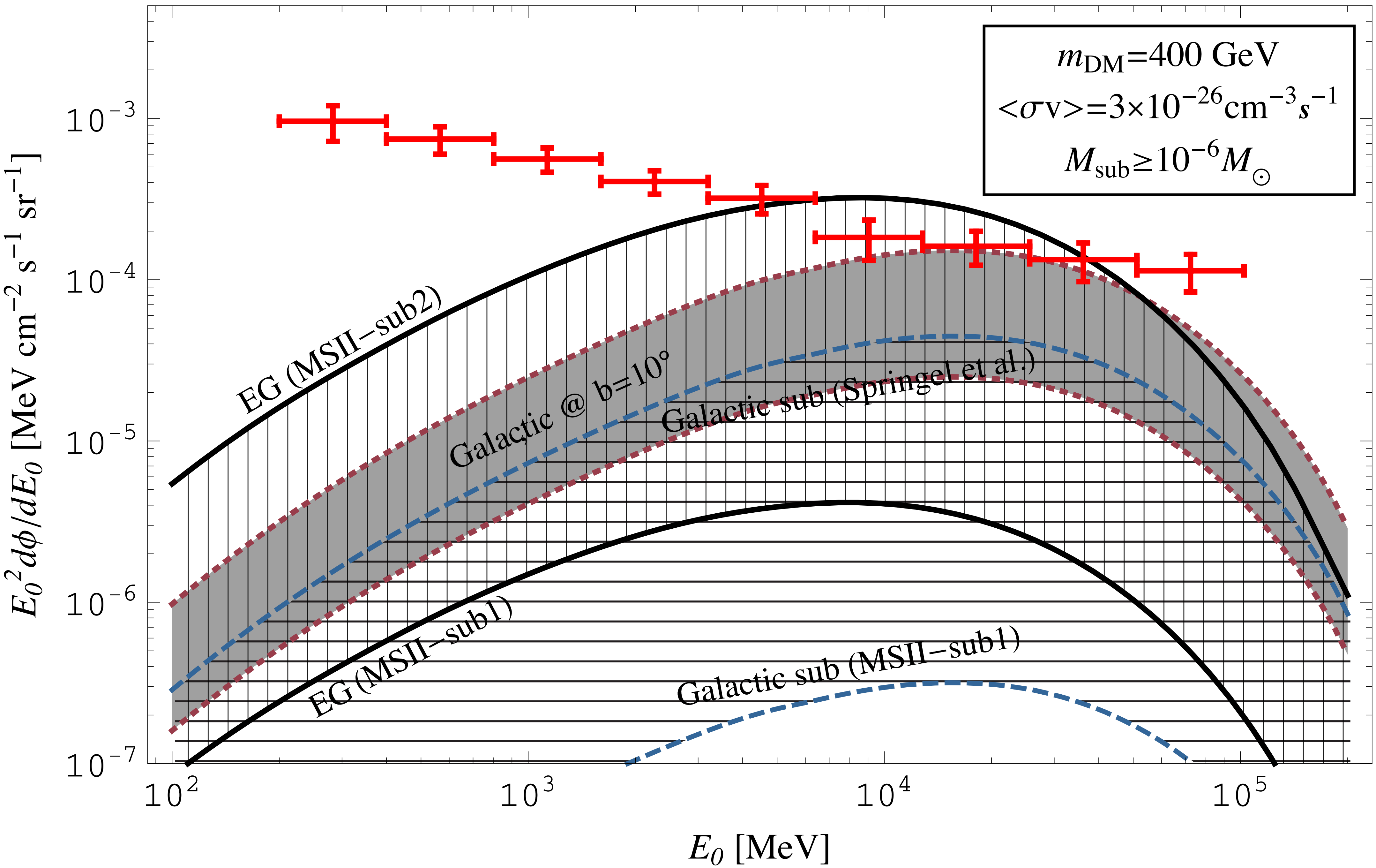
What is making the diffuse gamma-ray background?

Expected contribution of source populations to the IGRB



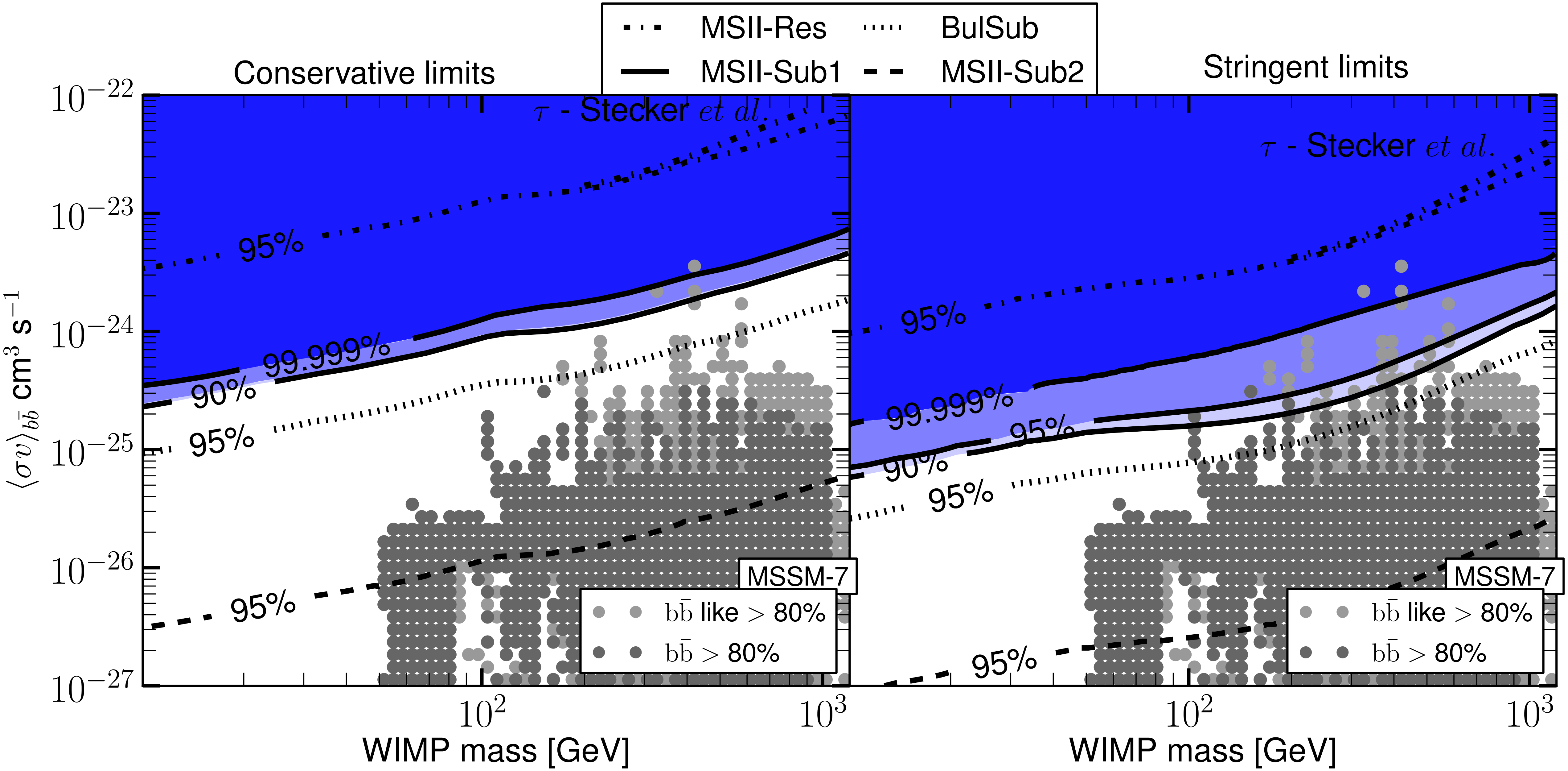
Sum is ~ 60-100% of IGRB intensity (energy-dependent)

