SMASH machine learning for science and humanities postdoctoral program | Univerza v Novi Gorici | Univerza v Ljubljani | Jožef Stefan Institute | IZUM Institute of Information Science Maribor | Republic of Slovenia Ministry of the Environment and Spatial Planning Slovenian Environment Agency | Co-funded by The European Union

Gamma rays from the Galactic Center strongly constrain thermal relic dark matter

— based on: arXiv:2511.03350 —

— in collaboration with S. Manconi, F. Calore and F. Donato —

Christopher Eckner (christopher.eckner@ung.si)

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University of Nova Gorica, Center for Astrophysics and Cosmology, Slovenia

TeVPA 2025 | Dark Matter: Indirect Detection

6th of November 2025 | Valencia, Spain

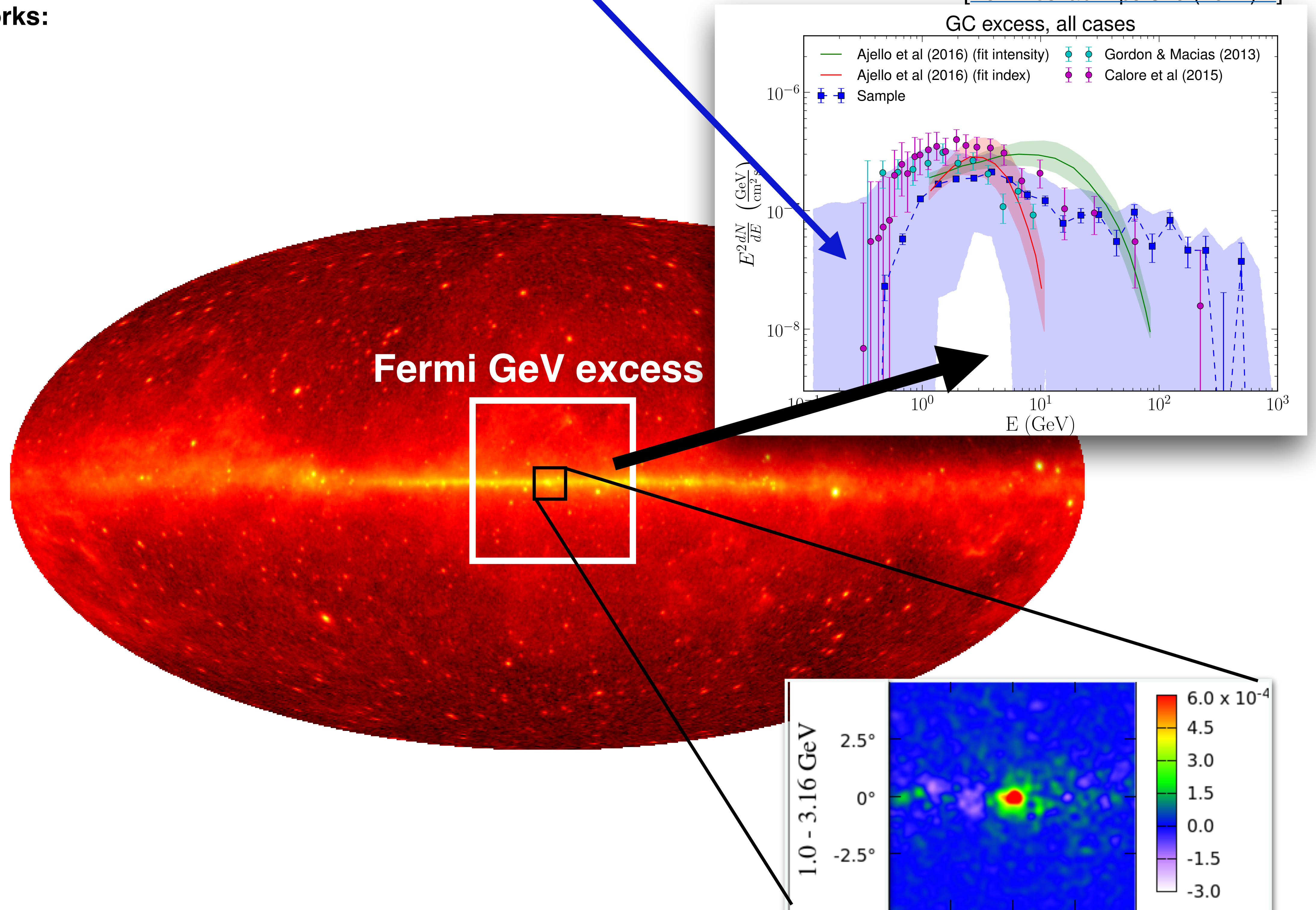
TeV Particle Astrophysics TeVPA Valencia 2025

What is the Fermi GeV excess?

We all agree: There is an excess of GeV gamma rays (GCE) toward the Galactic centre measured by the *Fermi* LAT **above known astrophysical backgrounds**.

[Fermi collab. ApJ 840 (2017) 1]

An incomplete list of works:
Goodenough & Hooper (2009)
Vitale & Morselli (2009)
Hooper & Goodenough (2011)
Hooper & Linden (2011)
Boyarsky et al (2011)
Abazajian & Kaplinghat (2012)
Gordon & Macias (2013)
Macias & Gordon (2014)
Abazajian et al (2014, 2015)
Calore et al (2014)
Daylan et al (2014)
Selig et al (2015)
Huang et al (2015)
Gaggero et al (2015)
Carlson et al (2015, 2016)
de Boer et al (2016)
Fermi Coll. (2016)
Horiuchi et al (2016)
Linden et al (2016)
Ackermann et al (2017)
Macias et al (2018)
Bartels et al (2018)
Balaji et al (2018)
Zhong et al (2019)
Macias et al (2019)
Chang et al (2020)
Buschmann et al (2020)
Leane & Slatyer (2020)
Abazajian et al (2020)
List et L (2020)
Di Mauro (2020)
Burns et al (2020)
Cholis et al (2022)
Pohl, Macias+ (2022)
McDermott et al (2023)
Manconi et al (2024)
Song et al (2024)
Ramirez et al (2025)
List et al (2025)
J. Koechler & M. di Mauro (2025)
M. Muru et al (2025)
…

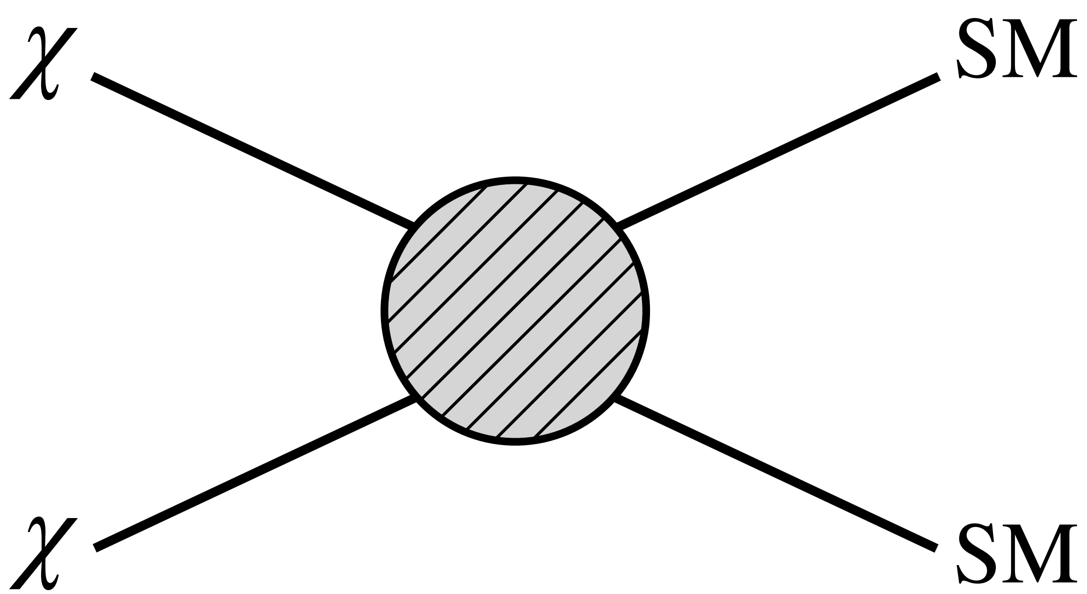


[Daylan et al., Phys.Dark Univ. 12 (2016)]

What produces the excess?

The excess is tantalising since it coincides well with the expectations for the sought-after signal of **thermal dark matter pair-annihilating** in the Galactic centre. However, **unresolved populations of gamma-ray sources** are a strong contender!

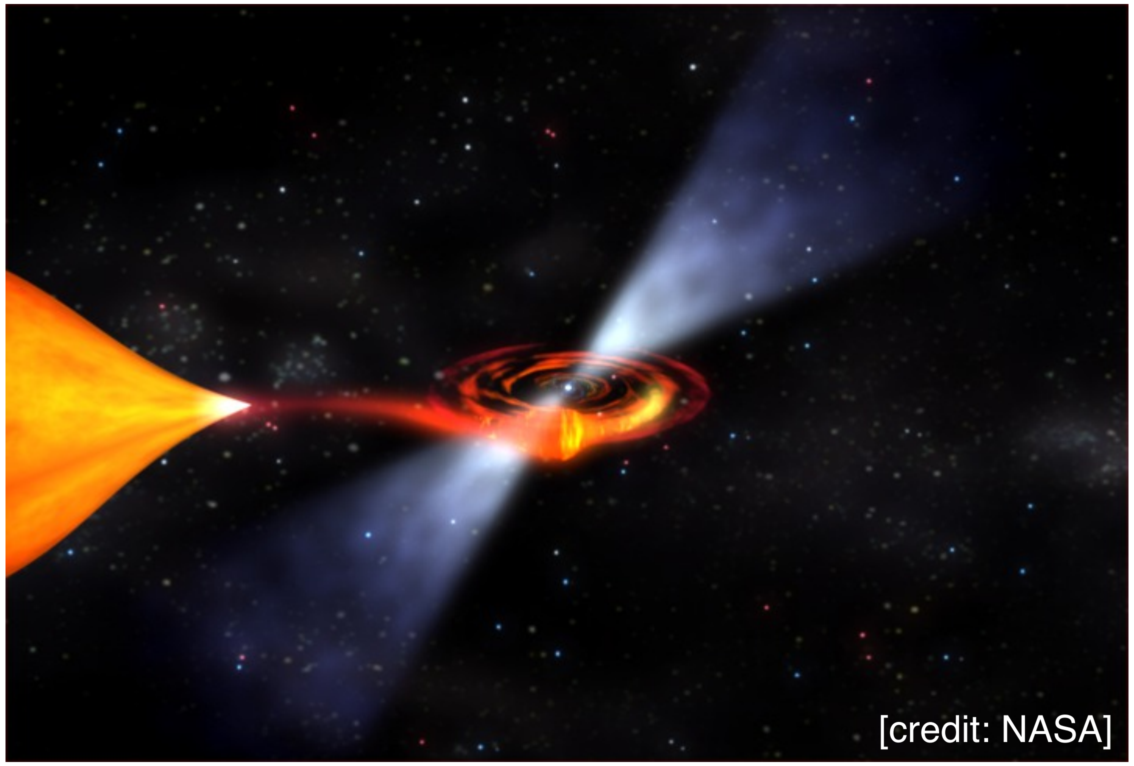
Thermal dark matter



supported by (incomplete collection):
[Fermi collab. ApJ 840 (2017) 1];
[R. K. Leane and T. R. Slatyer, PRL 123 (2019) 24];
[M. di Mauro, PRD 103 (2021) 6]; [I. Cholis et al., PRD 105 (2022) 10];
[S. D. McDermott et al., MNRAS 522 (2023) 1]

VS.

