Disentangling Gamma-Ray Signals: Template Analysis and Beyond

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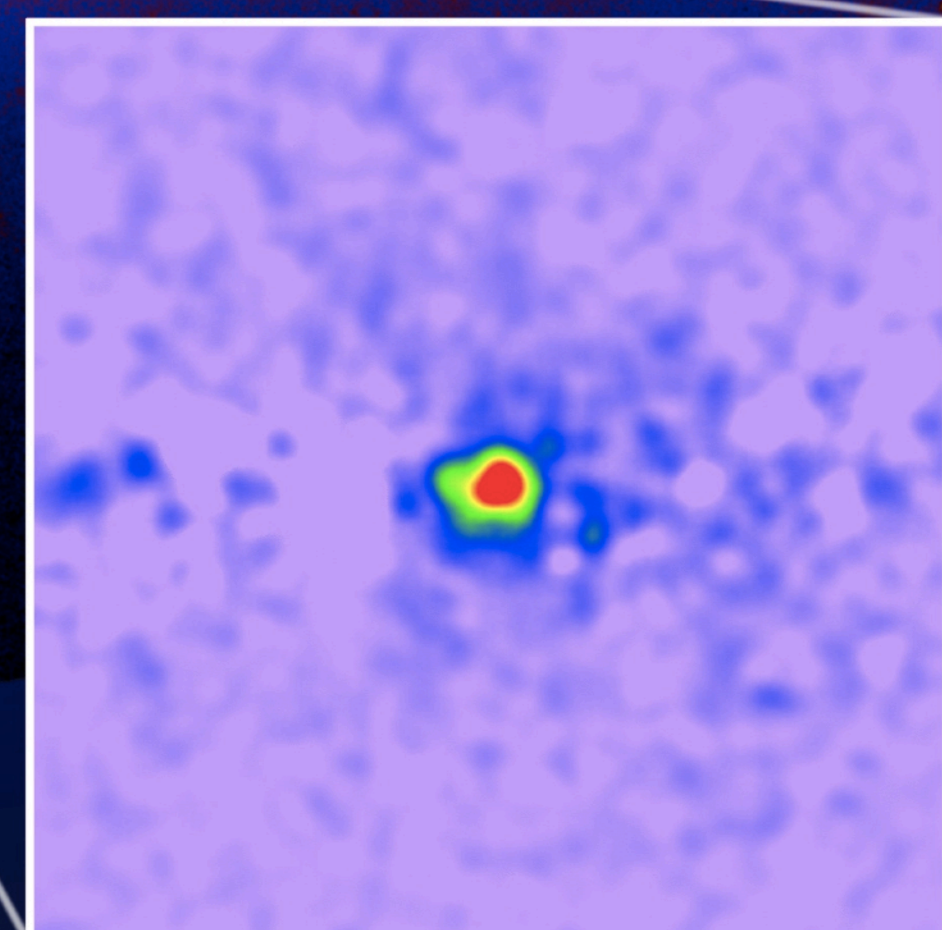
MIT

Georges Lemaitre Lecture Series
Lecture 3, 18 May 2022



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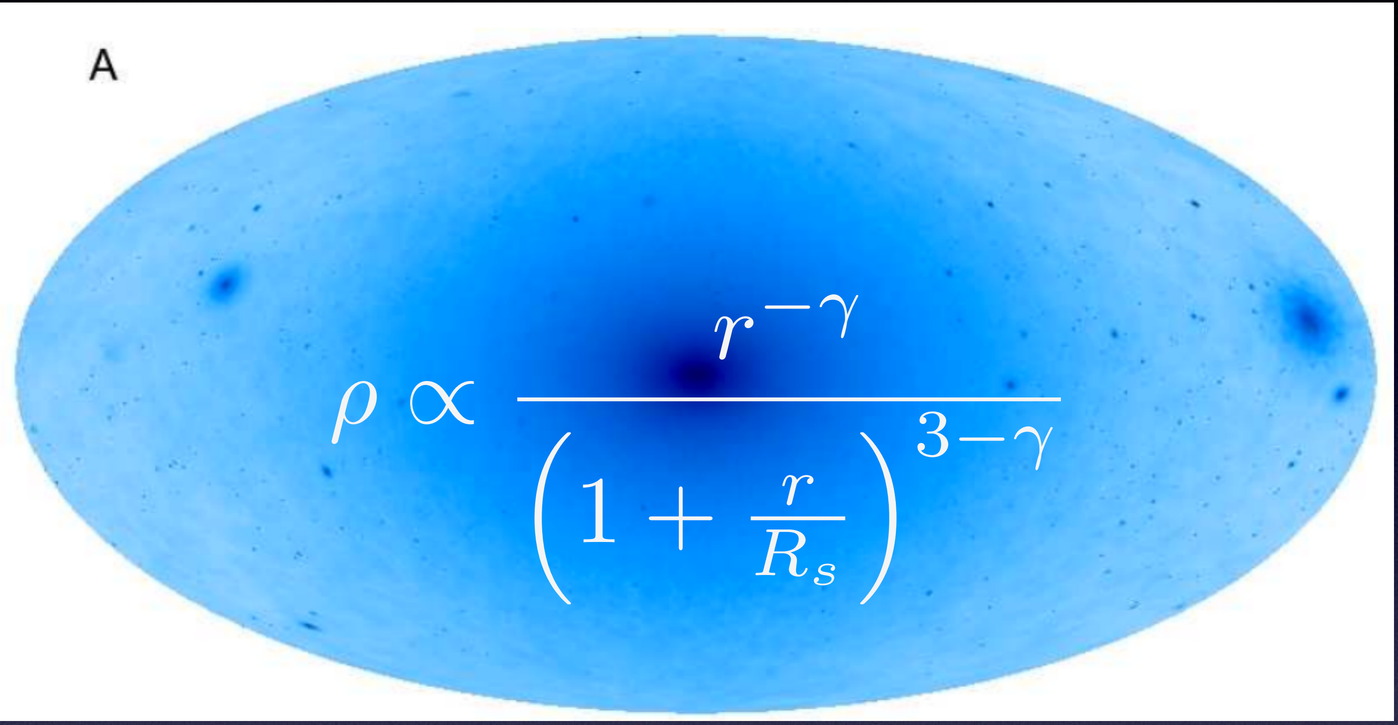
Goals for this lecture

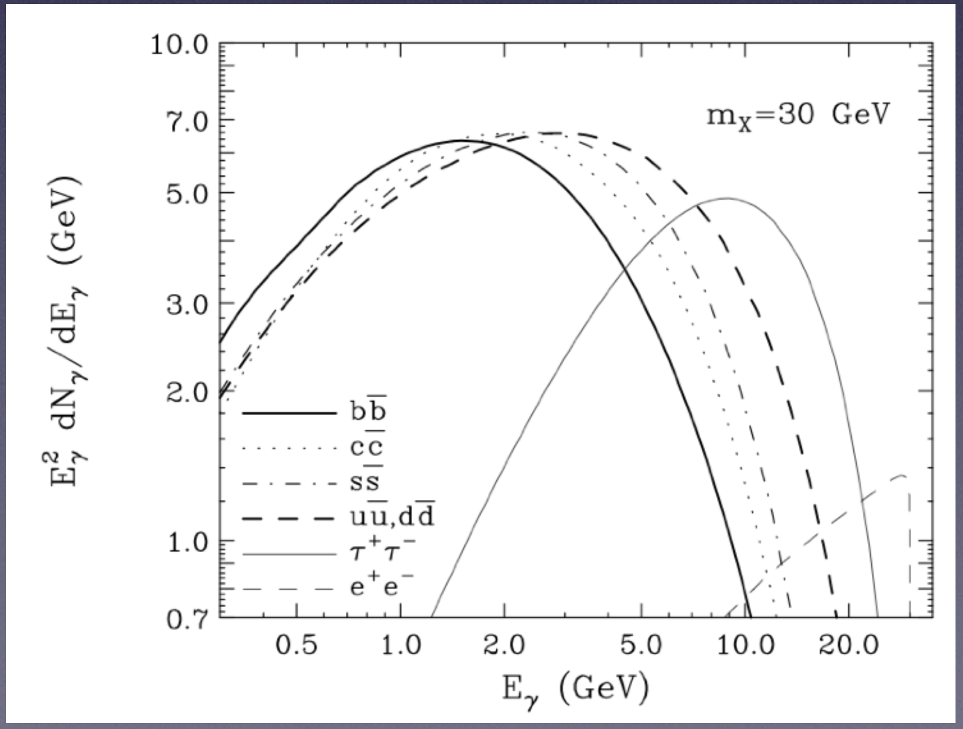
- Summarize the known sources of gamma-rays in our Galaxy, that provide backgrounds for WIMP searches
- Introduction to template-based likelihood analysis (Poissonian + non-Poissonian)
- Case study: the Galactic Center excess
  - DM interpretation
  - Astrophysical interpretations
  - Systematics in template fitting

Features of a DM signal

- Spatial information:
  - Backgrounds: brightest near Galactic plane
  - Signal: should follow DM halo, more spherical
- Spectral information:
  - Backgrounds: mostly smooth and power-law-like
  - Signal: can be peaked, scale set by DM mass
- Galactic center generally has brightest predicted signal - albeit backgrounds also most challenging there.



signal? (DM sim)



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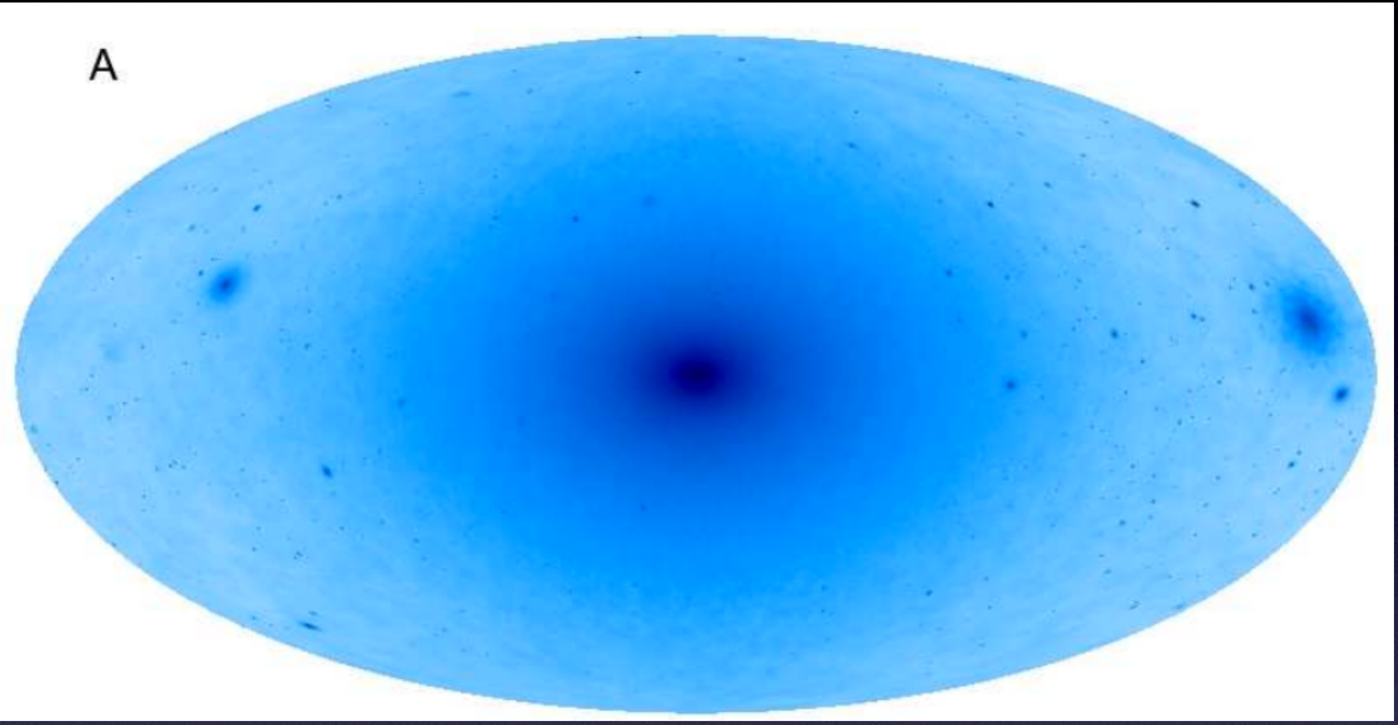

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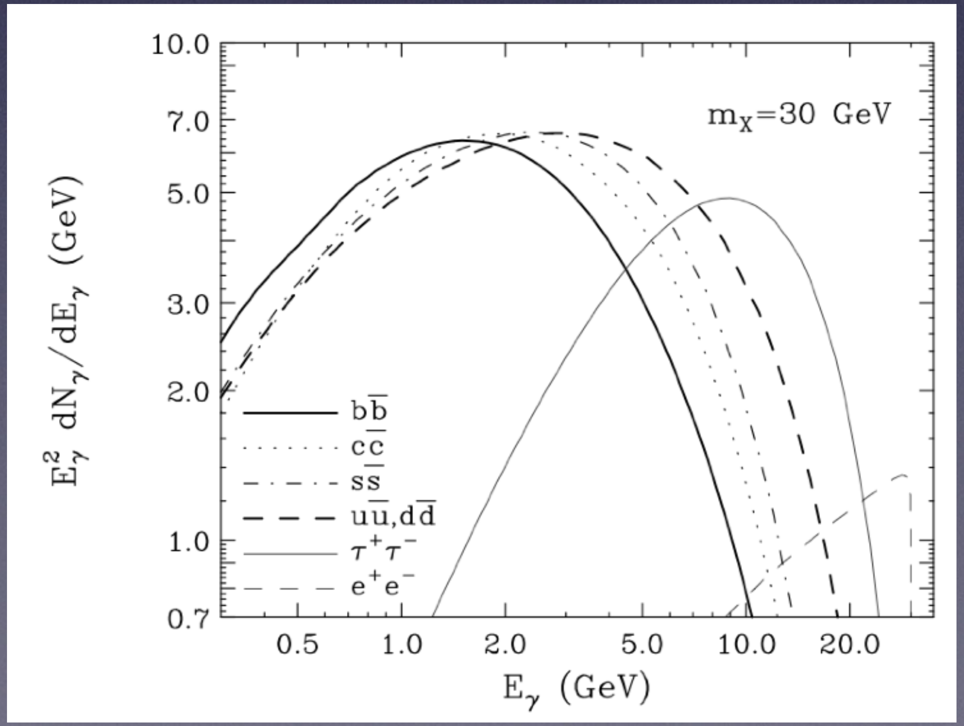
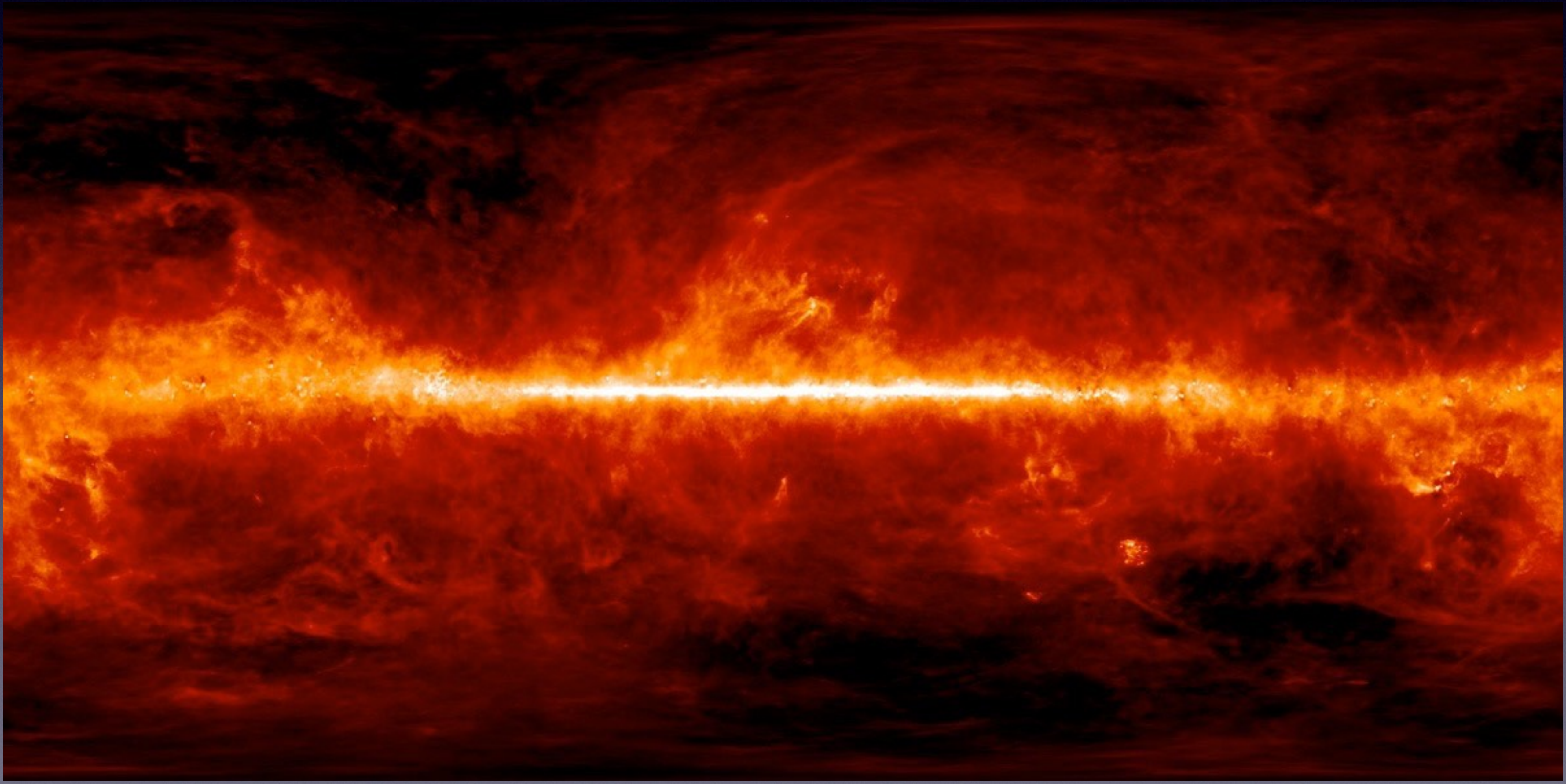


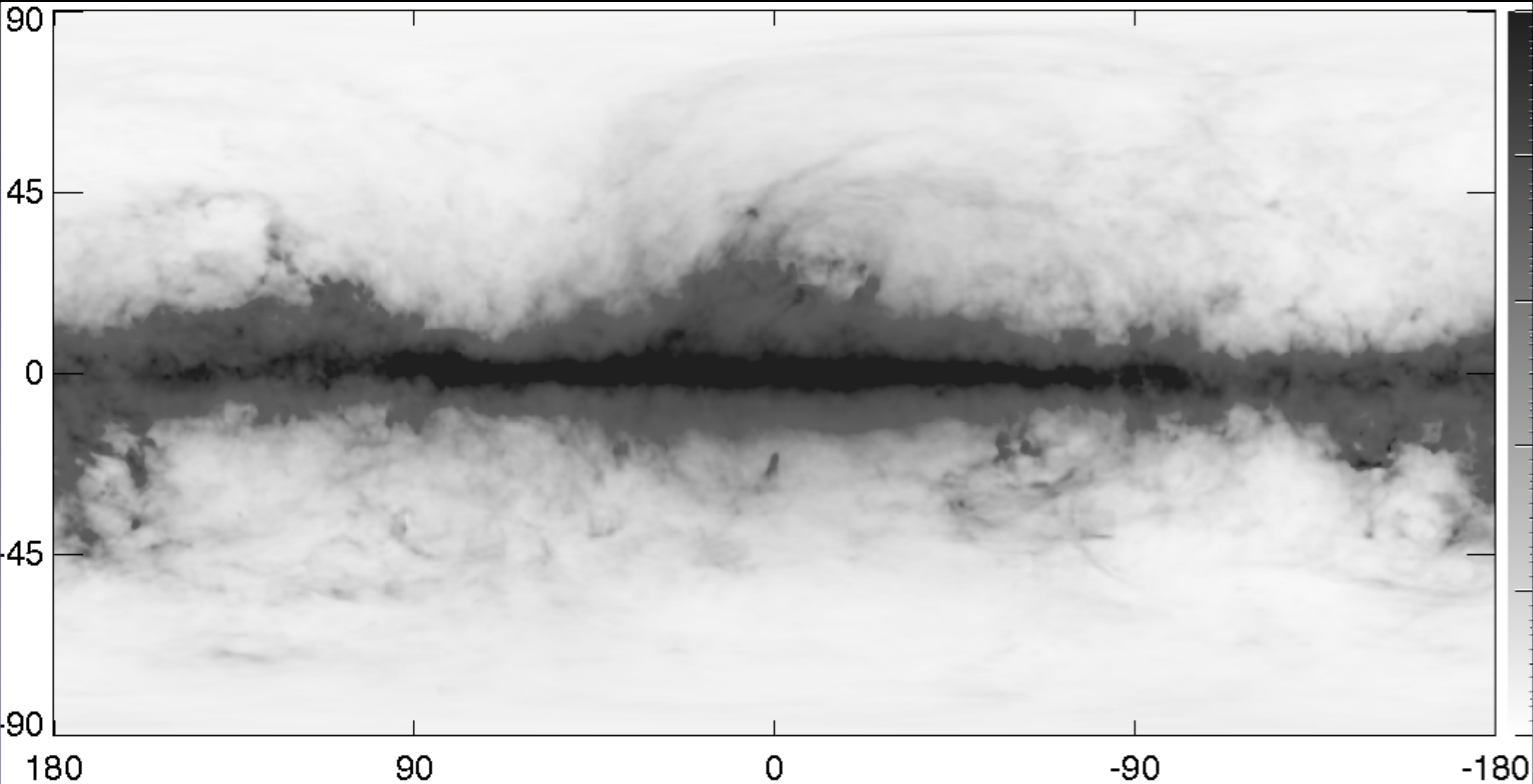
Main backgrounds

- Diffuse emission:
  - π^0 emission: neutral pion production from cosmic rays colliding with ambient gas, followed by $\pi^0 \rightarrow \gamma\gamma$ decay
  - Inverse Compton scattering (ICS): cosmic-ray electrons upscattering ambient photons to high energy
  - Bremsstrahlung ("brem"): cosmic-ray electrons scattering on interstellar gas
- Point sources (may be resolved or unresolved):
  - Galactic: e.g. pulsars, supernova remnants
  - Extragalactic: e.g. active galactic nuclei

