International Workshop on New Opportunities for Particle Physics 2025

Dark Matter interpretation of the Galactic Center Gamma-Ray Excess from the 16 years of Fermi-LAT data

Seodong Shin

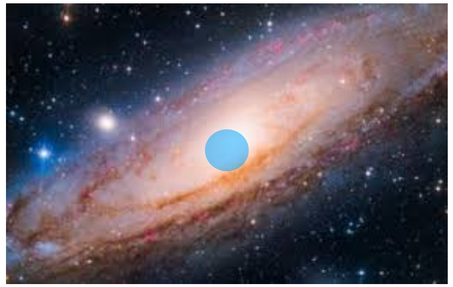
전북대학교
JEONBUK NATIONAL UNIVERSITY

Work in progress with Pouya Bakhti, Sang Hwan Kim, Meshkat Rajaee

Dark Matter Indirect Detection

Hints that can be the DM signals

Spherical morphology



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  511 keV line (Balloons, INTEGRAL/SPI)

- X-ray from galactic clusters & Andromeda: 3.5 keV line
  (XMM-Newton & Chandra) → Decaying DM?

- Positron: 10 GeV - 1 TeV
  (PAMELA, Fermi-LAT, AMS-02) → DM annihilation with $\mathcal{O}(100)$ boost factor?

- Anti-proton: 10 GeV (AMS-02) → 50 - 100 GeV DM?

within ~ 1kpc

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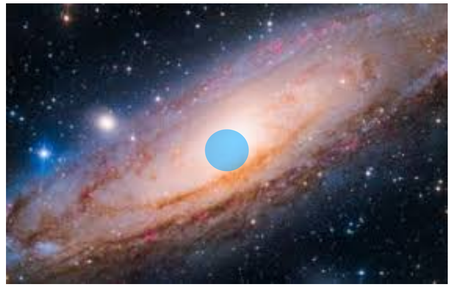

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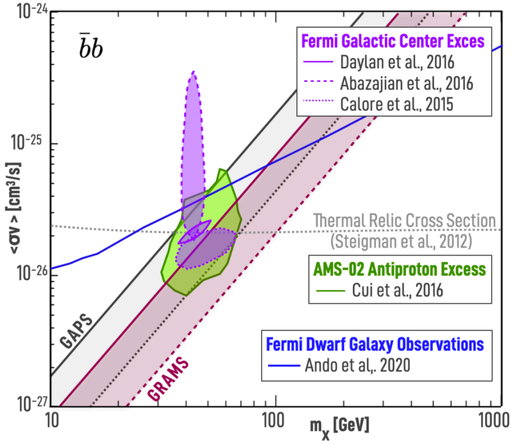
Aramaki, Adrian, Karagiorgi, Odaka, arXiv:1901.03430



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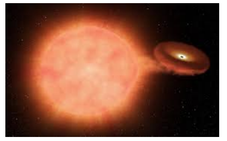
Update in diffuse emission model?

Other?

Type Ia SN



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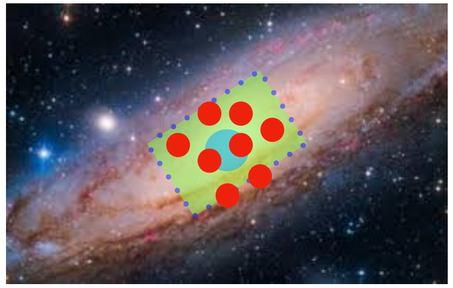

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X-ray binaries

CR outburst

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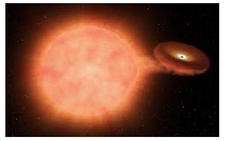

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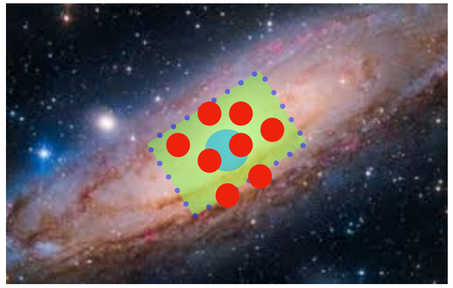

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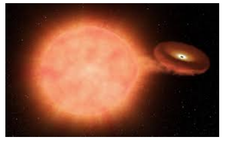

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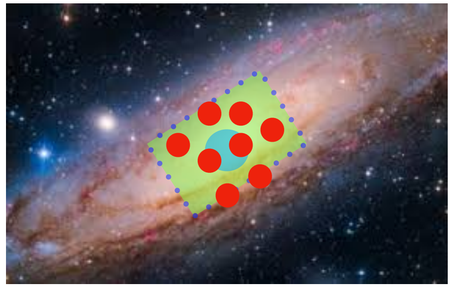

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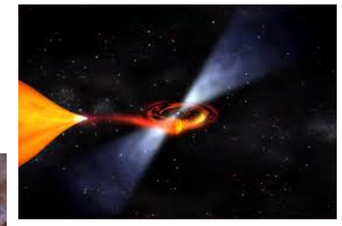

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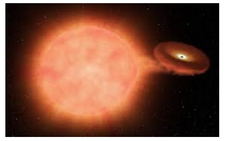

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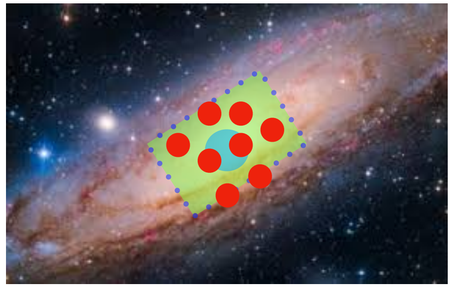

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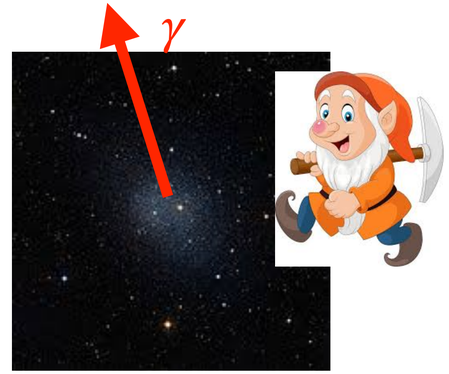

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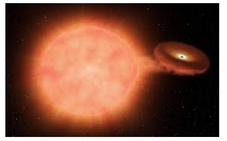

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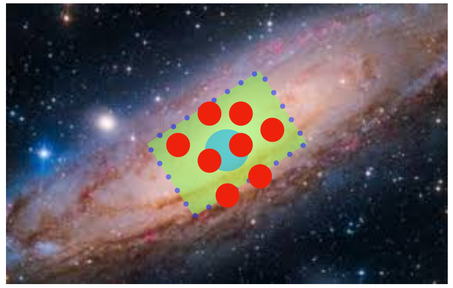

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e^+e^- in pulsar magnetospheres, along with subsequent acceleration in the surrounding pulsar wind nebula

~ 250pc from the Sun

X-ray by Chandra & Spitzer,
NASA/JPL-Caltech

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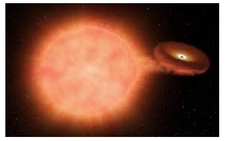

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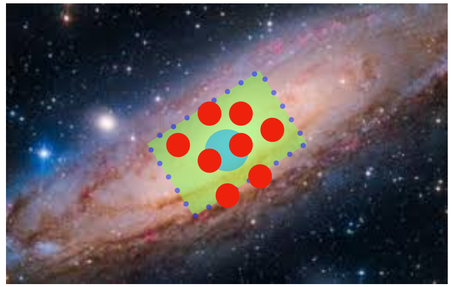

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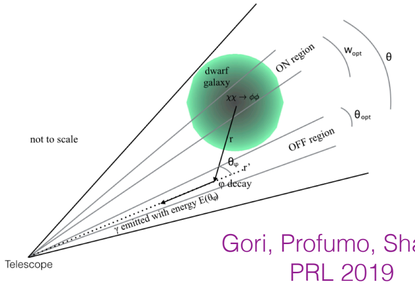
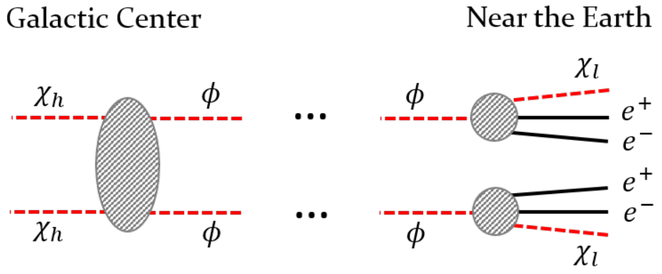
The only possible explanation with DM: long-lived particles

within ~ 1kpc

Effectively TRANSPORT
DM: GC → Earth



Gori, Profumo, Shakya
PRL 2019



Kim, Park, **SS**, JHEP 2018
arXiv:1702.02944

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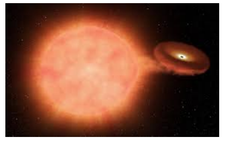

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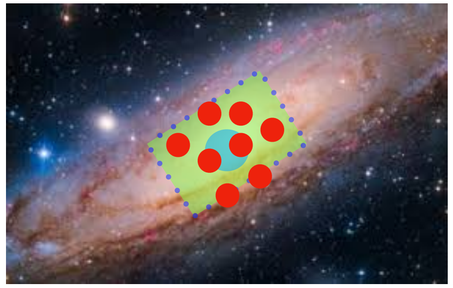

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Lack of published error correlation matrix by AMS-02

within ~ 1kpc

Uncertainties in cosmic-ray propagation & production cross section

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Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Snowmass2021 Cosmic Frontier White Paper: Puzzling Excesses in Dark Matter Searches and How to Resolve Them

