The Galactic Center GeV Excess: Have We Started to See Dark Matter?

Sam McDermott

Based on:

various observational works (Daylan et al 1402.6703, Calore et al 1409.0042, …)

SDM, I. Cholis, P. Fox, S. K. Lee
(preliminary / in progress)

Stony Brook University

GGI, 9/30/15

IS HINCHLIFFE'S RULE TRUE? *

Boris Peon

Abstract

Hinchliffe has asserted that whenever the title of a paper is a question with a yes/no answer, the answer is always no. This paper demonstrates that Hinchliffe's assertion is false, but only if it is true.

Outline

1. Observational facts (“introduction”)
    - how many photons? from where?
    - what is it?
2. A new observational idea

Basics

- Two kinds of analyses

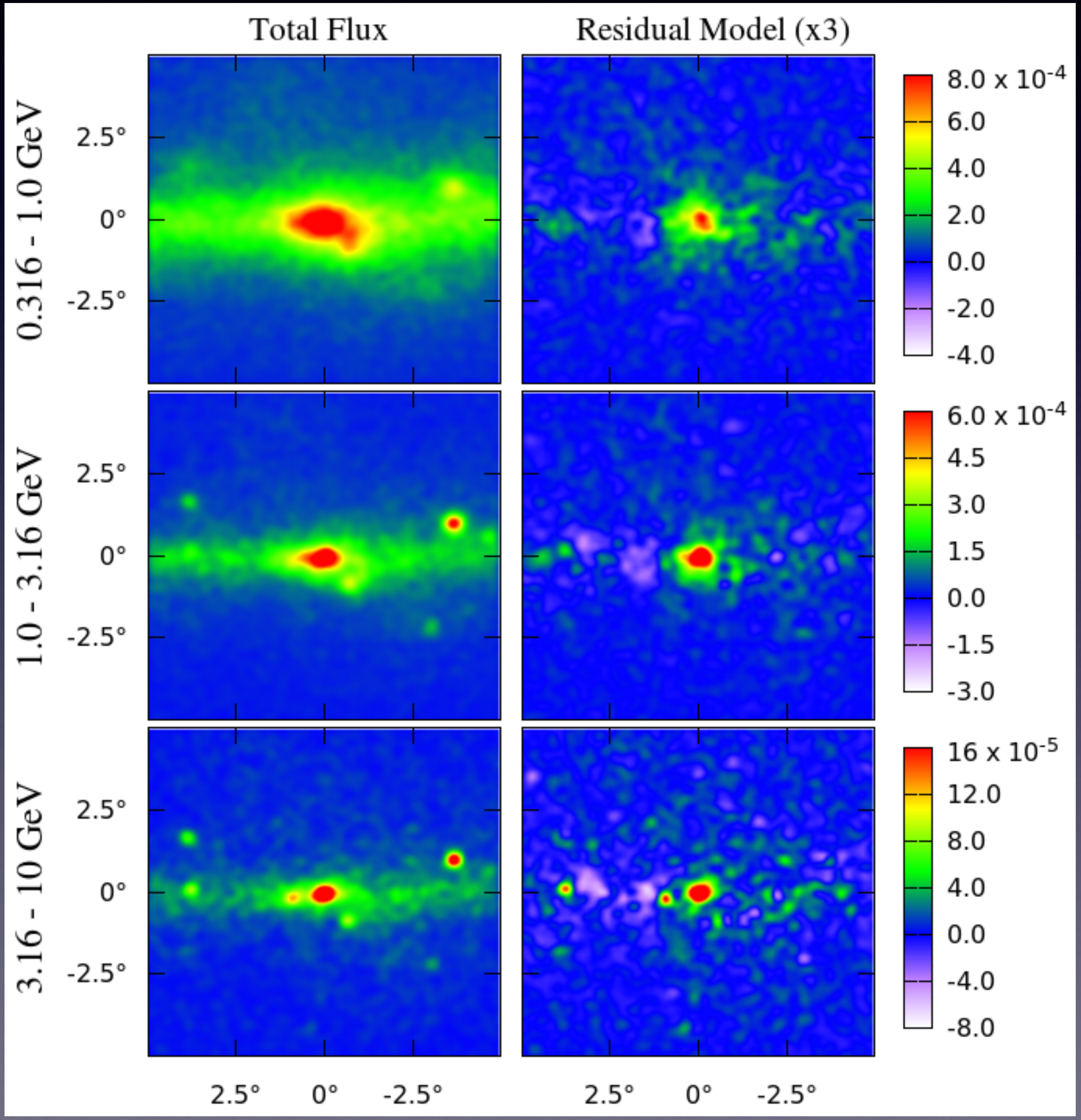
  - ***Galactic center*** — below the Bubbles

  - ***Inner Galaxy*** — excludes disk, goes out > O(10˚)

- "Excess" found both near and far from SgrA*

- Appears to be spherical and smooth; radial fall-off compatible with (gNFW profile)^2: $\rho_{gNFW}(x) \sim \rho_0/[x^{\gamma}(1+x)^{3-\gamma}]$

Galactic Center



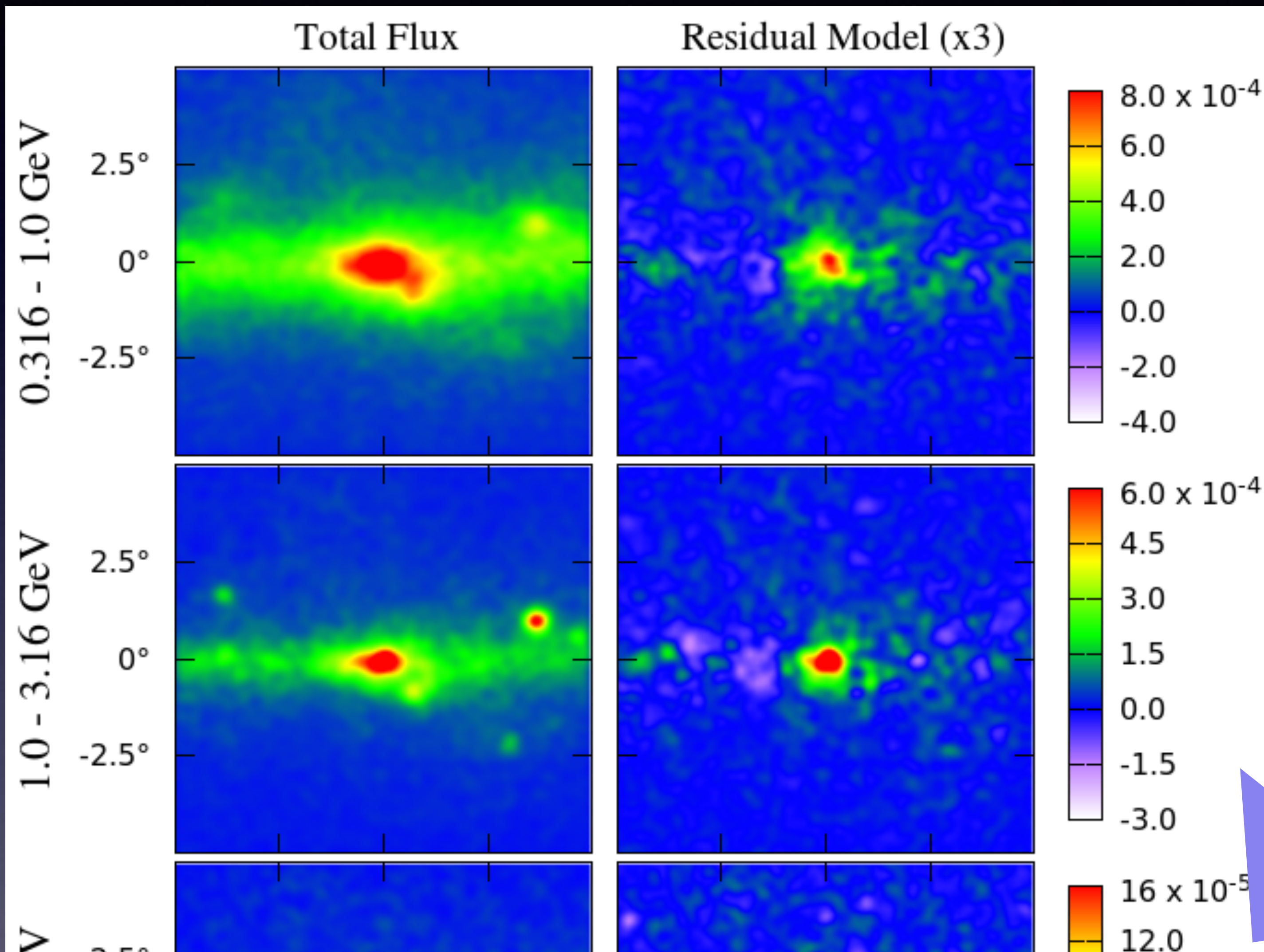
excess with normalization ~ 30% of raw!

point sources;
isotropic;
diffuse emission;
map of 20 cm synchrotron

$\int_{los}$(gNFW profile)^2 fits excess well

1402.6703

Galactic Center



excess with normalization ~ 30% of raw!

point sources;

diffuse emission:

synchrotron

(gNFW profile)^2

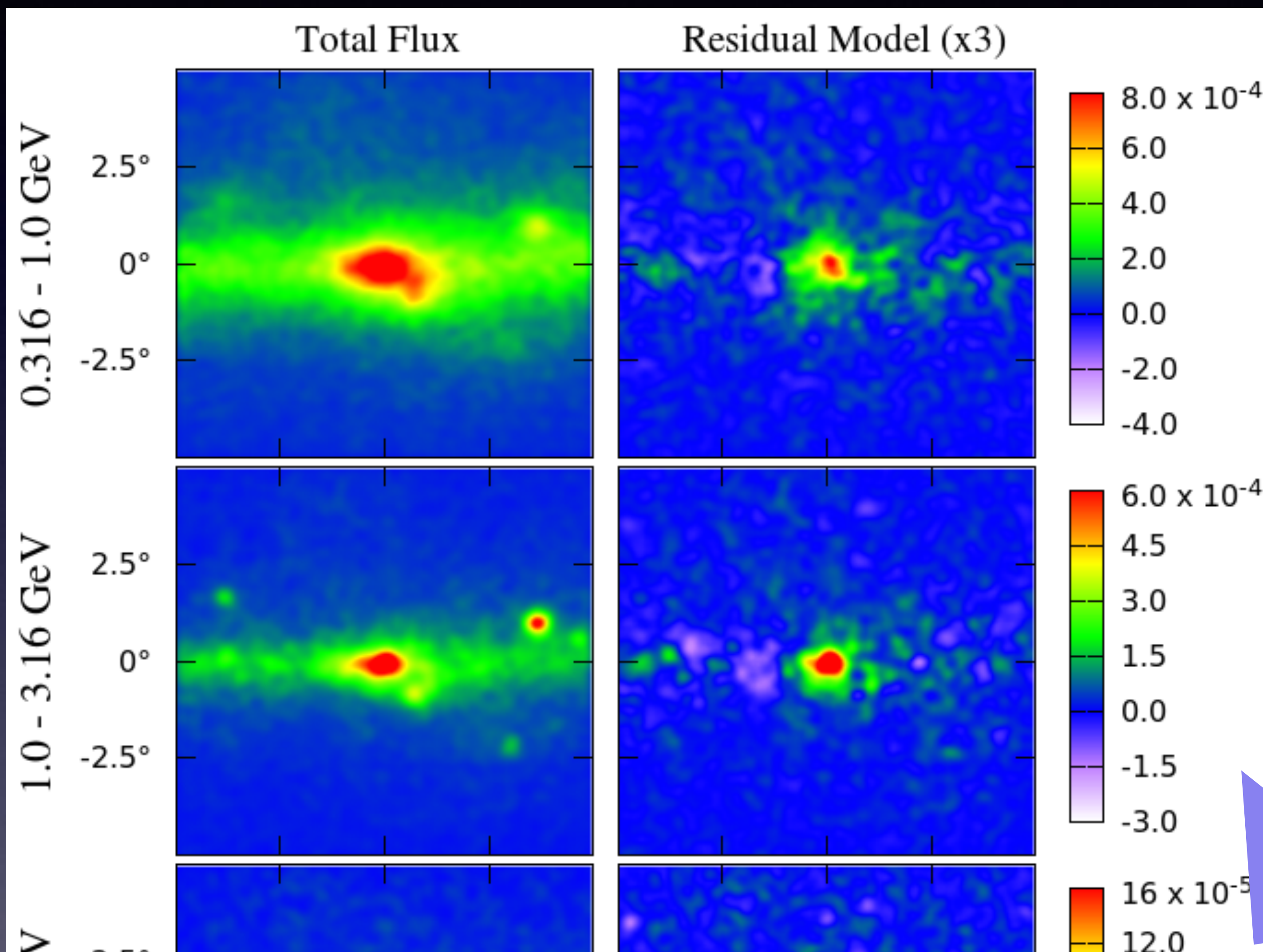
"π^0's" = hadronic CRs interacting with dust

"bremsstrahlung" = leptonic CRs interacting with dust

"ICS" = leptonic CRs interacting with background light

1402.6703

Galactic Center



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diffuse emission:

map of 20 cm synchrotron

∫ (gNFW profile)²

"π^0's" = ... ith dust

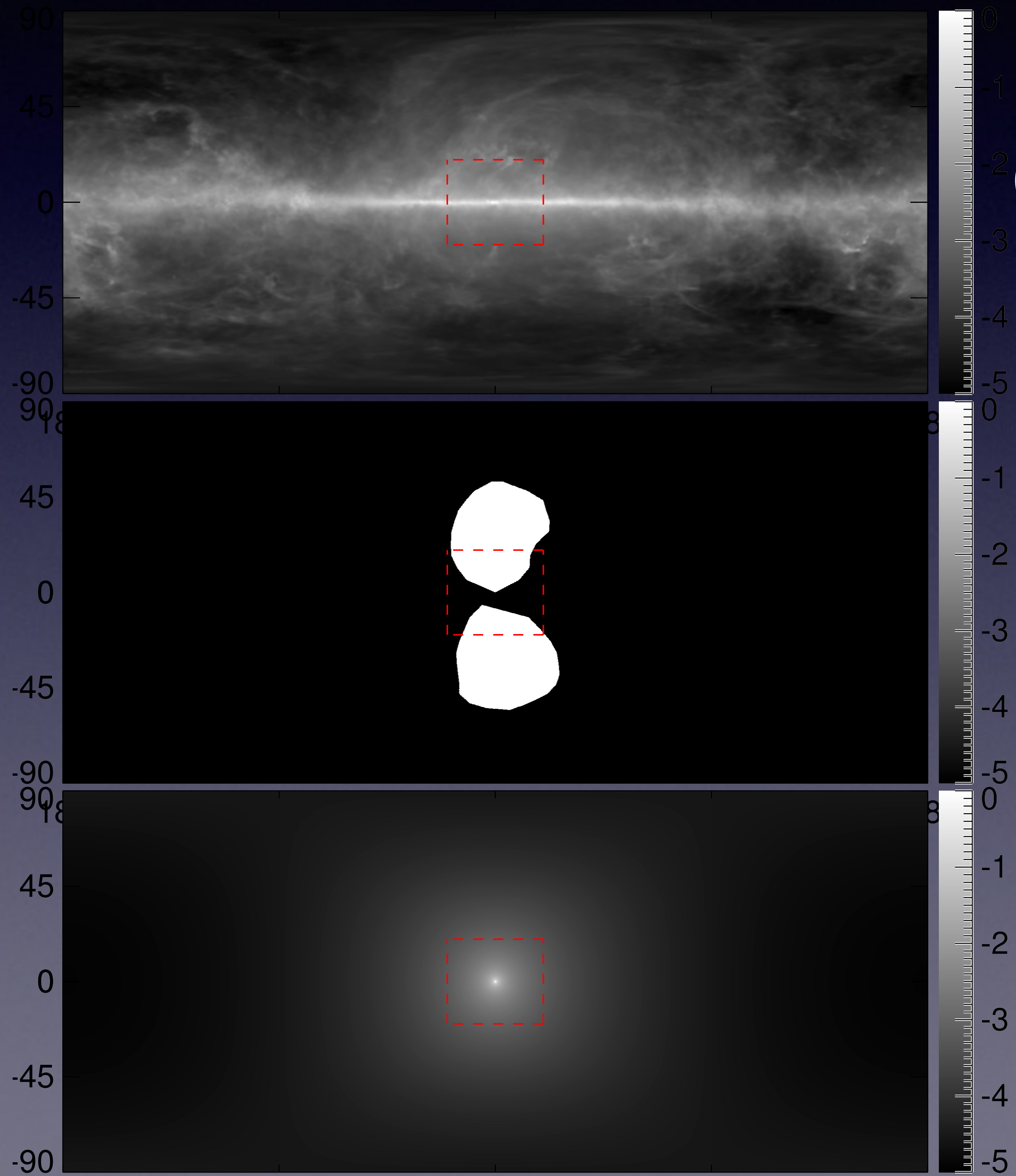
"bremsstrah ... ng with dust

"ICS" = lepto ... kground light

cosmic rays interacting with previously mapped stuff

1402.6703

Inner galaxy



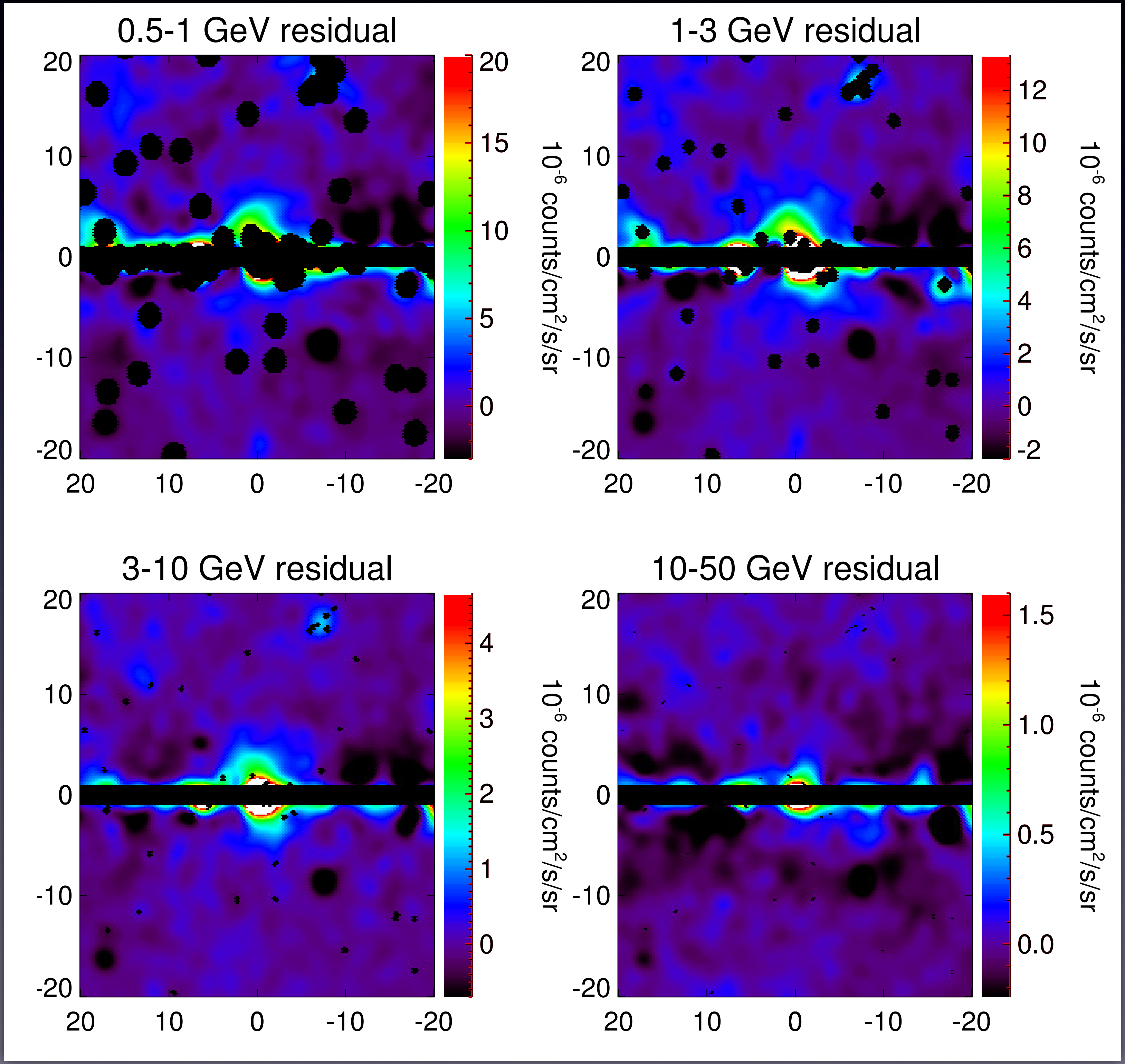
diffuse map

Fermi bubbles

NFW

1402.6703

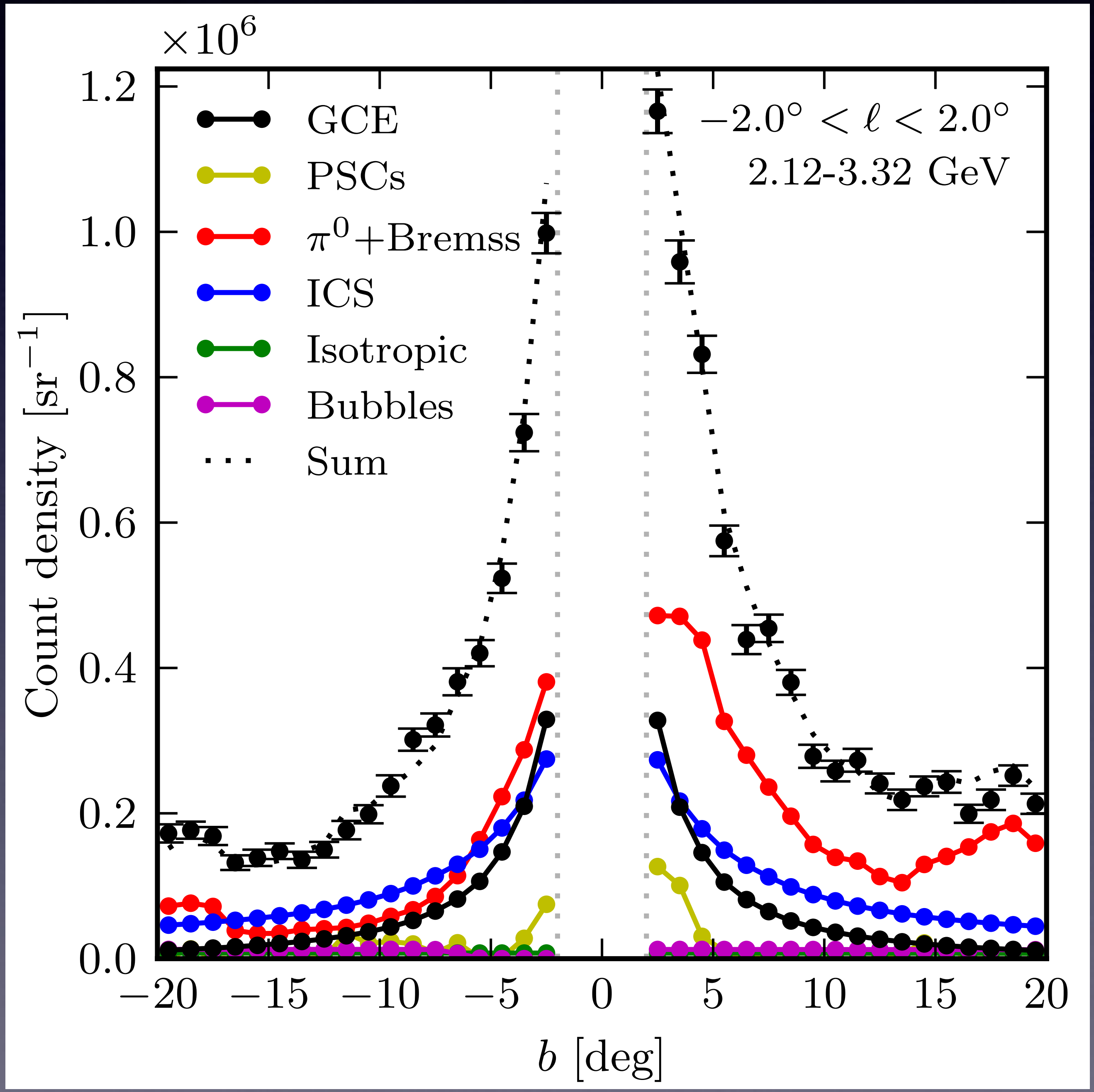
Inner galaxy



1402.6703

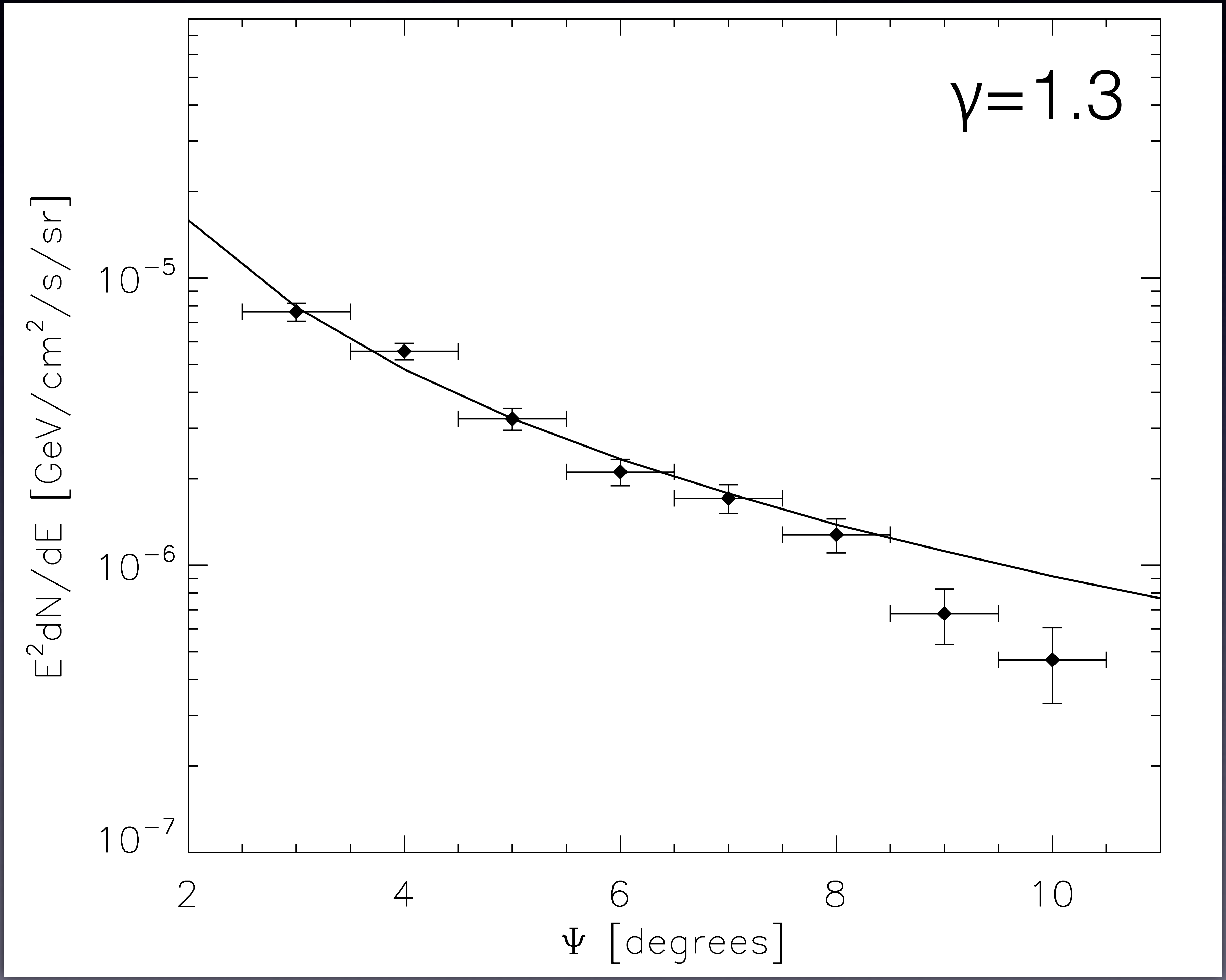
Total Normalization

at energies of interest, much brighter than Bubbles (~ O(30%) of total!)



