GRAPPA
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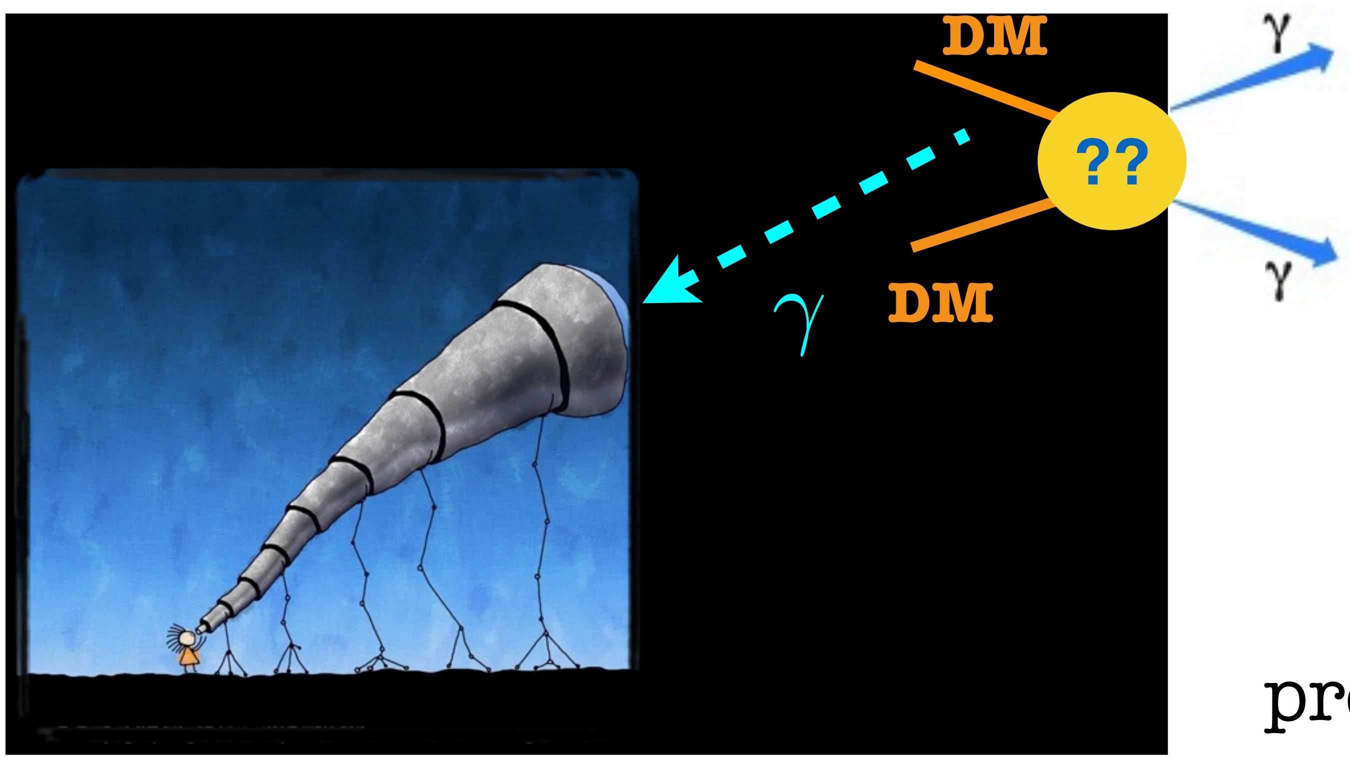
Dark matter signals from the gamma-ray sky?

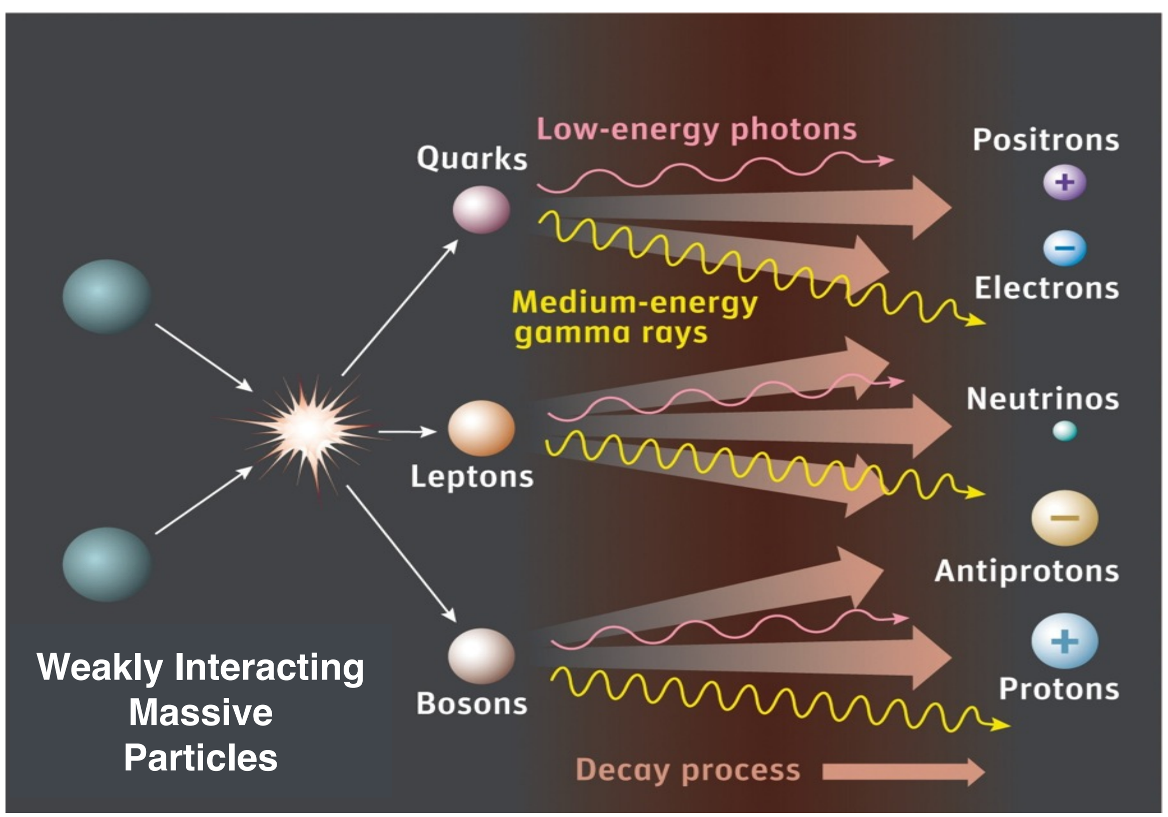
EPS-HEP 2015, Vienna
24th July 2015

Gamma rays from the sky



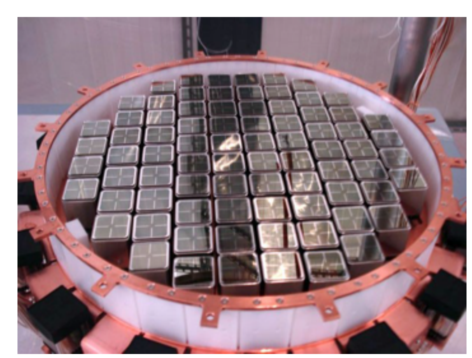
Gamma rays might be produced by DM annihilation in the halo of our Galaxy and in external galaxies.

Indirect searches
for DM annihilation or decay products in gamma rays and charged cosmic rays.

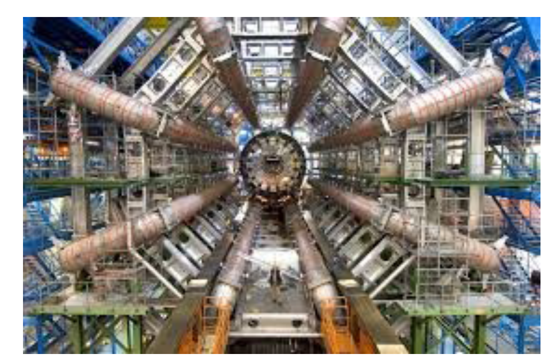


Other complementary probes:

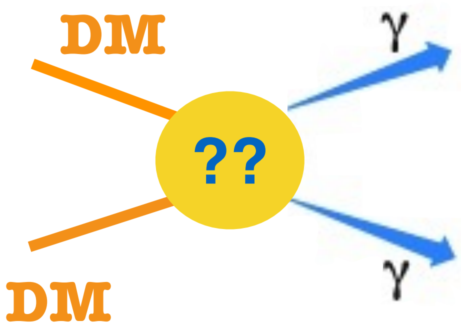
Direct detection searches



Collider searches

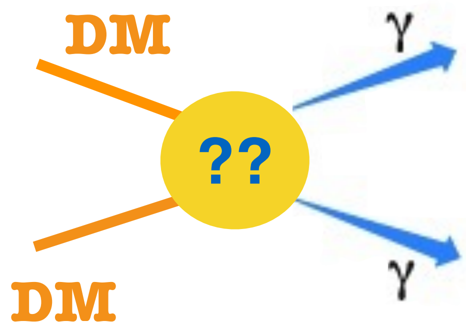


Where to look for dark matter?

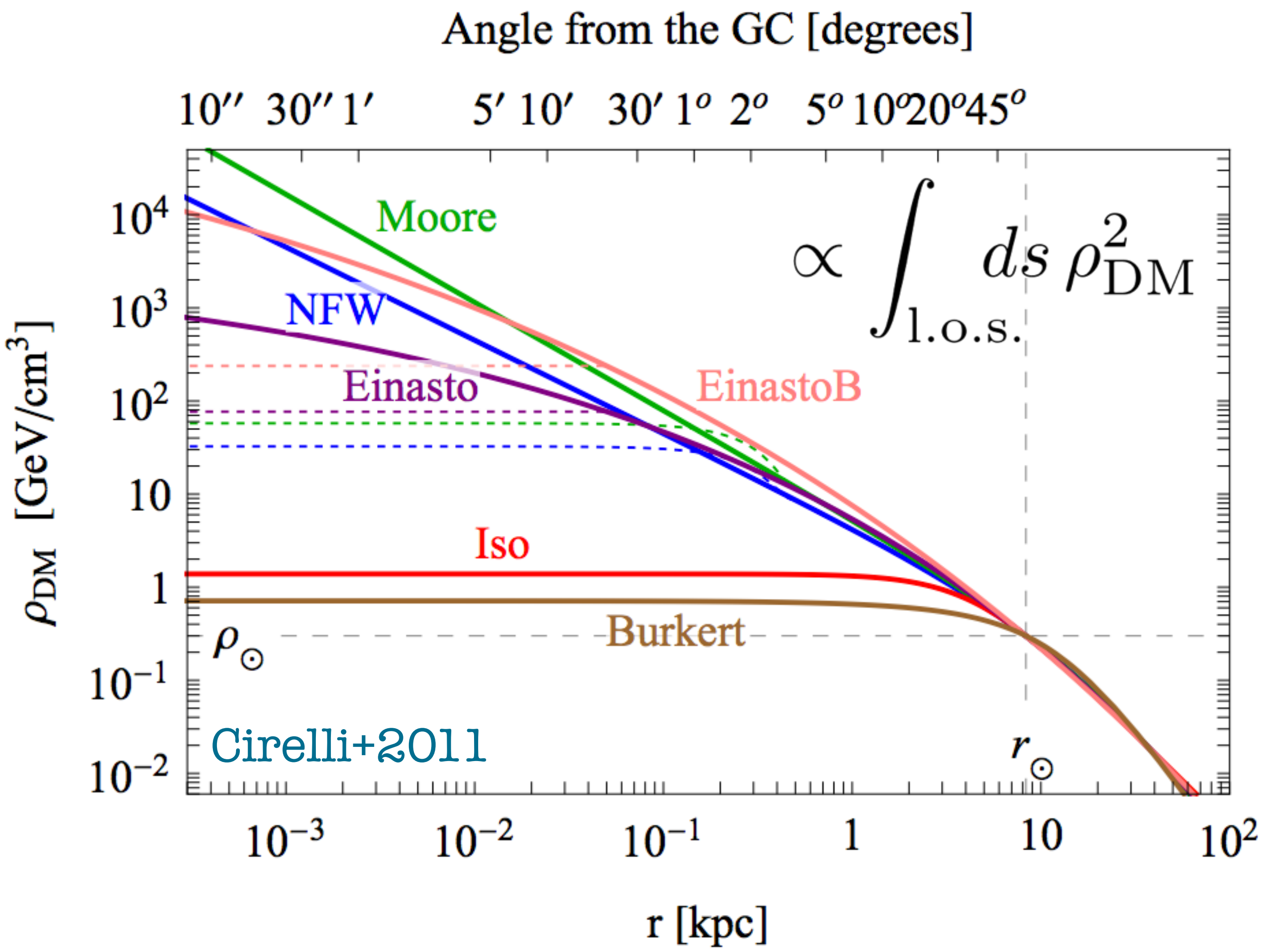


$$\frac{\mathrm{d}\Phi_\gamma}{\mathrm{d}E_\gamma}(E_\gamma,\phi,\theta,\Delta\Omega) = \frac{\langle\sigma v\rangle}{2m_\chi^2}\cdot\sum_i B_i\,\frac{dN_\gamma^i}{dE_\gamma}\,\frac{1}{4\pi}\int_0^{\Delta\Omega}\mathrm{d}\Omega\int_{\mathrm{l.o.s}}\rho^2(s(R,\phi,\theta))ds$$

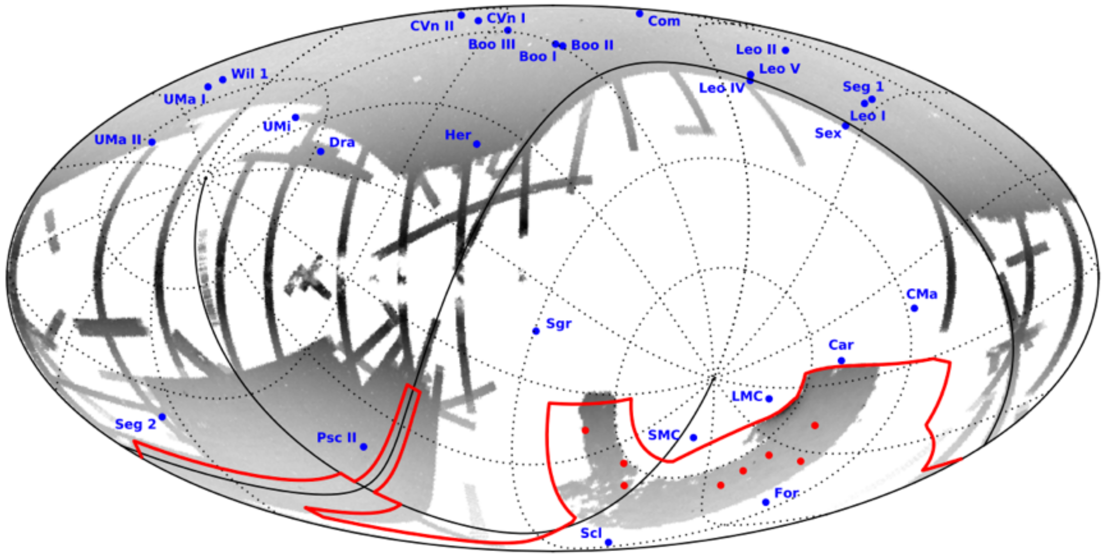
Dark matter gamma-ray signal



$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \phi, \theta, \Delta\Omega) = \frac{\langle \sigma v \rangle}{2m_\chi^2} \cdot \sum_i B_i \frac{dN_\gamma^i}{dE_\gamma} \frac{1}{4\pi} \int_0^{\Delta\Omega} d\Omega \int_{\rm l.o.s} \rho^2(s(R,\phi,\theta))ds$$