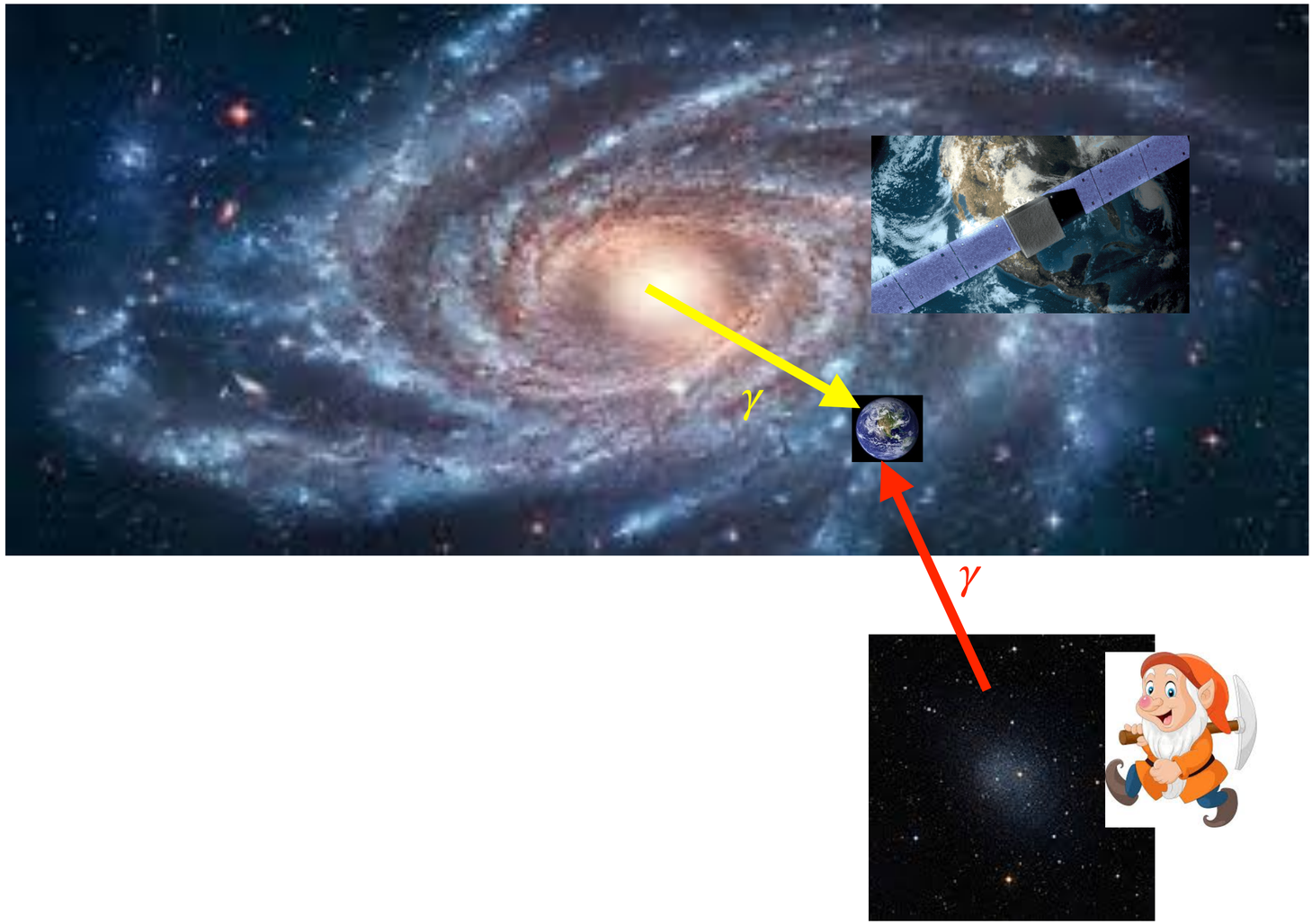
Rebecca K. Leane[*1,2], Seodong Shin[†3], Liang Yang[‡4], Govinda Adhikari[4], Haider Alhazmi[5], Tsuguo Aramaki[6], Daniel Baxter[7], Francesca Calore[8], Regina Caputo[9], Ilias Cholis[10], Tansu Daylan[11,12], Mattia Di Mauro[13], Philip von Doetinchem[14], Ke Han[15], Dan Hooper[16,17,18], Shunsaku Horiuchi[19,20], Doojin Kim[21], Kyoungchul Kong[22], Rafael F. Lang[23], Qing Lin[24,25], Tim Linden[26], Jianglai Liu[15,27,28], Oscar Macias[29], Siddharth Mishra-Sharma[30,31,32], Alexander Murphy[33], Meshkat Rajaee[3], Nicholas L. Rodd[34], Aditya Parikh[31], Jong-Chul Park[35], Maria Luisa Sarsa[36], Evan Shockley[18], Tracy R. Slatyer[32], Volodymyr Takhistov[20], Felix Wagner[37], Jingqiang Ye[38], Gabrijela Zaharijas[39], Yi-Ming Zhong[18], Ning Zhou[15], and Xiaopeng Zhou[40]

arXiv:2203.06859

Revisit of the GCE with 16 years of Fermi-LAT

- GeV γ-ray from the GC, called GCE
- Clean signal with precise directional information but many background events
- Fermi-LAT has collected the GCE data for 16 years with updated point source catalogue.
- The γ-ray data from the dwarf spheroidal galaxies (dSphs) is updated as well: **good test!**

Large Area Telescope (LAT) in Fermi γ-ray space telescope



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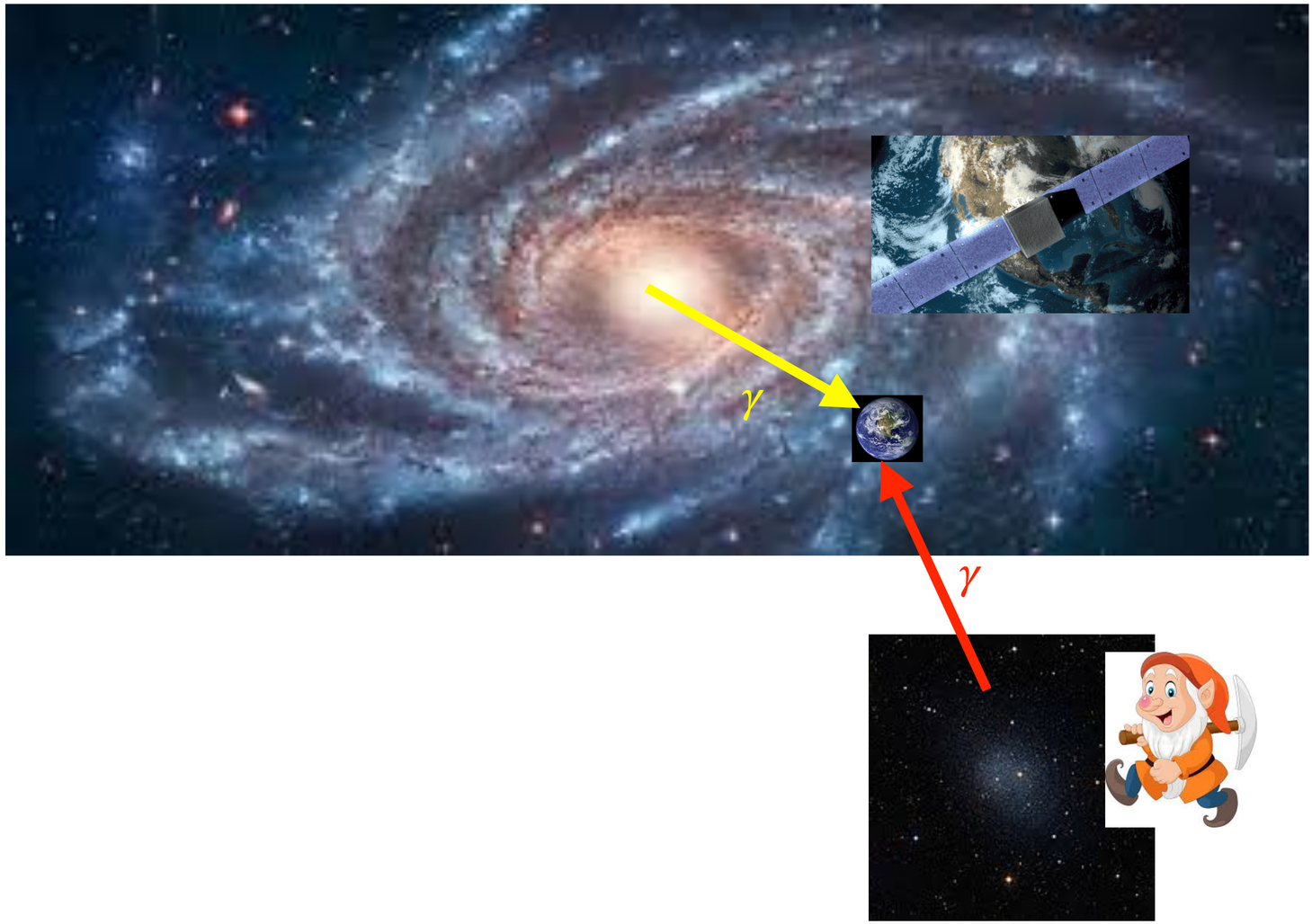