Dark matter signals in the IGRB



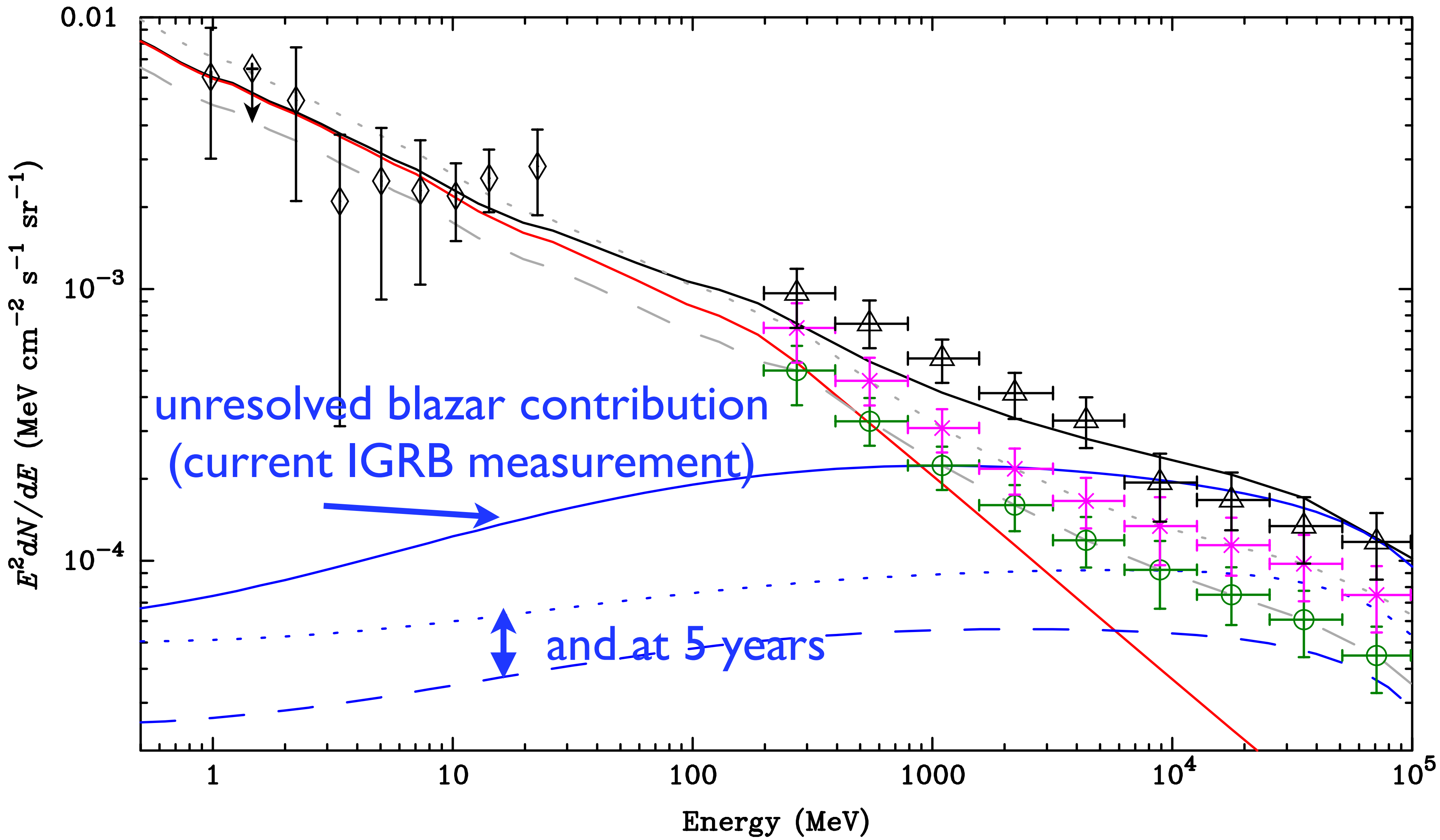
Abdo et al., JCAP 04 014 (2010)

Constraints from the IGRB



Abdo et al., JCAP 04 014 (2010)

Getting rid of the IGRB



Abazajian, Blanchet, Harding 2011

- the IGRB is time-dependent: will get less intense as more sources are resolved
- understanding of unresolved source contributions will also improve
- future IGRB measurements will lead to improved DM sensitivity

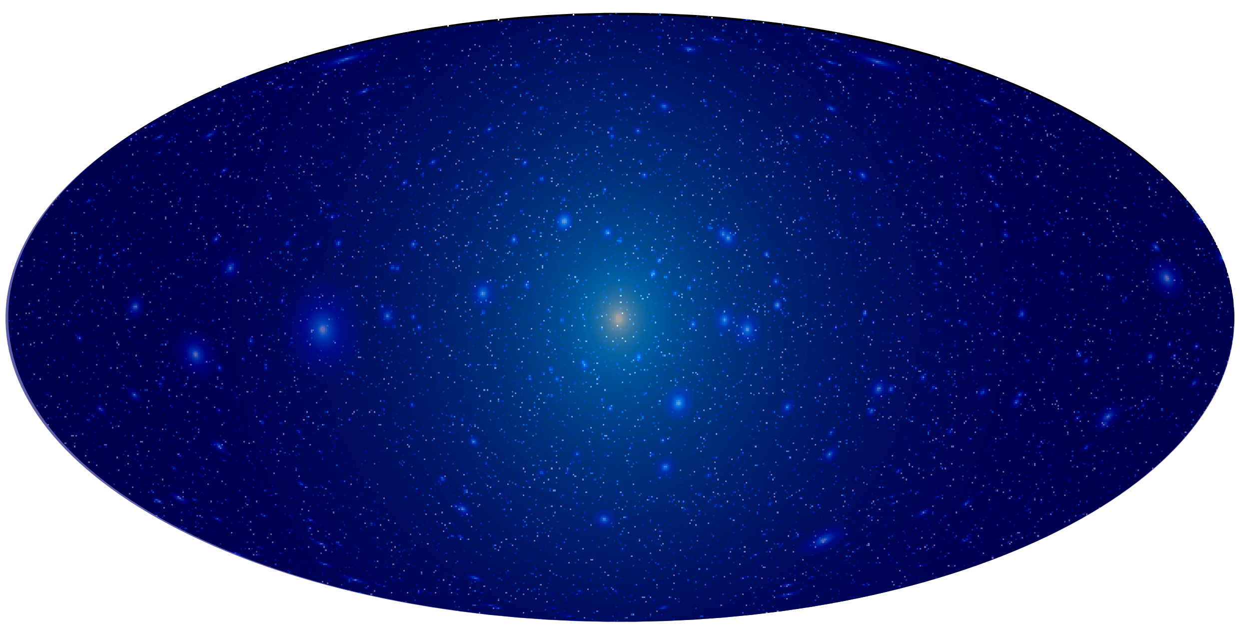
see also Abazajian, Blanchet, Harding 2012 but... we can do better than just detecting more of the unresolved sources:

we can model them or use other techniques and observables to identify their contribution to the IGRB

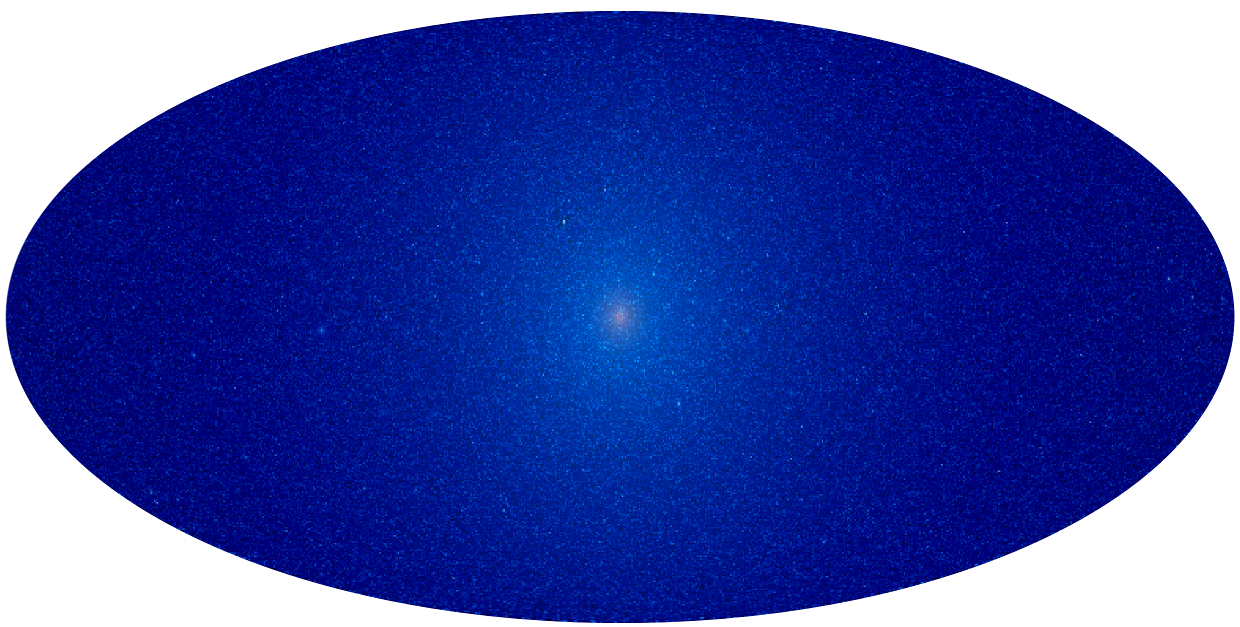
Gamma-ray anisotropies from dark matter

gamma rays from DM annihilation and decay in Galactic and extragalactic dark matter structures could imprint small angular scale fluctuations in the diffuse gamma-ray background

