“Annihilation Phenomenology”

Christoph Weniger
GRAPPA, University of Amsterdam

Thursday 26th March 2015, Effective Field Theories and Dark Matter, Mainz

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GRavitation AstroParticle Physics Amsterdam

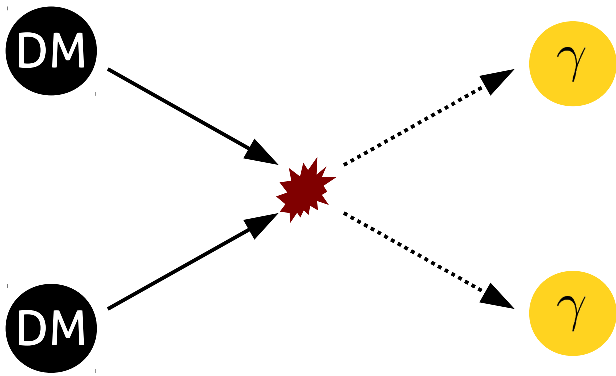
NWO

Overview

- Galactic center excess & PCA
- Best fit DM models
- HEP uncertainties in spectrum
- The last point of the pMSSM
- Constraints from dwarfs
- Cross correlations
- Antiprotons
- Future prospects

DM annihilation processes

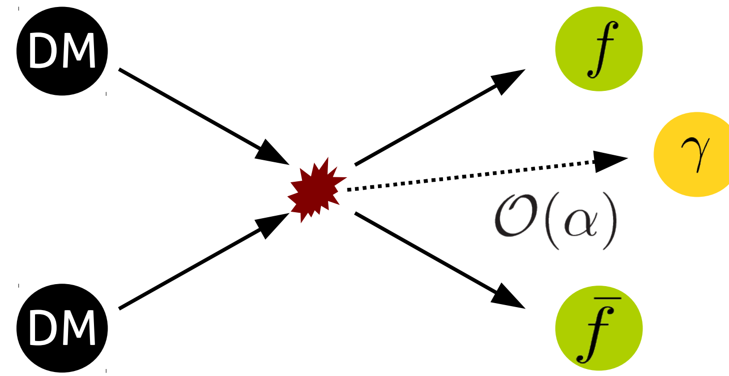
Gamma-ray lines:
Two-body annihilation into photons



[Bergström & Snellman (1988)]

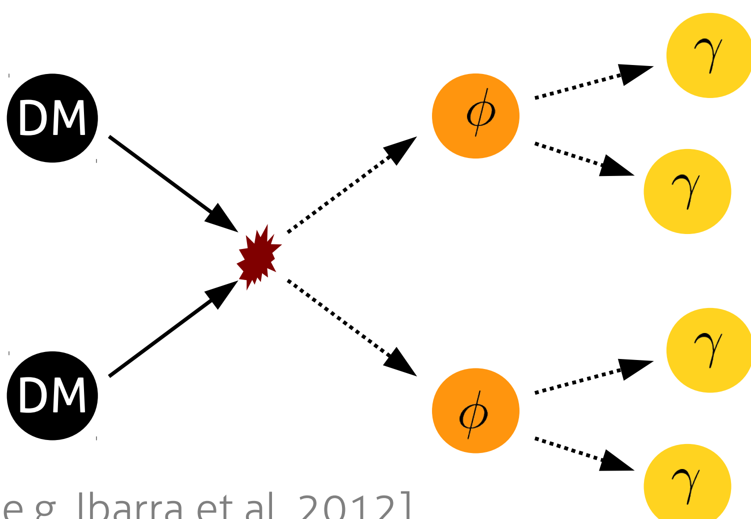
$$\mathrm{BR}(\chi\chi \to \gamma\gamma) \sim \alpha_{\mathrm{em}}^2 \sim 10^{-4}$$

Bremsstrahlung:
Photon production in “hard process”



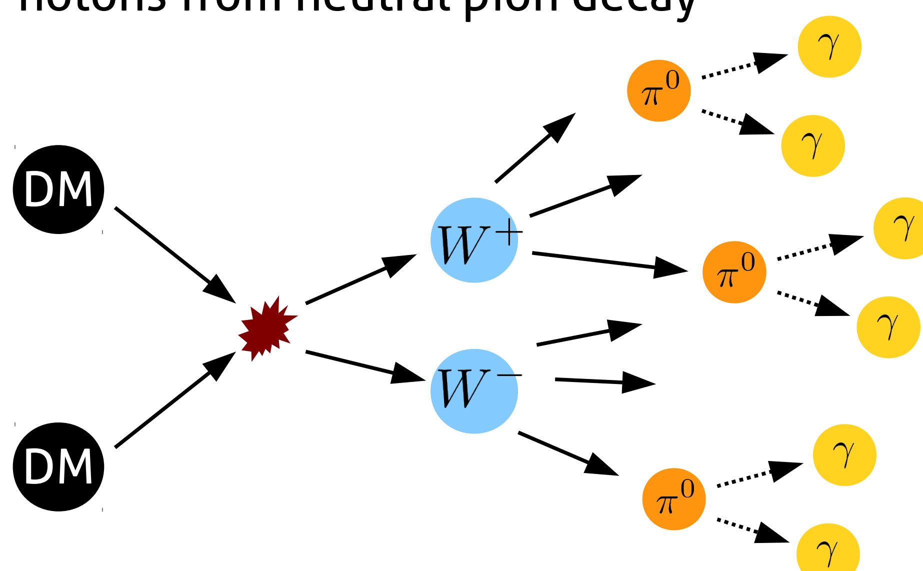
[e.g. Bringmann, Bergström & Edsjö (2008)]

Box-shaped spectra:
Photons from cascade decay

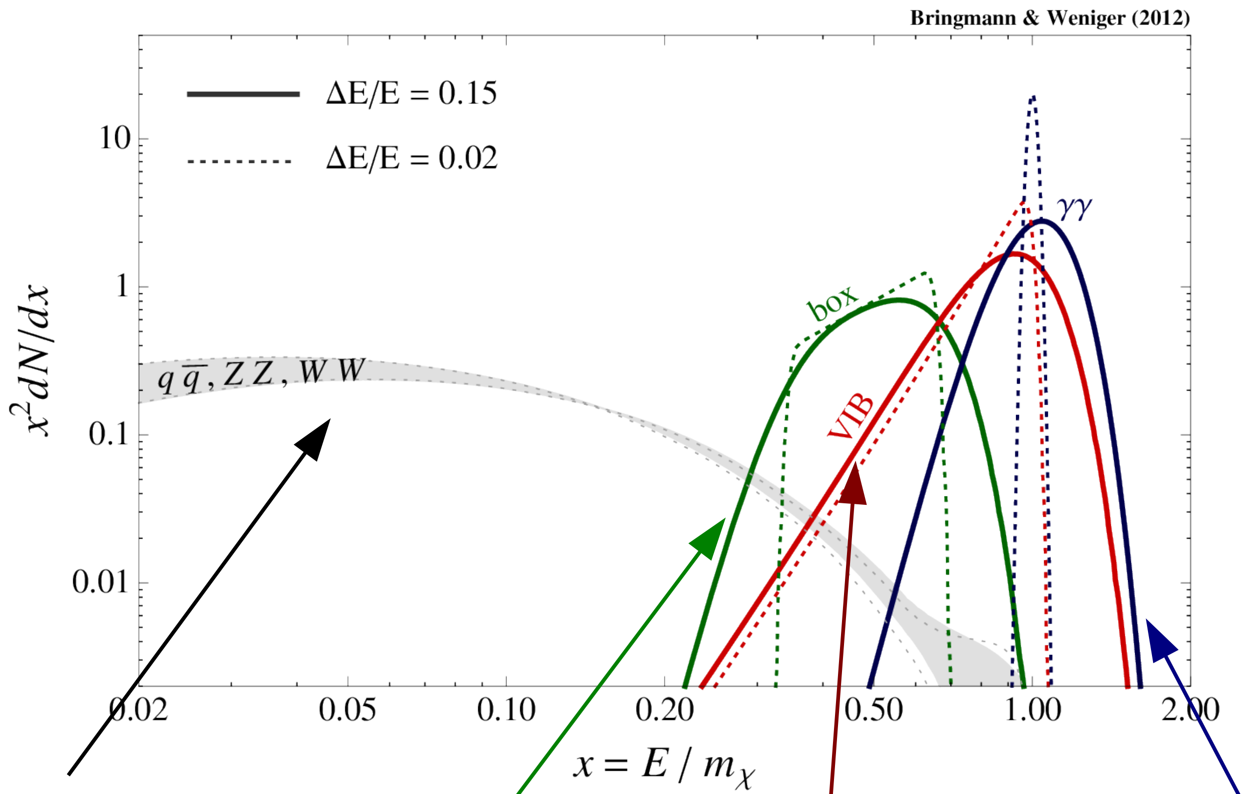


[e.g. Ibarra et al. 2012]

Continuum emission:
Photons from neutral pion decay



Spectral features in the case of photons



Continuum emission aka secondary photons

(from hadronic channels, as discussed above)

Cascade decays

$$\chi\chi \to \phi\phi \to \gamma\gamma\gamma\gamma$$

Internal Bremsstrahlung (IB)

$$\chi\chi \to \bar{f} f \gamma$$

Gamma-ray lines

$$\chi\chi \to \gamma\gamma$$

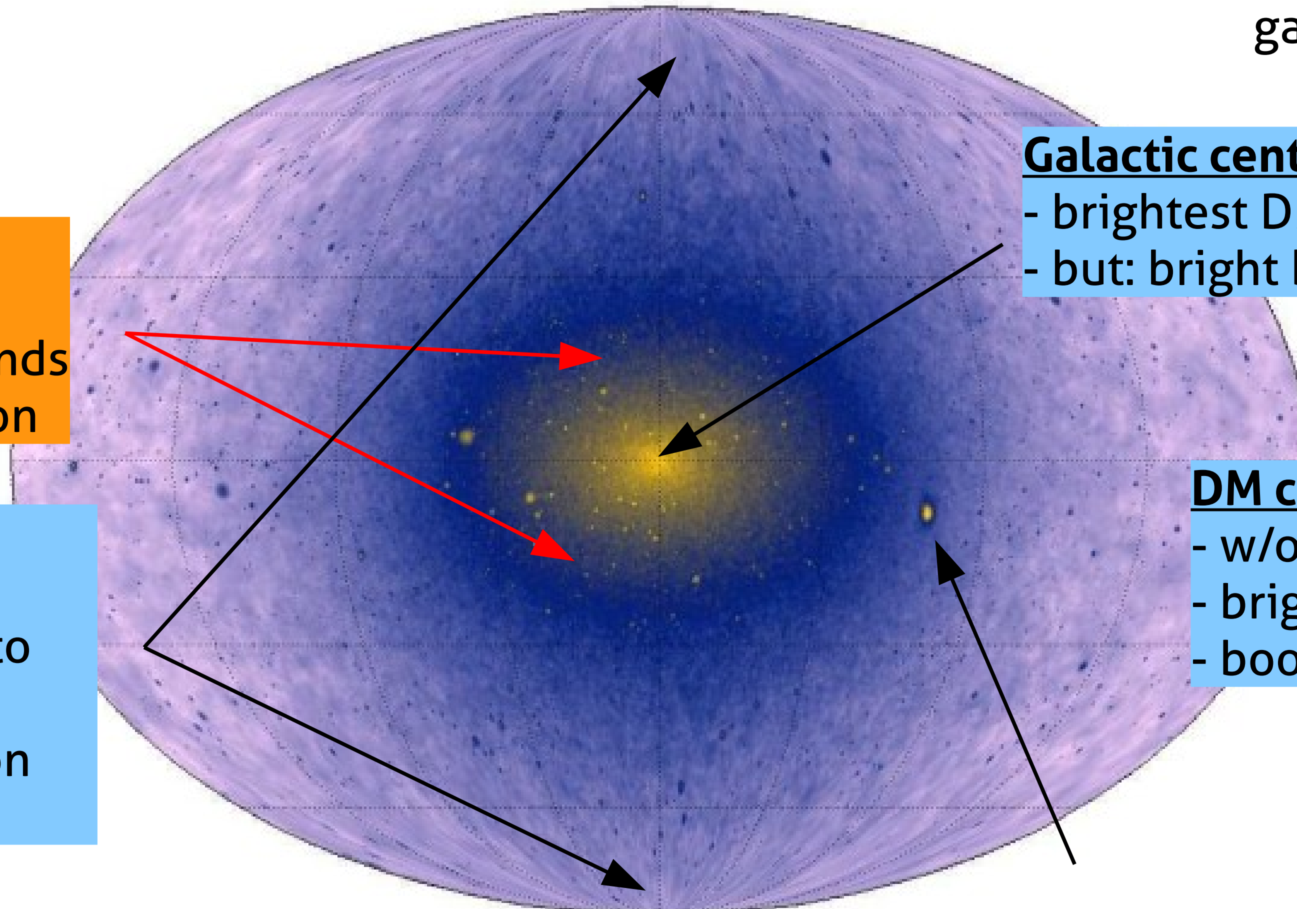
Potential targets for searches with photons

Signal is approx. proportional to column square density of DM:

$$\propto \int_{\mathrm{l.o.s.}} ds\, \rho_{\mathrm{DM}}^2$$

Extended or diffuse:
(for observations with gamma rays)

Point-like:
(for observations with gamma rays)



Galactic DM halo
- good S/N
- difficult backgrounds
- angular information

Extragalactic
- nearly isotropic
- only visible close to Galactic poles
- angular information
- Galaxy clusters?

Galactic center (~8.5 kpc)
- brightest DM source in sky
- but: bright backgrounds

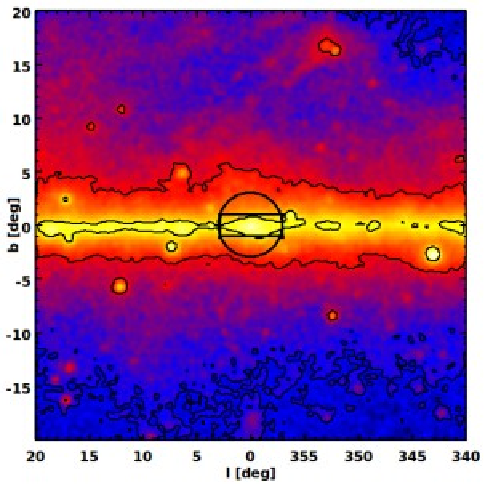
DM clumps
- w/o baryons
- bright enough?
- boost overall signal

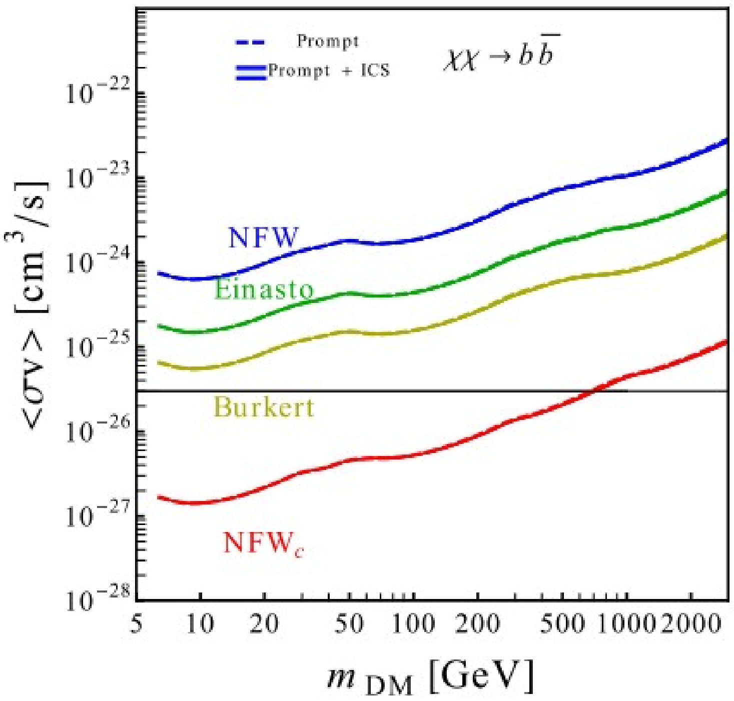
Dwarf Spheroidal Galaxies
- harbour small number of stars
- otherwise dark (no gamma-ray emission)

[review on N-body simulations: Kuhlen, Vogelsberger & Angulo (2012)]

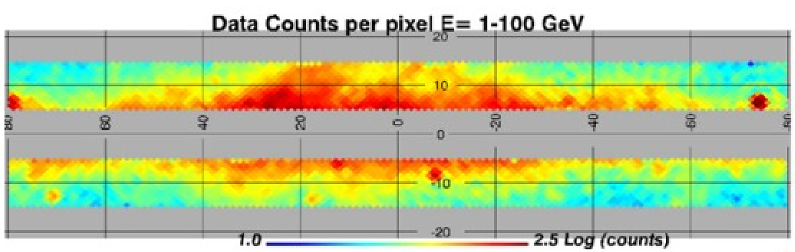
Galactic center analysis

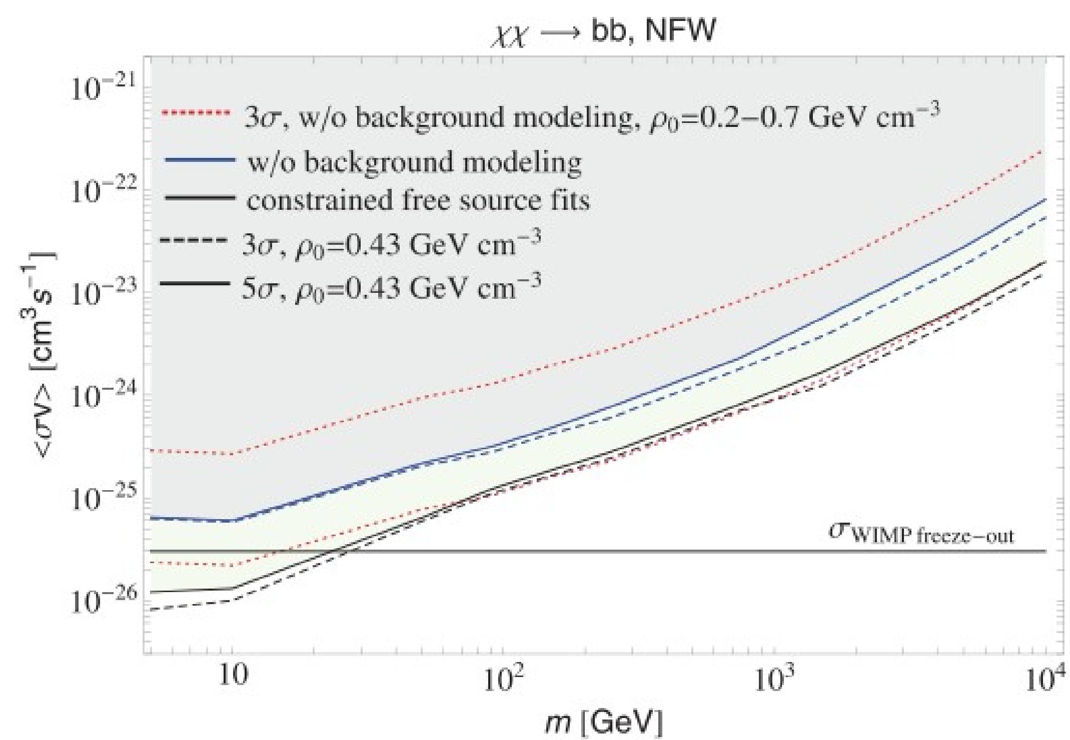
Constraints on WIMP Annihilation for Contracted Dark Matter in the Inner Galaxy with the Fermi-LAT [Gomez-Vargas+ 1308.3515]





Constraints on the Galactic Halo Dark Matter from Fermi-LAT diffuse measurements
[Ackermann+ 1205.6474]





Tavakoli+ 2014; Gomez-Vargas+ 2014; Ackermann+ 2011; Hooper & Linden 2011

Fermi GC excess: First appearance in 2009

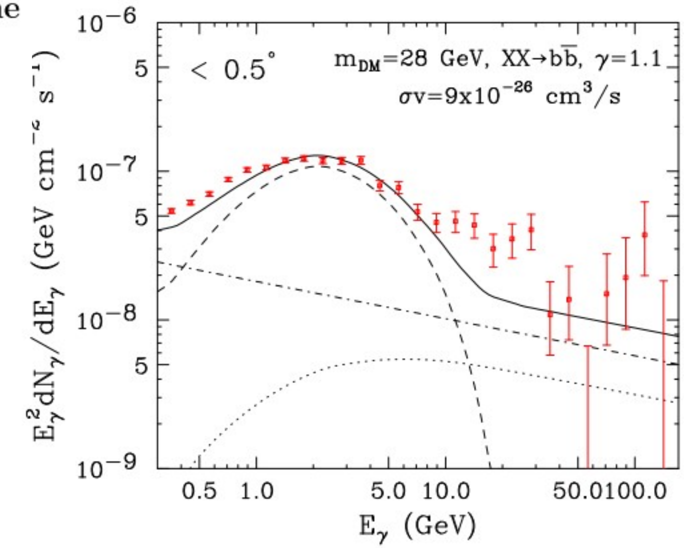
First clear statements about properties of *excess* emission (morphology, spectrum etc, subject to some changes in later analyses):

Possible Evidence For Dark Matter Annihilation In The Inner Milky Way From The Fermi Gamma Ray Space Telescope

Lisa Goodenough[1] and Dan Hooper[2,3]

[1] *Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003*
[2] *Center for Particle Astrophysics, Fermi National Accelerator Laboratory, Batavia, IL 60510*
[3] *Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637*

We study the gamma rays observed by the Fermi Gamma Ray Space Telescope from the direction of the Galactic Center and find that their angular distribution and energy spectrum are well described by a dark matter annihilation scenario. In particular, we find a good fit to the data for dark matter particles with a 25-30 GeV mass, an annihilation cross section of $\sim 9 \times 10^{-26}$ cm^3/s, and that are distributed with a cusped halo profile, $\rho(r) \propto r^{-1.1}$, within the inner kiloparsec of the Galaxy. We cannot, however, exclude the possibility that these photons originate from an astro-



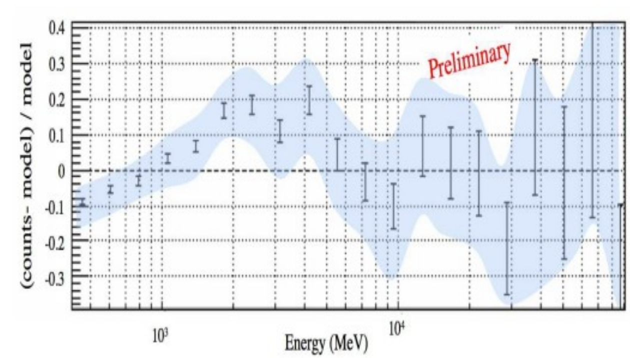
First very cautious comments by the LAT team, without any detailed characterization of the *residual*:

2009 Fermi Symposium, Washington, D.C., Nov. 2-5

Indirect Search for Dark Matter from the center of the Milky Way with the Fermi-Large Area Telescope

Vincenzo Vitale and Aldo Morselli, for the Fermi/LAT Collaboration
Istituto Nazionale di Fisica Nucleare, Sez. Roma Tor Vergata, Roma, Italy

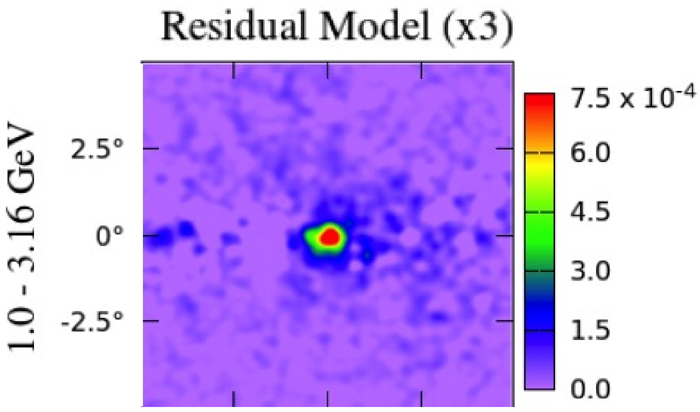
cations, is reported. The diffuse gamma ray backgrounds and discrete sources, as we know them today, can account for the large majority of the detected gamma-ray emission from the Galactic Center. Nevertheless a residual emission is left, not accounted for by the above models.
An improved model of the Galactic diffuse emission and a careful evaluation of new (possibly unresolved) sources (or source populations) will improve the sensitivity for a DM search.

