GRAPPA
GRavitation AstroParticle Physics Amsterdam

UNIVERSITY OF AMSTERDAM

erc

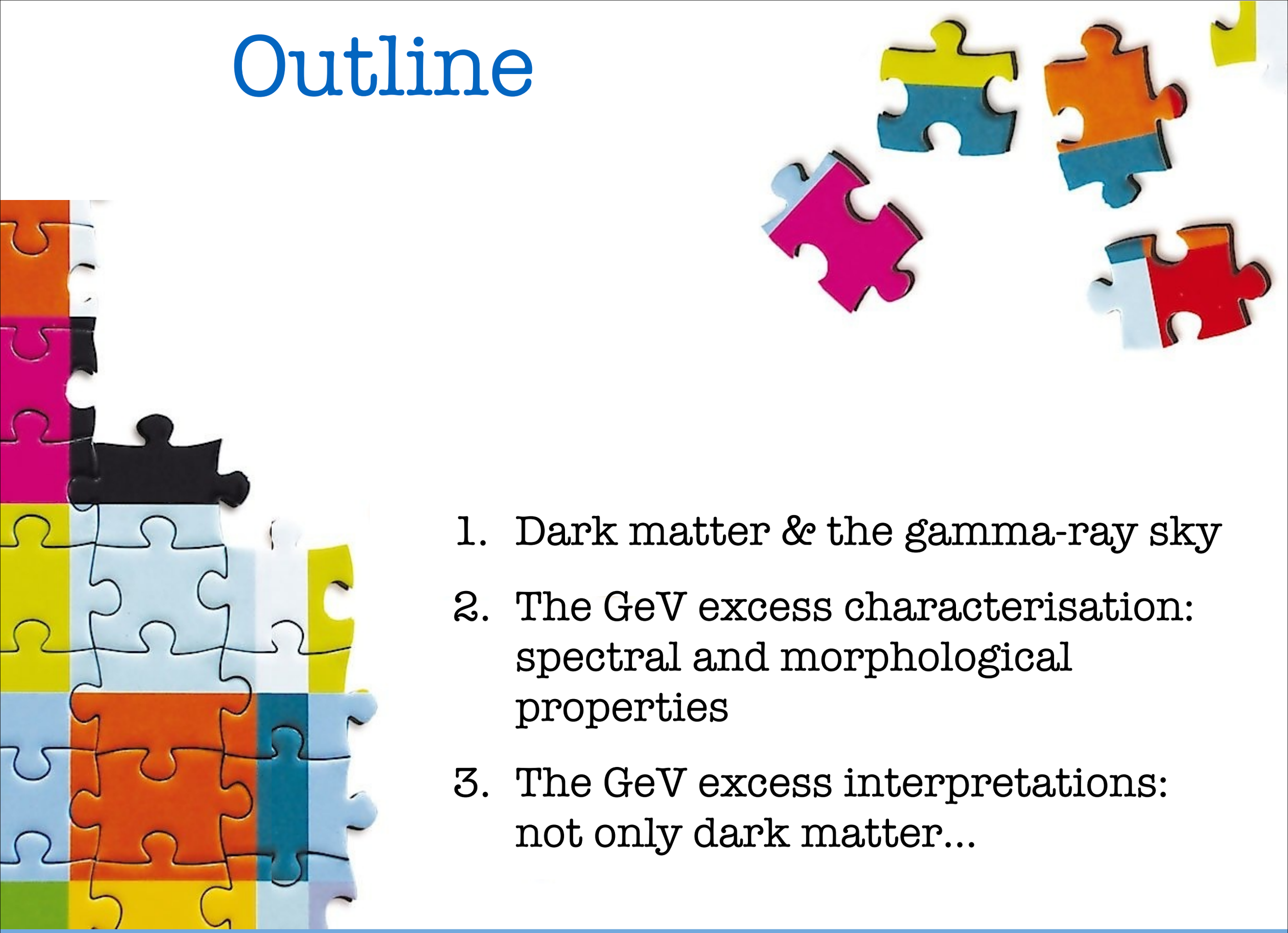
Francesca Calore

The Fermi GeV excess: characterisation and interpretations

ETDM2015, Mainz
26th March 2015

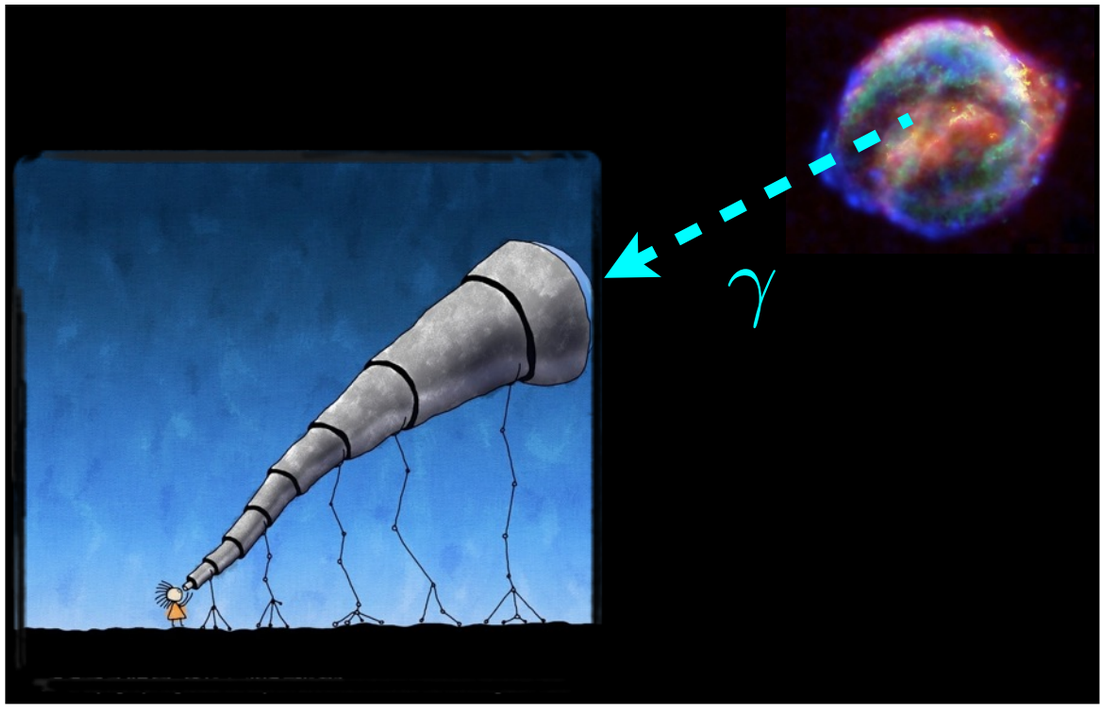
Based on:
F. Calore, I. Cholis & C. Weniger, arXiv:1409.0042
F. Calore, I. Cholis, C. McCabe & C. Weniger, arXiv:1411.4647
F. Calore, I. Cholis, C. Evoli, D. Hooper, T. Linden & C. Weniger, In prep.

Outline



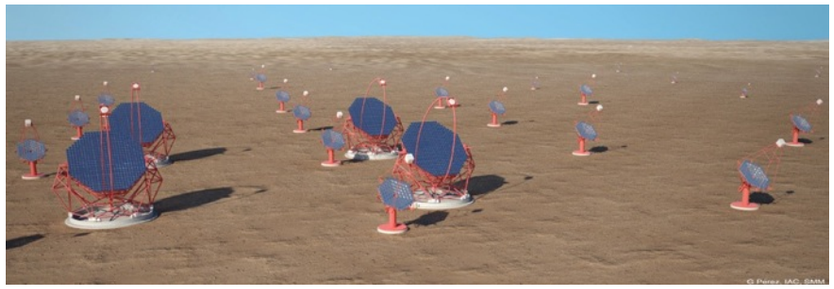
1. Dark matter & the gamma-ray sky
2. The GeV excess characterisation: spectral and morphological properties
3. The GeV excess interpretations: not only dark matter...

Gamma rays from the sky



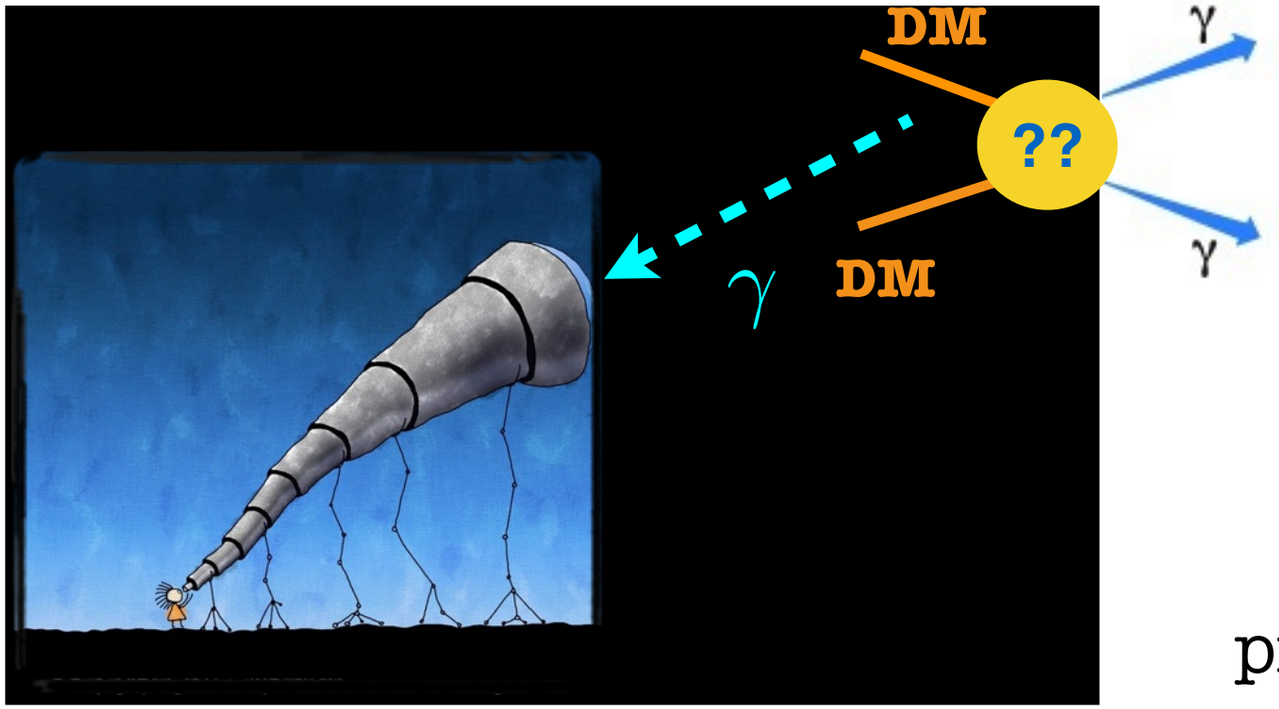
Ground- and space-based telescopes represent interplaying and complementary instruments.

Fermi-LAT
AGILE
AMS-02
Gamma-400
...



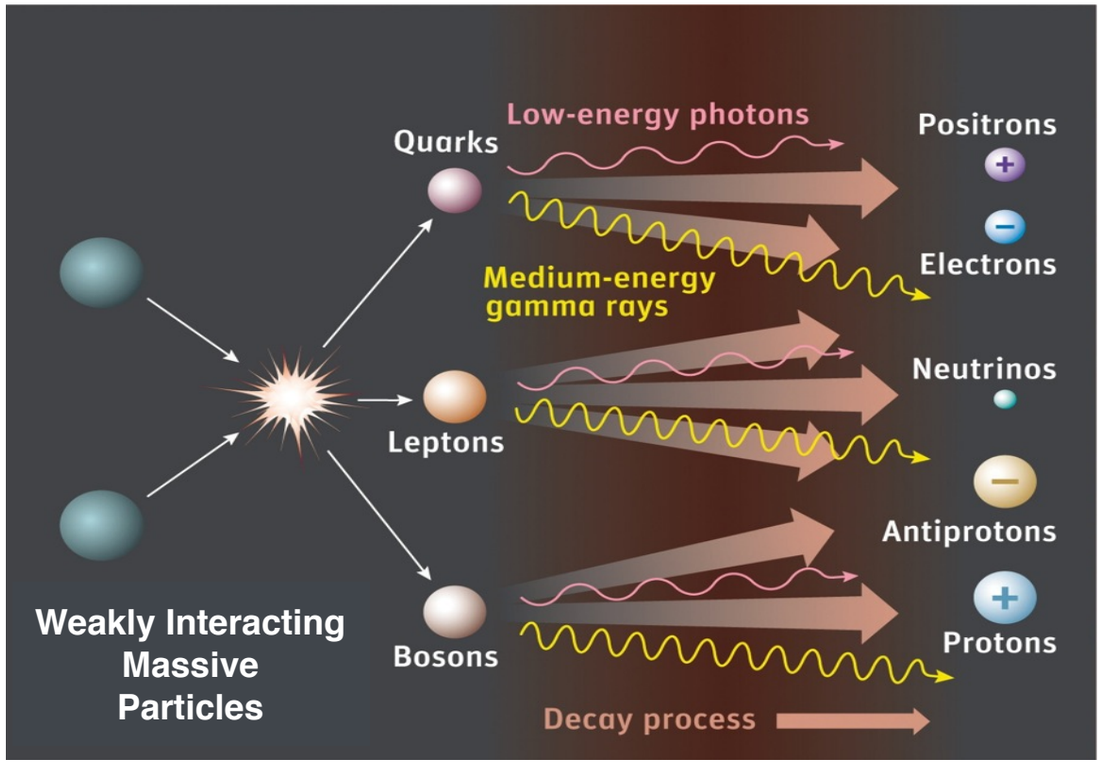
HESS
MAGIC
VERITAS
CTA
...

Gamma rays from the sky



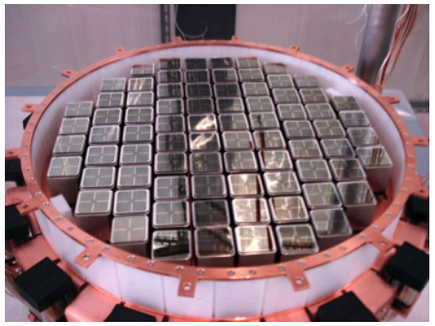
Gamma rays are produced also by DM annihilation in the halo of our Galaxy and in external galaxies.

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

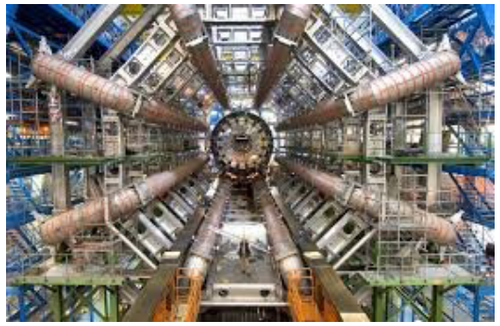


Other complementary probes:

Direct detection searches



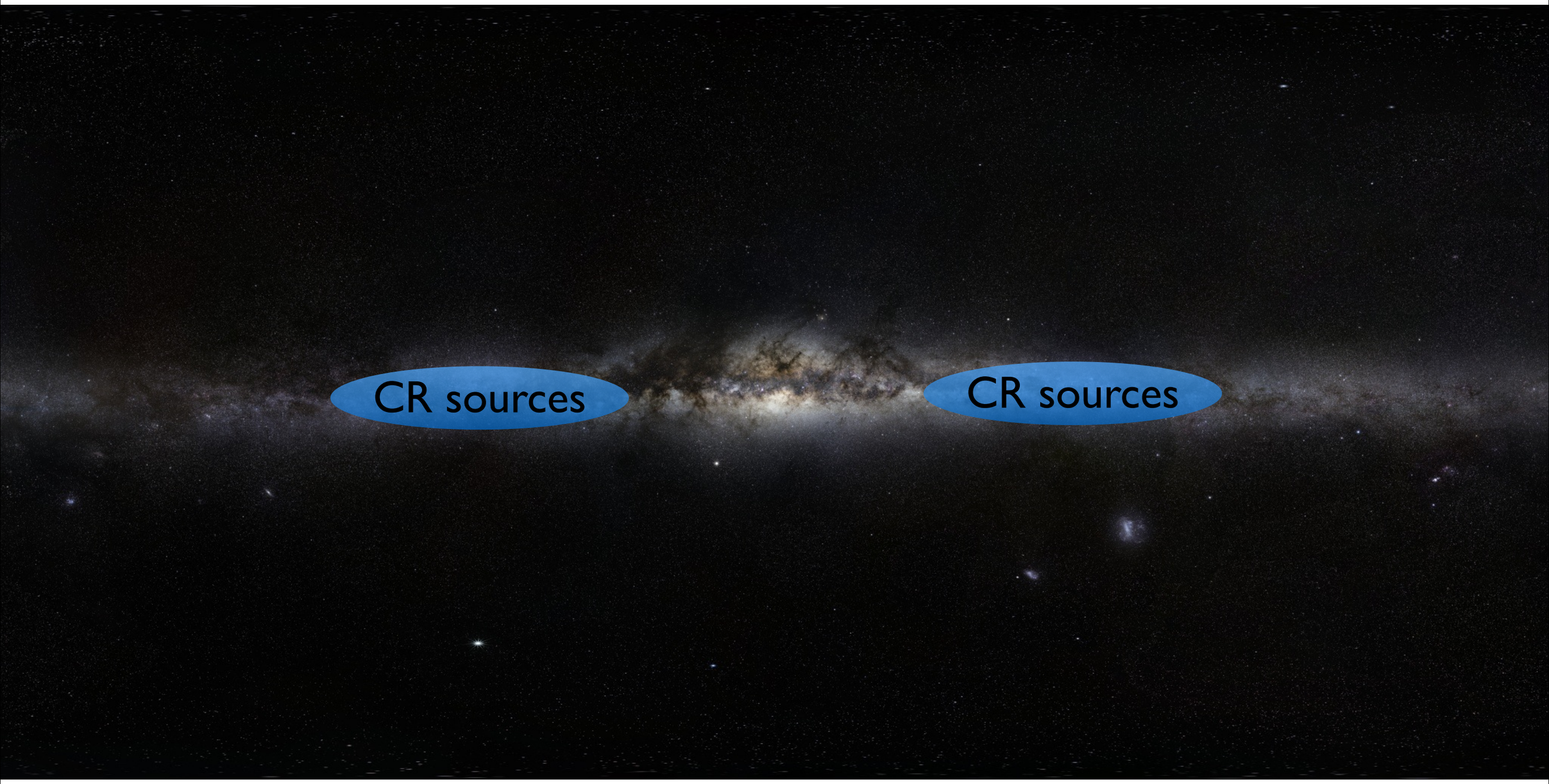
Collider searches



Gamma rays from our Galaxy

... the **standard** picture of cosmic-ray interactions in the Milky Way

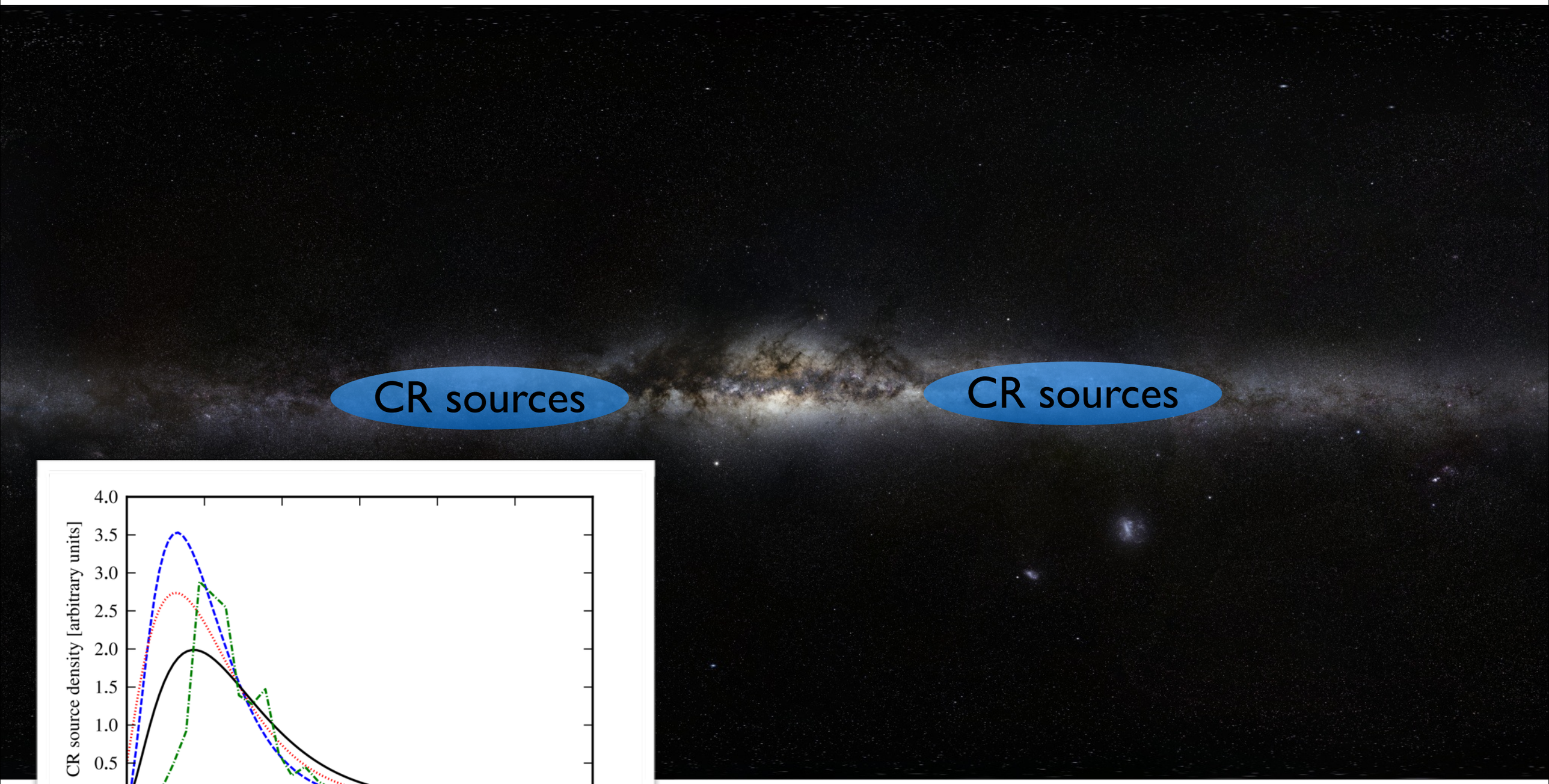
Gamma rays from our Galaxy

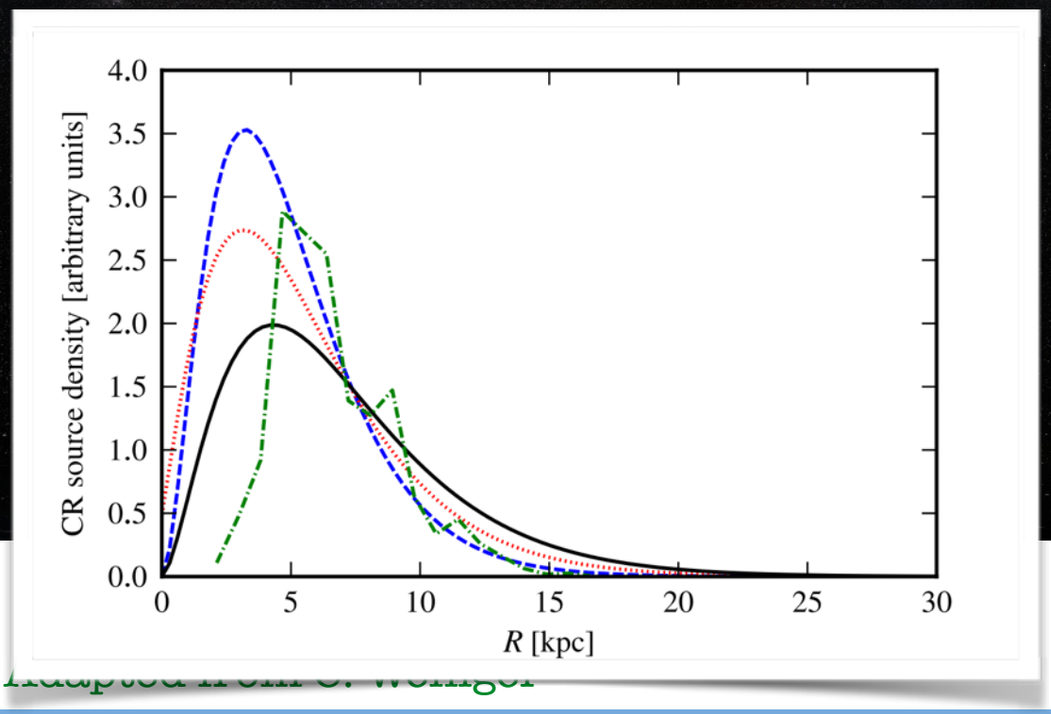


*not in scale

Adapted from C. Weniger

Gamma rays from our Galaxy





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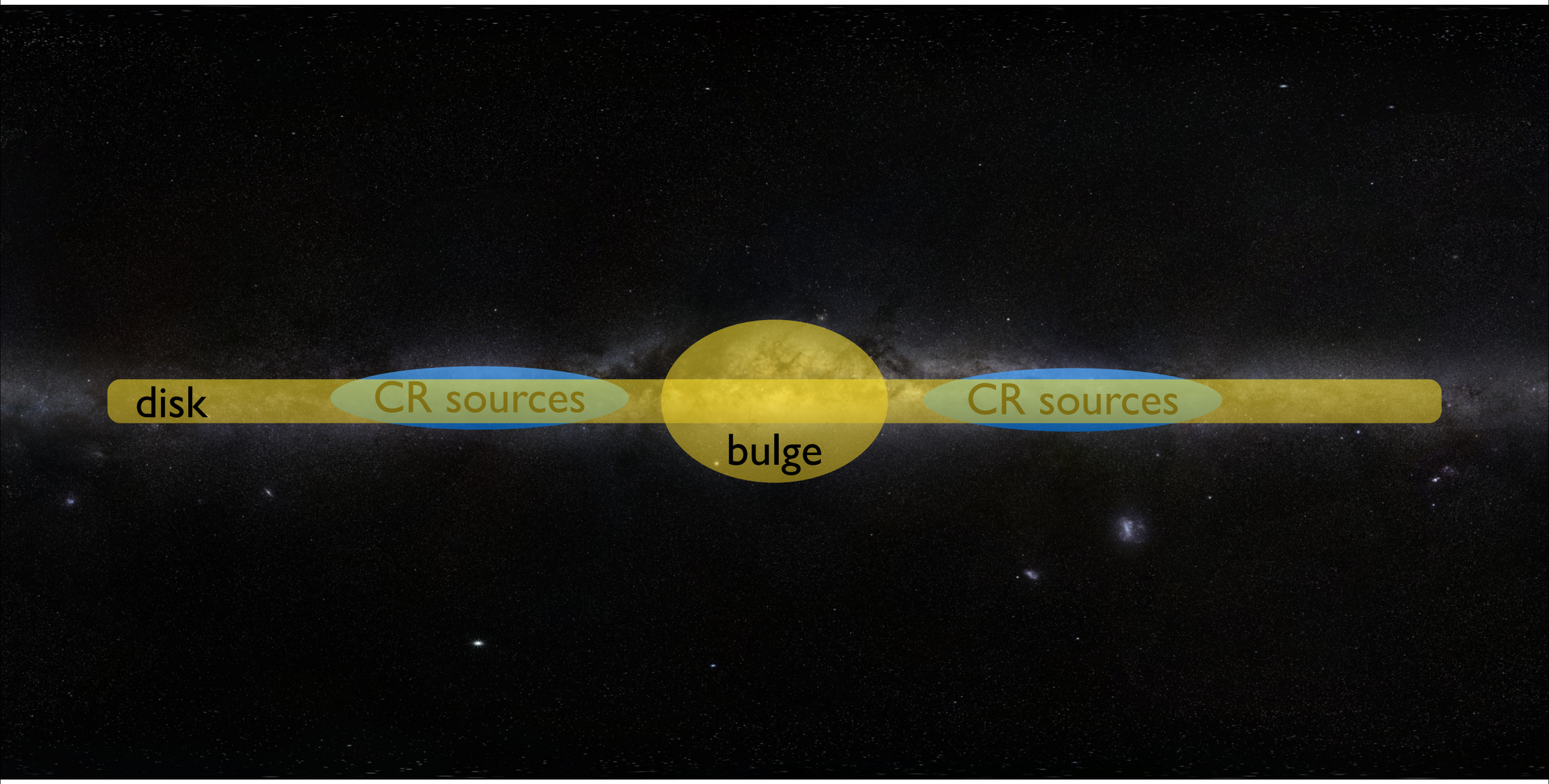
Gamma rays from our Galaxy