Gamma rays from Galactic DM



before accounting for instrument PSF



after convolving with 0.1° beam

JSG, JCAP 10(2008)040

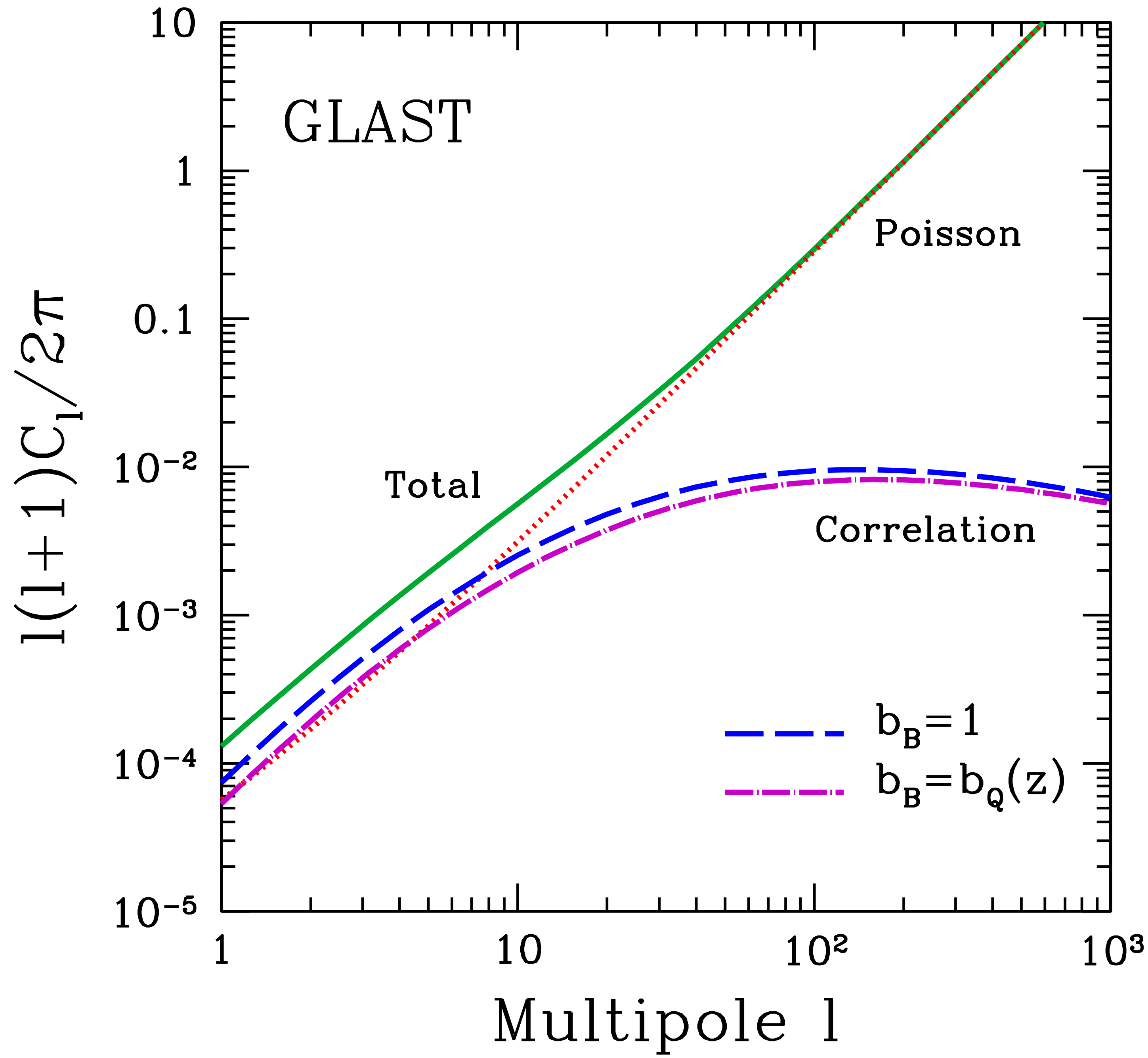
Angular power spectra of unresolved gamma-ray sources

- the angular power spectrum of many gamma-ray source classes (except dark matter) is dominated by the Poisson (shot noise) component for multipoles greater than ~ 10
- Poisson angular power arises from unclustered point sources and takes the same value at all multipoles

predicted fluctuation angular power $C_\ell/\langle I\rangle^2$ [sr] at l = 100 for a single source class (LARGE UNCERTAINTIES):

- blazars: ~ 2e-4
- starforming galaxies: ~ 2e-7
- dark matter: ~ 1e-6 to ~ 1e-4
- MSPs: ~ 0.03

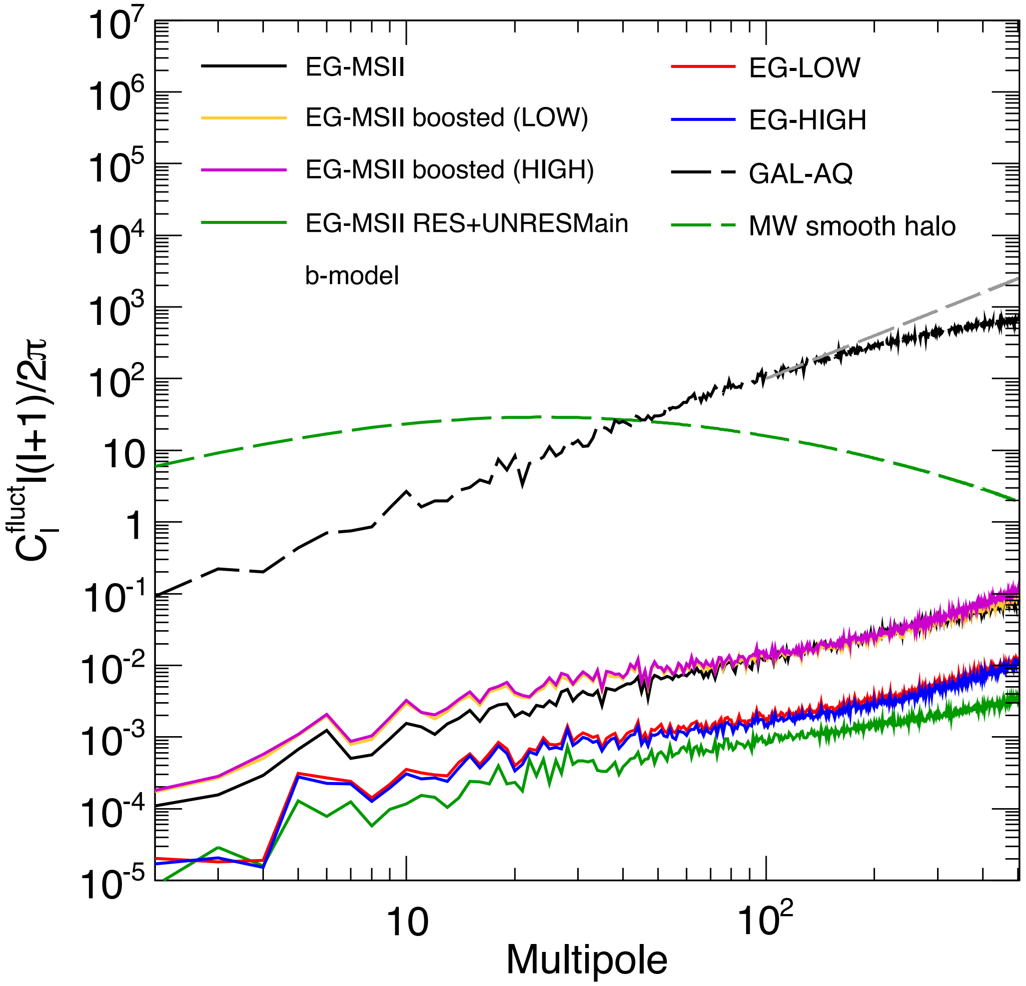
Predicted angular power spectrum of unresolved blazars