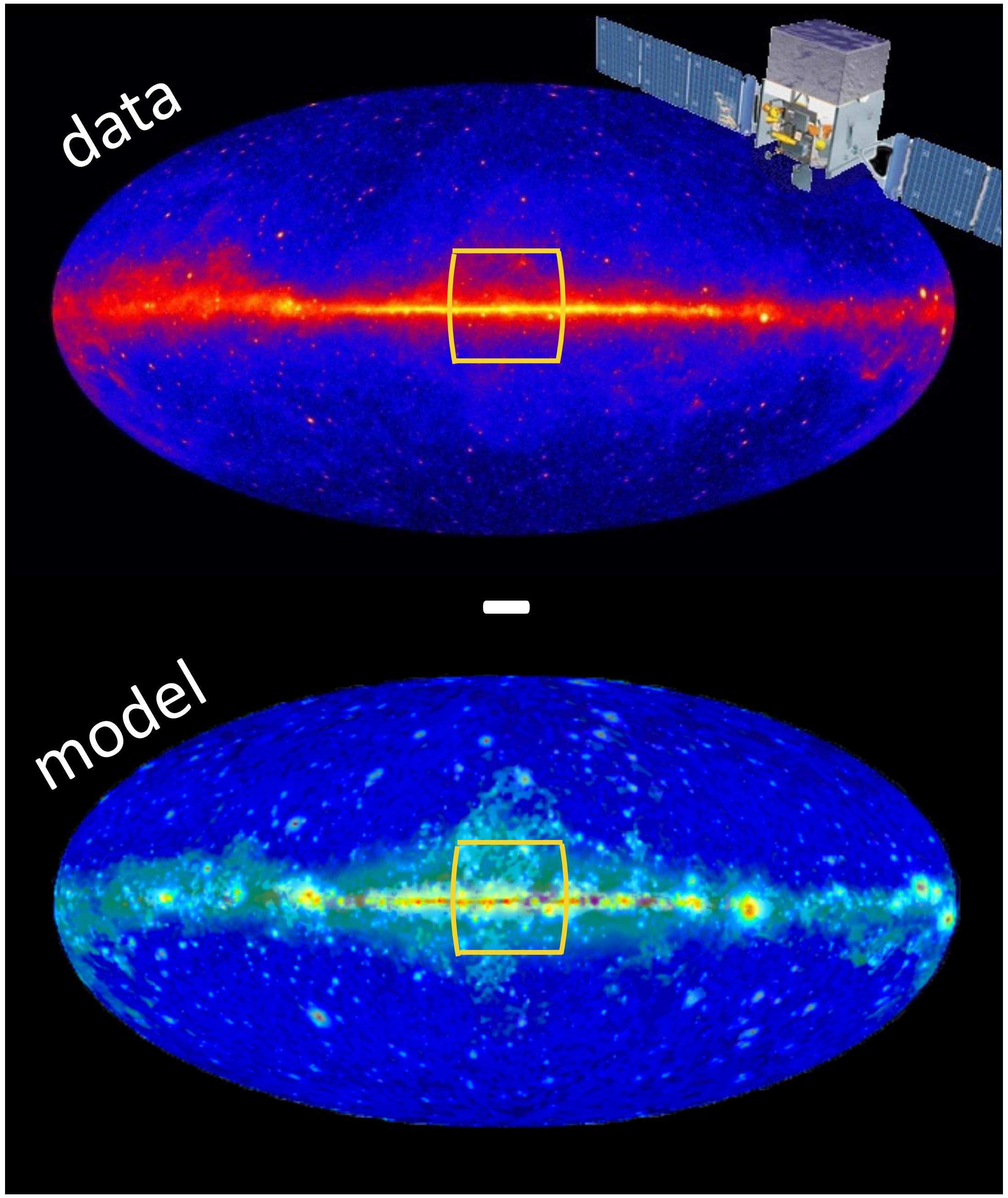


ESO VISTA telescope: the Milky Way



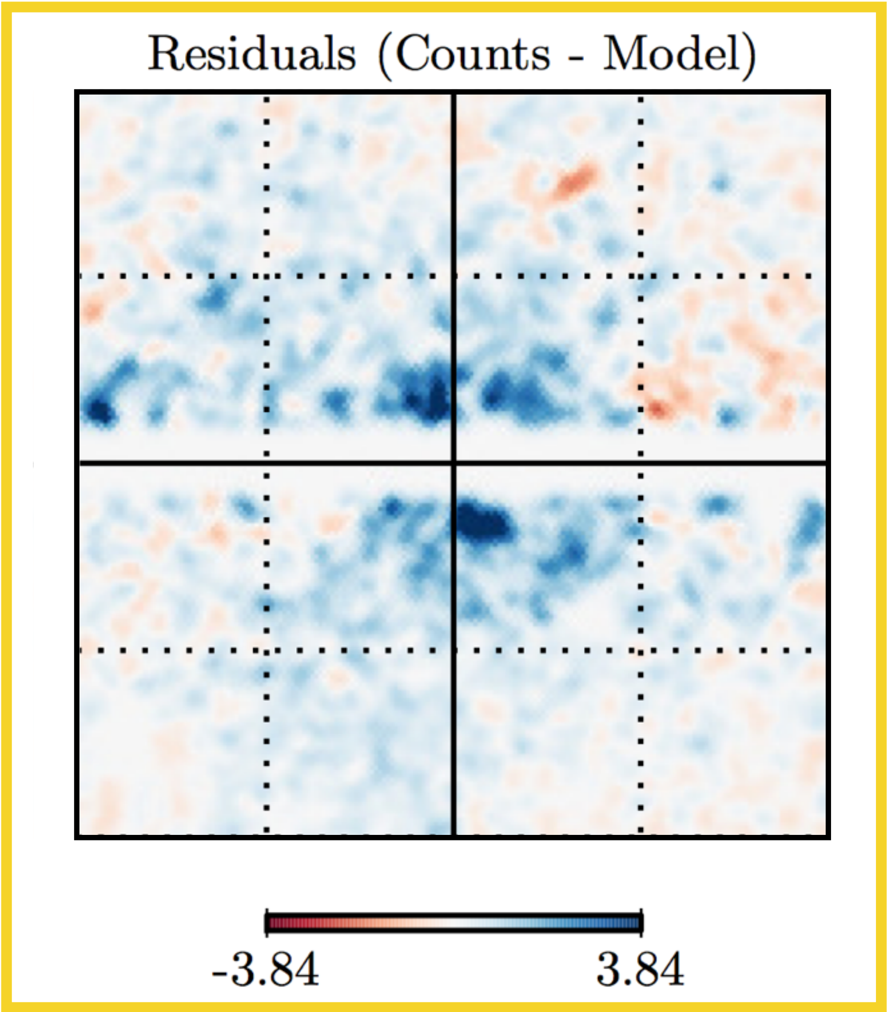
SDSS & DES: dwarf spheroidal galaxies

A mysterious excess



The **Galactic centre GeV excess**

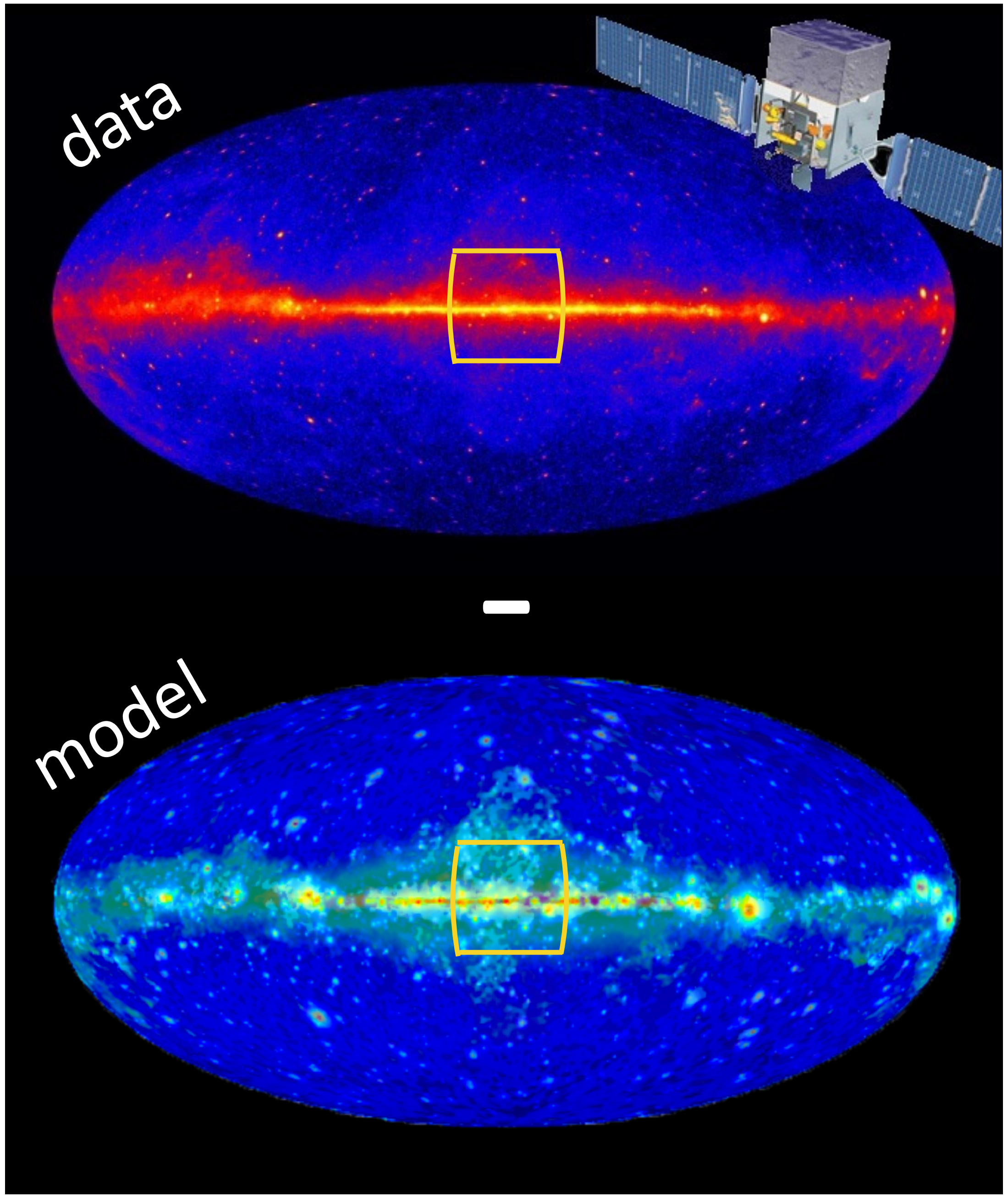
Hooper&Goodenough '09, Vitale&Morselli '09, etc.



Calore+ 2014

Excess emission **above the astrophysical foregrounds and backgrounds**, i.e. Galactic diffuse emission (standard cosmic-ray propagation), point sources and Fermi bubbles.