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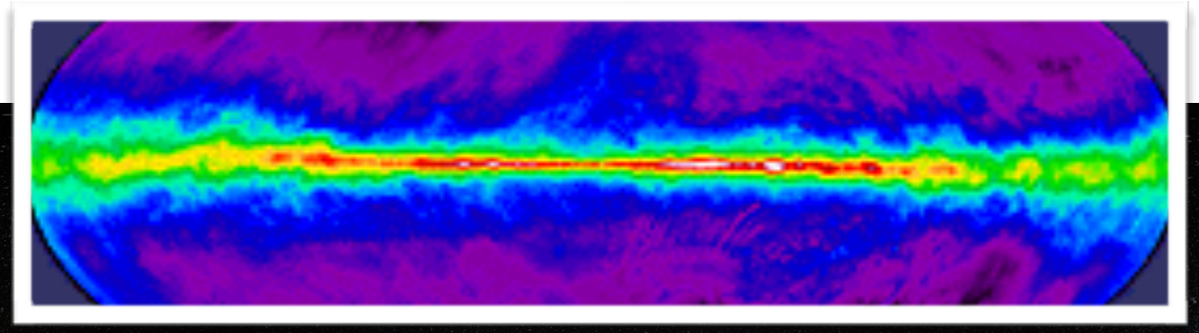
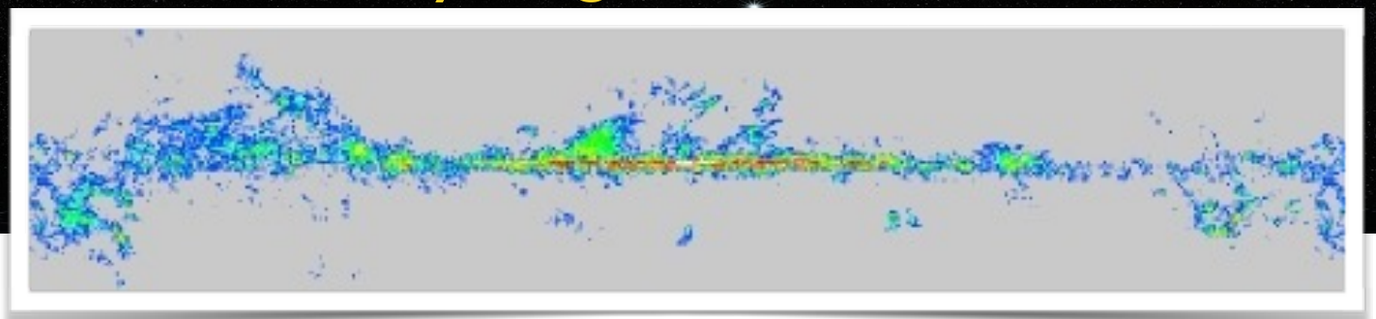


atomic hydrogen

molecular hydrogen



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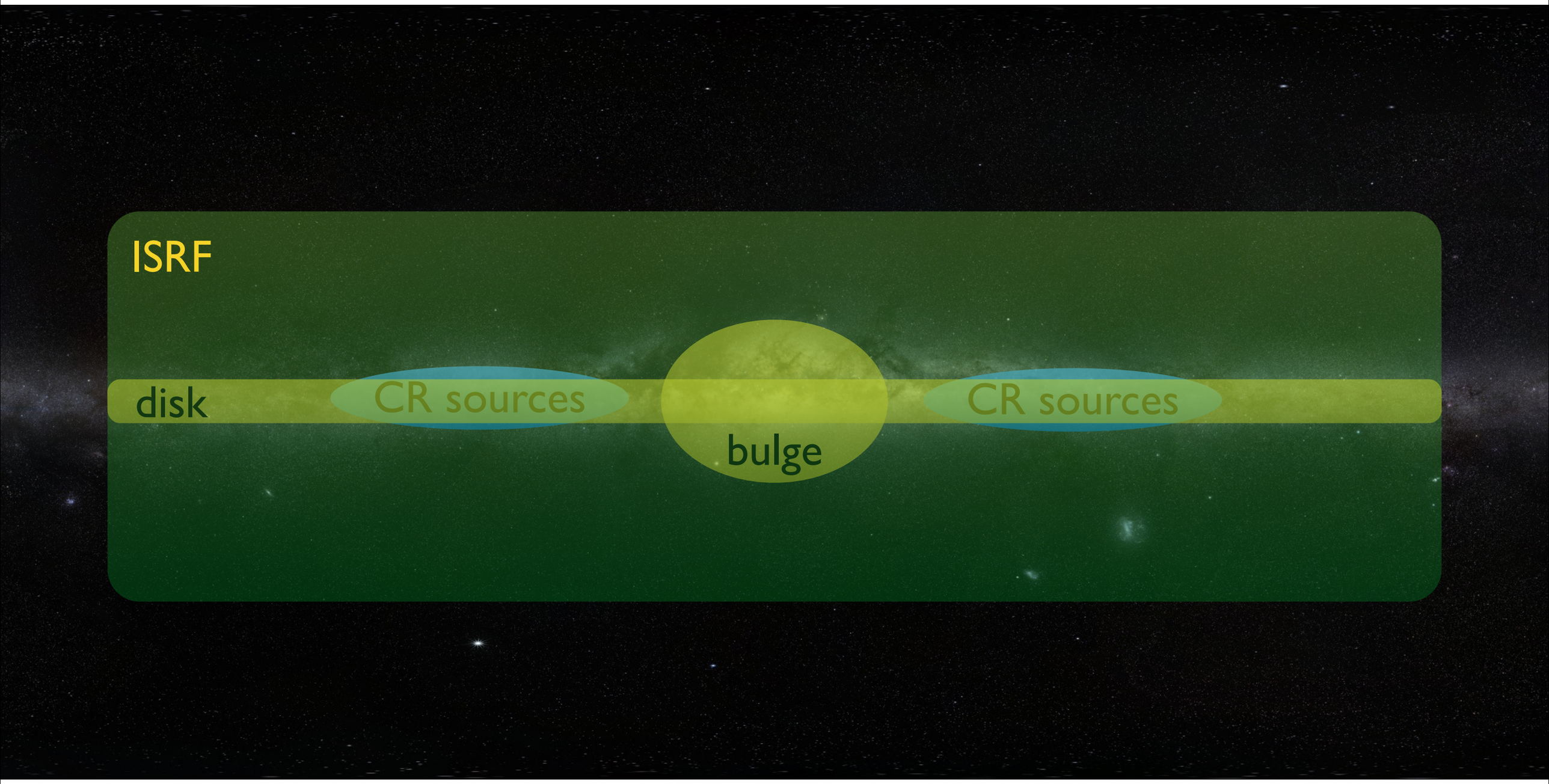
Gamma rays from our Galaxy



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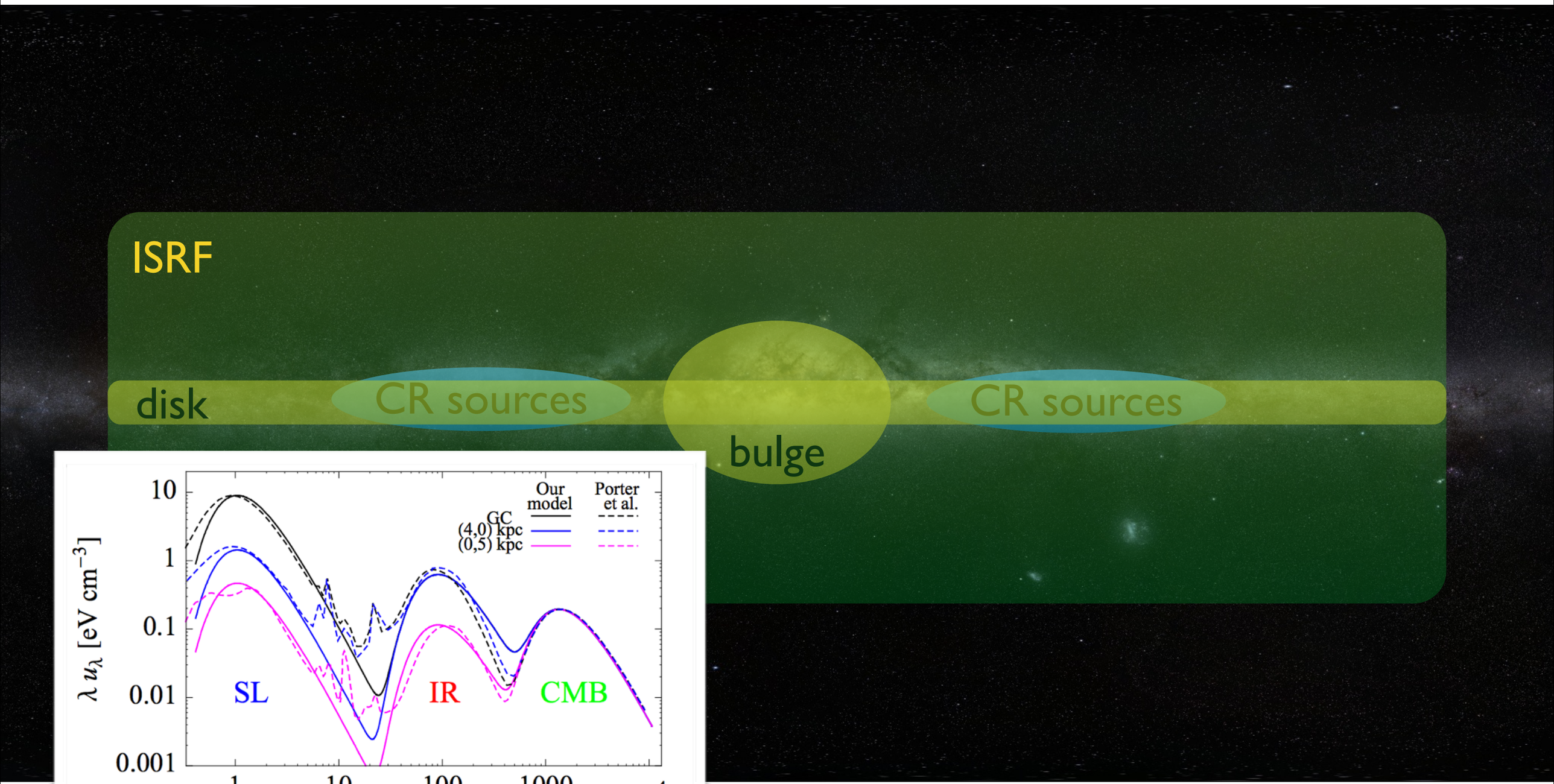

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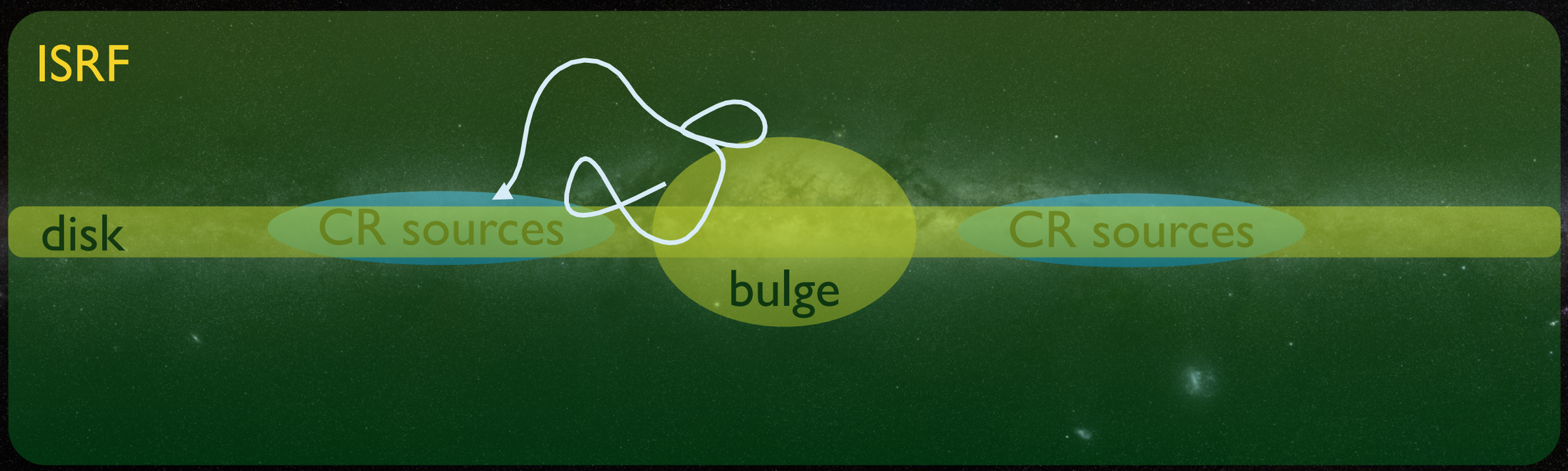

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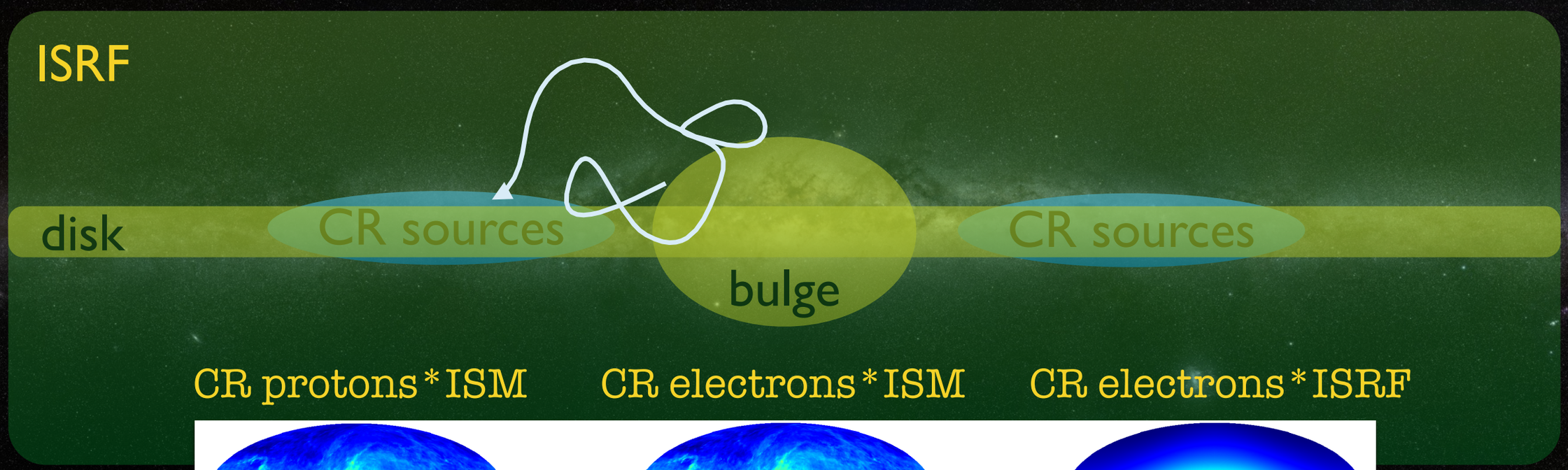
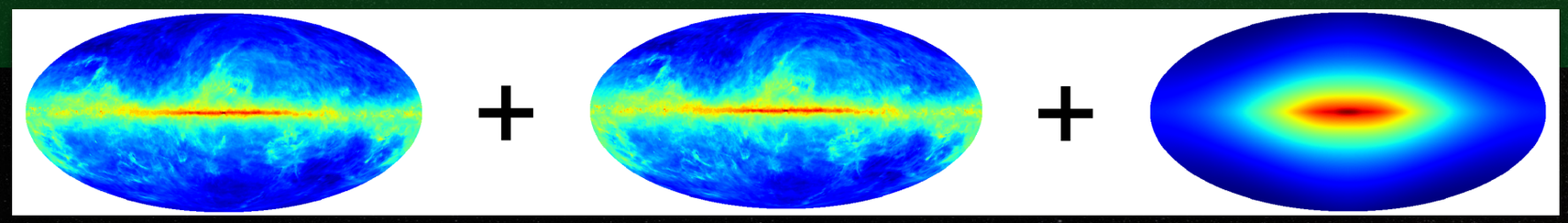


CR protons*ISM + CR electrons*ISM + CR electrons*ISRF



Pion Decay Bremsstrahlung Inverse Compton

*not in scale

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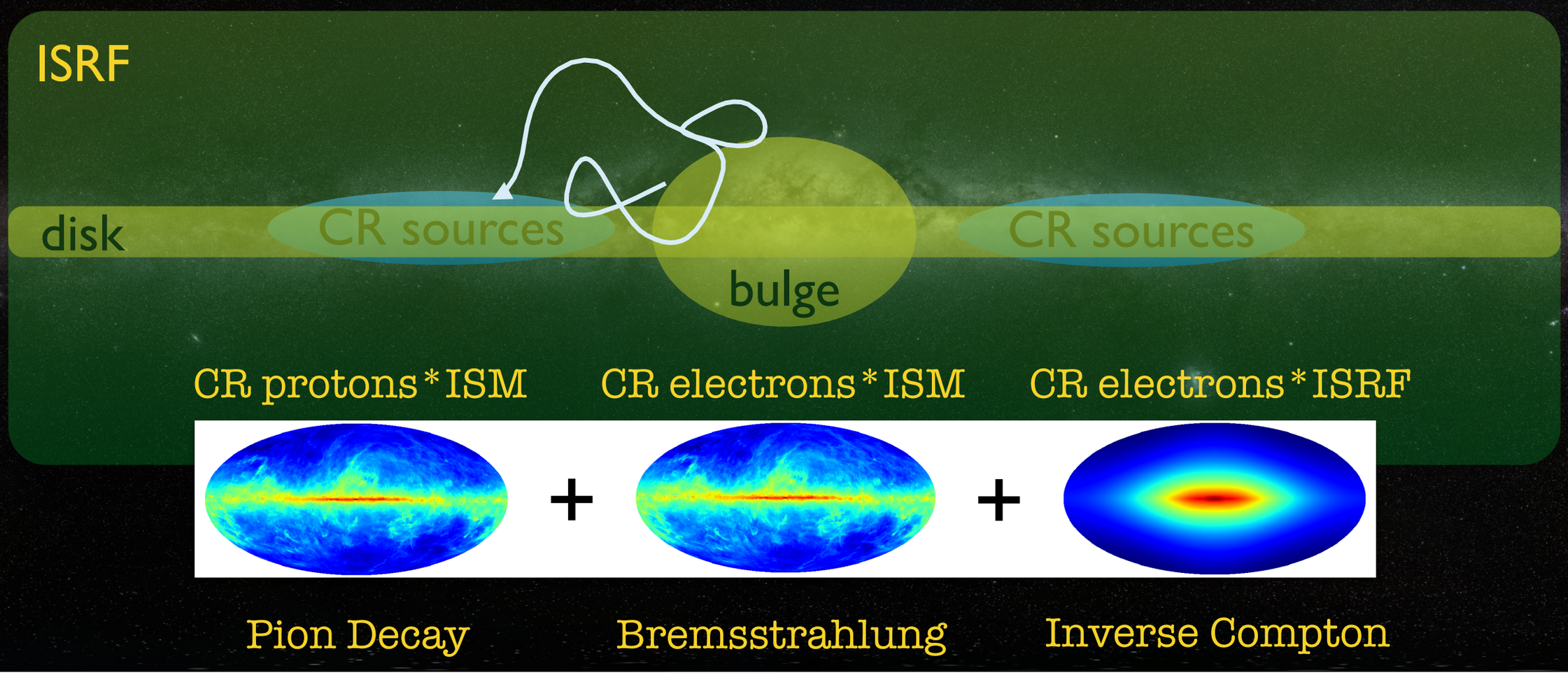
Gamma rays from our Galaxy

