SkyFACT:
A new analysis of Fermi-LAT gamma-ray data

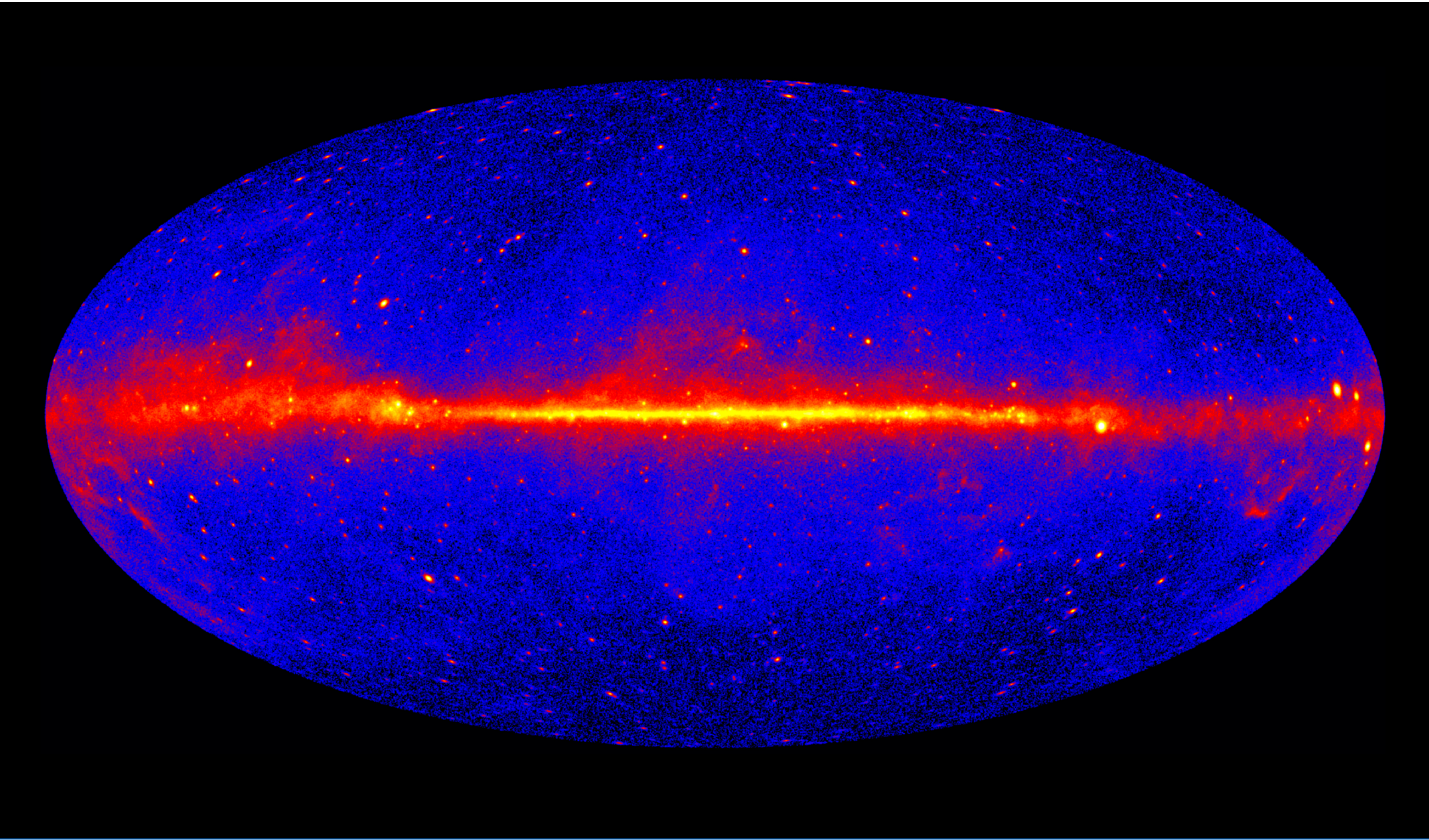
Francesca Calore*

*In collaboration with Richard Bartels, Emma Storm and Christoph Weniger

Columbus, OH — 09/08/2017

The Galactic centre GeV excess

Dedicated session on Monday afternoon



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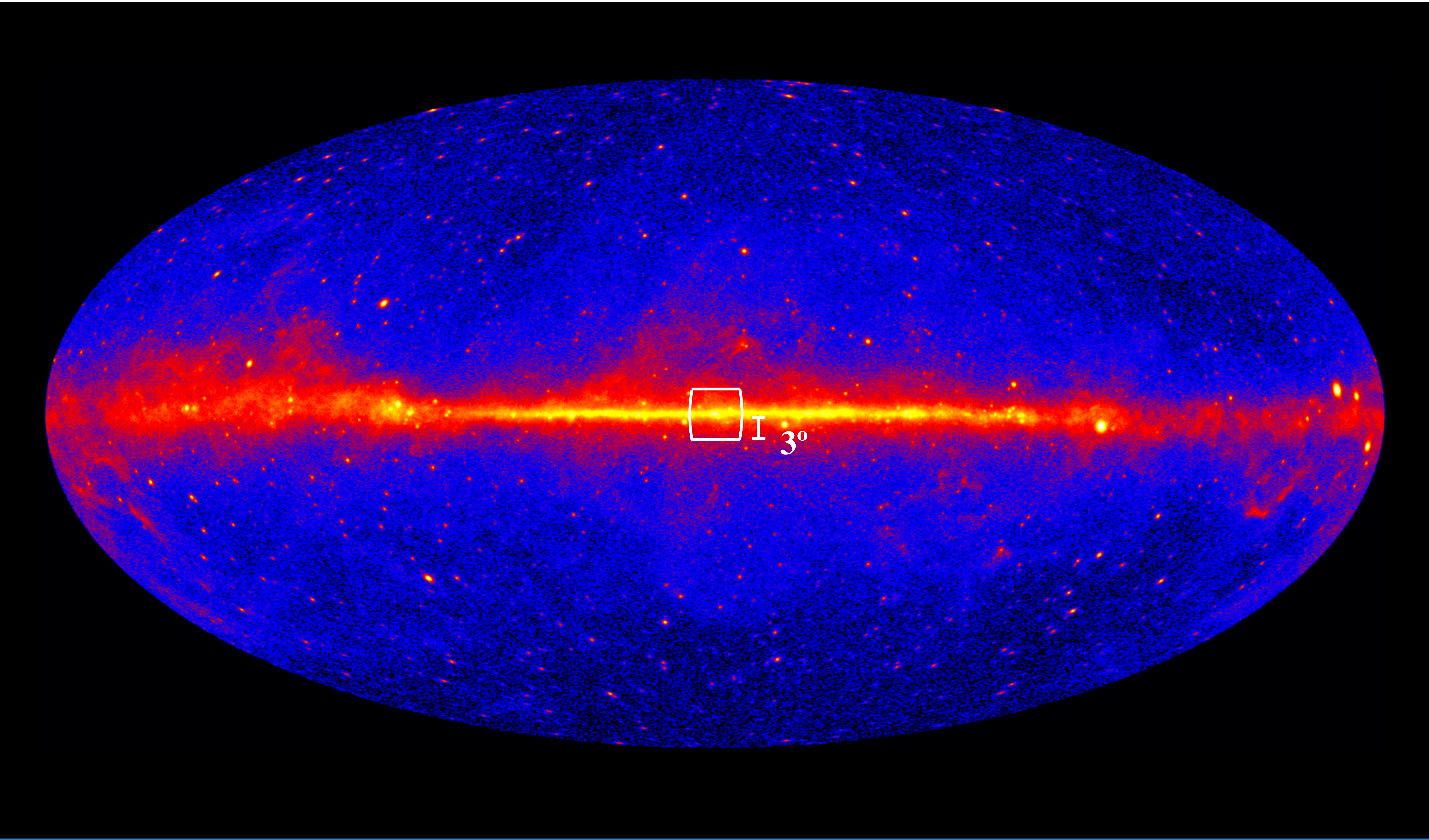

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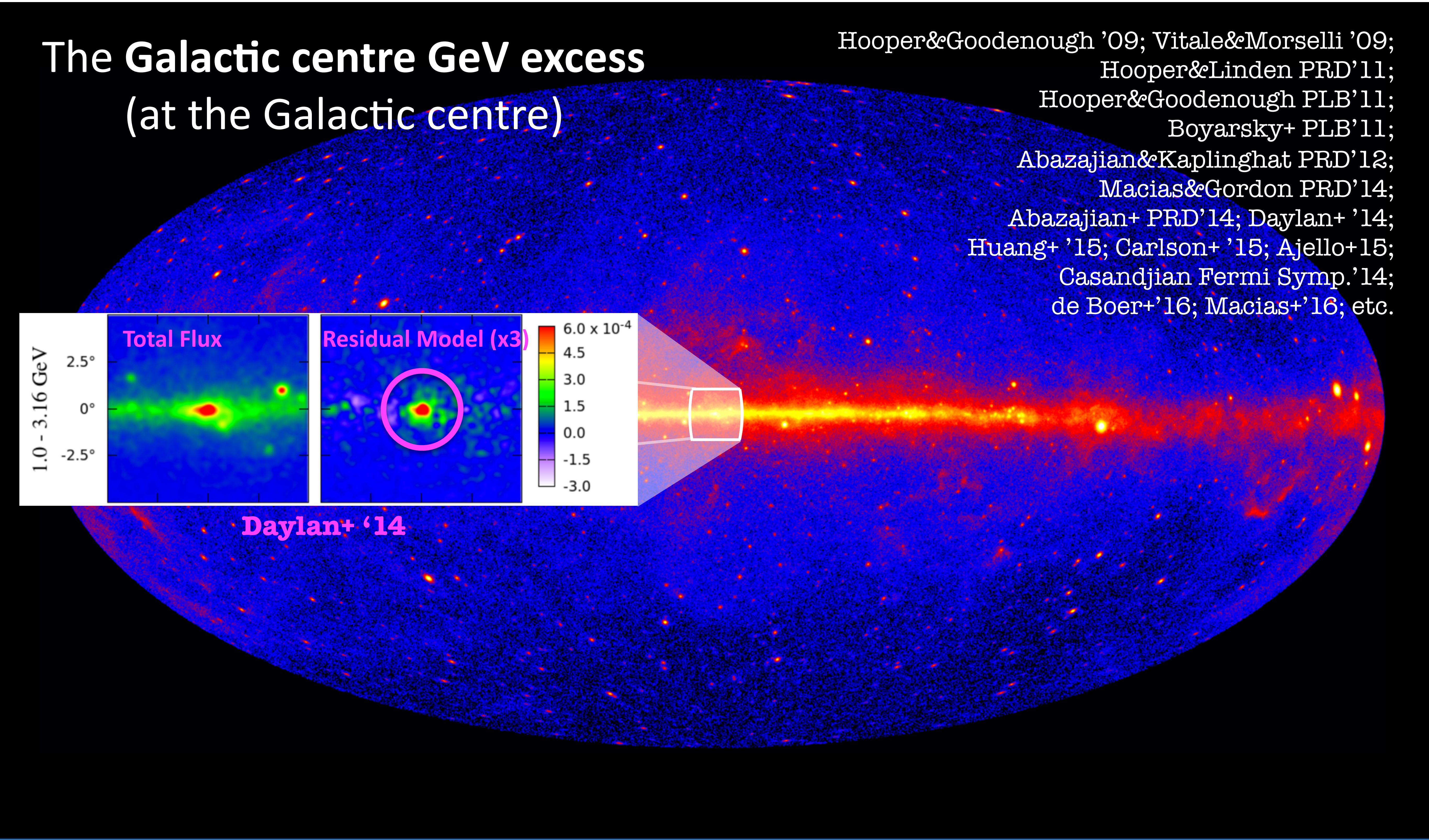

