“Walking the Milky Way”

Background systematics for dark matter searches *with gamma rays*

arXiv:1406.3430 (JCAP), with Fermi-LAT coll.
arXiv:1409.0042, with F. Calore and I. Cholis

Christoph Weniger

RICAP
3 Oct 2014
Noto, Italy

GRAPPA
GRavitation AstroParticle Physics Amsterdam

Searches for non-gravitational signatures of DM

Fermi LAT, XMM-Newton, AMS-02, LOFAR, MWA, PAMELA, GAPS, CTA, HESS, VERITAS, Chandra, ...

Indirect searches
for **DM annihilation or decay** products in cosmic rays.

$$\chi\chi \to \bar{X}X$$

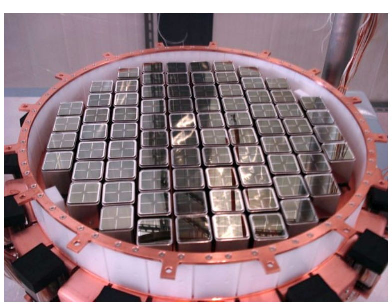
$$\chi \to \gamma\nu$$

Candidates

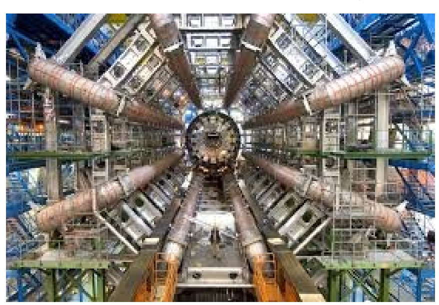
WIMPs (weakly interacting massive particles) 'Freeze-out mechanism'	**Sterile neutrinos** 'Dodelson-Widrow' mechanism”	**Gravitino DM** 'Freeze-in mechanism'

Different probes

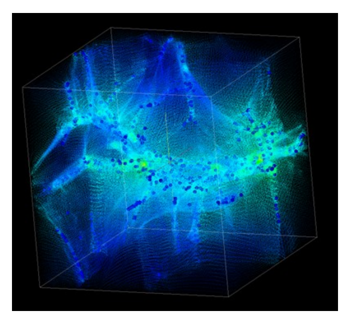
Atomic recoil



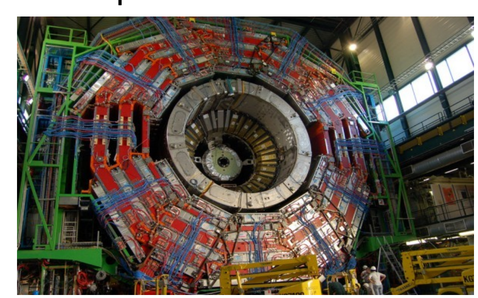
Missing energy



Small scale structure



Displaced vertices



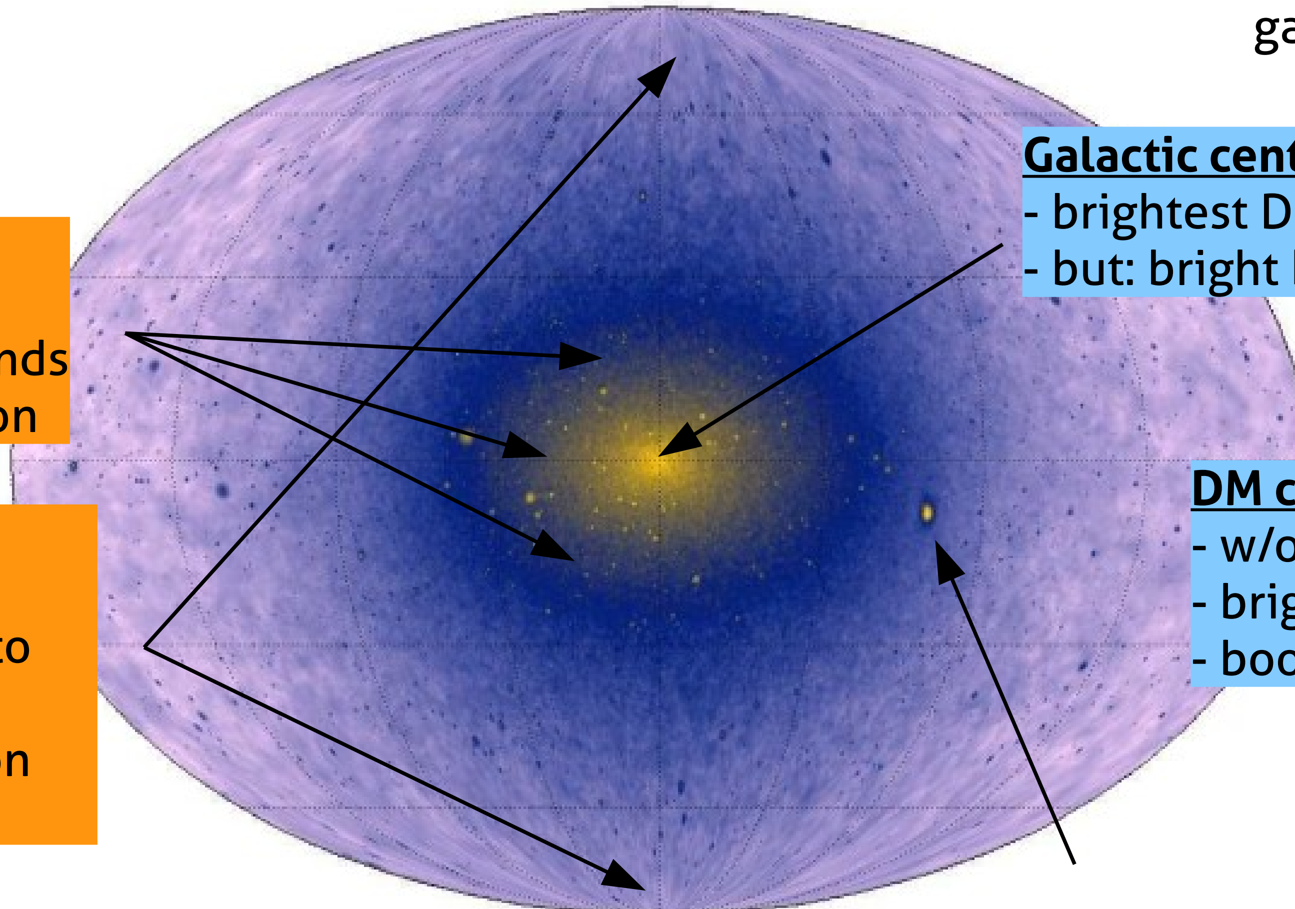
Potential targets for searches with photons

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)



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

<u>Extragalactic</u>
- nearly isotropic
- only visible close to Galactic poles
- angular information
- Galaxy clusters?

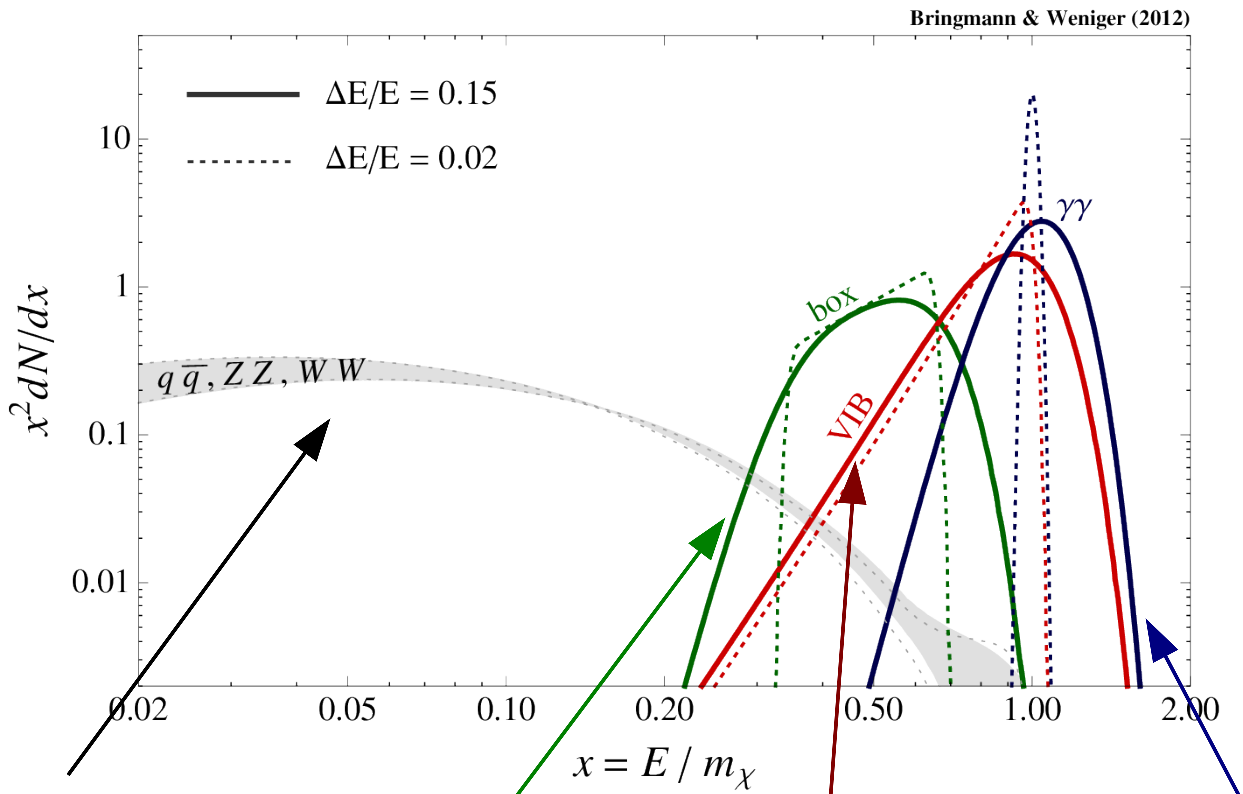
<u>Galactic center (~8.5 kpc)</u>
- brightest DM source in sky
- but: bright backgrounds

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

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

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

The photon energy spectrum



Continuum emission aka secondary photons

(from hadronic channels, as discussed above)

Internal Bremsstrahlung (IB)

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

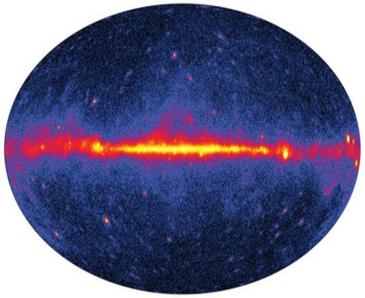
Gamma-ray lines

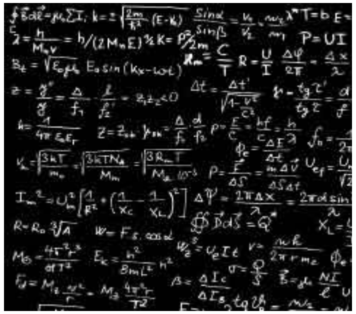
$$\chi\chi \to \gamma\gamma$$

Cascade decays

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

Overview





A. Gamma-ray lines*

B. Fermi GeV excess

C. Conclusions

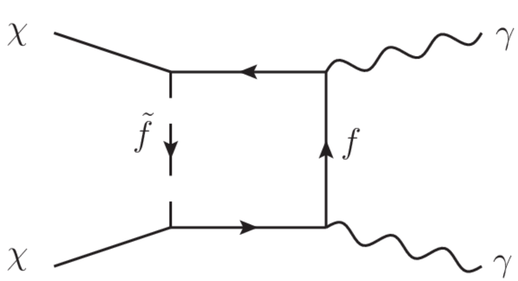
*Not the 130 GeV line.

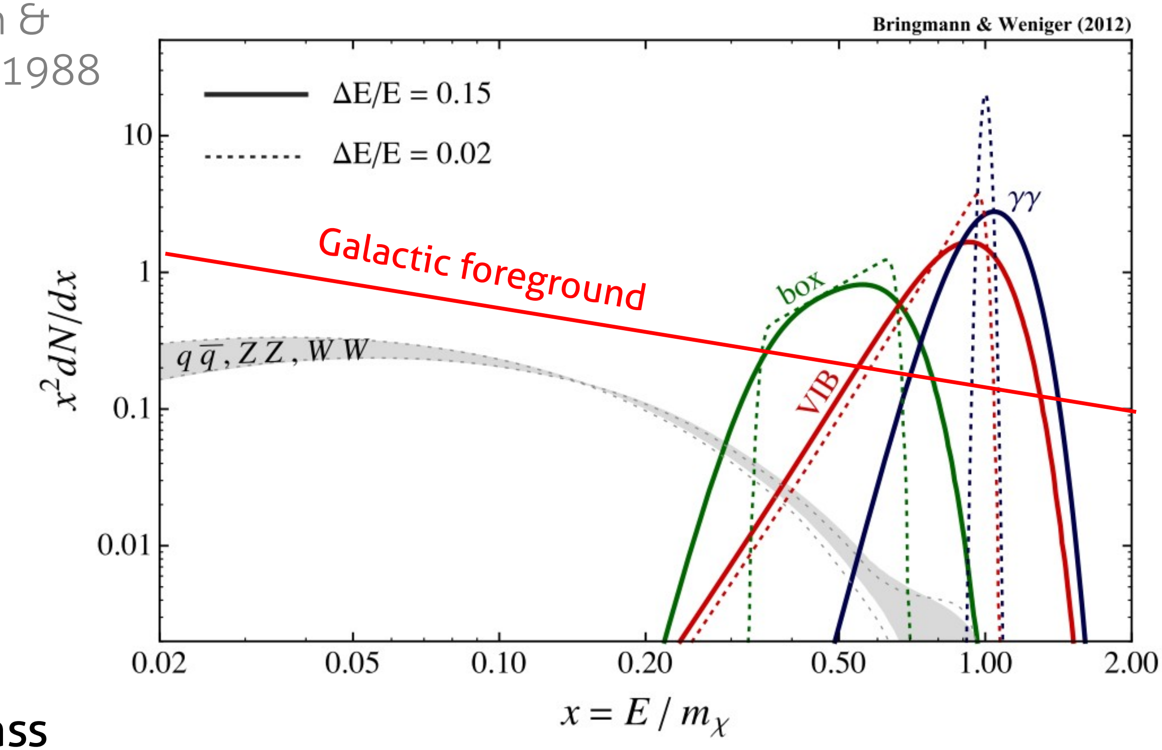
Gamma-ray lines

Smoking-gun signatures for DM annihilation

Gamma-ray lines

Bergström & Snellman 1988





- Generically small branching ratio:

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

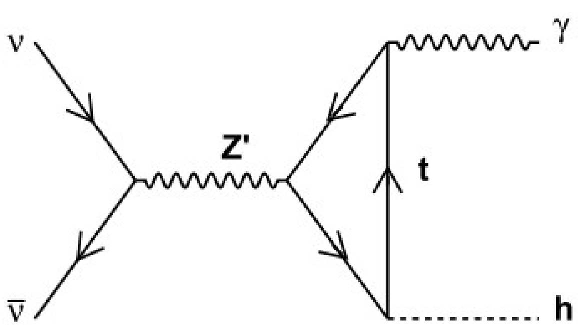
- Multiple lines

$$\chi\chi \to \gamma\gamma, \gamma Z^0, \gamma h^0$$

- Line energy is direct measure of DM mass

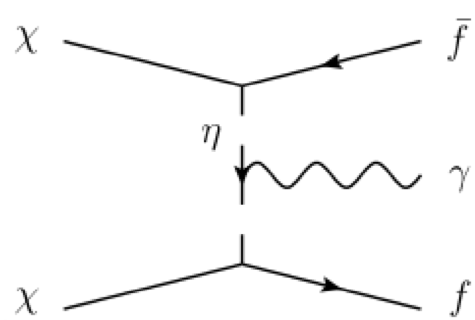
Examples with stronger line-like features:

Loop enhancement



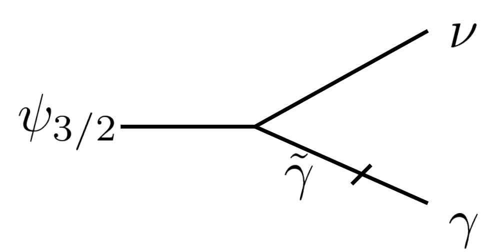
e.g. Jackson+ 2010

Internal Bremsstrahlung (IB)



