Francesca Calore

The GeV excess shining through: background model systematics for the inner Galaxy analysis

V Fermi Symposium
Nagoya, 22nd October 2014

Based on:
F. Calore, I. Cholis & C. Weniger, arXiv:1409.0042

The Fermi GeV excess

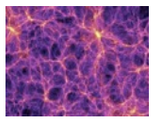
- **Gamma-ray excess emission** detected **over standard astrophysical background** in the inner regions of the Galaxy: "Galactic Center" and "Inner Galaxy" excess.

  Abazajian+ 2014; Macias & Gordon 2013; and others
  Daylan+ 2014; Huang+ 2013; Hooper & Slatyer 2013

  Talks by S. Murgia & T. Linden

- Excess extended emission, spherically symmetric about the Galactic Center, with spectral energy distribution peaked at few GeV, compatible with luminosity per volume $\propto r^{-2.5}$.

- Interpretations:

  
  Signal from dark matter annihilation?

  Talk by D. Hooper & A. Kwa

  
  Unresolved population of pulsars/milli-second pulsars?

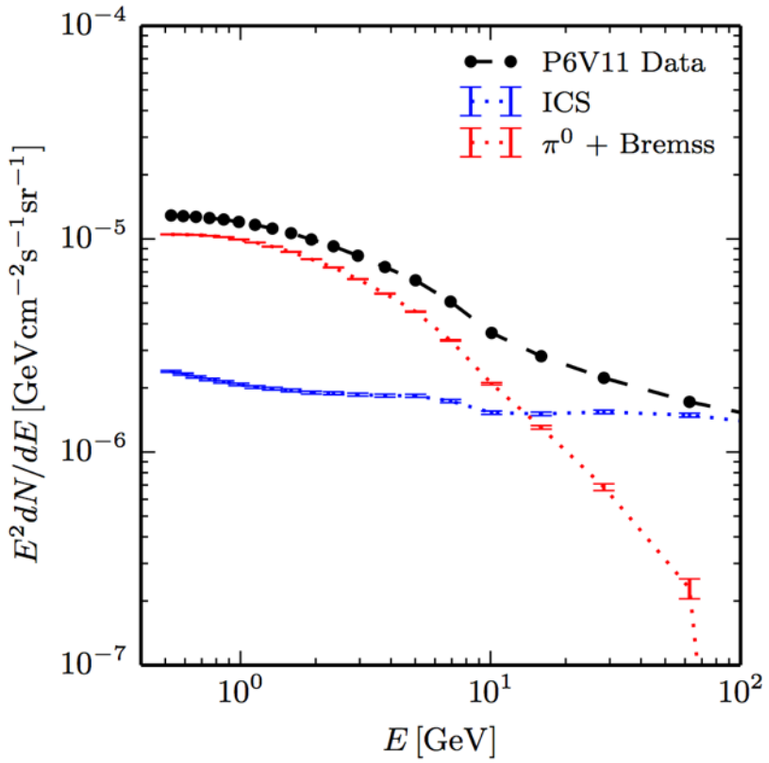
  
  Active past of the Galactic Center and leptonic interactions with the gas?

  Talk by G. Zaharijas

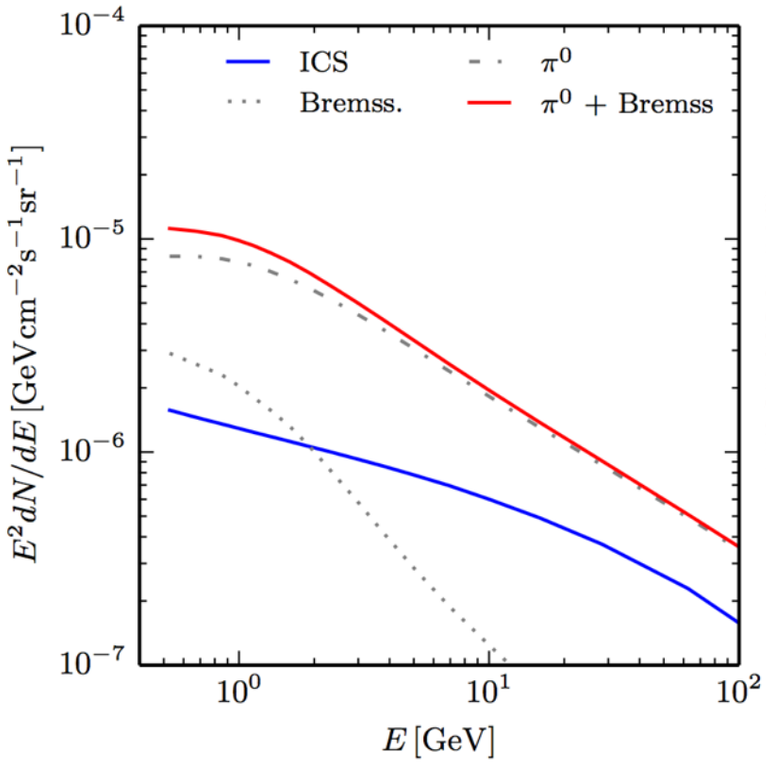
- Critical **subtraction of foreground** (galactic diffuse emission) **and background** (detected point sources and Fermi bubbles) emissions.

Caveats

1. Almost all previous analyses adopt, as Galactic diffuse emission model, Fermi diffuse models (*e.g.* P6V11, P7V6).



P6V11* mock data fit



GALPROP prediction**

Unphysical and too hard ICS component for E > 20 GeV!