A mysterious excess



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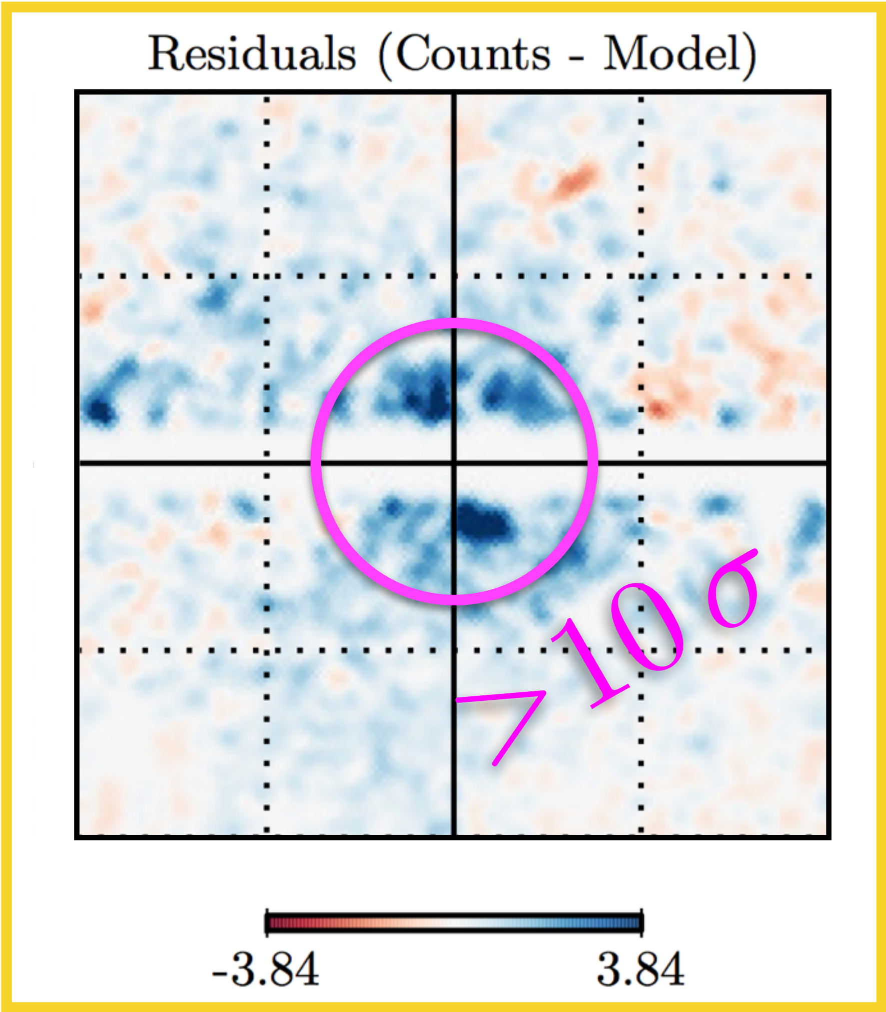
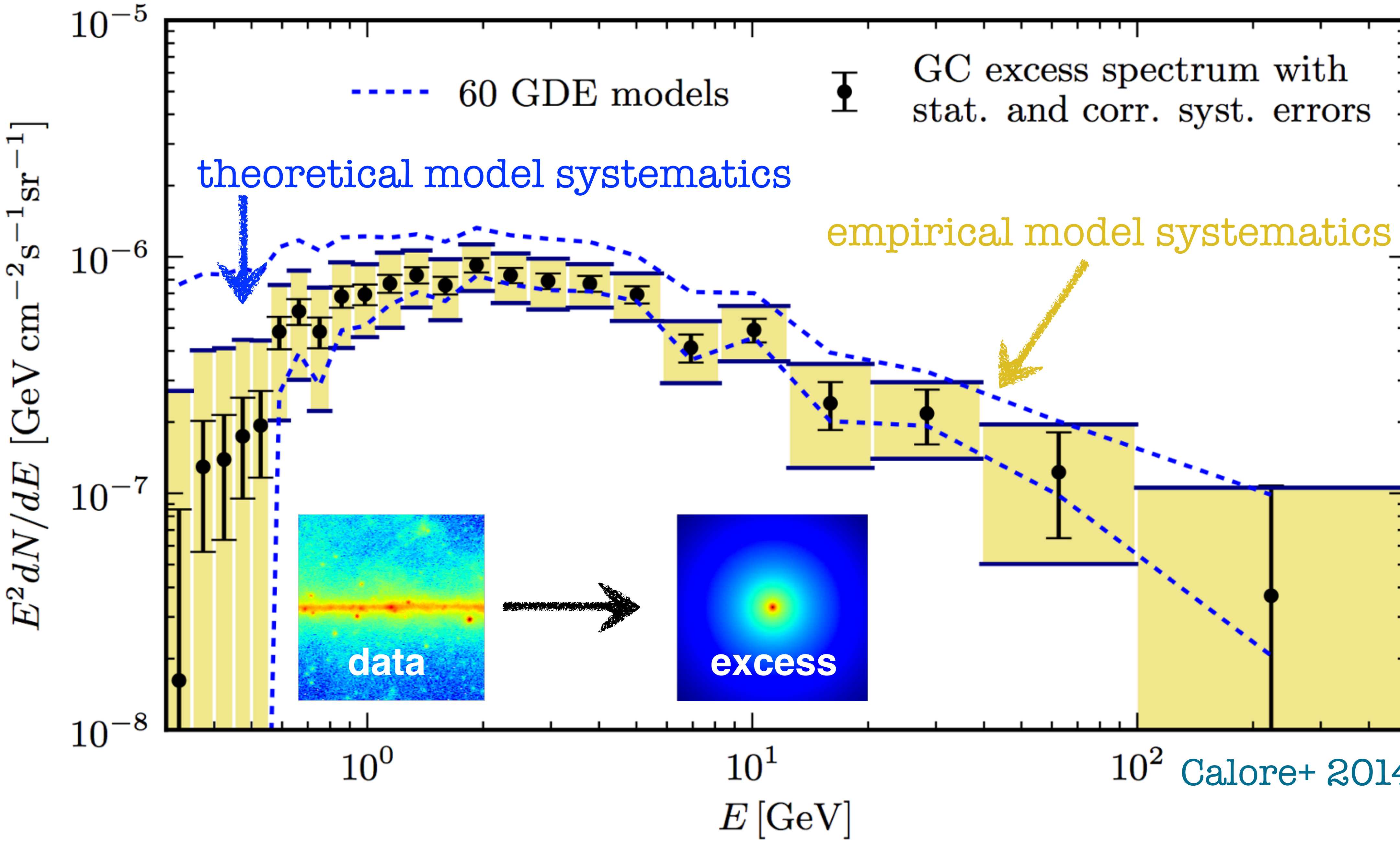


Calore+ 2014

Excess emission **above the astrophysical foregrounds and backgrounds**, i.e. Galactic diffuse emission (standard cosmic-ray propagation), point sources and Fermi bubbles.

The GeV excess spectrum

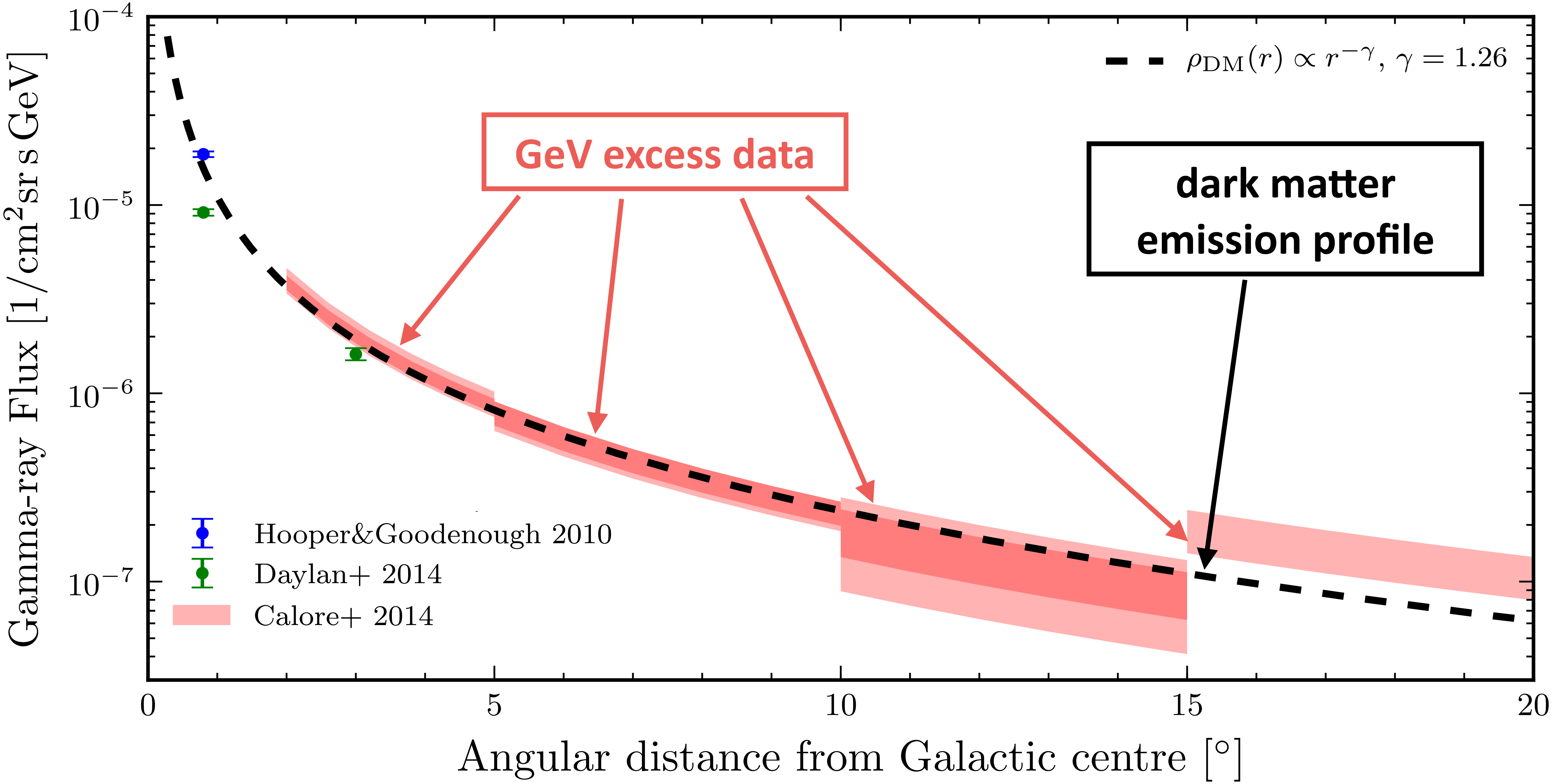


Calore+ 2014

- ✓ **Model systematics** from the variation of Galactic diffuse models (standard assumptions).
- ✓ **Empirical and theoretical systematics** from a scan along the Galactic disc (only diagonal part of covariance matrix shown).

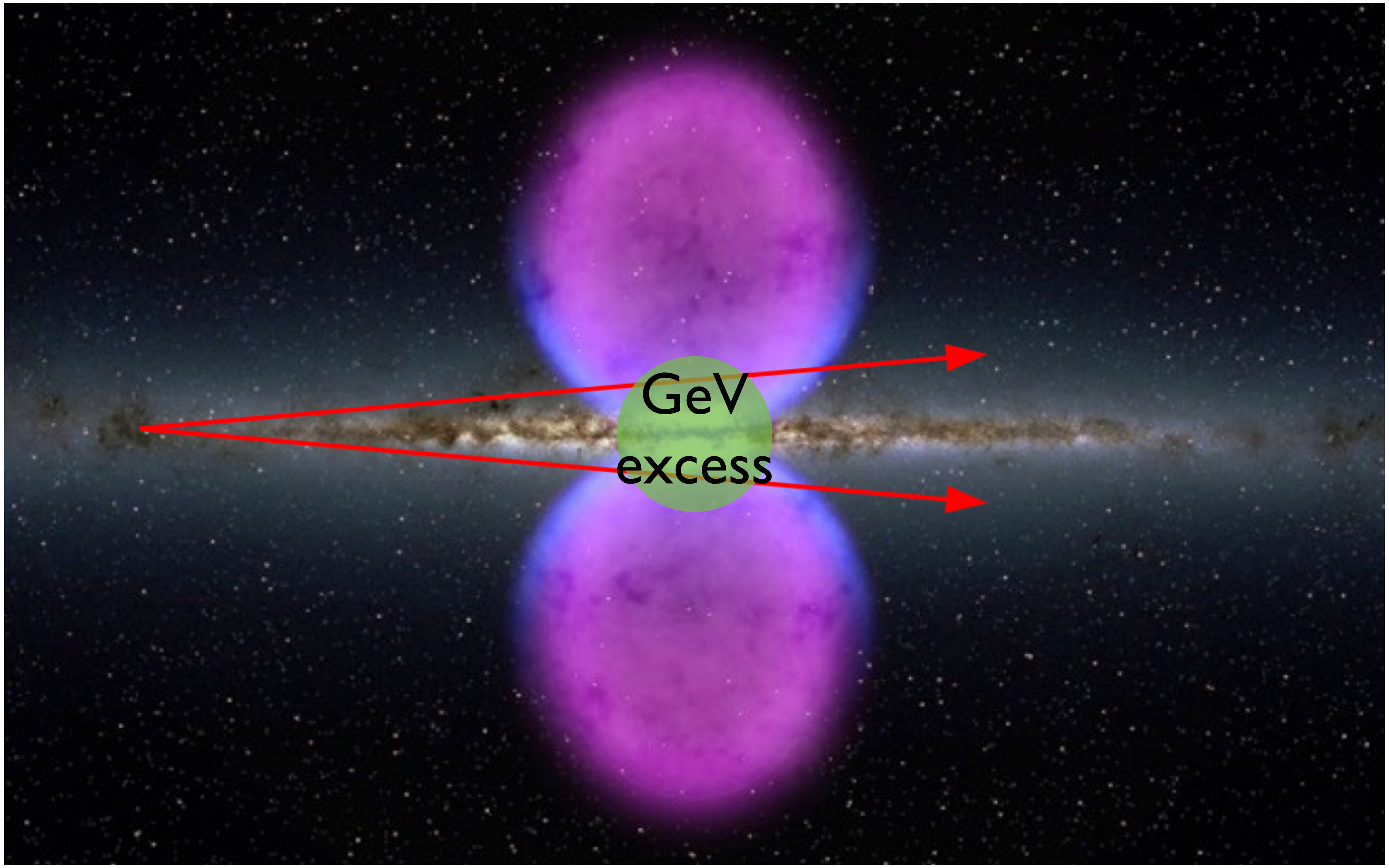
The GeV excess morphology

Calore+ 2014



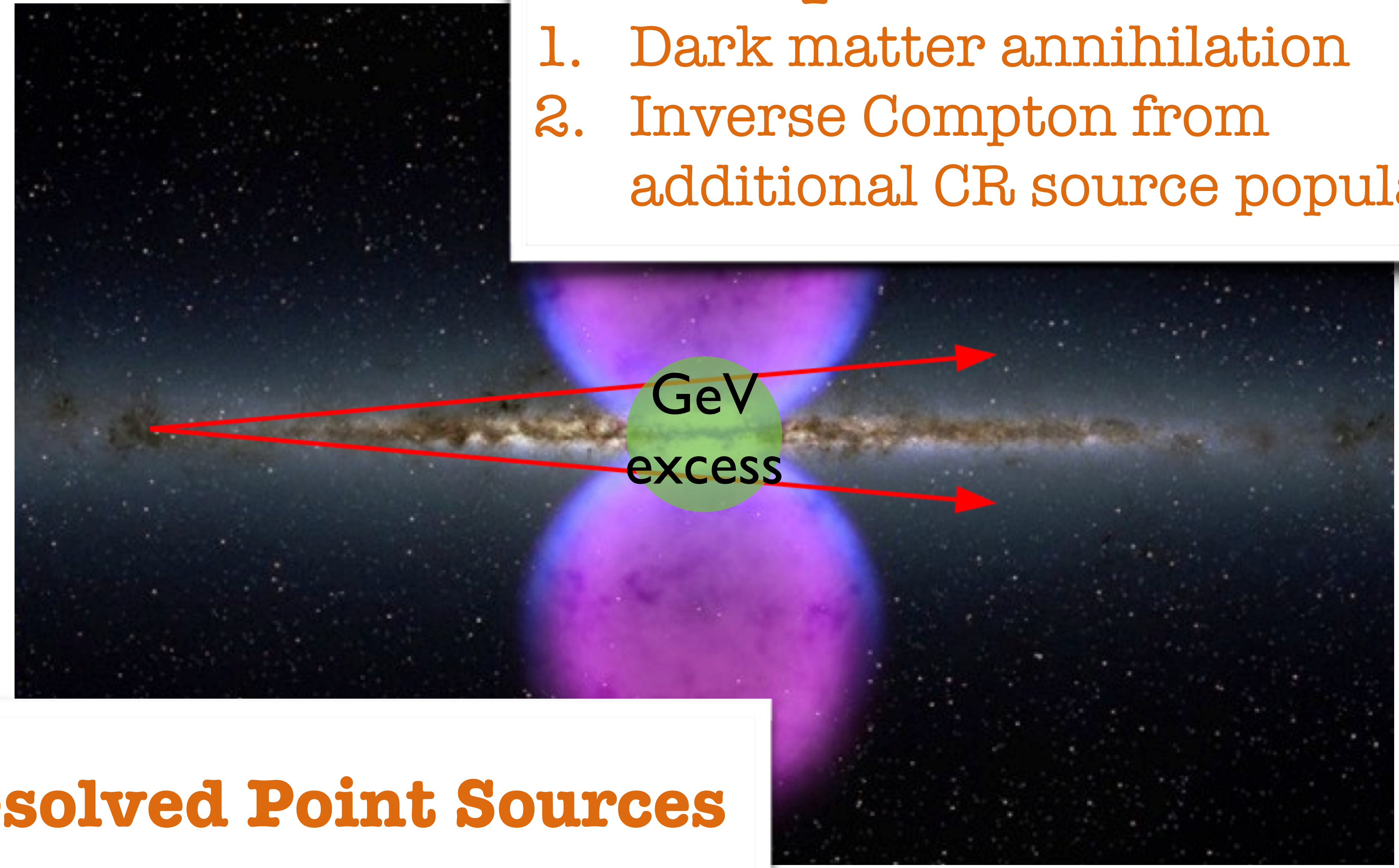
Radial extension of at least **1.48 kpc**, i.e. about **10 degrees**.