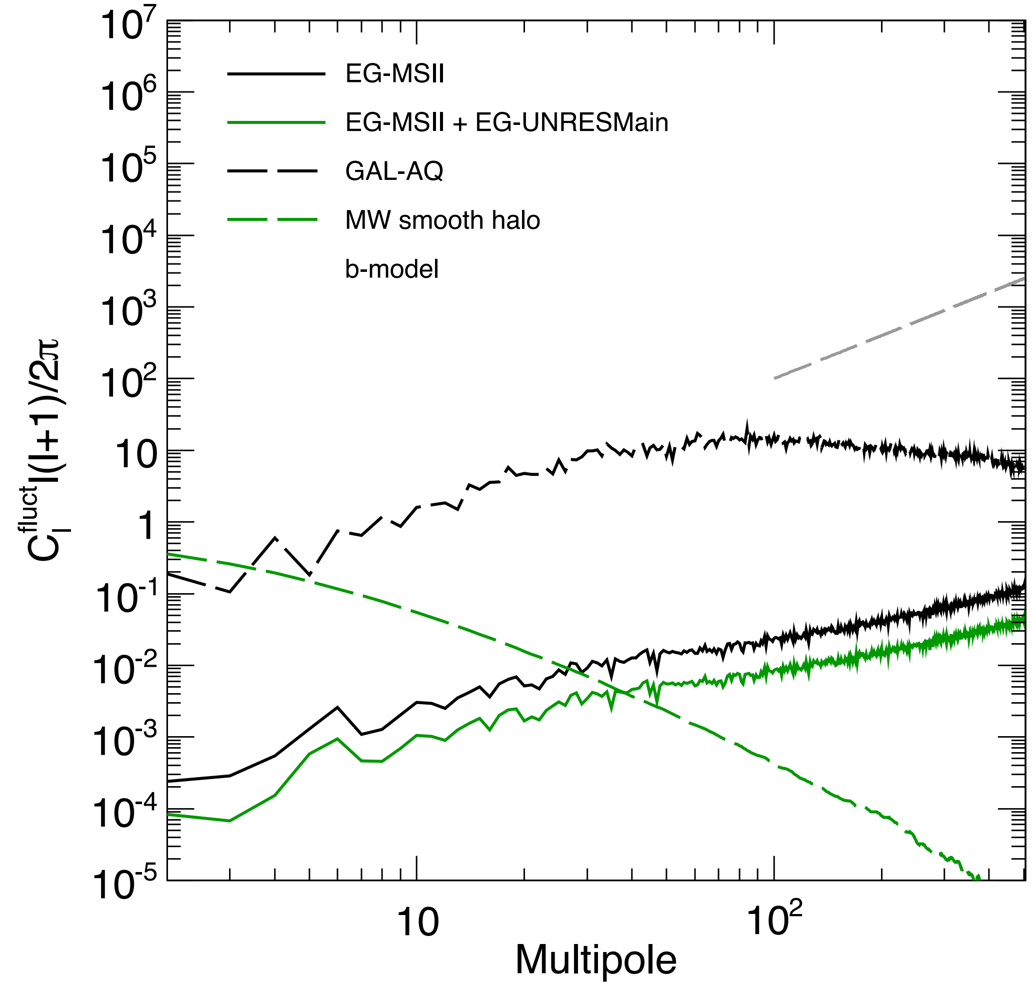
Ando, Komatsu, Narumoto & Totani 2007

Angular power spectra of dark matter signals

Predicted angular power spectrum of DM annihilation



Predicted angular power spectrum of DM decay



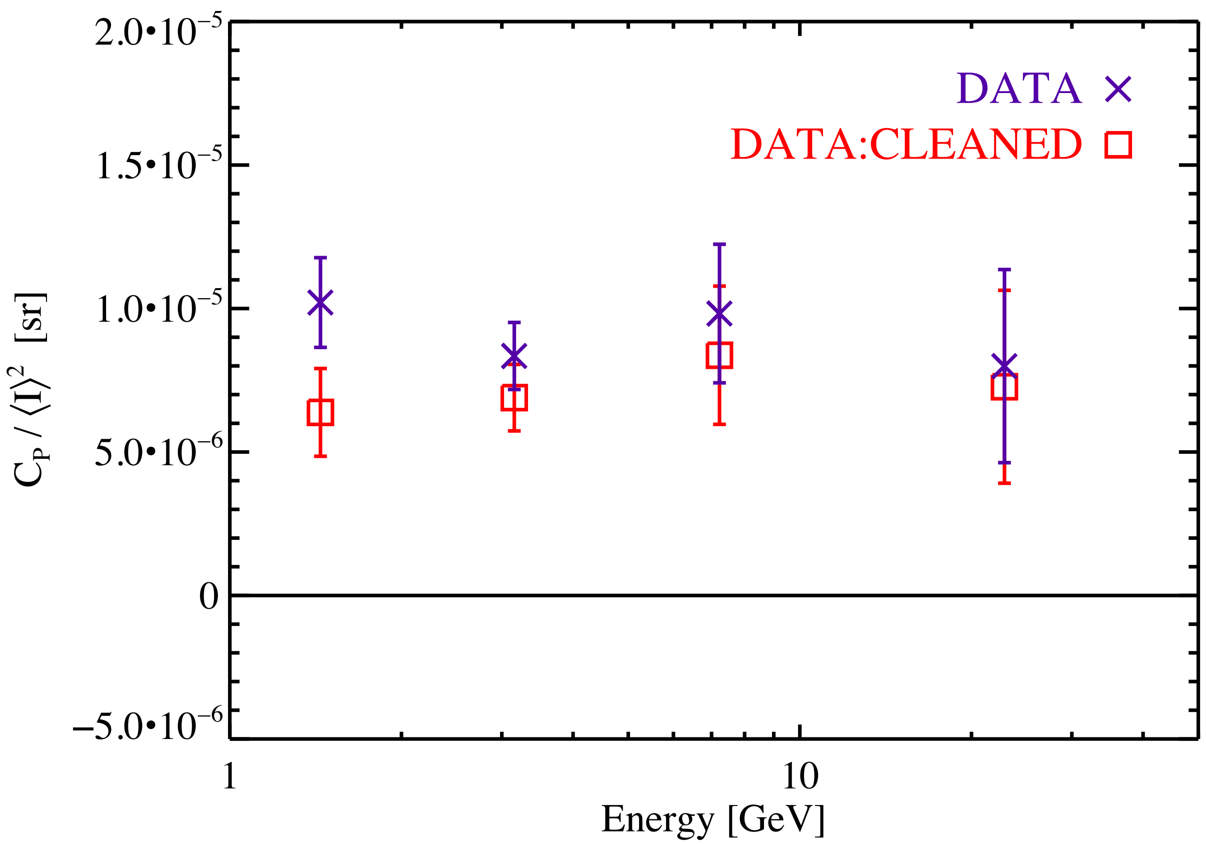
Fornasa, Zavala, Sanchez-Conde, JSG et al. 2012

- predictions derived from Millenium-II and Aquarius simulations and accurately account for redshifting and EBL attenuation for extragalactic DM, and secondary emission from Galactic DM
- the angular power spectrum of dark matter annihilation and decay falls off faster than Poisson at multipoles above ~ 100

Anisotropy constraints on dark matter

- small angular scale IGRB anisotropy measured for the first time with the Fermi LAT
- ~22 months of data
- angular power measurement constrains contribution of individual source classes, including DM, to the IGRB intensity

Fluctuation anisotropy energy spectrum



Ackermann et al. [Fermi LAT Collaboration] PRD 85, 083007 (2012)

Constraints from best-fit constant fluctuation angular power (l ≳ 150) measured in the data and foreground-cleaned data (1-50 GeV)

Source class	Predicted $C_{100}/\langle I \rangle^2$ [sr]	Maximum fraction of IGRB intensity DATA	DATA:CLEANED
Blazars	2×10^{-4}	21%	19%
Star-forming galaxies	2×10^{-7}	100%	100%
Extragalactic dark matter annihilation	1×10^{-5}	95%	83%
Galactic dark matter annihilation	5×10^{-5}	43%	37%
Millisecond pulsars	3×10^{-2}	1.7%	1.5%

The IGRB

1. spectrally: DM signal must be subdominant since a spectral signature is not obvious in the IGRB energy spectrum

2. spatially: signal and backgrounds are mostly isotropic but with potentially different small-scale features; future improved angular resolution could help distinguish contributions

3. know your backgrounds and impostor signals better: pinning down contribution from astrophysical sources could significantly improve dark matter sensitivity; sensitivity will increase regardless as more sources are resolved

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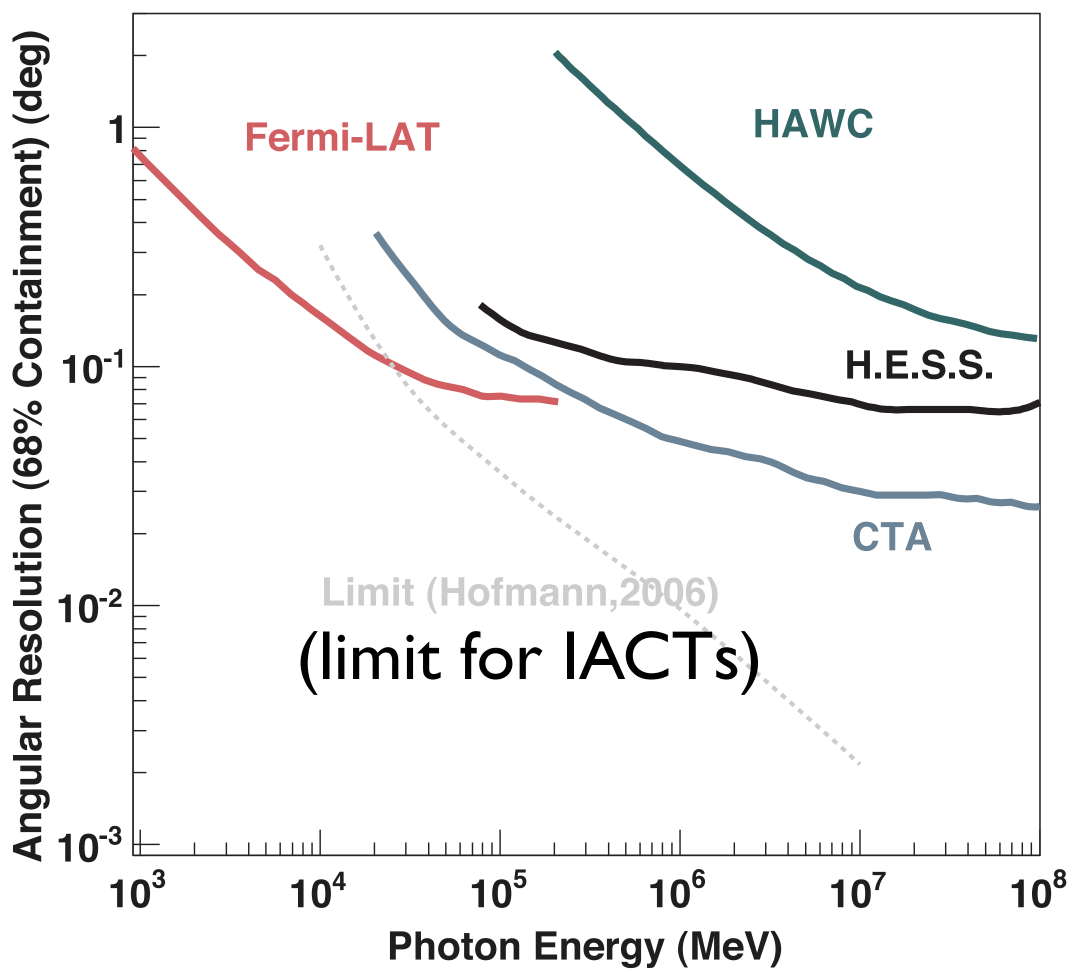
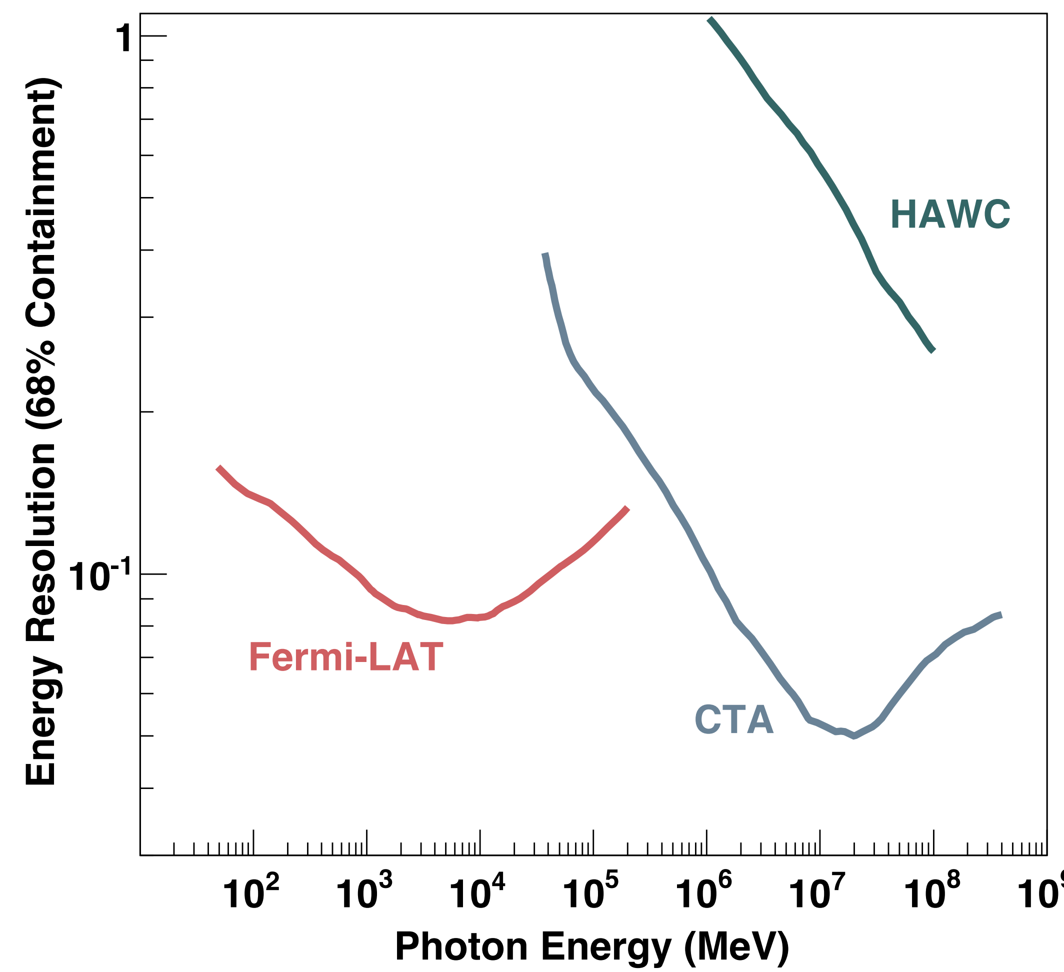
Summary

