

Revisiting the Galactic Center Excess with New High-Resolution Templates

Recent work with:

IC, Zhong, McDermott, Surdutovich, PRD 105, 103023 (2022) also related:

IC, Tim Linden, Dan Hooper, PRD 99, 103026 (2019)

IC, Tim Linden, Dan Hooper, PRD 102, 103019 (2020)

IC, Iason Krommydas, PRD 105, 023015 (2022)



Ilias Cholis, 08/06/2022 (or 06/08/2022, or 2022/06/08)

The challenges of Indirect Searches for WIMPs

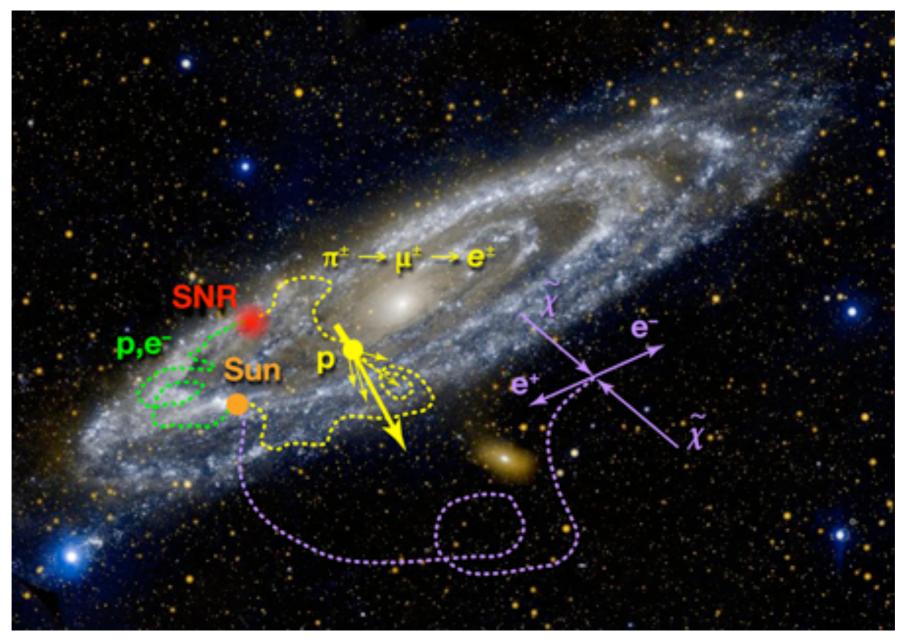
The Questions:

- Are we fully exploring the data? Is there a signal lurking within our observations?
- Do we have a good control of "systematics"? If Dark Matter is the Signal, do we understand the background astrophysical uncertainties & astrophysical alternatives?

Will discuss

- i) connection between cosmic rays and gamma rays in the and modeling the Milky Way
- ii) using gamma ray observations to search for dark matter iii) associations with antimatter cosmic rays

A rough sketch of the Milky Way



With CR spectral measurements we can understand the properties of the Interstellar Medium (ISM), and probe sources of high energy cosmic rays (CRs) including dark matter that could give a signal in antimatter.

The AMS-02 experiment on ISS

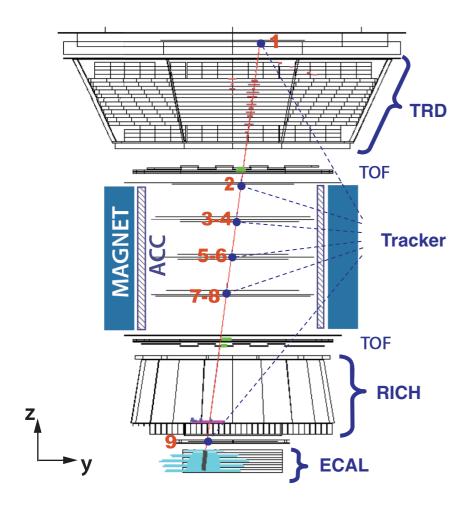


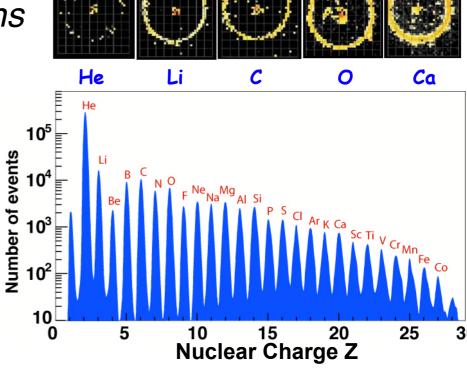
FIG. 1 (color). A 1.03 TeV electron event as measured by the AMS detector on the ISS in the bending (*y-z*) plane. Tracker planes 1–9 measure the particle charge and momentum. The TRD identifies the particle as an electron. The TOF measures the charge and ensures that the particle is downward-going. The RICH independently measures the charge and velocity. The ECAL measures the 3D shower profile, independently identifies the particle as an electron, and measures its energy. An electron

is identified by (i) an electron signa' signal in the ECAL, and (iii) the menergy and the momentum meas magnet.



Lunched on May 2011, will collect data for 20 yrs. Measuring all CR nuclei species up to Ni.

positron fraction, positrons, electrons spectra, antiproton/proton anti-nuclei? B/C, Be10/Be9



Modeling the ISM galactic production and propagation uncertainties for cosmic rays

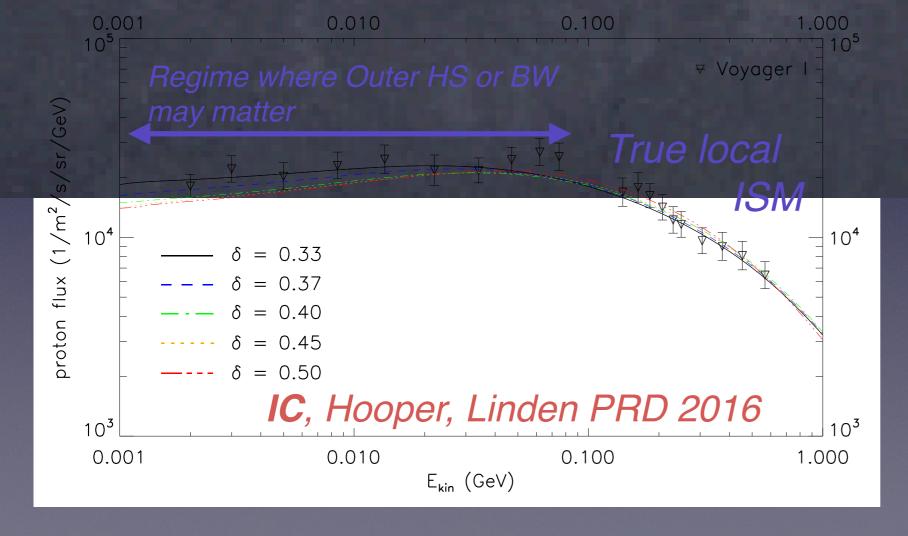
$$\frac{\partial \psi(r,p,t)}{\partial t} = \begin{matrix} \text{sources} & \text{diffusion} \\ q(r,p,t) + \vec{\nabla} \cdot (D_{xx}\vec{\nabla}\psi) \end{matrix} \\ + \frac{\partial}{\partial p} \Big[p^2 D_{pp} \frac{\partial}{\partial p} (\frac{\psi}{p^2}) \Big] + \frac{\partial}{\partial p} \Big[\frac{p}{3} (\vec{\nabla} \cdot \vec{V}) \psi \Big] \\ re-acceleration & convection \end{matrix}$$

Modeling the ISM galactic production and propagation uncertainties for cosmic rays

$$\frac{\partial \psi(r,p,t)}{\partial t} = \frac{\text{sources}}{q(r,p,t)} + \vec{\nabla} \cdot (D_{xx}\vec{\nabla}\psi)$$

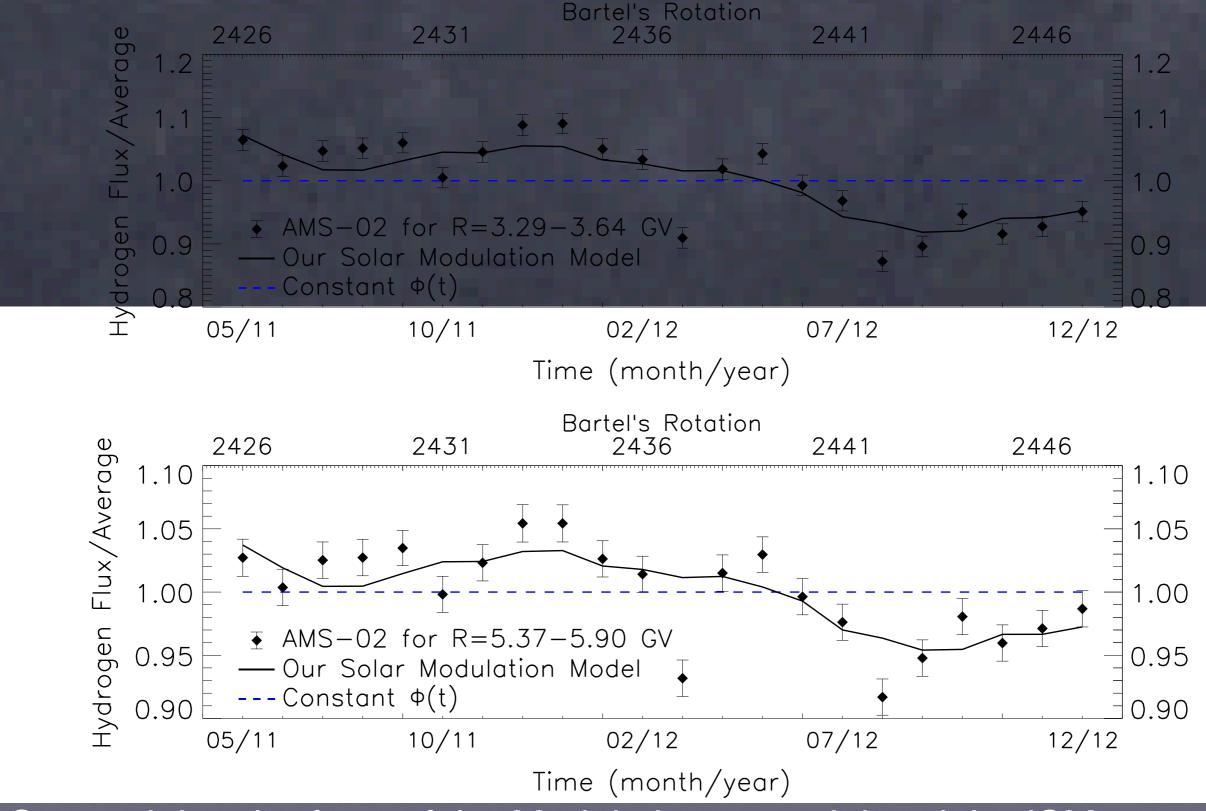
$$+ \frac{\partial}{\partial p} \left[p^2 D_{pp} \frac{\partial}{\partial p} (\frac{\psi}{p^2}) \right] + \frac{\partial}{\partial p} \left[\frac{p}{3} (\vec{\nabla} \cdot \vec{V}) \psi \right]$$
re-acceleration convection

Voyager 1 (ISM) proton flux:



We use GALPROP a numerical solver build by Moskalenko, Strong et al. as a starting point and build several models that are in agreement with CR measurements

Cross-checking with the PROTON data that account for the majority of observed cosmic rays; monthly AND total (i.e ISM & Solar Modulation):



Constraining the form of the Modulation potential and the ISM p spectrum in a recursive manner.

IC, Linden, Hooper (arXiv:2007.00669)

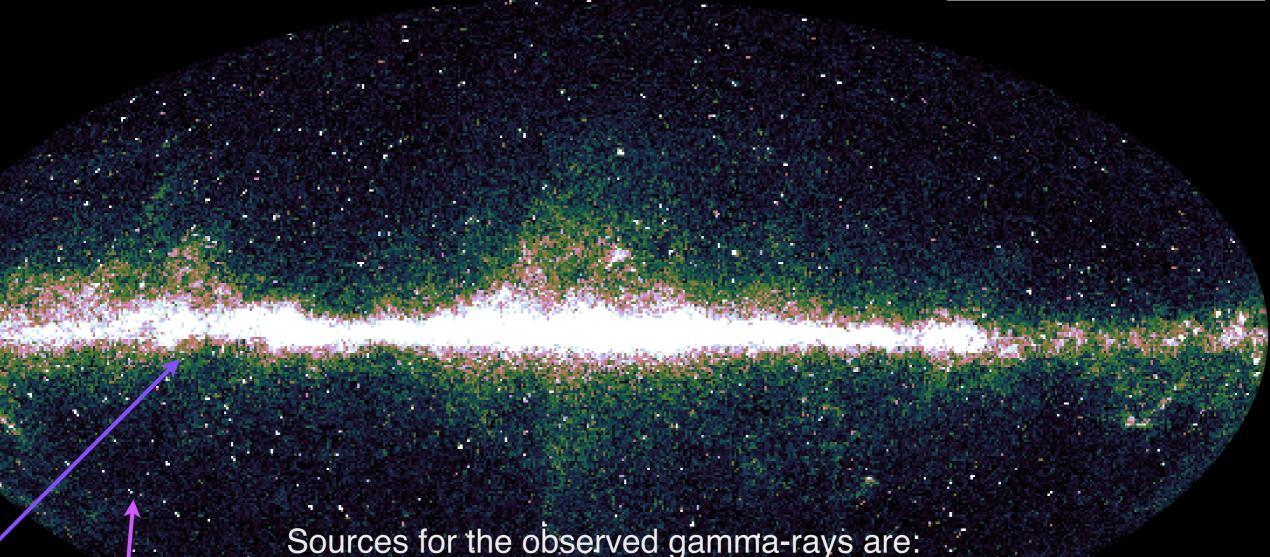
Repeating for multiple Cosmic-Ray species we can constrain the physical processes affecting the cosmic-ray production & propagation 1000 1000 ISM Spectrum Model C $R^2 \times d\Phi_H/dR$ (GV m⁻² s⁻¹ sr⁻¹) Modulated Spectrum Range AMS-02(6 ISM Spectrum Model C 100 100 Modulated Spectrum at BR 2426 Range (CL $R^2 \times d\Phi_{He}/dR$ Modulated Spectrum at BR 2445 Range (CLH) I AMS-02 at BR = 2426 I AMS-02 at BR = 2445 10 10 100 1000 R (GV) R (GV) 100 1000 10 100 1000 ISM Spectrum Model C ISM B/C Spectrum Model C Modulated Spectrum Range Modulated B/C Spectrum Range AMS-0210 10 $R^2 \times d\Phi_c/dR$ (GV m⁻² 0.1 10 100 1000 10 100 1000 R (GV) R (GV) 100 1000 10 100 1000 ISM C/O Spectrum Model C ISM Be/C Spectrum Model C Modulated C/O Spectrum Range Modulated Be/C Spectrum Range AMS-02 -0.1IC, Zhong, McDermott, Surdutovich, PRD 2022 (arXiv:2112.09706 100 1000 100 1000 R (GV) R (GV)

← Galactic longitude, ℓ

third dimension (not shown) — energy

The Fermi-LAT Gamma-ray SKY





i)Galactic Diffuse Emission: decay of pi0s (and other mesons) from pp (NN) collisions in the ISM, bremsstrahlung radiation off CR e, Inverse Compton scattering: up-scattering of CMB and IR optical photons from CR e

ii)from point sources (galactic or extra galactic)

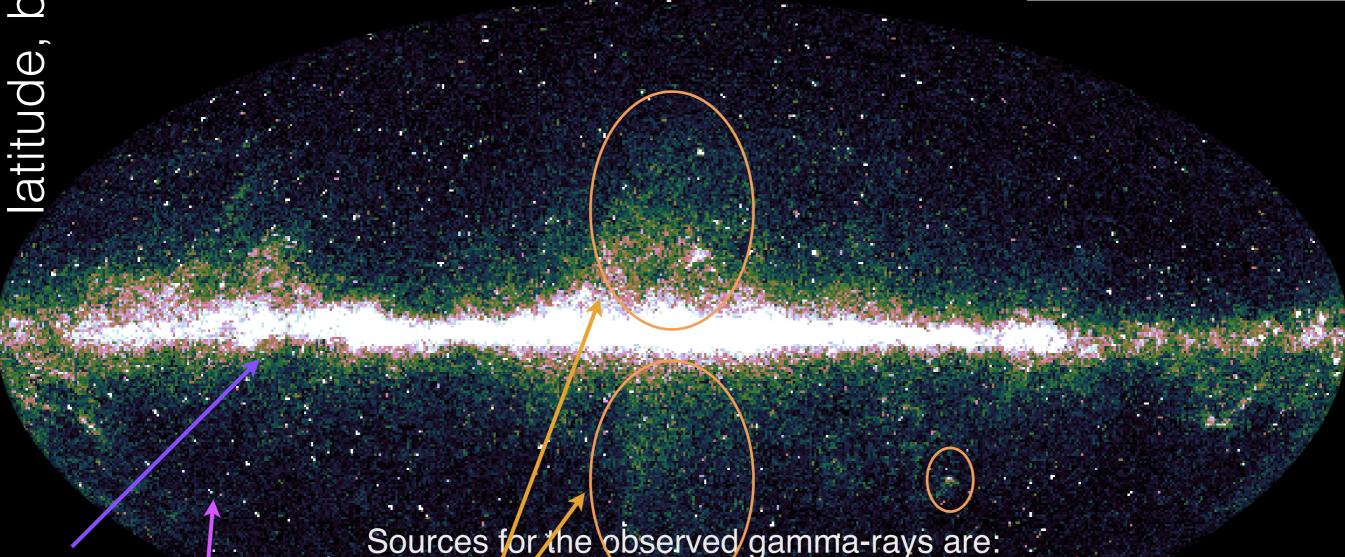
iii)Extragalactic Isotropic

atitude,

third dimension (not shown) — energy

The Fermi-LAT Gamma-ray SKY





i)Galactic Diffuse Emission: decay of pi0s (and other mesons) from pp (NN) collisions in the ISM, bremsstrahlung radiation off CR e, Inverse Compton scattering: up-scattering of CMP and ID, antical photons from CR e

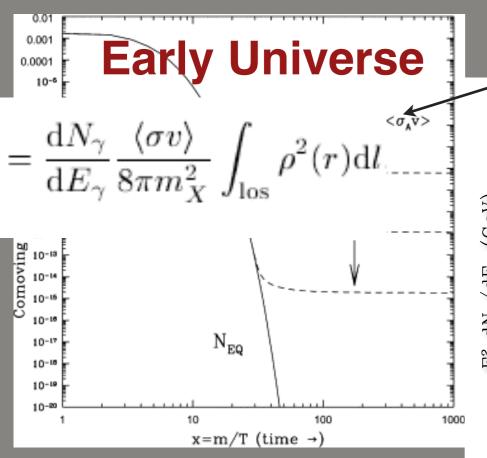
CMB and IR optical photons from CR e

- ii)from point sources (galactic or extra galactic)
- iii)Extragalactic Isotropic
- iv)"extended sources"(Fermi Bubbles, Geminga, Vela ...)
- iv)misidentified CRs (isotropic due to diffusion of CRs in the Galaxy)

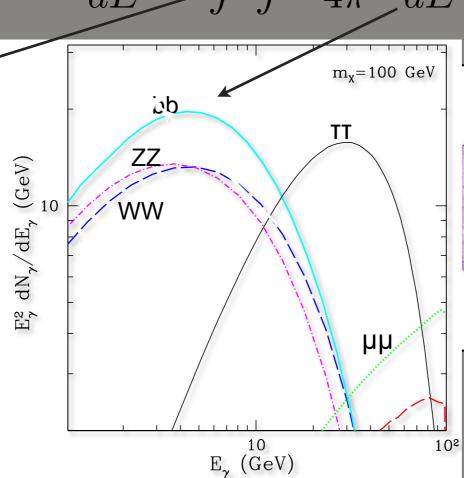
BUT ALSO the UNKOWN, e.g. Looking for DM annihilation signals

For a DM annihilation signal $d\Phi_{\gamma}$

We want to observe:

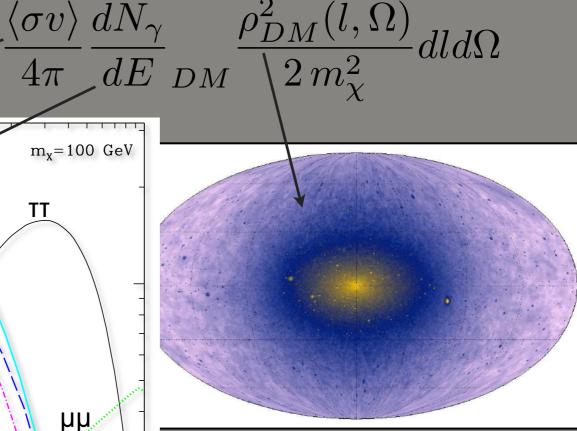


Steigman et al. 2012



Particle Physics

PYTHIA: Sjostrand et al. 2006 & 2007 HERWIG: Corcella et al. 2001



From Cosmological Simulations what we expect today

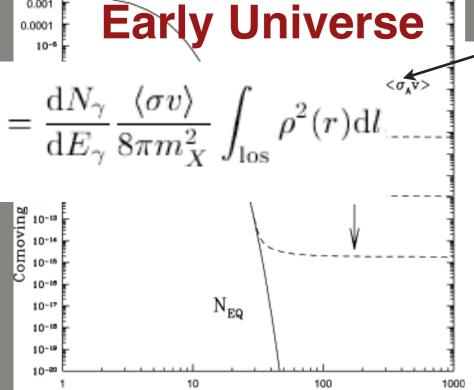
Springel et al. 2005, Kuhlen et al. 2012, Vera-Ciro et al. 2014

BUT ALSO the UNKOWN, e.g. Looking for DM annihilation signals

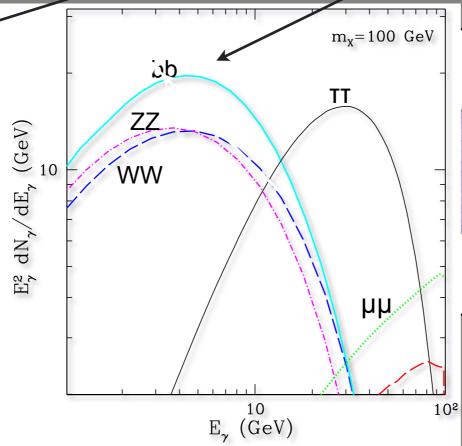
For a DM annihilation signal



 $\frac{\langle \sigma v \rangle}{4\pi} \frac{dN_{\gamma}}{dE} \frac{\rho_{DM}^{2}(l,\Omega)}{\sqrt{2m_{\chi}^{2}}} dld\Omega$



x=m/T (time \rightarrow)