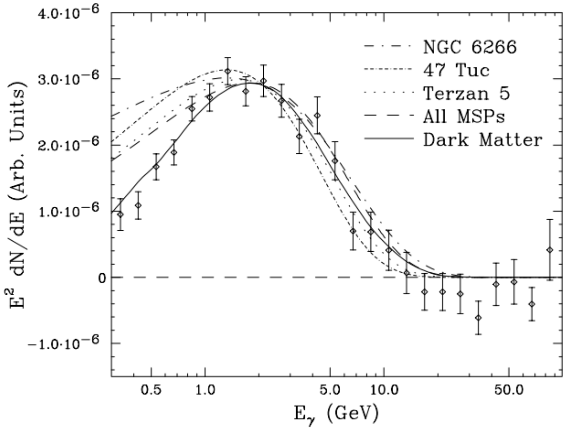


Follow-up studies

At the Galactic center (roughly 7deg x 7deg)

Goodenough & Hooper 2009
Hooper & Goodenough 2011
Hooper & Linden 2011
Boyarsky+ 2011
Abazajian & Kaplinghat 2012
Gordon & Macias 2013
Macias & Gordon 2014
Abazajian+ 2014
Daylan+2014

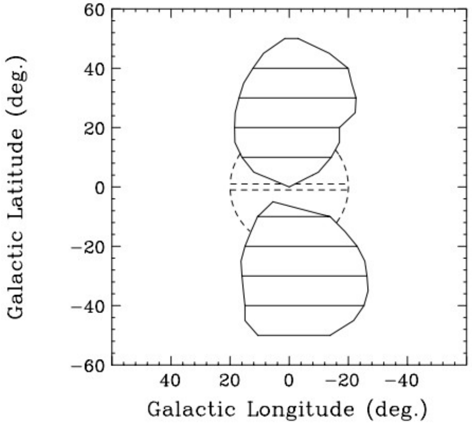


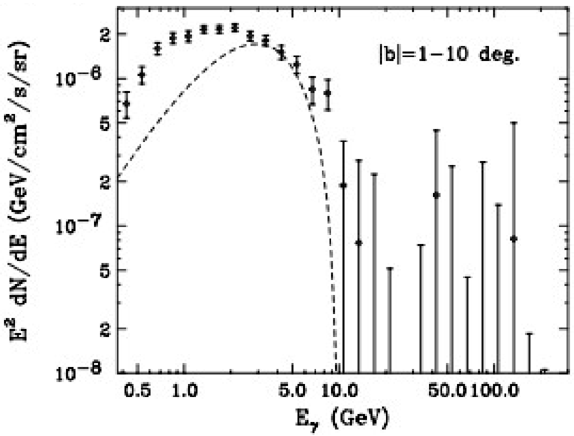


[Daylan+ 2014]

In the inner Galaxy (roughly |b|>1 deg to tens of deg)

Hooper & Slatyer 2013
Huang+ 2013
Zhou+ 2014
Daylan+ 2014

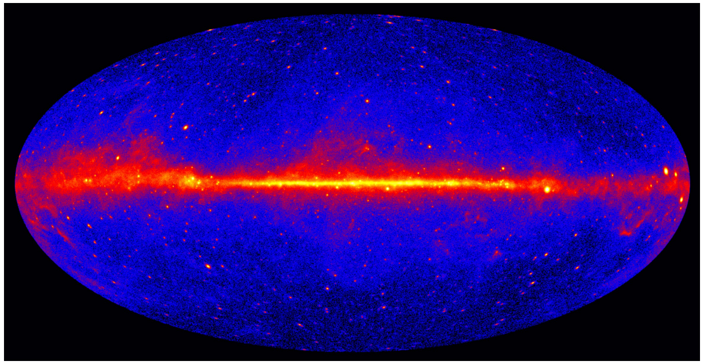




[Hooper & Slatyer 2013]

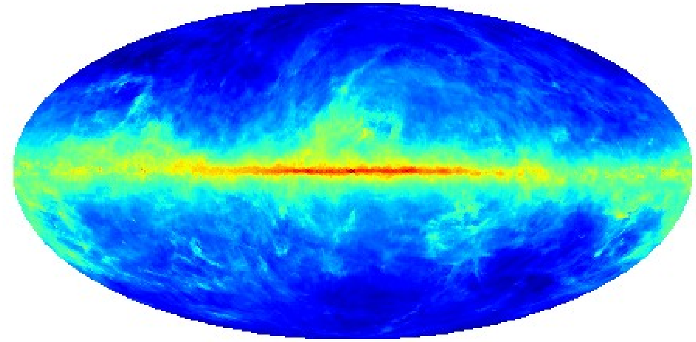
DM searches in the inner Galactic region with Fermi LAT

Fermi LAT; > 1 GeV

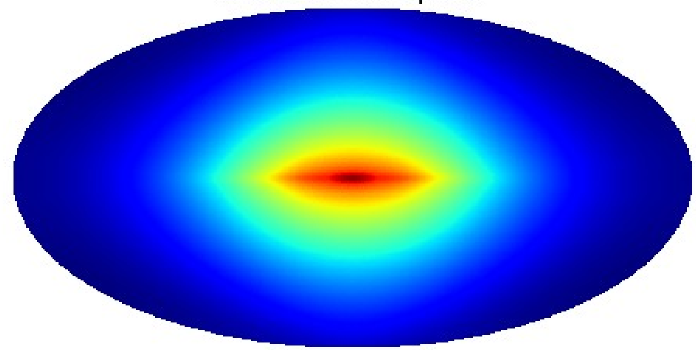


Subtract
1) Known point sources
2) Diffuse foregrounds

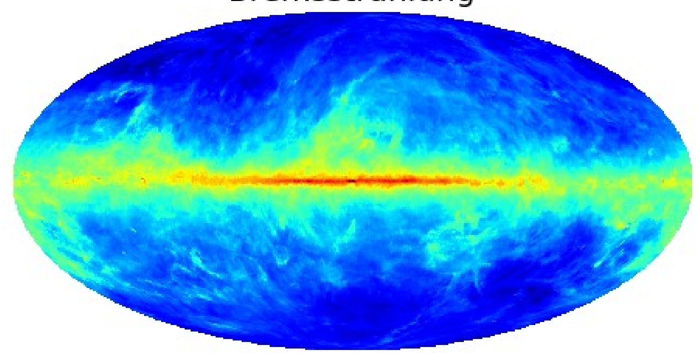
Pion decay



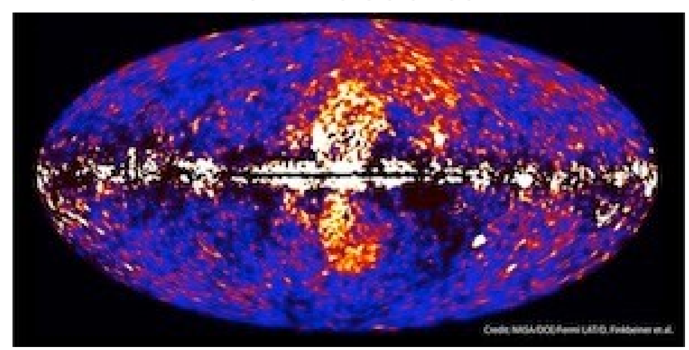
Inverse Compton



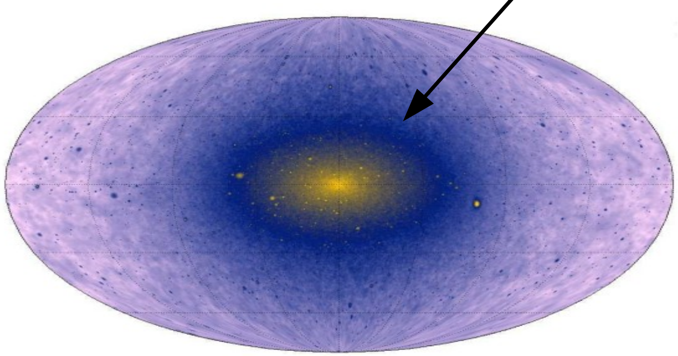
Bremsstrahlung



Fermi bubbles

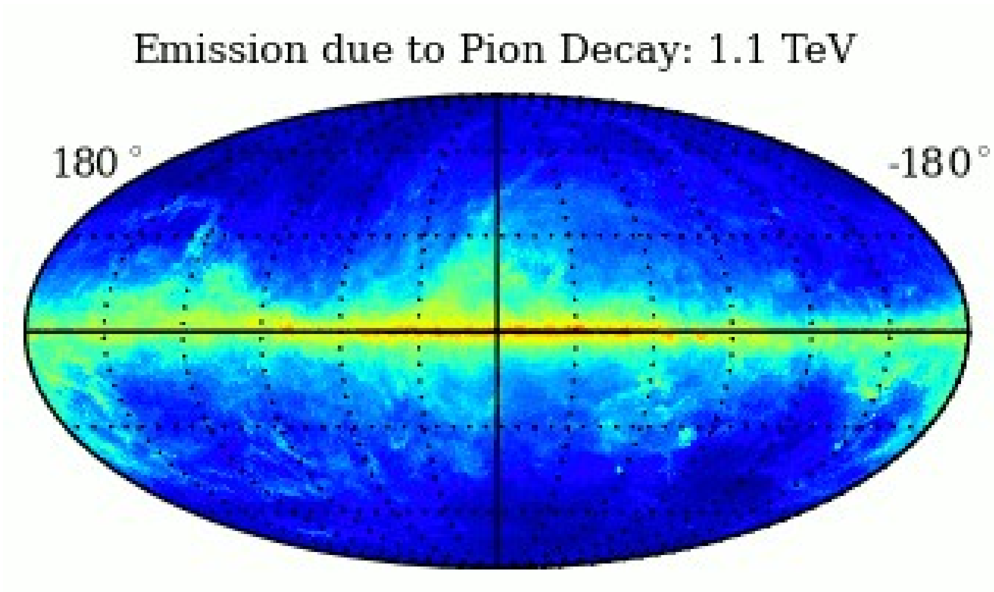


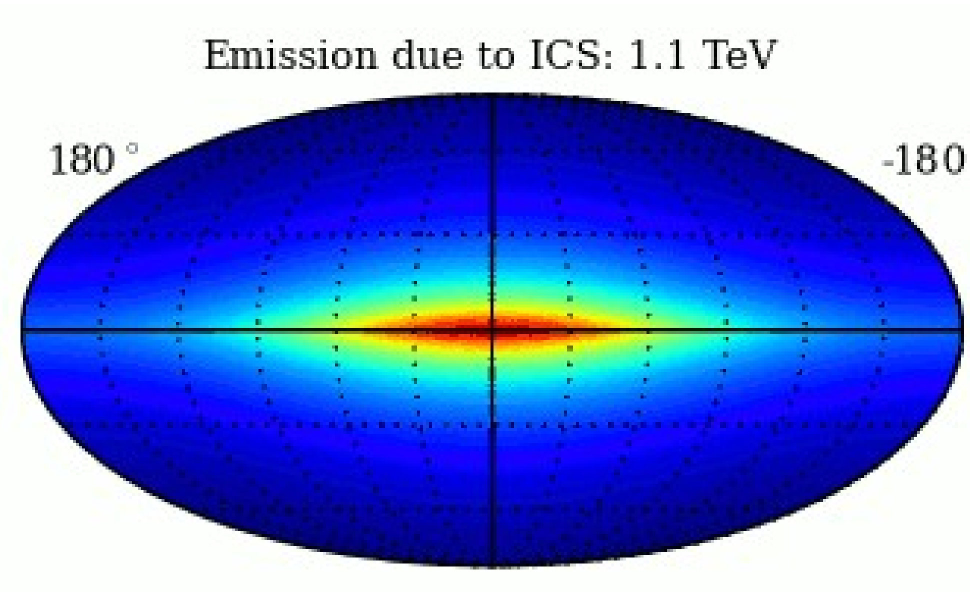
Do residuals look like this?



Diffuse Galactic backgrounds

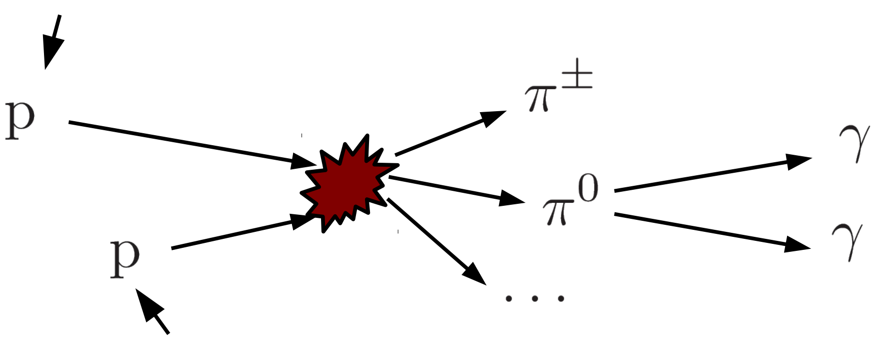
The diffuse gamma-ray emission from our Galaxy is produced by interaction of high energetic charged particles (electrons, protons, ...) with the interstellar medium (mostly Hydrogen and Helium) and interstellar radiation field (Cosmic Microwave background, starlight, dust radiation)





<u>Proton-proton collisions & subsequent neutral pion decay:</u>

high energy proton

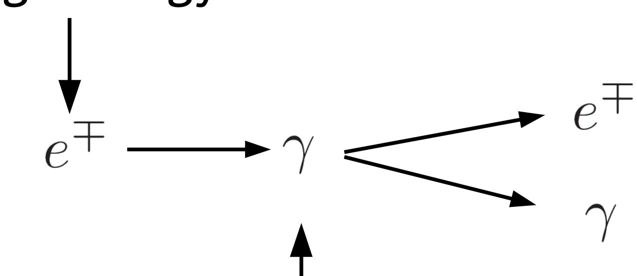


proton at rest

(at ~ sub-GeV energies also Bremsstrahlung)

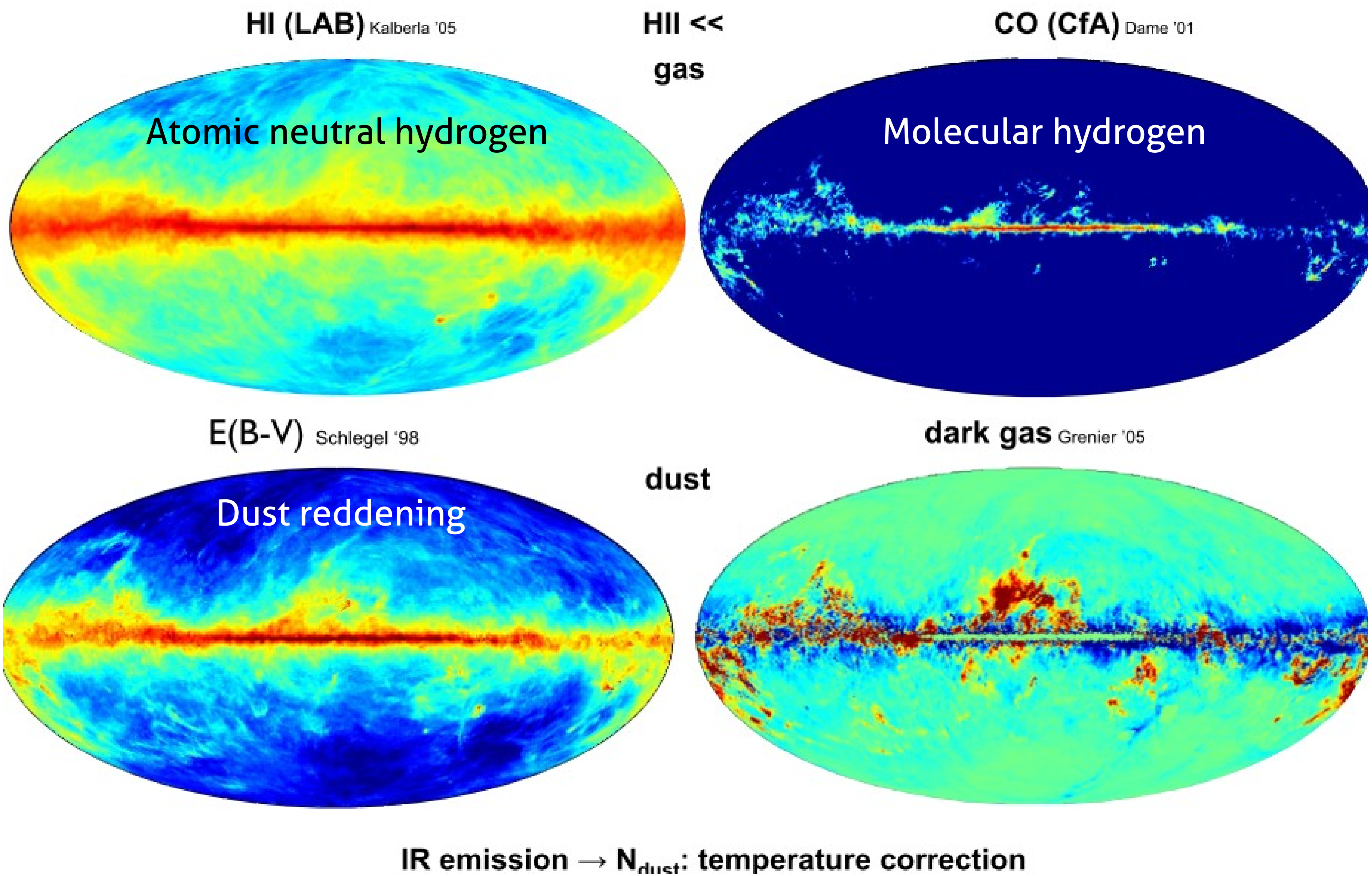
<u>Inverse Compton scattering:</u>

high energy electron



low energy photon
- cosmic microwave background
- starlight

Tracers of the interstellar medium

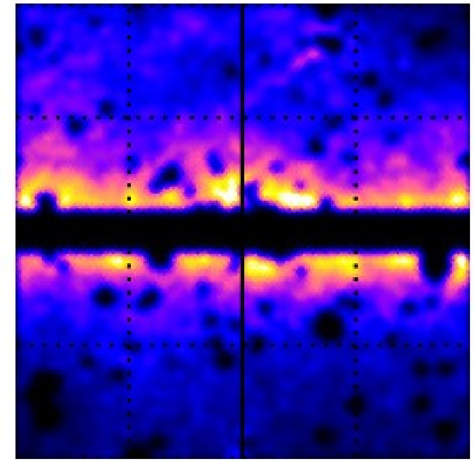


[slides borrowed from I. Grenier 2010]

Studying systematic uncertainties

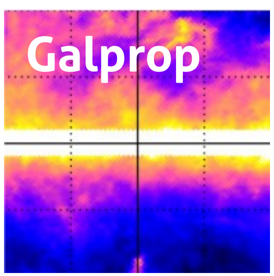
ROI:

- **"Inner Galaxy"**: $2^\circ \leq |b| \leq 20^\circ \quad \text{and} \quad |\ell| \leq 20^\circ$
- We mask all **point sources** from the 2FGL

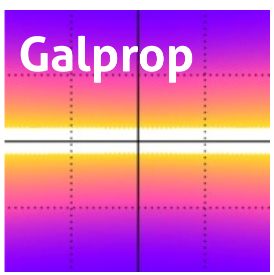


Components in the analysis:

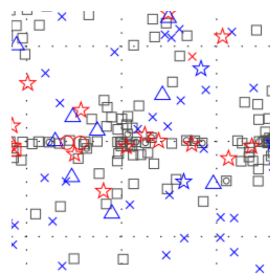
π^0+Bremss free



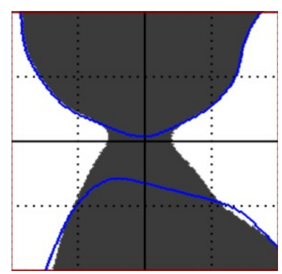
ICS free



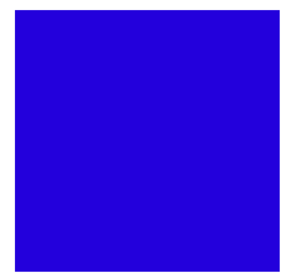
2FGL fixed



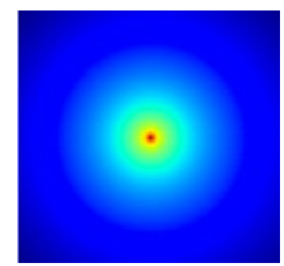
Bubbles constrained



Isotropic constrained



Excess template free

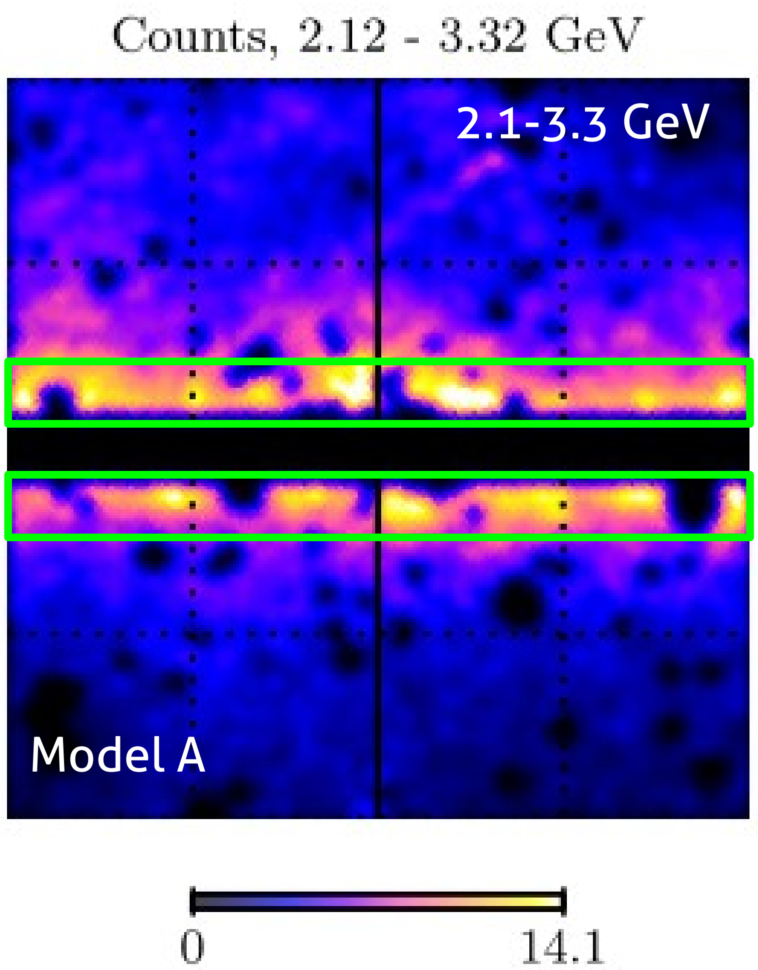


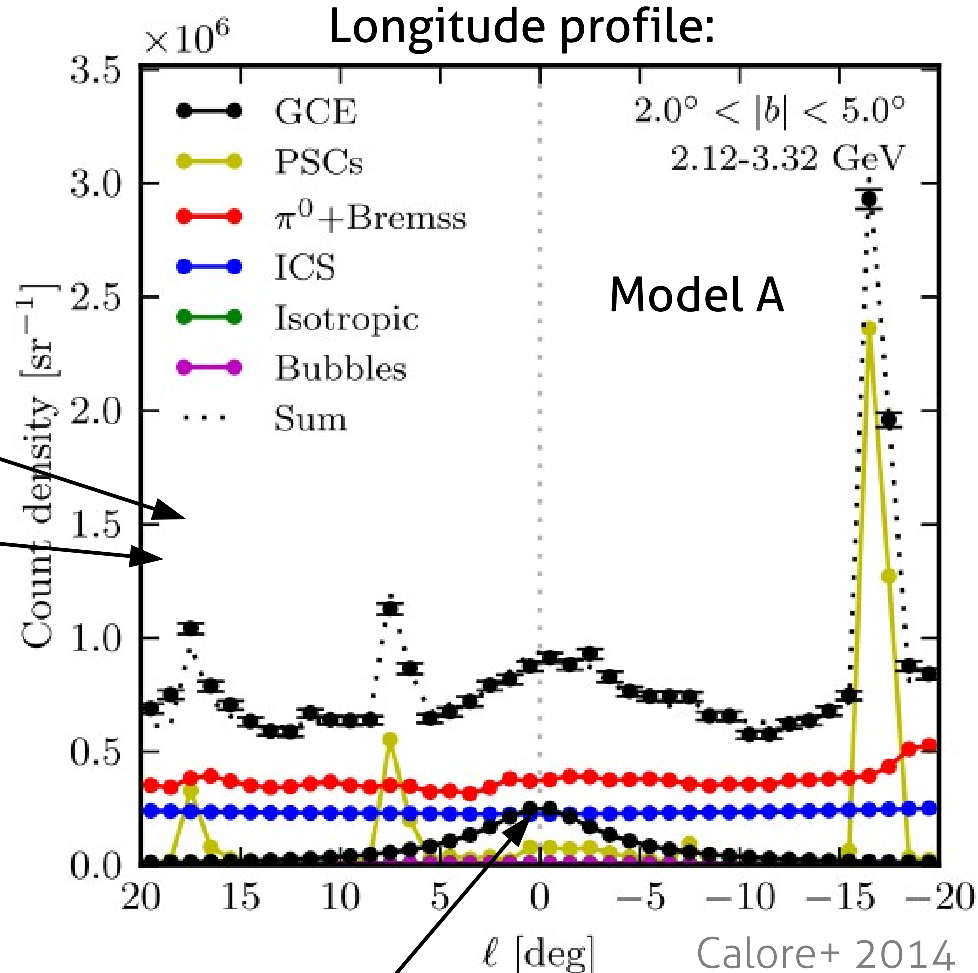
Energy dependent templates

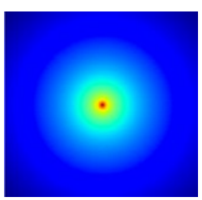
Energy independent templates

Fits independently in energy bins → Spectral information from Galprop models <u>is neglected</u>