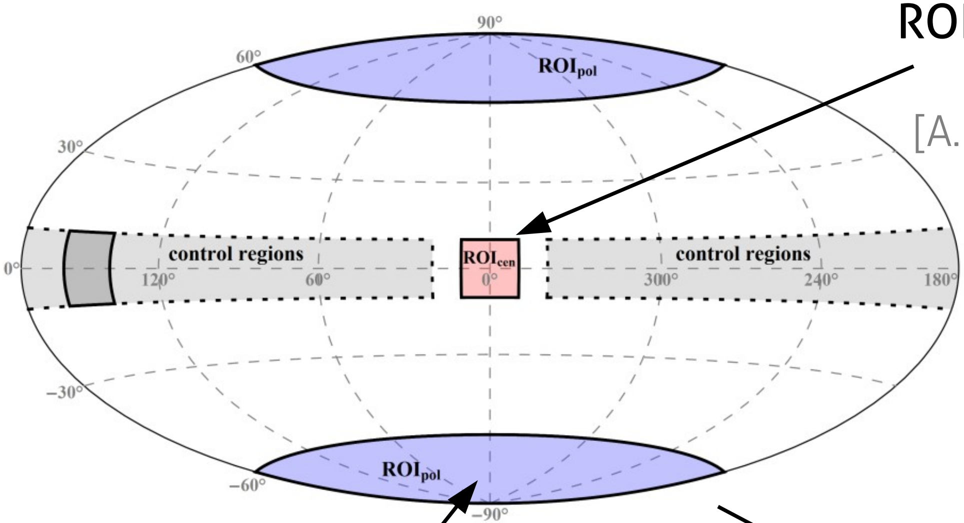
Bringmann+ 2008

DM decay (gravitinos)



e.g. Ibarra & Tran 2008

Gamma-ray line searches below 10 GeV



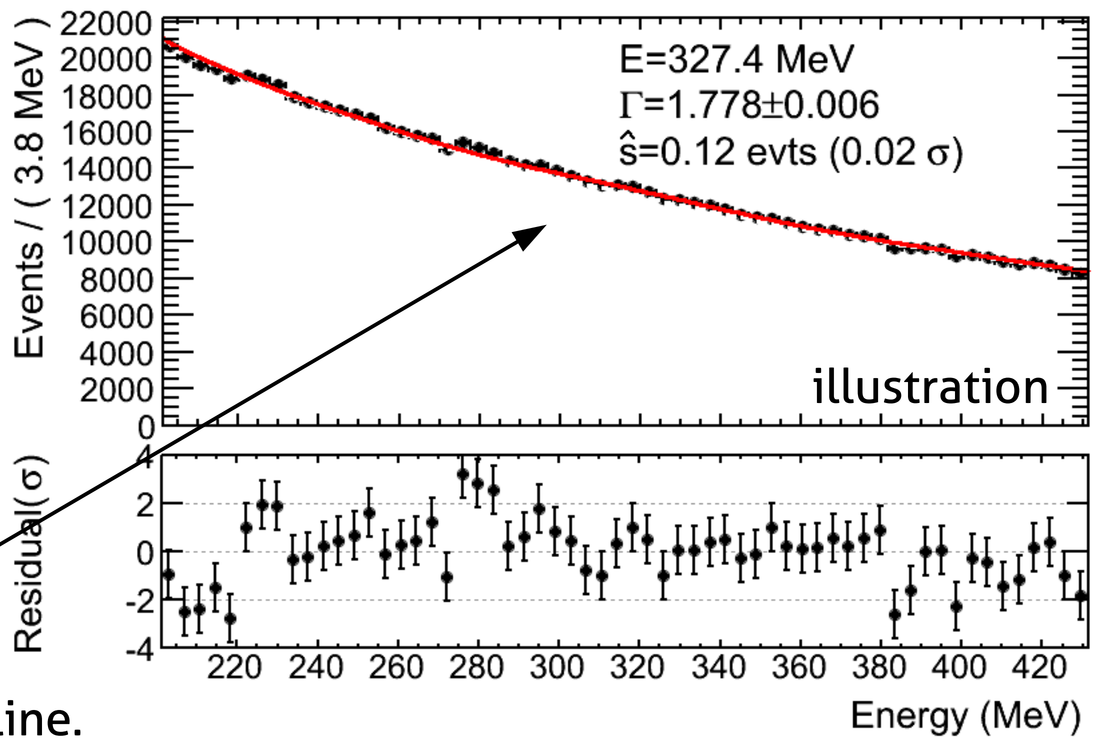
ROI for DM annihilation.

[A. Albert, CW, Fermi coll+ 2013]

ROI for DM decay.

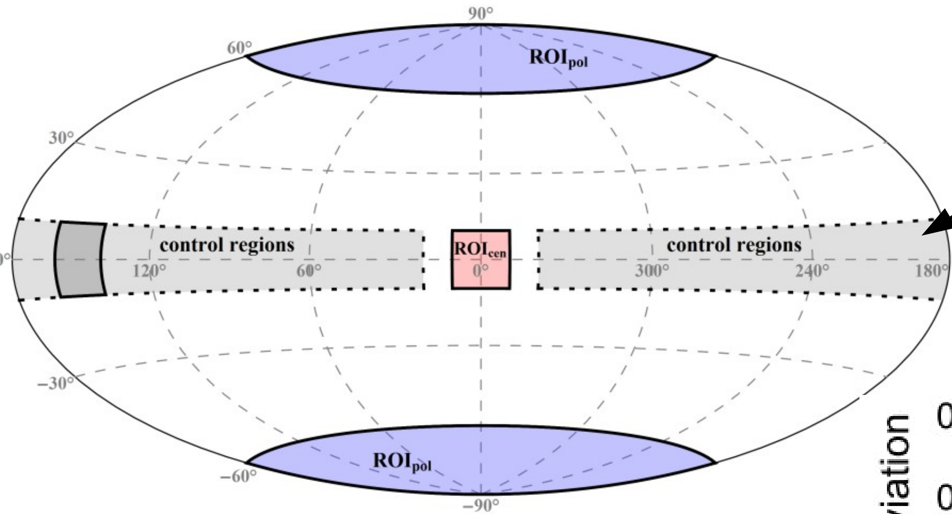
PL + line model fit to data

$$\frac{dJ}{dE} = S\ \delta(E - E_\gamma) + \beta E^{-\gamma}$$



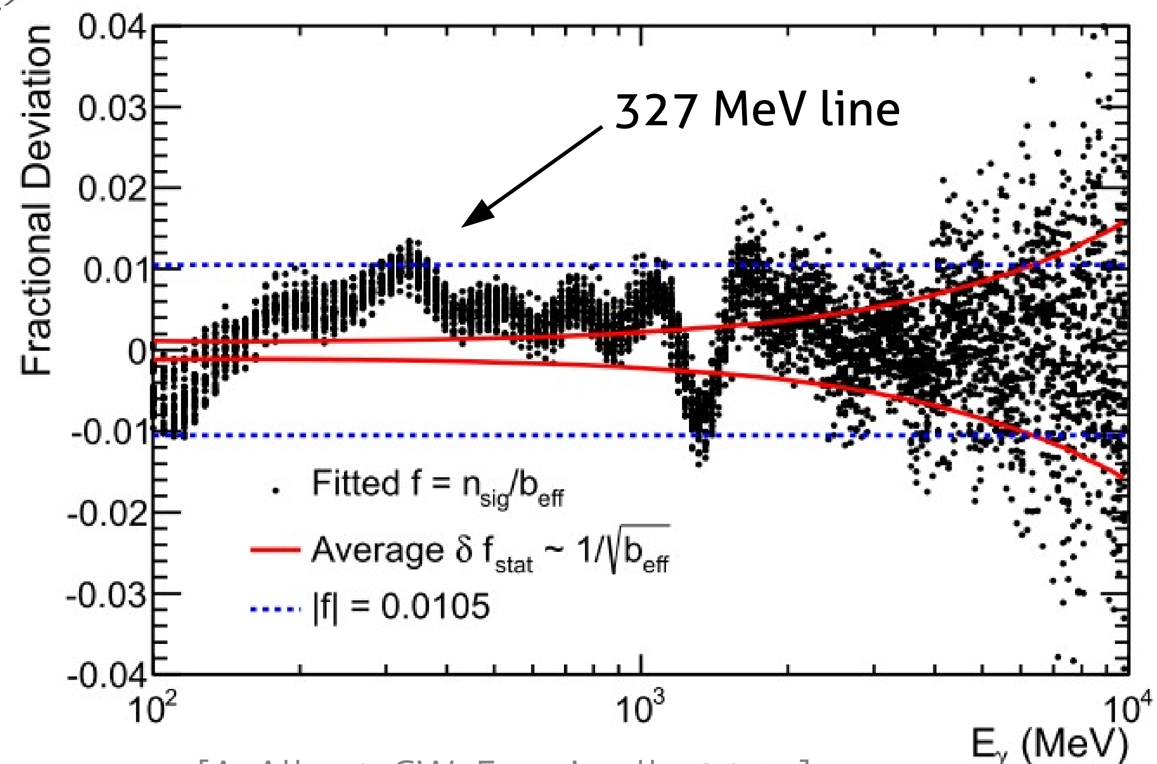
This is formally a ~9 sigma line.

Background systematics from the Galactic disk



Galactic disk can be used as control region.

Distribution of residuals



[A. Albert, CW, Fermi coll+ 2013]

Estimate fake signal events:

$$n_{\rm syst} = \frac{n_{\rm res,control}}{b_{\rm eff,control}} b_{\rm eff,signal}$$

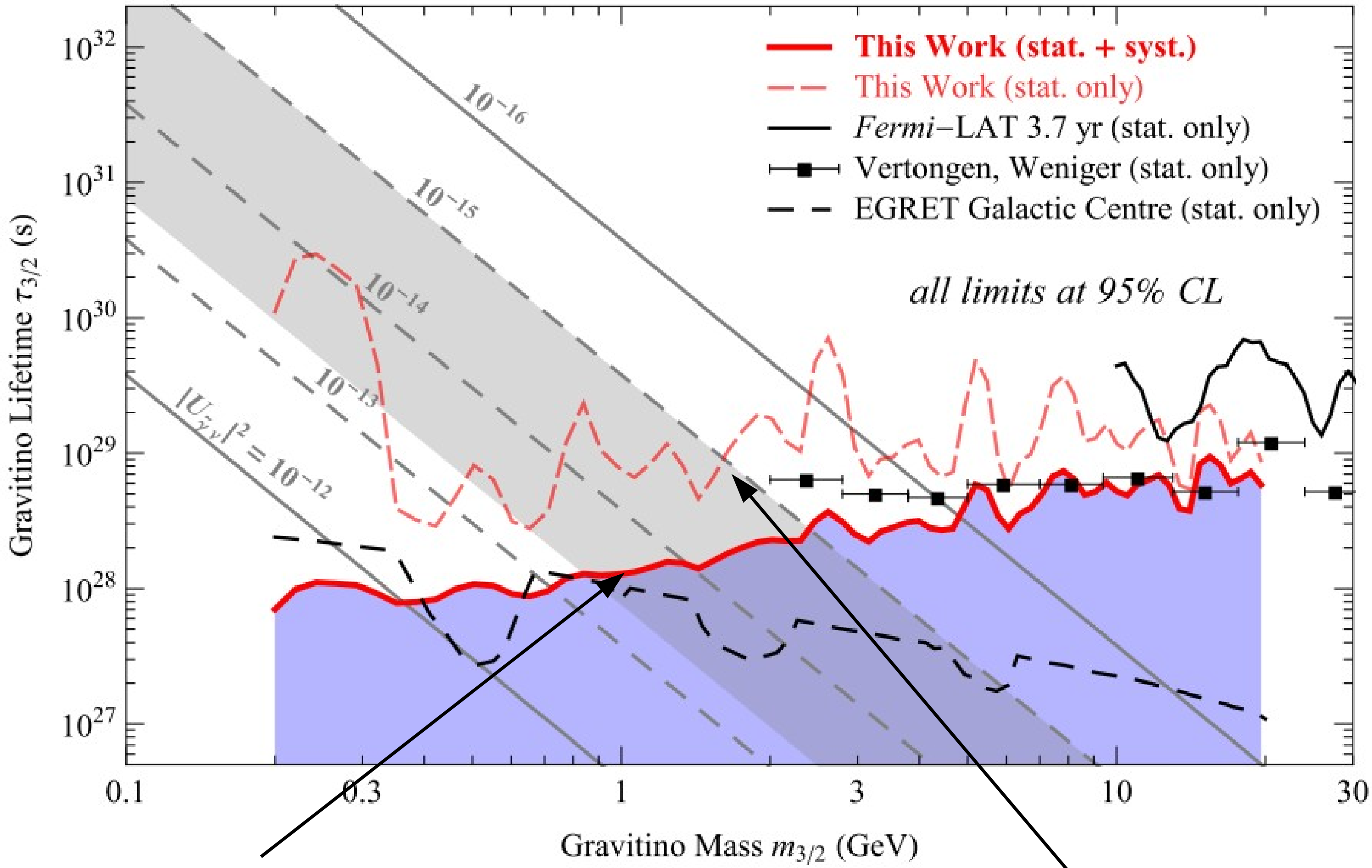
Fractional deviation

Total likelihood:

$$\mathcal{L}(\alpha, \Gamma, n_{\rm sig}, n_{\rm syst}) = P_{\mathcal{F}}(n_{\rm syst}, b_{\rm eff}) \prod_i P(c_i | \mu_i(\alpha, \Gamma, n_{\rm sig} + n_{\rm syst}))$$

Lower limits on gravitino lifetime

[A. Albert, CW, Fermi coll+ 2013]



Our result when main systematics are taken into account.

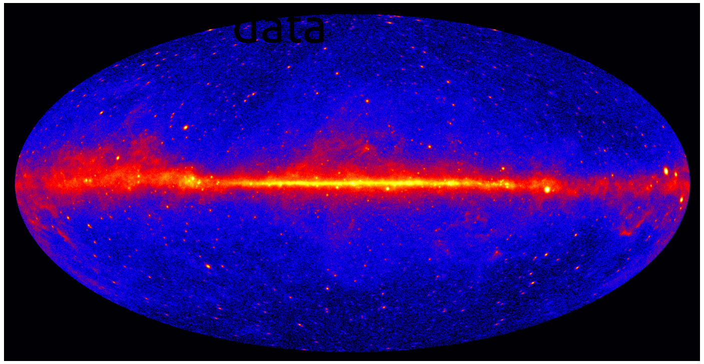
Purely statistical

- First study that consistently takes into account systematics
- We slightly improve over previous limits from EGRET

The 'Fermi GeV excess'

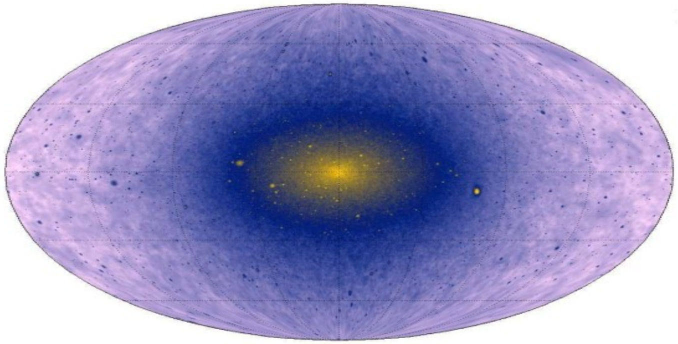
The Galactic halo
Foreground subtraction

Fermi LAT data

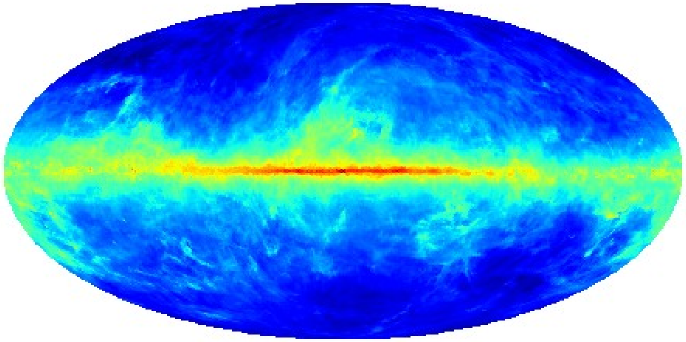


Subtract
- Diffuse foregrounds
- Point sources

Residual: Dark matter?