The interstellar medium (dust/gas)



A (diffuse) gamma-ray model

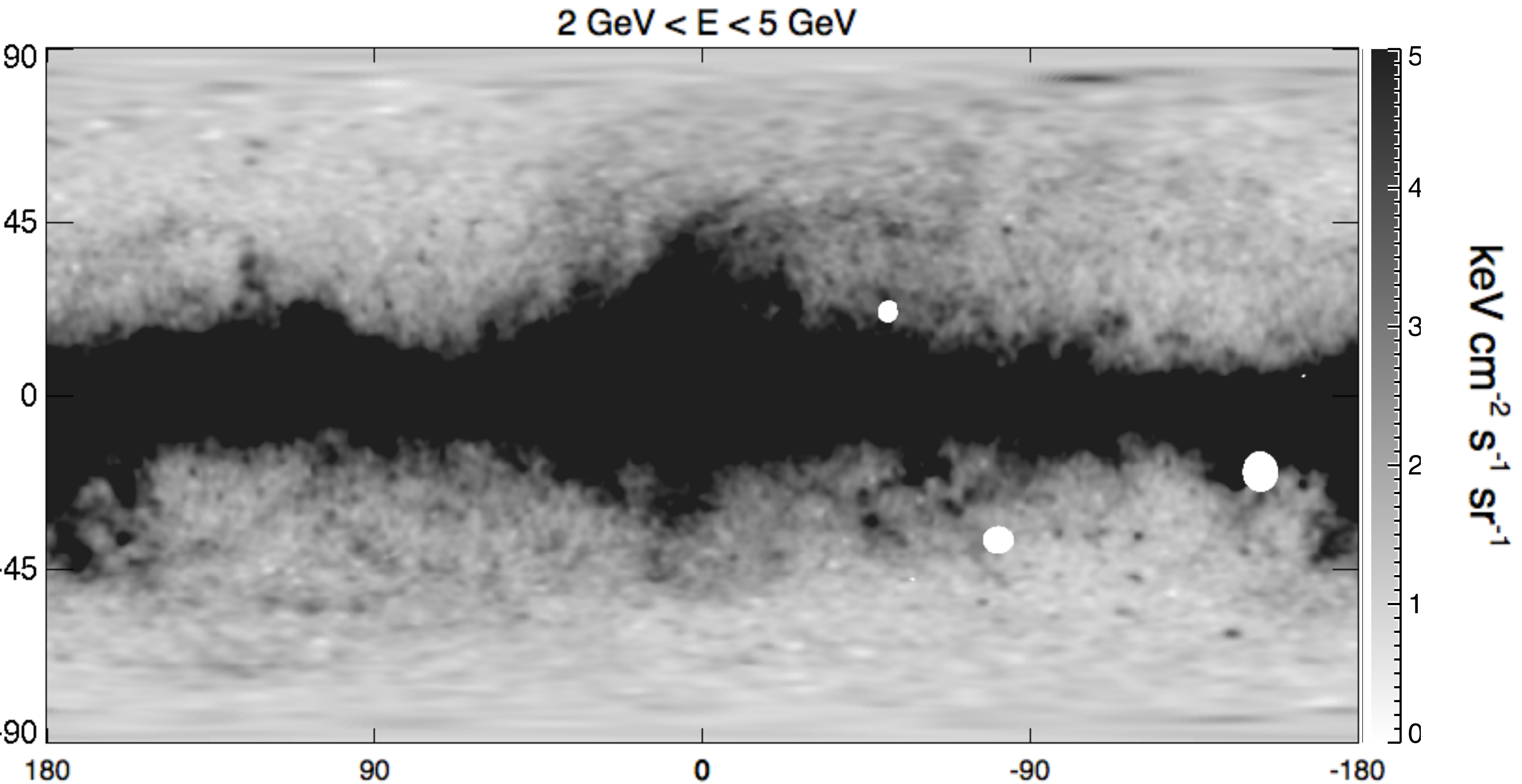


Physical models of the diffuse gamma-ray flux are constructed from gas maps and estimates of the interstellar radiation field and cosmic ray populations.

The Fermi Gamma-Ray Space Telescope

- Launched successfully from Cape Canaveral on 11 June 2008.
- Now in low-Earth orbit, 340 mile altitude.
- Scans the entire sky every two orbits (~3 hours).
- Sensitive to gamma-rays from 300 MeV up to several TeV.
- All data is public.
- Data consists of photon counts with (2D) positions + energies.

Data - model as of 2010
(diffuse model by Fermi Collaboration)



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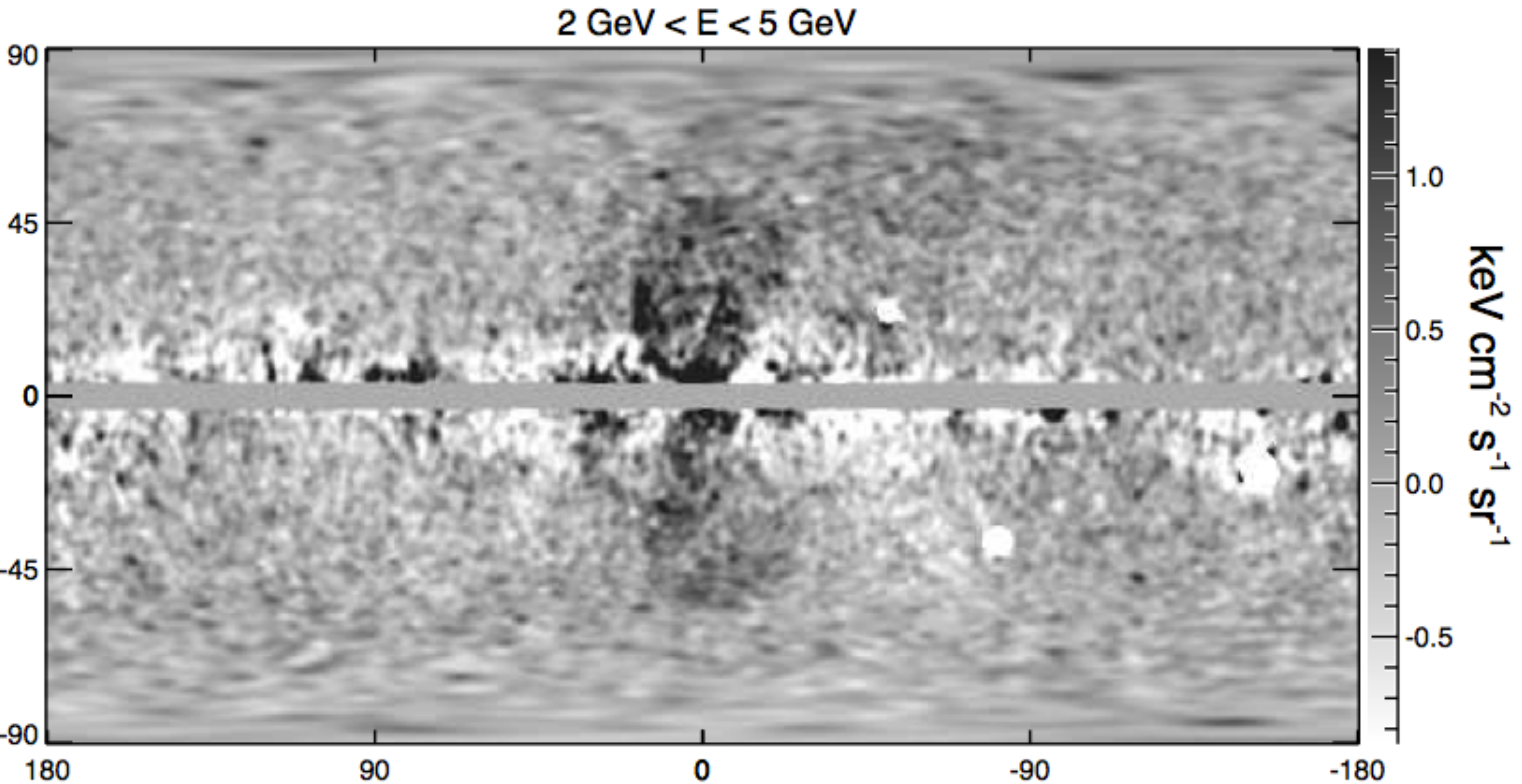

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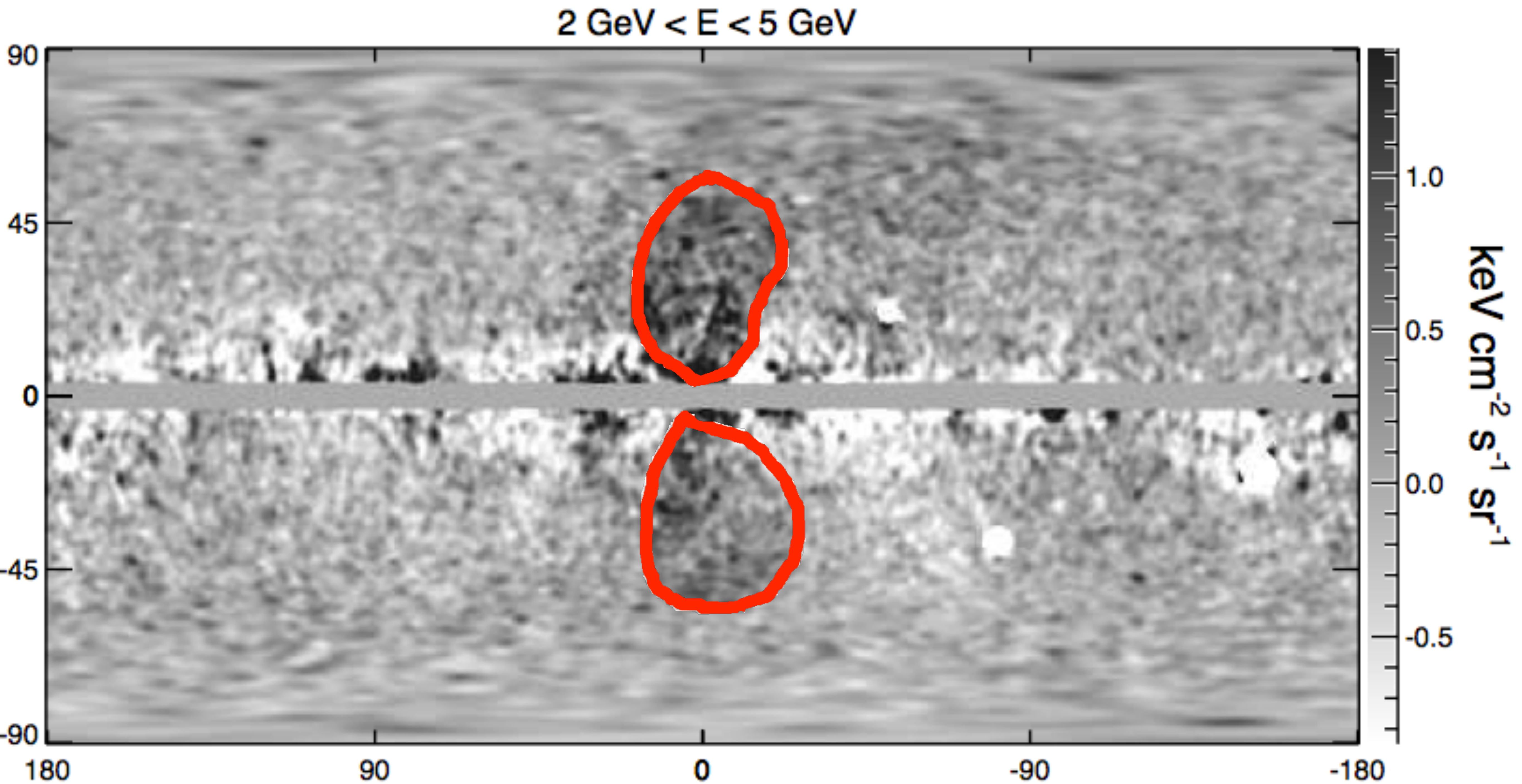
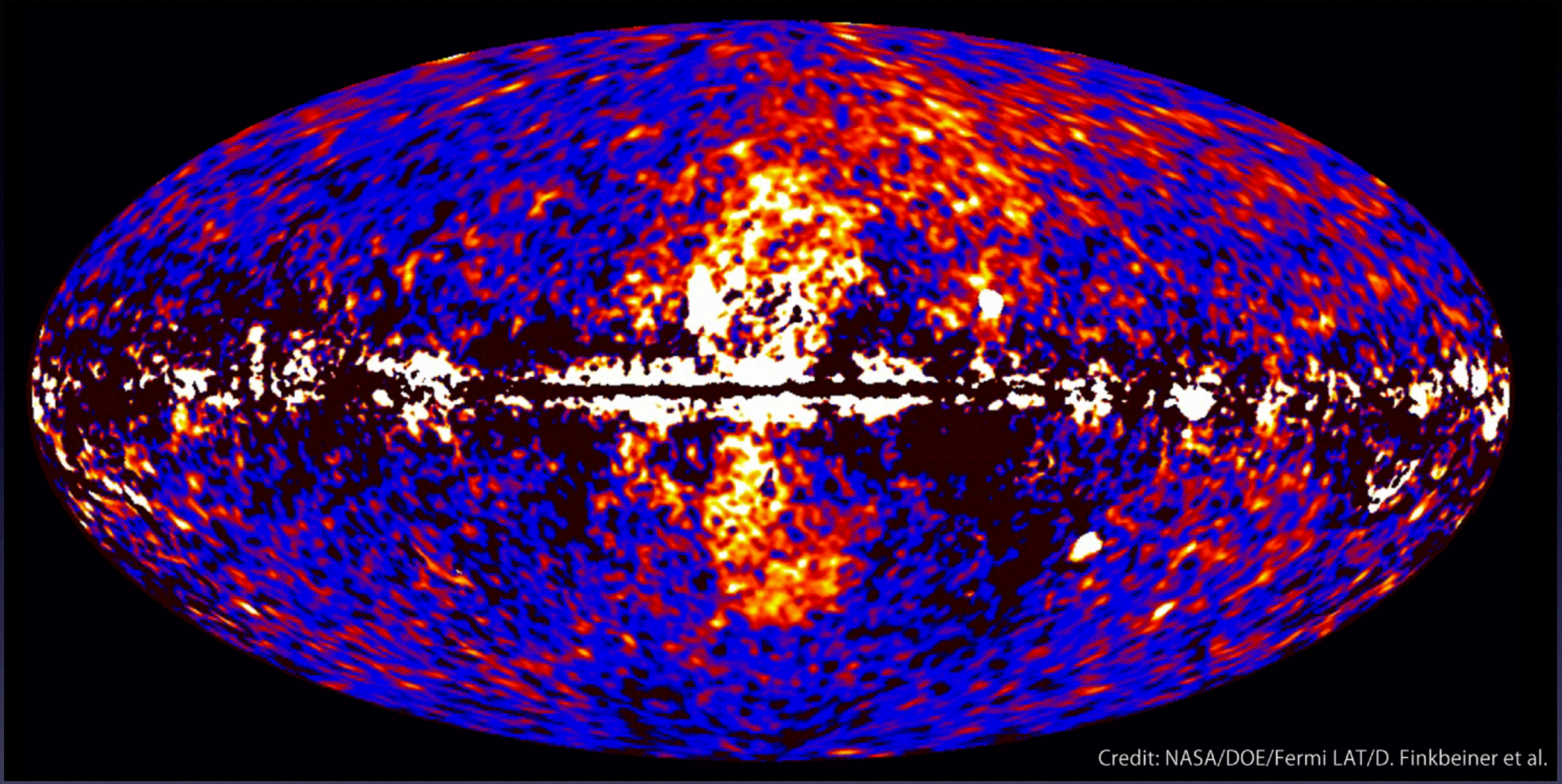
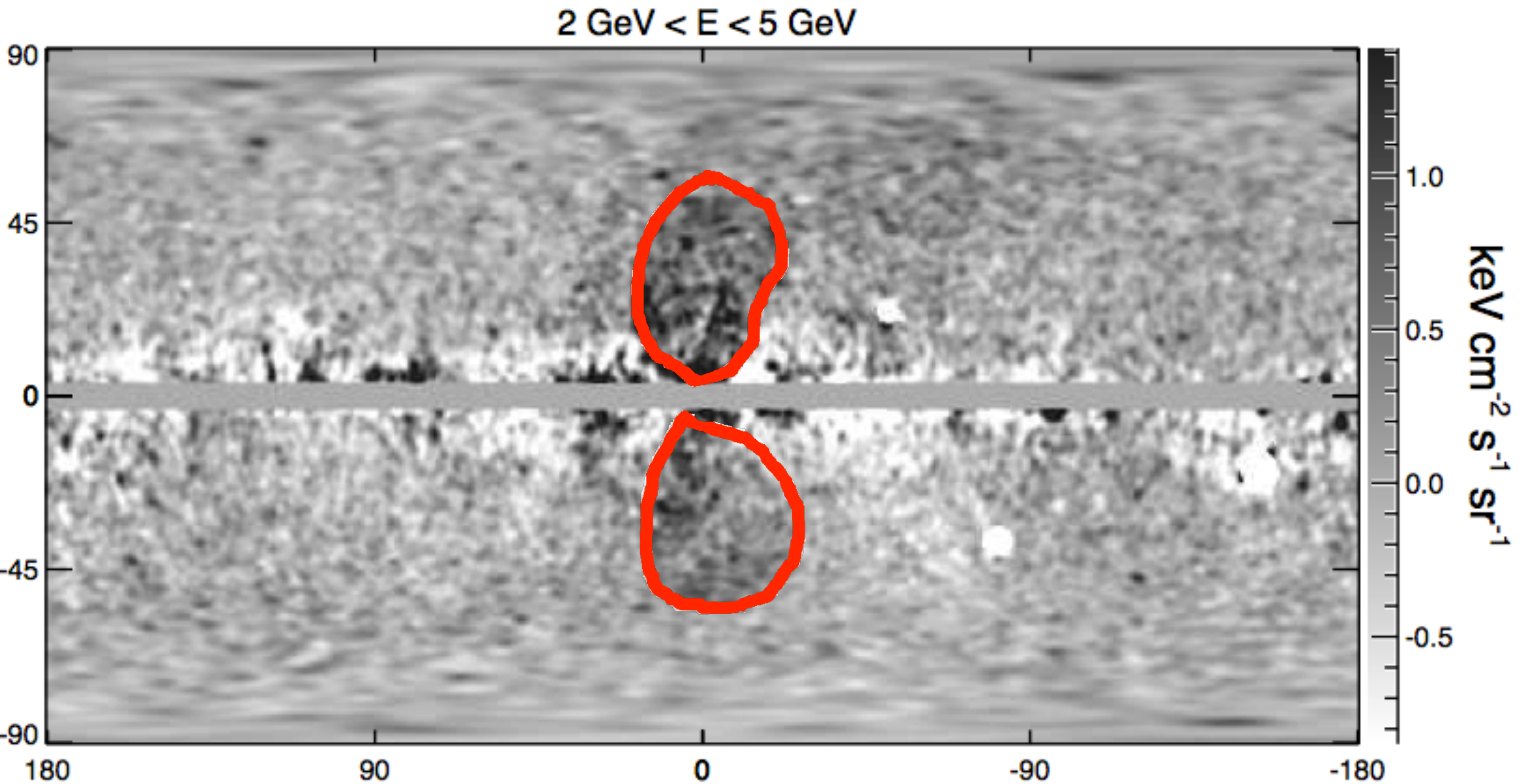


Large bubbles/lobes first described by Su, TRS & Finkbeiner in 2010.