Possible interpretations



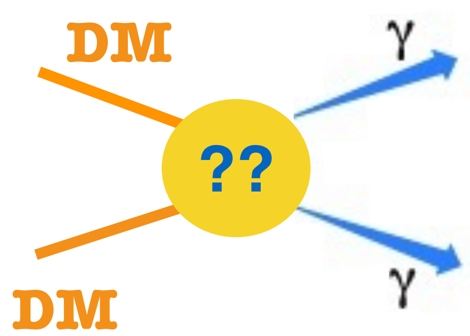
Possible interpretations

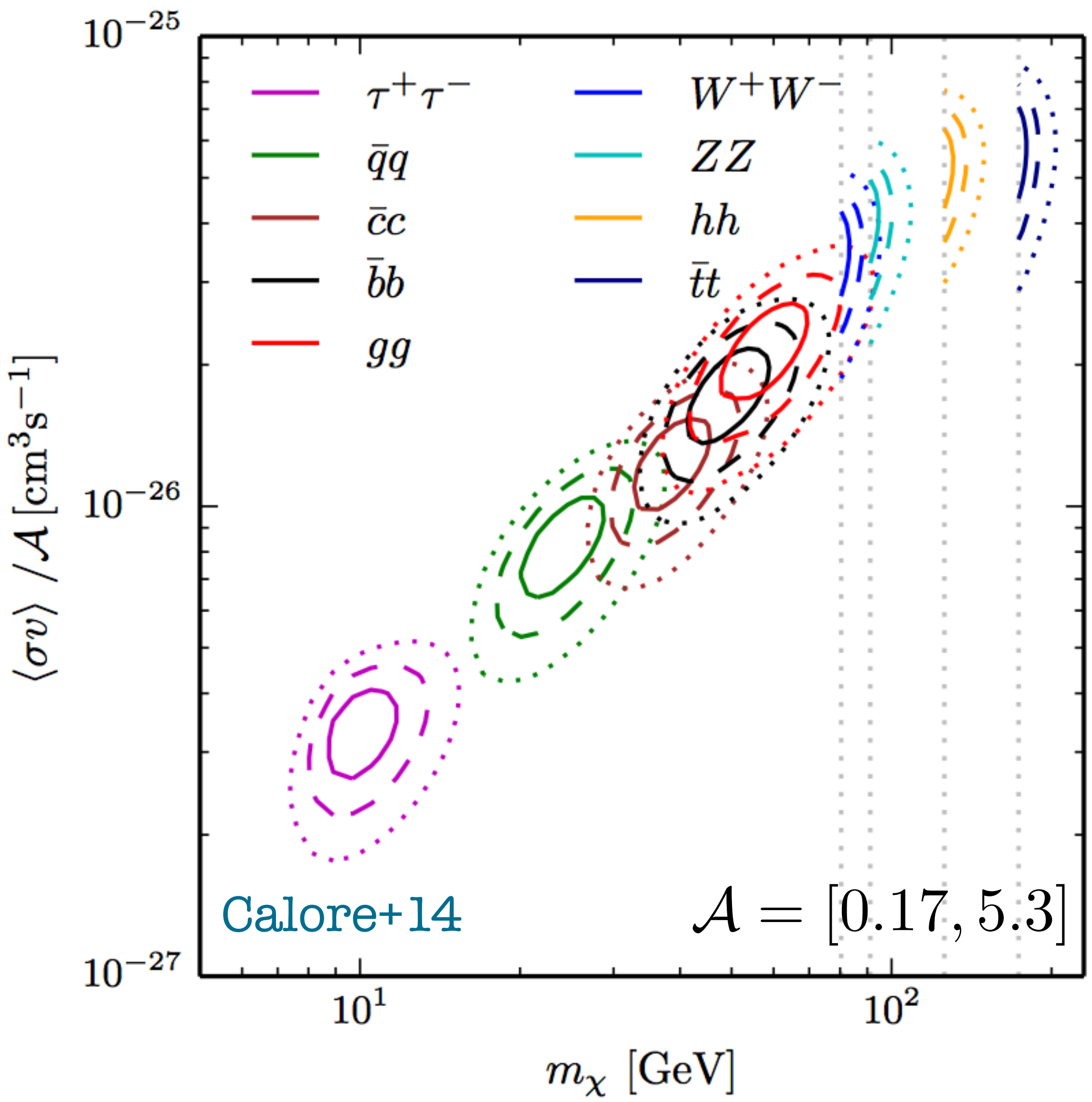
Diffuse processes:
1. Dark matter annihilation
2. Inverse Compton from additional CR source population



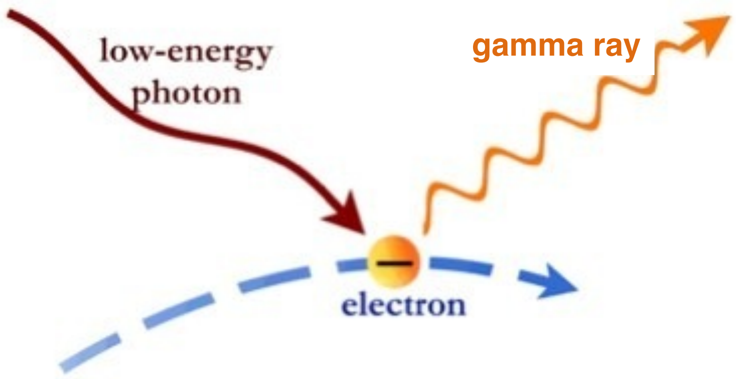
Unresolved Point Sources

Diffuse processes





S. Caron's talk



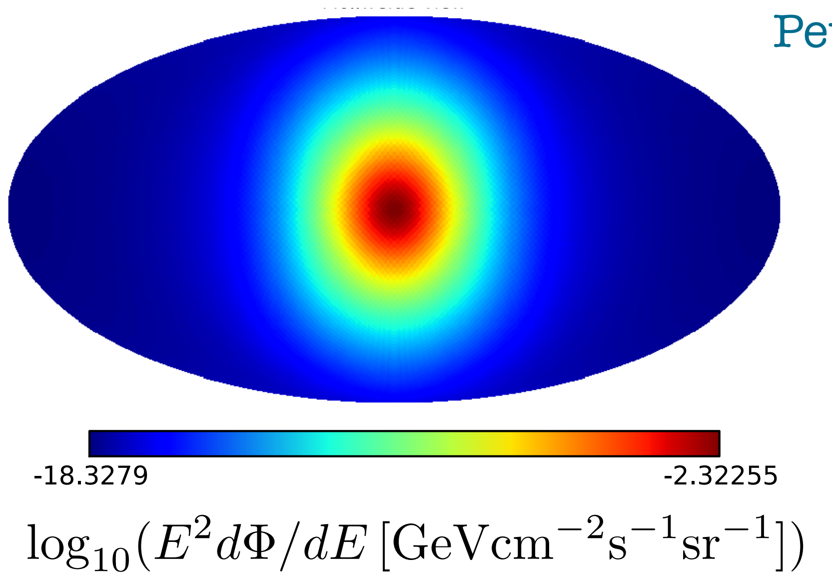
An additional population of leptonic cosmic-ray is required at the Galactic centre

a. Steady-state source term (from e.g. SN population)

Gaggero+15

b. Time-dependent source term (from e.g. outburst event)

Petrovic+2014
Cholis+15



Outburst models

- Energetics:

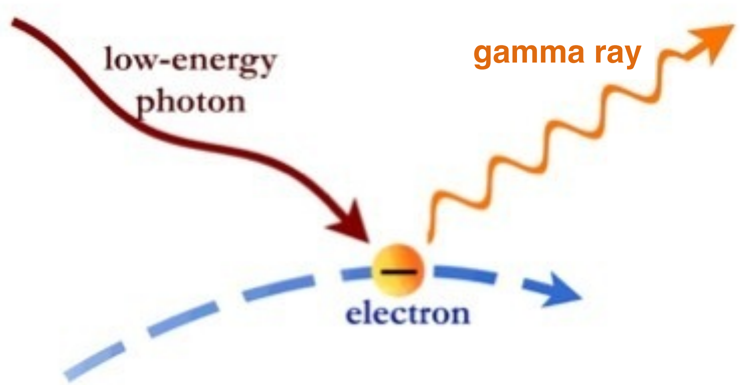
$$L_{\mathrm{GCE}} \sim 10^{37} \mathrm{erg/s} \qquad \mathrm{L_{bubbles}} \sim 4 \times 10^{37} \mathrm{erg/s}$$

Hooper & Slatyer 2013 Su+ 2010

- High-energy electrons injected

$$E_{\mathrm{tot}} \sim 10^{51} \mathrm{erg} \qquad \frac{dN_e}{dE_e} \propto E_e^{-\alpha} \exp(-E_e/E_{\mathrm{cut}})$$

- Propagation and energy losses



A single-burst model **cannot** account for the observed morphology of the signal

Cholis+15

Two-burst model?

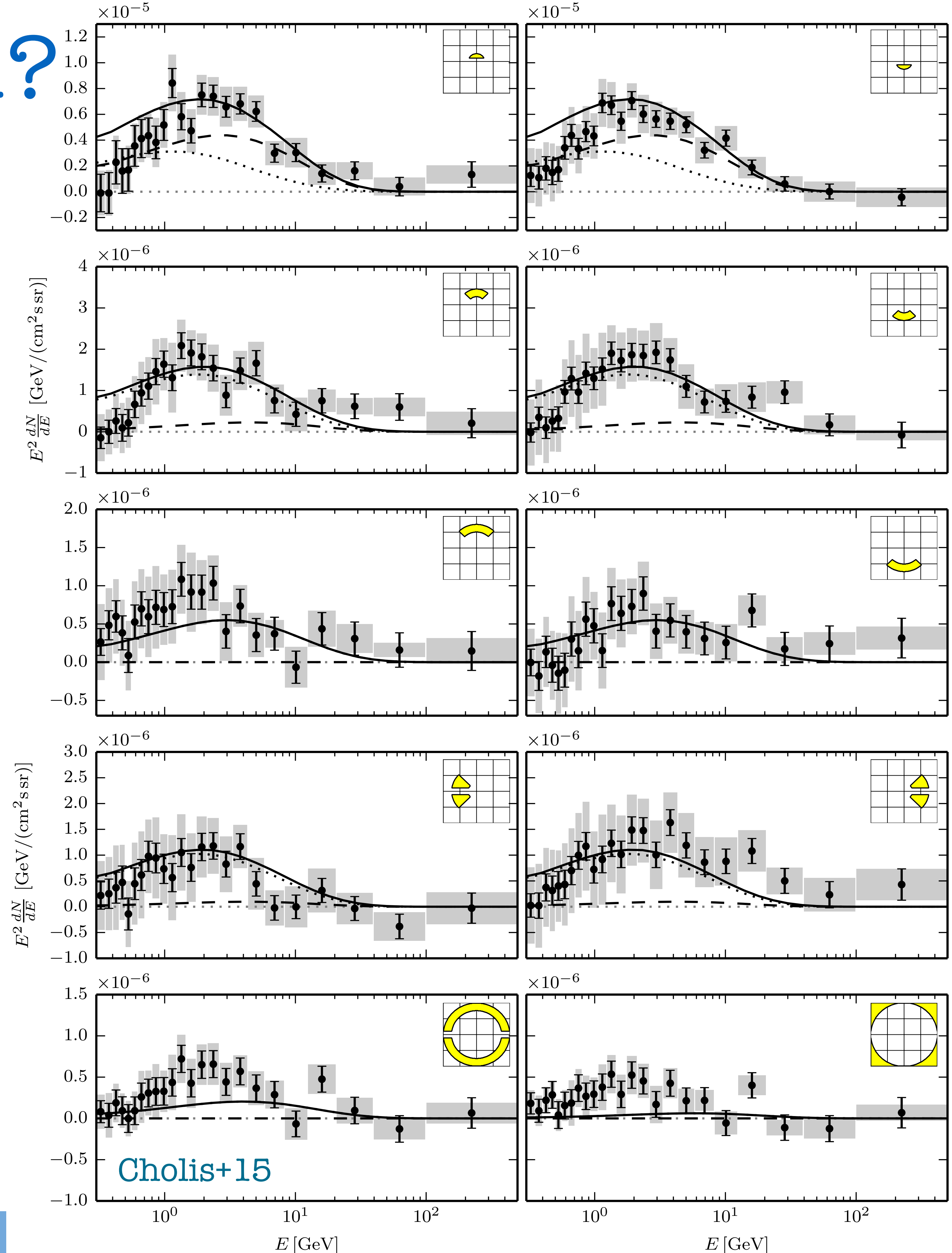
- High-energy electrons injected

  $\tau, \alpha, E_{\rm cut}, E_{\rm tot}$

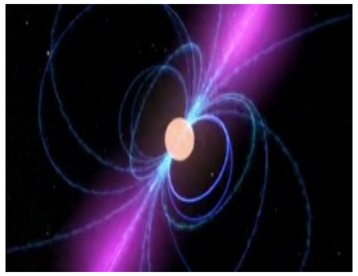
- Propagation and energy losses

  $\delta, D_0, D_{zz}/D_{xx},$
  $v_A, dv_c/dz,$
  ISRF,
  B_0, r_c, z_c

- Hard injection indices (<2)
- At least two bursts
- Tuning of diffusion parameters



