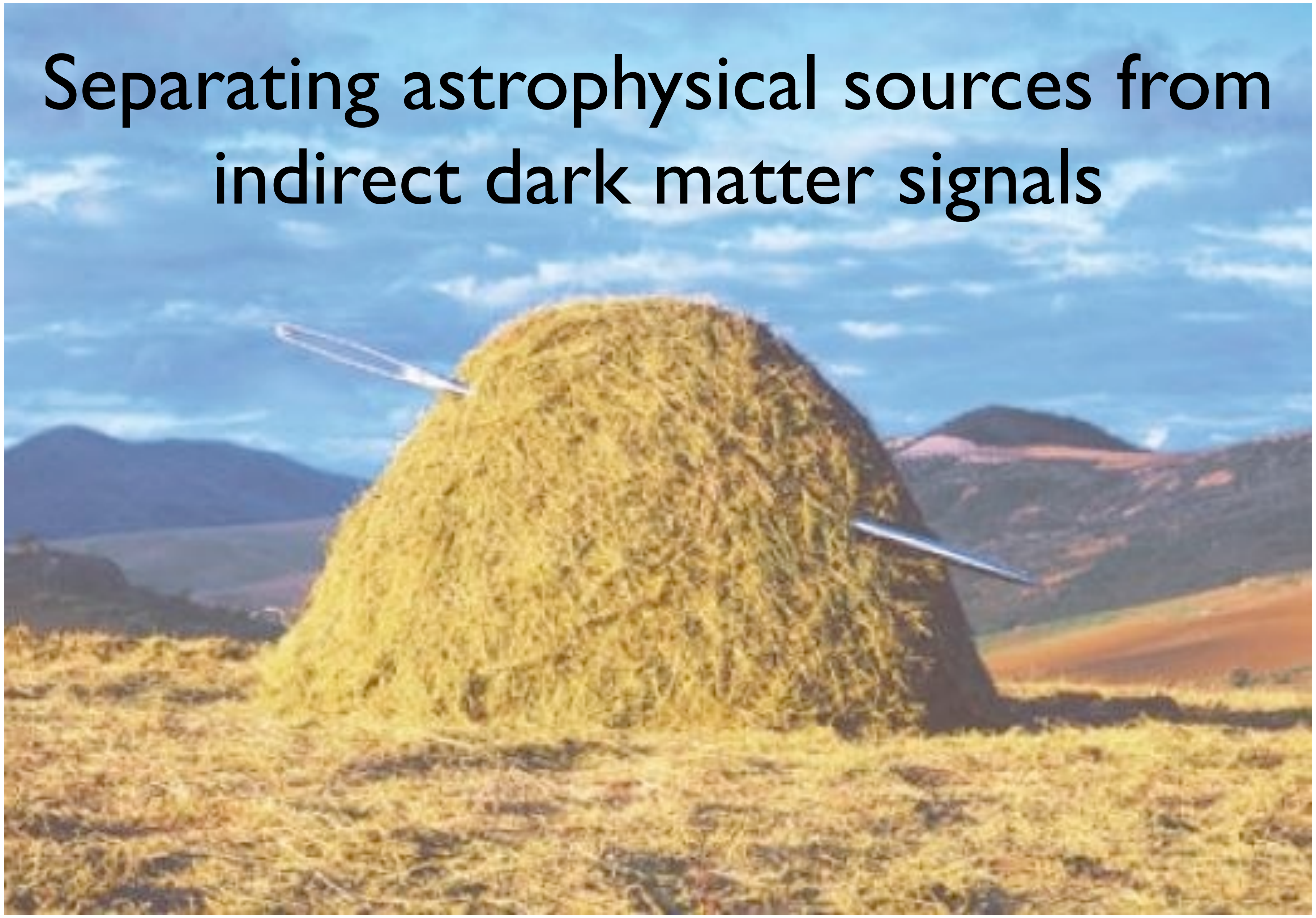
Separating astrophysical sources from indirect dark matter signals



Jennifer Siegal-Gaskins
Caltech

The nature of dark matter

Observational evidence indicates:

- non-baryonic
- neutral
- virtually collisionless

Additional assumptions for this talk:

- dark matter is a weakly-interacting massive particle (WIMP)
- GeV - TeV mass scale
- can pair annihilate or decay to produce standard model particles
- accounts for the measured dark matter density

The challenge

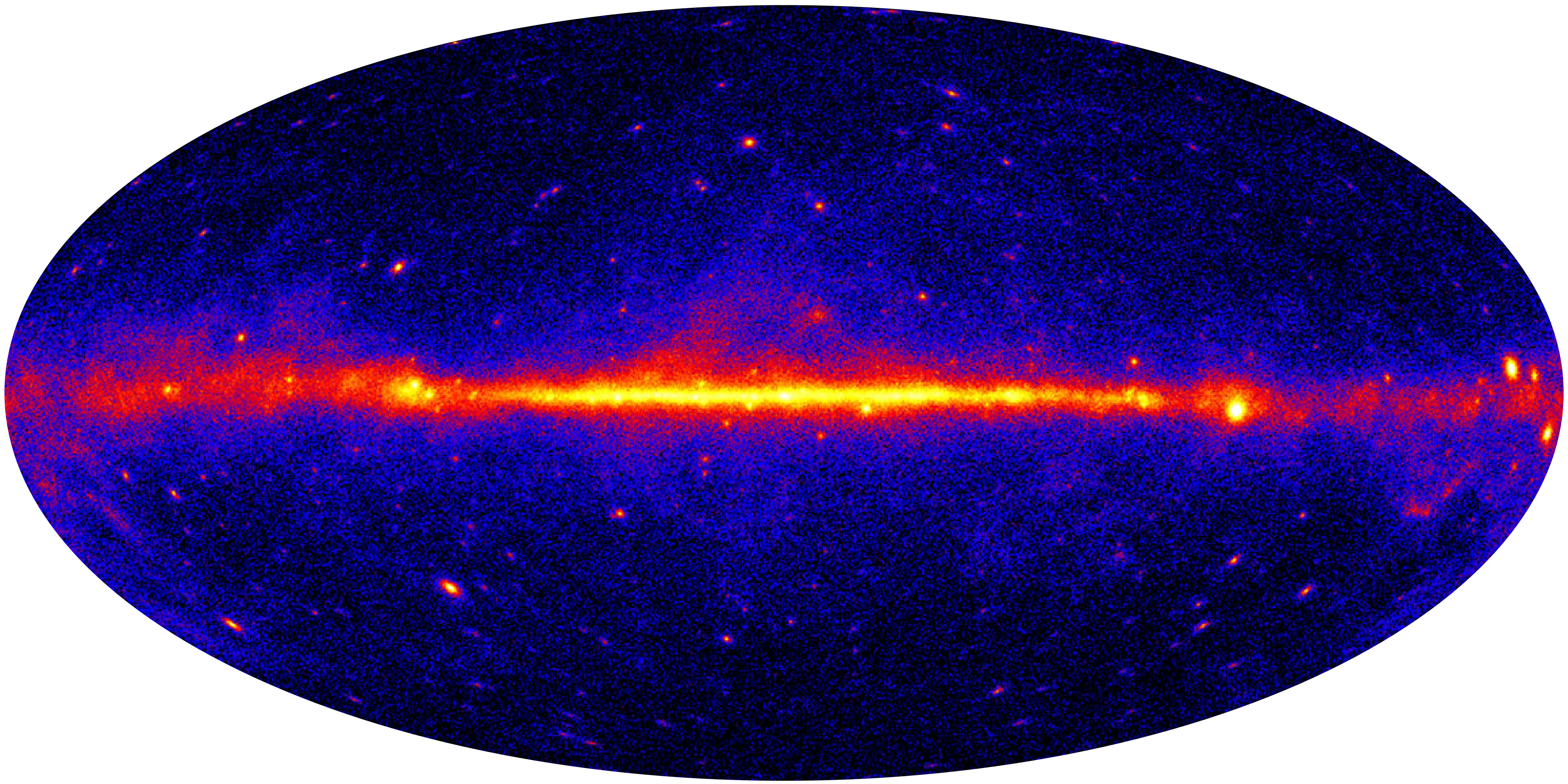
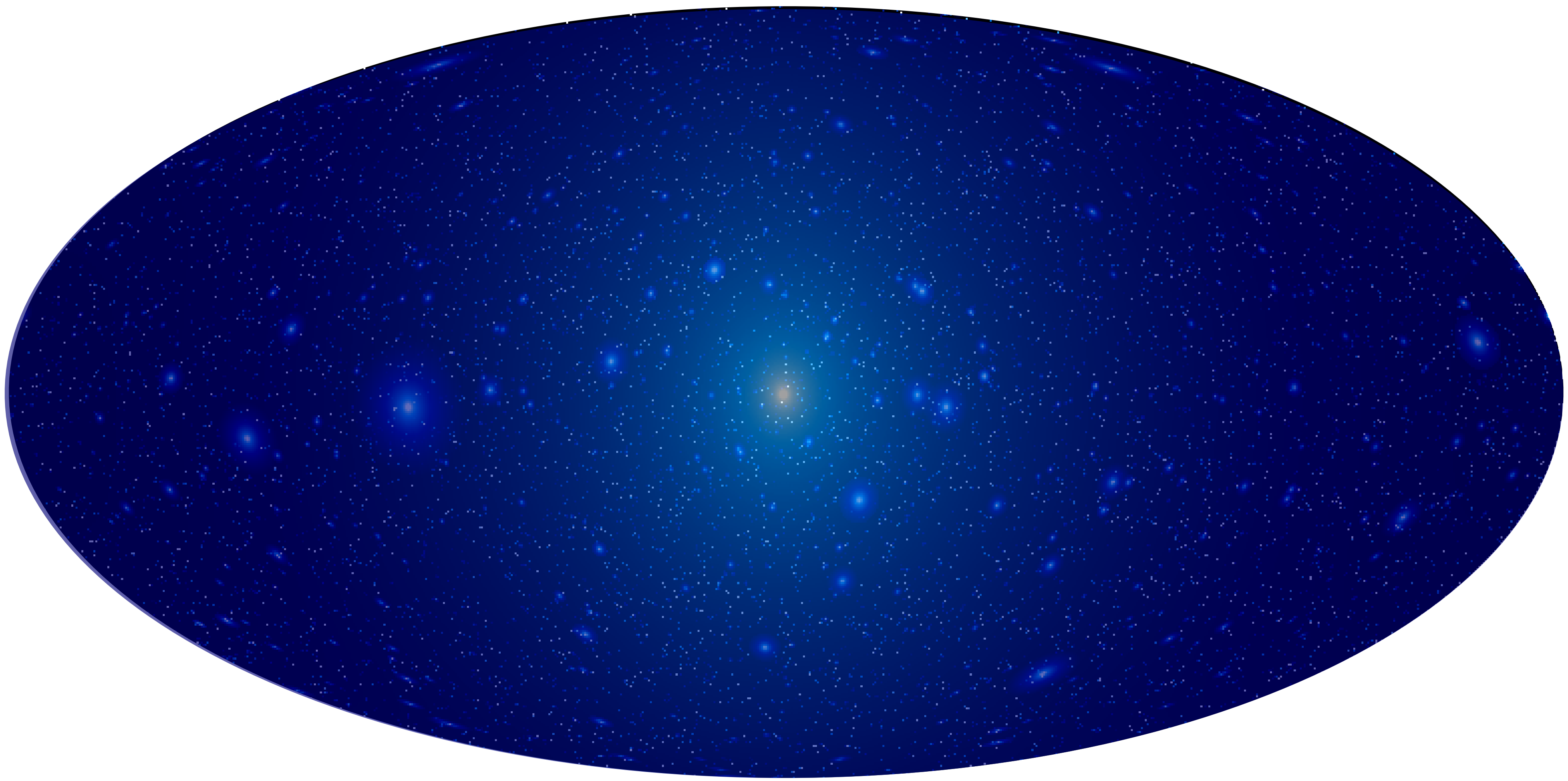


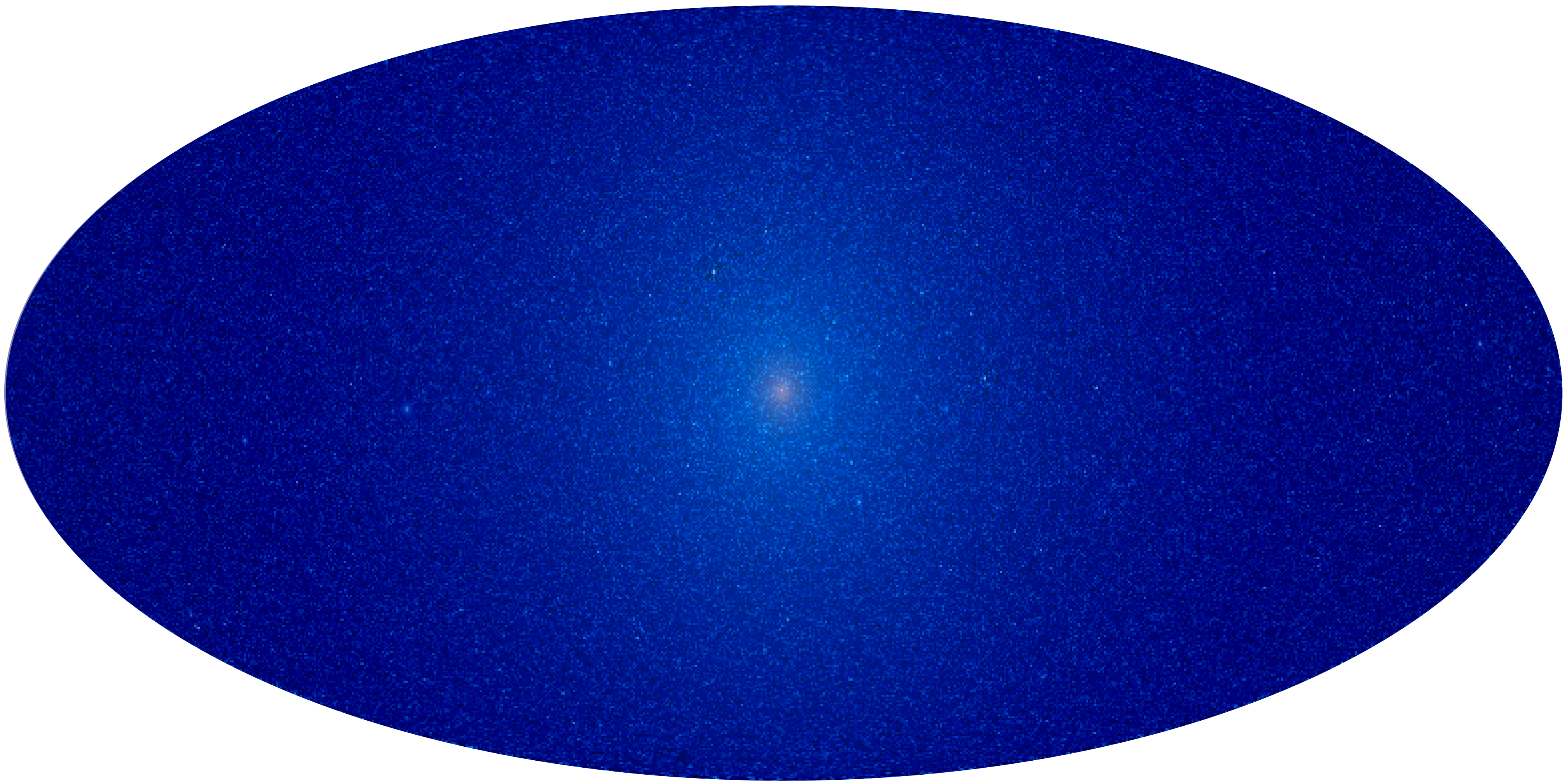
Image Credit: NASA/DOE/International LAT Team