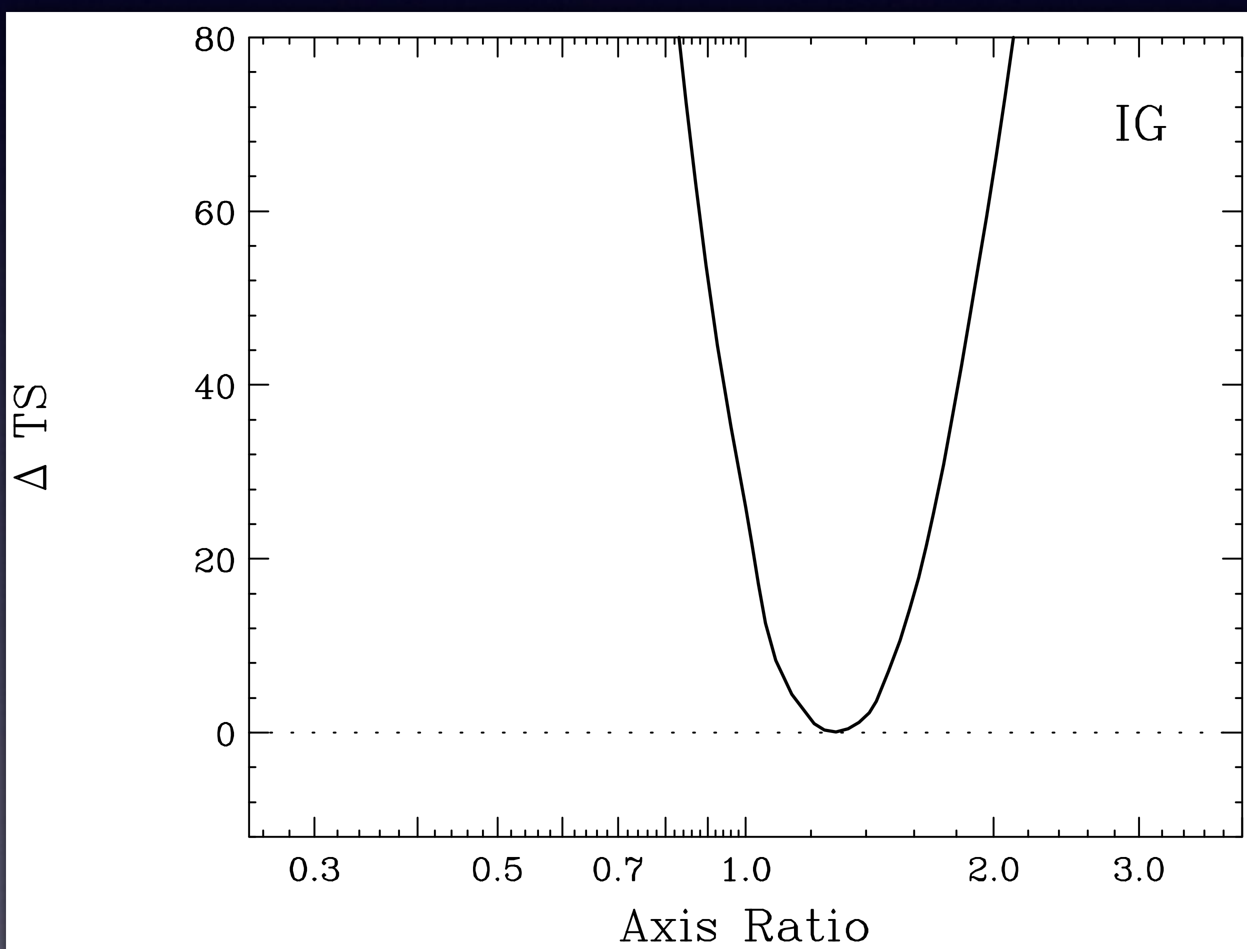
1409.0042

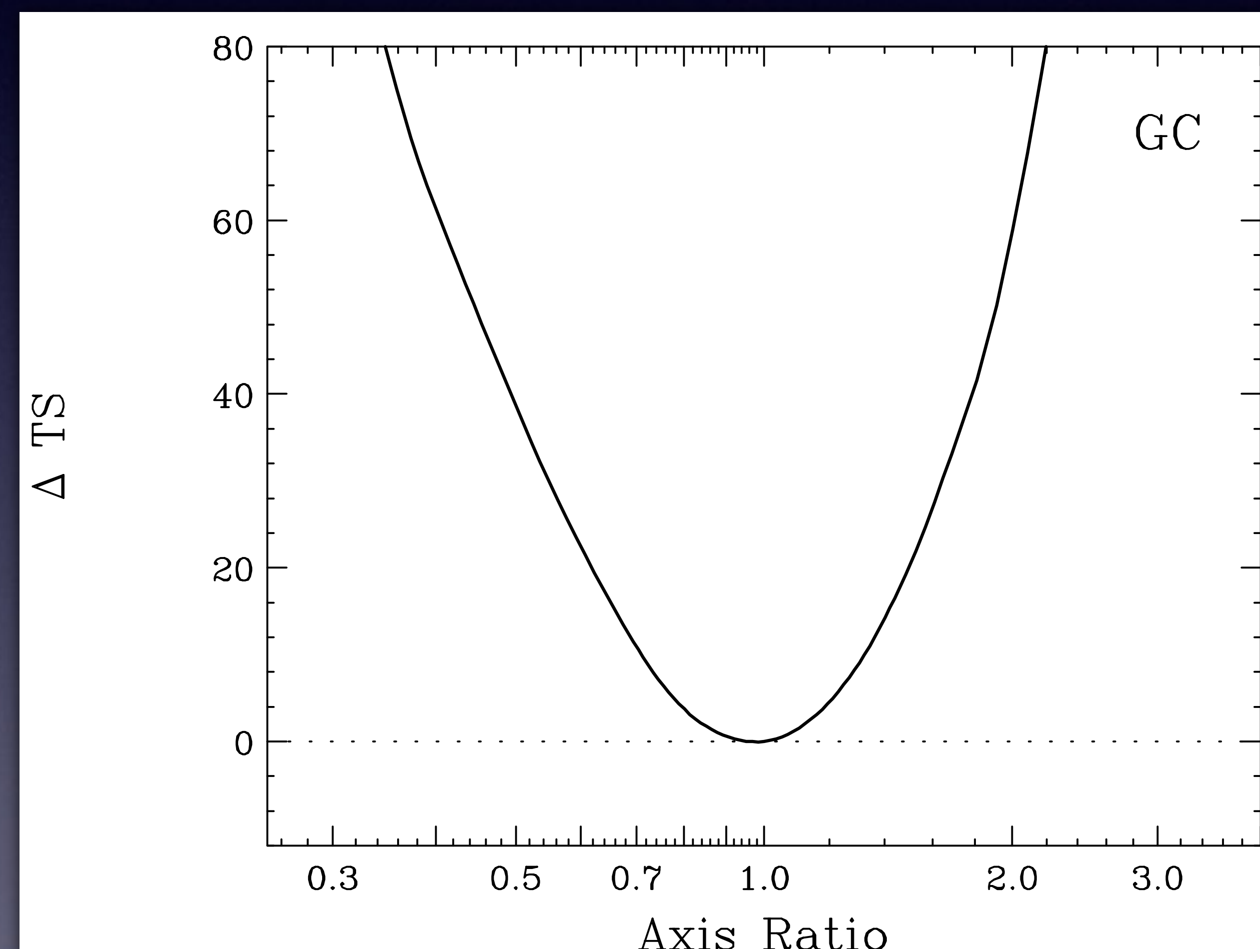
Seen out to > 10˚



1402.6703

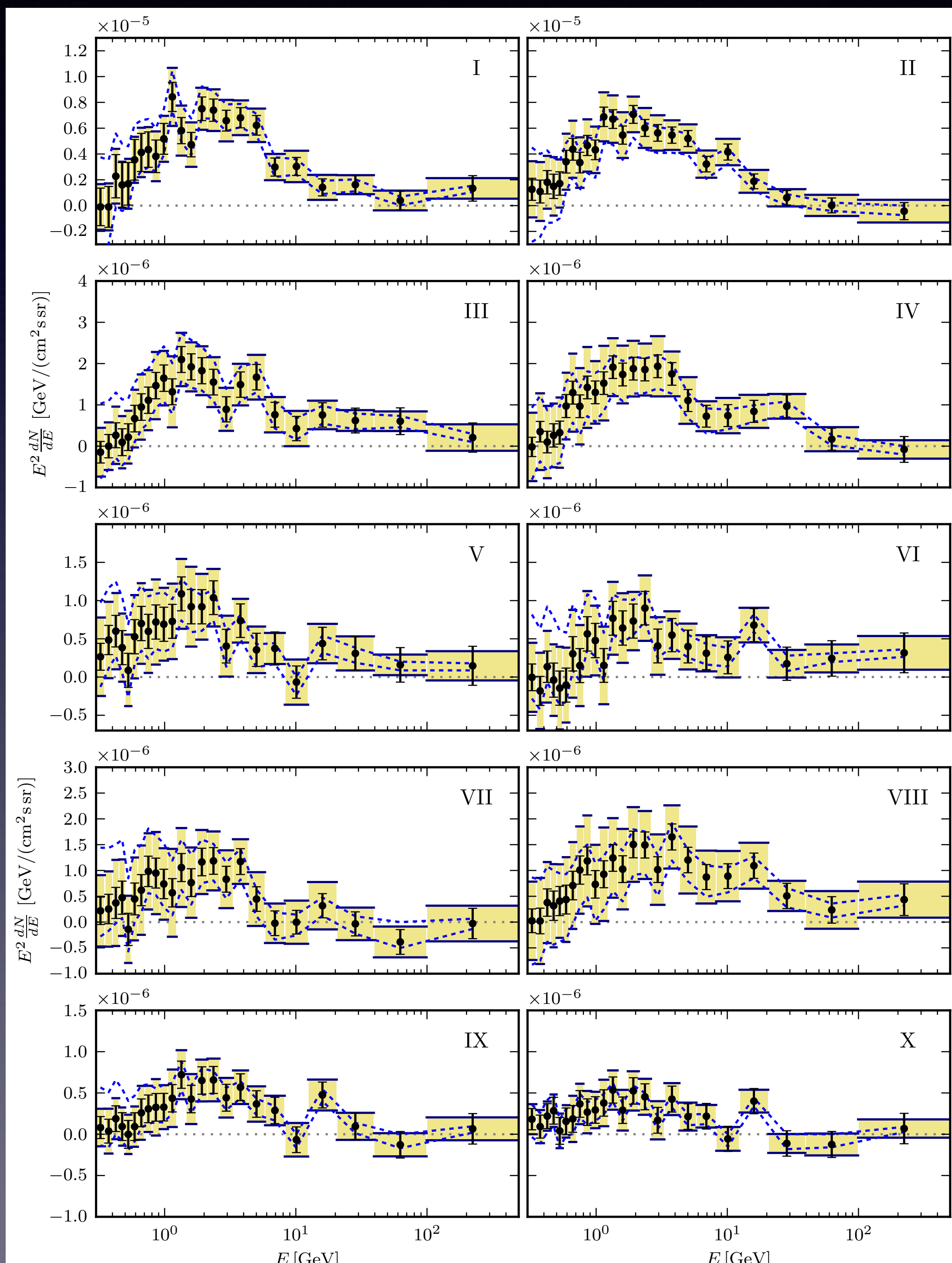
Highly spherical…





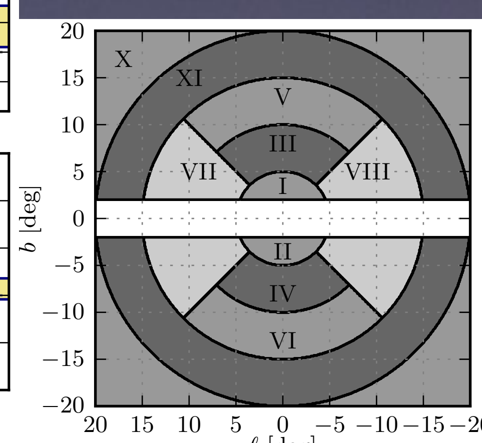
1402.6703

… robust to diffuse map



Presence of a signal with energy peak ~ 2 GeV is robust to changes in diffuse template

1409.0042



The existence of an excess is pretty well agreed upon (independent methods by independent groups* agree something is there)

*also see work by: Abazajian and collaborators (1207.6047, 1402.4090, 1410.6168); Gordon, Macias, and collaborators (1306.5725, 1312.6671, 1410.1678, 1410.7840); Murgia's Fermi symposium slides

Qualitative thing we are not yet sure of:

Is the excess from astrophysics or dark matter?

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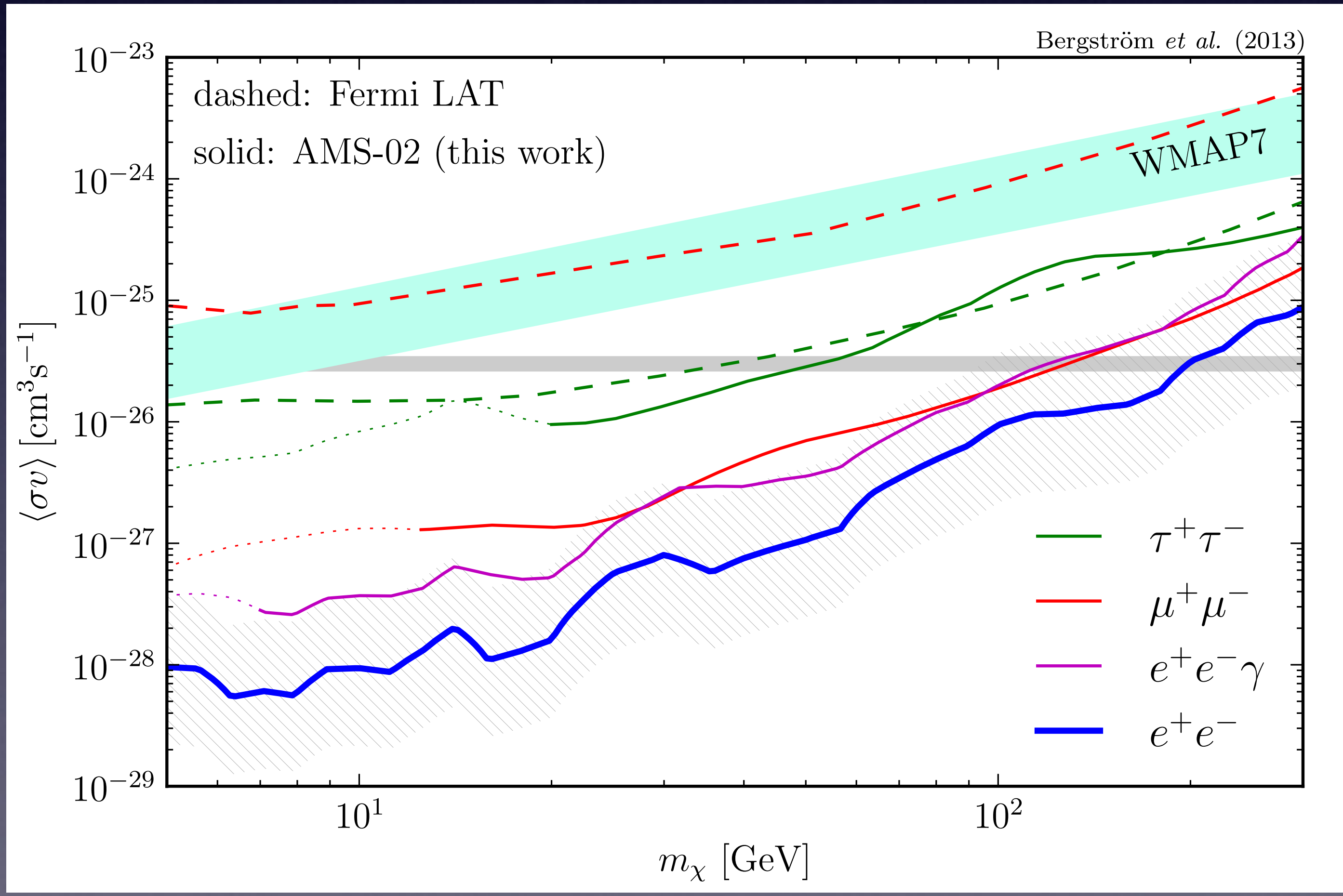
If DM, we need to confront other issues:

- are there other indirect detection signals? bounds?
- what are its interactions with the SM?
- what is the UV theory?

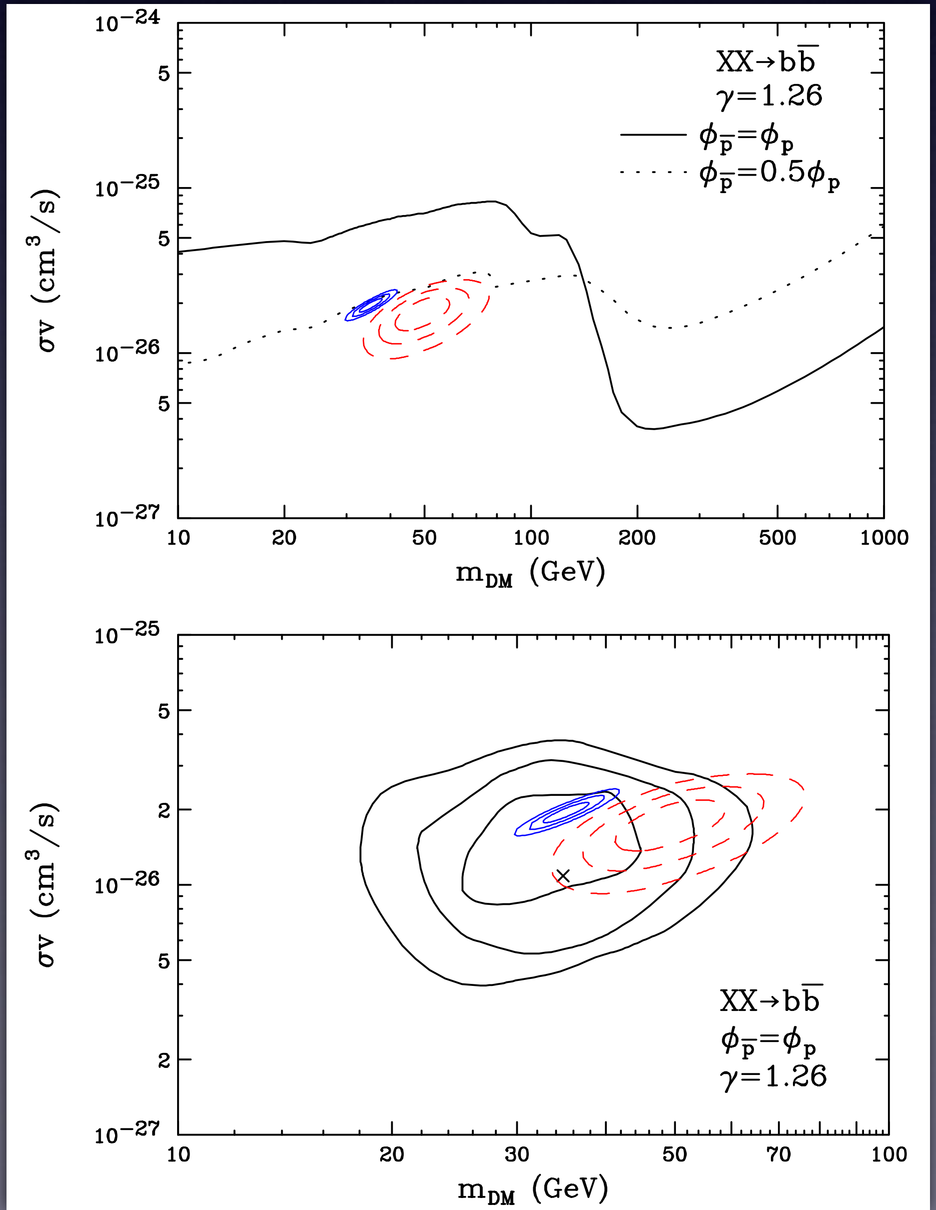
“Secondaries”

basic statements:
no positron “bump” found,
understanding of anti-baryons is murky

1410.1527



1306.3983

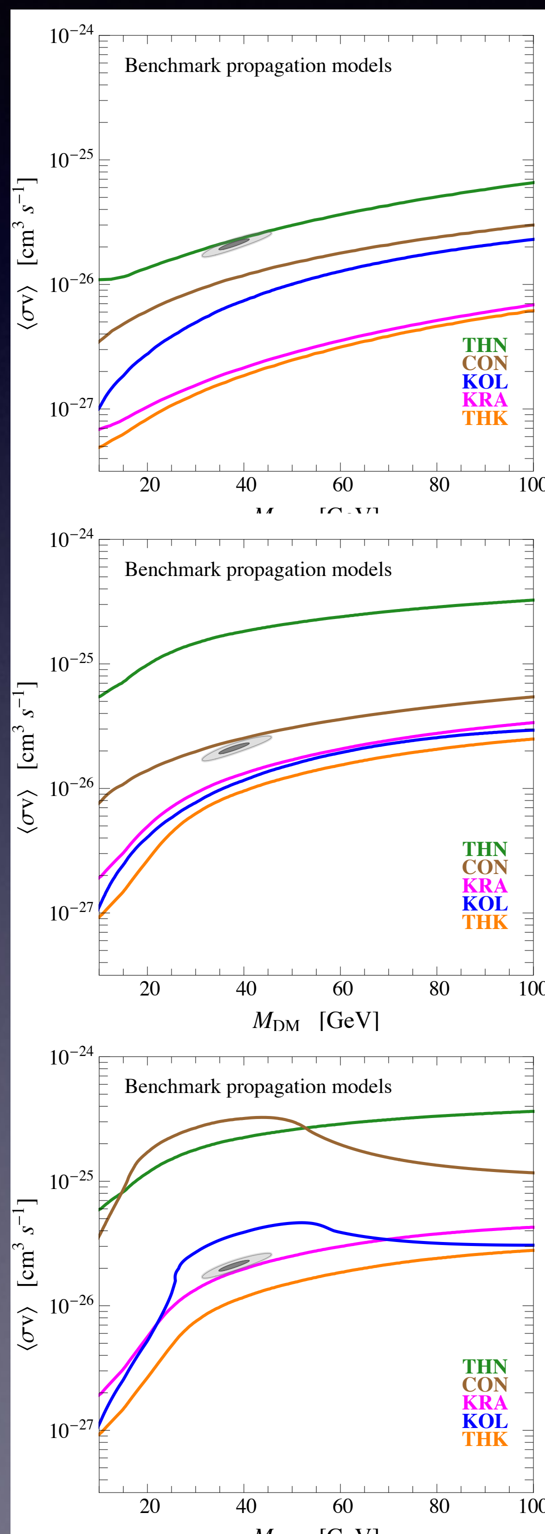


Cosmic Ray Constraints

$\phi_F^{\bar{p}} = \phi_F^{p}$ fixed

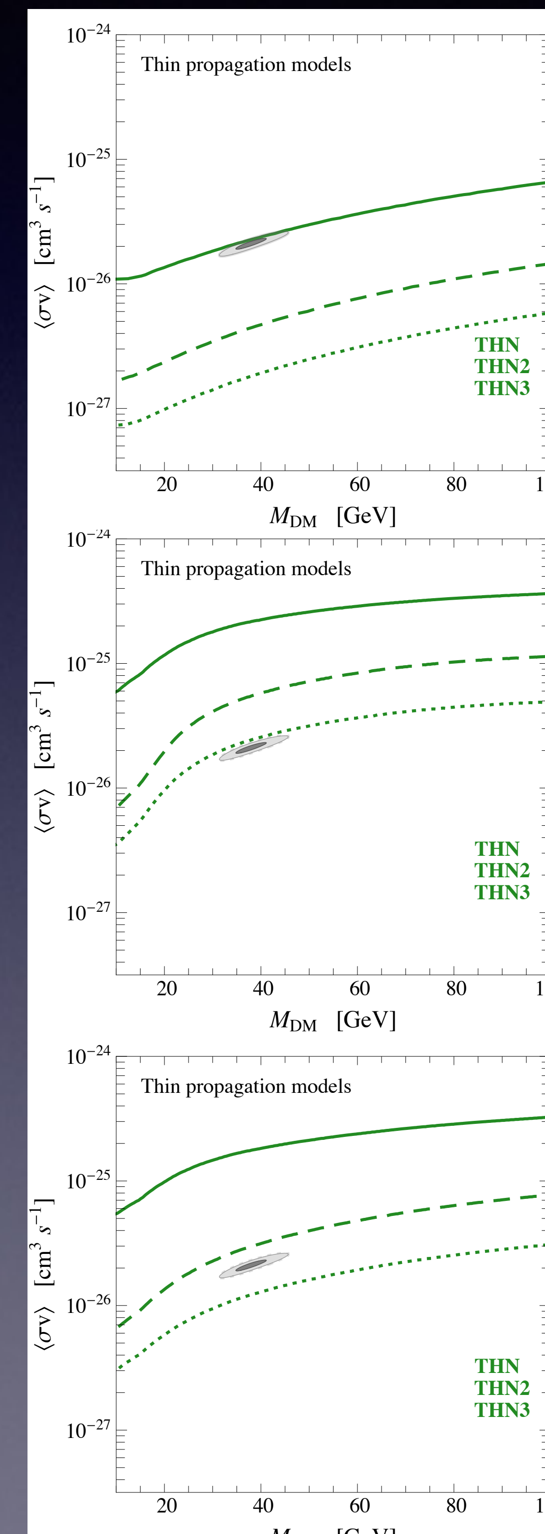
$\phi_F^{\bar{p}} = \phi_F^{p} \pm 50\%$