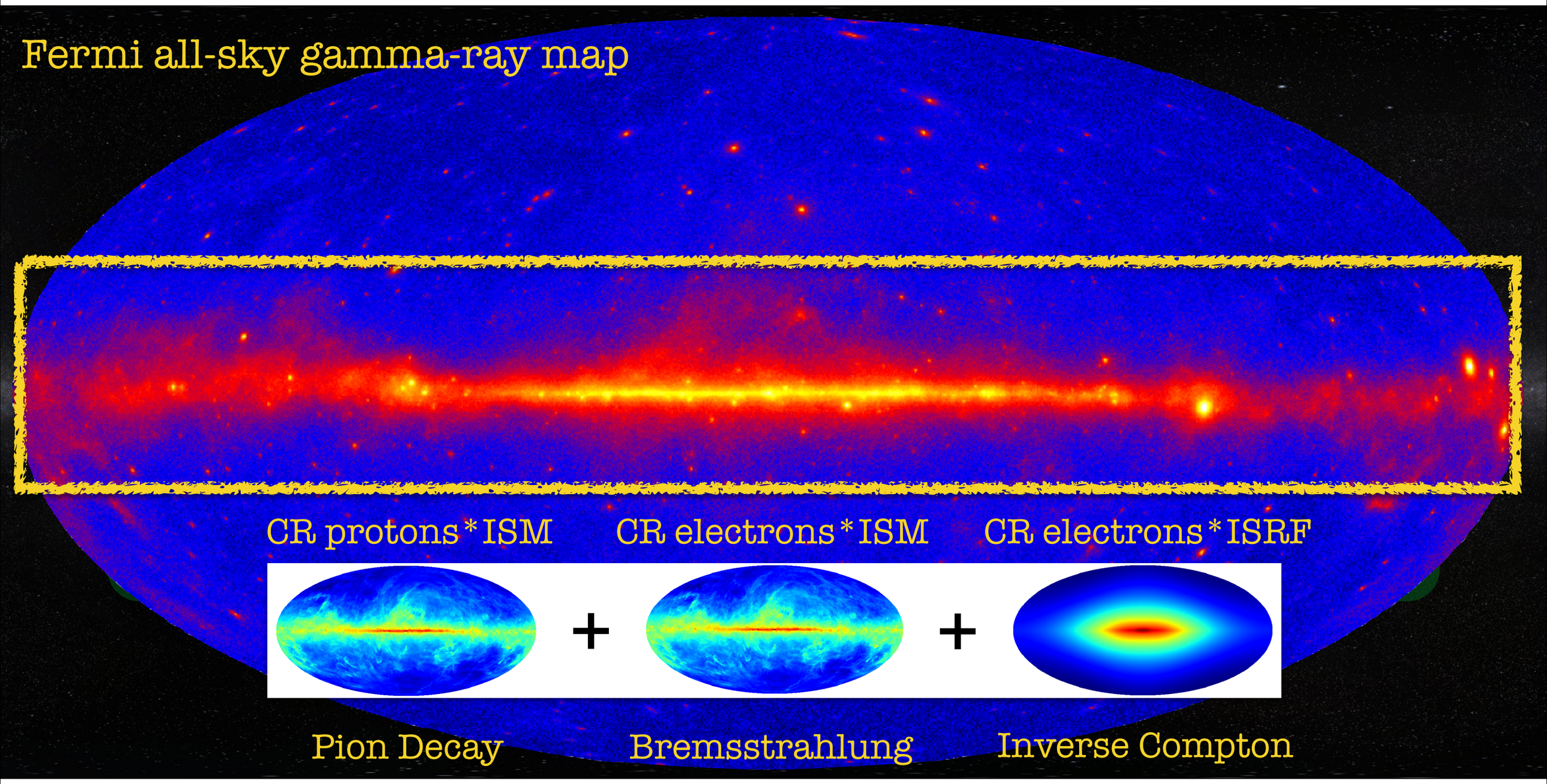


Galactic diffuse gamma-ray emission

*not in scale

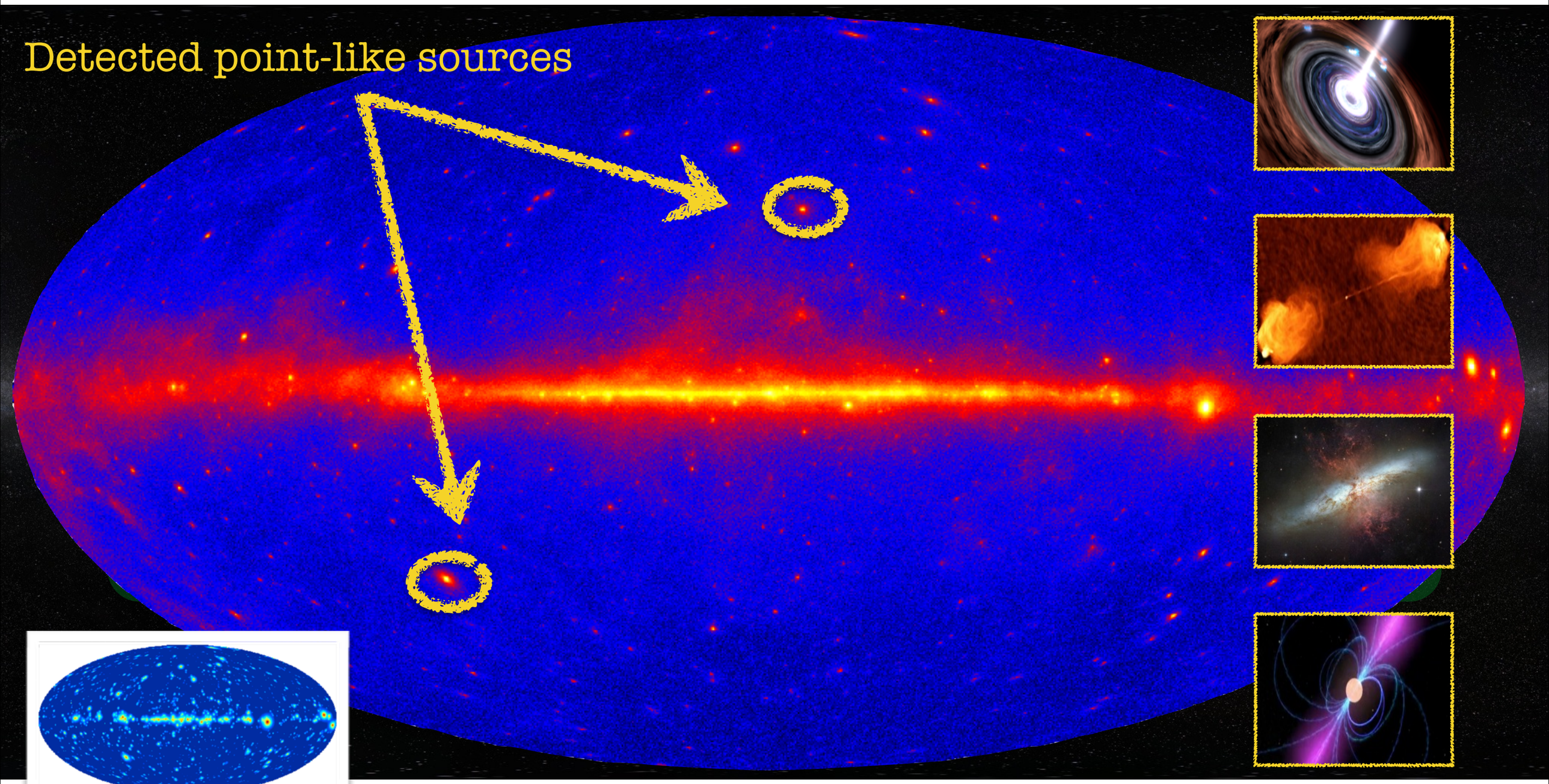
Adapted from C. Weniger

Gamma rays from our Galaxy



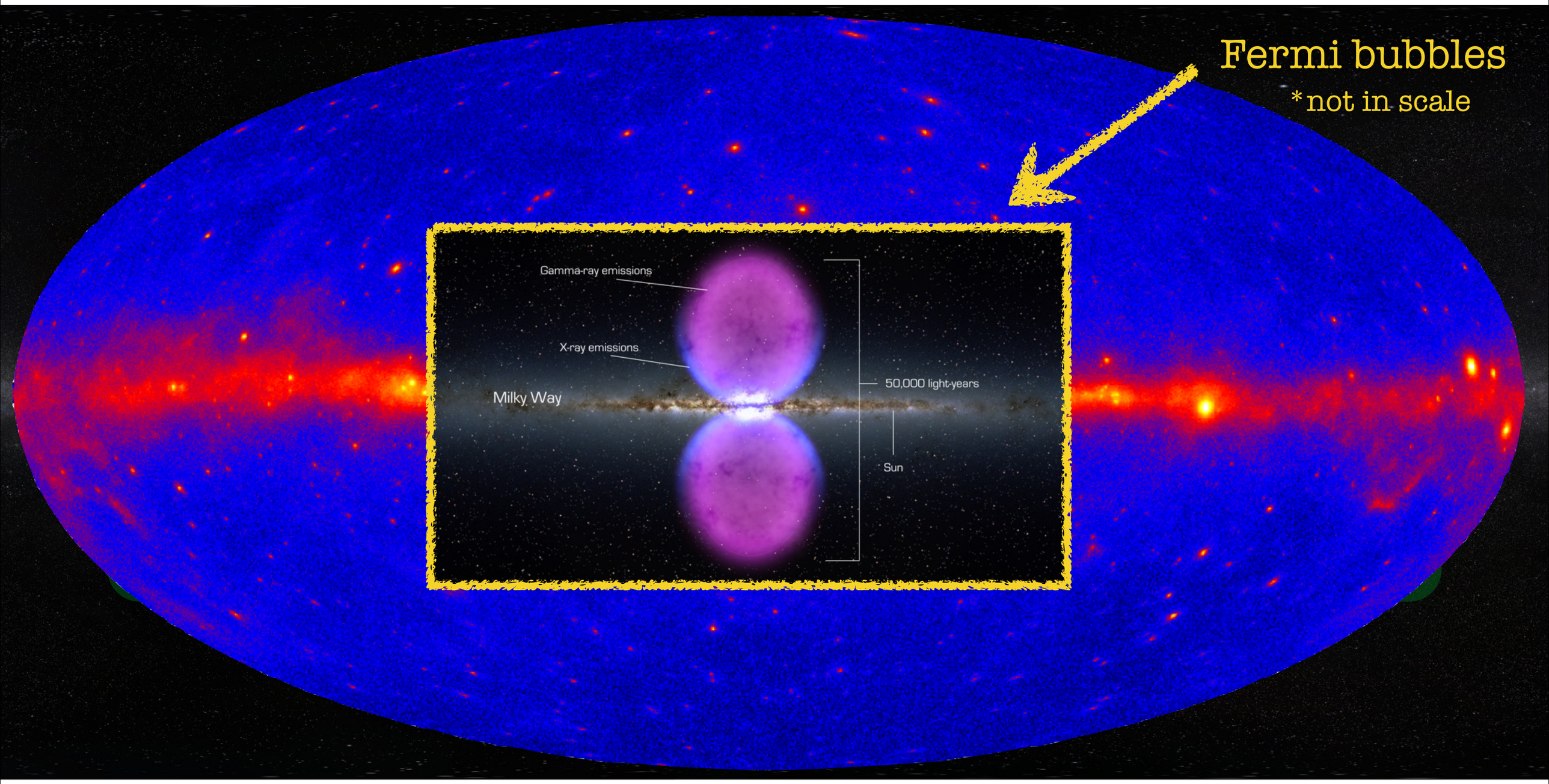
→ Galactic diffuse gamma-ray emission

Gamma rays from our Galaxy



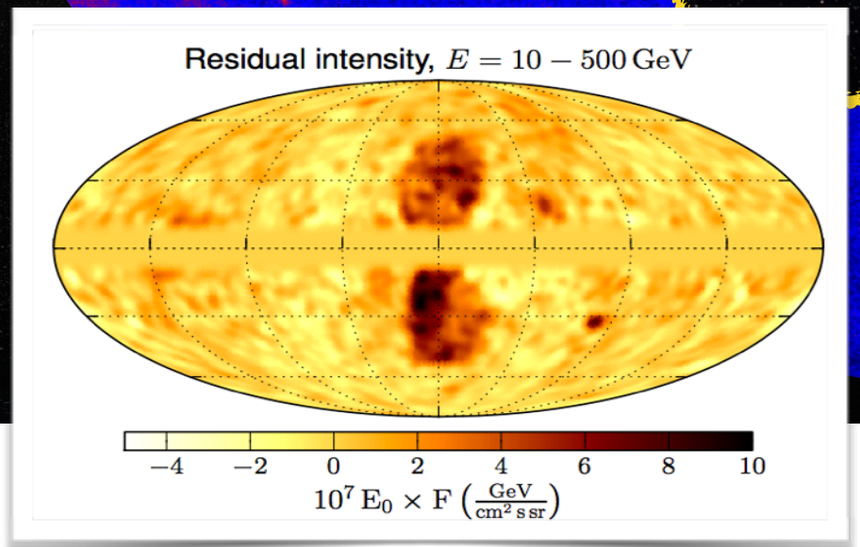
LAT 2-year Point Source Catalog @ http://fermi.gsfc.nasa.gov/ssc/data/access/lat/2yr_catalog/

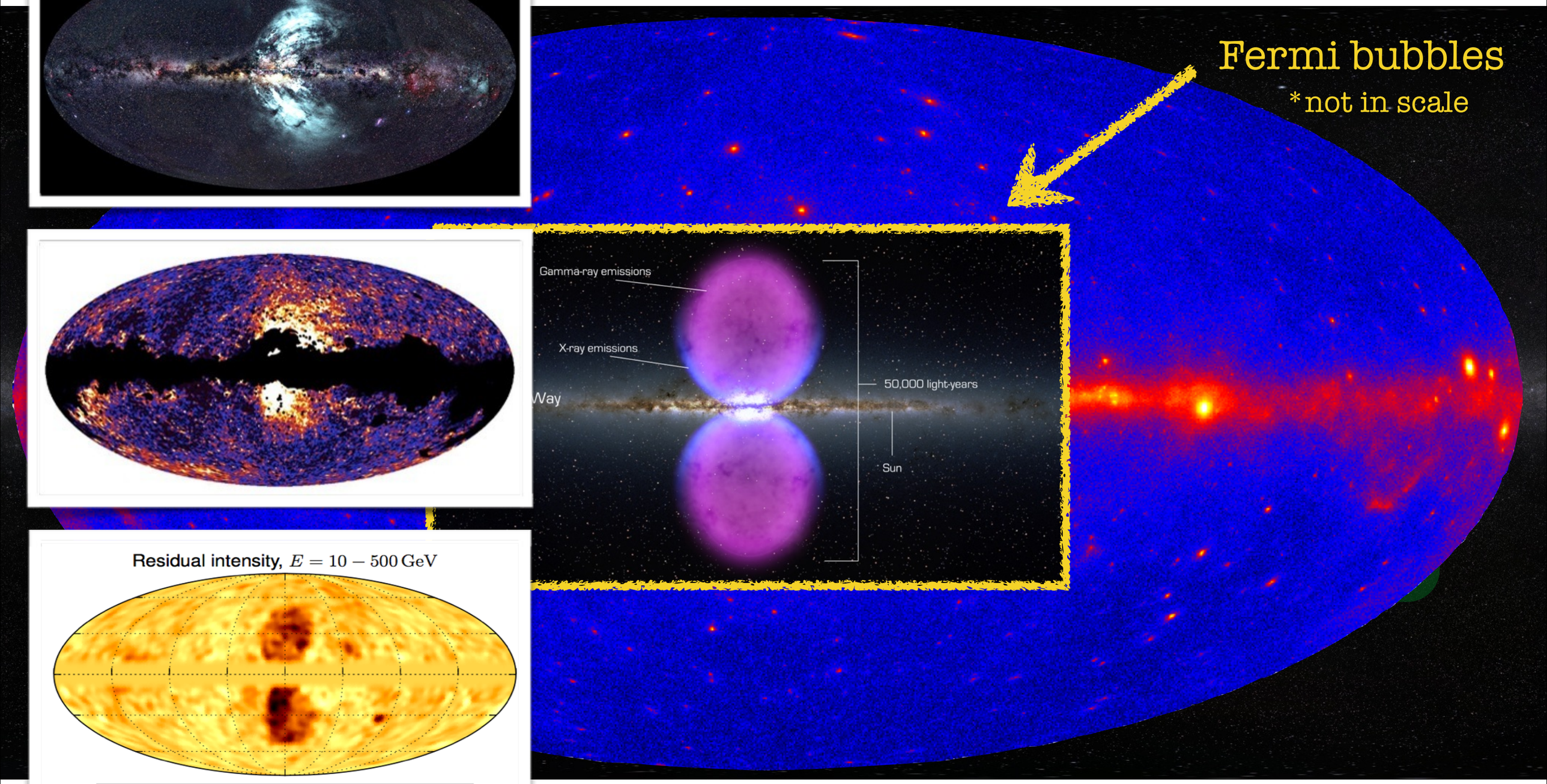
Gamma rays from our Galaxy



Su, Slatyer & Finkbeiner 2010;
Fermi-LAT Coll., arXiv:1407.7905

Gamma rays from our Galaxy





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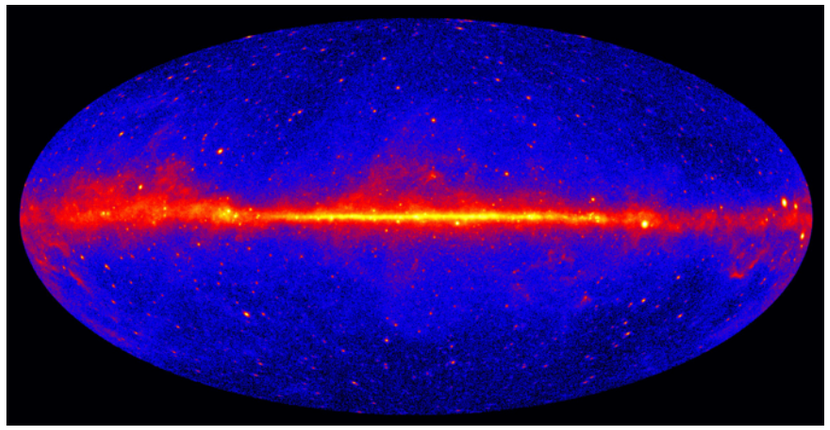
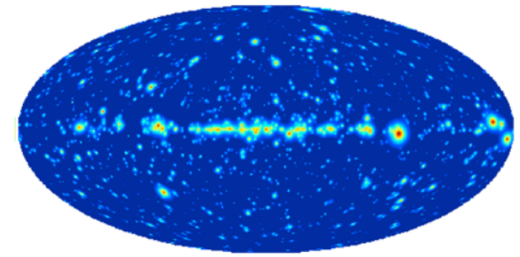
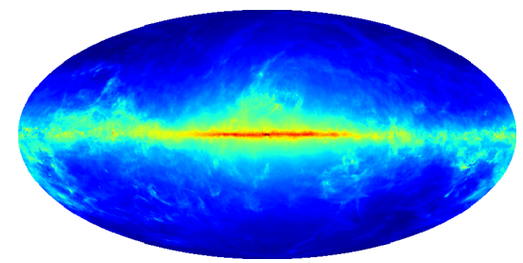
The Fermi-LAT gamma-ray sky



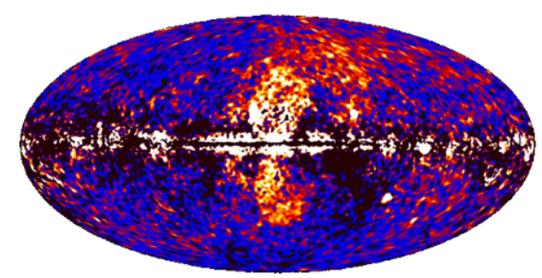
Foregrounds subtraction from raw Fermi-LAT data



Detected sources

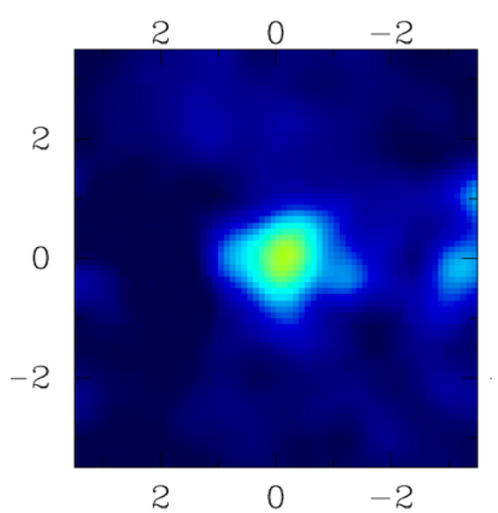


Galactic diffuse emission



Fermi bubbles

Residual emission?



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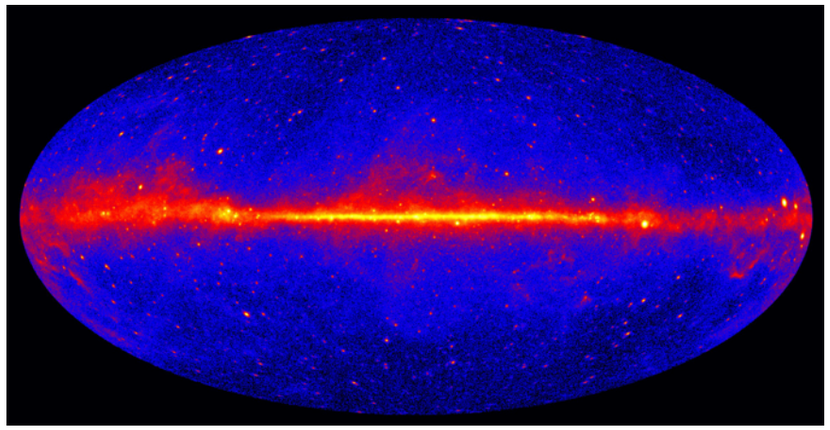

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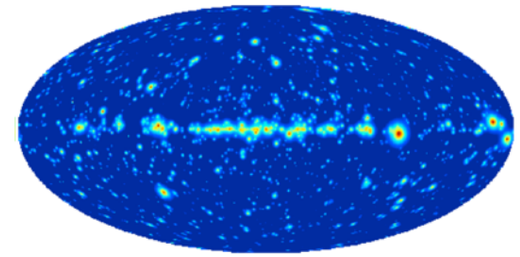

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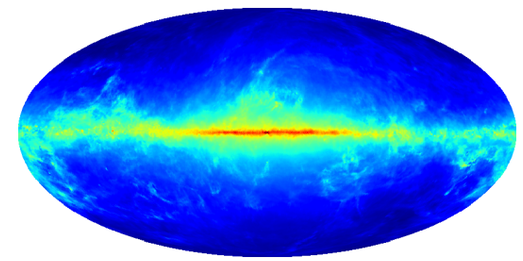

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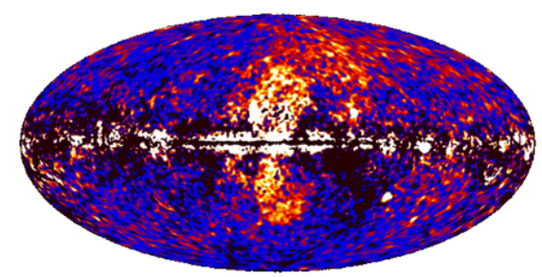

Fermi bubbles

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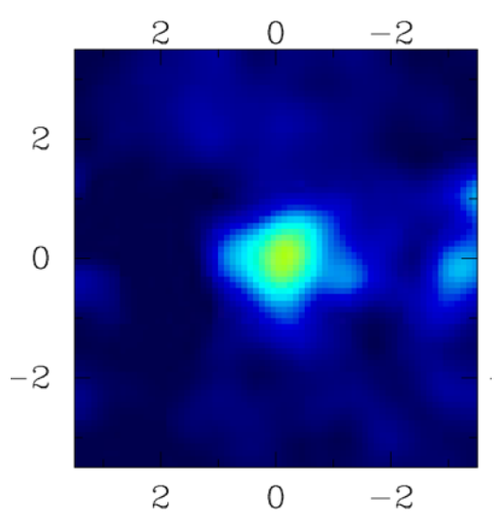
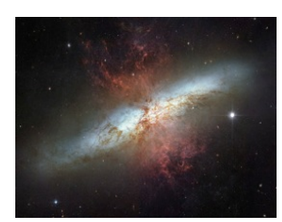
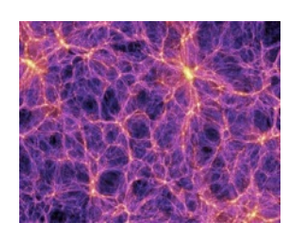


Astrophysical diffuse processes?

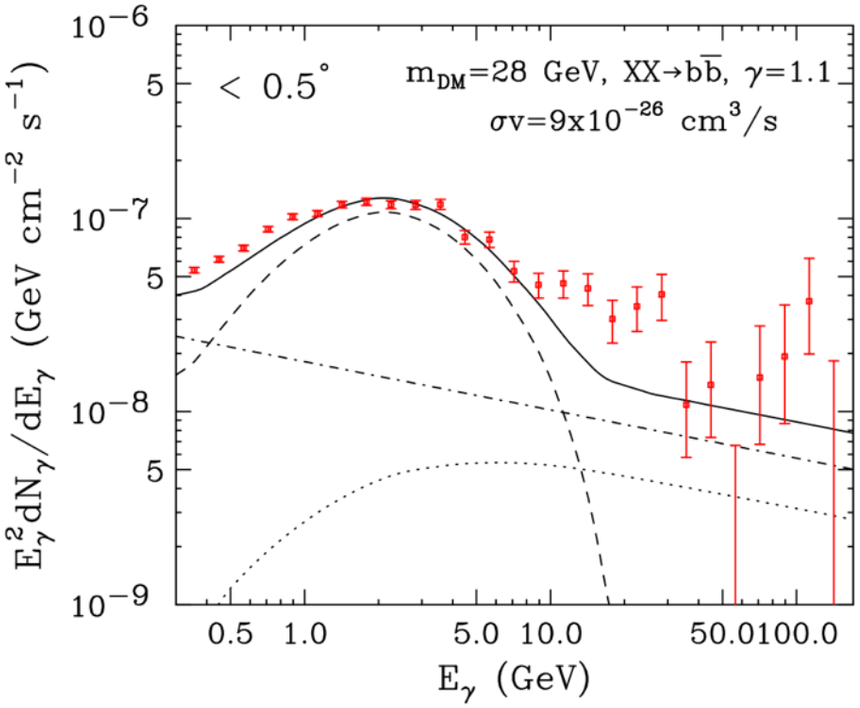


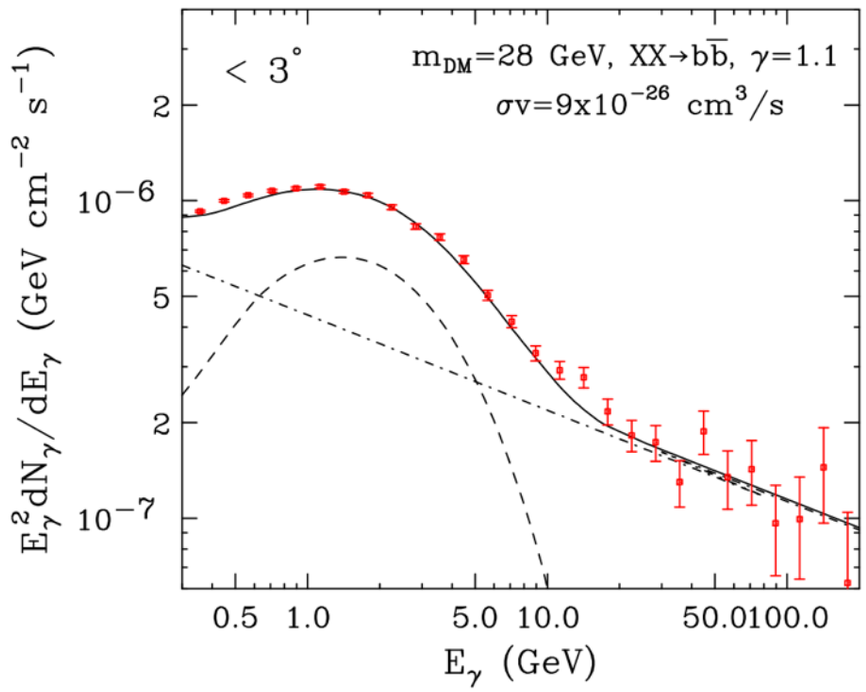
Unresolved sources?



Dark Matter?