Unresolved Galactic source population (here: millisecond pulsars [MSPs])

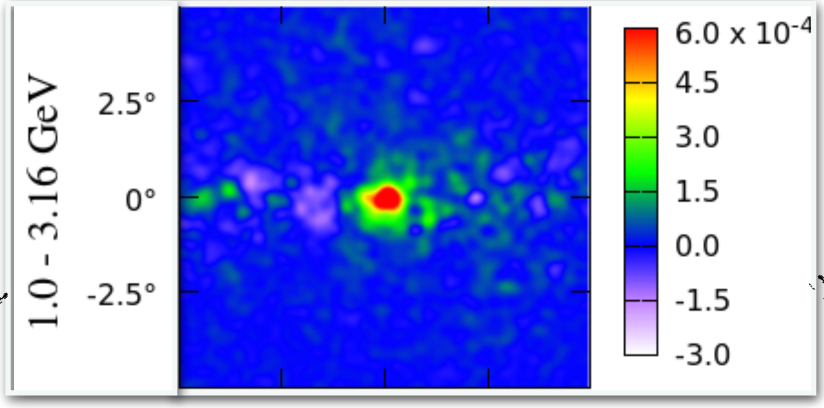


supported by (incomplete collection):
[R. Bartels et al., PRL 116 (2016) 5];
[R. Bartels et al., Nature Astron. 2 (2018) 10];
[O. Macias et al., JCAP 09 (2019) 042];
[F. Calore et al., PRL 127 (2021) 16];
[M. Pohl et al., ApJ 929 (2022) 2]

Other interpretations are cosmic-ray based, e.g., a past enhanced star formation/leptonic burst in the Galactic centre [E. Carlsom, S. Profumo; PRD 90 (2014) 2][J. Petrovic et al.; JCAP 10 (2014) 052][D. Gaggero et al., JCAP 12 (2015) 056].

What have we learned about the GeV excess?

We may understand the GCE studying its main properties:



[Daylan et al., Phys.Dark Univ. 12 (2016)]

spectrum **spatial morphology** **photon statistics**

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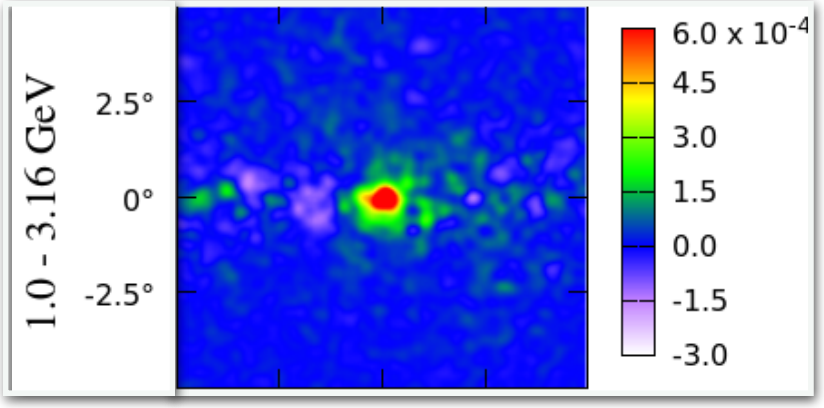
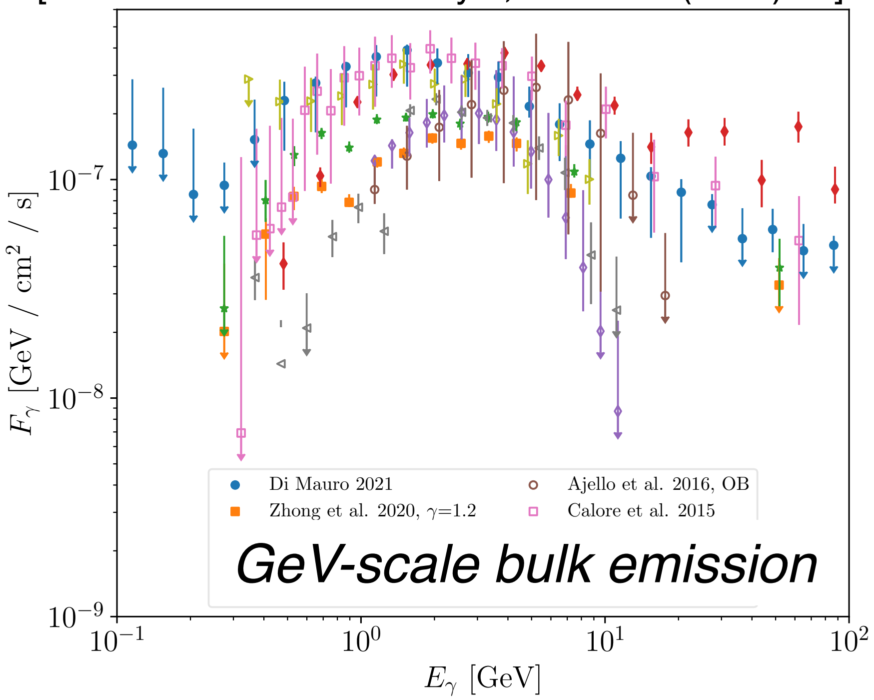


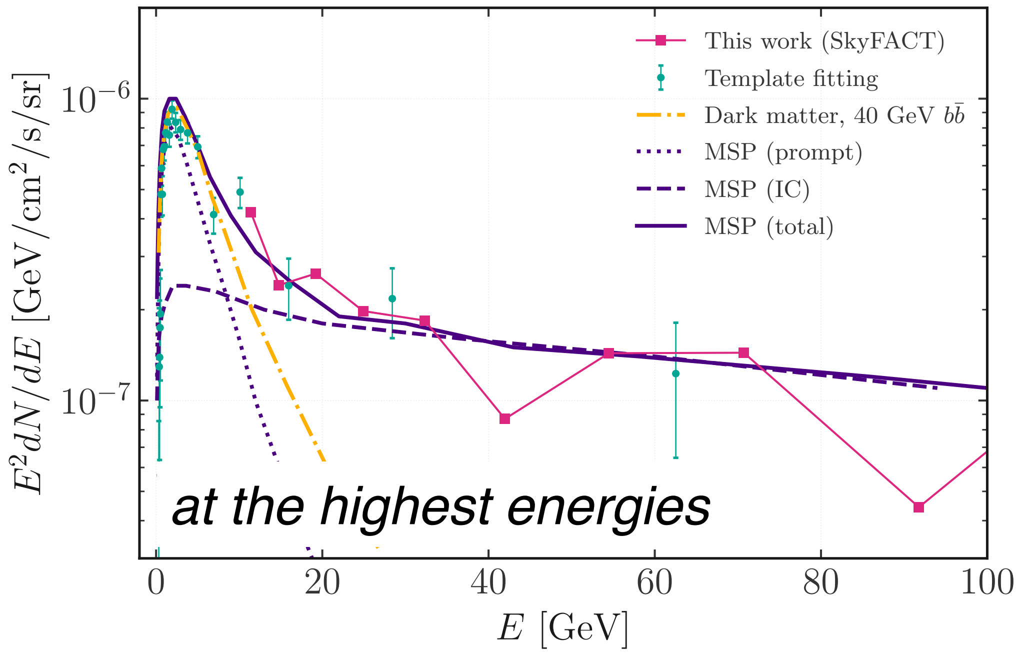
[Daylan et al., Phys.Dark Univ. 12 (2016)]

spectrum:

[J.T. Dinsmore & T.R. Slatyer, JCAP 06 (2022) 06]



[S. Manconi et al., PRD 109 (2024) 12]



1. GeV emission compatible with dark matter and MSP interpretation.
2. **Robust high-energy tail (> 20 GeV)**: natural explanation via inverse-Compton emission of $e^\pm$ originating in MSP population. [S. Manconi et al., PRD 109 (2024) 12] (multi-channel thermal DM can work too)

What have we learned about the GeV excess?