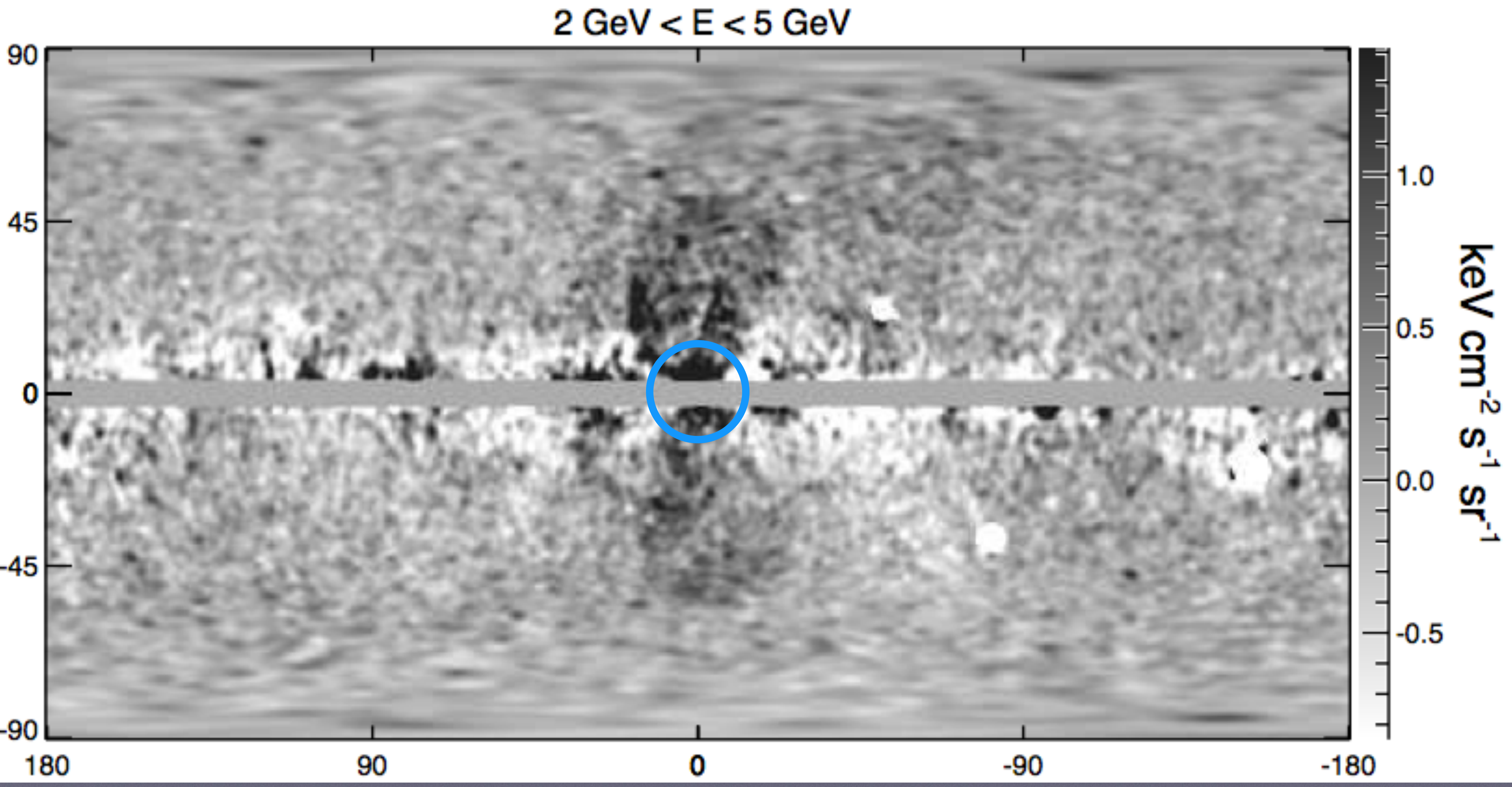
The Fermi Bubbles



- Giant, double-lobed structure centered at the Galactic Center, extending ~50 degrees to the north and south.
- Bright in 1-100 GeV gamma rays. Now also observed in X-ray and microwaves.
- May be a relic of activity of the black hole at the Galactic Center, or supernovae in the inner Galaxy, over the last several million years.
- Many puzzling features and their origin is still an open question.



2 GeV < E < 5 GeV
90
45
0
-45
-90
180
90
0
-90
-180
1.0
0.5
0.0
-0.5
keV cm^{-2} s^{-1} sr^{-1}



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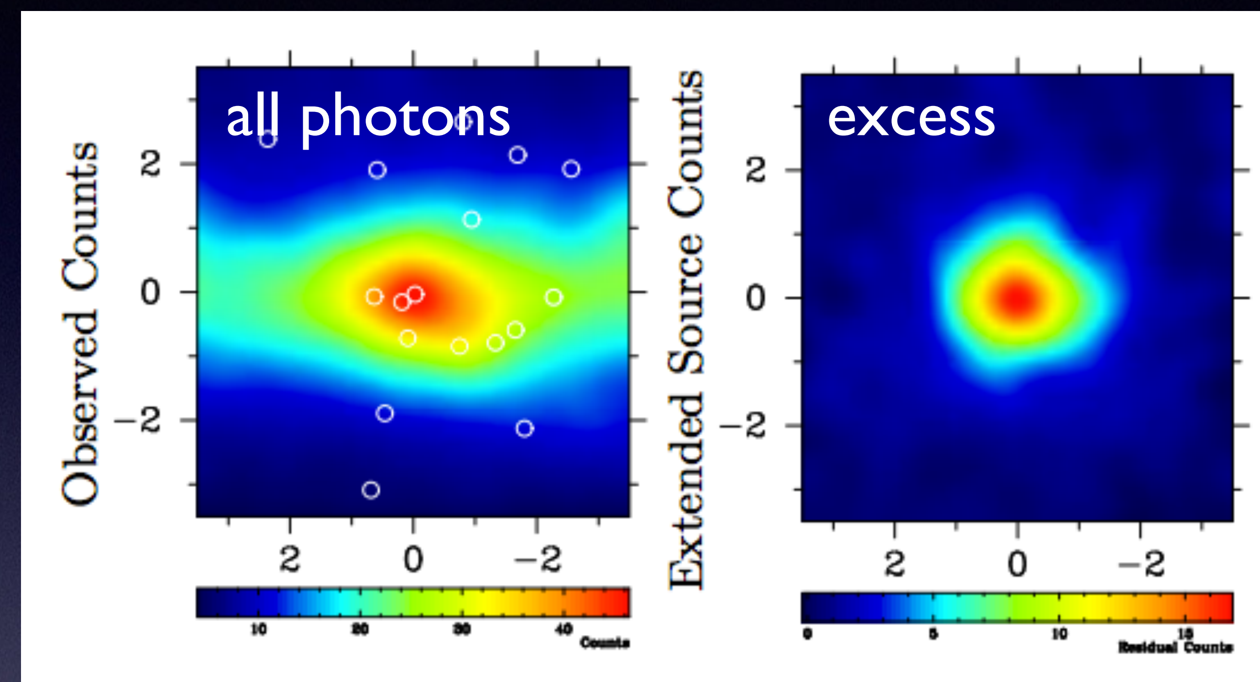
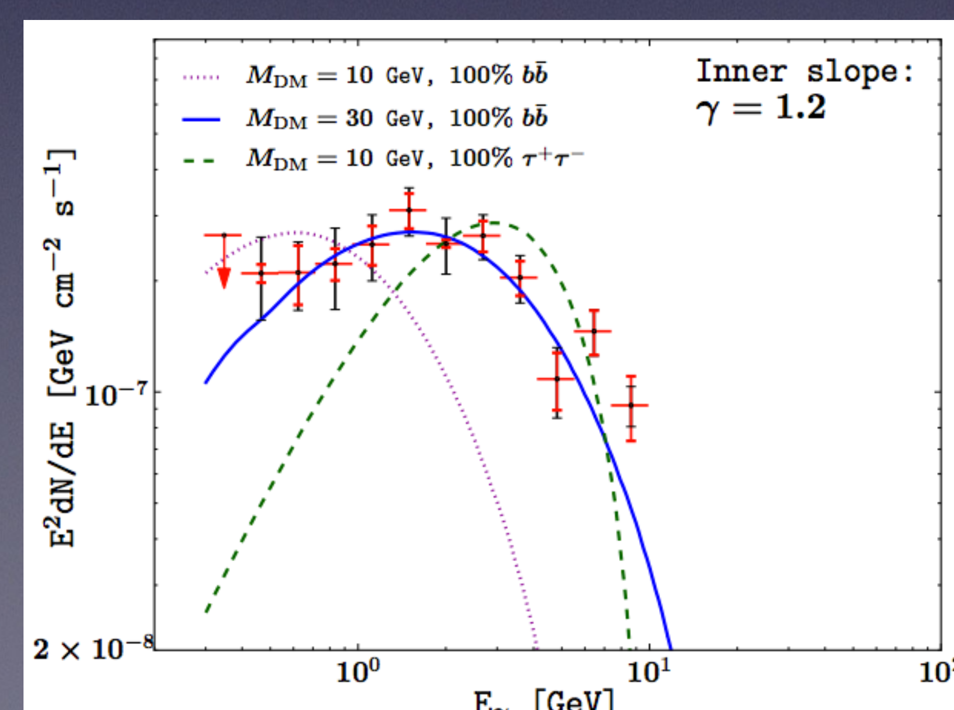
The Galactic Center Excess (GCE)

- Apparent new gamma-ray component found in Fermi Gamma-Ray Space Telescope public data
- Initial discovery '09 by Goodenough & Hooper, in the Galactic Center (GC)
- Discovered to extend outside the GC, into the inner Galaxy, by Hooper & TRS '13
- Confirmed by Fermi Collaboration in analysis of Ajello et al '16

spatial distribution Abazajian & Kaplinghat '12

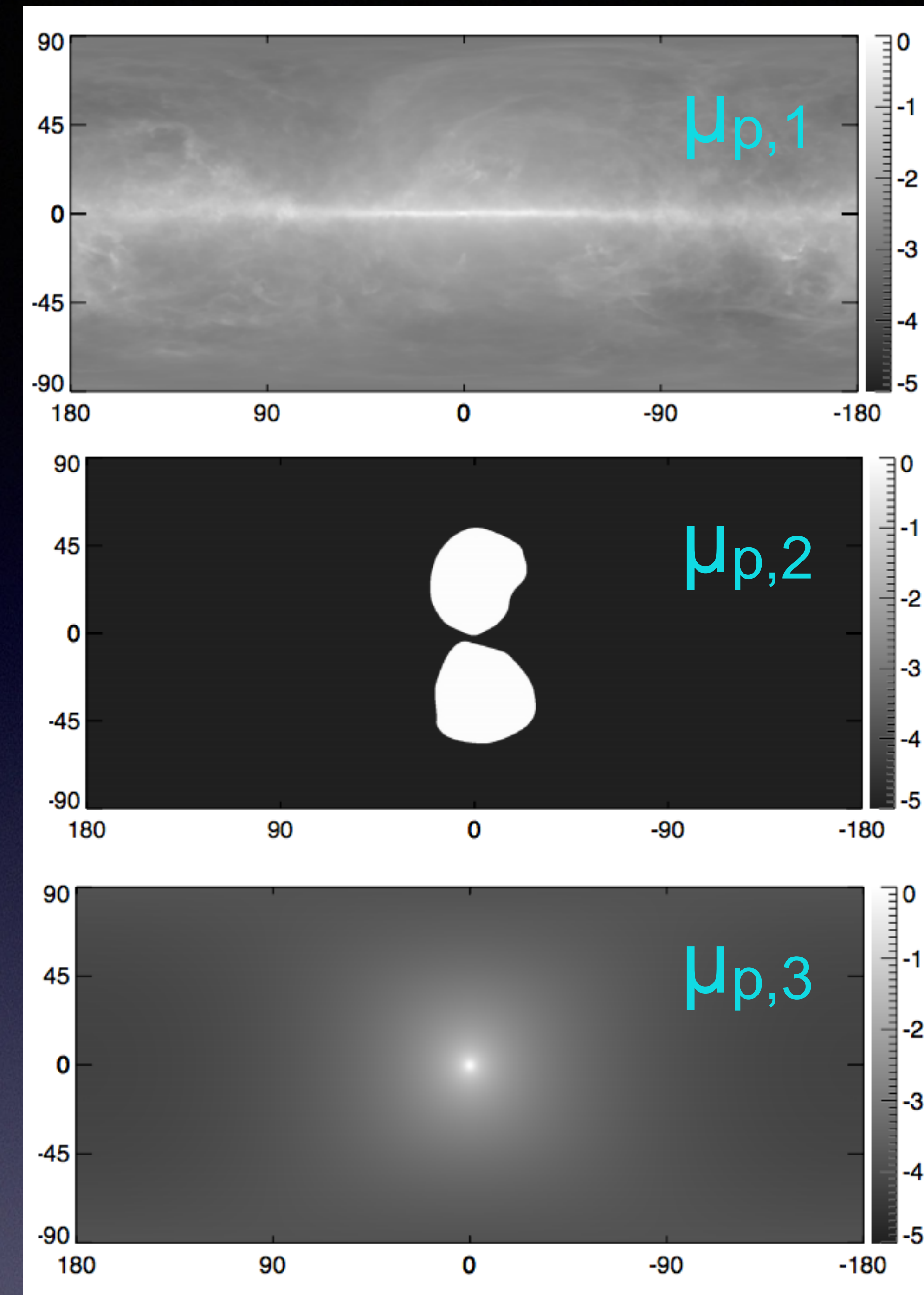


spectrum Gordon & Macias '13



Template fitting

- Model the photon counts (within some energy bin) as a linear combination of spatial templates $\mu_{p,l}$ (p=pixel number, l=template number)
- Templates are obtained by taking physical models or simple ansatzes, applying exposure and smoothing by Fermi point spread function (PSF).
- Given model (as a function of coefficients $\theta=\{\alpha_l\}$), overall likelihood is given by the product of the Poisson likelihoods for each (spatial) pixel.
- Maximize likelihood p(data|model) with respect to θ parameters (frequentist) or compute posterior probabilities (Bayesian)

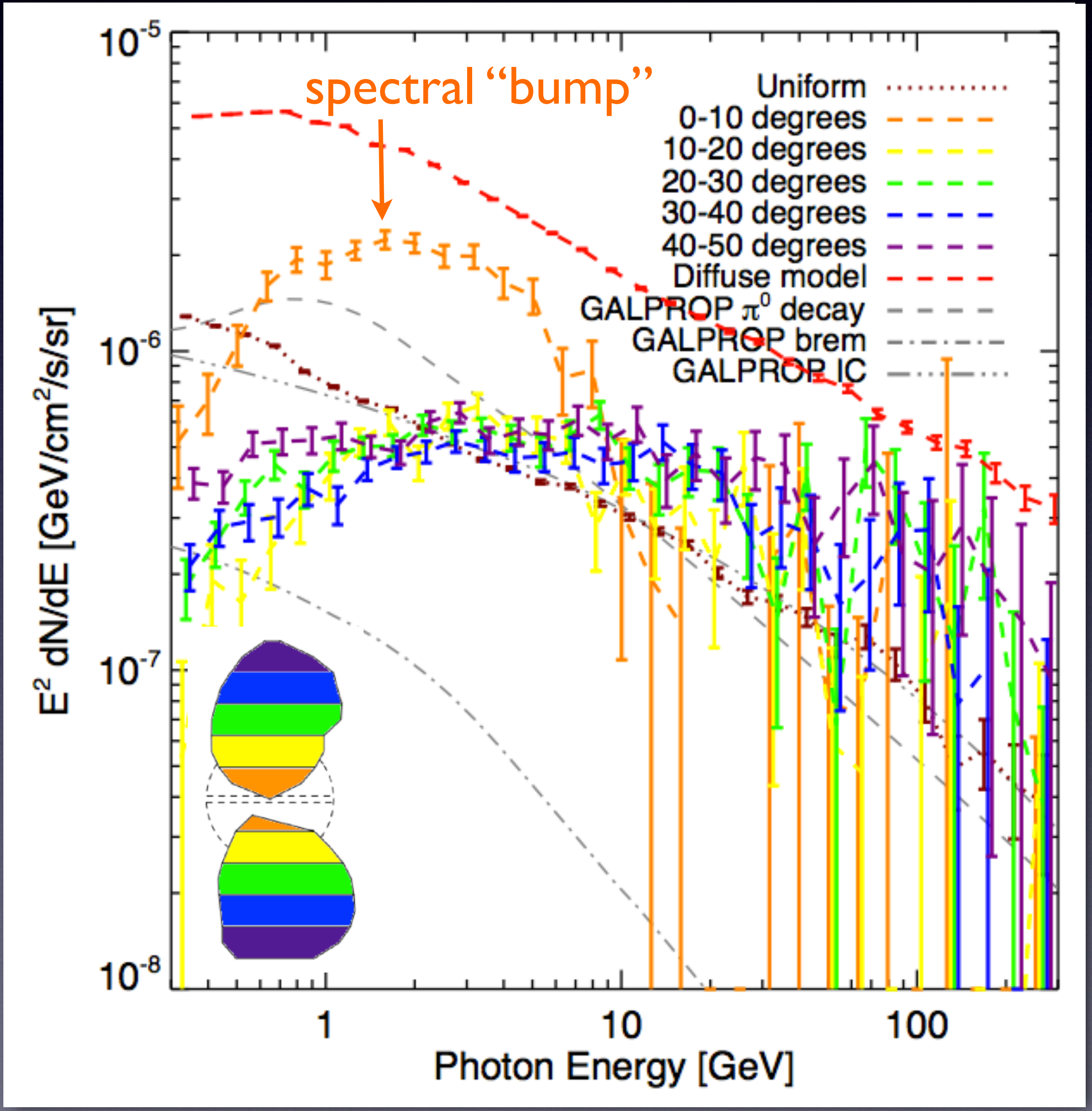


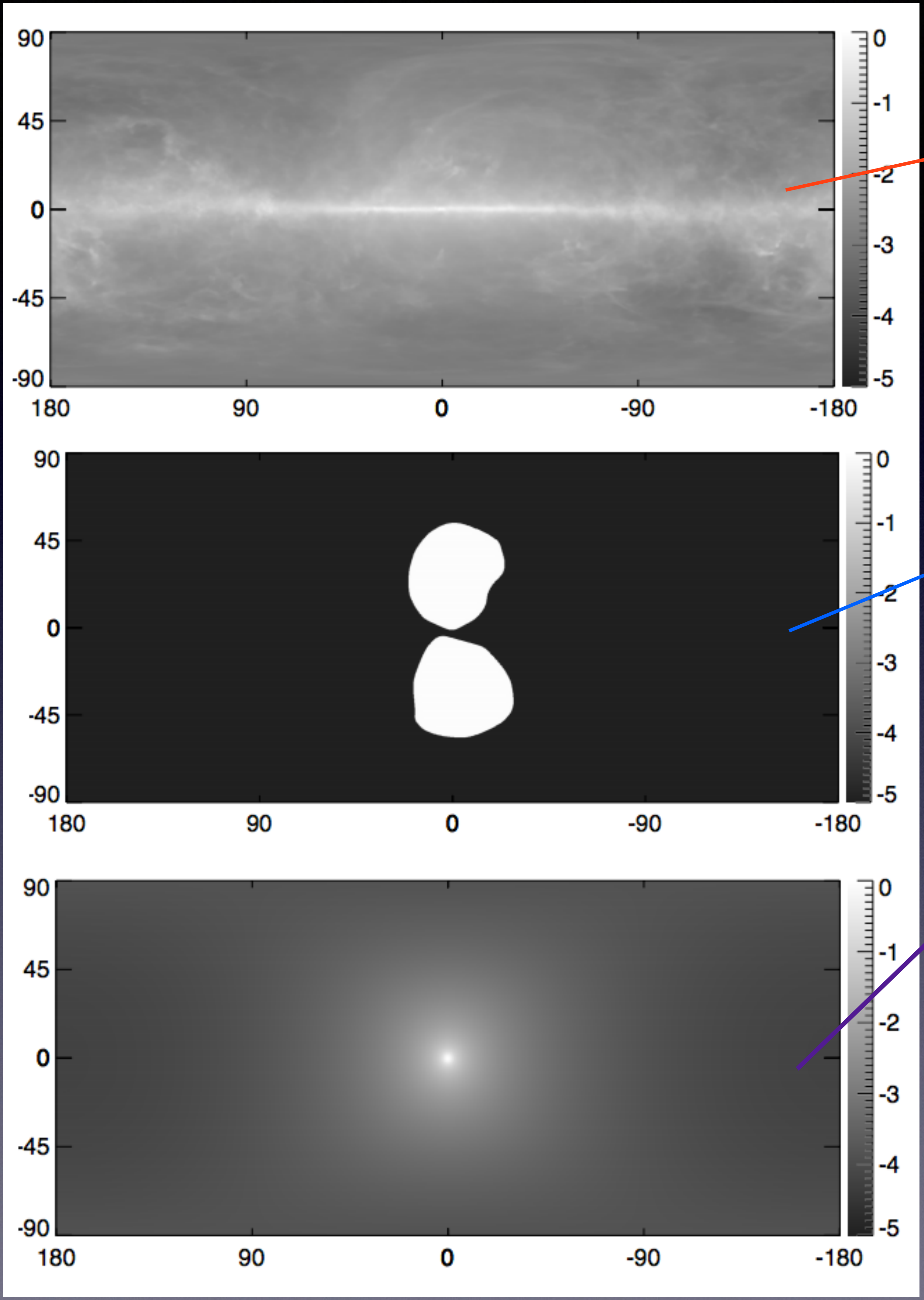
$$\mu_p = \sum_\ell \alpha_\ell \, \mu_{p,\ell} \qquad p_k^{(p)} = \frac{(\mu_p)^k \, e^{-\mu_p}}{k!}$$

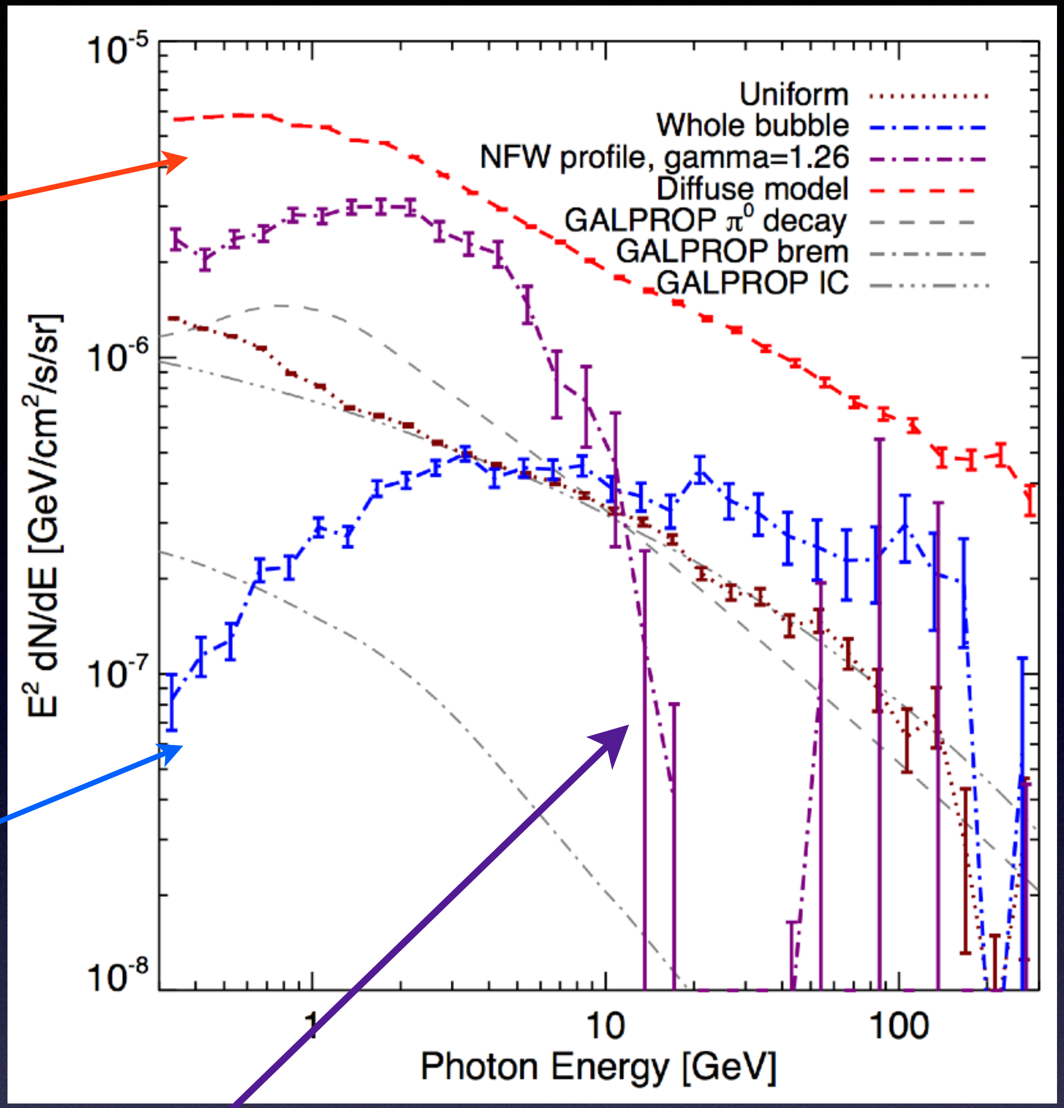
$$p(d|\theta, \mathcal{M}) = \prod_p p_{n_p}^{(p)}(\theta)$$

Beyond the Bubbles

- Hooper & TRS 2013: allow Bubbles spectrum to vary with latitude, fit for normalization of Bubbles energy-by-energy and latitude-by-latitude.
- We found the spectrum of the Bubbles develops pronounced curvature at low Galactic latitudes.
- Consistent with two components, one flat in E^2dN/dE and latitude, the other resembling the Galactic Center excess…
- … but now visible even when we remove all photons within 5 degrees of the Galactic plane.