* http://fermi.gsfc.nasa.gov/ssc/data/p6v11/access/lat/ring_for_FSSC_final4.pdf

** Model: SNR; z = 4 kpc; R = 20 kpc; T = 150 K; C = 5.

Talks by J. Casandjian & S. Murgia

Caveats

1. Almost all previous analyses adopt,, as Galactic diffuse emission model, Fermi diffuse models (*e.g.* P6V11, P7V6).

2. In general, any model for the Galactic diffuse emission will have large residuals.

When compared to data, none of the existing Galactic diffuse emission models fit "well" the data.

Typical values:

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

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

Quantifying the background model systematics is essential for making statistics based claims!

The GeV excess on trial

Calore, Cholis & Weniger, arXiv:1409:0042

Aims:

A. Robust identification of the excess despite of large **variations** in the **foreground models** (Galactic Center contribution generically subdominant, however Fermi bubbles).

B. Firmly characterise the **spectral** and **morphological properties** of the excess.

C. Making **statistically robust statements** about viable interpretations by including systematic uncertainties.

Does the excess survive when varying the background models?
What is the energy spectrum of the excess?
How far in latitude does it extend?
Is it compatible with a spherically symmetric signal?
Are spectrum and morphology uniform?

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Method:

A. Template regression technique to analyse Fermi-LAT data.

B. Assessment of **theoretical model systematics** related to the galactic diffuse emission model and its variations.

C. Assessment of **empirical model systematics** related to how well the diffuse models describe the data.

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C. Assessment of **empirical model systematics** related to how well the diffuse models describe the data. Talk by C. Weniger tomorrow

Analysis set-up

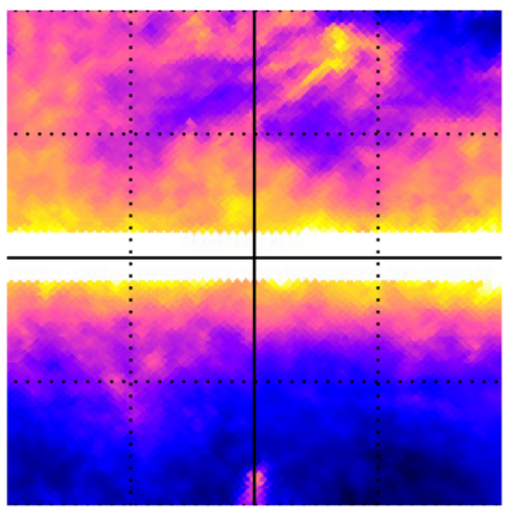
Data selection and standard preparation (284 weeks; 300MeV-500GeV).

ROI: $2^\circ \leq |b| \leq 20^\circ \,\&\, |l| \leq 20^\circ$

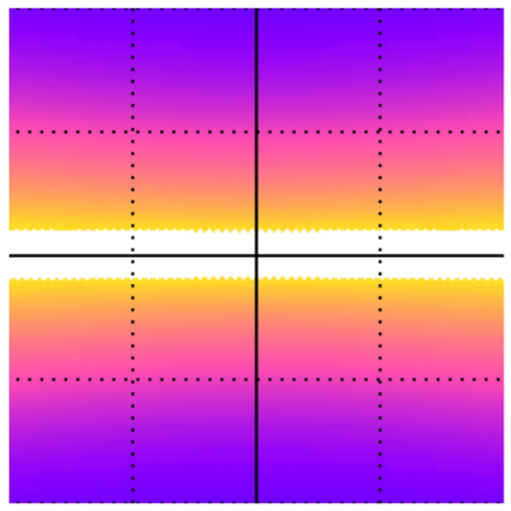
Point sources (2FGL) weighted adaptive mask.

Spatial templates used in the analysis (maximum likelihood method):

1. π^0 **+ Bremsstrahlung**
2. **ICS**



π^0 +Bremss



ICS

Importance of modelling Galactic diffuse emission components separately!

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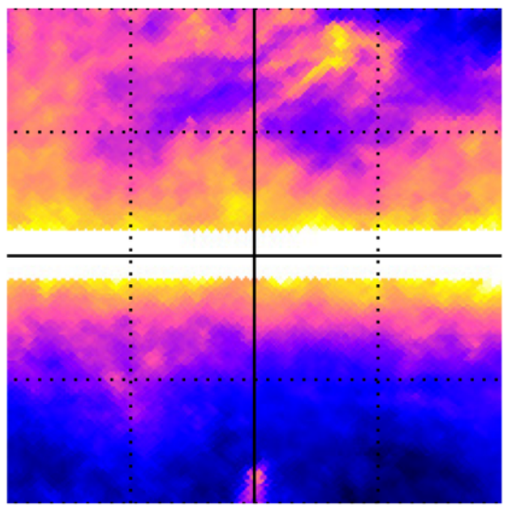
Home-brew diffuse models



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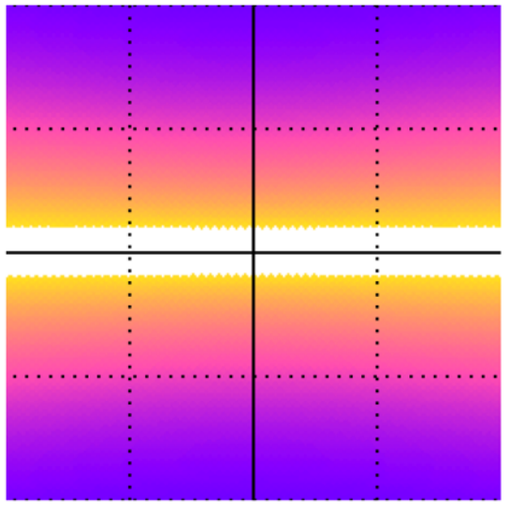

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Spatial templates used in the analysis (maximum likelihood method):

E dep.