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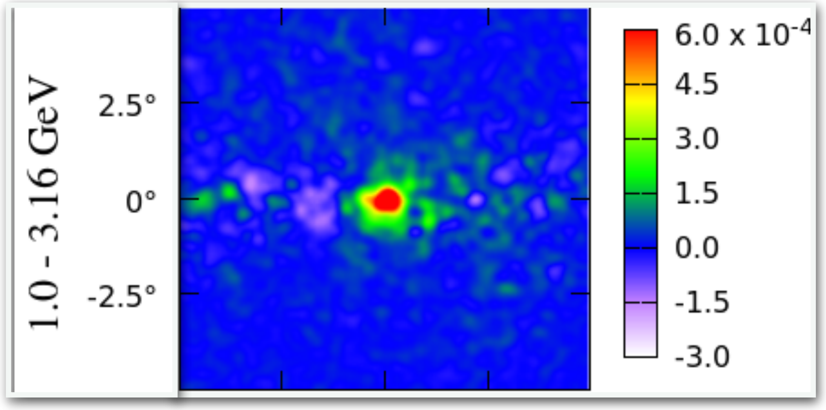
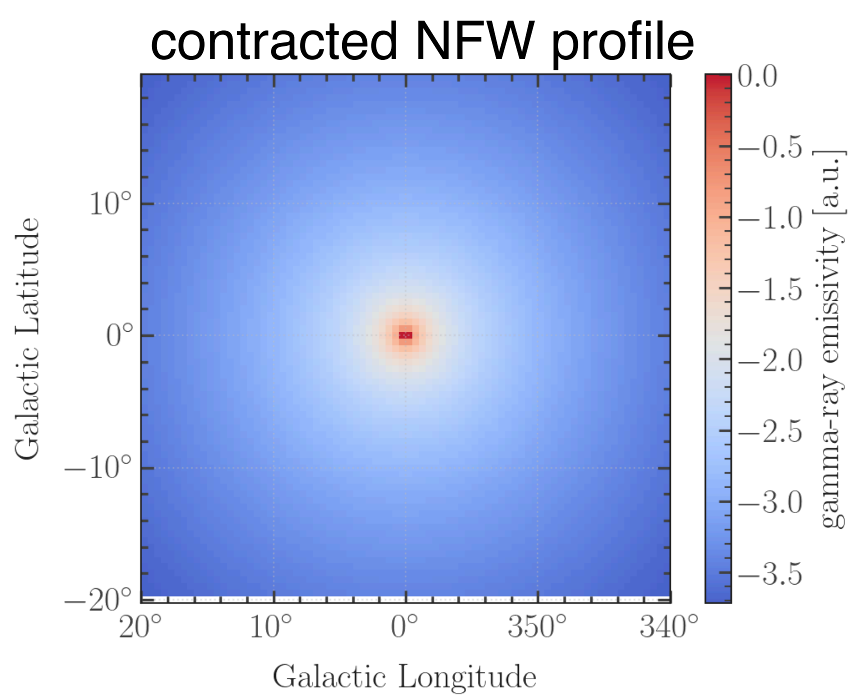
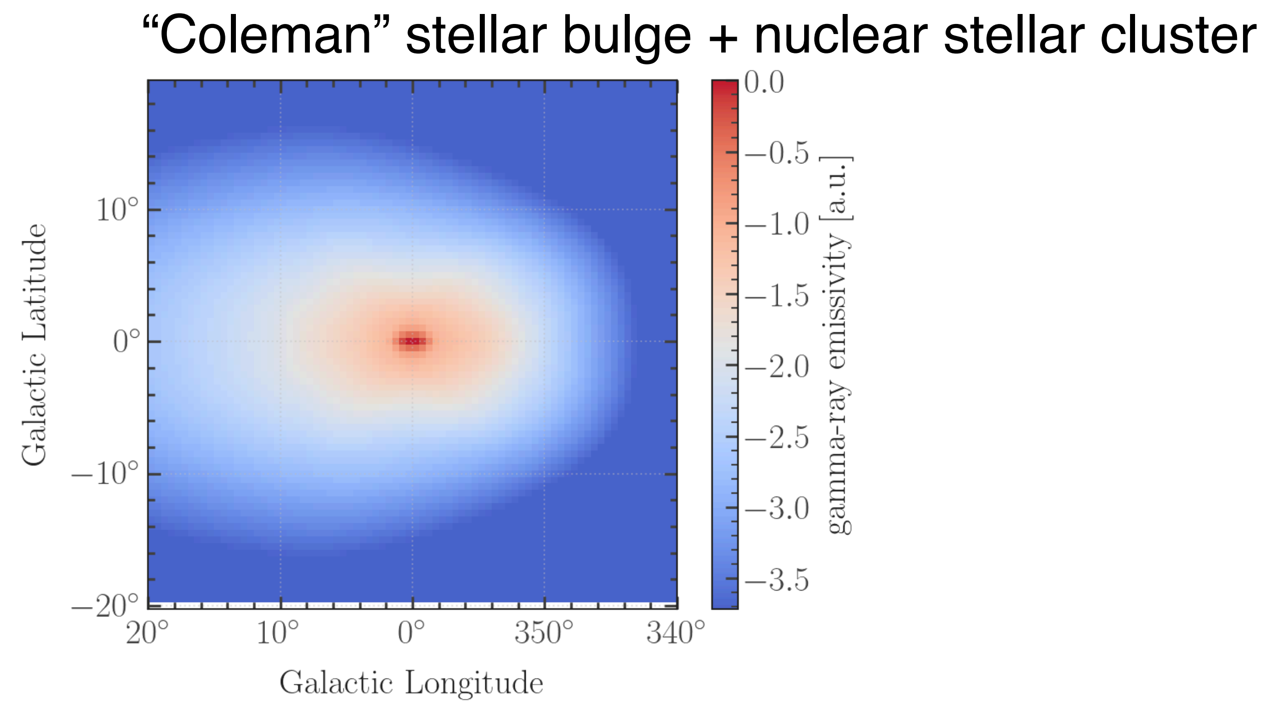


[Daylan et al., Phys.Dark Univ. 12 (2016)]

spatial morphology:

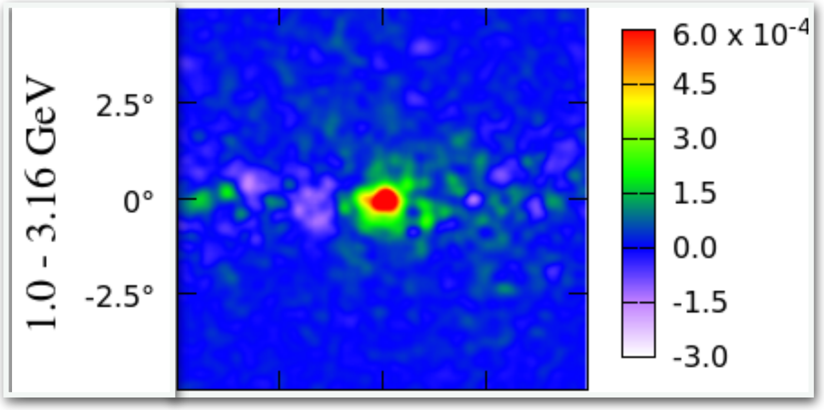




1. Non-spherical stellar bulge robustly yields a better fit. [D. Song, C. Eckner et al., MNRAS 530 (2024) 4]
2. Recent magnetohydrodynamical simulations of Milky-Way-like galaxies suggest that dark matter may exhibit similar asphericity as stellar bulge. [M. Muru et al., PRL 135 (2025) 16]

What have we learned about the GeV excess?

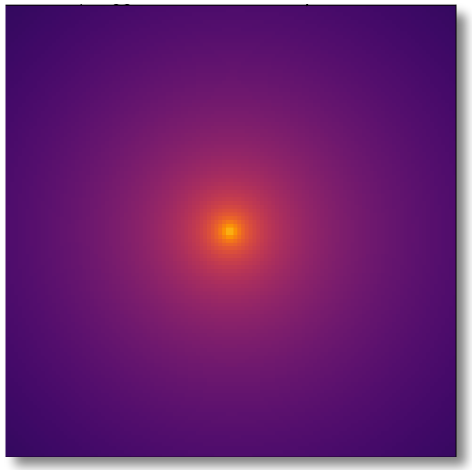
We may understand the GCE studying its main properties:



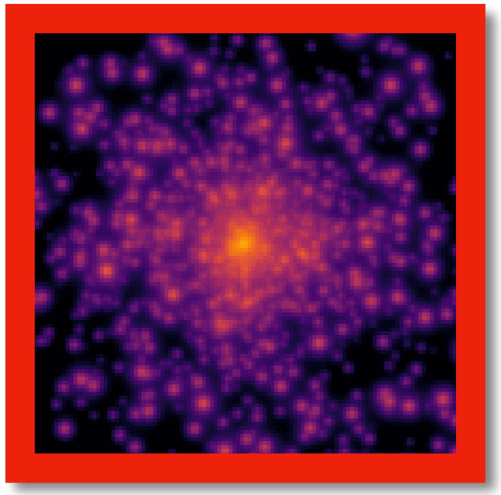
[Daylan et al., Phys.Dark Univ. 12 (2016)]

photon statistics:

Question: Can we identify a **non-Poissonian emission** component in the GCE's emission?
→ linked to: population of dim point-like sources below the LAT's detection threshold

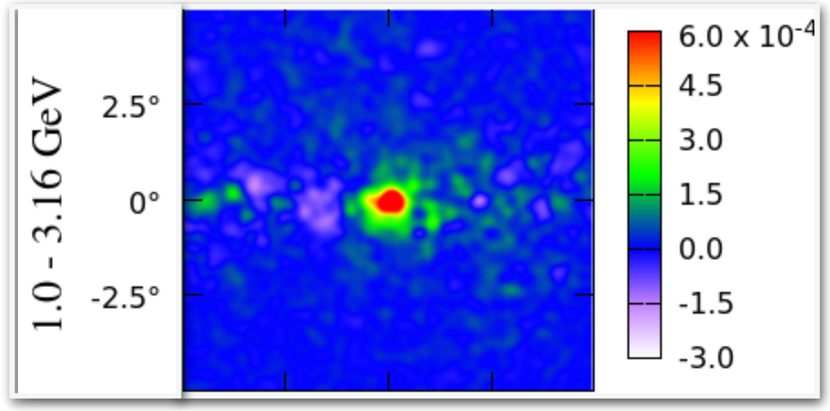


vs.



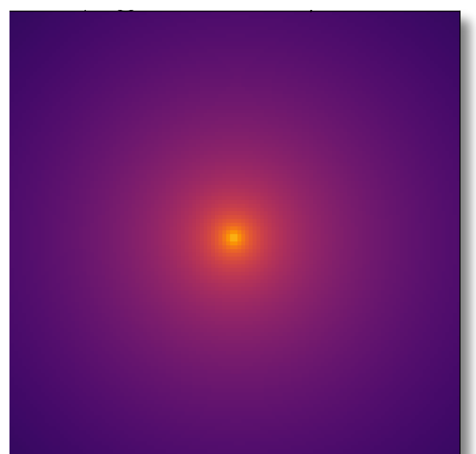
What have we learned about the GeV excess?

We may understand the GCE studying its main properties:

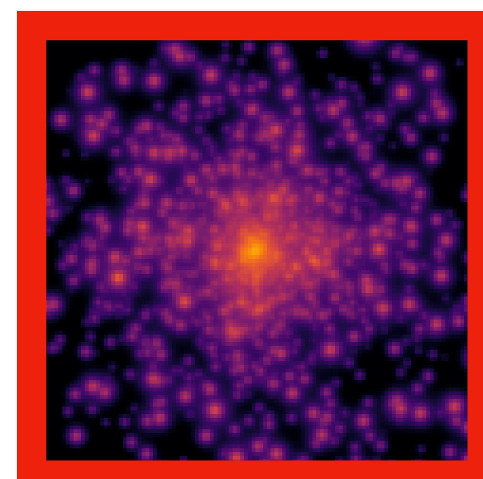


[Daylan et al., Phys.Dark Univ. 12 (2016)]

photon statistics:



vs.