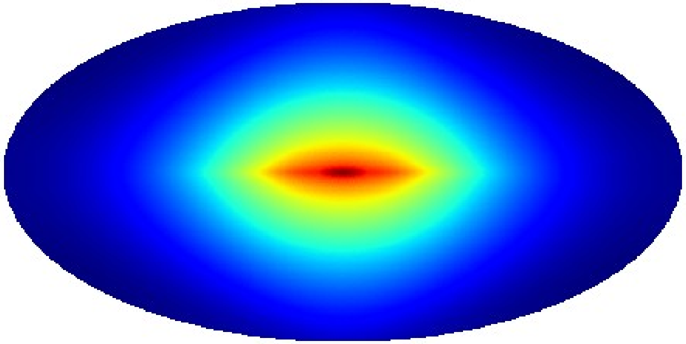


Pion decay



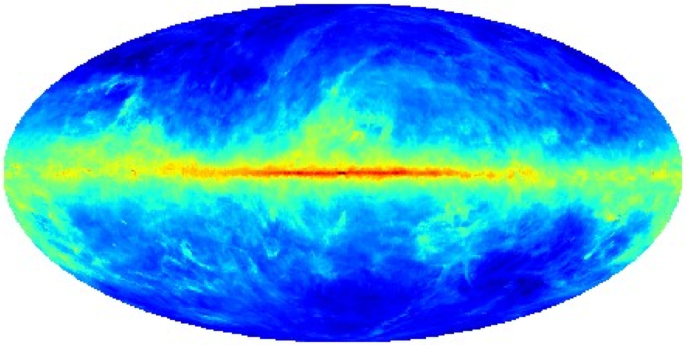
Traces
ISM*CR protons

Inverse Compton



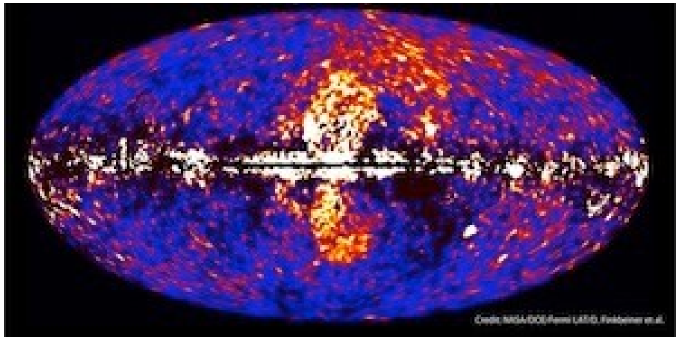
Traces
ISRF*CR electrons

Bremsstrahlung



Traces
ISM*CR electrons

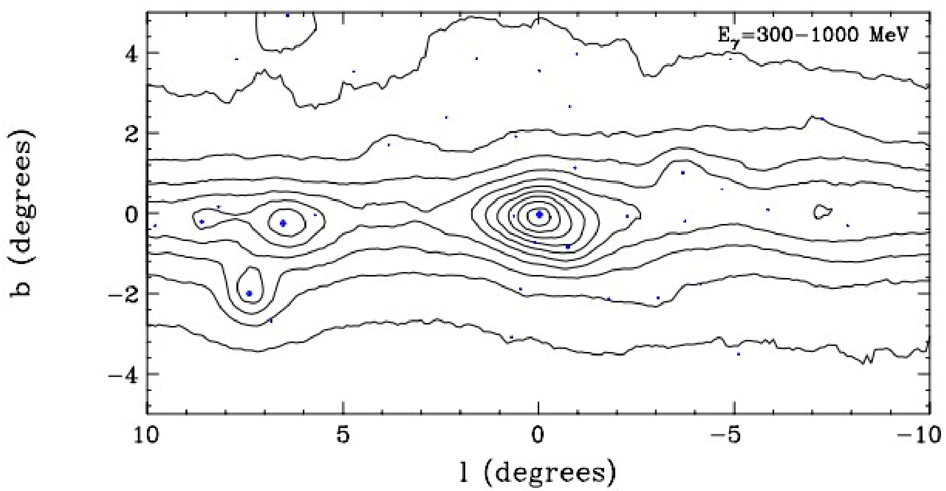
Fermi bubbles



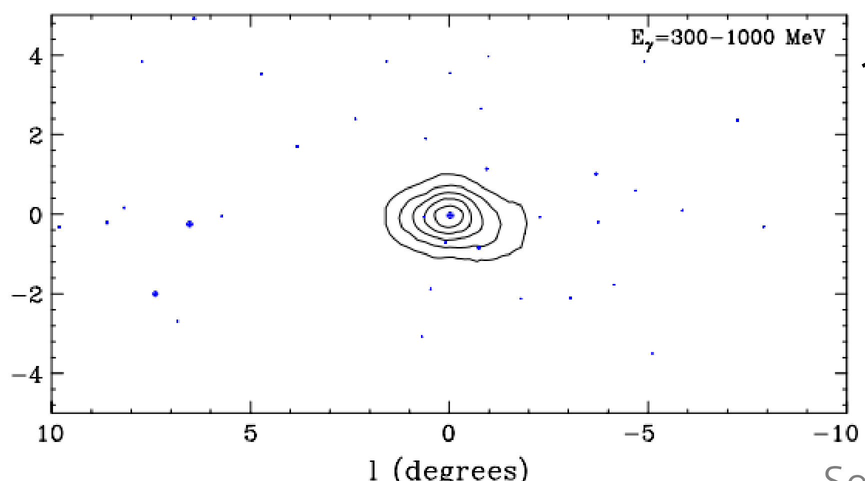
Effective template
Cause uncertain

The Fermi GeV excess

Claims for an extended emission of gamma-rays at the Galactic center

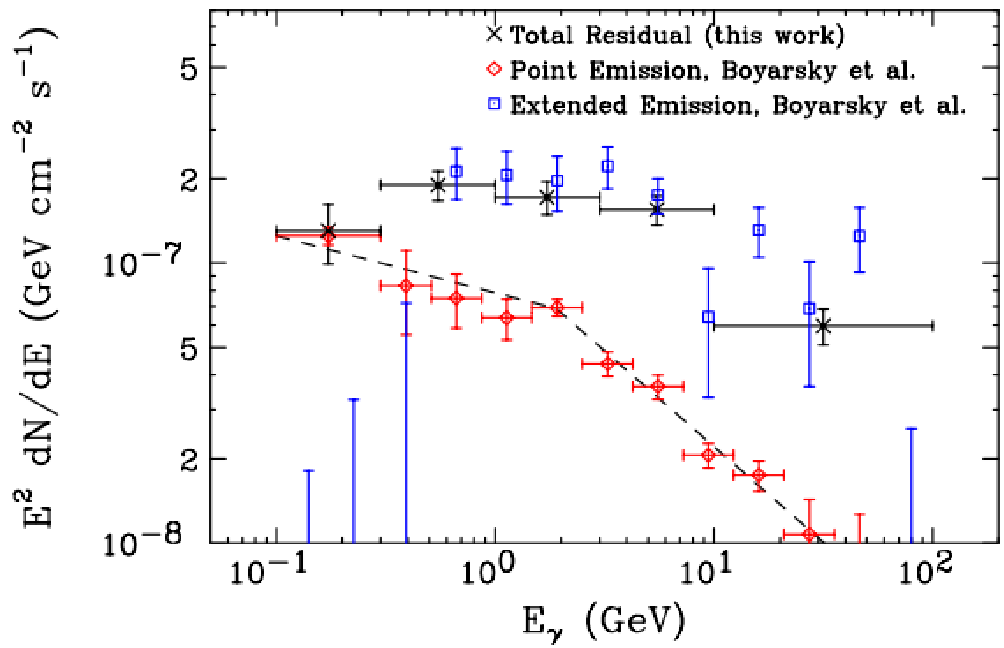


- point sources – "diffuse emission"
=



Hooper & Linden 2011

Extracted spectrum:

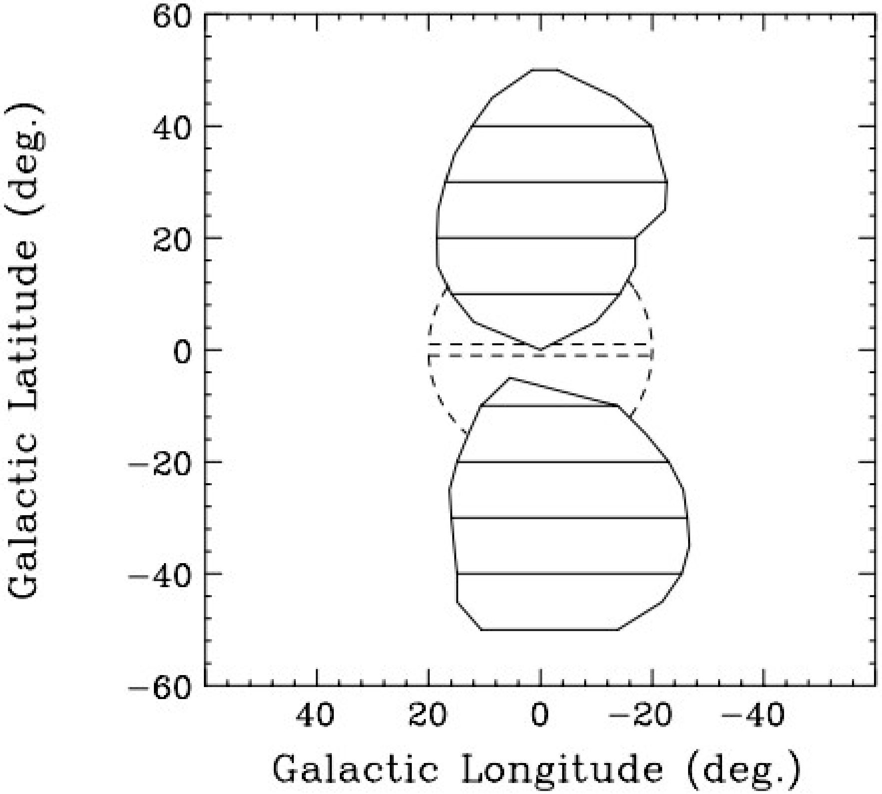


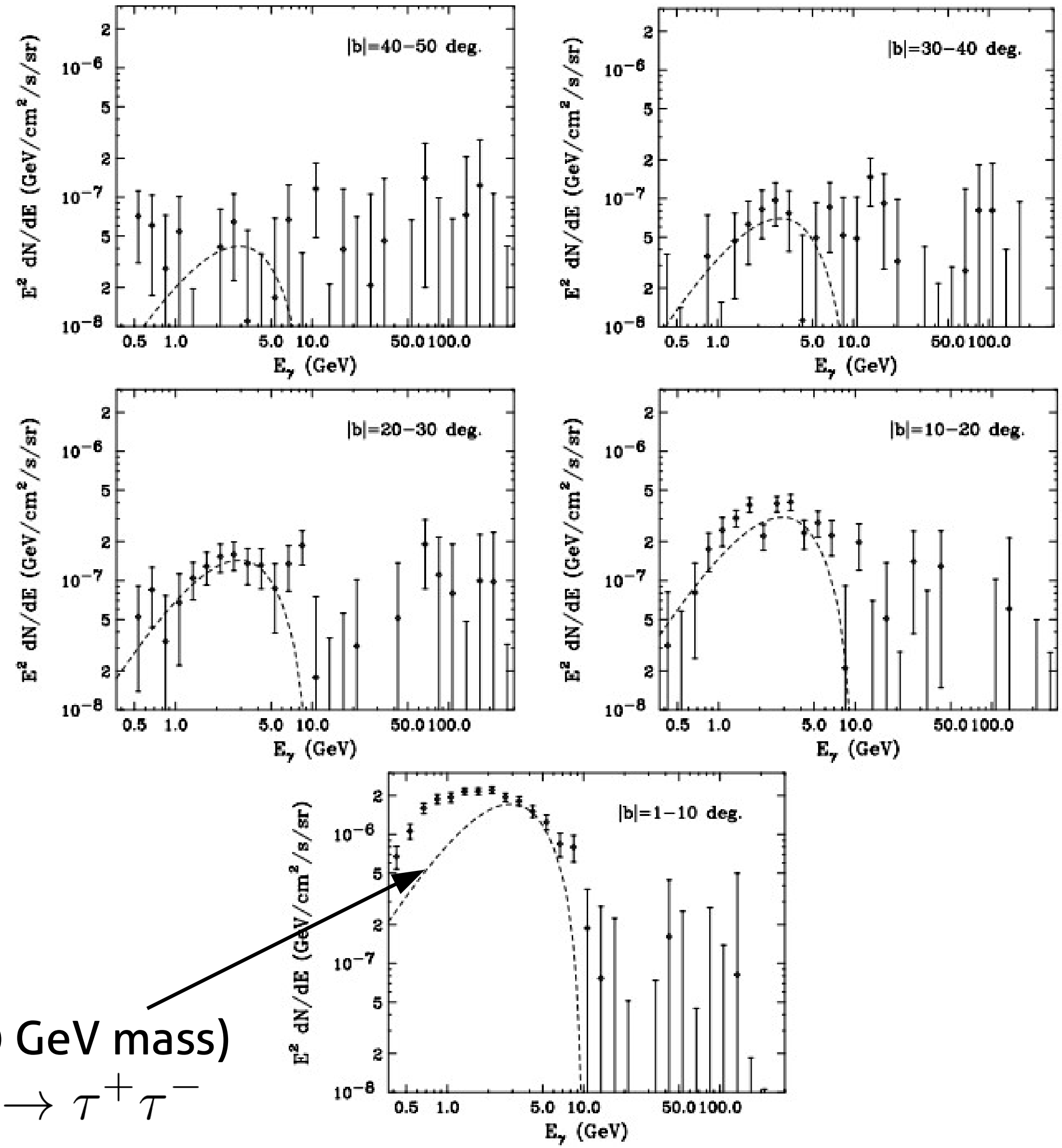
Dark matter interpretation:
- annihilation into e.g. tau+ tau-
- ~10 GeV DM mass
- contracted NFW profile

See also Hooper & Goodenough 2011; Boyarsky+ 2011; Abazajian & Kaplinghat 2012, Gordon & Macias 2013, Macias & Gordon 2014; Abazajian+ 2014; Daylan+ 2014

The Fermi GeV excess at high latitudes

Claims for the emission being extended up to high latitudes:





Hooper & Slatyer 2013

DM fit (10 GeV mass)

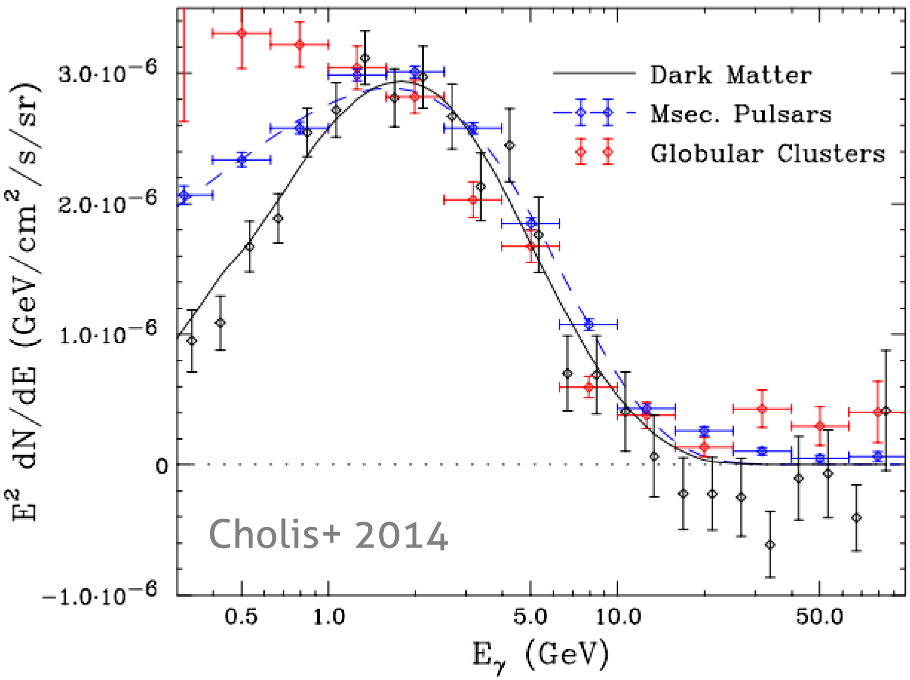
$\chi\chi \rightarrow \tau^+\tau^-$

Non-DM Interpretations

Milli-second pulsars:

Wang+ 2005; Abazajian 2011; Gordon & Macias 2013; Hooper+ 2013; Yuan & Zhang 2014; Hooper+ 2013; Calore+ 2014; Cholis+ 2014