1. π^0 **+ Bremsstrahlung**
2. **ICS**
3. **Point-like sources** (fixed @ 2FGL)

E indep.

4. **Fermi bubbles** uniform emission (spectrum constrained*)
5. **Isotropic background** uniform emission (spectrum constrained**)
6. **GeV excess (GCE) template**

$$J(\psi) = \int_{los} \rho^2(r) dl$$

$$\rho(r) = \rho_s \frac{(r/r_s)^{-\gamma}}{(1+r/r_s)^{3-\gamma}}, \quad \gamma = 1.2$$

generalised NFW profile

*A. Franckowiak and D. Malyshev, ICRC2013; ** M. Ackermann, 4th Fermi Symposium (2012)

Template regression techniques: the likelihood function

Technical improvements w.r.to previous analysis:

- Non-logarithmic binning of energies which facilitates flux measurements at high energies.
- Weighted adaptive masking of point sources.
- Proper treatment of the Fermi-LAT point-spread-function (PSF).

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

i energy bin
j pixel

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

Weighted adaptive mask of point sources

$f_{\rm PSC} = 0.1,\ \alpha_{\rm PSC} = 5$

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

Model components

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

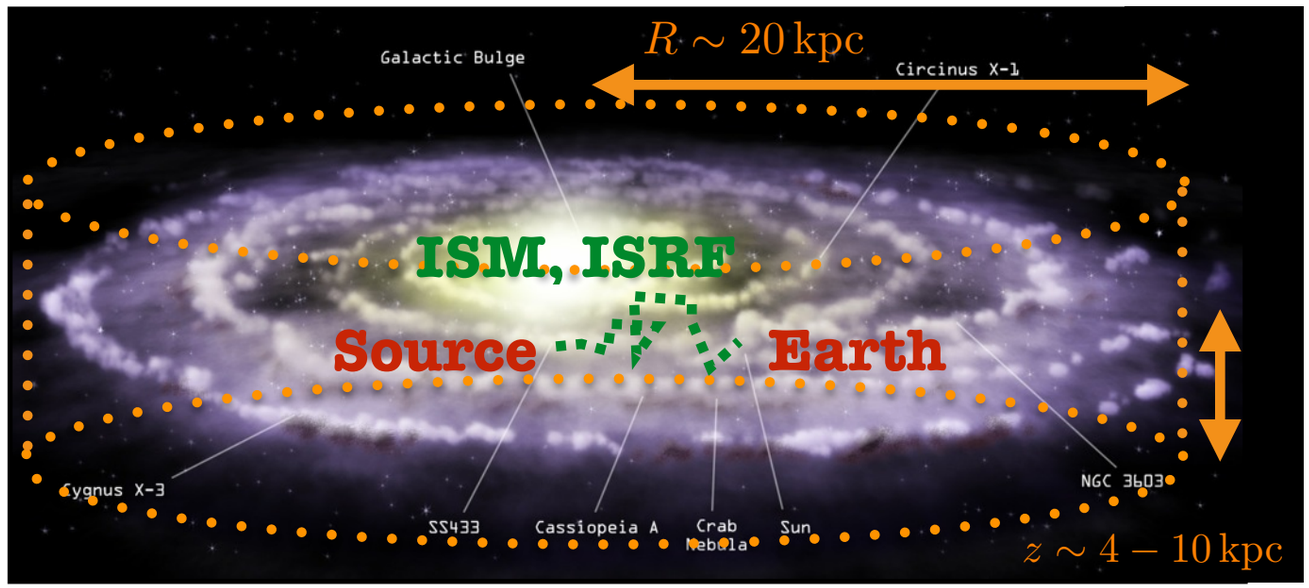
External constraints (isotropic background and Fermi bubbles)

Template analysis, i.e. **no spectral** information about the models is included in the fit.

60 Galactic diffuse home-brew models

Building models* for the diffuse Galactic emission, by varying CR propagation parameters.

→ Testing **local variations** of the **global foreground emission**.



- 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: $D_0 = 2 - 60 \times 10^{28}$ cm^2 s^{-1};
- Alfvén speed: $v_A = 0 - 100$ km s^{-1};
- gradient of convection velocity: $dv/dz = 0 - 500$ 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.

*Models from Ackermann+ 2012 (128 models) or from new GALPROP runs.

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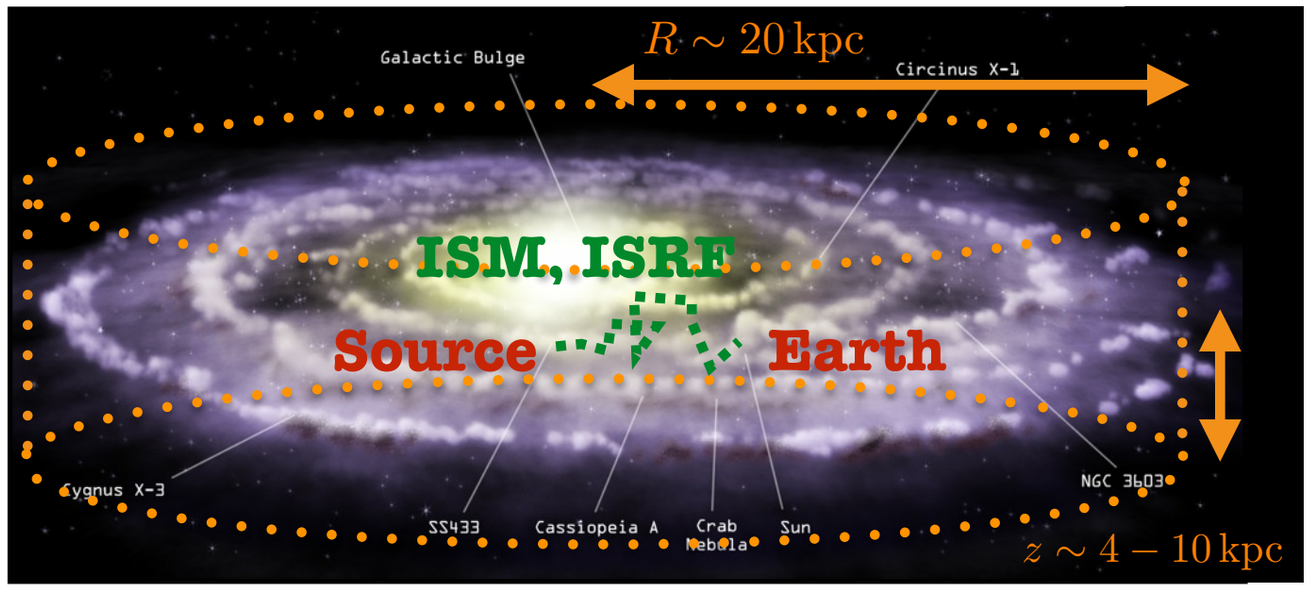