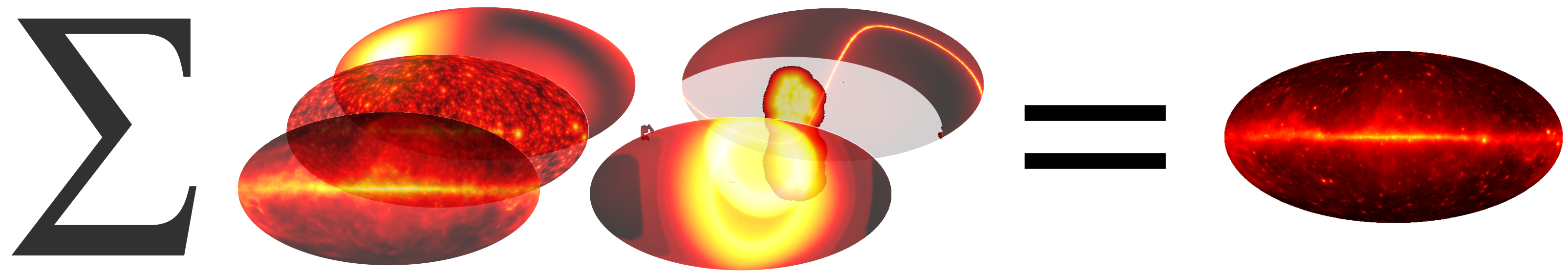
Addressed with conventional **likelihood-based** but also **machine-learning** methods:

1. One-point photon-count statistics analyses find strong evidence for a contribution of sub-threshold point-like sources to the GCE. [F. Calore et al., PRL 127 (2021) 16]
2. Machine-learning analyses typically find an admixture of DM and MSP emission to the GCE [S. Mishra-Sharma and K. Cranmer, PRD 105 (2022) 6] [F. List et al. PRL 125 (2020) 241102] [S. Caron, C. Eckner et al., JCAP 06 (2023) 013]
   → adding energy-dependence to the machine-learning analysis seems to indicate an almost Poisson-like sub-threshold source contribution (could be DM?) [F. List et al., arXiv:2507.17804]

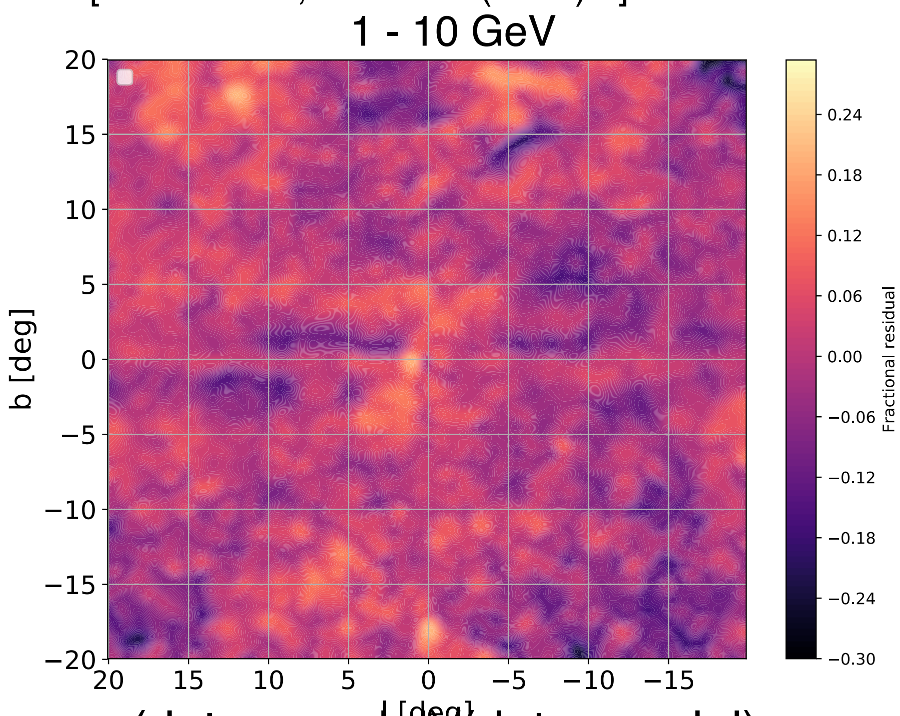
The obstacle in GCE template-based data analyses

Mismodelling of the large-scale diffuse foreground of the Milky Way.

Examples from a few recent studies using template-based fits:

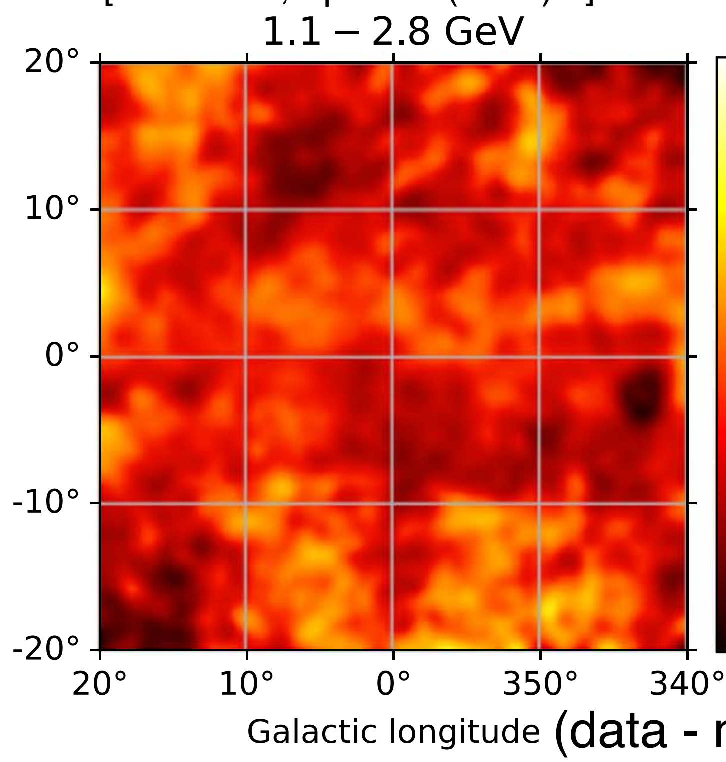


[M. di Mauro, PRD 103 (2021) 6]



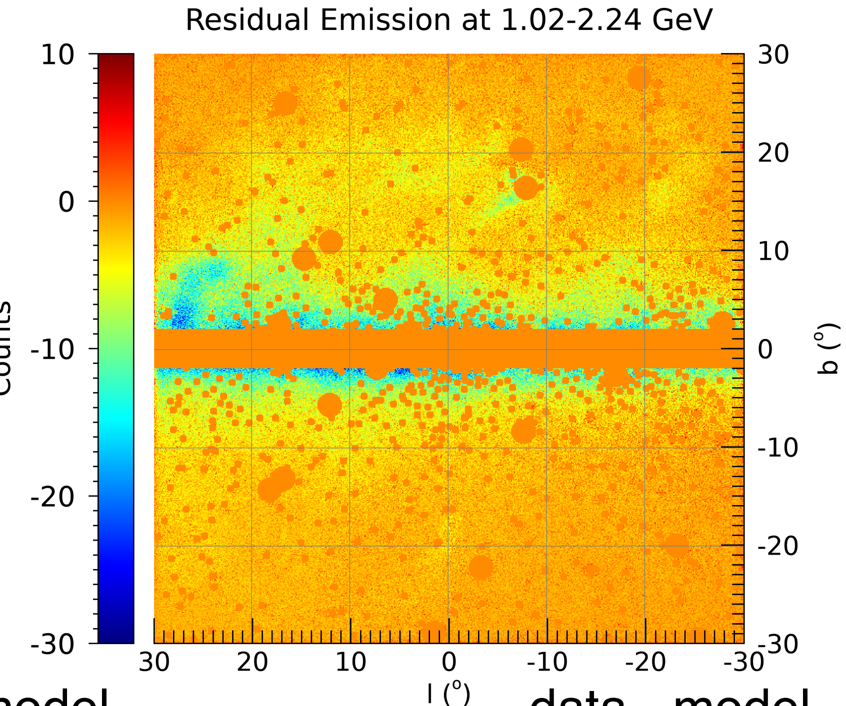
(data - model)/(data+model)

[Pohl et al., ApJ 929 (2022) 2]



(data - model)/model

[I. Cholis et al., PRD 105 (2022) 10]



data - model

1. Residuals of best-fitting models can still reach ~30% and exhibit "some structure".
2. Trade-off between masking complex regions and having physically motivated/realistic models.
3. Mis-modelling typically impacts small-scales: See spurious sources due to North-South asymmetry reported in [R. K. Leane and T. R. Slatyer, PRL 125 (2020) 12] [C. Karwin et al., arXiv:2206.02809]

Mitigating the mismodelling via `skyFACT`

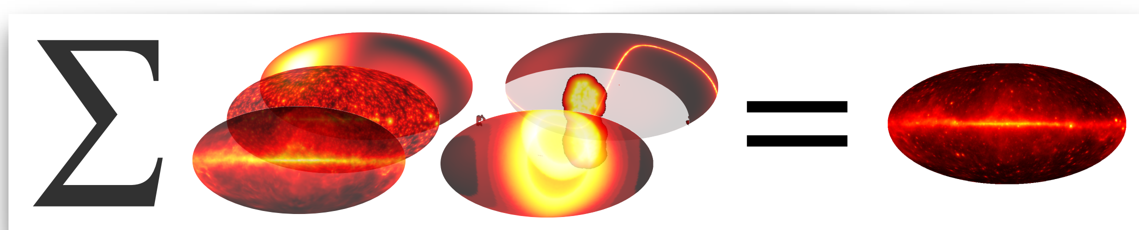
We mitigate diffuse background mismodelling via adaptive template fitting: `skyFACT`