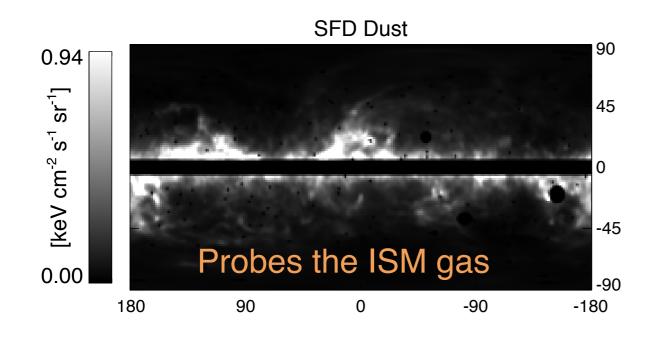
From Cosmological Simulations what we expect today

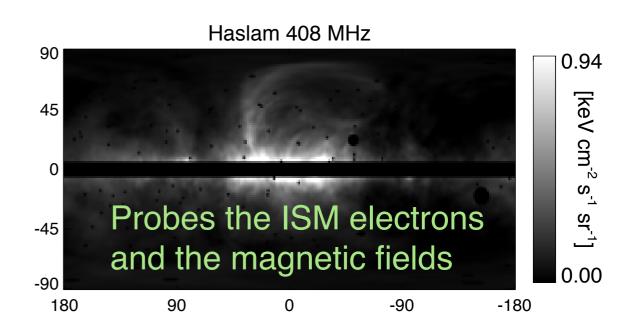
Particle Physics

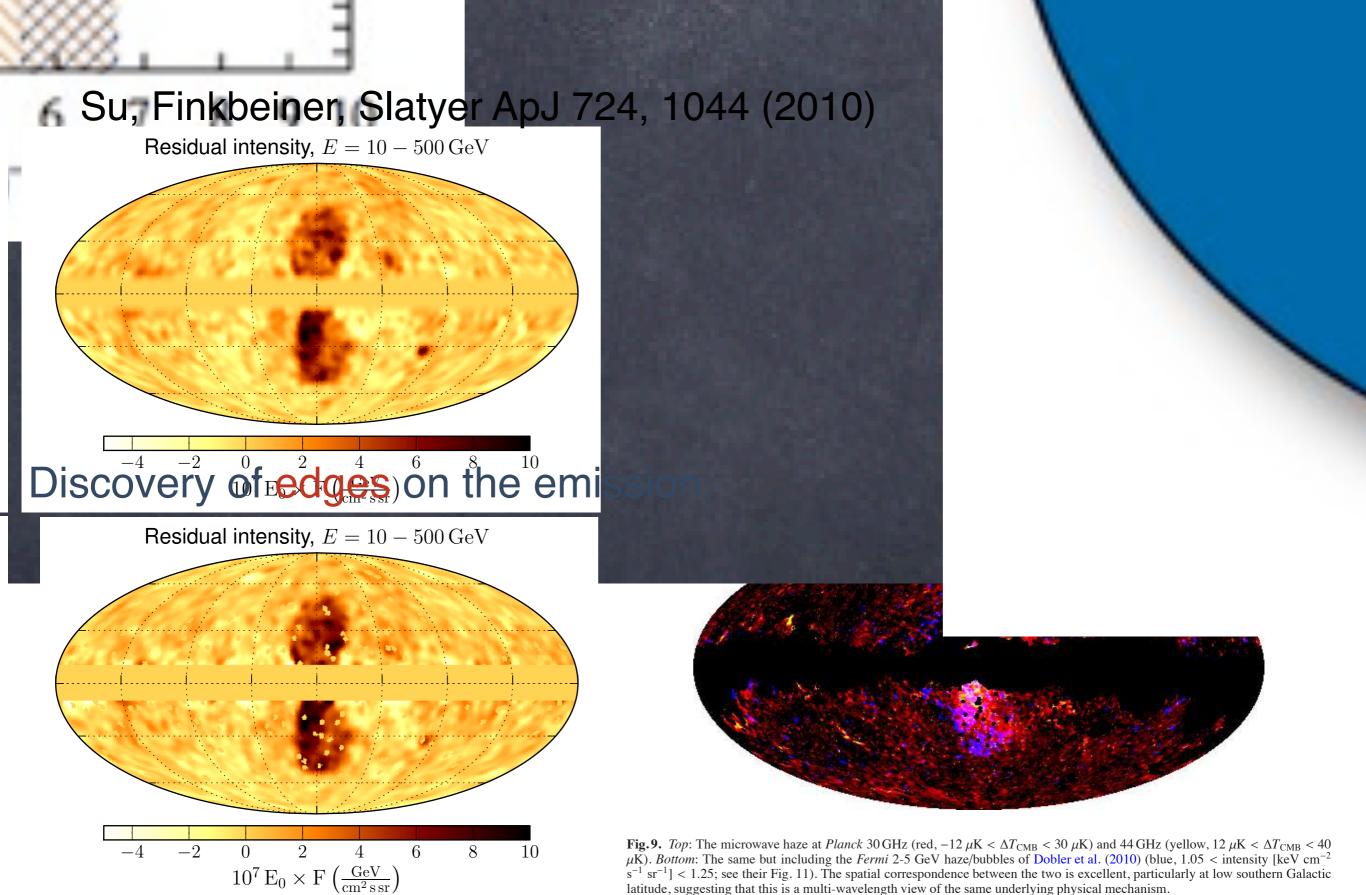
So How do we search for that ?

Using templates on Gamma-ray maps —> It's first use led to the discovery of the Fermi(Haze)-Bubbles

Dobler, Finkbeiner, IC, Slatyer, Weiner, ApJ, 2010

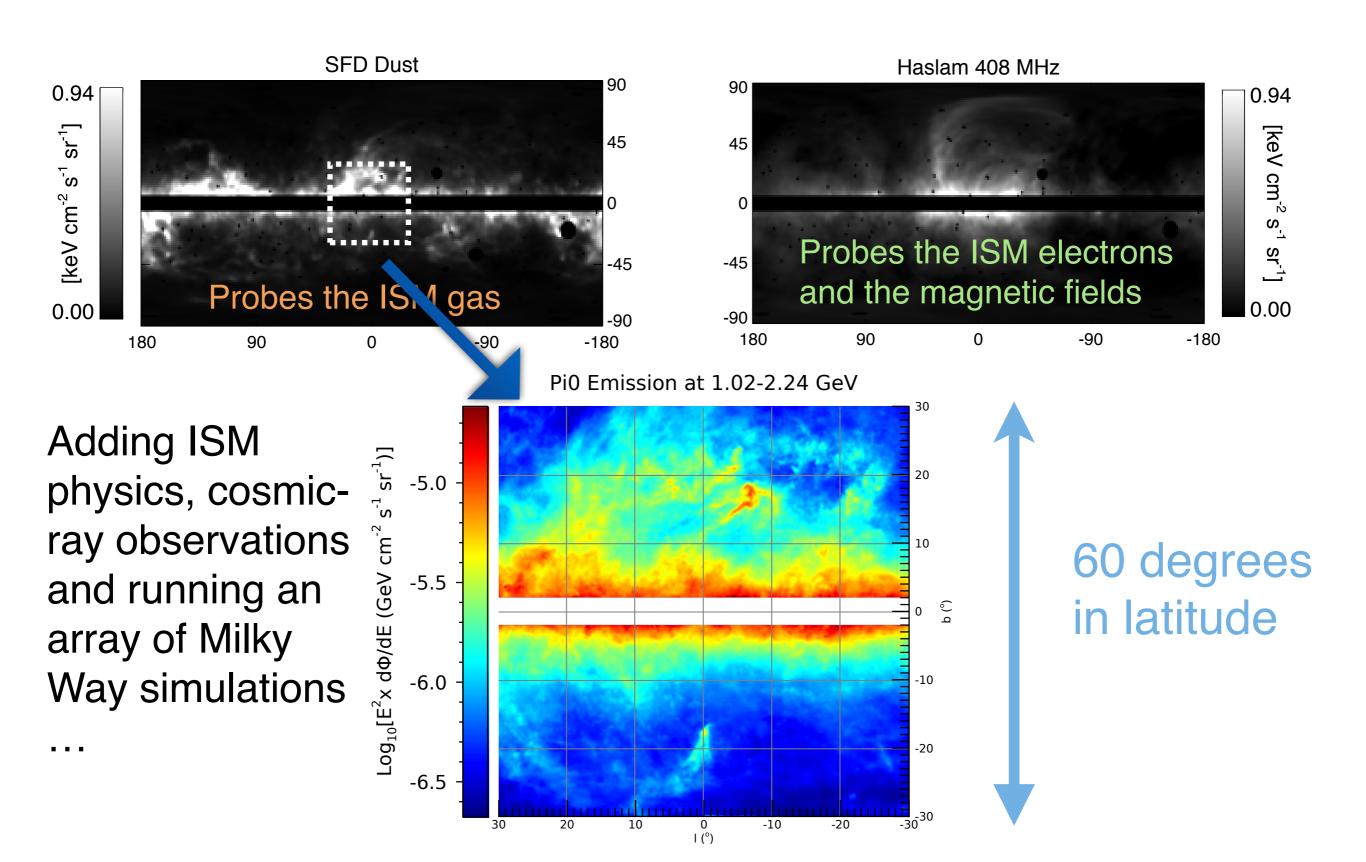




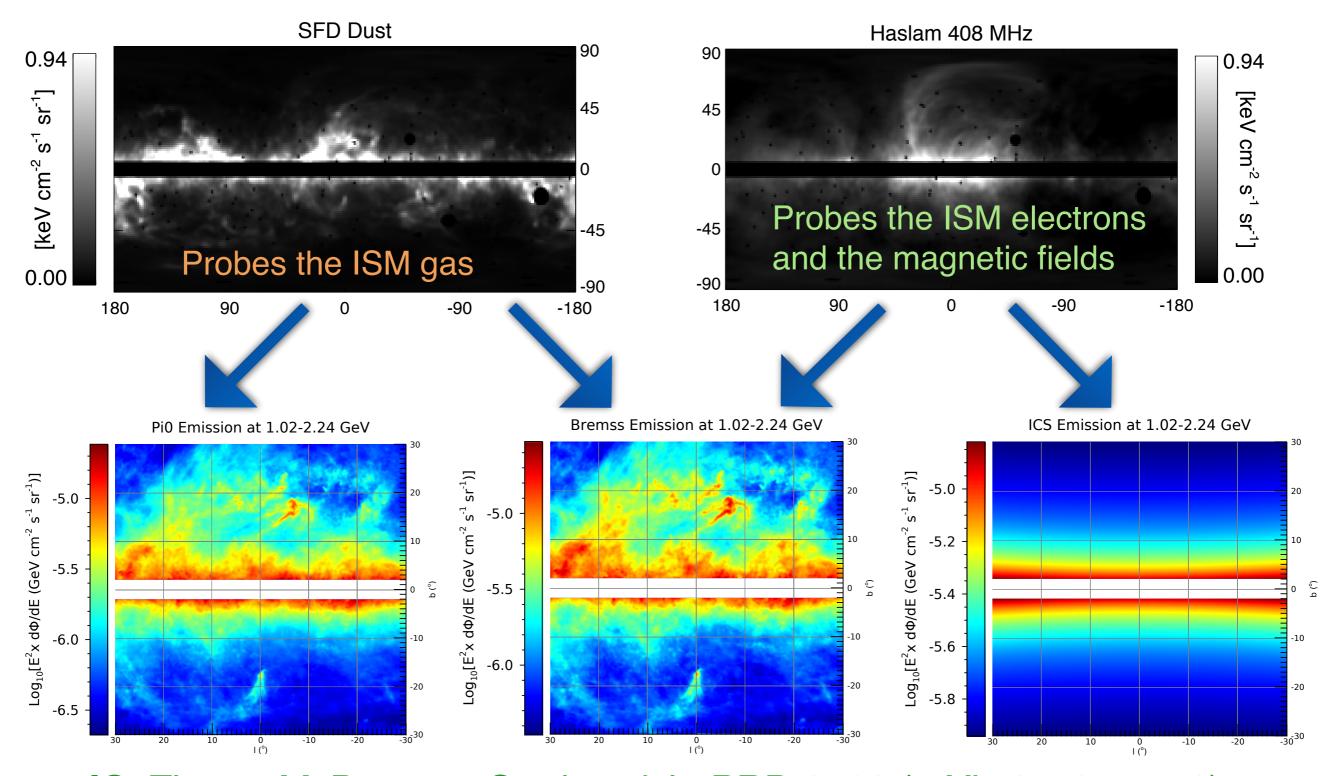


Fermi-LAT Collaboration Result ApJ 2014

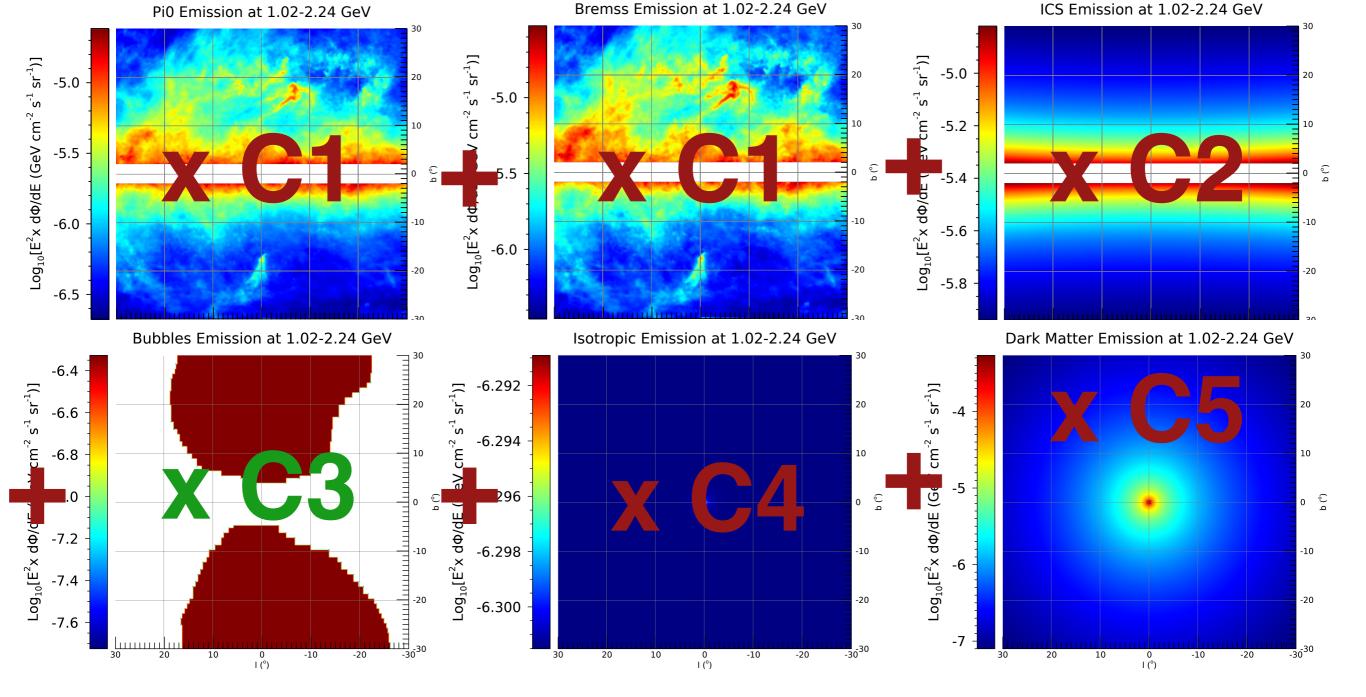
Using templates on Gamma-ray maps

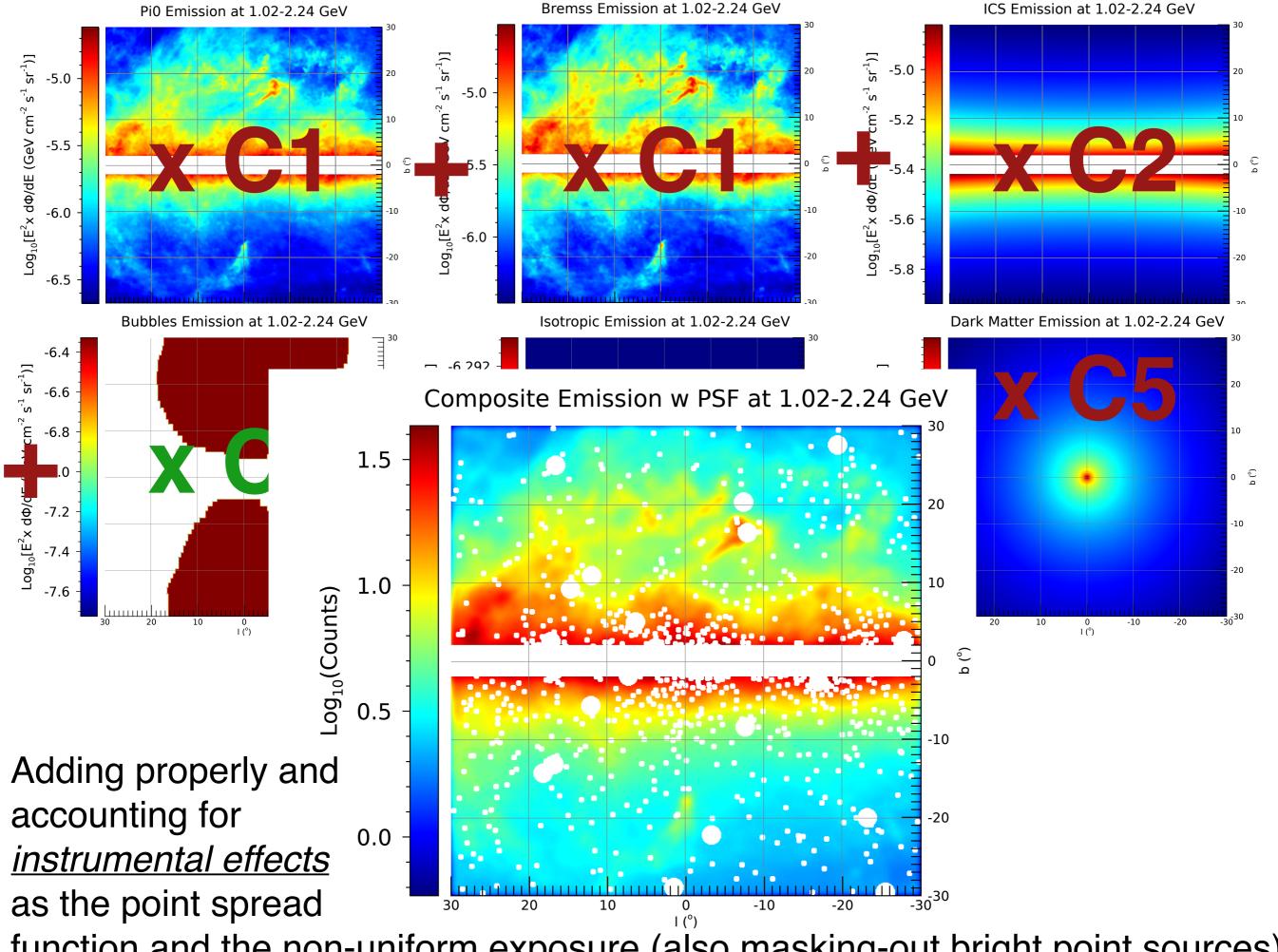


Using templates on Gamma-ray maps

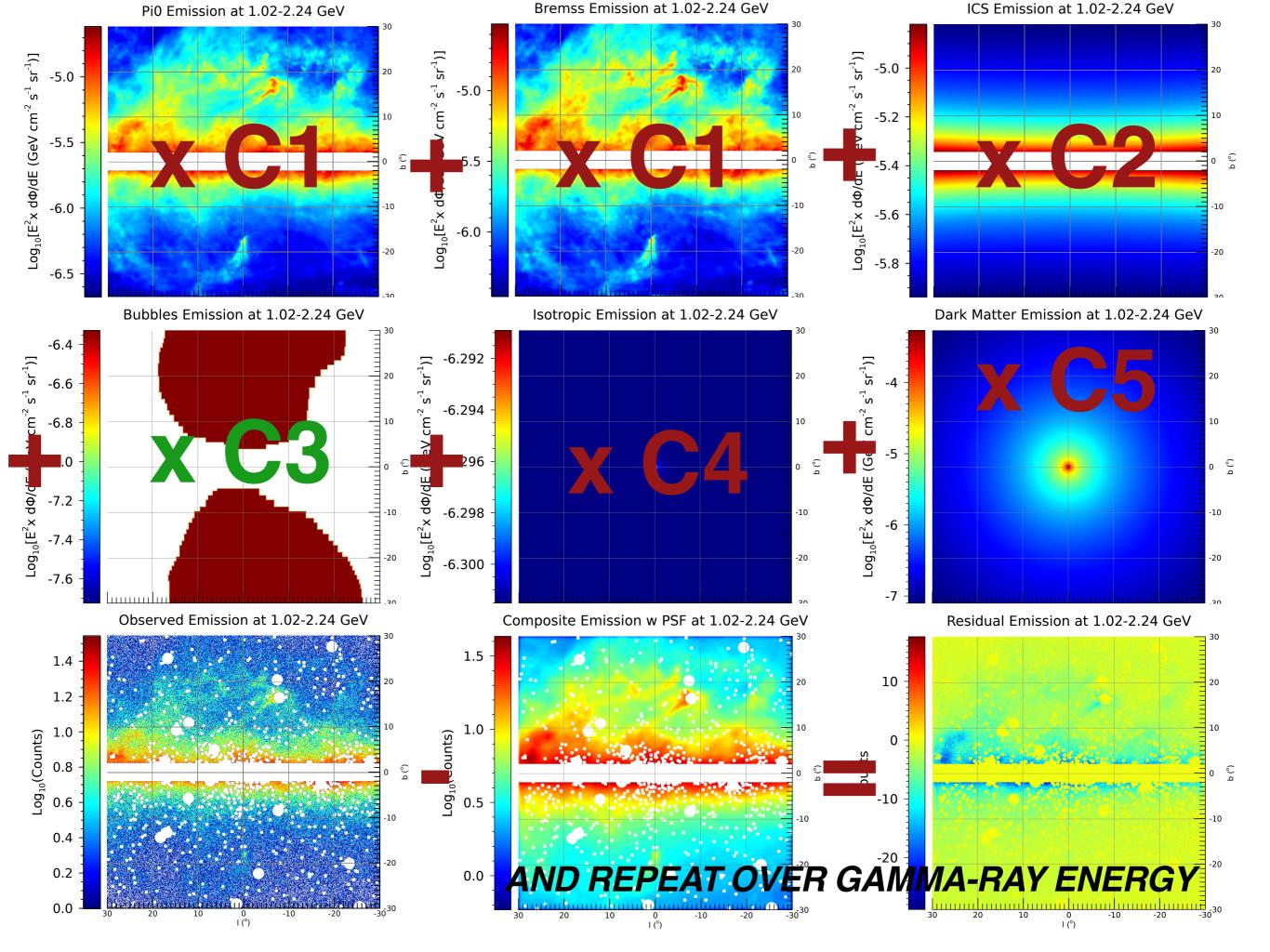


IC, Zhong, McDermott, Surdutovich, PRD 2022 (arXiv:2112.09706)