The challenge



JSG 2008

The challenge



The challenge

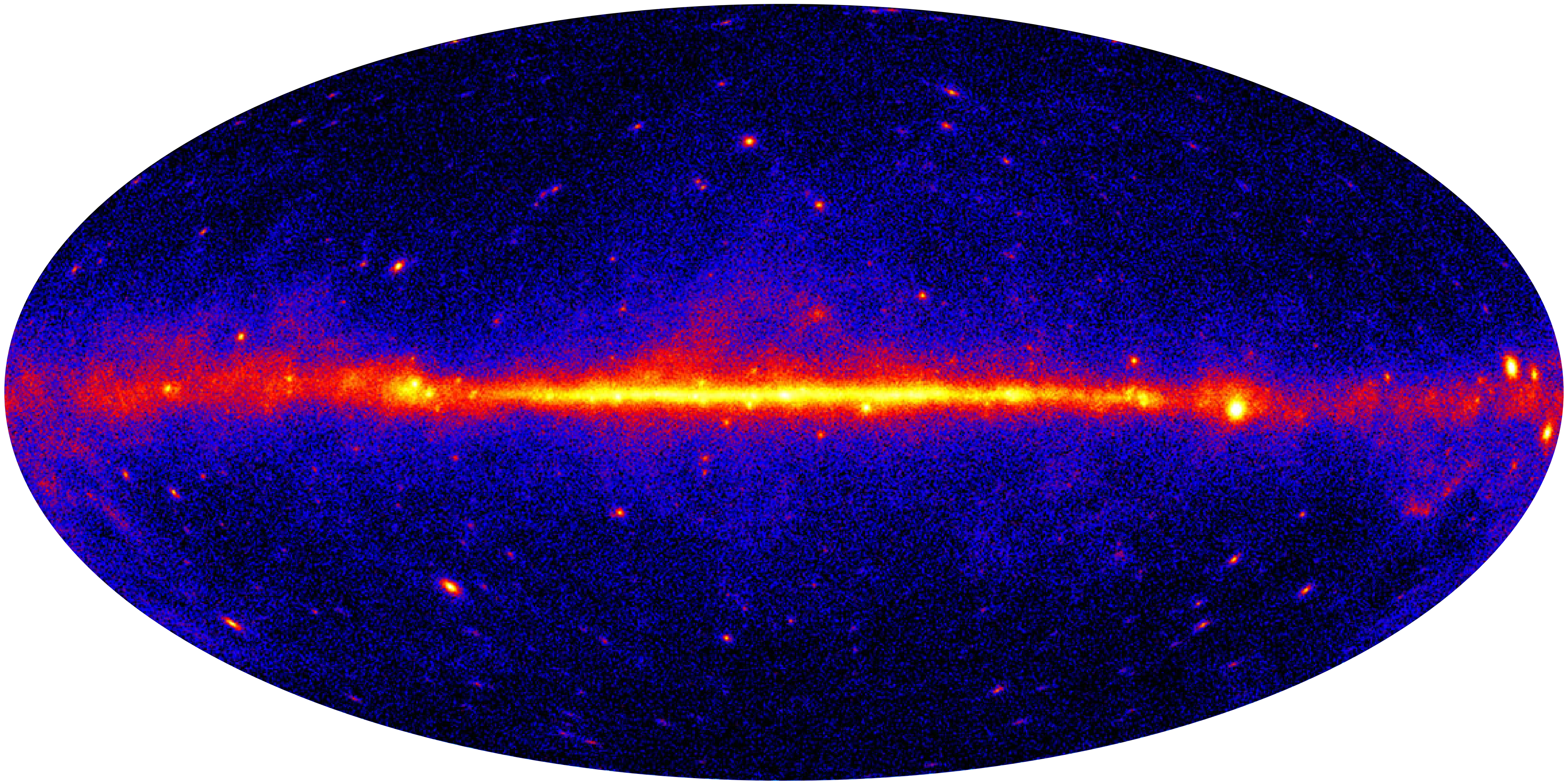


Image Credit: NASA/DOE/International LAT Team

The challenge

The challenge

The challenge

The challenge

The challenge

The challenge

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

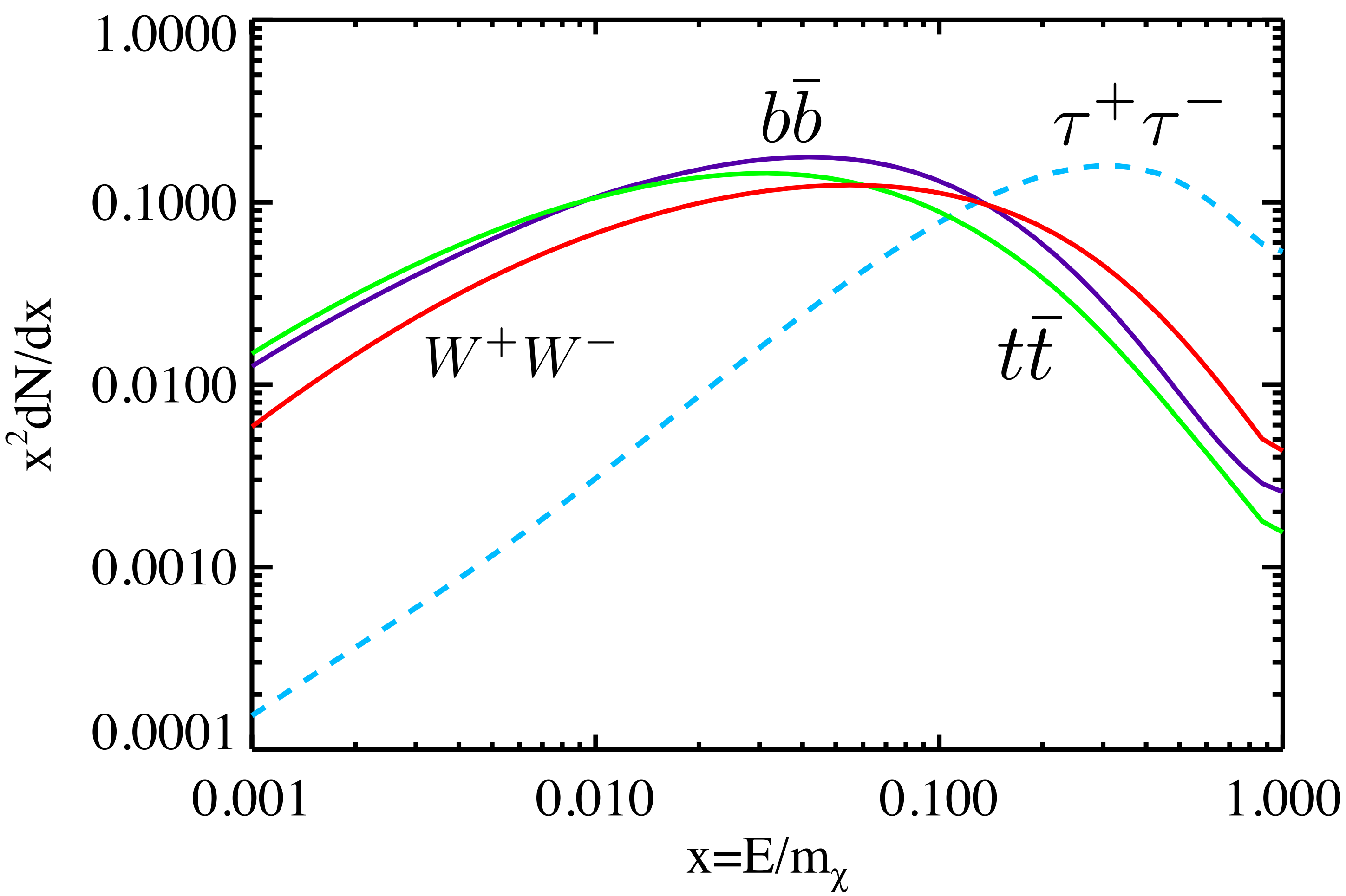
- the "best" approach depends on both the expected dark matter signal and the target source or emission
- complementarity is key for making the most of the data: info from other dark matter searches (indirect and otherwise) and from studies of astrophysical sources is essential
  - multiwavelength (and 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

Energy spectra

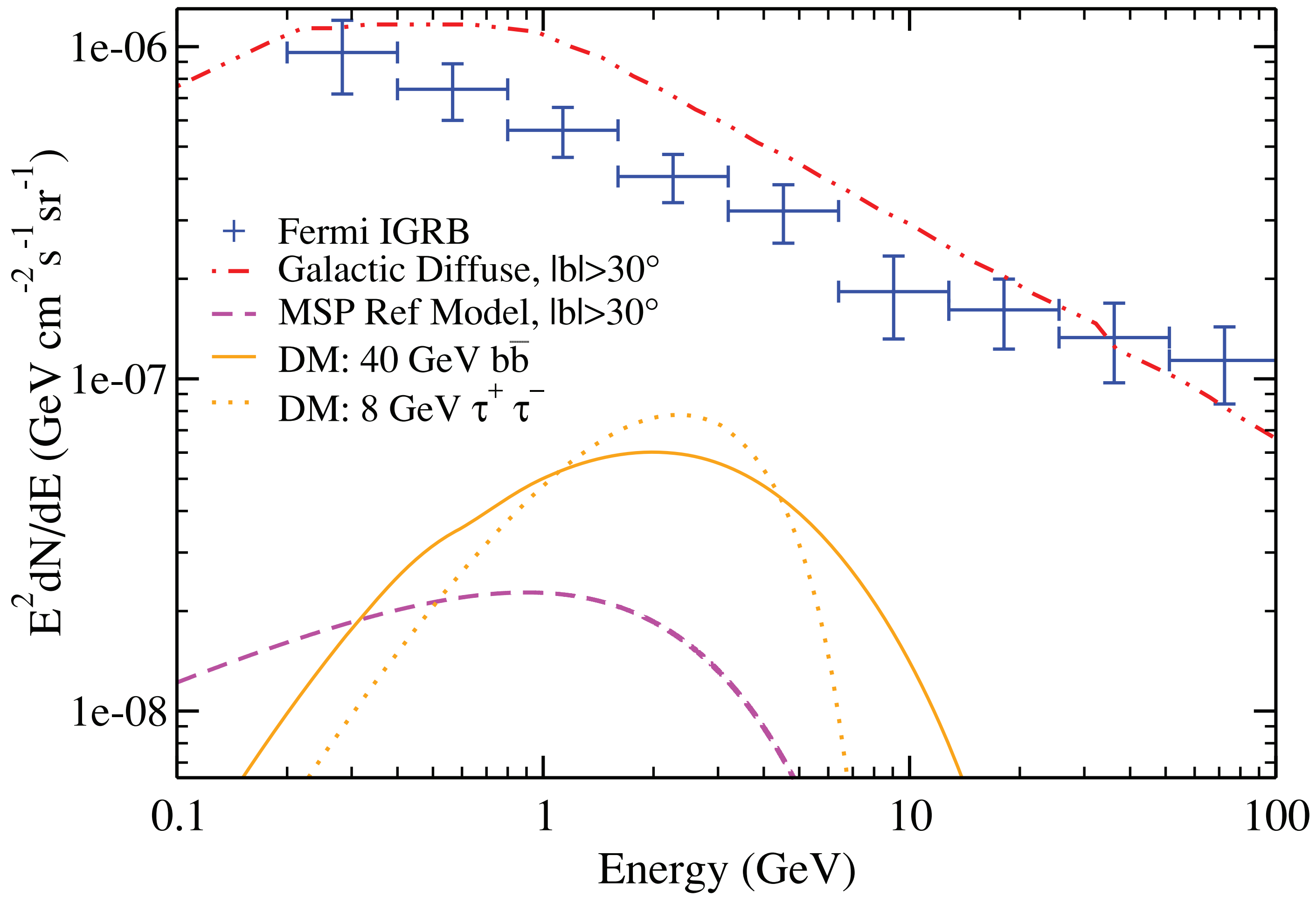
- dark matter gives bumps, lines, cut-offs
- many astrophysical sources make power laws and may have exponential cut-offs
- some astrophysical sources (e.g., pulsars) also give bumps



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

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

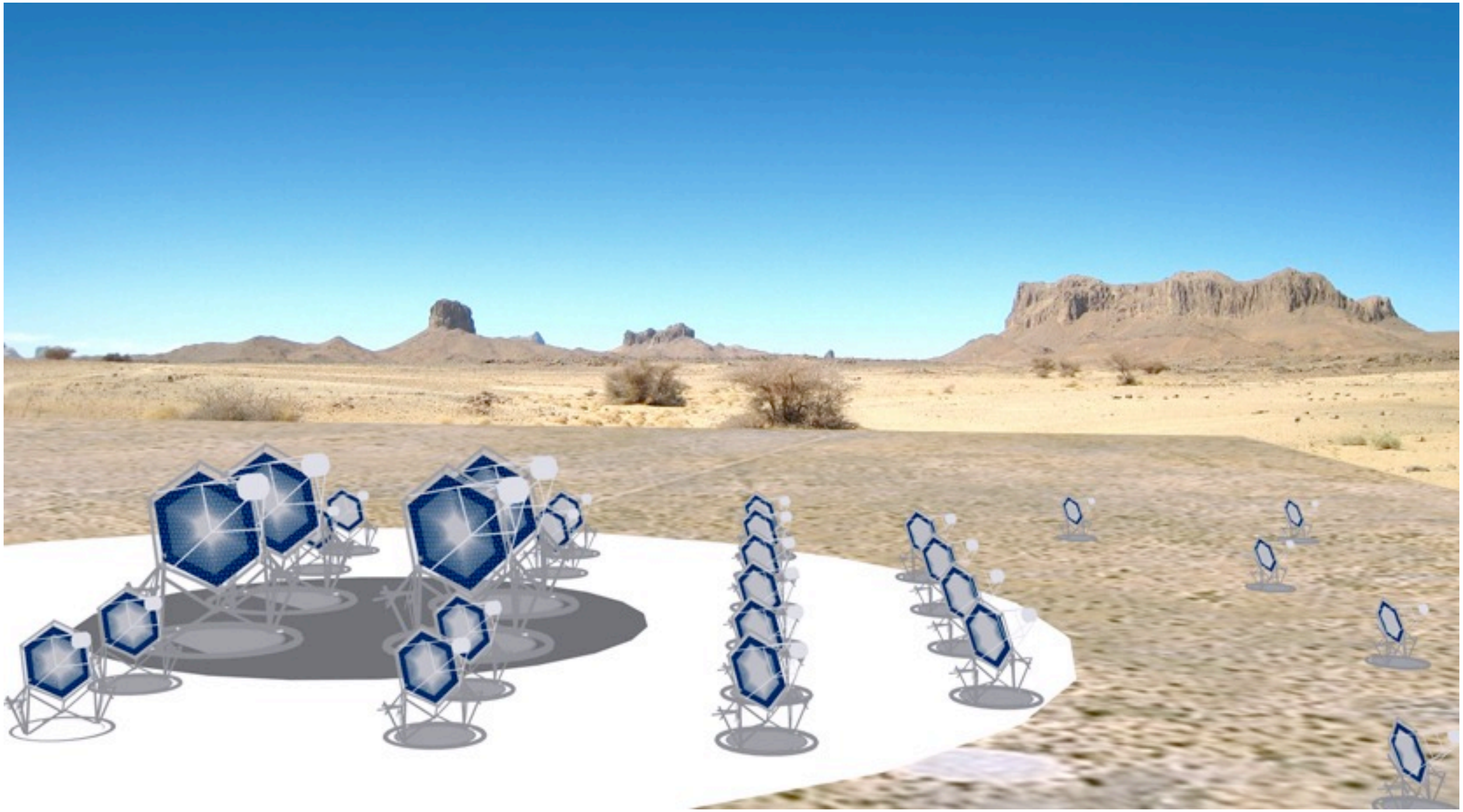


JSG et al. MNRAS 415, 1074–1082 (2011)

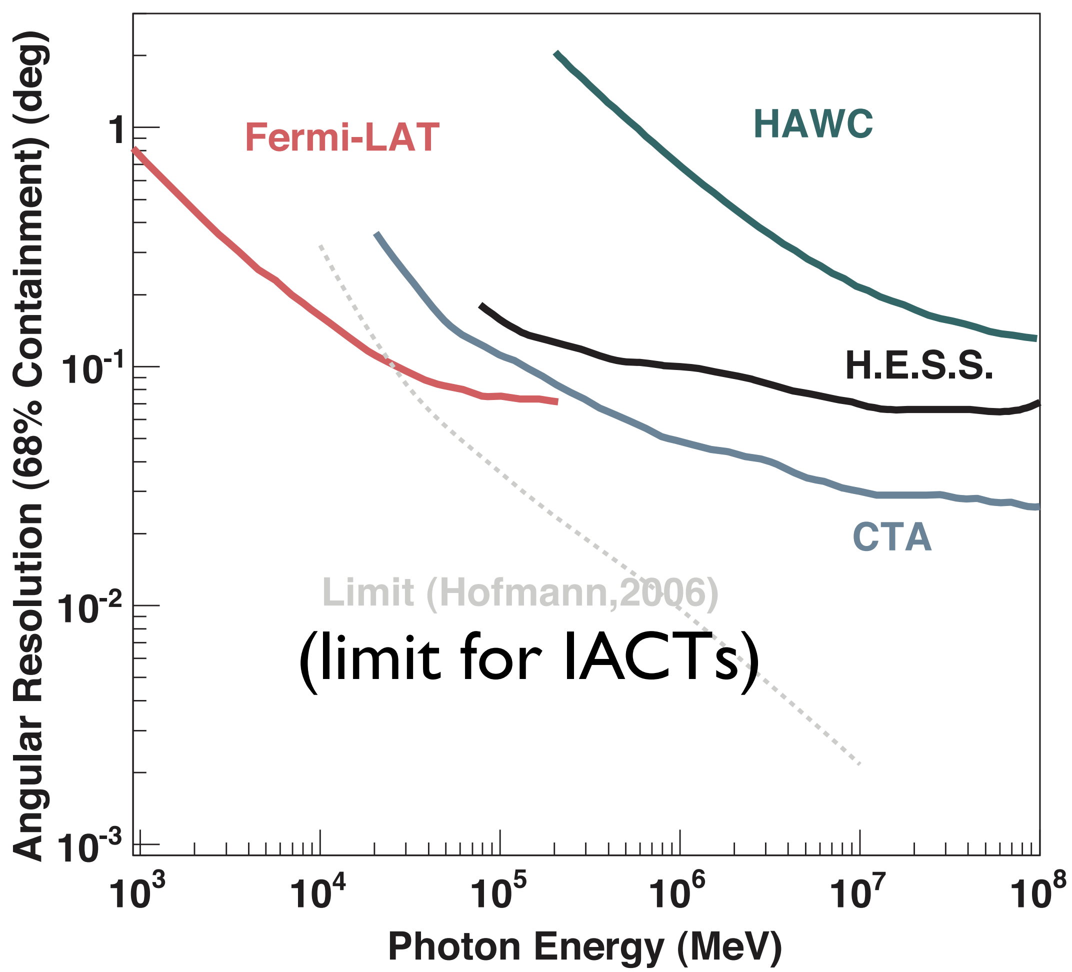
The Fermi Large Area Telescope (LAT)