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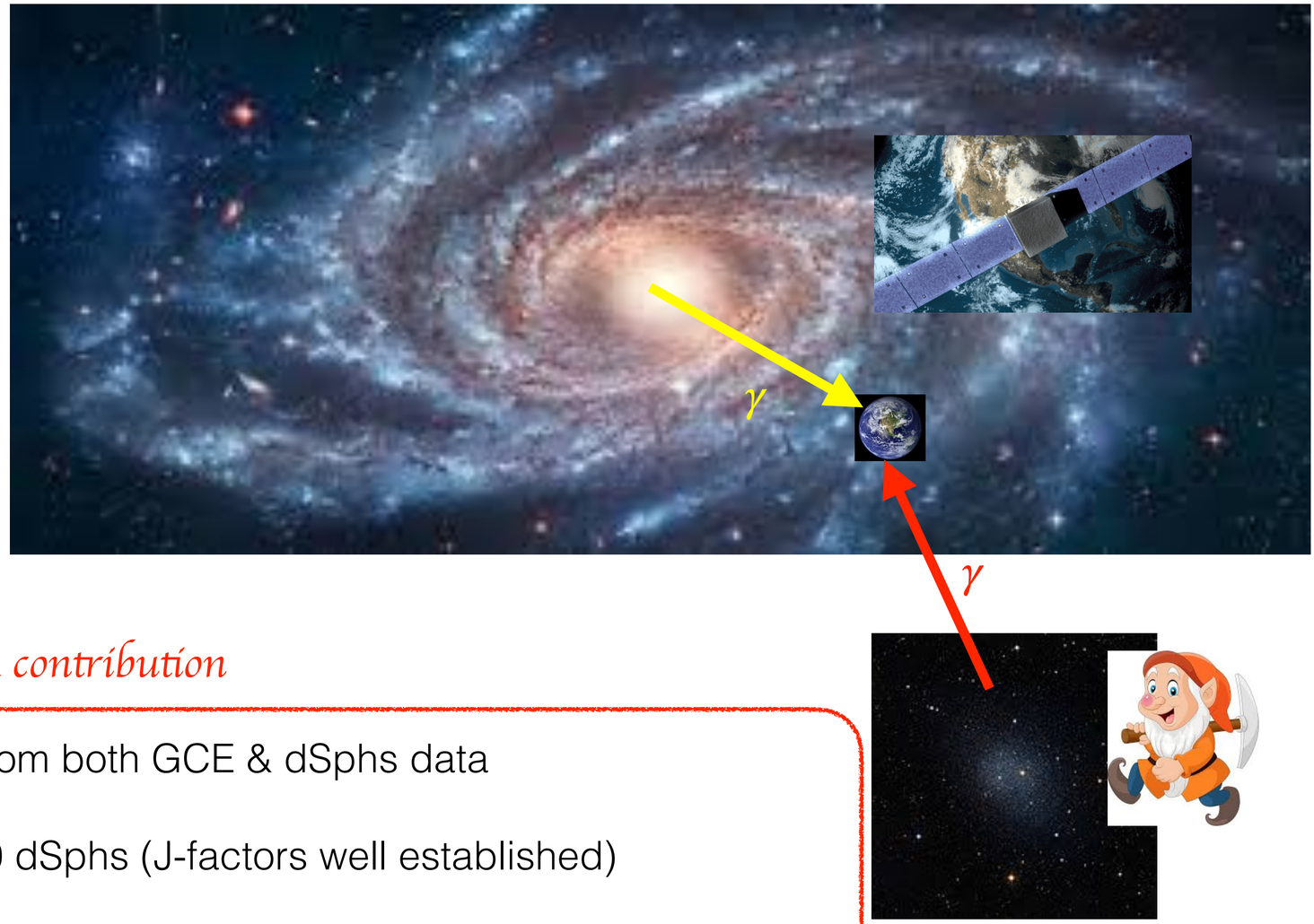


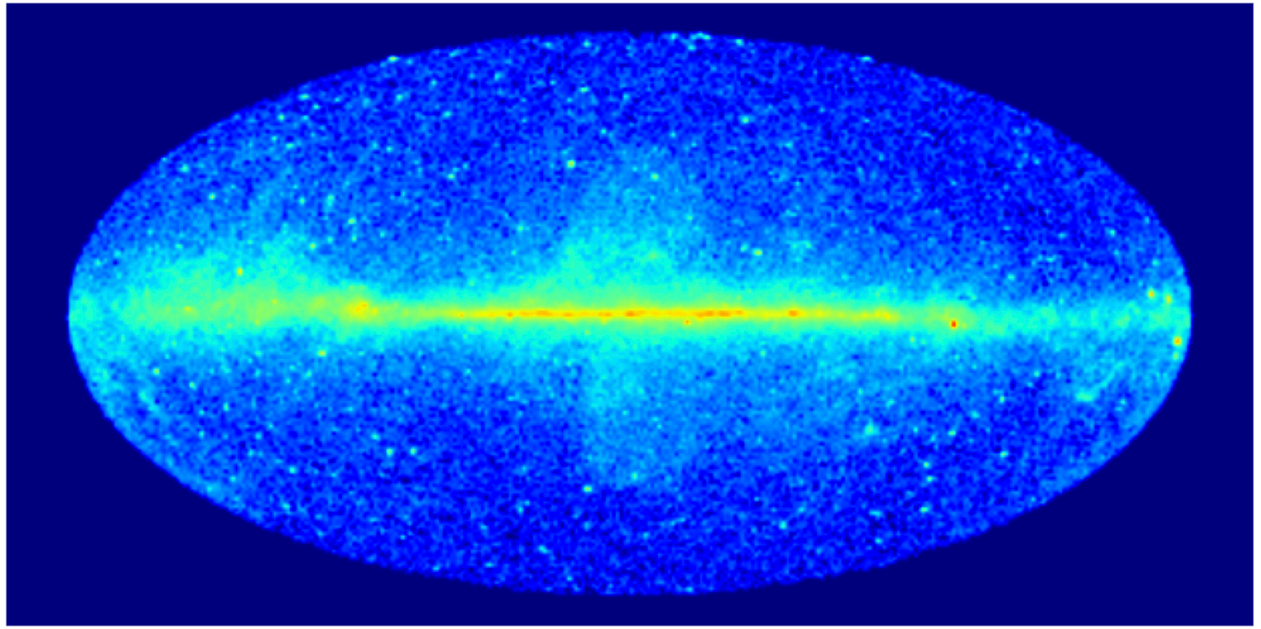
Analysis from the raw data assuming DM contribution

- Raw data analysis DM DM → 4-body final states from both GCE & dSphs data
- Consider 80 diffuse emission models for GCE & 30 dSphs (J-factors well established)
- Apply to a reference scenario: singlet fermionic dark matter (SFDM) to see effect of mediator mass

Not included in this talk

Gamma-ray observation at Fermi-LAT

Diffuse emission



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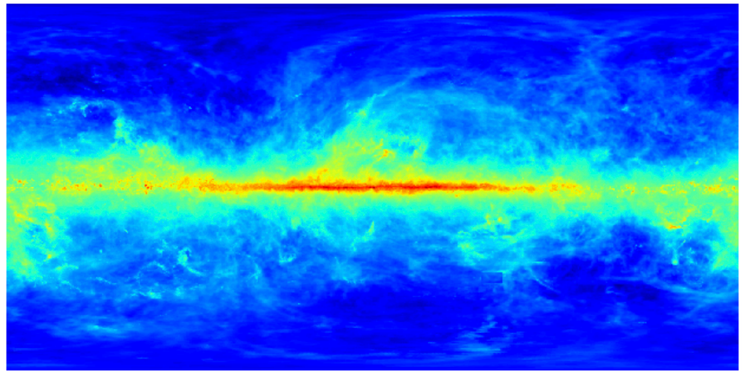
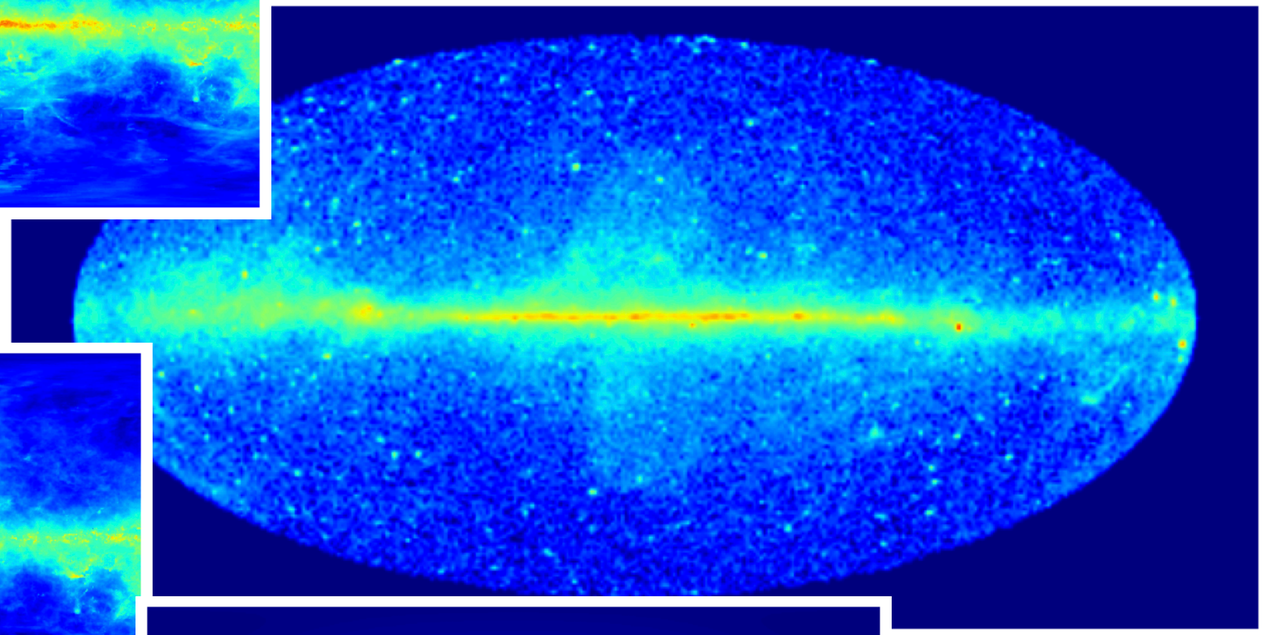
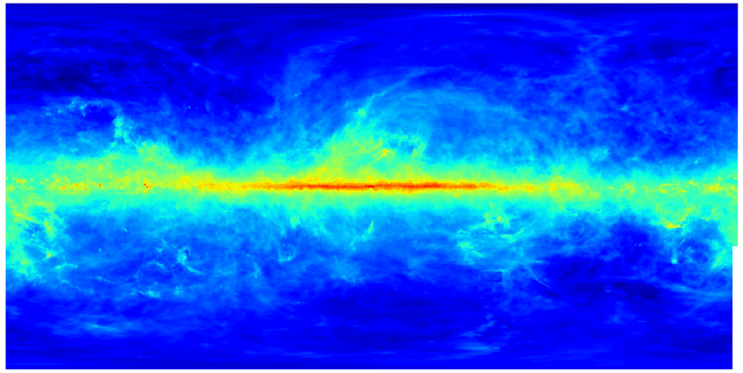
Bremsstrahlung