- multiwavelength studies can provide important clues about both dark matter and astrophysical sources
- improved angular resolution of future gamma-ray instruments may be key to disentangling a dark matter signal by separating emission regions, associating astrophysical sources, and mapping spatial signatures of a dark matter signal
- continued large-area survey in gamma rays will improve dark matter sensitivity by reducing IGRB and constraining other contributors

Additional slides

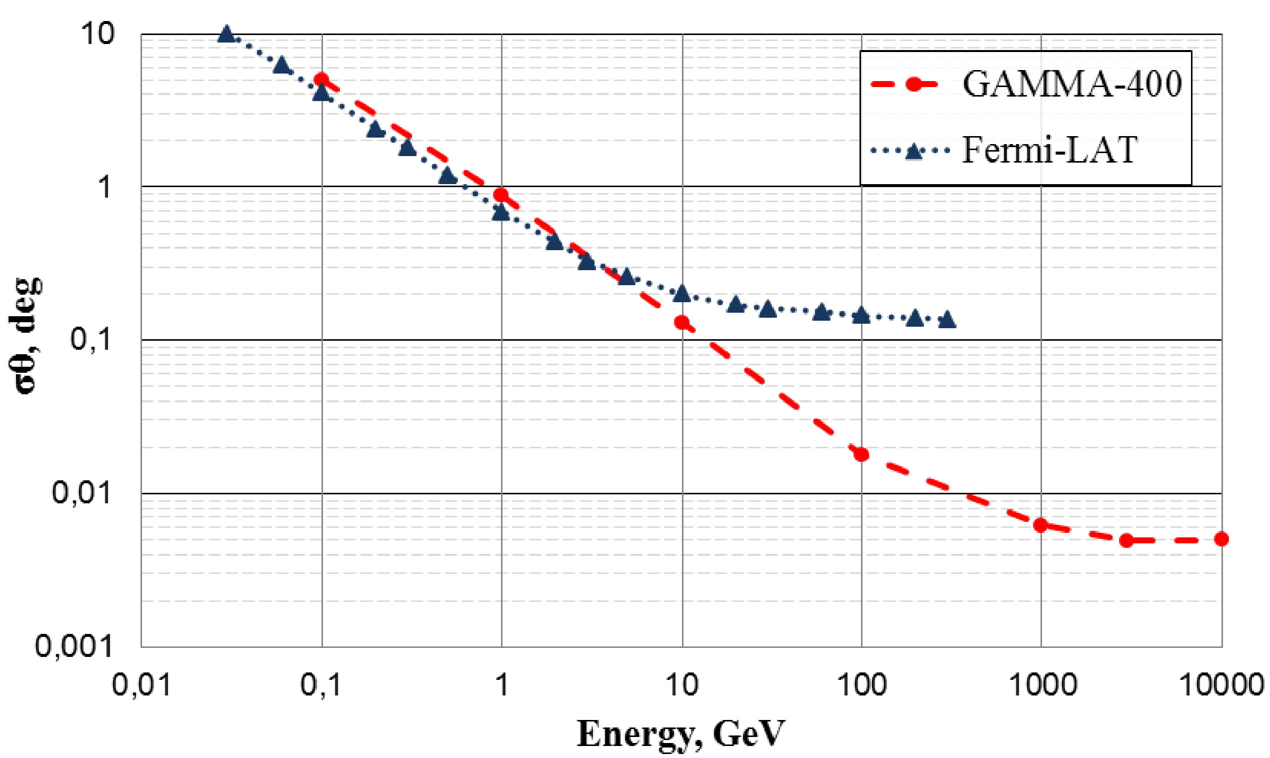
Current and future capabilities

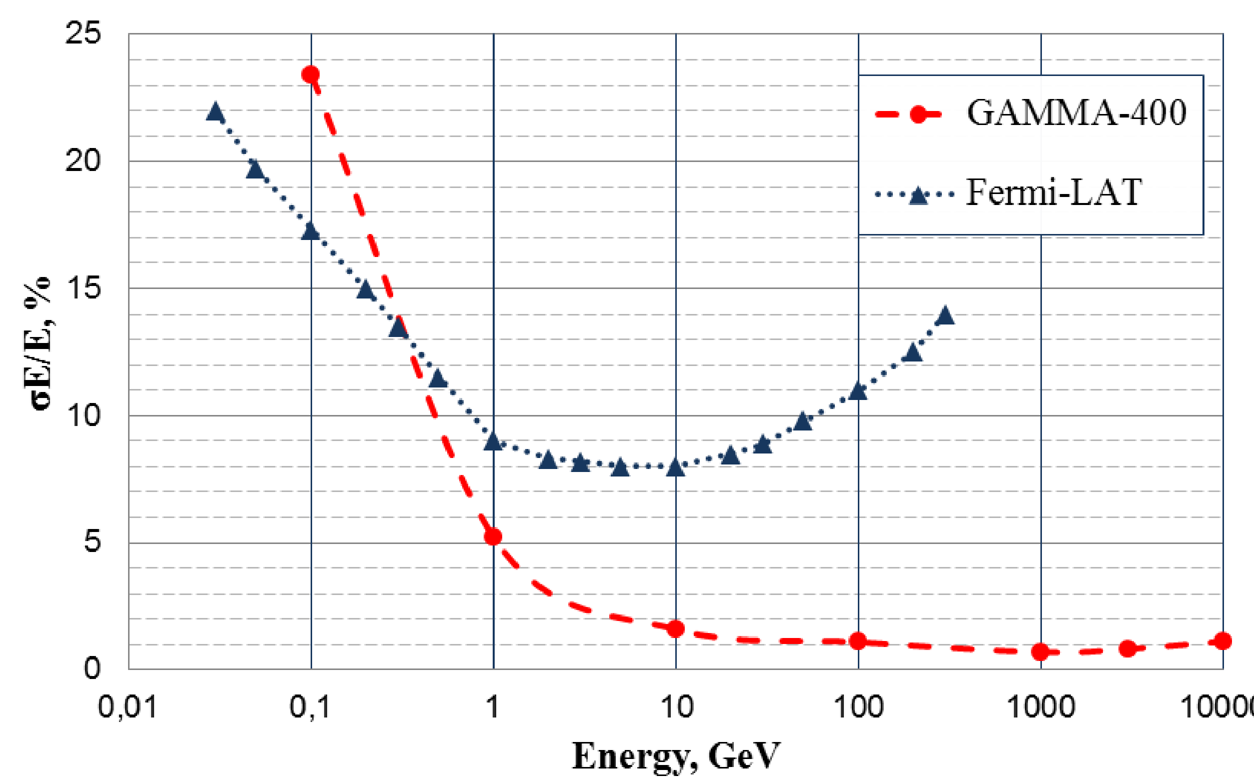




Funk et al. 2012

Fermi LAT and GAMMA-400 capabilities





Galper et al. 2012

but, GAMMA-400 has a smaller effective area and FOV

Comparison of gamma-ray experiments

	Space-based experiments			Ground-based experiments		
	Fermi	**AMS-2**	**GAMMA-400**	**H.E.S.S.-II**	**MAGIC**	**CTA**
Energy range, GeV	0.02-300	10-1000	**0.1-3000**	> 30	> 50	> 20
Field-of-view, sr	2.4	0.4	**~1.2**	0.01	0.01	0.1
Effective area, m^2	0.8	0.2	**~0.4**	10^5	10^5	10^6
Angular resolution (E_γ > 100 GeV)	0.2º	1.0º	**~0.01º**	0.07º	0.05º	0.06º
Energy resolution (E_γ > 100 GeV)	10%	2%	**~1%**	15%	15%	10%