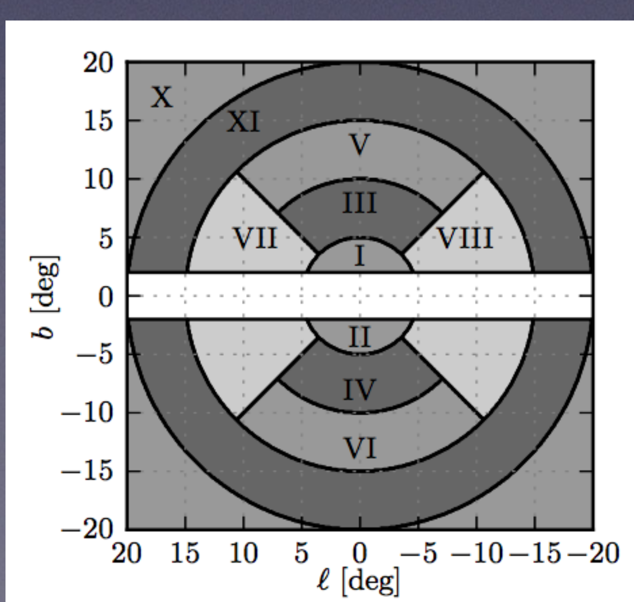




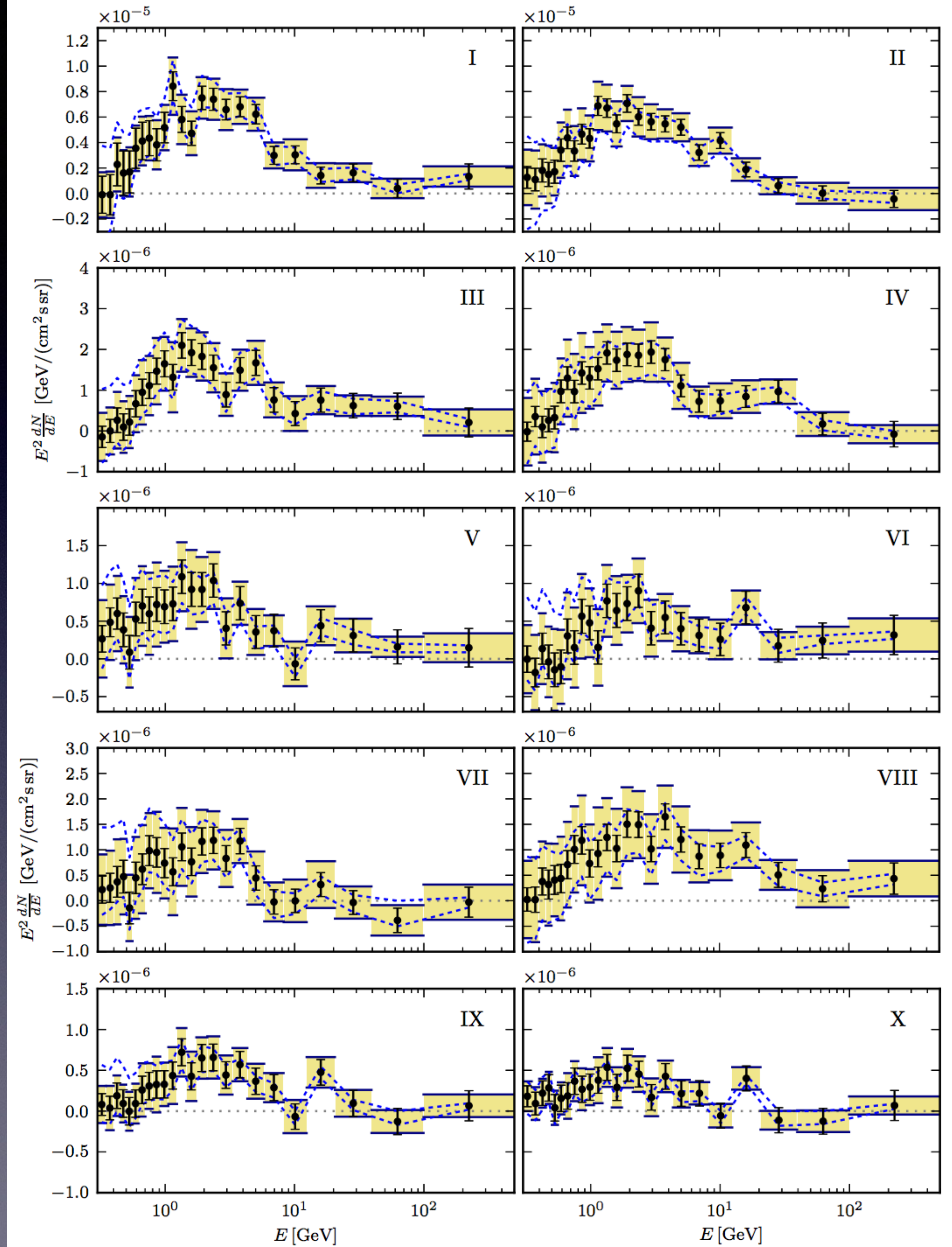
- Can add a model for a DM signal motivated by N-body simulations (or your favorite cored model) - generalized NFW profile, squared and projected along the line of sight.
- Fit the data as a linear combination of background(s) + signal, extract best-fit coefficient and error bars for each - “template fitting”.
- Repeat at each energy to find a spectrum for each component.

Properties

- Daylan, TRS et al '16 found that:
  - Photons peak around 1-3 GeV in energy
  - Excess is approximately symmetric around the GC, steeply peaked at GC. Can also be well-described as Galactic-Bulge-like extended emission + central ~symmetric core [Macias et al '18, Bartels et al '18, Macias et al '19, Abazajian et al '20].



Plots taken from Calore, Cholis & Weniger '14

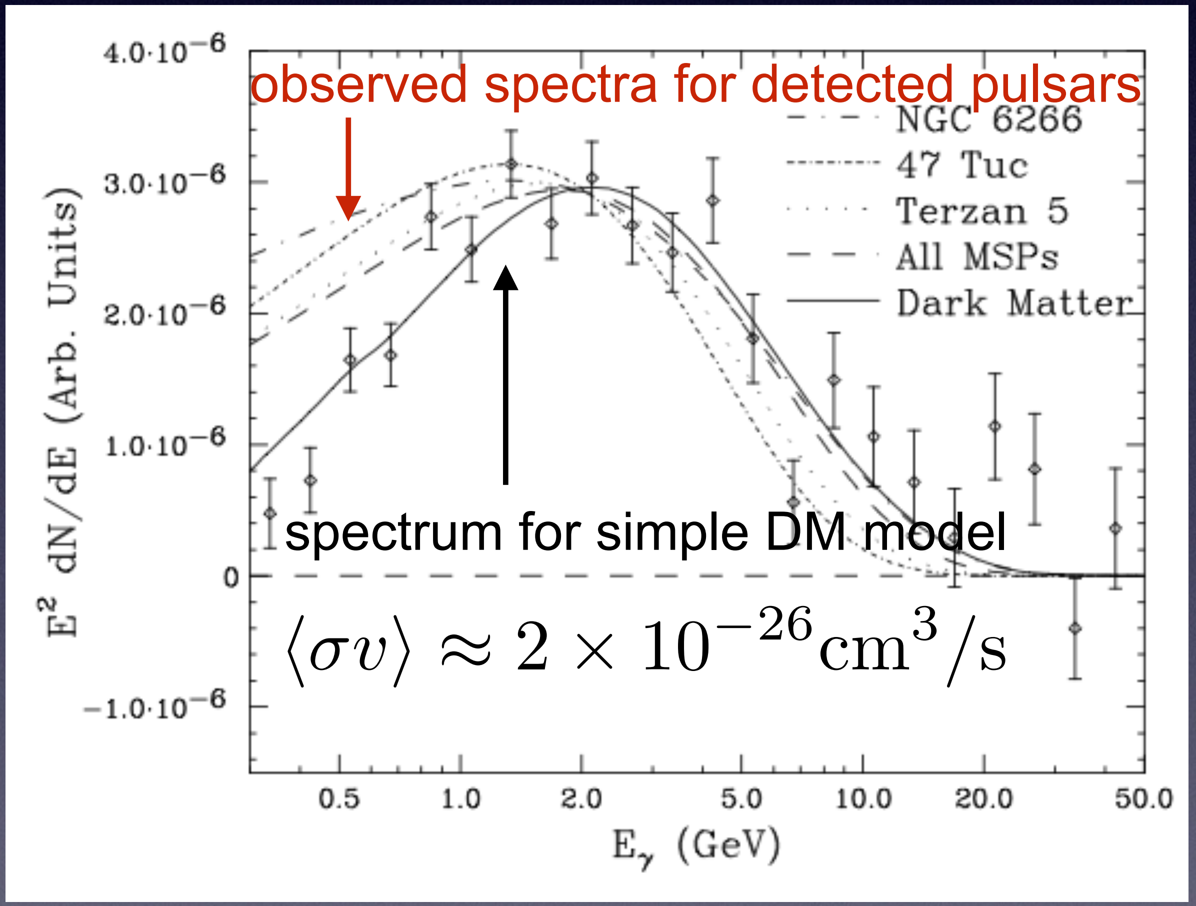


Hypotheses

- Dark matter annihilation.

Particle theorist: 😀

- "Conventional" astrophysics (i.e. not requiring physics beyond the Standard Model):
  - A new population of stars or other point sources - most discussed candidate is millisecond pulsars (MSPs), spinning neutron stars.
  - A new diffuse background - most discussed candidate is an outflow or burst from the Galactic Center.



Daylan, TRS et al '16

Particle theorist: 😕 Astrophysicist: 😀

DARK MATTER

Dark matter annihilation

Naturally explains:

The invariance of the spectrum with position + shape of spectrum.

The ~spherical morphology of the signal.

The profile: steeply peaked at the Galactic Center but extending out to at least 10 degrees, agrees well with (some, not all) simulations.

The rate: required annihilation cross section matches that required to explain observed dark matter abundance, in simple "thermal relic" scenario.

Model-building challenges

- Direct detection is very sensitive in this mass range, why haven't we seen it?
  - Annihilation may be resonant
  - Direct detection may be dominantly spin-dependent or otherwise suppressed (although in many models, upcoming direct detection experiments have sensitivity anyway)
  - Annihilation may be 2→4 and the intermediate particles may have small couplings to the SM
- What about bounds from colliders?
  - Sensitivity is reduced in the presence of light mediators, which may be needed to raise the cross section to thermal relic values
  - Nonetheless, substantial classes of simplified models can be ruled out.
- There are existence proofs of UV-complete models that satisfy all constraints.

Effective field theory…

(a) Operators for Dirac fermion DM

Name	Operator	Dimension	SI/SD
D1	$\frac{m_q}{\Lambda^3}\bar{\chi}\chi\bar{q}q$	7	SI
D2	$\frac{im_q}{\Lambda^3}\bar{\chi}\gamma^5\chi\bar{q}q$	7	N/A
D3	$\frac{im_q}{\Lambda^3}\bar{\chi}\chi\bar{q}\gamma^5 q$	7	N/A
D4	$\frac{m_q}{\Lambda^3}\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	7	N/A
D5	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	6	SI
D6	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	6	N/A
D7	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	6	N/A
D8	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	6	SD
D9	$\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu} q$	6	SD
D10	$\frac{i}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\mu\nu} q$	6	N/A
D11	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\chi G^{\mu\nu}G_{\mu\nu}$	7	SI
D12	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\gamma^5\chi G^{\mu\nu}G_{\mu\nu}$	7	N/A
D13	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\chi G^{\mu\nu}\tilde{G}_{\mu\nu}$	7	N/A
D14	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\gamma^5\chi G^{\mu\nu}\tilde{G}_{\mu\nu}$	7	N/A

(b) Operators for Complex scalar DM

Name	Operator	Dimension	SI/SD
C1	$\frac{m_q}{\Lambda^2}\phi^\dagger\phi\bar{q}q$	6	SI
C2	$\frac{m_q}{\Lambda^2}\phi^\dagger\phi\bar{q}\gamma^5 q$	6	N/A
C3	$\frac{1}{\Lambda^2}\phi^\dagger\overleftrightarrow{\partial}_\mu\phi\bar{q}\gamma^\mu q$	6	SI
C4	$\frac{1}{\Lambda^2}\phi^\dagger\overleftrightarrow{\partial}_\mu\phi\bar{q}\gamma^\mu\gamma^5 q$	6	N/A
C5	$\frac{\alpha_s}{\Lambda^3}\phi^\dagger\phi G^{\mu\nu}G_{\mu\nu}$	6	SI
C6	$\frac{\alpha_s}{\Lambda^3}\phi^\dagger\phi G^{\mu\nu}\tilde{G}_{\mu\nu}$	6	N/A

Study couplings to
hadronic states only

Alves et al
1403.5027

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ruled out by DD

Study couplings to hadronic states only

Alves et al 1403.5027

Effective field theory...

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Alves et al 1403.5027

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- ruled out by DD
- cannot fit signal
- ruled out by LHC

Study couplings to hadronic states only

Alves et al 1403.5027

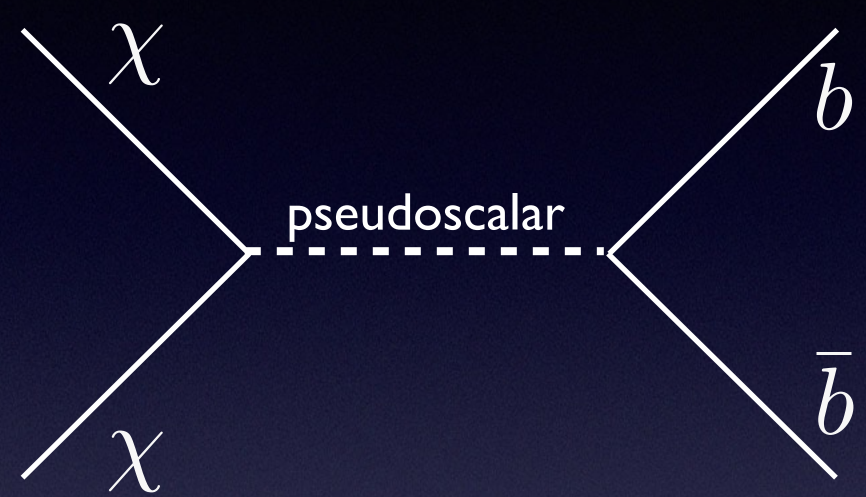
… and beyond

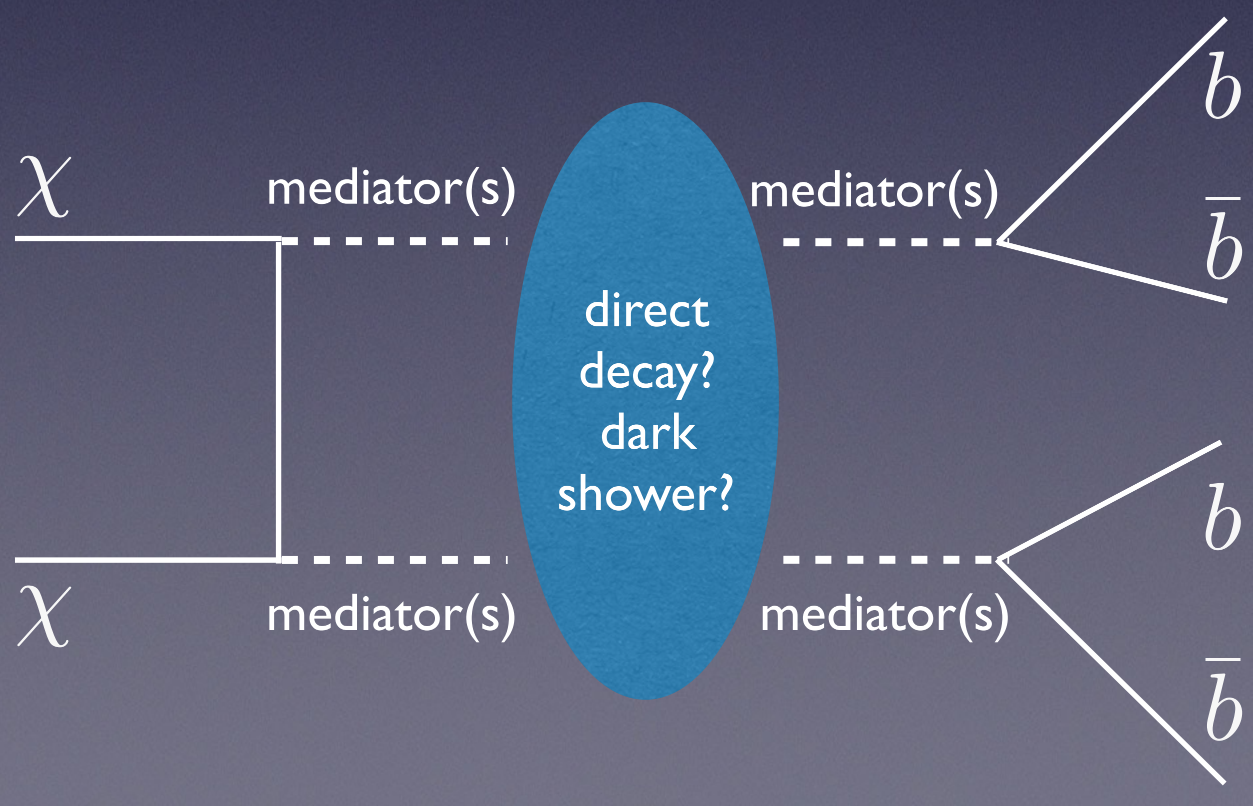
Berlin et al 1404.0022 (simplified models)

Model Number	*DM*	*Mediator*	*Interactions*	Elastic Scattering	Near Future Reach? Direct	LHC
1	Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
1	Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
2	Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
2	Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
3	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi$, $\bar{b}\gamma_\mu b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Maybe
4	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi$, $\bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$ or $\sigma_{\rm SD} \sim (q/2m_\chi)^2$	Never	Maybe
5	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi$, $\bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
5	Majorana Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi$, $\bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
6	Complex Scalar	Spin-0	$\phi^\dagger\phi$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
6	Real Scalar	Spin-0	ϕ^2, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
6	Complex Vector	Spin-0	$B^\dagger_\mu B^\mu$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
6	Real Vector	Spin-0	$B_\mu B^\mu$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
7	Dirac Fermion	Spin-0 (*t*-ch.)	$\bar{\chi}(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
7	Dirac Fermion	Spin-1 (*t*-ch.)	$\bar{\chi}\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
8	Complex Vector	Spin-1/2 (*t*-ch.)	$X^\dagger_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
8	Real Vector	Spin-1/2 (*t*-ch.)	$X_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes

Examples

- Annihilation through a pseudoscalar to b's (e.g. "coy DM" of 1401.6458)
  - Renormalizable model presented in 1404.3716, pseudoscalar mixes with CP-odd component of 2HDM
  - Z_3 NMSSM implementation in 1406.6372, bino/higgsino DM annihilates through light MSSM-like pseudoscalar. General NMSSM study in 1409.1573.
- 2→4 models - DM annihilates to an on-shell mediator, subsequently decays to SM particles (e.g. 1404.5257, 1404.6528, 1405.0272, dark photon and NMSSM implementations in 1405.5204, dark-sector showering in 1410.3818).