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Total of about 60 models for the Galactic diffuse emission that test **extreme** variations in the parameter space.

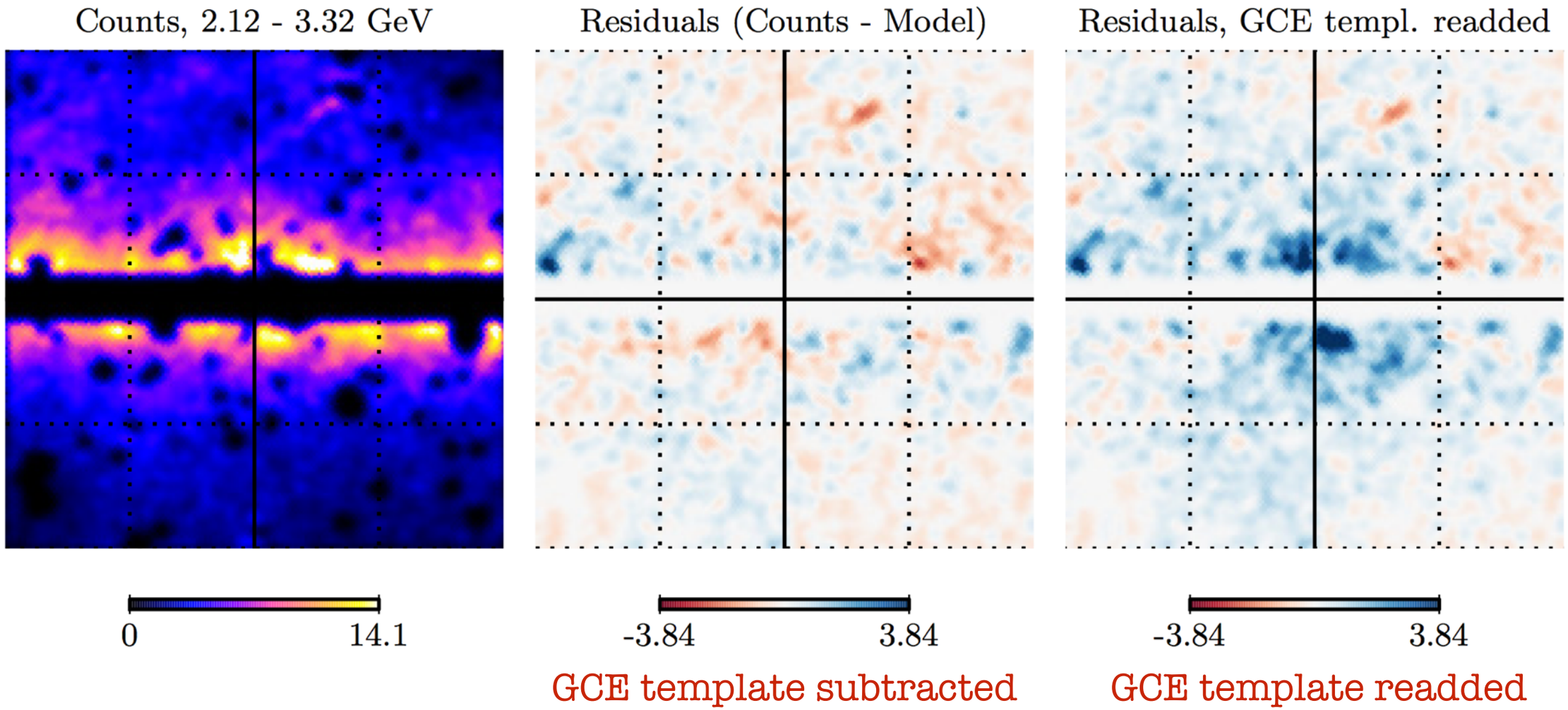
*Models from Ackermann+ 2012 (128 models) or from new GALPROP runs.

60 Galactic diffuse home-brew models

Some **limitations** of the adopted approach:

- 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.