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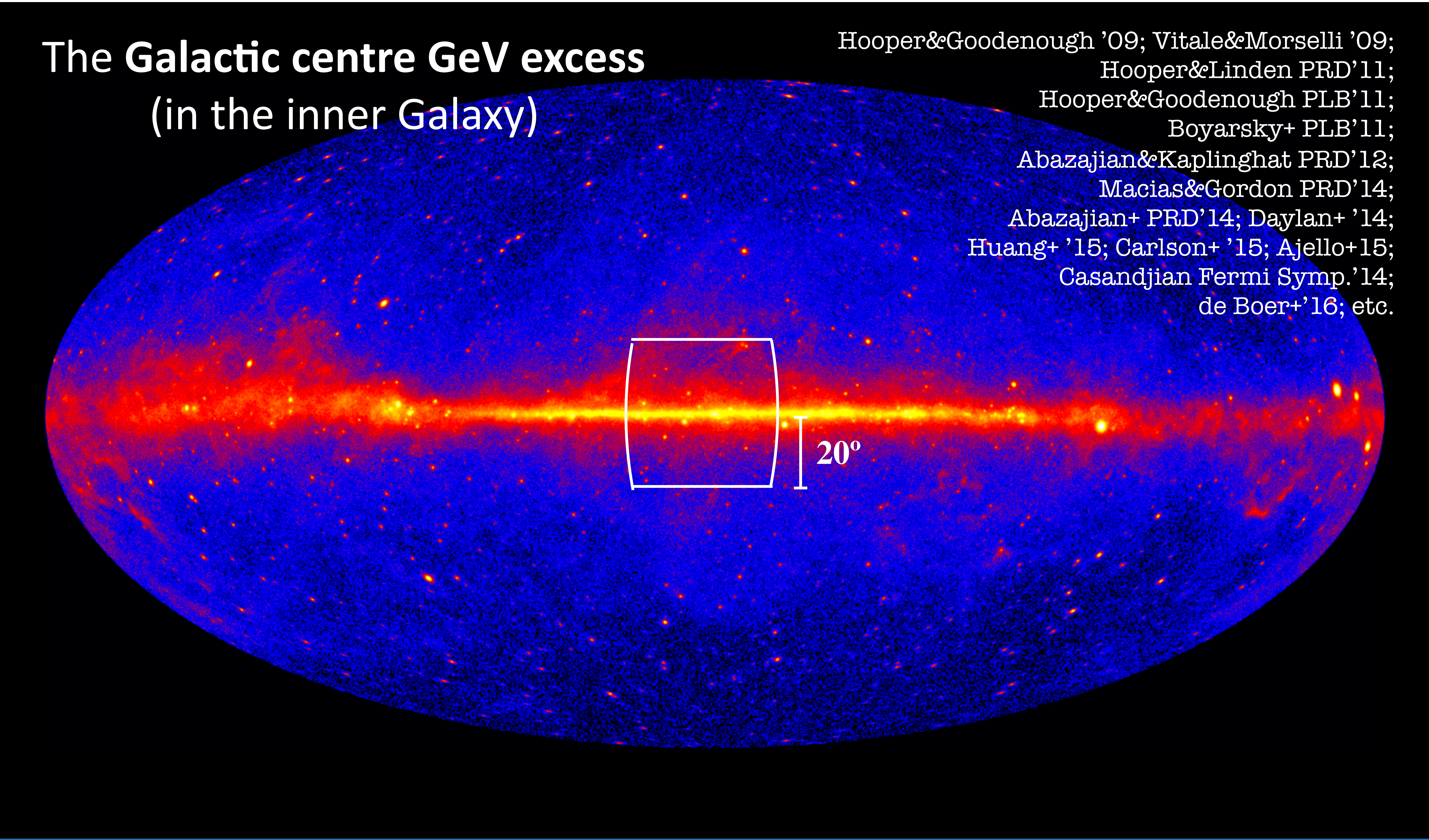
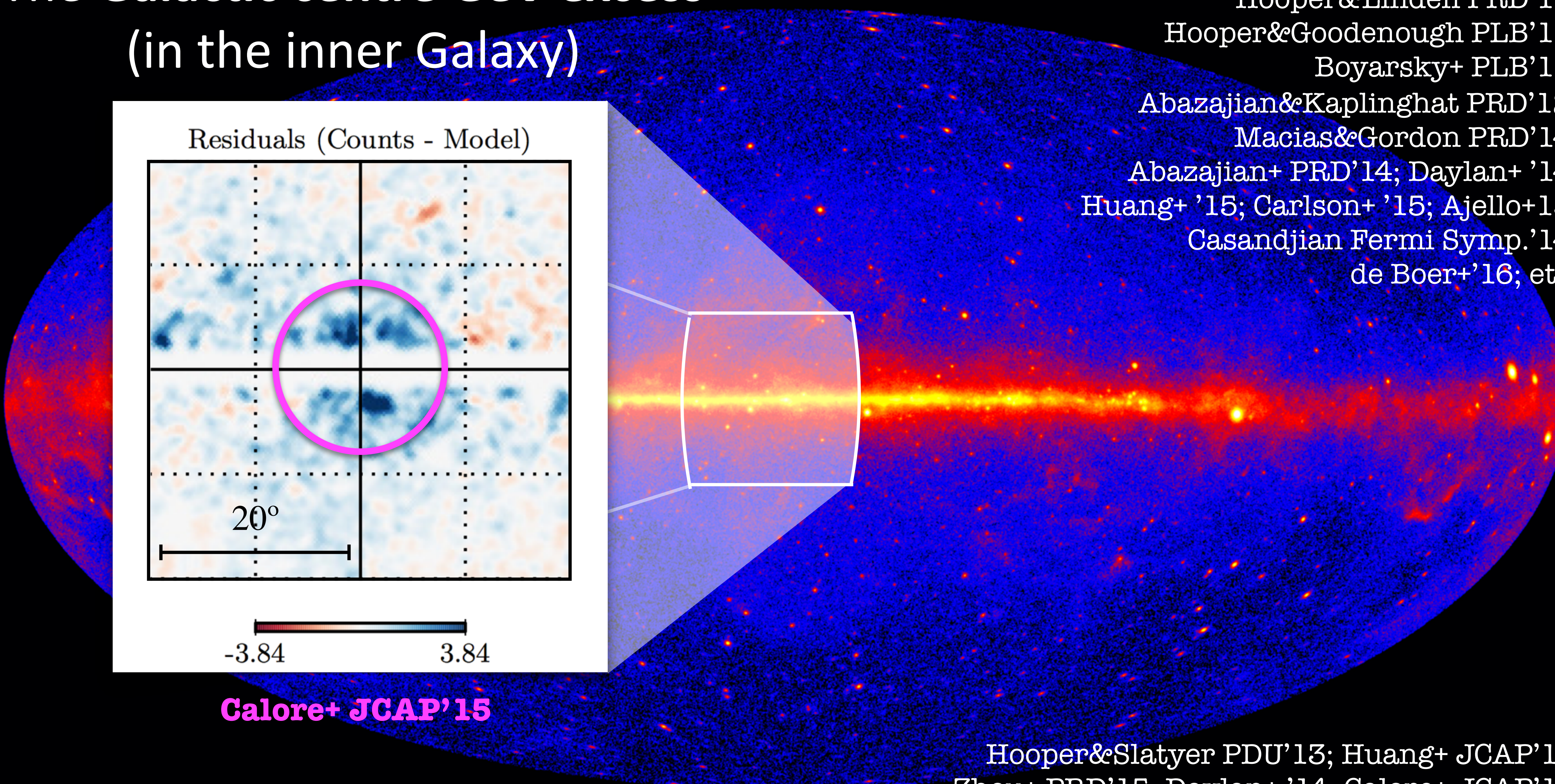


The Galactic centre GeV excess

The **Galactic centre GeV excess**
(in the inner Galaxy)

Hooper&Goodenough '09; Vitale&Morselli '09;
Hooper&Linden PRD'11;
Hooper&Goodenough PLB'11;
Boyarsky+ PLB'11;
Abazajian&Kaplinghat PRD'12;
Macias&Gordon PRD'14;
Abazajian+ PRD'14; Daylan+ '14;
Huang+ '15; Carlson+ '15; Ajello+15;
Casandjian Fermi Symp.'14;
de Boer+'16; etc.



Calore+ JCAP'15

Hooper&Slatyer PDU'13; Huang+ JCAP'13;
Zhou+ PRD'15; Daylan+ '14; Calore+ JCAP'15;
Gaggero+ 2015; Ajello+ 2015; Huang+JCAP '15
Linden+PRD'16; Horiuchi+'16; Ackermann+ApJ'17; Ackermann+2017; etc.

Some open questions and challenges

- ✓ What is the role of non-standard cosmic-ray source distributions and cosmic-ray propagation?

  Gaggero+ JCAP'15; Carlson+'15

- ✓ Can we find a large population of dim sources that would be associated with the bulge in other wavelengths?

  Calore+ ApJ'16

- ✓ Is the spectrum of the GeV excess truly uniform up to 10 degrees above and below the Galactic disc?

  Linden+ PRD'16

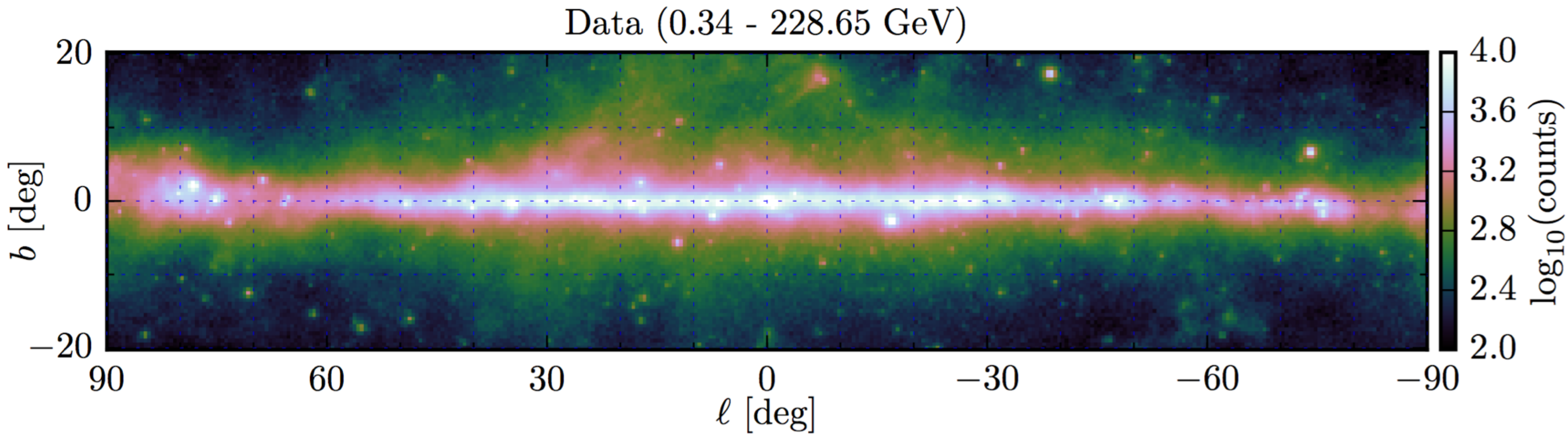
- ✓ How much is the GeV excess component degenerate with the Fermi bubbles?