$\phi_F^{\bar{p}} \in [0.1, 1.1]$ GV



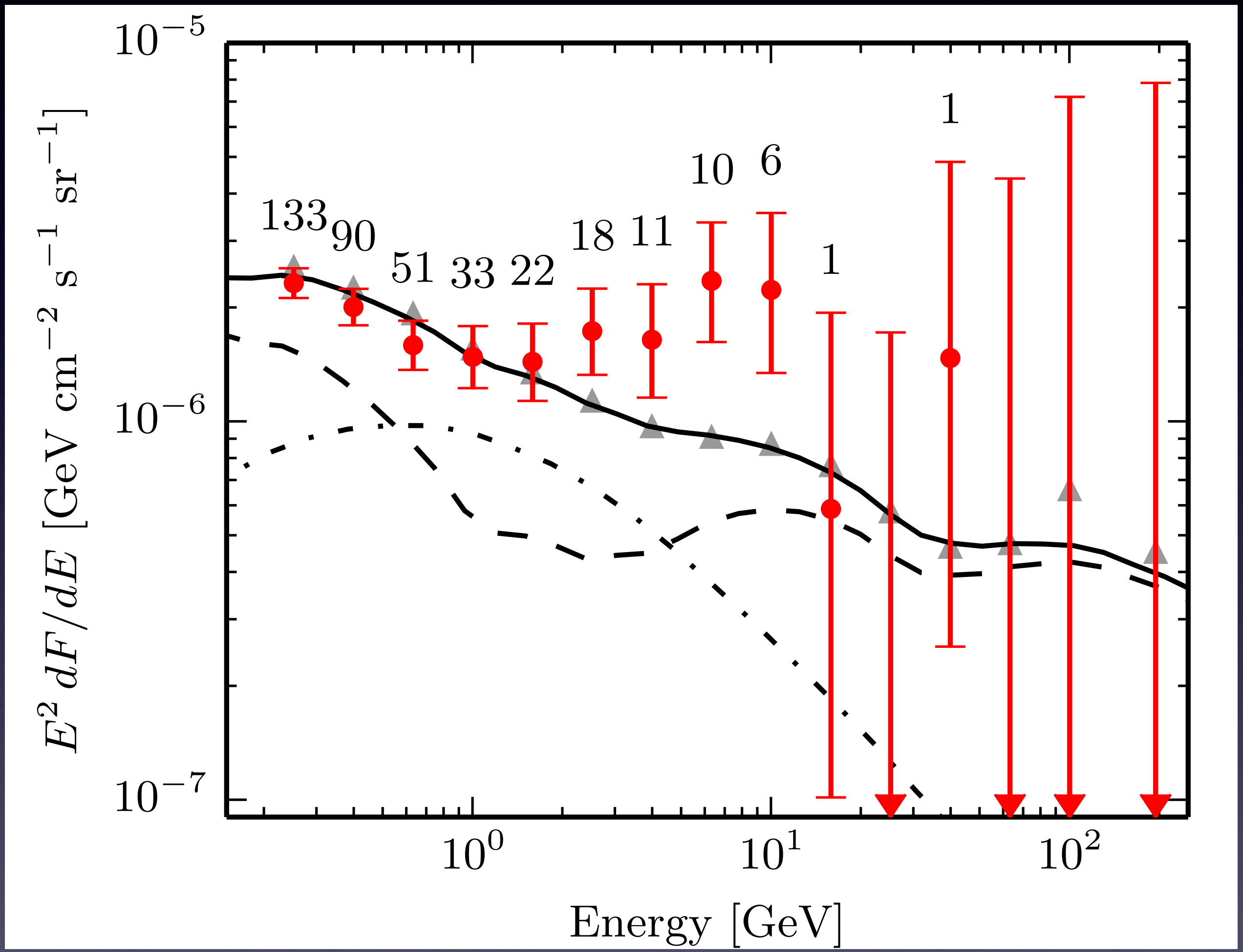
different colors: different choices of diffusion zone parameters

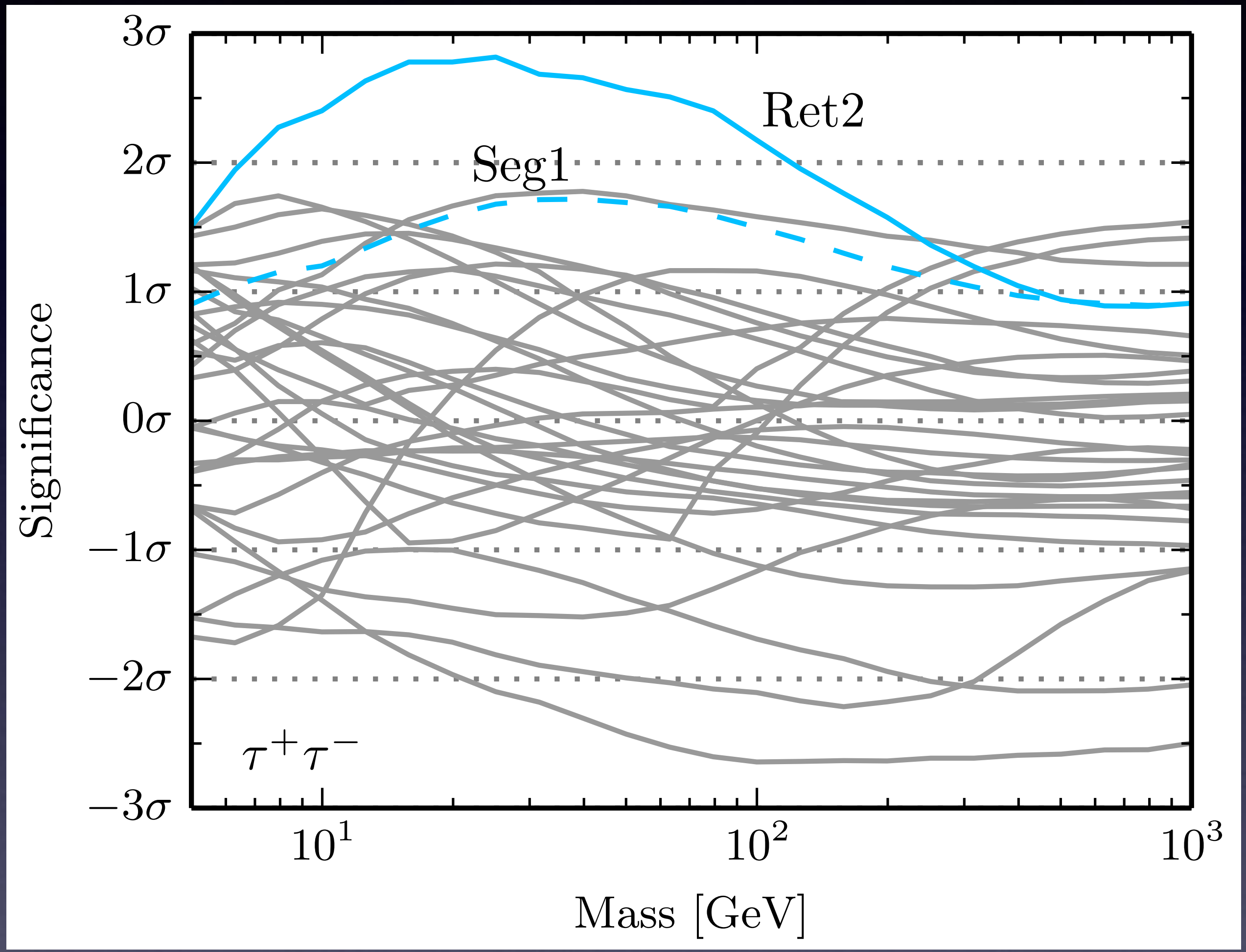
different rows: different choices of relation b/w ϕ_F^{p} and $\phi_F^{\bar{p}}$ local and Galactic



1407.2173

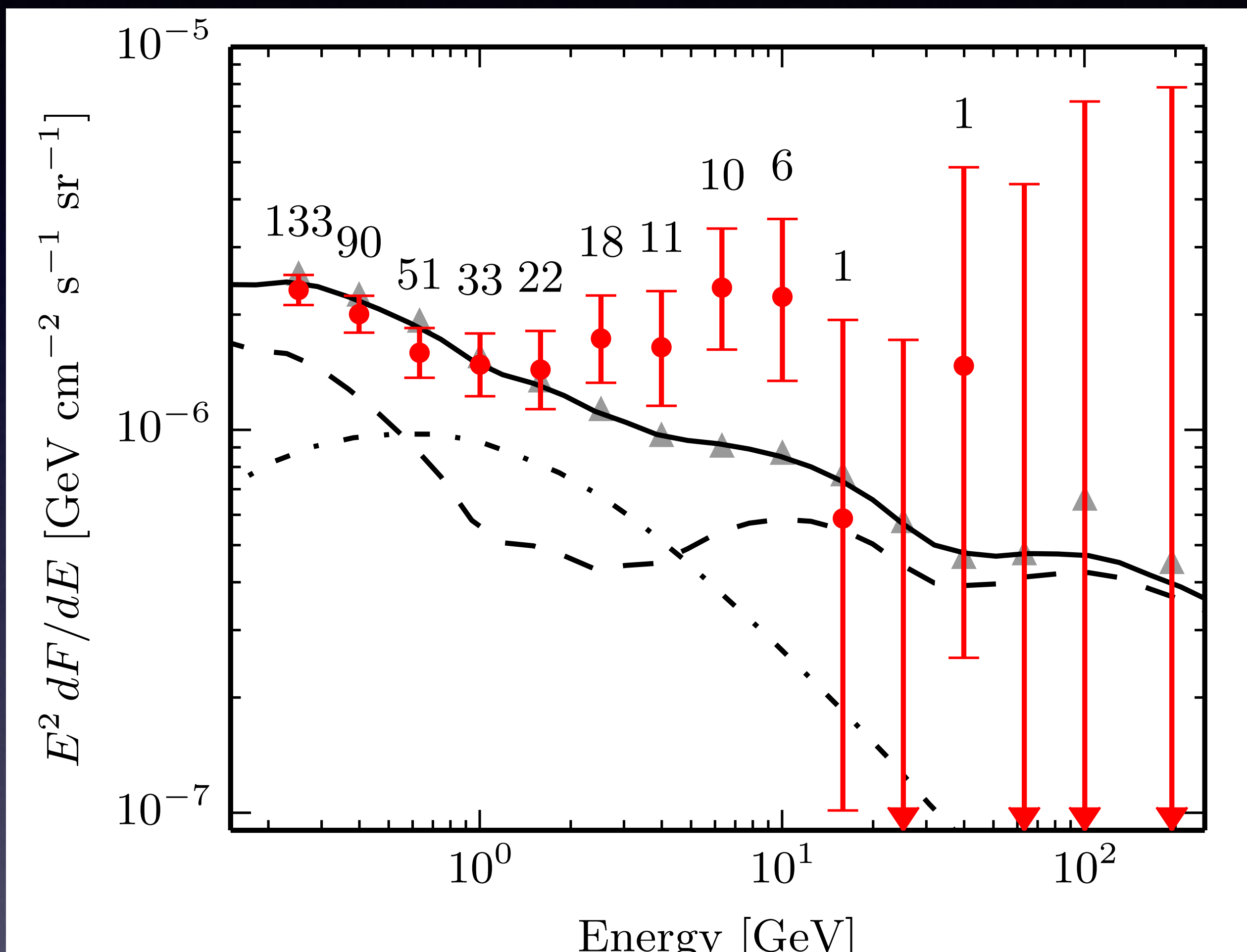
Dwarf Galaxies

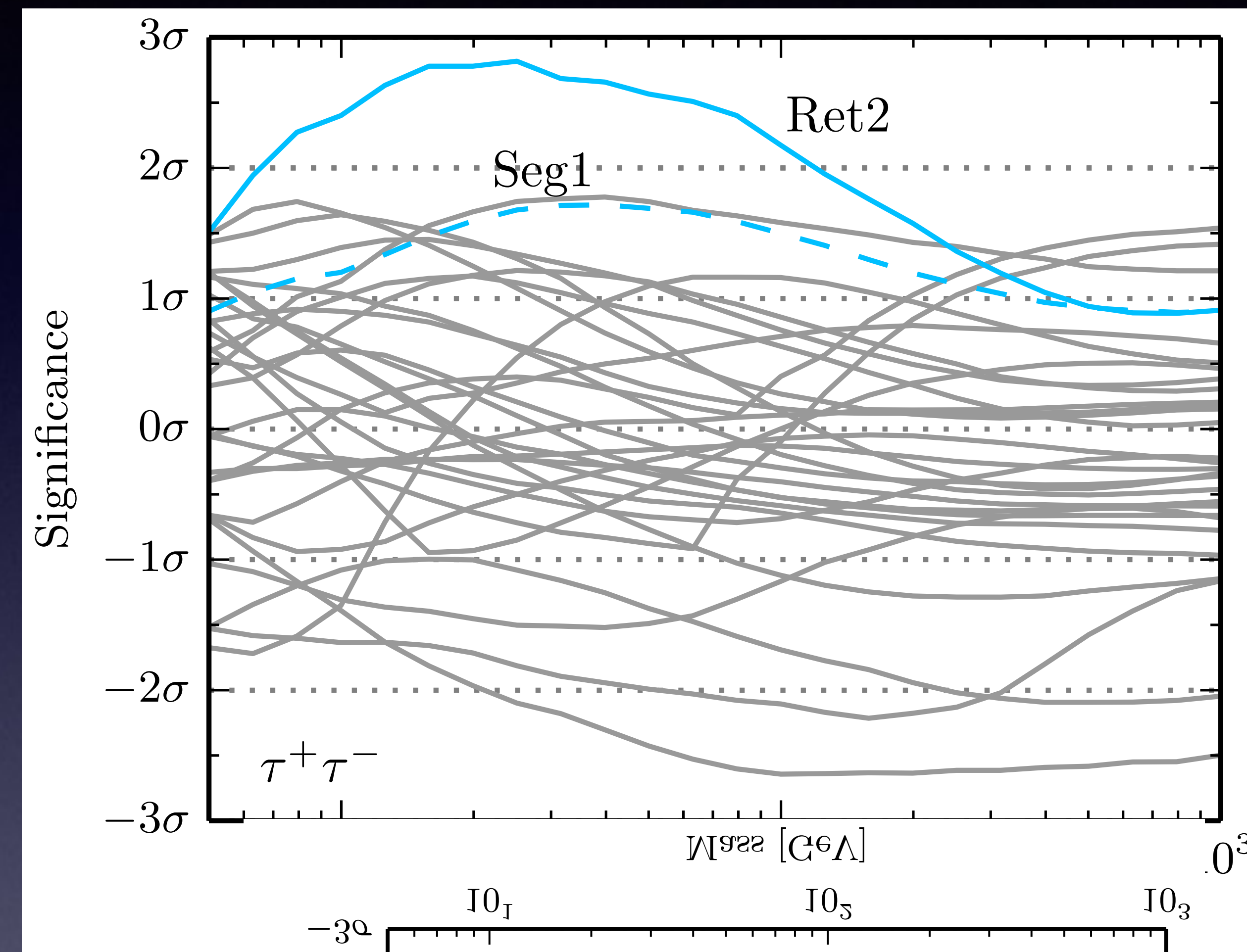


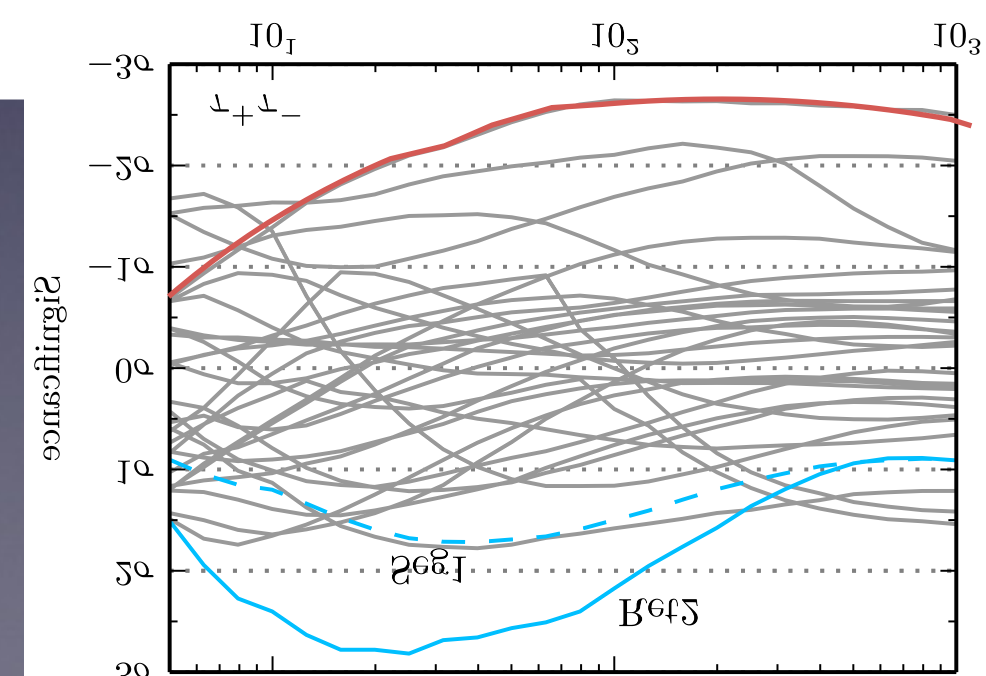


Geringer-Sameth et al, 1503.02320

Dwarf Galaxies

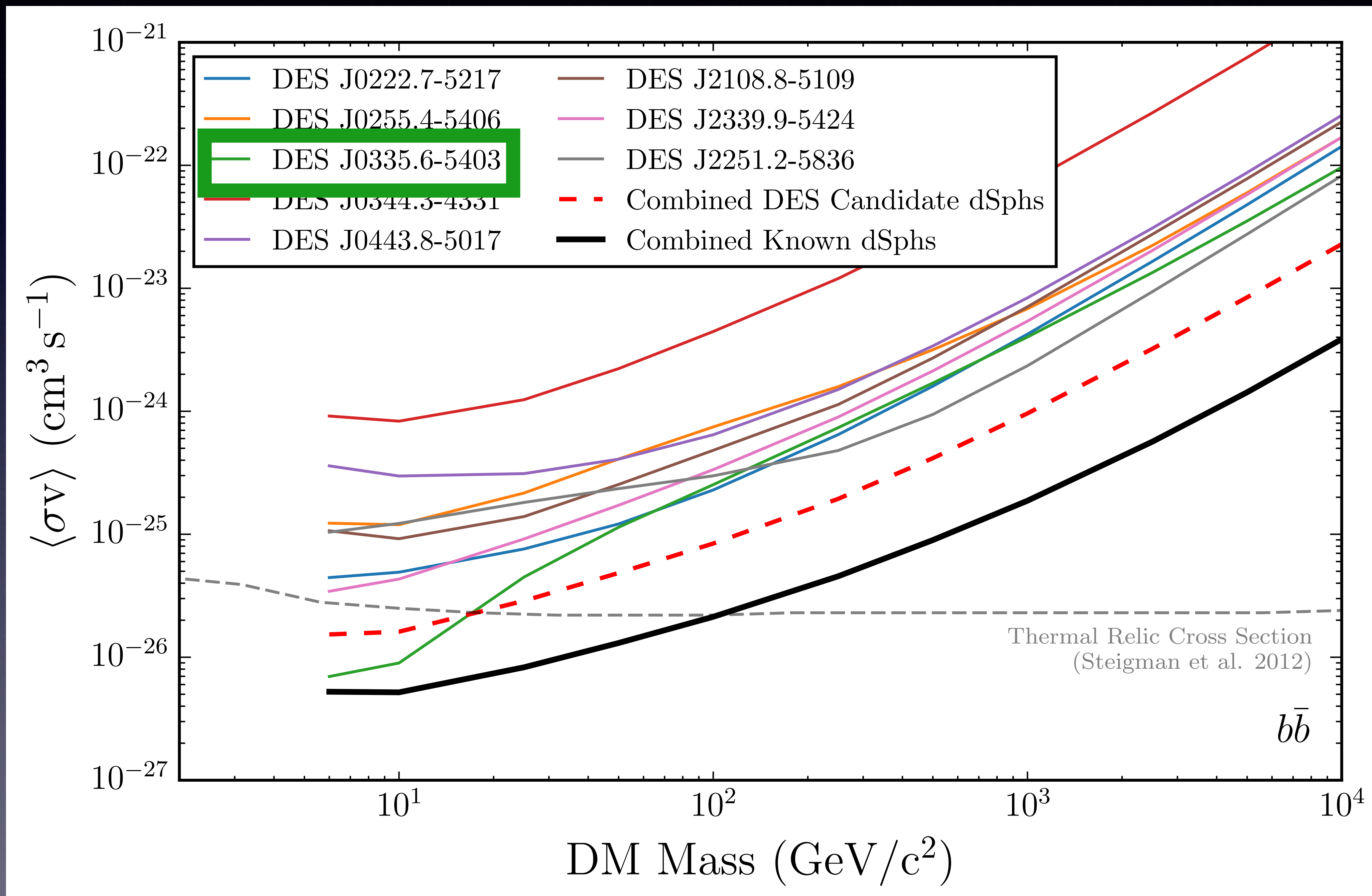






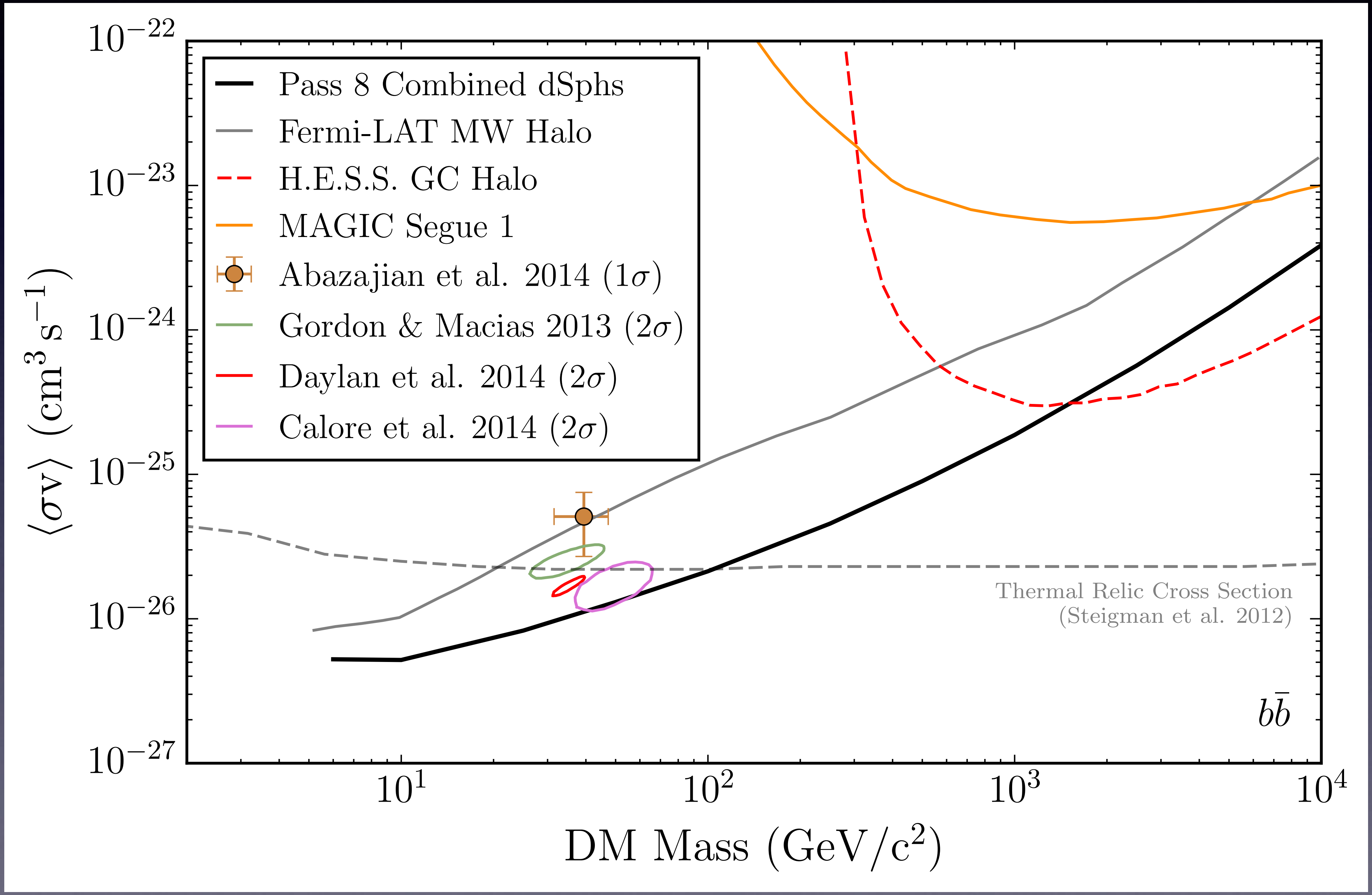
Geringer-Sameth et al, 1503.02320

Dwarf Galaxies



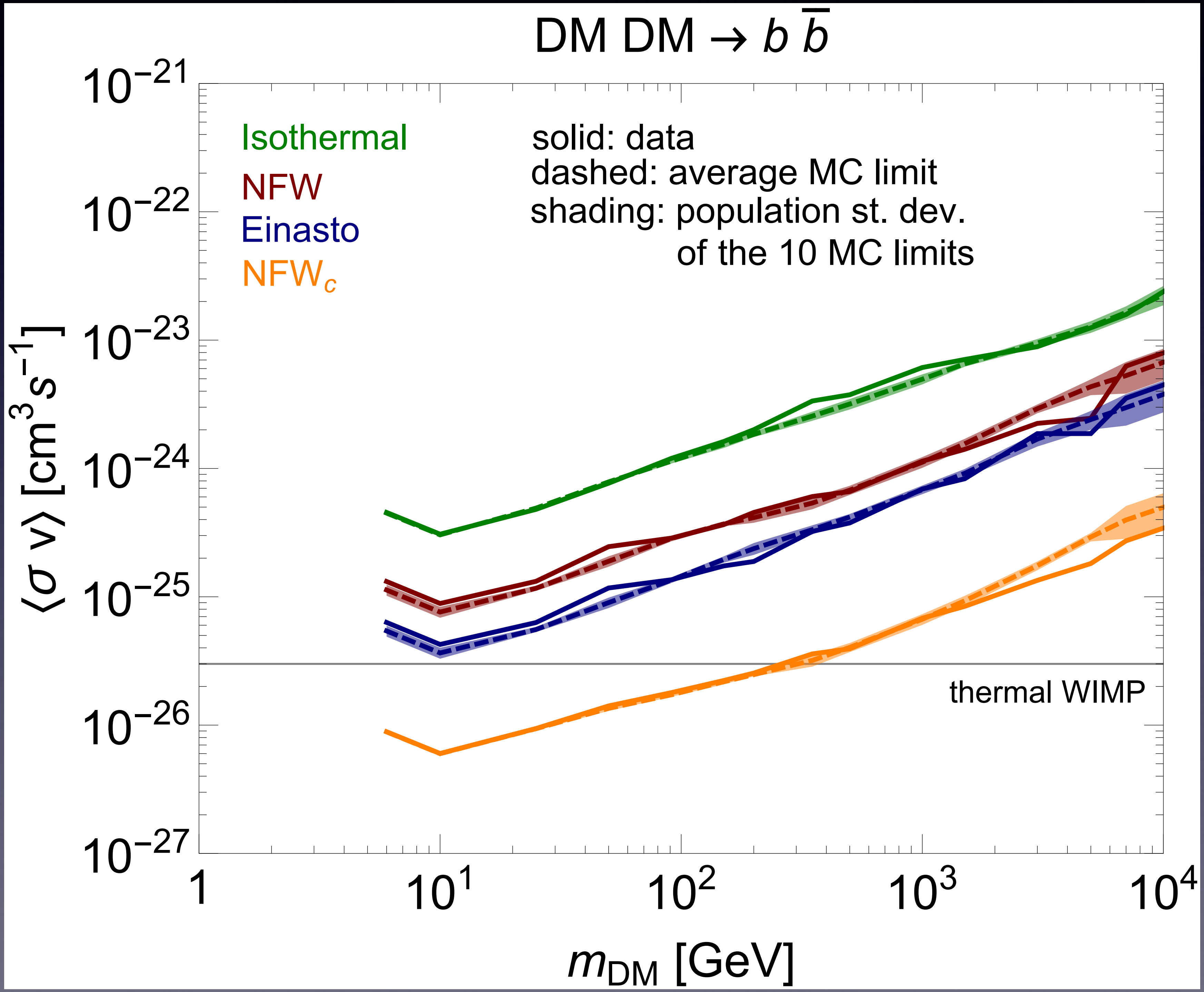
Drlica-Wagner et al, 1503.02632

Dwarf Galaxies



B. Anderson et al, 1503.02632

How Bright?