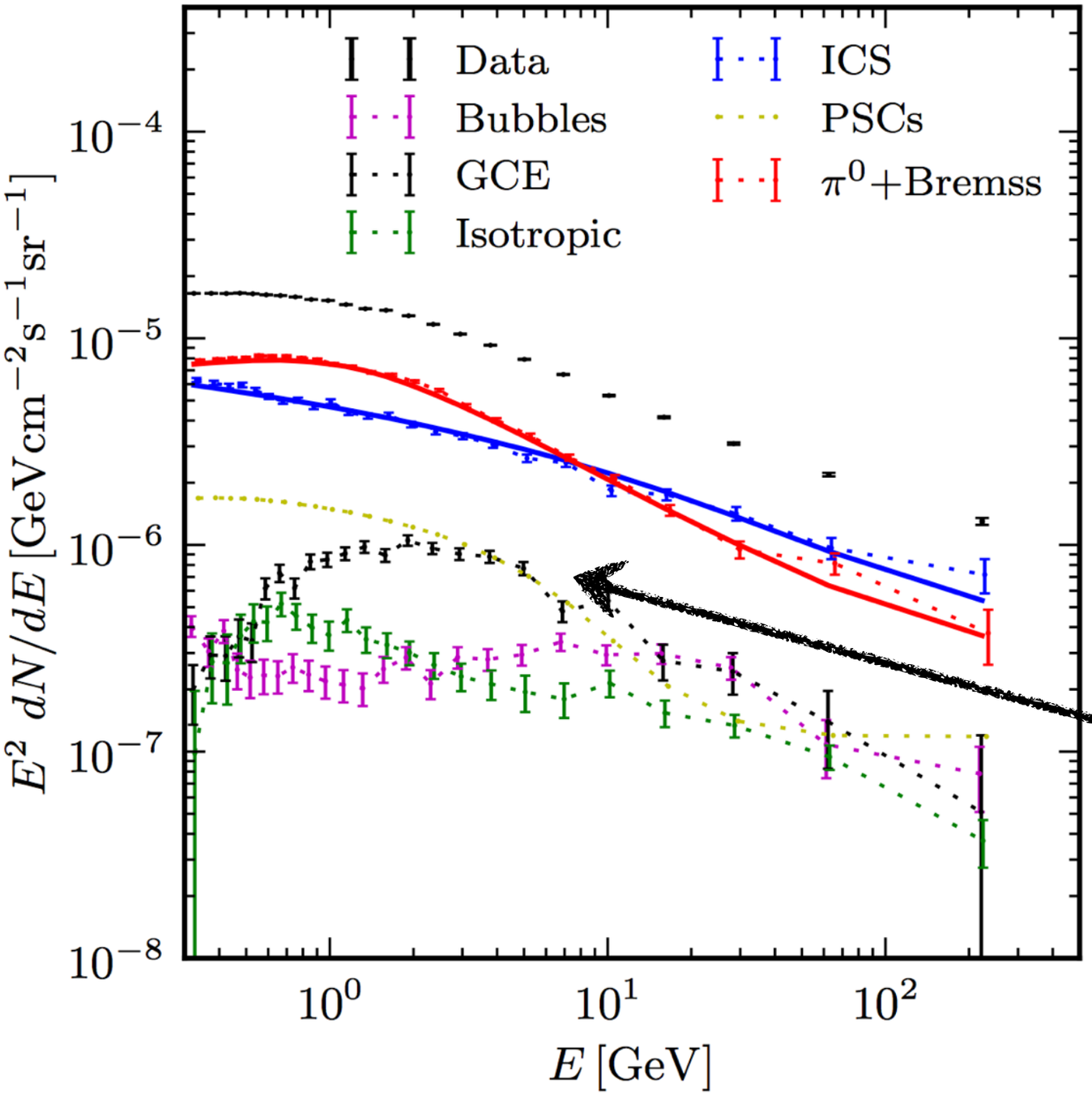
Results: excess emission residuals*



- ✓ Point-source mask visible.
- ✓ Observed residuals are for **all** models at the level of 20%.
- ✓ Clear evidence of an excess when GCE template is re-added.
- ✓ Typical background residuals in the ROI are significantly smaller than GCE.

*Results for one typical Galactic diffuse model.

Results: different spectral components*



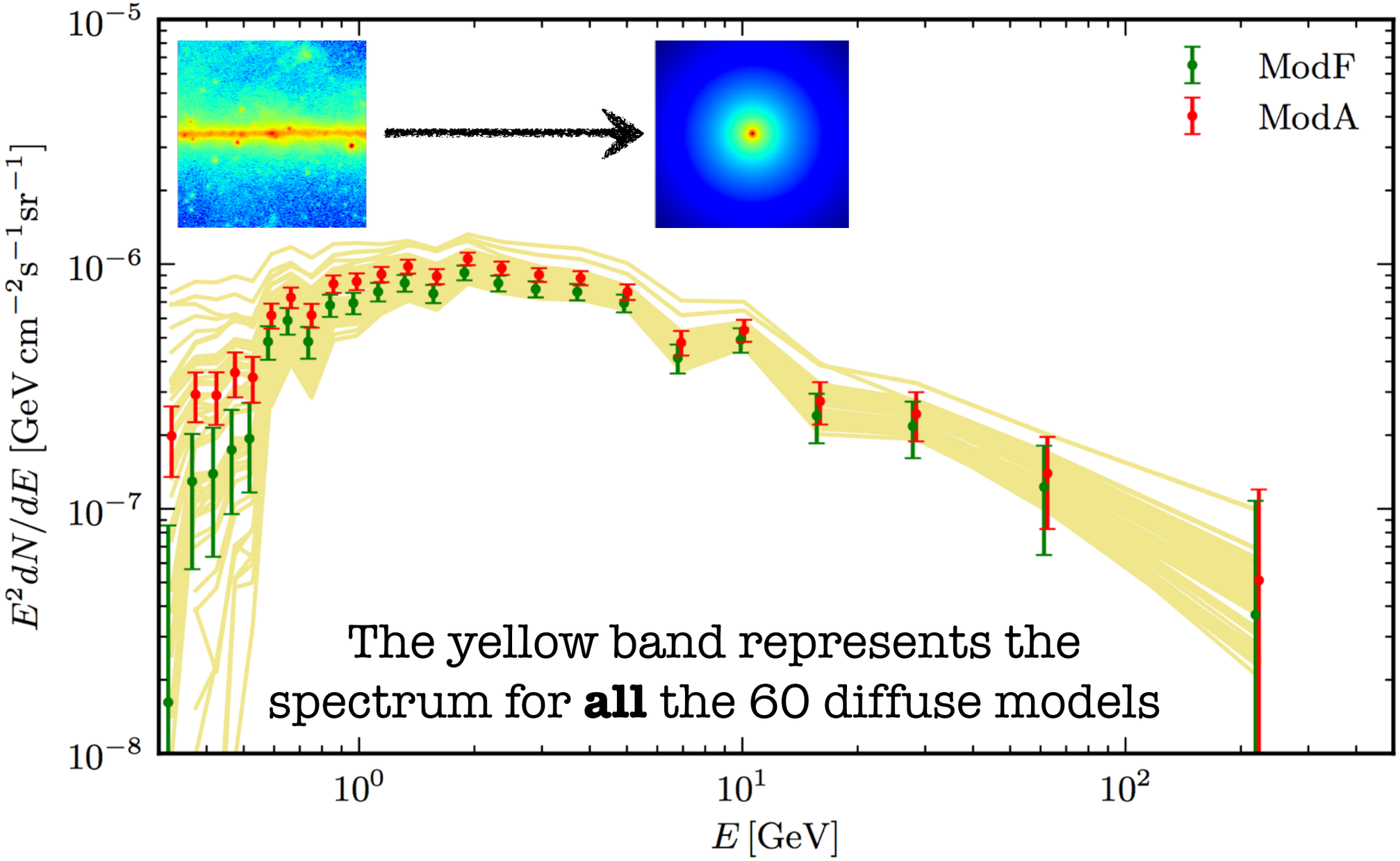
Spectra associated with the different spatial templates.