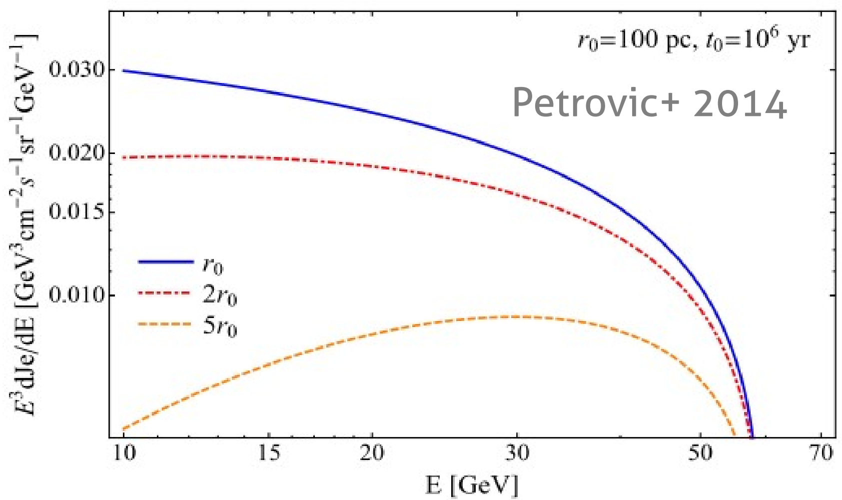
- Spectrum of known MSPs agrees reasonably well with claimed GCE spectrum (<u>except at sub-GeV energies</u>)
- Observed luminosity function is claimed to be incompatible with GCE (we don't see resolved MSPs at GC) Hooper+, Calore+, Cholis+ 2013
- Compatible with distribution of low-mass X-ray binaries (possible MSP progenitors)



Recent active past of GC:

Petrovic+ 2014; Carlson+ 2014

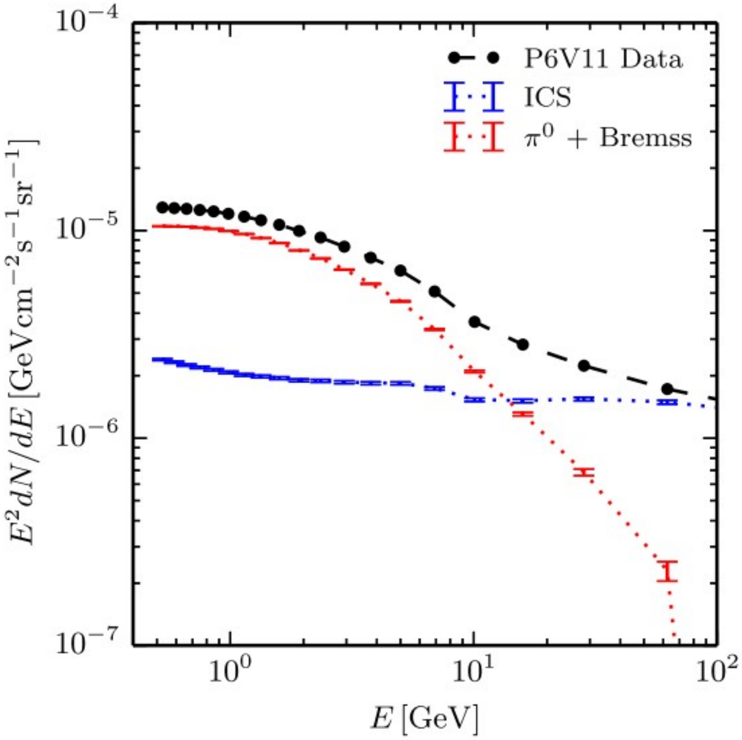
- Recent injection of CR in Galactic center
- Diffuse out → approx. spherical profile
- Plausible possibility
- **Spectra will depend on latitude**

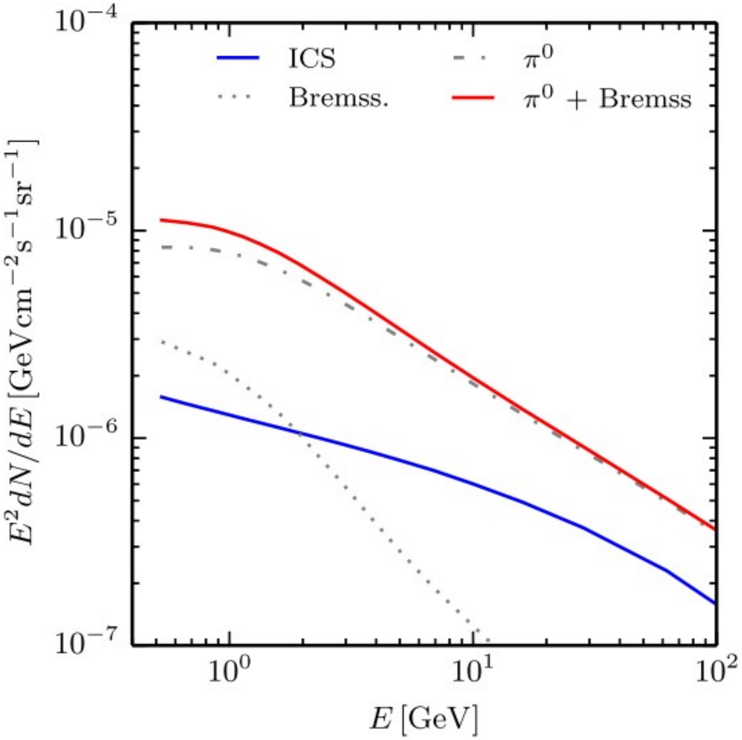


Other possible interpretations fail to explain the high-latitude component.

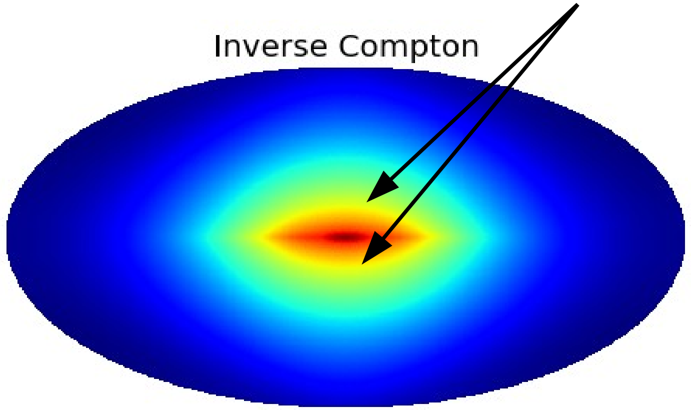
Problem I: Most analyses adopt the P6V11 BG model

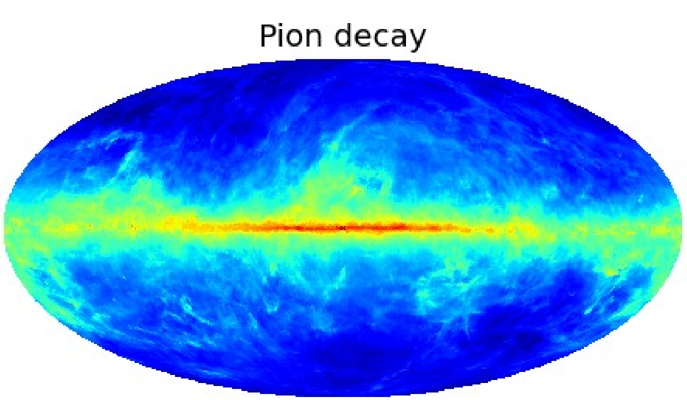
Decomposition of P6V11 in Inverse Compton and pi0+Bremss. components:





ICS component **very hard** at >10 GeV energies
→ **oversubtraction guaranteed**





Problem II: <u>All</u> GDE models give a bad fit to data

None of the existing GDE models gives a "good" fit to the data in the statistical sense.

Typical values are

$$\chi^2_{\rm red} \sim 1.1$$

which corresponds to ridiculously small p-values:

$$p \lesssim 10^{-300}$$

→ Check background model systematics before make statistics based claims.

Central Questions

- What is the **energy spectrum** of the excess?
- **How far** does the excess extend to high latitudes?
- Is the energy spectrum the **same everywhere**?
- Is the excess **spherically symmetric**?

To this end, we estimated…

…theoretical model systematics

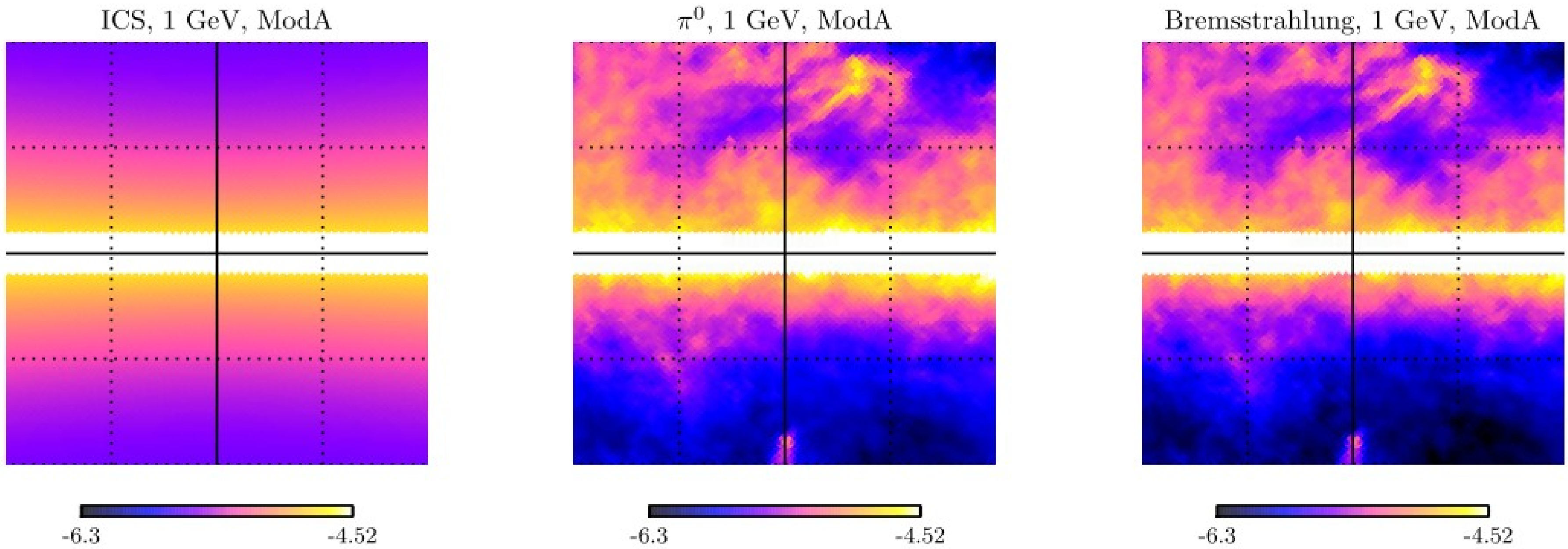
- What is the impact of **extreme** variations – within certain boundaries – of the Galactic diffuse emission (GDE) model on the GeV excess?

…empirical model systematics

- How well do GDE models describe the data?
- What are the characteristics of residuals?

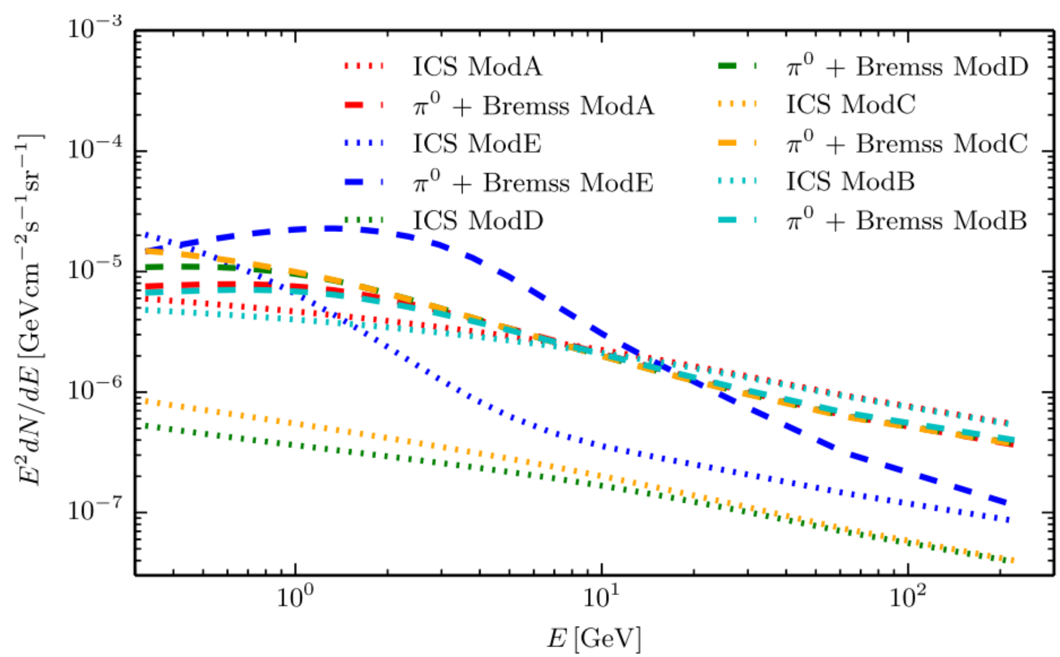
Theoretical model uncertainties

60 Galactic Diffuse Emission (GDE) models



Our region of interest:

$$|\ell| < 20^\circ \quad \& \quad 2^\circ < |b| < 20^\circ$$



Galactic Center Excess (GCE) template derived from generalized NFW profile:

$$\rho(r) = \rho_0 \frac{r_s^3}{r^\gamma (r_s + r)^{3-\gamma}}$$

In the fits, background model spectra will be **neglected**!

What we varied and what we kept fixed

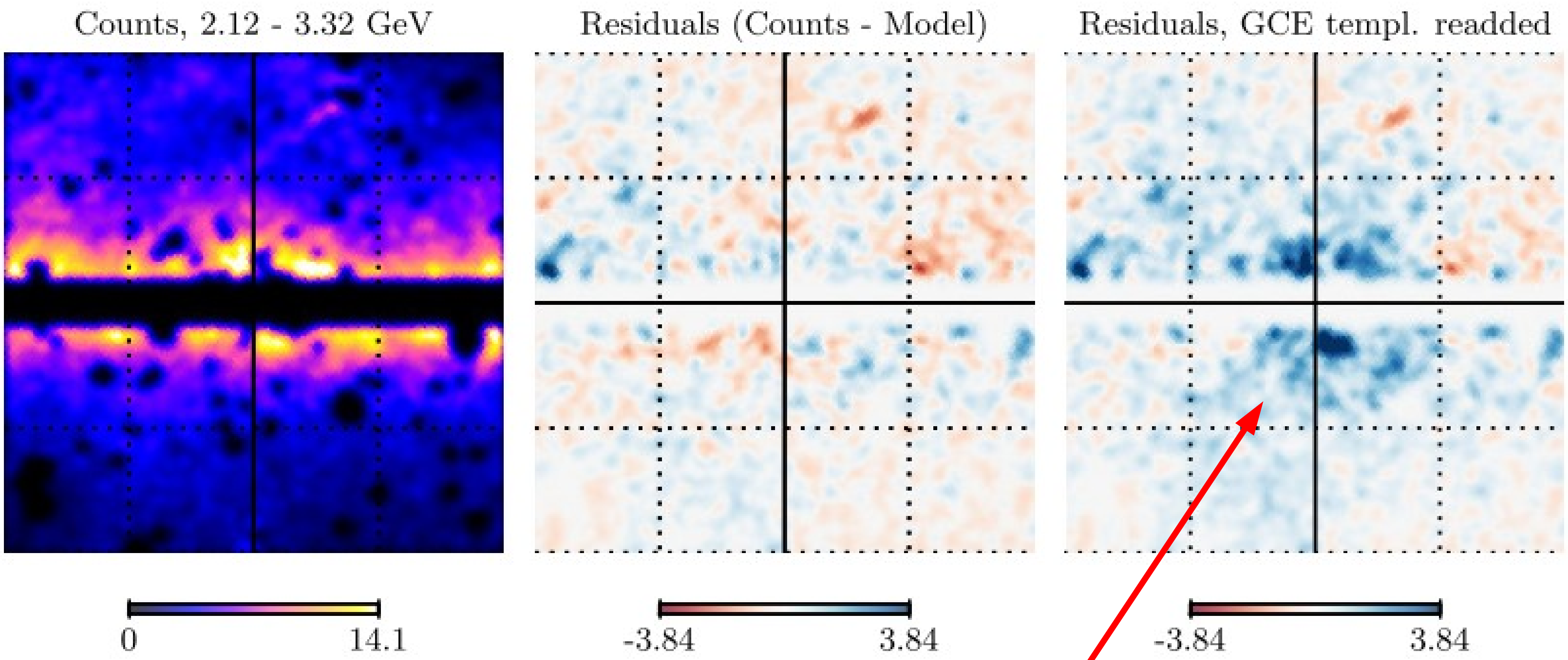
Variations:

- geometry of the diffusion zone: $4 \leq z_D \leq 10$ kpc and $r_D = 20$ or 30 kpc;
- source distributions: SNR, pulsars, OB stars;
- diffusion coefficient at 4 GV: $D_0 = 2 - 60 \times 10^{28}\ \mathrm{cm^2\,s^{-1}}$;
- Alfvén speed: $v_A = 0 - 100\ \mathrm{km\,s^{-1}}$;
- gradient of convection velocity: $dv/dz = 0 - 500\ \mathrm{km\,s^{-1}\,kpc^{-1}}$;
- ISRF model factors (for optical and infrared emission): 0.5 – 1.5;
- B-field parameters: $5 \leq r_c \leq 10$ kpc, $1 \leq z_c \leq 2$ kpc, and $5.8 \leq B(r = 0, z = 0) \leq 117$ μG.