Flux absorbed by the excess template

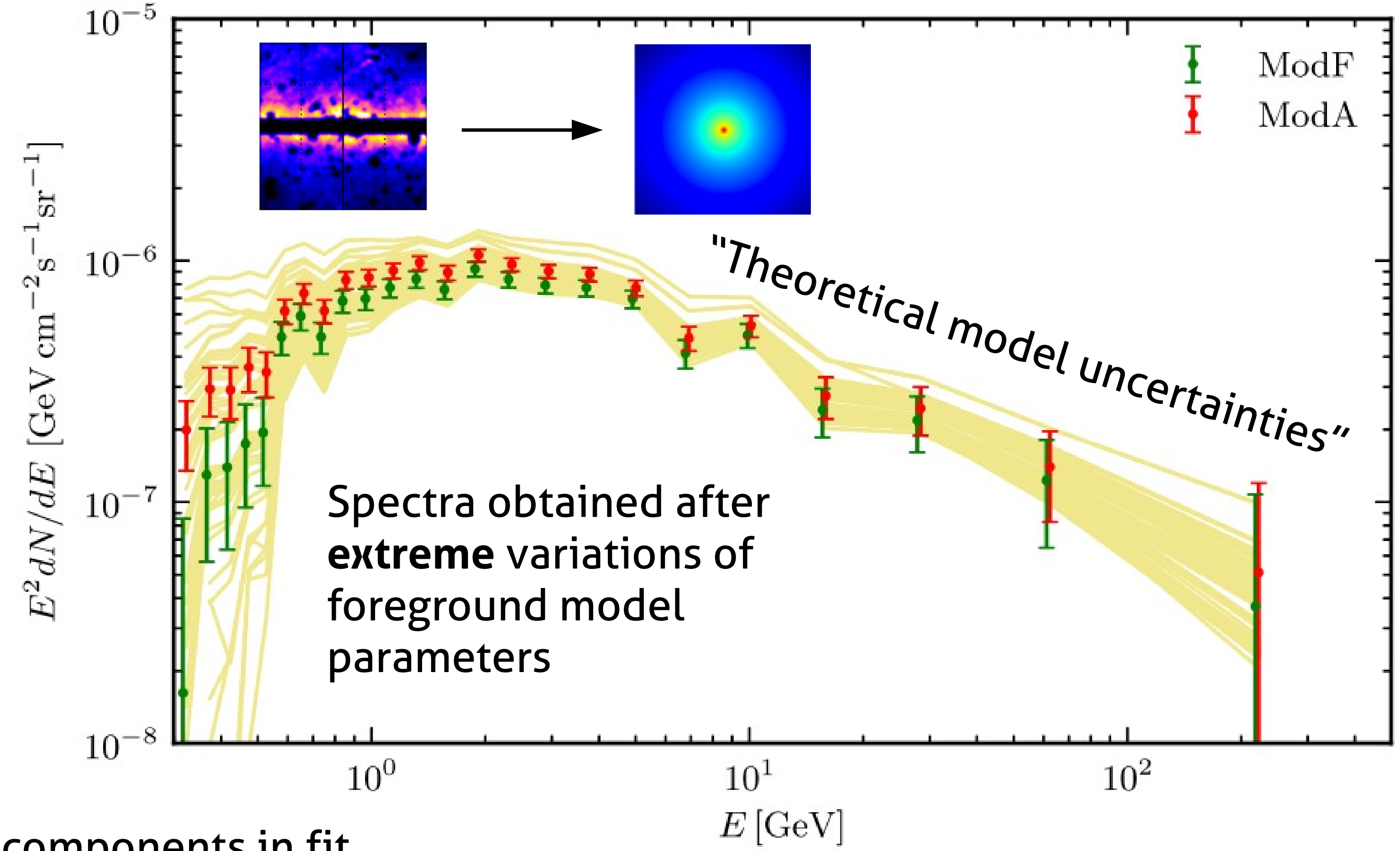




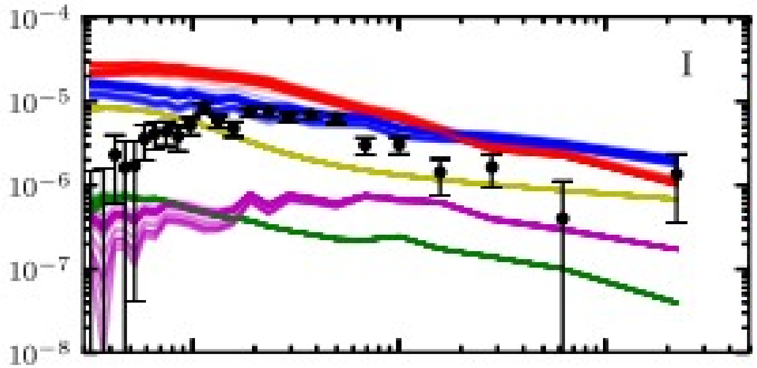


Flux in excess template exceeds expected ICS flux from inner region of Galaxy (for Model A) by a factor of ~ 5 to 20.

Theoretical model uncertainties



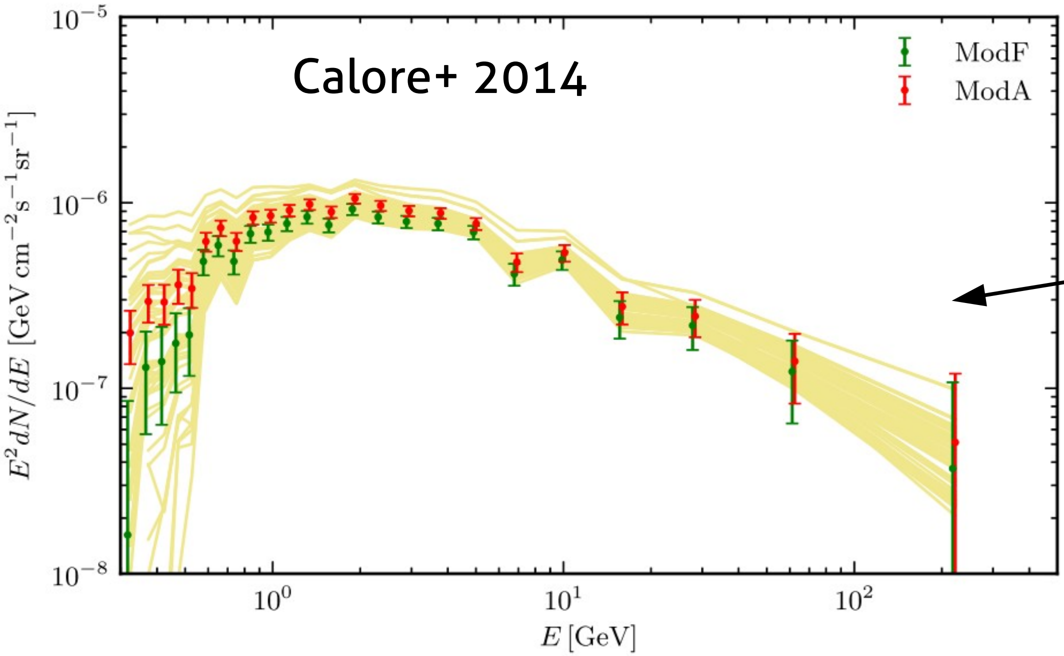
Individual components in fit only vary by ~O(2).



In all cases, the excess template spectrum

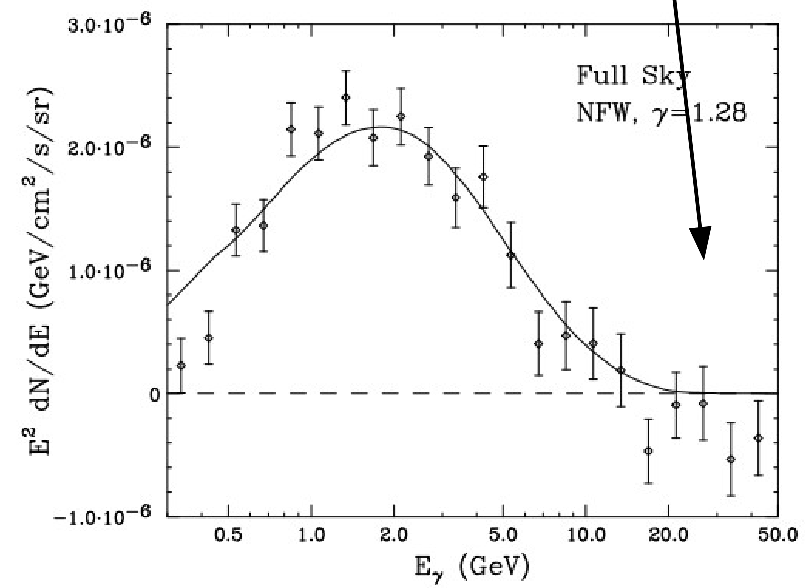
- rises from 300 MeV to ~1 GeV
- peaks at 1-3 GeV
- falls power-law like above 3 GeV **(no cutoff at >10 GeV energies as previously claimed)**

Does the spectrum have a high-energy tail?



?

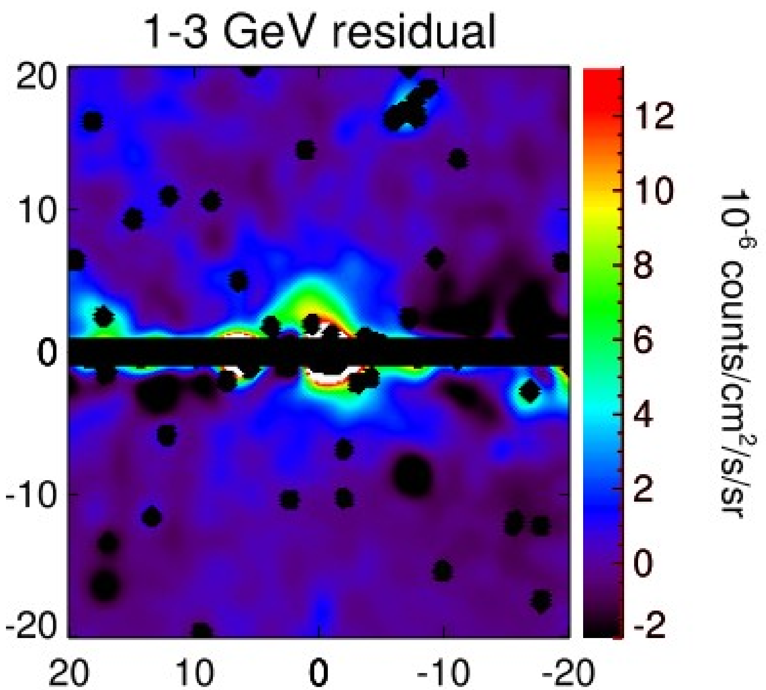
Daylan+ 2014

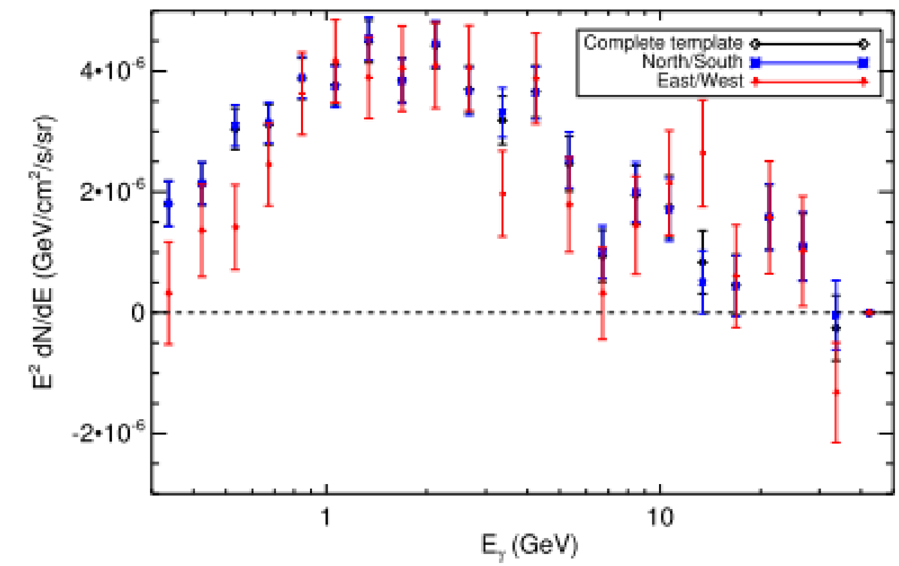


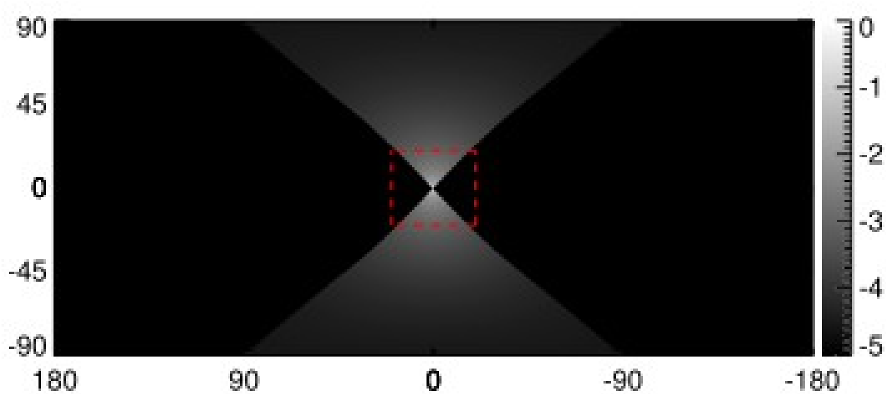
Morphology: Spherical?

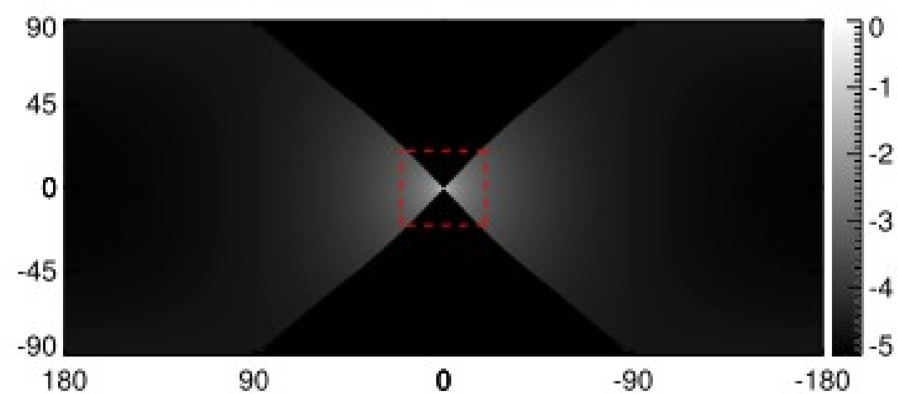
Look at (north+south) / (east+west)

Daylan+ 2014 (v2)



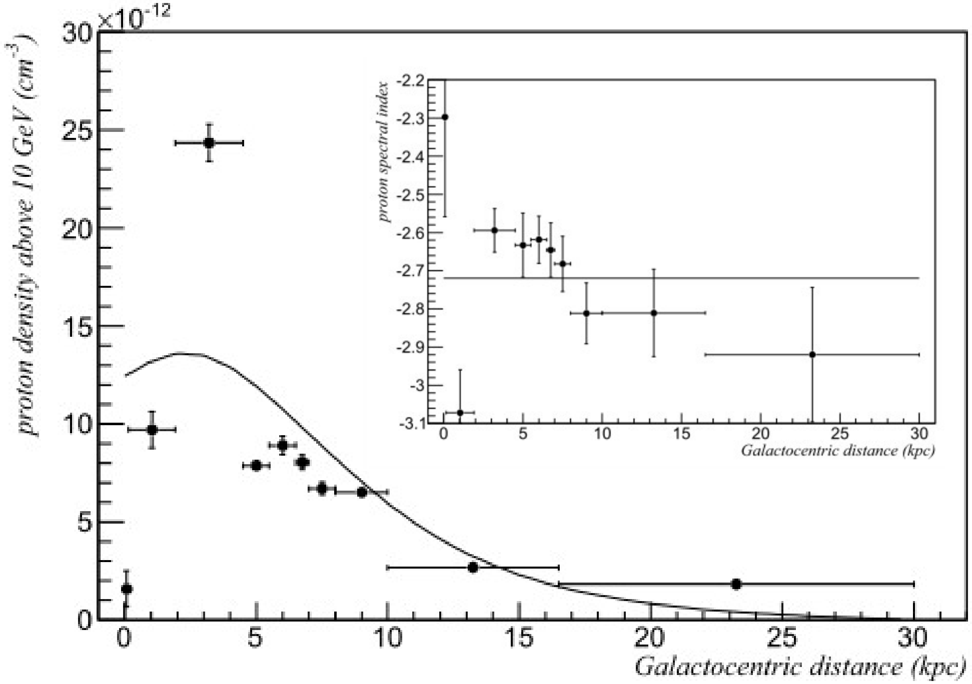






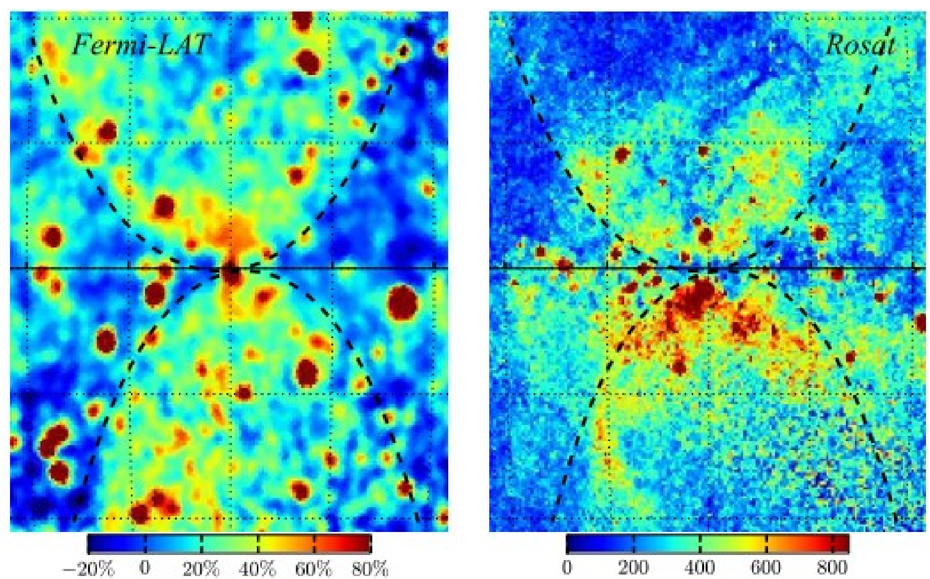
Morphology: "Catenary at base"?

$$N_{pred}(E) = \sum_{i=H\ templates} q_i(E)\widetilde{I}_{H_i} + N_{IC}(E)\widetilde{I}_{IC_p}(E)$$
$$+N_{iso}(E)\widetilde{I}_{iso} + N_{LoopI}(E)\widetilde{I}_{LoopI} + \sum_{i=patch} N_{patch_i}(E)\widetilde{I}_{patch_i}$$
$$+N_{limb}(E)\widetilde{I}_{limb} + \sum_{i=point\ src} N_{pt_i}(E)\widetilde{\delta}(i)$$
$$+ \sum_{i=extend\ src} N_{ext_i}(E)\widetilde{I}_{ext_i} + \widetilde{I}_{sun\_moon}(E)$$



Casandjian et al., 2014 (Fermi LAT background model for PASS7)

- Fit of gas emissivities in Galacto-centric rings → Differences w.r.t. Galprop predictions
- Inverse Compton template from Galprop
- Large-scale residuals remain → "We observe that the Fermi bubbles have a shape similar to a catenary at their base".

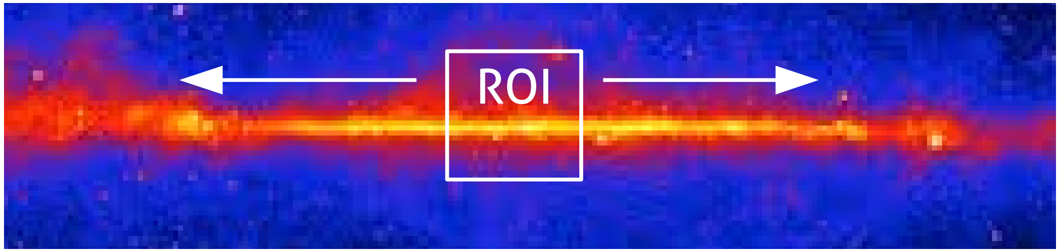


- Differences might be due to over/under-subtraction of gas or ICS emission along the Galactic disk
- Hard to interpret, since spectra of the residuals are not presented

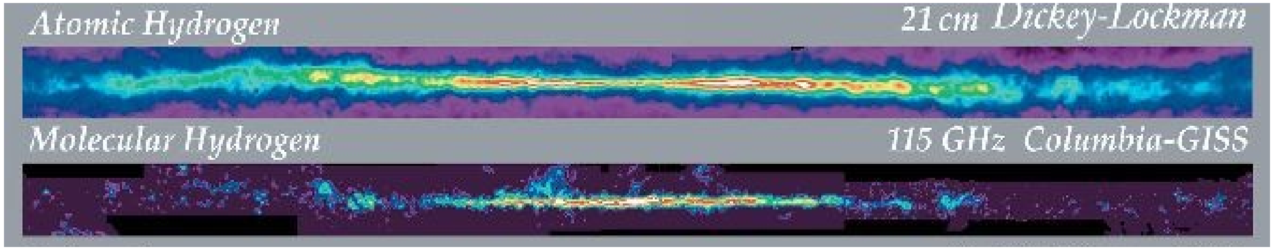
Empirical model systematics:
An estimate from residuals in the Galactic disk

We can use Galactic disk as test region to estimate the impact of uncertainties in **gas maps**, modeled **CR distribution**, **point source fits** and masking, and **instrumental effects** on excess template fit at Galactic center.