A remarkable agreement between diffuse model predictions and fitted spectral components is possible for selected models!

GeV excess template

*Results for one typical Galactic diffuse model.

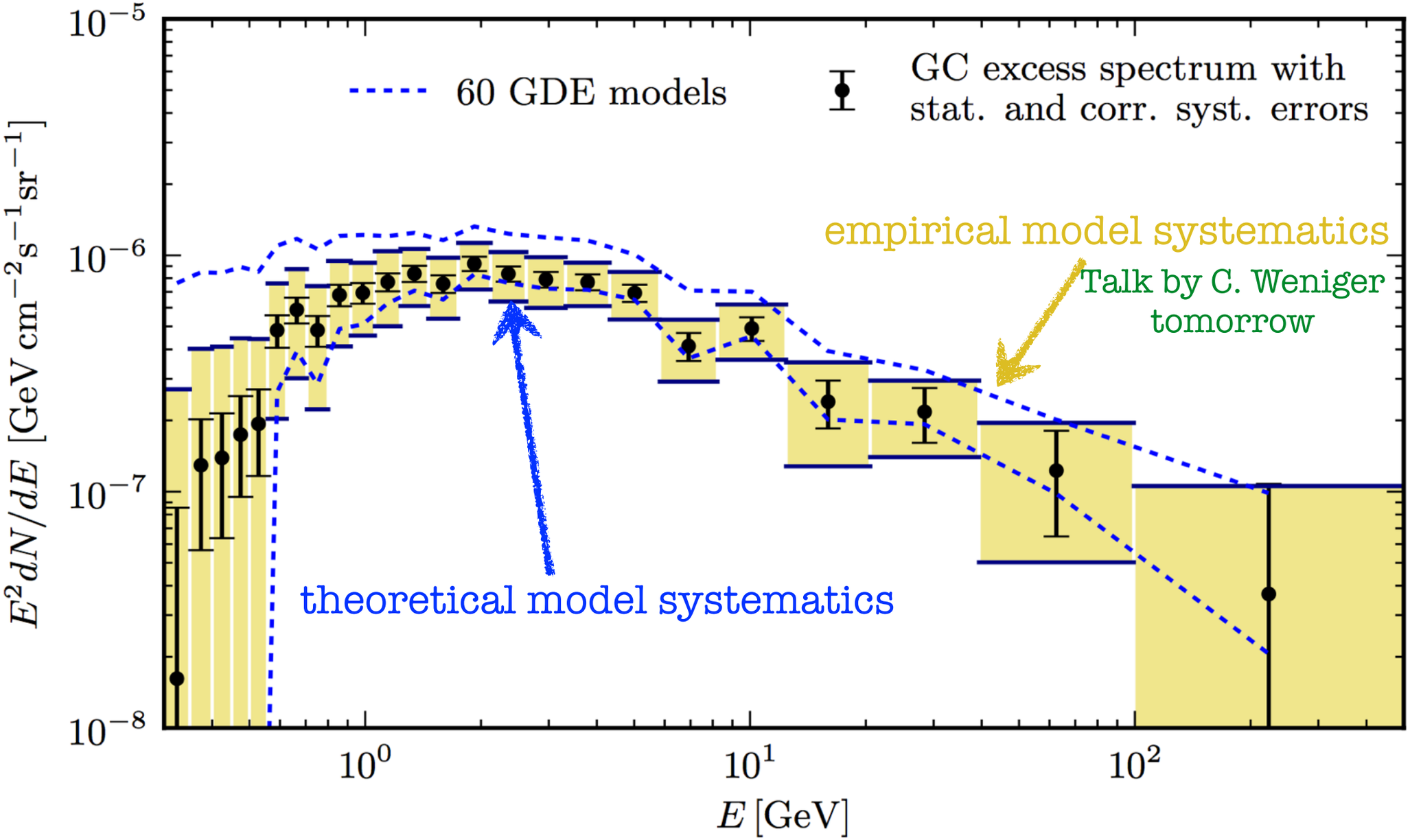
Results: excess emission spectrum



- ✓ Existence of an extended excess emission associated with the GCE template.
- ✓ Energy spectrum peaked at 1-3 GeV and rising at low energies.
- ✓ Excess still significant at high energies, for the **whole** set of diffuse models.