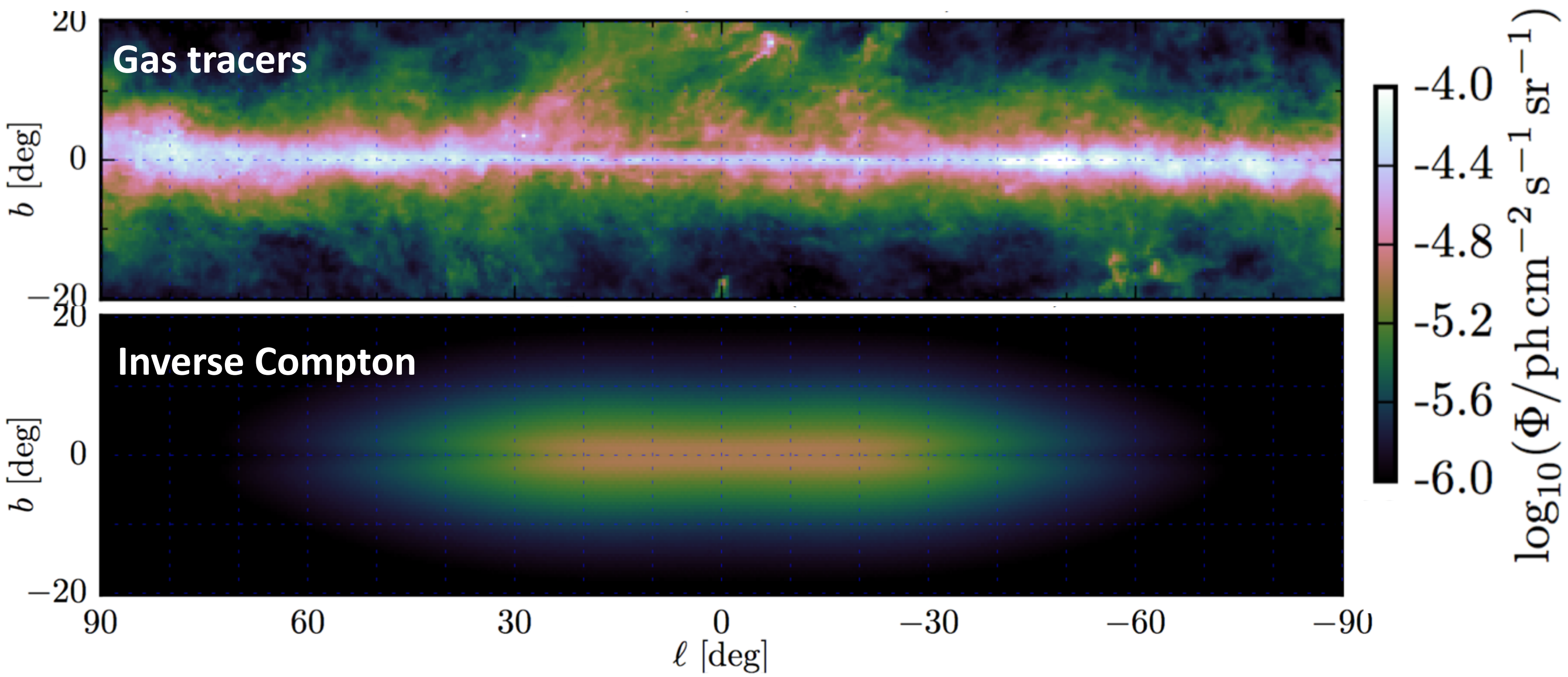
  Ackermann+ ApJ'17

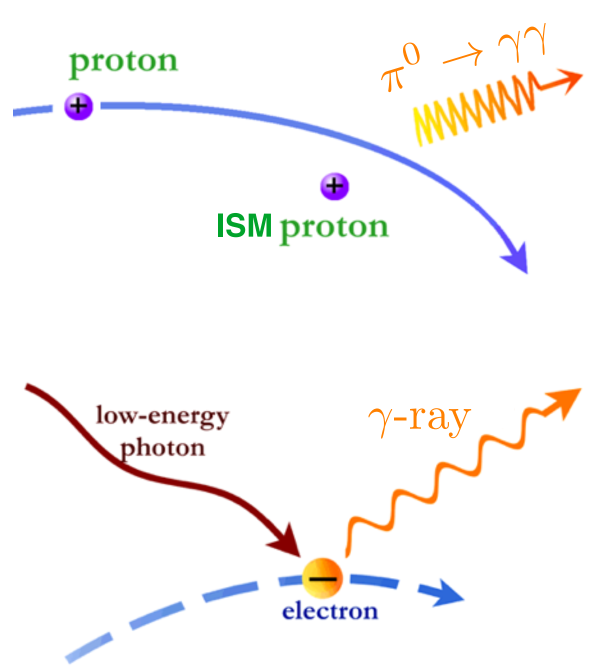
The range of explored uncertainties, albeit larger than in any other study to date, is yet not a full representation of the uncertainties in the modeling, because residuals persist in all cases considered.

Ackermann+ ApJ'17

Fitting the gamma-ray sky

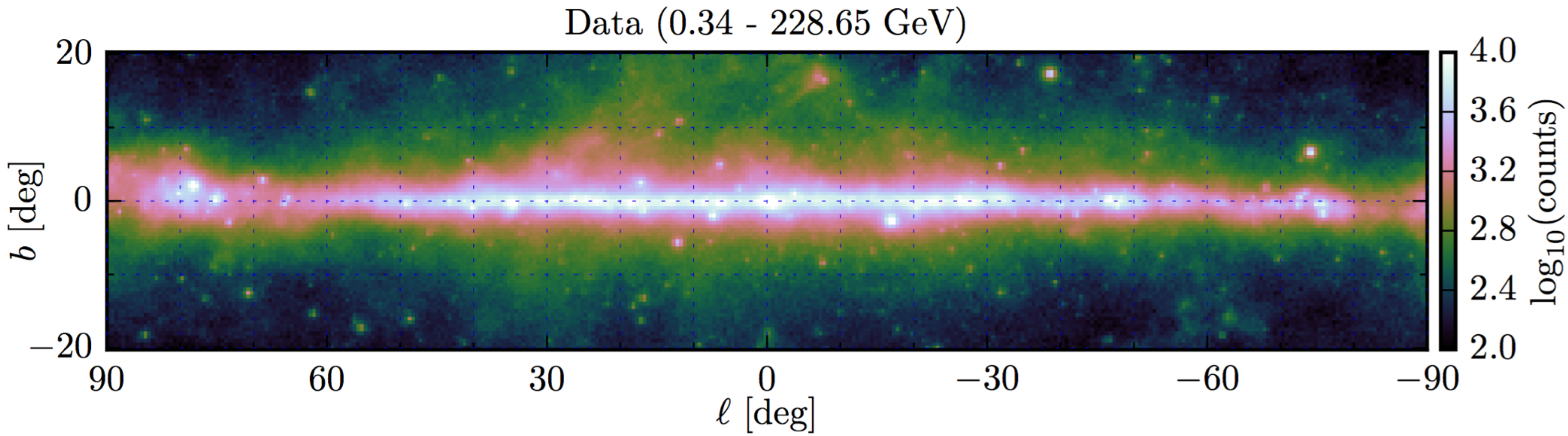


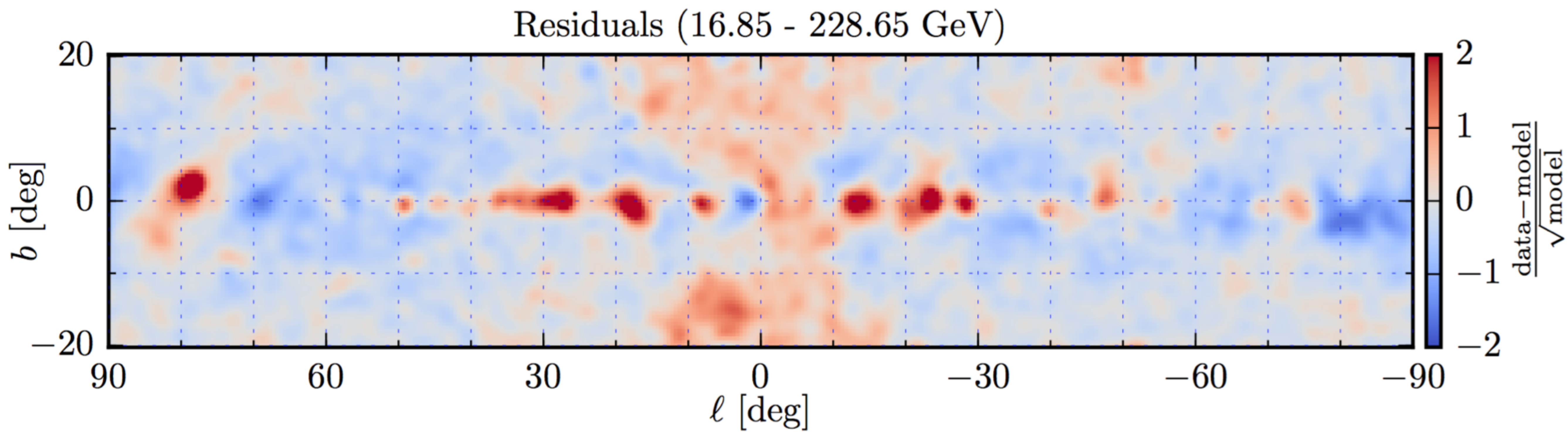




+ 3FGL point sources

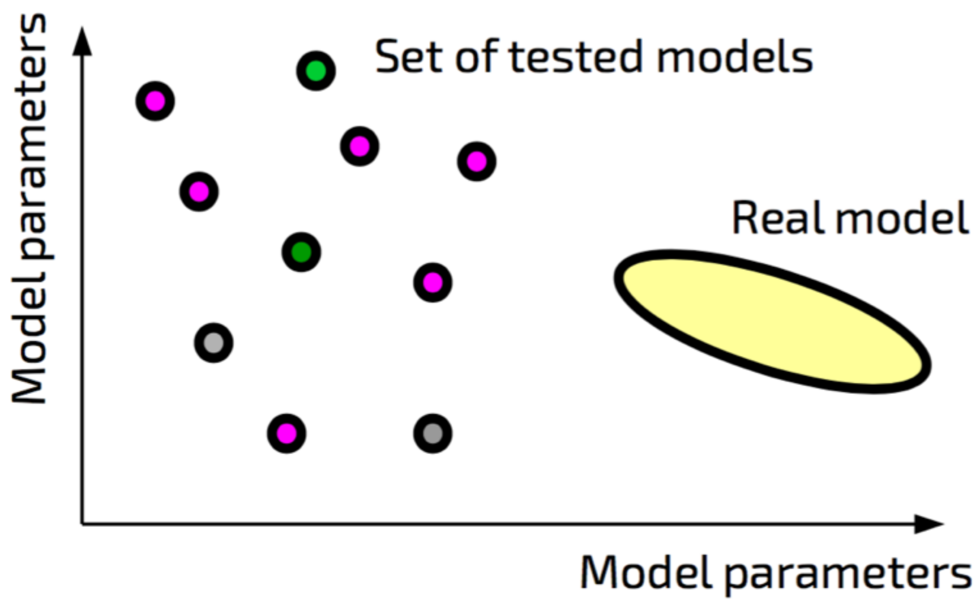
Fitting the gamma-ray sky





Large residuals (~30%) remain in the sky with this simple model, but clear structures emerge (extended sources, Fermi bubbles)

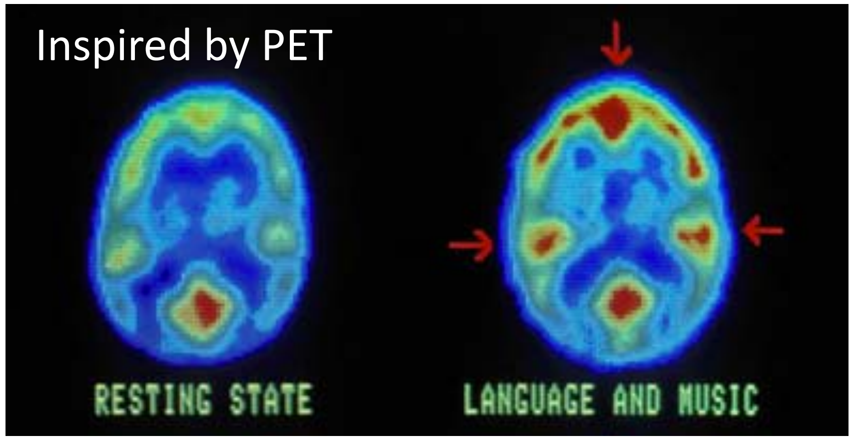
A way forward



Imperfect modelling might lead to severely **biased estimators**, above all for extended emission features.