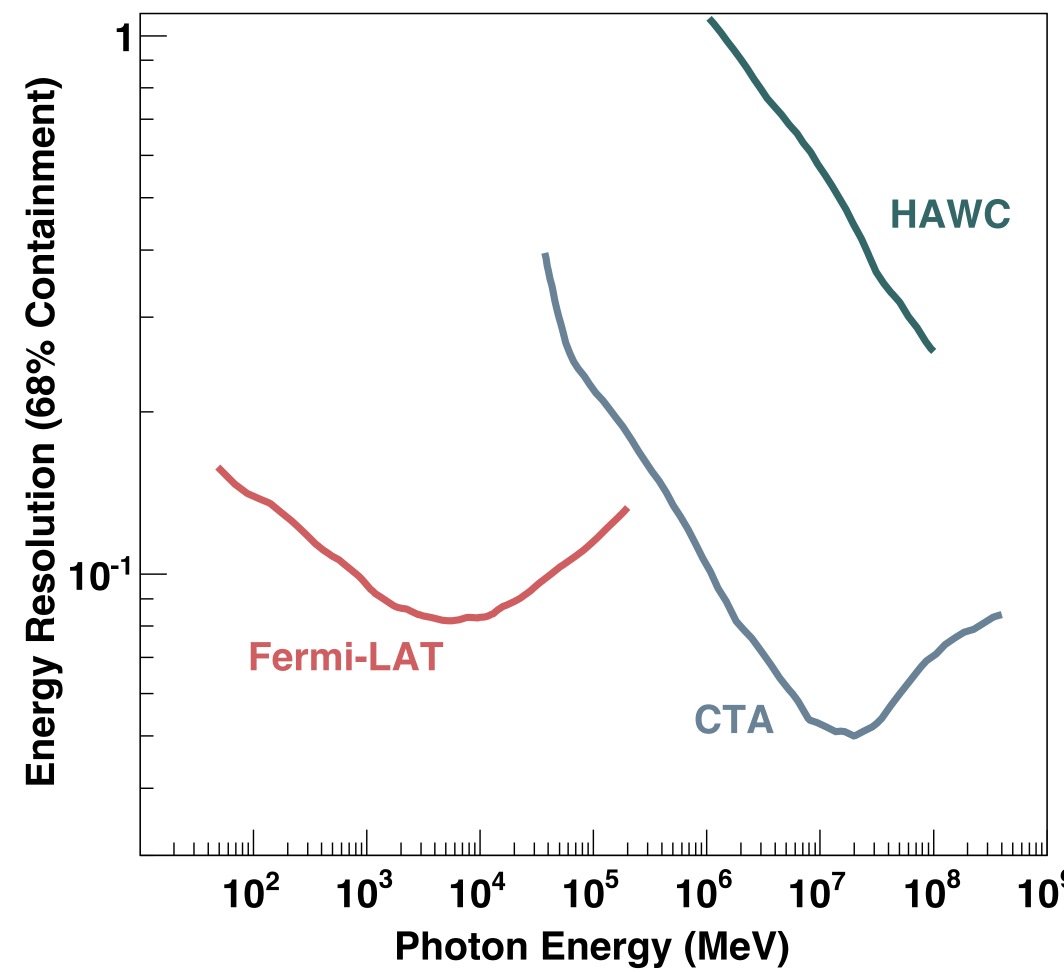
Credit: NASA/General Dynamics

The Cherenkov Telescope Array (CTA)



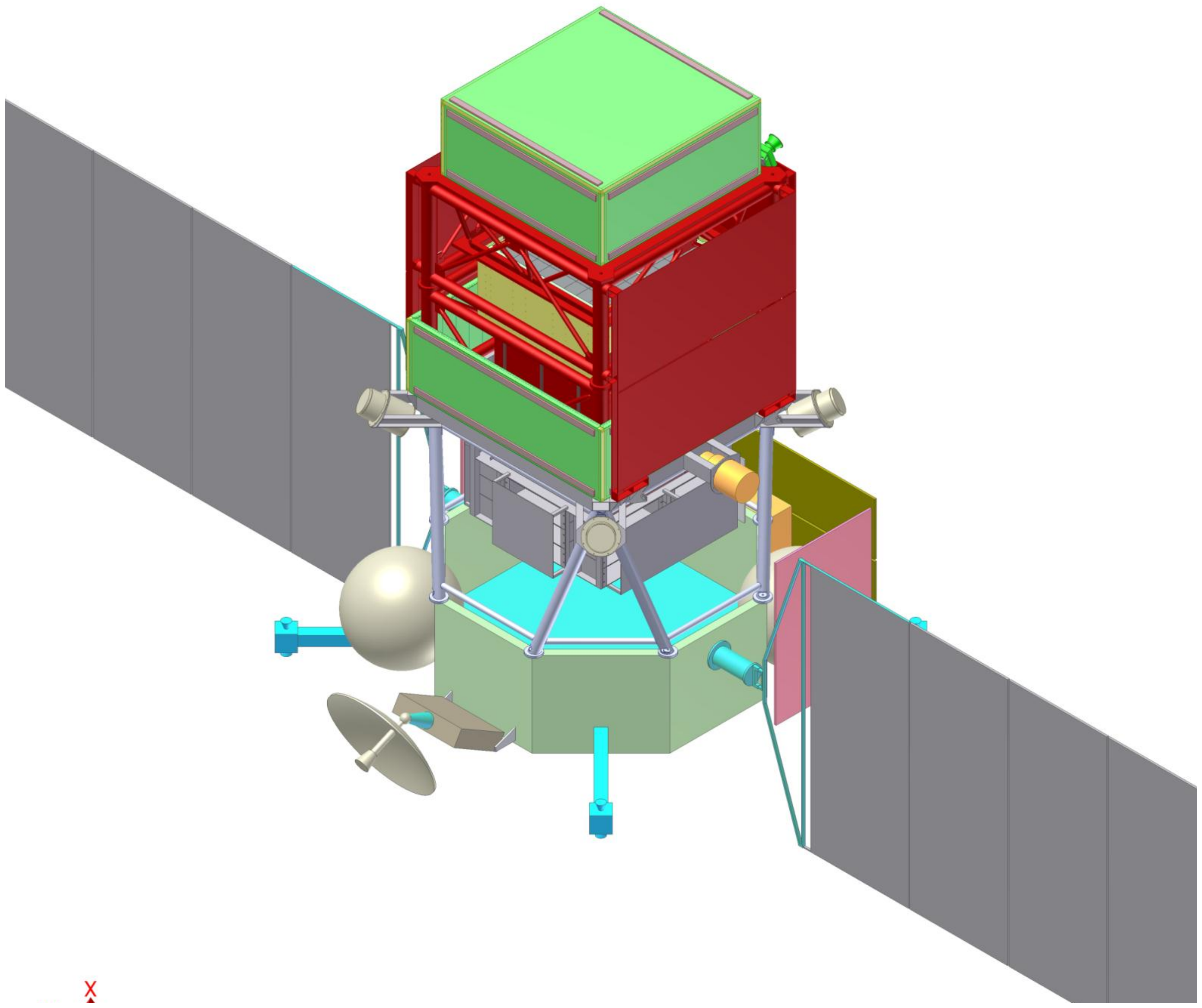
Current and future capabilities





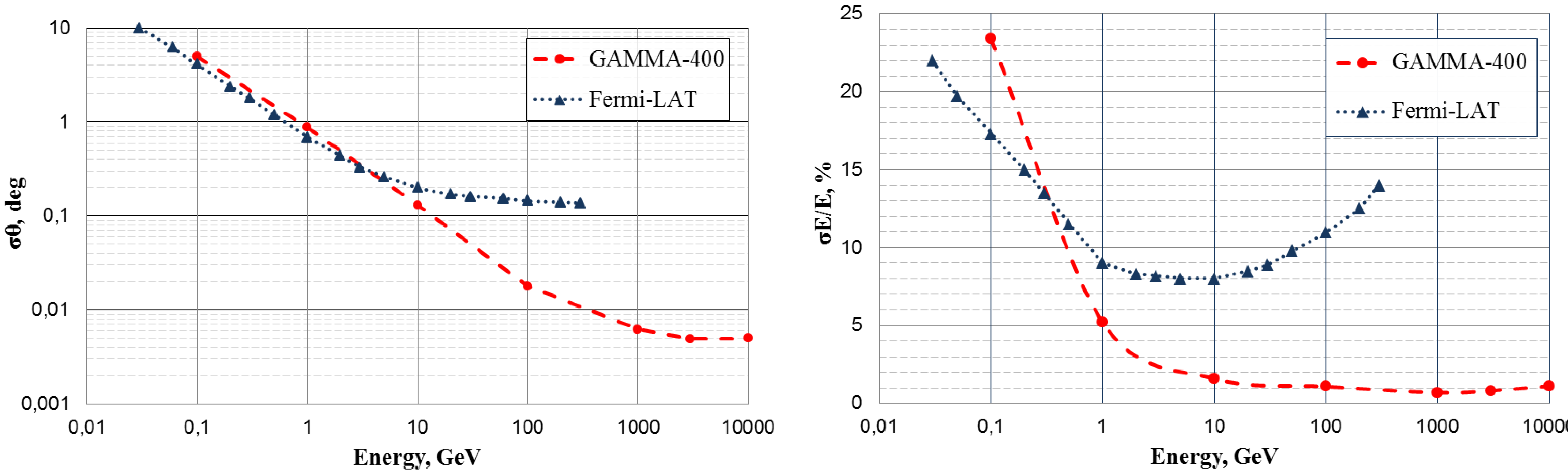
Funk et al. 2012

GAMMA-400



launch scheduled for 2018

Fermi LAT and GAMMA-400 capabilities



Galper et al. 2012

but, GAMMA-400 has a smaller effective area

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

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)	0.2°	1.0°	**~0.01°**	0.07°	0.05°	0.06°
Energy resolution (E_γ > 100 GeV)	10%	2%	**~1%**	15%	15%	10%

Galper et al. 2012

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)	0.2°	1.0°	**~0.01°**	0.07°	0.05°	0.06°
Energy resolution (E_γ > 100 GeV)	10%	2%	**~1%**	15%	15%	10%

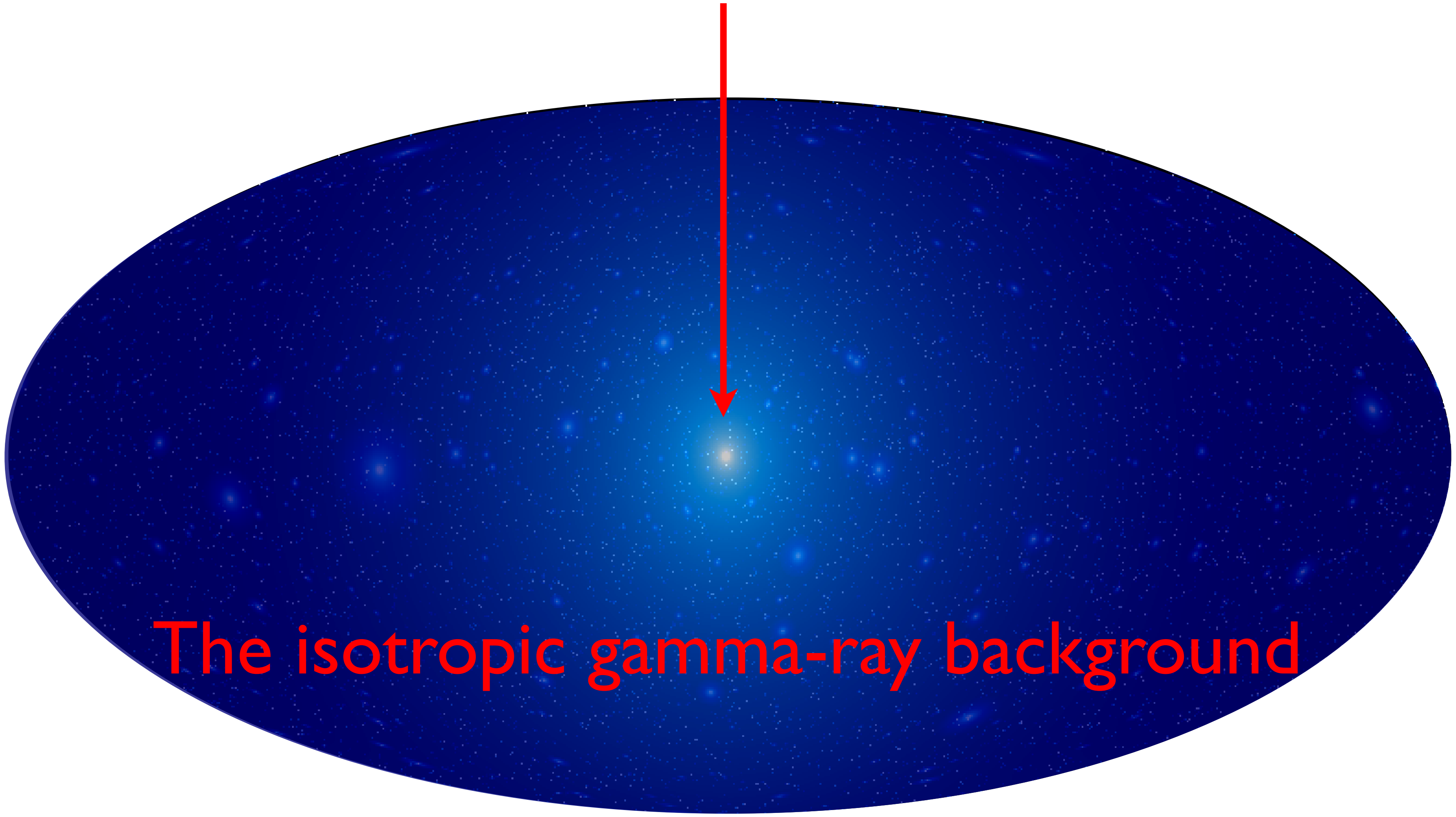
Galper et al. 2012

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)	0.2°	1.0°	**~0.01°**	0.07°	0.05°	0.06°
Energy resolution (E_γ > 100 GeV)	10%	2%	**~1%**	15%	15%	10%