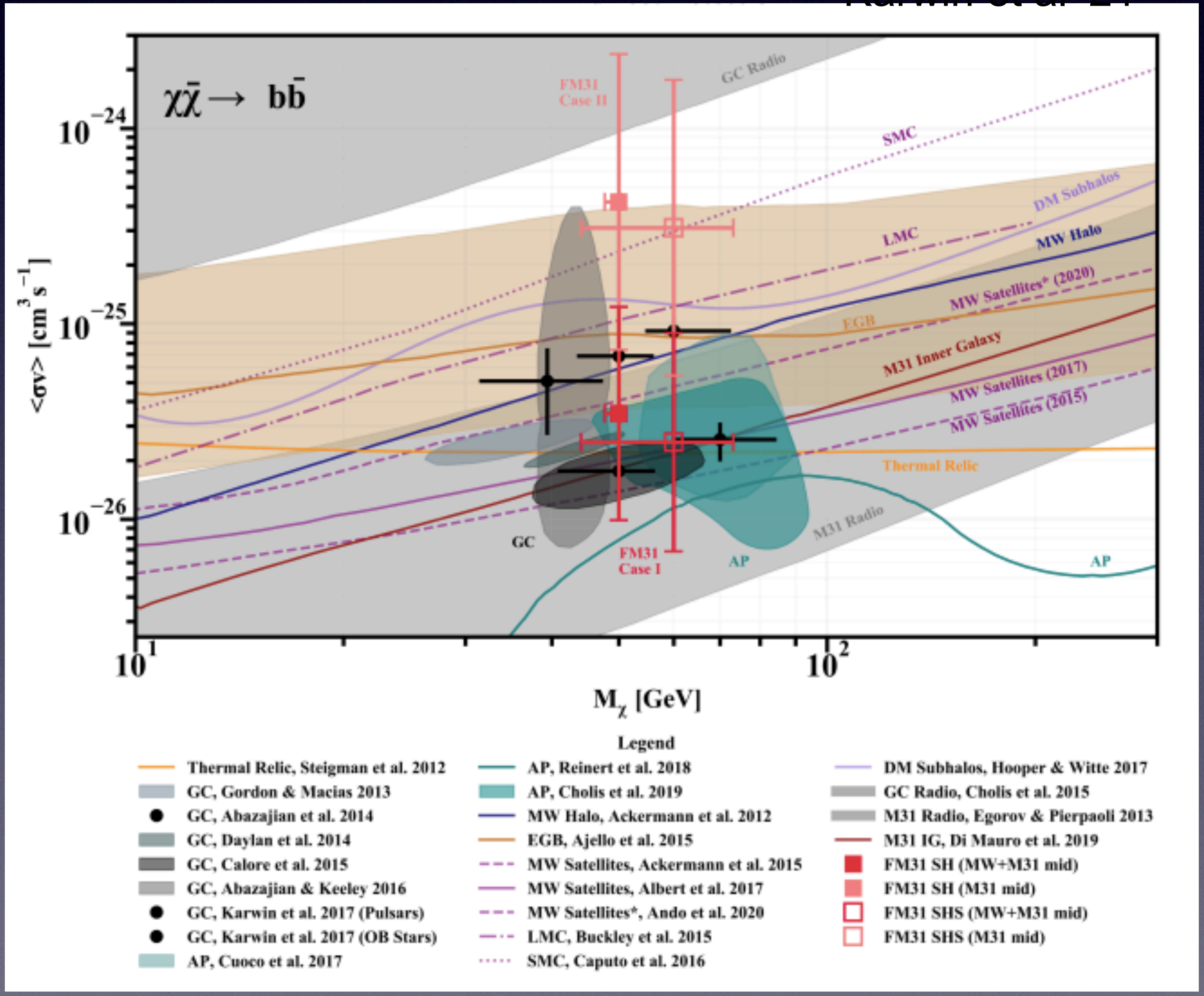




What about dwarf galaxy bounds?

- The most model-independent limit would come from gamma-ray counterpart searches in other systems
- Cleanest are dwarf satellite galaxies - but sensitivity is not quite good enough for exclusion
- Possible strong constraints from antiprotons and M31 radio - but also claims of counterparts in those channels (and updates to M31 work give weaker limits, Egorov '22)

Karwin et al '21



OUTFLOWS

Outflows from the Galactic Center

- Some transient event in the Galactic Center produces an outflow of high-energy cosmic rays.
- These scatter on the gas/starlight to produce gamma rays (e.g. Carlson & Profumo '14, Petrovic et al '14, Cholis et al '15, Gaggero et al '15).
- Such outflows have almost certainly occurred in the past - Fermi Bubbles may be a consequence.

Proton outflow

- Some transient event in the Galactic Center produces an outflow of high-energy protons, which scatter on the gas to produce pions which decay to gamma rays:

PRO:

Evidence for supernova outbursts and activity of the black hole at the Galactic Center in the past - outflows are physically reasonable.

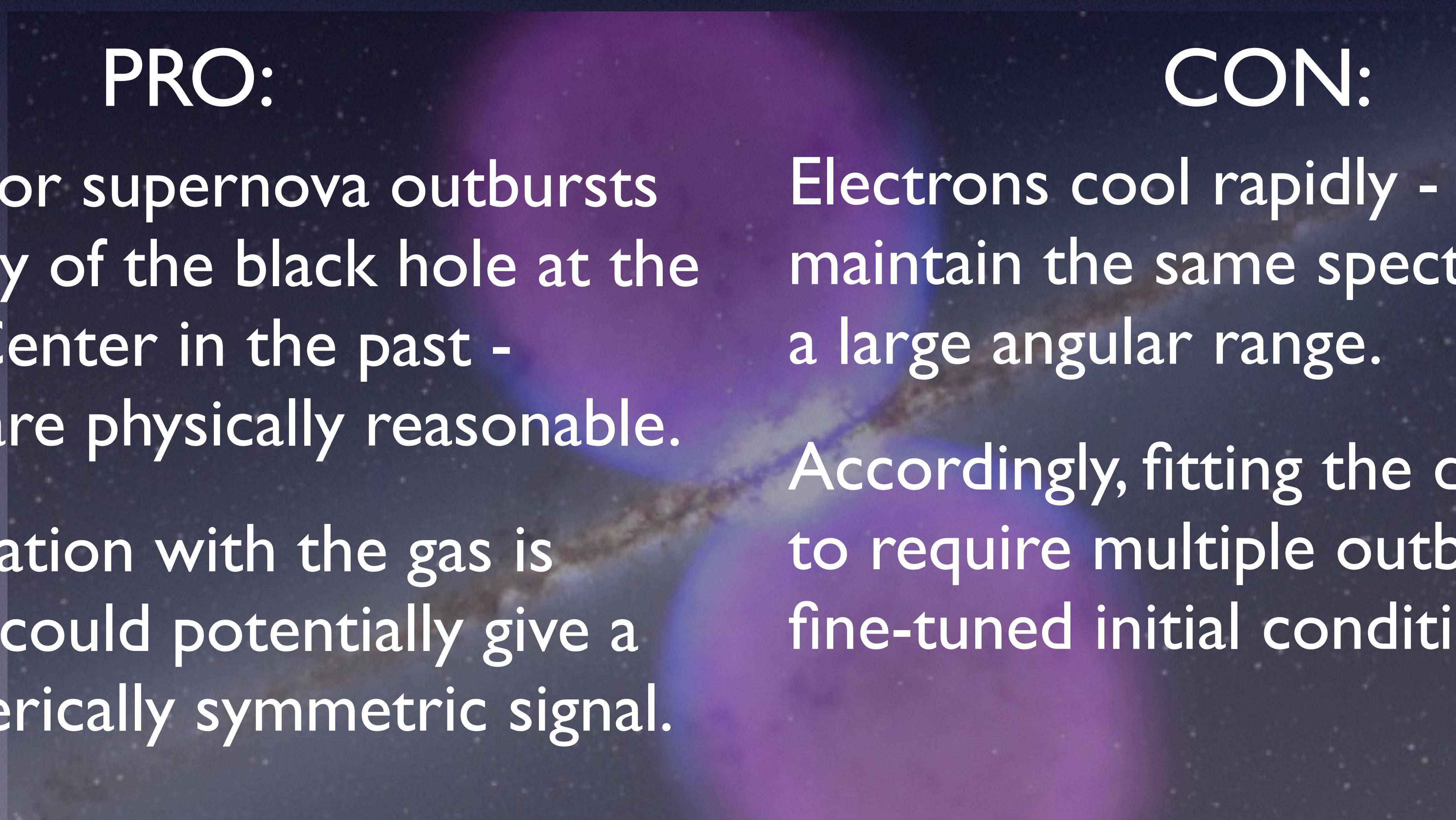
CON:

Excess appears highly spherically symmetric and uncorrelated with the gas. When outflow templates from current models are added to fit, not preferred by the data.

Spectrum requires a sharp kink in the proton spectrum - difficult to justify physically.

Electron outflow

- Some transient event in the Galactic Center produces an outflow of high-energy electrons, which upscatter photons of the radiation field to gamma-ray energies:



PRO:

Evidence for supernova outbursts and activity of the black hole at the Galactic Center in the past - outflows are physically reasonable.

No correlation with the gas is expected, could potentially give a more spherically symmetric signal.

CON:

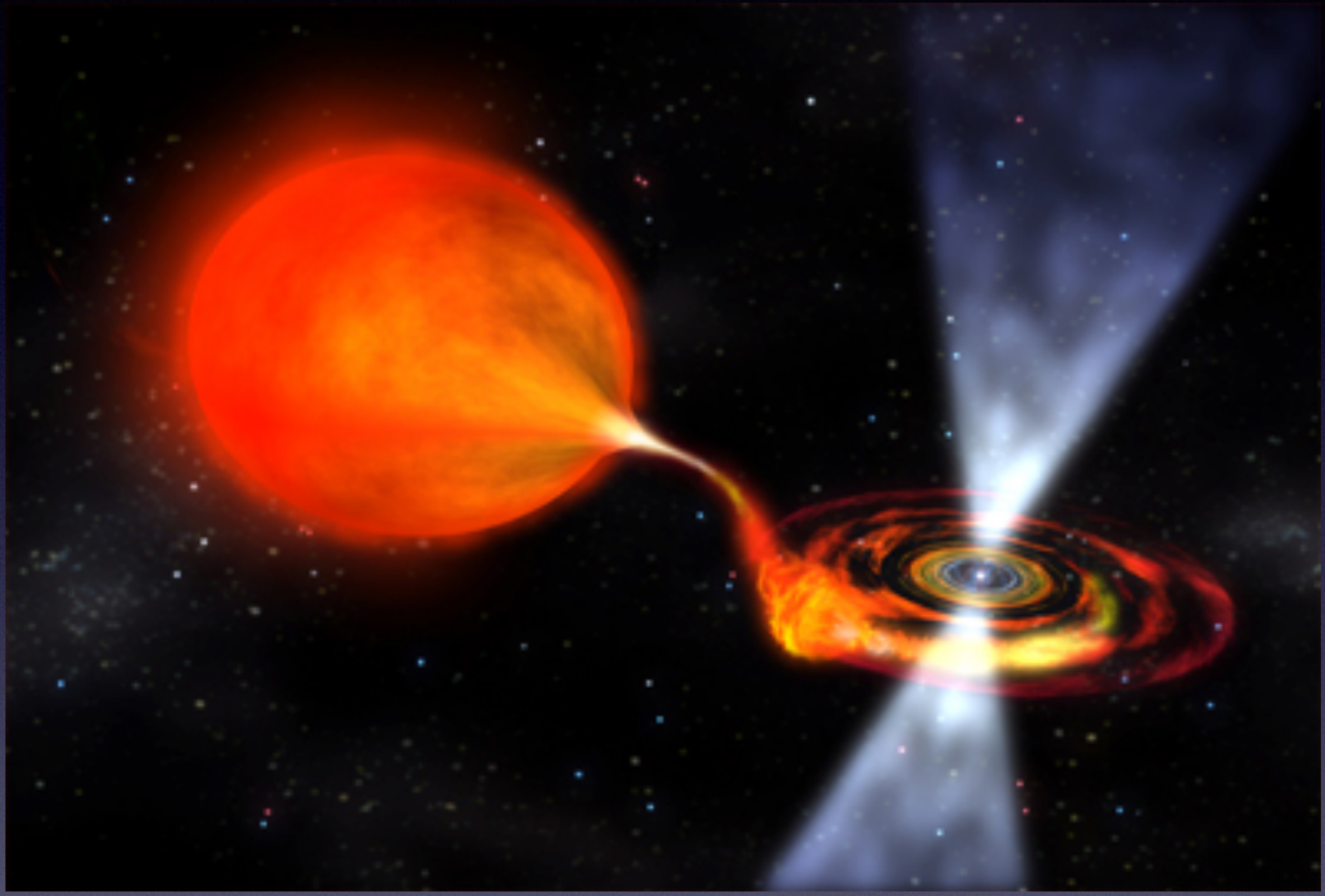
Electrons cool rapidly - difficult to maintain the same spectrum over a large angular range.

Accordingly, fitting the data seems to require multiple outbursts with fine-tuned initial conditions.

PULSARS

What is a pulsar?

- Rapidly rotating star, composed of ultradense neutrons, that emits a beam of radiation as it spins
- Can emit in radio, X-ray and gamma-ray wavelengths



- Millisecond pulsars are those with very short (millisecond) periods
  - They lose energy slowly - long lifetimes
  - Thought to be old pulsars that are spun up by accretion from a partner star

Pulsars

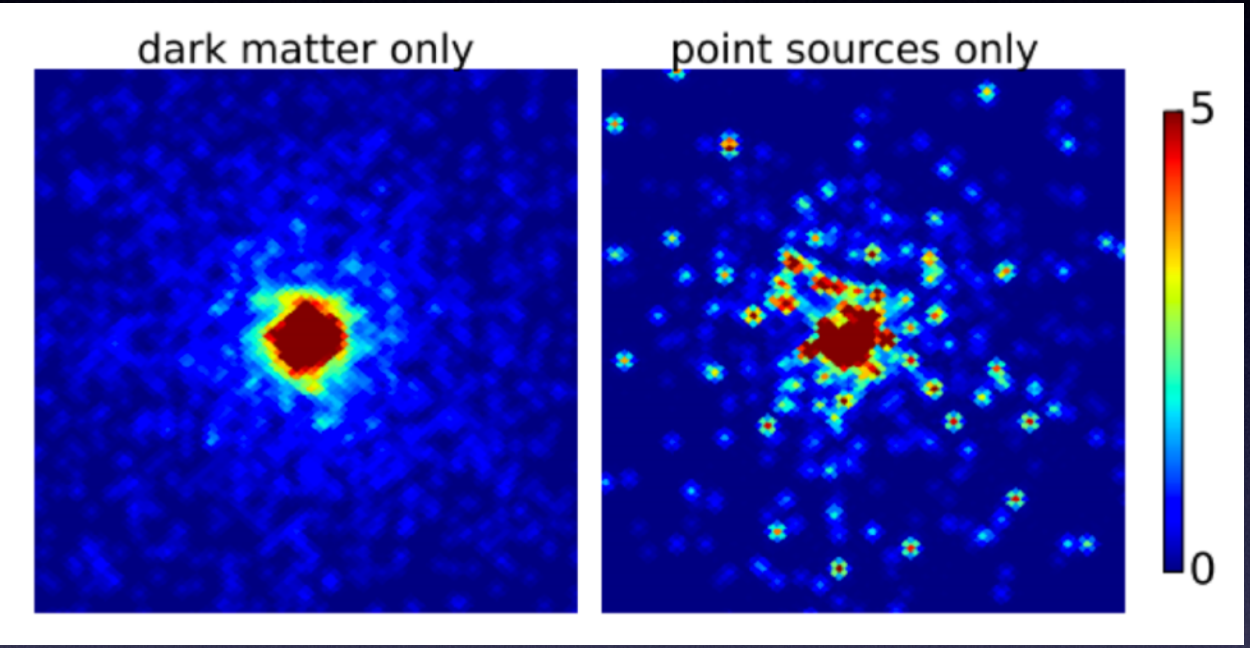
Naturally explains:

- Spectrum: observed MSPs match excess well at energies above 1 GeV.
- Can accommodate the observed morphology:
  - MSPs originate from binary systems, can naturally explain steep slope of profile (and observed X-ray binaries in Andromeda have ~right profile).
  - Globular cluster disruption could give rise to ~spherical distribution [Brandt & Kocsis '15].
  - If morphology is confirmed to resemble stellar bulge rather than spherical halo, will strongly support stellar interpretation.

Deciphering the GCE with photon statistics

<u>DM origin hypothesis</u>

signal traces DM density squared, expected to be ~smooth near GC with subdominant small-scale structure



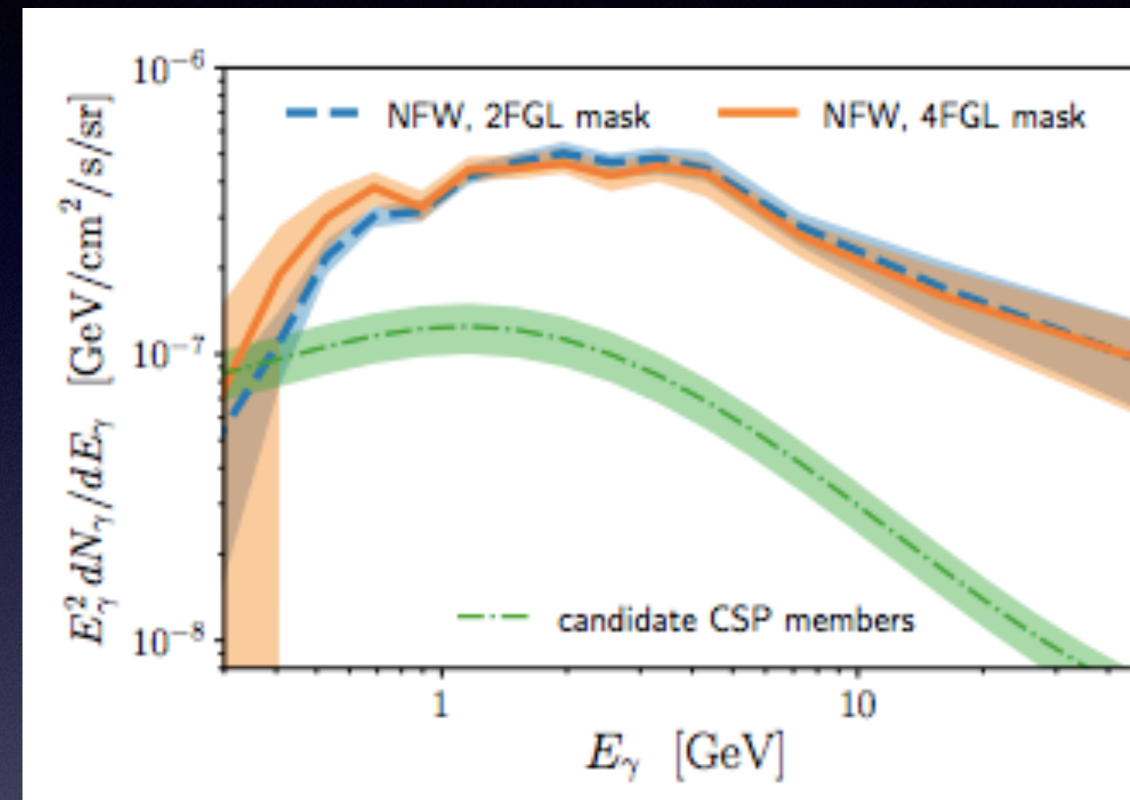
<u>Pulsar origin hypothesis</u>

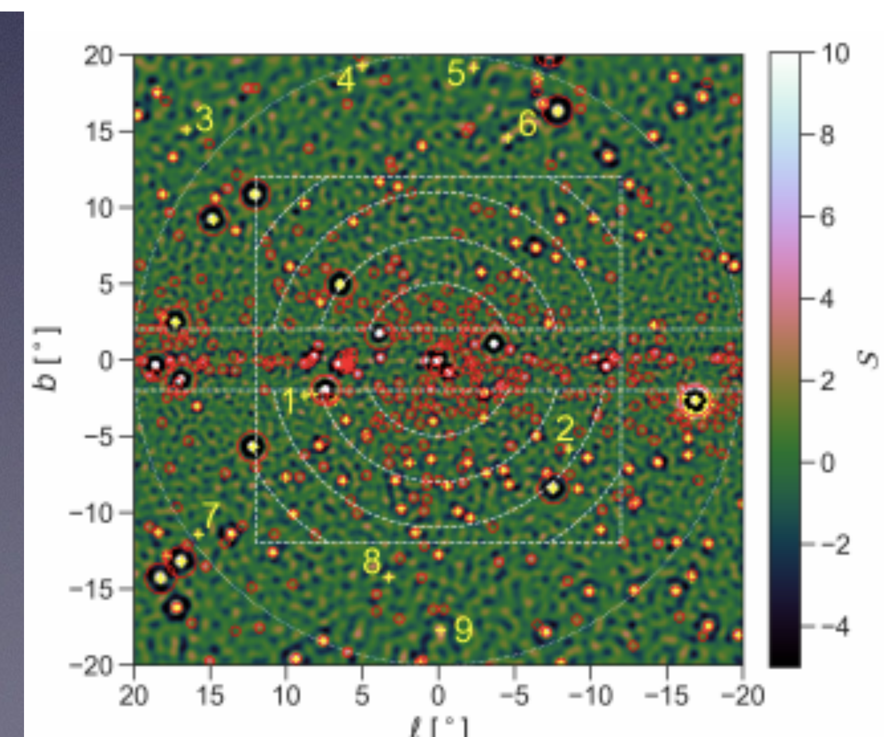
signal originates from a collection of compact objects, each one a faint gamma-ray point source

- Hope to distinguish between hypotheses by looking at granularity of the photon signal - presence or absence of "hot spots".
- Two main analyses in 2016, both claimed evidence for point source populations:
  - Exploiting non-Poissonian statistics of fluctuations from an unknown point source distribution [Malyshev & Hogg '11; Lee, Lisanti & Safdi '15; Lee, Lisanti, Safdi, TRS & Xue '16].
  - Using wavelet-based method to look for small-scale power above expectations from diffuse backgrounds [Bartels et al '16].