Intrinsic uncertainties in spectral/spatial predictions must be fully taken into account by a very large number of nuisance parameters.

Penalised Poisson likelihood with regularisation conditions: **Sky F**actorisation with **A**daptive **C**onstraining **T**emplates (**SkyFACT**)



Collaboration with **Emma Storm** and **Christoph Weniger** (GRAPPA, University of Amsterdam)

Storm, Weniger & Calore JCAP'17 [arXiv:1705.04065]

General: Fit to gamma-ray data

$$\text{Model} = \sum_k \text{Spectrum} \times \text{Morphology}$$

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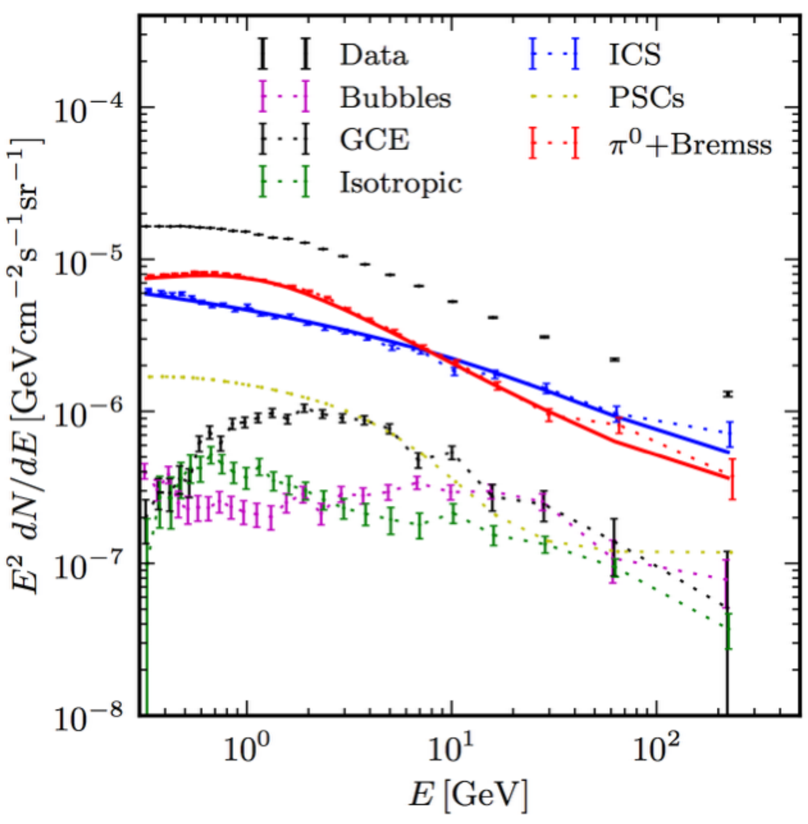

$$\phi_{pb} = \sum_k T_p^{(k)} \sigma_b^{(k)}$$

k: model component
p: spatial pixel
b: energy bin

Hooper+ PDU'13; Huang+ JCAP'13; Daylan+ '14; Calore+ JCAP'15; Ajello+ ApJ'15; Gaggero+ JCAP'15

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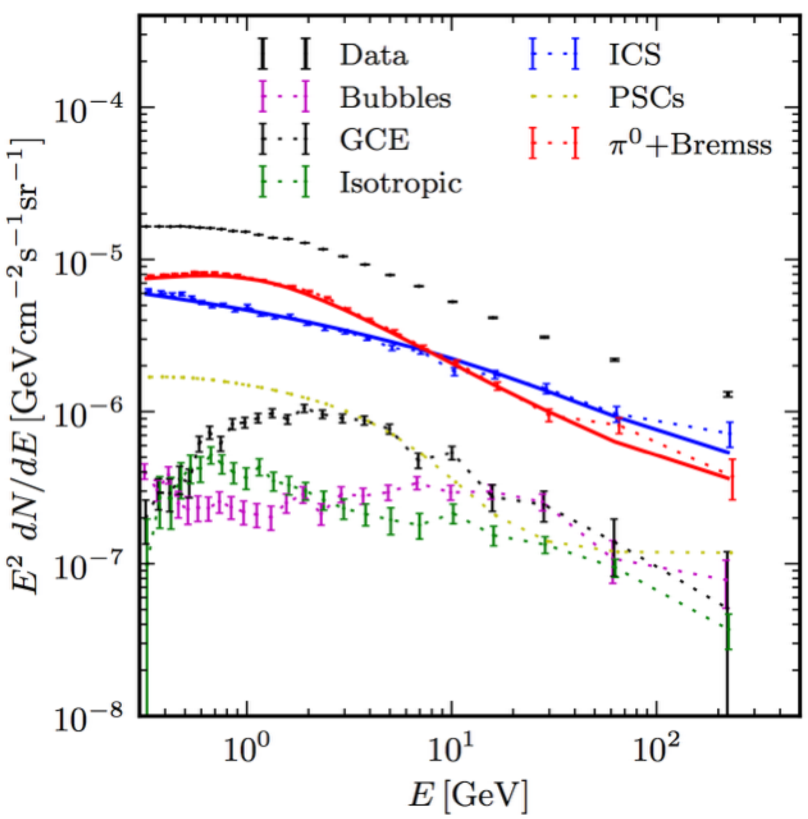
$$\text{Model} = \sum_k \text{Spectrum} \times \text{Morphology}$$



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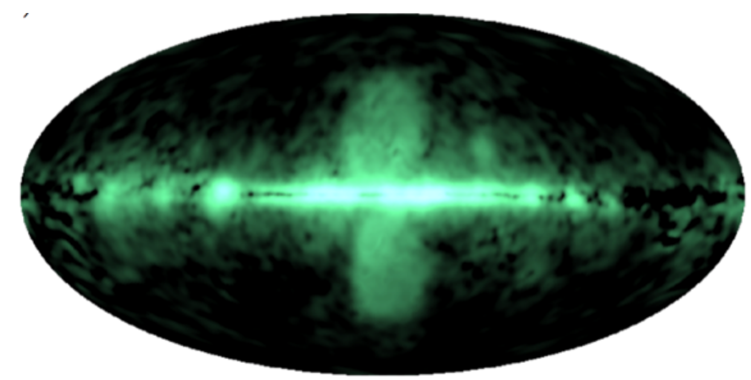
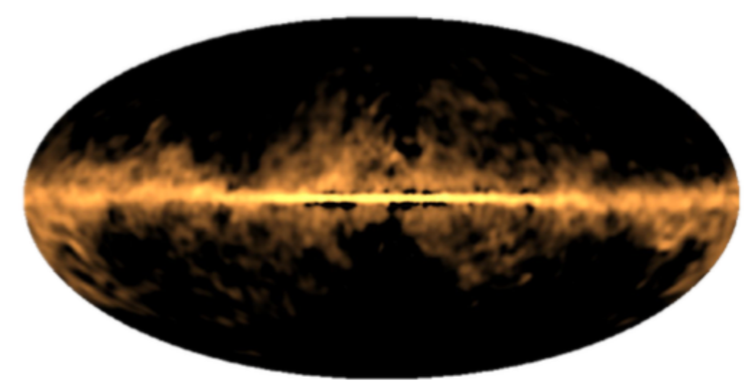
Hooper+ PDU'13; Huang+ JCAP'13; Daylan+ '14; Calore+ JCAP'15; Ajello+ ApJ'15; Gaggero+ JCAP'15

$$\phi_{pb} = \sum_k S_b^{(k)} \tau_p^{(k)}$$

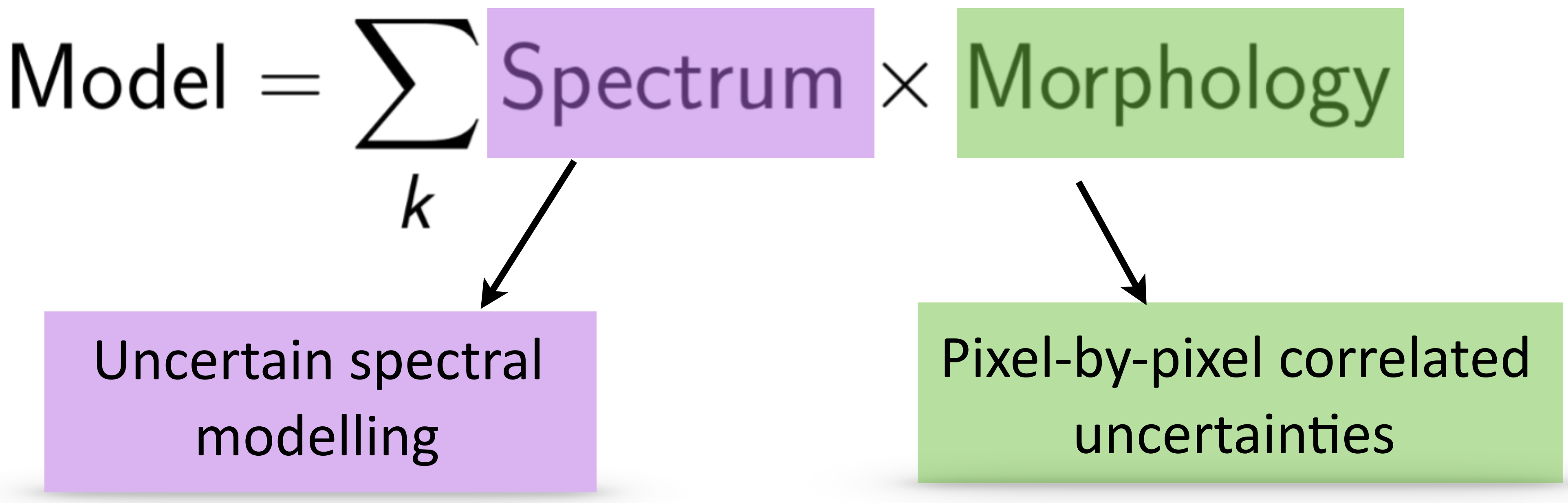
k: model component
p: spatial pixel
b: energy bin