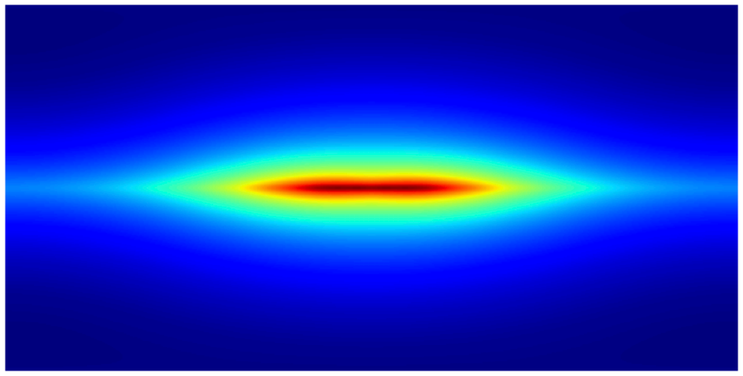


Accelerated CR → ISM



$\pi^0 \rightarrow \gamma\gamma$





Inverse Compton Scattering (ICS)

Gamma-ray observation at Fermi-LAT

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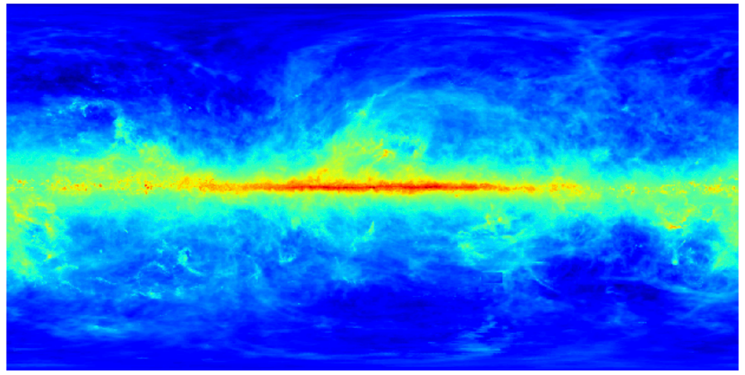

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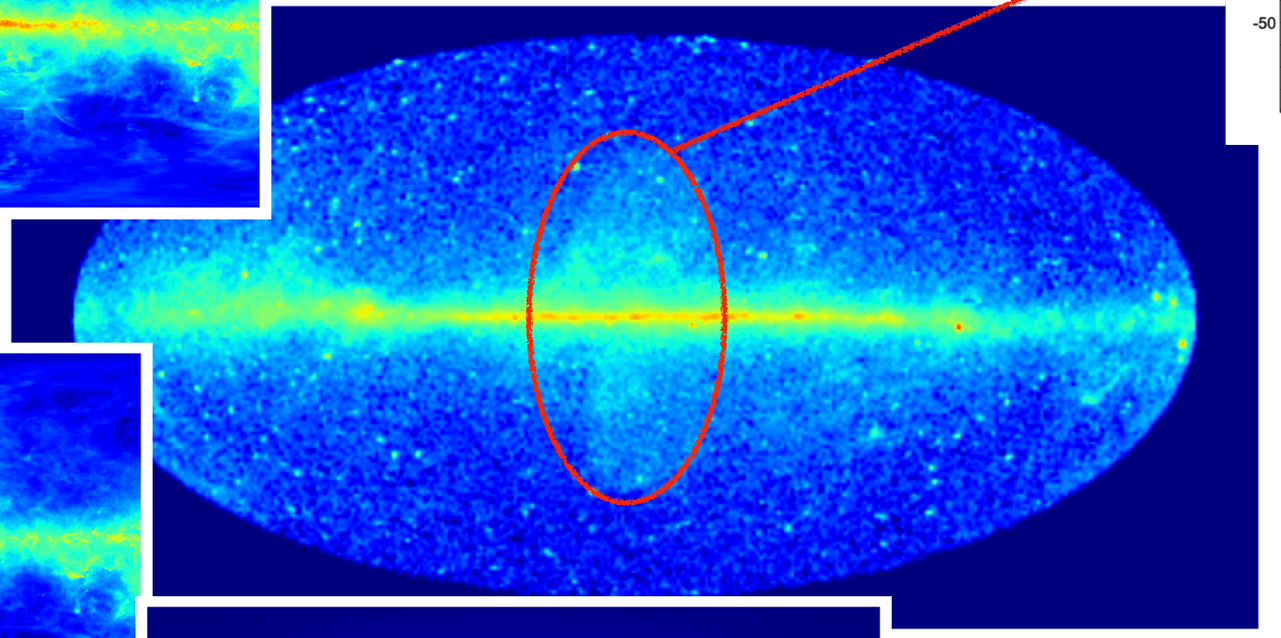

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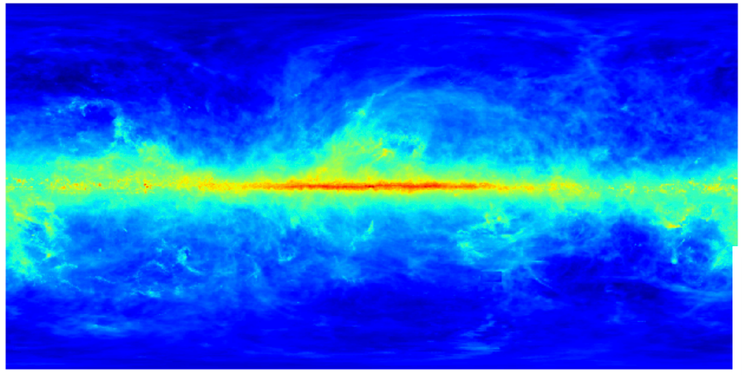
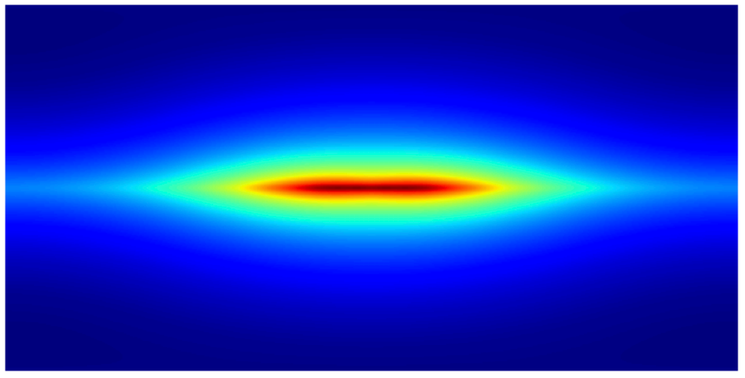
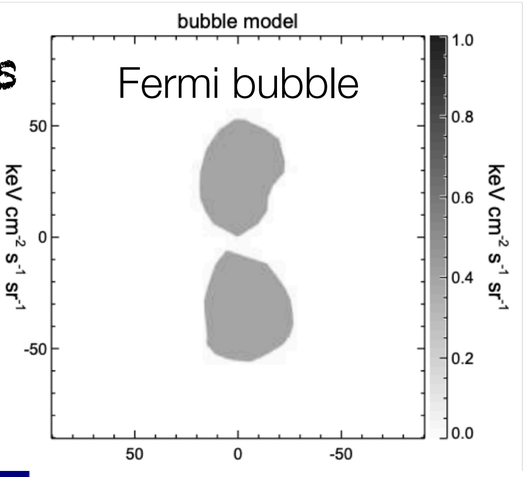




Inverse Compton Scattering (ICS)

More backgrounds

arXiv:1005.5480



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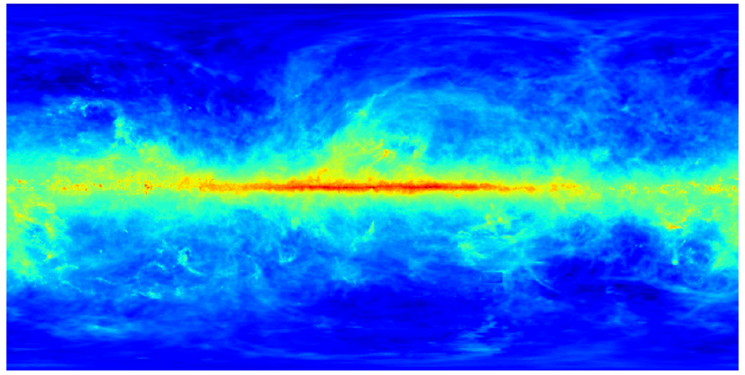

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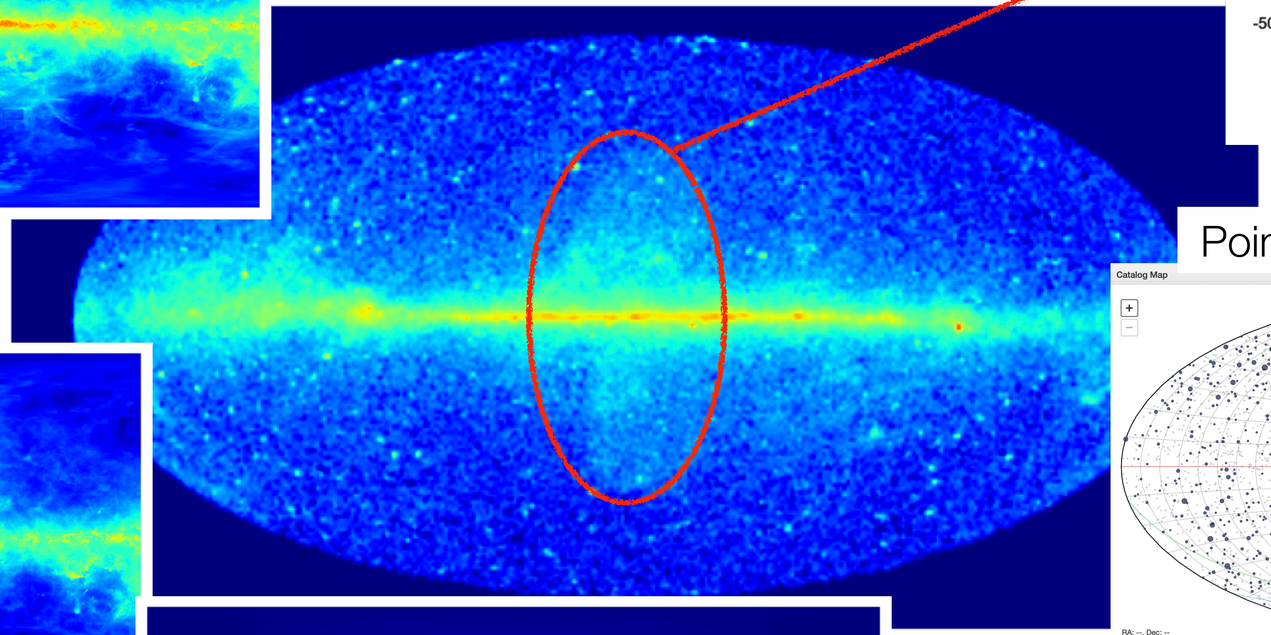