Galper et al. 2012

Selected gamma-ray dark matter search targets

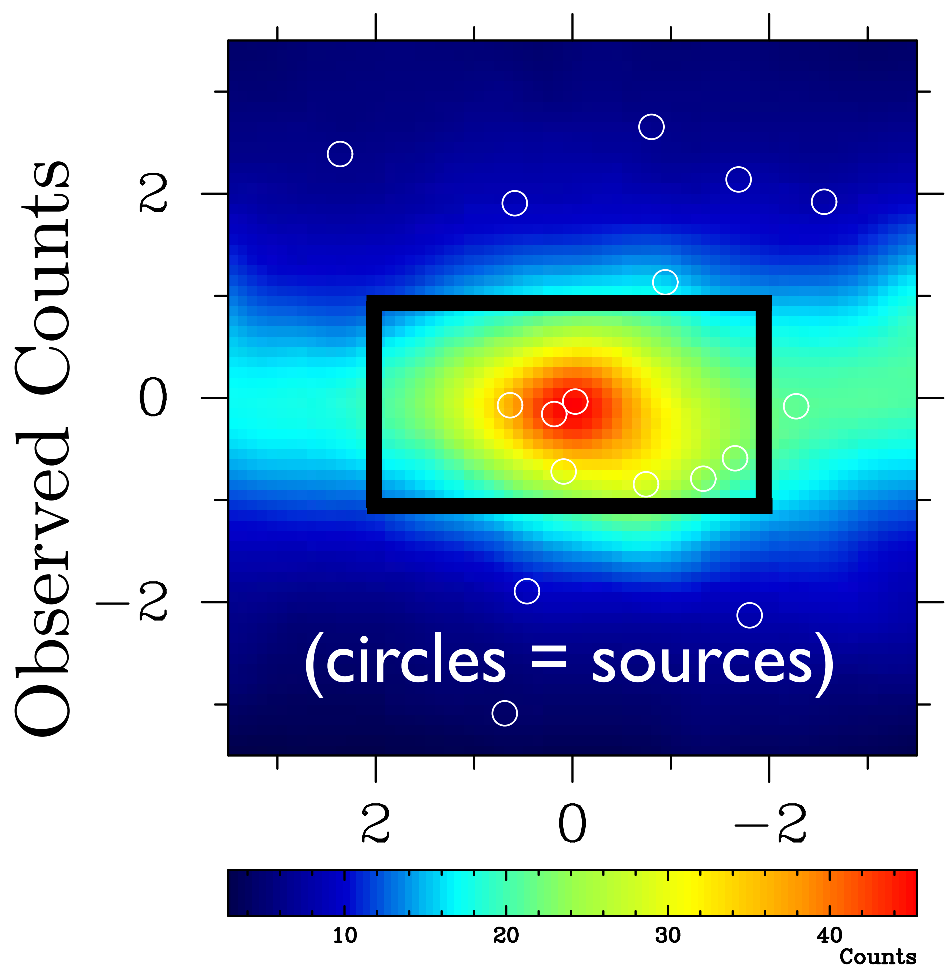


The inner galaxy

The high-energy inner galaxy

Fermi LAT ~ 1 GeV

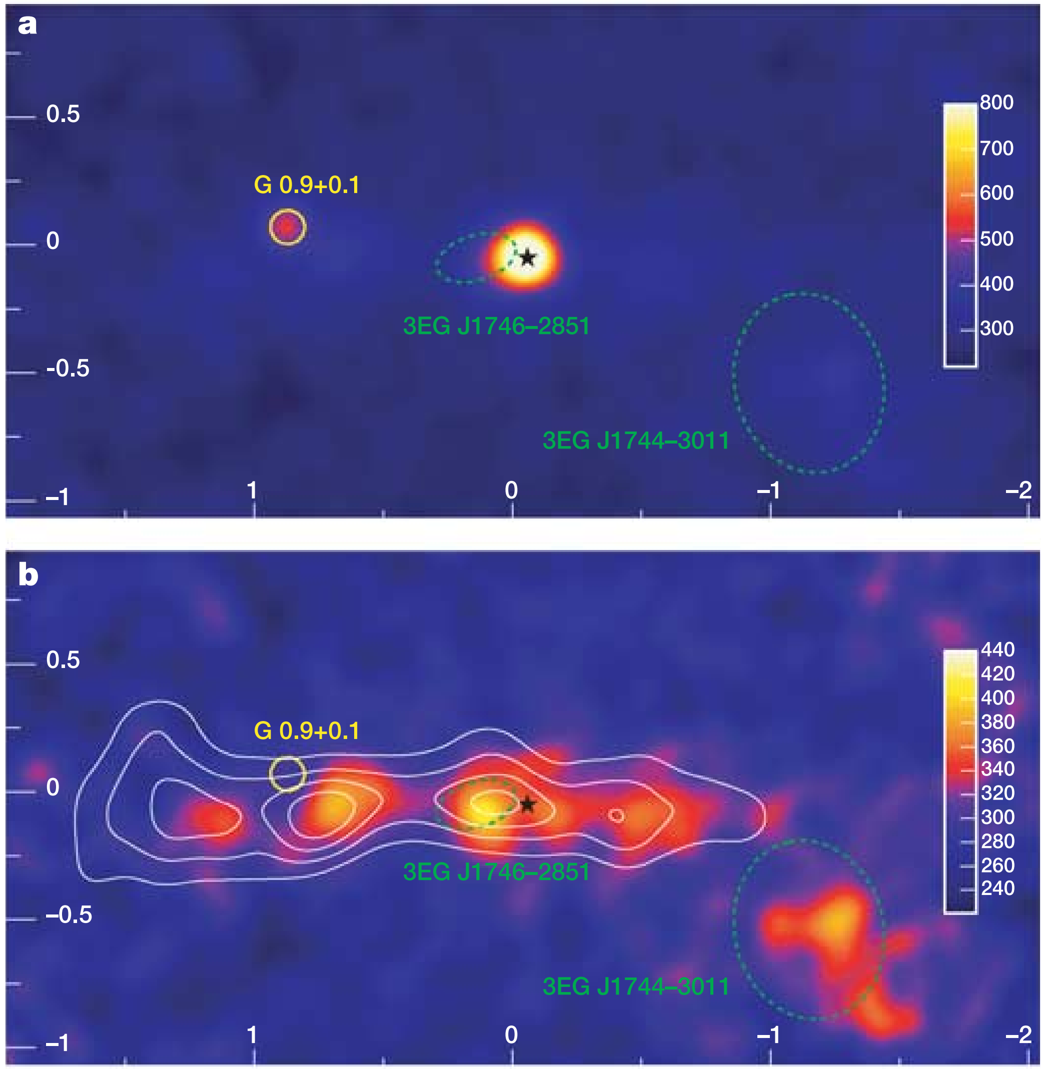
$0.69 - 0.95$ GeV



Abazajian & Kaplinghat 2012

spatially extended emission

HESS > 380 GeV



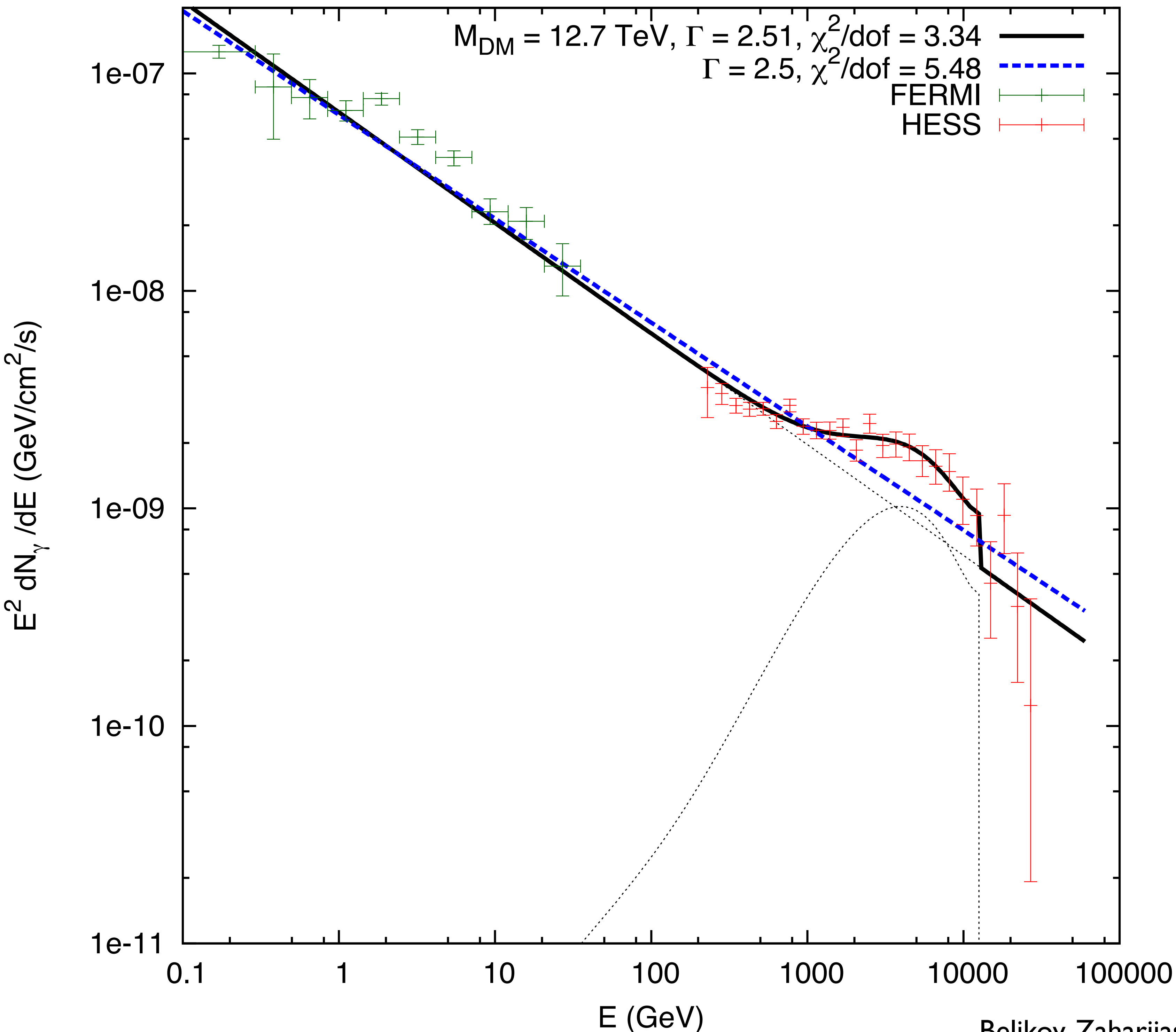
Aharonian et al. 2006

consistent with point source

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

Fermi + HESS GC energy spectrum

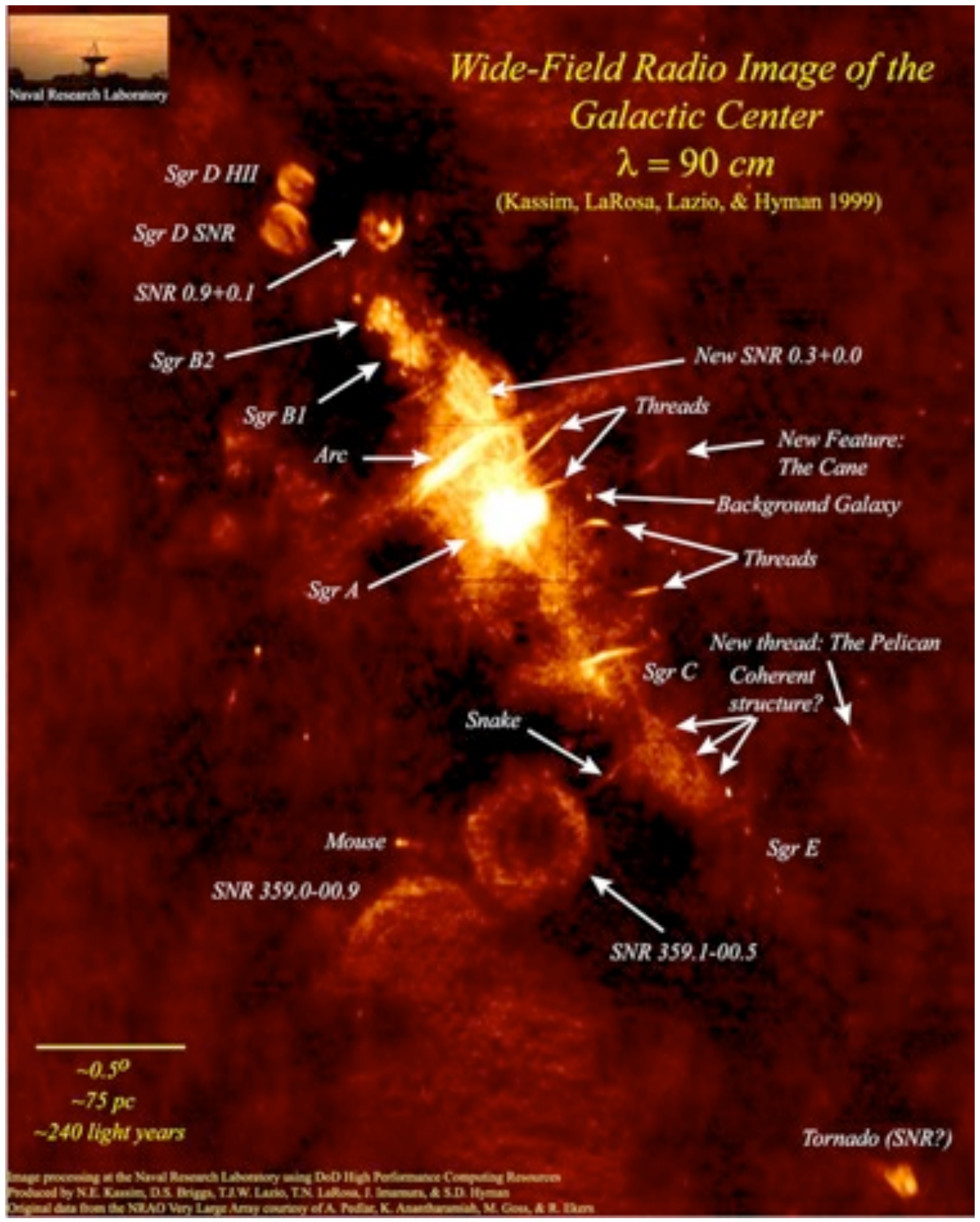
Cases G.1 and G.2 (data set A)