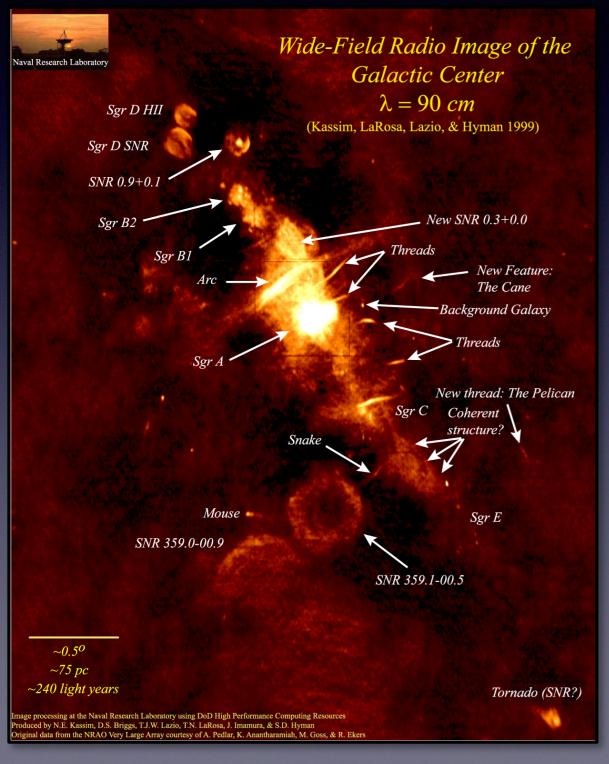


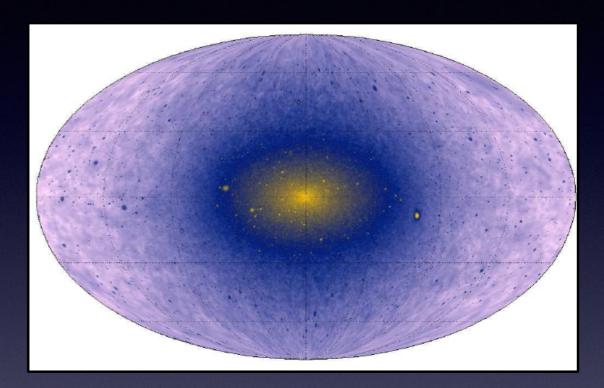


function and the non-uniform exposure (also masking-out bright point sources)



The galactic center A place to look for Dark Matter Annihilation

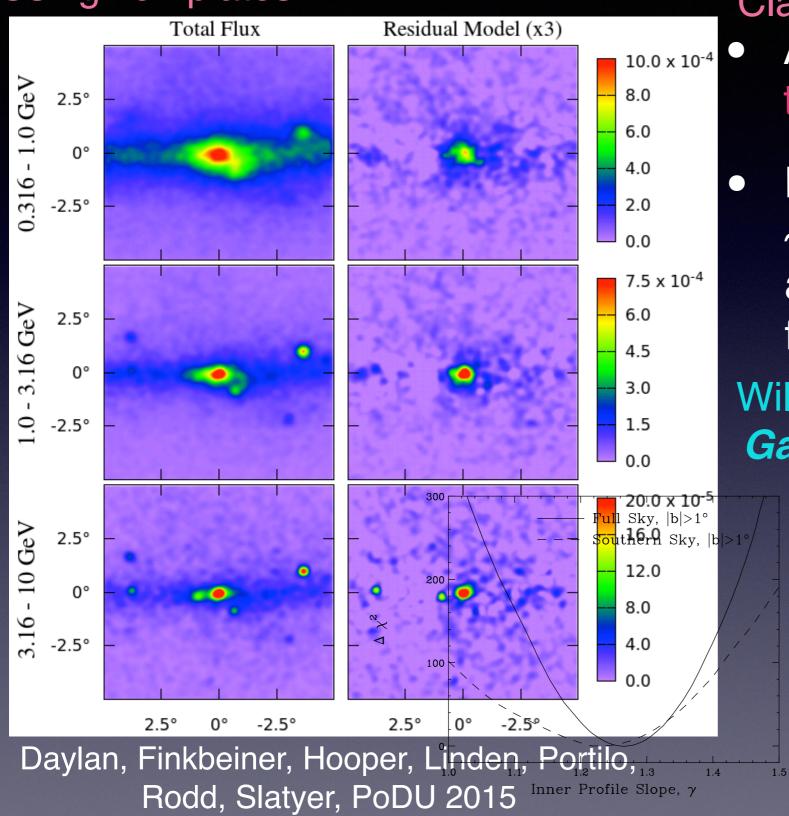




- The region of the galactic center is complex with large uncertainties.
- A DM annihilation signal peaks but also has significant uncertainties..
- Take advantage of multi-wavelength searches.

Looking for excesses in the galactic center

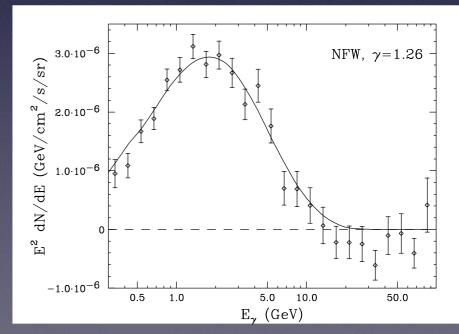
Using Templates:



Claim:

- A clear excess emission in the galactic center emerges
- Excess emission cuts-off at ~10 GeV (is in some disagreement with later findings)

Will call this excess emission the Galactic Center Excess (GCE)

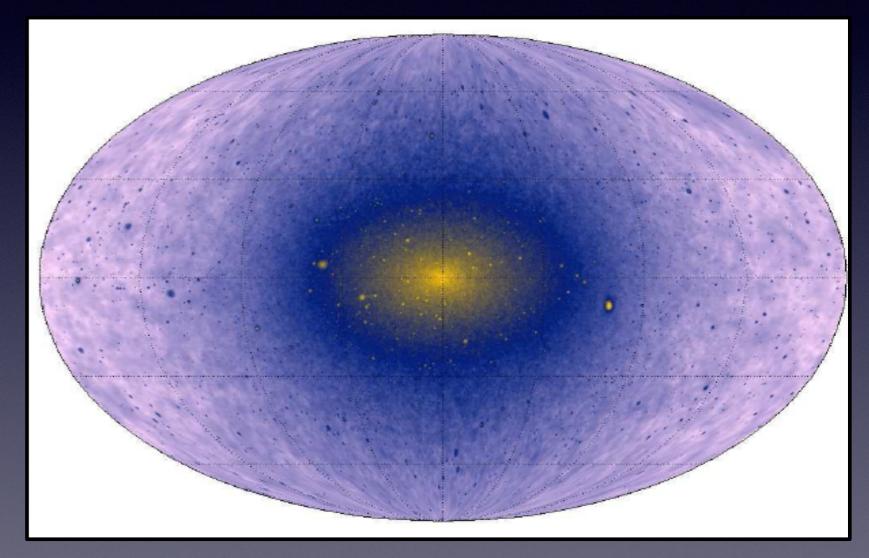


Also: Hooper & Goodenough PRL 2011, Abazajian JCAP 2011, Hooper & Linden PRD 2011, Gordon & Macias PRD 2014, Zhou et al. PRD 2015, Ajello et al. ApJ 2016

Going to High Latitudes (Inner Galaxy)

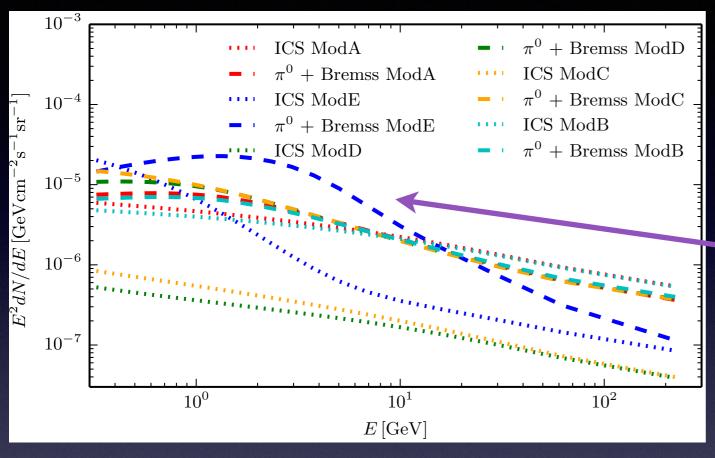
Advantages of looking further away from the center:

i)For a DM signal, you now have a prediction on the spectrum and its normalization based on the DM distribution.



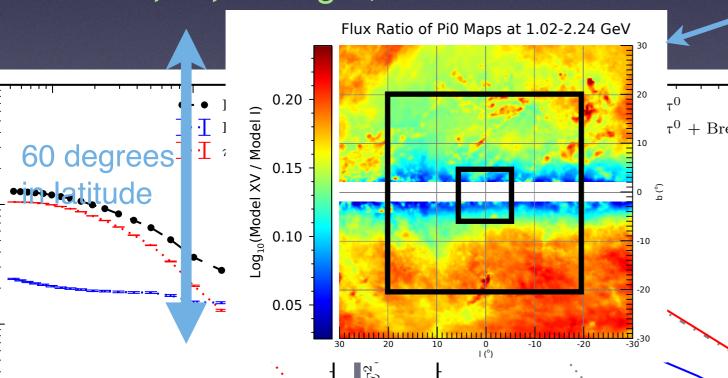
ii) Different region on the galactic sky suffers from different uncertainties in the background gamma-ray flux.

Modeling the background gamma-ray sky: Interplay with Cosmic-Rays & the ISM

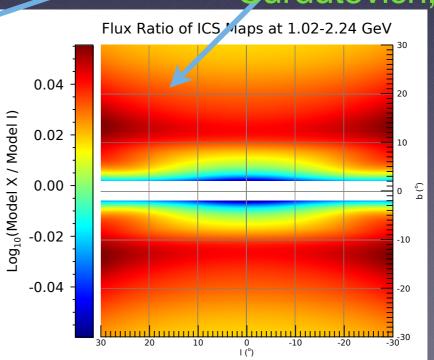


The exact astrophysics model assumptions can affect both the gamma-ray background spectrum and its morphology on the galactic sky.





IC. Zhong, McDermott, Sardutovich, PRD 2022



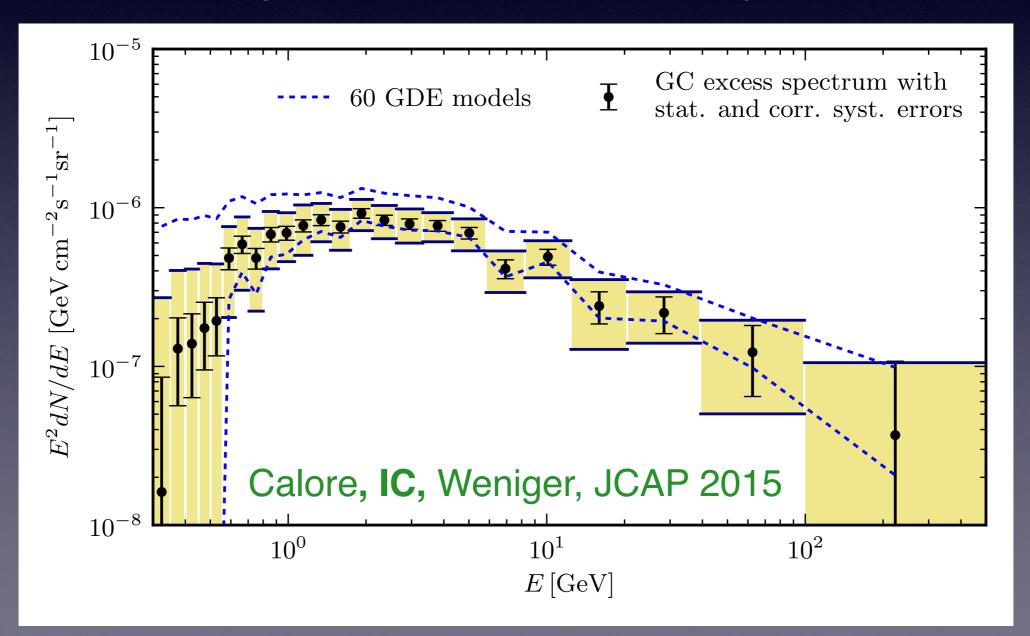
Accounting for the galactic diffuse emission uncertainties

We use models, accounting for uncertainties related to the diffusion of CRs, the presence of convective winds, diffusive re-acceleration, energy losses, CR injection sources, gas and other interstellar medium properties. From the existing literature and in 2015 we created our own (60) models—> 6660 different Templates!

Accounting for the galactic diffuse emission uncertainties

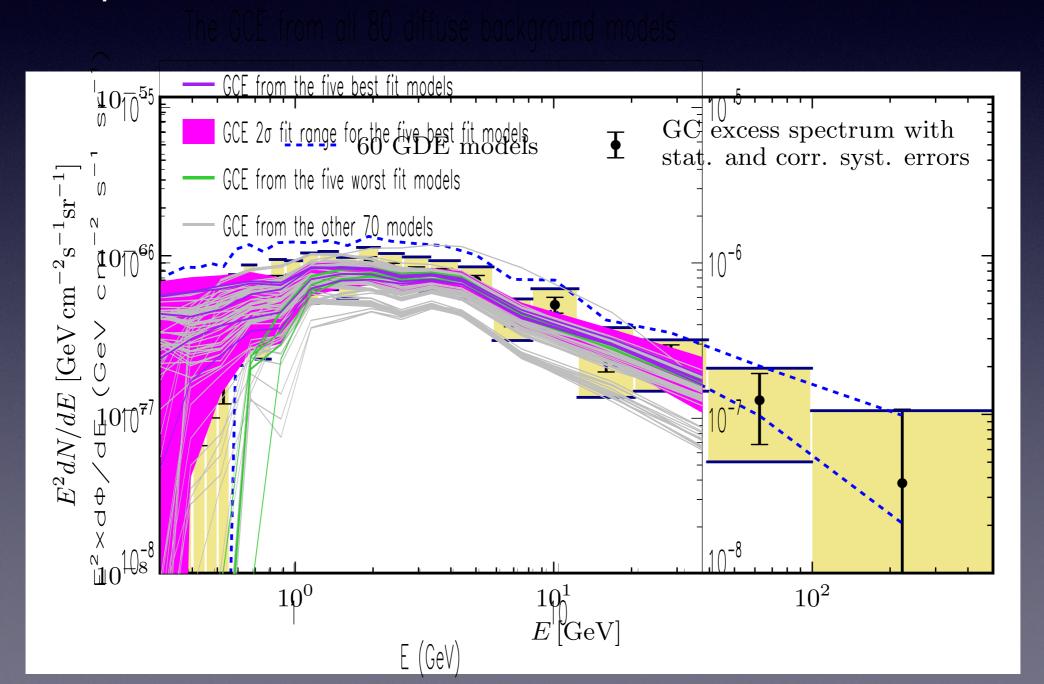
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It turns out that it actually does not affect dramatically the excess spectrum:



Accounting for the galactic diffuse emission uncertainties

We use models, accounting for uncertainties related to the diffusion of CRs, the presence of convective winds, diffusive re-acceleration, energy losses, CR injection sources, gas and other interstellar medium properties. To account for new observations in 2020-2021 we created and tested 45K high resolution templates.



Maps, Astrophysical Models and Correlated Errors publicly available via Zenodo

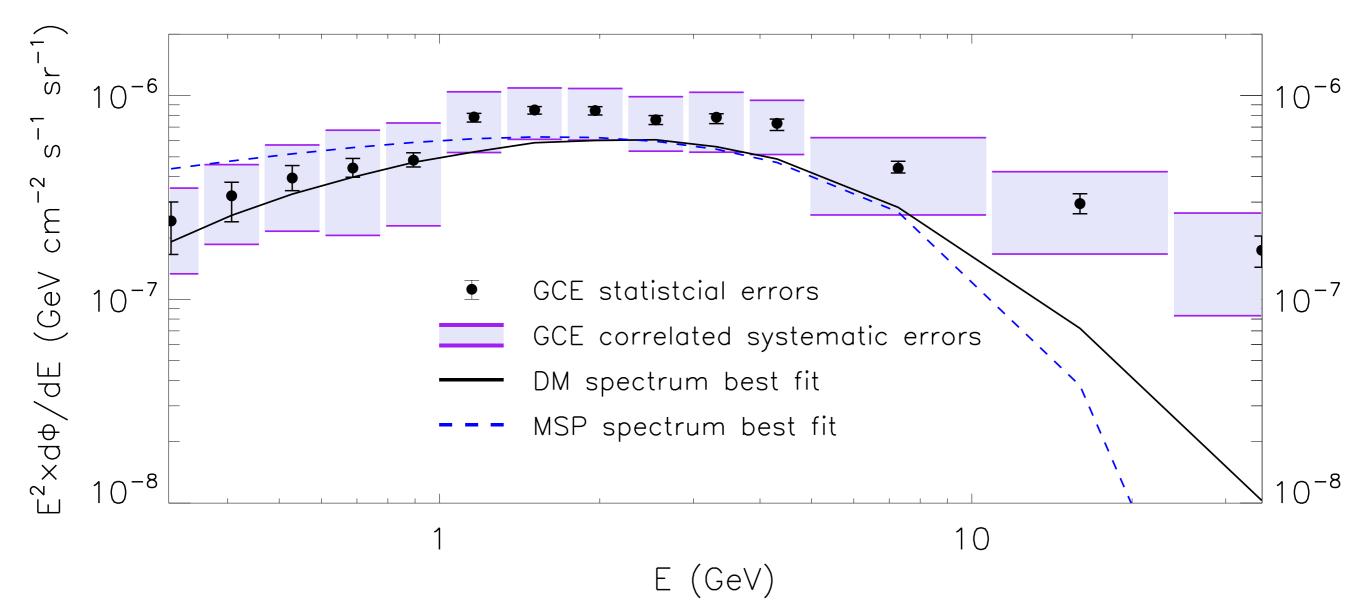
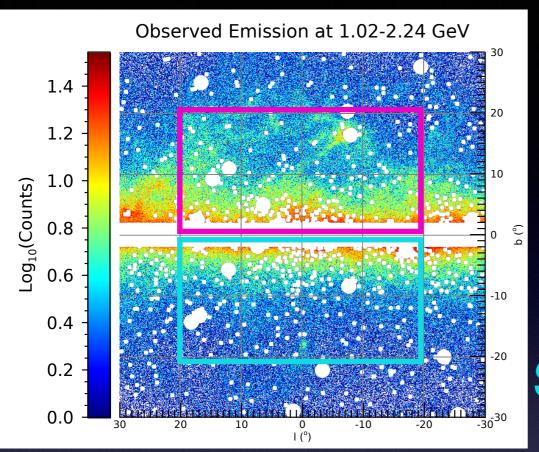


TABLE V. The first four principal components of the systematic uncertainty contribution to the covariance matrix, defined as in Eq. (16), in units of 10^{-7} GeV cm⁻² s⁻¹ sr⁻¹.

$\overline{\mathrm{PC}_i}$	Φ_1	Φ_2	Φ_3	Φ_4	Φ_5	Φ_6	Φ_7	Φ_8	Φ_9	Φ_{10}	Φ ₁₁	Φ_{12}	Φ_{13}	Φ_{14}
PC_1	2.52	2.37	2.47	2.43	2.19	2.35	2.08	1.83	1.65	1.69	1.38	1.09	0.67	0.34
PC_2	-1.70	-1.07	-0.16	0.14	0.54	0.42	0.40	0.31	0.58	0.41	0.56	0.48	0.41	0.33
PC_3	0.27	0.06	-0.53	-0.22	-0.21	-0.18	-0.08	0.25	0.04	0.45	0.23	0.24	0.20	0.24
PC_4	0.20	-0.15	0.15	-0.14	0.06	-0.04	-0.04	-0.27	0.08	-0.25	0.11	0.25	0.27	0.17

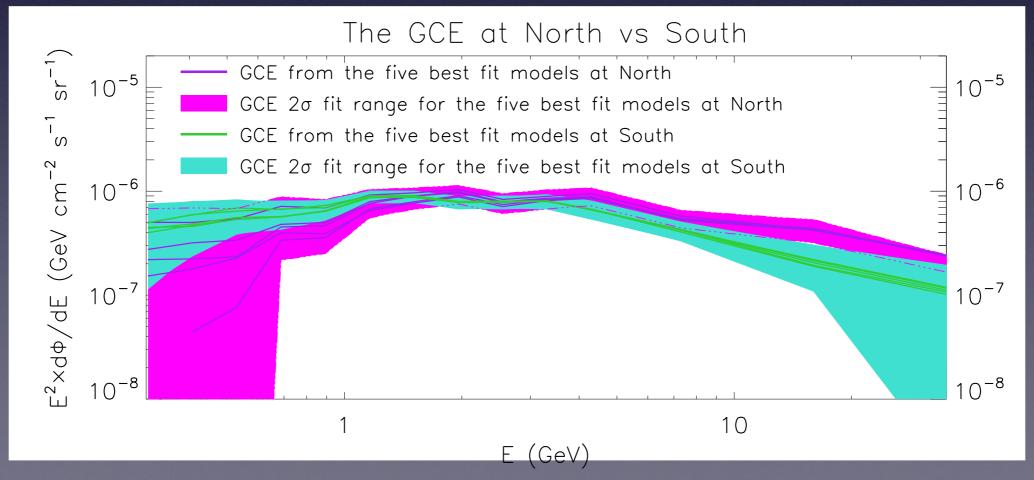
The profile for the GCE. Does it look like a DM signal?



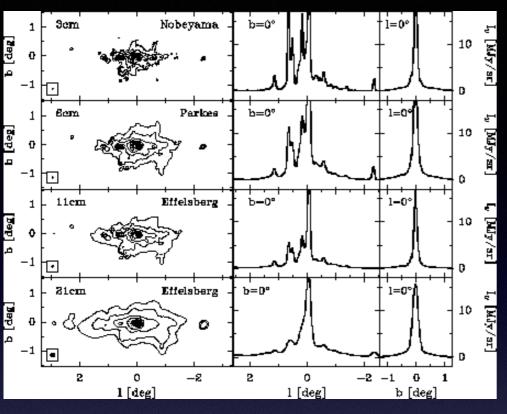
IC, Zhong, McDermott, Surdutovich, PRD 2022

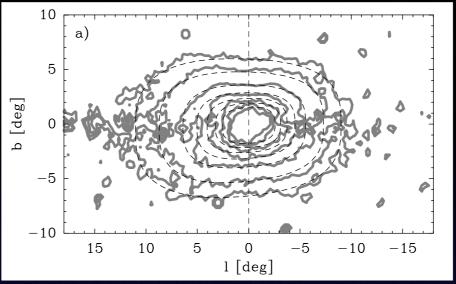
North

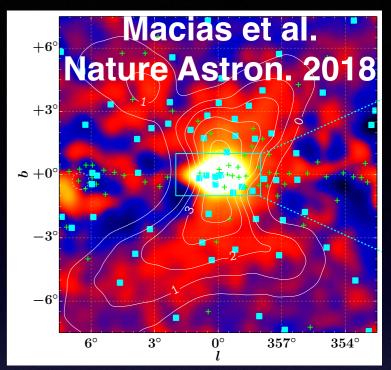
Roughly consistent between southern and northern galactic hemisphere as expected from dark matter



The profile for the GCE. Does it look like a DM signal?