Selig+ A&A'14; Huang+ JCAP'16; de Boer+'16

SkyFACT



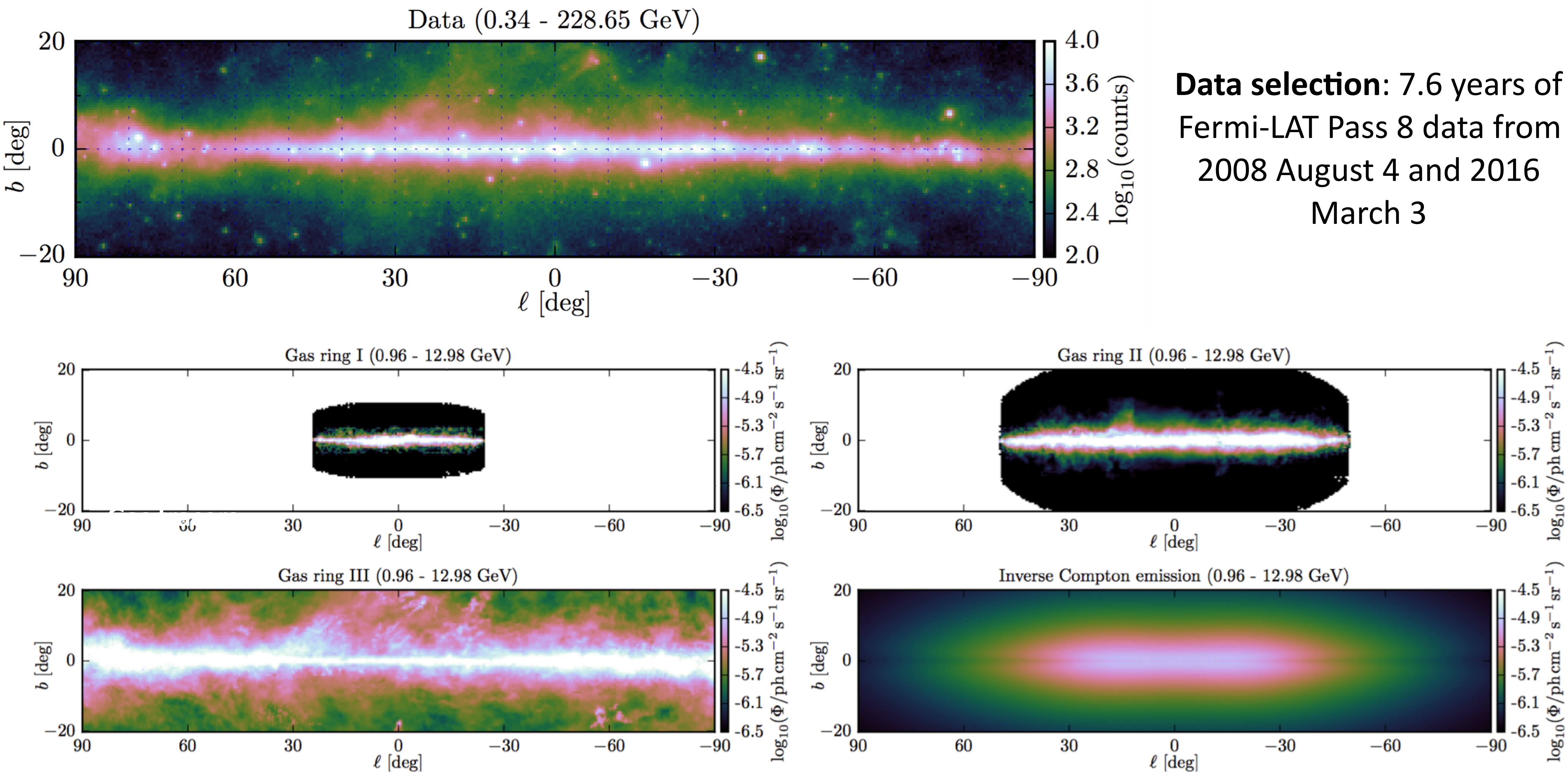
$$\phi_{pb} = \sum_k T_p^{(k)} \tau_p^{(k)} \cdot S_b^{(k)} \sigma_b^{(k)} \cdot \nu^{(k)}$$

$$\ln \mathcal{L} = \ln \mathcal{L}_{\mathrm{P}} + \ln \mathcal{L}_{\mathrm{R}}(\lambda, \lambda', \lambda'', \eta, \eta')$$

Penalized Poisson likelihood with regularisation conditions

- ➡ Facilitate component separation in scenarios where only partial knowledge about the spatio/spectral characteristics of the components is available.
- ➡ Introduce a sufficient number of nuisance parameters in the analysis such that we can obtain formally good fits and perform model comparison.

Modelling the Galactic diffuse emission



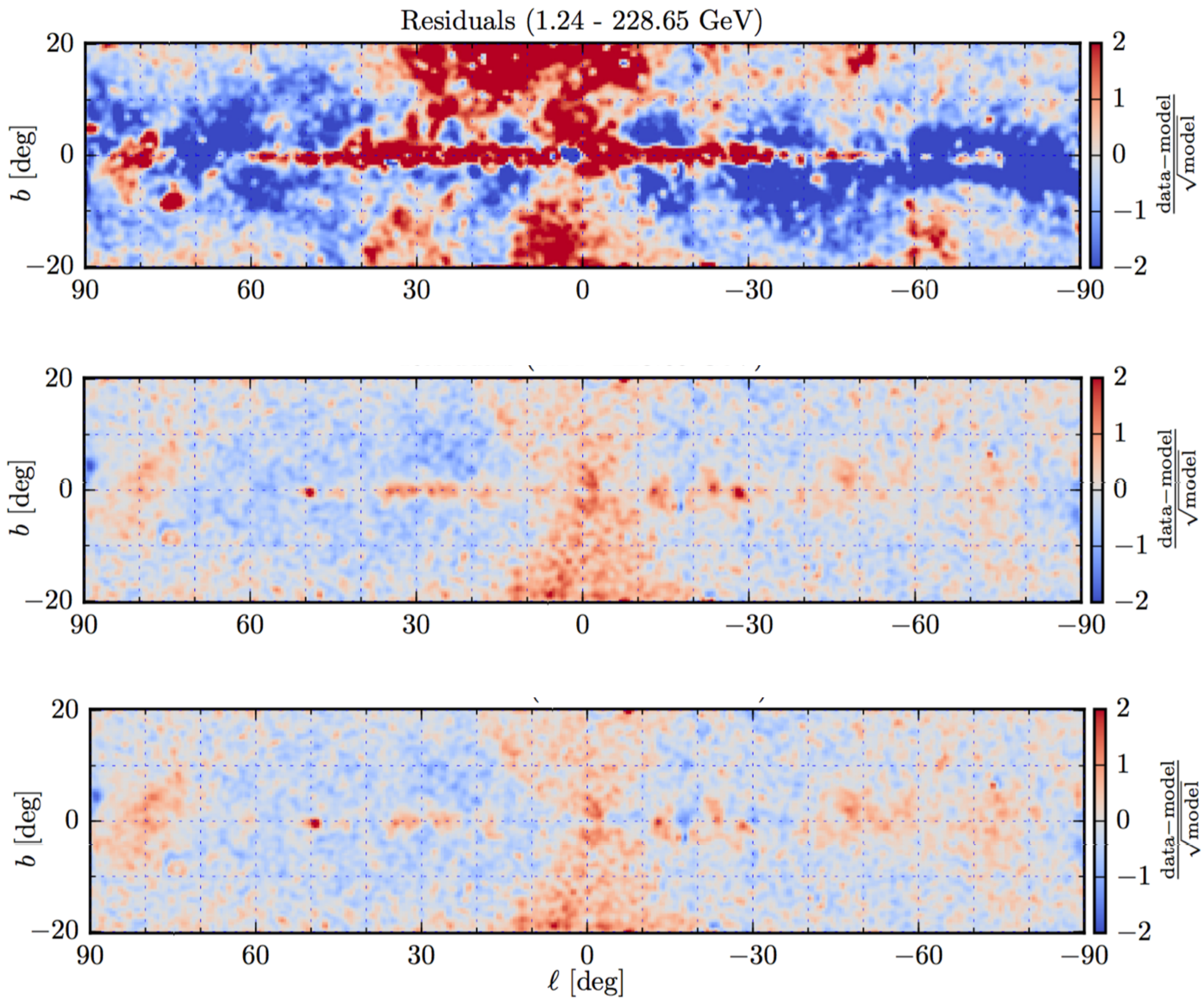
Data selection: 7.6 years of Fermi-LAT Pass 8 data from 2008 August 4 and 2016 March 3

Gas templates: Sum of gas column densities for atomic and molecular hydrogen (from GALPROP public release); No dark gas correction (=> will show up in modulation parameters); Radial binning (0–3.5 kpc, 3.5–6.5 kpc, and 6.5–19 kpc)

Inverse Compton: standard modelling (ISRF from public GALPROP, propagation with DRAGON)

Input spectra from Ackermann+2012

A "minimal model" for the Galactic emission



Run 1: gas/ICS/3FGL spectra constrained (~20-25%); 30% residuals remain

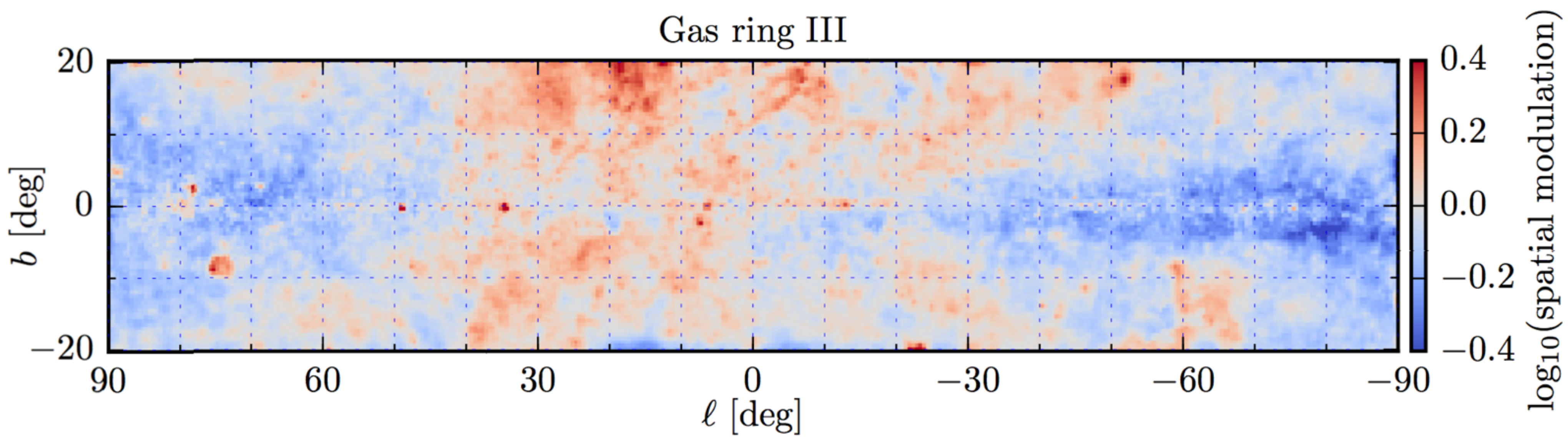
Run 2: spatial modulation (33% for gas; 100% for ICS) and smoothing (20% for gas; 10% for ICS); < 10% residuals remain

Run 3: radial binning of gas templates; further reduction of residuals along the disk

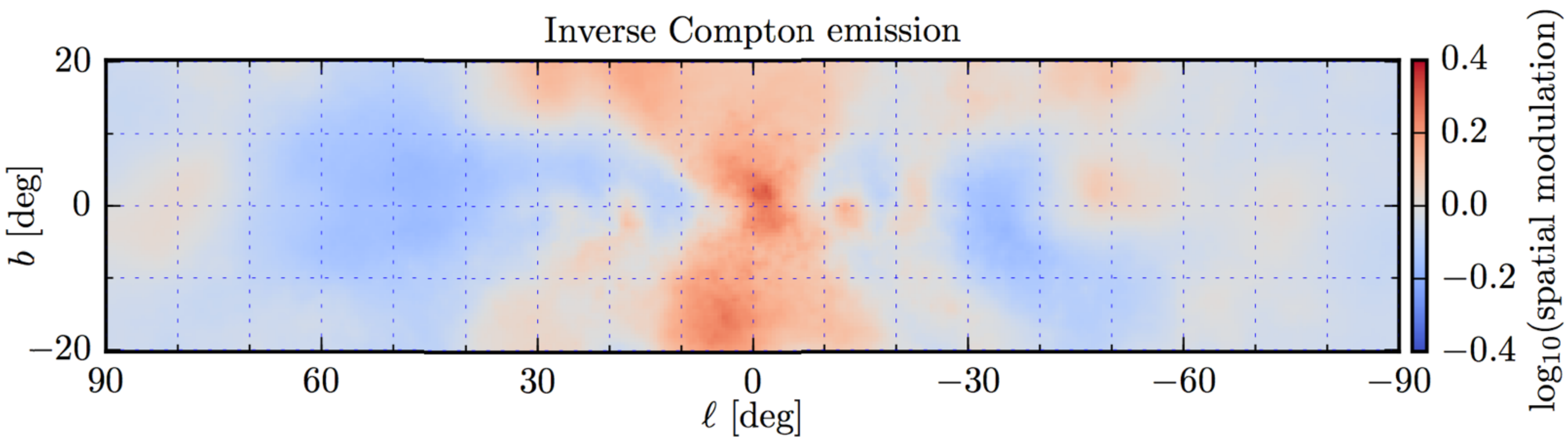
*IGRB spectral uncertainties (~25%)