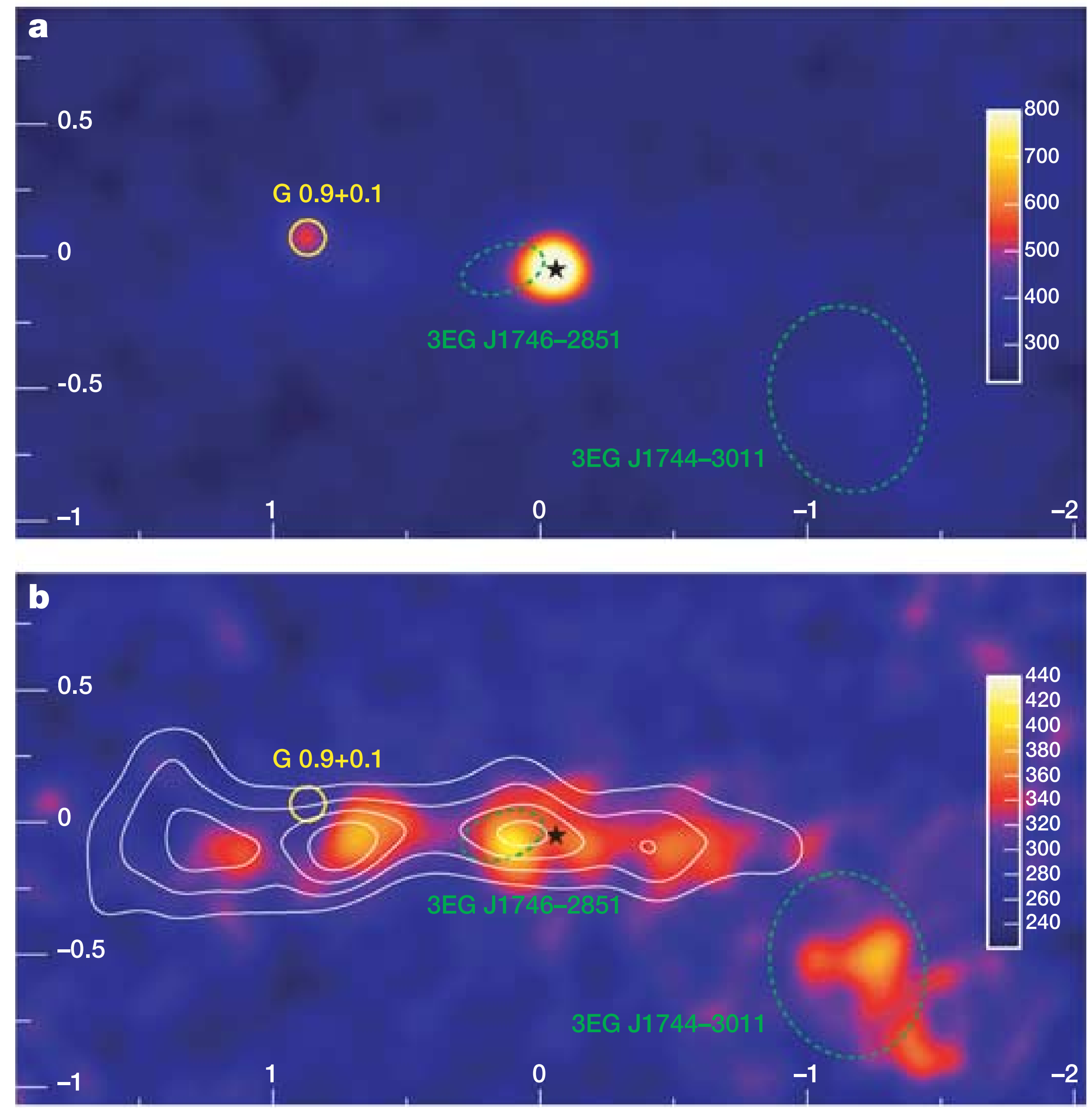
Belikov, Zaharijas, & Silk 2012

The multiwavelength inner galaxy

VLA @ 330 MHz

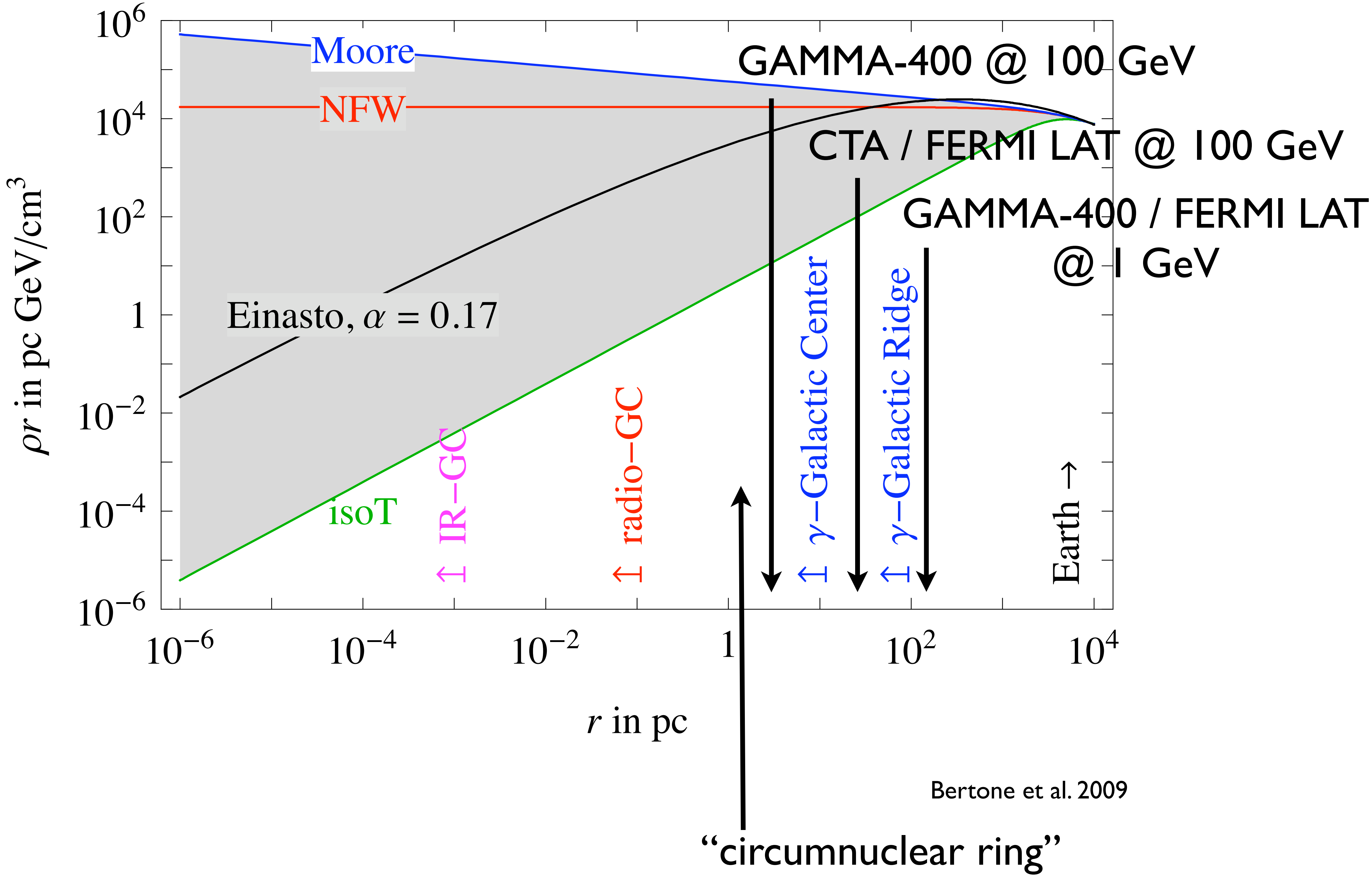


HESS > 380 GeV



Aharonian et al. 2006

Dark matter in the inner galaxy

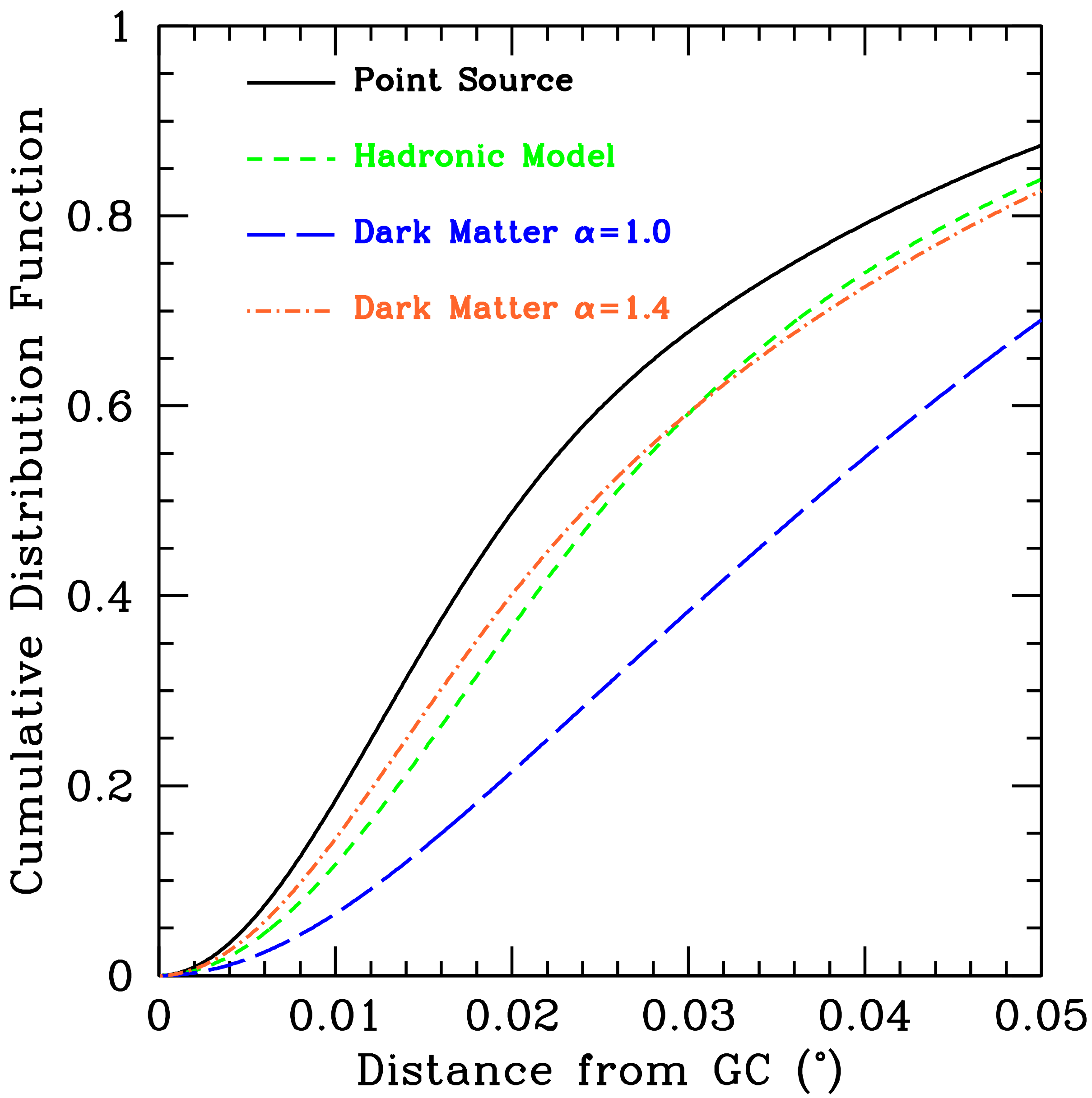


Bertone et al. 2009

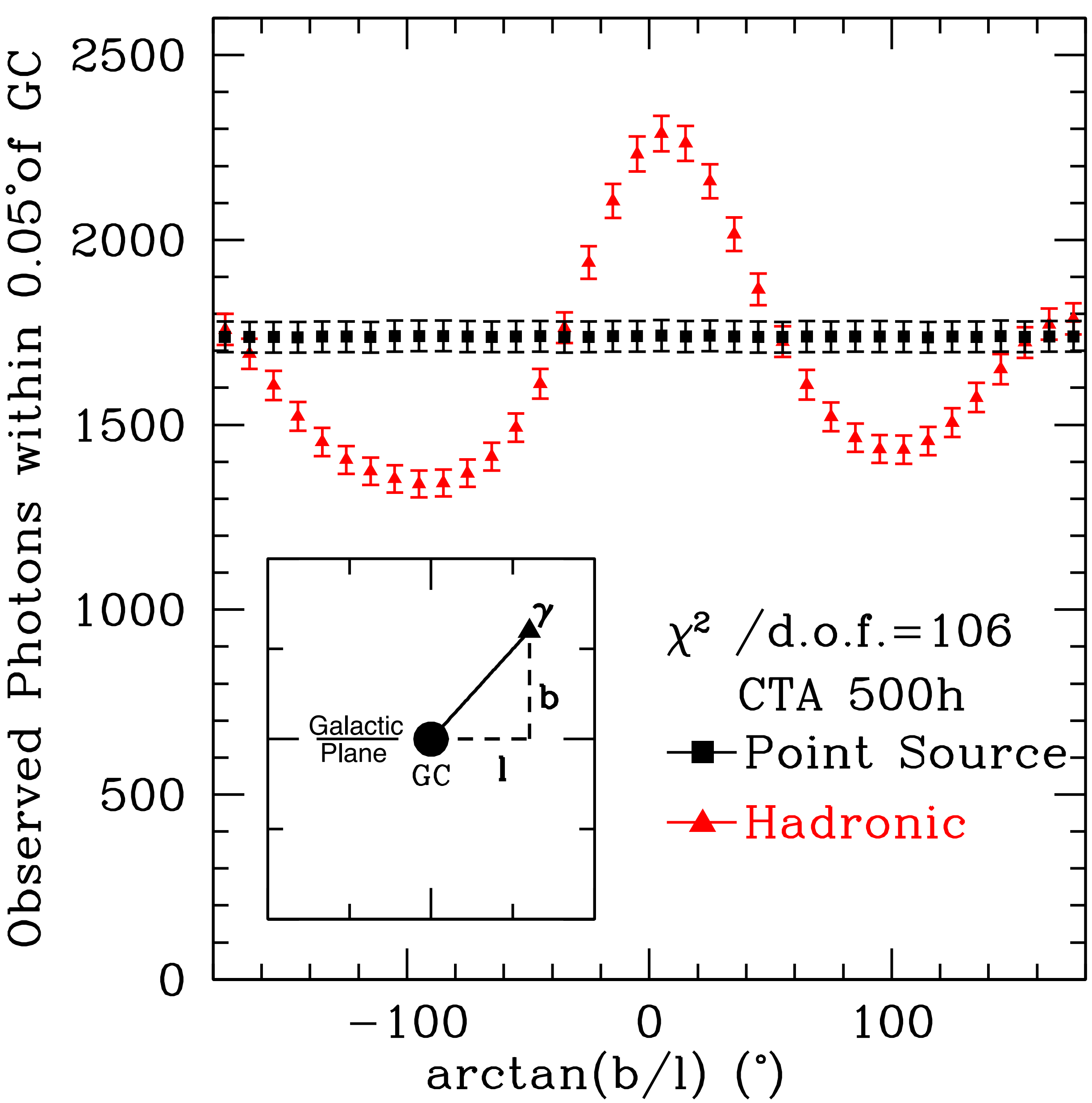
Point source or extended emission?

Testing this hypothesis with CTA

Cumulative counts



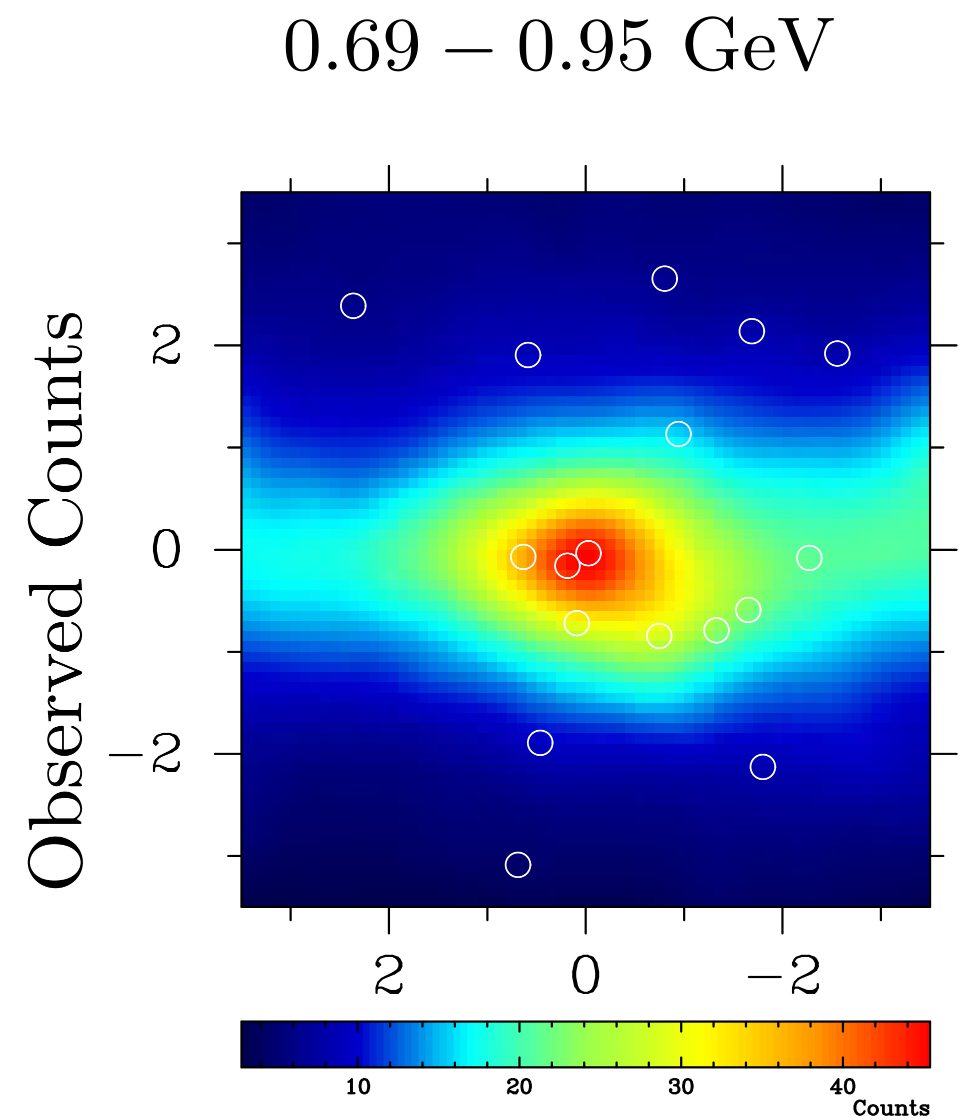
Azimuthal counts distribution



Linden & Profumo 2012

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, hadronic emission...