2020: wavelets → 4FGL

- Recent analysis repeats wavelet analysis of Bartels et al '16, but now compares identified high-significance peaks to latest gamma-ray source catalog (4FGL) [Zhong et al '20].
- Of 115 peaks, 107 are near a source; 40 of these are potential members of the GCE.
- Wavelet analysis thus essentially gives a subset of the 4FGL catalog.
- Masking 4FGL sources does not reduce GCE.
- Total emission from candidate GCE sources is a factor ~4-5 below GCE.
- Implies bulk of emission should be diffuse or originating from faint sources.





Statistics for point sources

Imagine I expect 10 photons per pixel, in some region of the sky. What is my probability of finding 0 photons? 12 photons? 100 photons?

Case 1: diffuse emission, Poissonian statistics

P(12 photons) = $10^{12} e^{-10}/12! \sim 0.1$
Likewise P(0 photons) ~ 5×10^{-5}, P(100 photons) ~ 5×10^{-63}

Case 2: population of rare sources.
Expect 100 photons/source, 0.1 sources/pixel - same expected mean # of photons

P(0 photons) ~ 0.9, P(12 photons) ~ $0.1 \times 100^{12} e^{-100}/12! \sim 10^{-29}$,
P(100 photons) ~ 4×10^{-3}

(plus terms from multiple sources/pixel, which I am not including in this quick illustration)

The non-Poissonian likelihood

- We can work out the likelihood for a population of sources quantitatively, using the method of generating functions (Malyshev & Hogg '11)
- This method also allows us to include smooth/diffuse components - correspond to faint source limit

expected number of m-photon sources in a pixel

$$x_m = \frac{\Omega_{\rm pix}}{4\pi} \int_0^\infty dS \frac{dN}{dS}(S) \int df \rho(f) \frac{(fS)^m}{m!} e^{-fS}.$$

generating function for point source population

$$\sum_{k=0}^{\infty} p_k t^k = \exp\left[\sum_{m=1}^{\infty} x_m (t^m - 1)\right] \equiv P(t)$$

For comparison, in Poisson case:

$$\mathcal{P}^{(p)}(t) = \exp[\mu_p (t-1)]$$

Overall generating function $\mathcal{P}^{(p)}(t)$ is given by product of generating functions for each template. Then:

pixel likelihood

$$p_k^{(p)} = \frac{1}{k!} \frac{d^k \mathcal{P}^{(p)}}{dt^k}\bigg|_{t=0}$$

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Number of sources providing S counts, including position-dependent normalization

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Number of sources providing S counts, including position-dependent normalization

Poisson draw for actual number of photons, given f S expected

generating function for point source population

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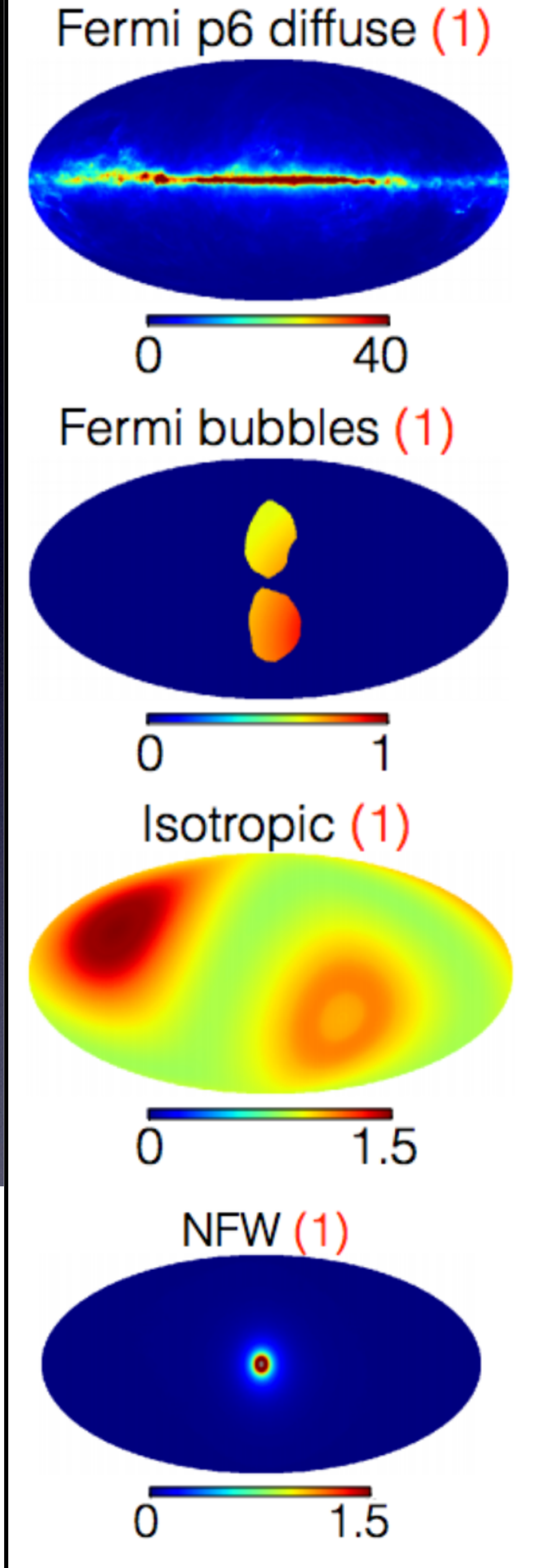
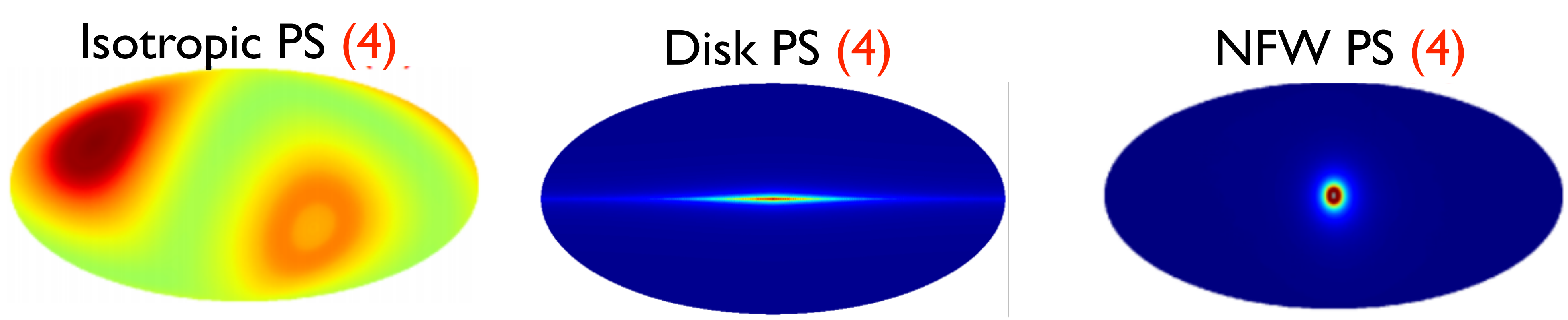
Non-Poissonian template fitting

- As previously, model sky (within some energy bin) as linear combination of spatial templates, and evaluate p(data|model)
- Now templates may have two different kinds of statistics:
  - Poissonian statistics (as previously)
  - Point-source-like statistics - extra degrees of freedom describing number of sources as a function of brightness





Point source templates

The source count function

- By default we assume the source count function for all PS templates is a singly broken power law:

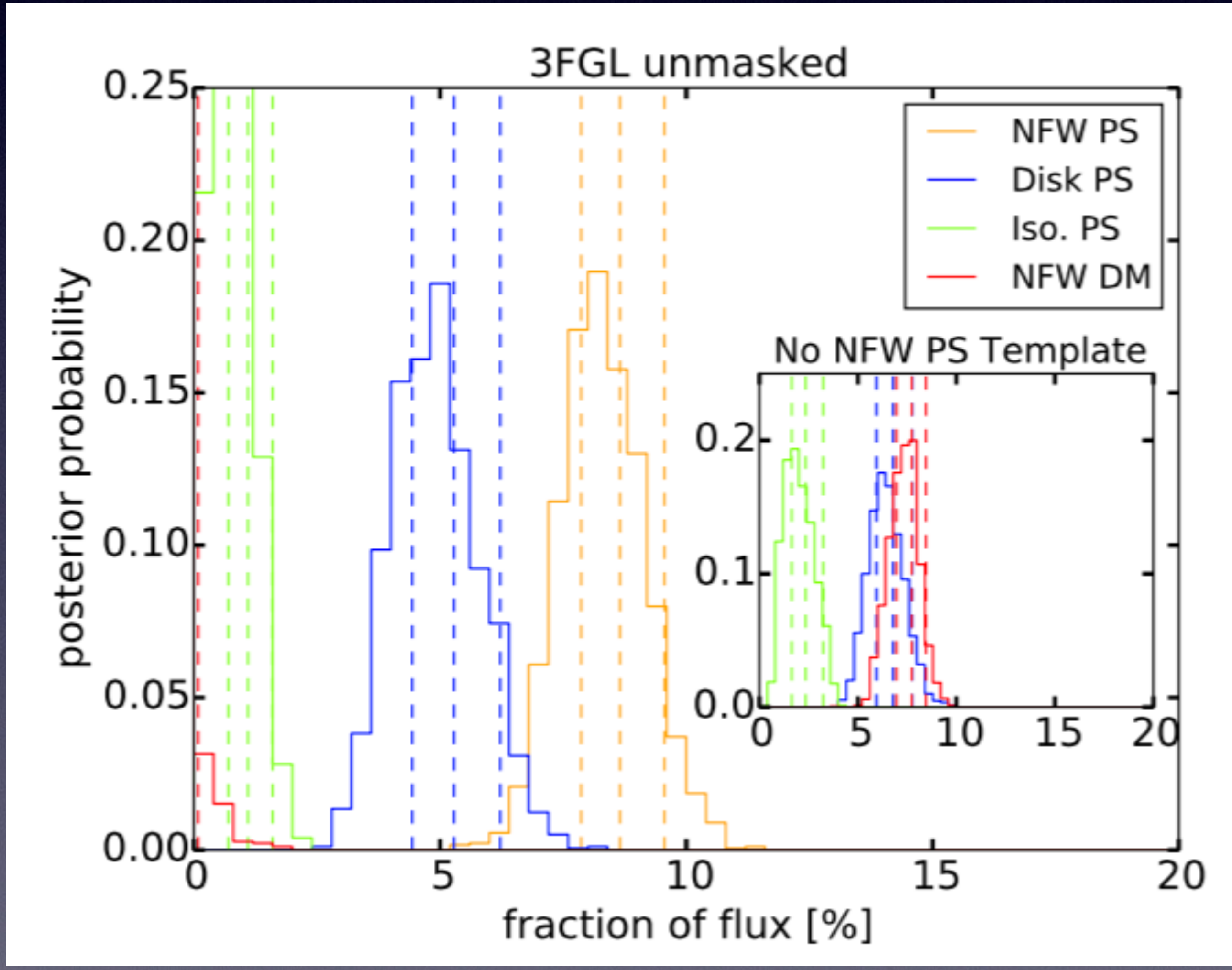
follows a spatial template ↓

$$\frac{dN_p(S)}{dS} = A_p \begin{cases} \left(\frac{S}{S_b}\right)^{-n_1} & S \geq S_b \\ \left(\frac{S}{S_b}\right)^{-n_2} & S < S_b \end{cases}$$

- Source count functions float independently for each PS template.
- Thus each PS template has 3 extra degrees of freedom, beyond the overall normalization parameterized by the spatial template.
- Source count function assumed constant over sky, only normalization is controlled by position (via spatial template).
- Restrict to a single broad energy bin (2-12 GeV) - no extraction of spectrum.

2016: a preference for point sources

- Restrict to region within 30° of Galactic Center, mask plane at ±2°.
- Compare fit with and without point-source (PS) template peaked toward GC, "NFW PS".
- In both cases there is a smooth "DM" template peaked toward GC, "NFW DM".
- If "NFW PS" is absent, "NFW DM" template absorbs excess. If "NFW PS" is present, "NFW PS" absorbs full excess, drives "NFW DM" to zero.



Lee, TRS et al '16

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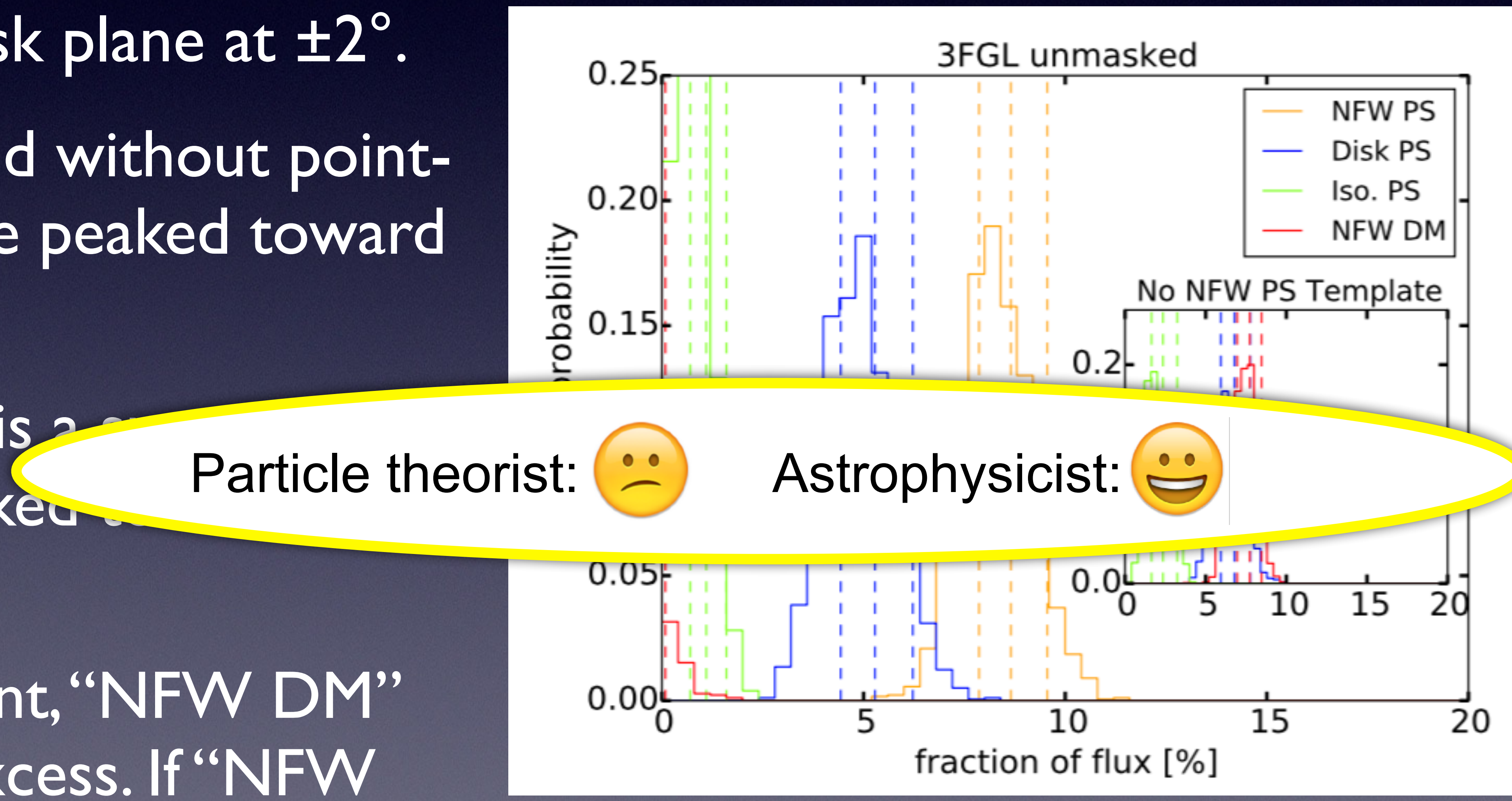
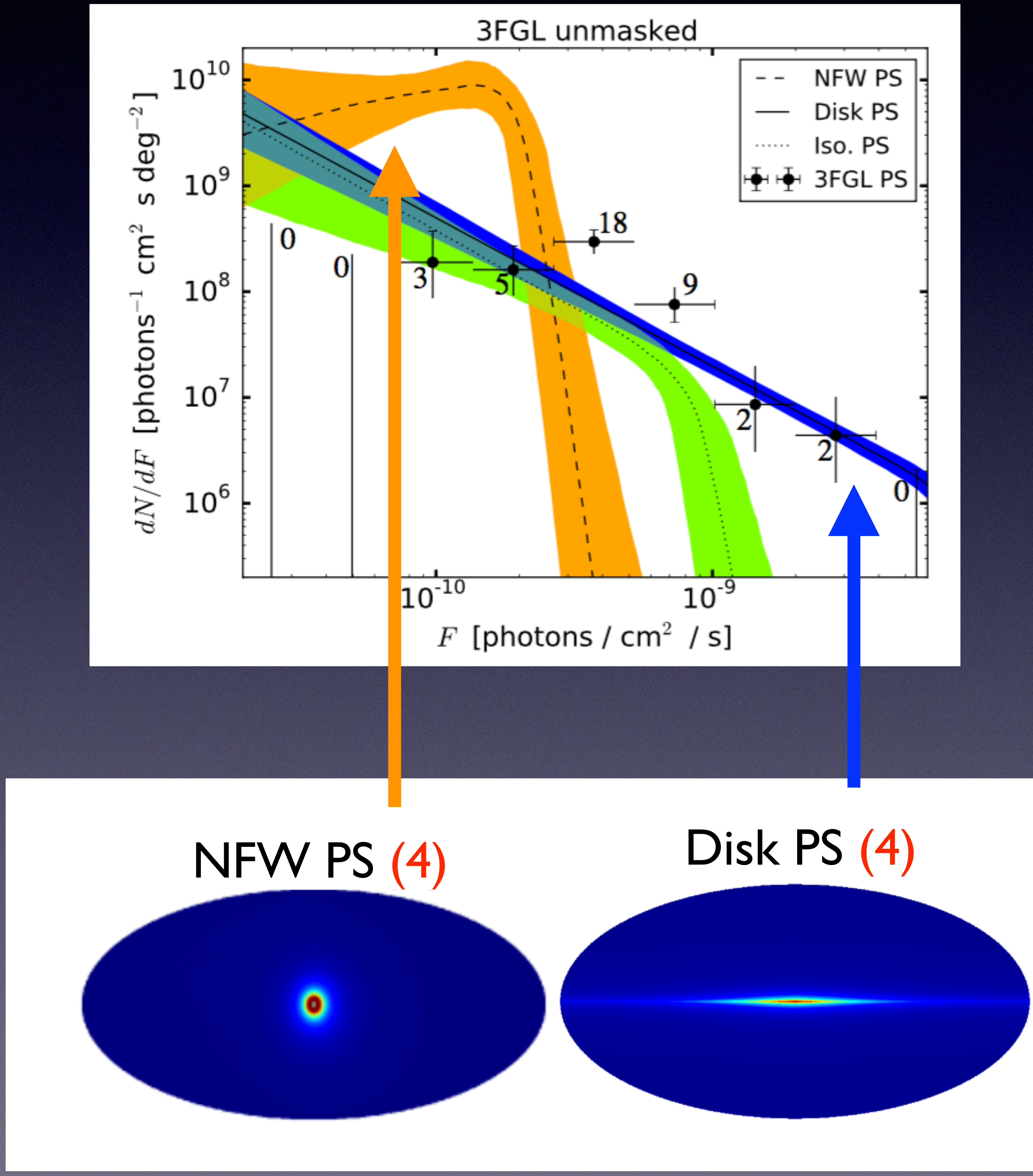


Lee, TRS et al '16

Properties of the sources

- Results suggest that known sources follow a disk-like distribution
- New sources appear to be different in two ways:
  - spherical distribution (vs disk-like)
  - characteristic brightness just below sensitivity threshold
- This second point is a bit surprising… coincidence?



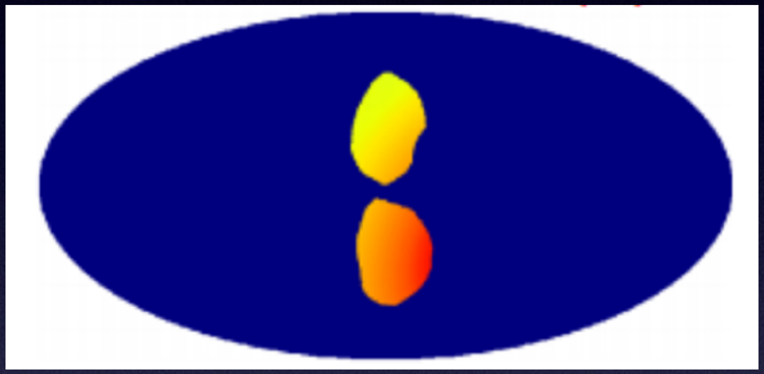
2019-2020: the NPTF and systematic errors

- If the diffuse background is mismodeled, could this mismodeling be absorbed into the PS template, leading to a spurious detection? (studied in 2016)
  - tested method in other regions with model/data discrepancies, didn't find strong preference for PSs
  - tested method in mock data built with one diffuse model and fitted with a different one, found biases to GCE PSs were modest
  - split the excess into different spatial regions with different diffuse emission (e.g. north/south), found consistent PS-population properties in all regions
- If unrelated PS populations are mismodeled, could we mistake that error for a GCE signal?
- What if the GCE <u>signal</u> is mismodeled - could we mistake an error in the template for a preference for point sources?