Limitations:

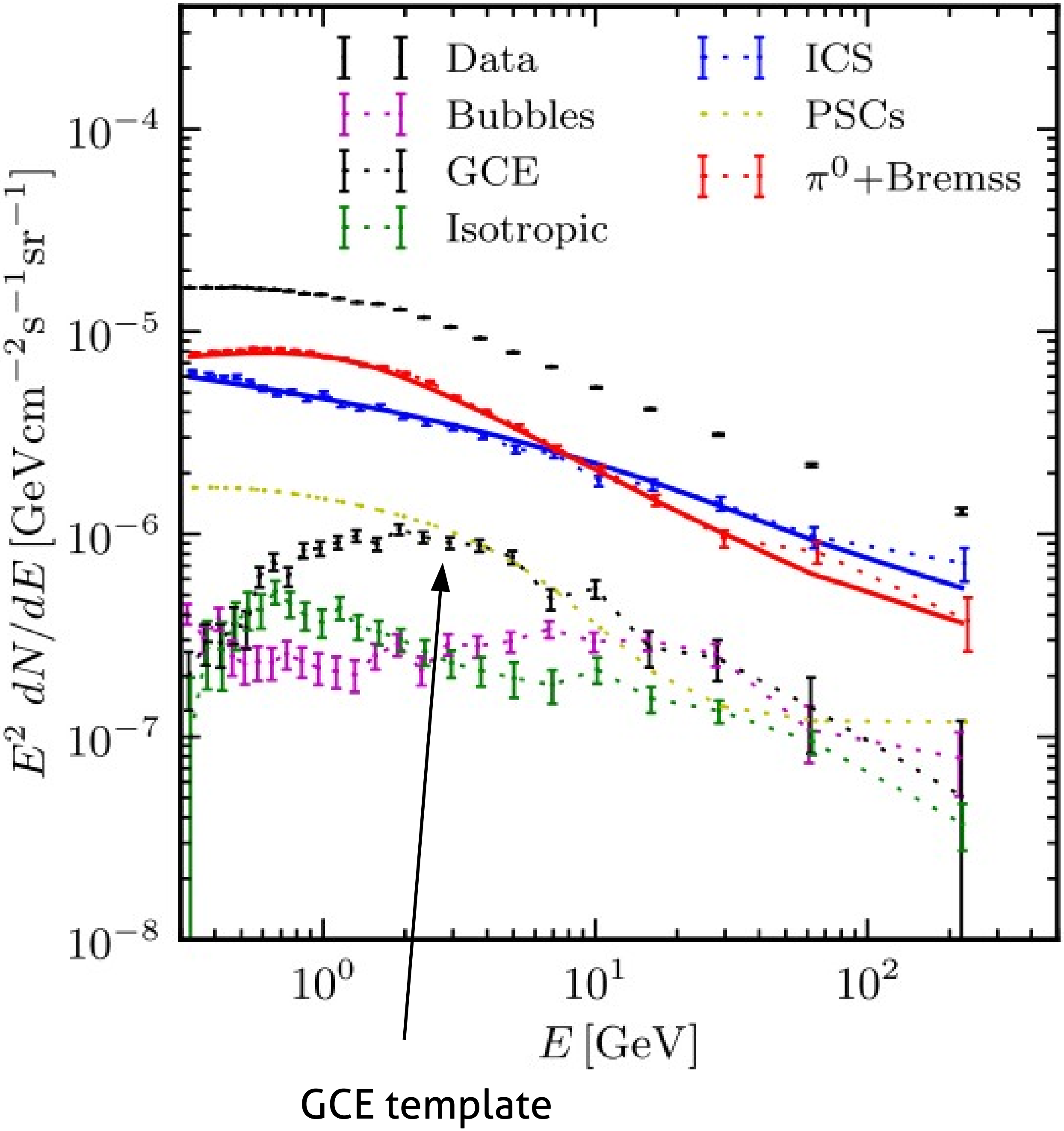
- assumption of homogeneity and isotropy of CR diffusion, eq. (3.1);
- assumption of homogeneity of CR re-acceleration, described through a scalar quantity, eq. (3.2);
- lack of radial dependence of CR convection;
- assumption of radial symmetry of CR source distribution in the Galactic disk, not fully accounting for the spiral arms;
- assuming a steady state solution for the CRs, excluding transient phenomena;
- same spatial distribution of hadronic and leptonic CR sources;
- lack of a physical model for the *Fermi* bubbles.

Results: Typical residuals for one FG model



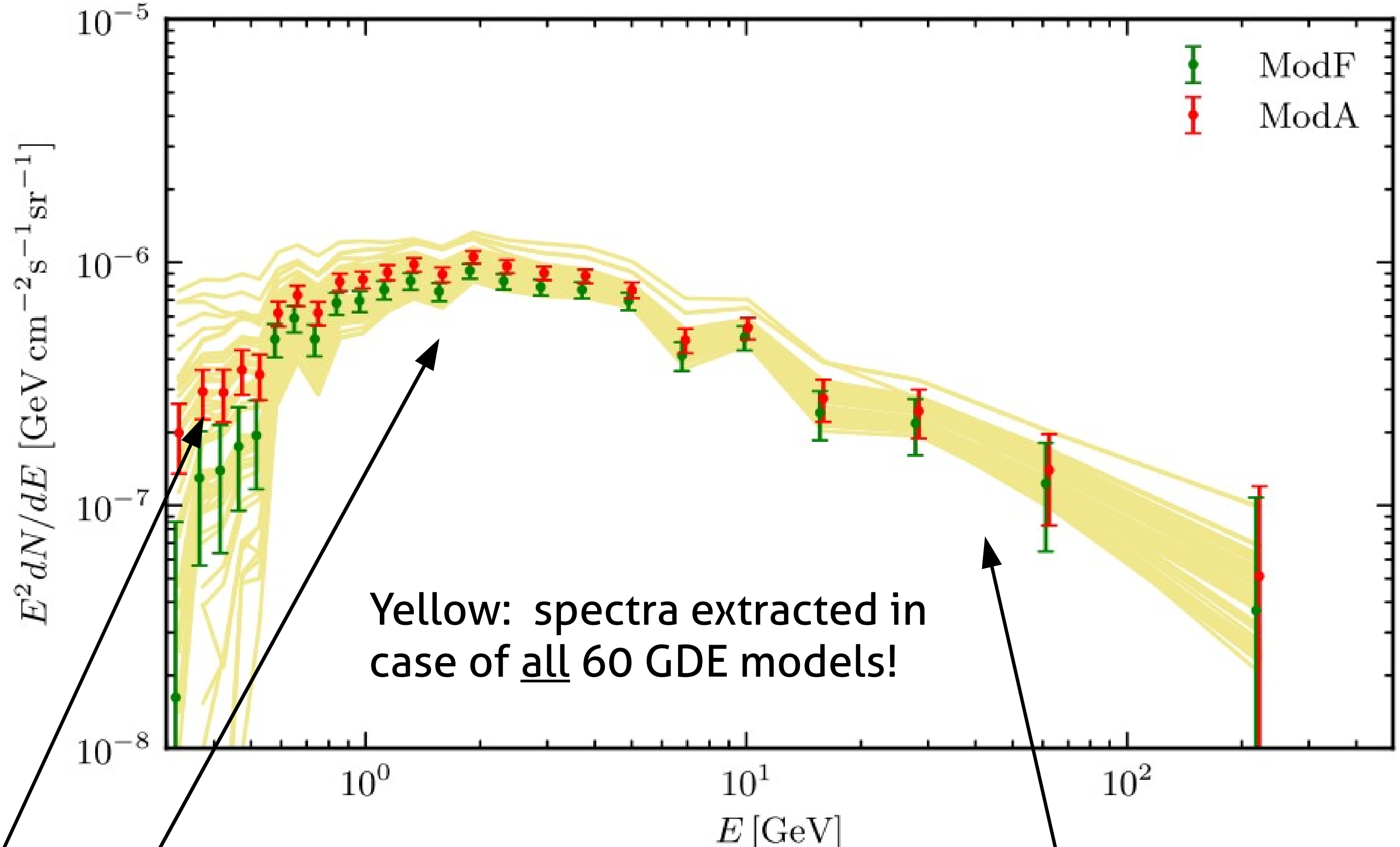
- Point source mask clearly visible
- Residuals at the level of <20% are observed
- Co-adding the DM template clearly shows an extended excess around the GC

Component spectra



Solid lines: model prediction (for model A)

GeV excess spectra



Peak at 1-3 GeV

Steep rise

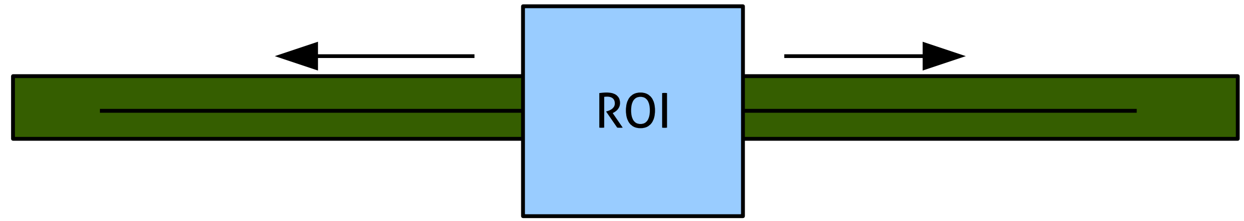
No cutoff at >10 GeV energies as observed previously.

Why should one trust this result?

Empirical model uncertainties

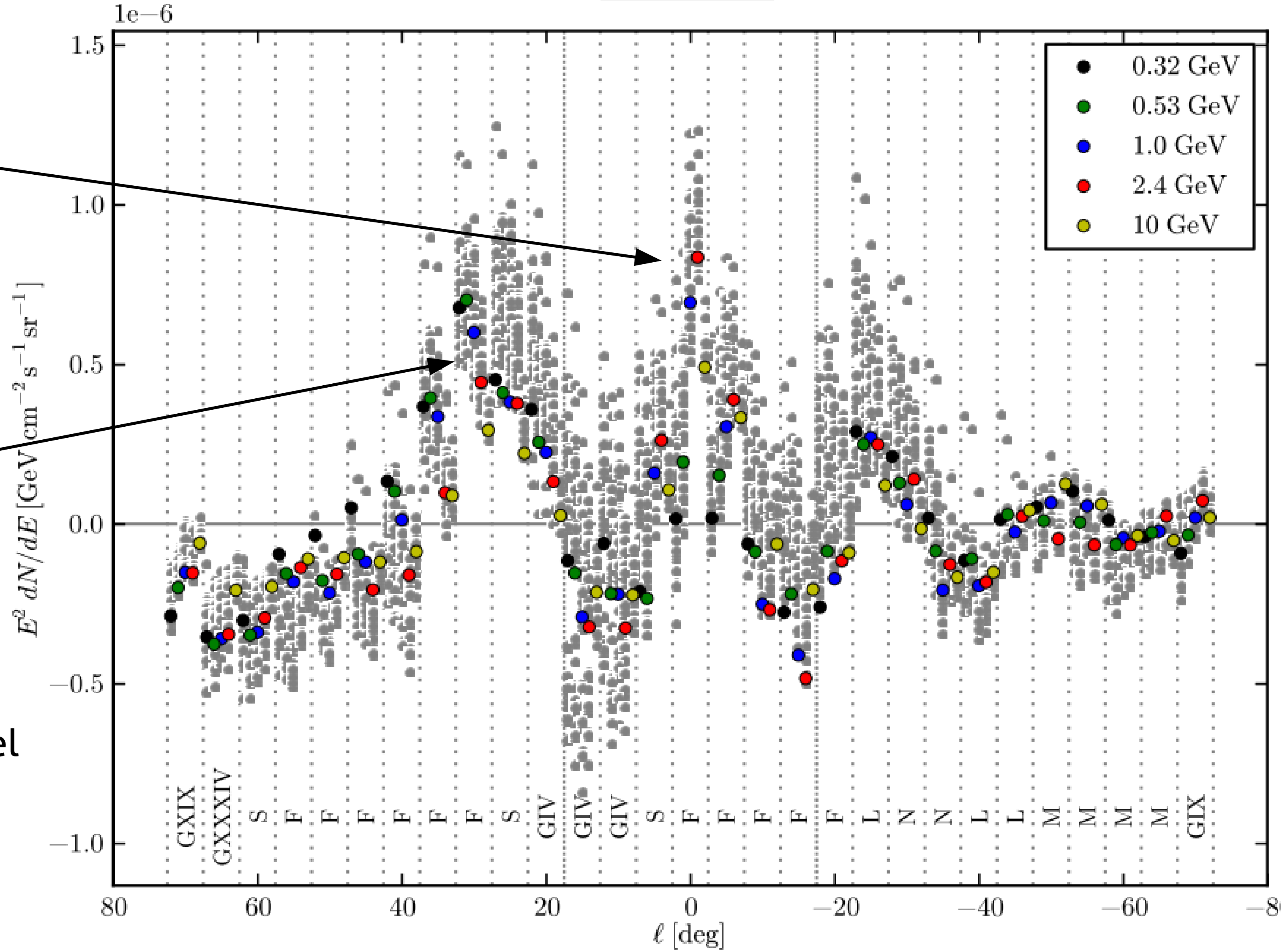
Estimating residuals: "Walking the Milky Way"

Analyze residuals along Galactic disk:



The Galactic center excess.