The inner galaxy

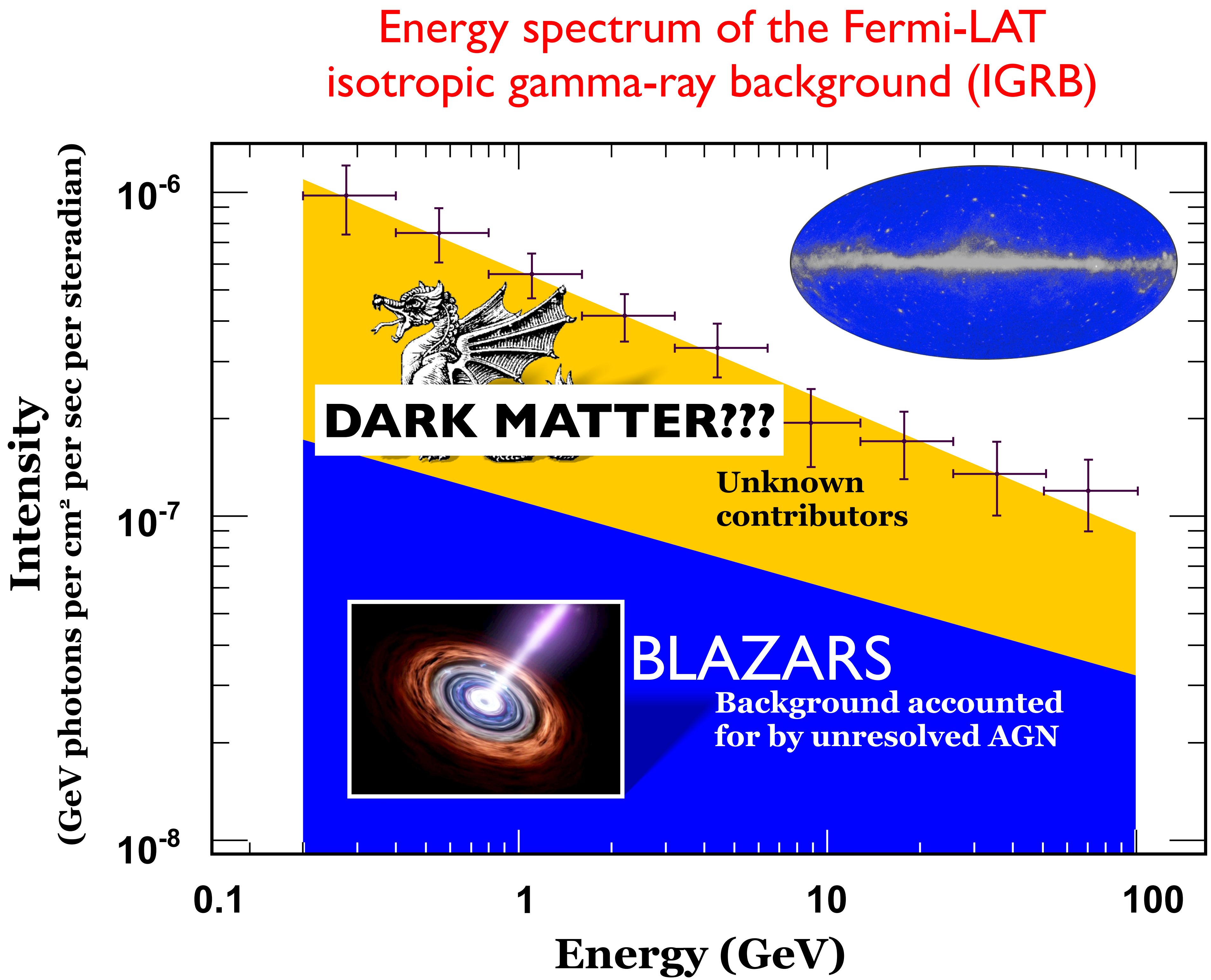
1. spectrally: DM signal may be subdominant, making a spectral signature difficult to identify
2. spatially: strong spatial signatures may be present (source of uncertainty), but not accessible with current data
3. know your backgrounds and impostor signals better: pulsars and other astrophysical sources,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

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

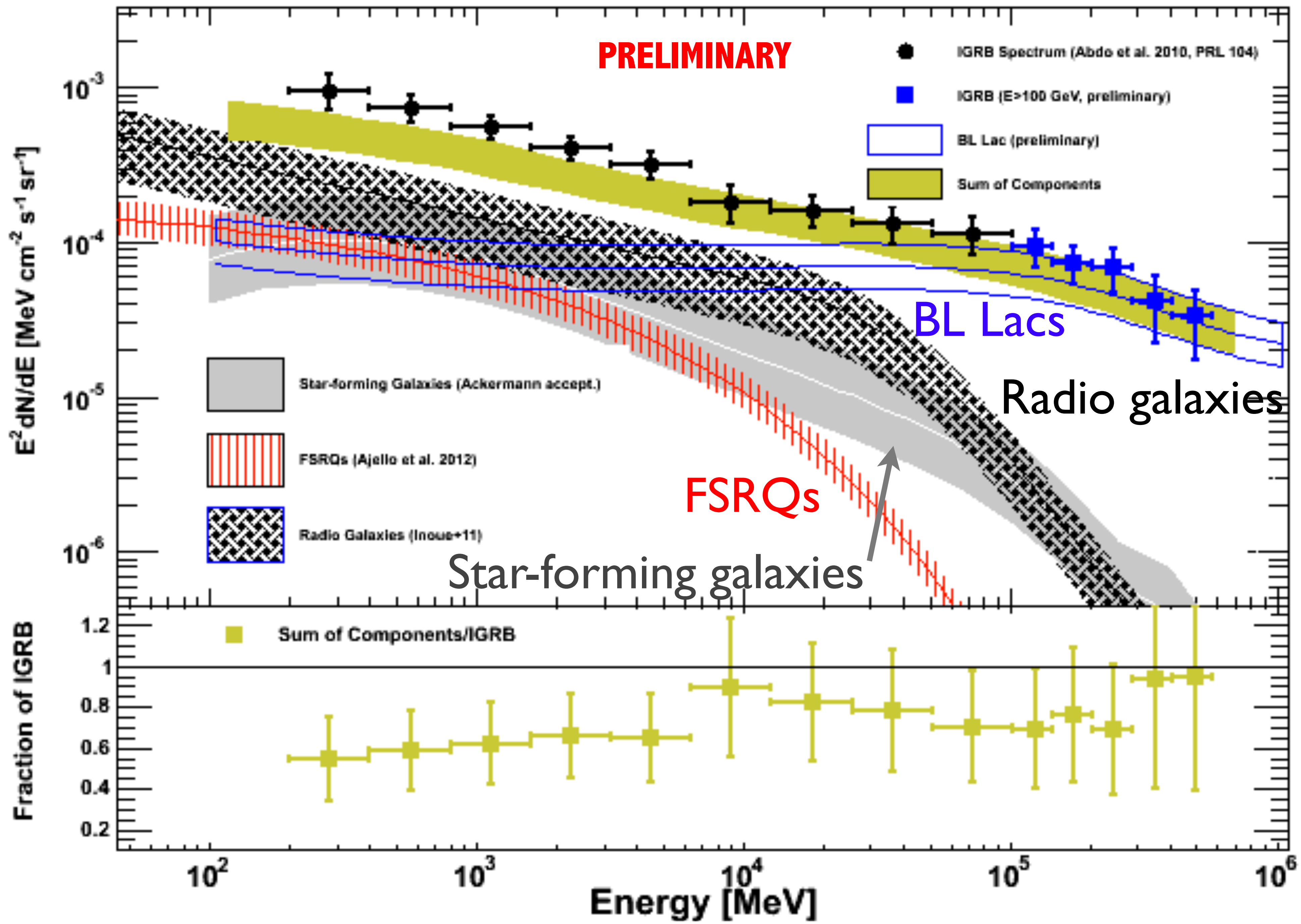
What is making the diffuse gamma-ray background?



Credit: NASA/DOE/Fermi LAT Collaboration

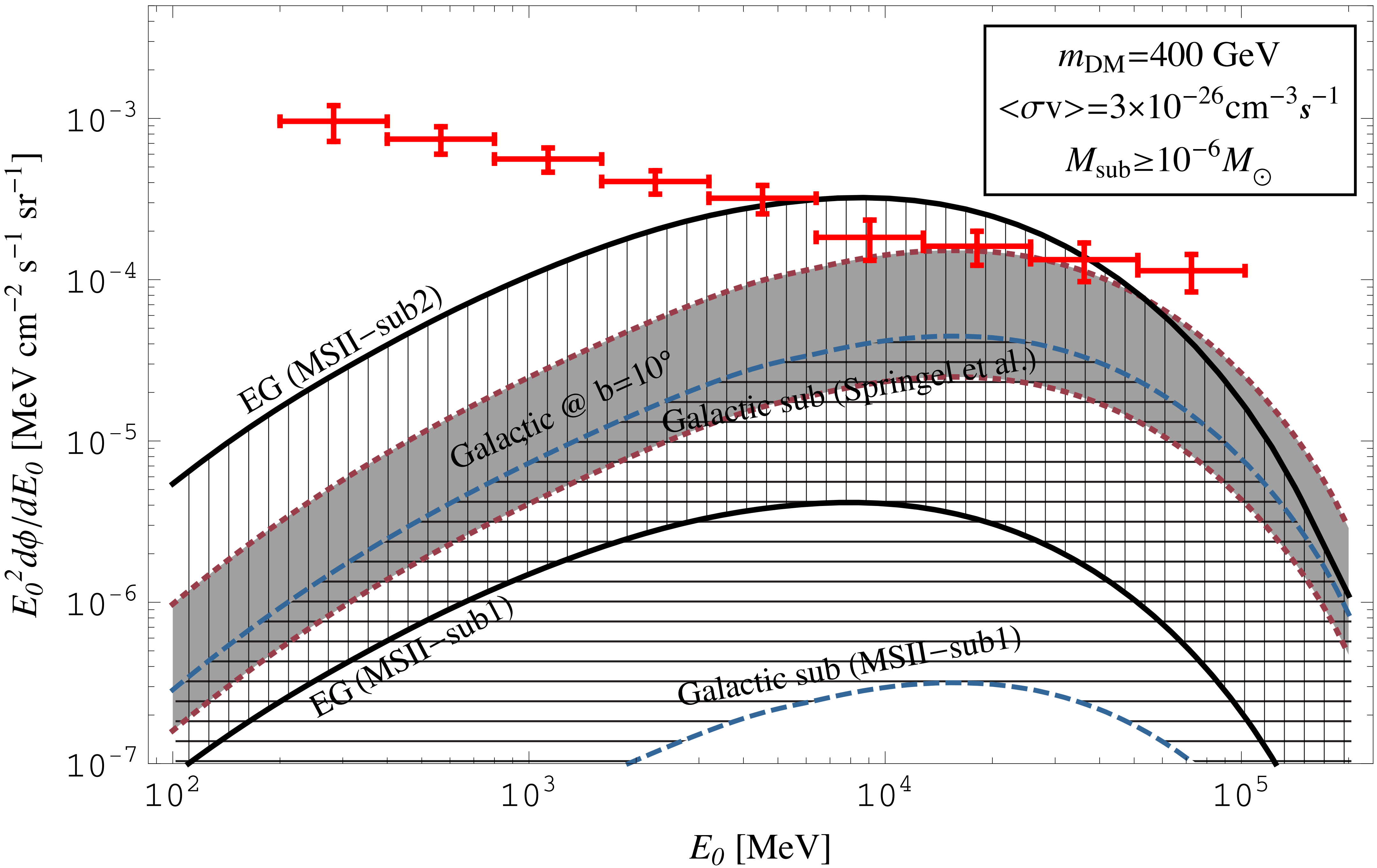
What is making the diffuse gamma-ray background?

Expected contribution of source populations to the IGRB



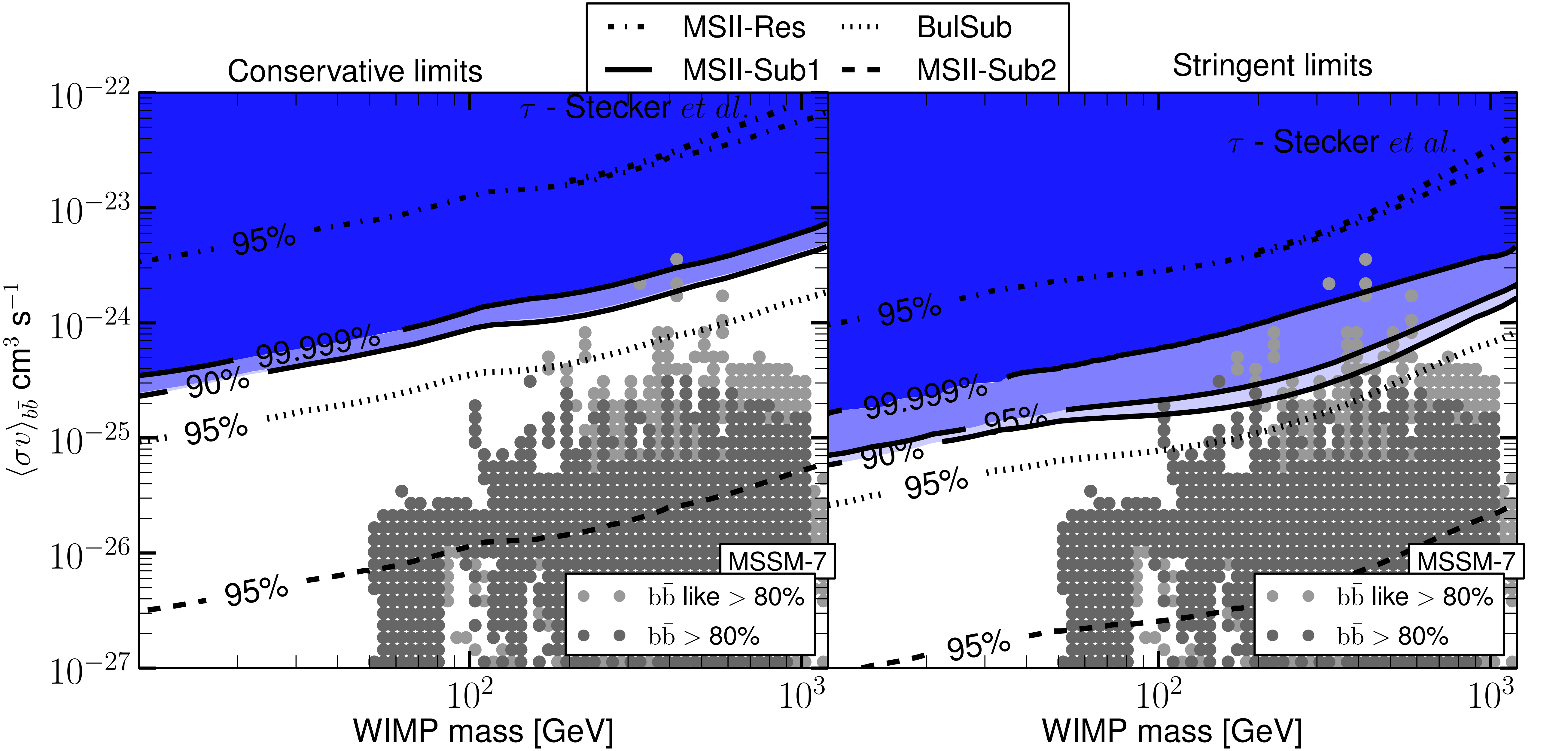
Sum is ~ 60-100% of IGRB intensity (energy-dependent)

Dark matter signals in the IGRB



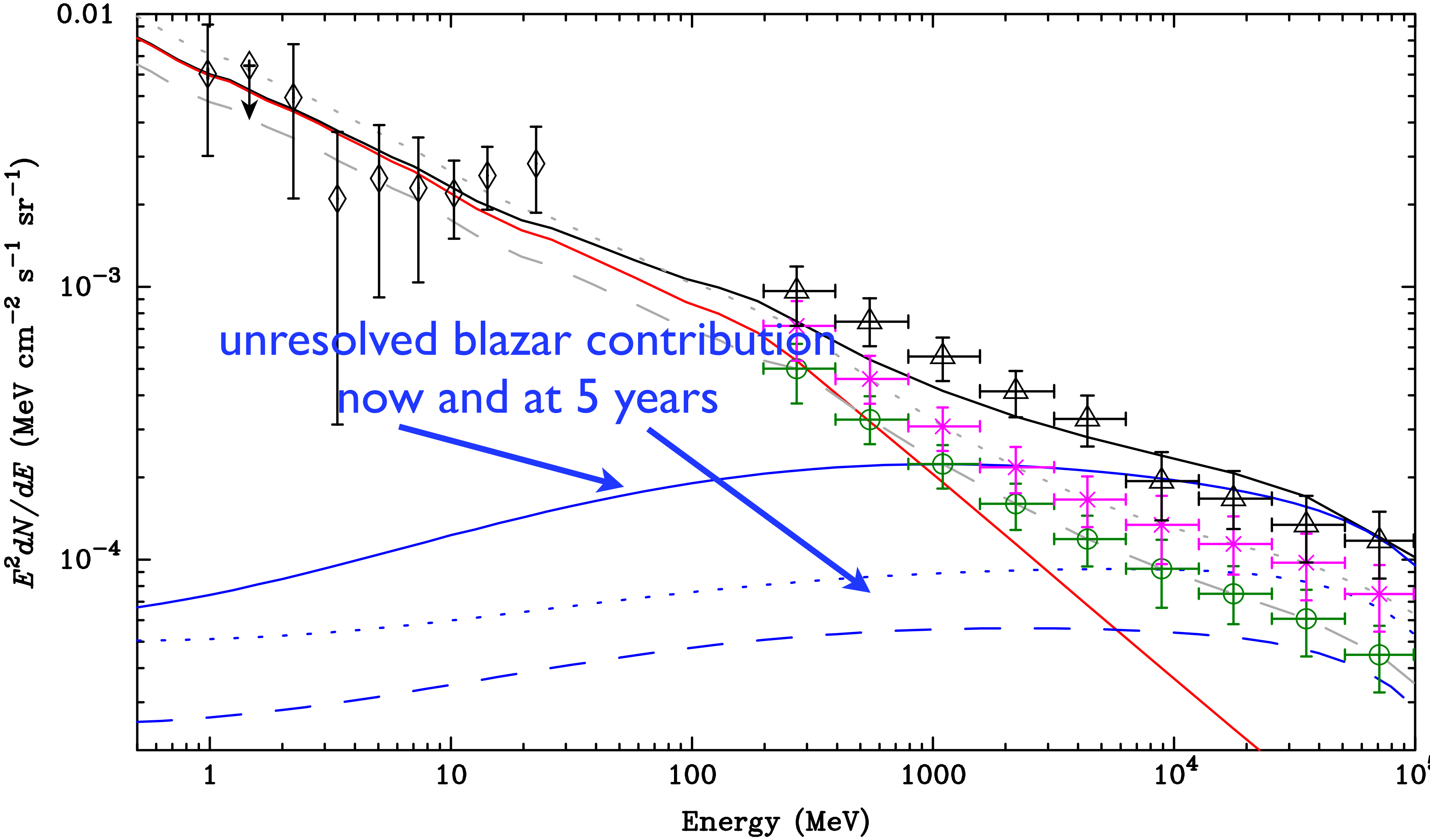
Abdo et al., JCAP 04 014 (2010)