Galper et al. 2012

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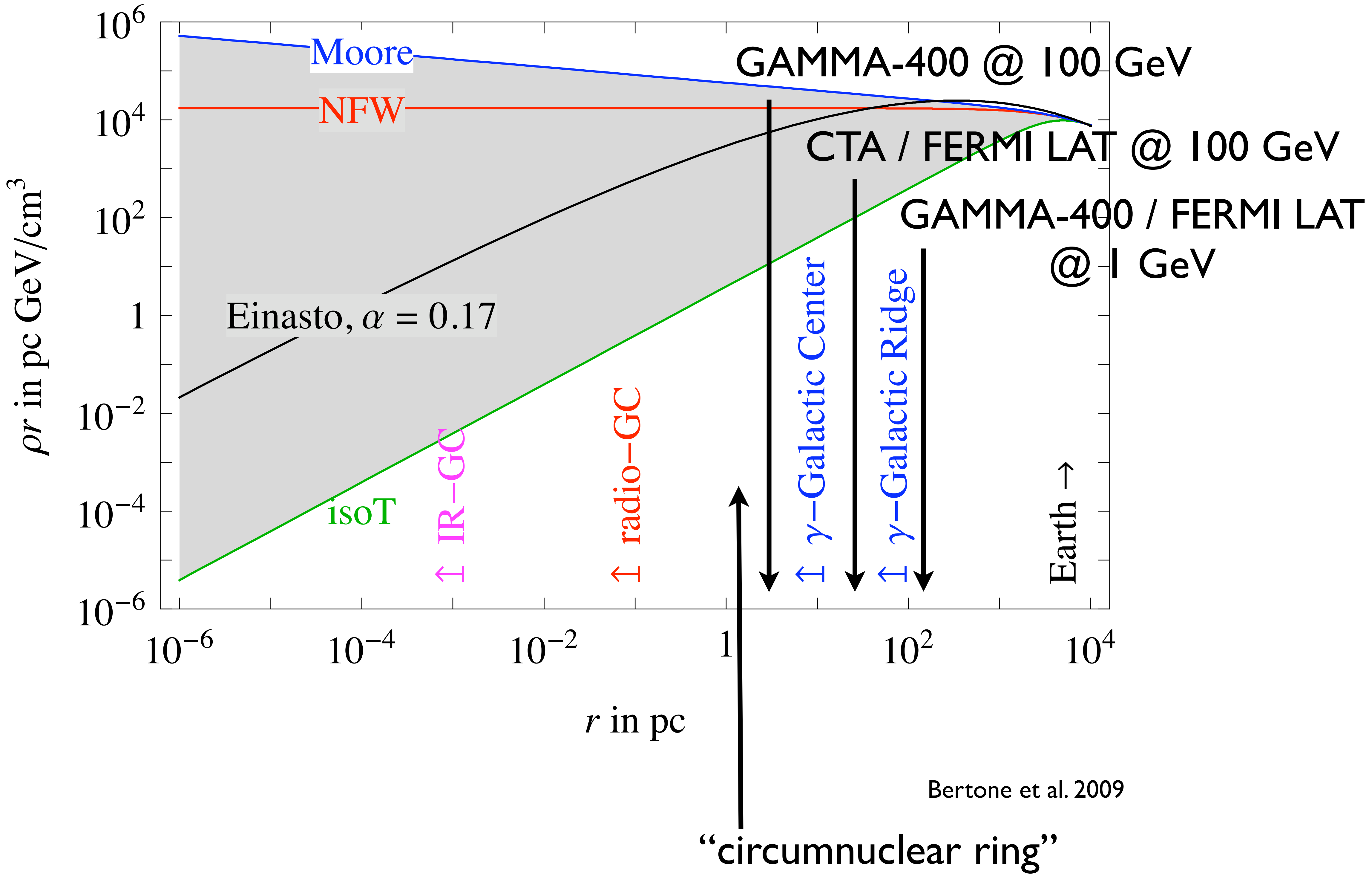
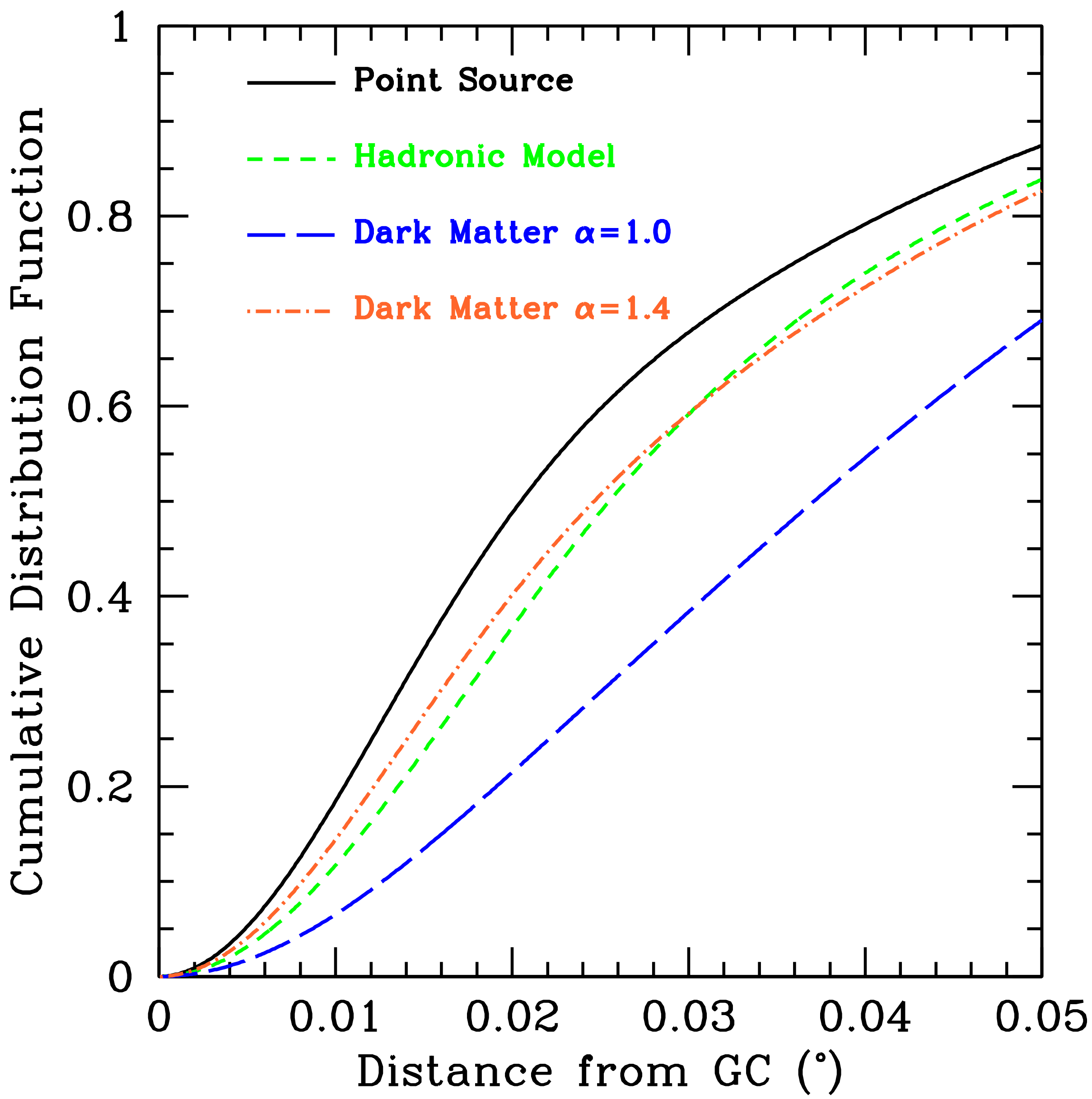
Galper et al. 2012