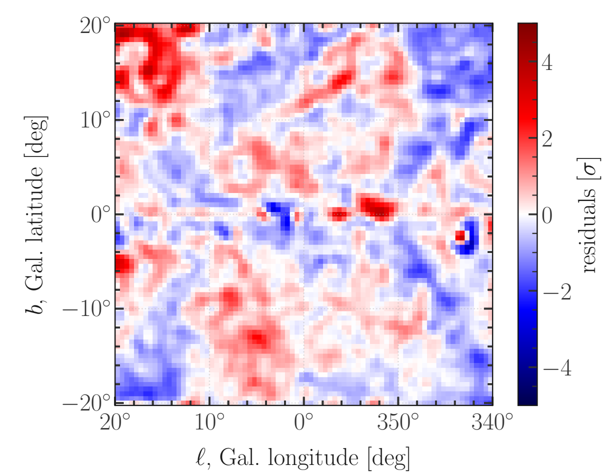
$$\text{Model} \sim \sum_k T_p^{(k)} \tau_p^{(k)} \otimes S_b^{(k)} \sigma_b^{(k)} \cdot \nu^{(k)}$$

k : component
p : spatial pixel
b : energy bin

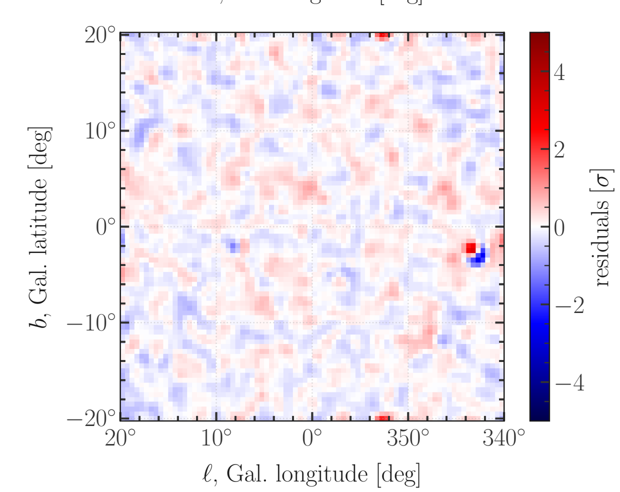
spatial + spectral templates ($T_p^{(k)}$, $S_b^{(k)}$) **modulation parameters** ($\tau_p^{(k)}$, $\sigma_b^{(k)}$, $\nu^{(k)}$)

Constraints on the modulation parameters by penalising likelihood function contribution on top of the Poisson likelihood: $\ln \mathscr{L} = \ln \mathscr{L}_P + \ln \mathscr{L}_R$.





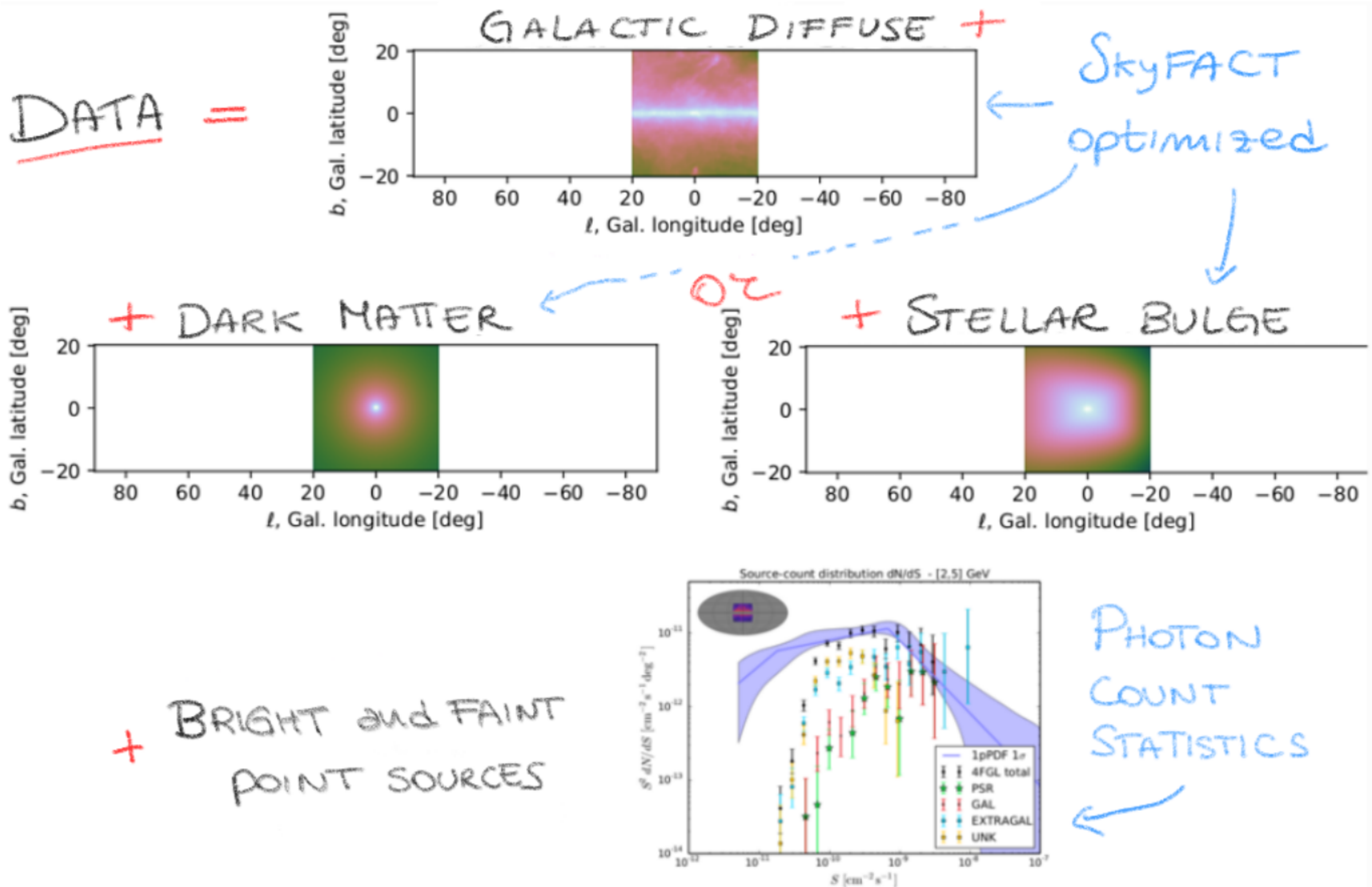
`skyFACT`



[E. Storm et al., JCAP 08 (2017) 022] [R. Bartels et al., Nature Astron. 2 (2018) 10]
[C. Armand & F. Calore, PRD 103 (2021) 8] [F. Calore & S. Manconi, PRL 127 (2021) 16]
[S. Manconi et al., PRD 109 (2024) 12] [D. Song, C. Eckner et al., MNRAS 530 (2024) 4]
[C. Eckner et al., PRD 110 (2024) 12]

Understanding the GCE's properties

This work is the culmination point of a series of works joining `skyFACT` with photon-count statistics[1]!



[image credit: Silvia Manconi]

[1] implementation via: **1p-PDF technique** → decomposes dataset based on photon-count statistics into emission components and the source-count distribution of discrete gamma-ray sources (bright + dim)

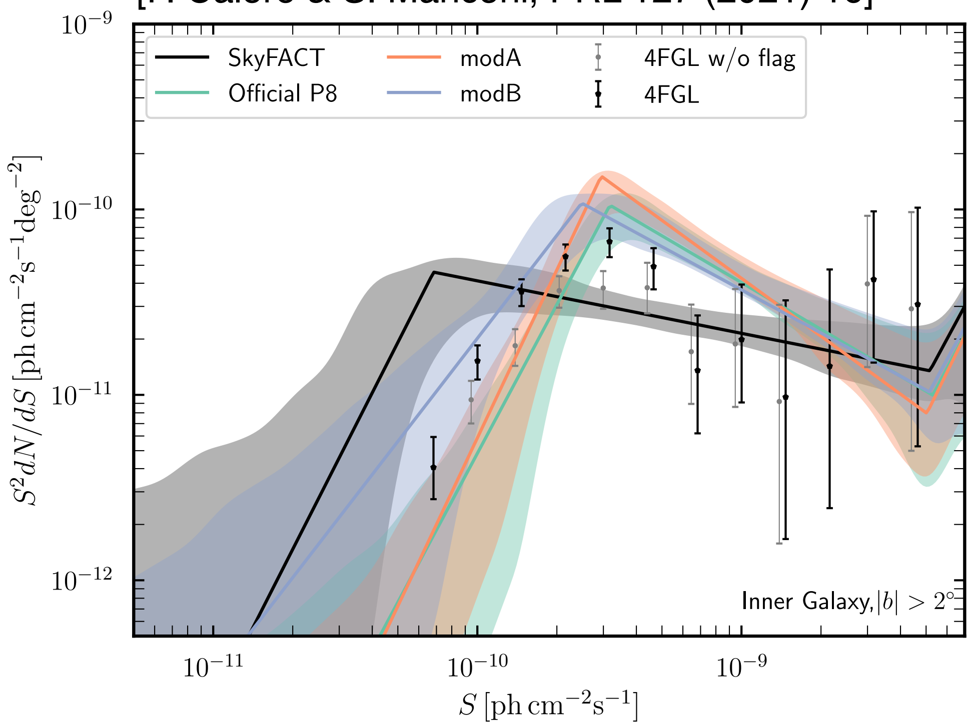
[H. Zechlin et al., ApJS 225 (2016) 2]