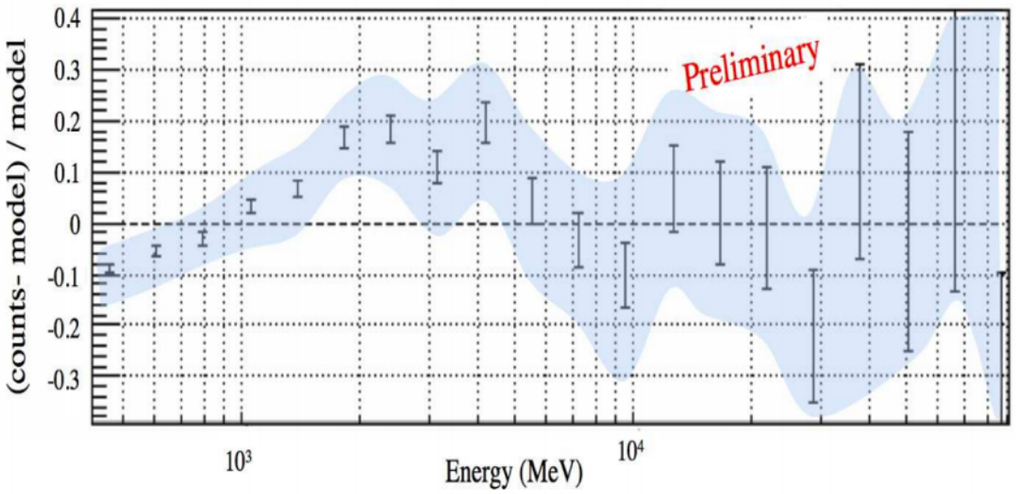
First hints of a GeV excess





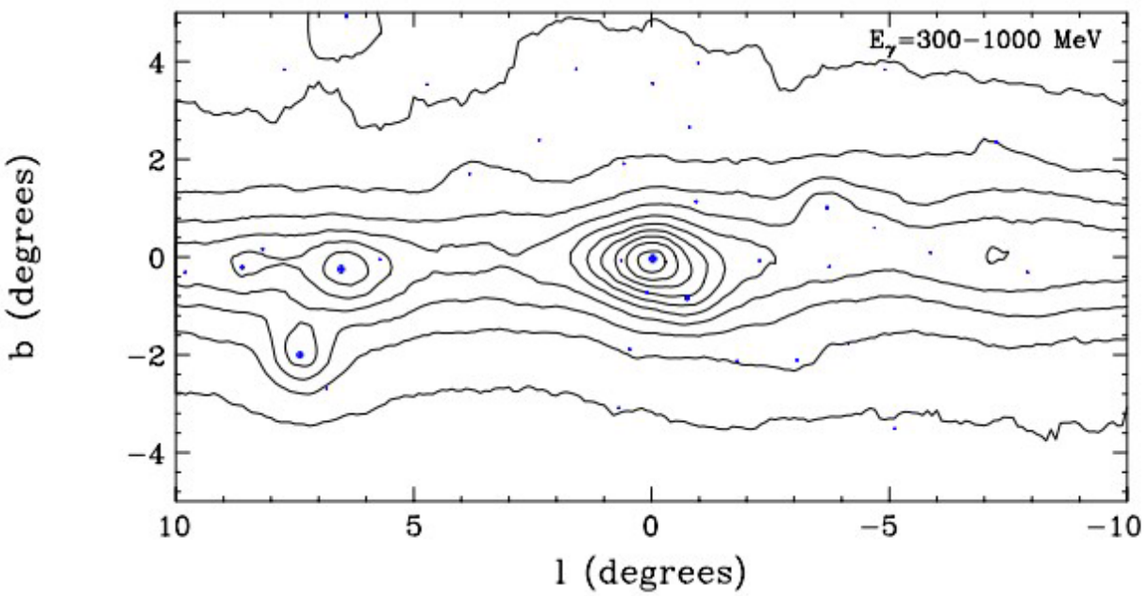
Goodenough & Hooper 2009

Vitale & Morselli, for the Fermi-LAT Collab. 2009



The "Galactic center" GeV excess

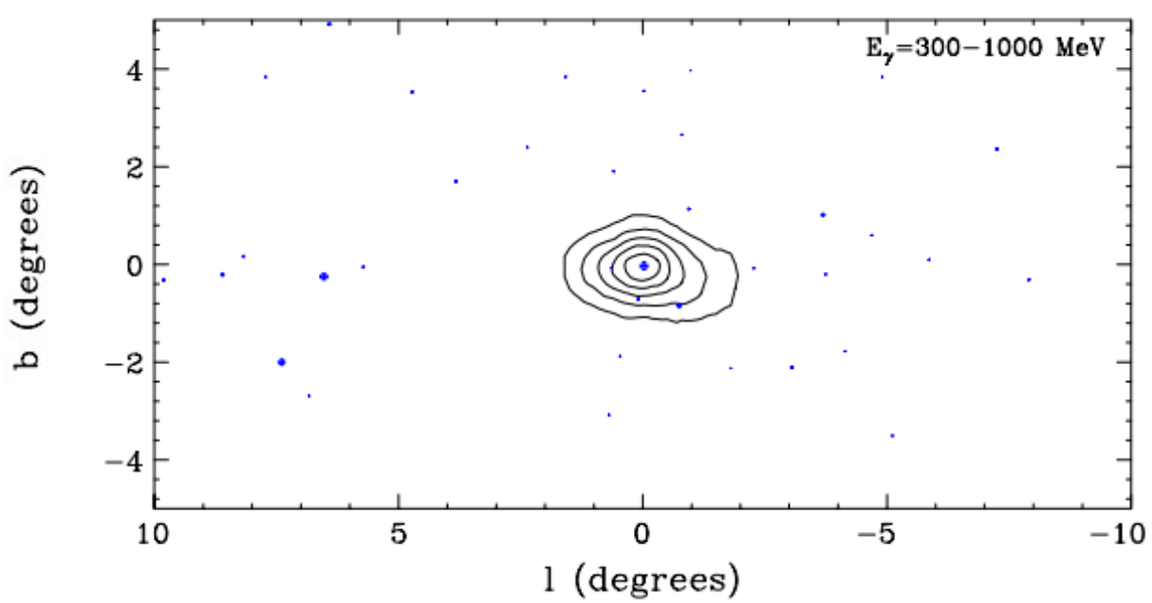
Data

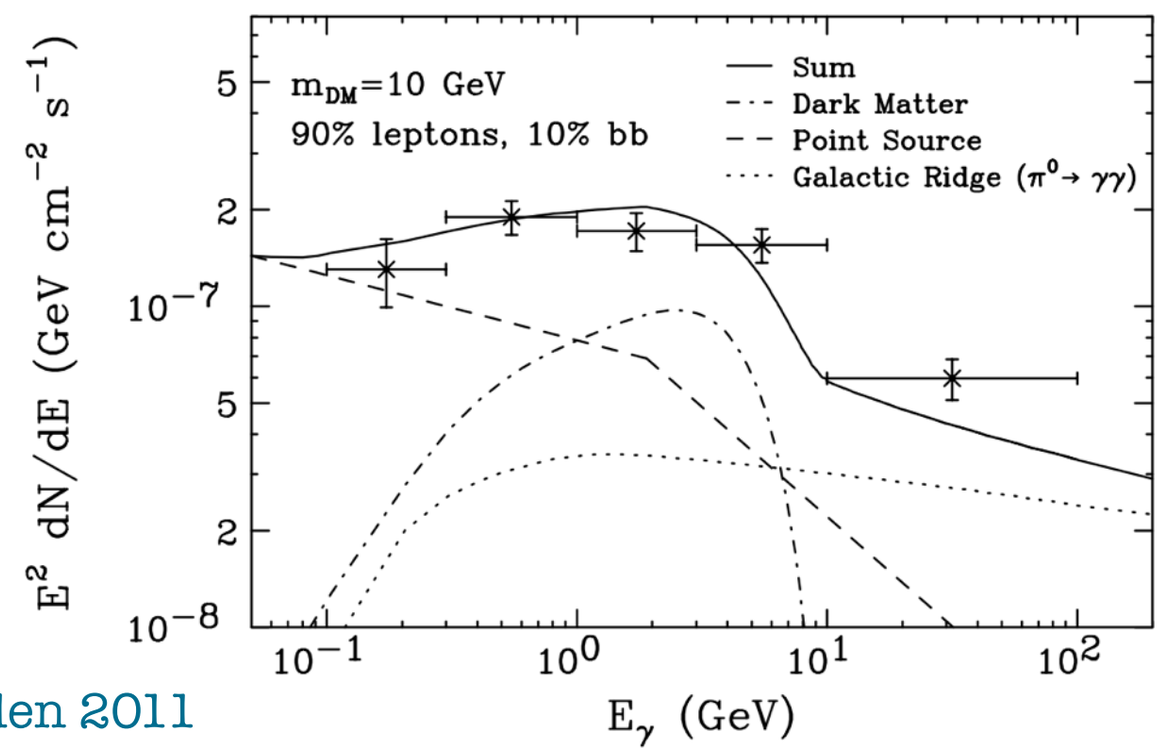


Claims for an extended emission of gamma rays **at the Galactic center**, in the inner few degrees.

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

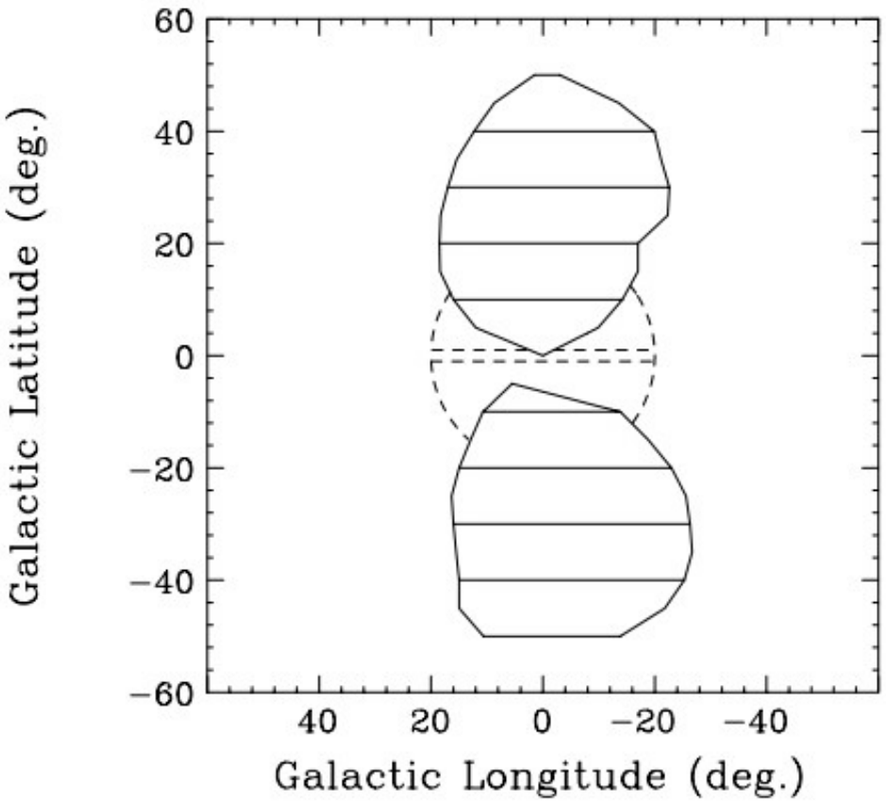
Subtraction of point sources and diffuse emission → Derived spectrum





Hooper & Linden 2011

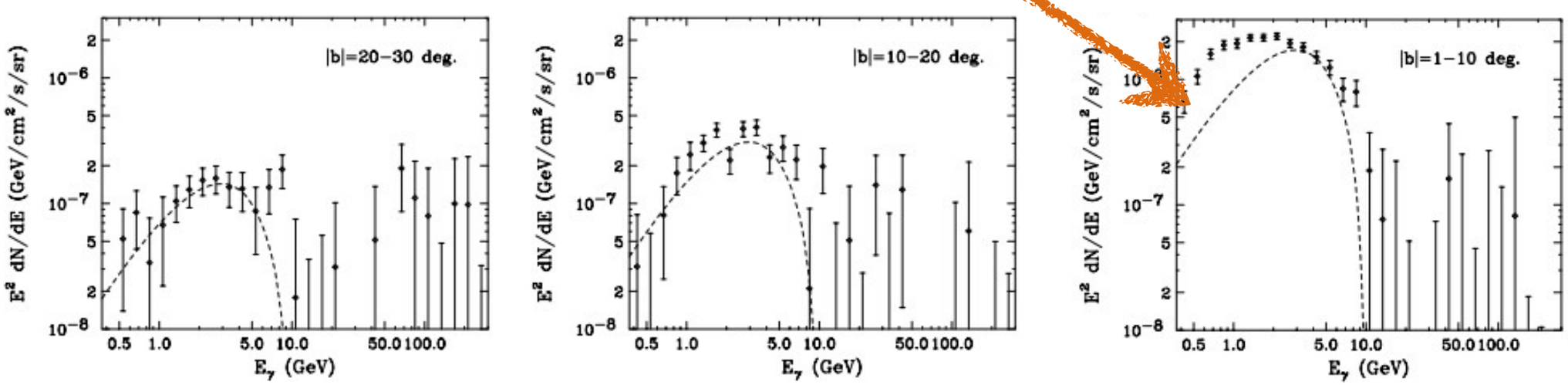
The "Inner Galaxy" GeV excess



Claims for an extended emission of gamma rays in the "**Inner Galaxy**", extension up to tens of degrees.

- Latitude variation of the Fermi bubbles spectrum.
- Possible extended counterpart (up to 2-3 kpc) of the Galactic Center excess.
- Non-Inverse Compton origin.
- Compatible with the signal from DM annihilation into tau+tau- for a DM mass of about 10 GeV.

$$DMDM \rightarrow \tau^+\tau^- \rightarrow \gamma$$

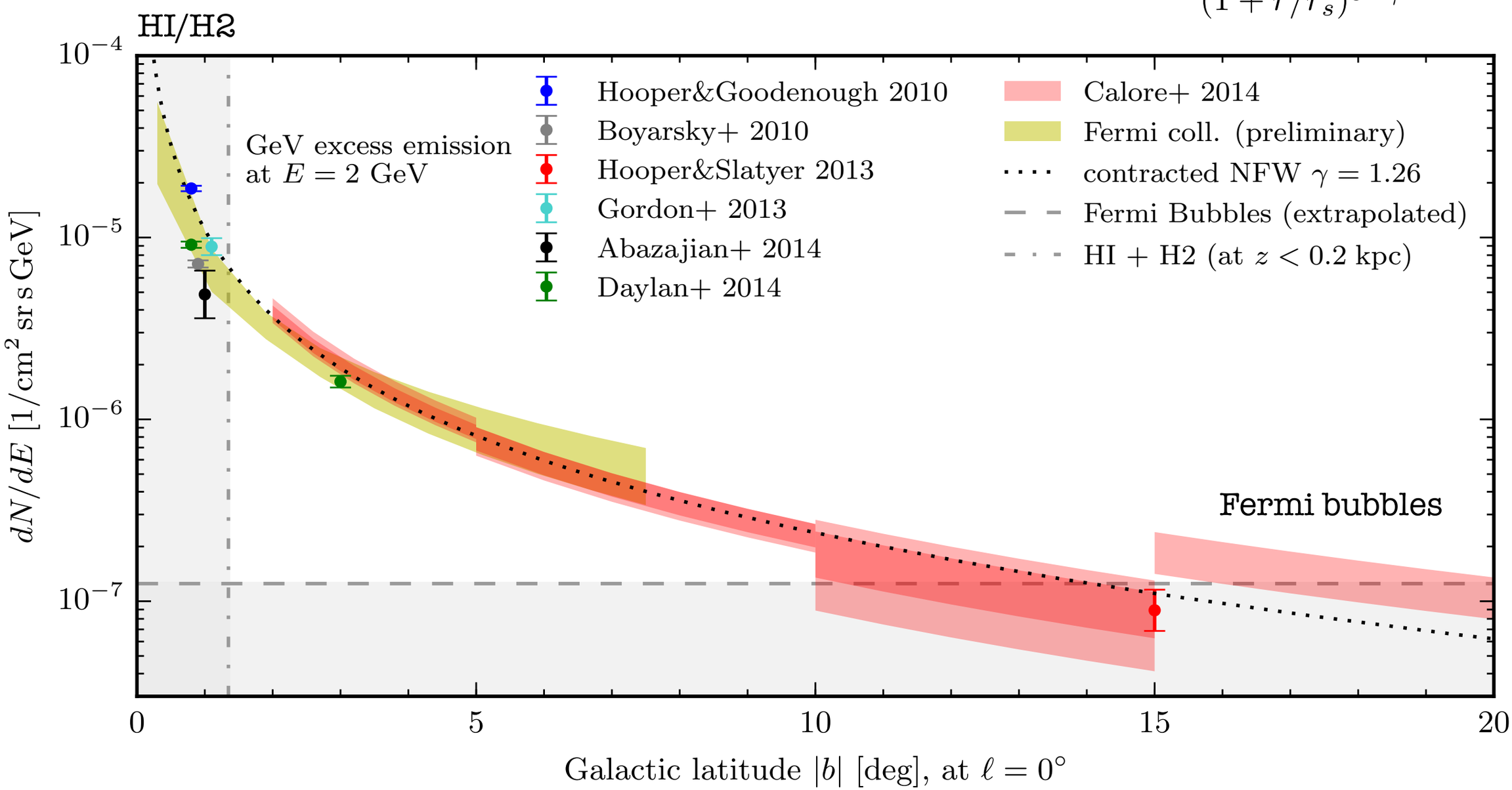


Hooper & Slatyer 2013

Follow-up studies: Huang+ 2013, Zhou+ 2014, Daylan+ 2014, Calore+ 2014

The Fermi GeV excess today: a summary

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



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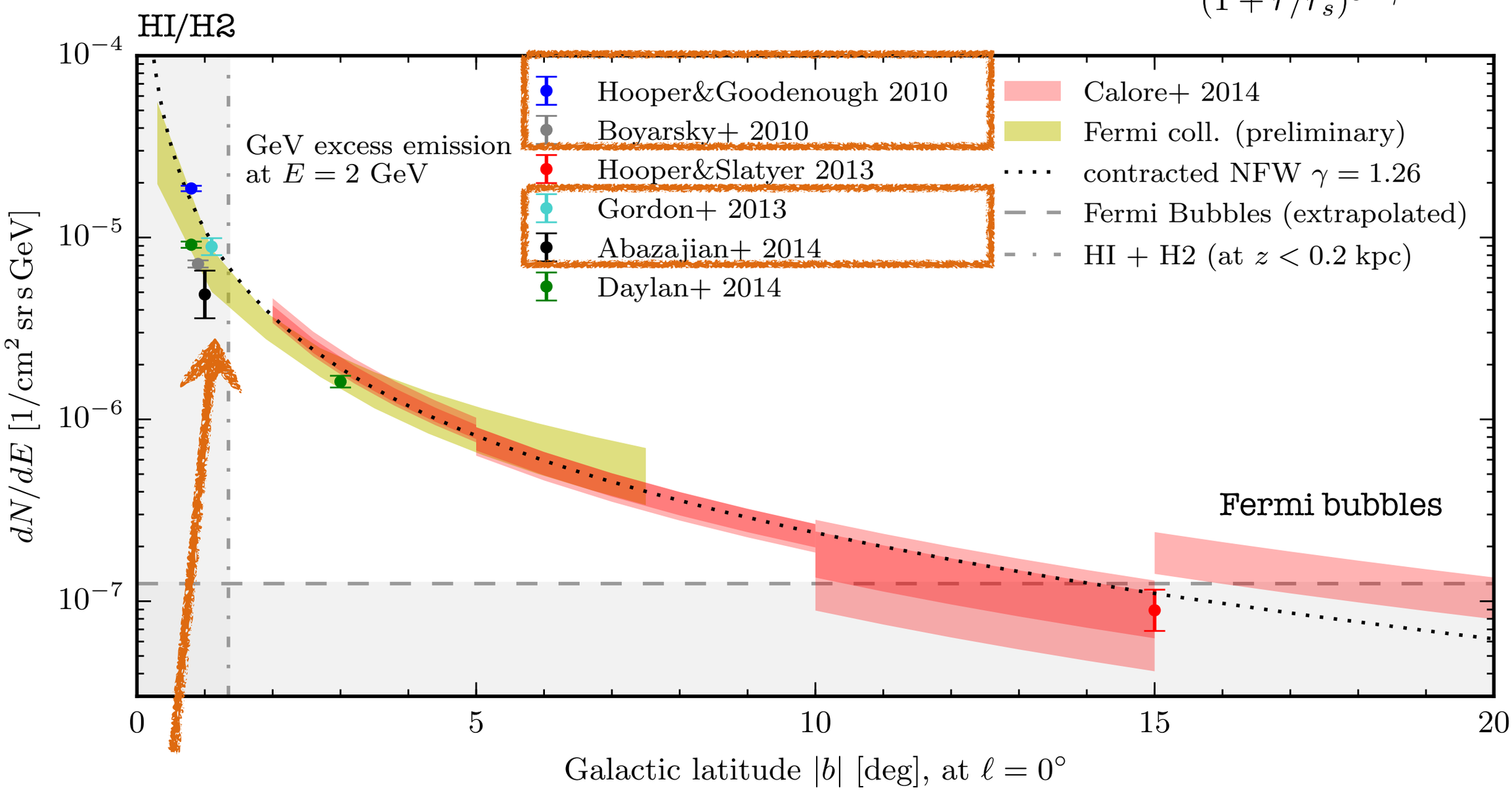

Galactic center analyses

The Fermi GeV excess today: a summary

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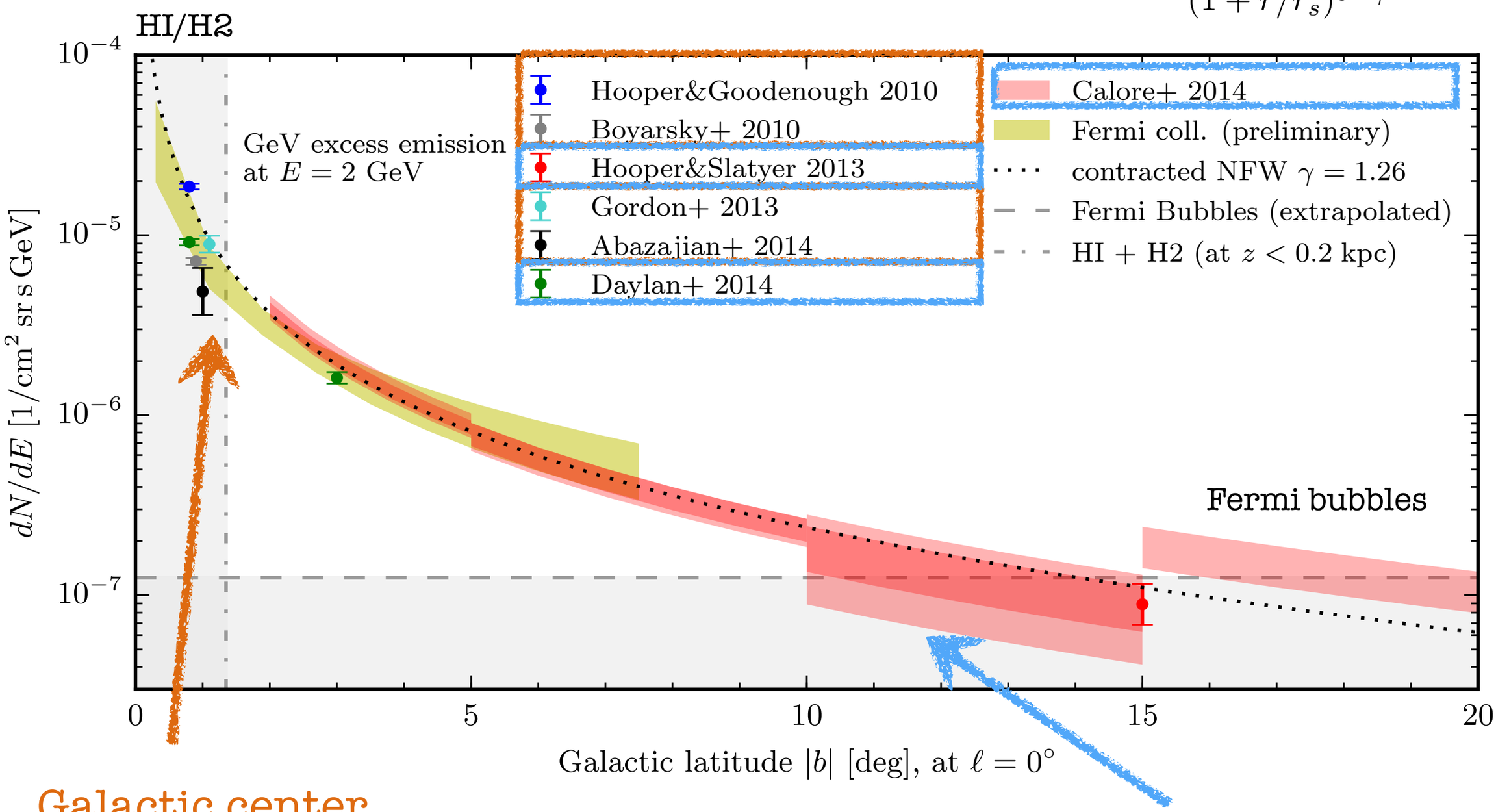

Galactic center analyses

"Inner" Galaxy analyses

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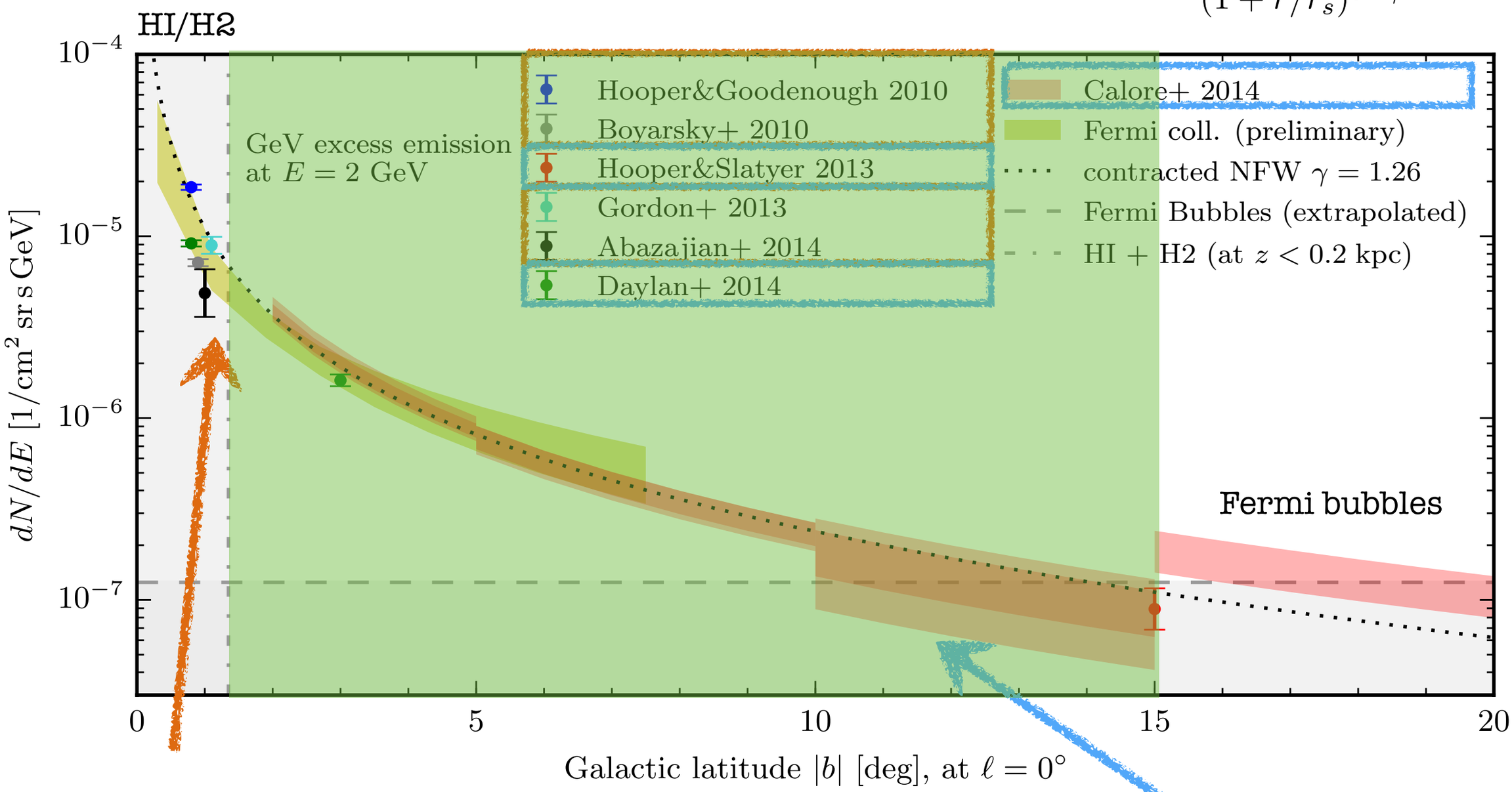

Galactic center analyses

"Inner" Galaxy analyses

An excess above what?

The excess emission is defined **above the astrophysical foregrounds and backgrounds**, namely the Galactic diffuse emission, point sources and extended sources, modelled in the data analysis.

Most previous analyses: Galactic diffuse emission models from the Fermi Collab. with caveats!