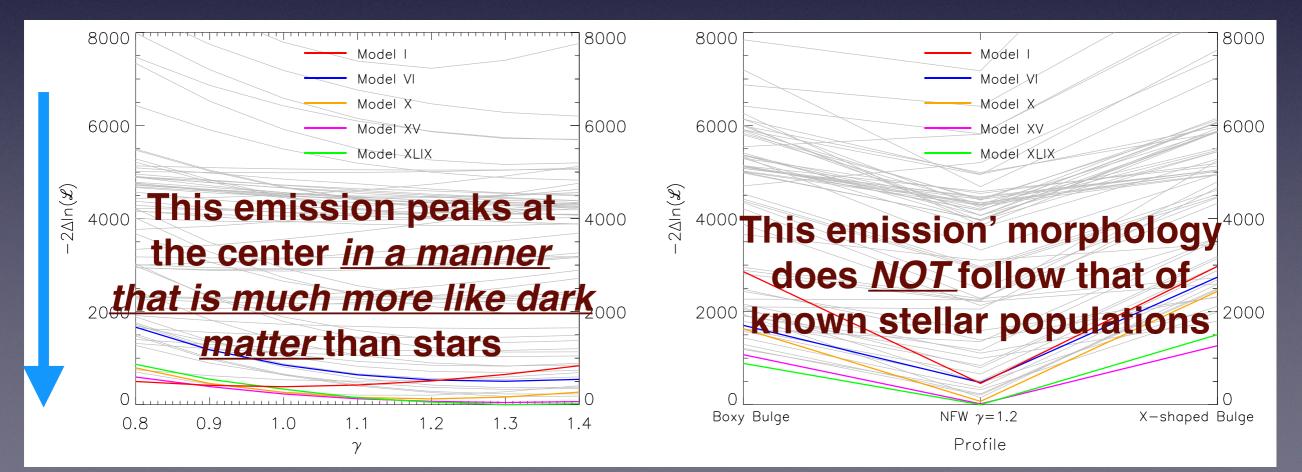


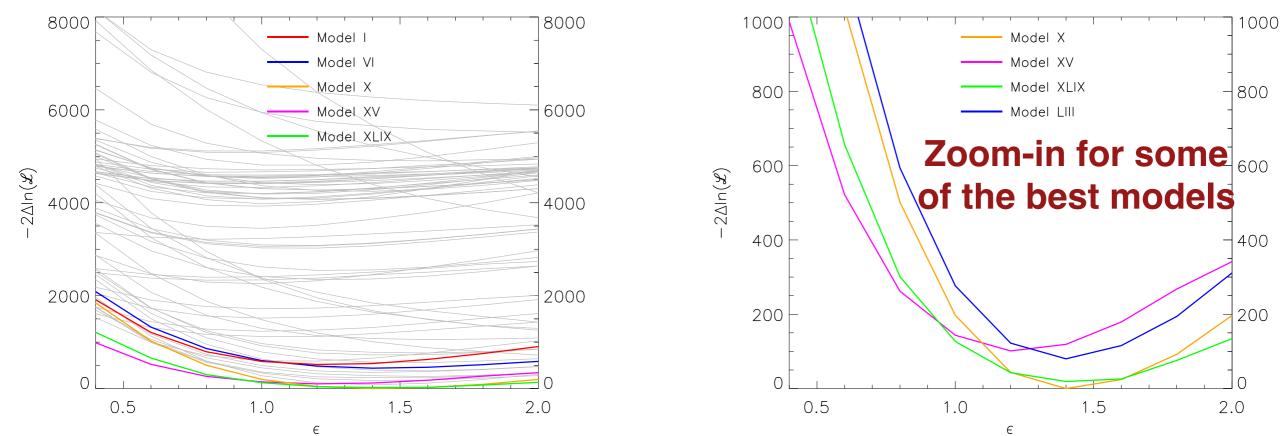
Boxy Bulge @ 2-5 µm

Launhardt et al. A&A 2002

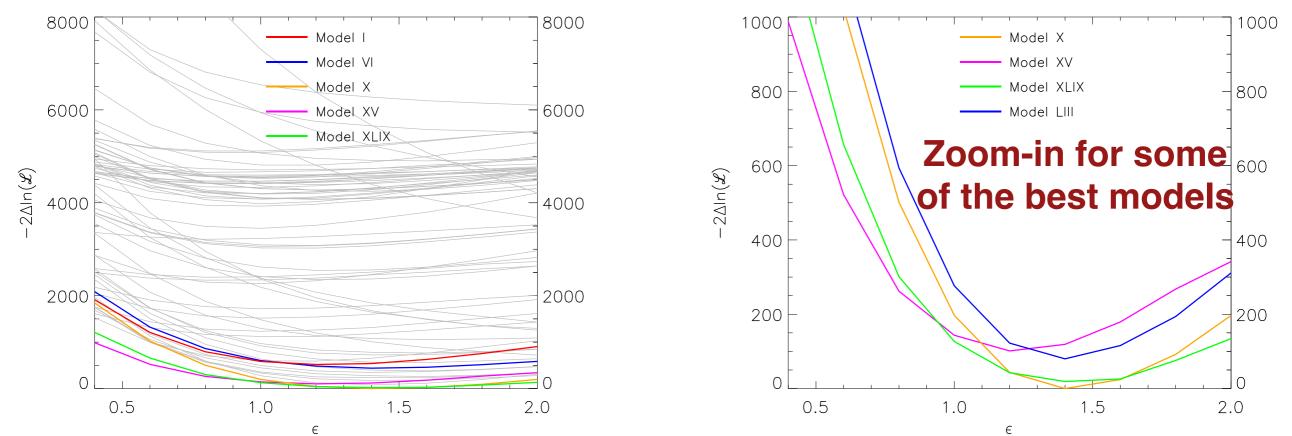
Nuclear Bulge @ Radio





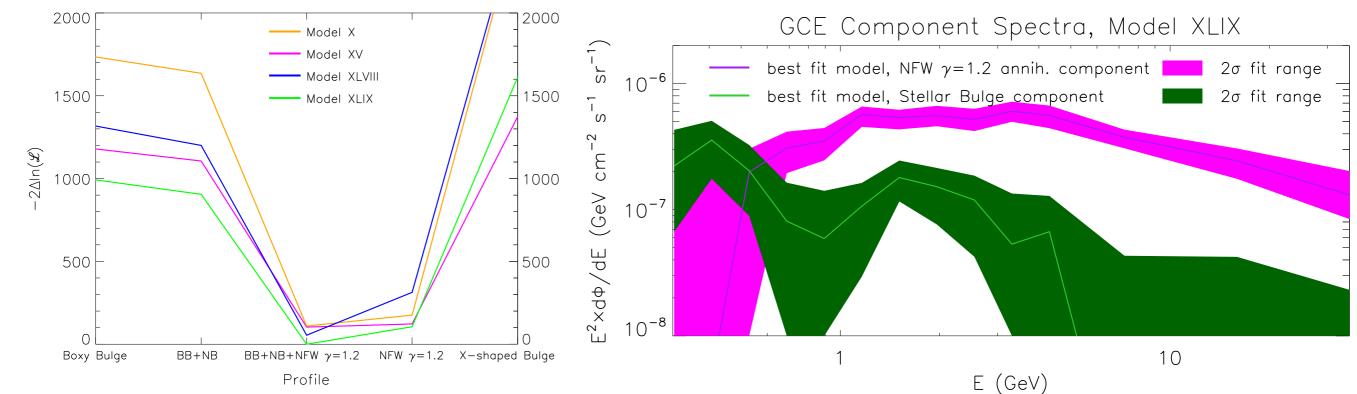


Results do not change substantively between 4FGL, 4FGL-DR2 (and also 4FGL-DR3) point source catalogues



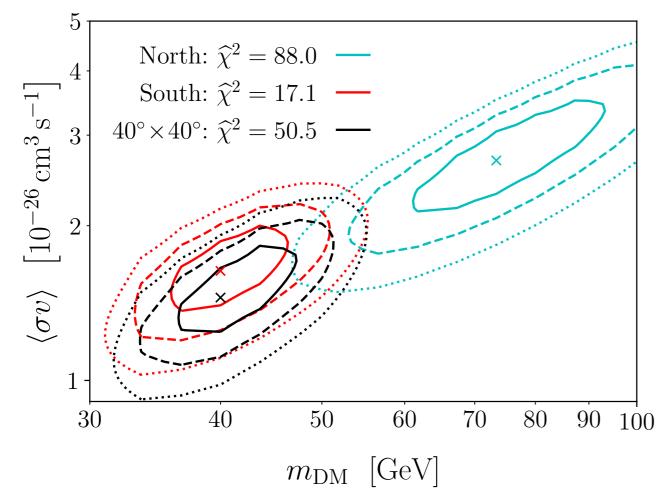
Results do not change substantively between 4FGL, 4FGL-DR2 (and also 4FGL-DR3) point source catalogues

Even when we allow for an additional stellar bulge component (probing MSPs) component, we still get preference for a dominant cuspy NFW-like profile



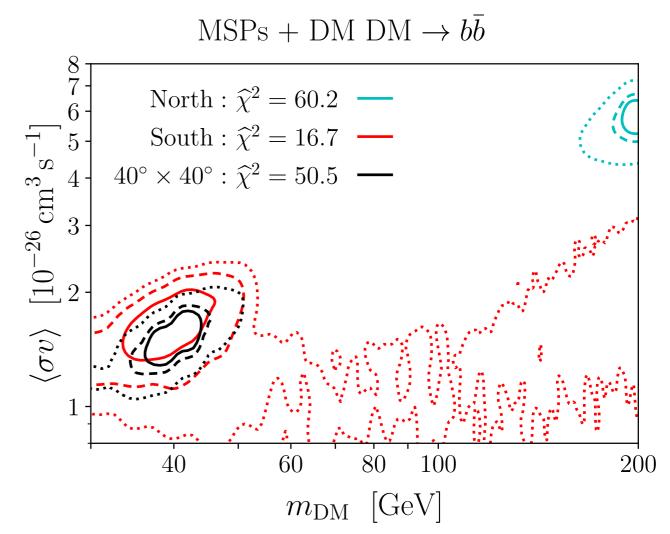
If this is a DM annihilation signal what do we learn about the particle physics?

 $DM DM \rightarrow b\bar{b}$



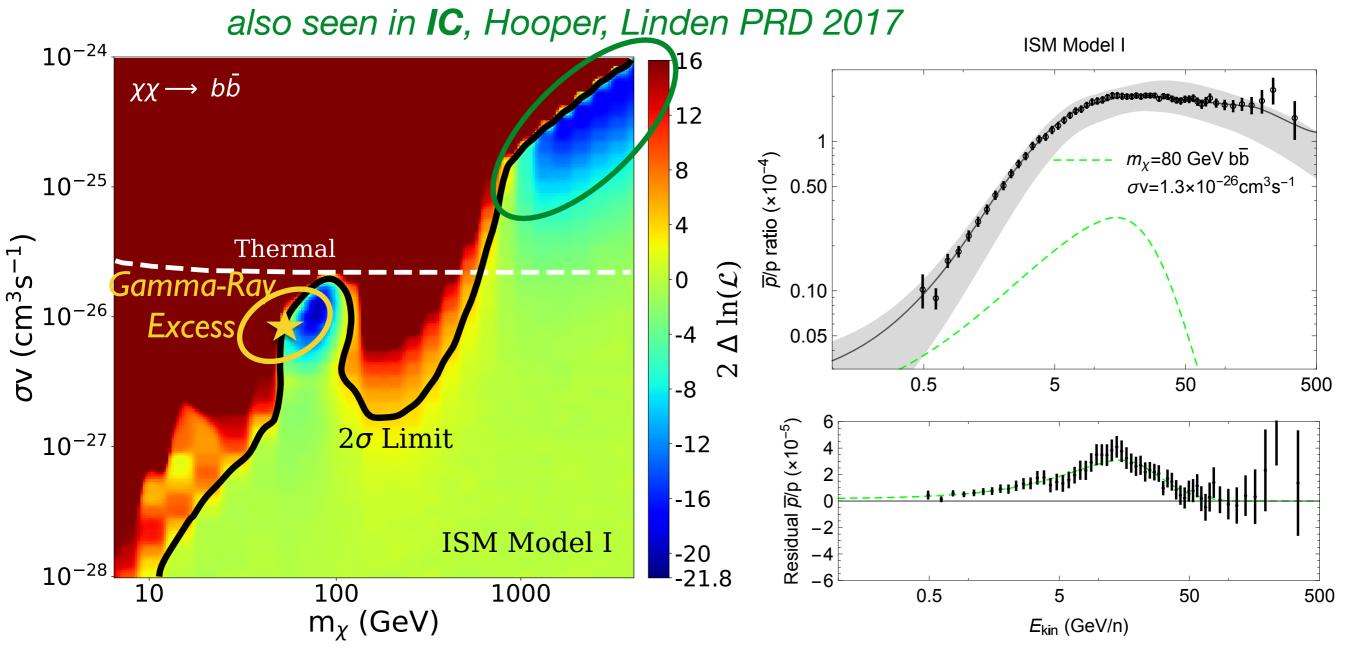
Adding an MSP component affects the fits on the more "dirty" (more galactic gas) Northern Hemisphere, but the Southern Hemisphere and the overall Inner Galaxy fit are fairly unaffected.

The mass range preferred very much within the WIMP range.



Looking at the antiproton to proton ratio find an the excess at~3 sigma

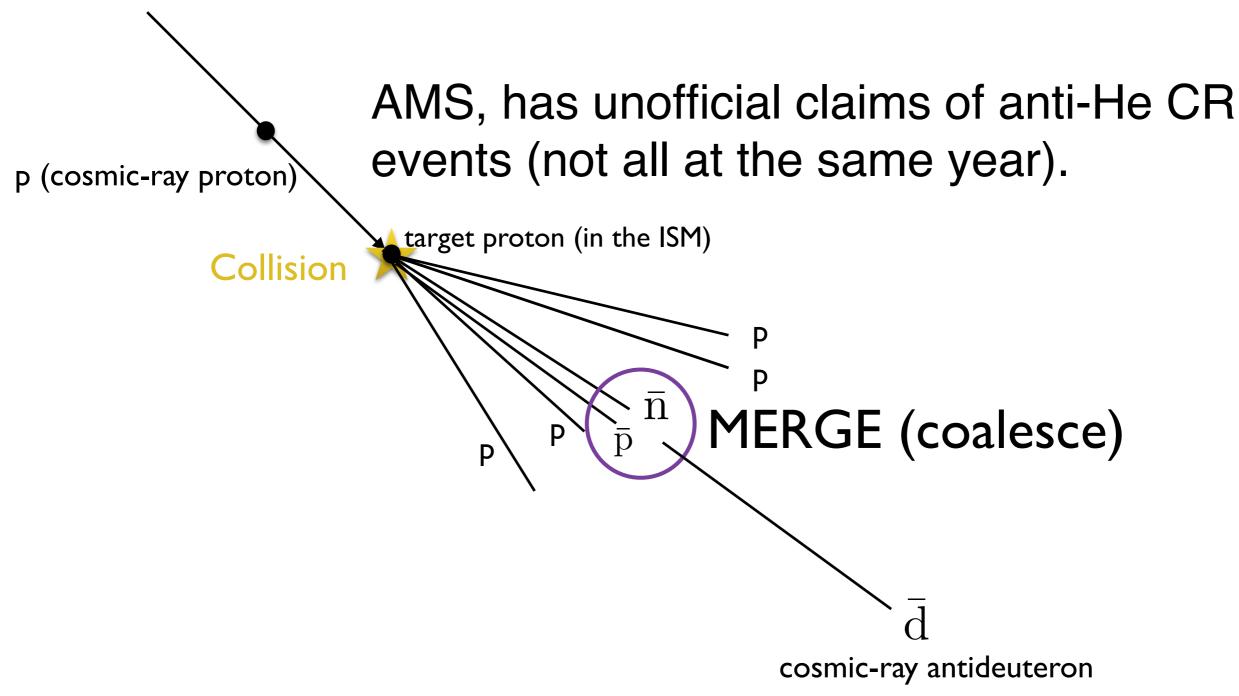
Supernova,



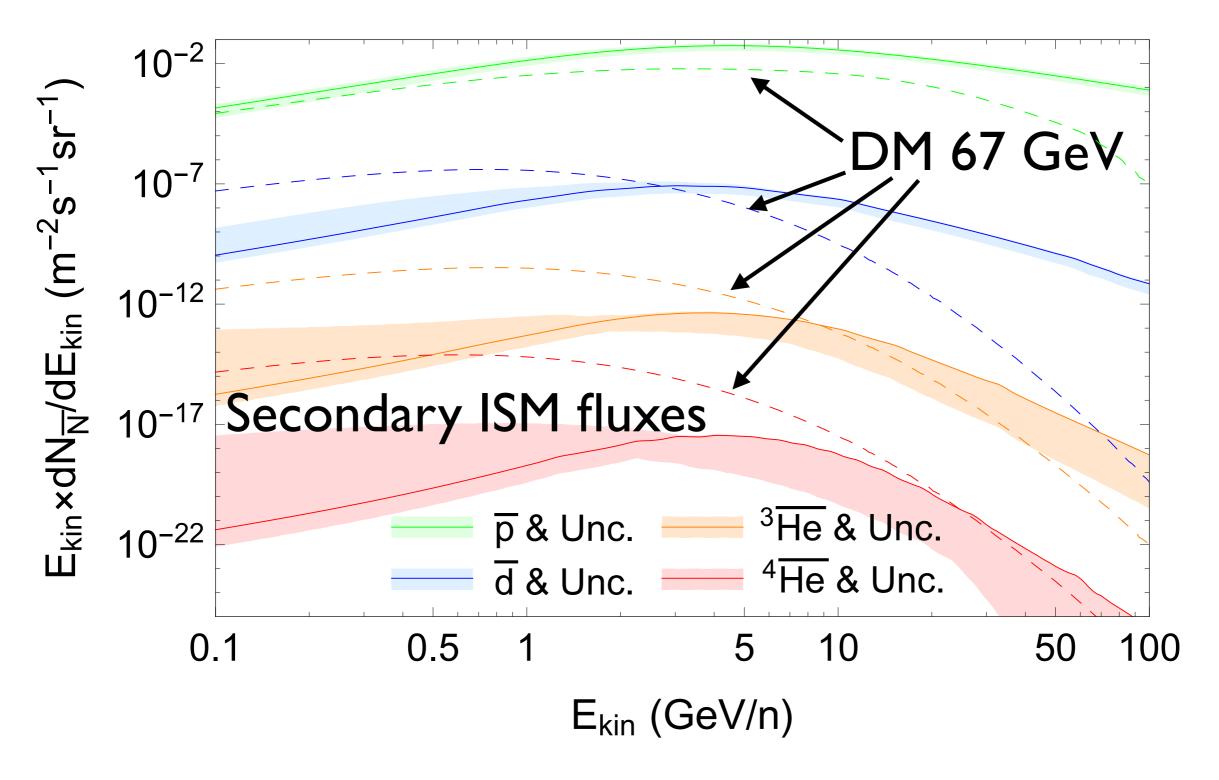
IC, Tim Linden, Dan Hooper PRD 2019

See also A. Cuoco et al. PRD 2019 Earlier results: Cuoco et al. PLR 2017, Cui et al. PRL 2017

How about heavier nuclei?

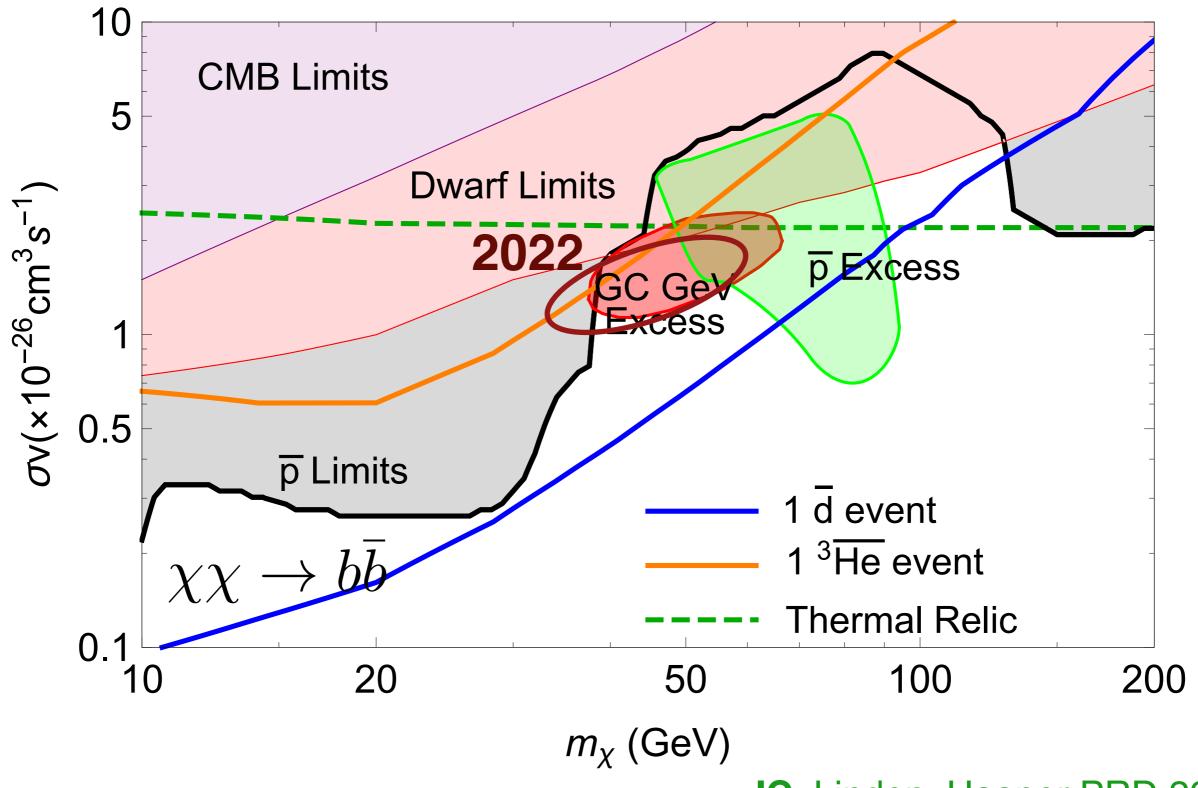


Antimatter flux Uncertainties



IC, Linden, Hooper PRD 2020

Combining all Indirect DM searches



IC, Linden, Hooper PRD 2020

And a little extra positrons....