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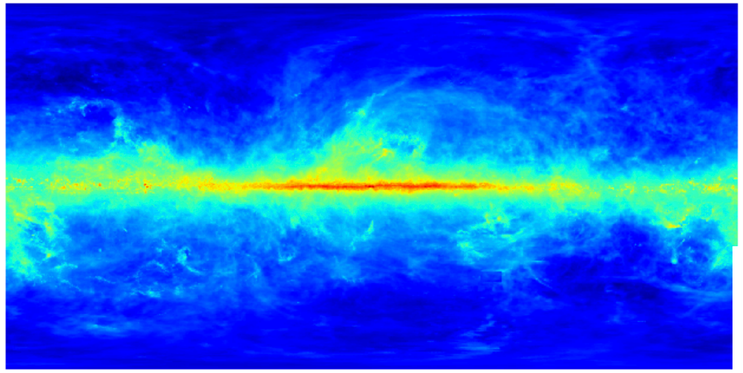
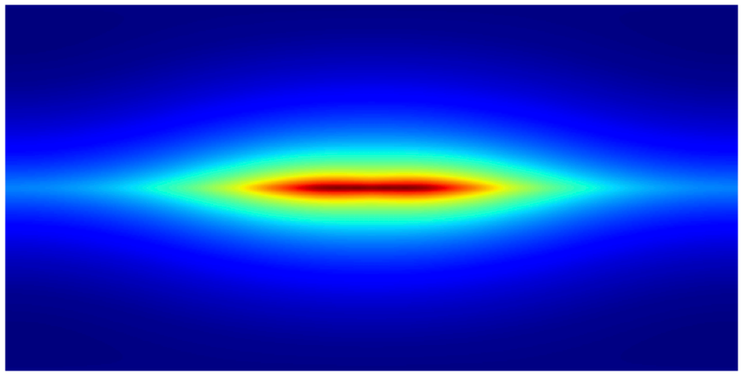
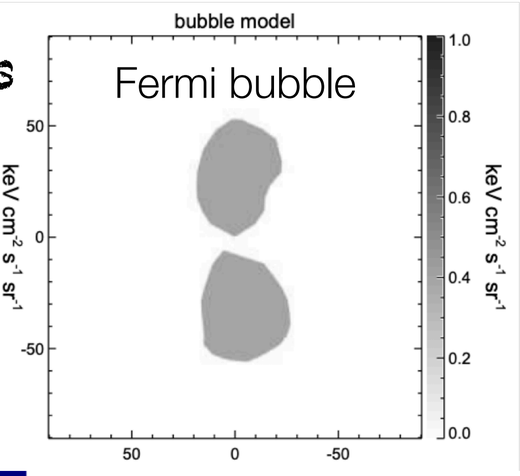




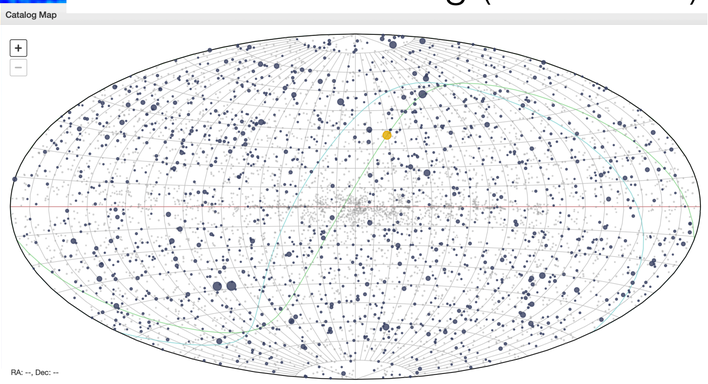
Inverse Compton Scattering (ICS)

More backgrounds

arXiv:1005.5480



Point source catalog (4FGL-DR4)



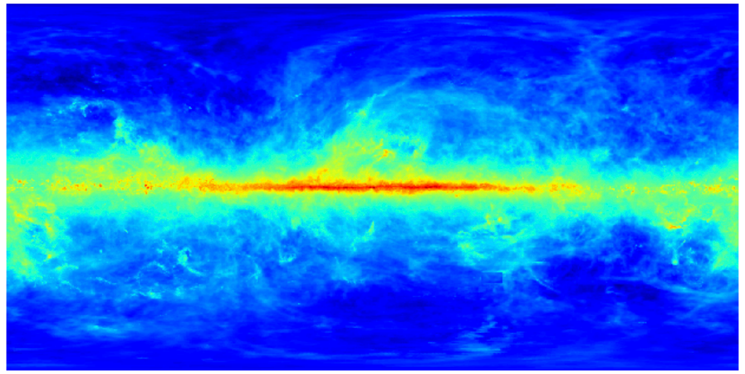
MSP, normal pulsar, PWN, X-ray binaries, SNR, …

https://fermi.gsfc.nasa.gov/ssc/data/access/lat/LightCurveRepository/

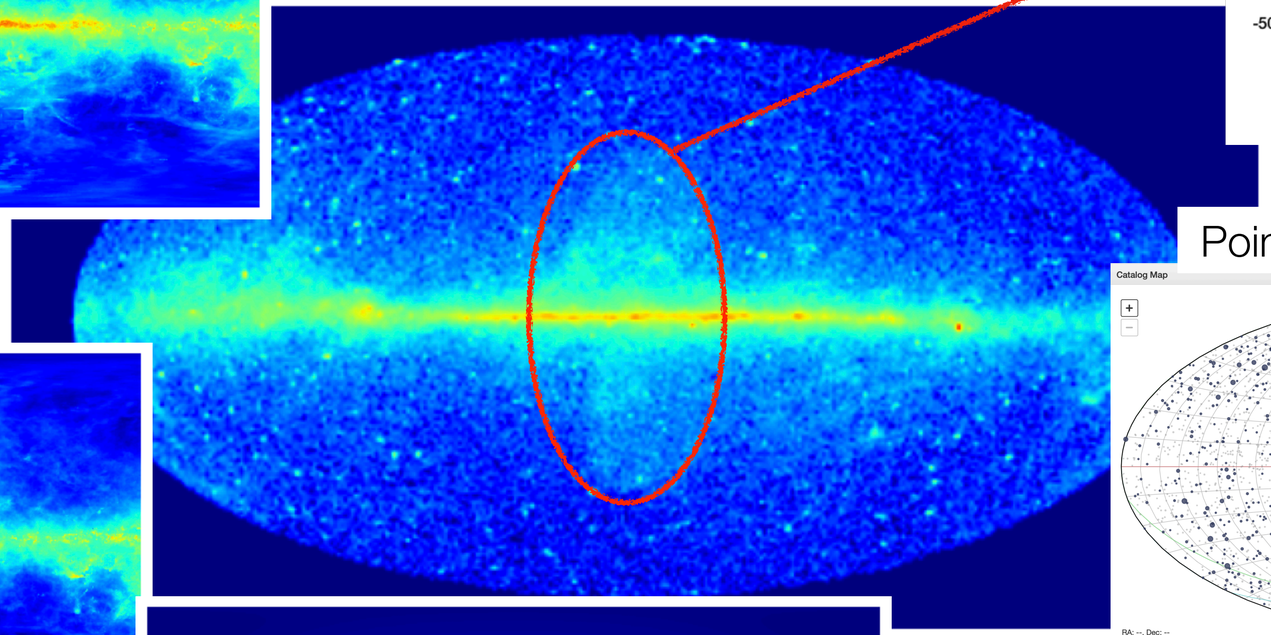
Gamma-ray observation at Fermi-LAT

Diffuse emission

Bremsstrahlung



Accelerated CR → ISM



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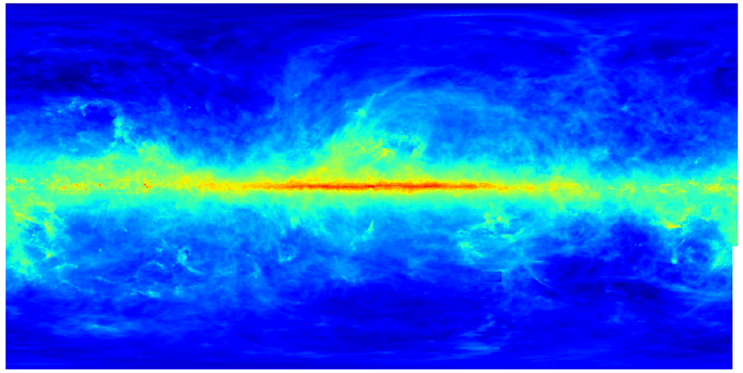