Essig, Massari, et al 1503.07169

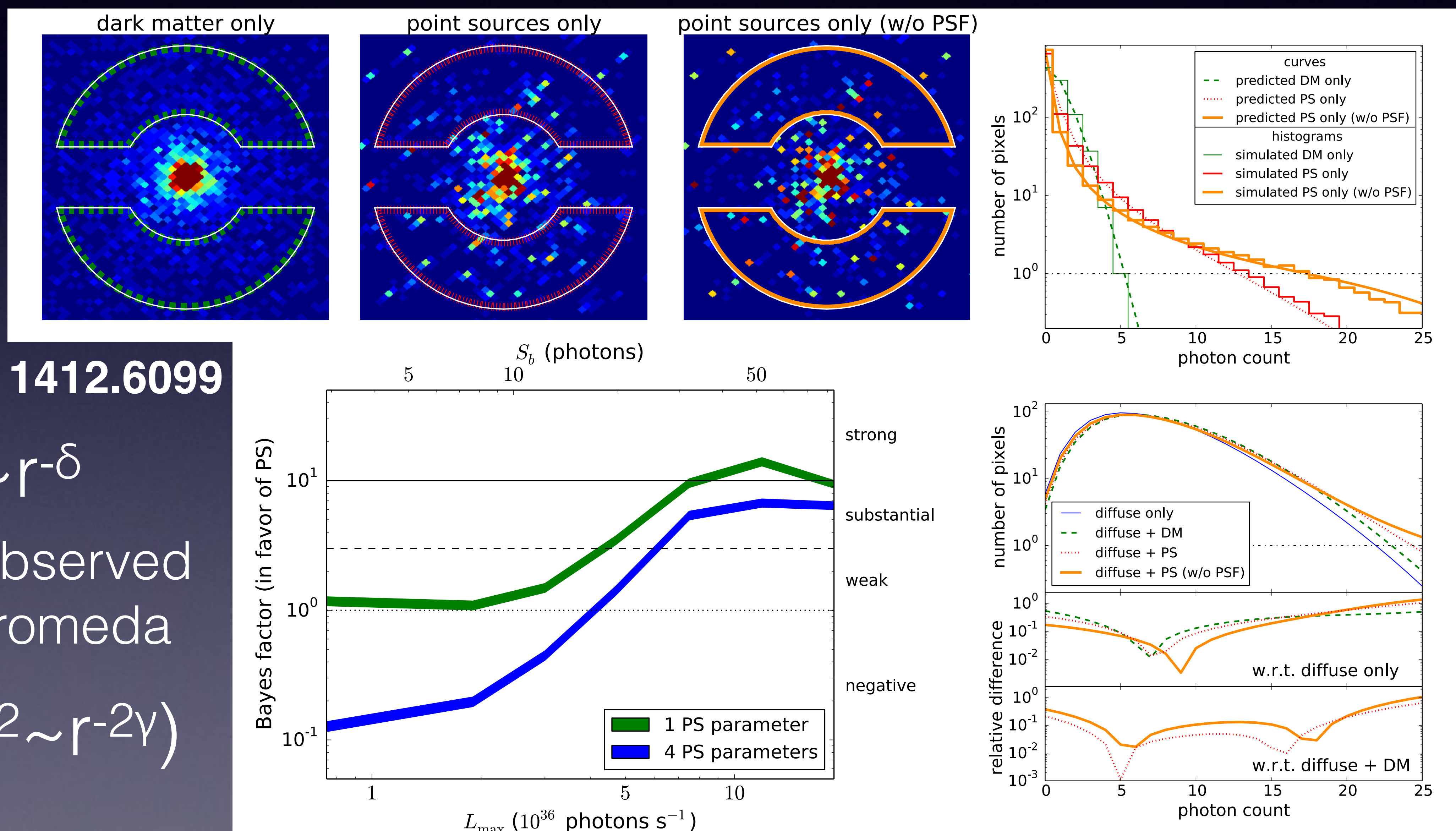
Qualitative thing we are not yet sure of:

Is the excess from astrophysics or dark matter?

If SM, we need a consistent explanation:

- existence of the Fermi bubbles is suggestive; but hard to get smooth structure from this kind of burst
- millisecond pulsars show up over the correct scales range with plausibly correct morphology; but…

Point Sources



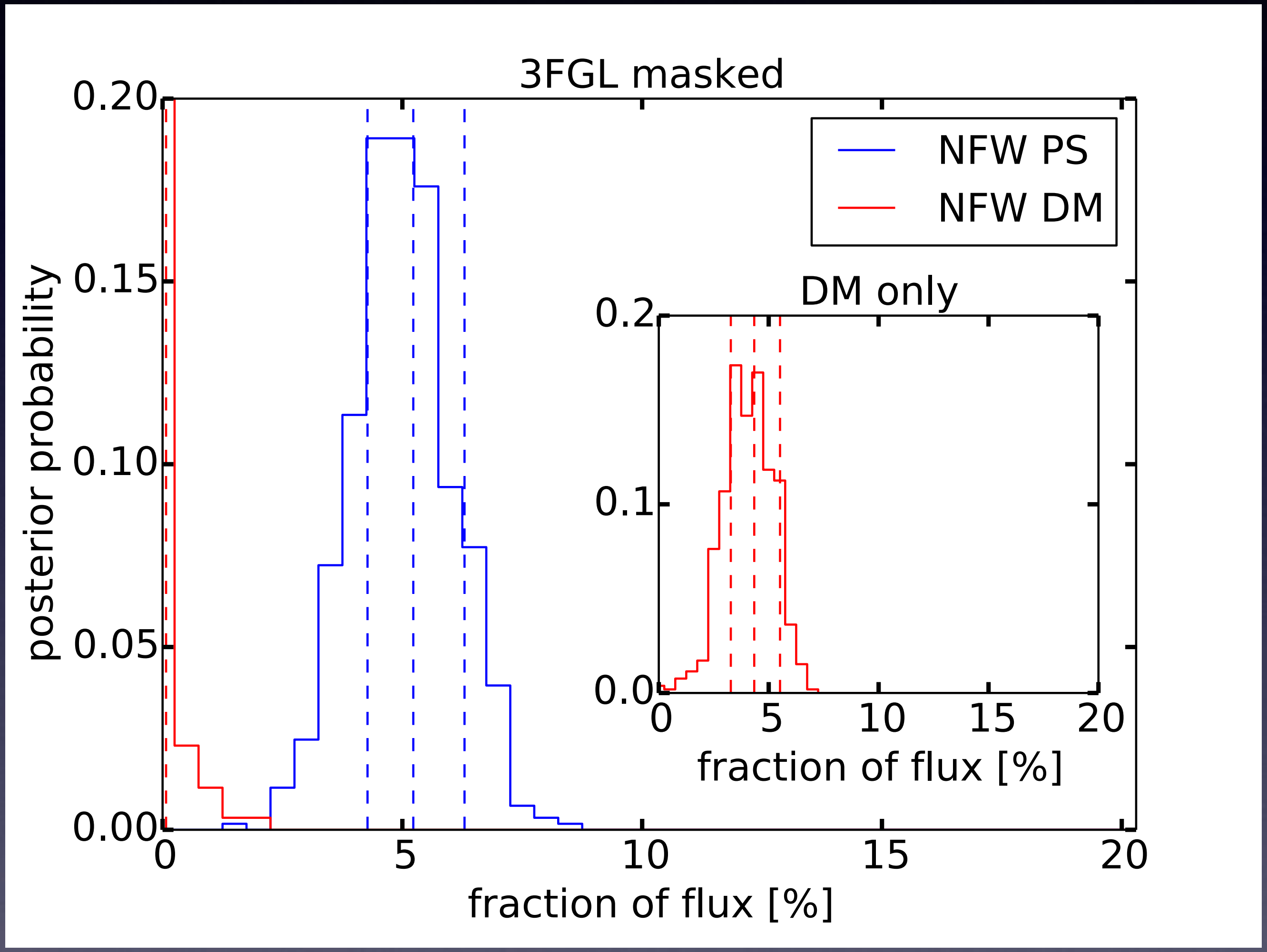
1412.6099

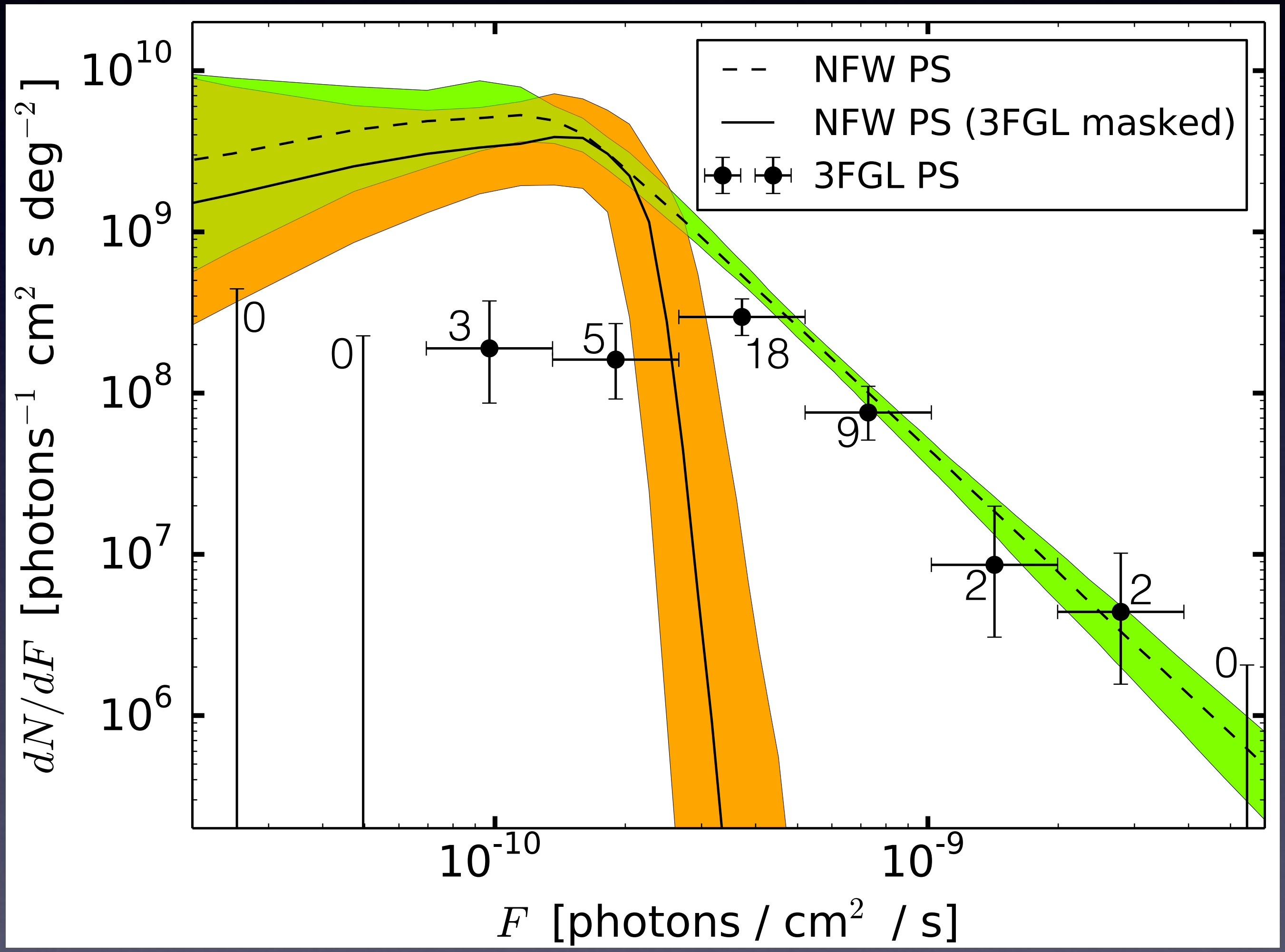
$n \sim r^{-\delta}$

$\delta \sim 2.5$ observed in Andromeda

(cf. $\rho^2 \sim r^{-2\gamma}$)

Point Source Fits



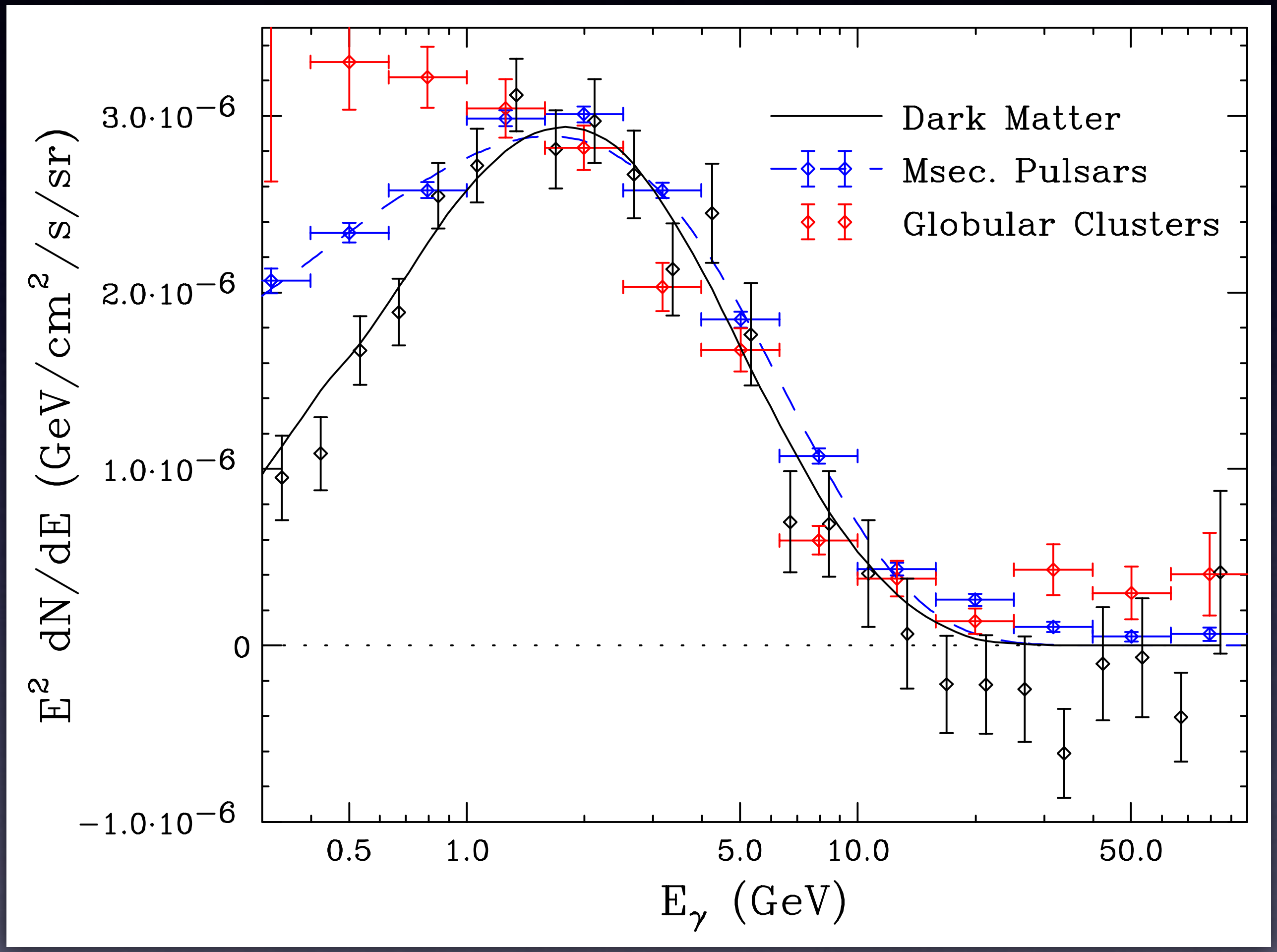


1506.05124

based on non-Poissonian template fit, point sources can account for excess

Millisecond Pulsars

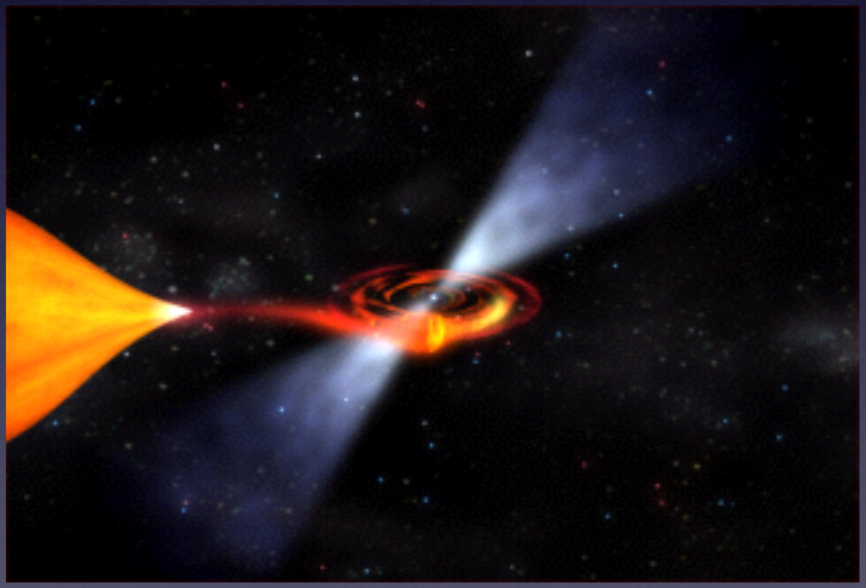
- Spectra are "significantly" different
- Should have resolved many more MSPs in inner 1.8 kpc (~few°) given "reasonable" luminosity function: N(L>10^{34} erg/s) ~ 200, N(L>10^{35} erg/s) ~ 60



1407.5625

Globular Clusters

- globular clusters are dense stellar environments (=> star-star encounters are common)
- Some star-star encounters create X-ray binaries, some create MSPs
- X-ray binaries fizzle out sooner than MSPs

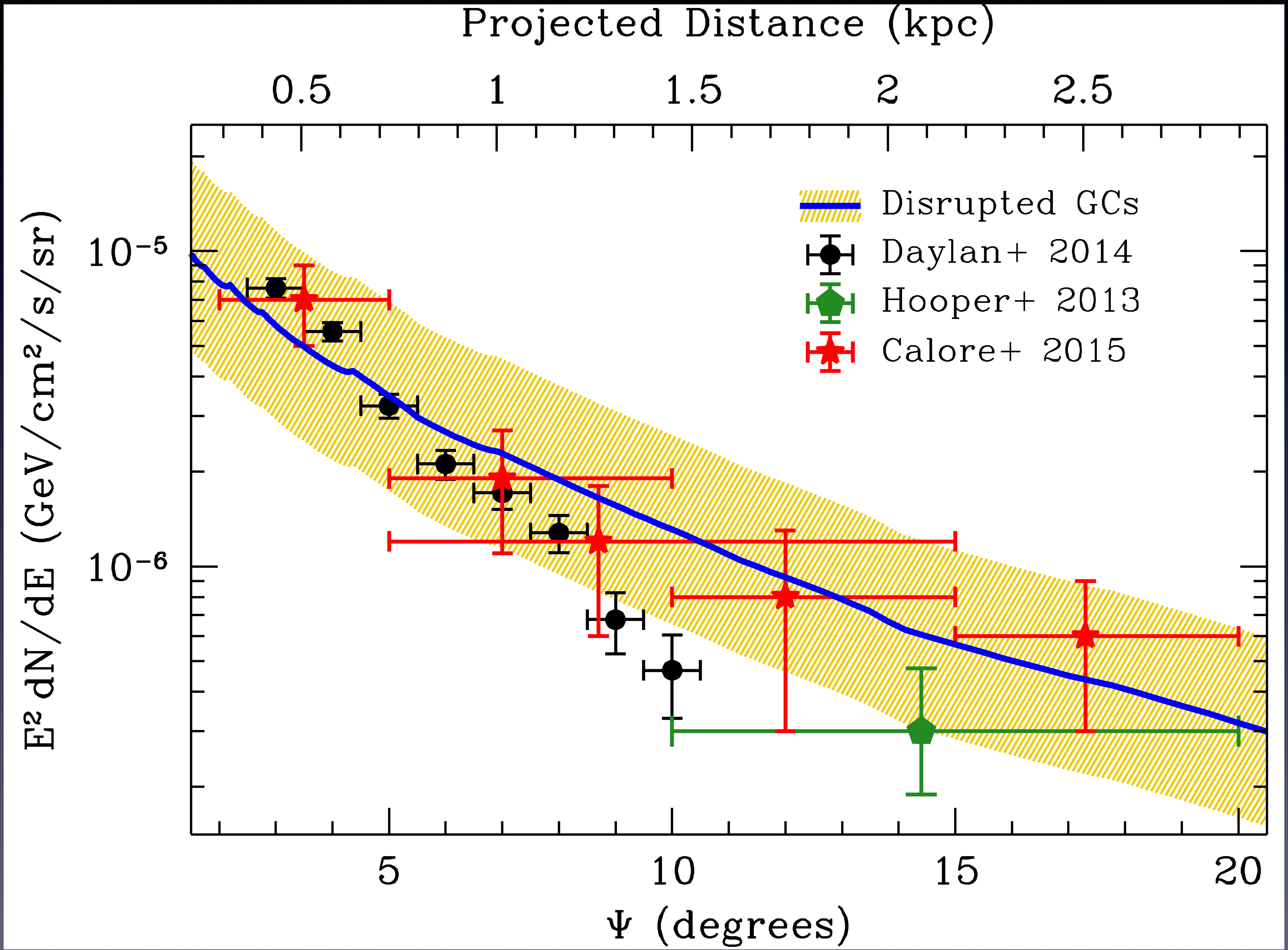


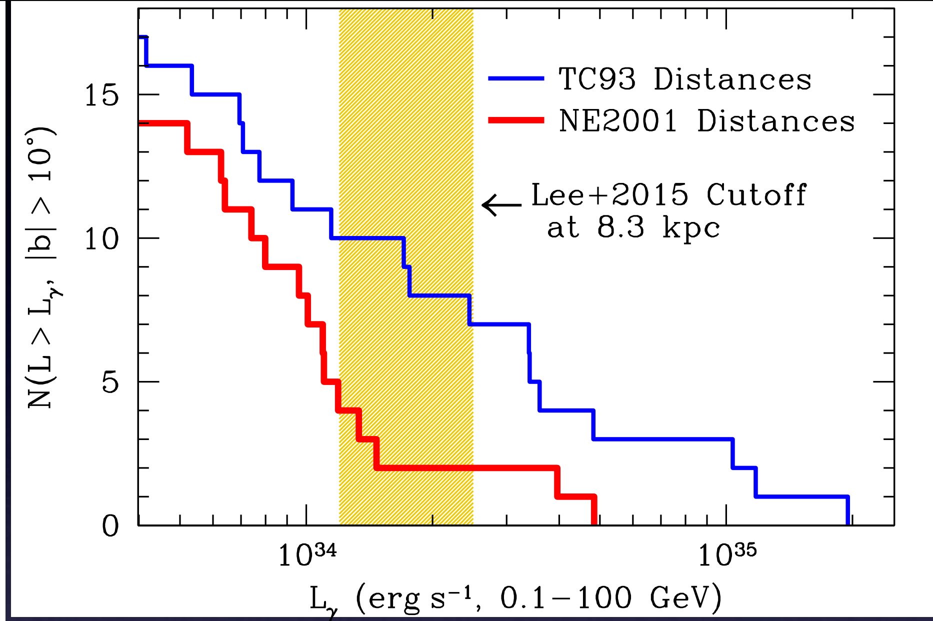
1507.05616

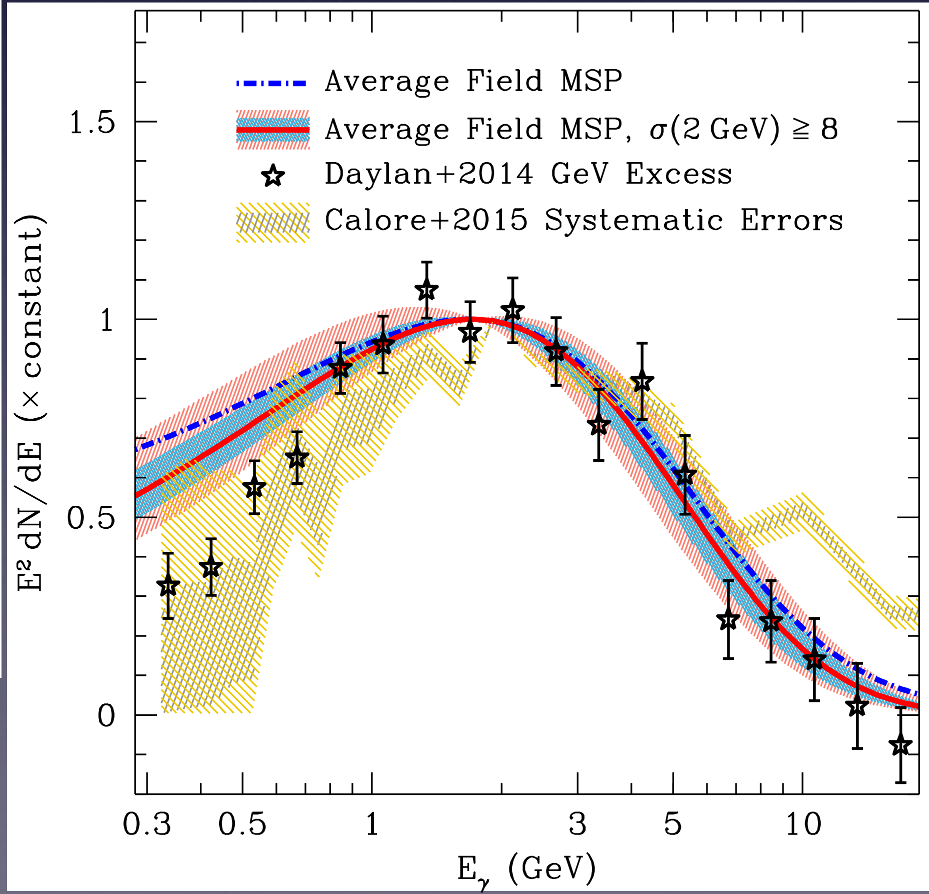
DISRUPTED GLOBULAR CLUSTERS CAN EXPLAIN THE GALACTIC CENTER GAMMA RAY EXCESS

Timothy D. Brandt[1,3] and Bence Kocsis[1,2]