Talk by S.Murgia

GCE spectrum: theoretical & empirical model systematics*



- ✓ **Model systematics** are significantly larger than the statistical error over the entire energy.
- ✓ **Empirical and theoretical systematics** are roughly of the same order in the considered energy range and ROI (only diagonal part of covariance matrix shown).

*Results for one typical galactic diffuse model.

Potential problems

Credit: C. Weniger tomorrow's talk

Bad Fermi LAT PSF below 1 GeV

- Point source confusion / mix with Galactic diffuse emission
- Masking of point sources not sufficient (leakage)

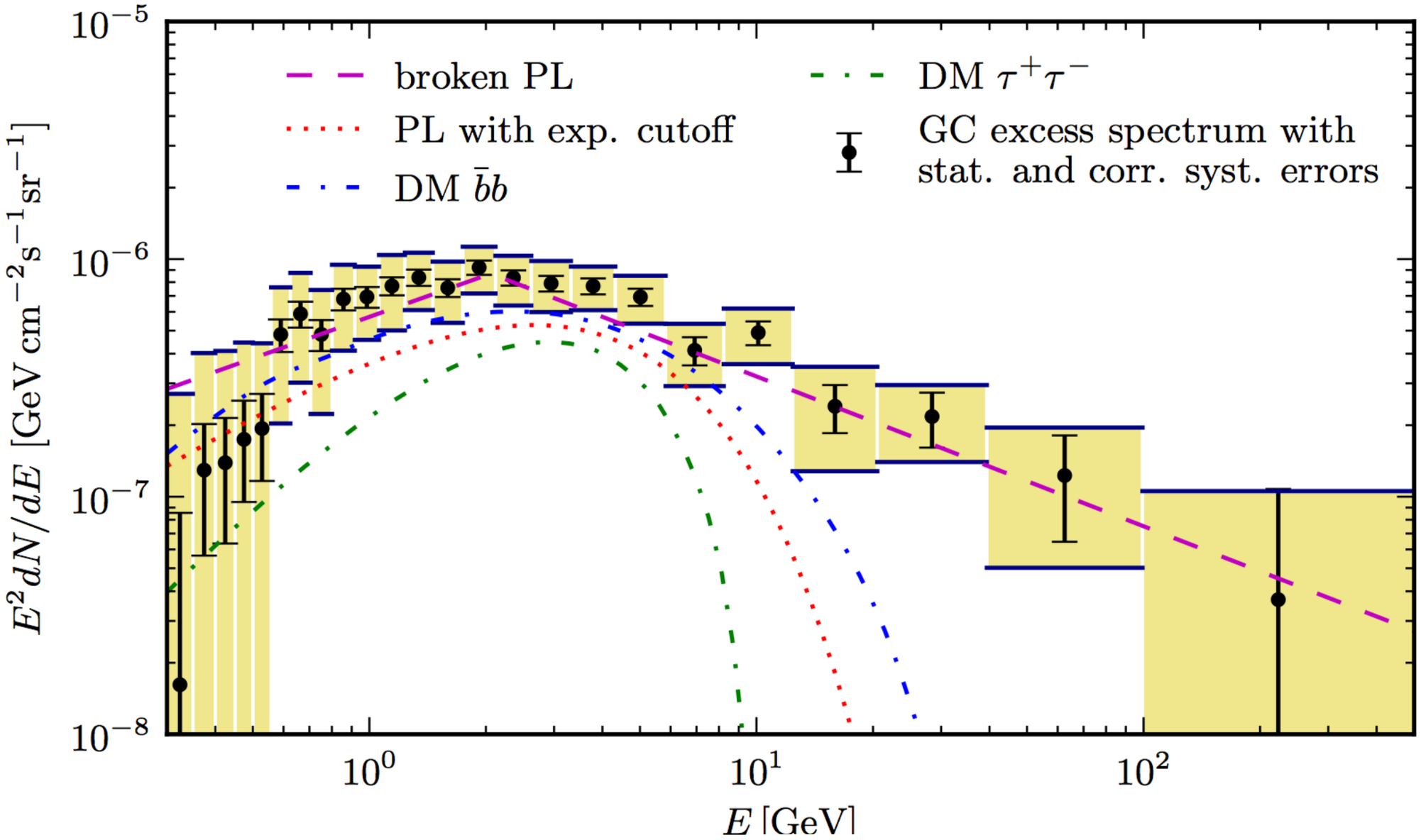
Instrumental effects

- Effective area drops rapidly below 1 GeV

Galactic diffuse emission model

- Large unknowns related to interstellar gas
- Extreme foreground models are not extreme enough
- Diffusion properties at Galactic center weakly constrained
- No physical model for Fermi bubbles
- Many unresolved point sources in Galactic bulge