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 smaller as more sources are resolved
- 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

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

Detecting unresolved sources with anisotropies

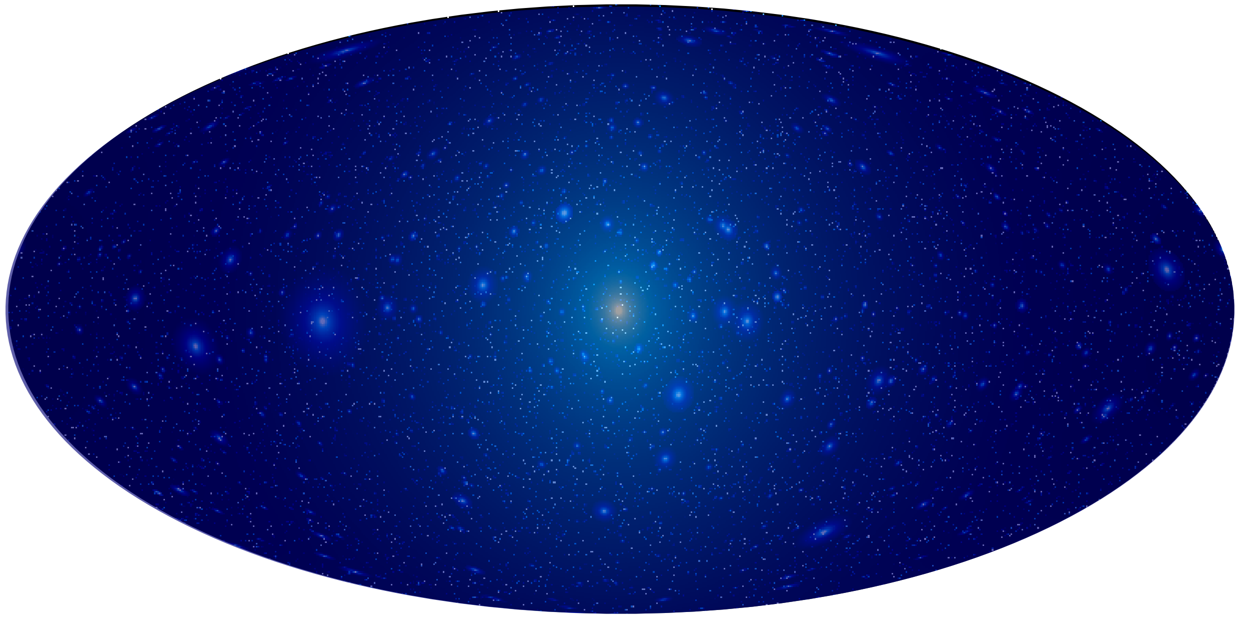
- diffuse emission that originates from one or more unresolved source populations will contain fluctuations on small angular scales due to variations in the number density of sources in different sky directions
- the amplitude and energy dependence of the anisotropy can reveal the presence of multiple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

Anisotropy is another IGRB observable!!!

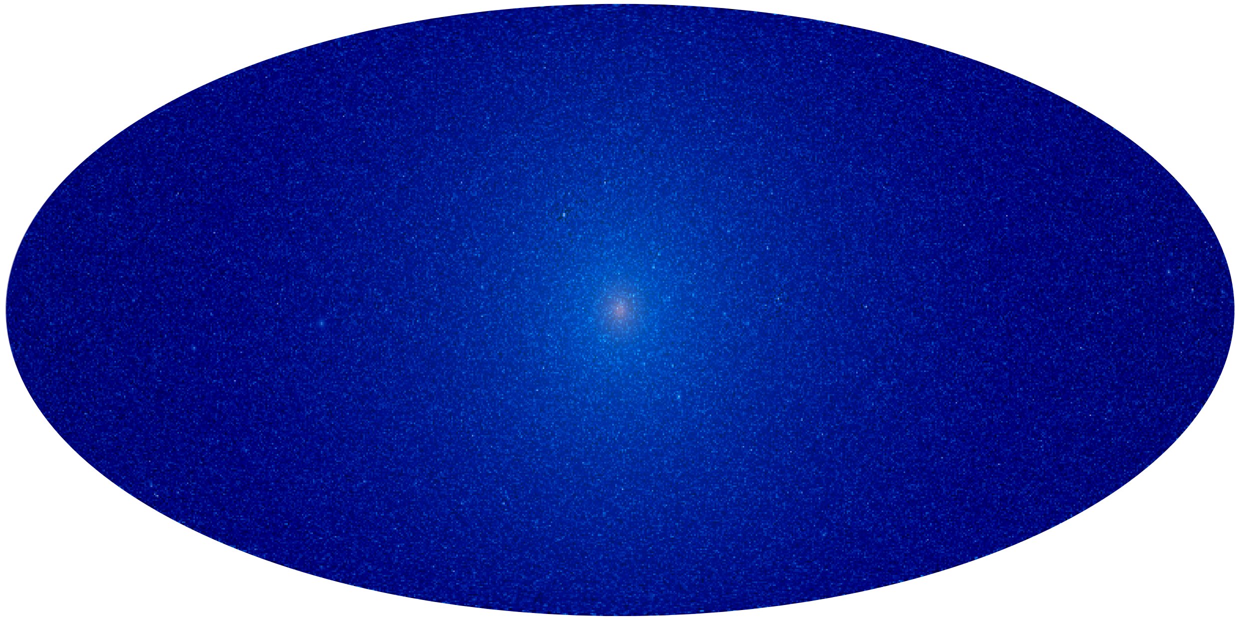
Gamma-ray anisotropies from dark matter

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

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)

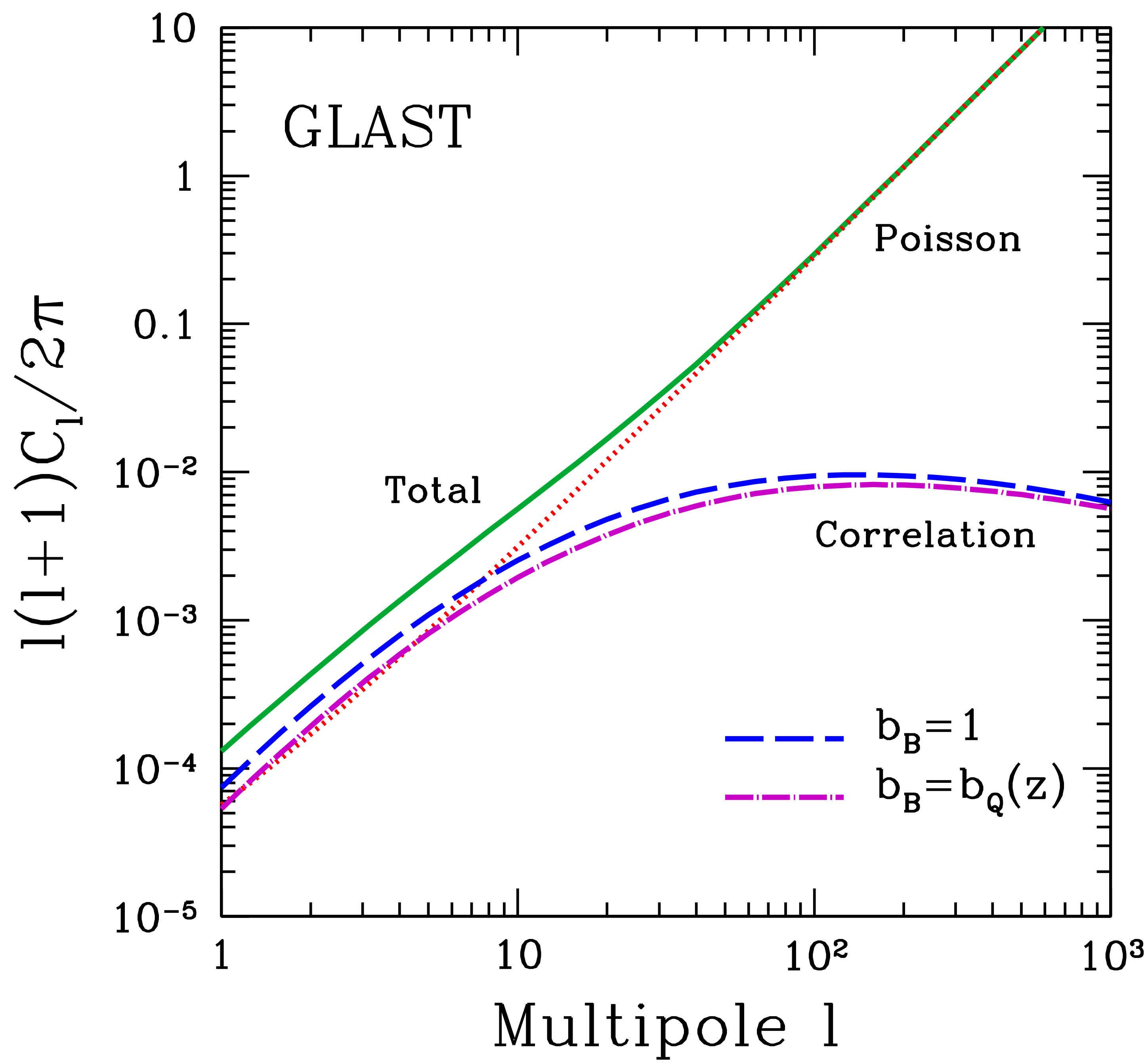
Angular power spectra of unresolved gamma-ray sources

- 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 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):

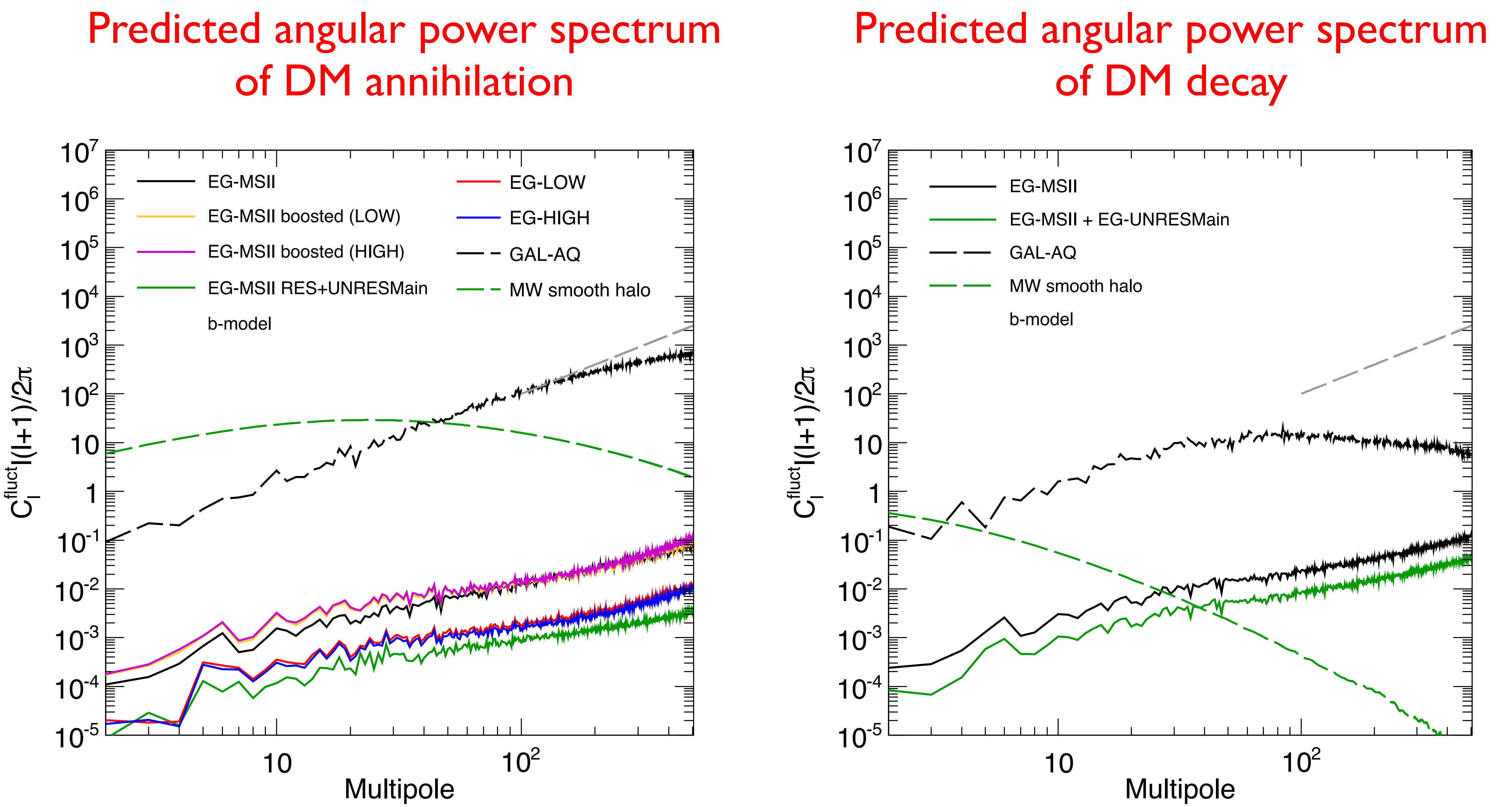
- blazars: ~ 2e-4
- starforming galaxies: ~ 2e-7
- dark matter: ~ 1e-6 to ~ 1e-4
- MSPs: ~ 0.03