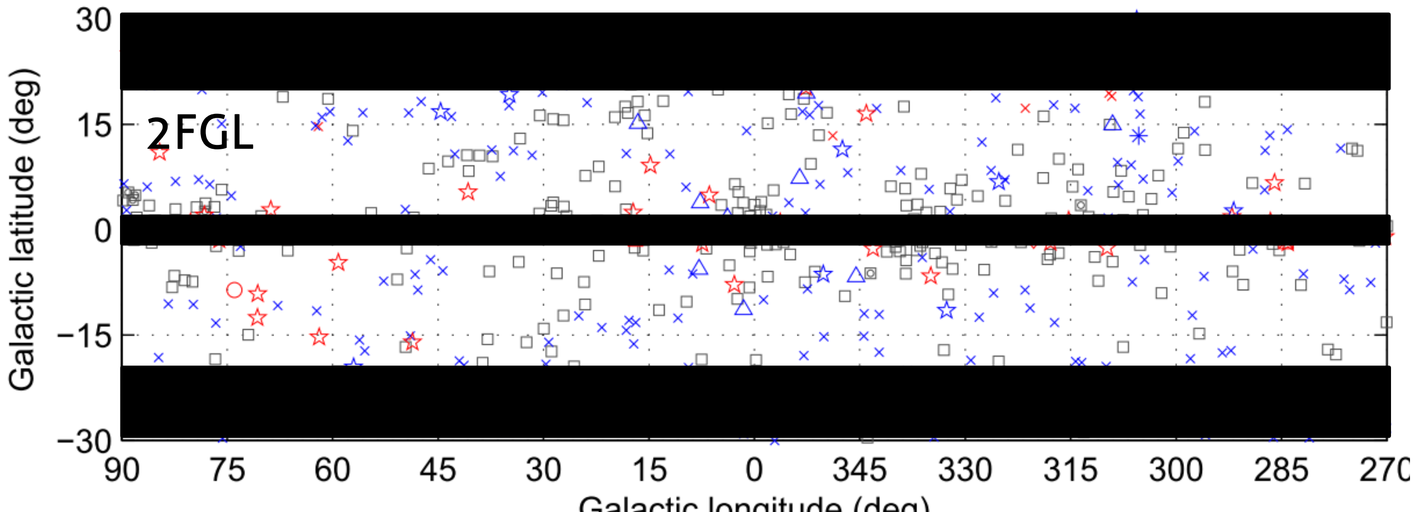
We move the ROI and excess template along disk, and redo our fits.



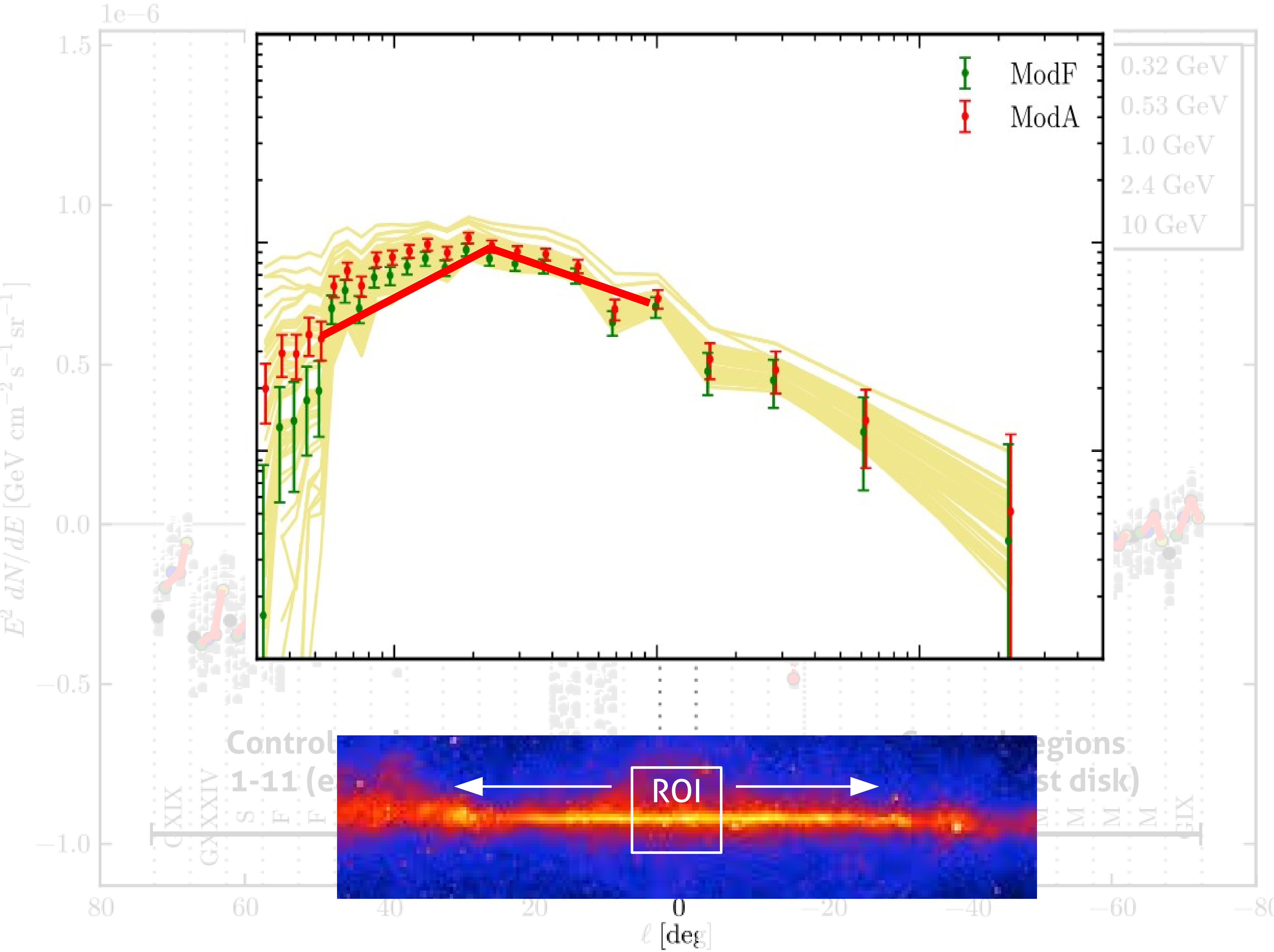
Longitudinal variations photon sources are relatively mild.



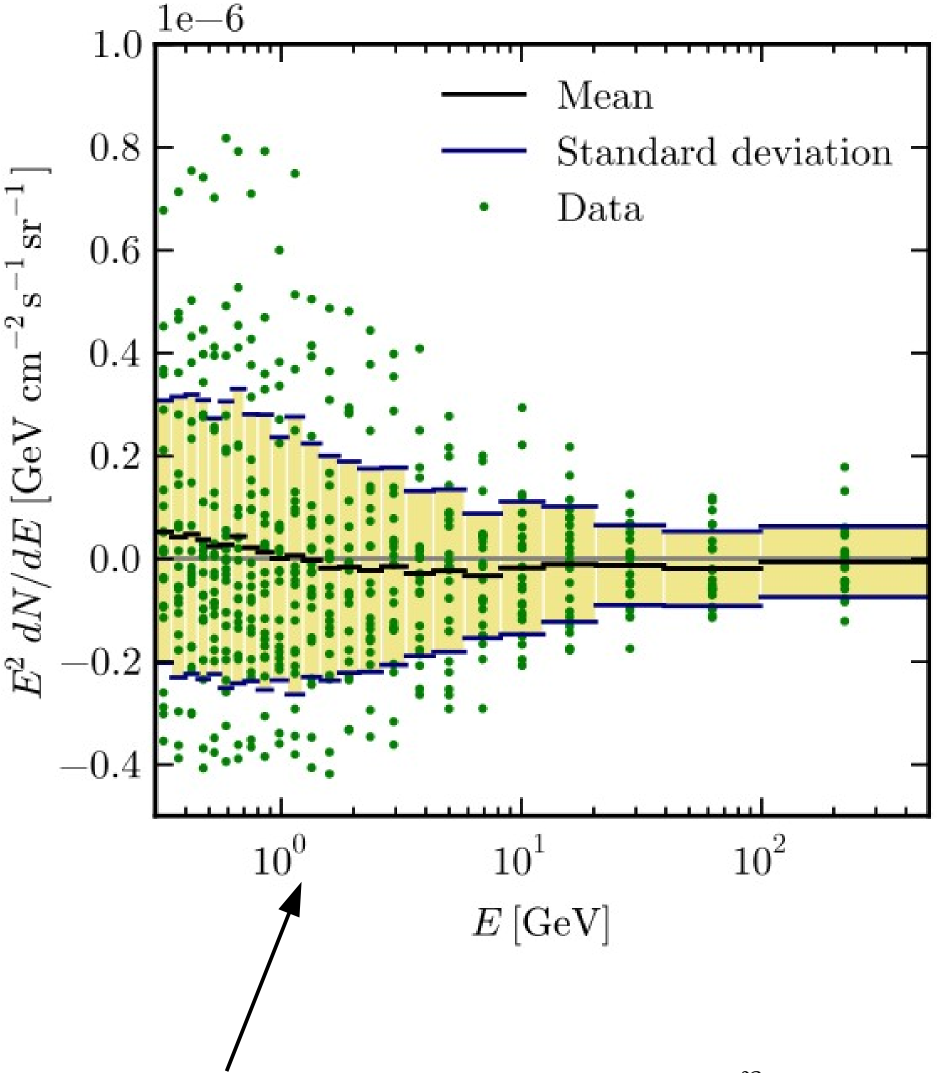
Relevant latitude range



Flux in excess template shifted along the Galactic plane



Residual spectra



We call "residual" the component that is absorbed by the excess template when performing fits in our test regions along the Galactic disk.

$$\Phi_{\rm res}(E) = 0 \Leftrightarrow \delta x_i = 0,\ \delta\gamma_i = 0$$

$$\Phi_{\rm res}(E) = \Phi_{\rm data}(E) - \sum_{i={\rm ICS},\pi^0}^{n_{\rm comp}} (x_i + \delta x_i)\Phi_i(E)\ (E/E_*)^{-\delta\gamma_i}$$

What do these residuals tell us about the uncertainties in the BG subtraction (normalization and slope?).

Covariance matrix of residual spectra

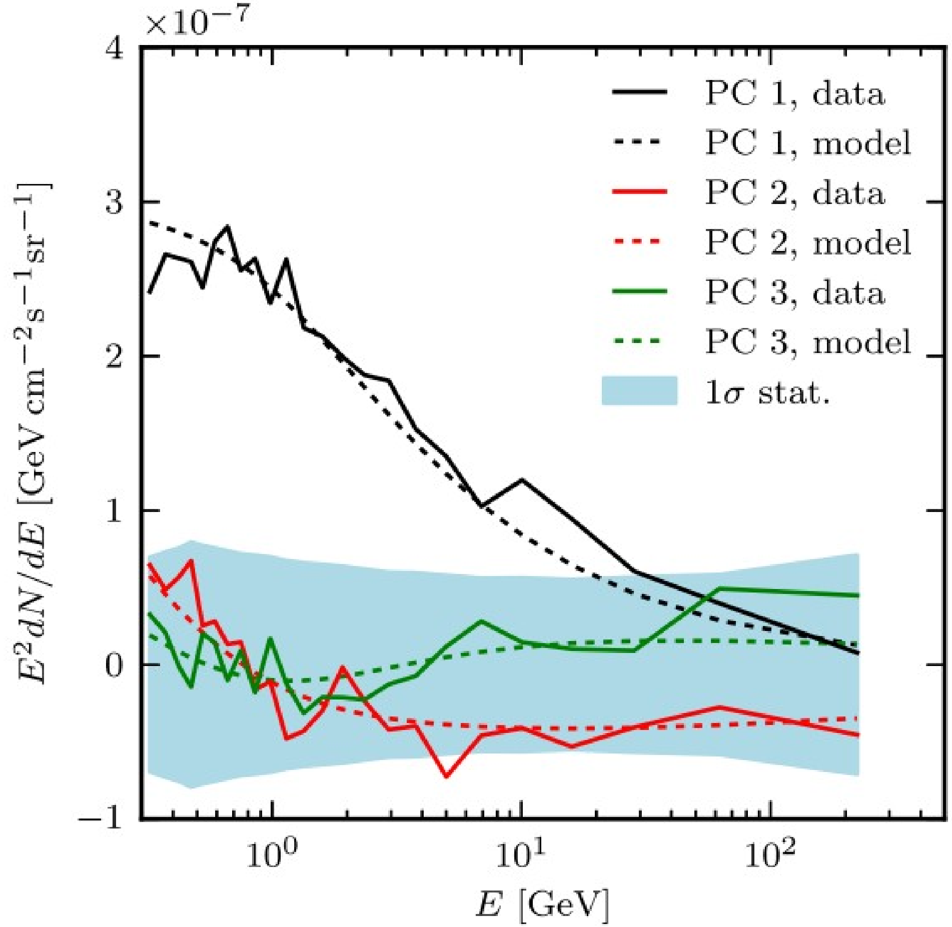
Look at covariance matrix: Residuals seen in the 24 energy bins and 22 test regions define a 24x24 covariance matrix:

$$\Sigma_{ij} = \langle \Phi_{\mathrm{res}}(E_i)\Phi_{\mathrm{res}}(E_j)\rangle - \langle \Phi_{\mathrm{res}}(E_i)\rangle\langle \Phi_{\mathrm{res}}(E_j)\rangle$$

i, j = 1, …, 24; averaged over 22 test regions

Principal components

Remember: These are the eigenvectors of the correlation matrix with largest eigenvalues. They carry most of the relevant variance.



Principal component analysis

Ansatz for the correlation matrix: Main contributions come from mis-modeling of pi0 and ICS component normalization and slope → four free variances

$$\Sigma_{ij} = \sum_{k=\mathrm{ICS},\pi^0} \left(\Delta x_k^2 + \Delta\gamma_k^2 \ln\frac{E_i}{E_*} \ln\frac{E_j}{E_*} \right) \Phi_k(E_i)\Phi_k(E_j)$$

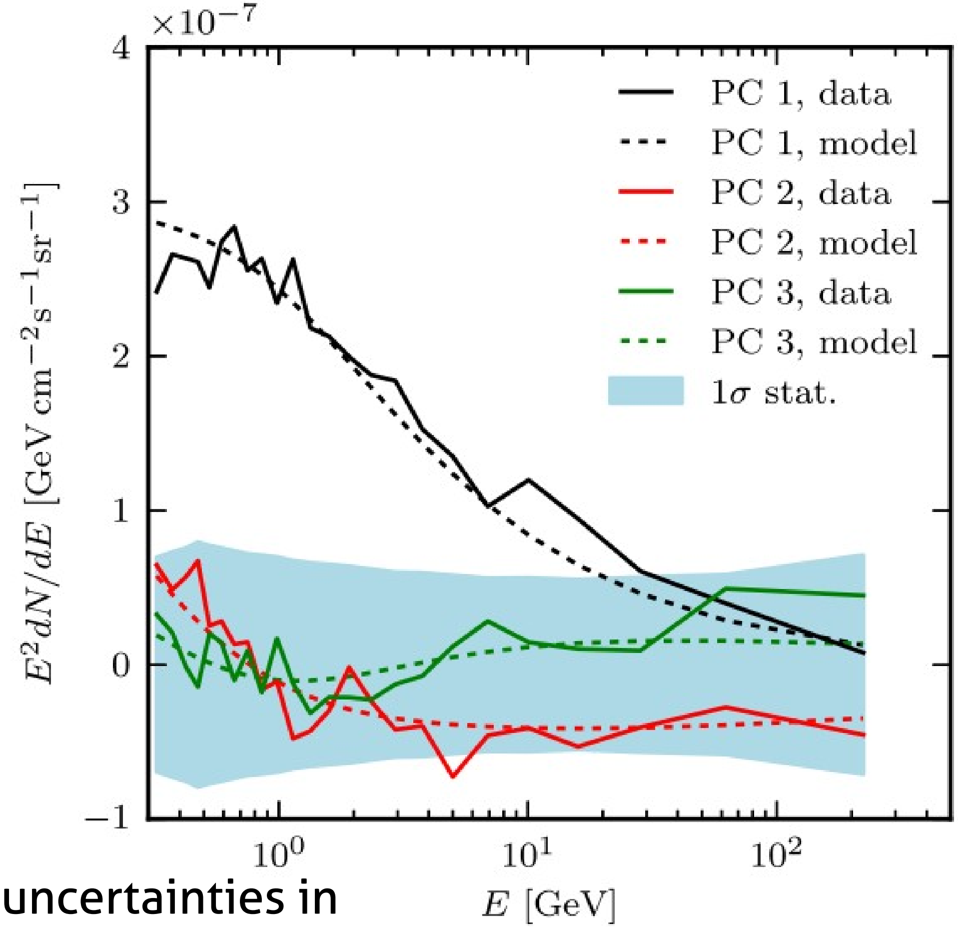
$$\Delta x_i^2 \equiv \mathrm{var}(\delta x_i)$$
$$\Delta \gamma_i^2 \equiv \mathrm{var}(\delta \gamma_i)$$

The first three PCs of this modeled covariance matrix can be fit to the observed components.

→ Normalization variance of <3%
→ Slope variance < 0.01

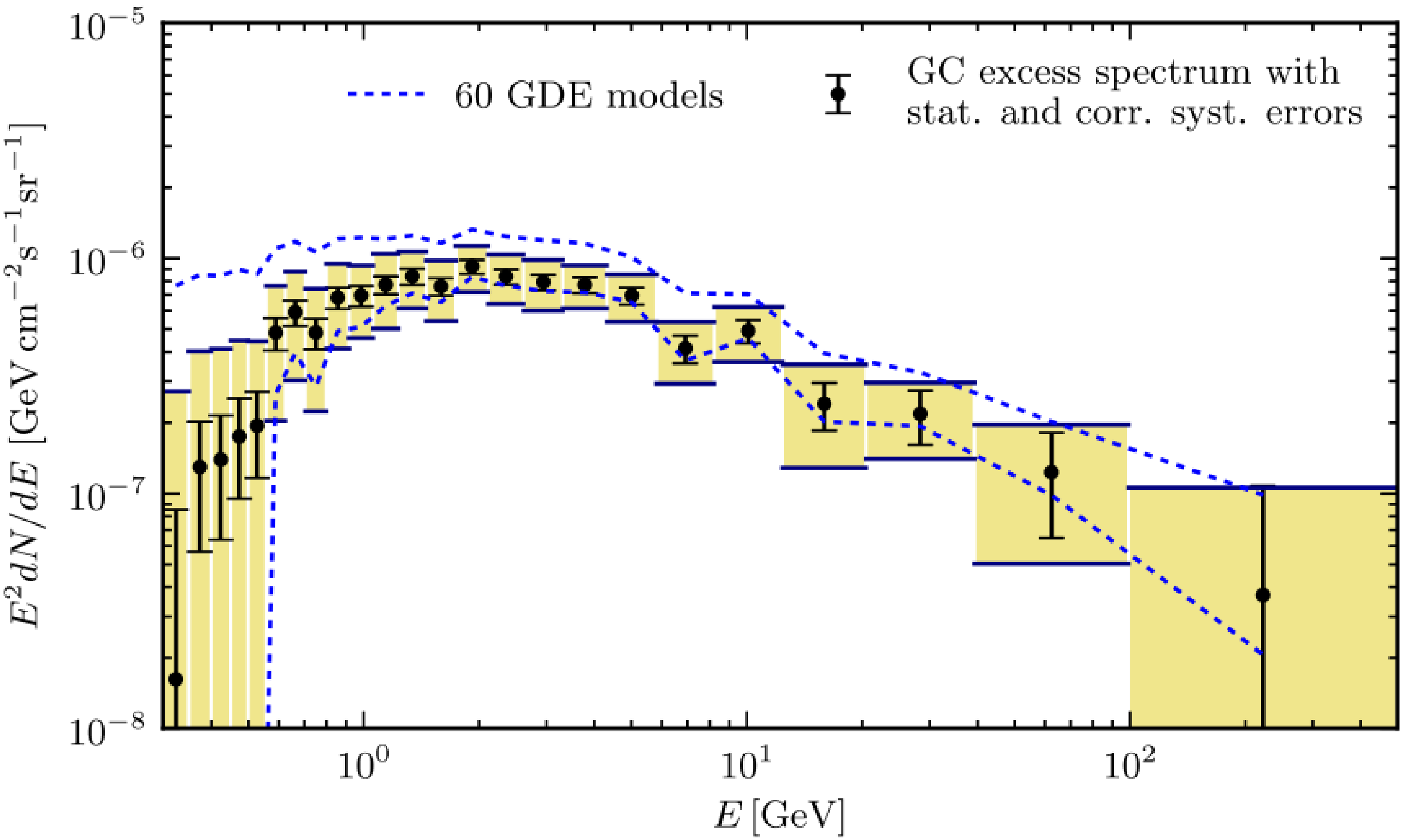
The agreement is between modeled and observed PCs is remarkable.

→ We understand the (main) contribution to our large residuals, and they are exactly what one would expect.



These uncertainties are a (lower) limit on the uncertainties in observations towards the Galactic center.