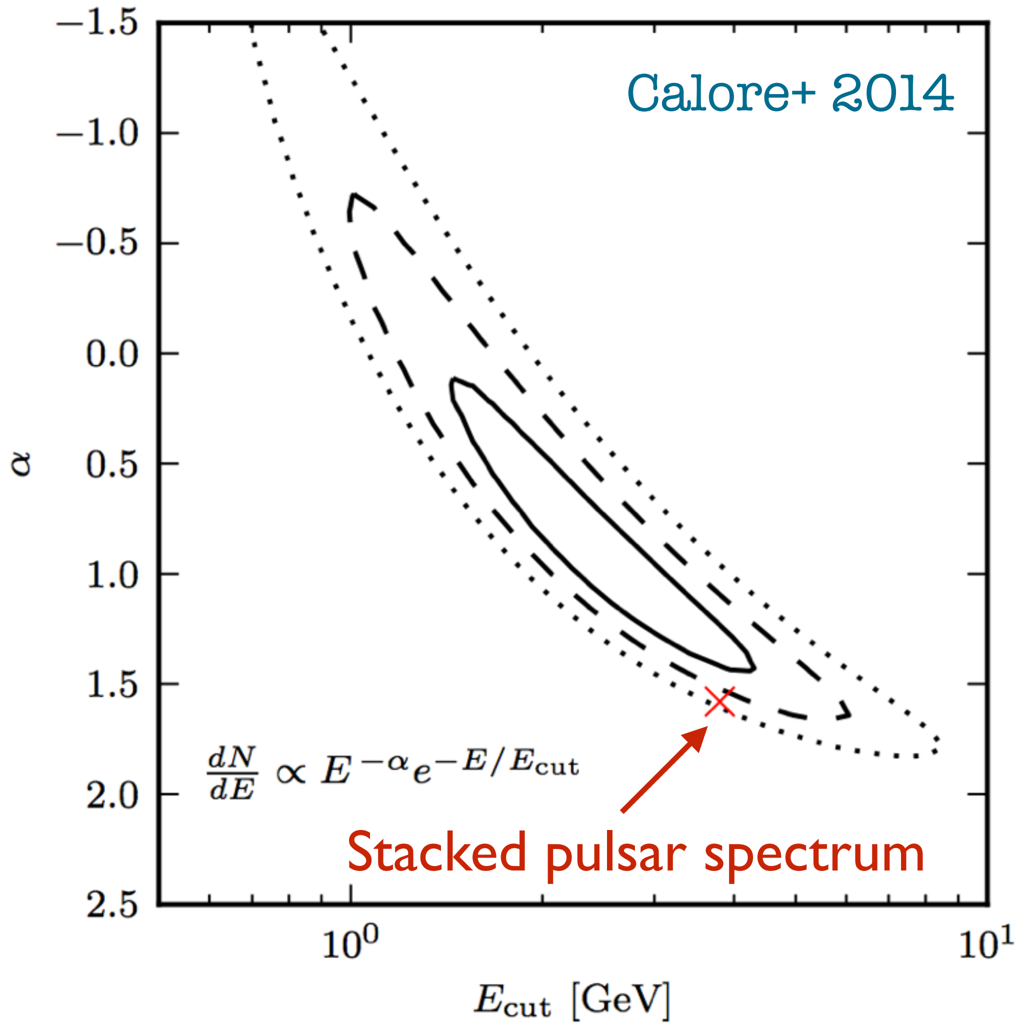
Unresolved point sources



Young Pulsars and Millisecond Pulsars

Wang+ 2005; Abazajian 2011;
Gordon & Macias 2013;
Hooper+ 2013; Yuan & Zhang 2014;
Hooper+ 2013; Calore+ 2014;
Cholis+ 2014; Petrovic+2014;
Yuang+2014;
and many others

Spectrum?



Morphology?

- **disc-like** population => at most 10% of the excess emission.

Calore+ 2014

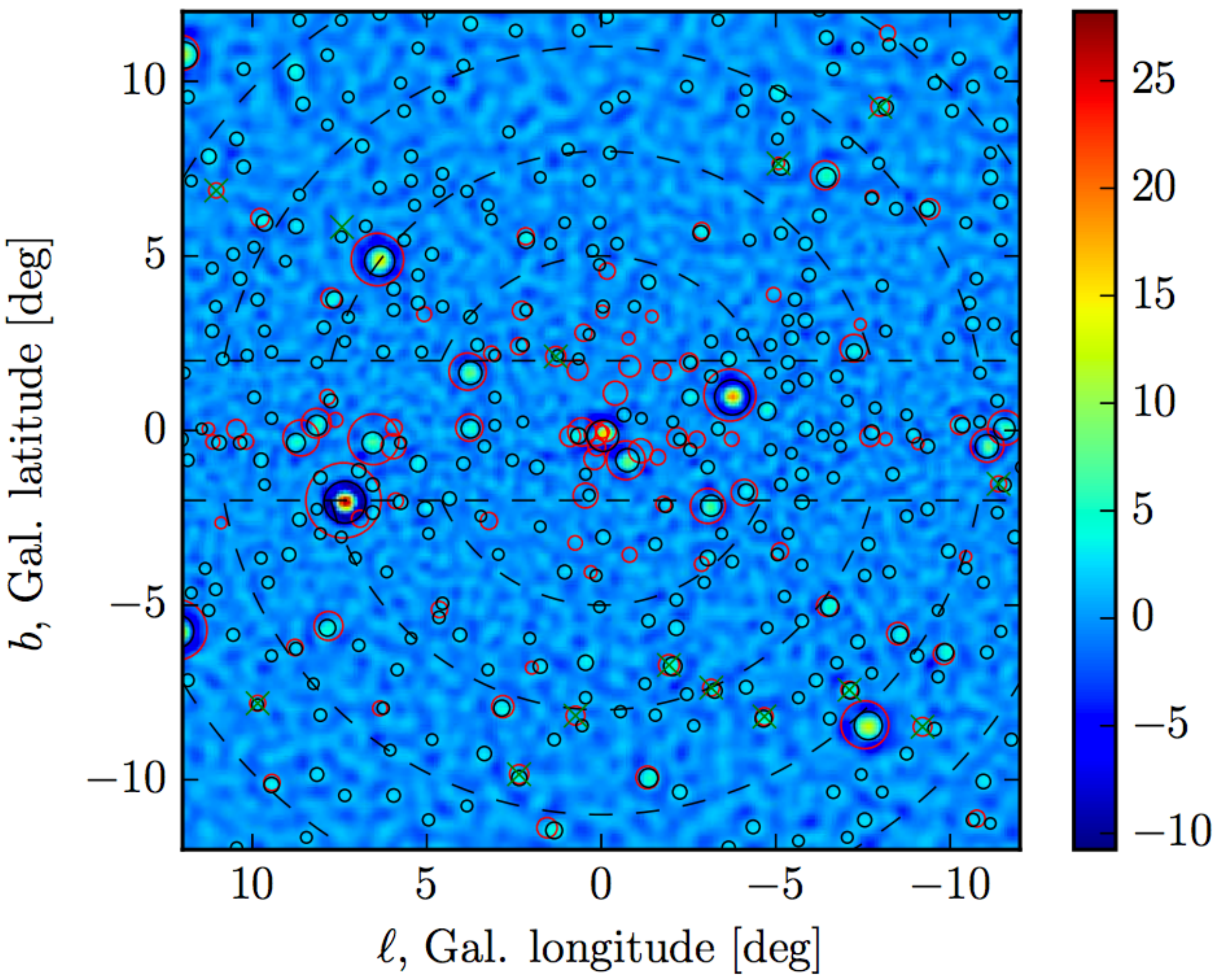
- **bulge** population => viable explanation.

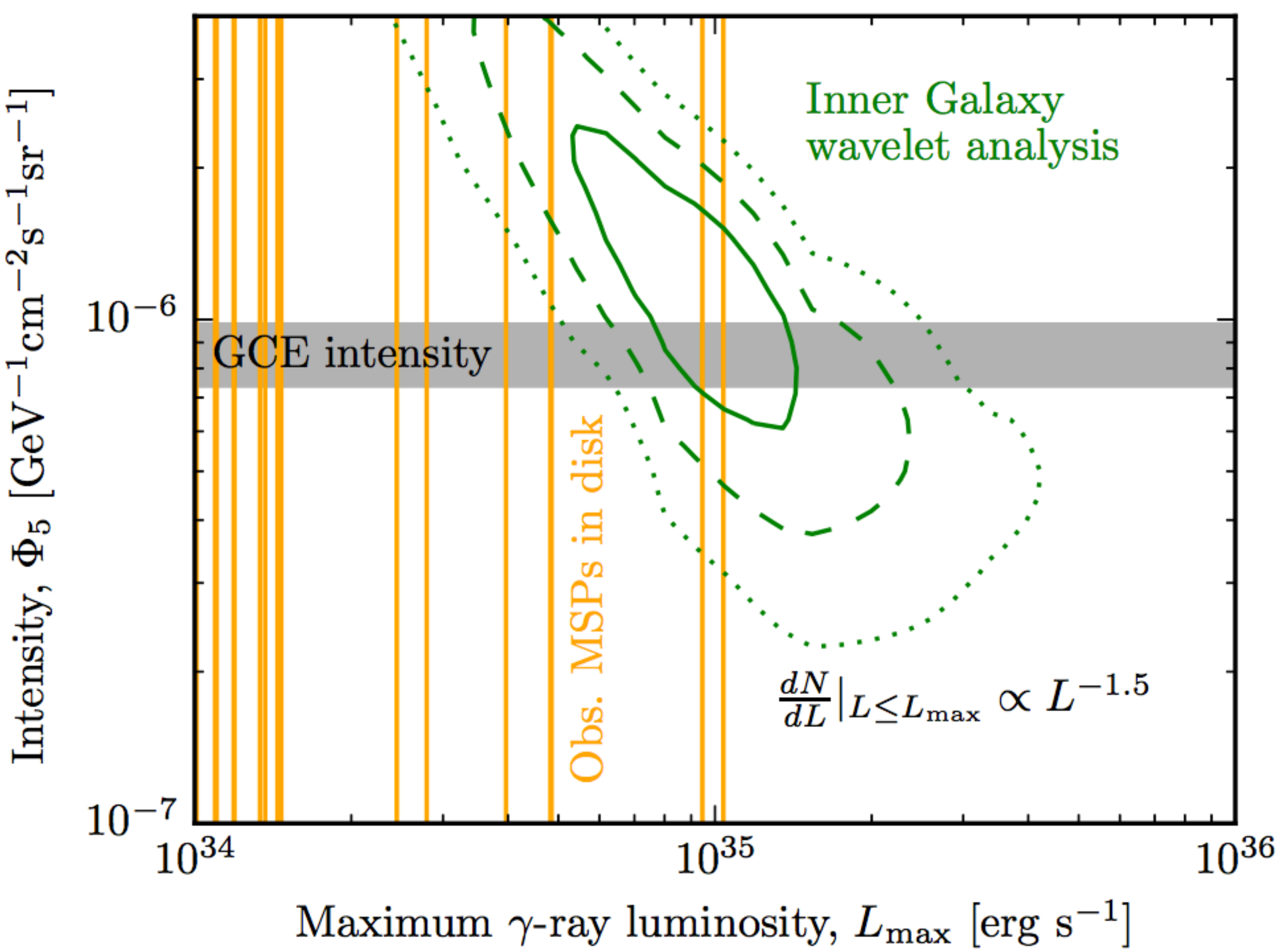
Petrovic+2014, Yuang+2014
O'Leary+2015
Lee+2015, Bartels+2015

How to discriminate?

Wavelet decomposition of the gamma-ray sky and
the statistics of Gaussian random fields

Bartels+20015





see also Lee+2015 for an independent method

How to discriminate?

Wavelet decomposition of the gamma-ray sky and
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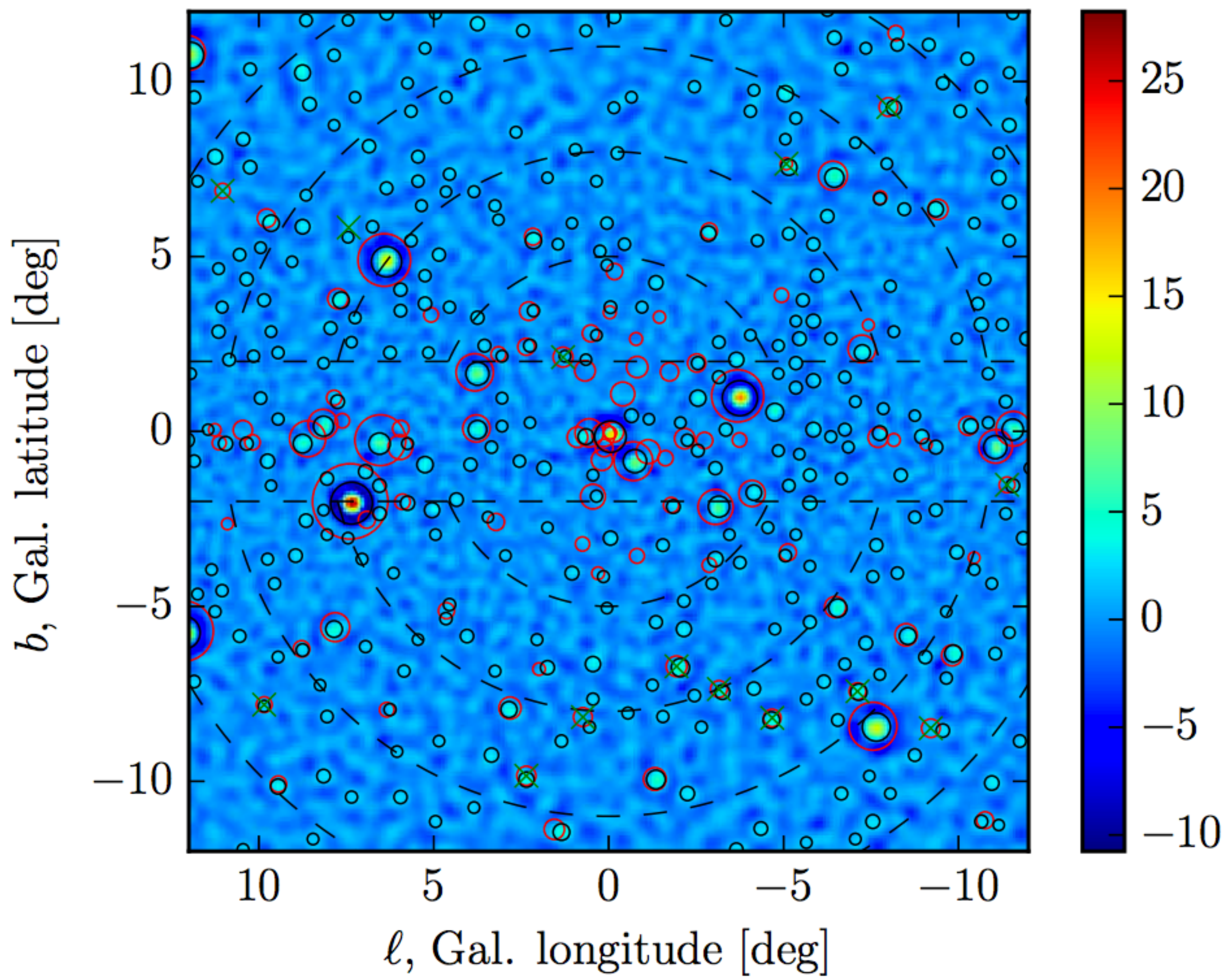
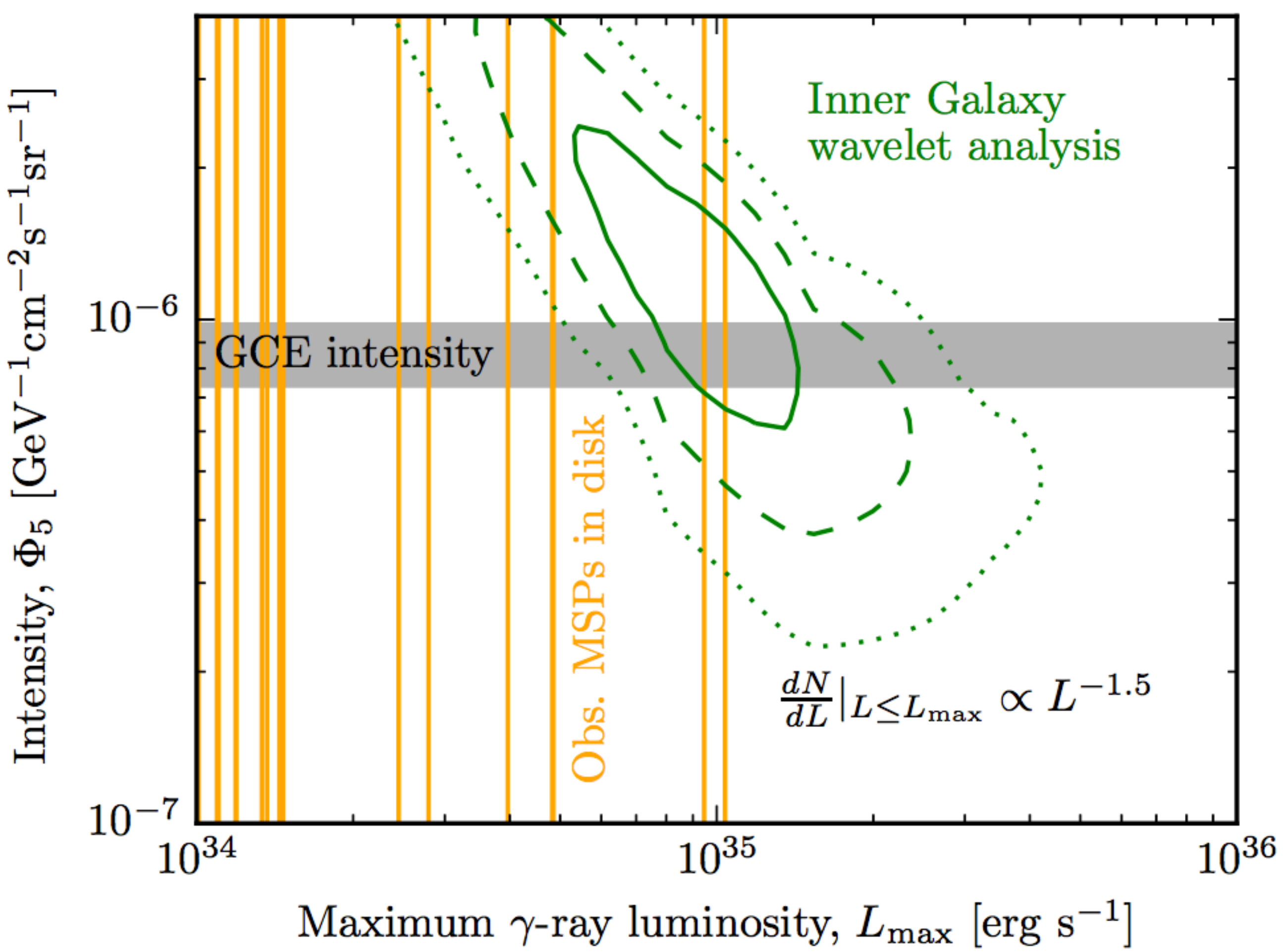
Bartels+20015