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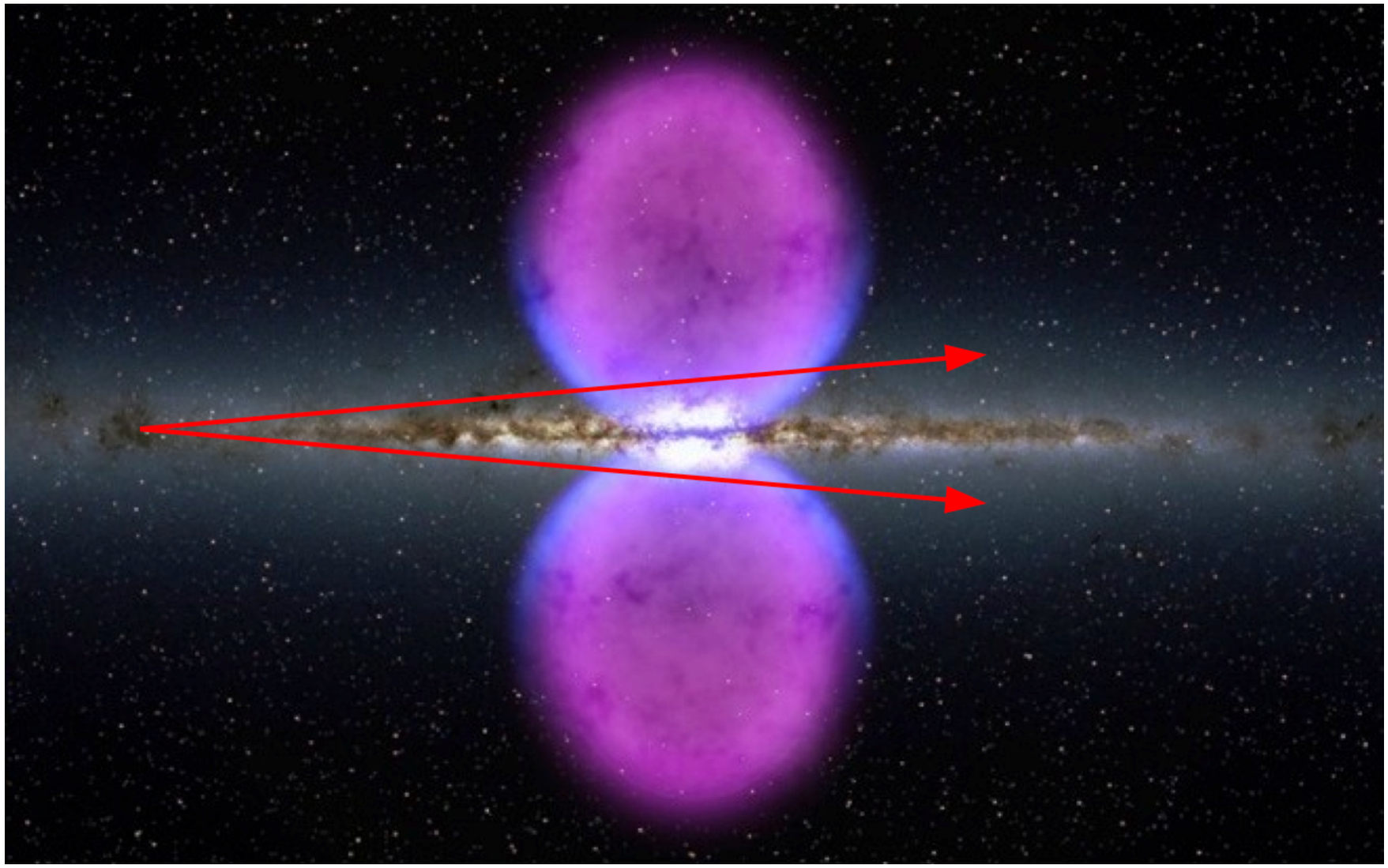
This work: large set of Galactic diffuse emission models from GALPROP runs

Calore, Cholis & Weniger, arXiv:1409:0042



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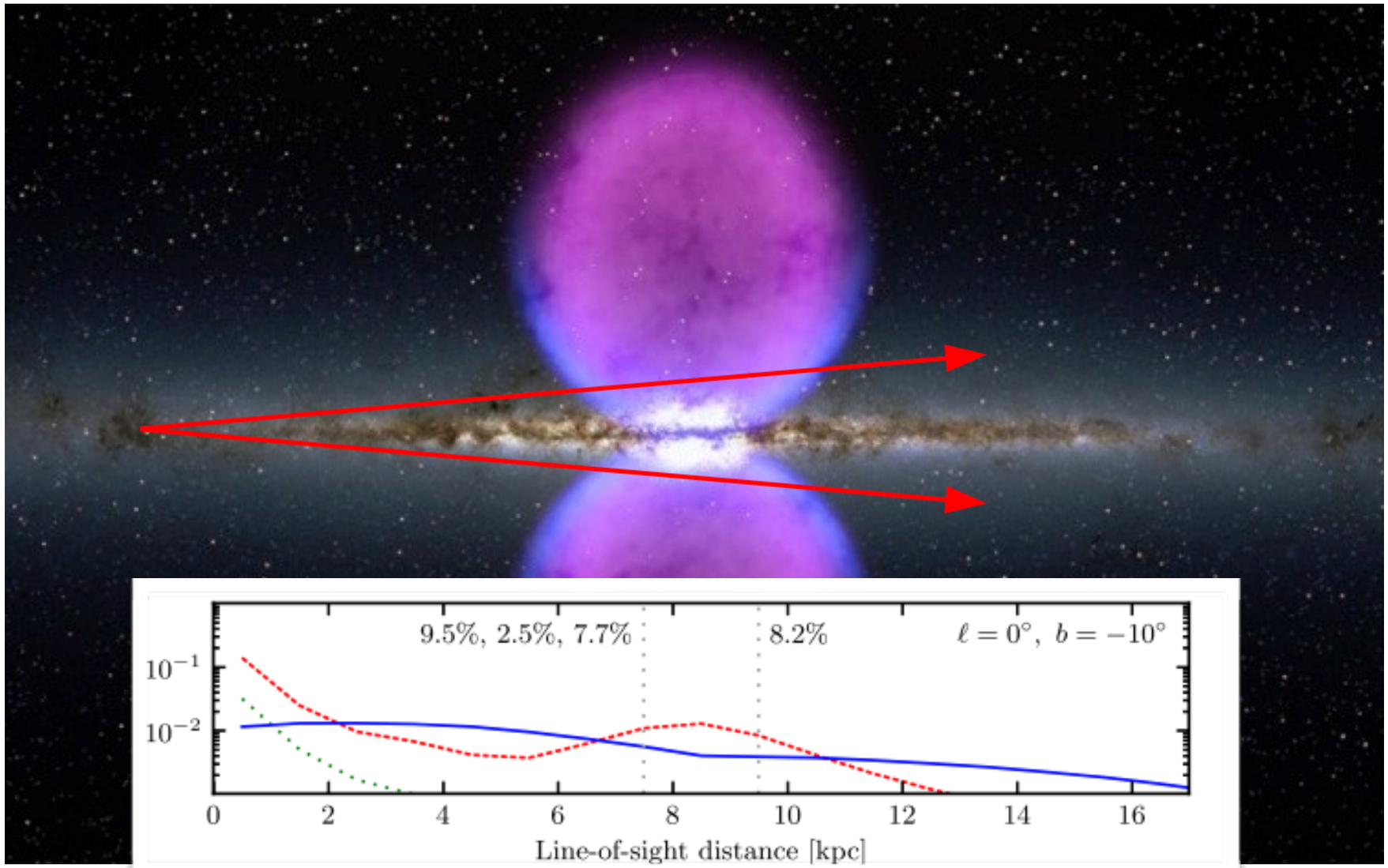

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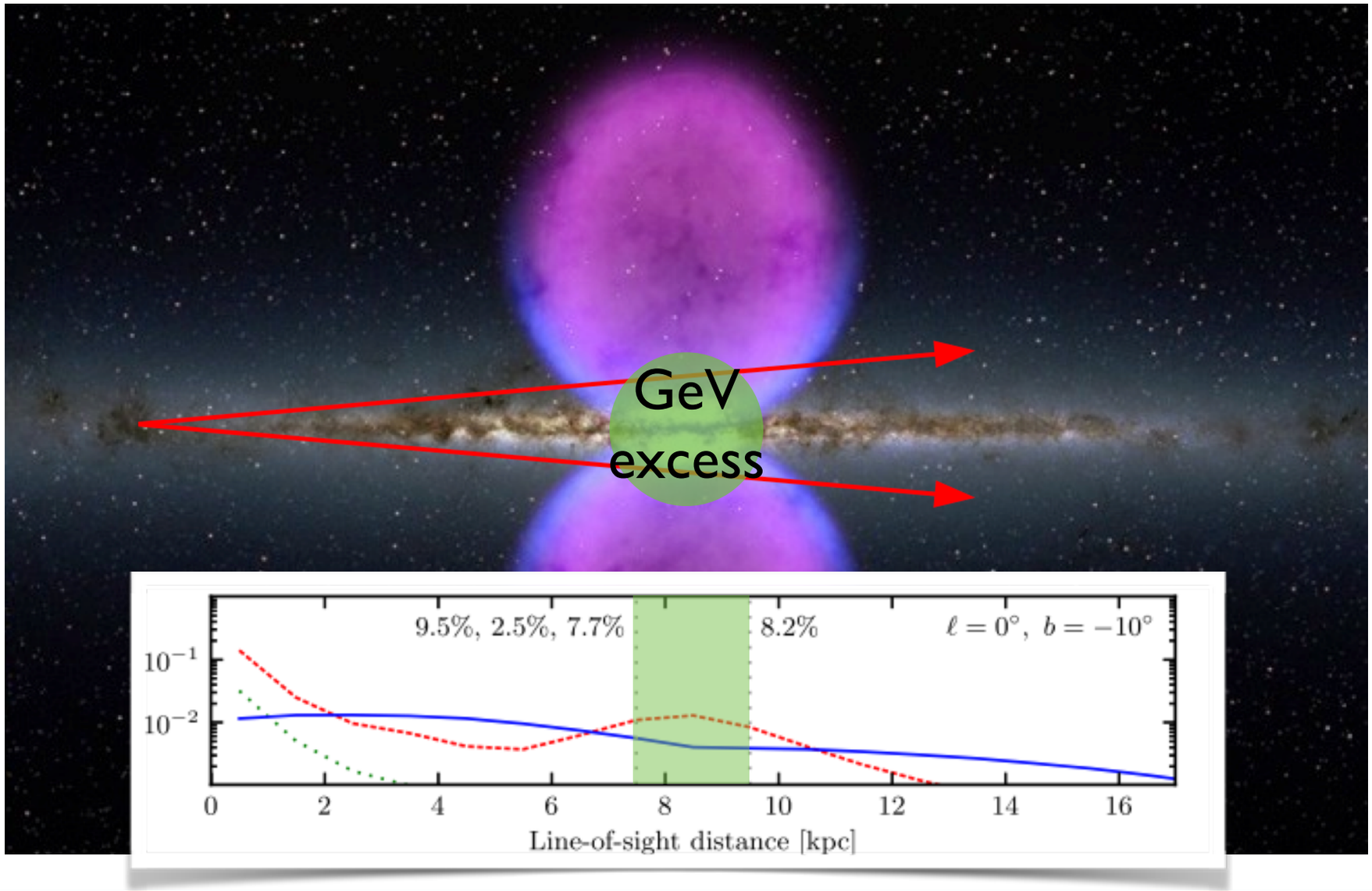
This work: large set of Galactic diffuse emission models from GALPROP runs

Calore, Cholis & Weniger, arXiv:1409:0042



The GeV excess on trial

Calore, Cholis & Weniger, arXiv:1409:0042

Aims:

A. Robust identification of the excess despite of large variations of the background models.

B. Firm characterisation the spectral and morphological properties of the excess.

C. Making statistics based statement about the viable interpretations by including systematic uncertainties in the fits.

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?

The GeV excess on trial

Calore, Cholis & Weniger, arXiv:1409:0042

Aims:

A. Robust identification of the excess despite of large variations of the background models.

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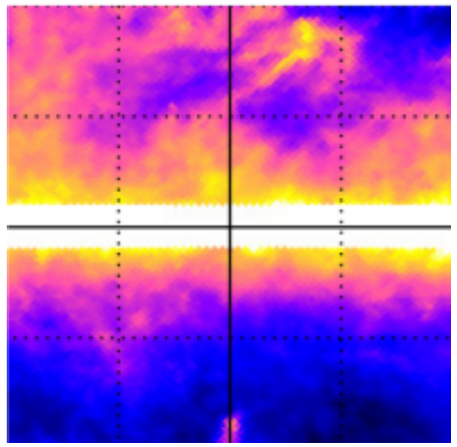
Method:

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 GDE models describe the data.

Basics of the template regression technique

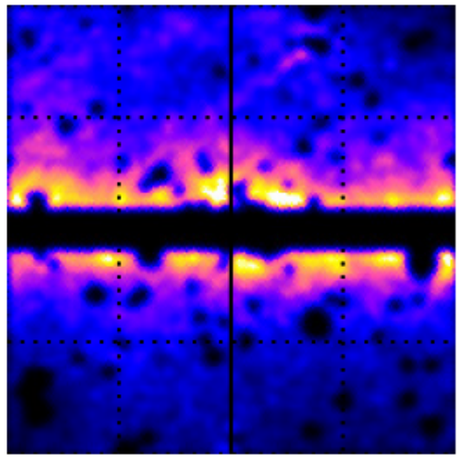


Model counts

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

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

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



Data counts

$$k_{i,j}$$

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

Analysis set-up

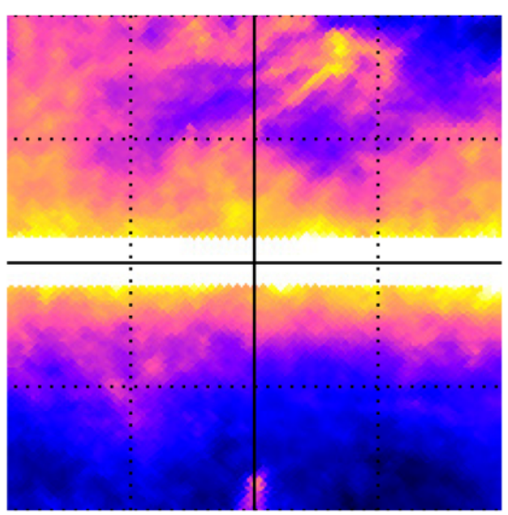
Data selection and standard preparation (284 weeks; 300MeV-500GeV).

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

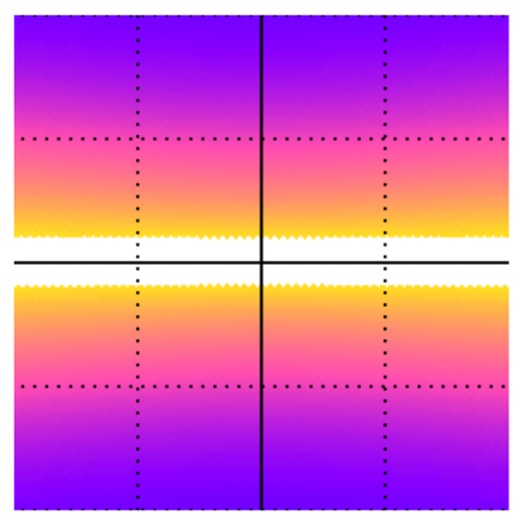
Point sources (2FGL) weighted adaptive mask.

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!

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

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

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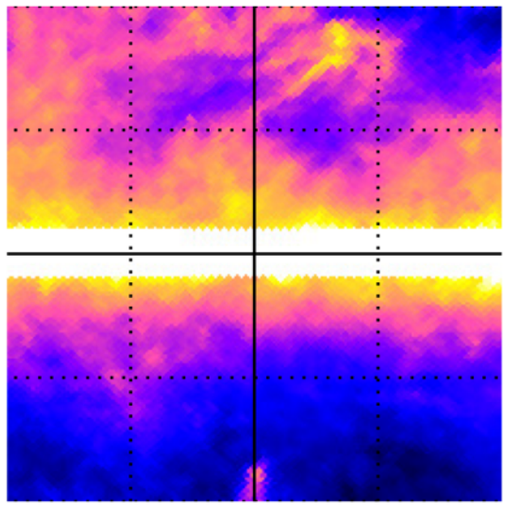
Home-brew diffuse models



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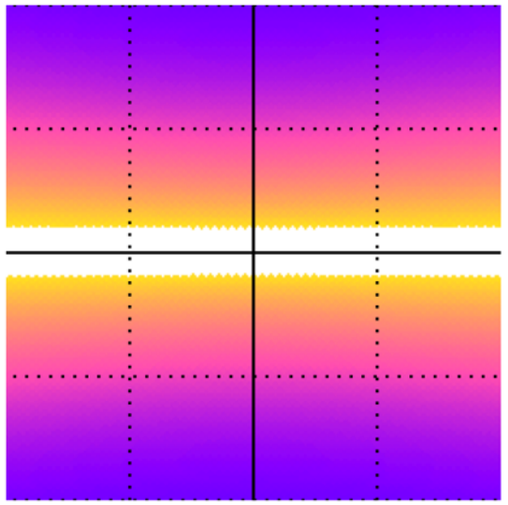

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Point sources (2FGL) weighted adaptive mask.

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**

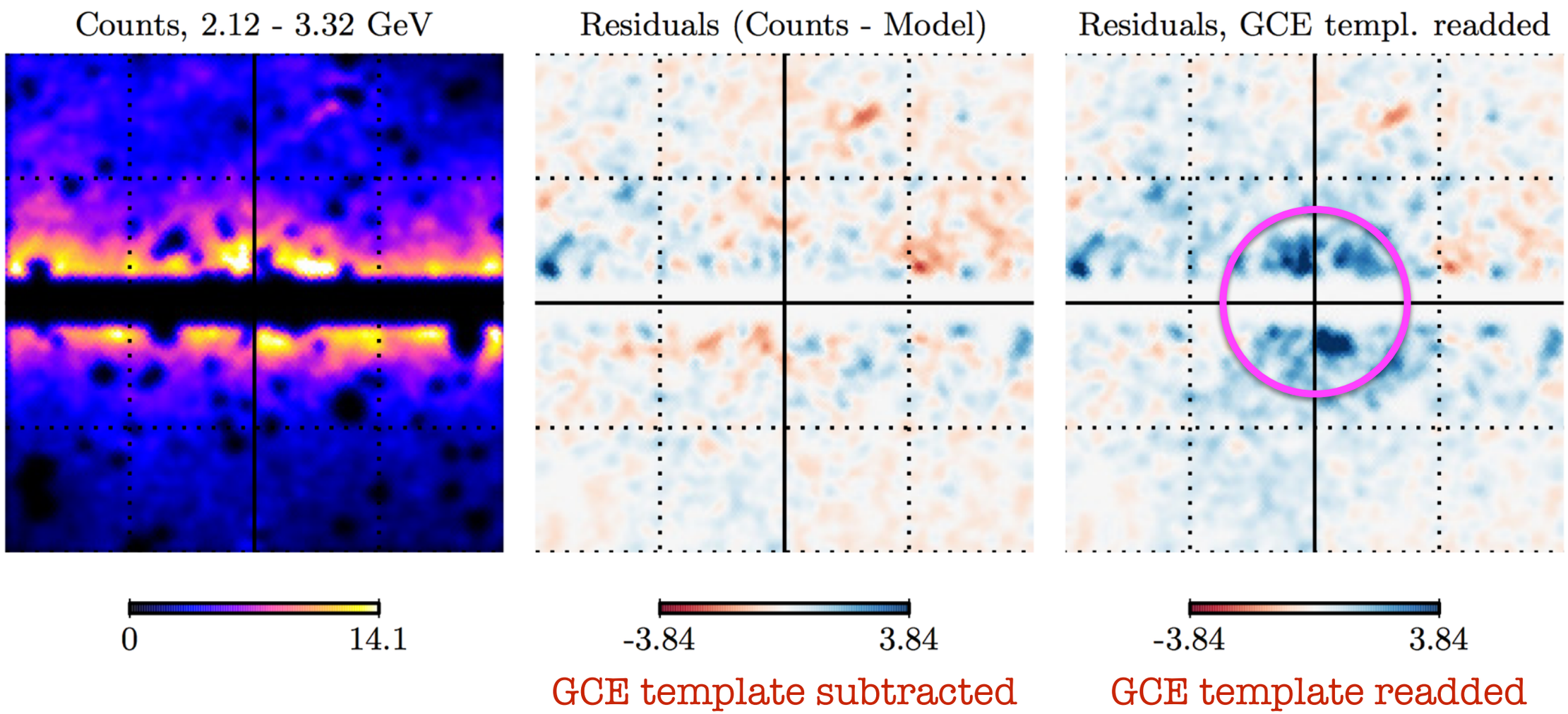
$$J(\psi) = \int_{los} \rho^2(r) dl$$

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

generalised NFW profile

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

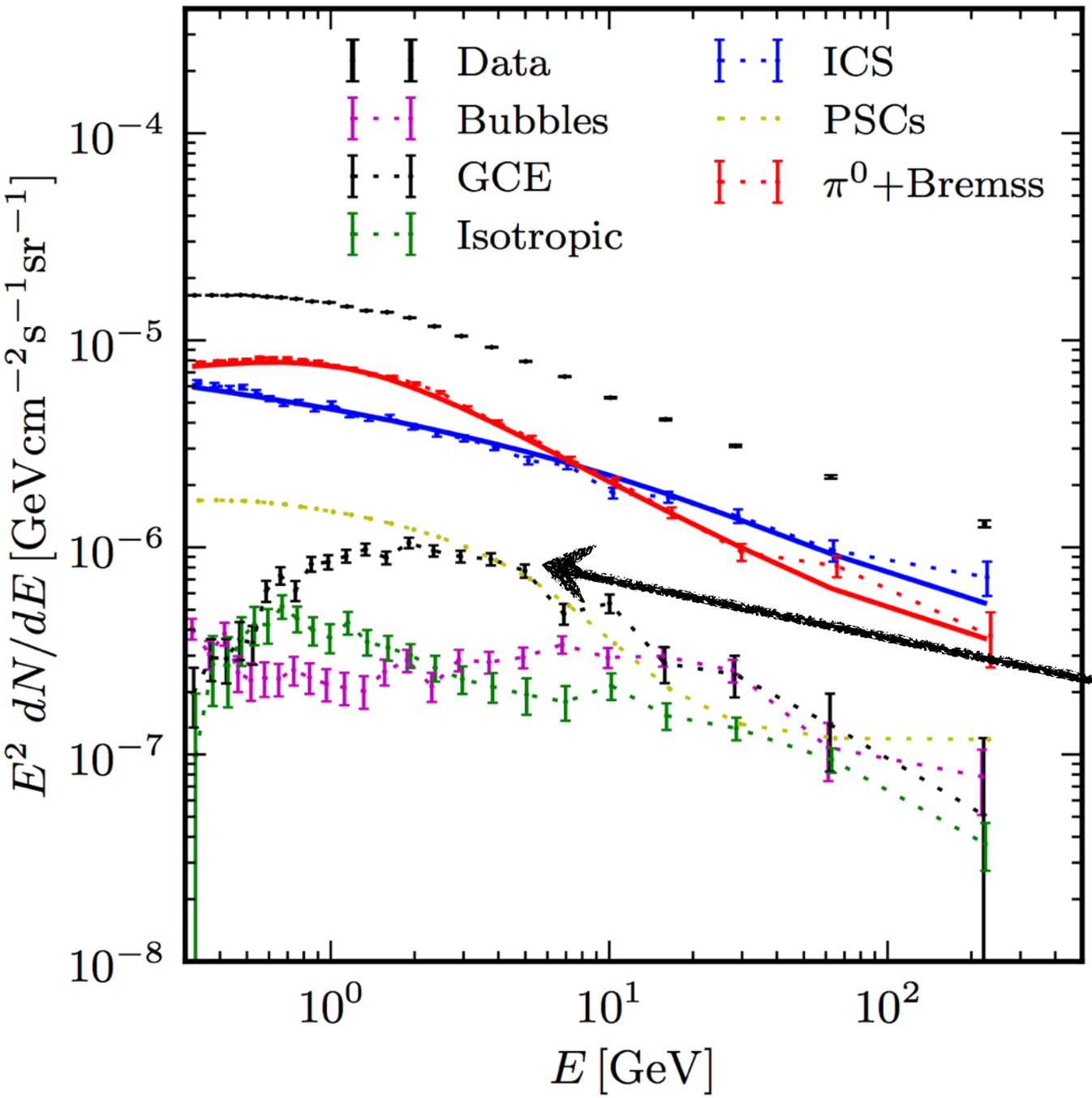
The flux absorbed by the excess template*



- ✓ 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.

Spectral components*



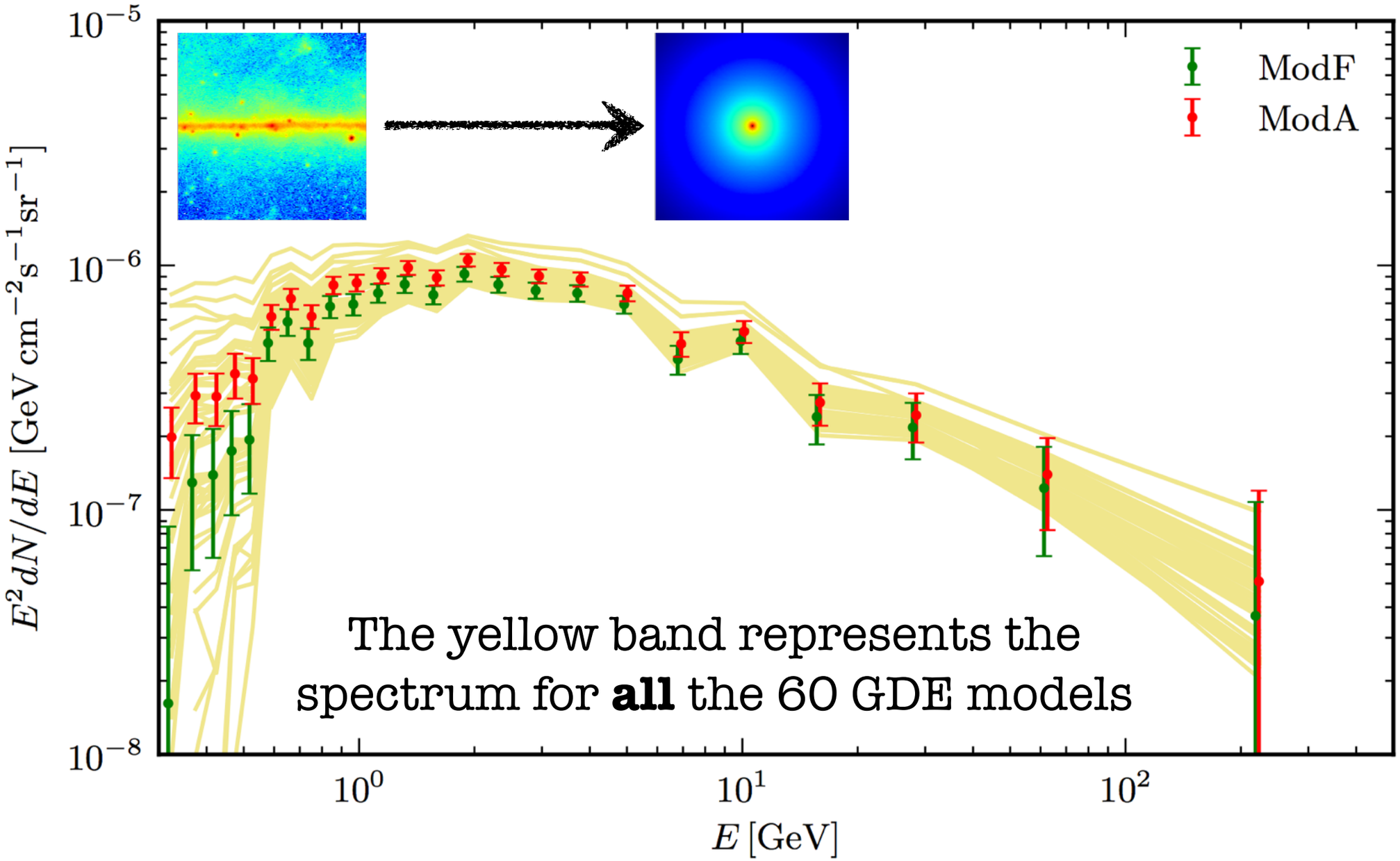
Spectra associated with the different spatial templates.