Theoretical vs. empirical model systematics

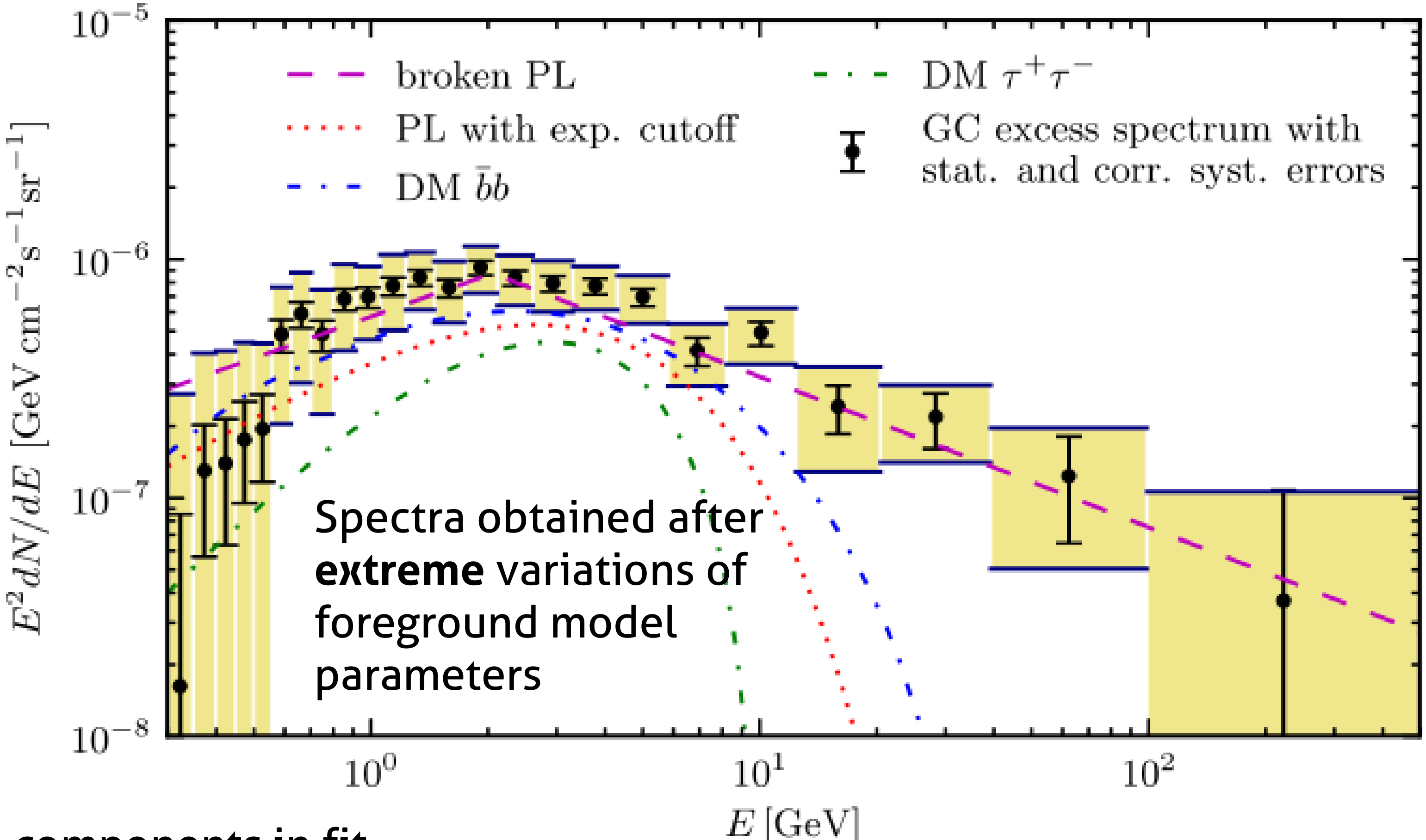


Empirical model uncertainties (yellow) and theoretical model uncertainties (blue lines) are significantly larger than the statistical error over the entire energy range.

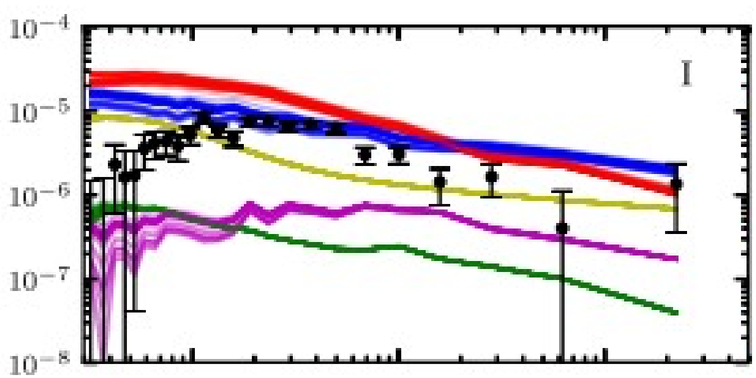
Have to take into account systematics to get meaningful results in spectral fits.

Systematic uncertainties of the spectrum

Calore+ 2014



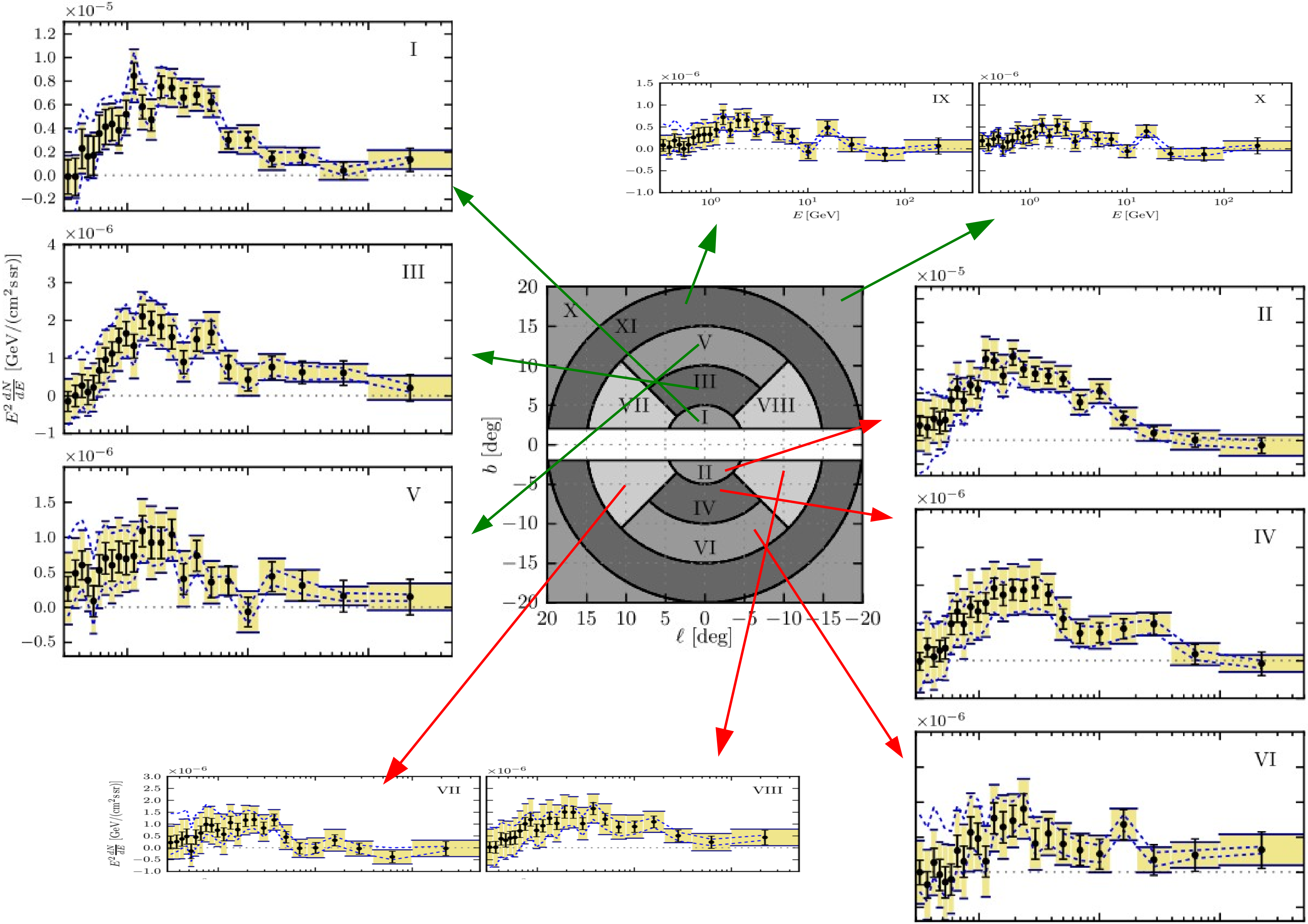
Individual components in fit only vary by ~O(2).



In all cases, the excess template spectrum

- rises from 300 MeV to ~1 GeV
- peaks at 1-3 GeV
- falls power-law like above 3 GeV **(no cutoff at >10 GeV energies as previously claimed)**

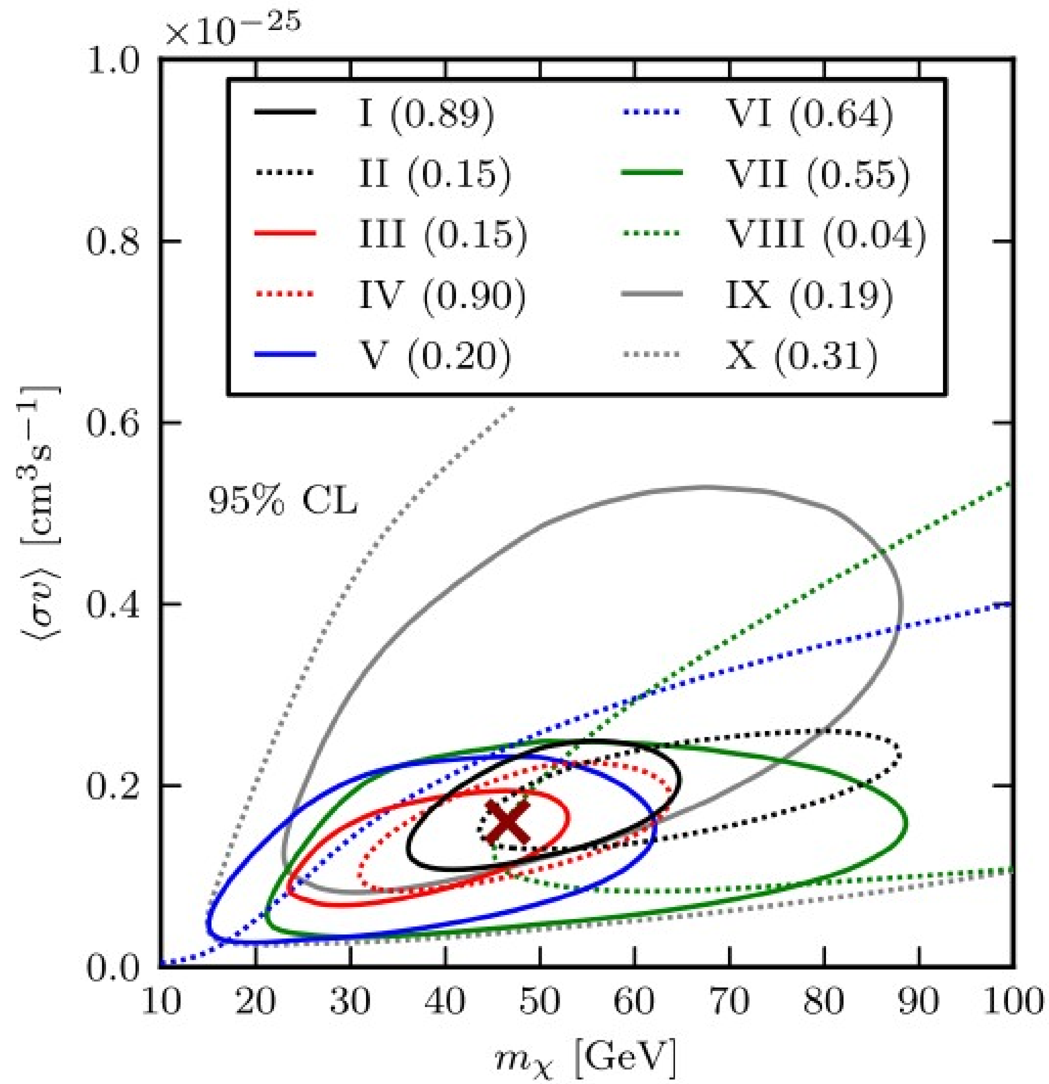
Same procedure, but for ten GCE segments



Parametric analysis of excess morphology

Simple example with DM fit:

- bb spectrum from DM annihilation (free mass and normalization)
- Generalized NFW profile with 1.26 slope



Result

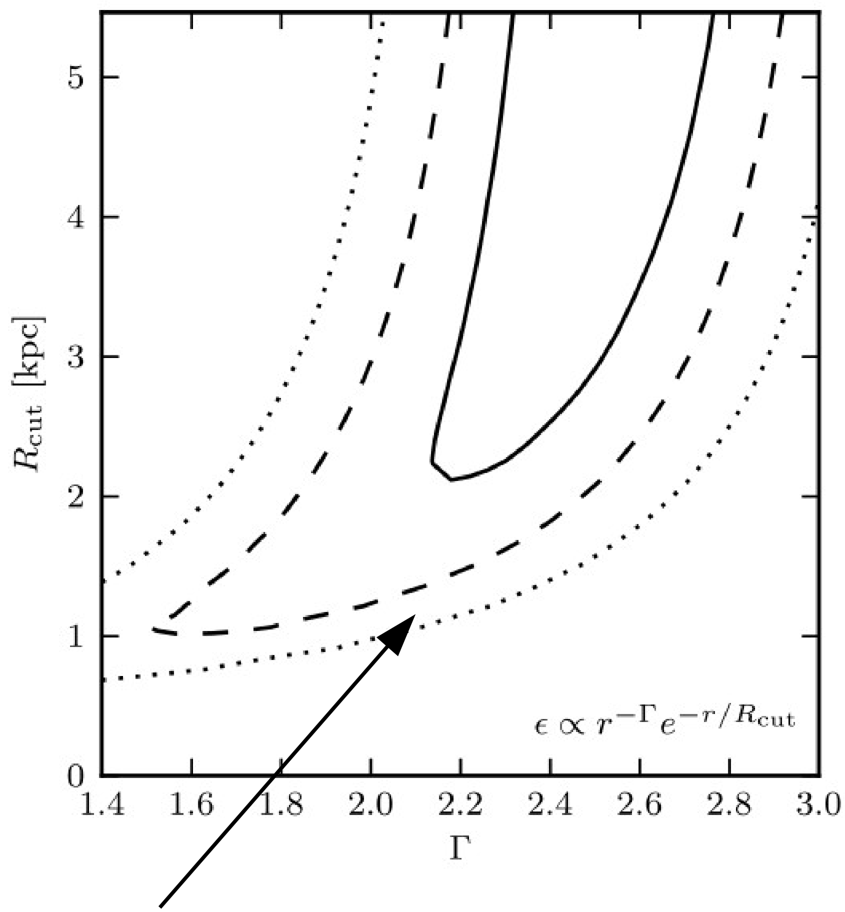
- In all ten regions, the 95% CL contours include the best-fit value
- Nonzero signal are preferred in all but one region
- No north/south or east/west asymmetry

Parametric fit with DM spectrum indicates that results are consistent with hypothesis of <u>one</u> single uniform spectrum at 95% CL.

How far does the excess extend from the GC?

To explore the **extension of the excess to high latitudes**, we consider a hypothetical source with volume emissivity profile

$$q \propto r^{-\Gamma} e^{-r/R_{\rm cut}}$$



We find a lower limit on the extension of at least 1.48 kpc
(corresponding to more than 10 degrees).

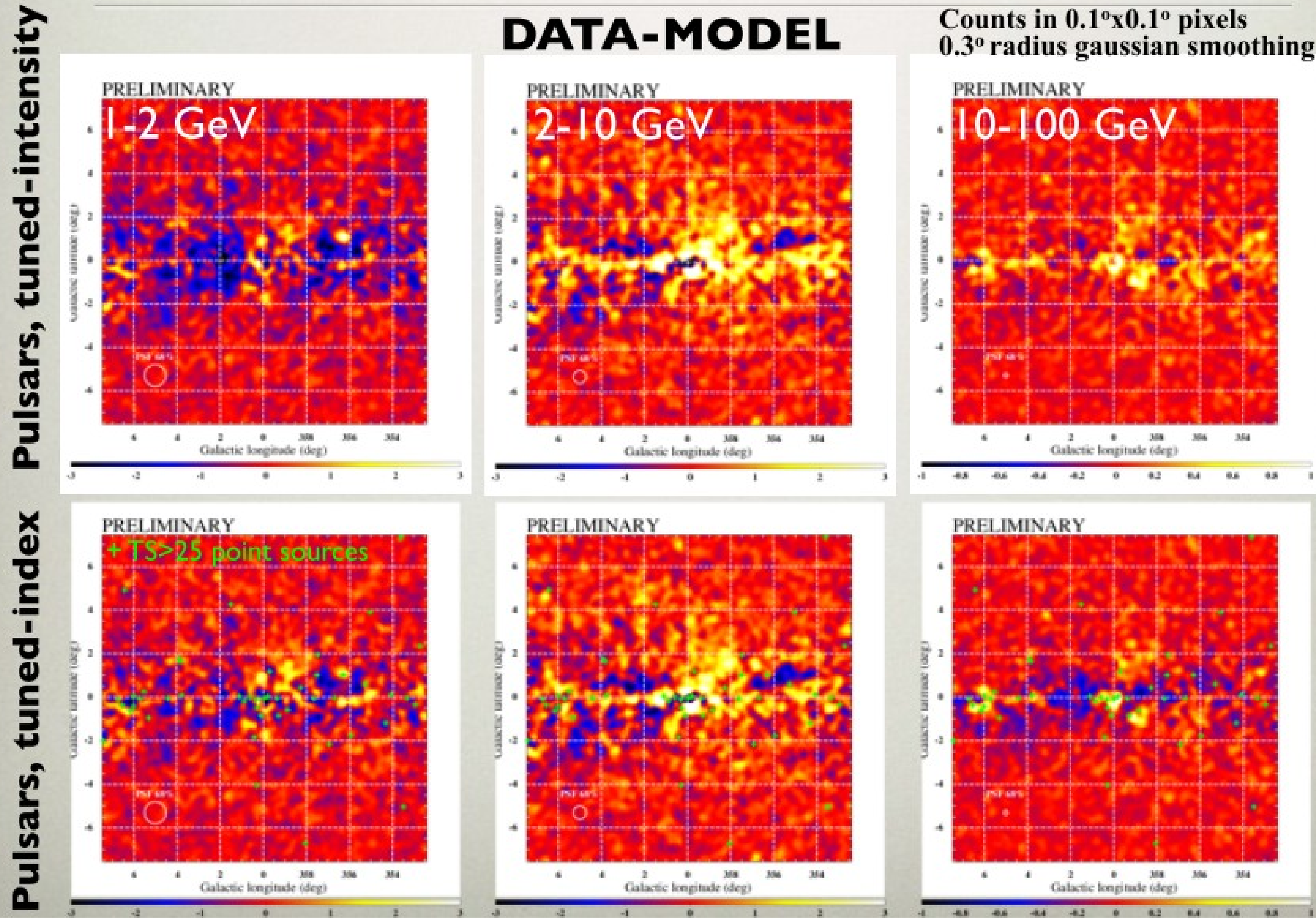
$$\psi > 10.0^\circ \quad 95\%\mathrm{CL}$$

S. Murgia, slides from Fermi Symposium 2014, Nagoya

RESULTS - RESIDUAL MAPS

DATA-MODEL

Counts in 0.1°x0.1° pixels
0.3° radius gaussian smoothing



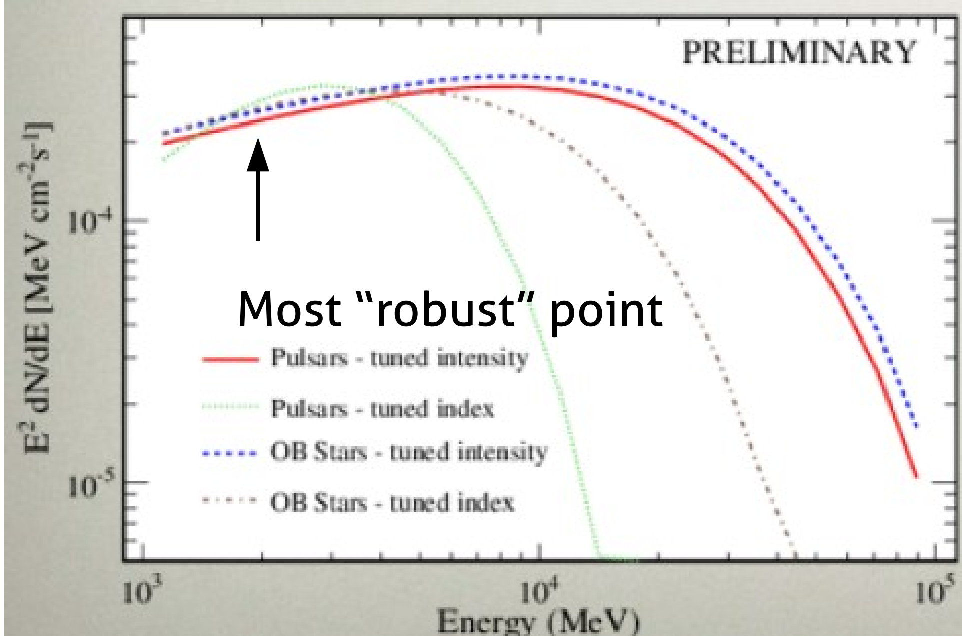
S. Murgia, slides from Fermi Symposium 2014, Nagoya

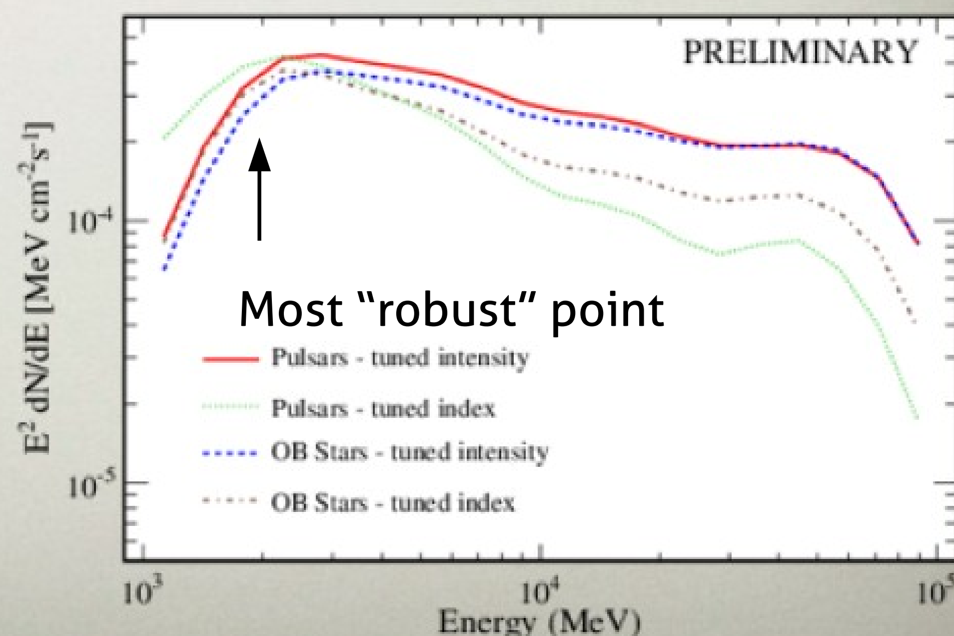
Note: All eight lines from this slide were used to fit DM spectra in the literature. This introduces unknown systematics, and likely leads (in the case of "tuned intensity") to biased results.
→ Just wait for the LAT paper!

- We tes
  gaussia
- Peaked profiles with long tails (NFW, NFW contracted) yield the most significant improvements in the data-model agreement for the four variants of the foreground/background models. IC ring I contribution ~2-3x smaller than without additional component and HI ring I contribution is ~2-5x larger

➡ The predicted spectrum depends on the foreground/background models.