(with zero free parameters)







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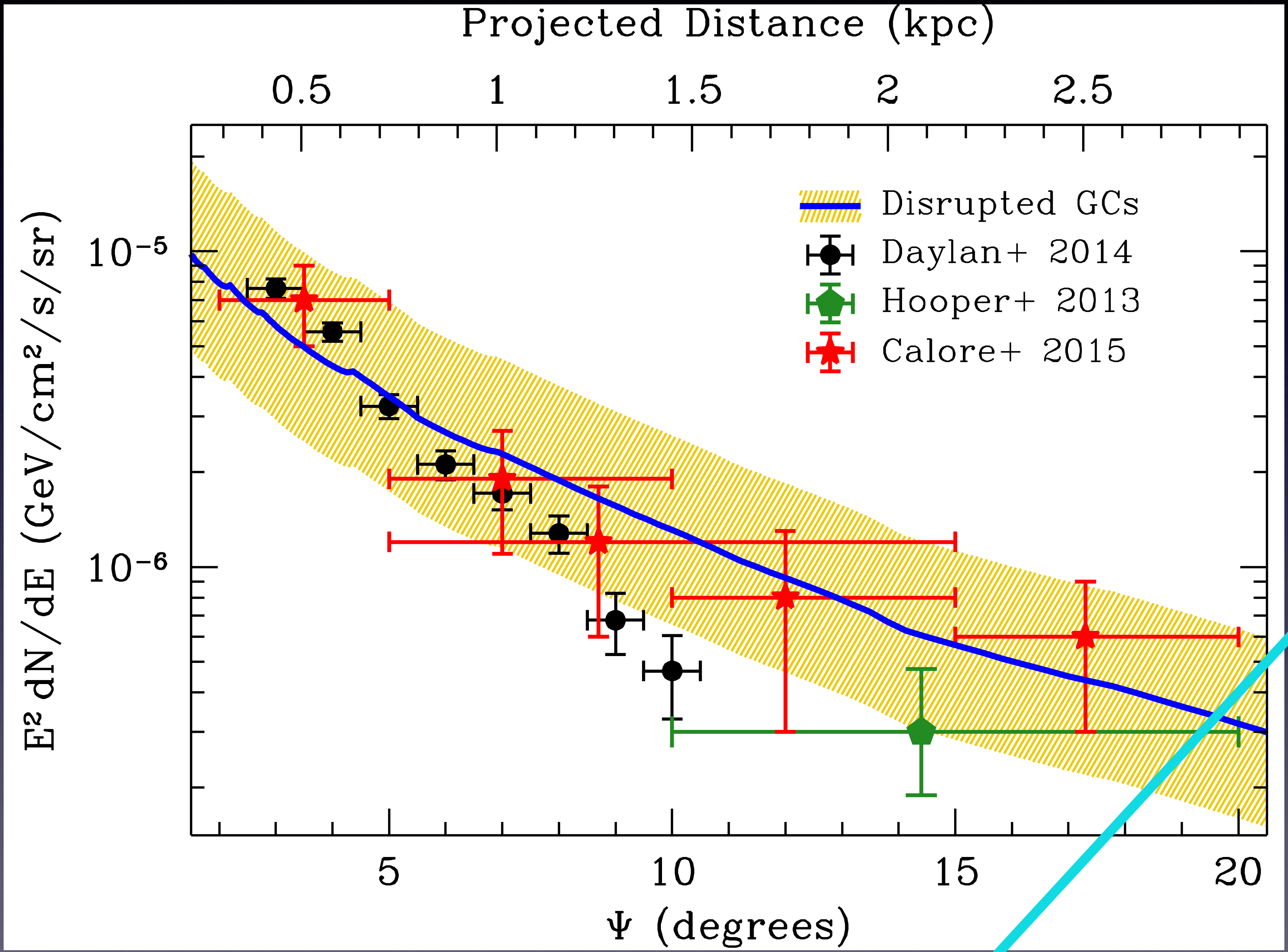
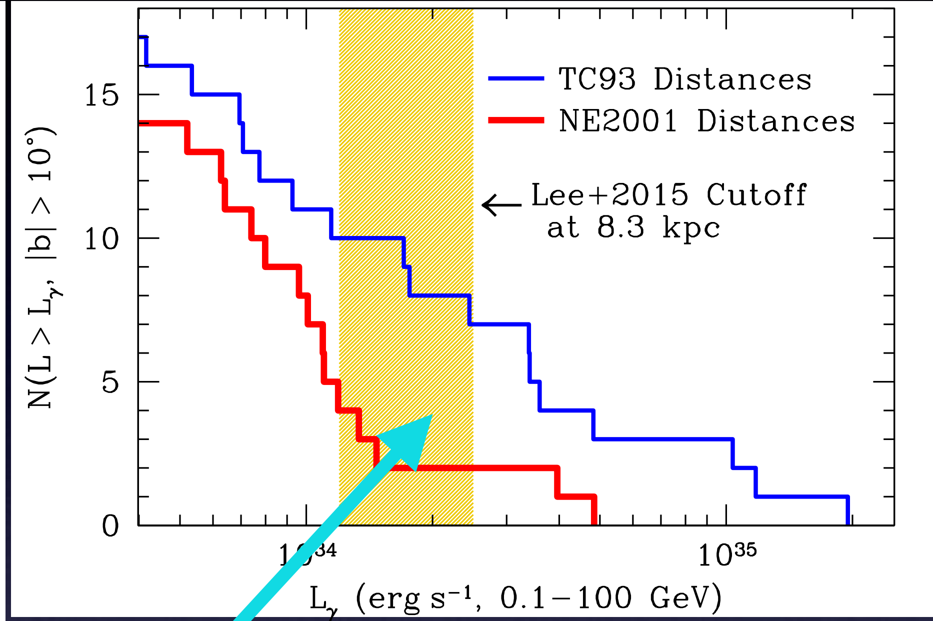
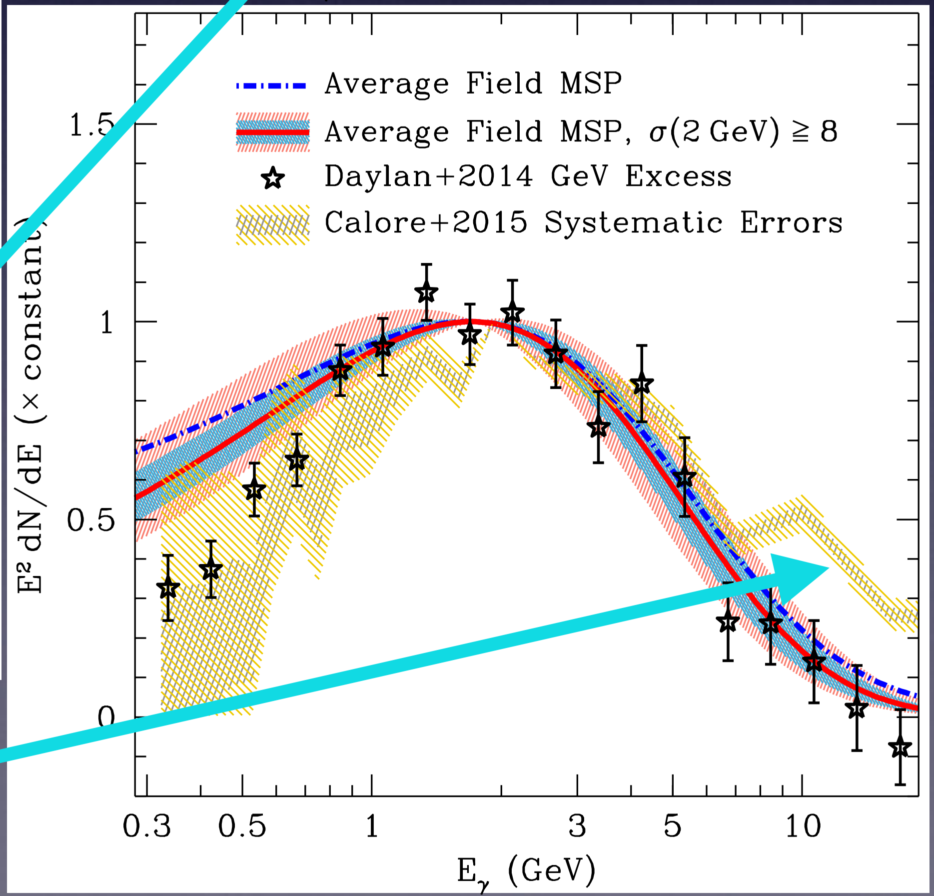
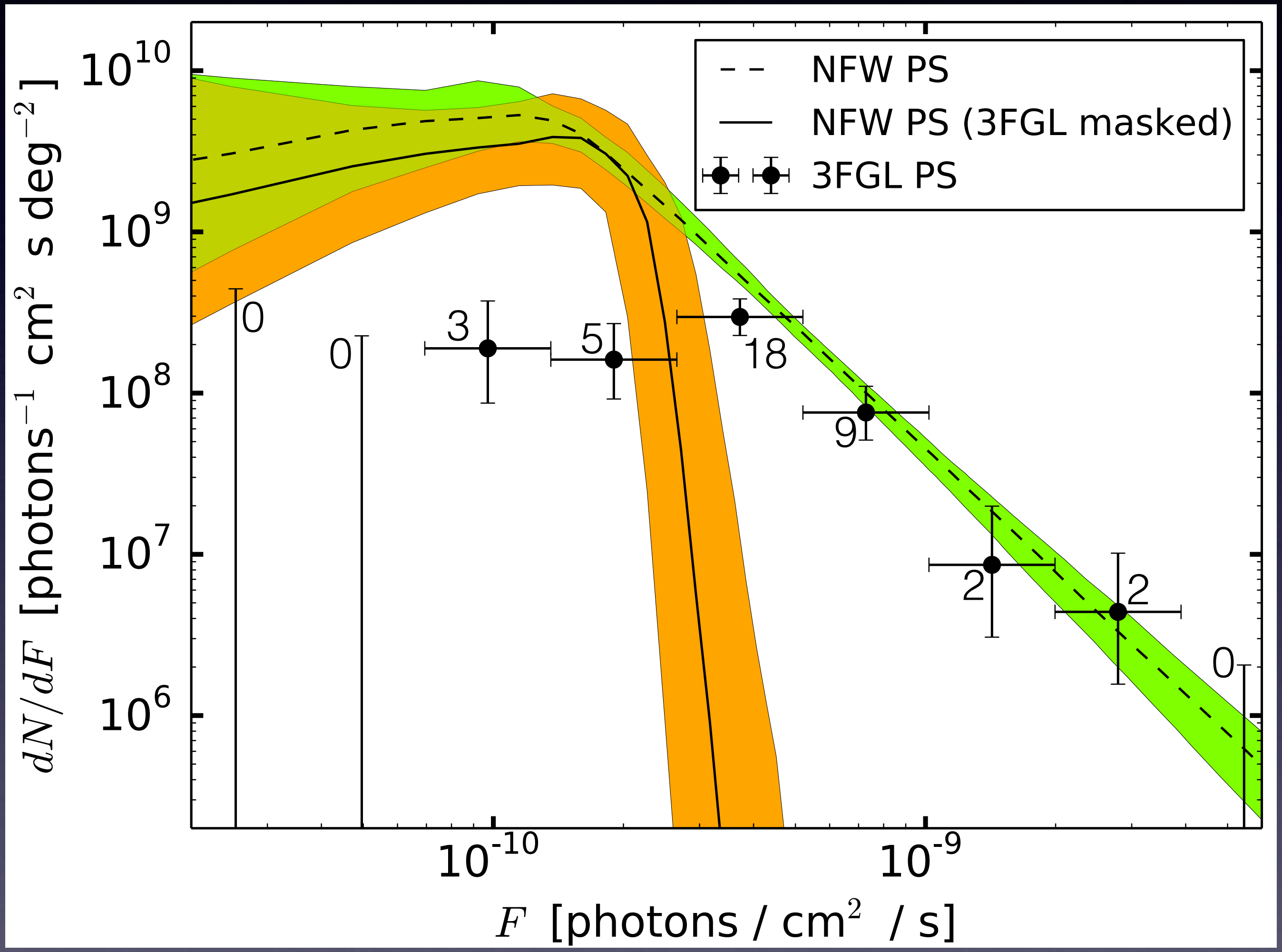


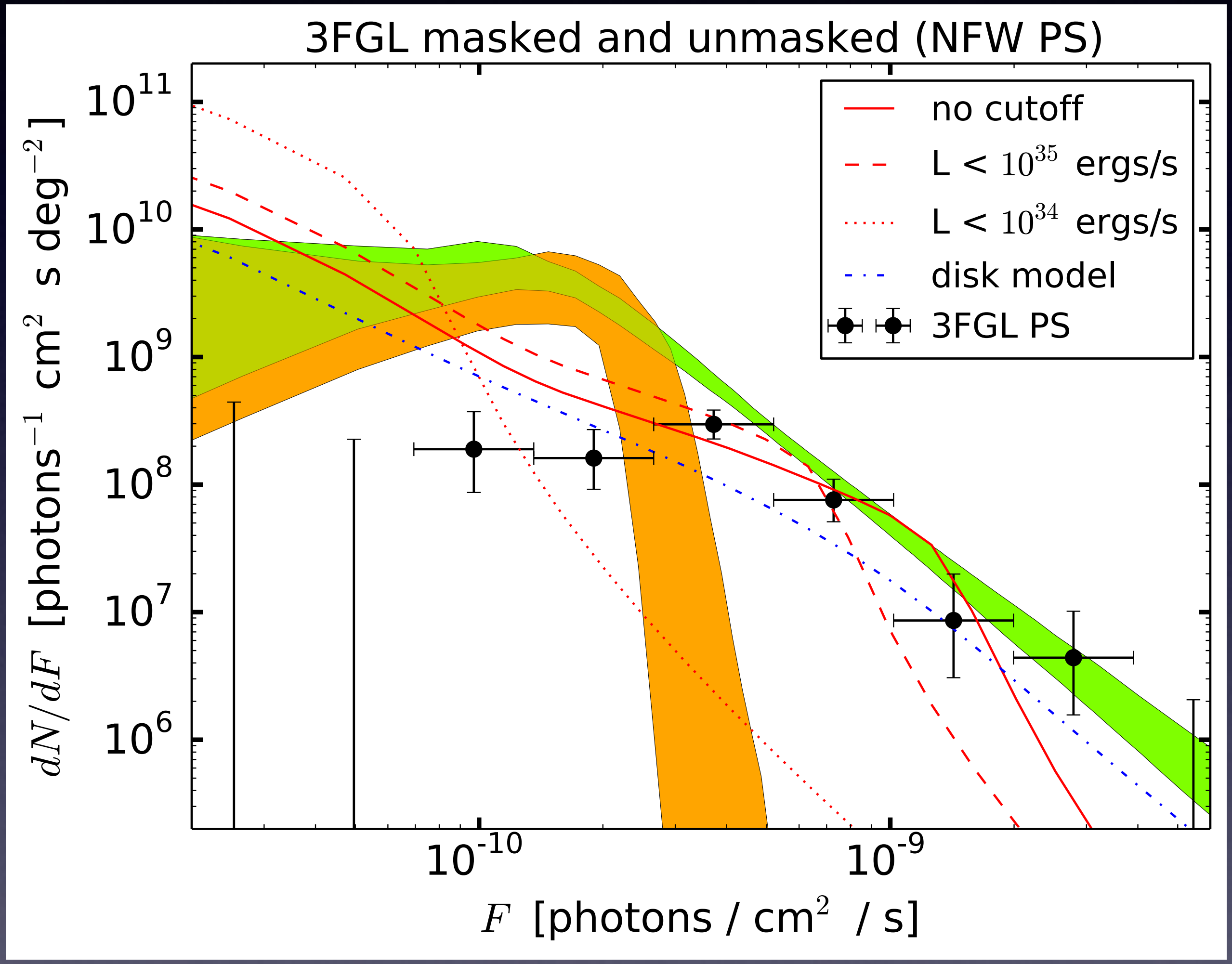




some concerns, still

Point Sources, II





1506.05124

still some missing point sources?

Lessons

existence of a signal is pretty robust, but…

- … diffuse templates house large, energy-dependent uncertainties
- … serious caution and healthy skepticism are required when interpreting as BSM physics
- … a few opportunities so far that "could" have been convincing (either way) have not panned out

How else can we convince ourselves this is or isn’t dark matter?

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Particle physics ideas

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New observational ideas

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New observational ideas

work in progress with Ilias Cholis, Paddy Fox, and Samuel K. Lee
1510.$#%@&!

Current Technique

Test *assumption of dark matter annihilation*:

- statistical discrimination (χ^2 test) between fits with and without signal template
- fits with template do better

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…but what if there is a *totally different shape* on the sky that was not adequately tested?

Current Technique

Test *assumption of dark matter annihilation*:

- ween
  late
-

It would be nice to find evidence without making this assumption!

…but what if there is a *totally different shape* on the sky that was not adequately tested?

Wavelets

Allow analysis sensitive to both location and scale

Used for a wide variety of industrial and academic applications:

- image compression (JPEG-2000)
- fast astrophysical signal identification
- cochlear transforms (mimic hearing)
- image denoising
- jets (this is still in its infancy…)
- etc.**

What are wavelets?

wavelet coefficients

original signal

$$W(a,b) = \frac{1}{\sqrt{a}} \int f(x) \psi^* \left(\frac{x-b}{a} \right) dx$$

scale

position

mother wavelet
(different choices)

$$\int \psi(x) dx = 0$$

$$\int |\psi(x)|^2 dx = 1$$

$\psi(x) \in \mathbb{L}^2(\mathbb{R})$ and

$$\frac{1}{\sqrt{a}} \psi \left(\frac{x-b}{a} \right) \in \mathbb{L}^2(\mathbb{R})$$

for $a, b \in \mathbb{Z}$

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ent choices)

How (and why) do they work?

$$\int \psi(x)dx = 0$$

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$$\frac{1}{\sqrt{a}}\psi\left(\frac{x-b}{a}\right) \in \mathbb{L}^2(\mathbb{R})$$

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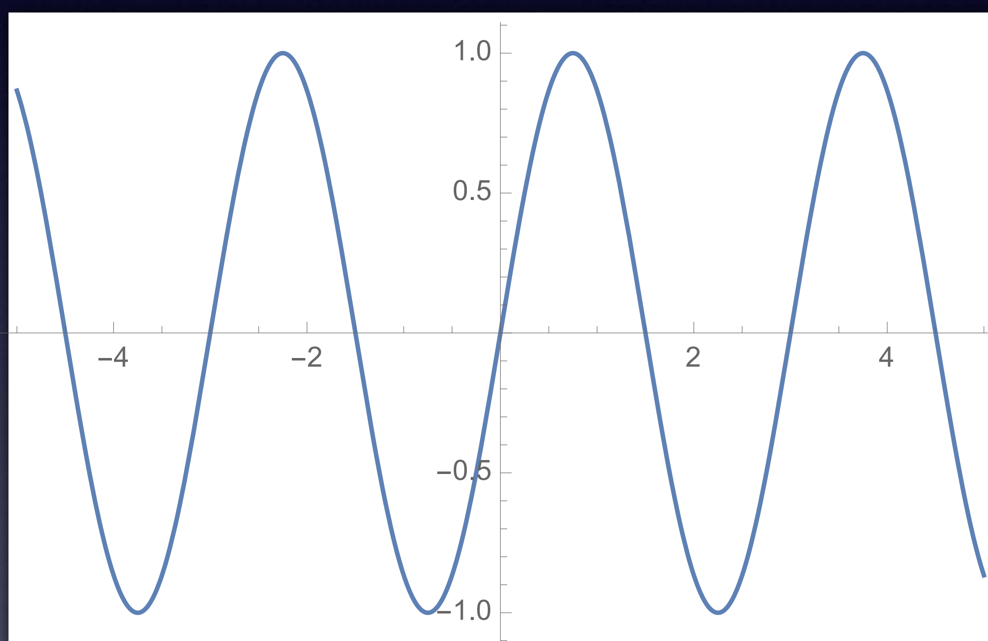
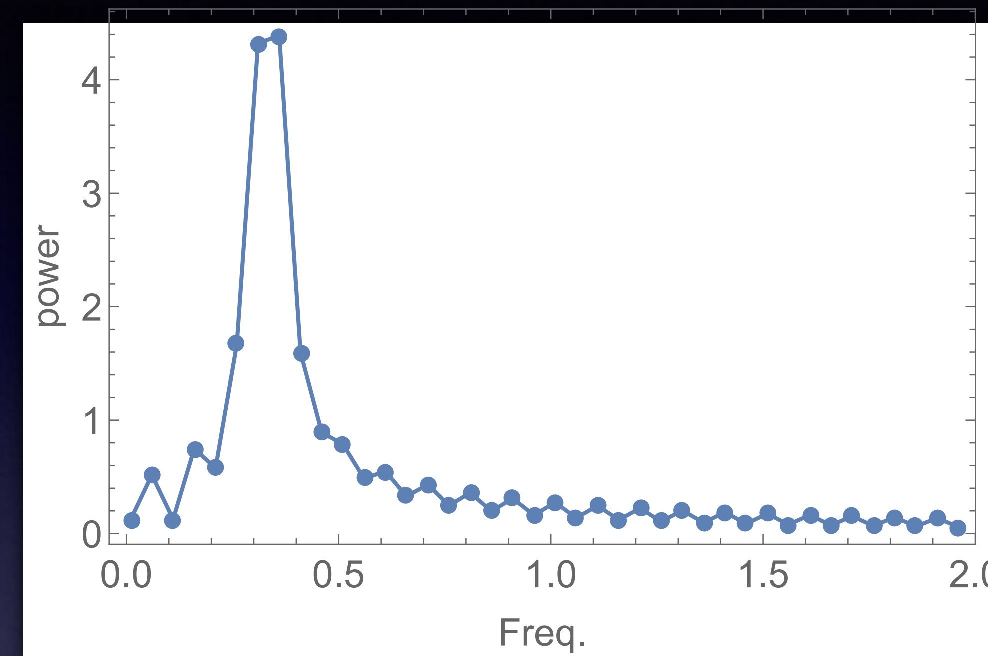
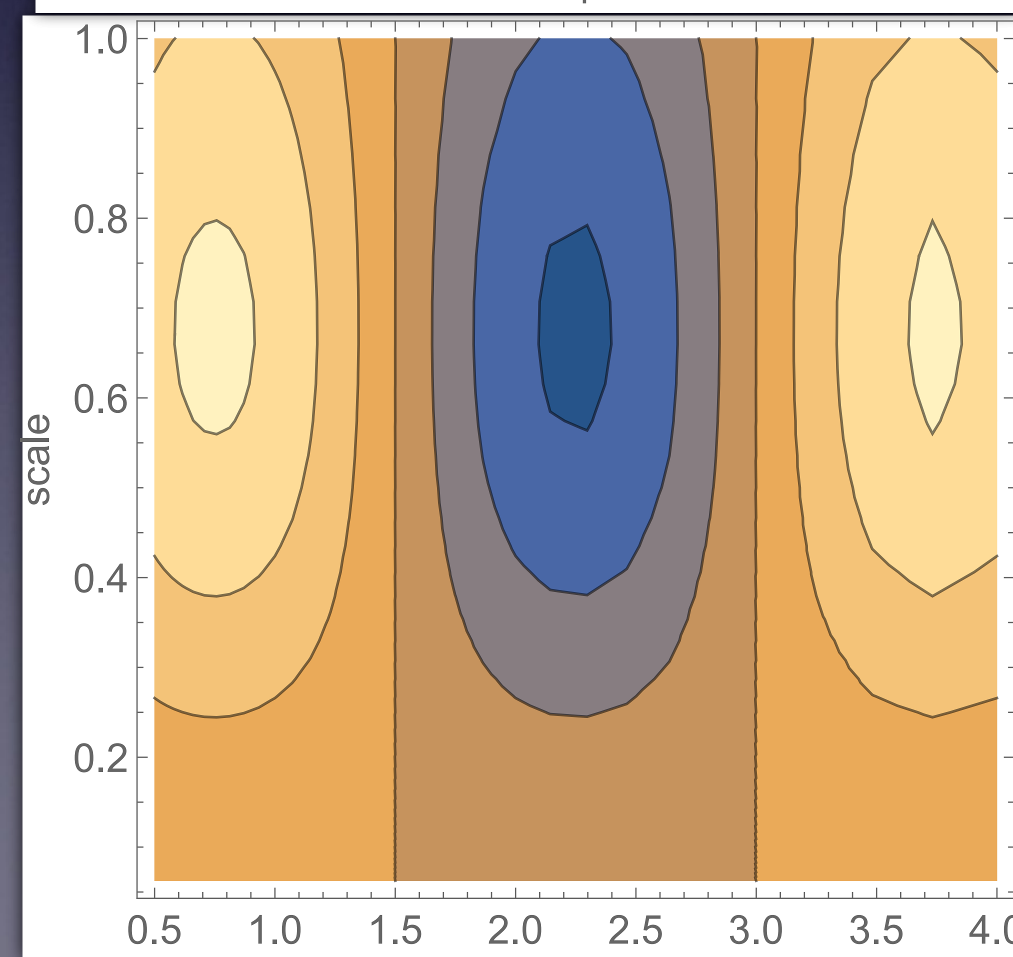
sine wave