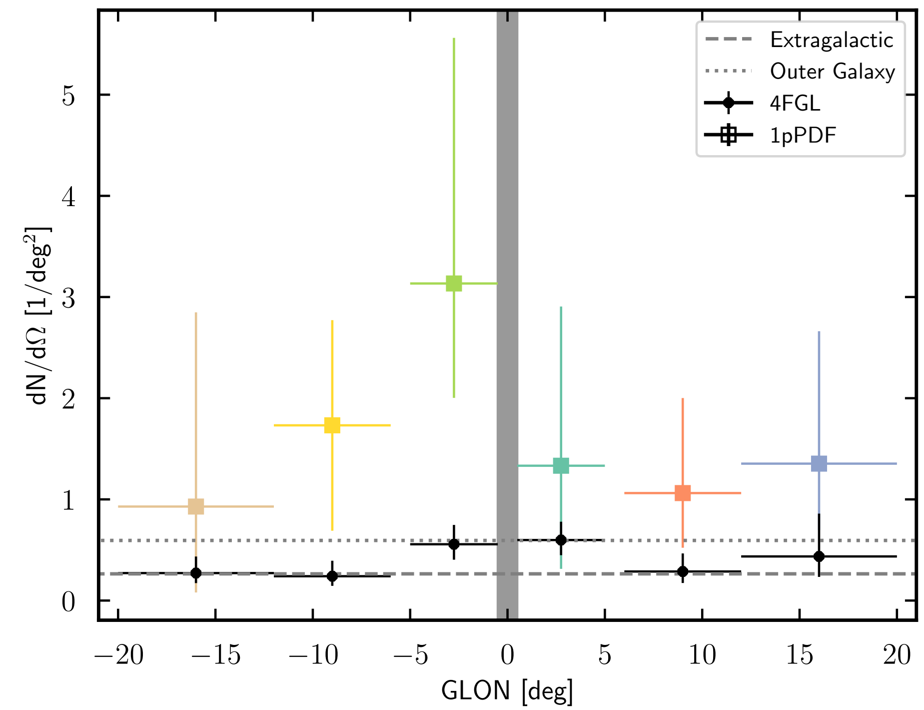
Understanding the GCE's properties

This work is the culmination point of a series of works joining `skyFACT` with pixel-count statistics! → previous results

focus: 2 — 5 GeV

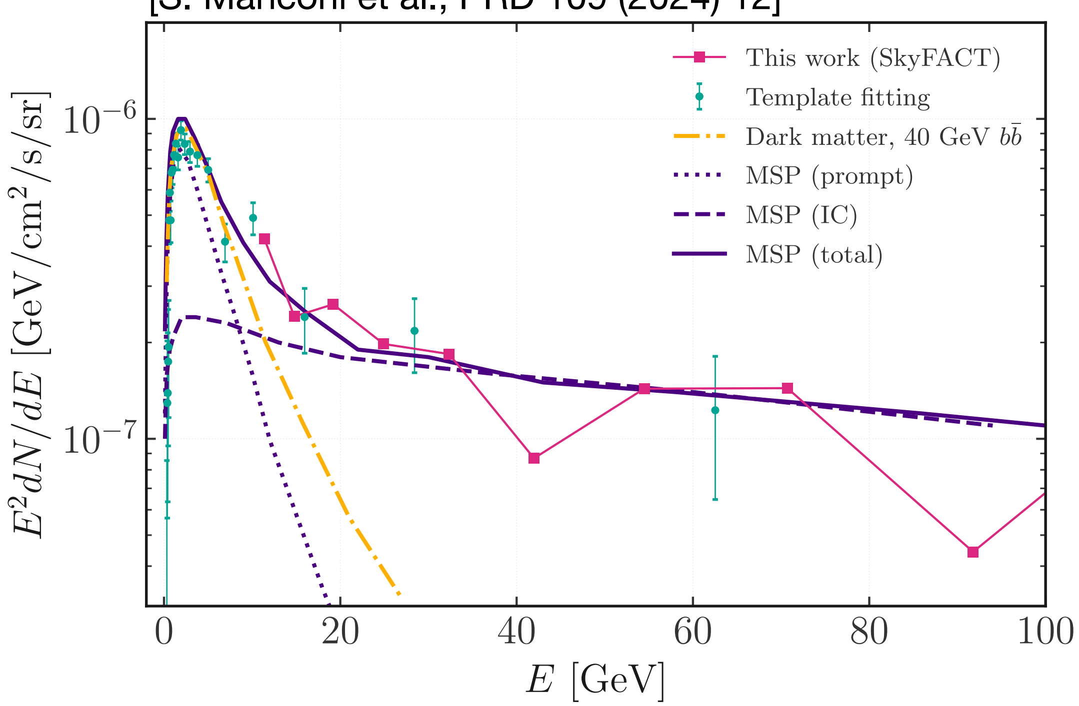
[F. Calore & S. Manconi, PRL 127 (2021) 16]





focus: > 10 GeV

[S. Manconi et al., PRD 109 (2024) 12]



- stellar bulge preferred spatial morphology of GCE (2 — 5 & > 10 GeV regime)
- robust high-energy emission from GCE
- 1p-PDF has sensitivity beyond 4FGL catalog detection threshold
- slight non-symmetric discrete source density in Galactic longitude

Constraining particle dark matter with the GCE

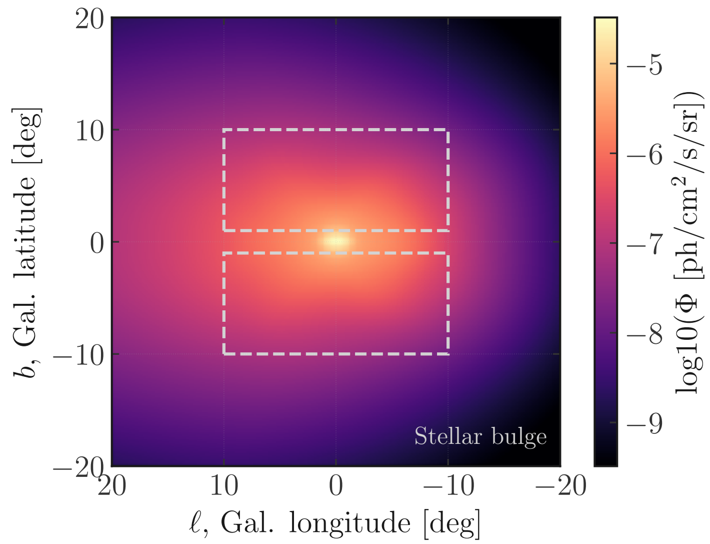
This work is the culmination point of a series of works joining `skyFACT` with pixel-count statistics! → **now: derive constraints on particle dark matter**

Strategy:
Start from **null hypothesis** — GCE is of stellar origin.

1. `skyFACT` optimisation with full model in full energy range (0.5-300 GeV):

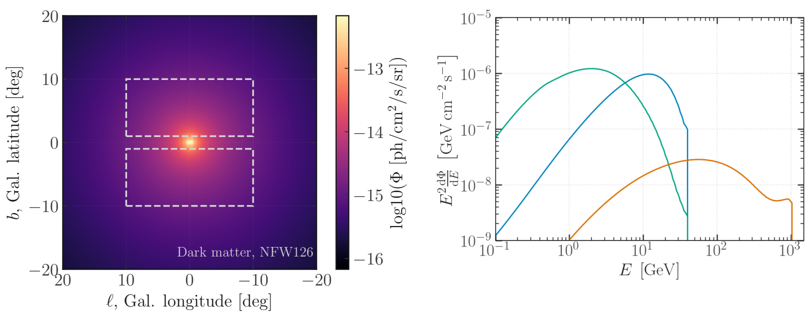
`skyFACT` diffuse & discrete source model (as in previous works)

+



+

DM scenario: $(\rho_{\mathrm{DM}}, m_{\mathrm{DM}}, f\bar{f})$



(or NFW, Einasto, Burkert)
[M. Benito et al., Phys.Dark Univ. 32 (2021)]

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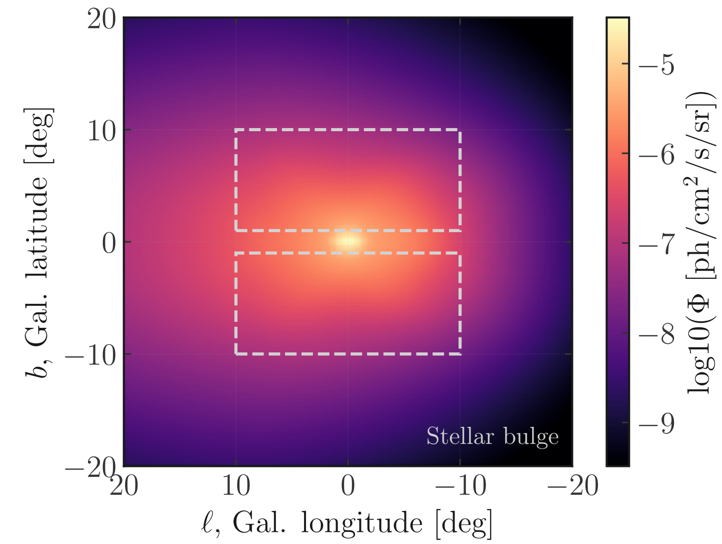

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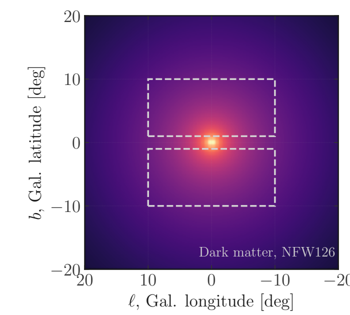
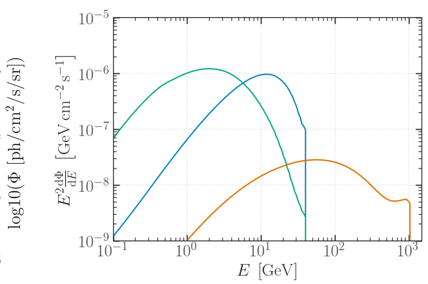
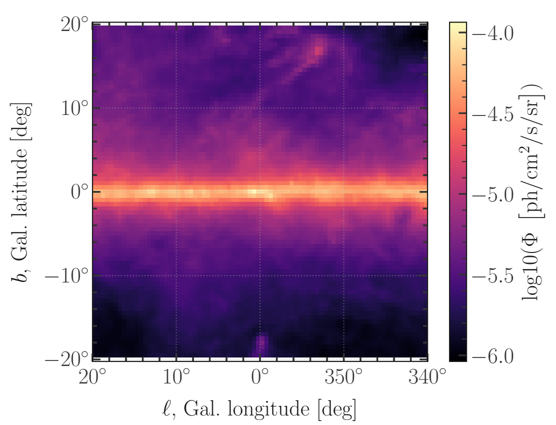




(or NFW, Einasto, Burkert)
[M. Benito et al., Phys.Dark Univ. 32 (2021)]

2. extract `skyFACT`-optimized diffuse template (2 — 5 GeV); fit DM & stellar bulge with 1p-PDF method:



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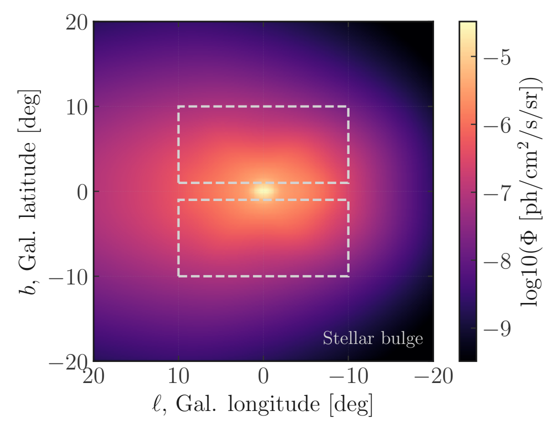