up to 100% of the GeV excess emission might come from unresolved sources!

Conclusions

What do we know?

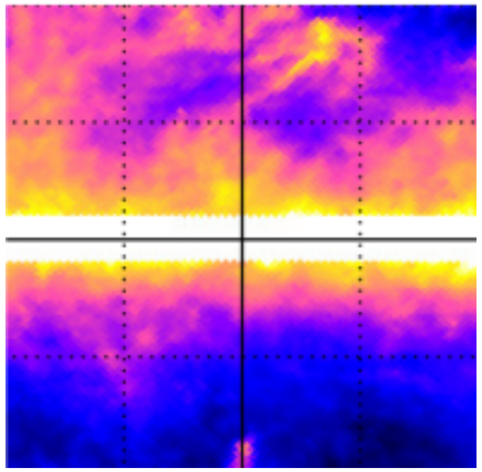
- ✓ An **extended source in the inner part of Galaxy**, consistent with a spherically symmetric density profile, does exist.
- ✓ Spectrum and morphology are now robustly characterised.
- ✓ The excess extends up to at least **10 deg in latitude** and it is compatible with a **unique spherically symmetric component**.
- ✓ However, owing to the **background model systematics**, there is large freedom for models fitting the excess.

What can it be?

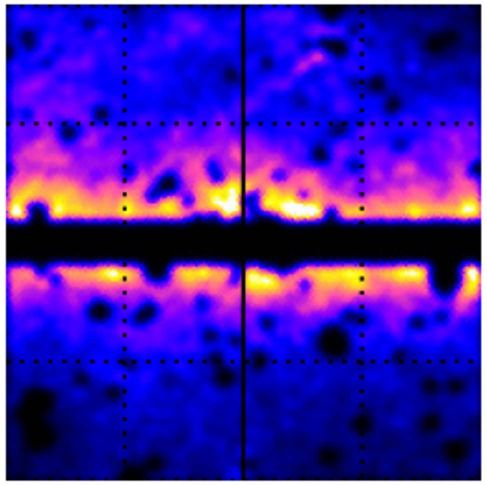
- ✓ **Dark matter** : does an incredibly good job in fitting the excess but….
- ✓ **Diffuse processes from activity of the Galactic centre**: might work but with a fine tuning of the parameters that seems unlikely to occur.
- ✓ **Unresolved sources**: are compatible to cover 100% of the emission but further evidence is needed.

Backup

Basics of the template regression technique



Model counts



Data counts

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

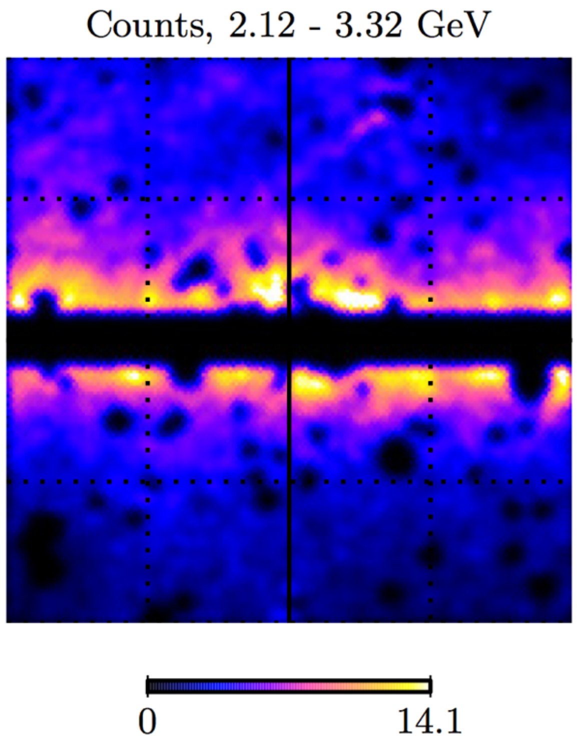
$$k_{i,j}$$

$\mu_{i,j}^k$ model counts in i-th energy bin and j-th pixel

$\theta_{i,k}$ free normalisation of the model component

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

Analysis set-up



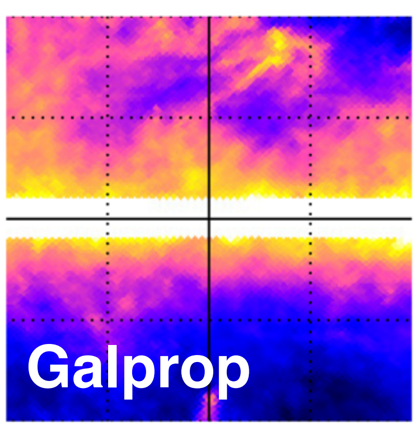
Data selection and standard preparation

284 weeks; 300 MeV—500 GeV

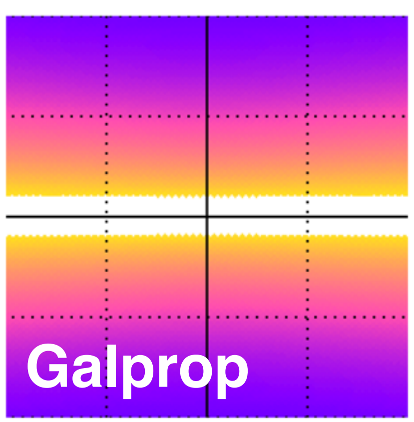
ROI: $2^\circ \leq |b| \leq 20^\circ \;\&\; |l| \leq 20^\circ$

Point sources (2FGL) weighted adaptive mask.

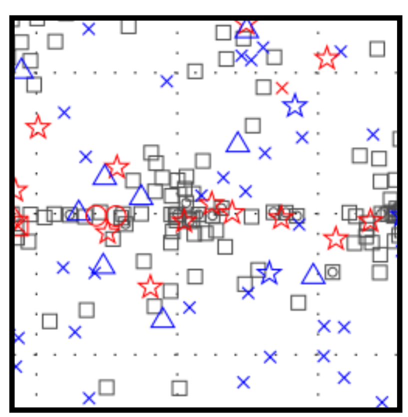
Spatial templates used in the analysis (maximum likelihood method):



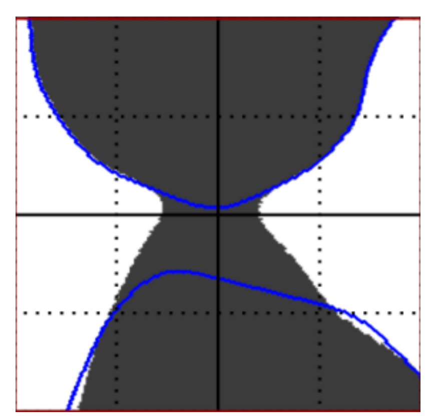
1. π^0+ Brems (free)



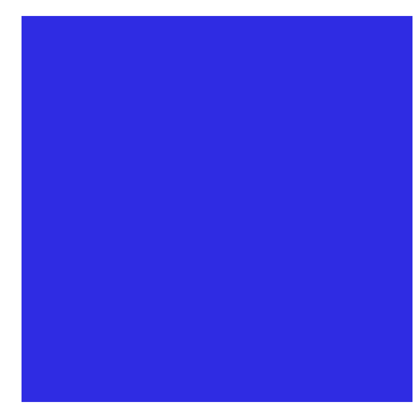
2. ICS (free)



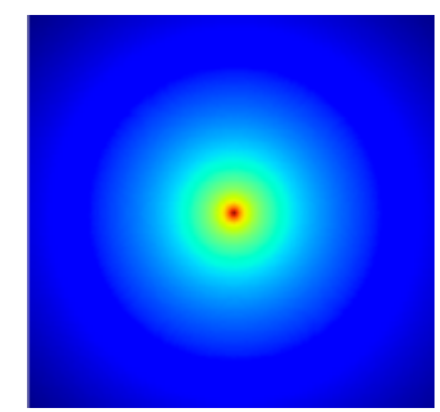
3. 2FGL (fixed)