Utilizing cosmic-ray positron and electron observations to probe the averaged properties of Milky Way pulsars

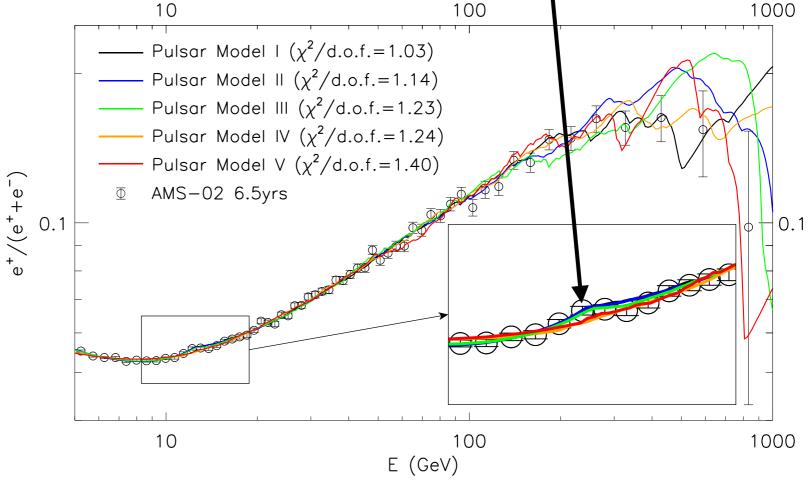
Ilias Cholis^{1*} and Iason Krommydas^{2†}

¹Department of Physics, Oakland University, Rochester, Michigan 48309, USA ²Physics Division, National Technical University of Athens, Zografou, Athens 15780, Greece

(Received 19 November 2021; accepted 4 January 2022; published 14 January 2022)

Pulsars have long been studied in the electromagnetic spectrum. Their environments are rich in highenergy cosmic-ray electrons and positrons likely enriching the interstellar medium (ISM) with such particles. In this work we use recent cosmic-ray observations from the AMS-02, CALET, and DAMPE

and likely release O(10%) of their rotational energy to cosmic rays in the ISM. Finally, we find at $\simeq 12$ GeV positrons a spectral feature that suggests a new subpopulation of positron sources contributing at these energies.



Acknowledgements

My Collaborators: Dan Hooper (Fermilab/U. Chicago), Tim Linden (U. Stockholm), Sam McDermott (Fermilab), Yi-Ming Zhong (KICP)

My Students: Jenna Bacon (OU), Iason Krommydas (NTUA), Ian McKinnon (OU), Osip Surdutovich (Carleton College)



MSGC, NASA No. NNX15AJ20H MSGC, NASA No. 80NSSC20M0124

Oakland University Research Fellowship

Department of Energy, DE-SC0022352

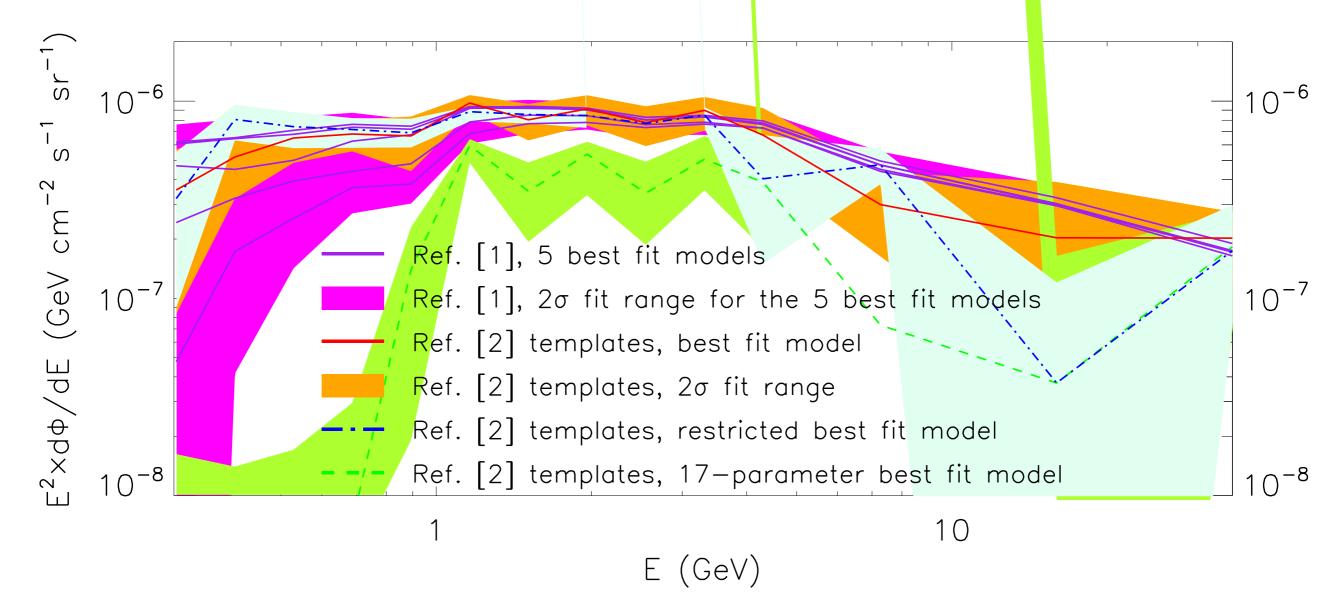


Thank you!

Extra

Ongoing Preliminary:

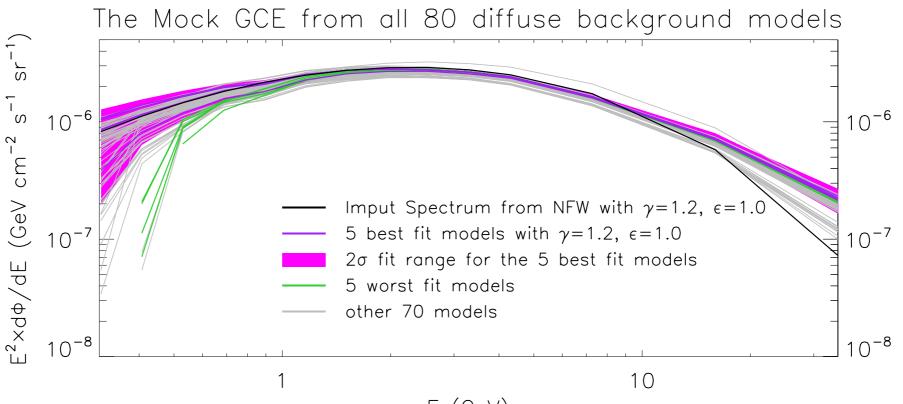
Comparison with Abazajian et al. 2020 results. We use their templates and still find a NFW-like GCE irrespective of the fitting method.



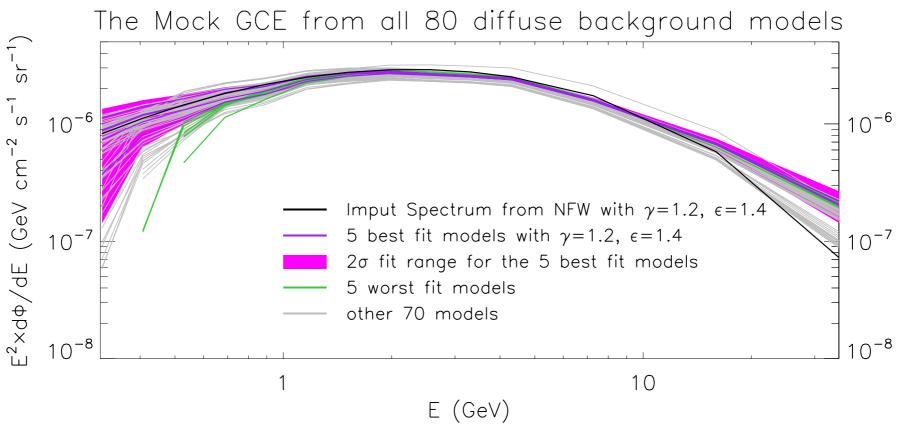
McDermott, Zhong, Cholis (2022 in prep.)

Ongoing Preliminary:

Further Tests of injected Mock Maps versus what we recover from the fits:



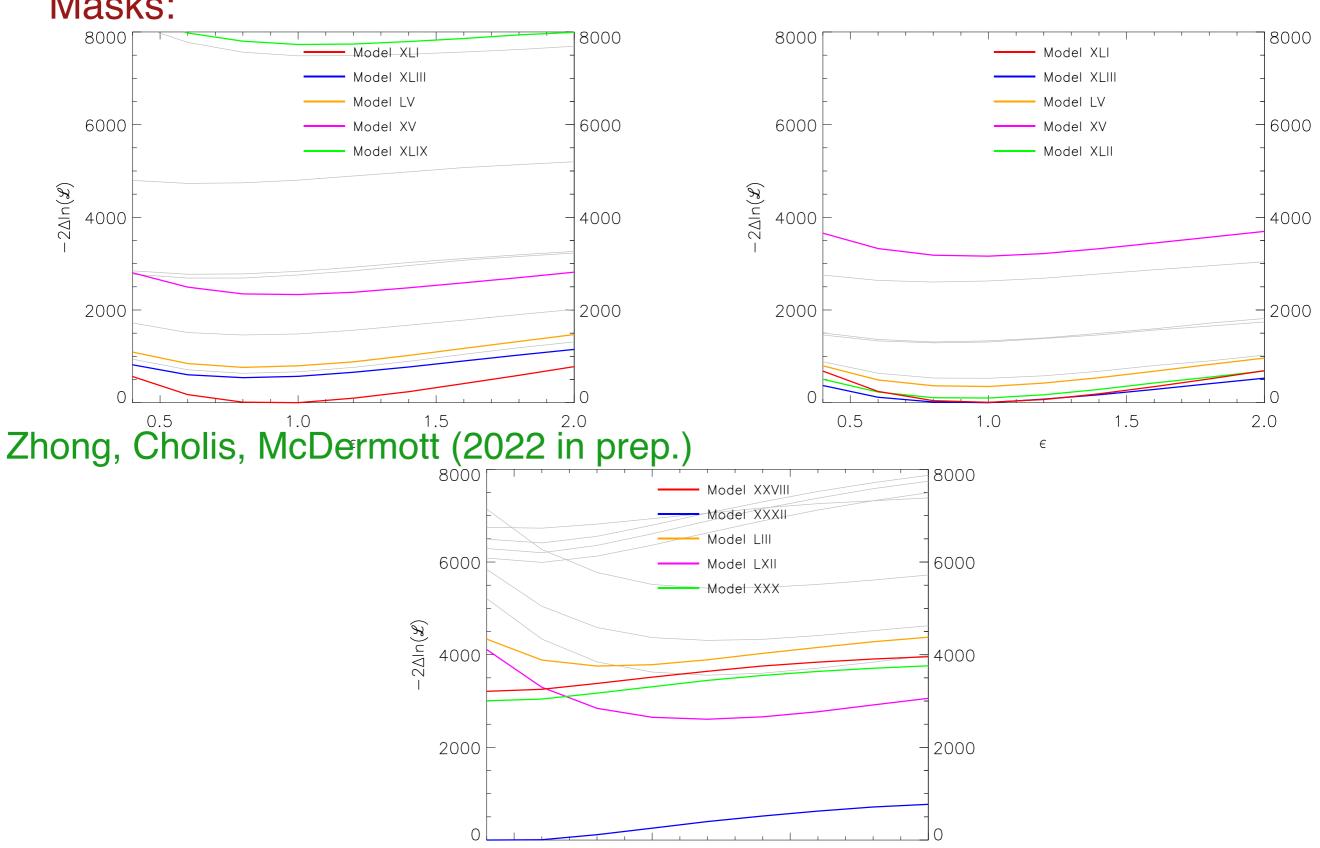
Zhong, Cholis, McDermott (2022 in prep.)



Ongoing Preliminary:

Further Tests on the GCE morphology with Alternative Wavelet based

Masks:



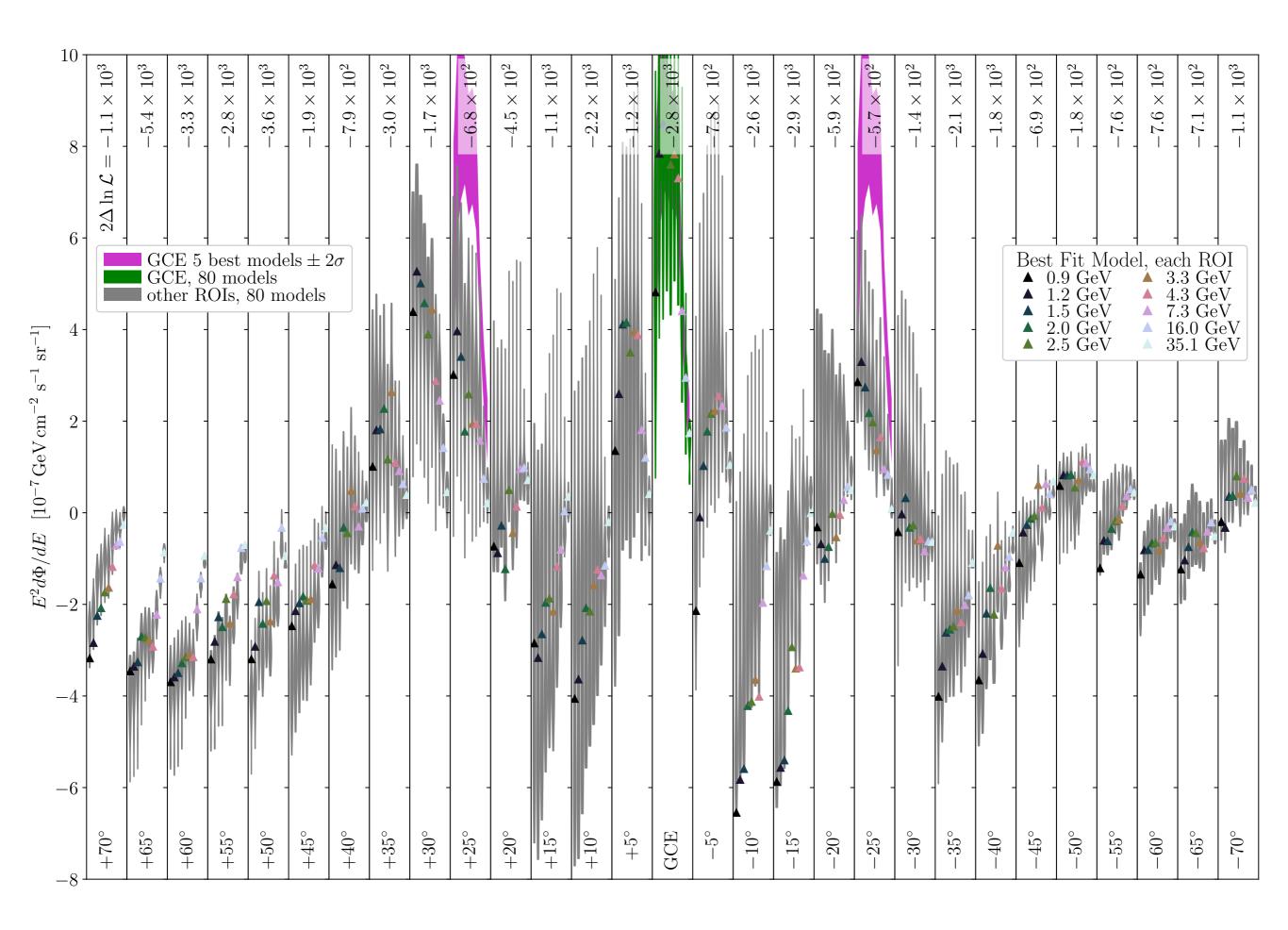
1.0

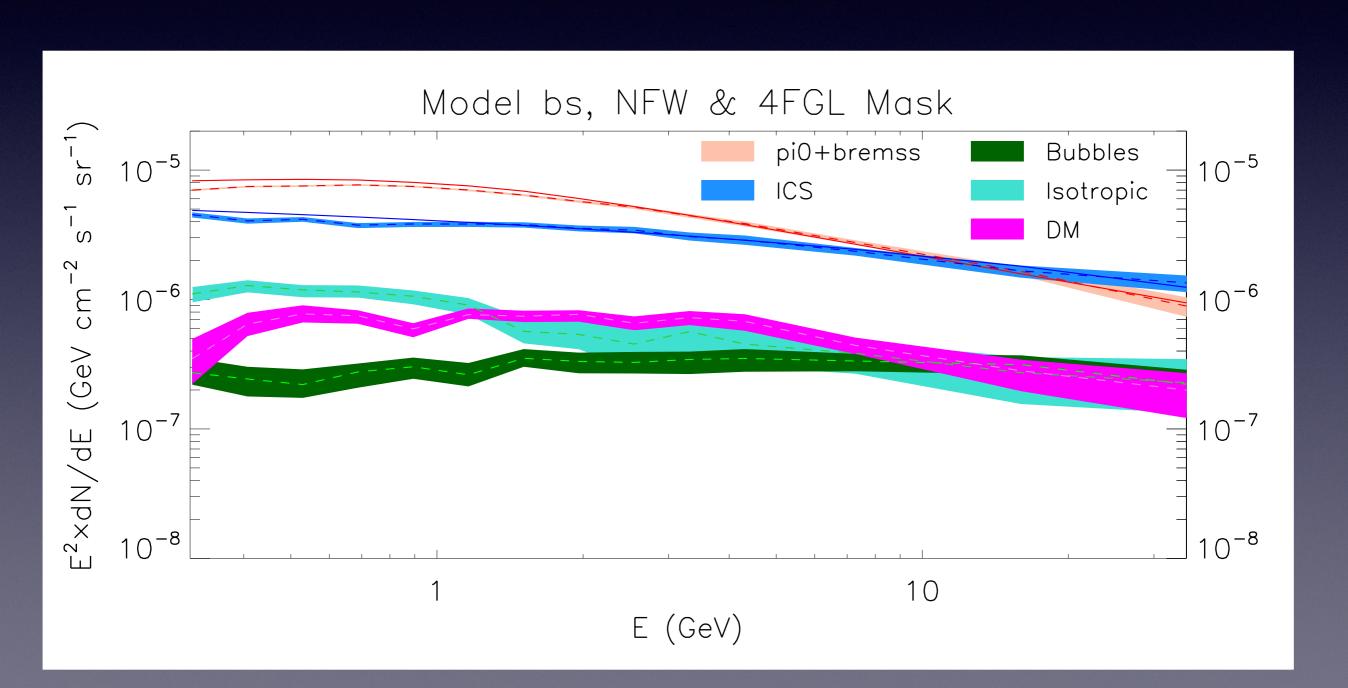
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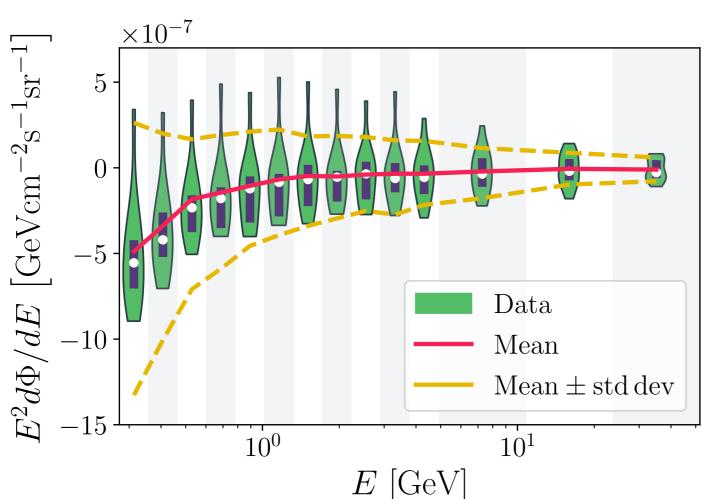
1.5

2.0

0.5







The covariance matrix:

$$\Sigma_{ij,\text{mod}} = \left\langle E^4 \frac{d\Phi}{dE_i} \frac{d\Phi}{dE_j} \right\rangle - \left\langle E^2 \frac{d\Phi}{dE_i} \right\rangle \left\langle E^2 \frac{d\Phi}{dE_j} \right\rangle$$

Its truncated version:

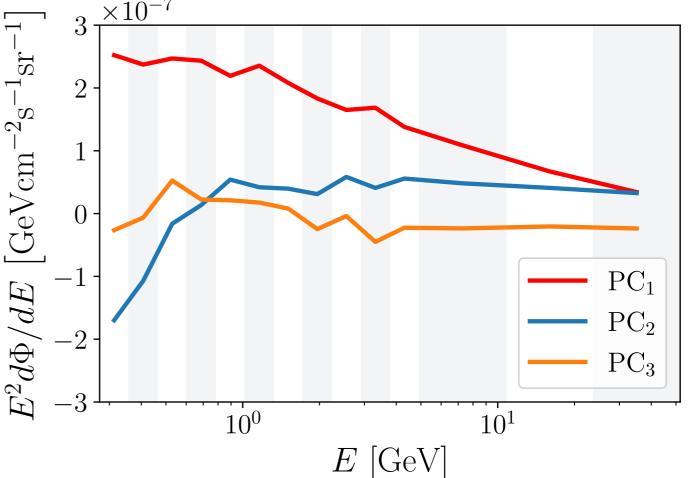
$$\Sigma_{jk,\text{mod}} \simeq \Sigma_{jk,\text{mod}}^{\text{trunc}} \equiv \sum_{i=1}^{3} PC_{ij}^{\mathsf{T}} PC_{ik}$$

The formal fit:

$$\chi^2 = \sum_{ij} \left(\text{GCE}_i - \sum_k f_{ik}(\theta_k) \right) C_{ij}^{-1} \left(\text{GCE}_j - \sum_{\ell} f_{j\ell}(\theta_{\ell}) \right)$$

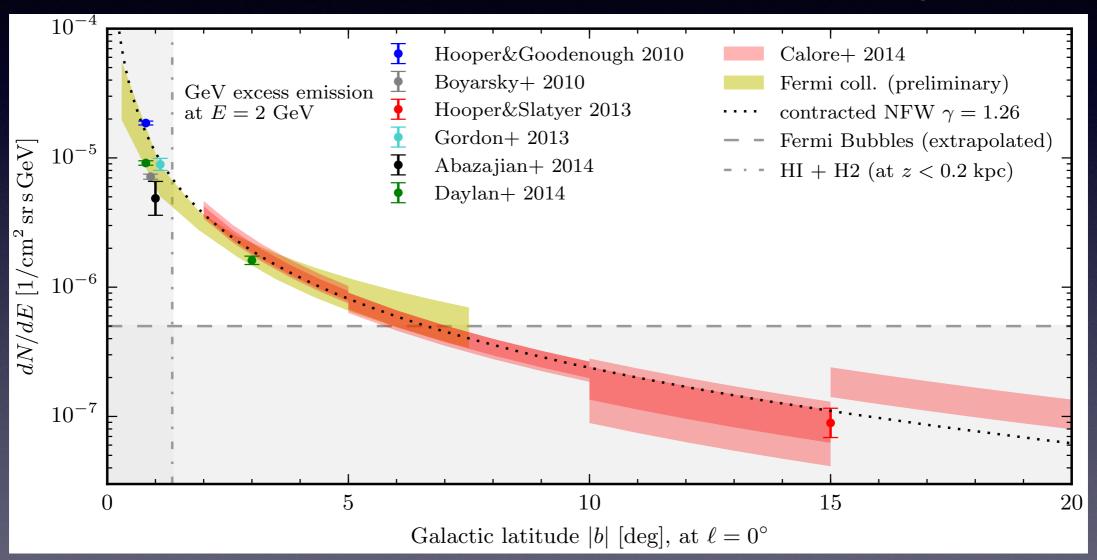
Where:

$$C_{ij} = \sigma_i^2 \delta_{ij} + \Sigma_{ij,\text{mod}}$$



The profile for the GEV excess. Does it look like a DM signal?