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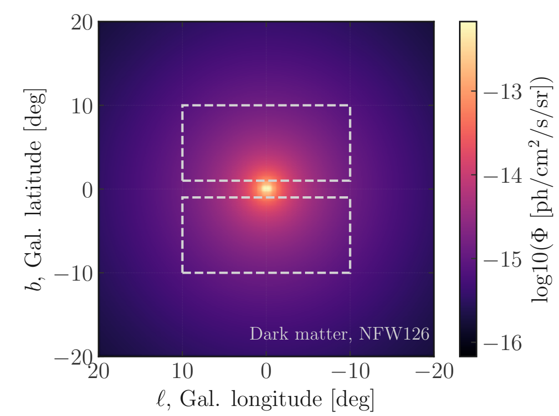
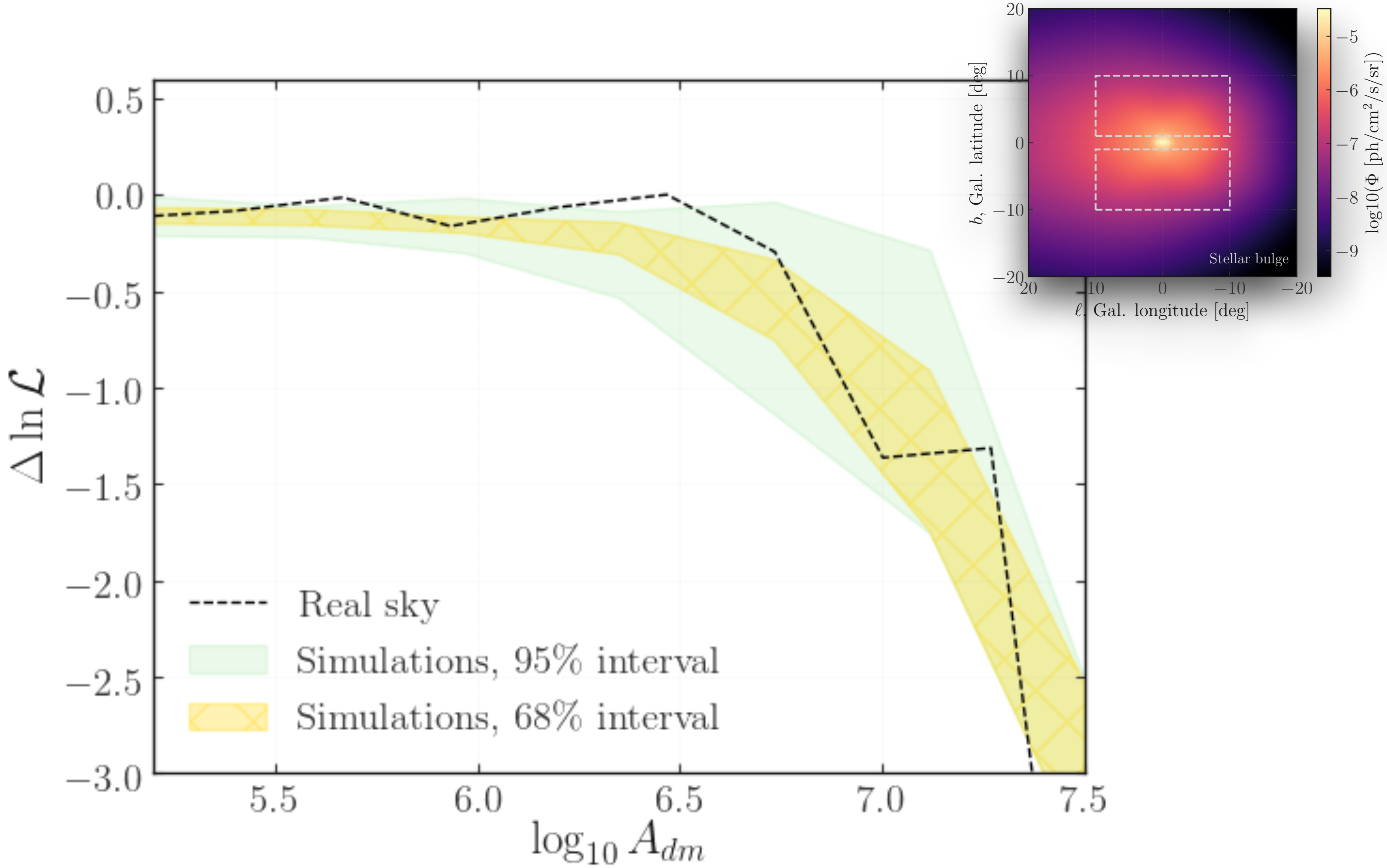


⟹ best-fit DM cross-section

Validation and results

We selected a region in the sky that yields statistically well-behaved upper limits on the dark matter annihilation strength.



Null hypothesis test with 1p-PDF:

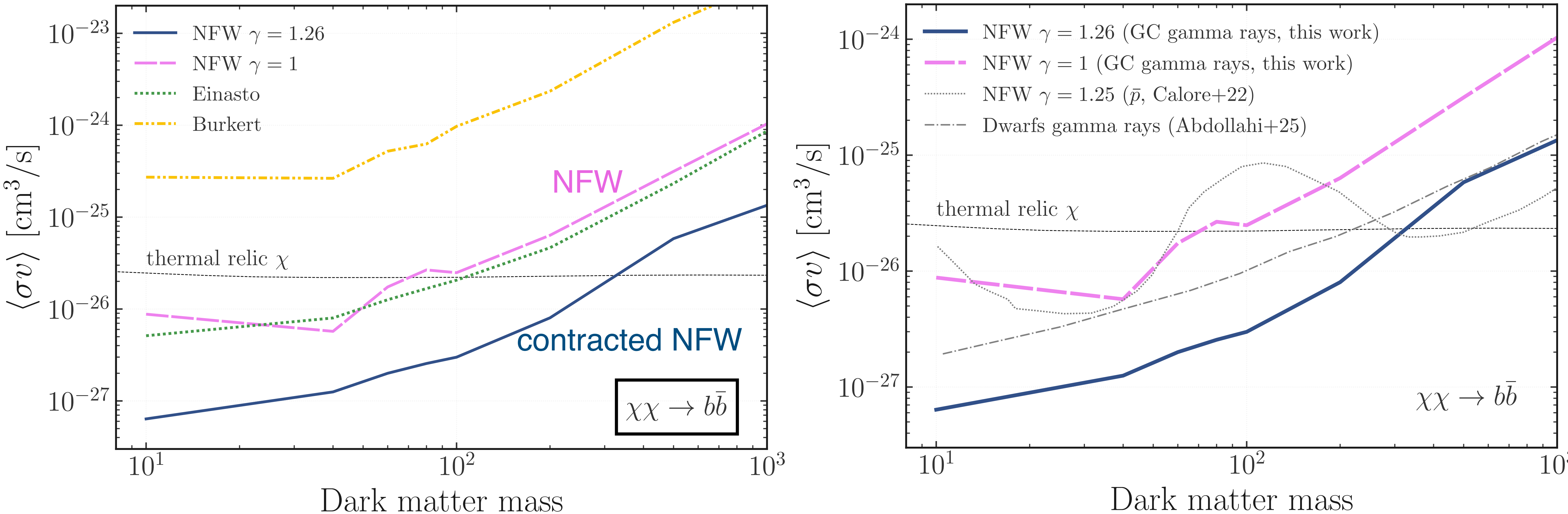
→ 20 simulated LAT datasets from null hypothesis `skyFACT`-optimized templates.

→ Real sky performance within 68% confidence interval.

Validation and results

In most of the dark matter scenarios $(\rho_{\rm DM}, m_{\rm DM}, f\bar{f})$, the `skyFACT` fit recovers DM contributions compatible with zero (or in a handful of cases very low normalisations)**.**

(upper limits leveraging photon energies from ~ 2 to 6 GeV)