A "minimal model" for the Galactic emission

Additional components appear in spatial modulation parameters

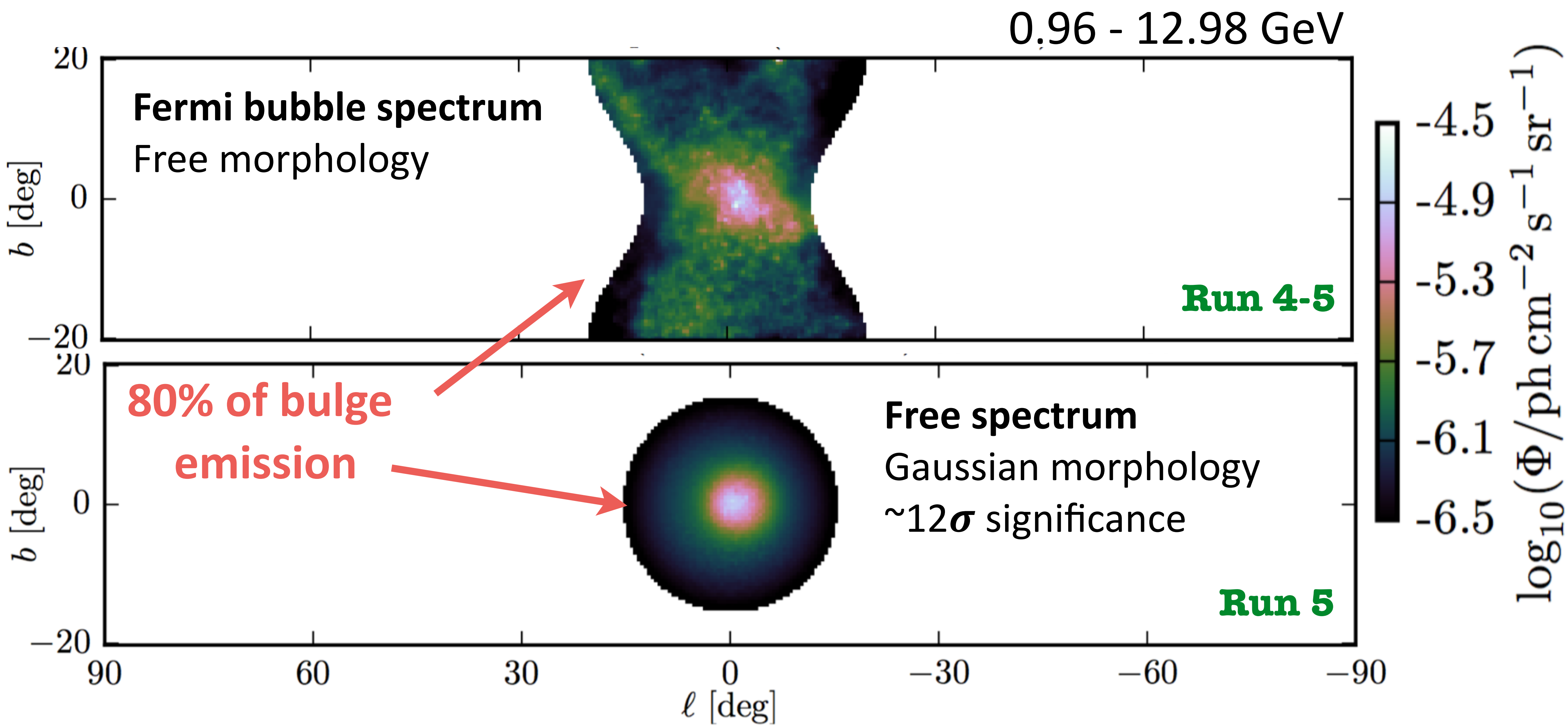


Dark gas



Fermi bubbles

Extracting the bulge emission



- ✓ Strong degeneracy between Fermi bubbles and bulge emission (aka GeV excess)
- ✓ Once again, strong evidence for GeV excess (12σ significance), although more oblate morphology than previous studies
- ✓ Robust characterisation of the GeV excess allows to discriminate among models for the bulge emission and supports its stellar origin

See R. Bartels's talk on Monday

Bartels, Storm, Weniger & Calore, In preparation

Some future directions and applications

- ✓ Full parameters scan over GALPROP/DRAGON predictions for CR diffusion and gamma-ray emission.
- ✓ Investigation of CR gradient, hardening of the proton spectrum towards GC and substructures in 3D inverse Compton emission.
- ✓ Observability of spiral arms structures in gamma-ray emission?
- ✓ Characterisation of Fermi bubbles at low latitudes and of possible degeneracies with the GeV excess.

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Thanks for your attention

Backup slides

Diffuse components

$$\phi_{pb} = \sum_k T_p^{(k)} \tau_p^{(k)} \cdot S_b^{(k)} \sigma_b^{(k)} \cdot \nu^{(k)}$$

$$\sigma_b^{(k)}, \tau_p^{(k)}, \nu^{(k)} \geq 0$$

$$\mu_{pb}^{\mathrm{D}} = \sum_{p'} \mathcal{P}_{bpp'} \mathcal{E}_{bp'} \phi_{p'b}$$

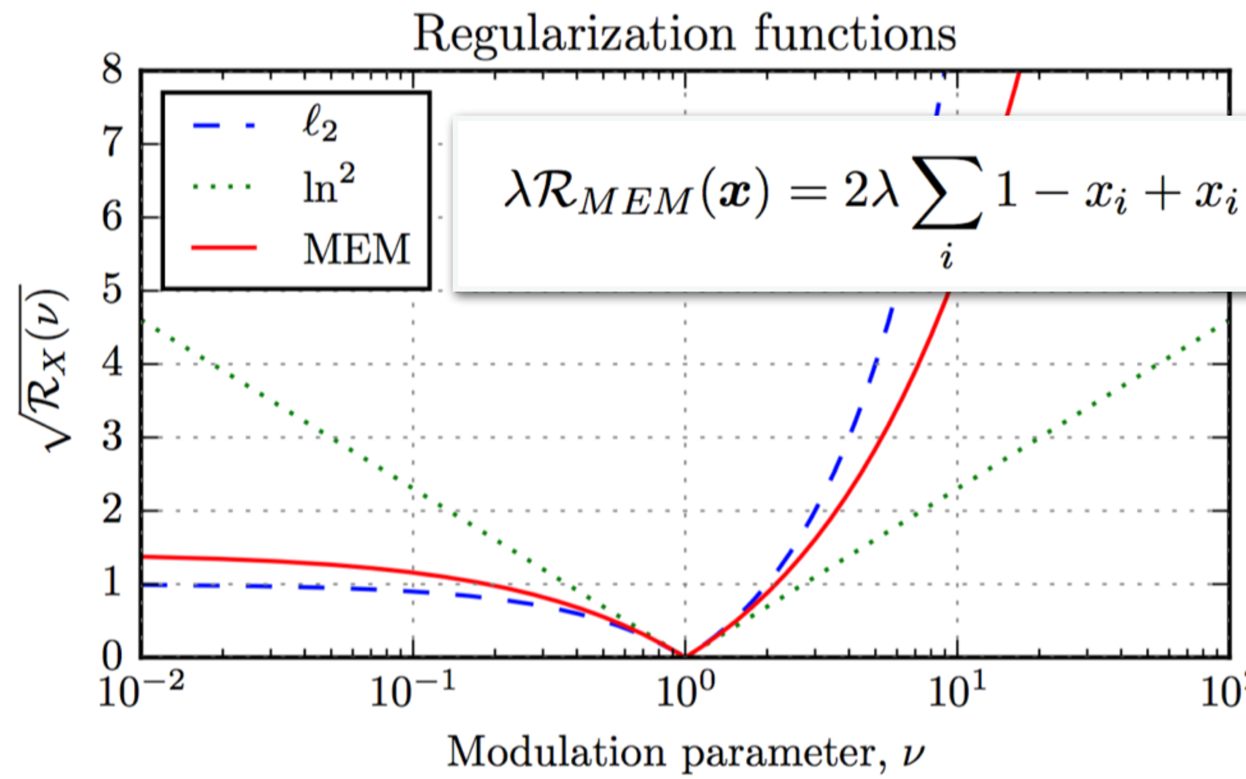
Point sources

$$\mu_{pb}^{\mathrm{P}} = \sum_s \mathcal{P}_{bp}(\boldsymbol{\Omega_s}) \mathcal{E}_b(\boldsymbol{\Omega_s}) \cdot S_b^{(s)} \sigma_b^{(s)} \cdot \nu^{(s)}$$

The likelihood

$$\ln \mathcal{L} = \ln \mathcal{L}_{\mathrm{P}} + \ln \mathcal{L}_{\mathrm{R}}$$

$$\ln \mathcal{L}_{\mathrm{P}} = \sum_{pb} c_{pb} - \mu_{pb} + c_{pb} \ln \frac{\mu_{pb}}{c_{pb}}$$



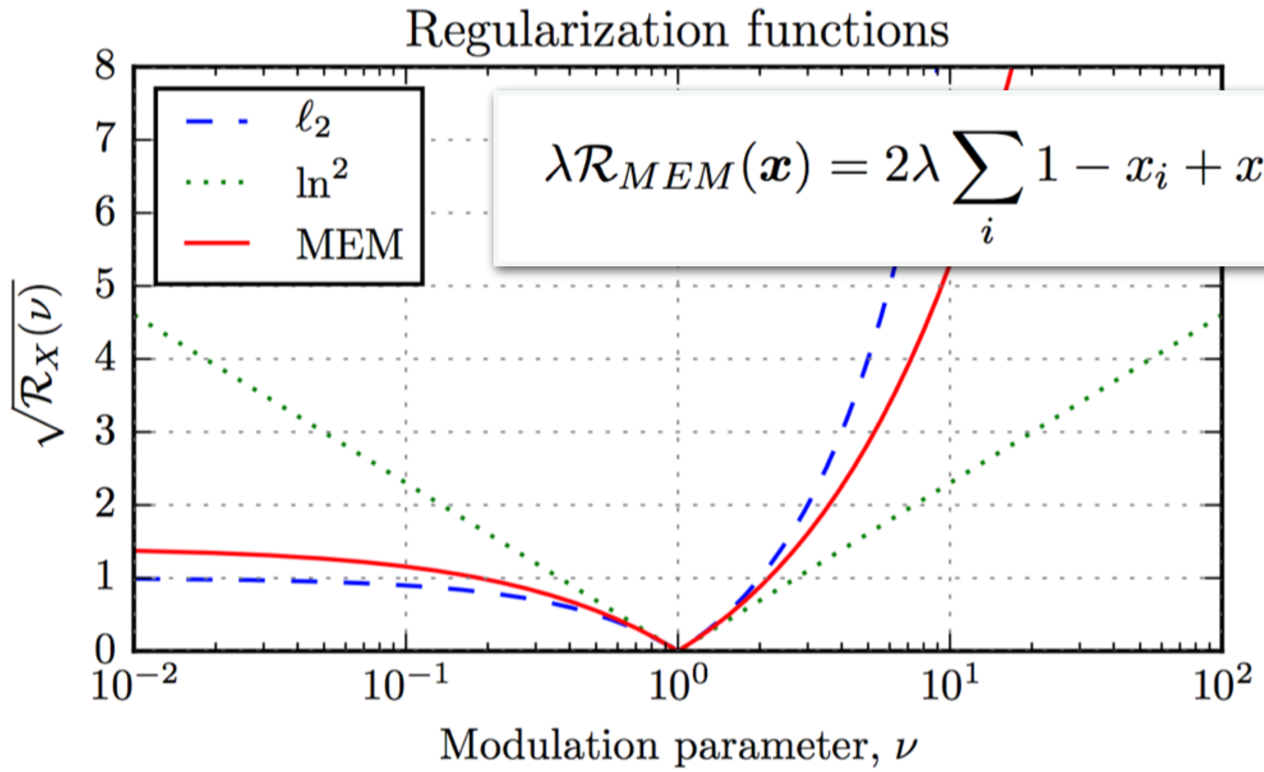
$$\lambda \mathcal{R}_{MEM}(\boldsymbol{x}) = 2\lambda \sum_i 1 - x_i + x_i \ln x_i$$

$$-2 \ln \mathcal{L}_R = \sum_k \lambda_k \mathcal{R}_X(\boldsymbol{\tau}^{(k)}) + \lambda'_k \mathcal{R}_X(\boldsymbol{\sigma}^{(k)}) + \lambda''_k \mathcal{R}_X(\nu^{(k)}) + \eta_k \mathcal{S}_1(\boldsymbol{\tau}^{(k)}) + \eta'_k \mathcal{S}_2(\boldsymbol{\sigma}^{(k)})$$

$$+ \sum_s \lambda'_s \mathcal{R}_X(\boldsymbol{\sigma}^{(s)}) + \lambda''_s \mathcal{R}_X(\nu^{(s)}) + \eta'_s \mathcal{S}_2(\boldsymbol{\sigma}^{(s)}) \ ,$$