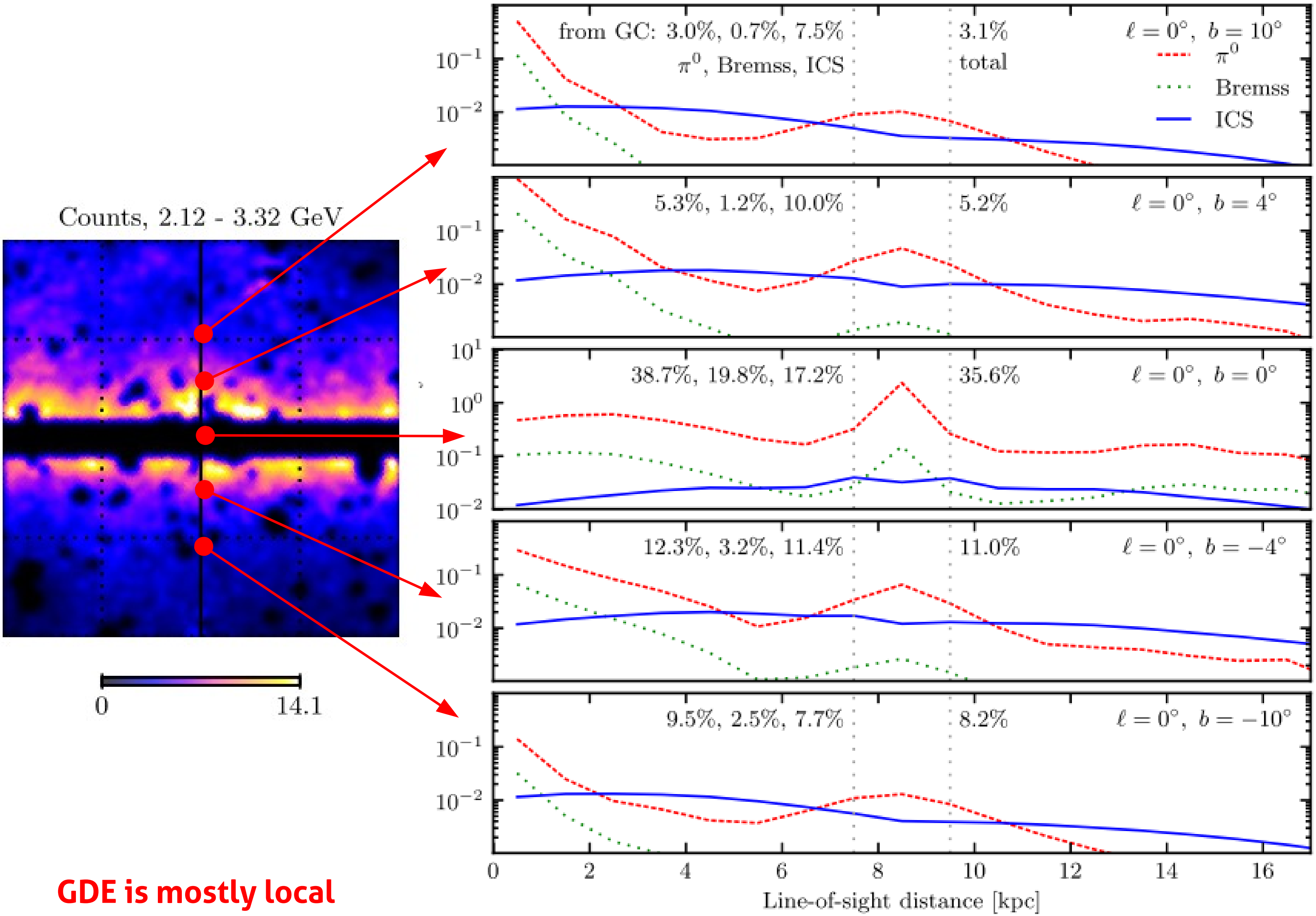
Other excess



Colored dots:
Best-fit GDE model

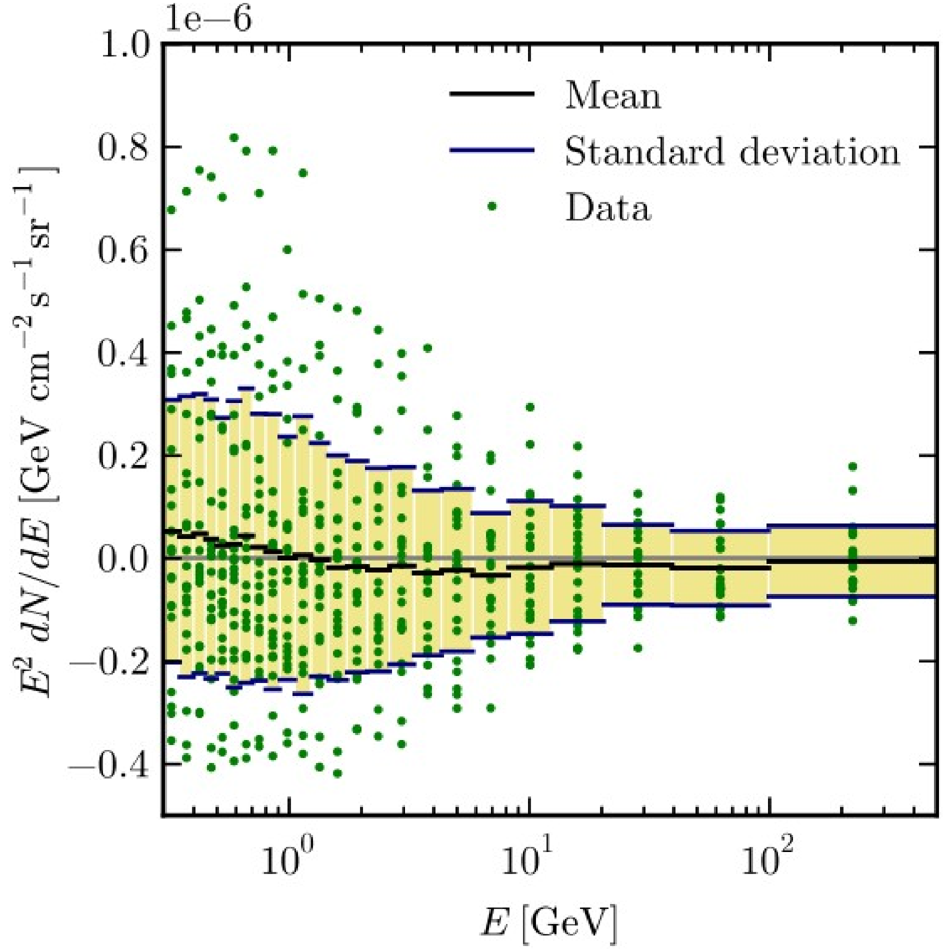
Gray dots:
All other models

Line-of-sight emissivity



GDE is mostly local

Covariance matrix of residual spectra

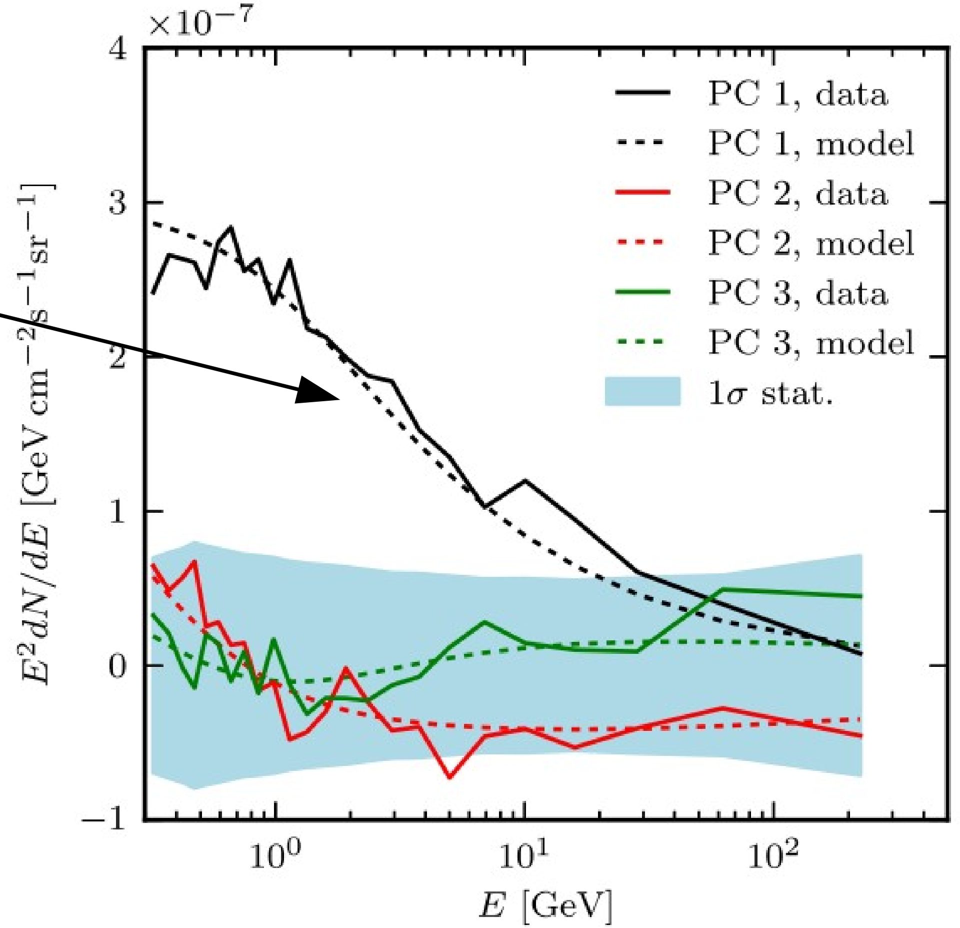


Fluctuations define an empirical
covariance matrix:

$$\Sigma_{ij,\,\mathrm{mod}} = \left\langle \frac{dN}{dE_i}\frac{dN}{dE_j} \right\rangle - \left\langle \frac{dN}{dE_i} \right\rangle \left\langle \frac{dN}{dE_j} \right\rangle$$

Principal component analysis of covariance matrix

First three **principal components** of the covariance matrix.



This can be understood in terms of small variations in the ICS and pi0 backgrounds.

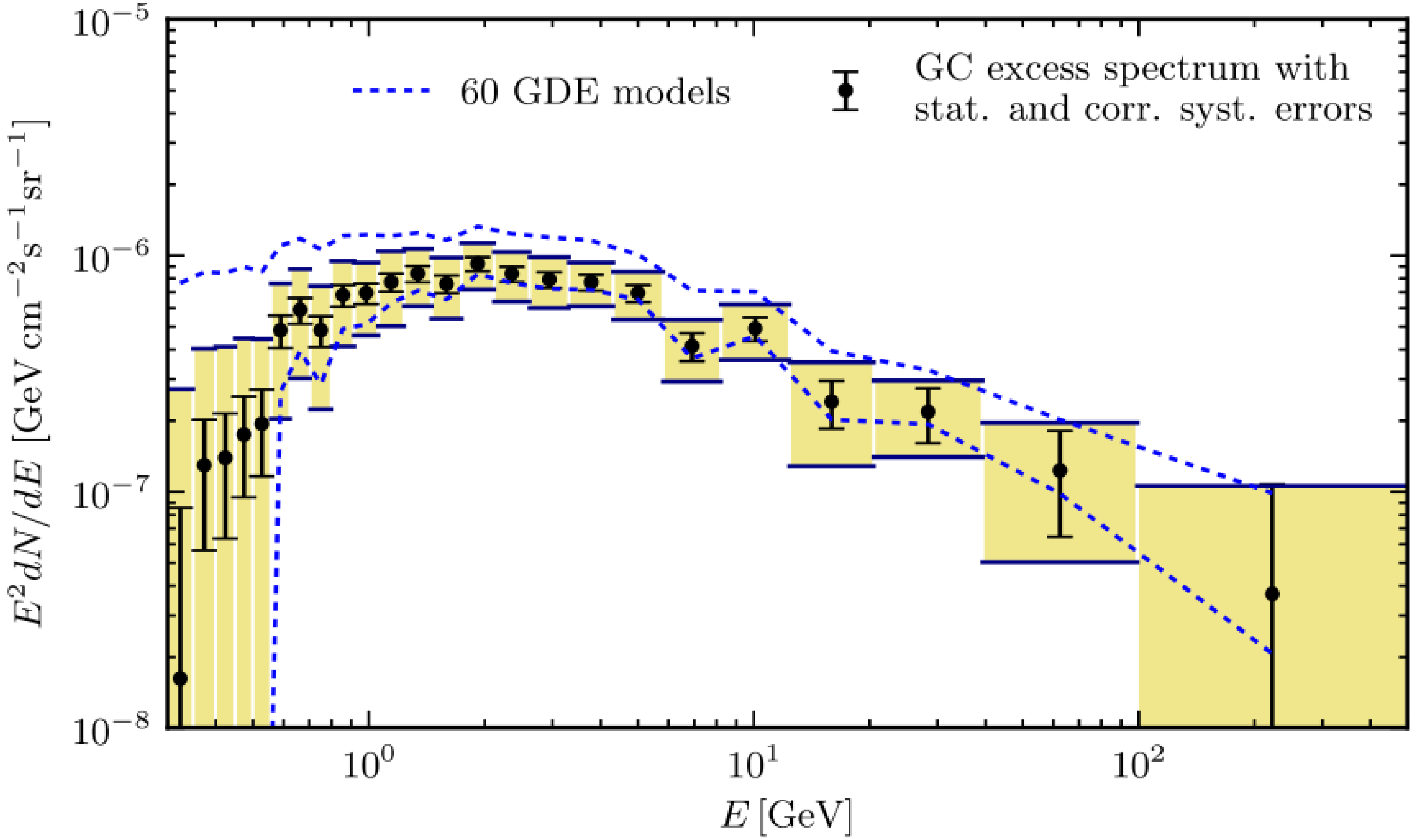
$$\Sigma_{ij,\,\mathrm{mod}} \simeq \sum_k \left(\Delta\alpha_k^2 + \Delta\gamma_k^2 \ln\frac{E_i}{E_{\mathrm{ref}}} \ln\frac{E_j}{E_{\mathrm{ref}}}\right) \frac{dN_k}{dE_i}\frac{dN_k}{dE_j}$$

Normalization error <3% (from fit)

Spectral slope error <0.01 (from fit)

ICS and pi0 spectra

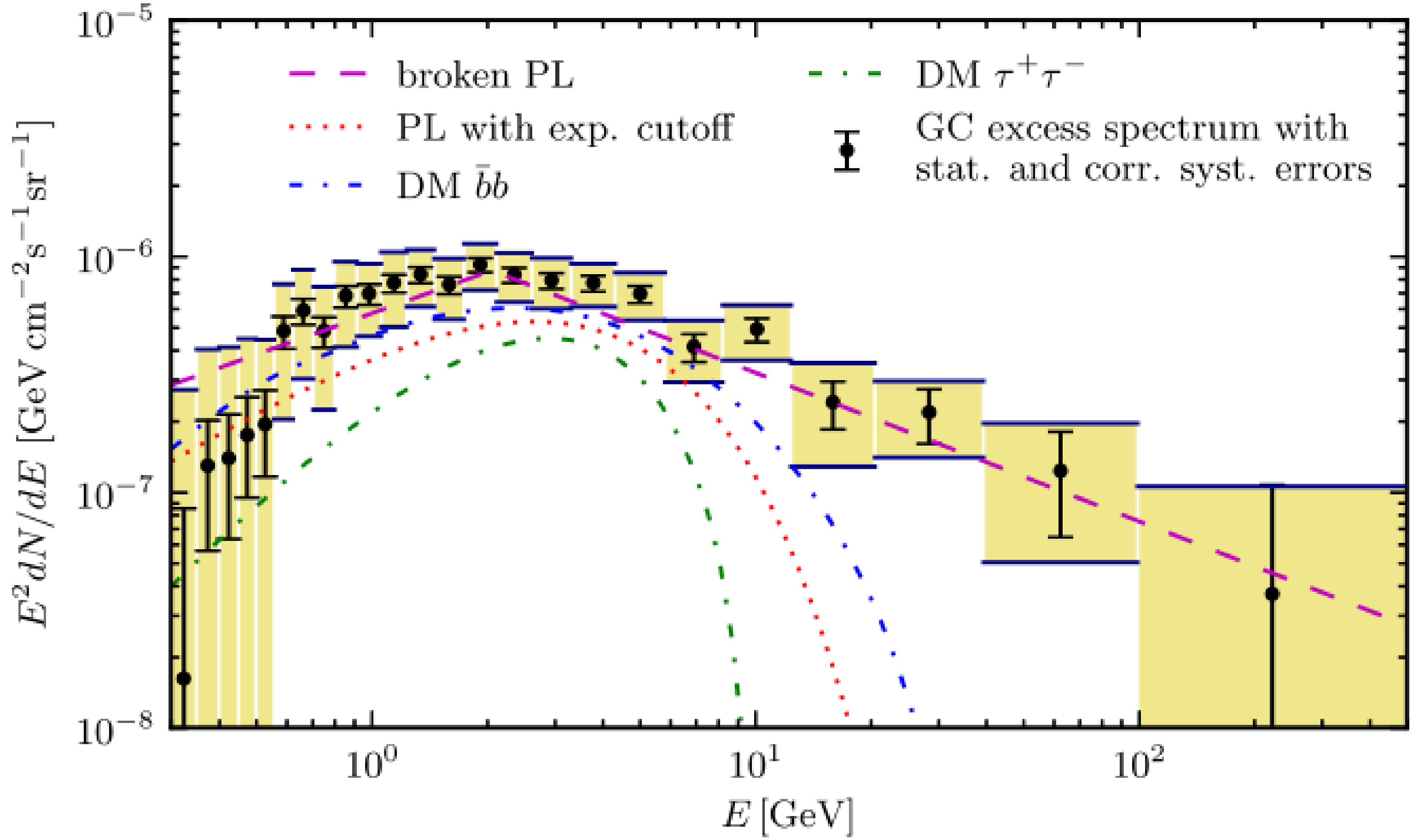
Theoretical vs. empirical model systematics