Integrated flux in 15°x15° ROI, NFW component

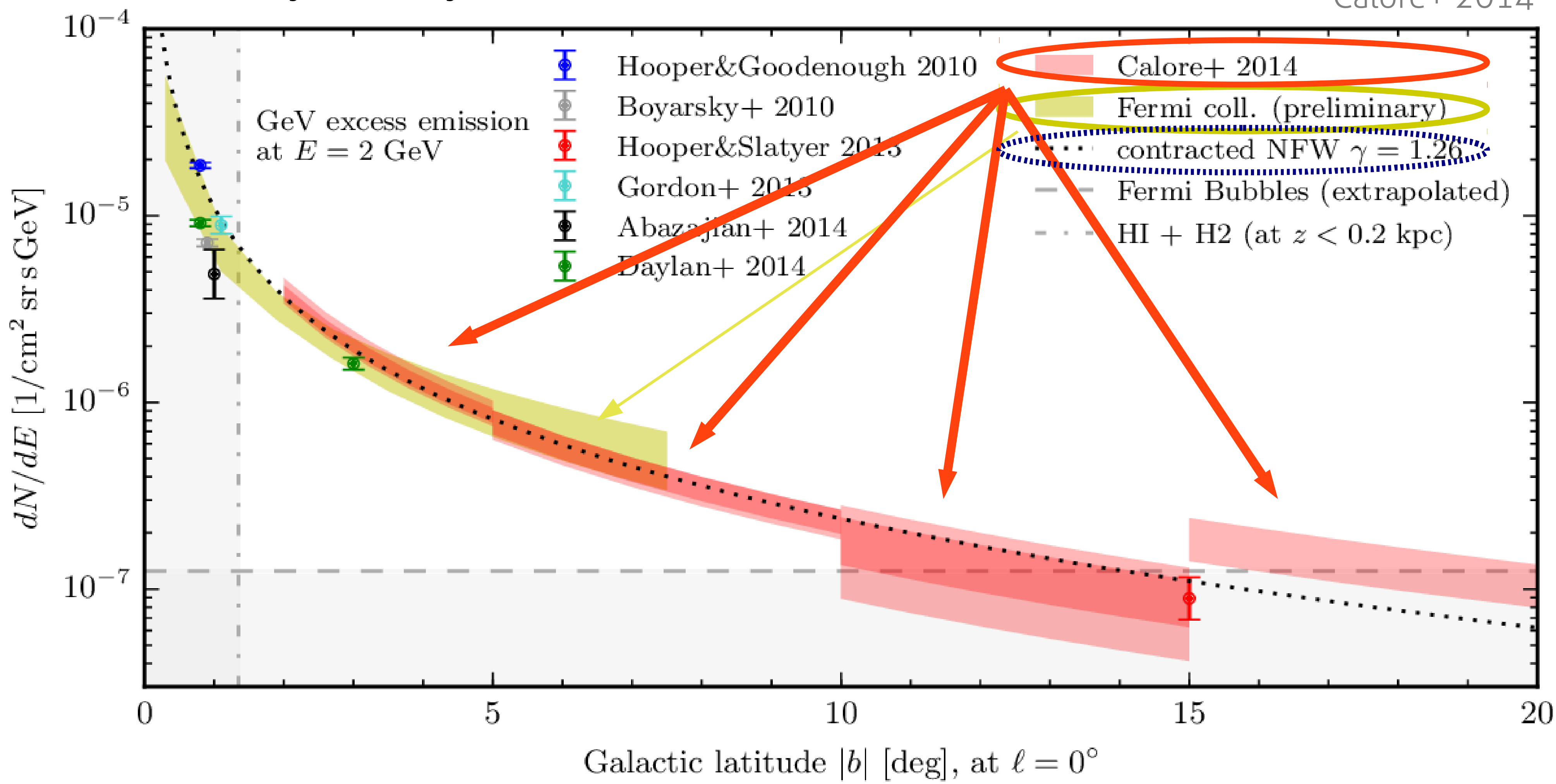




The higher-latitude tail of the Fermi GeV excess

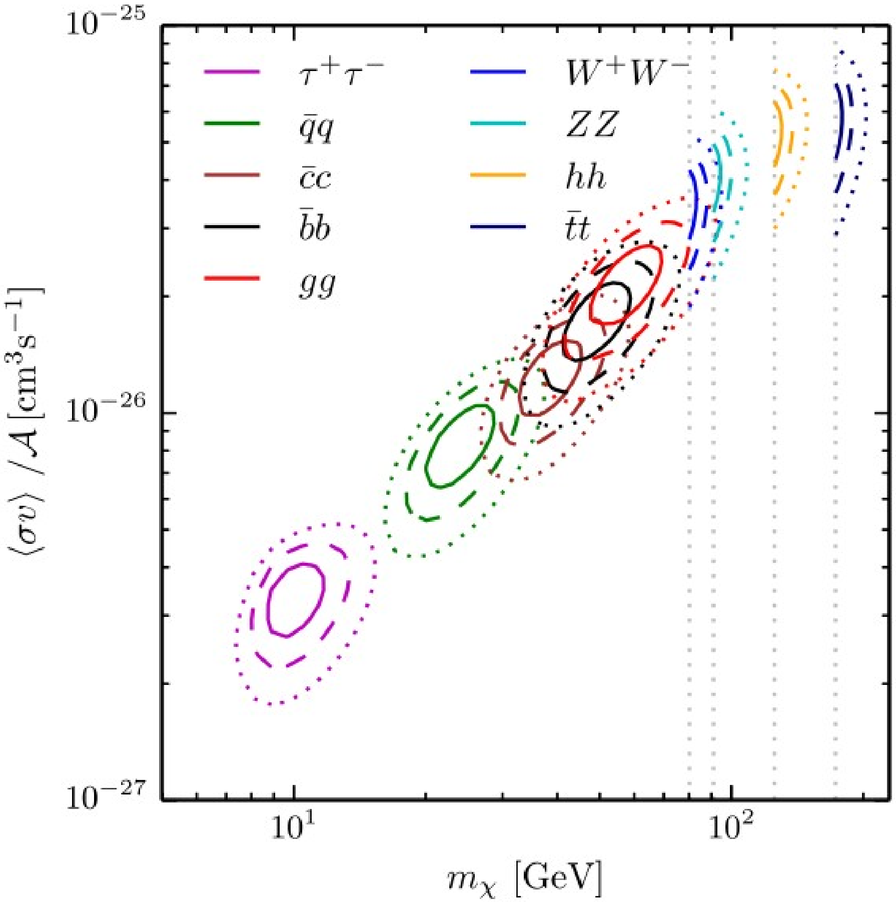
Gamma-ray intensity at 2 GeV:

Calore+ 2014



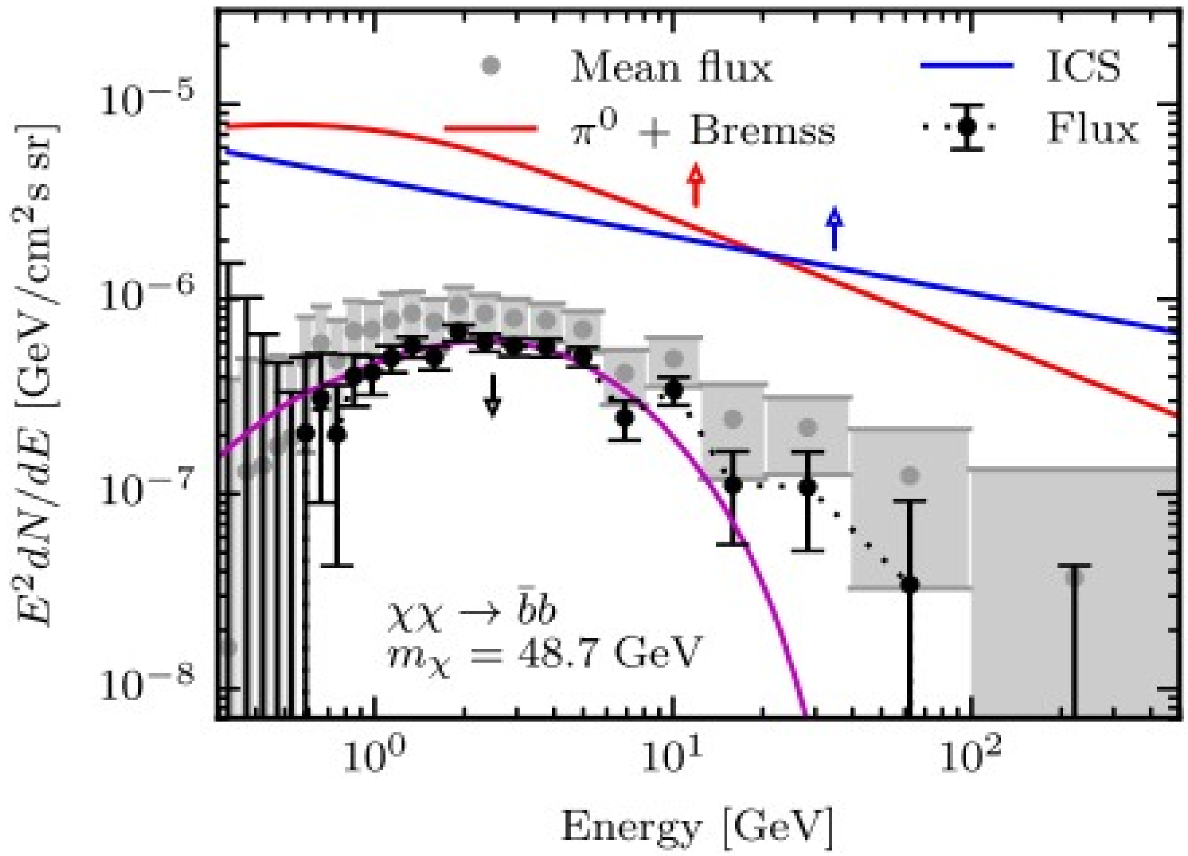
- Most previous results agree within a factor of ~2, but <u>disagree</u> within error bars.
- The profile is compatible with the expectations from a DM annihilation signal with contracted DM profile / power-law. **No indications for radial cutoff.**

Fits with dark matter annihilation spectra



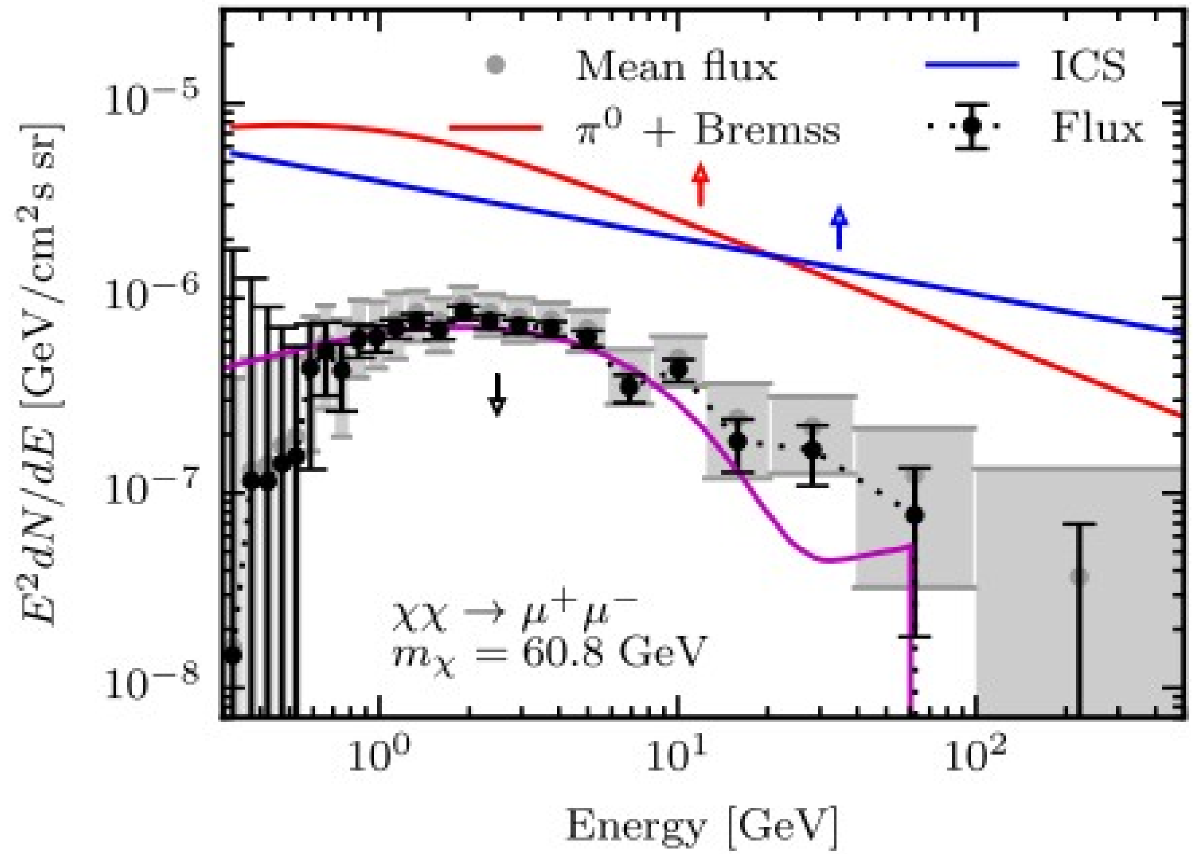
Channel	$\langle\sigma v\rangle$ (10^{-26} cm^3 s^{-1})	m_χ (GeV)	$\chi^2_{\rm min}$	p-value
$\bar{q}q$	$0.83^{+0.15}_{-0.13}$	$23.8^{+3.2}_{-2.6}$	26.7	0.22
$\bar{c}c$	$1.24^{+0.15}_{-0.15}$	$38.2^{+4.7}_{-3.9}$	23.6	0.37
$\bar{b}b$	$1.75^{+0.28}_{-0.26}$	$48.7^{+6.4}_{-5.2}$	23.9	0.35
$\bar{t}t$	$5.8^{+0.8}_{-0.8}$	$173.3^{+2.8}_{-0}$	43.9	0.003
gg	$2.16^{+0.35}_{-0.32}$	$57.5^{+7.5}_{-6.3}$	24.5	0.32
W^+W^-	$3.52^{+0.48}_{-0.48}$	$80.4^{+1.3}_{-0}$	36.7	0.026
ZZ	$4.12^{+0.55}_{-0.55}$	$91.2^{+1.53}_{-0}$	35.3	0.036
hh	$5.33^{+0.68}_{-0.68}$	$125.7^{+3.1}_{-0}$	29.5	0.13
$\tau^+\tau^-$	$0.337^{+0.047}_{-0.048}$	$9.96^{+1.05}_{-0.91}$	33.5	0.055
[$\mu^+\mu^-$	$1.57^{+0.23}_{-0.23}$	$5.23^{+0.22}_{-0.27}$	43.9	0.0036]$_{\rm ICS}$

DM DM → b b

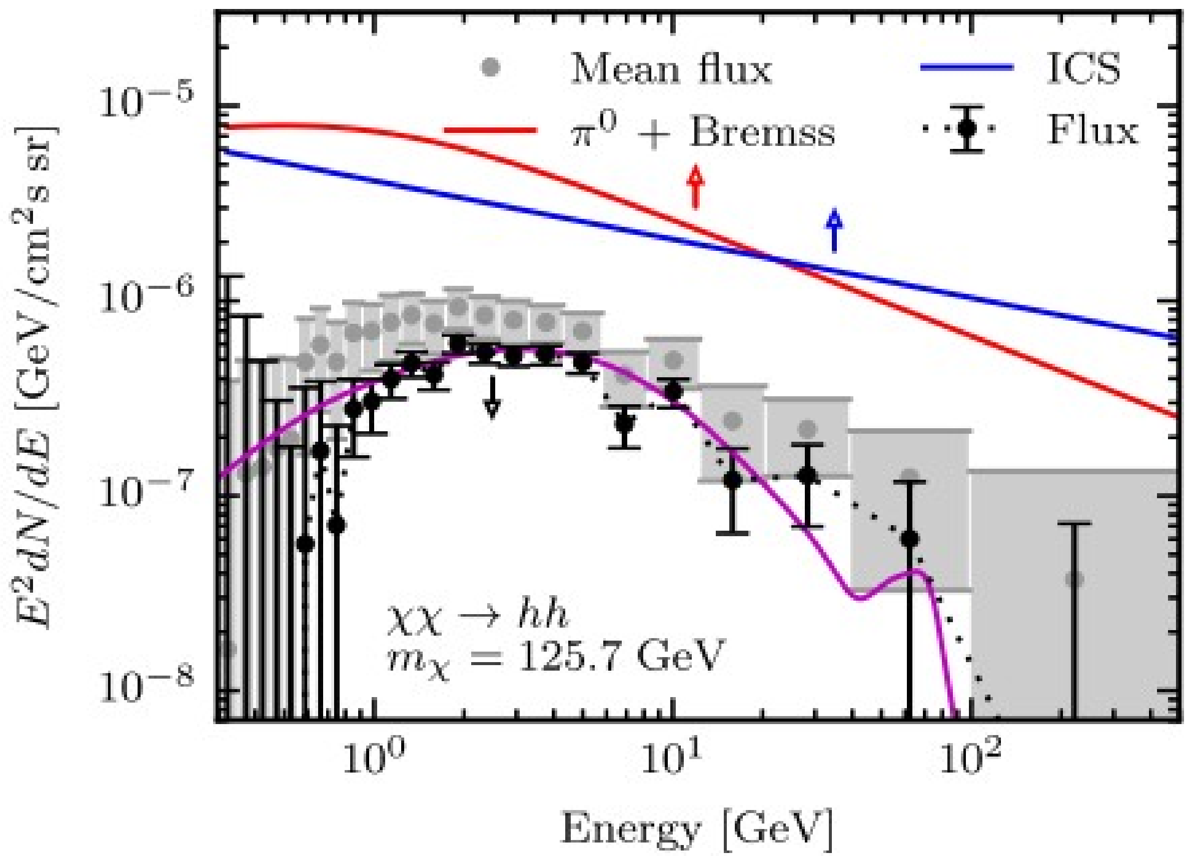


Mean flux
ICS
π^0 + Bremss
Flux
$\chi\chi \to \bar{b}b$
$m_\chi = 48.7$ GeV
$E^2 dN/dE$ [GeV/cm^{2}s sr]
Energy [GeV]

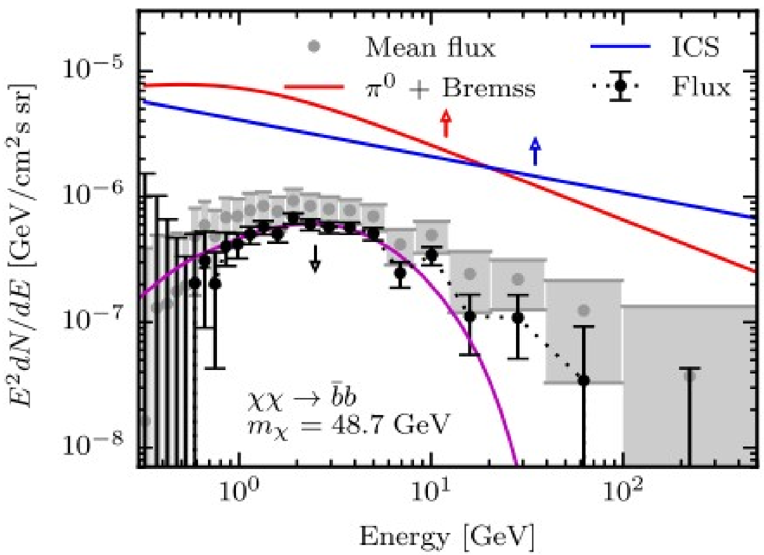
DM DM → muon muon

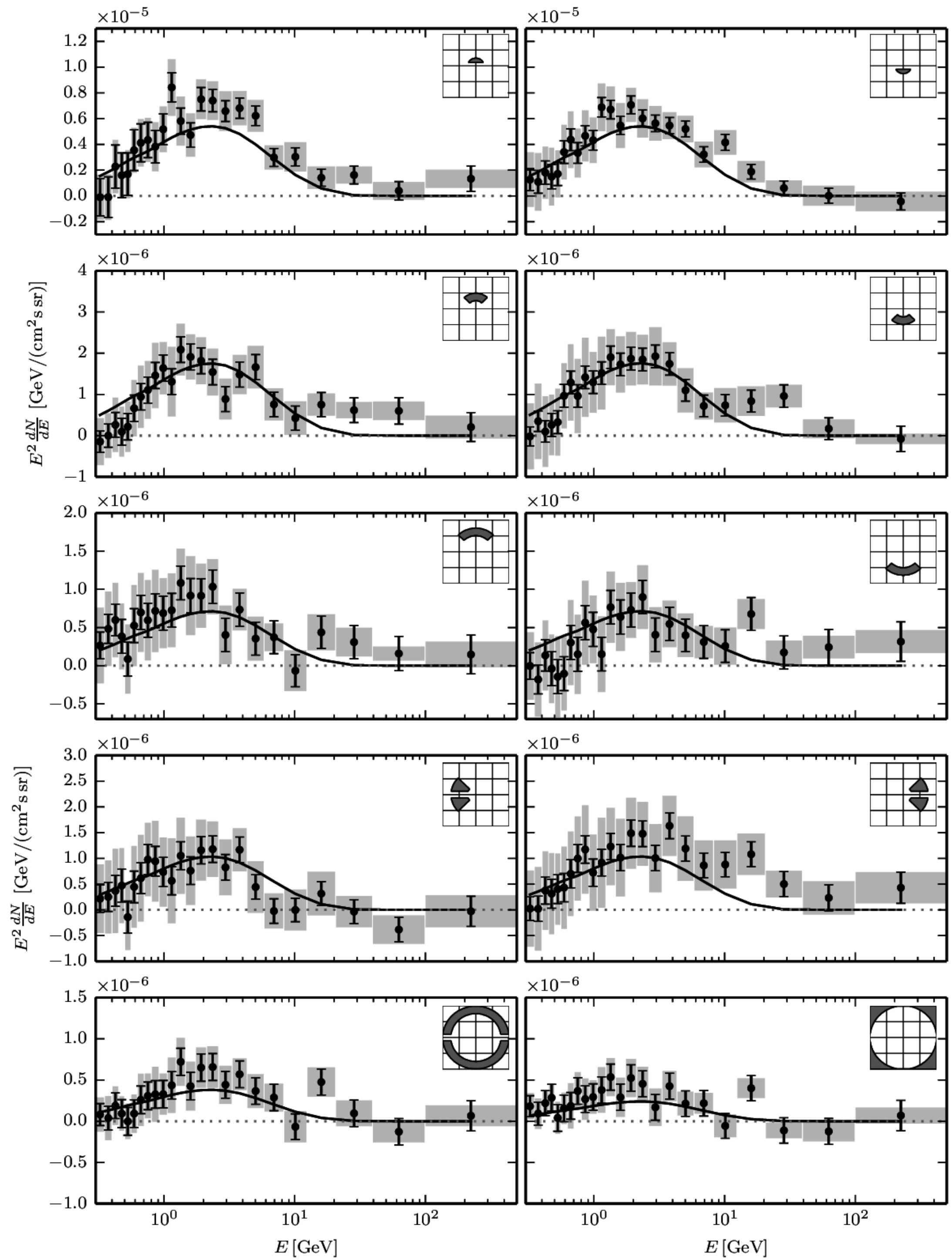


DM DM → h h

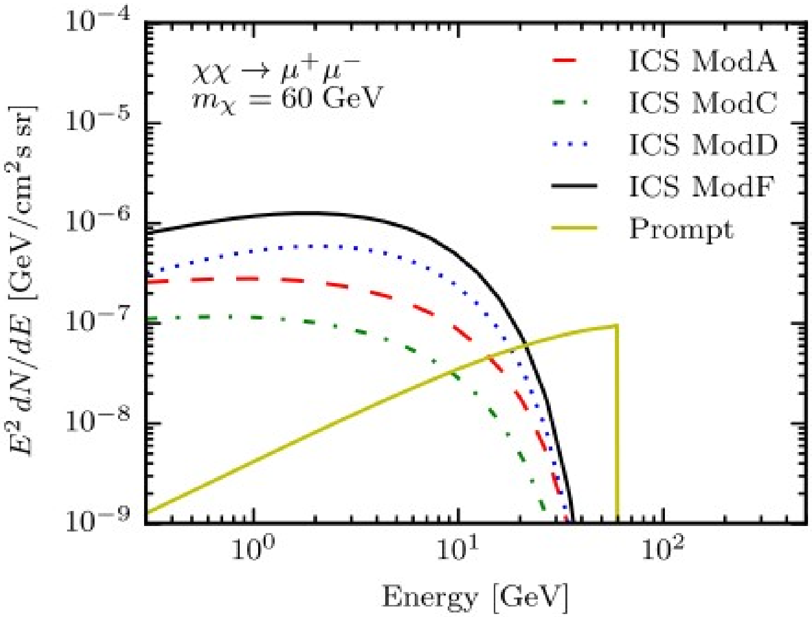

Mean flux
ICS
π^0 + Bremss
Flux
$\chi\chi \to hh$
$m_\chi = 125.7$ GeV
$E^2 dN/dE$ [GeV/cm^{2}s sr]
Energy [GeV]
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^0
10^1
10^2