The regularisation

$$-2\ln\mathcal{L}_R = \sum_k \lambda_k \mathcal{R}_X(\boldsymbol{\tau}^{(k)}) + \lambda'_k \mathcal{R}_X(\boldsymbol{\sigma}^{(k)}) + \lambda''_k \mathcal{R}_X(\nu^{(k)}) + \eta_k \mathcal{S}_1(\boldsymbol{\tau}^{(k)}) + \eta'_k \mathcal{S}_2(\boldsymbol{\sigma}^{(k)})$$
$$+ \sum_s \lambda'_s \mathcal{R}_X(\boldsymbol{\sigma}^{(s)}) + \lambda''_s \mathcal{R}_X(\nu^{(s)}) + \eta'_s \mathcal{S}_2(\boldsymbol{\sigma}^{(s)}) \ ,$$



$$\lambda\mathcal{R}_{MEM}(\boldsymbol{x}) = 2\lambda\sum_i 1 - x_i + x_i \ln x_i$$

Spatial smoothing (gradient)

$$\eta\mathcal{S}_1(\boldsymbol{x}) = \eta \sum_{(p,p')\in\mathcal{N}} (\ln x_p - \ln x_{p'})^2$$

Spectral smoothing (II deriv.)

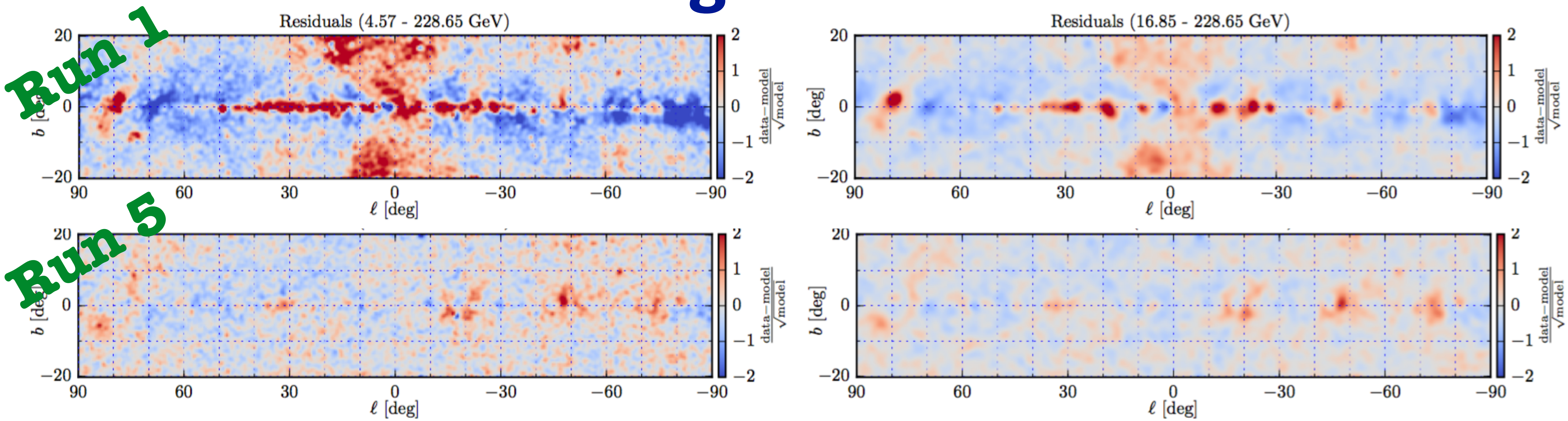
$$\eta\mathcal{S}_2(\boldsymbol{x}) = \eta\sum_b (\ln x_{b-1} - 2\ln x_b + \ln x_{b+1})^2$$

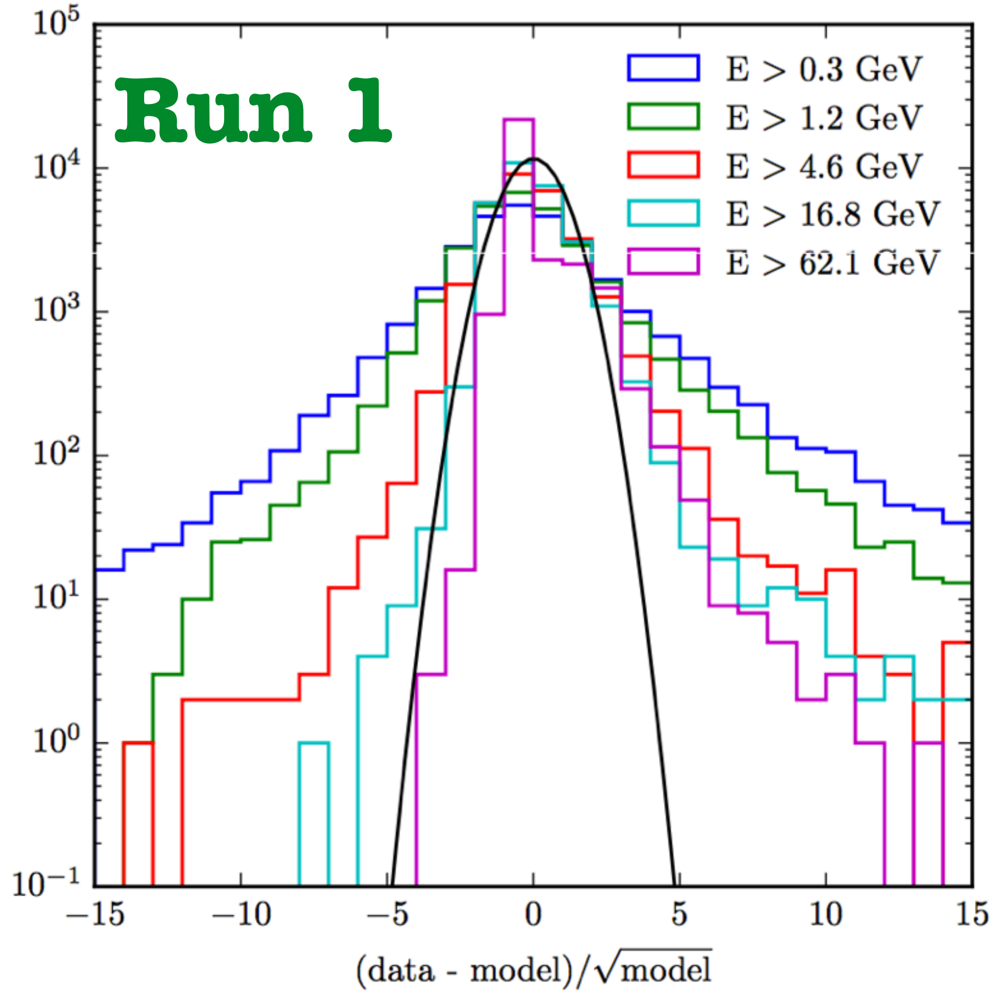
- parameter optimisation with L-BFGS-B
- converge criterium similar to Minuit
- error estimate by sampling from inverse Fisher matrix at bestfit point
- object function is convex as long as model components non-degenerate (modulo smoothing)