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

Results

Fits with DM and astro spectra



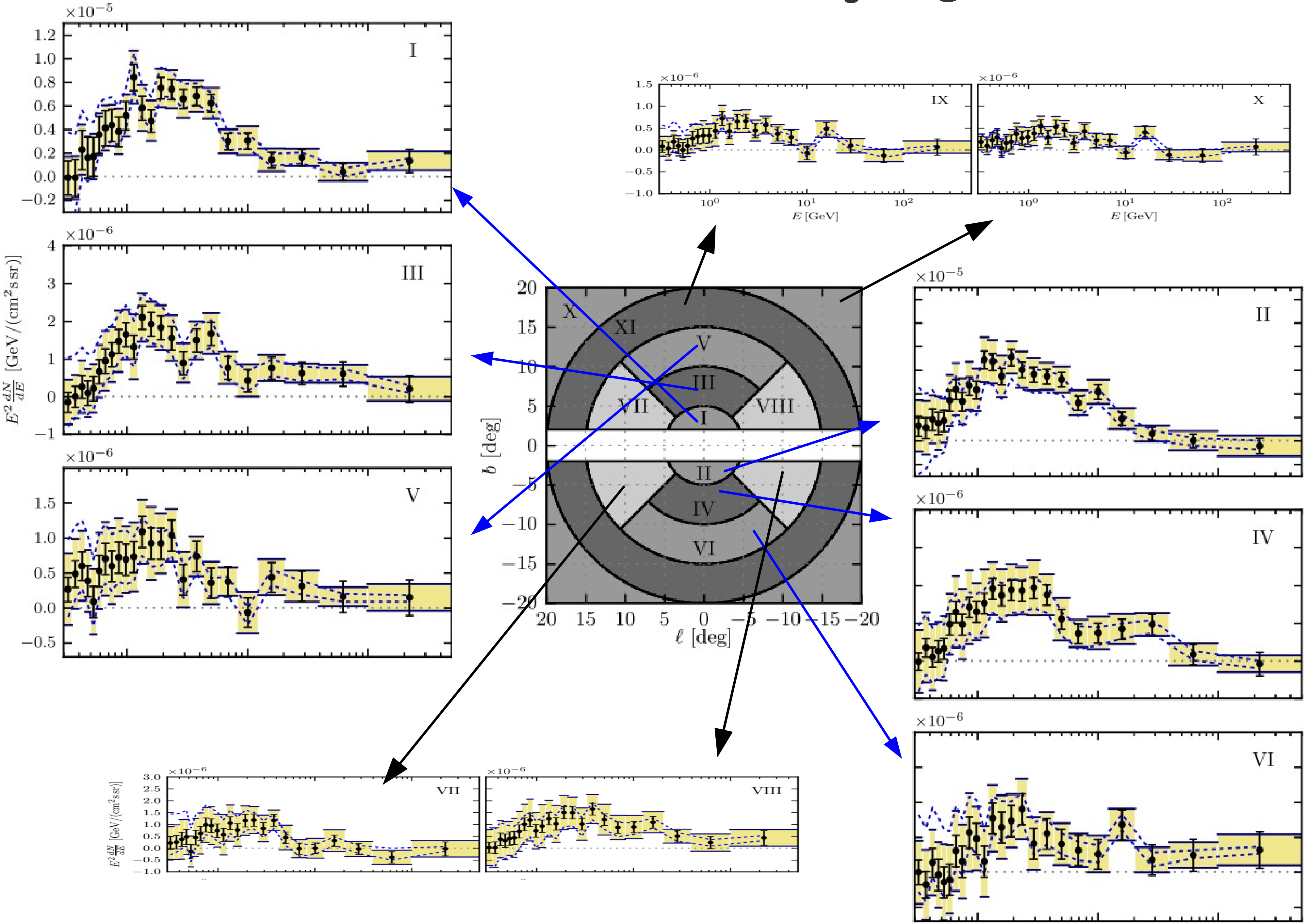
Relevant chi2:

$$\chi^2 = \sum_{ij} \left(\frac{d\bar{N}}{dE_i}(\boldsymbol{\theta}) - \frac{dN}{dE_i} \right) \Sigma_{ij}^{-1} \left(\frac{d\bar{N}}{dE_j}(\boldsymbol{\theta}) - \frac{dN}{dE_j} \right)$$

Good fits to data with:
- Simple broken power-law
- DM annihilation into bb

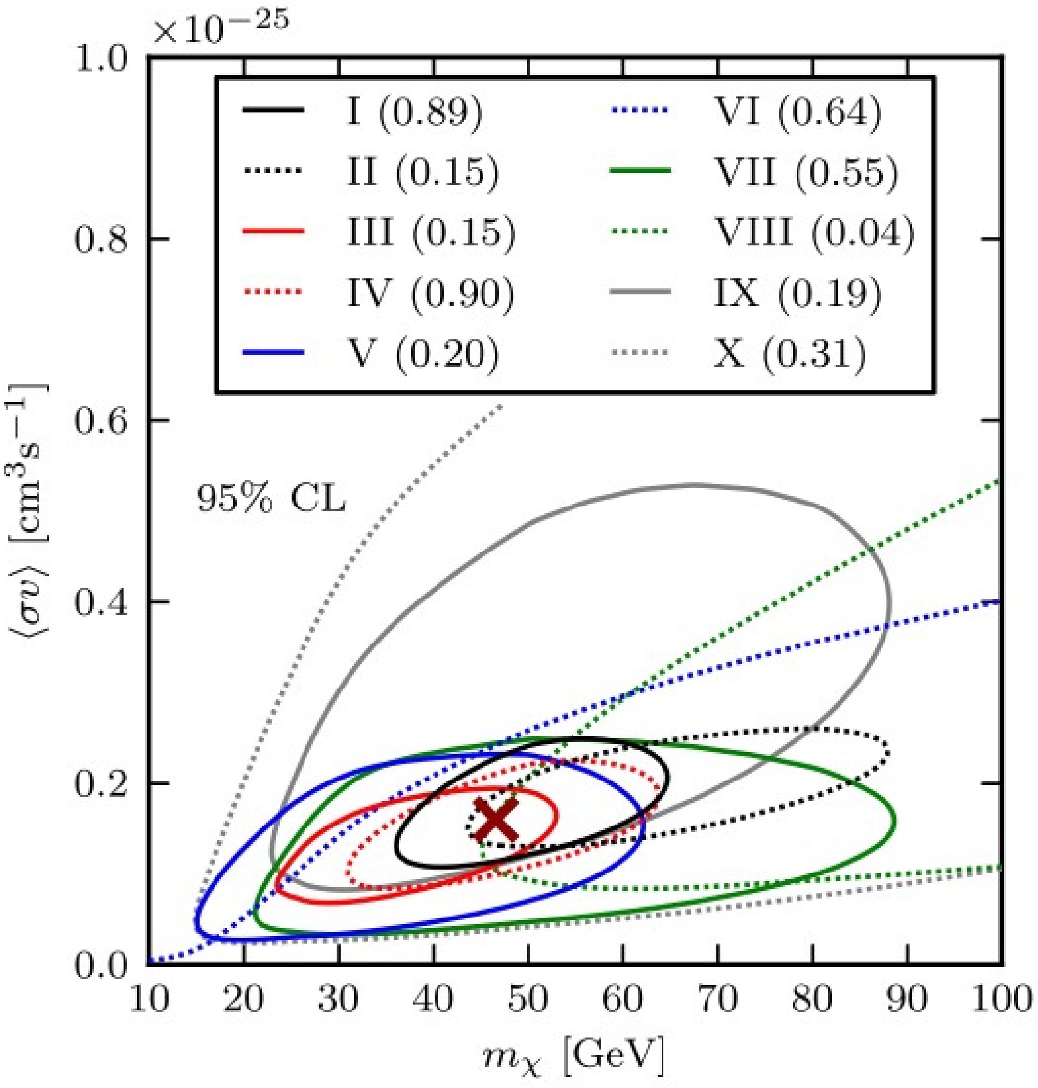
Both scenarios have comparable p-values

The GCE in ten different sky segments



Spectra in different segments are mutually compatible

A fit of DM bb spectra in each of the ten segments

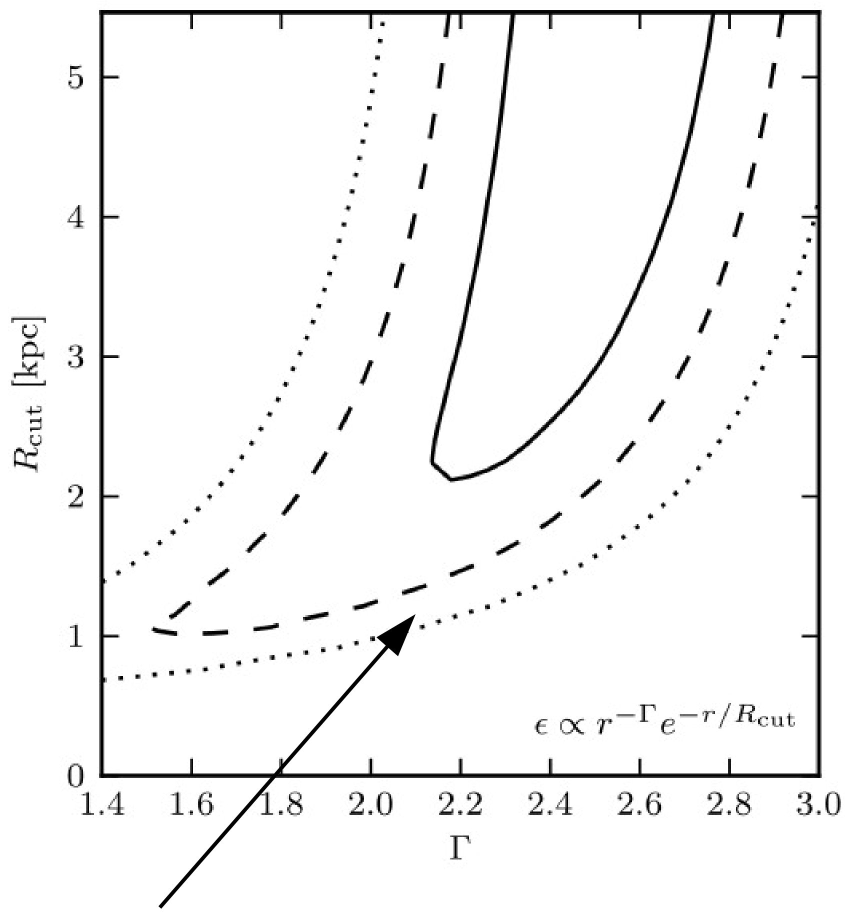


Results are consistent with hypothesis of <u>one</u> single spectrum at 95% CL!

How far does the excess reach in the sky?

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

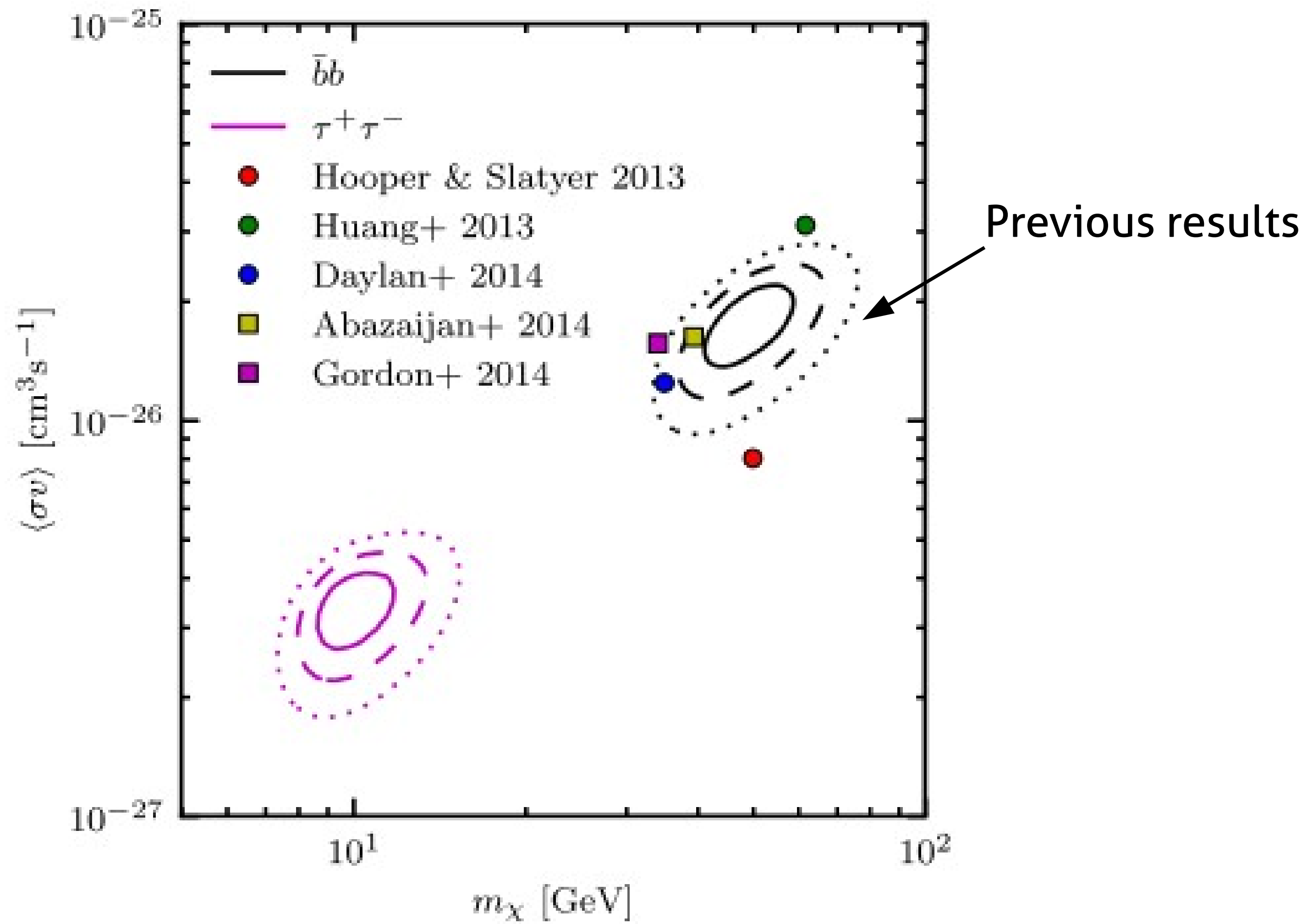
$$q \propto r^{-\Gamma} e^{-r/R_{\rm cut}}$$



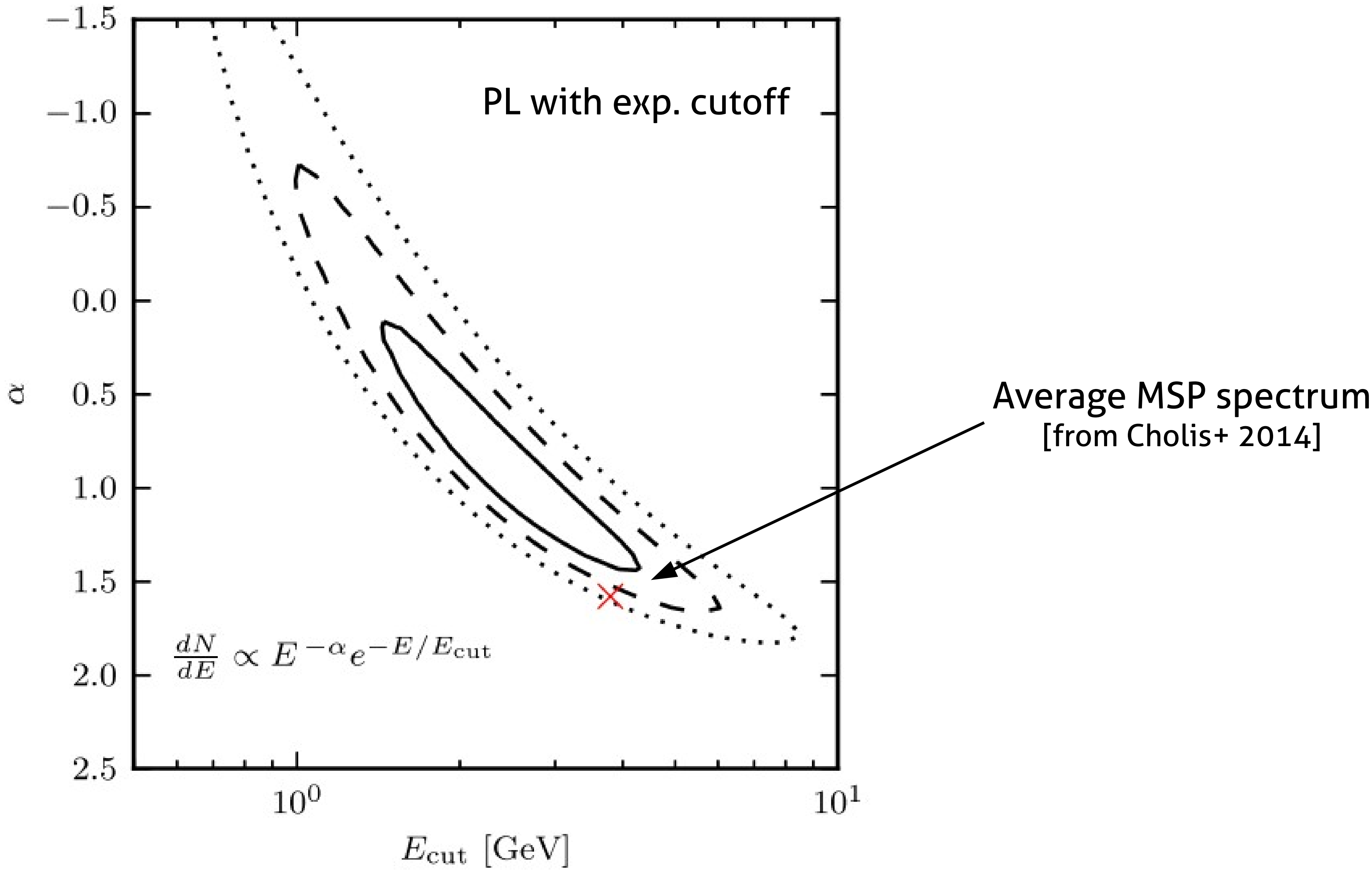
We find a lower limit on the extension of at least 1.48 kpc
(corresponding to more than 10 degrees).