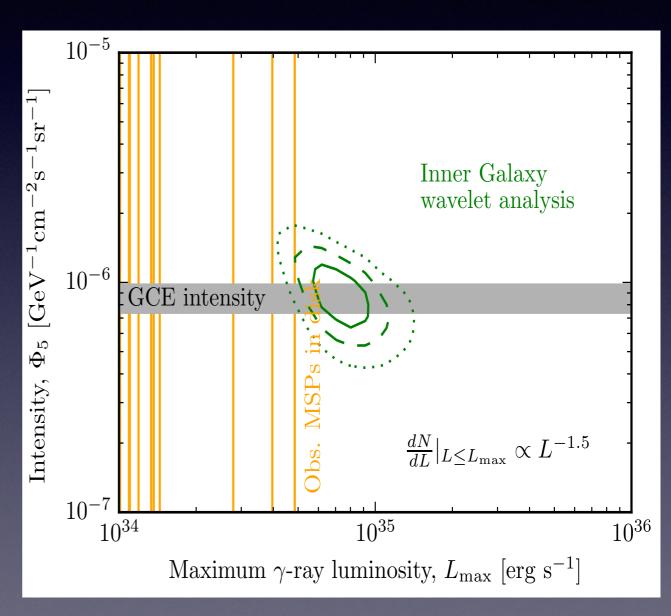
The flux associated to the excess emission at 2 GeV vs galactic latitude: Calore, IC, McCabe, Weniger, PRD 2015



The excess signals from different analyses, agree within a factor of less than 2 in terms of total emission.

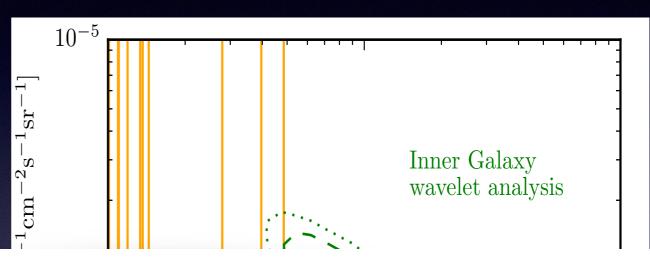
A simple Question: Can the CSP Be Bright Enough?

- Given an assumption about the "luminosity function" (the dependence of N_{PS} on L_{PS}), can ask if "point source-y" PSs are compatible with unresolved PSs accounting for the GCE
- Claim in 2015 was "yes" if the luminosity function had a power-law index α_L=1.5



An alternative Millisecond pulsars (recycled pulsars)

 Given an assumption about the "luminosity function" (the dependence of N_{PS} on L_{PS}), can ask if "point source-y" PSs

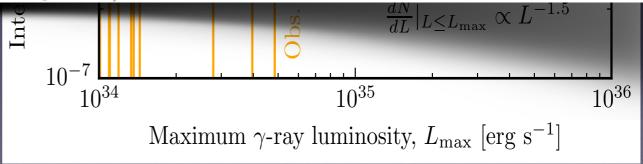


Strong Support for the Millisecond Pulsar Origin of the Galactic Center GeV Excess

Richard Bartels,^{1,*} Suraj Krishnamurthy,^{1,†} and Christoph Weniger^{1,‡}

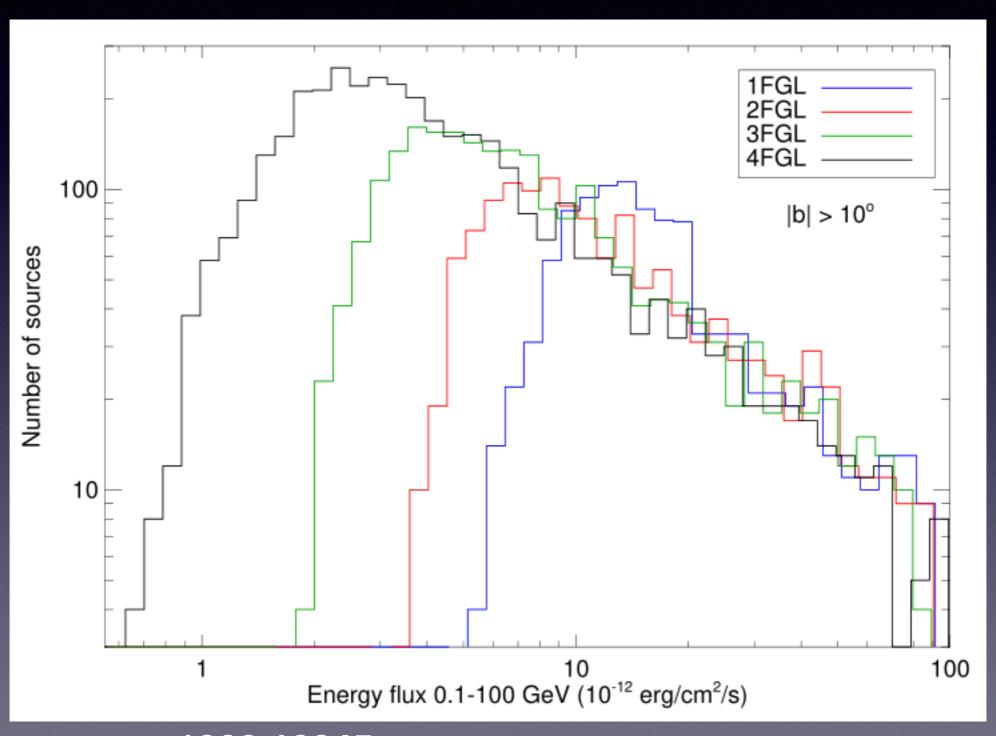
¹ GRAPPA Institute, University of Amsterdam, Science Park 904, 1090 GL Amsterdam, Netherlands (Dated: 4 February 2016)

luminosity function had a power-law index $\alpha_L=1.5$

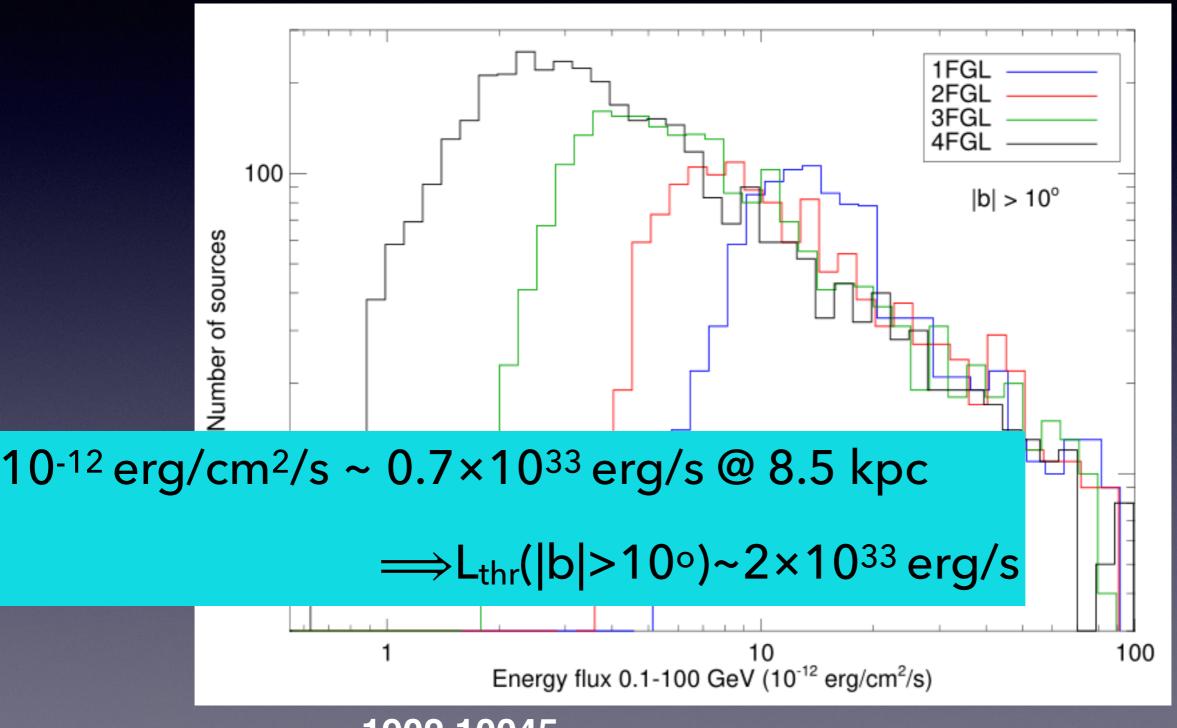


Bartels et al., 1506.05104

The 4FGL Catalog

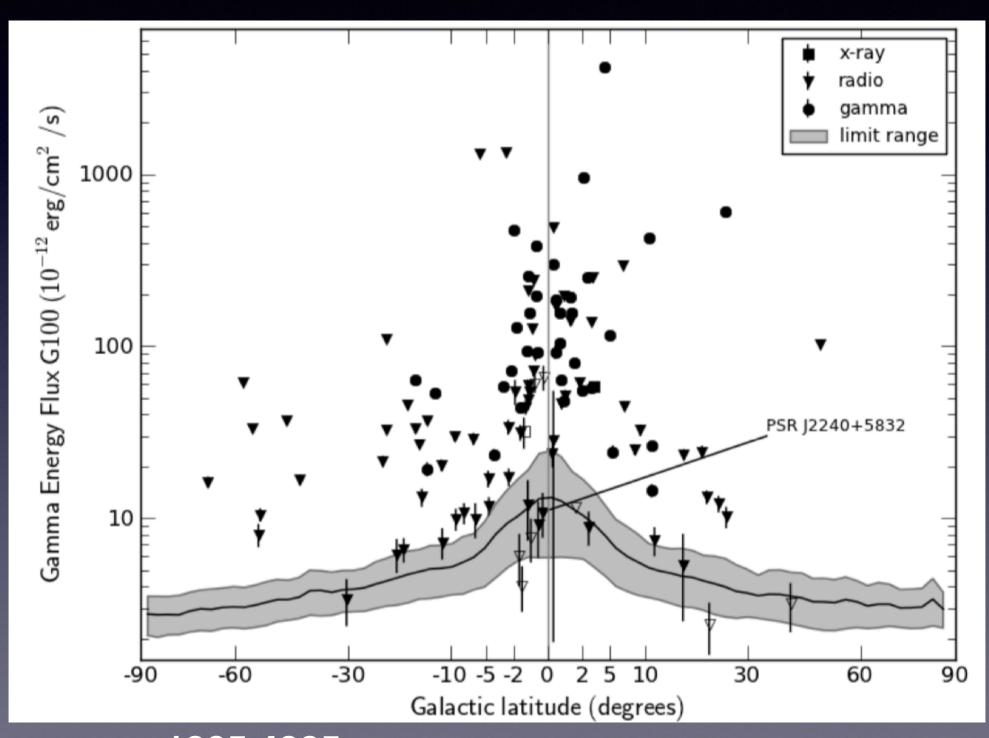


The 4FGL Catalog

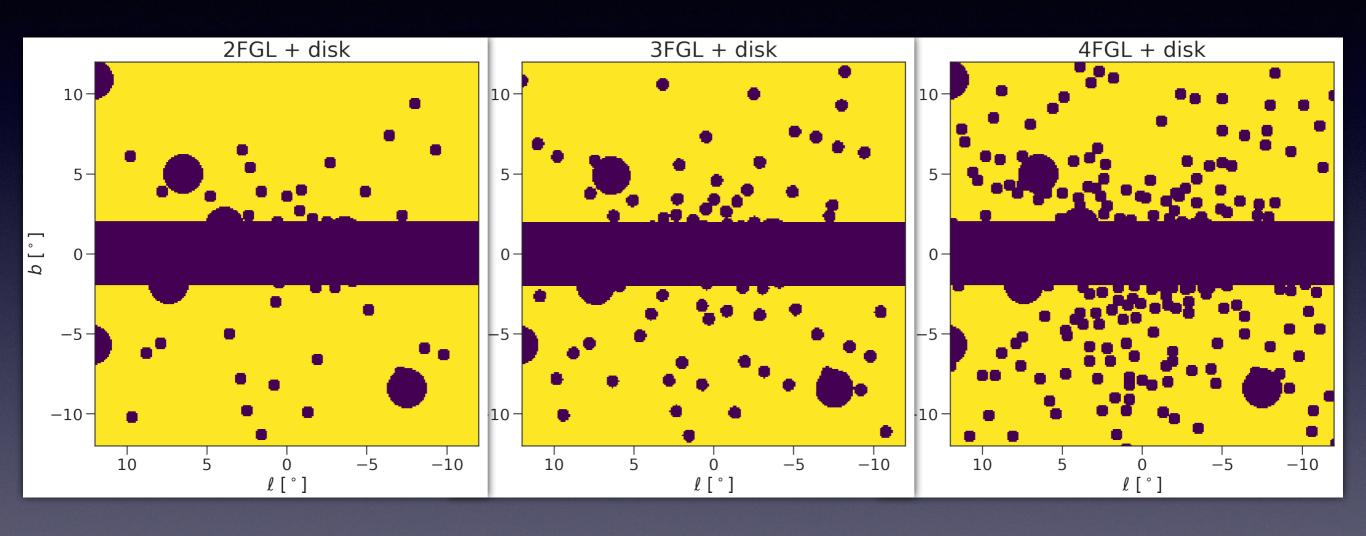


Abdollahi et al., 1902.10045

b-dependence of detection



The Masks of different Fermi Catalogs (#FGL)

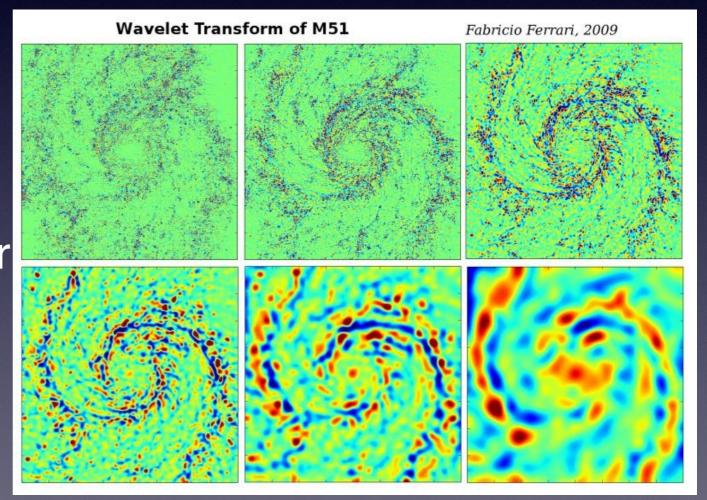


What are wavelets?

Wavelets have been used in image compression (JPEG), denoising, fast signal identification, even in HEP data

Allow analysis of data in both time/space and frequency space

Different type of structures will have a different power at different levels of the decomposition (e.g. edges and other small scale structures vs larger scale variations).

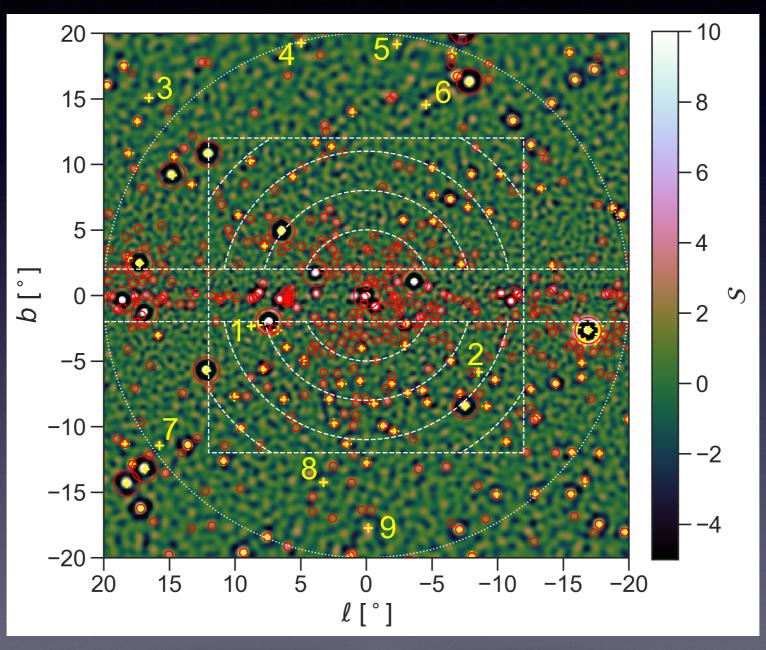




Wavelets can find these different structures.

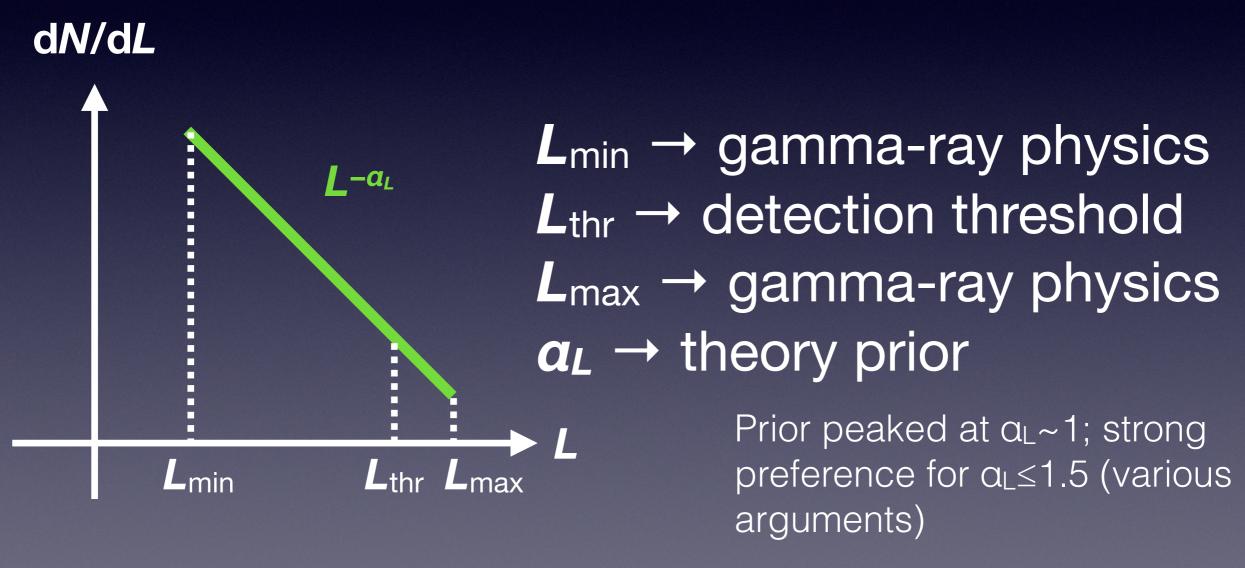
GCE: "Wavelet" search for point-like gamma-ray sources

Zhong, McDermott, IC, Fox, PRL 2020 (1911.12369)

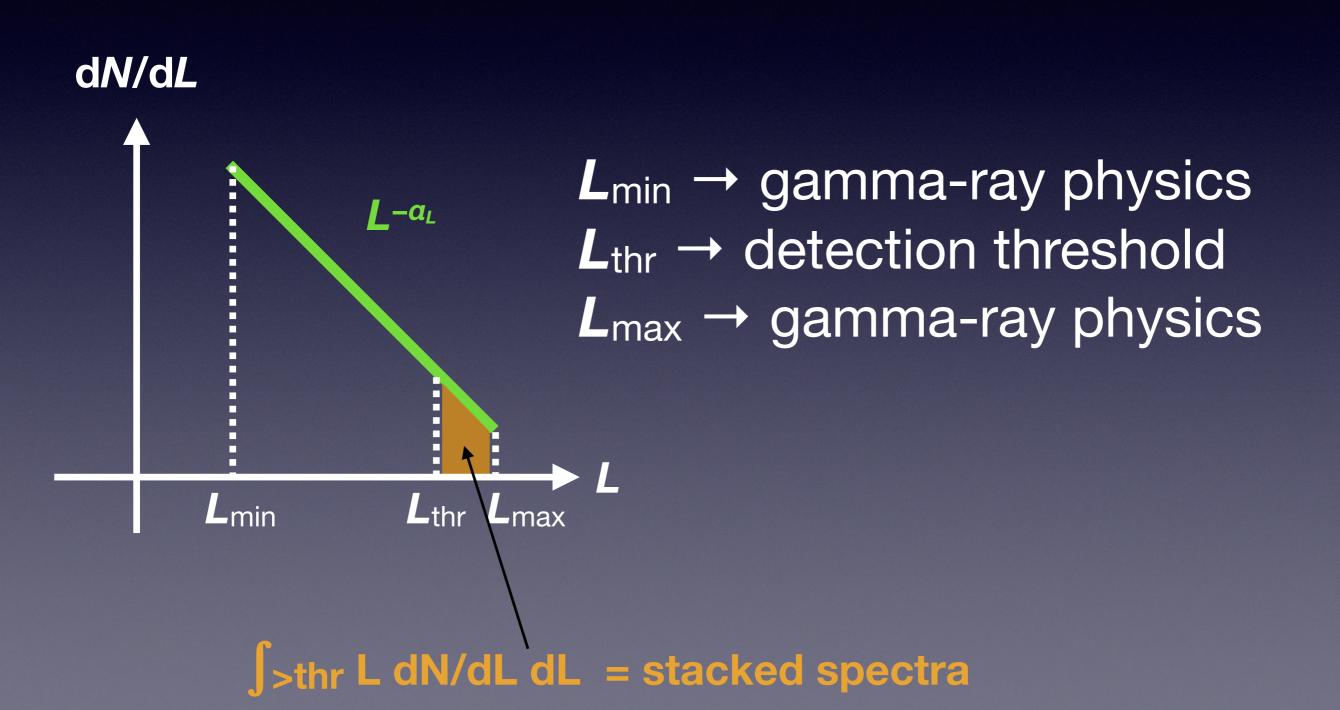


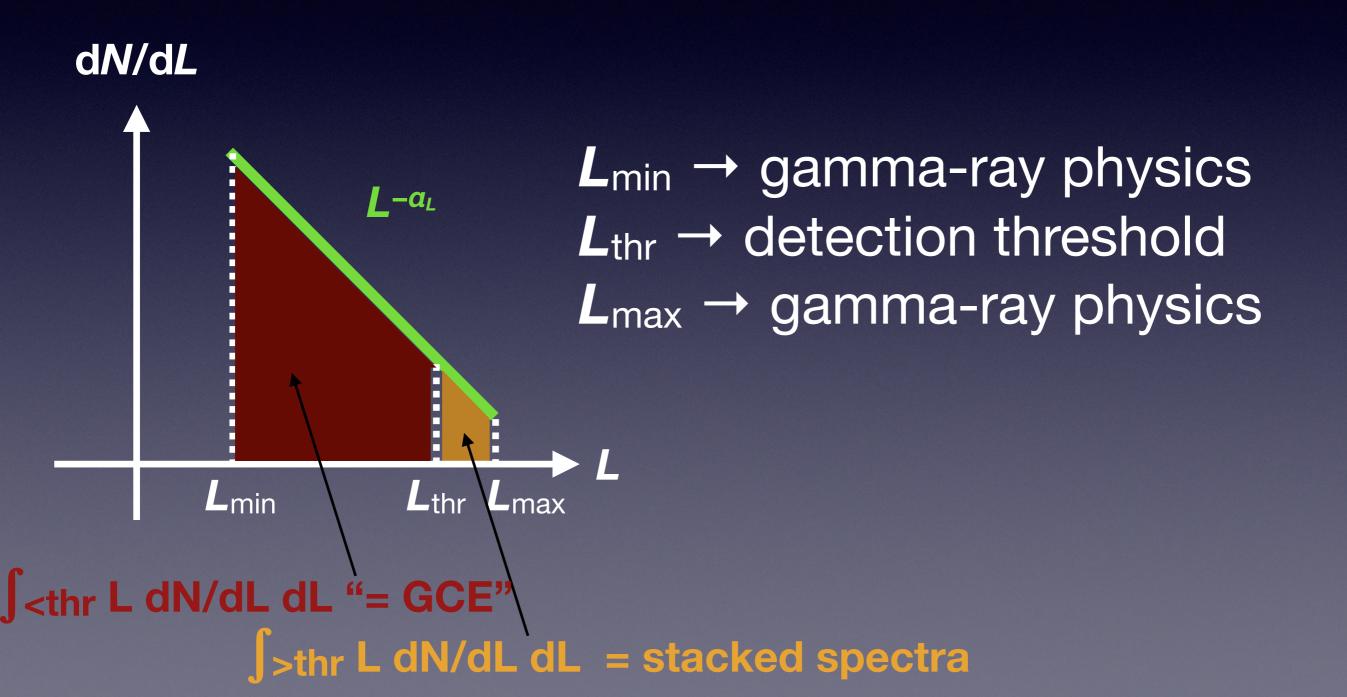
117 peaks (w/ S>4) > 109 peaks near 4FGL