Importance of **self-consistent** GDE models (solid lines represent the GDE model predicted spectra).

GeV excess template

*Results for one typical GDE model.

The GeV excess 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 GDE models.

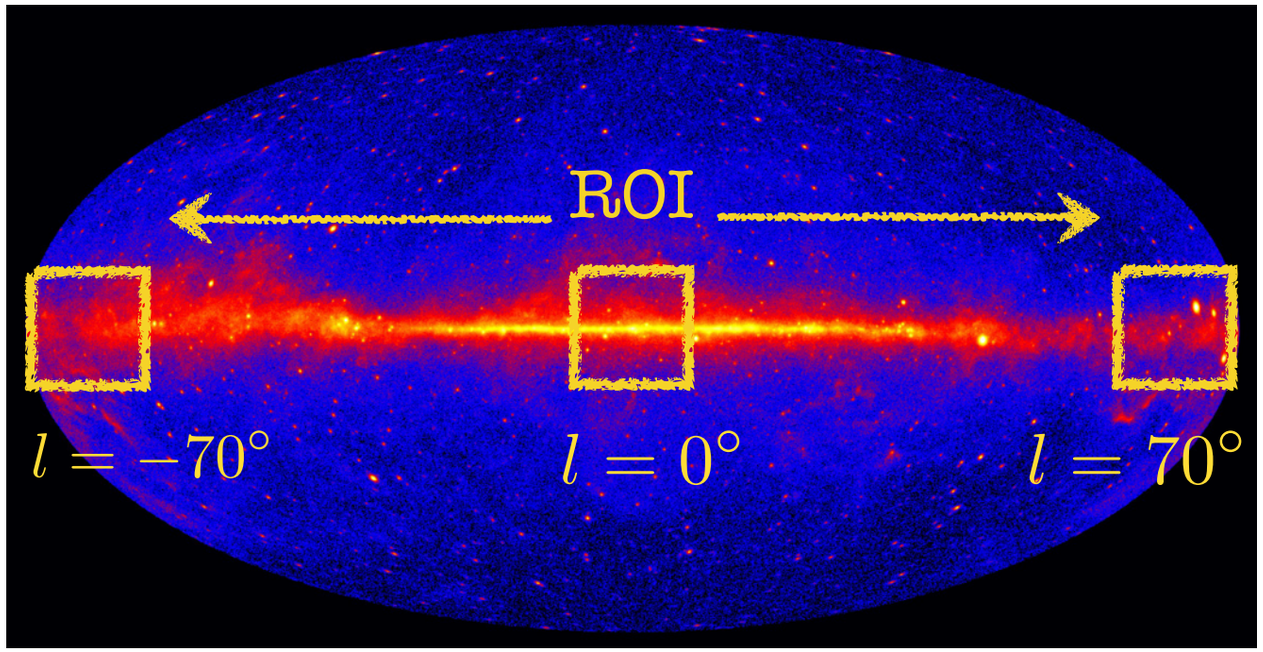
Empirical model systematics

How robust are the results?

Idea:

Quantifying the typical residuals above the predicted GDE along the Galactic disk, away from the Galactic center.

$\longrightarrow$ Consider variations in the longitude range $|l| < 90^\circ$, and use them to estimate the **empirical model systematics** at the GC.



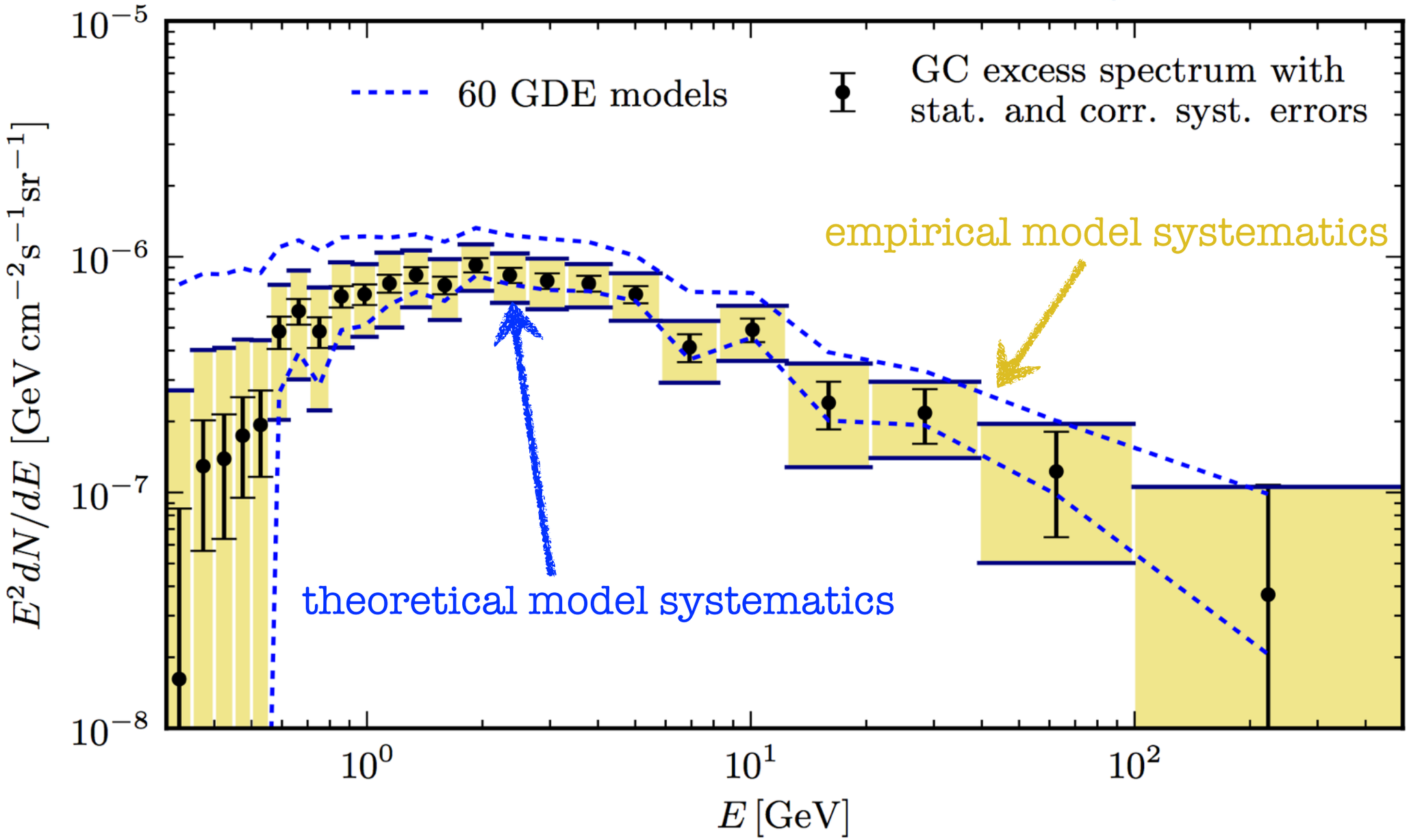
See C. Weniger talk

$\longrightarrow$ Definition of the **covariance matrix**

$\longrightarrow$ Principal components analysis

$\longrightarrow$ **Correlated systematic errors** and connection with background uncertainties

GCE spectrum: theoretical & empirical model systematics



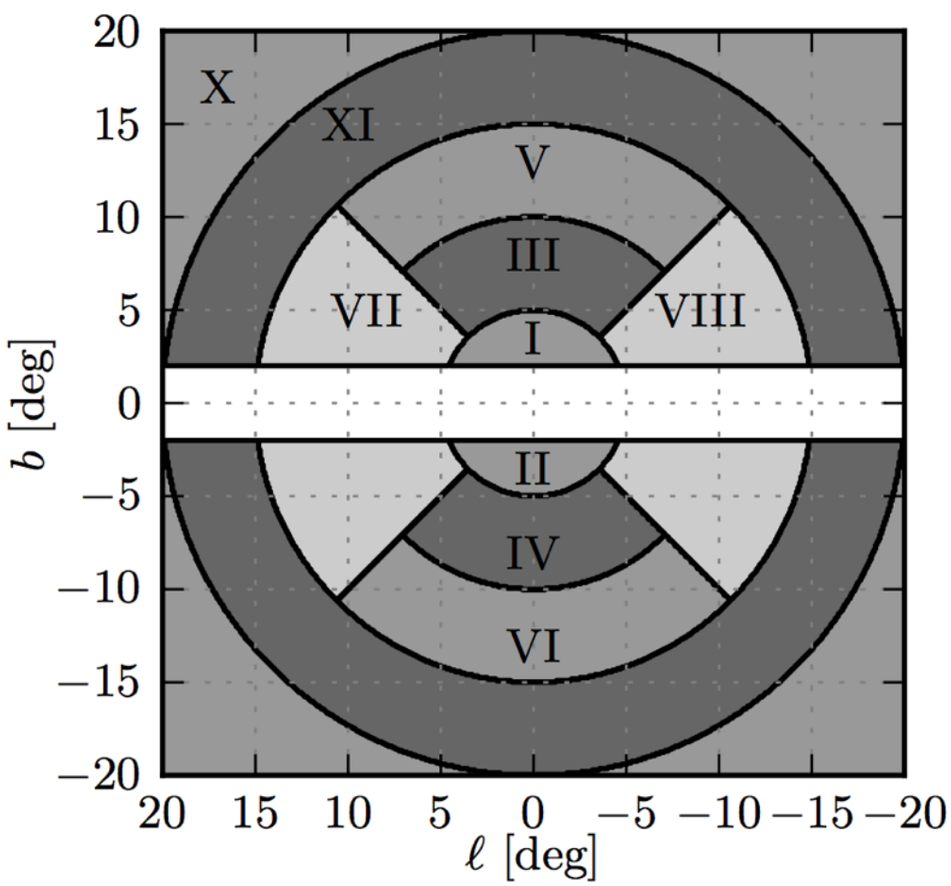
- ✓ **Model systematics** are significantly larger than the statistical error over the entire energy.
- ✓ **Empirical and theoretical systematics** are roughly of the same order in the considered energy range and ROI (only diagonal part of covariance matrix shown).

The segmented sky

How far in latitude does the excess extend?

Is it compatible with being spherically symmetric?

Is it showing uniform properties in different sky regions?

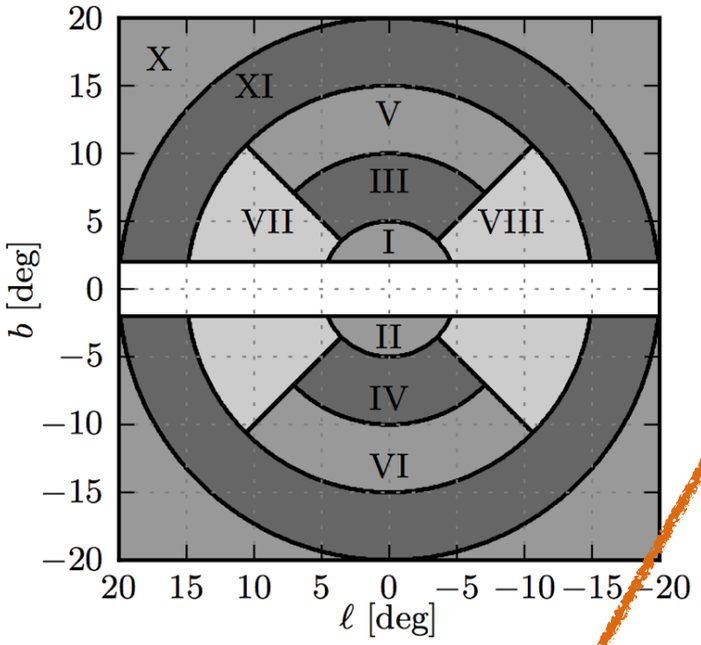


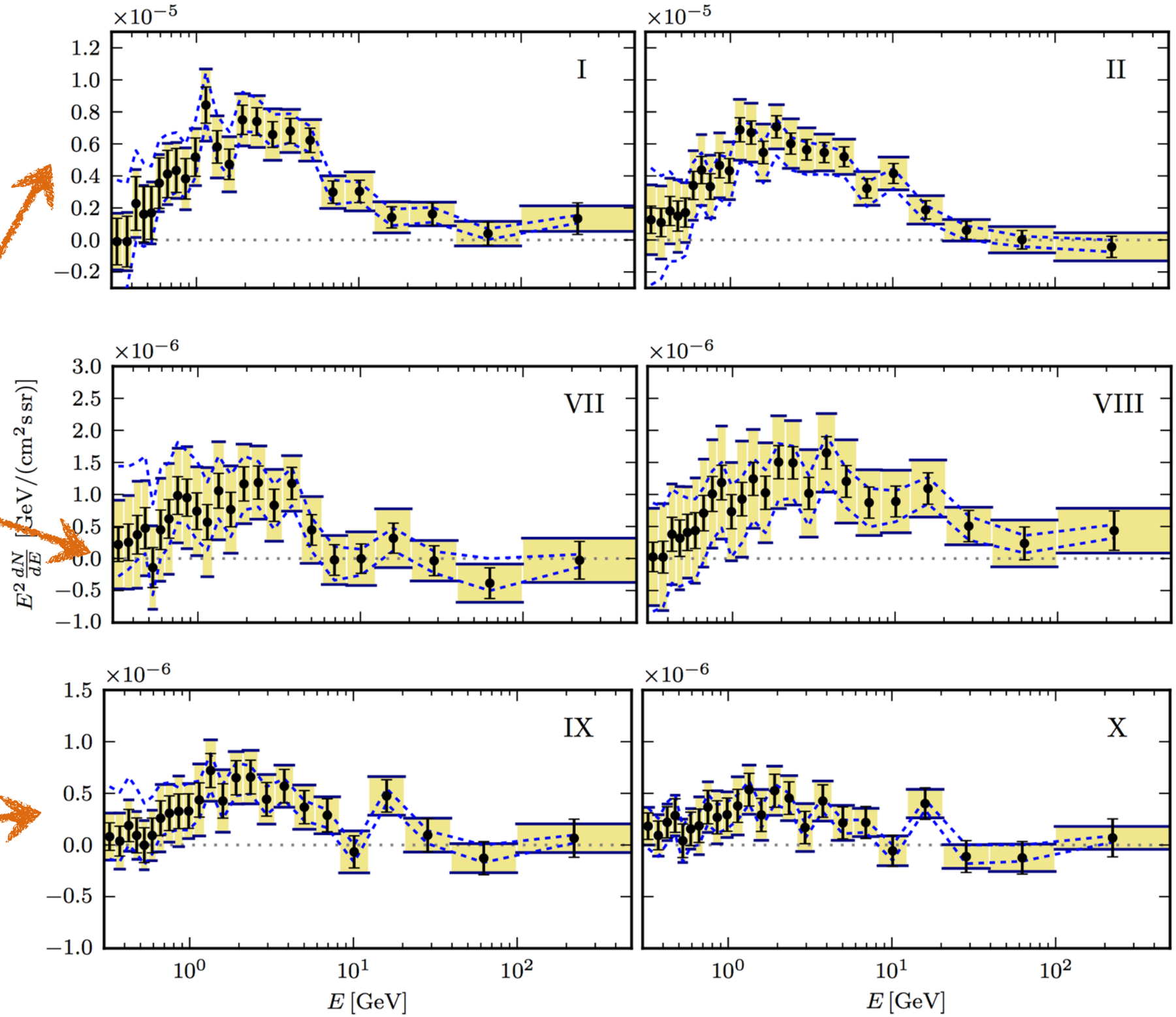
Idea:

In the main ROI, divide the GCE template in 10 segments and leave free their normalisations independently.

- Test the symmetry properties of the excess (North/South/West/East).
- Test the extension in latitude.

The segmented sky

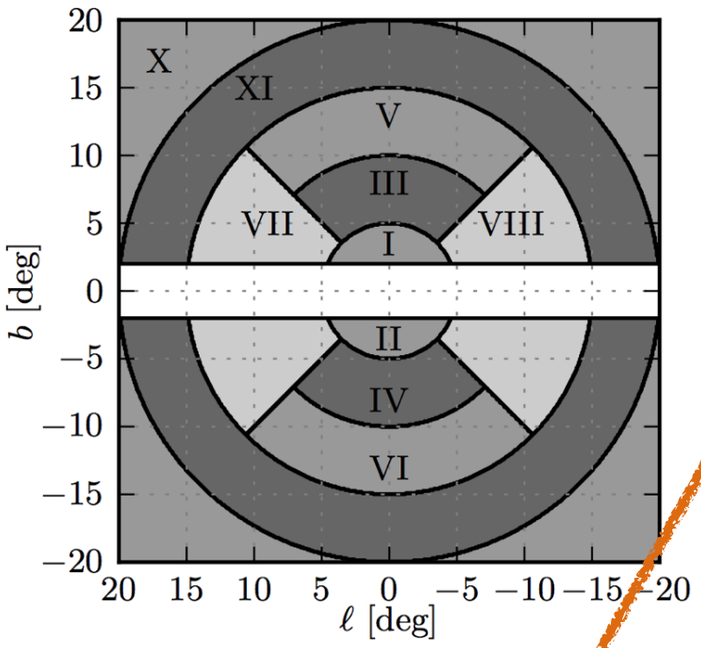


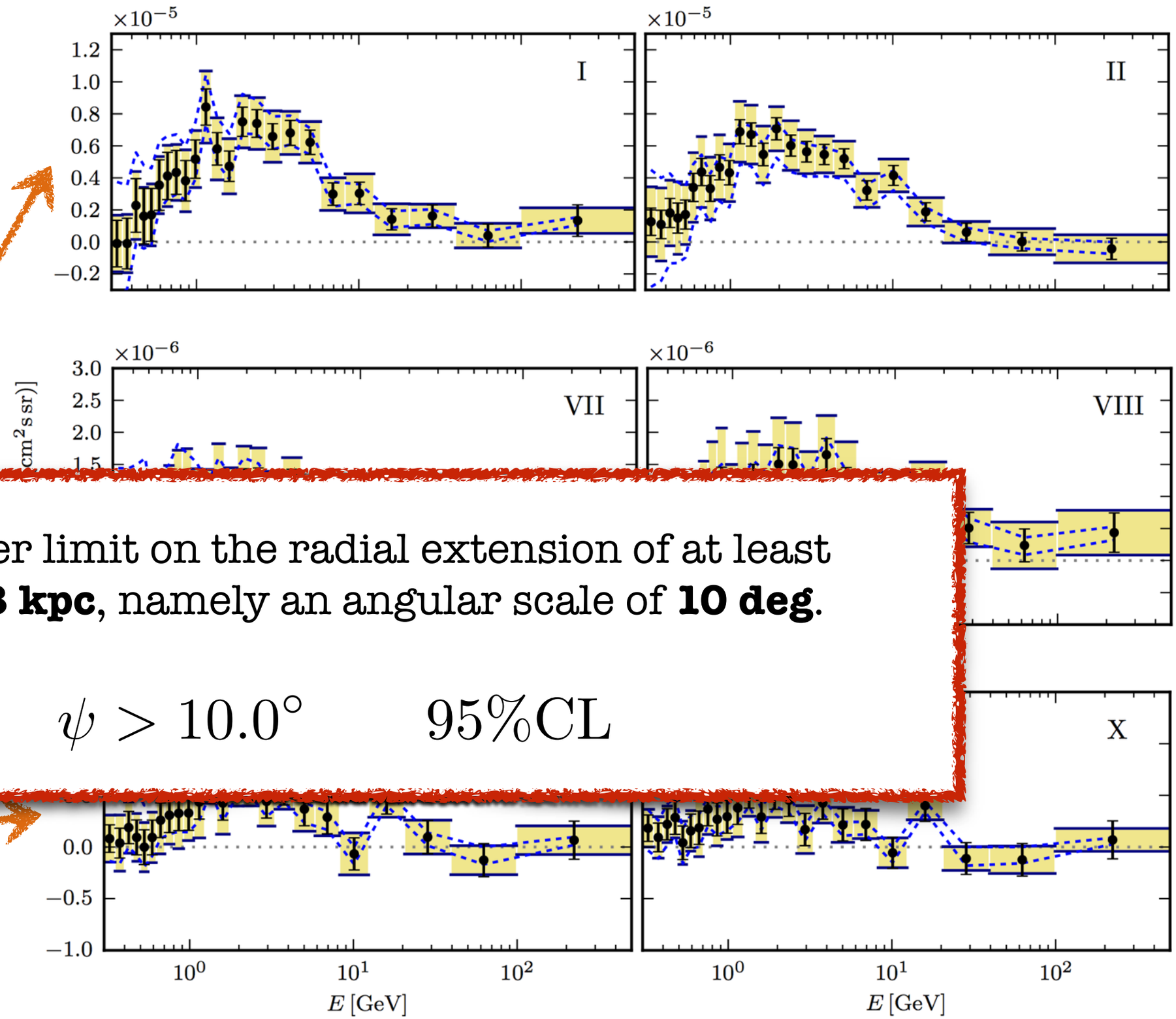


Symmetry properties

Latitude extension

The segmented sky





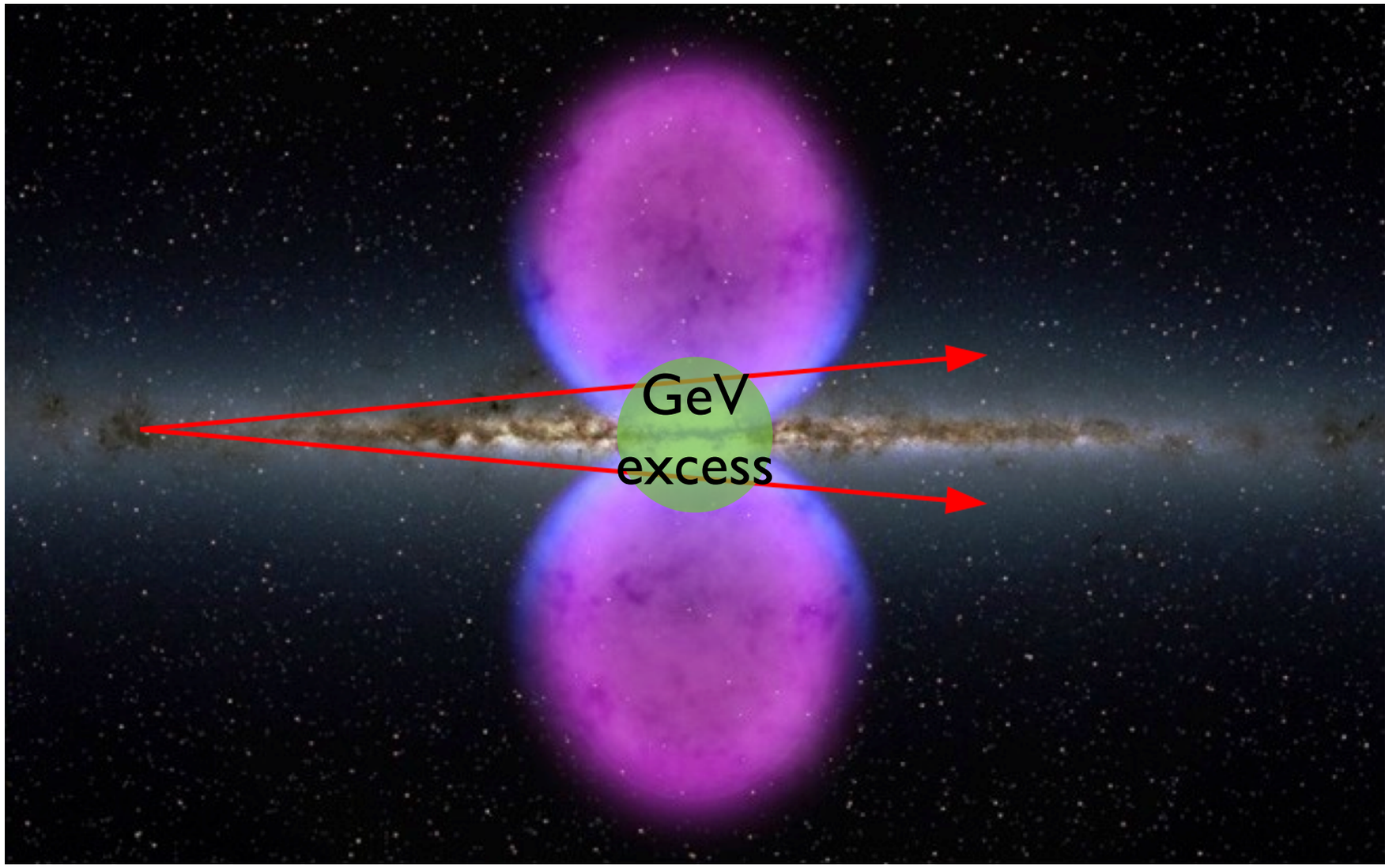
Symmetry properties

Latitude extension

Lower limit on the radial extension of at least **1.48 kpc**, namely an angular scale of **10 deg**.