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

Fits with DM spectra



Fit with PL with exponential cutoff



Conclusions

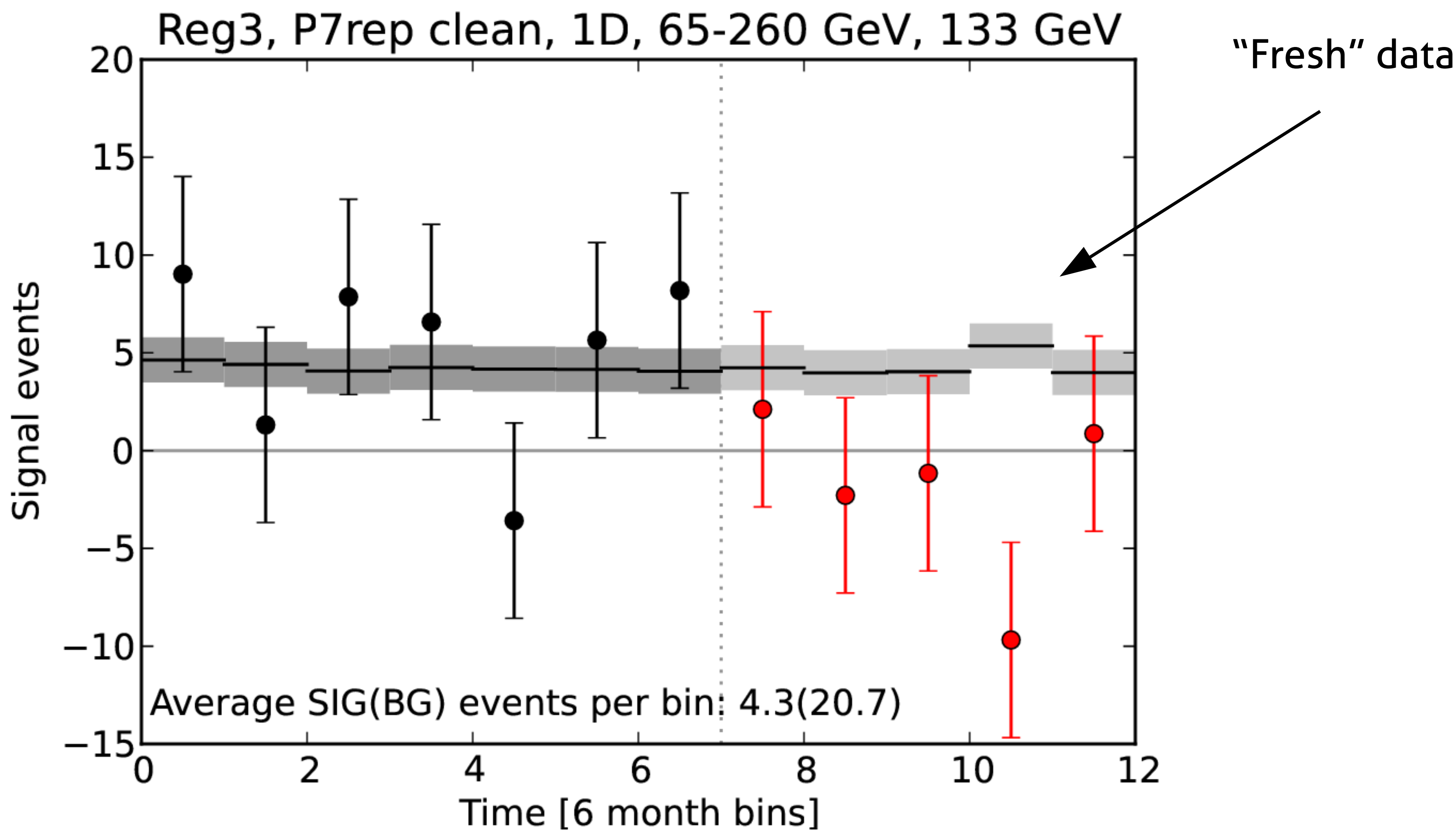
- The Galactic disk is an excellent test region for indirect dark matter searches → Use It!
- After including systematics, no **gamma-ray line emission** from DM decay/annihilation was found at 300 MeV to 10 GeV energies
  → Most robust lower limits on gravitino DM lifetime

- Previously adopted BG subtraction for "Fermi GeV excess" was deficient and overly constraining
- We estimate **theoretical model systematics** with 60 GDE models
- We estimate **empirical model systematics** (and quality of GDE models) from scan along the Galactic disk
- Results for GCE:
  - can be fit with broken PL and with DM spectra
  - is compatible with **spherical symmetry and uniform spectrum**
  - robustly extends far from the GC (10 deg and more)

Outlook: Multi-wavelength, one-point fluctuations and point sources, dynamical leptonic models, cross-correlations with 2MASS…

Backup

No signal photons since Summer 2012



P-value (assuming P7rep best-fit; 21.5±11.2 expected, -9.0 observed):

[Bringmann *et al.*; CW; Su & Finkbeiner **2012**; many others]

$$p \lesssim 0.001$$

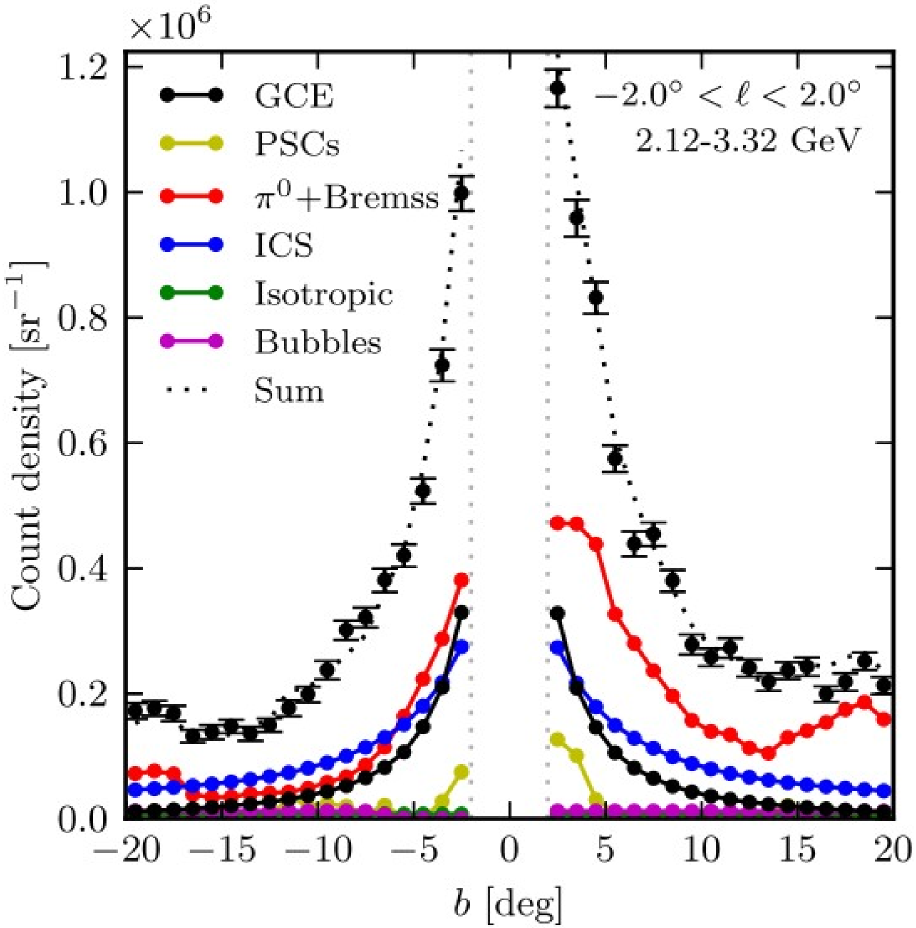
Using Fermi LAT data alone, the signal hypothesis can be excluded at more than 3 sigma.

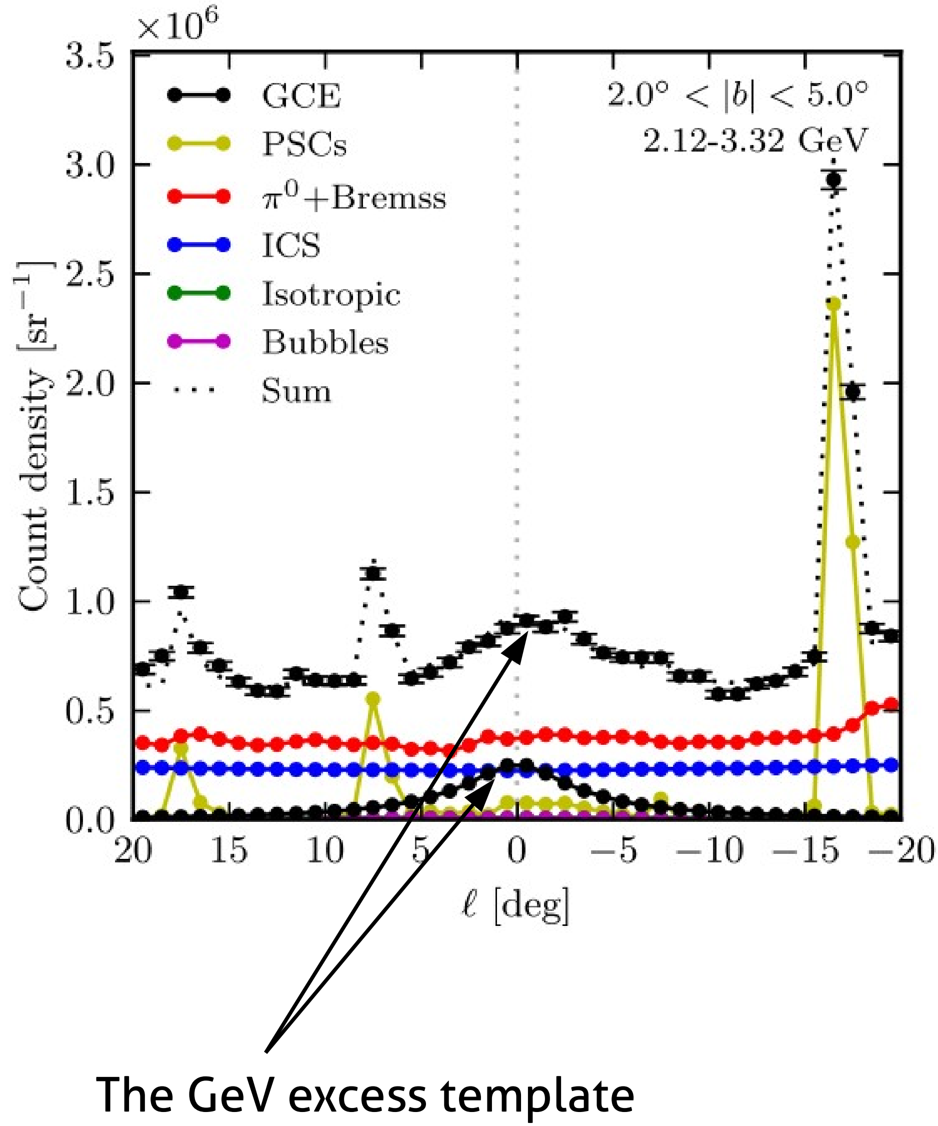
GDE: Ingredients

Name	z_D	D_0	v_A	dv/dz	Source	$\alpha_e(\alpha_p)$	$N_e(N_p)$	B-field	ISRF
A	4	5.0	32.7	50	SNR	2.43(2.47)	2.03(5.8)	090050020	1.36,1.36,1.0
B	4	28.0	31.0	0	SNR	2.43(2.39)	1.00(4.9)	105050015	1.4,1.4,1.0
C	4	5.0	32.7	0	SNR	2.43(2.39)	0.40(4.9)	250100020	1.0,1.0,1.0
D	4	5.2	32.7	0	SNR	2.43(2.39)	0.40(4.9)	050100020	0.5,0.5,1.0
E	4	2.0	32.7	0	SNR	2.43(2.39)	0.40(4.9)	050100020	1.0,1.0,1.0

Table 2. The properties of GDE models A–E. Here, z_D is in kpc, while r_D is taken to be 20 kpc. D_0 is in units of 10^{28} $\mathrm{cm^2\,s^{-1}}$, v_A is in $\mathrm{km\,s^{-1}}$ and dv/dz in $\mathrm{km\,s^{-1}\,kpc^{-1}}$. The CR electron and proton normalizations are $N_e(N_p)$ in units 10^{-9} $\mathrm{cm^{-2}\,sr^{-1}\,s^{-1}\,MeV^{-1}}$ and refer to the differential flux at E_{kin} of 34.5 and 100 GeV. α_e and α_p are the electron and proton injection indices above rigidities of 2.18 and 11.3 GV, respectively (and are respectively equal to 1.6 and 1.89 below these rigidities). For the gas assumptions we take, $T_S = 150$ K and an E(B-V) magnitude cut of 5 (see discussion in section 3.2). For model A the magnetic field "090050020" denotes in eq. (3.3) $B_0 = 9.0\ \mu$G, $r_c = 5$ kpc and $z_c = 2$ kpc (similarly for the other models). Finally, the three numbers in the "ISRF" column refer to the multiplication factors of the "optical", "IR" and CMB components of the ISRF model used in `Galprop v54` webrun.

Typical residuals and morphological fits





Likelihood function

Name	Notes
PSC	Spectra fixed to 2FGL
Fermi bubbles	Flat emission — Spectrum constrained
IGRB	Constant emission — Spectrum constrained
GCE	Generalized NFW profile with inner slope γ
Ackermann+ GDE models (×13)	$(\pi^0$ + Bremss) + ICS
Additional GDE models (×47)	$(\pi^0$ + Bremss) + ICS

$$-2\ln\mathcal{L} = 2\sum_{i,j} w_{i,j}(\mu_{i,j} - k_{i,j}\ln\mu_{i,j}) + \chi^2_{\rm ext}$$

i[th] energy bin

j[th] pixel

PSC mask

Model components

External constraints

$$w_{i,j} = \frac{1}{\left(\frac{\mu^{\rm PSC}_{i,j}}{f_{\rm PSC}\ \mu^{BG}_{i,j}}\right)^{\alpha_{\rm PSC}} + 1}$$

$$\mu_{i,j} = \sum_k \theta_{i,k}\mu^{(k)}_{i,j}$$

$$\chi^2_{\rm ext} = \sum_{i,k}\left(\frac{\phi_{i,k} - \bar{\phi}_{i,k}}{\Delta\phi_{i,k}}\right)^2$$

We refit in every energy bin → throw away spectral information!