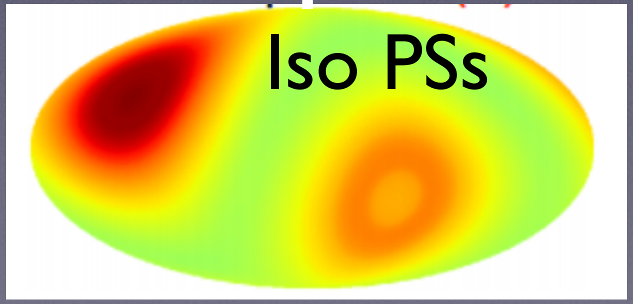
Effects of an unmodeled PS population

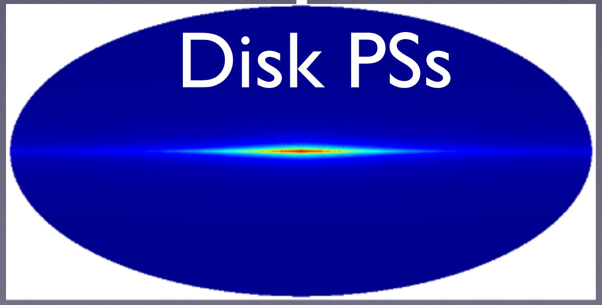
- Suppose there is a new PS population present, not well-described by disk + isotropic sources - e.g. PSs correlated with the Fermi Bubbles or (a subcomponent of) the Galactic bulge
- This population might drive up normalization of "NFW PS" template, to explain bright non-disk non-isotropic sources
- This in turn could drive "NFW DM" template normalization downward, to preserve total flux in the GCE

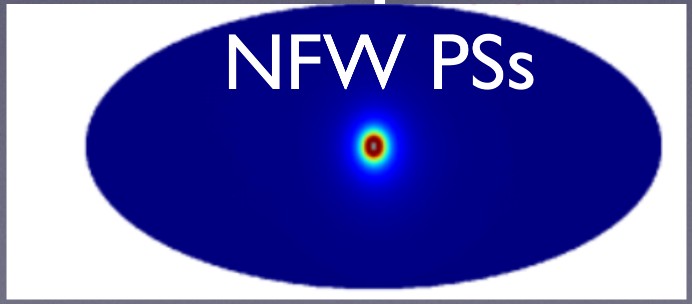
New PSs

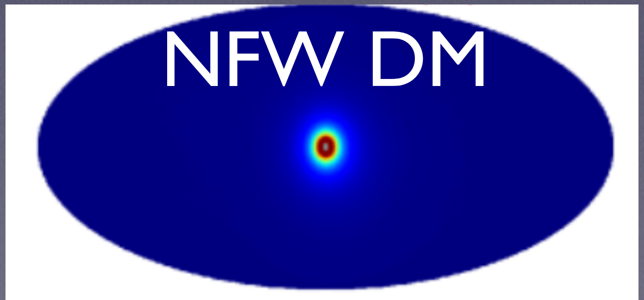


(Hypothetically) present in data, but not available as a (PS) template in fit



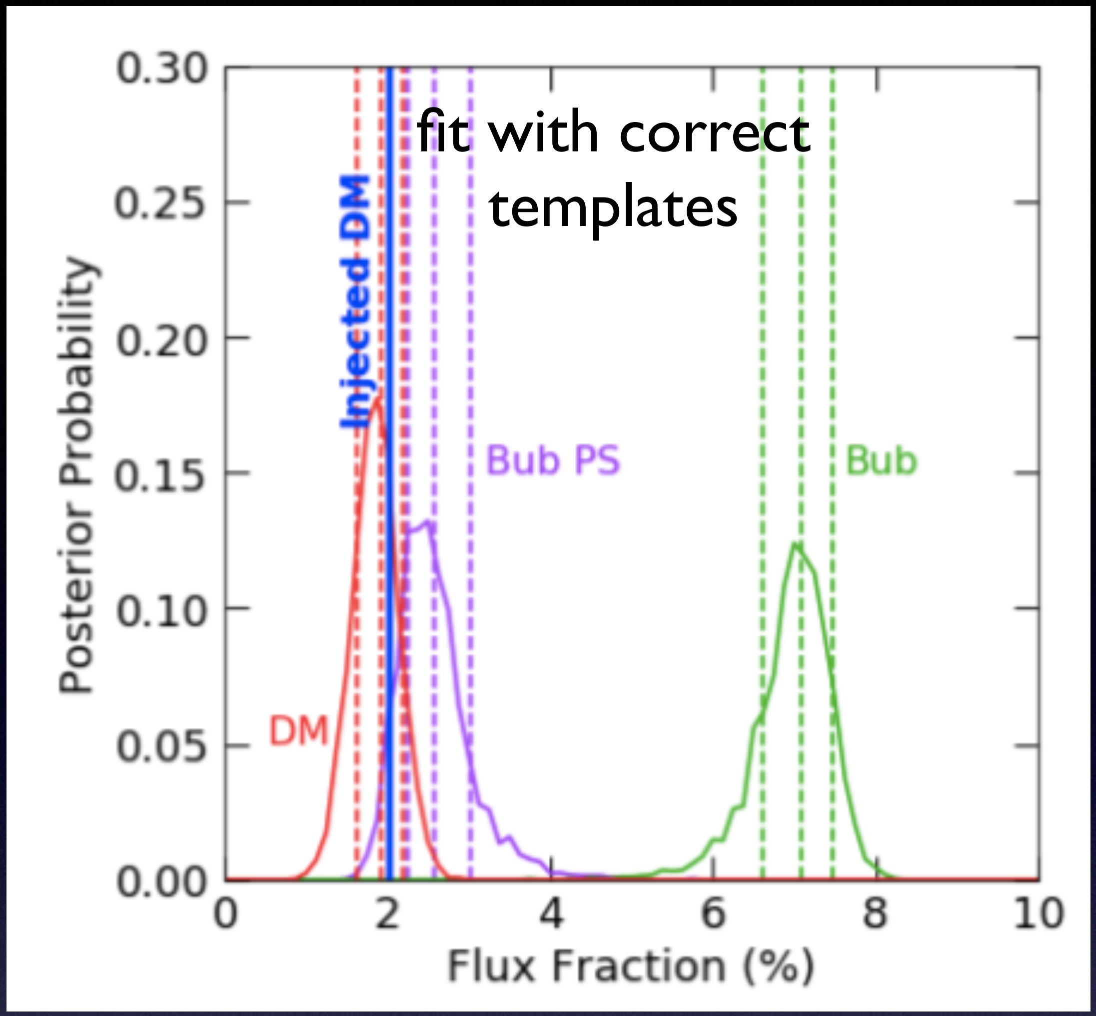


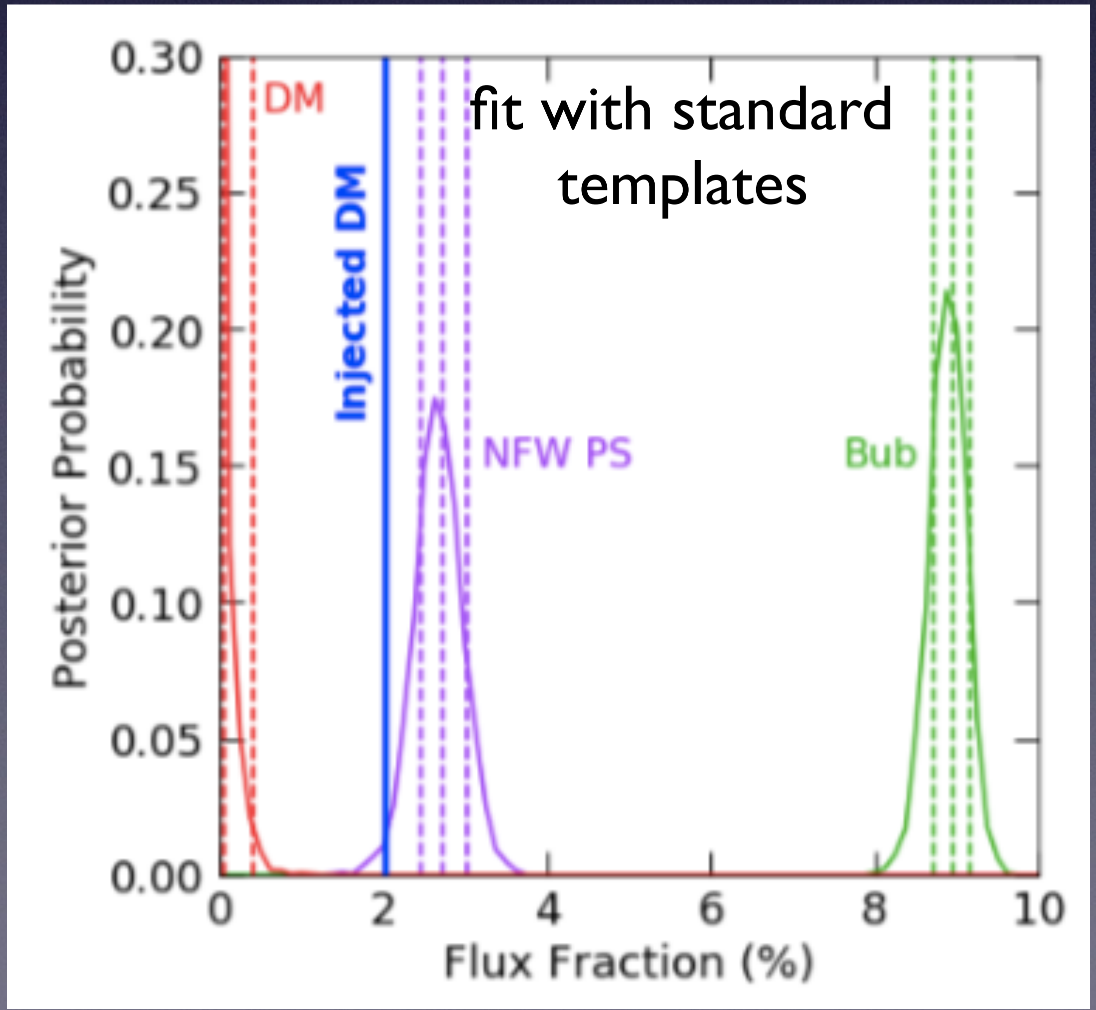




A mock-data example

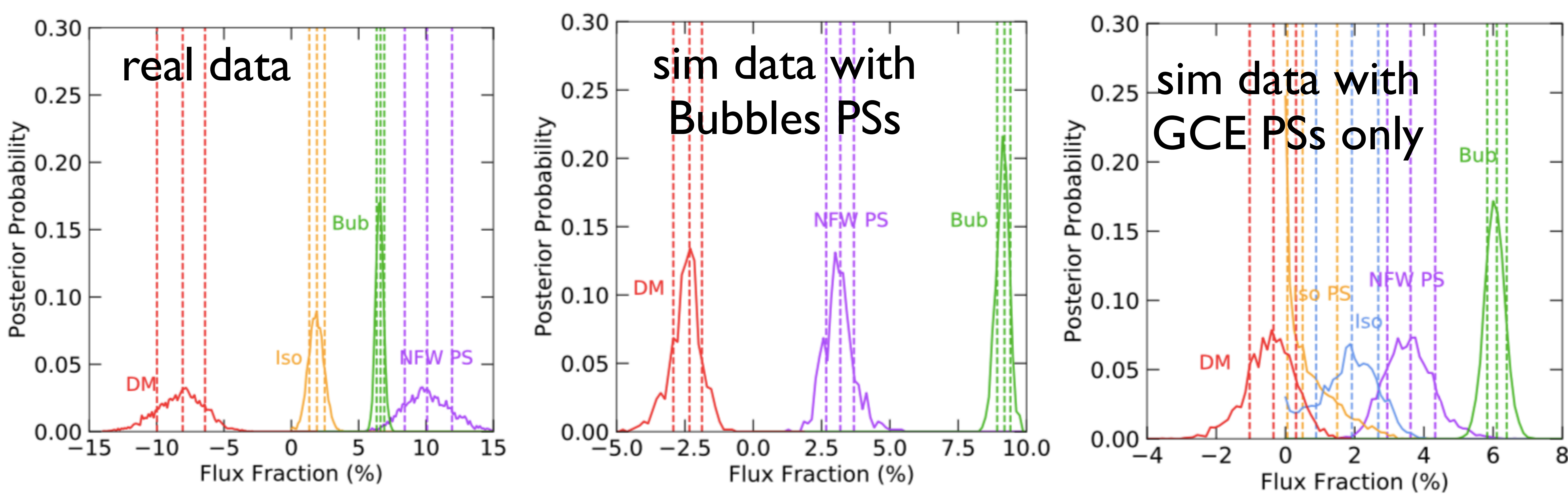
- Construct mock dataset using all standard templates (w/ best-fit values) except NFW PS, a GCE-like DM signal, and point sources spatially correlated with the Fermi Bubbles.
- Fit with same templates except replacing Bubbles-correlated PSs with GCE PSs.
- Result: fit prefers to assign all flux in GCE-like DM signal to GCE PS template, zero flux to DM template!
- That said we do not find a Bubbles PS population in the real data when we look - this is an example of what can happen if PSs are mismodeled





Testing for biases

- While this <u>exact</u> problem does not seem to be occurring, it can give us clues on how to test for similar issues - in the mock-data example, the DM template doesn't just prefer a zero value, it would like to go <u>negative</u>
- Not physical - but we can allow this to happen, see if the fit is driven to unphysical region
- In real data we find the fit prefers a very negative DM coefficient - indication of <u>some</u> kind of mismodeling, could it hide a real DM signal?



Improving the background model

- Galactic diffuse emission model is the largest background component, maybe it is responsible for the problem?
- Chang et al '19, Buschmann et al '20:
  - can quantitatively explain the observed preference for a negative flux by imperfections in the Galactic diffuse emission model
  - can construct newer models which do not prefer a (unphysical) negative coefficient for the smooth/DM component
  - with these models, there is still a preference for a PS population, albeit at lower significance (Bayes factor ~10^{3-4}, analogous to 3-4σ, vs ~6σ in 2016) and depending on the region-of-interest and priors

But what about the signal model?

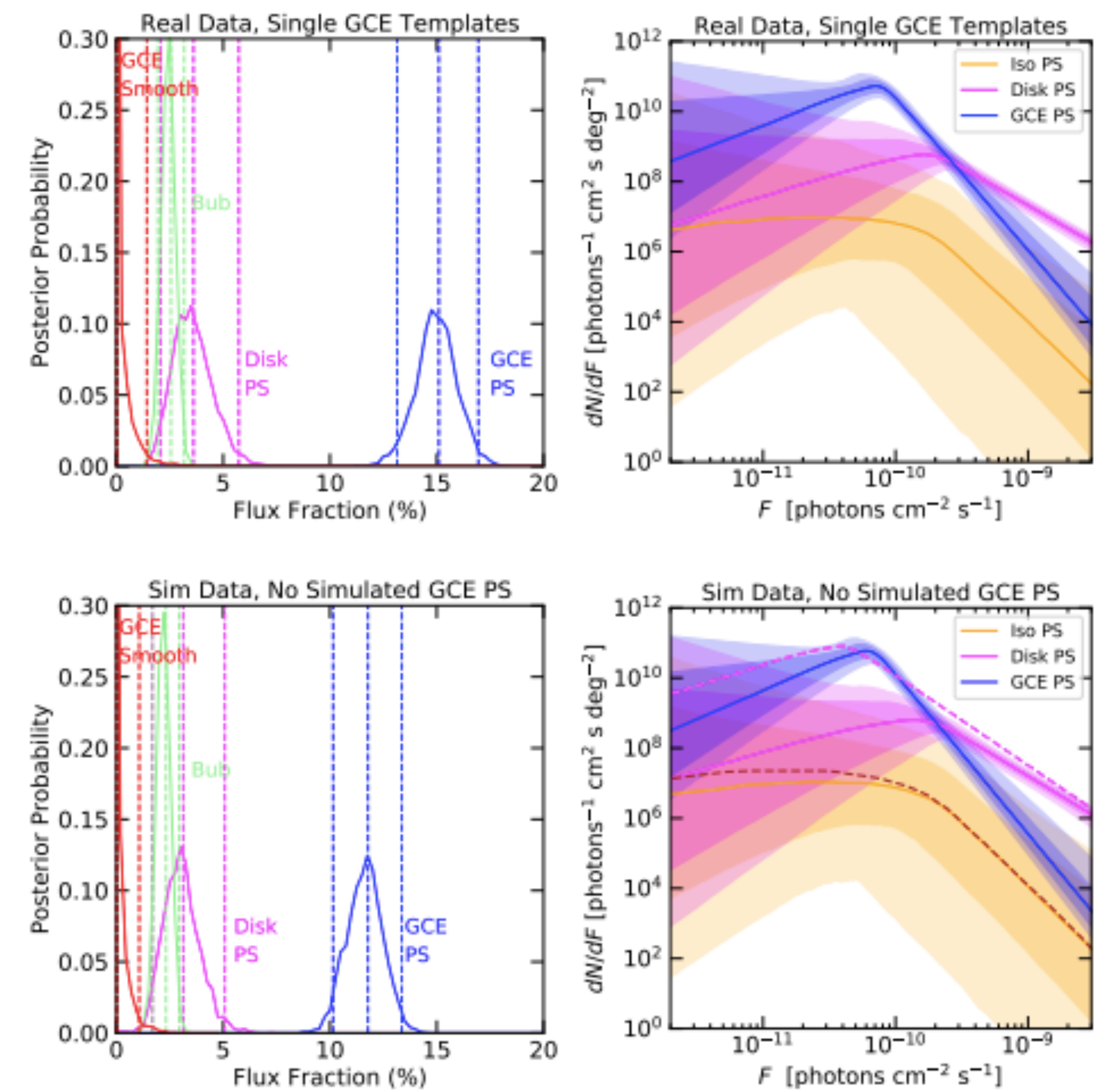
- General idea: suppose the fit prefers a somewhat different spatial distribution for the signal than specified by the signal template
- Higher pixel-to-pixel variance for point-source population makes it easier to accommodate such differences
- The fit can prefer a point-source population based solely on this increased variance (i.e. inflating the error bars makes the fit better) - nothing to do with small-scale granularity
- Toy example: suppose I observe 2000 photons in one region and 1000 photons in another. If I know the underlying physics is the same in both regions, which can more easily explain my results? (1) statistical fluctuation of homogeneous smooth emission, or (2) point sources produce ~1000 photons each, there are three sources total

Does this happen in the real data?

- Yes!
- We focused on a 10° radius region surrounding the GC
- In this region there is a clear mismatch between the standard template and the fit's preference - data prefers a north/south asymmetry (up to 2:1 depending on analysis choices)
- When we assume symmetric signal templates (standard analysis), point sources are initially strongly preferred (Bayes factor > 10^{15} with default background model).
- Once signal template is allowed to be asymmetric, preference for PSs drops to insignificance (BF~7).
- The preference for PSs (in this specific analysis) is really just a preference for N/S asymmetry!