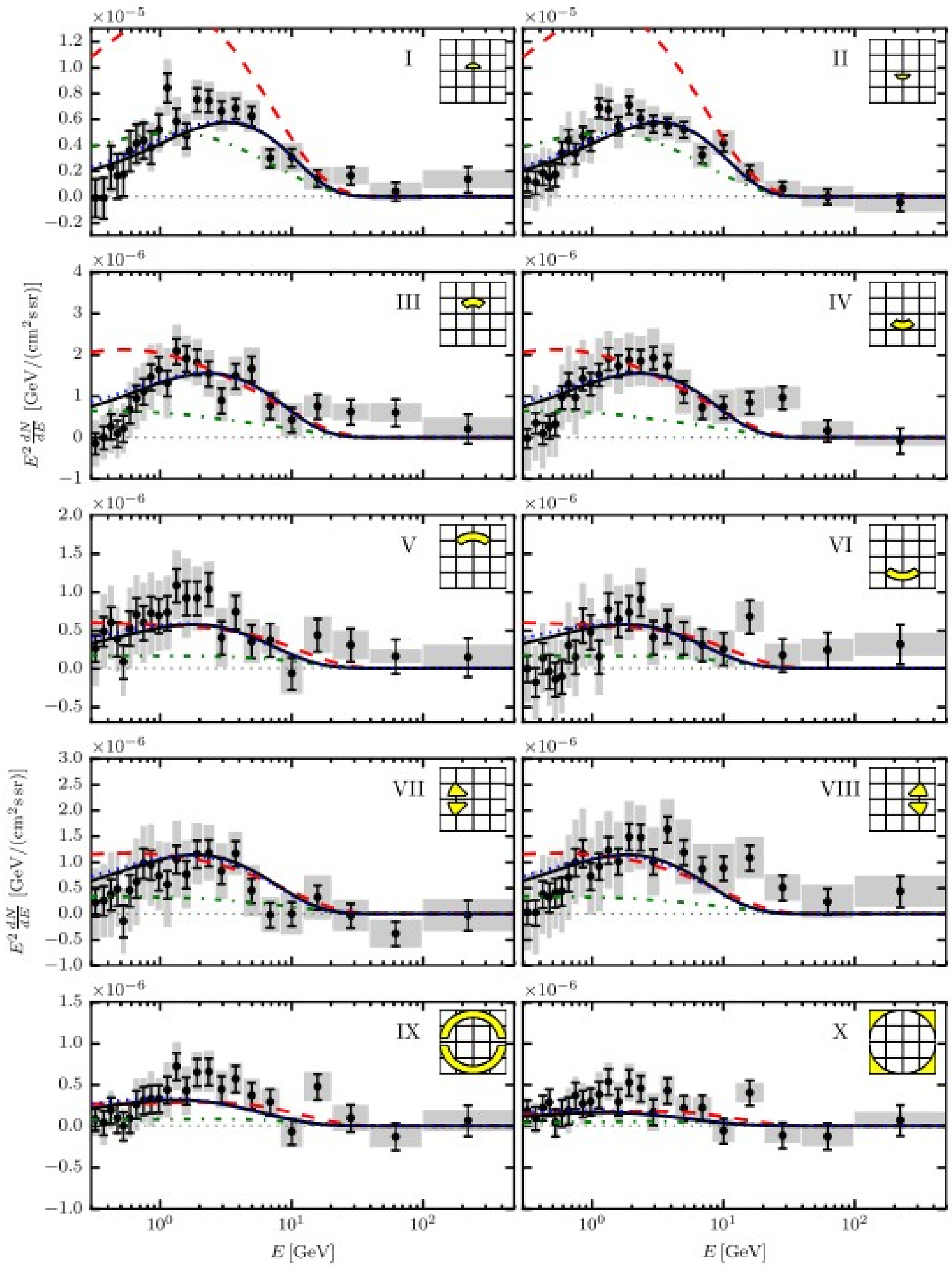
Prompt emission works just well





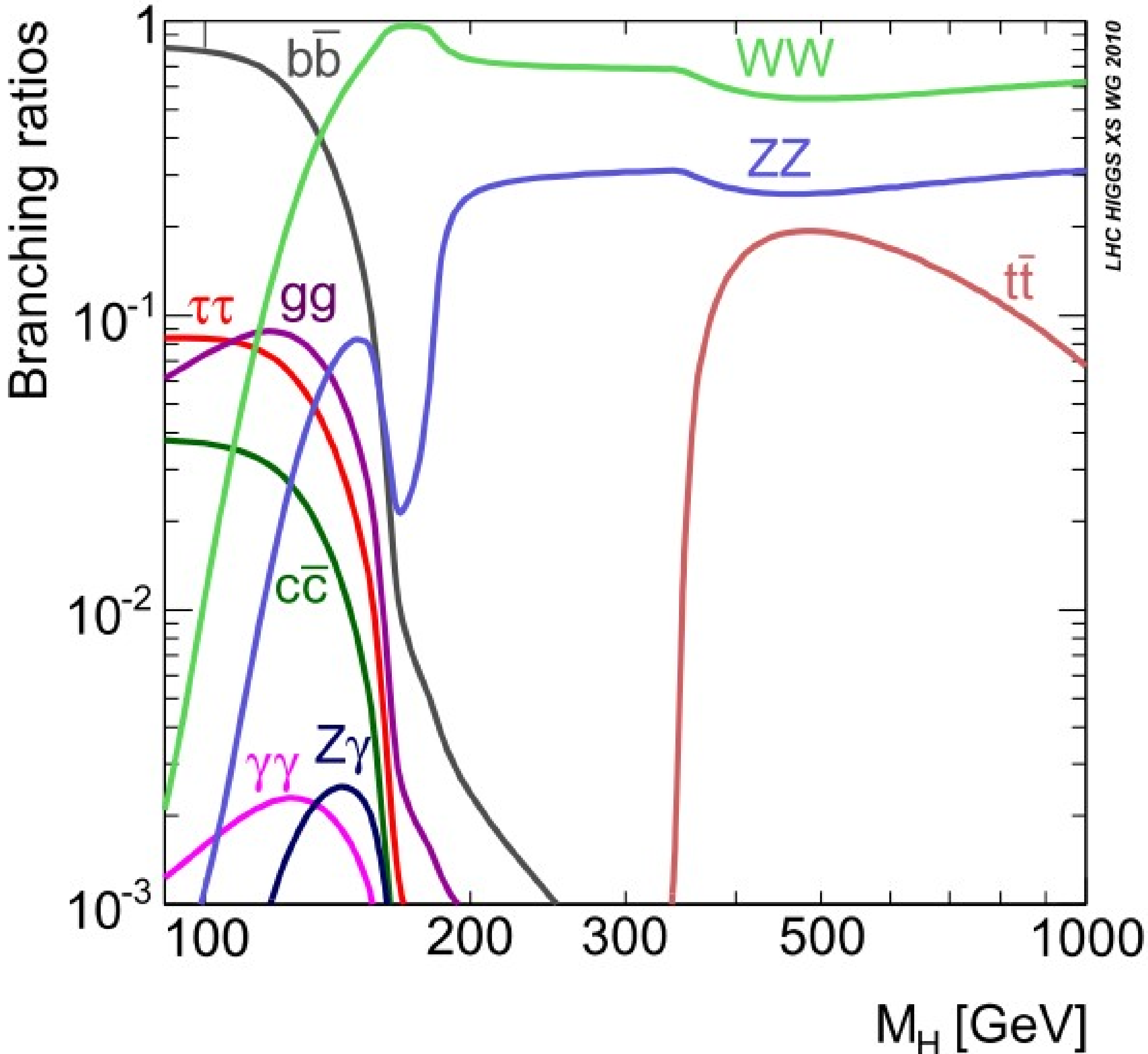
Fit with muon final states (mostly ICS emission)





$$\chi\chi \to \mu^+\mu^-$$

Higgs boson final states and gamma-ray lines



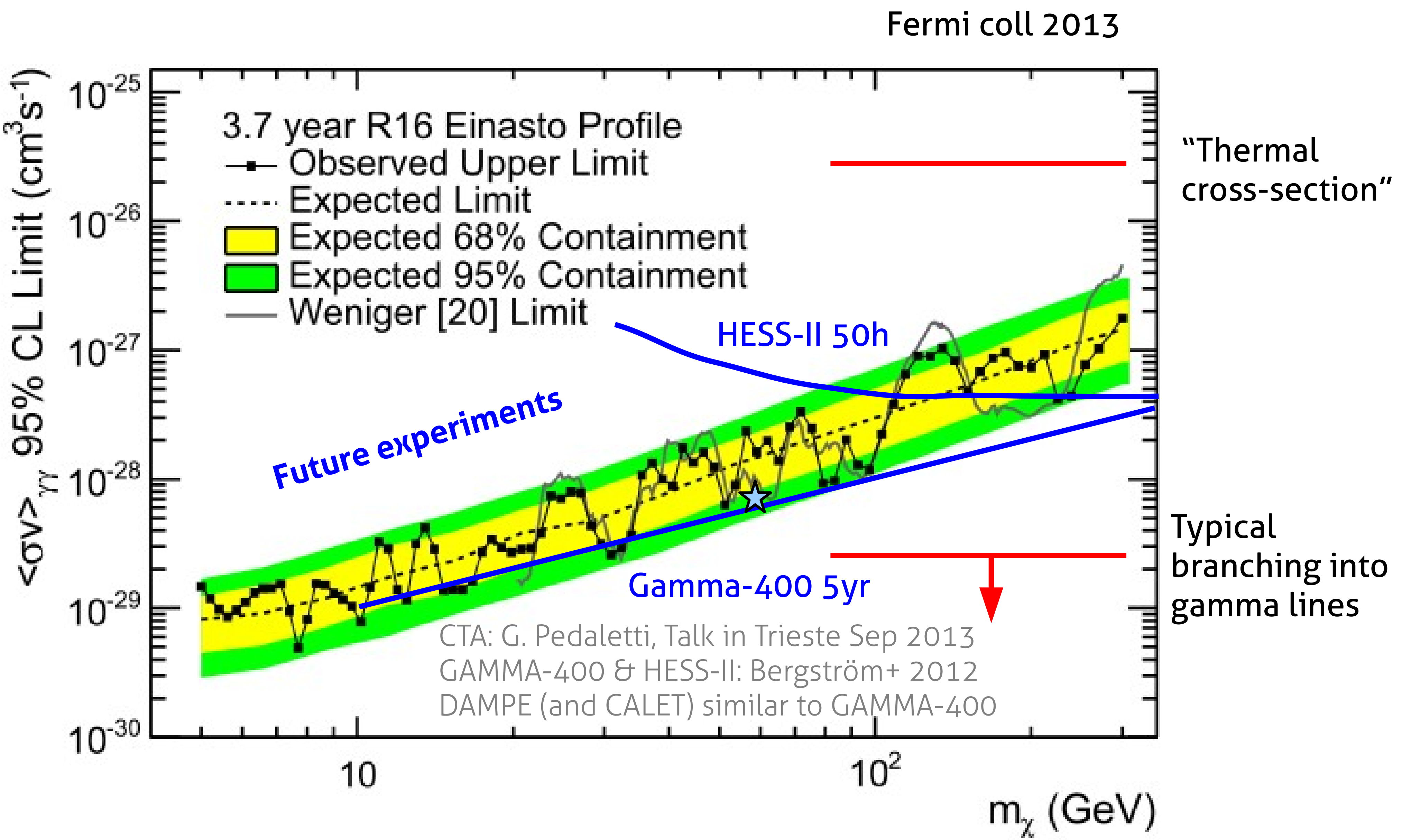
[Dittmaier+ 2011]

$$BR(h^0 \to \gamma\gamma) \simeq 2.3 \times 10^{-3}$$

$$\chi\chi \to h^0 h^0 \to \gamma\gamma X$$

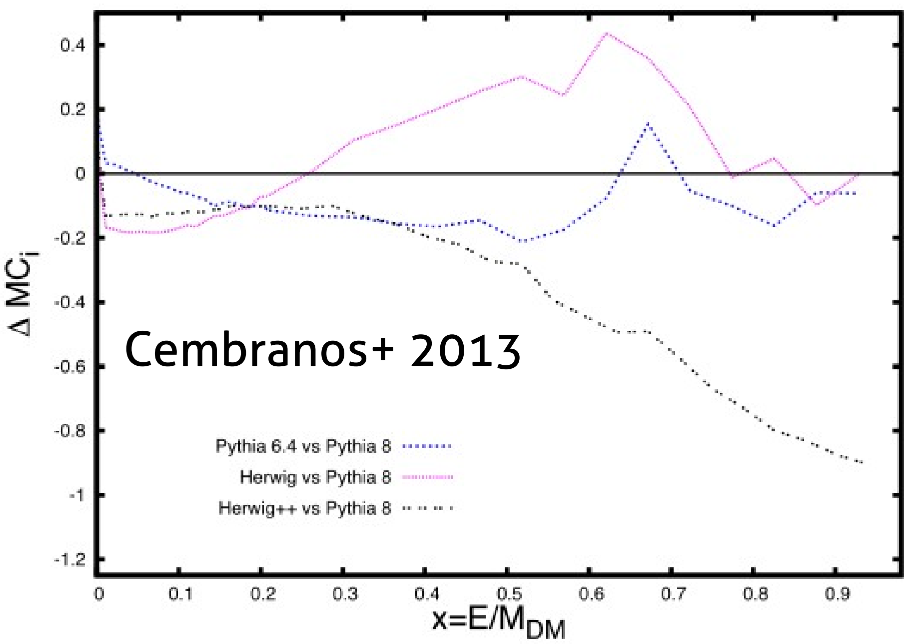
[Bernal+ 2013; Agrawal+ 2014; Calore+ 2014]

Gamma ray lines and boxes

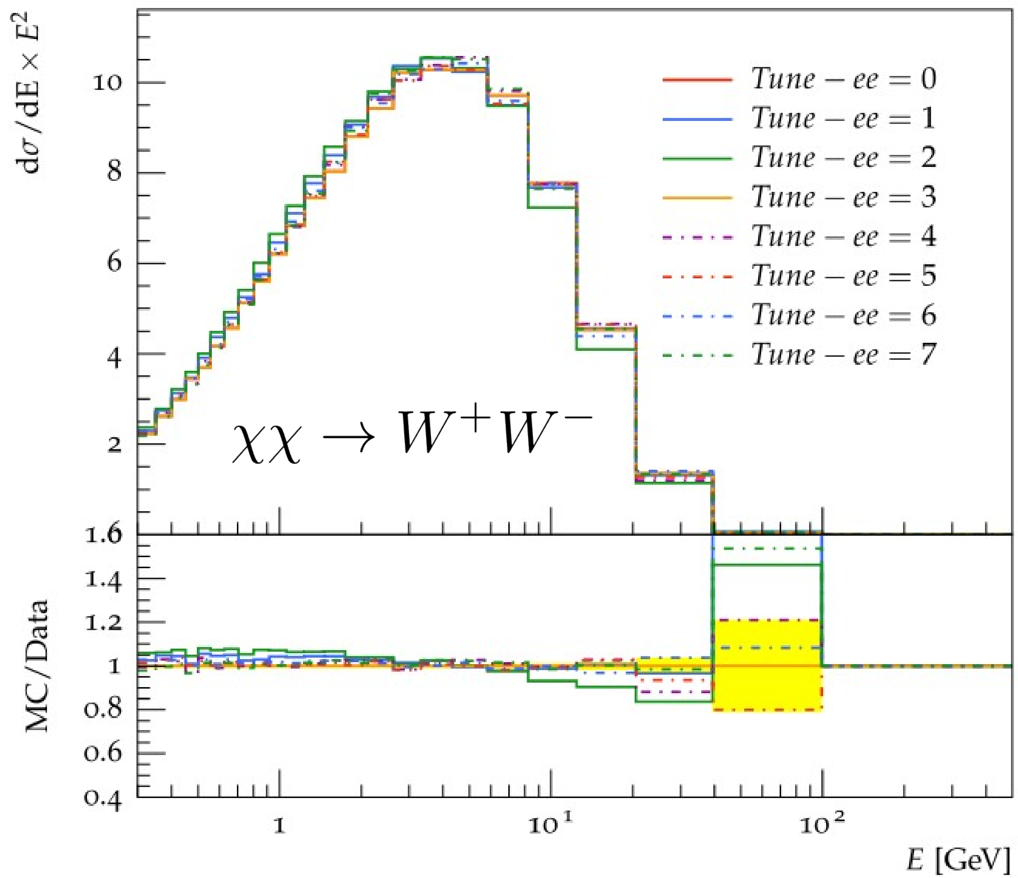


- Limits are nominally extremely strong
- But: expected branching ratio is very small in most cases

HEP uncertainties in spectrum prediction

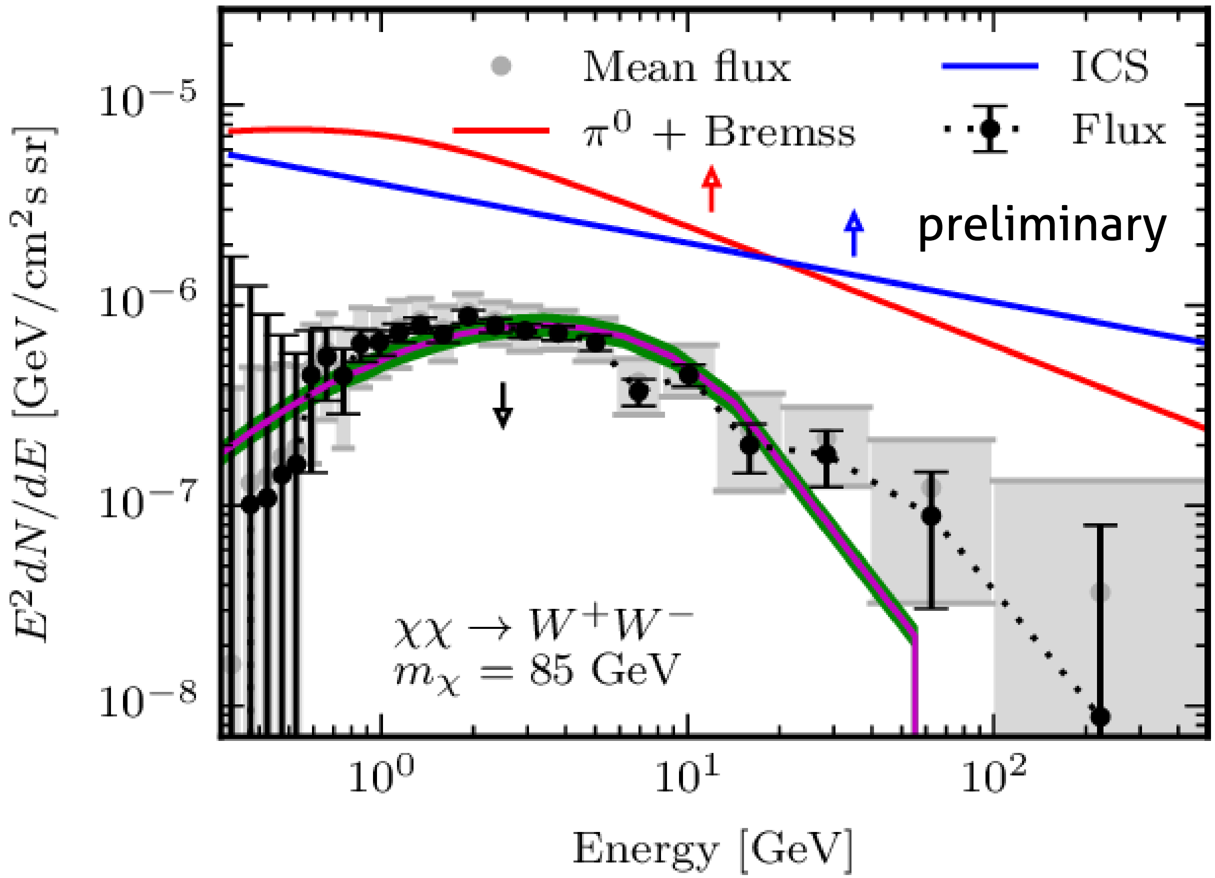


(a) W^+W^- channel



8 different Pythia tunes
→ 5-10% variations in spectrum
Preliminary
Caron et al., in preparation

Fit with WW final states



see also
Agrawal+ 2014

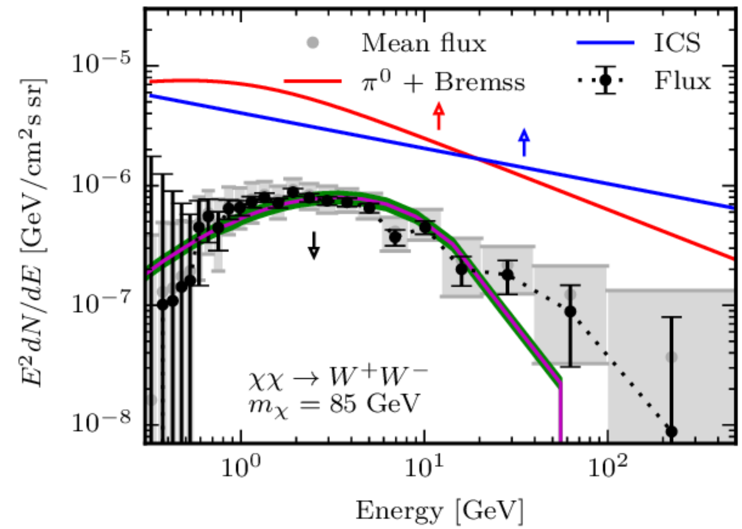
Taking Pythia 6 spectra and our astro-BG systematics at face value, WW final states have a low p-value of p=0.026. However, including a 10% additional uncorrelated HEP systematics in the signal prediction raises this p-value well above 0.1.
Caveat: These HEP systematics *are not uncorrelated* → Requires further investigation.