Parametric fits to the GeV excess

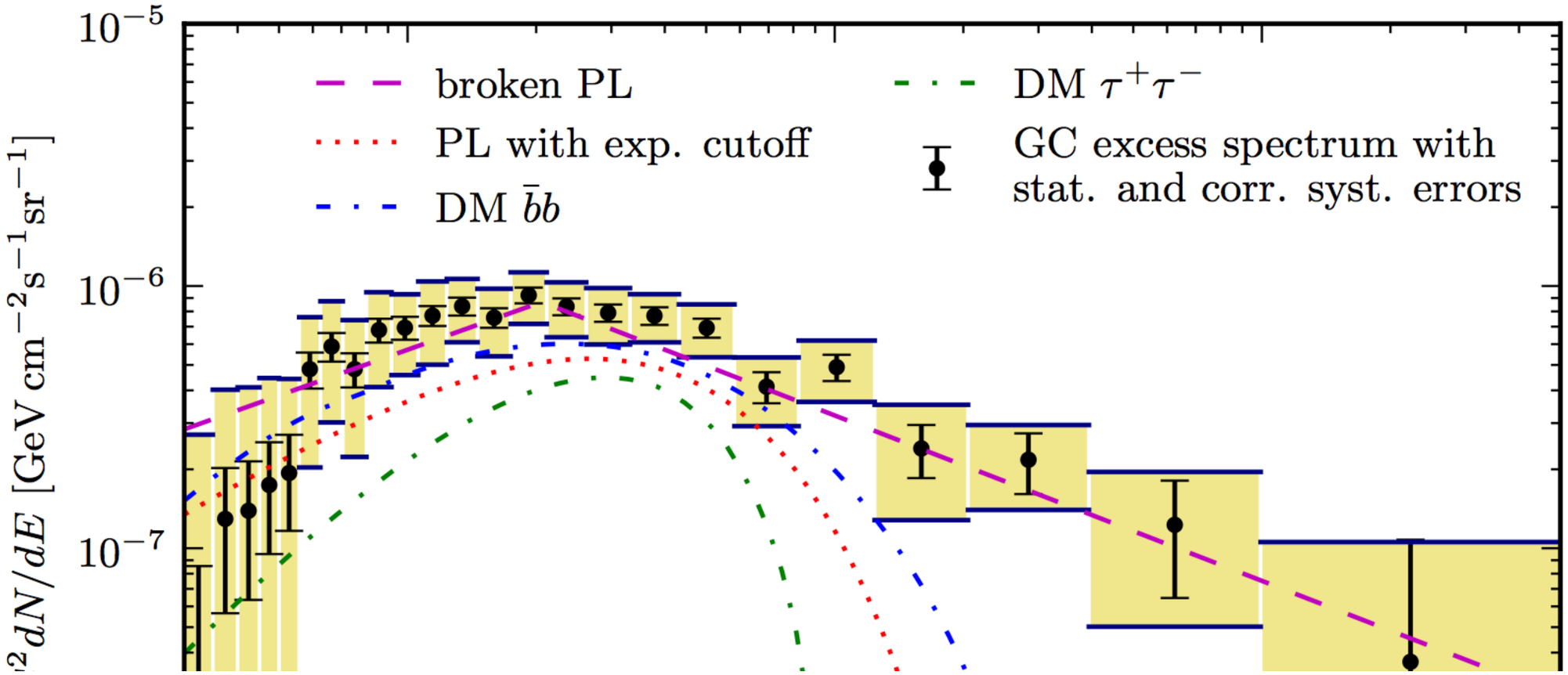


Fit with correlated errors
(empirical model systematics only)

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

$$\Sigma_{ij} = (\sigma_i^{\text{stat.}})^2 \delta_{ij} + \Sigma_{ij,\,\text{mod}}^{\text{trunc}} + \Sigma_{ij,\,\text{res}}$$

Parametric fits to the GeV excess



Spectrum	Parameters	χ^2/dof	p-value
broken PL	$\alpha_1 = 1.42^{+0.22}_{-0.31}$, $\alpha_2 = 2.63^{+0.13}_{-0.095}$, $E_{\rm break} = 2.06^{+0.23}_{-0.17}$ GeV	1.06	0.47
DM $\chi\chi \to \bar{b}b$	$\langle\sigma v\rangle = 1.76^{+0.28}_{-0.27} \times 10^{-26}$ cm^3 s^{-1}, $m_\chi = 49^{+6.4}_{-5.4}$ GeV	1.08	0.43
DM $\chi\chi \to \bar{c}c$	$\langle\sigma v\rangle = 1.25^{+0.2}_{-0.18} \times 10^{-26}$ cm^3 s^{-1}, $m_\chi = 38.2^{+4.6}_{-3.9}$ GeV	1.07	0.44
PL with exp. cutoff	$E_{\rm cut} = 2.53^{+1.1}_{-0.77}$ GeV, $\alpha = 0.945^{+0.36}_{-0.5}$	1.37	0.16
DM $\chi\chi \to \tau^+\tau^-$	$\langle\sigma v\rangle = 0.337^{+0.047}_{-0.048} \times 10^{-26}$ cm^3 s^{-1}, $m_\chi = 9.96^{+1.1}_{-0.91}$ GeV	1.52	0.065

Conclusions

- ✓ We do confirm the presence of an **extended source in the inner part of Galaxy**, consistent with a spherically symmetric density profile.
- ✓ The spectrum of the GCE excess shows a rising below 1 GeV, it is **peaked at 2-3 GeV** and, differently from previous findings, it extends to energy **above 10 GeV** (no sharp cutoff).

Talk by S. Murgia

- ✓ The results are robust against extreme **local variations of models for the Galactic diffuse emission** (theoretical model systematics).
- ✓ Parametric fits with correlated errors show **equal preference** for a **broken power-law spectrum** as well as the **spectrum from dark matter annihilation into b quarks**.
- ➡ We quantify **empirical model systematics** from testing the GCE template associated emission against Galactic diffuse model predictions along the disk, far away from the Galactic Center.
- ➡ We show that the excess is compatible with a **spherically symmetric component** with **uniform spectrum and morphology**.
- ➡ The excess extends up to at least **10 deg in latitude**.
- ➡ Many open questions!

Talk by C. Weniger tomorrow