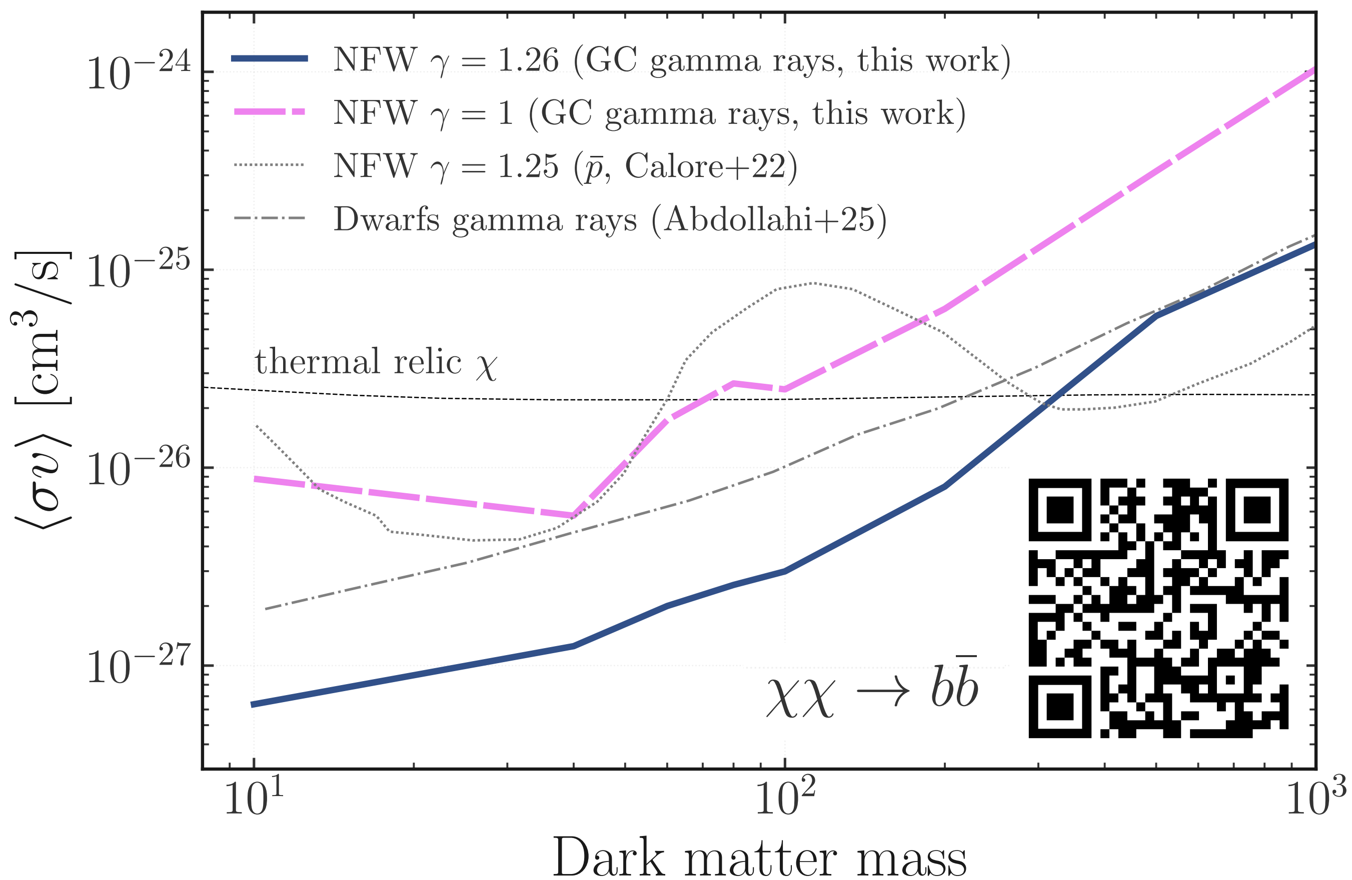


→ Depending on the dark matter profile in the Milky Way's centre, our constraints can **exclude thermal dark matter of up to a mass of 300 GeV for the hadronic channel** (80 GeV for leptonic channels).

Summary and Conclusions

- We employed the **combination of adaptive-template fitting and one-point photon-count statistics** to **constrain dark matter annihilation in the Galactic centre**.
- We **optimise all diffuse background components** in presence of a GCE represented by a stellar and dark matter component **for each dark matter scenario individually**.
- **We find no significant dark matter signal that could explain the GCE.**
- We perform **injection and recovery checks of `skyFACT` and the 1p-PDF method** on simulated data (for details ask me after the talk!).

A peaked dark matter density in the Milky Way's centre leads to very **stringent constraints** on thermal dark matter of **masses below 300 GeV** (hadronic channels).



Summary and Conclusions

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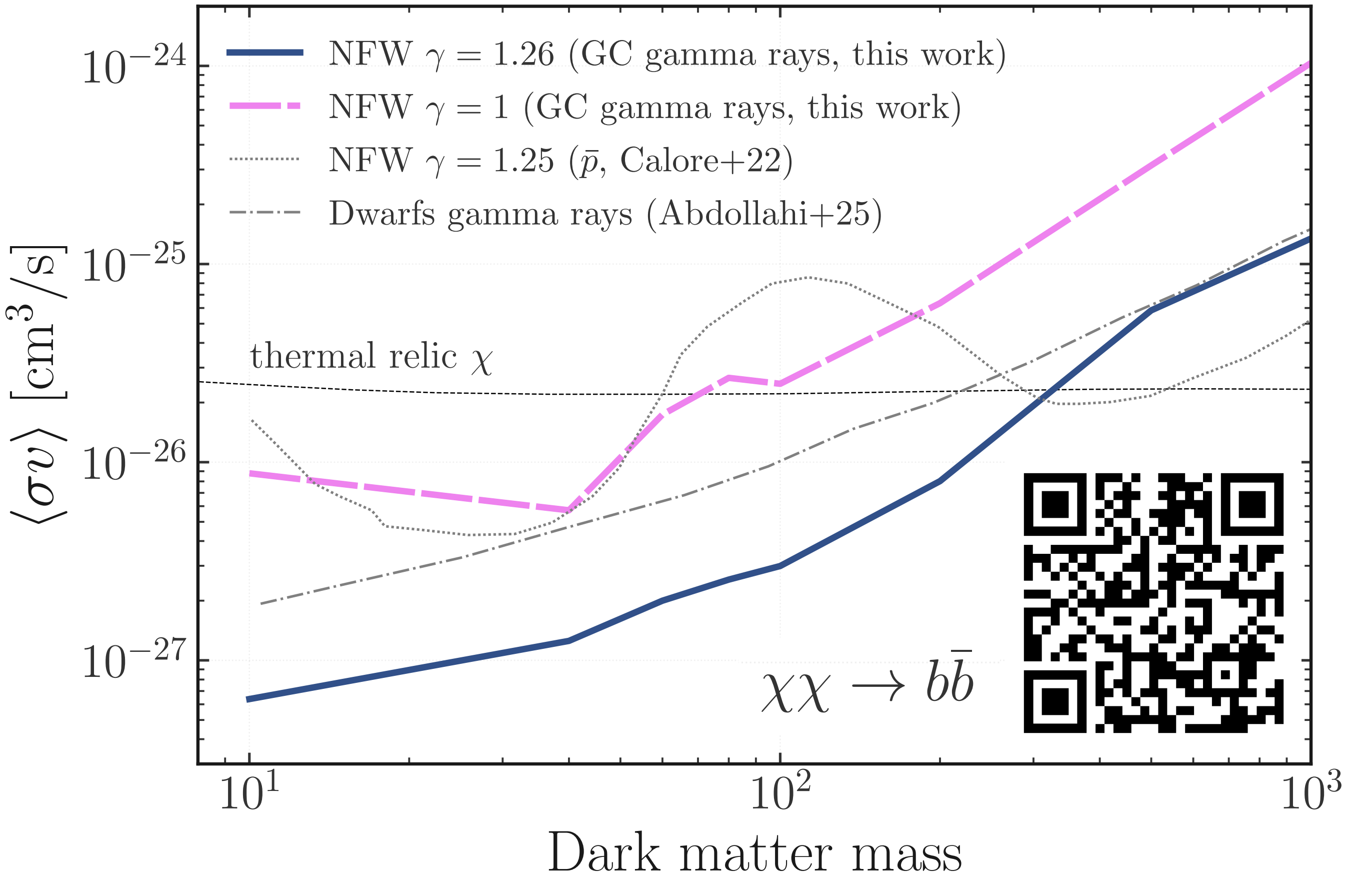


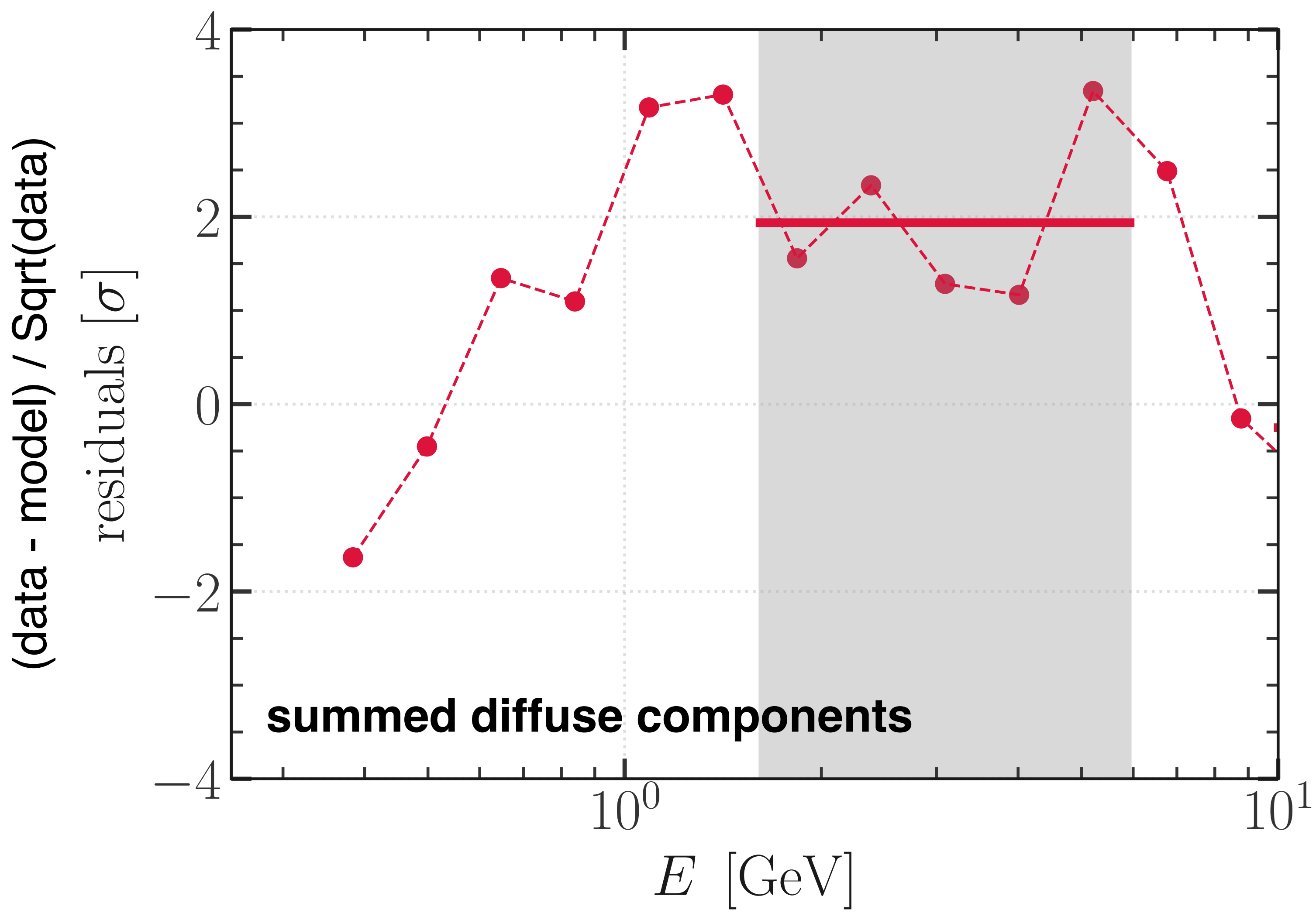
Thank you for listening!

Backup slides

Validation tests of `skyFACT`

Given that our null hypothesis is true: What level of residual mismodelling can we expect in the optimised diffuse templates?

→ Prepare simulated data with composition reflecting the null hypothesis!
(some caveats and details: ask me later)



In our 1p-PDF analysis range, the residuals show an average residual level of 2σ.