Dark Matter Annihilation in pMSSM

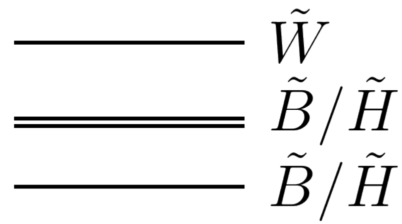
Most relevant constraints from:
- Galactic center excess
- LUX
- IceCube 79 string

$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow W^+ W^-$ Achterberg+ 2015

$M_1, M_2, \mu, \tan\beta, M_A, \widetilde{d}_3, \widetilde{Q}_3, A_t$

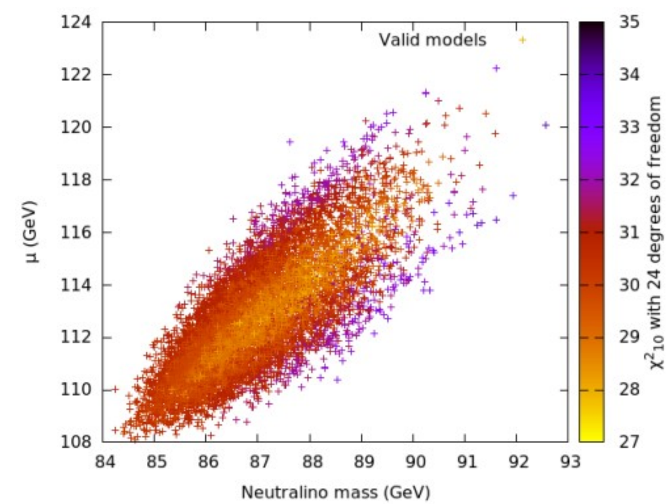


Scenario requires quite some tuning
- Large DM density at Galactic center
- Cancellation of contributions to SI cross section to avoid LUX constraints
- Exploitation of form factors for SD cross section to avoid IceCube constraints
- Allow addition uncertainty in the modeling of the gamma-ray signal to obtain agreement with excess emission



Features:
- Point is *very* constrained
- Almost perfect agreement with observed relic density
- *This scenario will be tested in the very near future in various ways.*

$$-103\text{GeV} < \text{M}_1 < -116\text{GeV}\ ,$$
$$M_2 > 250\text{GeV}\ ,$$
$$108 < \mu < 122\ ,$$
$$8 < \tan\beta < 50\ .$$



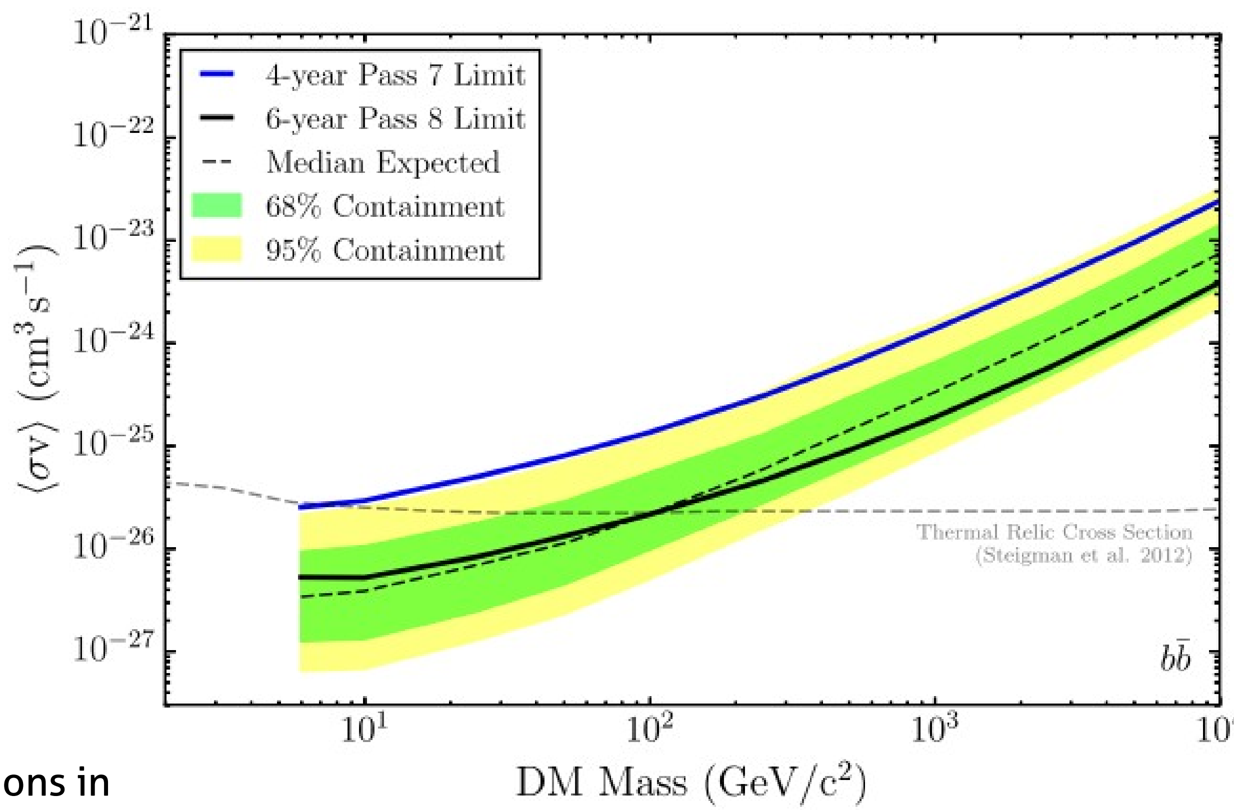
LHC signatures:
- Chargino + Neutralino production
- Monojets
- Squark and gluino searches

New 6 years limits from 15 dSphs

Searching for Dark Matter Annihilation from Milky Way Dwarf Spheroidal Galaxies with Six Years of Fermi-LAT Data

(The Fermi-LAT Collaboration)

The dwarf spheroidal satellite galaxies (dSphs) of the Milky Way are some of the most dark matter (DM) dominated objects known. We report on gamma-ray observations of Milky Way dSphs based on 6 years of *Fermi* Large Area Telescope data processed with the new Pass 8 event-level analysis. None of the dSphs are significantly detected in gamma rays, and we present upper limits on the DM annihilation cross section from a combined analysis of 15 dSphs. These constraints are among the strongest and most robust to date and lie below the canonical thermal relic cross section for DM of mass $\lesssim 100\,\mathrm{GeV}$ annihilating via quark and τ-lepton channels.



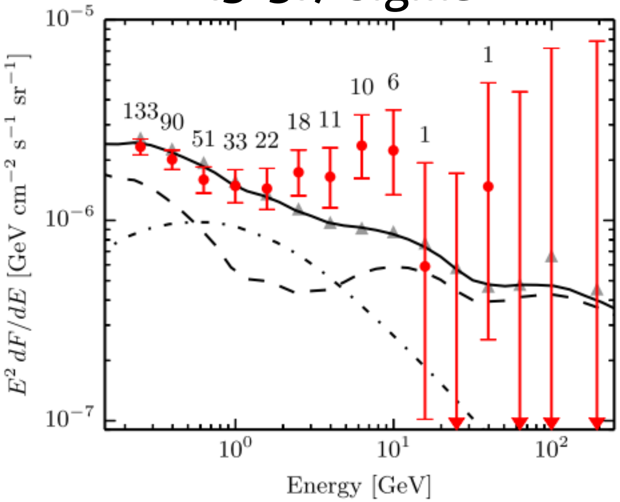
Recent developments

- 8-9 new dwarfs from DES observations [astro-ph/0510346; Koposov+ 2015]
- Possible excess emission in Reticulum 2 [1503.02320; but see 1503.02632]

For a discussion about underlying assumptions in the Jeans analysis see: Bonnivard+ 1407.7822

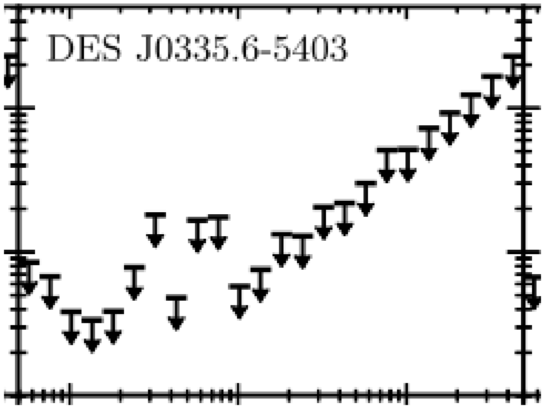
Reticulum II ?

2.3-3.7 sigma

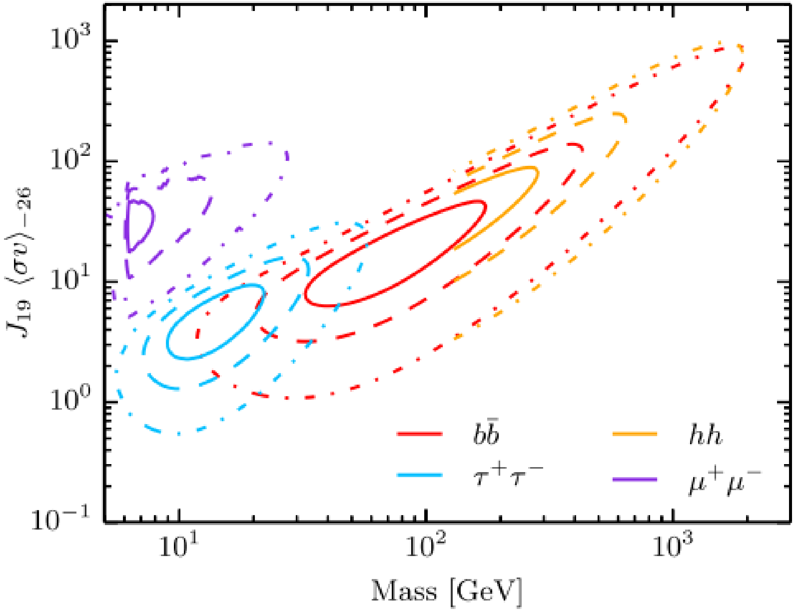


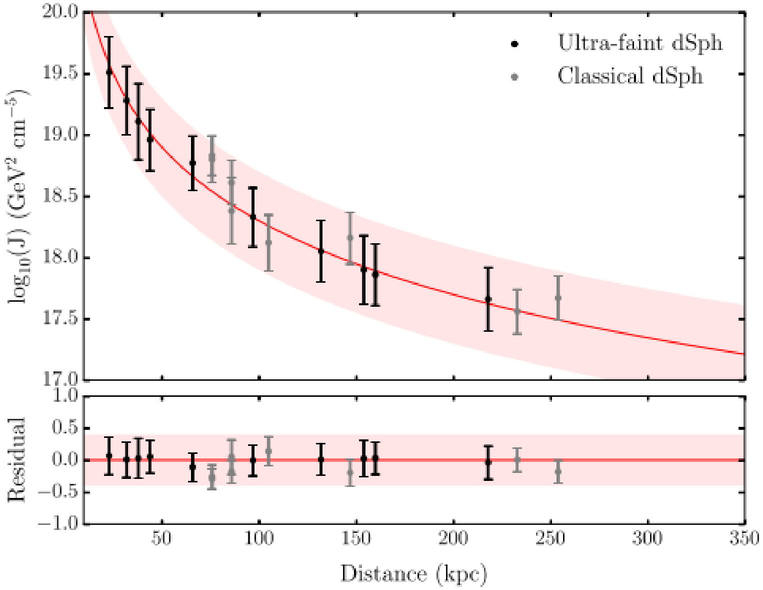
Geringer-Sameth+ 2015

1.5 sigma



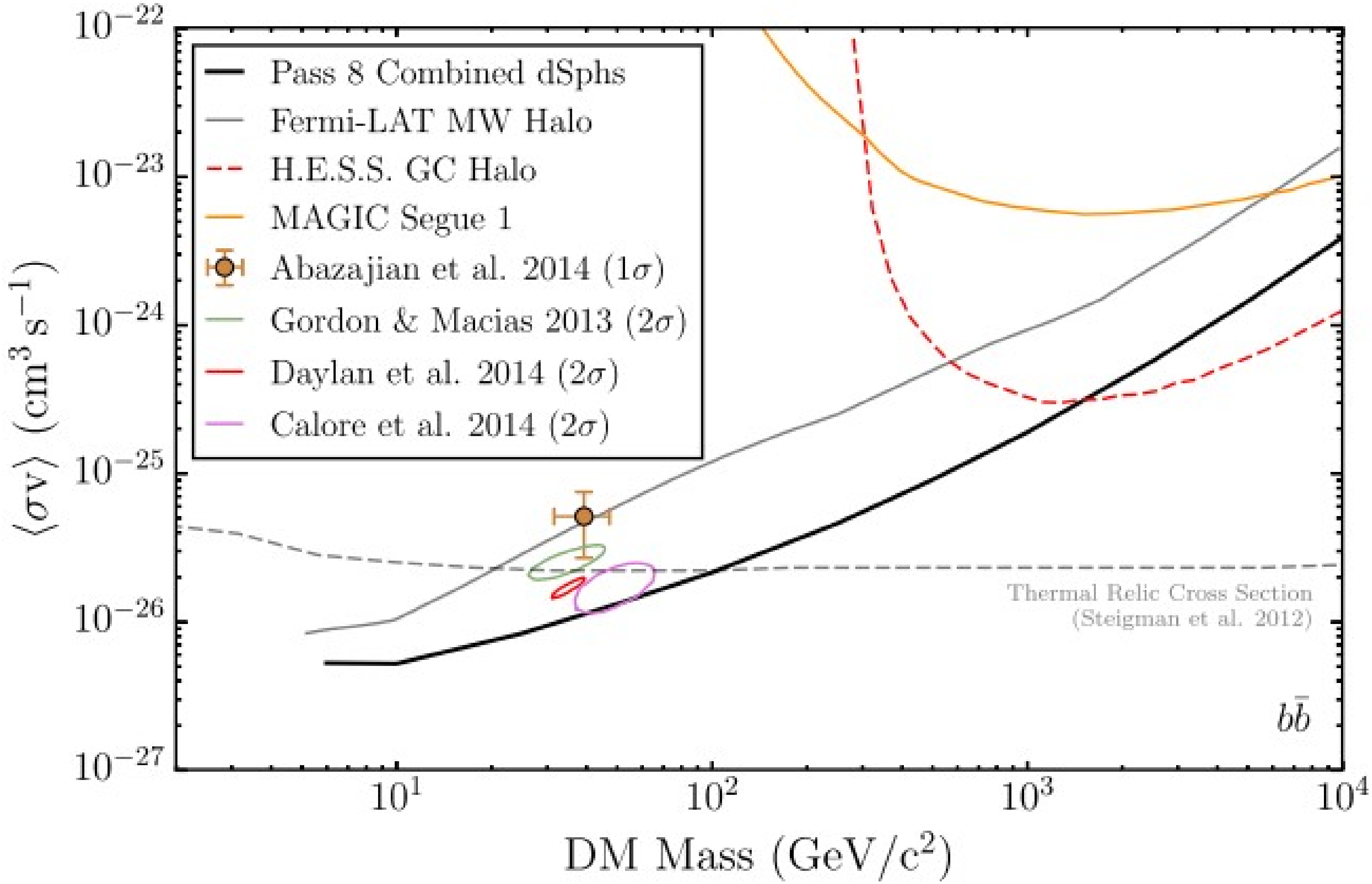
Drlica-Wagner+ 2015



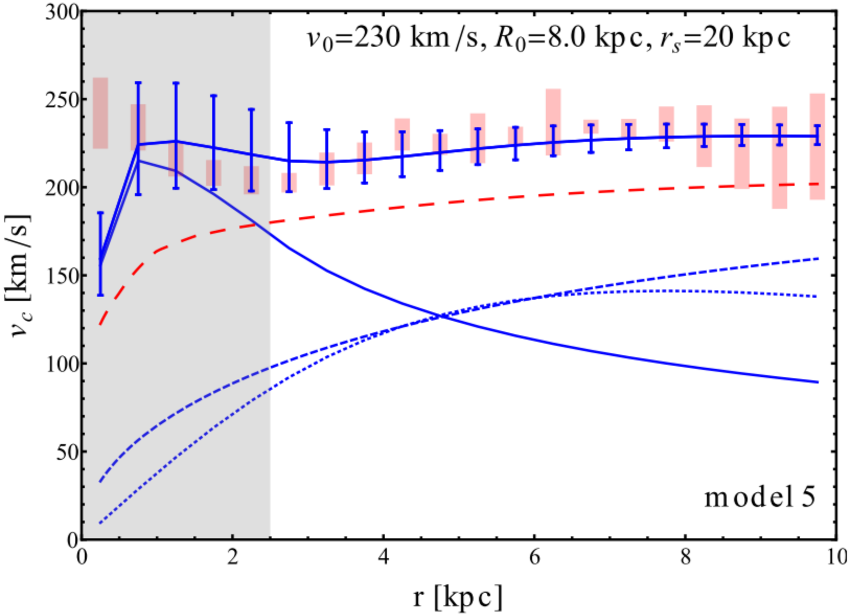


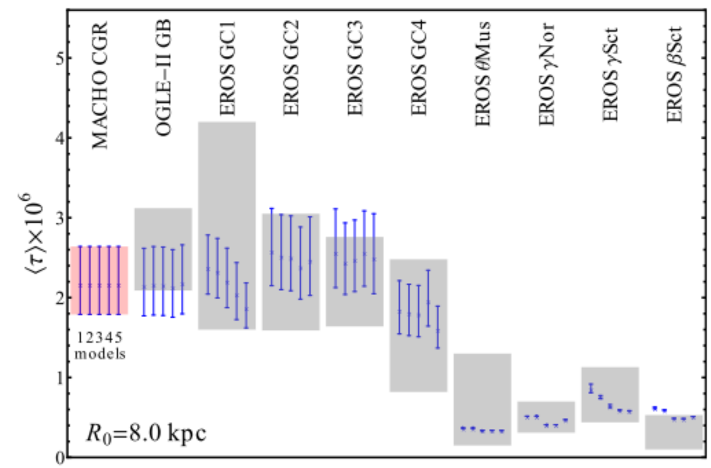
$$\log_{10}(J/\mathrm{GeV}^2/\mathrm{cm}^5) \gtrsim 19.6$$

New Fermi Limits compared with GC excess



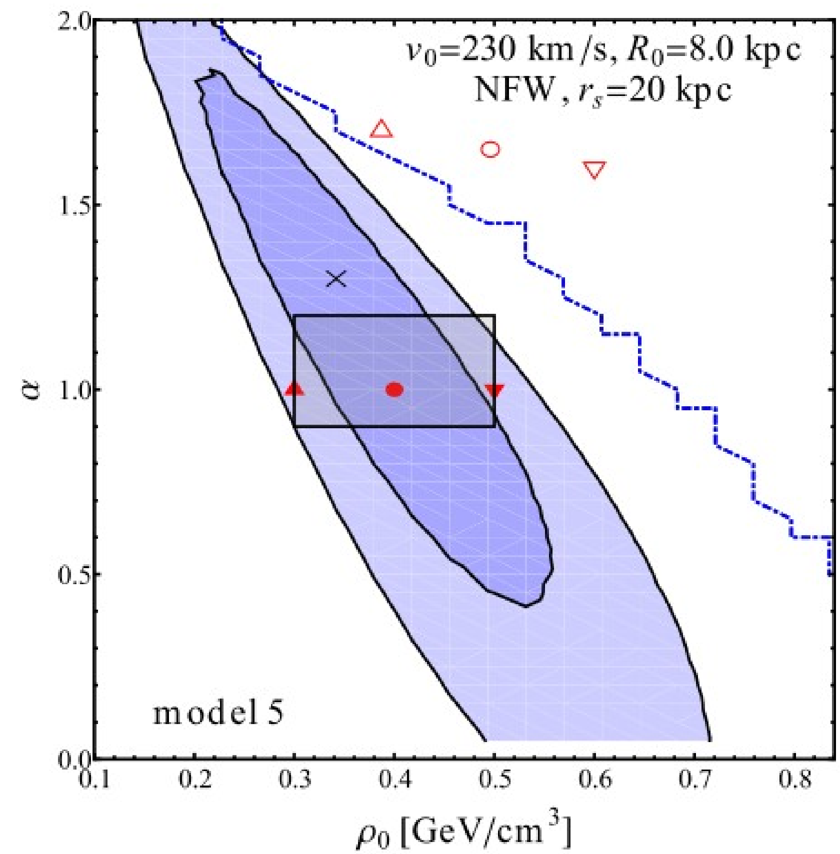
Results from rotation curves





Iocco+ 2011

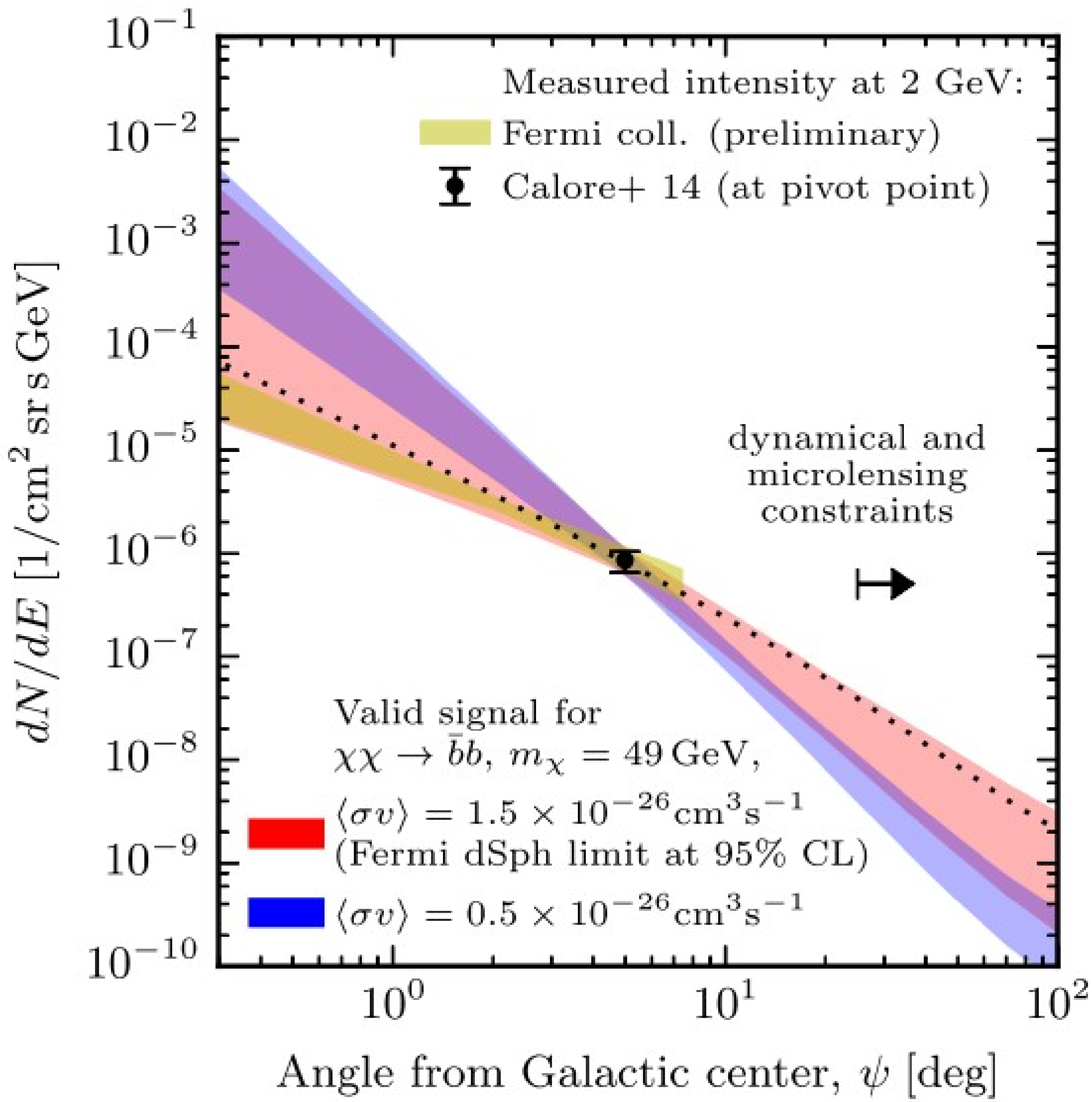
$$\tau(\ell, b, D_s) = \frac{4\pi G}{c^2} \int_0^{D_s} dD_l \;\rho_l(\ell, b, D_l)\, D_l \left(1 - \frac{D_l}{D_s}\right)$$



Rotation curve observations:

- Constraints from
- Thermal cross-section should be reachable if systematics are under control at sub-percent level.

Dwarf spheroidal limits



For cross-sections at the 95% CL exclusion limit from dwarf spheroidal galaxies, current dynamical and microlensing constraints still allow DM halo profiles that give rise to a signal morphology consistent with the observations.

Conclusions

- We performed first comprehensive analysis of BG systematics for the Fermi GeV excess in the inner Galaxy
  - Theoretical model systematics: From 60 GDE models
  - Empirical model systematics: From PCA of residuals
- We defined robust statistical tools to describe spectral and morphological properties of the excess emission

Results

- We robustly confirm the existence of the Fermi GeV excess in the inner Galaxy
- The spectrum features a peak at 1-3 GeV and is best fit with a broken power law. Excellent fits also with DM spectra possible.
- GeV excess extends to at least 10 degree away from GC at 95% CL
- Compatible with uniform spectrum and spherical symmetry within 95% CL
- This suggests: DM annihilation, unresolved point sources, maybe leptonic burst event, …
- Outlook: Multi-wavelength, multi-messenger, …