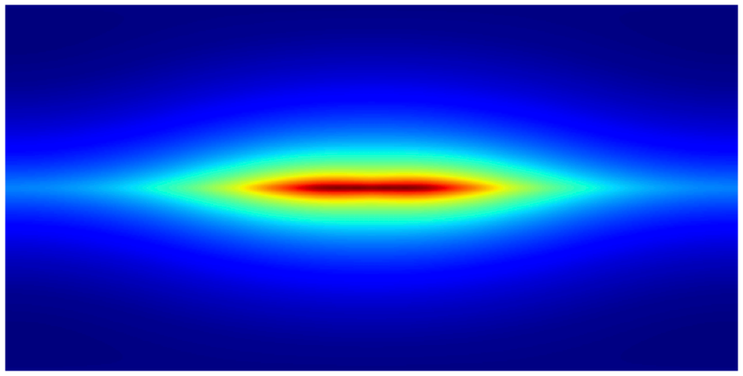

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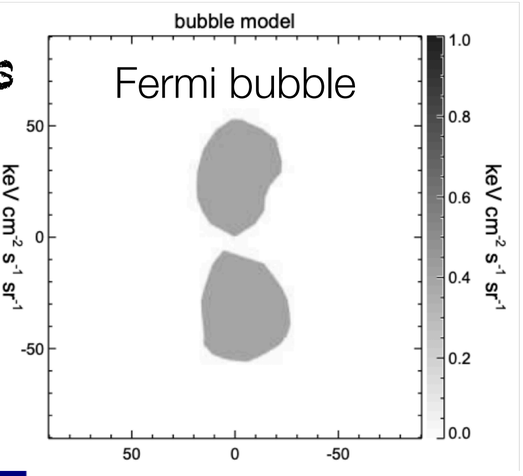

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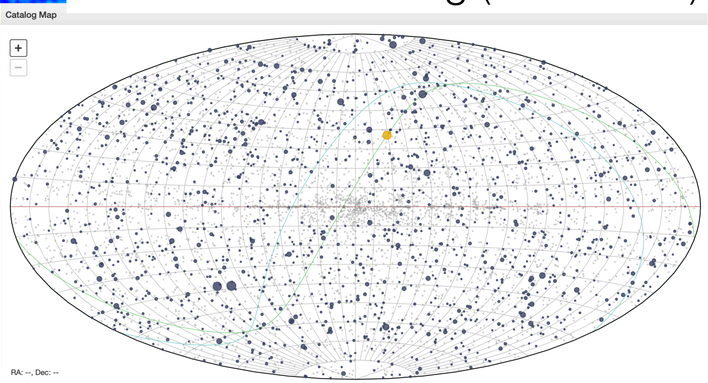

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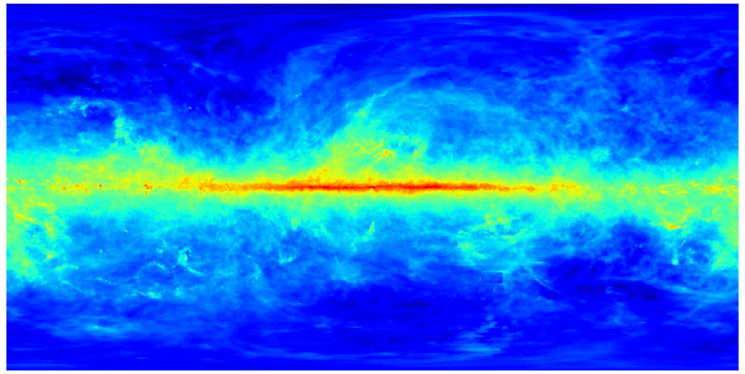
Extragalactic sources, …

Isotropic γ-ray

Gamma-ray observation at Fermi-LAT

Bremsstrahlung



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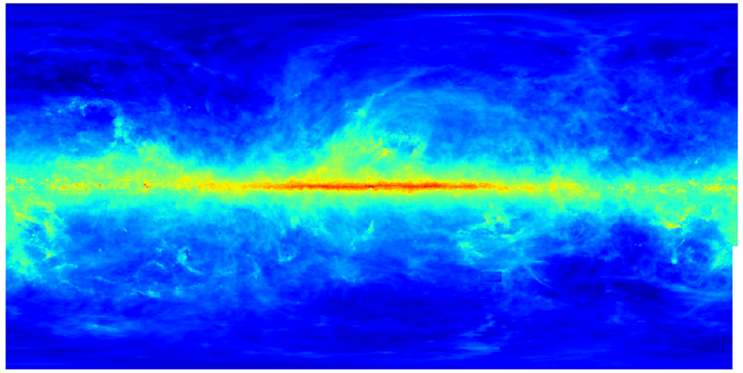

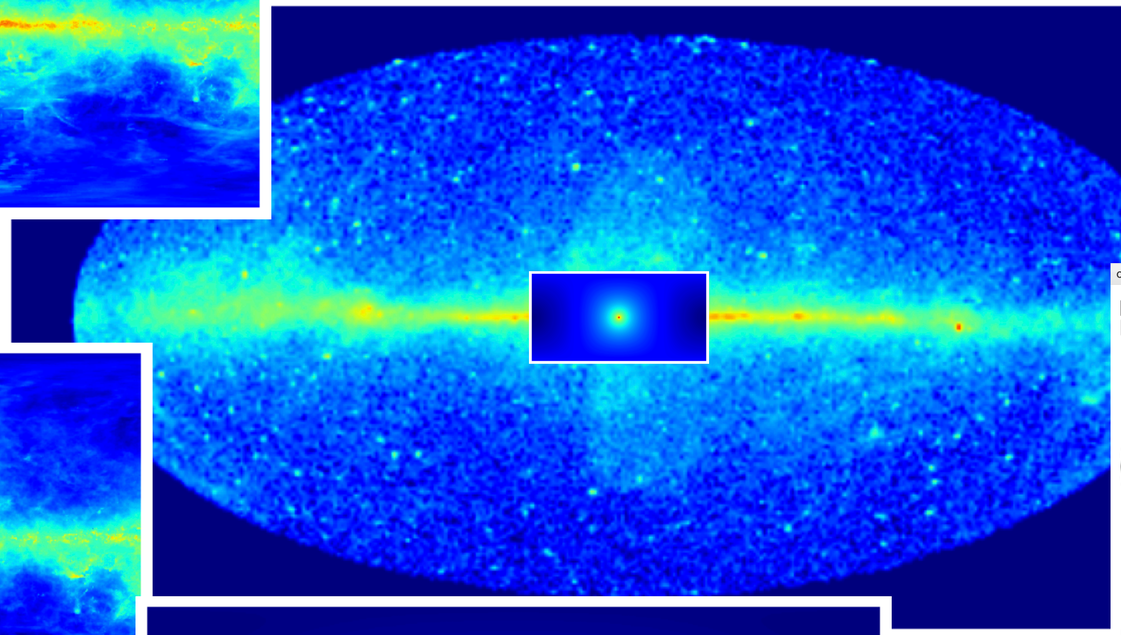

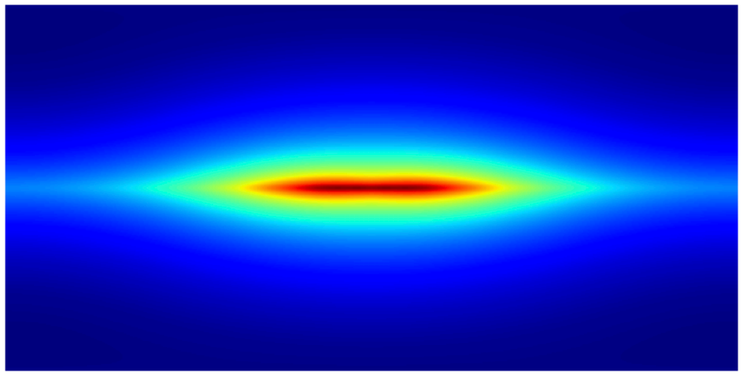

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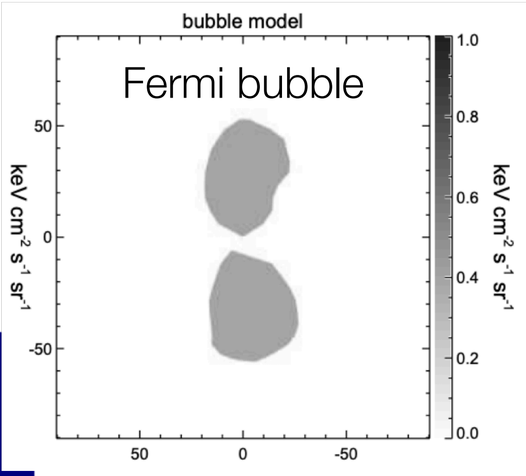

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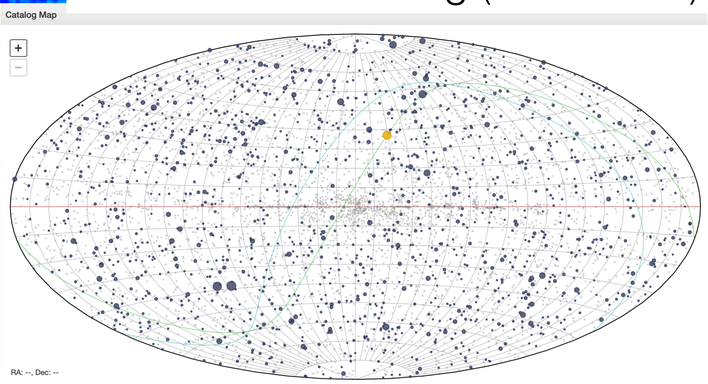

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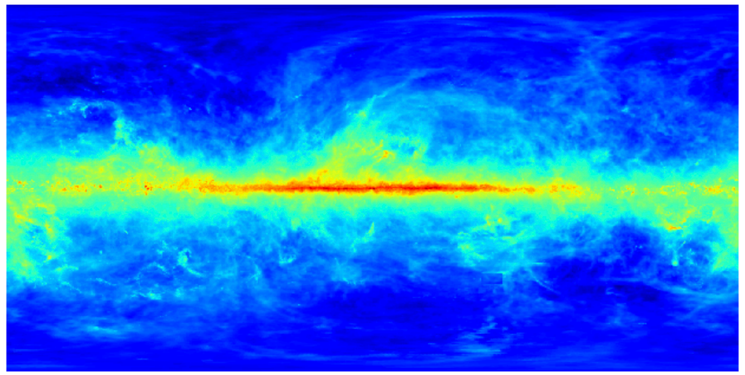