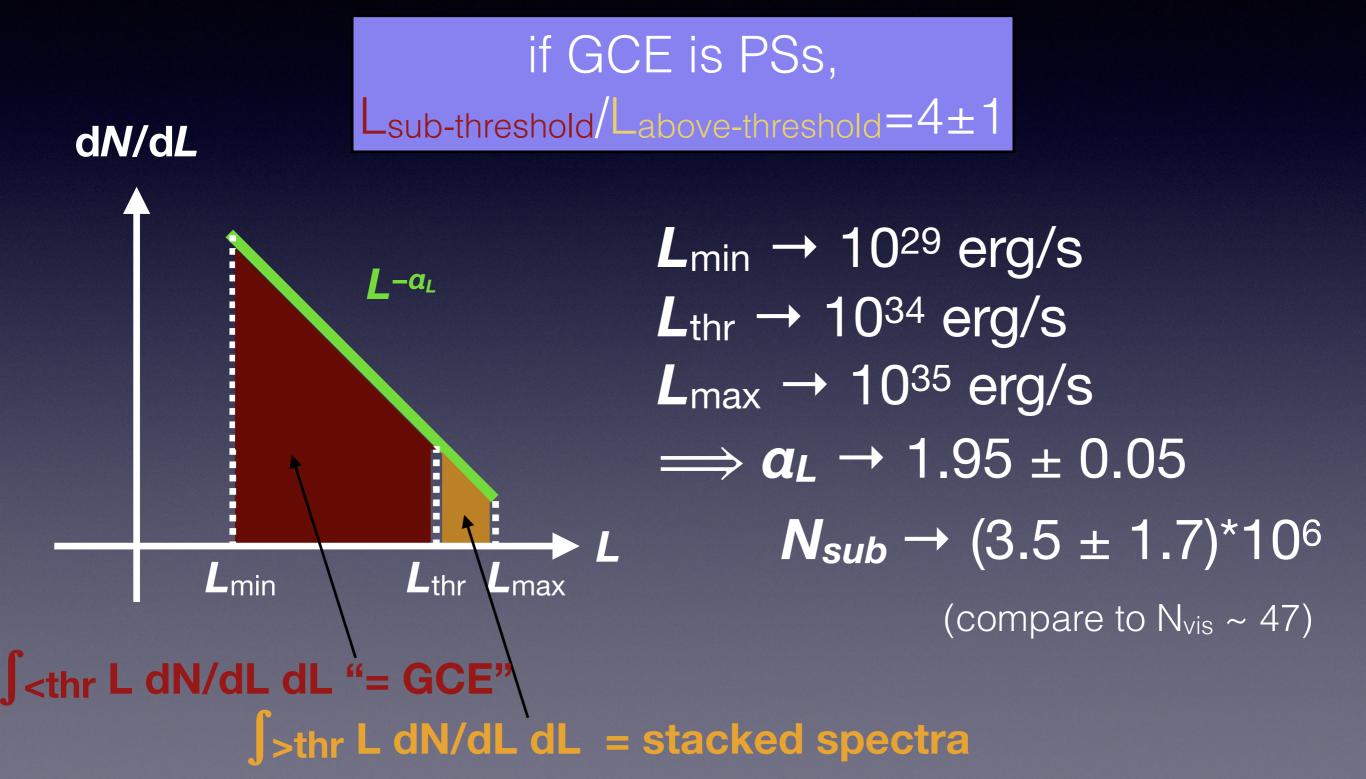
How to characterize a Central Source Population?

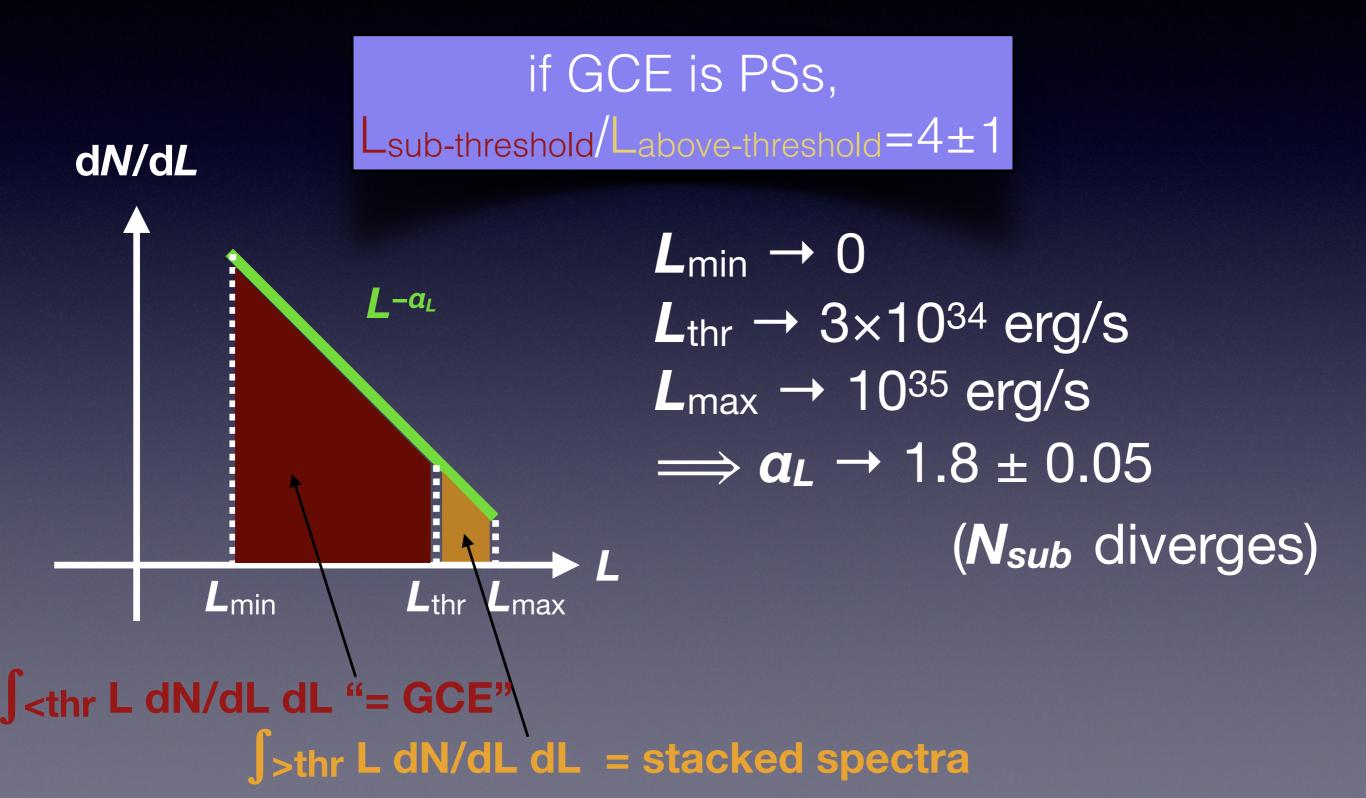


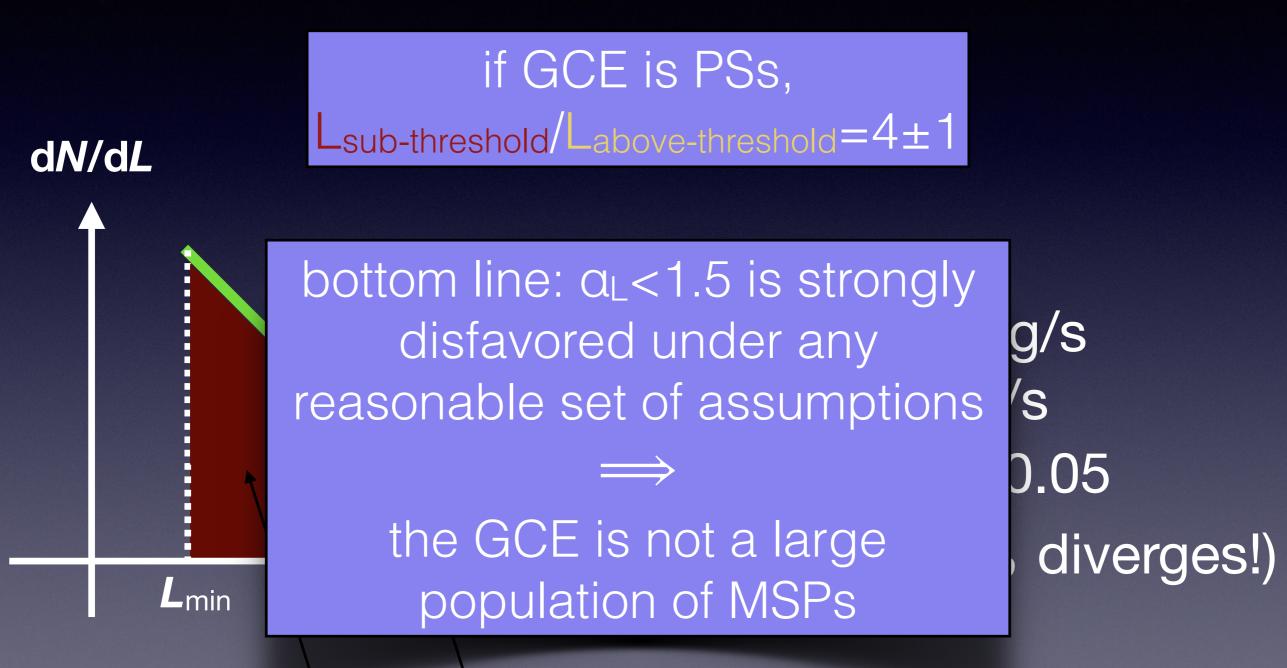
0609359, 0610649, 1407.5583, 1411.0559, 1411.2980, ...





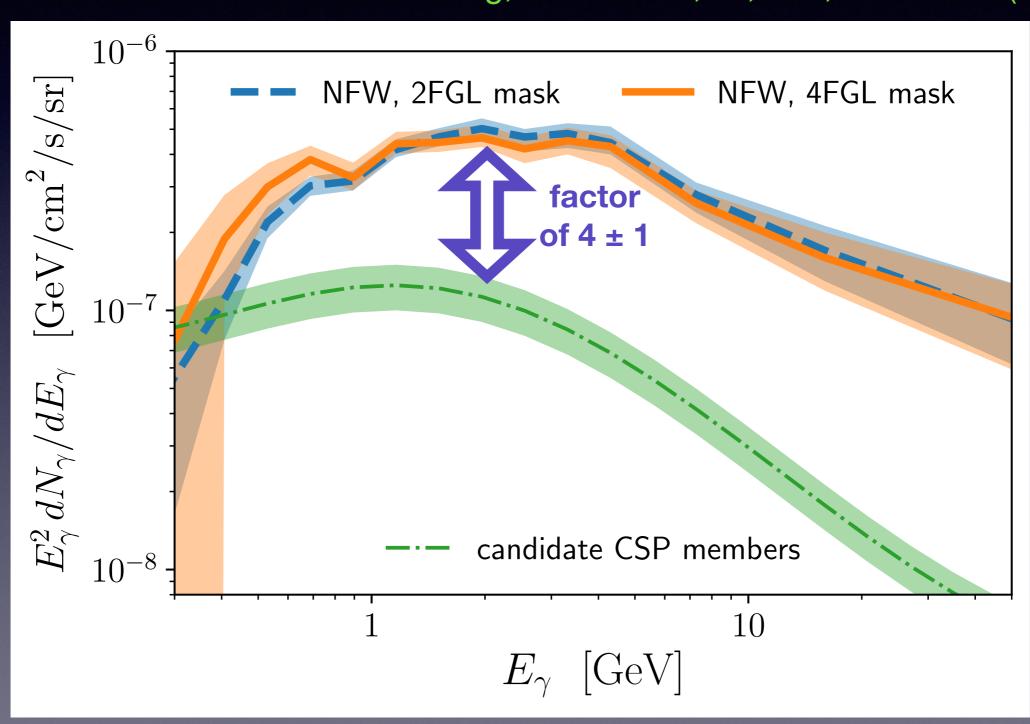




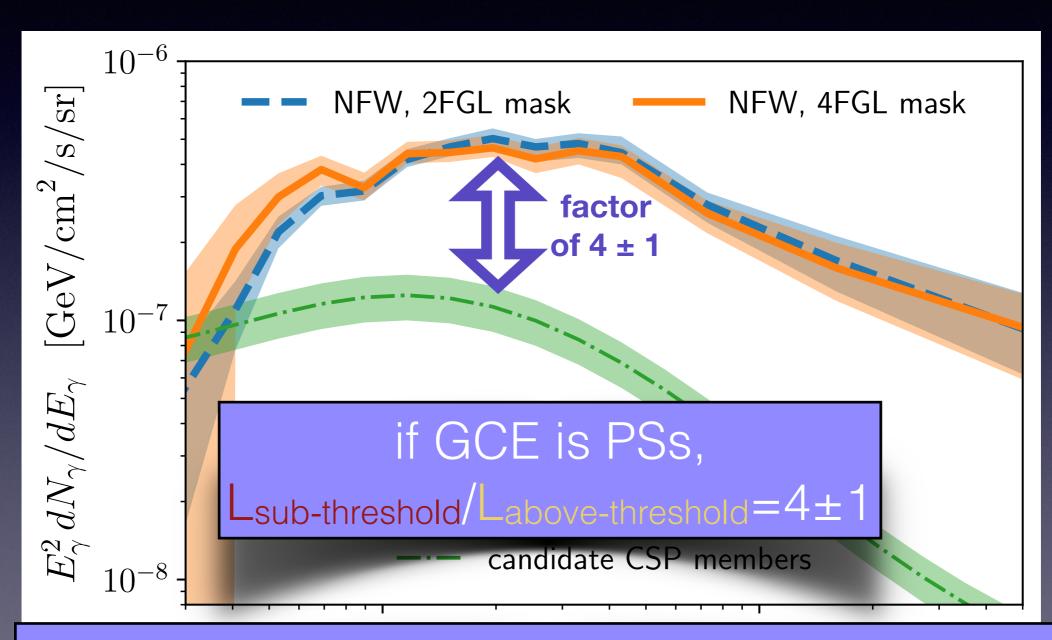


Compare Spectra

Zhong, McDermott, IC, Fox, PRL 2020 (1911.12369)



Implications for GCE

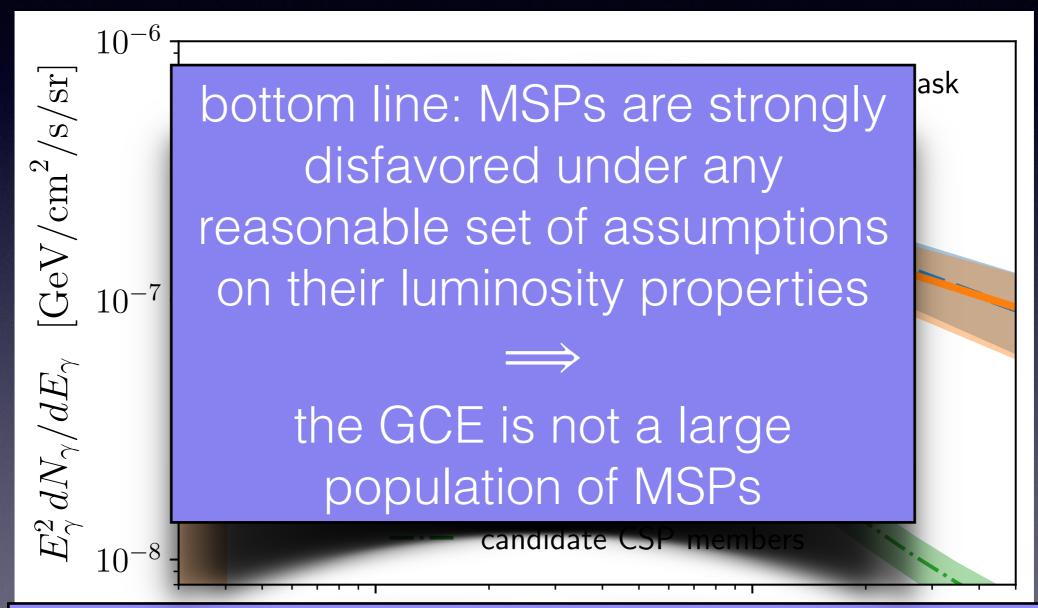


(and: spectrum must be substantially different)

Implications for GCE

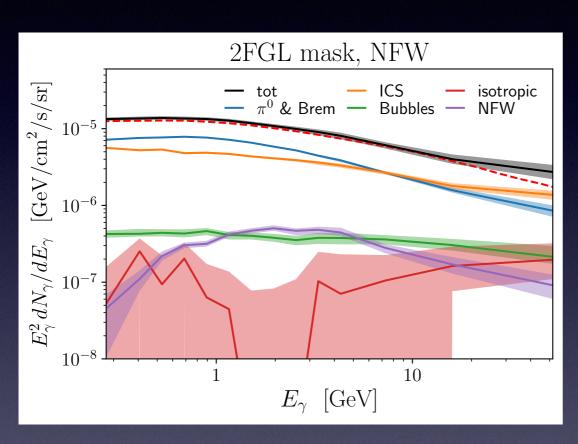
Zhong, McDermott, IC, Fox, PRL 2020 (1911.12369)

Leane & Slatyer PRD 2020

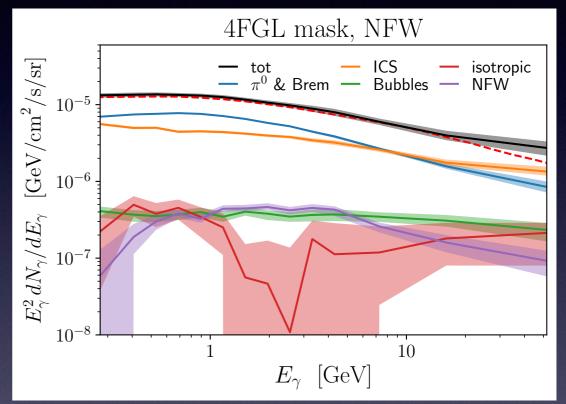


(and: spectrum must be substantially different)

GCE: Template Fit Results



Zhong, McDermott, IC, Fox, PRL 2020

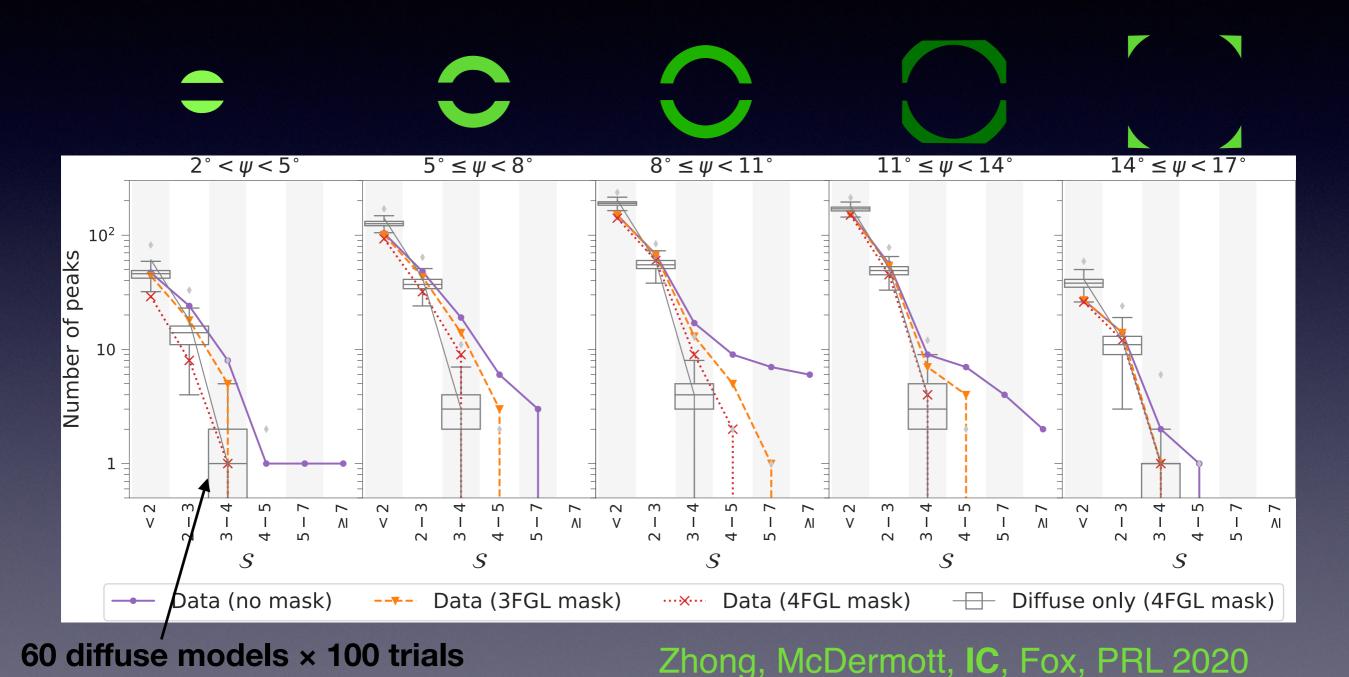


preference slightly smaller (fewer photons)

TABLE I. Difference in $-2 \ln \lambda$ (lower numbers are better) at the best fit points of each model, summed over energy bins, compared to our best fit for each mask.