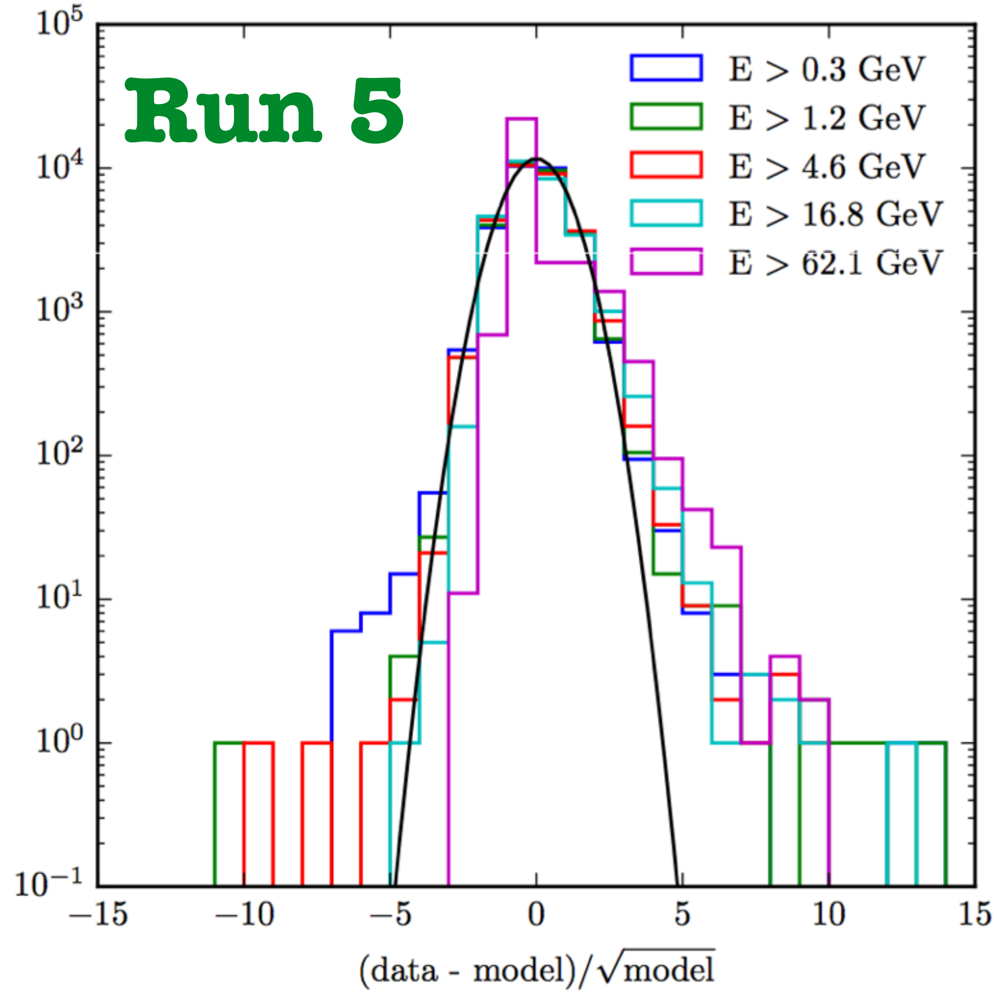
Towards a minimal model

Components	RUN1	RUN2	RUN3	RUN4	RUN5
	Regularization hyper-parameters: $\begin{bmatrix} \lambda & \lambda' & \lambda'' \\ \eta & \eta' & \cdot \end{bmatrix}$				
IGRB	$\begin{bmatrix} \infty & 16 & \infty \\ 0 & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} \infty & 16 & \infty \\ 0 & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} \infty & 16 & \infty \\ 0 & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} \infty & 16 & \infty \\ 0 & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} \infty & 16 & \infty \\ 0 & 0 & \cdot \end{bmatrix}$
3FGL PSC	$\begin{bmatrix} \cdot & 25 & 0 \\ \cdot & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & 25 & 0 \\ \cdot & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & 25 & 0 \\ \cdot & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & 25 & 0 \\ \cdot & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & 25 & 0 \\ \cdot & 0 & \cdot \end{bmatrix}$
Gas (0–19 kpc)	$\begin{bmatrix} \infty & 16 & 0 \\ 0 & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} 10 & 16 & 0 \\ 25 & 0 & \cdot \end{bmatrix}$	—	—	—
Gas ring I (0–3.5 kpc)	—	—	$\begin{bmatrix} 10 & 16 & 0 \\ 25 & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} 10 & 16 & 0 \\ 25 & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} 10 & 16 & 0 \\ 25 & 0 & \cdot \end{bmatrix}$
Gas ring II (3.5–6.5 kpc)	—	—	$\begin{bmatrix} 10 & 16 & 0 \\ 25 & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} 10 & 16 & 0 \\ 25 & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} 10 & 16 & 0 \\ 25 & 0 & \cdot \end{bmatrix}$
Gas ring III (6.5–19 kpc)	—	—	$\begin{bmatrix} 4 & 16 & 0 \\ 25 & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} 4 & 16 & 0 \\ 25 & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} 4 & 16 & 0 \\ 25 & 0 & \cdot \end{bmatrix}$
Extended sources	—	—	—	$\begin{bmatrix} 0 & 1 & \infty \\ 4 & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} 0 & 1 & \infty \\ 4 & 0 & \cdot \end{bmatrix}$
Inverse Compton	$\begin{bmatrix} \infty & 16 & 0 \\ 0 & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} 1 & 16 & 0 \\ 100 & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} 1 & 16 & 0 \\ 100 & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} 1 & 16 & 0 \\ 100 & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} 1 & 16 & 0 \\ 100 & 0 & \cdot \end{bmatrix}$
Fermi bubbles	—	—	—	$\begin{bmatrix} 0 & 400 & \infty \\ 4 & 0 & \cdot \end{bmatrix}$	$\begin{bmatrix} 0 & 400 & \infty \\ 4 & 0 & \cdot \end{bmatrix}$
511 keV template	—	—	—	—	$\begin{bmatrix} 25 & 0 & \infty \\ 0 & 0 & \cdot \end{bmatrix}$

Reducing the residuals

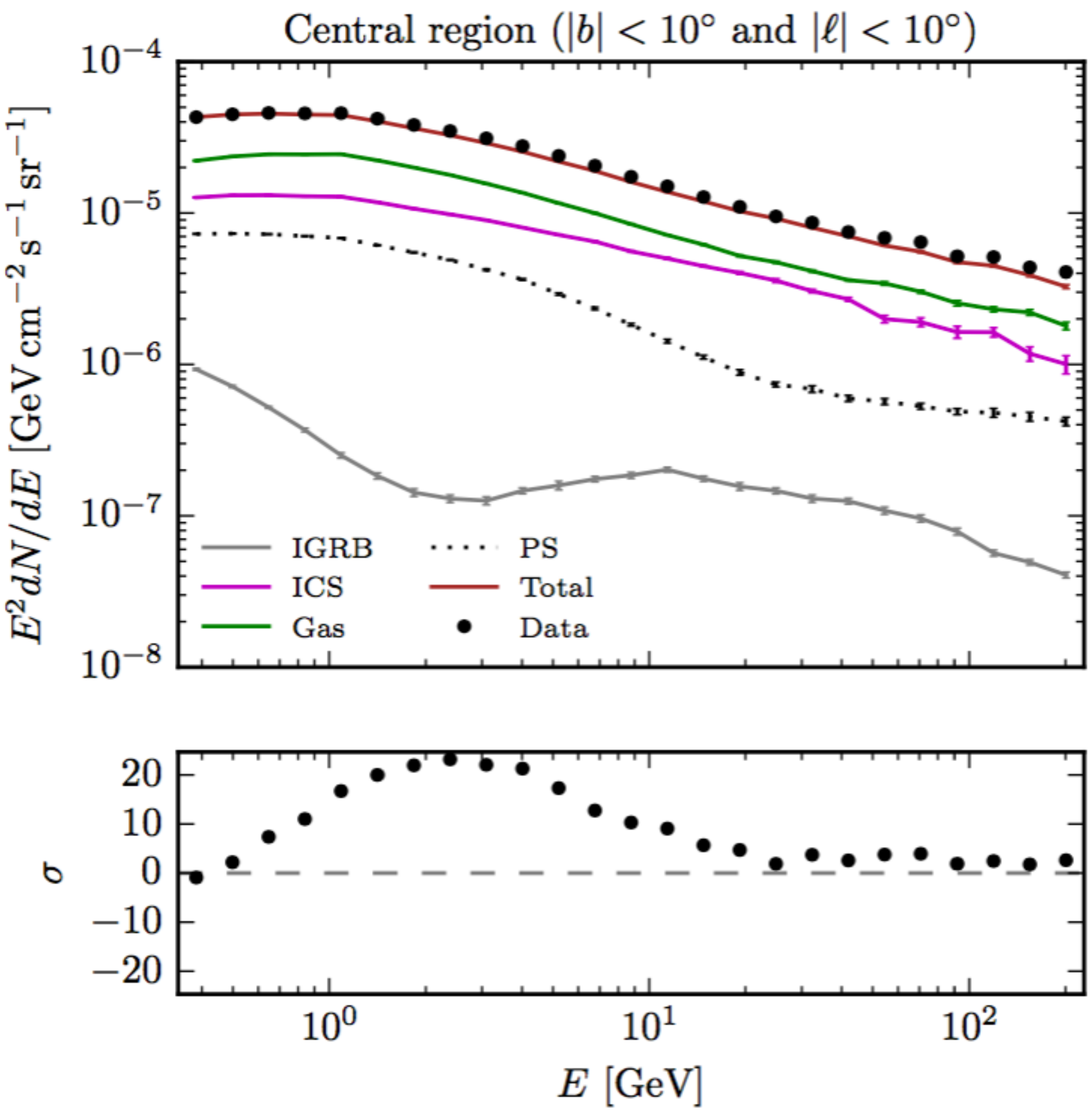




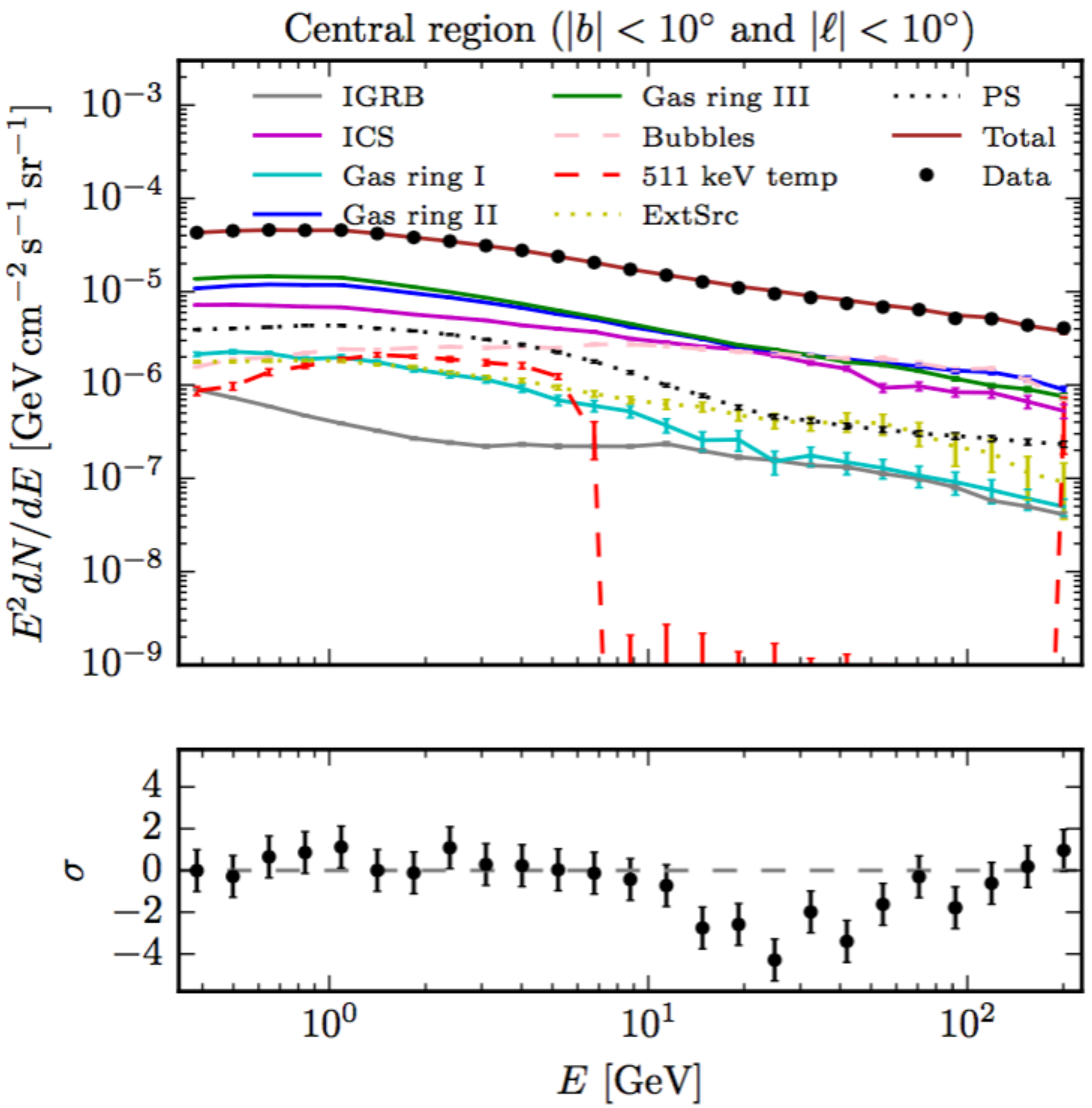


Spectral results

Run 1



Run 5



Degrees of freedom

Naively:

$$N_{\rm data} = N_{\rm pix} \times N_{\rm ebin} = 360 \times 81 \times 25 = 7290000$$

$$N_{\rm param}$$

$$N_{\rm DOF} = N_{\rm ebin} \times N_{\rm pix} - N_{\rm param}$$

But:

No Gaussian regime, degeneracies in model parameters, and penalisation constraints

What is the real number of effective **free** model parameters?

$$N_{\rm DOF}^{\rm eff} \sim \langle -2 \ln \mathcal{L}_P \rangle_{\rm mock}$$

$$N_{\rm data}^{\rm eff} \equiv \langle -2 \ln \mathcal{L}_P(\boldsymbol{\theta}) \rangle_{\mathcal{D}(\boldsymbol{\theta})}$$

Run 5

Naive model parameters, $N_{\rm param}$	107639
Naive DOF	621361
Eff. model parameters, $N_{\rm param}^{\rm eff}$	12800
Eff. data bins, $N_{\rm data}^{\rm eff}$	619000
Eff. DOF, k	606200