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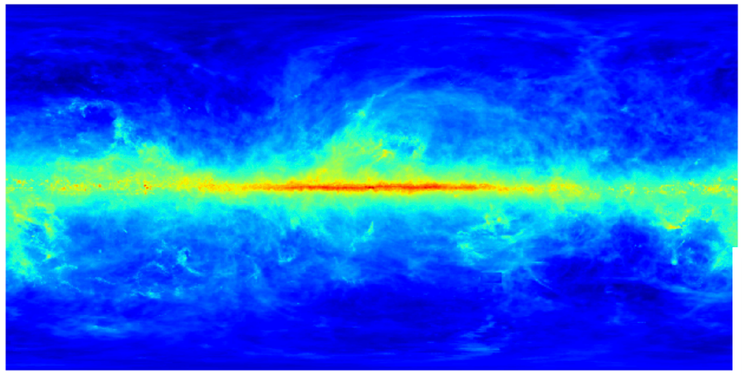

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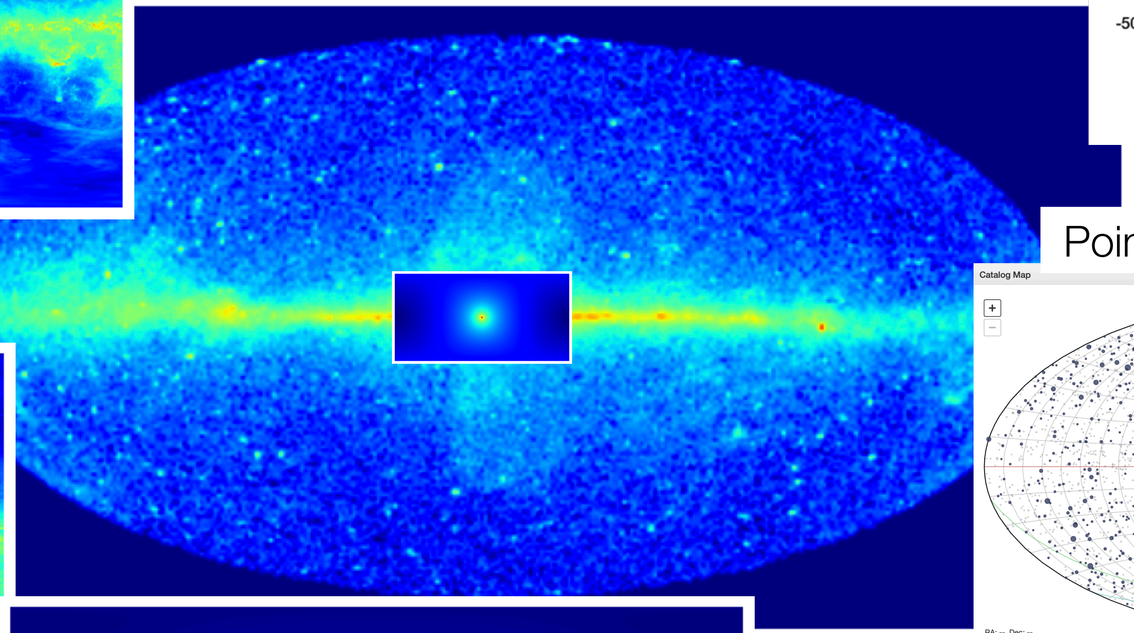
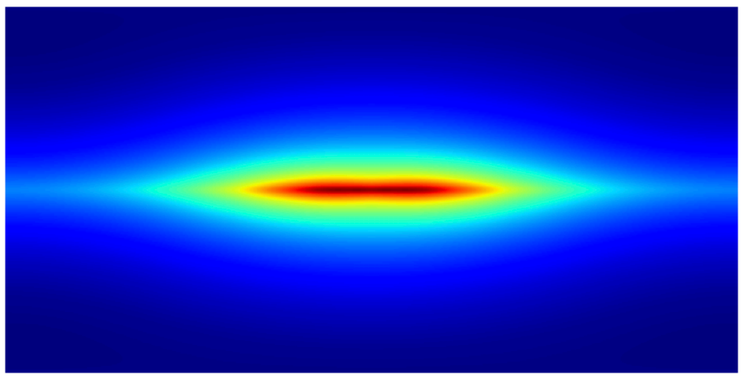
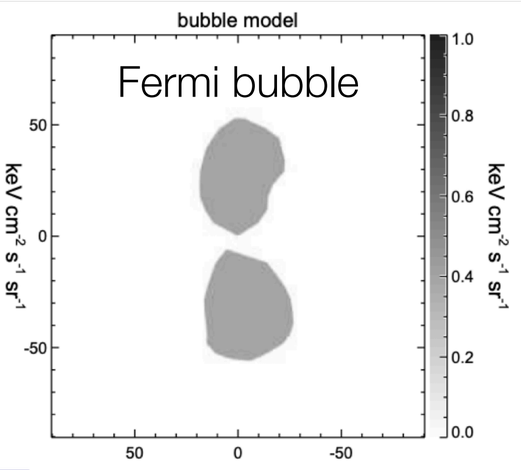




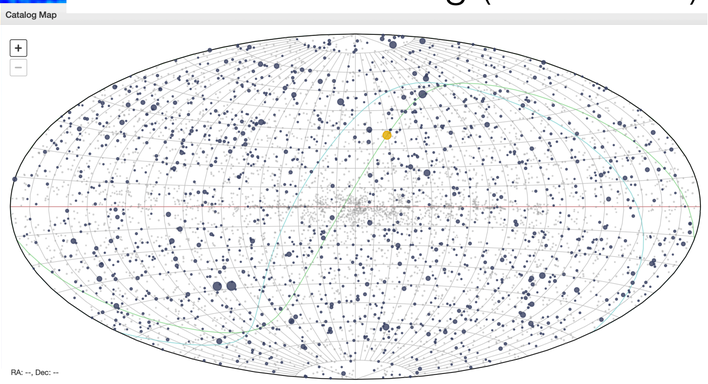
Use improved diffuse emission templates by CR observations

Cholis, Zhong, McDermott, Surdutovich, arXiv:2112.09706

arXiv:1005.5480



Point source catalog (4FGL-DR4)



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Extragalactic sources, …

Isotropic γ-ray

Data analysis

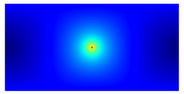
Data taking strategy

- ROI: 40°×40° Inner galaxy region

- E_γ: 0.3 GeV - 556 GeV

- Mask out $|b| < 2°$ (disk) & all 4FGL-DR4 point sources

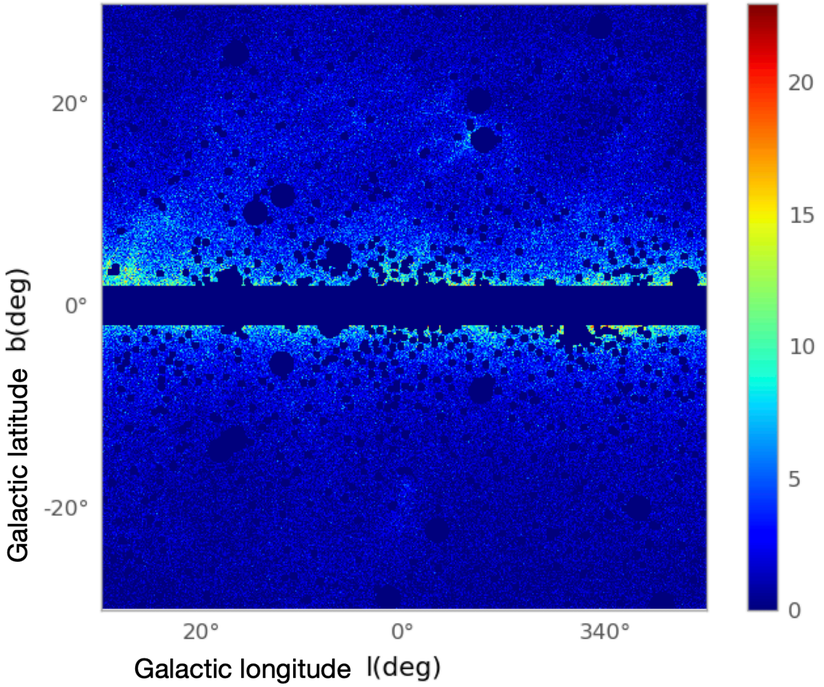
- GCE template: contracted NFW



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

γ = 1.2, r_c = 20kpc

ρ(8.5kpc) = 0.4 GeV/cm^3



- Bin-by-bin likelihood fitting since we don't know the exact flux of the background sources

$$-2 \log \mathcal{L} = 2 \sum_{i,j} (\mu_{i,j} - d_{i,j} \log \mu_{i,j}) + \chi^2_{\rm ext}$$