Dark matter in the inner galaxy

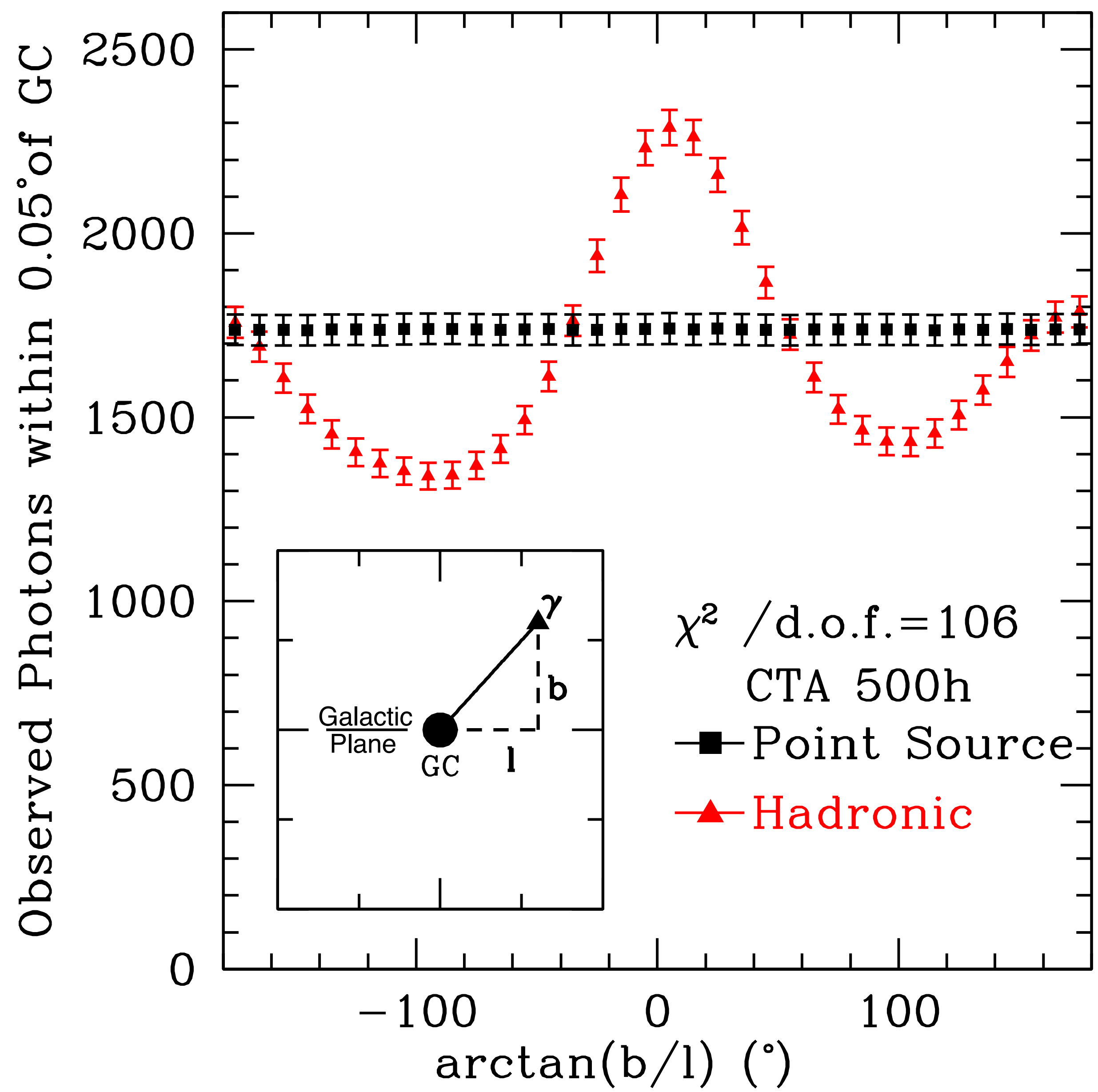


Point source or extended emission?
Testing this hypothesis with CTA

Cumulative counts



Azimuthal counts distribution



Linden & Profumo 2012

The angular power spectrum

$$I(\psi) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\psi) \qquad C_\ell = \langle |a_{\ell m}|^2 \rangle$$

- intensity angular power spectrum: C_ℓ
  - indicates *dimensionful* amplitude of anisotropy
- fluctuation angular power spectrum: $\frac{C_\ell}{\langle I \rangle^2}$
  - *dimensionless*, independent of intensity normalization
  - amplitude for a single source class is the same in all energy bins (if all members have same energy spectrum)

Angular power spectra of unresolved gamma-ray sources

- the angular power spectrum of many gamma-ray source classes (except dark matter) is dominated by the Poisson (shot noise) component for multipoles greater than ~ 10
- Poisson angular power arises from unclustered point sources and <u>takes the same value at all multipoles</u>

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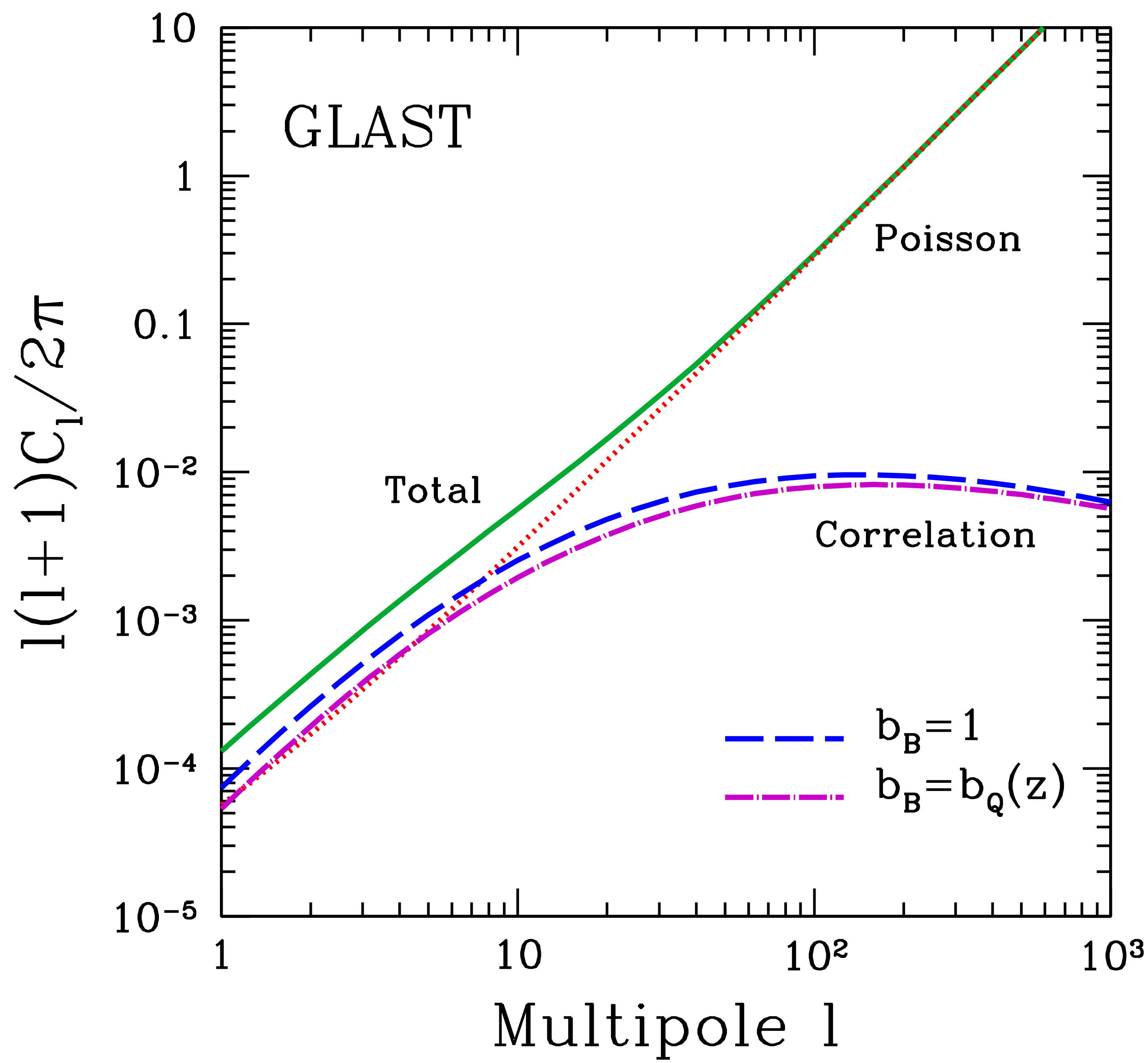
Predicted angular power spectrum of unresolved blazars