Type of Mask	NFW	gNFW	no excess
2FGL	_	476	5430
4FGL	_	368	3600

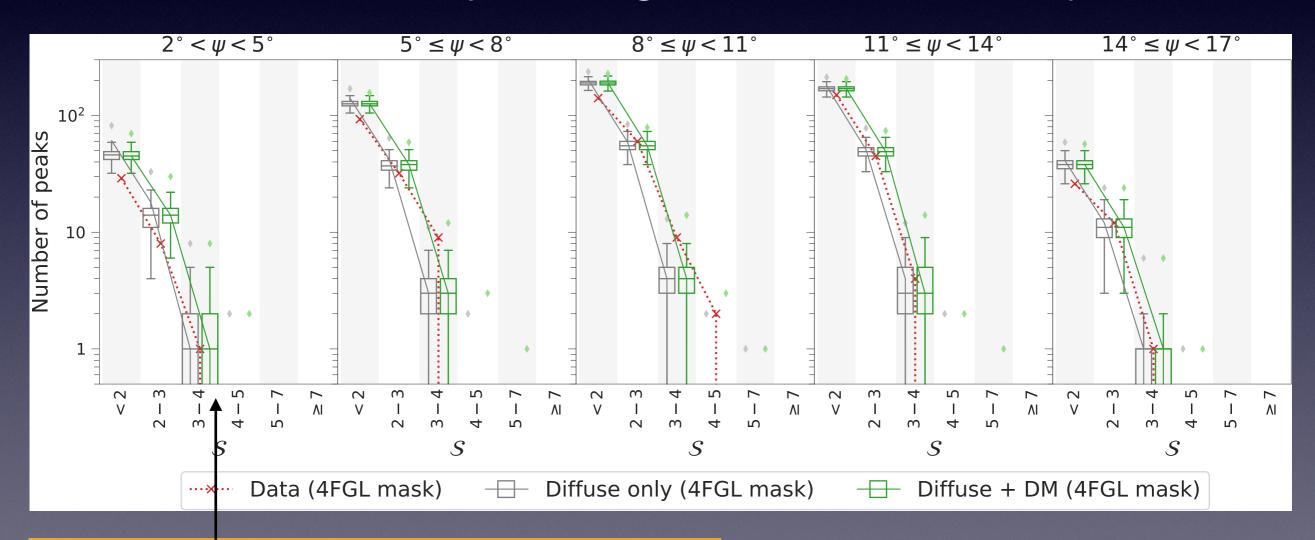
Counting "Wavelet" Peaks



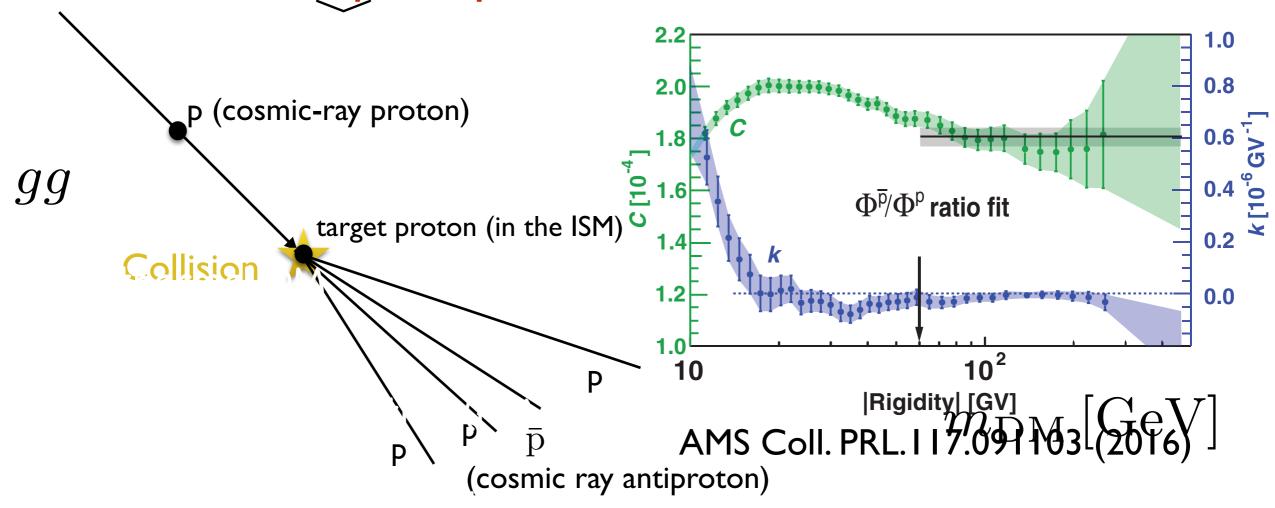
wavelet statistics change qualitatively with 4FGL!

DM or Cosmic-Ray Burst activity still work

No additional small-scale structure, so it looks just as good as diffuse-only



AMS-02 pbar/p ratio and Dark Matter



nels: gg (cyan), WW^* (green), $b\bar{b}$ (red),

e. We show the 1, 2, at 13σ contours.

norizontal line

Could we have an additional contribution?

asses and tinitation cross sections

are frequentist contour plots of the

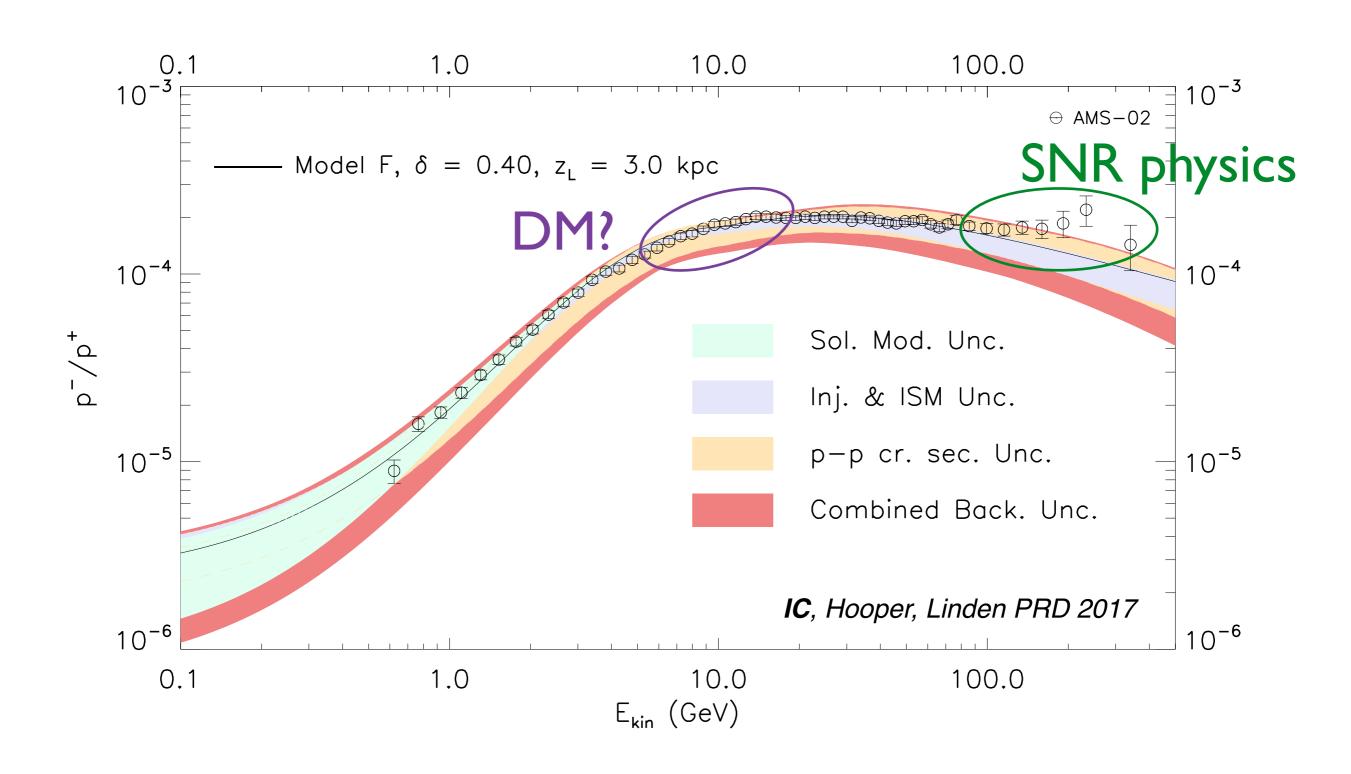
What about the Antiproton to Proton Ratio Uncertainties?

Antiprotons background uncertainties are very large.

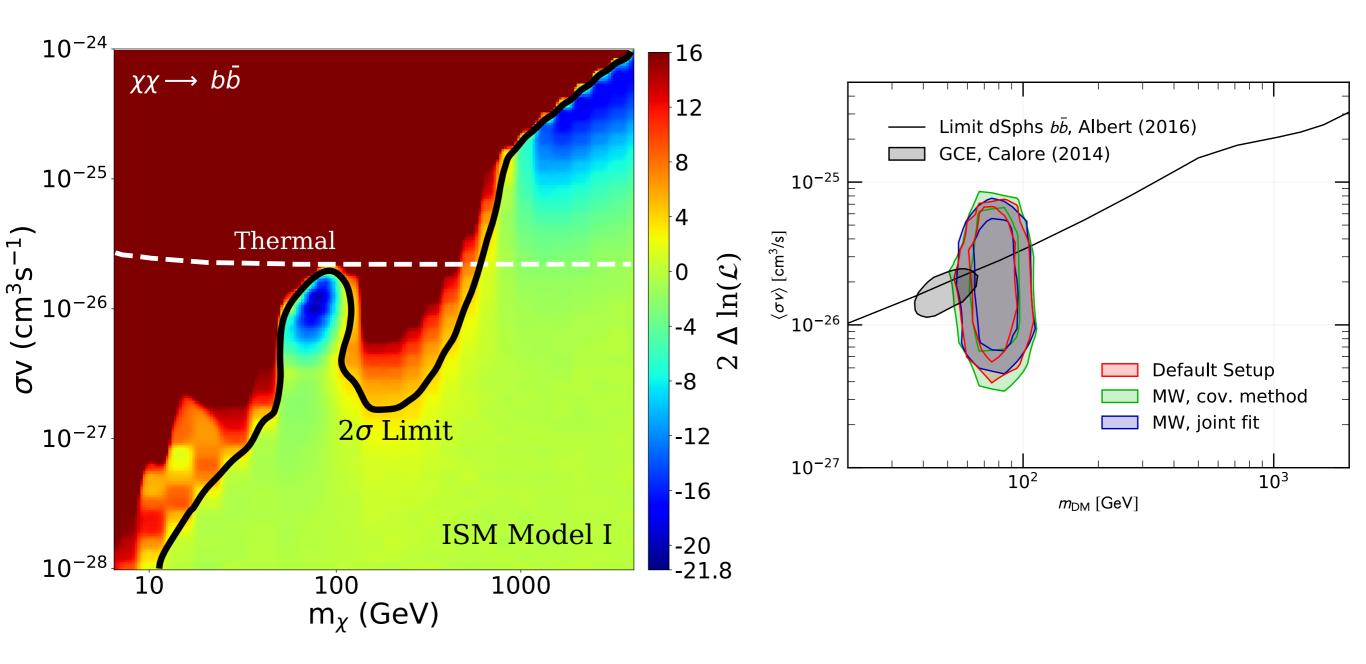
They are associated with:

- i) the antiproton production cross-section from CR protons and heavier nuclei collisions with the ISM gas
- ii) the propagation of CRs through the ISM
- iii) Solar Modulation (the propagation of CRs through the Heliosphere)

Combining all uncertainties together and marginalizing over them:

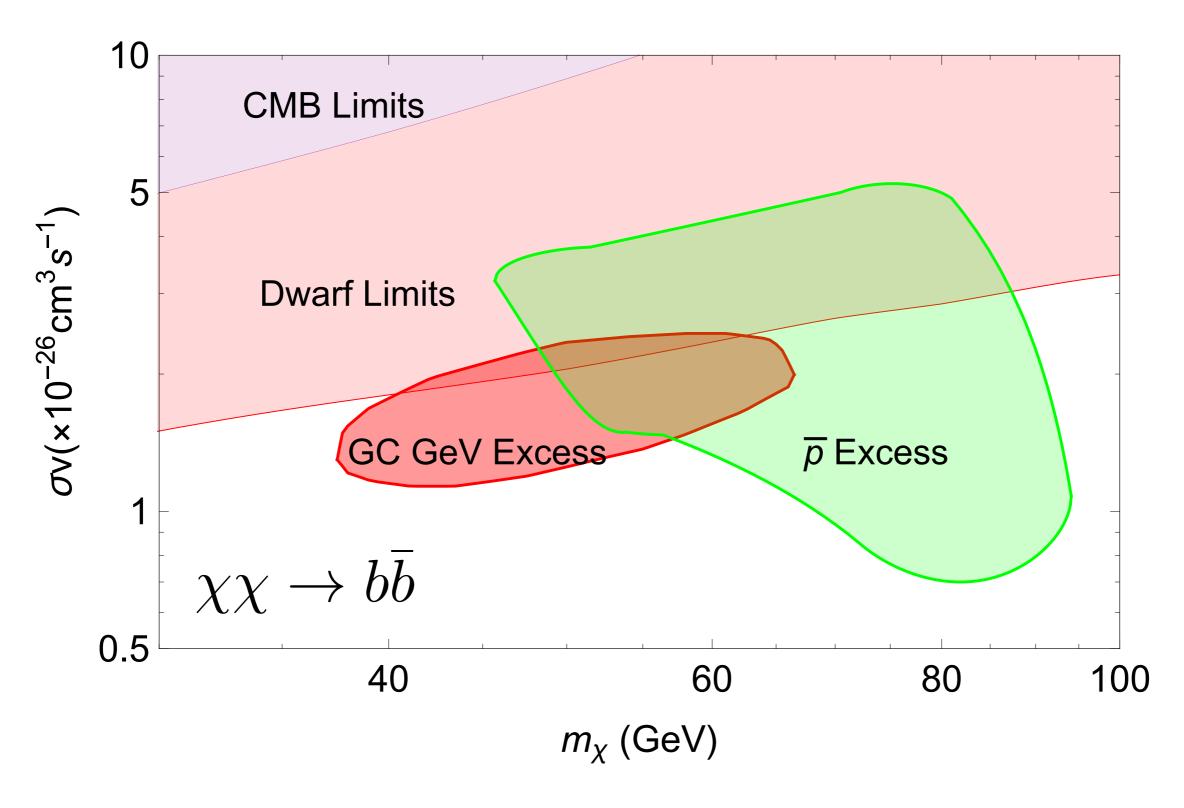


Looking at the antiproton to proton ratio find an the excess at~3 sigma

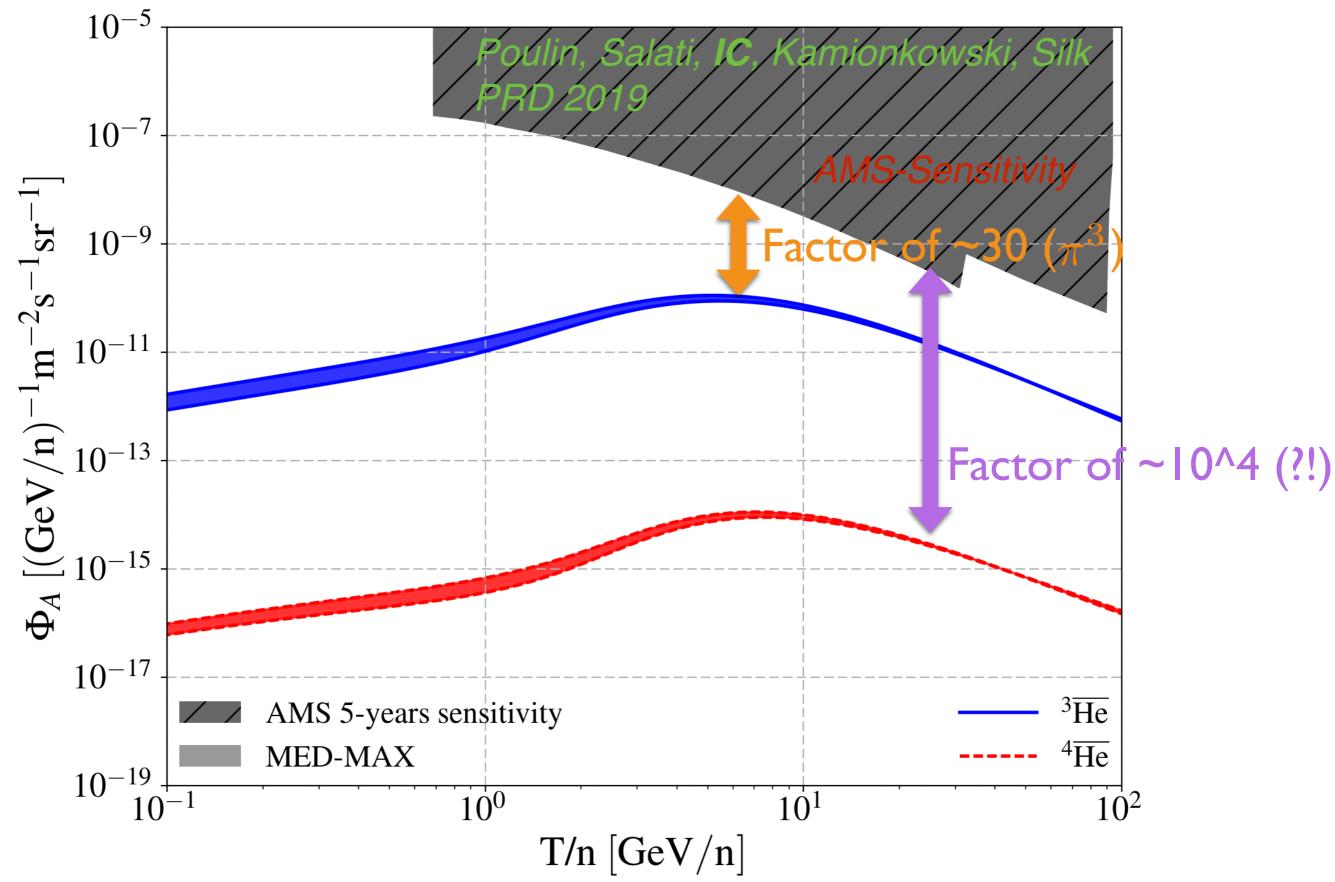


IC, Tim Linden, Dan Hooper PRD 2019

A. Cuoco et al. PRD 2019

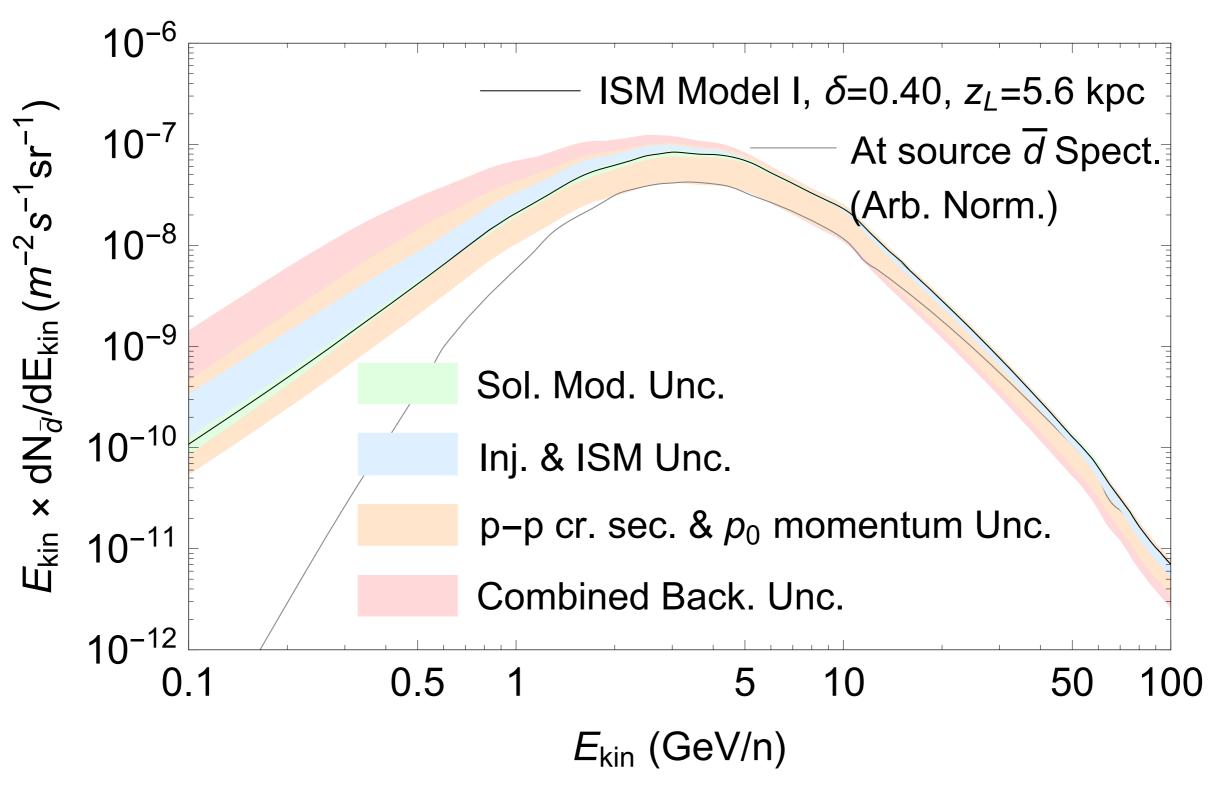


IC, Linden, Hooper PRD 2019

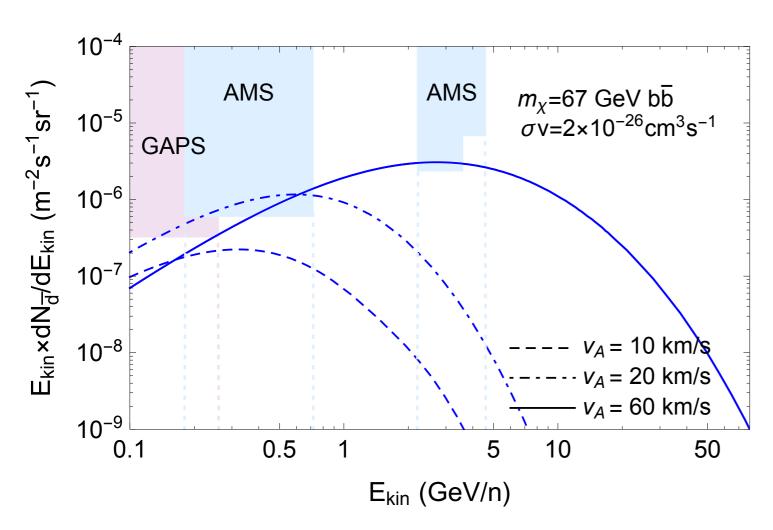


There is an unexpected amplitude on the flux of anti-He

Anti-deuterons Uncertainties



IC, Linden, Hooper PRD 2020



Diffusive re-acceleration in regions of high turbulence can reshape antimatter cosmic-ray spectra from energies where instruments can not detect them to energies where AMS02 and future GAPS can.

IC, Linden, Hooper PRD 2020