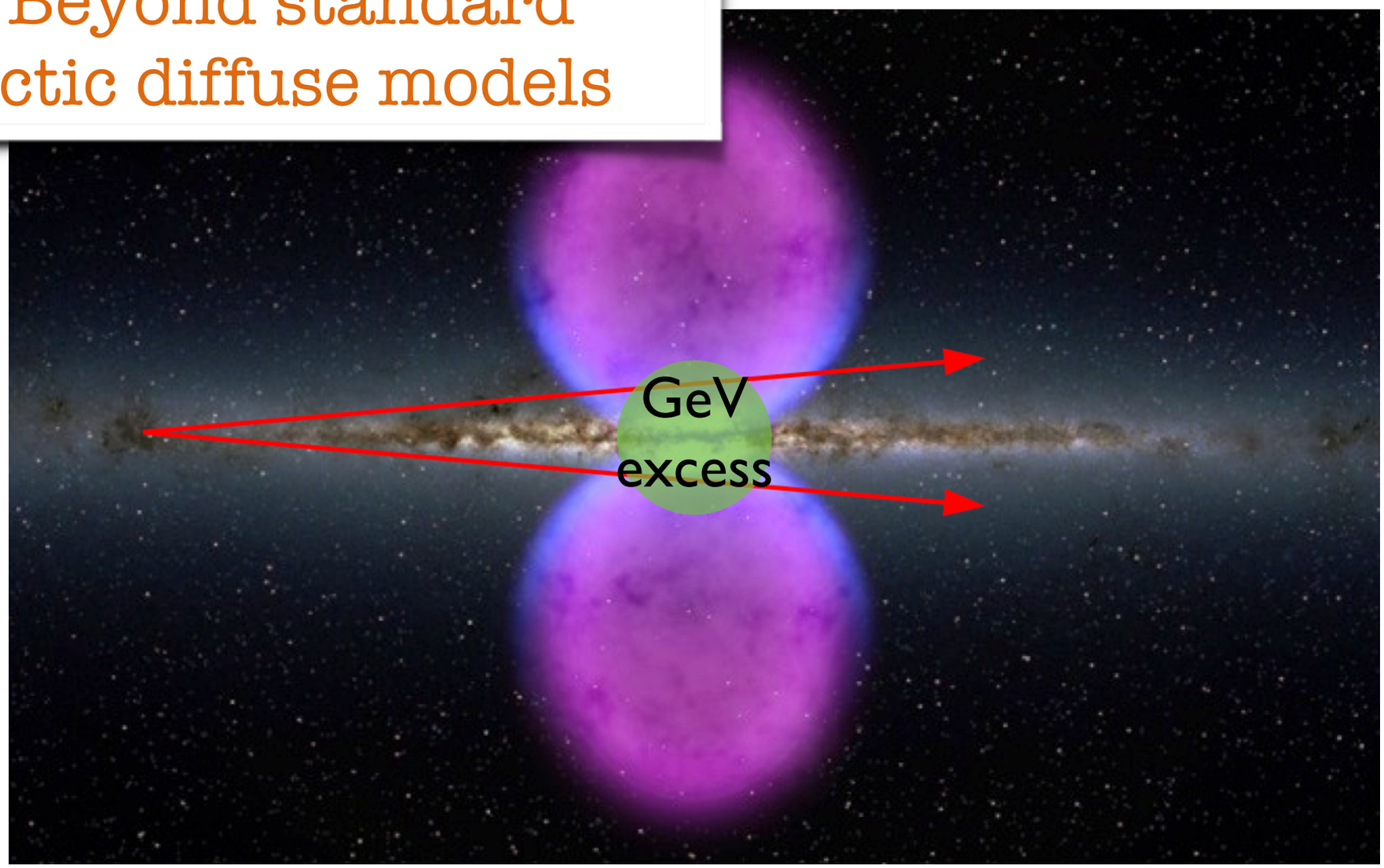
$$\psi > 10.0^\circ \qquad 95\%\mathrm{CL}$$

Interpretations of the GeV excess



Interpretations of the GeV excess

(a) Beyond standard Galactic diffuse models



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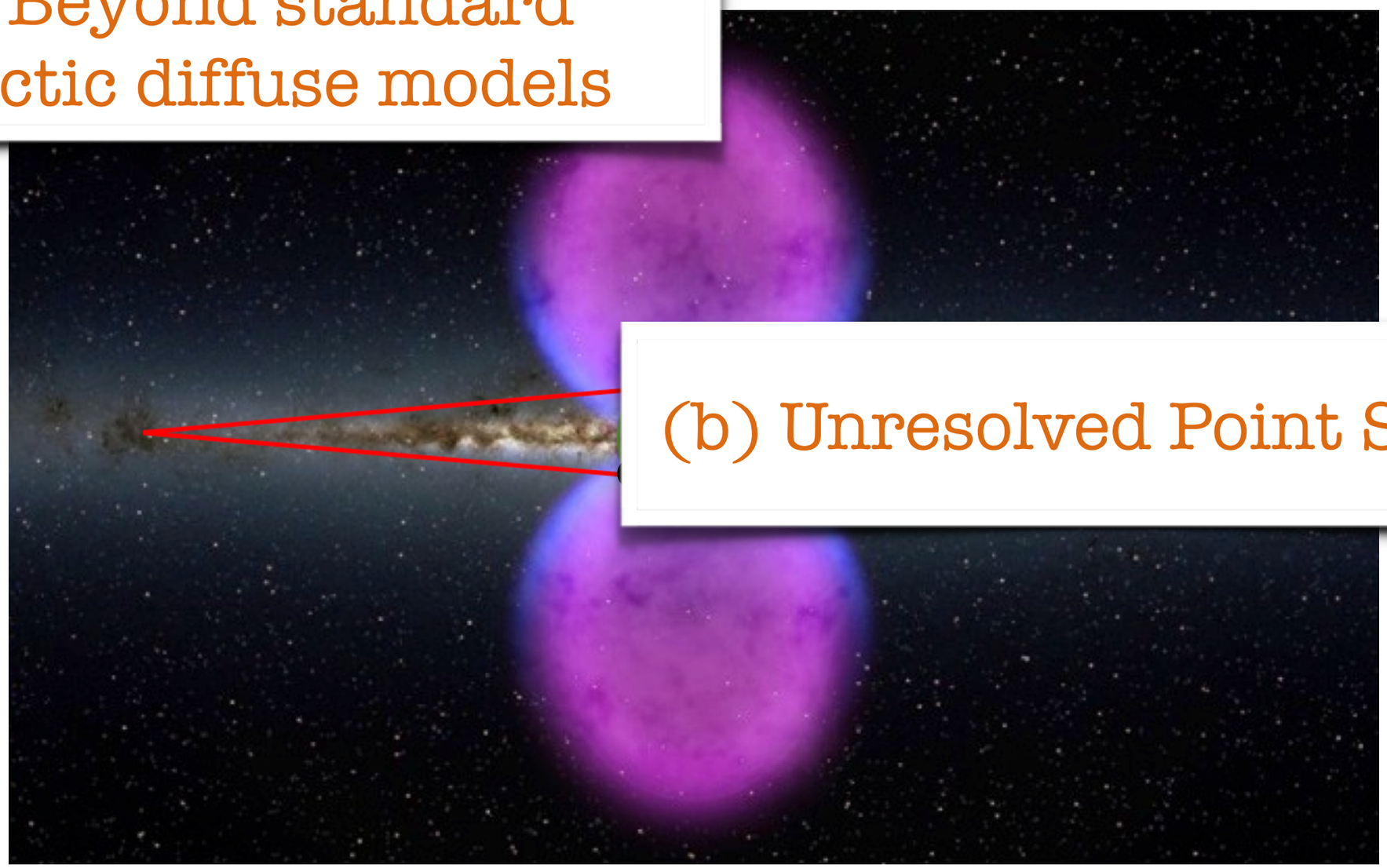
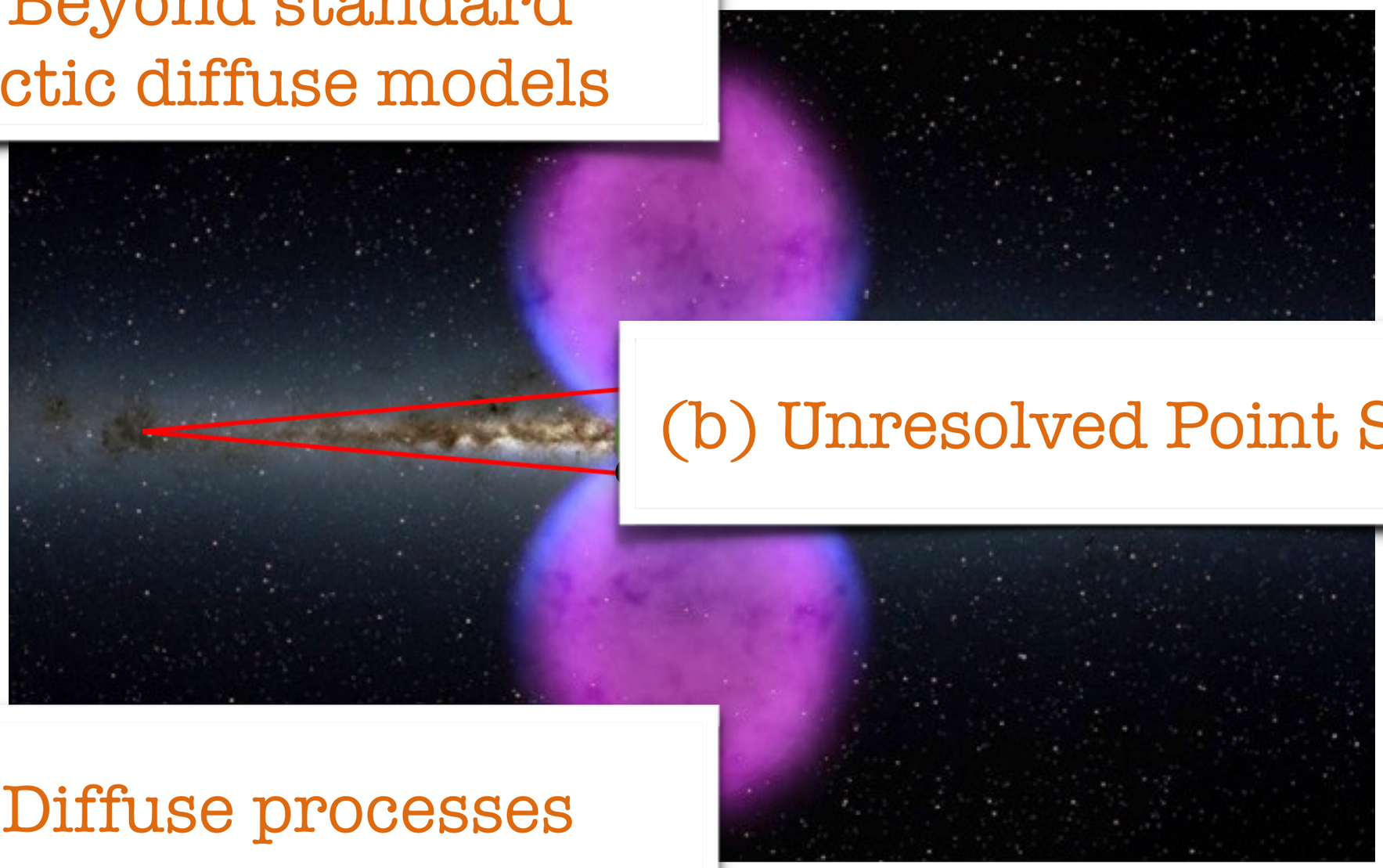


(b) Unresolved Point Sources

Interpretations of the GeV excess

(a) Beyond standard Galactic diffuse models

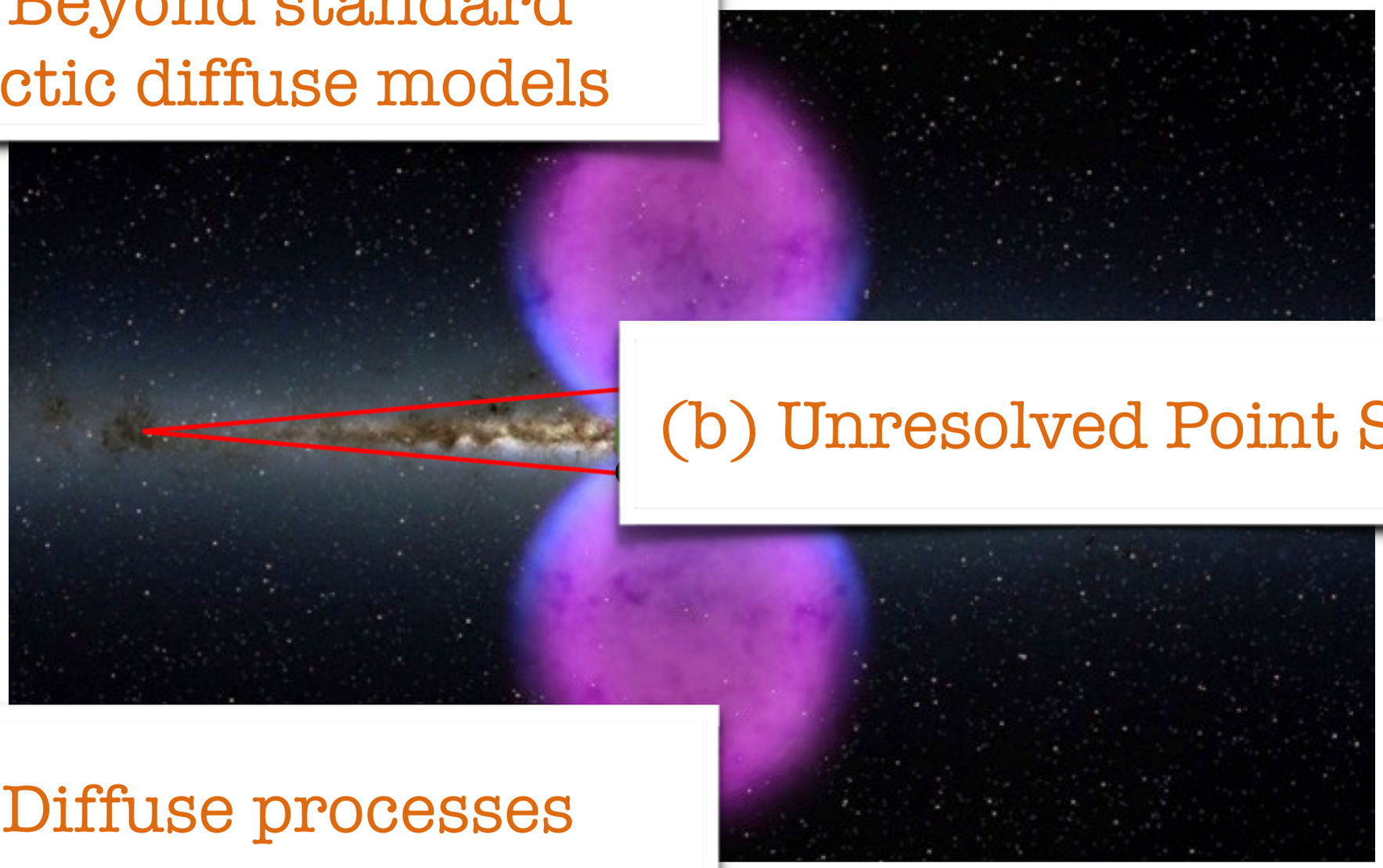


(b) Unresolved Point Sources

(c) Diffuse processes

Interpretations of the GeV excess

(a) Beyond standard Galactic diffuse models



(b) Unresolved Point Sources

(c) Diffuse processes

Constraints:

(a) Spectrum & Morphology of the excess? (b) Emission in other wavelengths?

“Standard” Galactic diffuse models

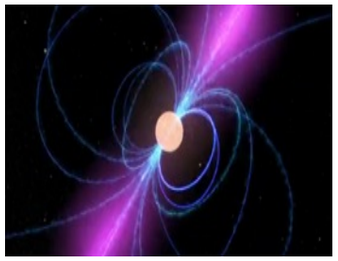
Standard assumptions (limitations) of the adopted approach:

- assumption of homogeneity and isotropy of CR diffusion
- assumption of homogeneity of CR re-acceleration, described through a scalar quantity
- 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.

Existing independent motivations to go beyond those propagation scenarios

→ Radial gradient in cosmic-ray transport Evoli+ PRL’12, Gaggero+ 2014

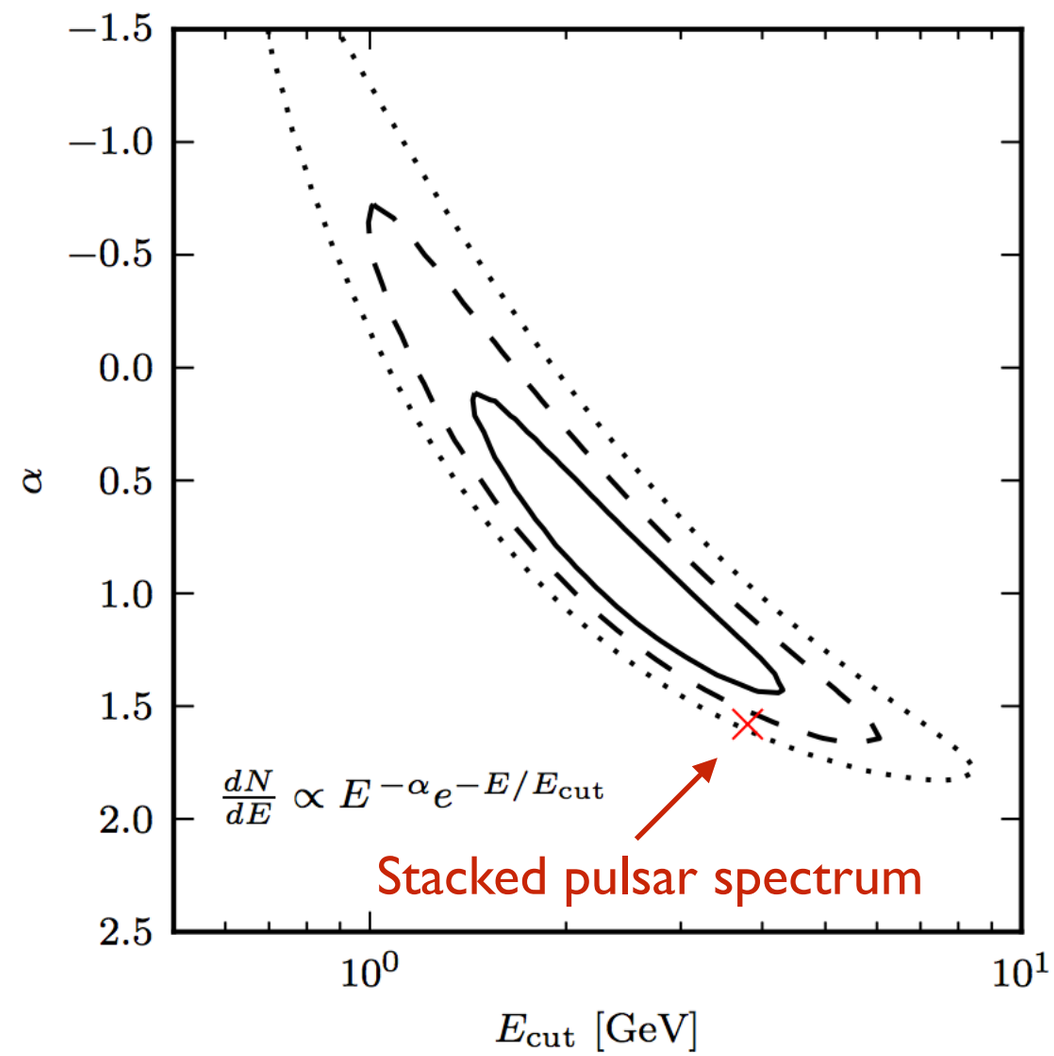
Unresolved point sources



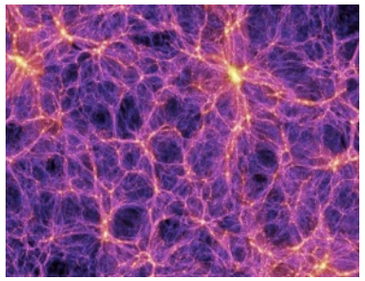
Millisecond Pulsars

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

- GeV excess spectrum consistent with observed pulsar gamma-ray properties.
- The emission from unresolved pulsars can account for **at most 10%** of the excess emission in both the Galactic Center and Inner Galaxy regions.
- The source distribution is well compatible with a disk-like population.
- Possible explanation by adding a "bulge" component.



Diffuse Processes



DM annihilation

Spectrum compatible with a **40 GeV** DM candidate annihilating into **b quarks** with thermal cross section

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

+ O(100) model building papers...

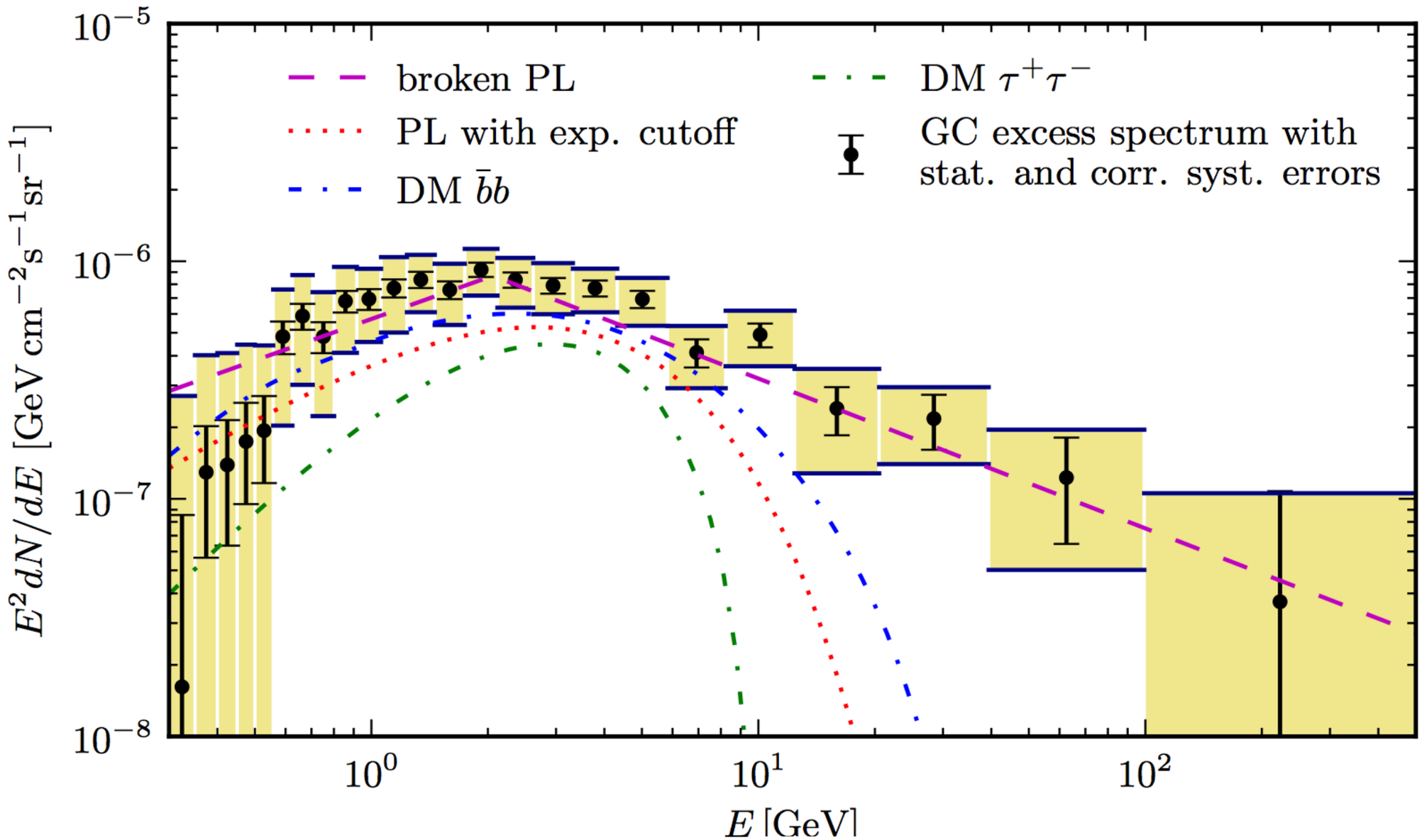
Burst-like events from an active past of the GC

Injection of high energetic protons or electrons during an explosive event some Myr ago.

Petrovic+2014; Carlson+2014

See W. Shepherd talk — EFT

Parametric fits to the GeV excess

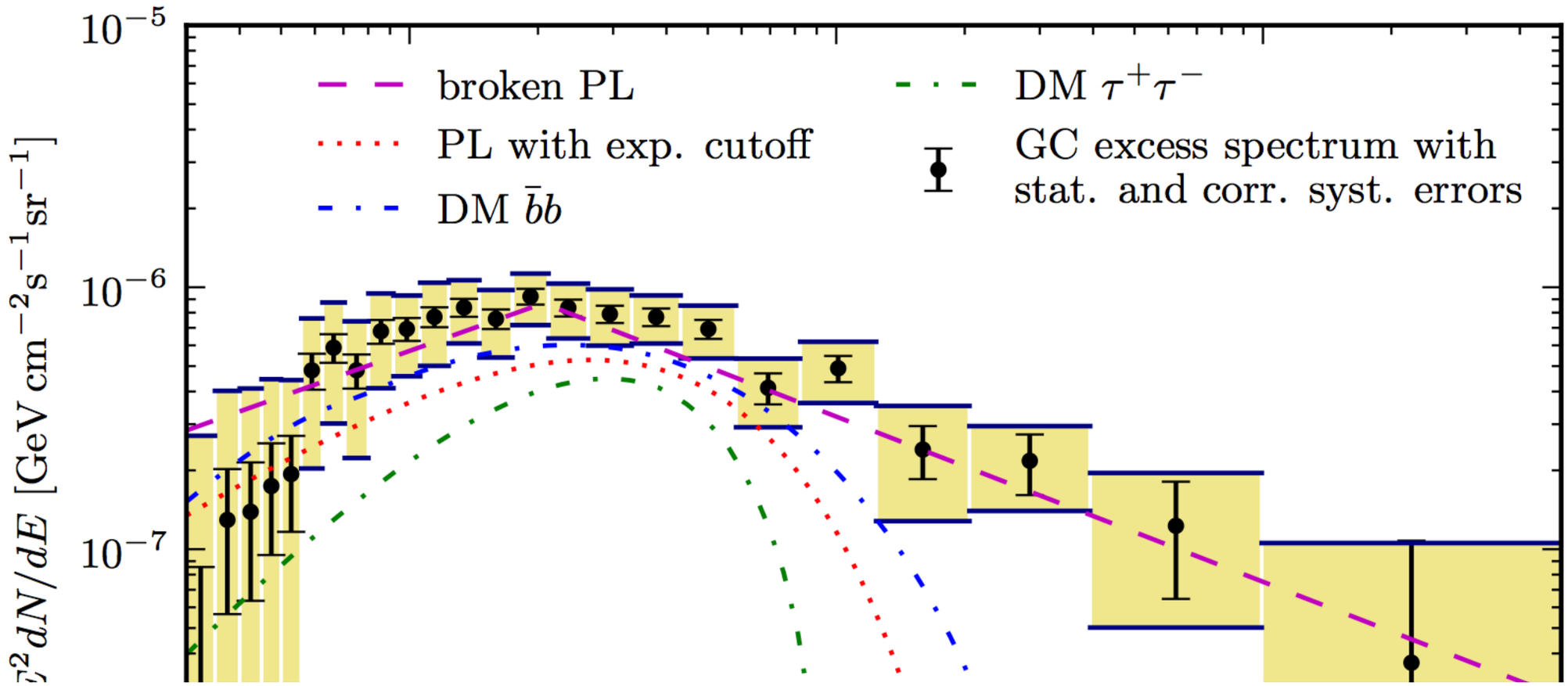


Fit with correlated errors
(empirical model systematics only)

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

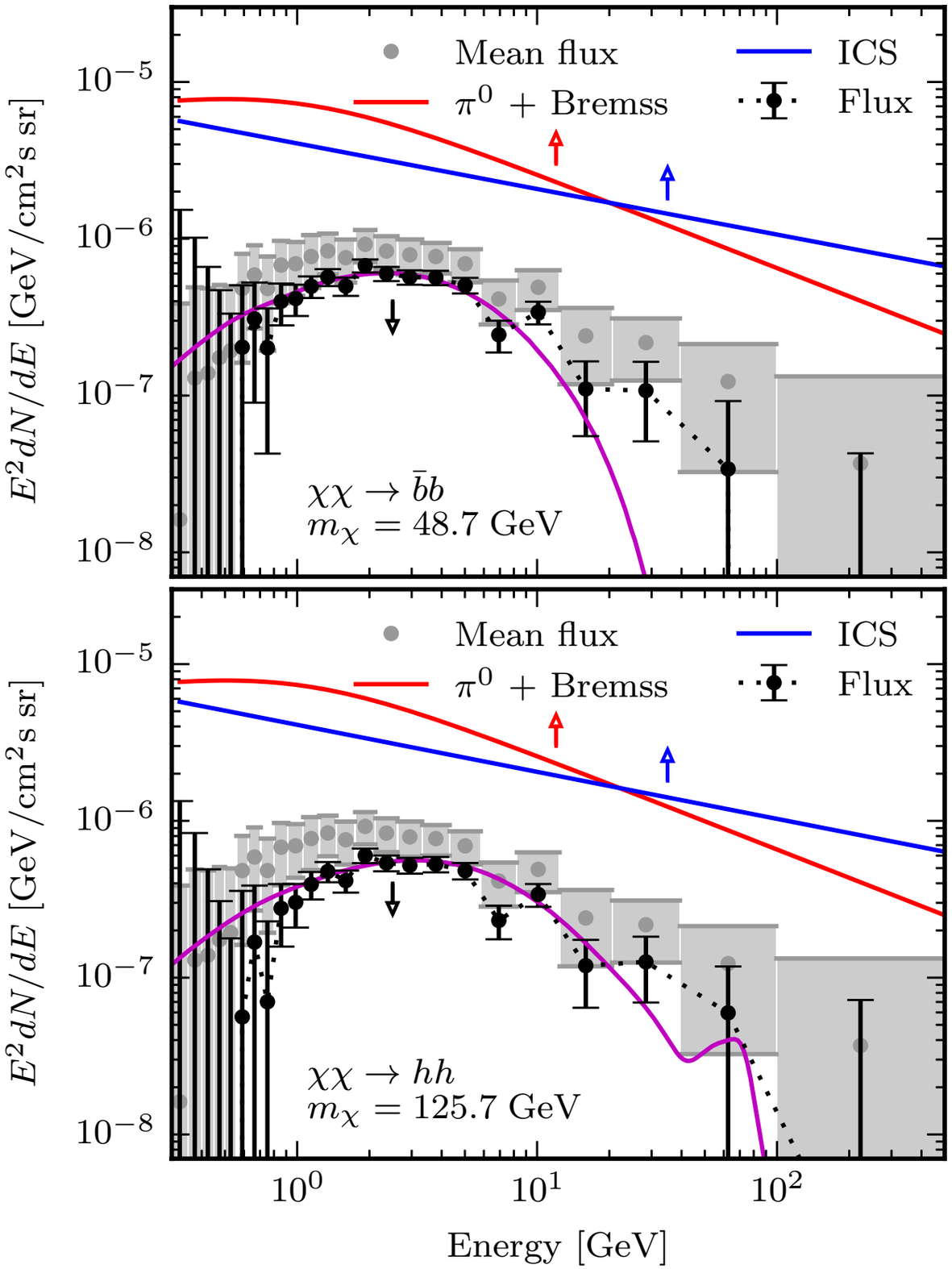
$$\Sigma_{ij} = (\sigma_i^{\text{stat.}})^2 \delta_{ij} + \Sigma_{ij,\,\text{mod}}^{\text{trunc}} + \Sigma_{ij,\,\text{res}}$$

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

DM fits: why they do such a good job?