Comparison with simulations

- We can see (and quantitatively explain) this effect in simulations
- Simulate smooth GCE with asymmetry, fit as linear combination of symmetric smooth template + symmetric PS template
- The observed behavior matches what we see (for the same fit) in the real data very closely, although in the simulations we <u>know</u> the PS population isn't real



One example realization

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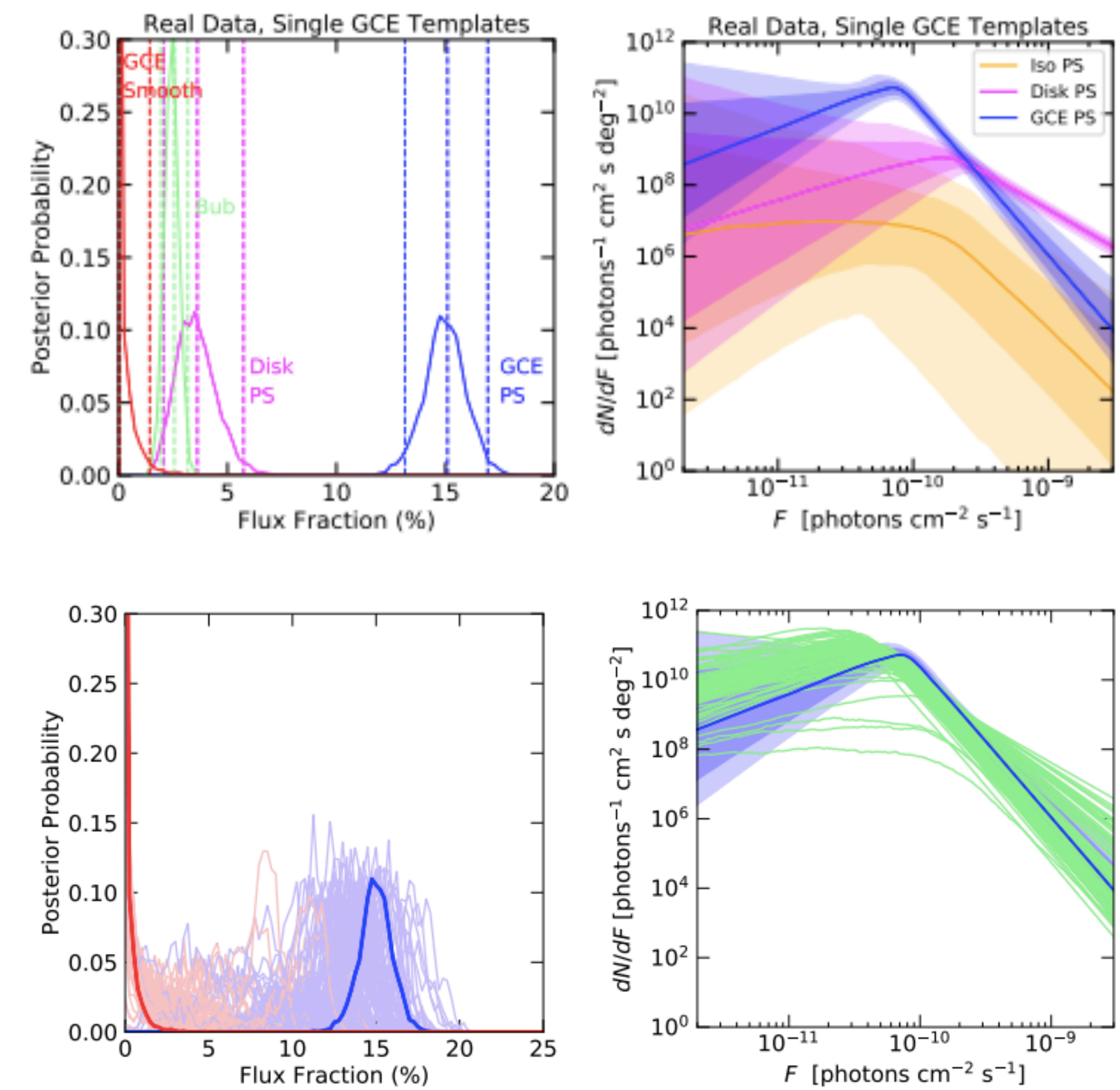
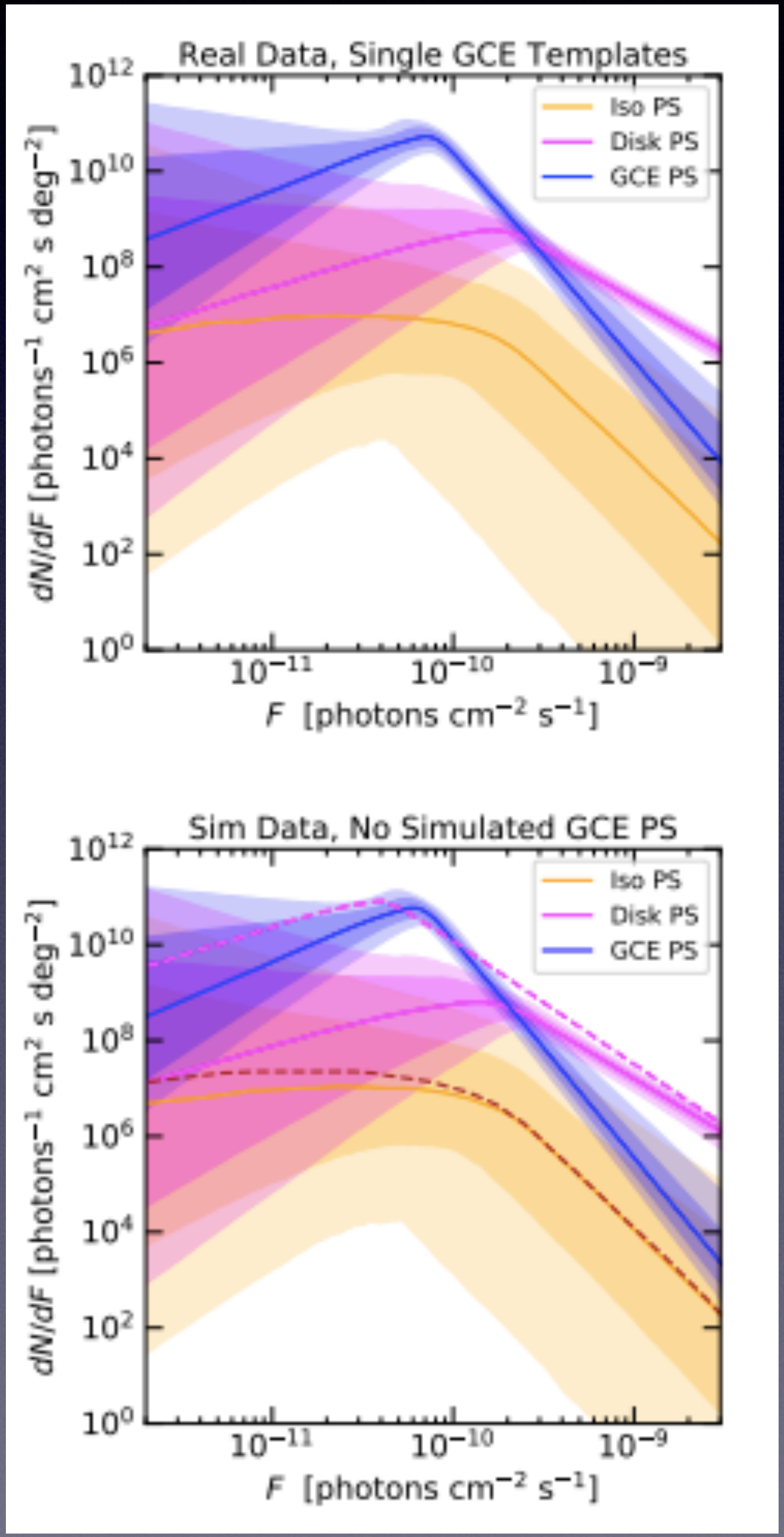


100 realizations

Properties of the (fake) sources

- Recall we said previously that it was surprising the sources peaked right below the detection threshold, and the source # fell off rapidly at higher fluxes
- A range of NPTF analyses have found very similar behavior - seems stable
- Now we see this behavior is also exactly what we get in simulations with no GCE PSs but a mismodeled smooth signal
- Reason for caution about apparent PS populations with similar brightness distribution in other NPTF analyses



So is the GCE asymmetric?

- A robust detection of N/S asymmetry would be very interesting - and imply the GCE is probably not dark matter
- But not so fast - we find whether or not the asymmetry is present is sensitive to systematic effects (e.g. choice of background model, choice of fit region)
- Our argument is just that if there is a mismatch between the signal model and the shape preferred by the fit (with N/S asymmetry as one example), then it can give a very convincing-looking but spurious preference for point sources
- Reason for caution in all NPTF analyses - especially if inferred source count function looks like expectations for spurious PSs

How to improve (gamma-rays)?

- Specific pipeline described here makes several approximations / ad hoc choices:
  - assumes the source count function is the same in all spatial pixels (and has a simple form)
  - simplified model for instrumental effects (angular resolution, exposure correction)
  - choice of how priors are implemented can affect results
- "Compound Poisson generator" approach improves on these issues (Collin et al '21)
- But perhaps more importantly, the template approach does not use information on which pixels are next to each other - full likelihood is just a product of pixel likelihoods
- The current pipeline also does not use energy information

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potential for improved signal/background separation?

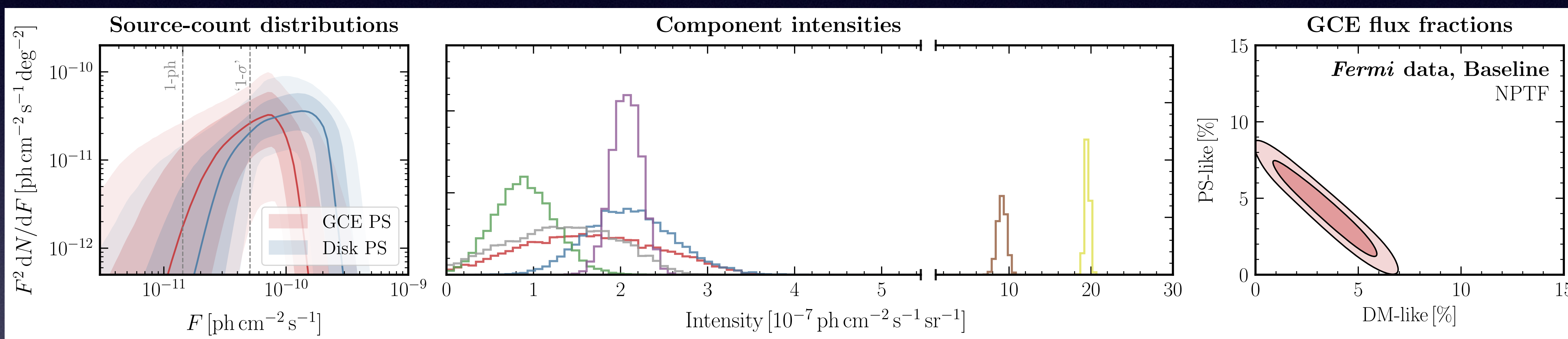
Neural networks for the GCE

- General idea: train neural networks on simulations based on template models
  - seek to distinguish diffuse emission from source populations
  - capture information in multi-pixel structure not just single-pixel likelihoods
- Complementary methods by List et al (2020, 2021) [neural-network-based histogram regression] and Mishra-Sharma & Kranmer (2021) [normalizing flows].
- The most recent results from the first approach find the GCE should be <66% diffuse at 95% confidence; the second approach finds a PS fraction of 38^{+9}_{-19}%.
- In at least some cases, shown to be more robust to errors in the signal/background templates, although they still rely on templates for training
- Currently not using energy information, but that is a natural future direction

NN methods (tentatively) still detect some point sources

Plots provided by Siddharth Mishra-Sharma

1-point PDF



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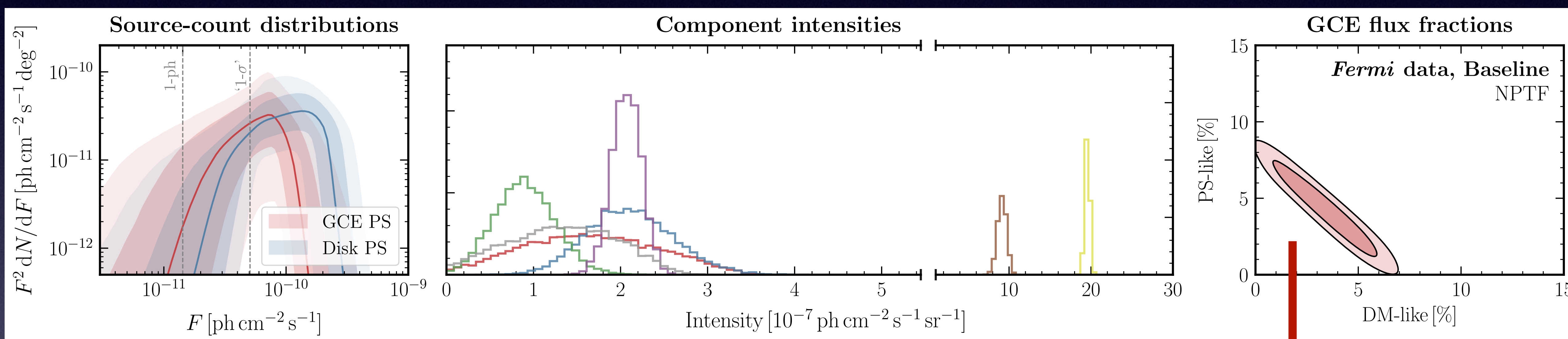
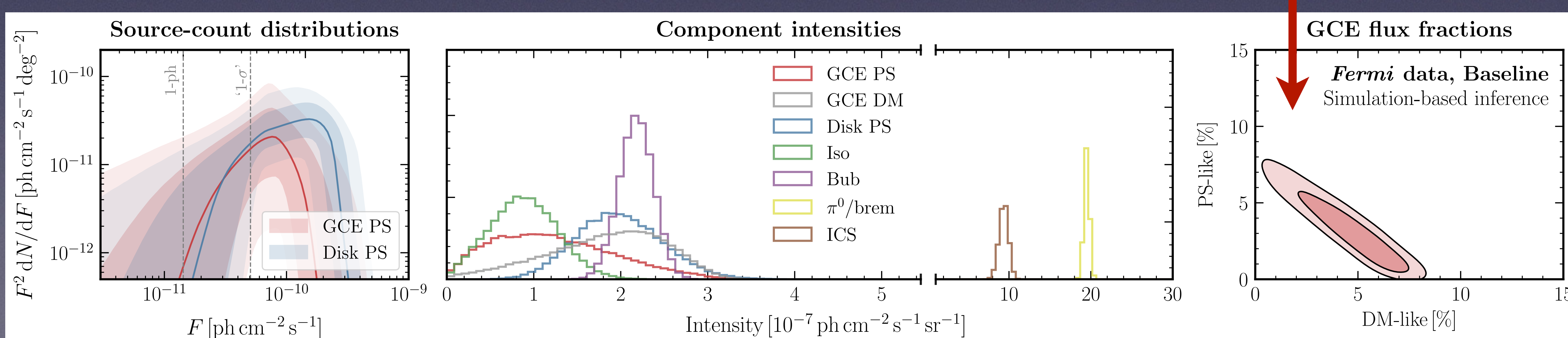


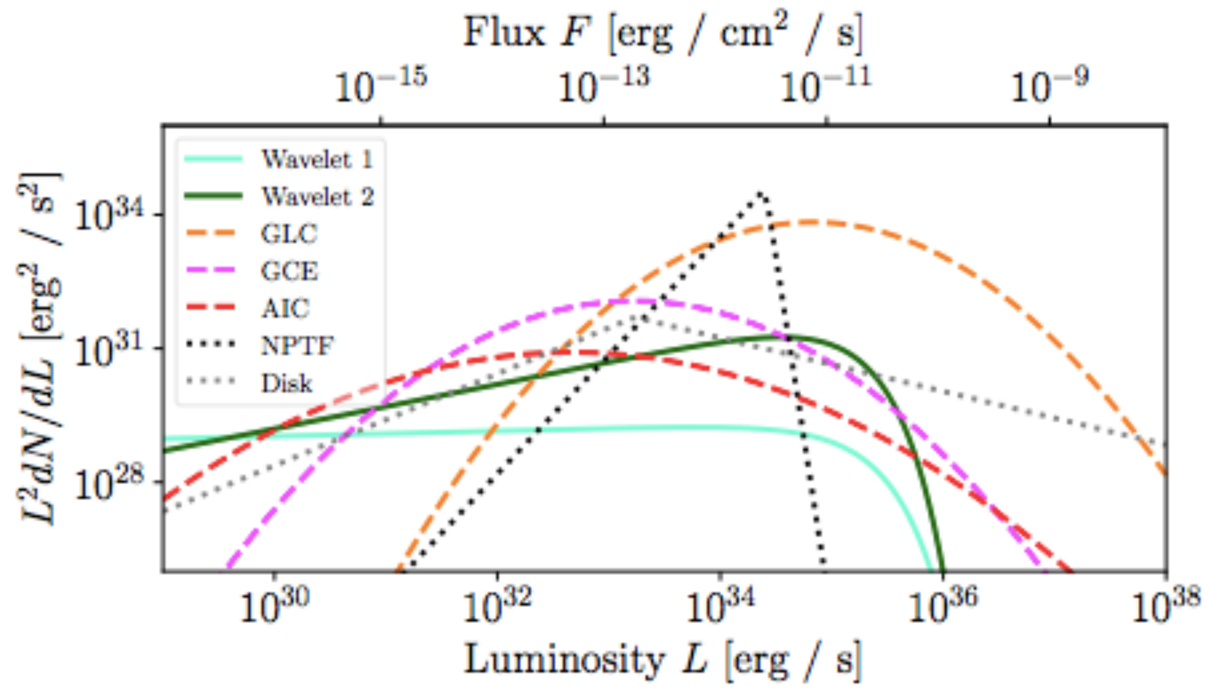
Normalizing flows



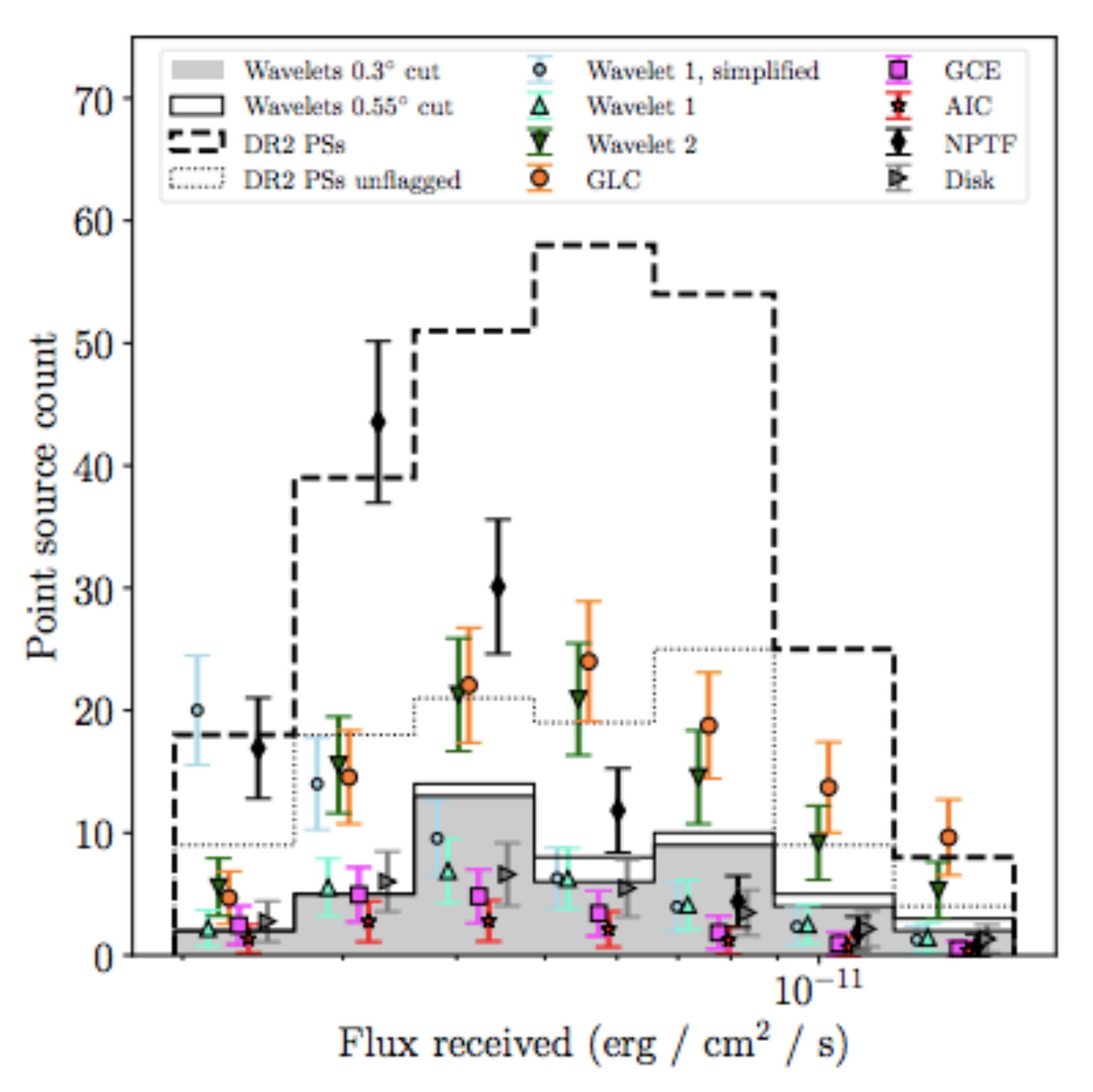
How plausible are pulsars?

- There has been considerable debate in the literature about the plausibility of the pulsar interpretation
- If many very faint sources are required, explaining how these are produced or accumulate in the inner Galaxy could be challenging
- A key question is the expected luminosity function - how many bright (potentially detectable) sources should be visible, compared to the number of fainter sources?
- e.g. original NPTF studies found a preference for all sources to be ~at threshold, needing only O(1000) total
- Zhong et al '20 quoted an estimate of ~3 x 10^6 pulsars to explain the whole excess, mostly very faint

How many pulsars are needed?



- We considered a range of luminosity functions from the literature
- Found there are simple luminosity functions predicting O(10,000) point sources and very few detected high-significance sources



Dinsmore & TRS '21

Other approaches

- Focus on improving background model - photon-count analysis using adaptive background models finds evidence for both unresolved PSs and significant smooth emission in GCE region (but unresolved PSs may be due to known populations, which are not separated out) [Calore et al '21]
- Focus on overall morphology rather than PS detection - but also sensitive to background modeling
- Pulsars are expected to radiate in the X-rays/radio as well - search for counterpart pulsar signals at other wavelengths [Calore et al '16, Berteaud et al '20]
- Search for possible counterpart DM signals:
  - Long-standing claim of consistent antiproton excess in AMS-02 data [Cui et al '17, Cuoco et al '17] but statistical significance is unclear once systematic uncertainties + correlations are taken into account [e.g. Boudaud et al '19, Heisig et al '20]
  - Recent claims of possible Andromeda counterparts in gamma-rays [Karwin et al '19, '21, Burns et al '21] and radio [Chan et al '21]

Summary (GCE case study)

- The Galactic Center Excess (GCE) is a robust feature of the central region of the Milky Way; leading explanations are a population of millisecond pulsars or an exotic signal from annihilating dark matter.
- Modeling the GCE as a combination of a population of point sources (PSs) and a smooth diffuse component, non-Poissonian template fitting methods initially found a strong preference for most/all of the GCE to be attributed to the PSs.
- We have shown that searches for Galactic Center Excess (GCE)-correlated PS populations can obtain spurious detections due to signal mis-modeling, at high apparent significance, with properties closely matching previous claims of detected PS populations.
- We do not claim to exclude PS-based scenarios for the GCE - a true PS population could be hiding beneath these systematic effects - but advise against discarding non-PS models for the GCE on these grounds.
- Active work is in progress to improve both analysis methods for inner Galaxy gamma-rays and searches for counterparts at other wavelengths/locations.