1.0
0.5
−0.5
−1.0
−4
−2
2
4

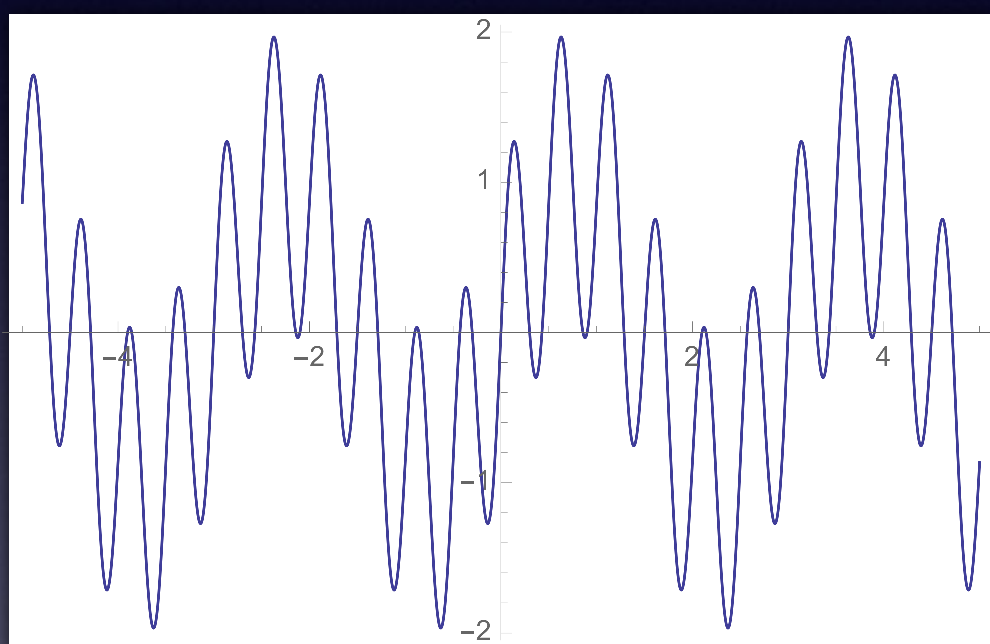

Fourier

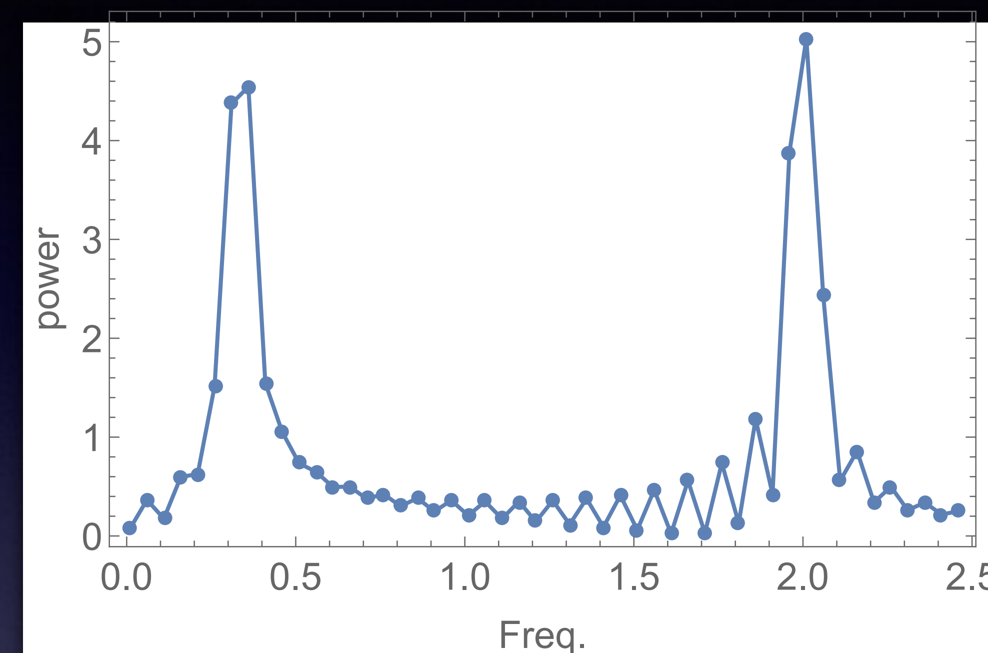

power
Freq.
0
1
2
3
4
0.0
0.5
1.0
1.5
2.0

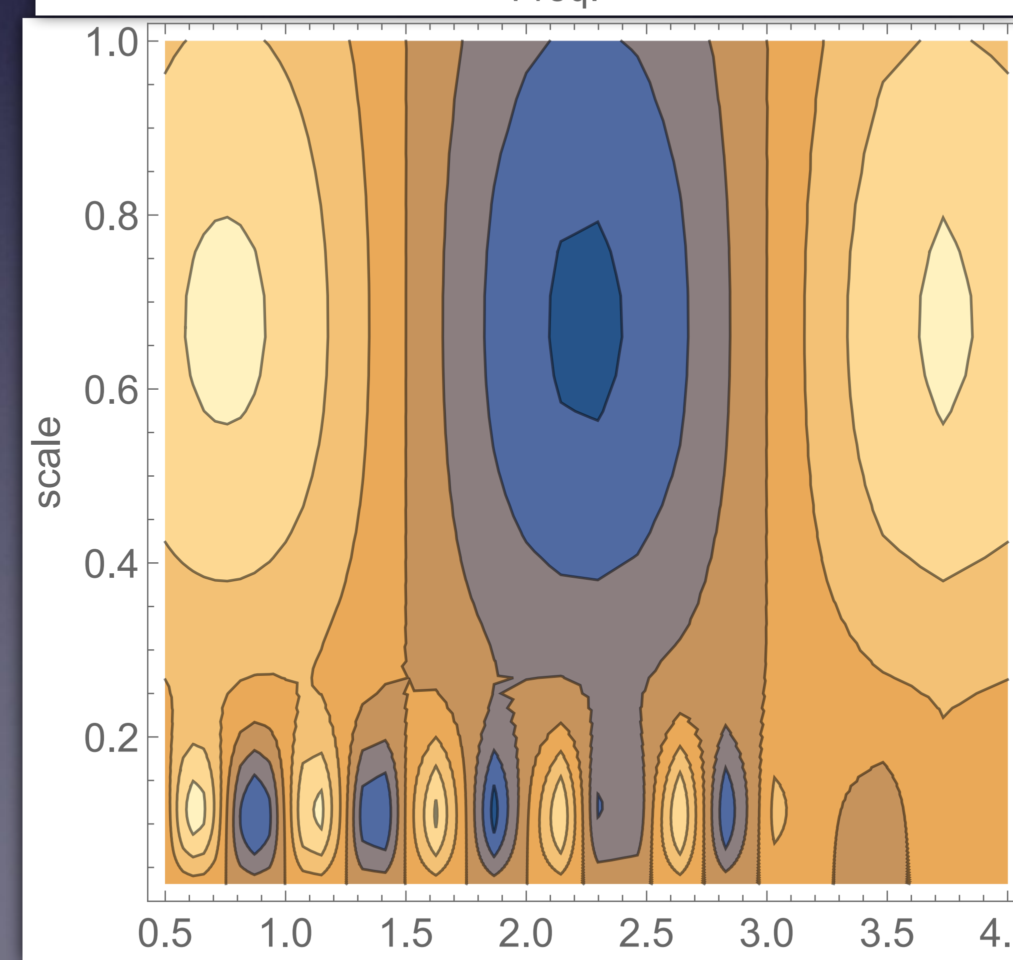

wavelet
Mex. hat


scale
1.0
0.8
0.6
0.4
0.2
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0

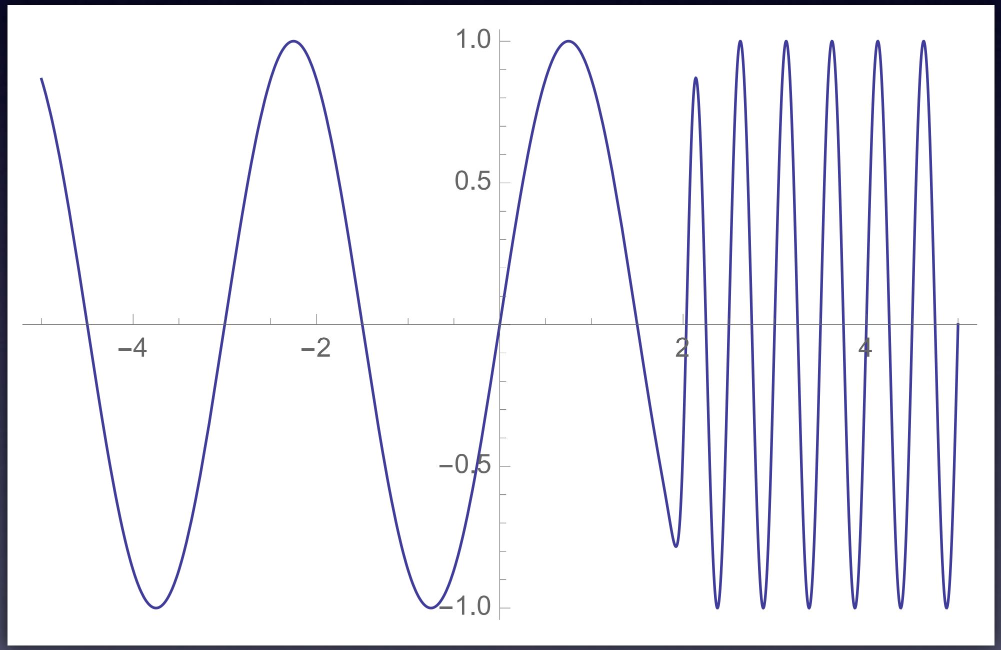
two sine waves



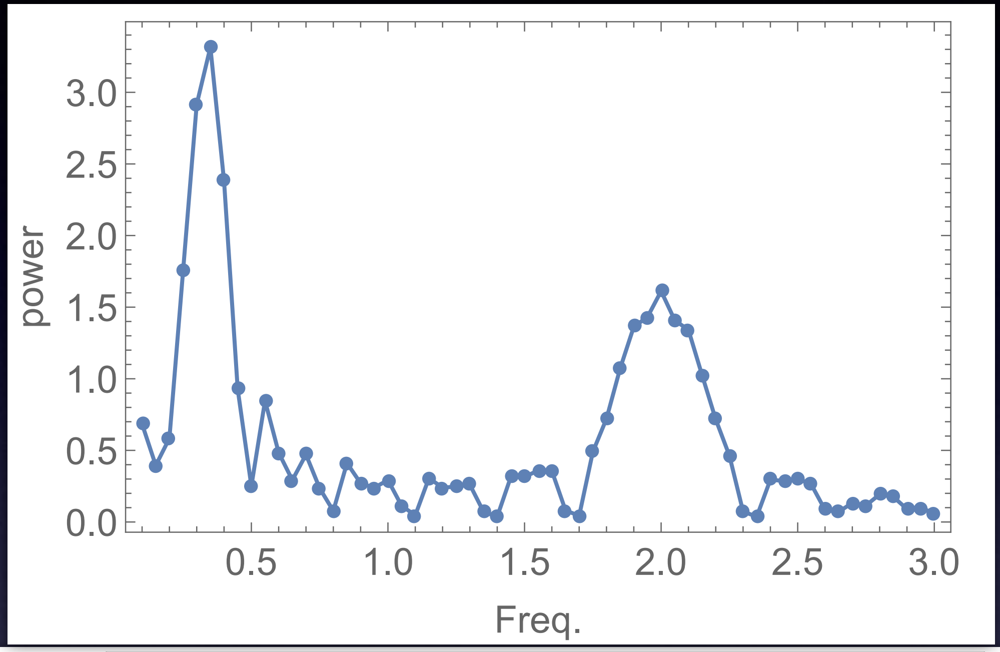




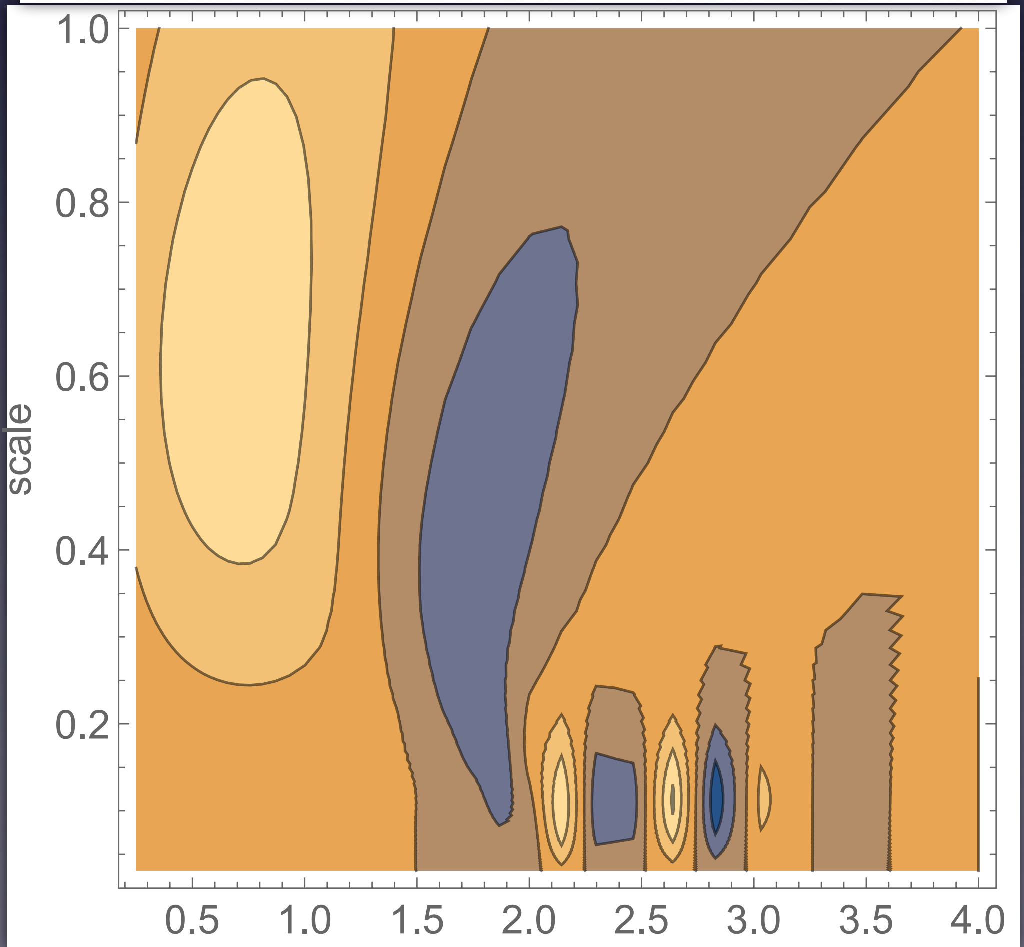
sine waves with transition



Fourier



wavelet
Mex. hat



How might this approach improve upon templates?

GeV sky can be thought of as a high resolution picture; wavelets can find structures in it

Poisson noise and SM uncertainty dominate at scales that are small relative to bubbles or NFW, and the wavelets can identify those scales

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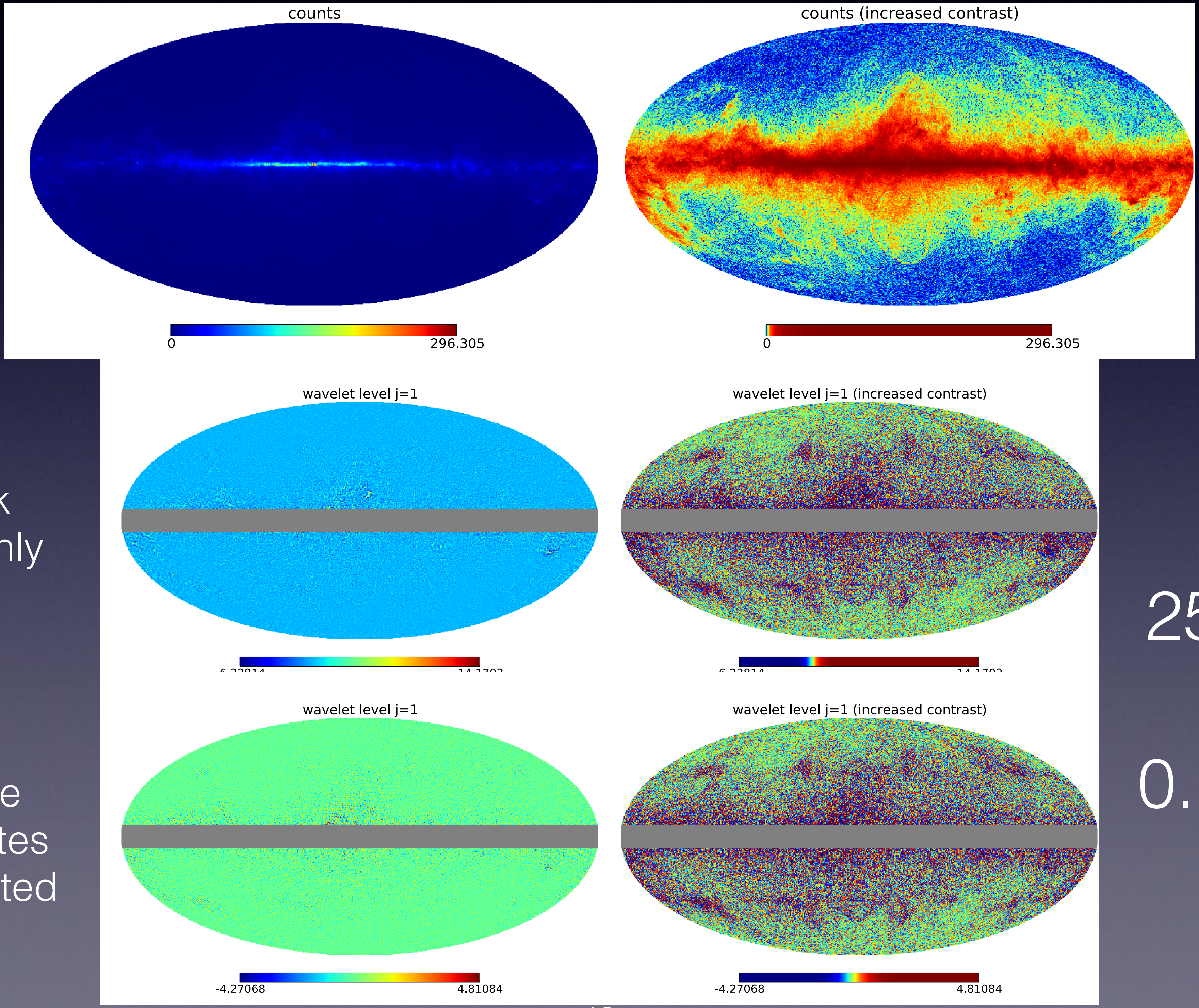
Poisson noise and SM uncertainty dominate at scales that are small relative to bubbles or NFW, and the wavelets can identify those scales

by identifying and removing such structures, wavelets provide a background expectation that is (relatively) robust against systematic astrophysics uncertainties

Example (mock data)



$\ell_{max}=512$

mock
data only

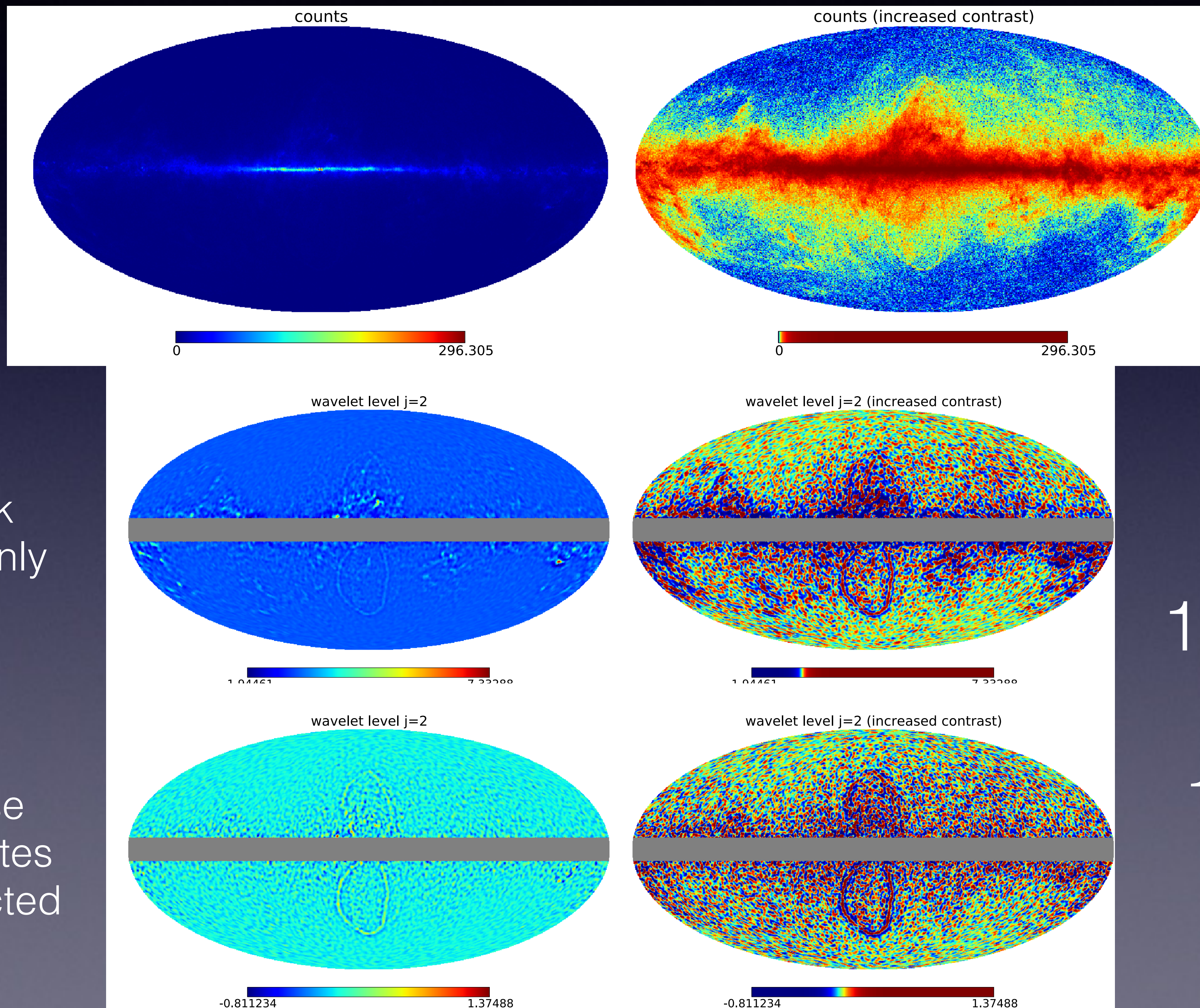
diffuse
templates
subtracted

$256<\ell<512$

$\Downarrow$

$0.7^\circ<\theta<1.4^\circ$

Example (mock data)