The correlated errors are derived by the fluctuations above the GDE model prediction.

Correlated errors can be reduced to **variations of the slope and normalisation** of the main **GDE components**.

See C. Weniger talk

Those residuals, in the fit, are partially absorbed by the GCE template that might change not only in normalisation but also in slope(s).

"A Tail of Tails!"

Calore, Cholis, McCabe & Weniger, arXiv:1411.4647

+ HEP uncertainties here neglected!

See C. Weniger talk

Activity of the Galactic center

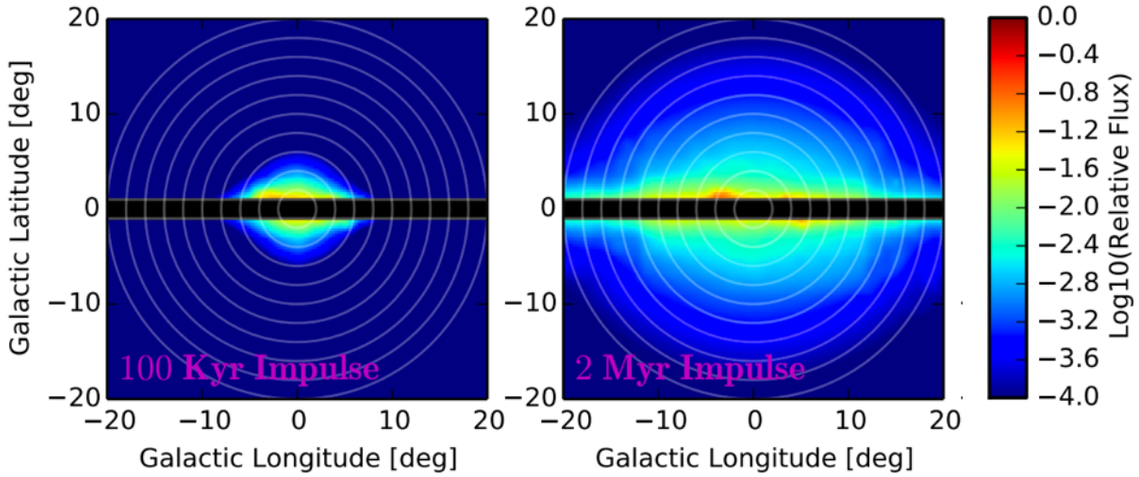
Injection of high energetic cosmic rays at the Galactic center during a burst-like event in the past.

$$f(r) \propto \frac{\exp[-r^2/R^2_{\rm dif}(t_i)]}{R^3_{\rm dif}(t_i)}$$

$$E_{\rm tot} \sim 10^{53}{\rm erg}$$

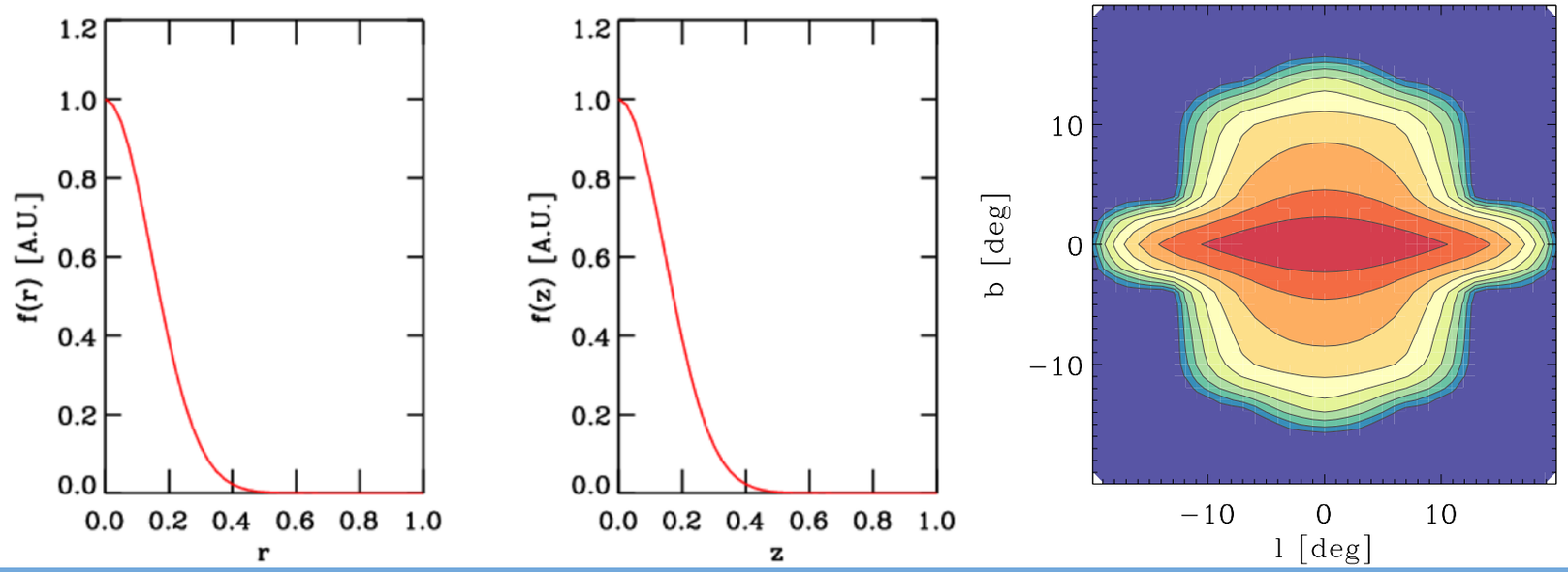
Proton injection

Carlson+2014



Electron injection

Petrovic+2014



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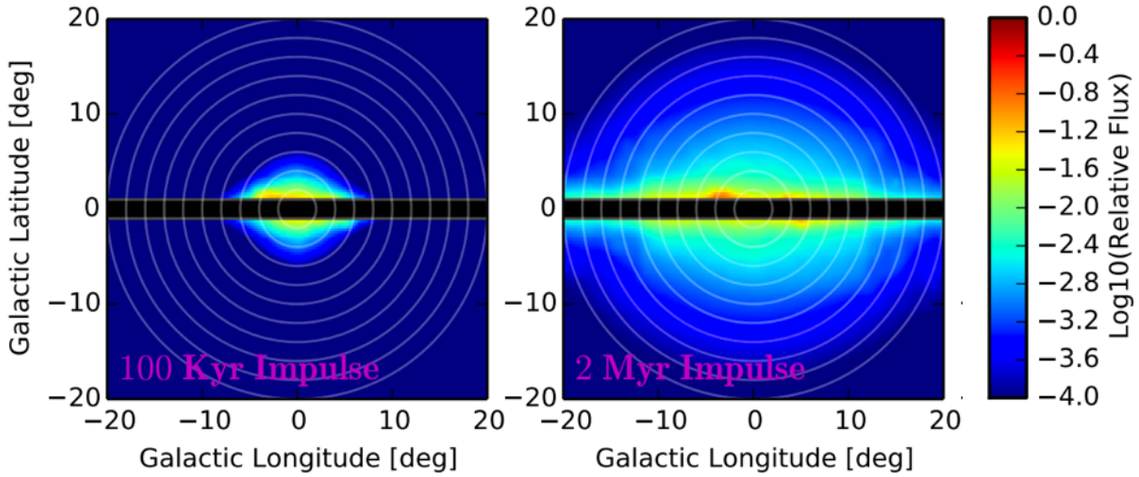
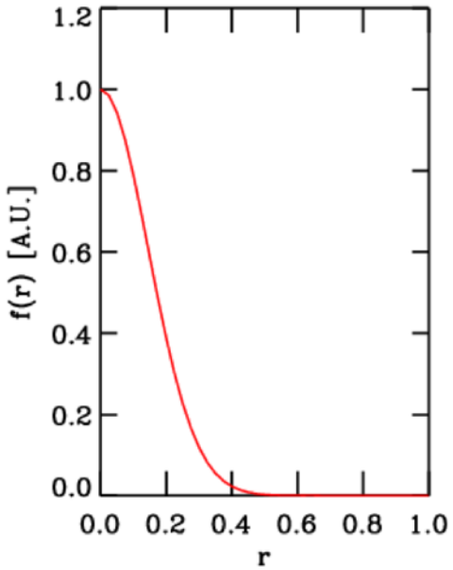
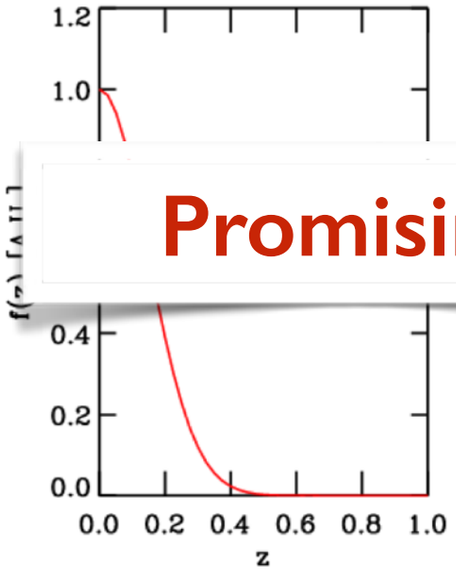
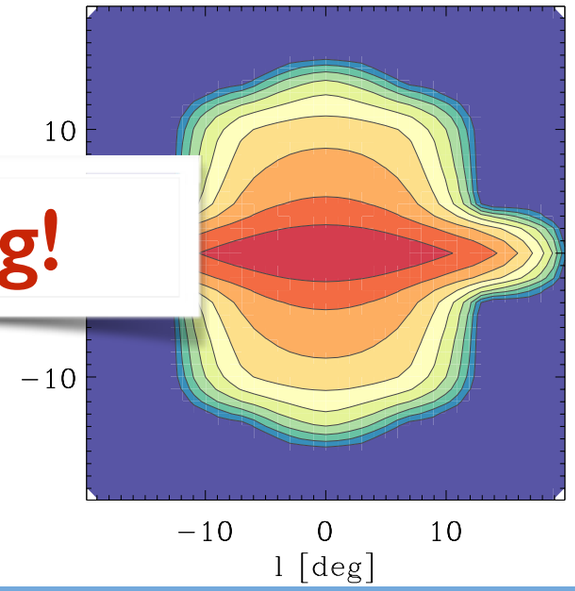


Electron injection

Petrovic+2014



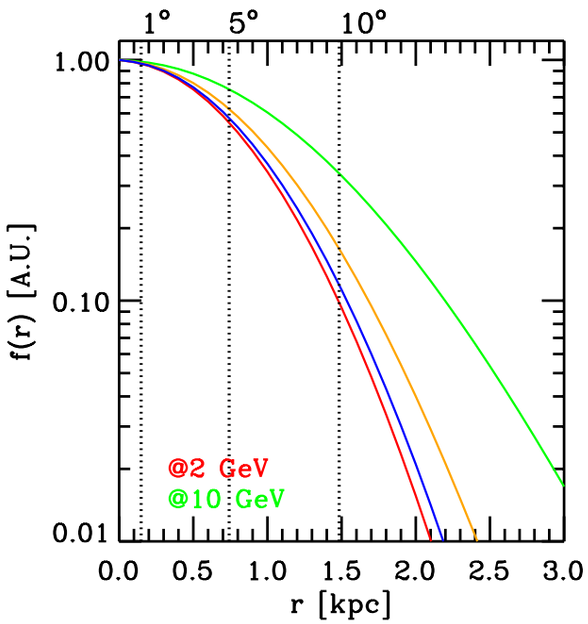


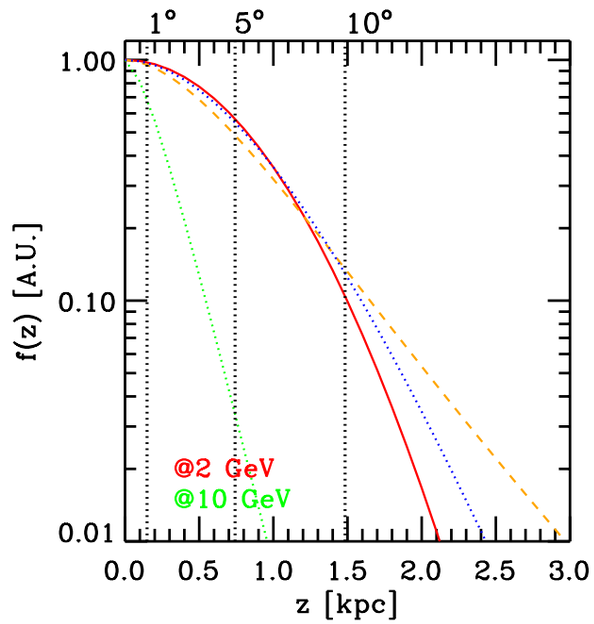


Promising!

Electron burst models

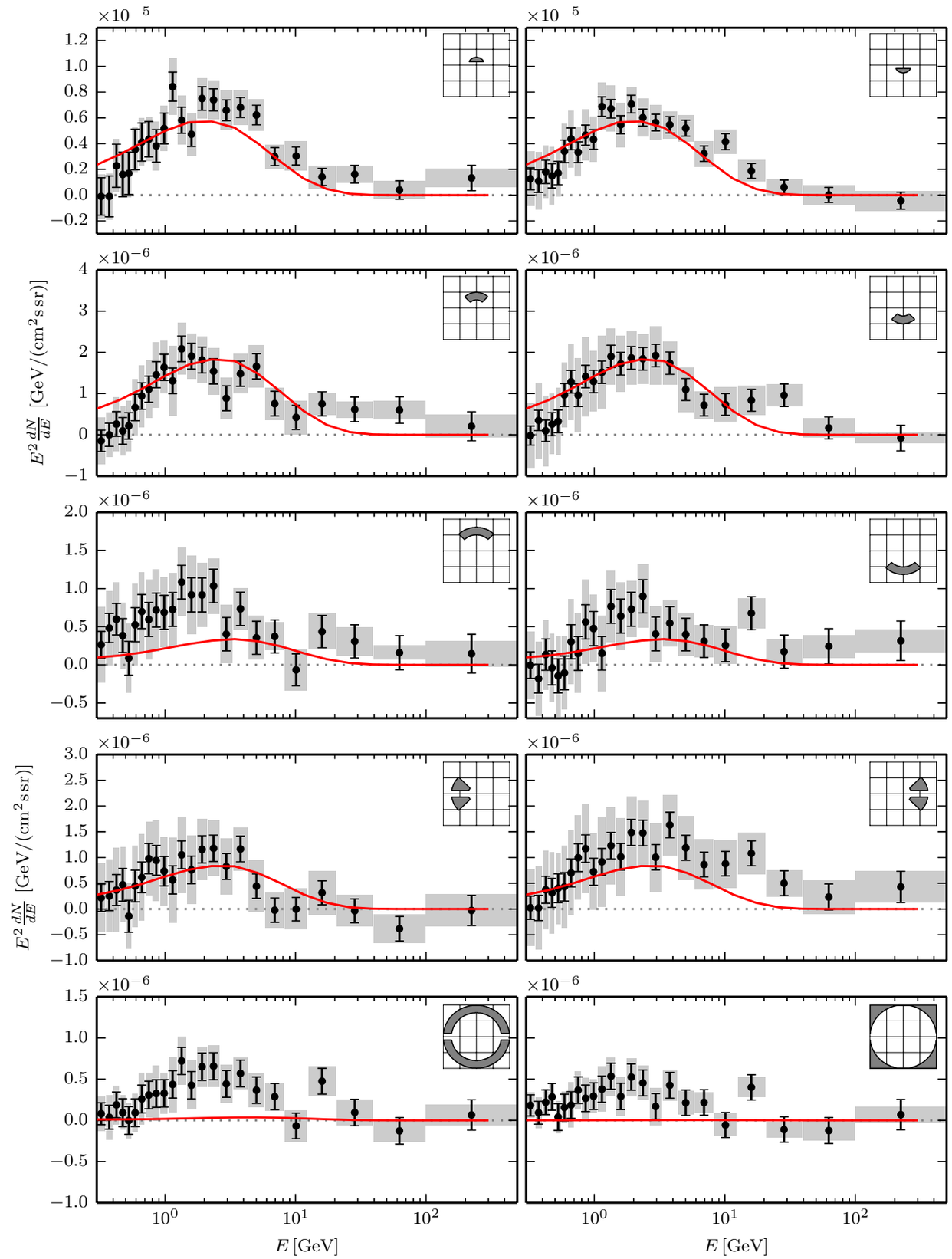
Calore, Cholis, Evoli, Hooper, Linden & Weniger, In prep.





Electron distribution
Full solution with DRAGON*

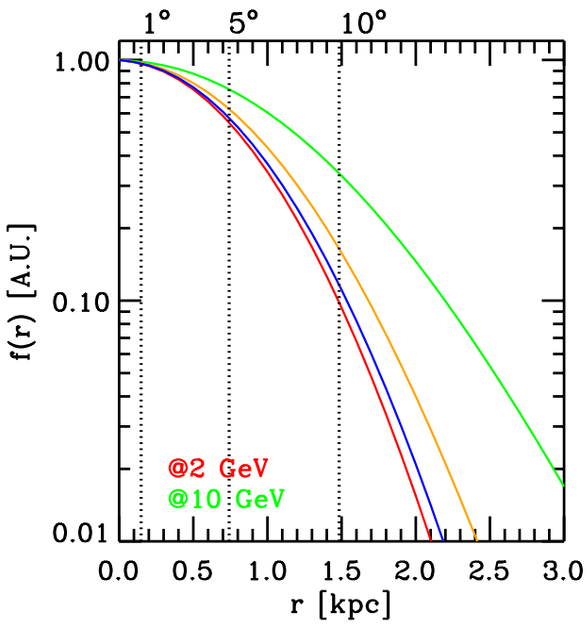
Gamma-ray emission from the model
and fit to GeV excess data

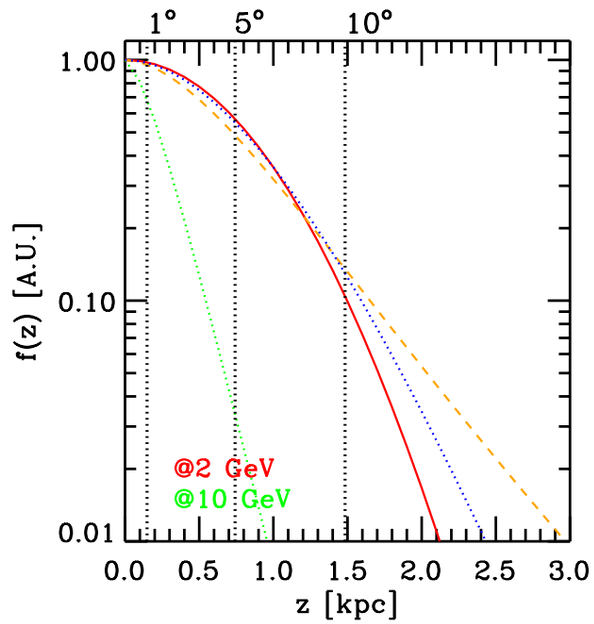


*Evoli+ http://www.dragonproject.org/Home.html

Electron burst models

Calore, Cholis, Evoli, Hooper, Linden & Weniger, In prep.



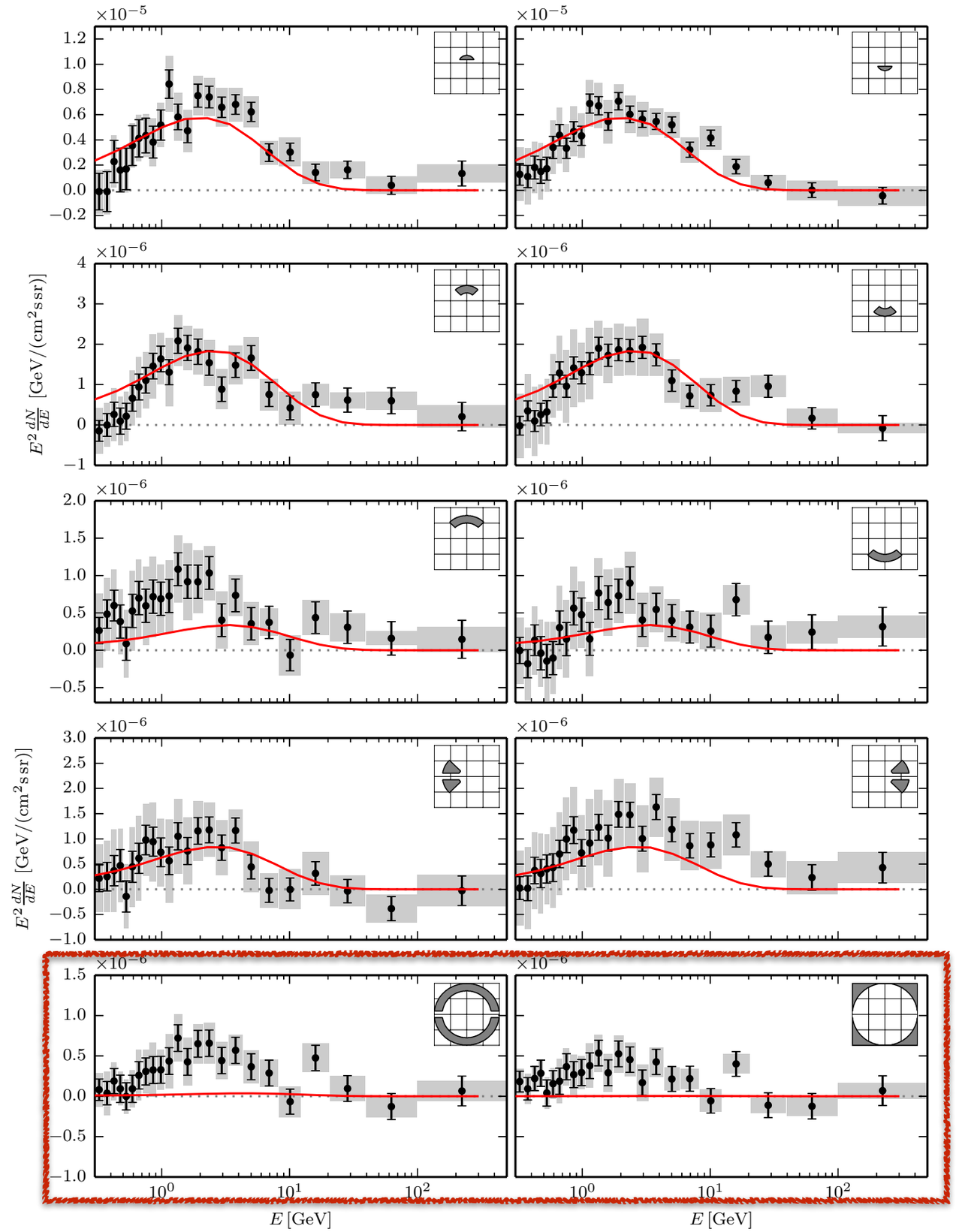


Electron distribution
Full solution with DRAGON*

Gamma-ray emission from the model and fit to GeV excess data

Good fit but difficult to push to high latitudes!?

*DRAGON: http://www.dragonproject.org/Home.html



Conclusions: an astro-particle perspective

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.

Conclusions: an astro-particle perspective

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- ✓ An **extended source in the inner part of Galaxy** symmetric density profile, does exist.
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What can we do?

- ✓ **Astro-** : investigate extreme cosmic rays propagation conditions; scrutinise viable astrophysical interpretations (point sources, bursts) through a multi-wavelengths approach.
- ✓ **Particle-** : look for corroborating evidence of the GeV excess in well-motivated models for dark matter.

See P. Agrawal, T. Rizzo & C. Weniger talks

- ✓ **Astro-particle**: search for dark matter with other targets (dwarfs?) and messengers (antiprotons?).

See C. Weniger talk