4. Fermi bubbles (constrained)

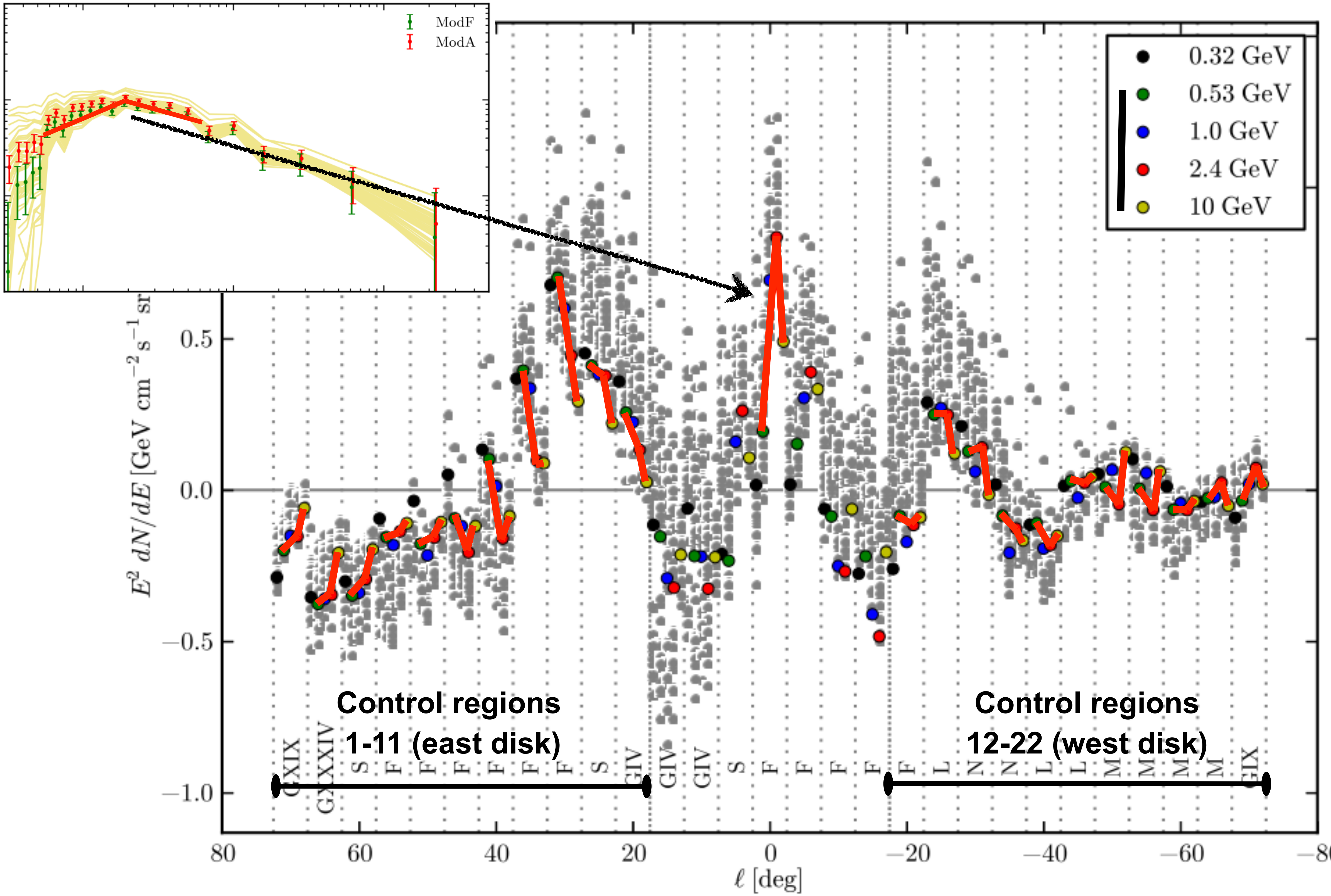


5. Isotropic diffuse bkg (constrained)

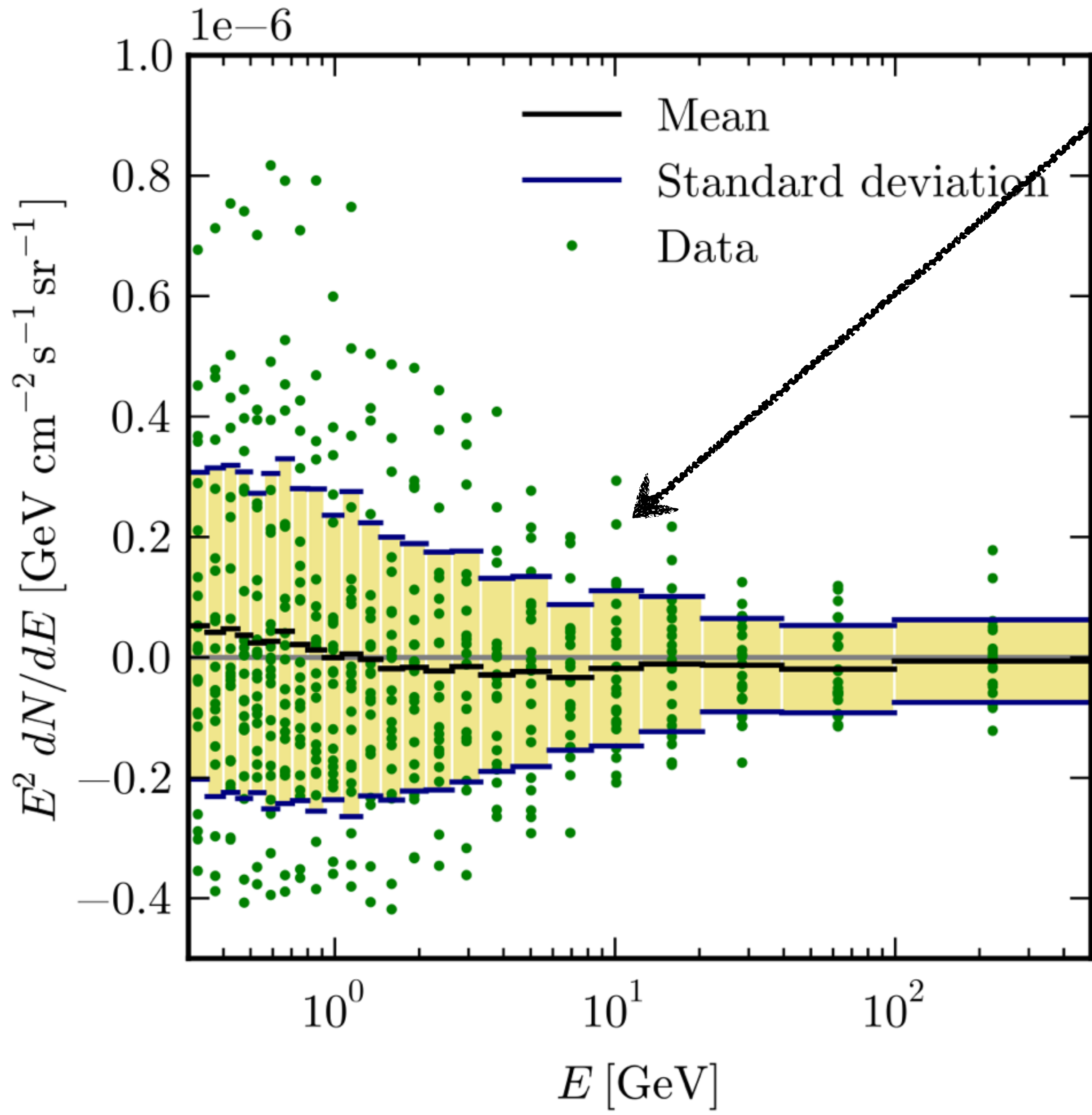


6. GeV excess template (free)

Empirical model systematics



The covariance matrix



Flux absorbed by excess template in 22 test regions along the Galactic disk.

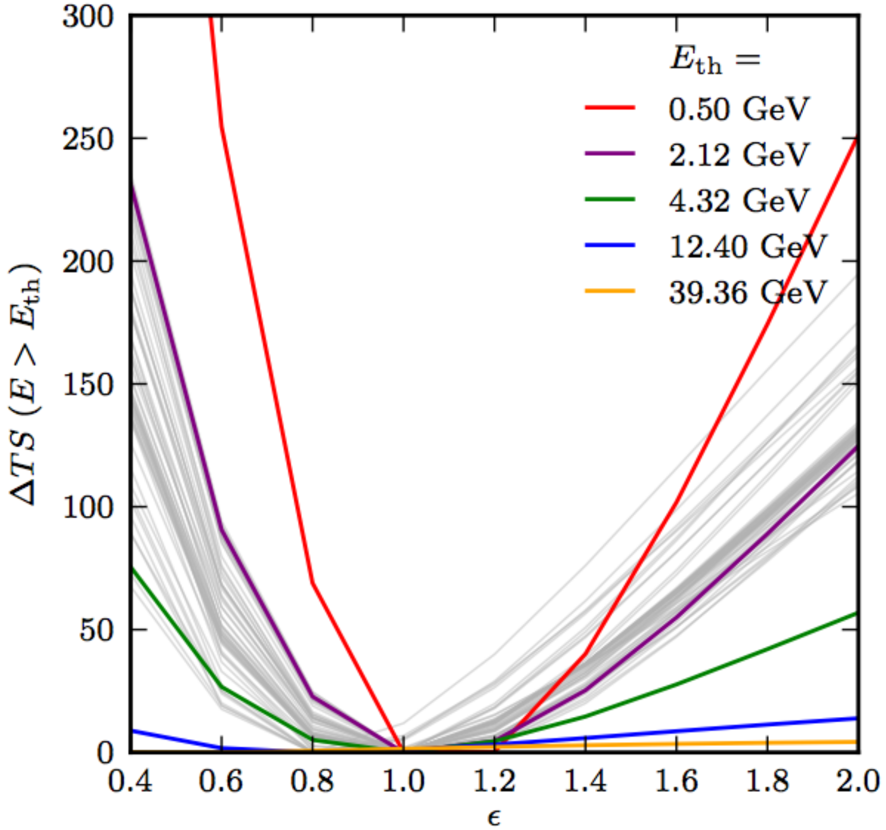
Standard deviation is a first estimate for how inaccuracies in the foreground modelling affect the excess template.

Observed variations along the disk are correlated in energy.
$\longrightarrow$ Define the **covariance matrix:**

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

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

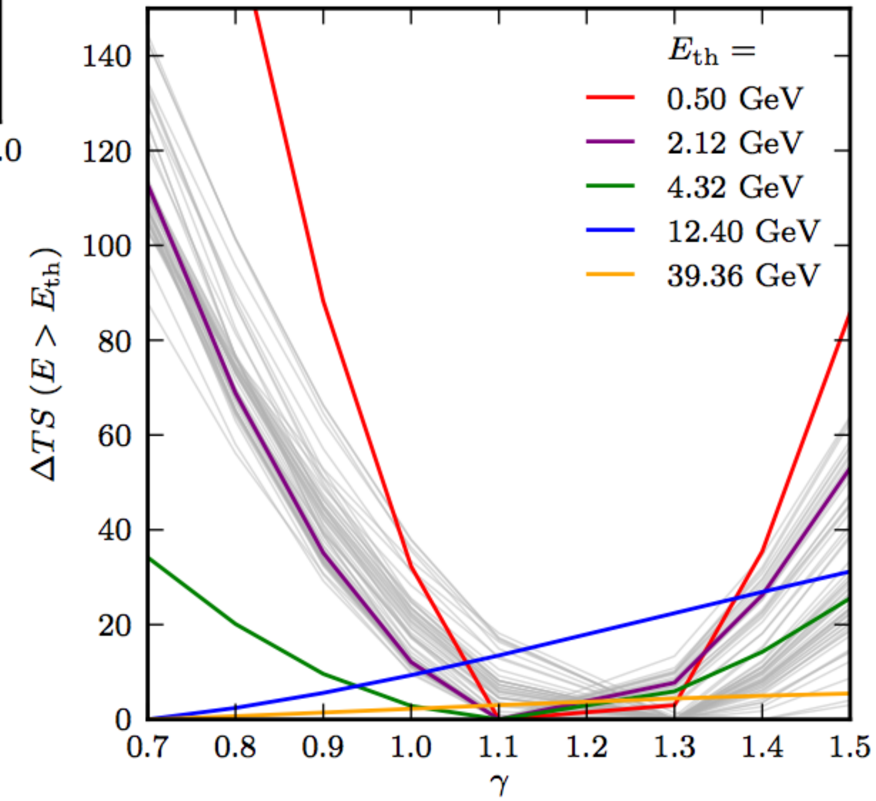
About the morphology



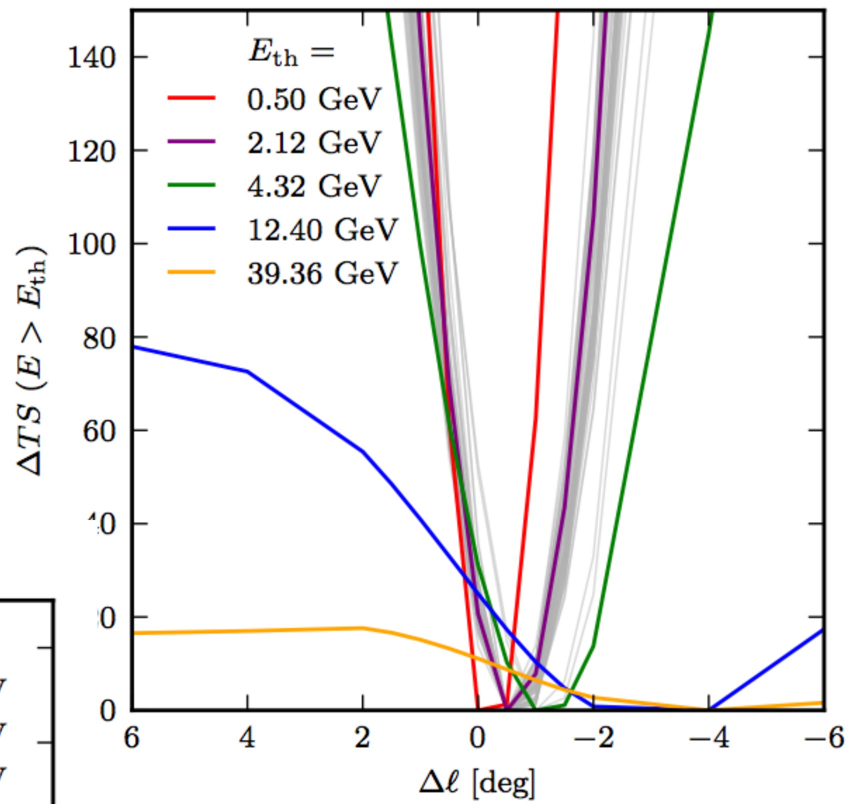
Testing the elongation perpendicularly (epsilon<1) and along (epsilon>1) the disk.

$$\rho(r) = \rho_0 \frac{(r/r_s)^{-\gamma}}{(1+r/r_s)^{3-\gamma}}$$

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



Testing the slope of the GCE template distribution.