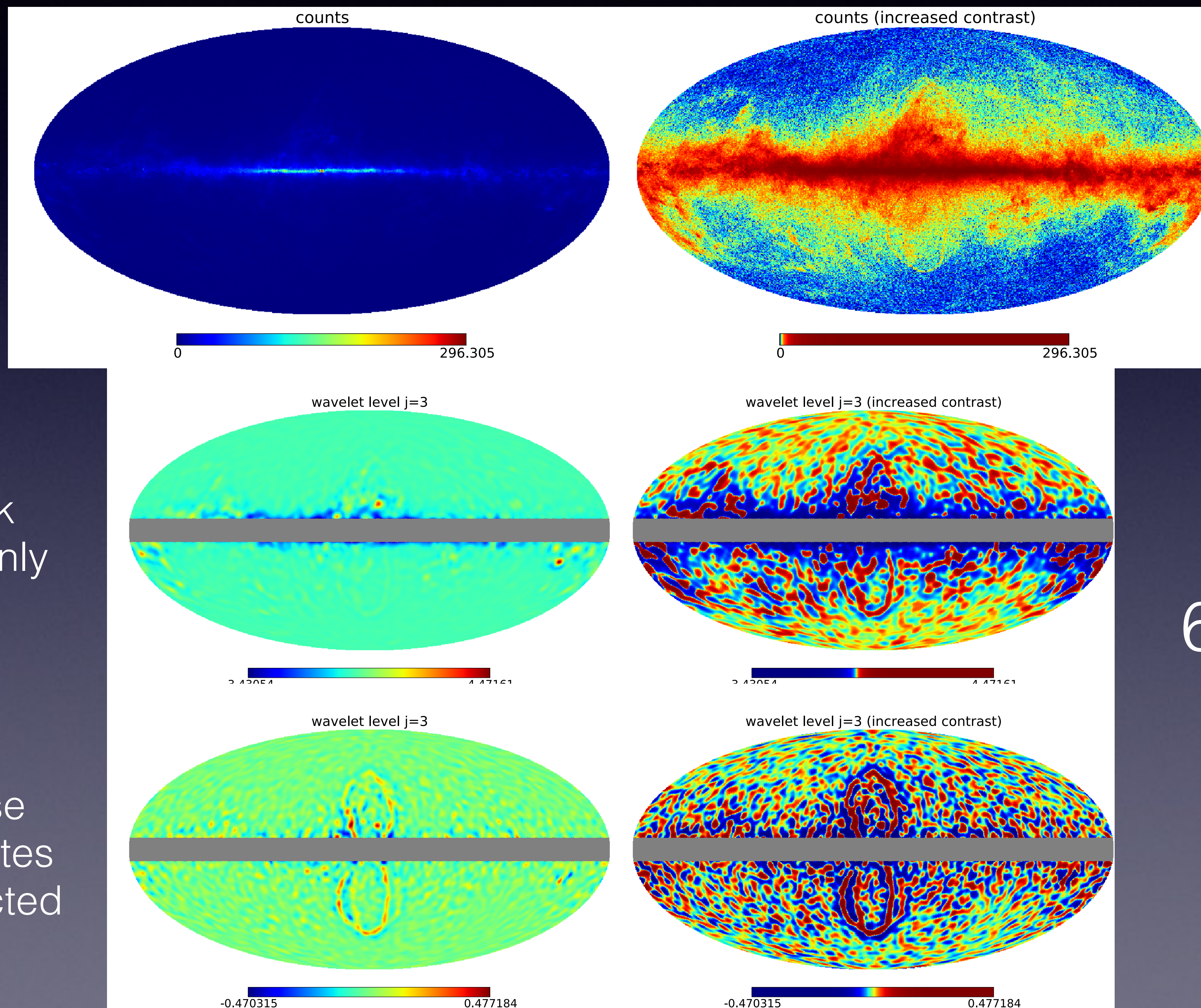
ℓ_{max}=512

mock
data only

128<ℓ<256
⇓
1.4°<θ<3°

diffuse
templates
subtracted

Example (mock data)



$\ell_{max}=512$

mock data only

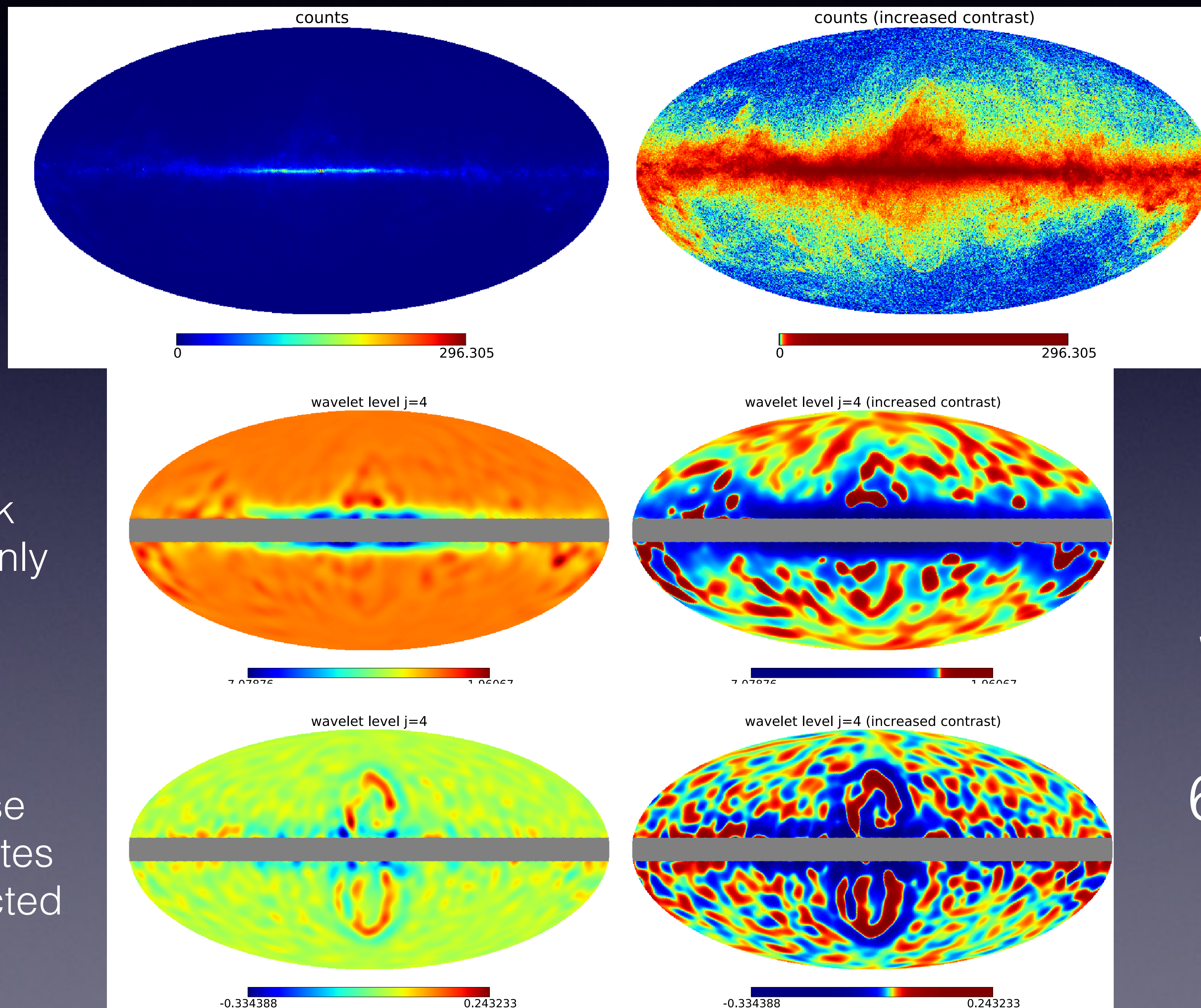
diffuse templates subtracted

$64<\ell<128$

$\Downarrow$

$3^\circ<\theta<6^\circ$

Example (mock data)



$\ell_{max}=512$

mock data only

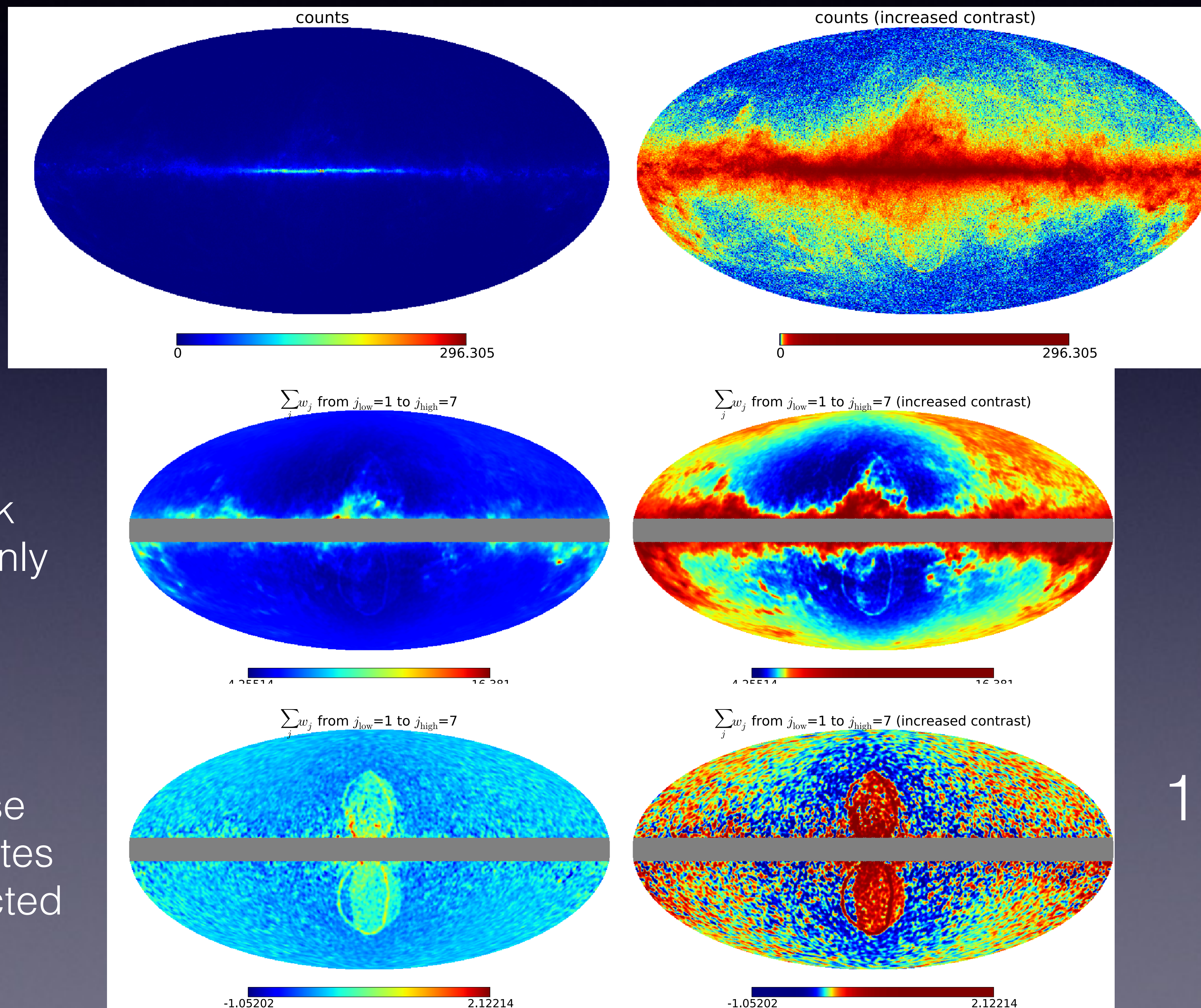
diffuse templates subtracted

$32<\ell<64$

$\Downarrow$

$6^\circ<\theta<10^\circ$

Example (mock data)



ℓ_{max}=512

mock data only

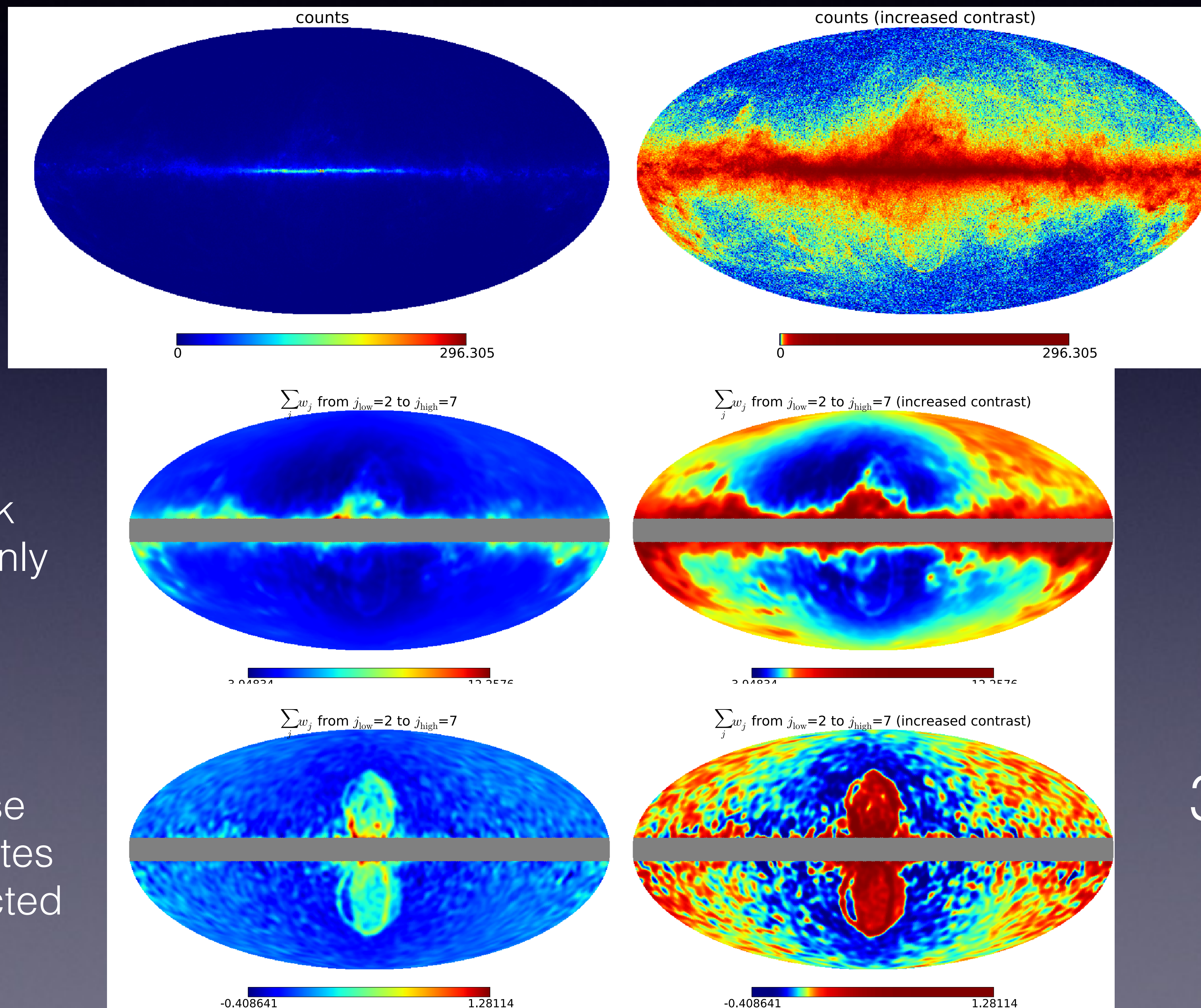
diffuse templates subtracted

$4<\ell<256$

⇓

$1.4^\circ<\theta<90^\circ$

Example (mock data)



ℓ_{max}=512

mock
data only

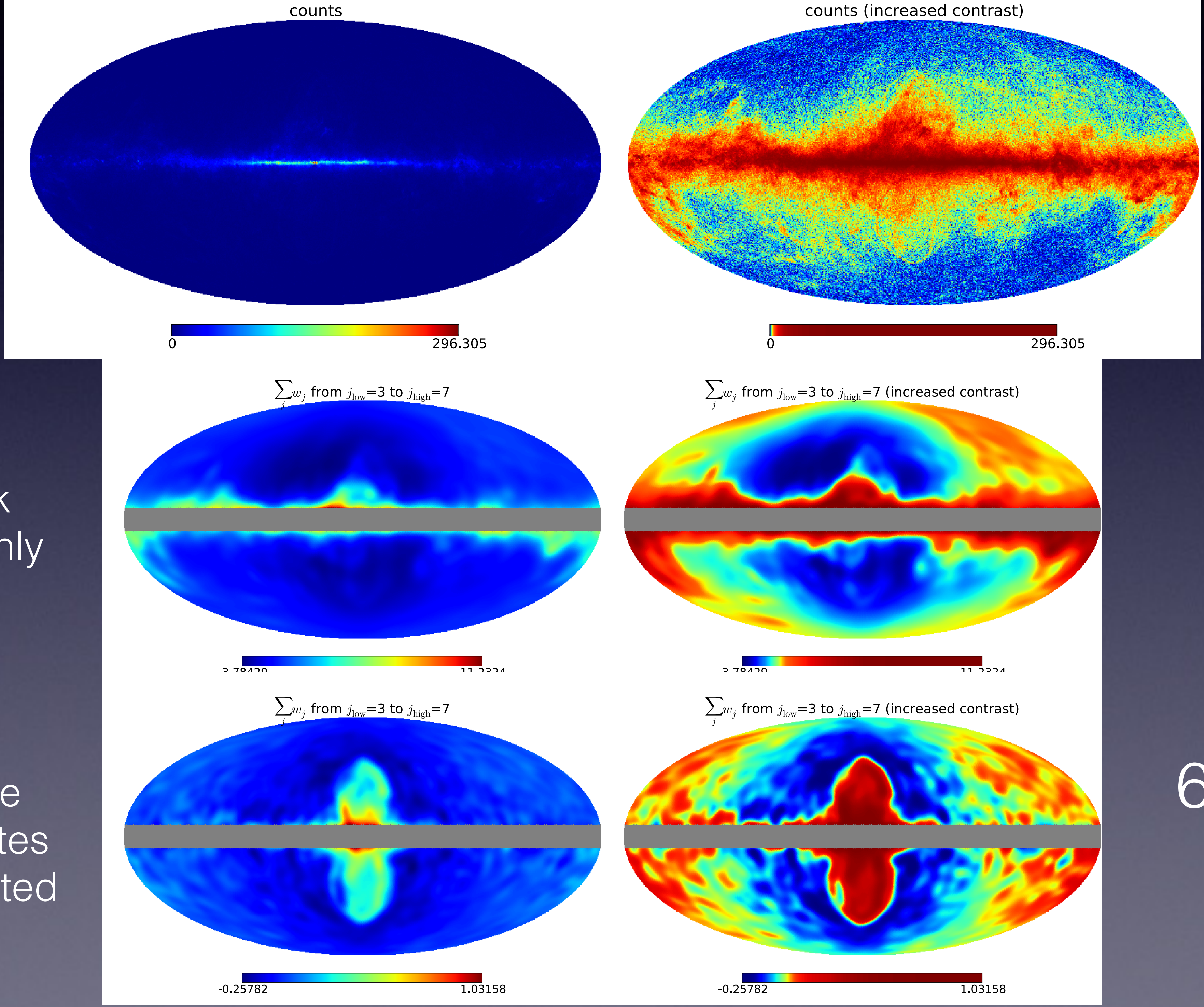
diffuse
templates
subtracted

$4<\ell<128$

$\Downarrow$

$3^\circ<\theta<90^\circ$

Example (mock data)



ℓ_{max}=512

mock
data only

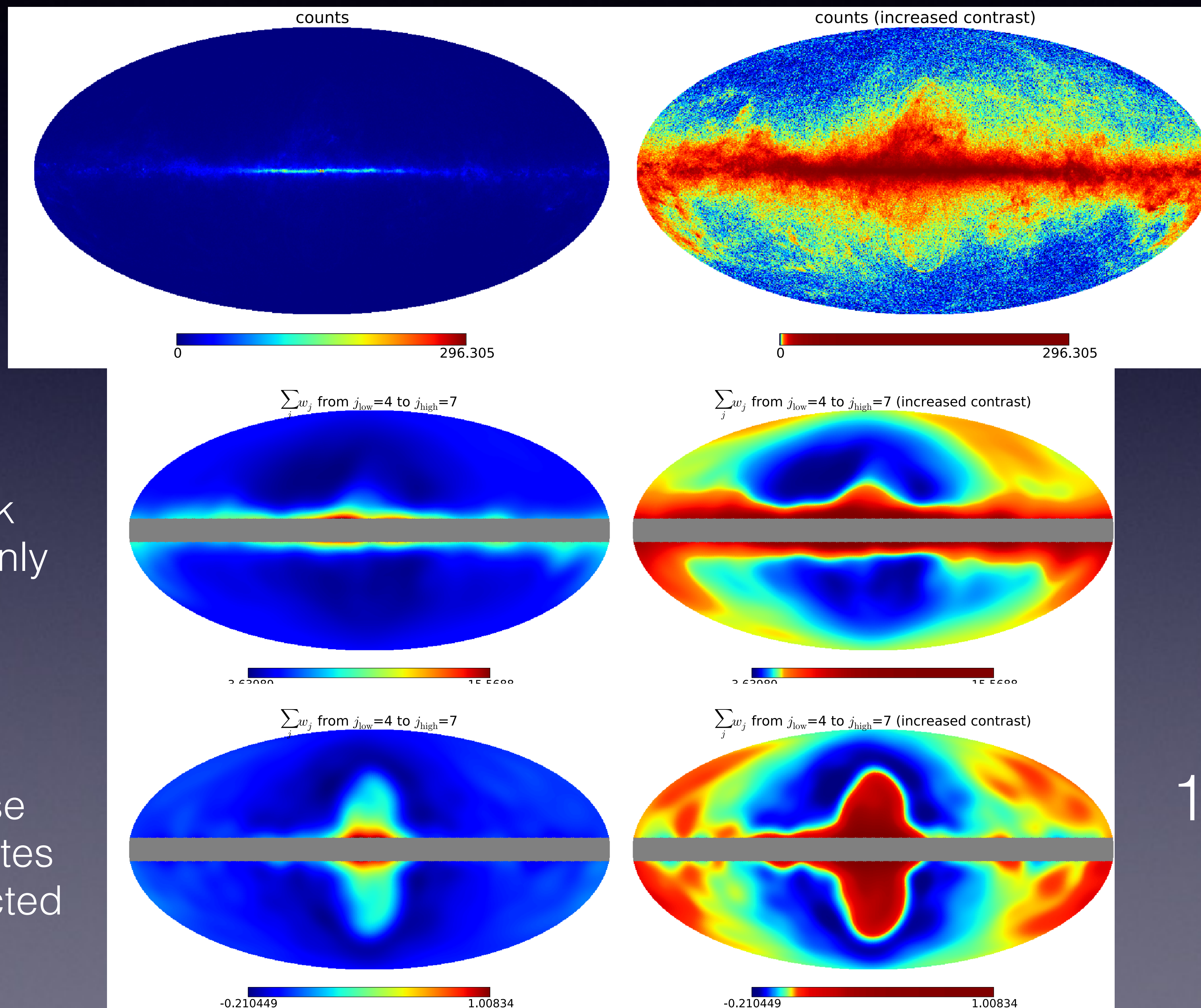
diffuse
templates
subtracted

$4<\ell<64$

$\Downarrow$

$6^\circ<\theta<90^\circ$

Example (mock data)



ℓ_{max}=512

mock data only

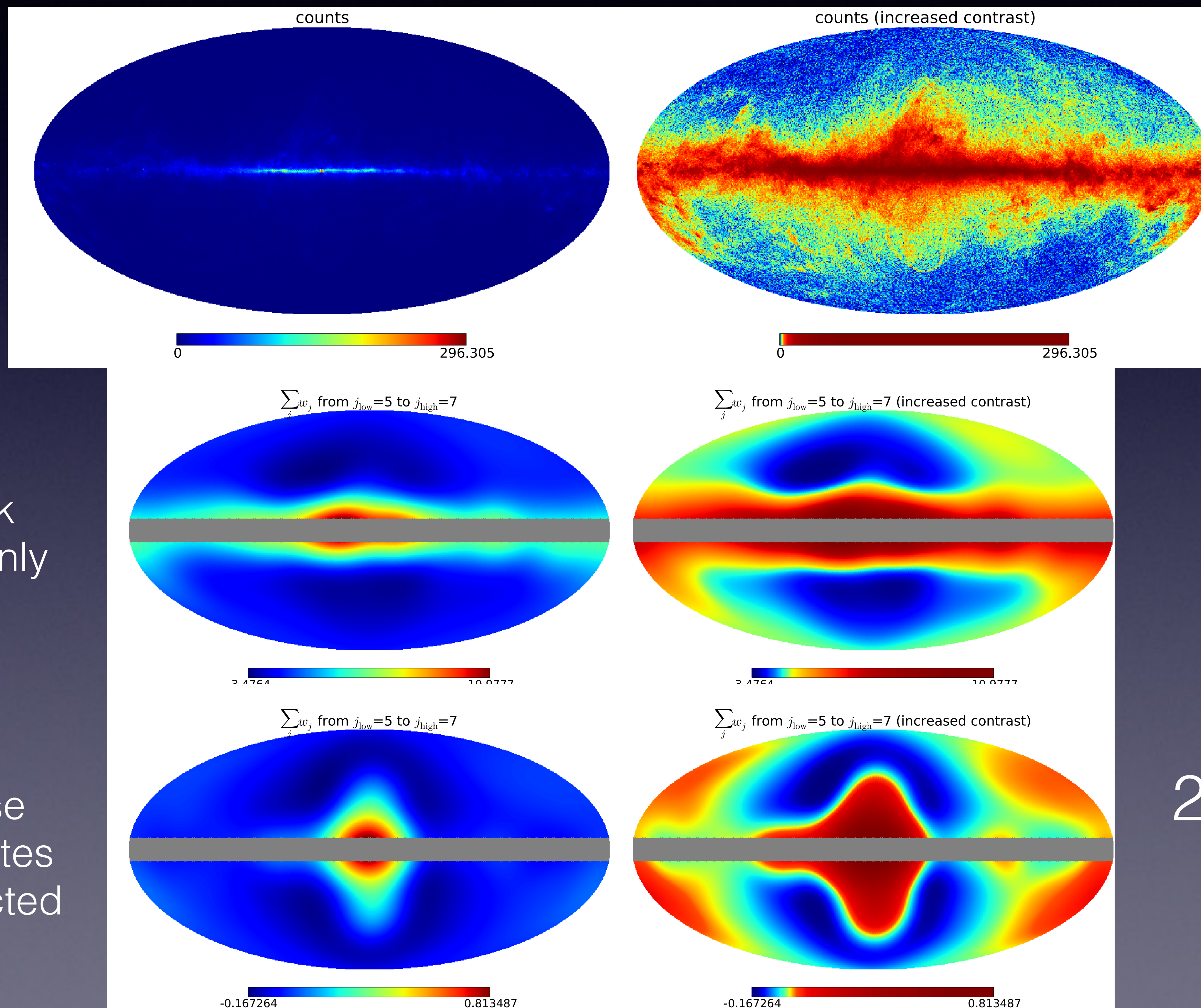
diffuse templates subtracted

$4<\ell<32$

$\Downarrow$

$10^\circ<\theta<90^\circ$

Example (mock data)



$\ell_{max}=512$

mock data only

diffuse templates subtracted

$4<\ell<16$

$\Downarrow$

$22^\circ<\theta<90^\circ$

Lesson:

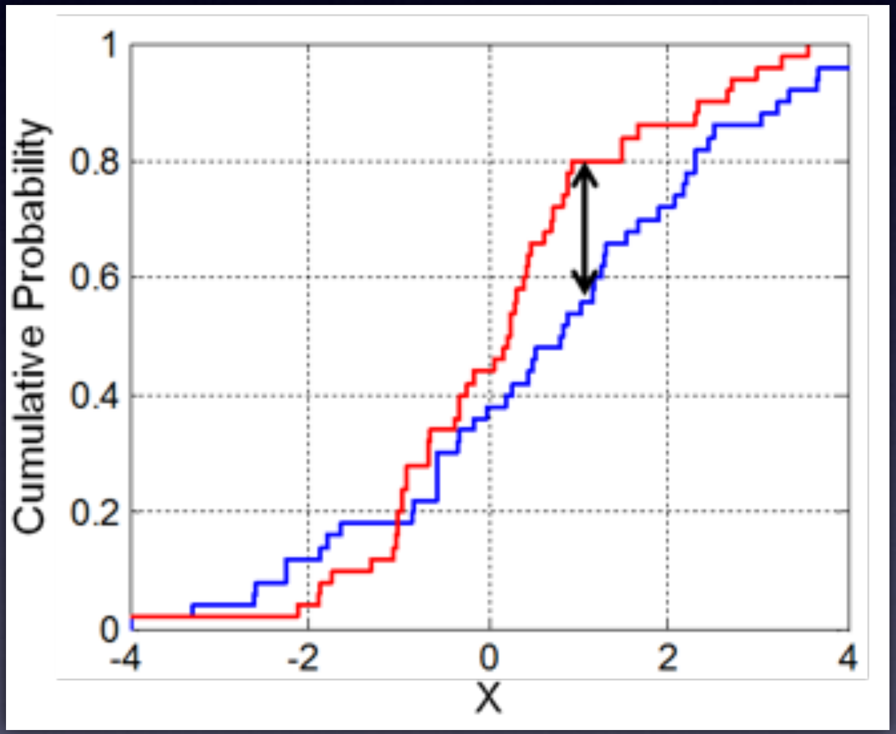
Getting rid of some wavelet levels can provide a much clearer picture of a signal

Question:

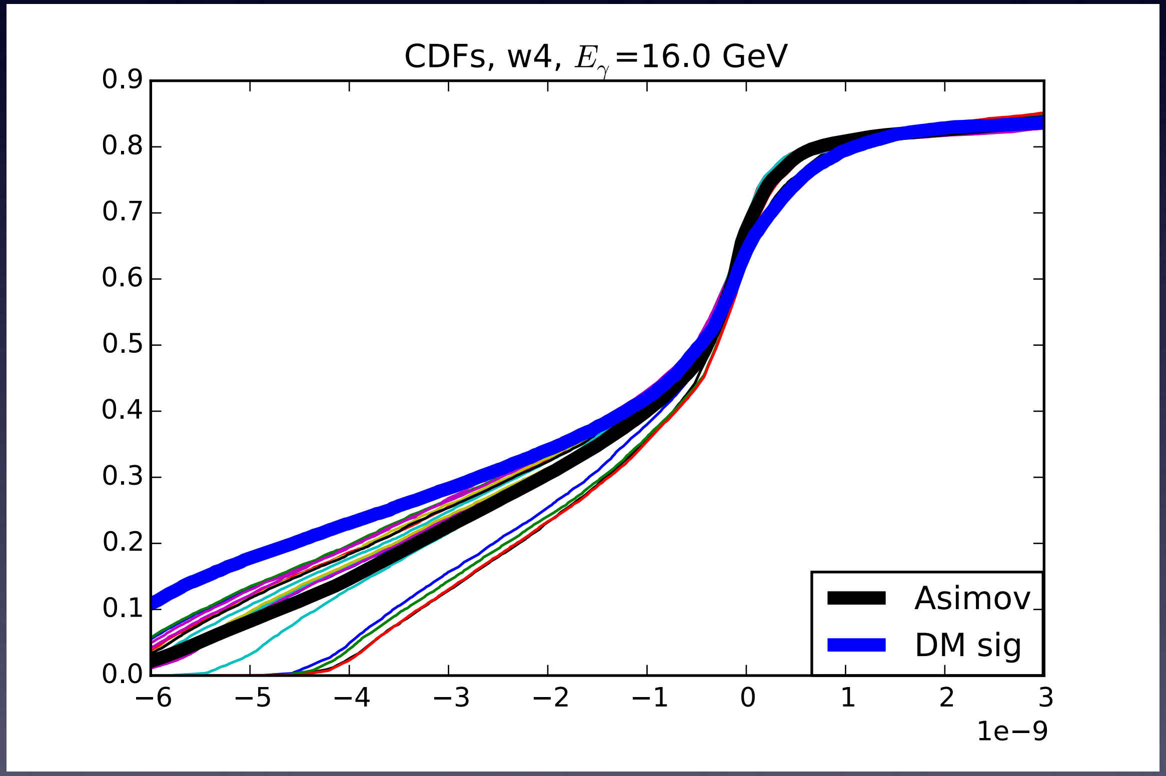
How can we do this in a data-driven (model-independent) (unbiased) (etc….) way?

Kolmogorov-Smirnov Test

maximum distance between two CDFs

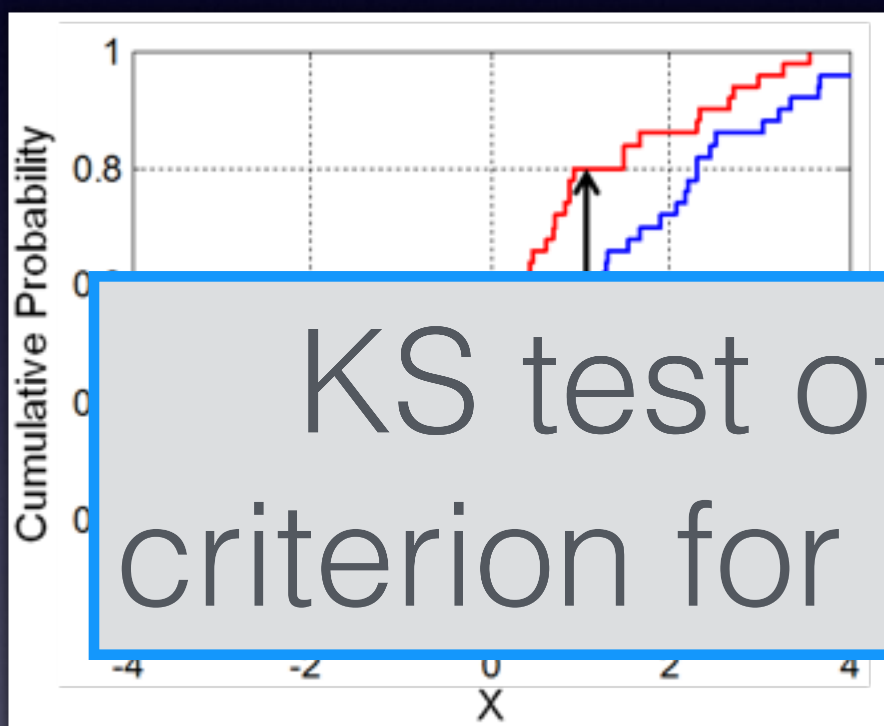


"KS2 Example" by Bscan - Own work. Licensed under CC0 via Commons - https://commons.wikimedia.org/wiki/File:KS2_Example.png#/media/File:KS2_Example.png

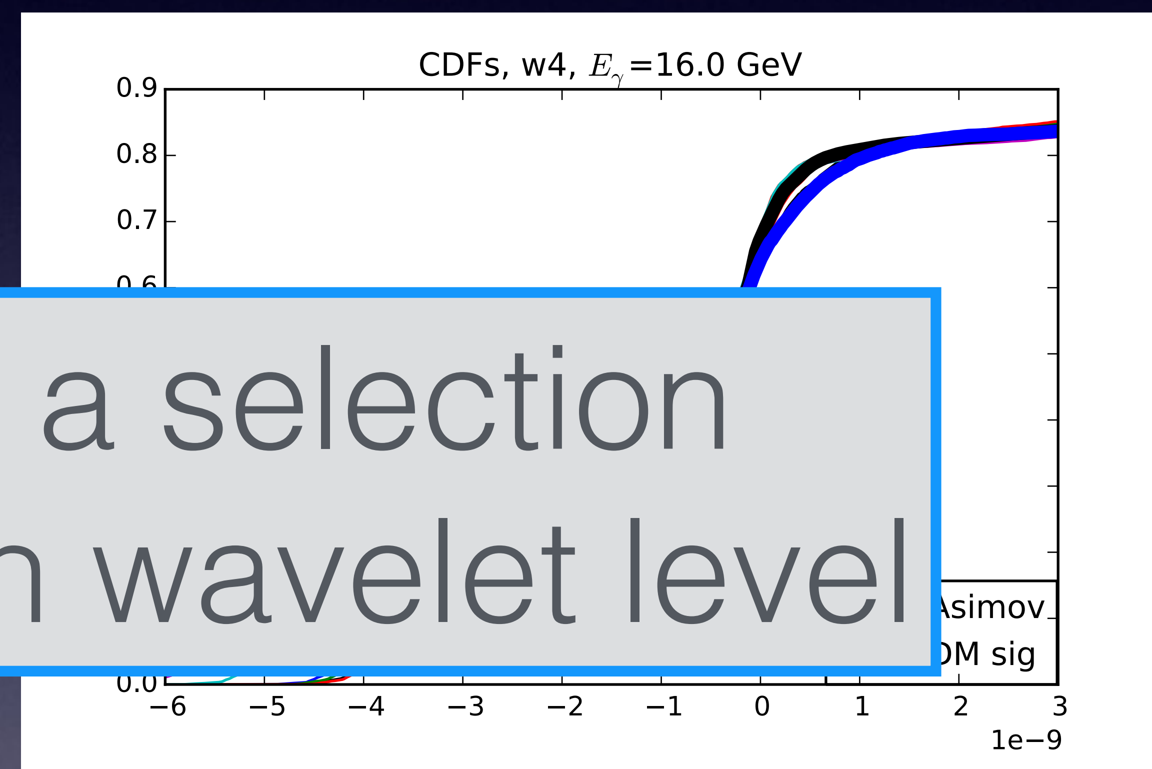


Kolmogorov-Smirnov Test

maximum distance between two CDFs



"KS2 Example" by Bscan - Own work. Licensed under CC0 via Commons - https://commons.wikimedia.org/wiki/File:KS2_Example.png#/media/File:KS2_Example.png



KS test offers a selection criterion for each wavelet level

“Thresholded” wavelets

signal = S
set of backgrounds = $\{B_i\}$

$$w_j^{>} = \begin{cases} w_j & \text{if KS(S | Asimov) > 40\% KS}(B_i \text{ | Asimov}) \\ 0 & \text{otherwise} \end{cases}$$

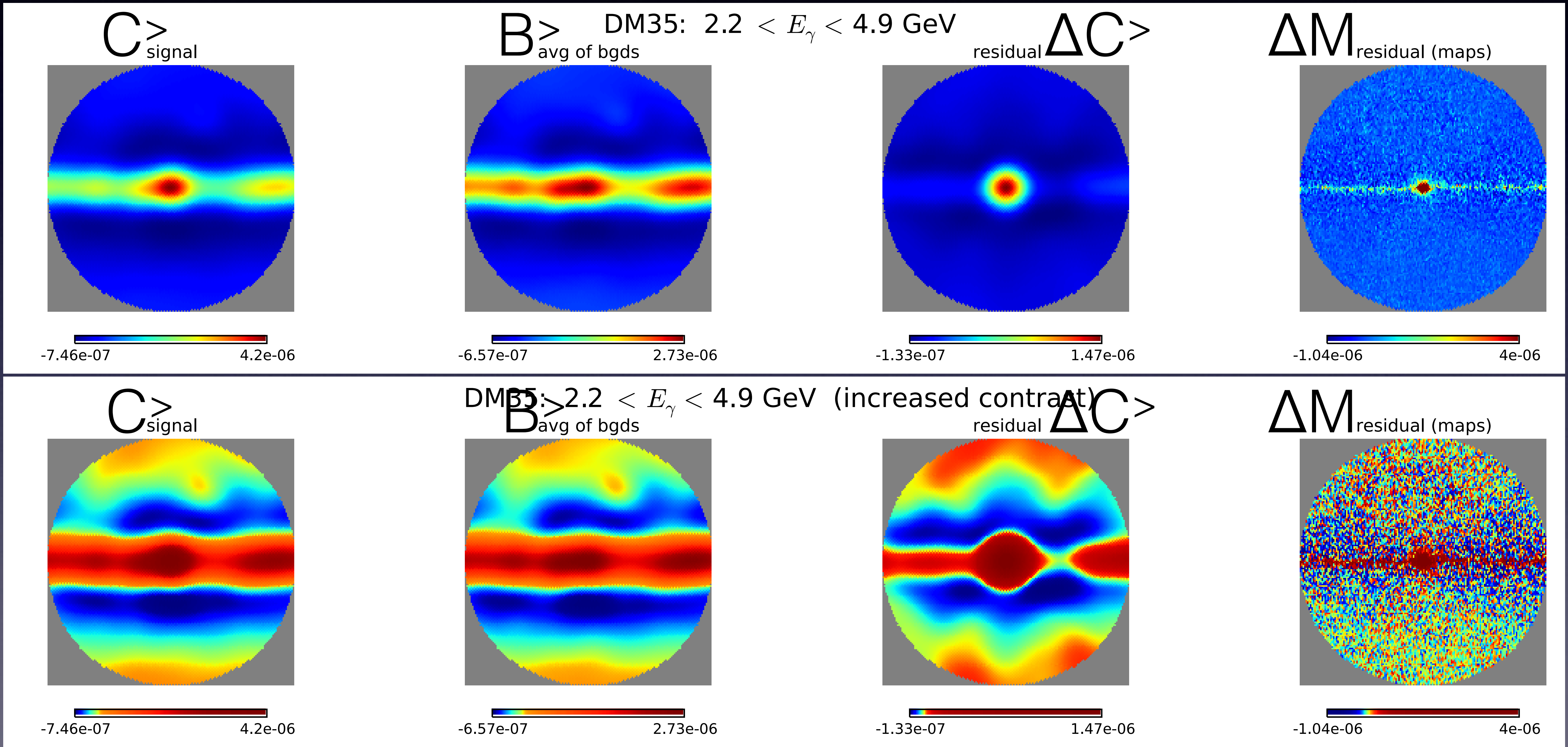
define “cleaned maps:” $C^{>} = \Sigma^{8}_{j=2}\, w_j^{>}(S)$

$B_i^{>} = \Sigma^{8}_{j=2}\, w_j^{>}(B_i)\Theta[w_j^{>}(S)]$

$B^{>} = \text{avg}(\{B_i^{>}\})$

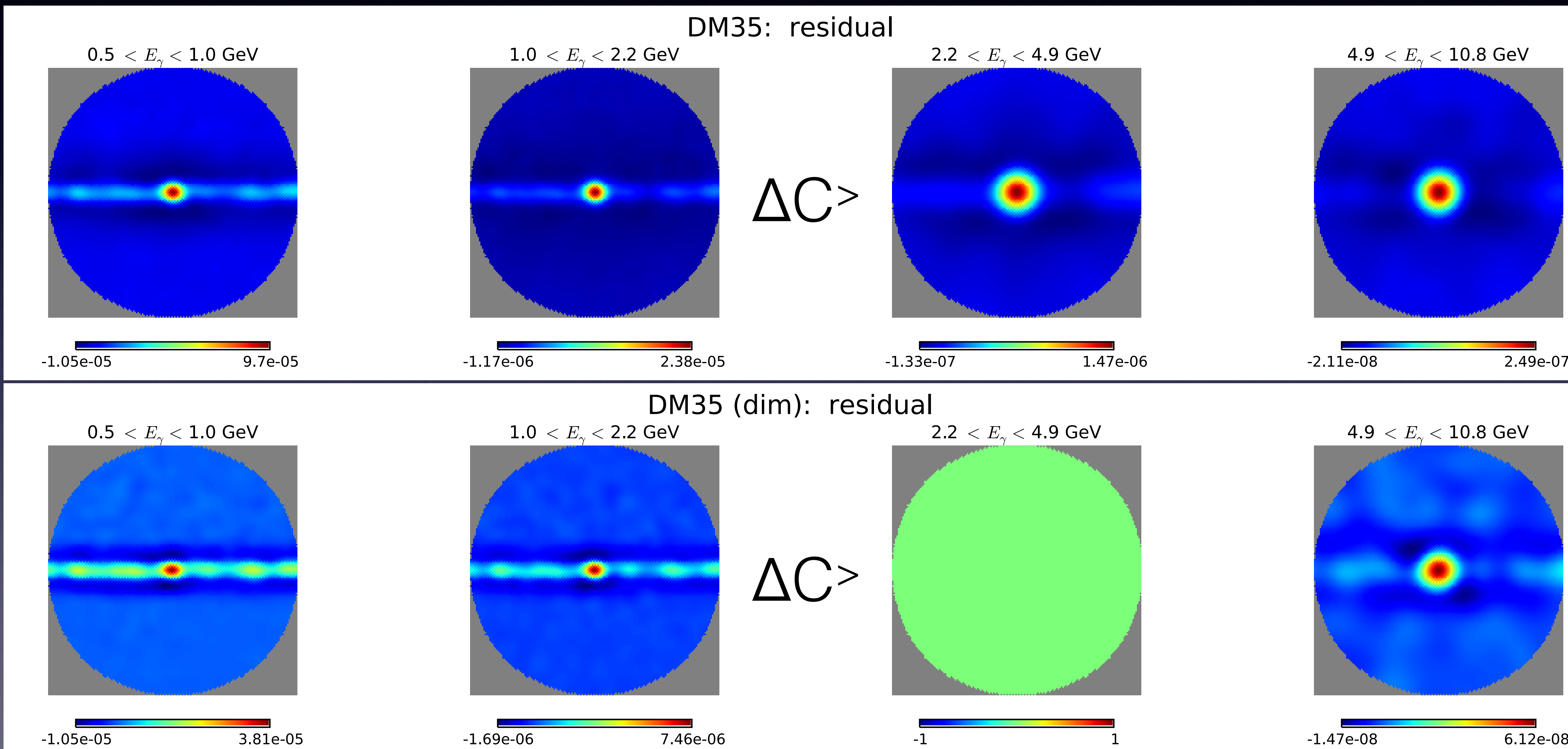
and “cleaned residual:” $\Delta C^{>} = C^{>} - B^{>}$

Cleaned Map Method



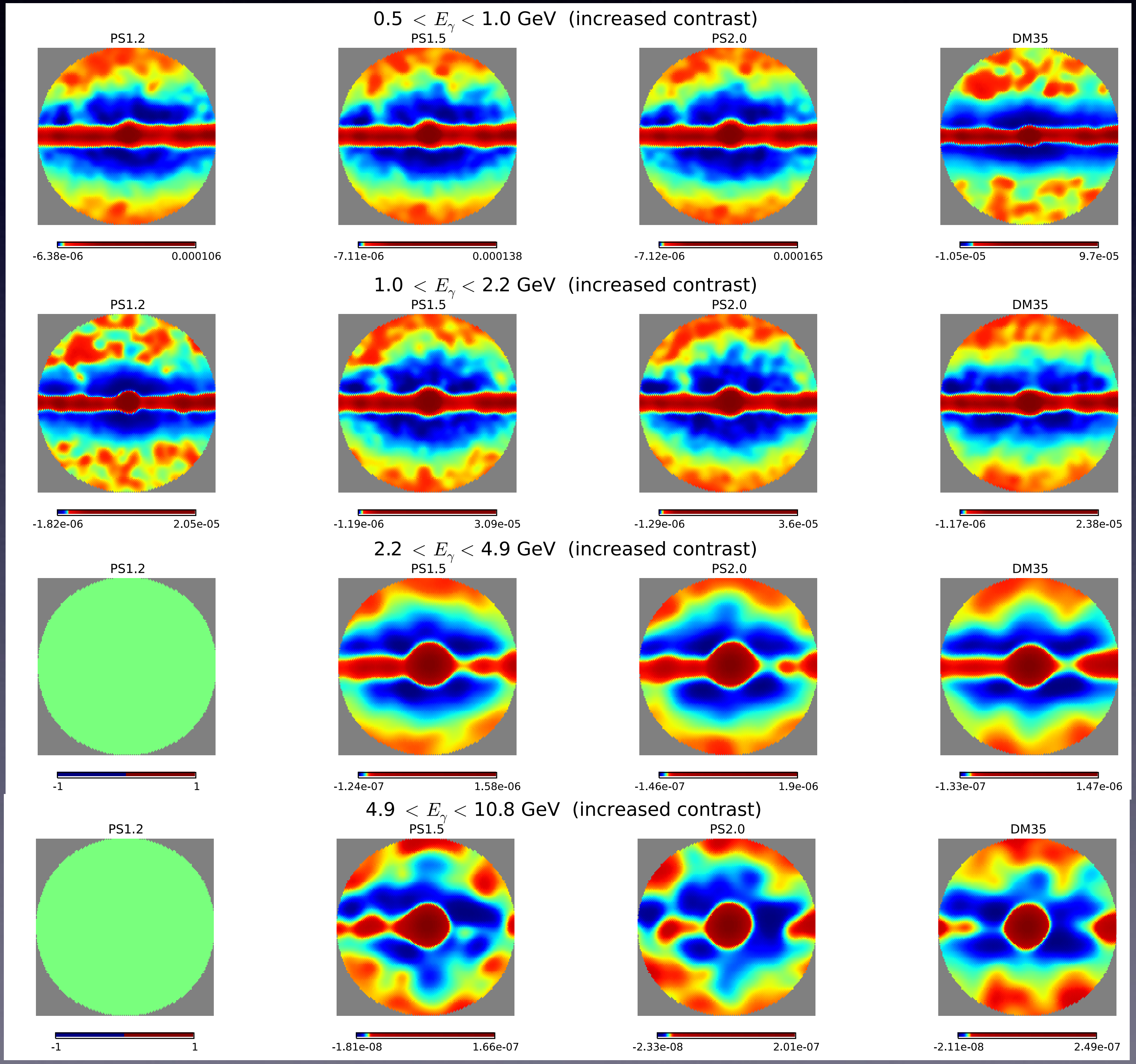
wavelets provide clearer residual than maps

Cleaned Map Threshold

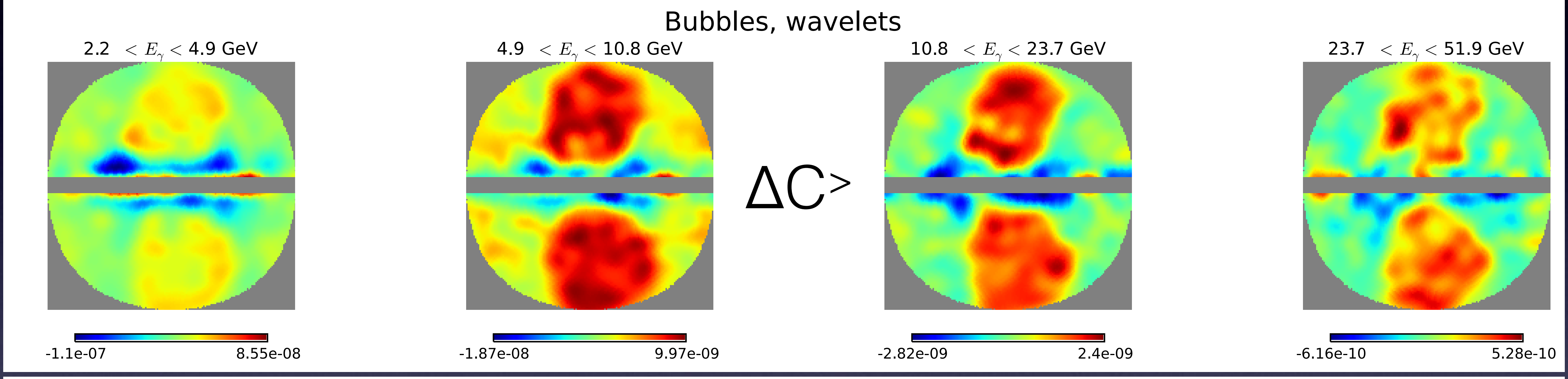


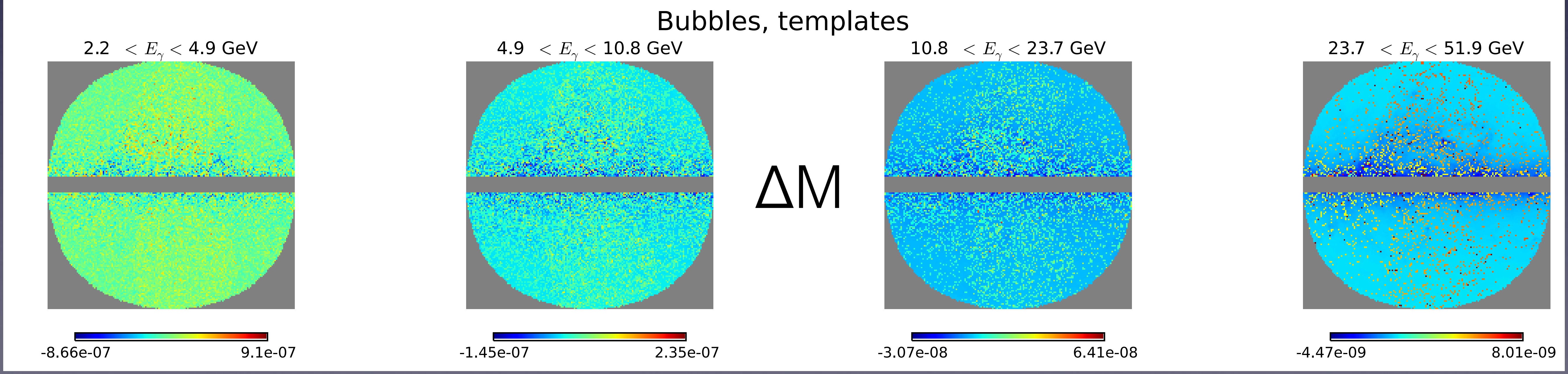
30% as bright is much harder to see

DM vs. Point Sources?



Cleaned Map, Bubbles





What are wavelets?

Allow analysis sensitive to both position and size

↓

different structures have “power” at different levels of the decomposition (edges = sharp variation, important first; larger scale objects = broader variation, important later)

↓

wavelets find structures, and the GCE is a qualitatively new structure that we ought to learn more about

Conclusions

Galactic center gamma ray excess is exciting to follow, but still so much more to learn about it

Need some less-model-dependent information

Wavelets are a promising tool for learning about this data

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Much more to do!

Thanks!