Ando, Komatsu, Narumoto & Totani 2007

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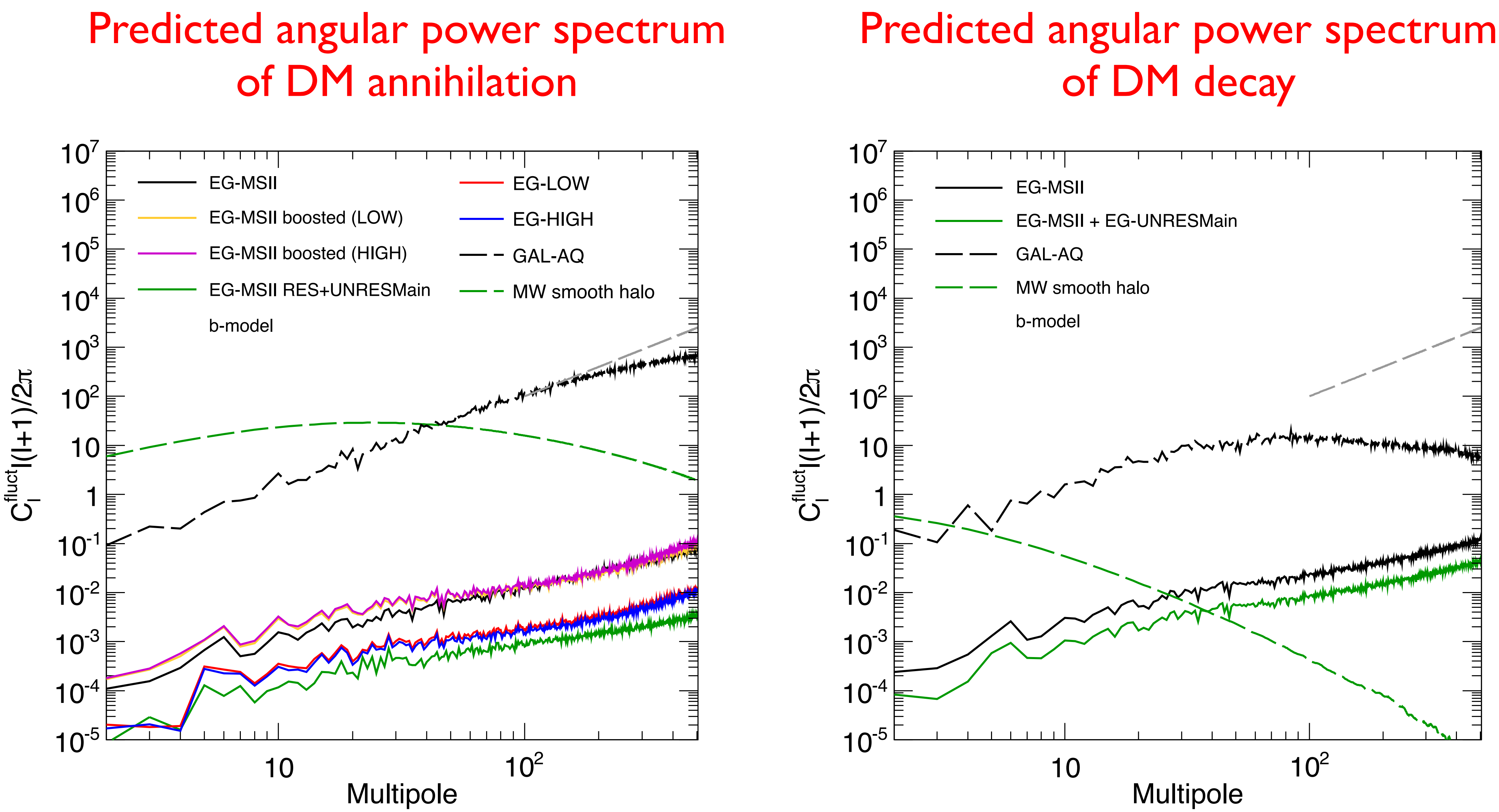
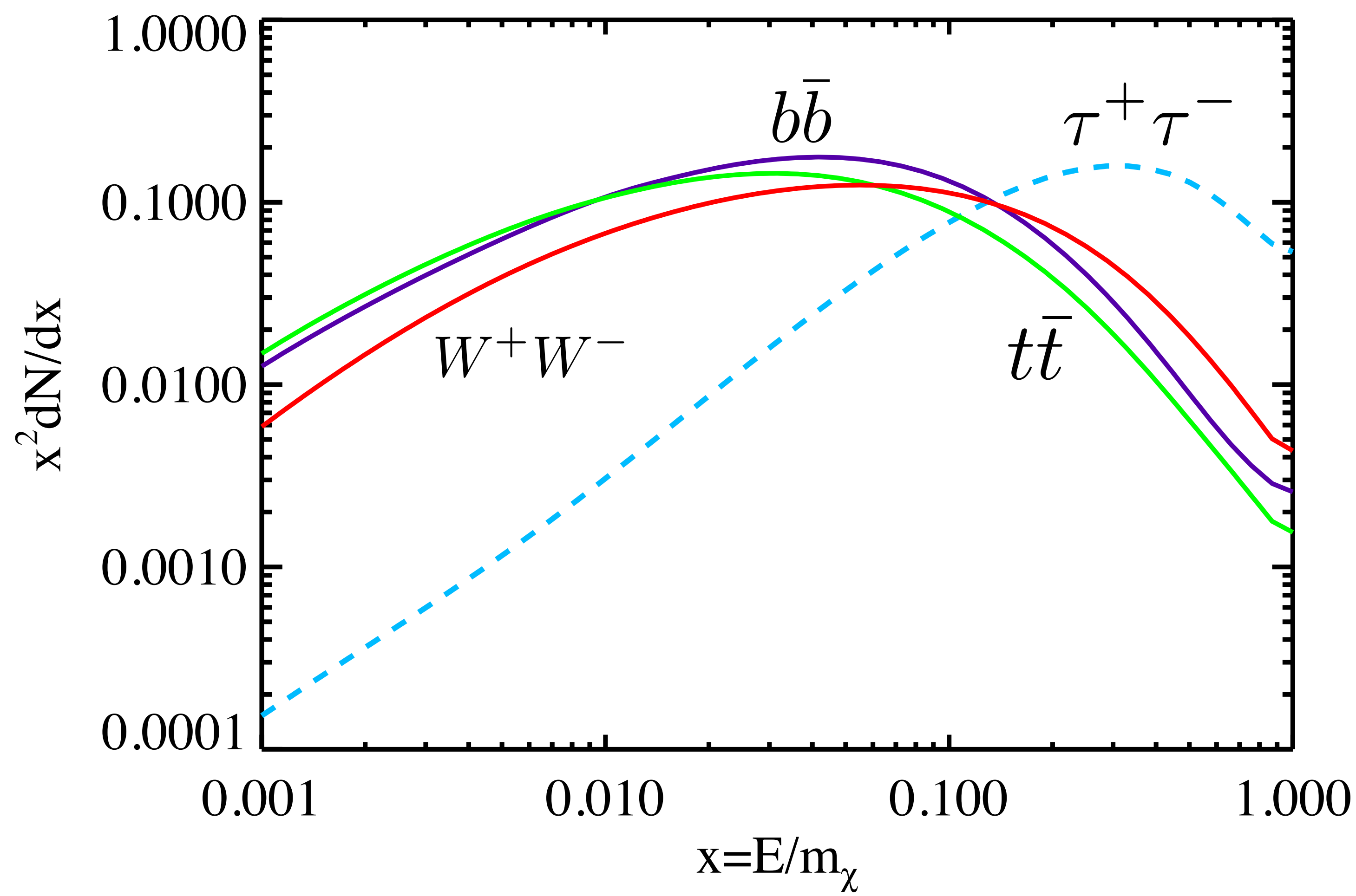


Fornasa, Zavala, Sanchez-Conde et al. 2012

- the angular power spectrum of dark matter annihilation and decay falls off faster than Poisson at multipoles above ~ 100
- current measurement uncertainties are too large to identify a dark matter component via scale dependence; may be possible with future measurements

Energy spectra

- dark matter gives bumps, lines, cut-offs
- many astrophysical sources make power laws and may have exponential cut-offs
- some astrophysical sources (e.g., pulsars) also give bumps



Spectra calculated with PPPC 4 DM ID [Cirelli et al. 2010]

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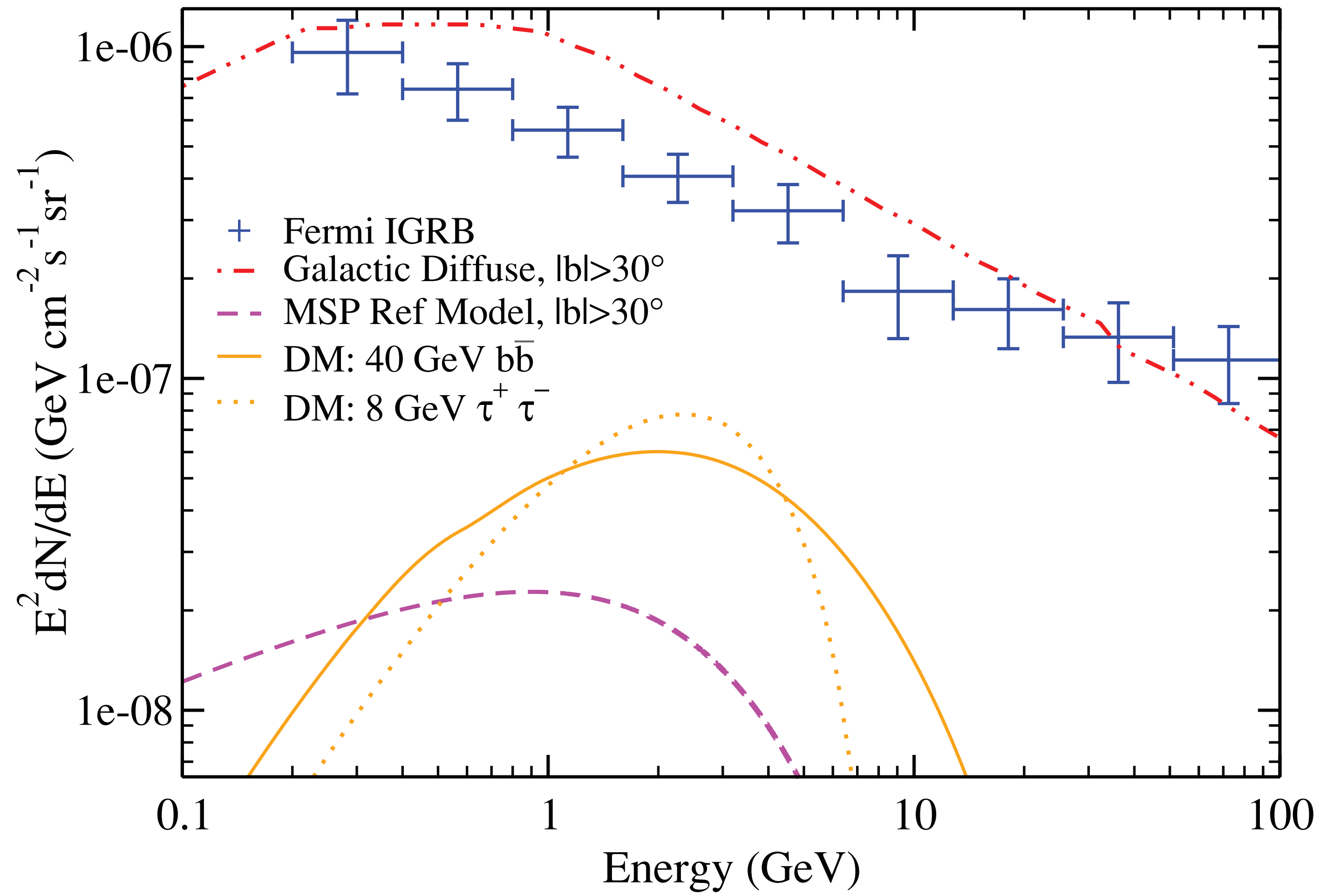

JSG et al. MNRAS 415, 1074–1082 (2011)

Detecting unresolved sources with anisotropies

- diffuse emission that originates from one or more unresolved source populations will contain fluctuations on small angular scales due to variations in the number density of sources in different sky directions
- the amplitude and energy dependence of the anisotropy can reveal the presence of multiple source populations and constrain their properties

Anisotropy is another IGRB observable!!!