Predicted angular power spectrum of unresolved blazars



Ando, Komatsu, Narumoto & Totani 2007

Angular power spectra of dark matter signals



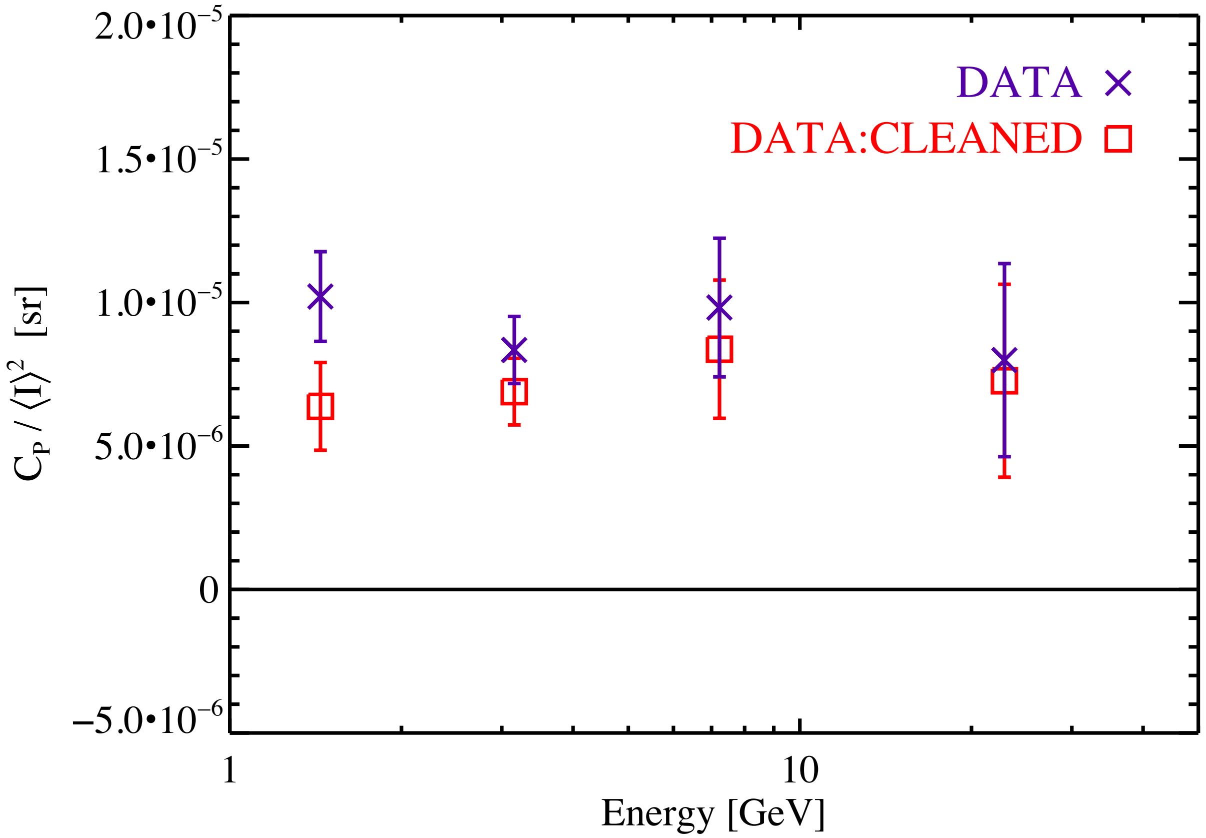
Fornasa, Zavala, Sanchez-Conde et al. 2012

- 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

Anisotropy constraints on dark matter

- small angular scale IGRB anisotropy measured for the first time with the Fermi LAT
- 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 ($l \gtrsim 150$) measured in the data and foreground-cleaned data

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%

Identifying IGRB contributions

in a two-component IGRB scenario,

where the components are uncorrelated,

and one component dominates the anisotropy at low energies,

features observed in the anisotropy energy spectrum can be used to extract each component's intensity spectrum

without a priori *assumptions about the shape of the intensity spectra or anisotropy properties!*

$$I_{\rm tot}(E) = I_1(E) + I_2(E)$$

$$C_{\ell,{\rm tot}}(E) = C_{\ell,1}(E) + C_{\ell,2}(E)$$

$$\hat{C}_{\ell,{\rm tot}}(E) = \left(\frac{I_1(E)}{I_{\rm tot}(E)}\right)^2 \hat{C}_{\ell,1} + \left(\frac{I_2(E)}{I_{\rm tot}(E)}\right)^2 \hat{C}_{\ell,2}$$

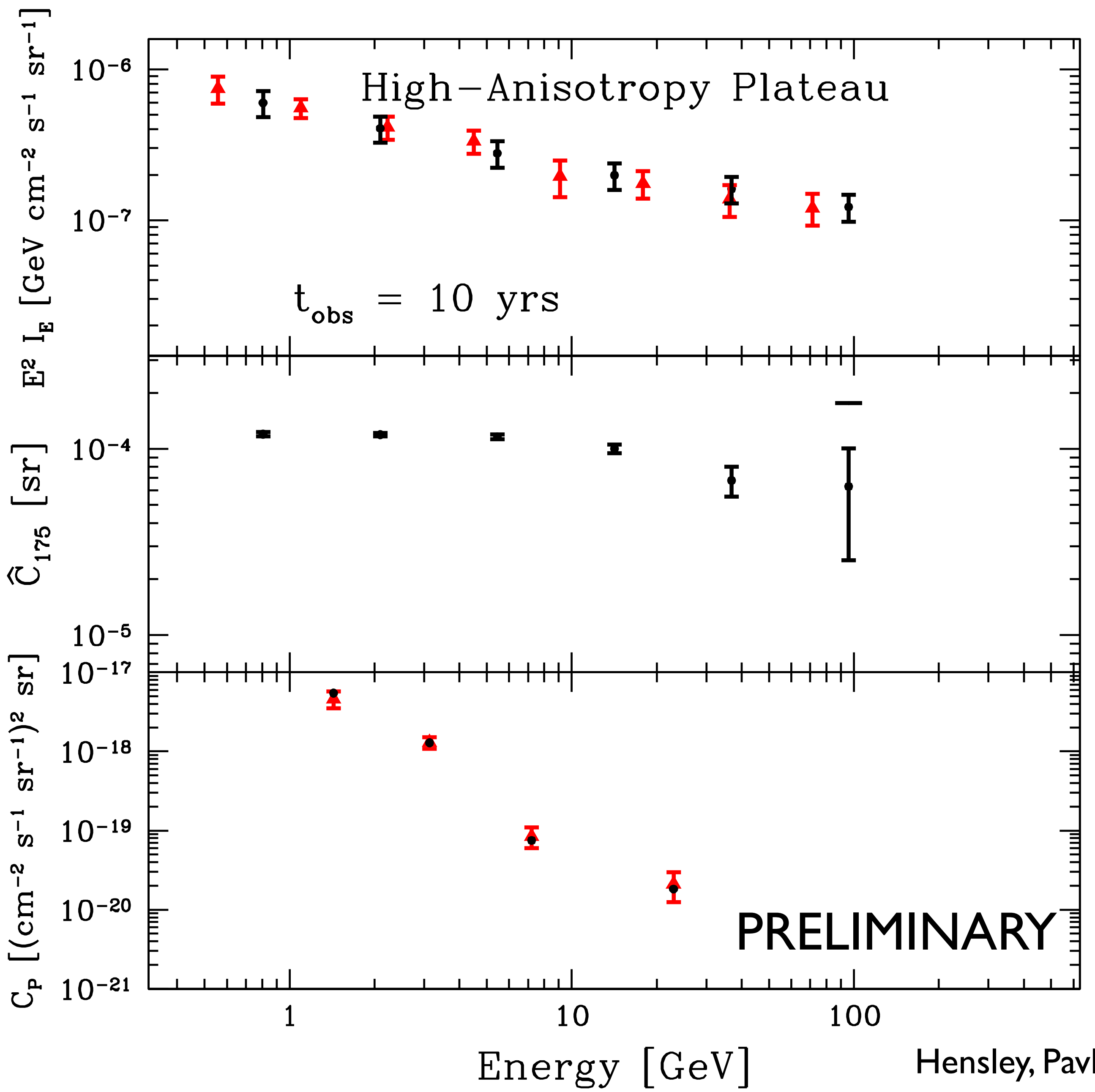
Separating signals with energy-dependent anisotropy

TABLE I: Summary of two-component decomposition techniques.

Method	Observational Signature	Inferred Properties of Components	Intensity Normalization Recovered?	Fluctuation Angular Power Recovered?
Double plateau	Plateaus at both high and low energies observed in anisotropy energy spectrum	One source dominant in anisotropy at low energies, other source dominant at high energies	Yes	Yes
Low-Anisotropy Plateau	Anisotropy energy spectrum rises from (falls to) a low-anisotropy plateau at low (high) energy	Source that is subdominant in intensity is much more anisotropic than the dominant source	No	No
High-Anisotropy Plateau	Anisotropy energy spectrum falls from (rises to) a high-anisotropy plateau at low (high) energy	Source that is subdominant in intensity is much less anisotropic than the dominant source	Yes	No
Known Zero-Anisotropy Component	None; requires *a priori* knowledge that one of the two components is isotropic	One source is completely isotropic	No	No
Minimum	Minimum observed in the anisotropy energy spectrum	Both source components have comparable intensity and anisotropy such that Eq. 20 is satisfied at some energy	Yes	Yes
Multiple-ℓ Measurements	Two distinct anisotropy energy spectra can be obtained at two different ℓ	$\hat{C}_\ell$ is a function of ℓ for at least one source such that two distinct anisotropy energy spectra can be obtained at different ℓ	Yes	Yes

Example IGRB decomposition

Example observed intensity spectrum and anisotropy energy spectrum



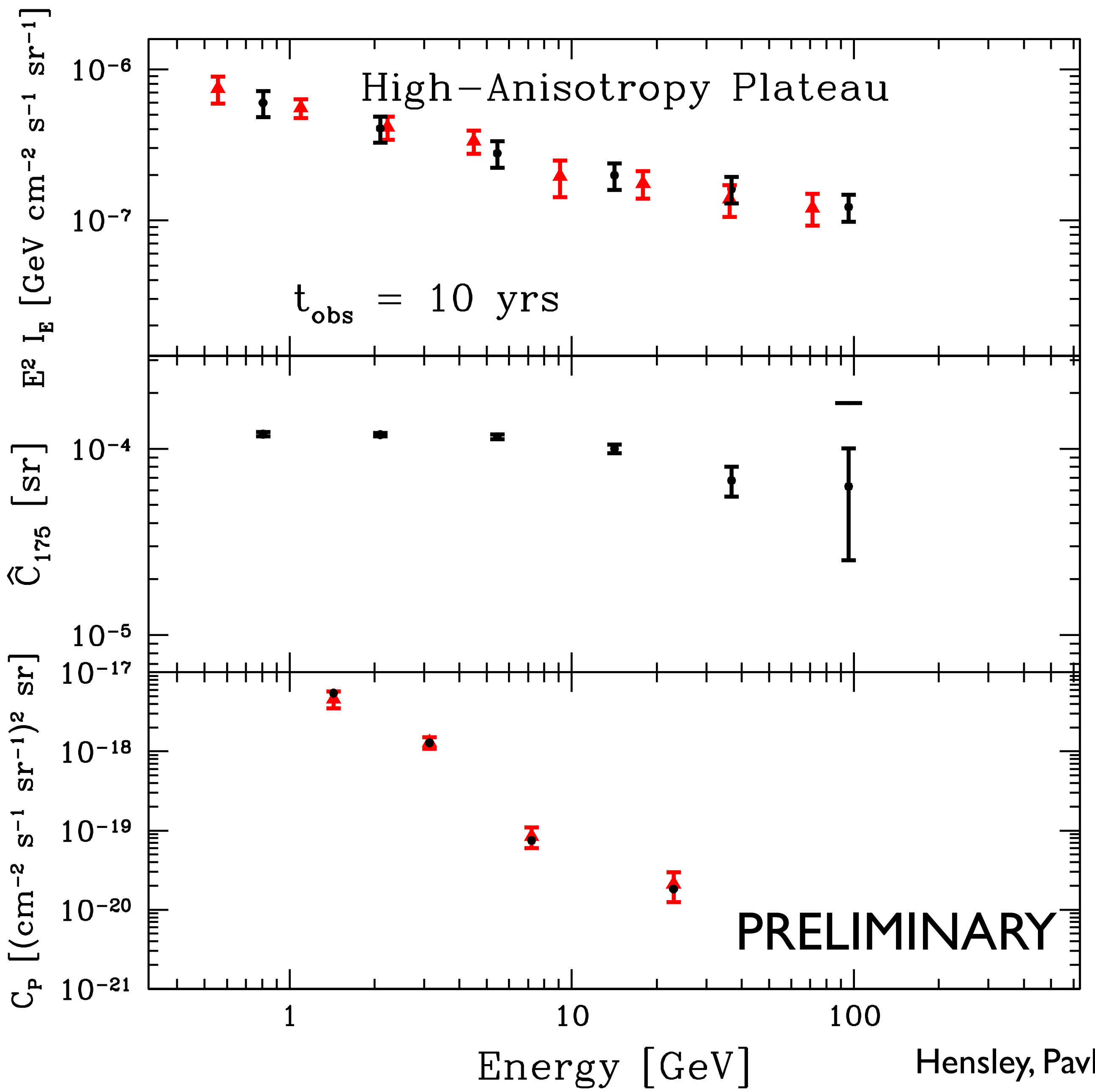
Hensley, Pavlidou & JSG (in prep)

red = published LAT measurements

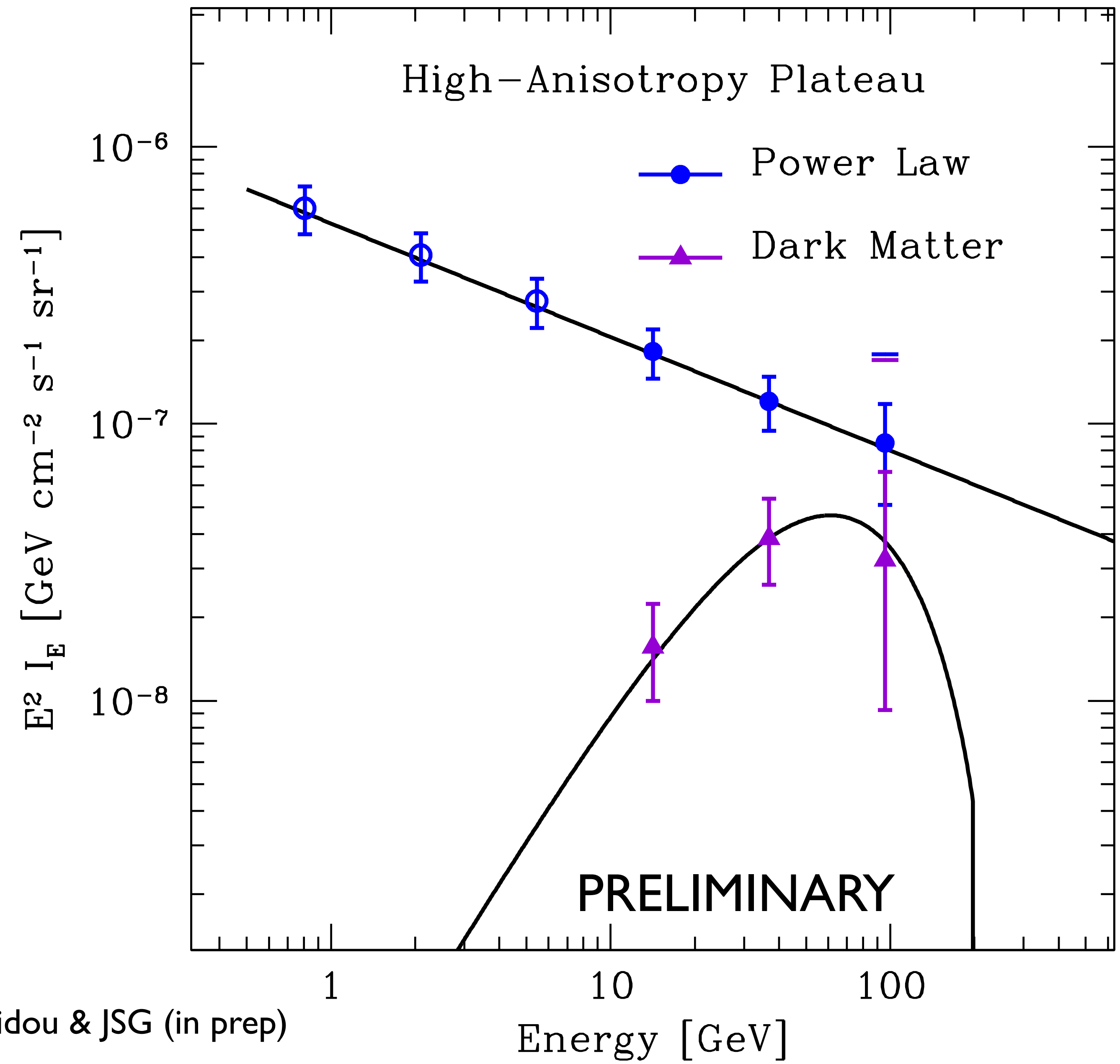
black = example scenario for 10 yrs LAT observations

Example IGRB decomposition

Example observed intensity spectrum and anisotropy energy spectrum



Decomposed energy spectra



Hensley, Pavlidou & JSG (in prep)

red = published LAT measurements

black = example scenario for 10 yrs LAT observations

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

3. know your backgrounds and impostor signals better: pinning down contribution from astrophysical sources a major challenge but could significantly improve dark matter sensitivity

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

3. know your backgrounds and impostor signals better: pinning down contribution from astrophysical sources a major challenge but could significantly improve dark matter sensitivity

1+2 = combining spectral and spatial information could allow contributions from multiple components to be disentangled

Summary

- this is an exciting time! searches already reaching interesting regions of parameter space and some targets show hints of a detection!
- search strategies need to be optimized for different dark matter models, targets, and instruments
- complementarity should be an important factor in designing searches and should be taken advantage of wherever possible
- 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
- combining spectral and spatial features can improve sensitivity to subdominant signals