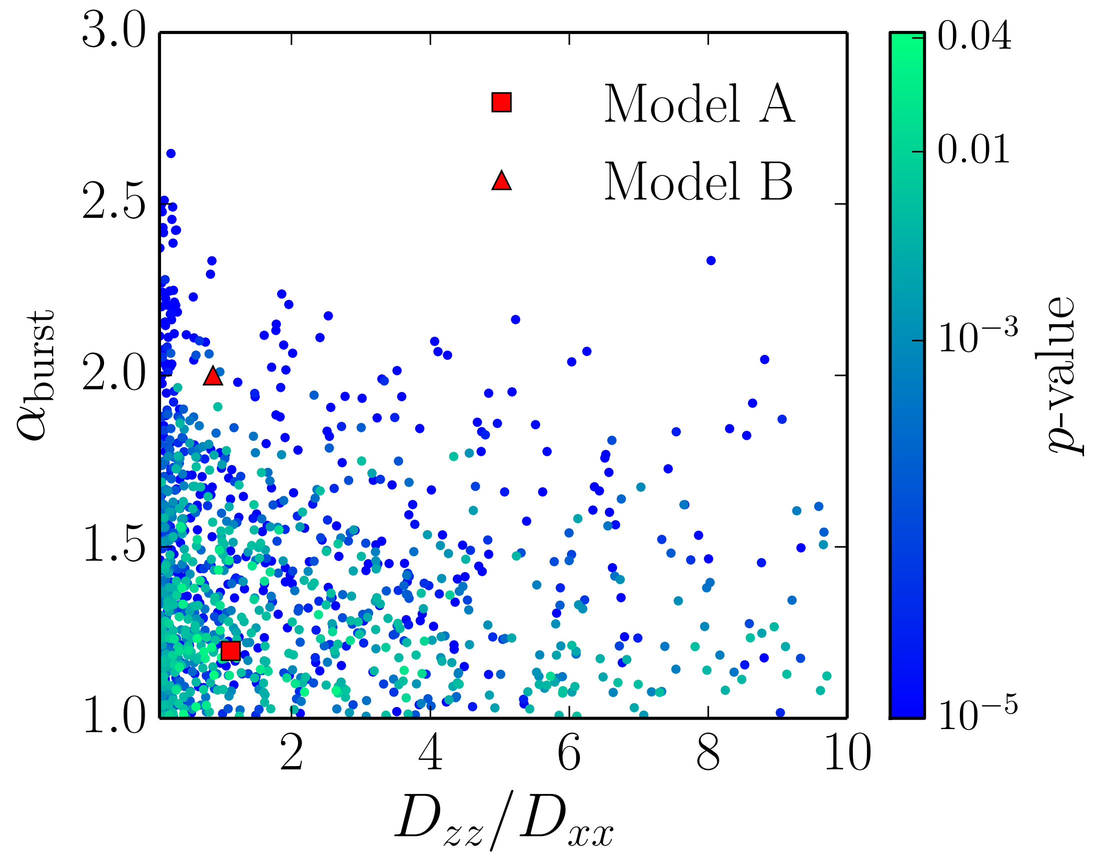


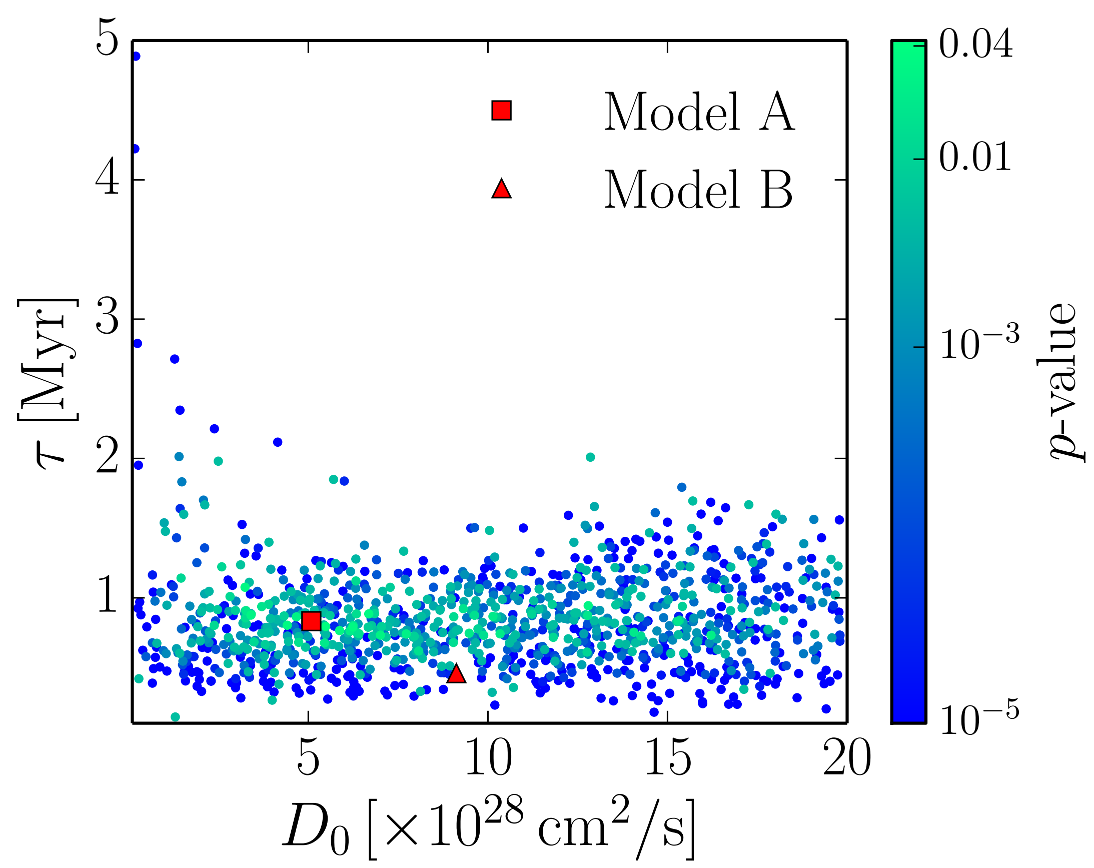
Testing where (in longitude) the excess is centered.

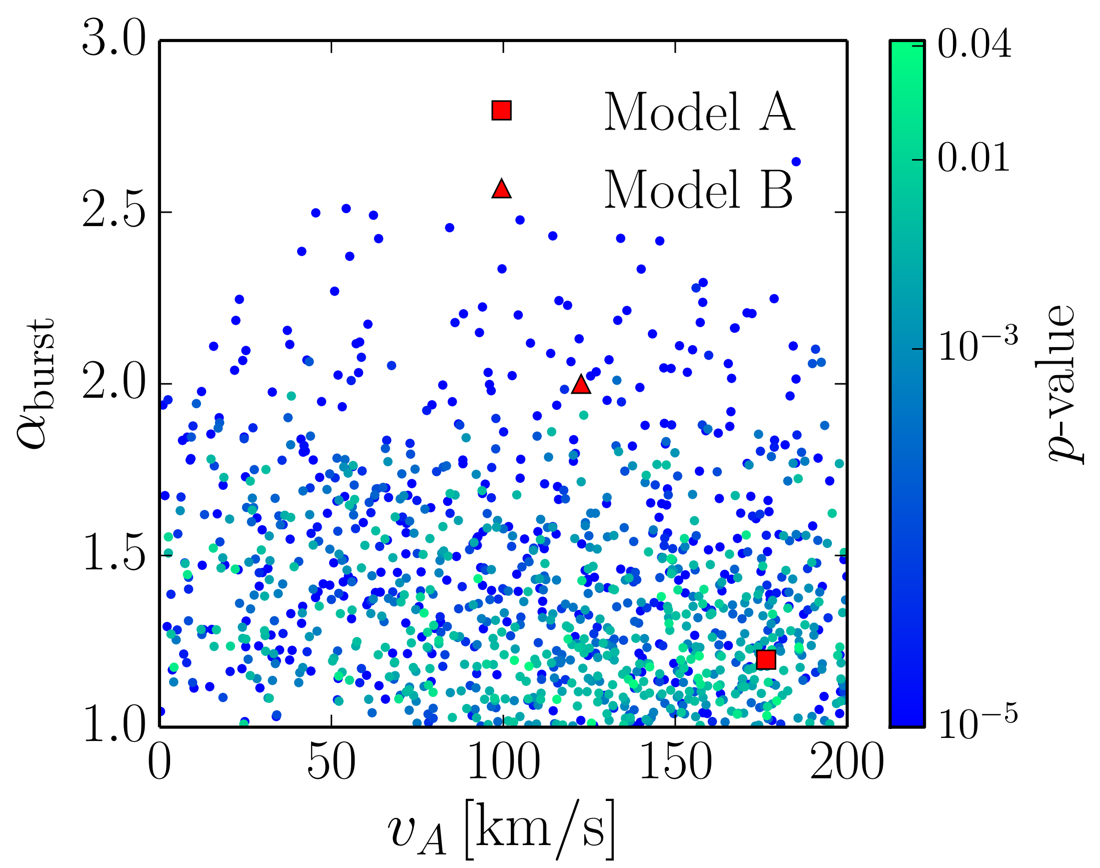
$$\cos(\psi) = \cos(b)\cos(l - l_0)$$

One leptonic burst?

Parameter	Units	Range	Prior
α		1–3	lin
δ		0.1–1.0	lin
D_0	$10^{28}\,\mathrm{cm^2/s}$	0.1–20	lin
D_{zz}/D_{xx}		0.1–10	log
v_A	km/s	0–200	lin
τ	Myr	0.1–5	lin

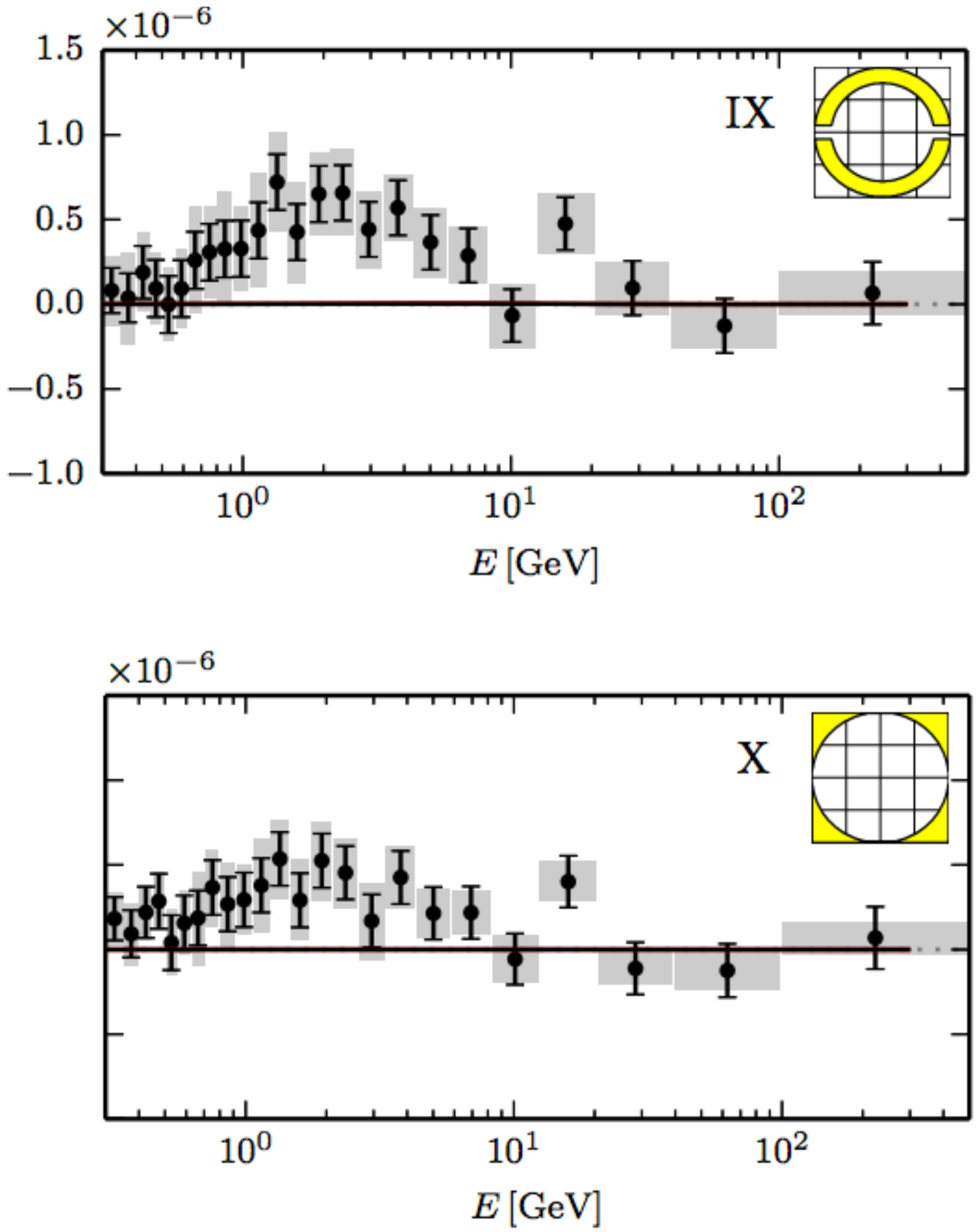




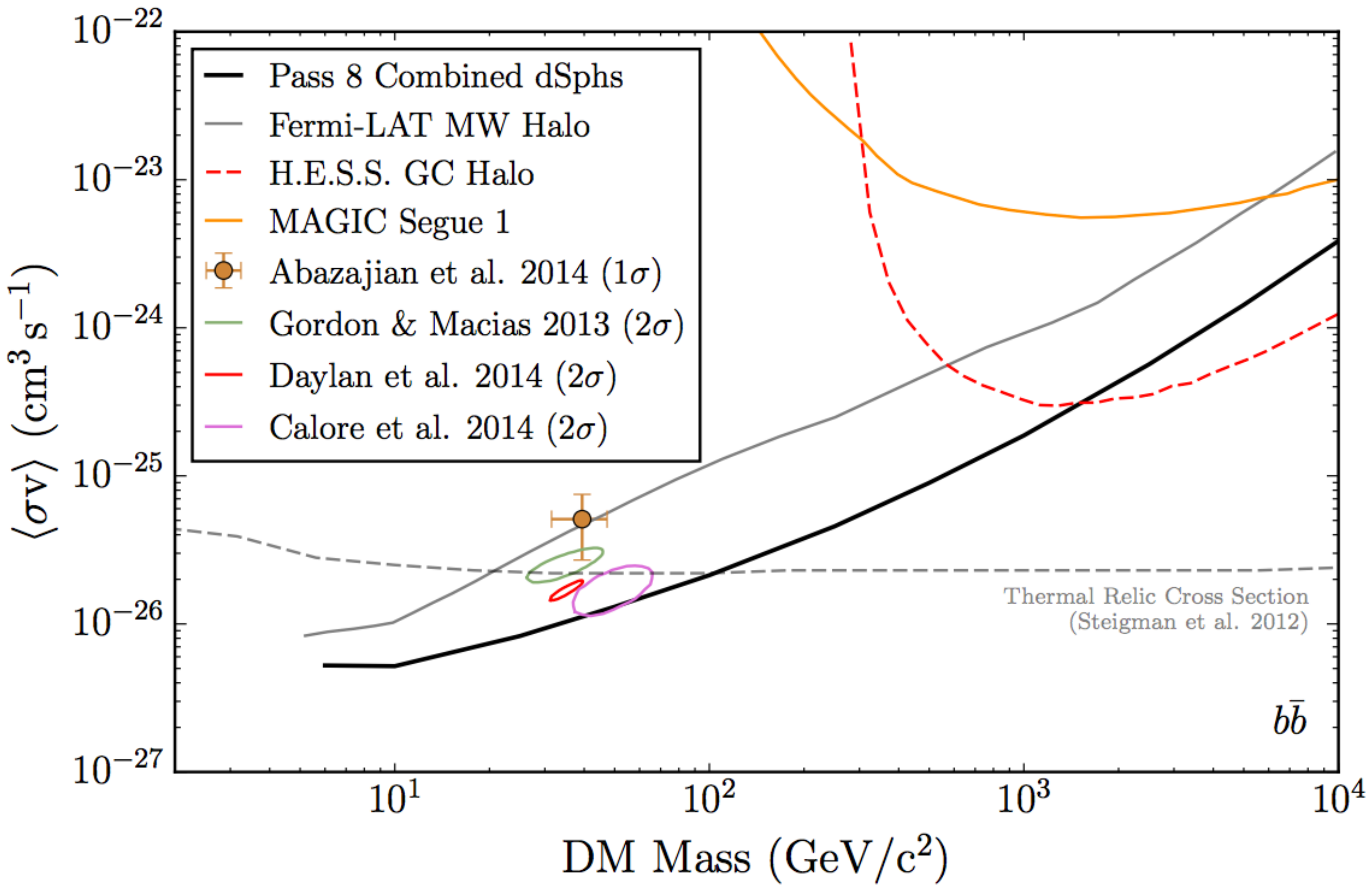


One leptonic burst?

Parameter	Model A	Model B
α_1	1.2	2.0
α_2	NA	NA
$E_{cut,1}$	1 TeV	1 TeV
$E_{cut,2}$	NA	NA
τ_1 (Myr)	0.83	0.46
τ_2 (Myr)	NA	NA
N_1 (10^{51} erg)	2.89	9.87
N_2 (10^{51} erg)	NA	NA
δ	0.20	0.23
D_0 (10^{28} cm^2/s)	5.08	9.12
D_{zz}/D_{xx}	1.12	0.87
v_A (km/s)	176	122
B_0 (μG)	11.5	11.5
r_c (kpc)	10.0	10.0
z_c (kpc)	2.0	2.0
dv_c/dz (km/s/kpc)	0.0	0.0
ISRF	1.0, 1.0	1.0, 1.0
χ^2 ($p-$value)	277 (0.04)	317 (0.0004)



Consistency with dSph: present and future



Consistency with dSph: present and future