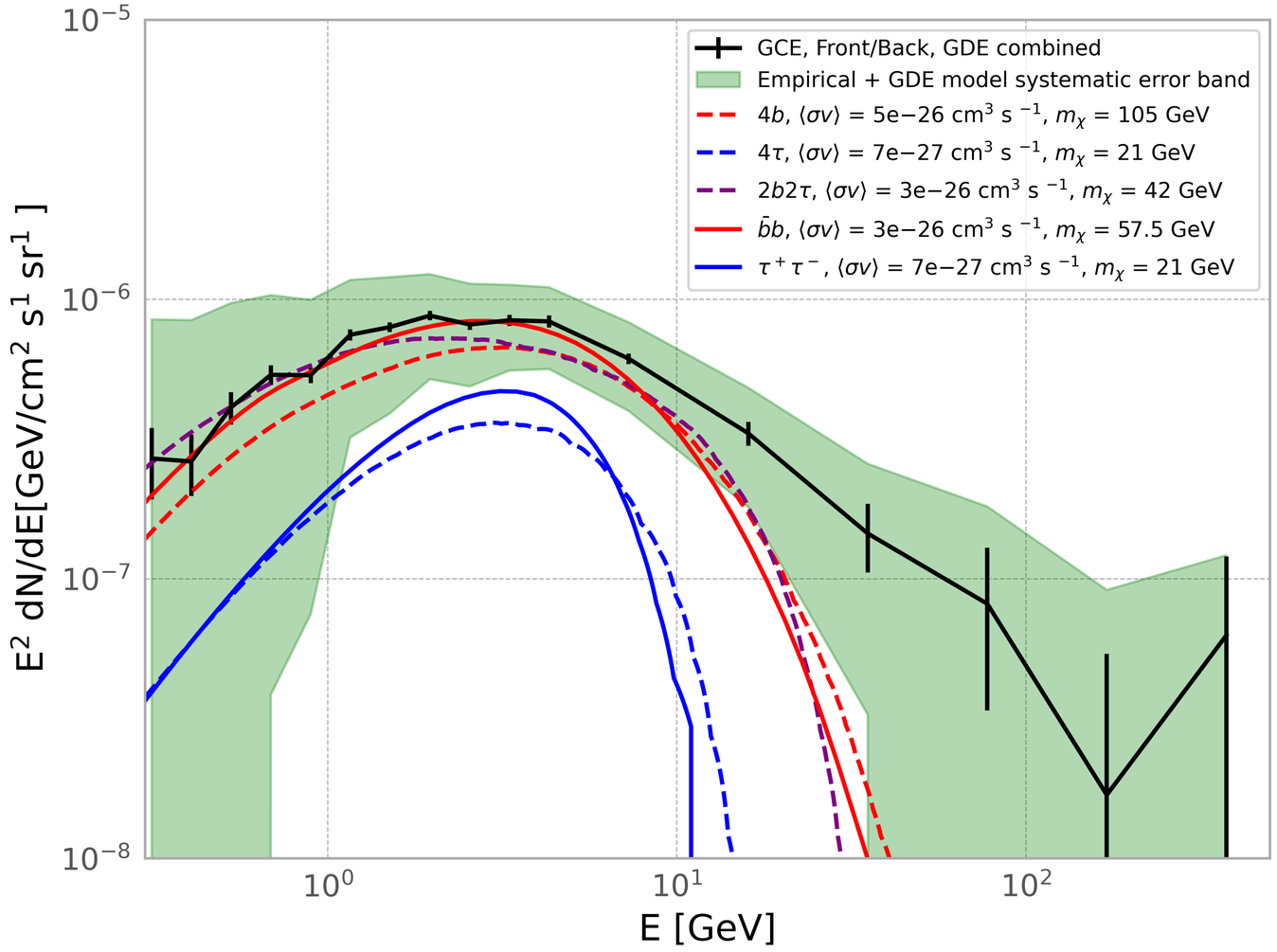
External penalty term for the extended objects
(Fermi bubble & isotropic spectrum)
since we don't know their emissivities at low $|b|$.

i: energy bin, j: pixel μ_{ij}: expected numbers, d_{ij}: observed numbersl

Data analysis

GCE after inclusion of the systematics: average over the 80 diffuse emission models

SED of DM candidates for Front GCE < 560 GeV (GDE model combined)



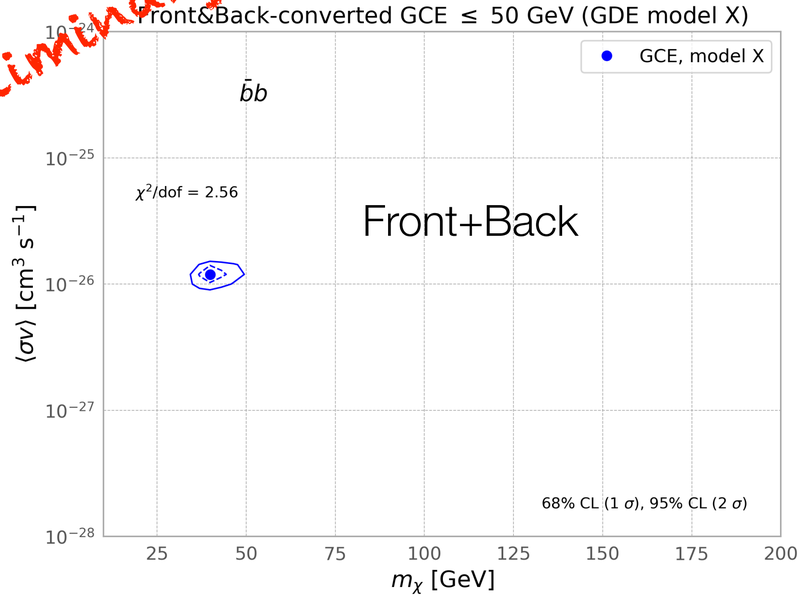
DM DM → SM 2-body or 4-body final states provide the good fits for the excess.

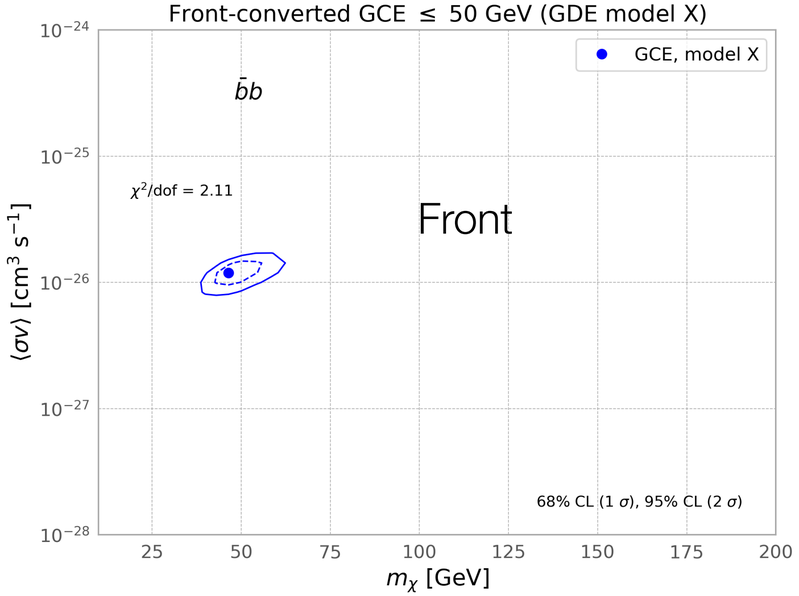
Data analysis

Model X

Preliminary

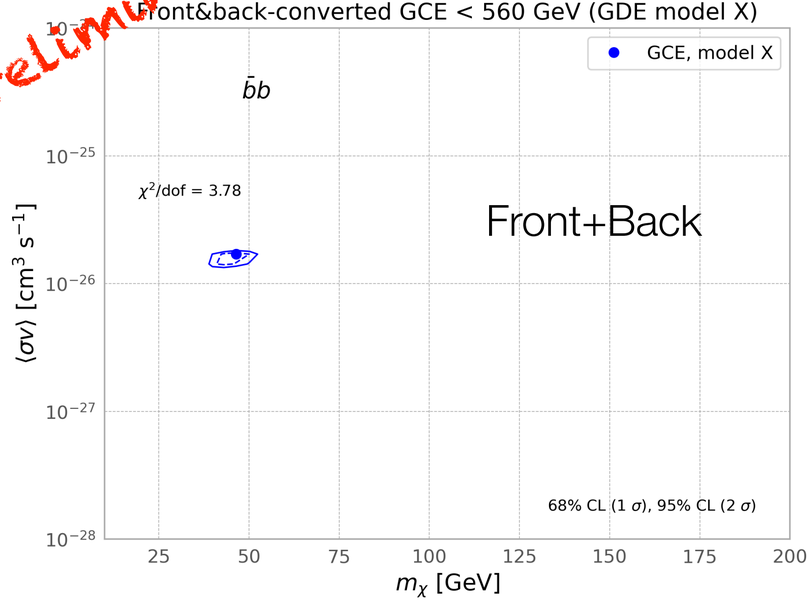
Up to 50 GeV bin

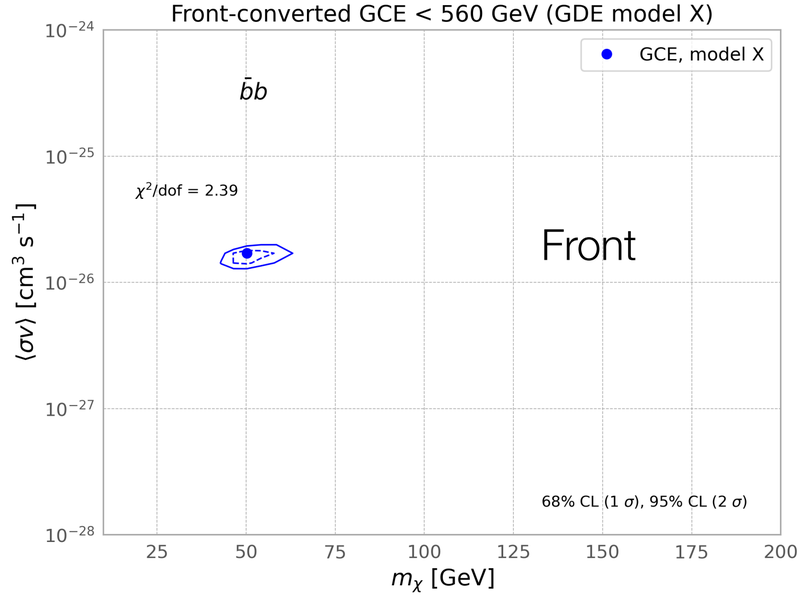


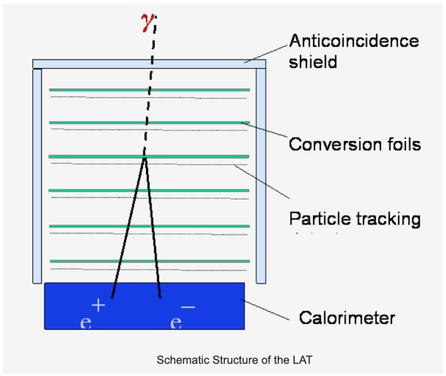


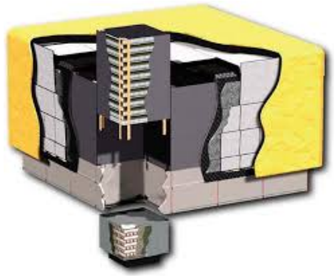
Preliminary

Up to 560 GeV bin









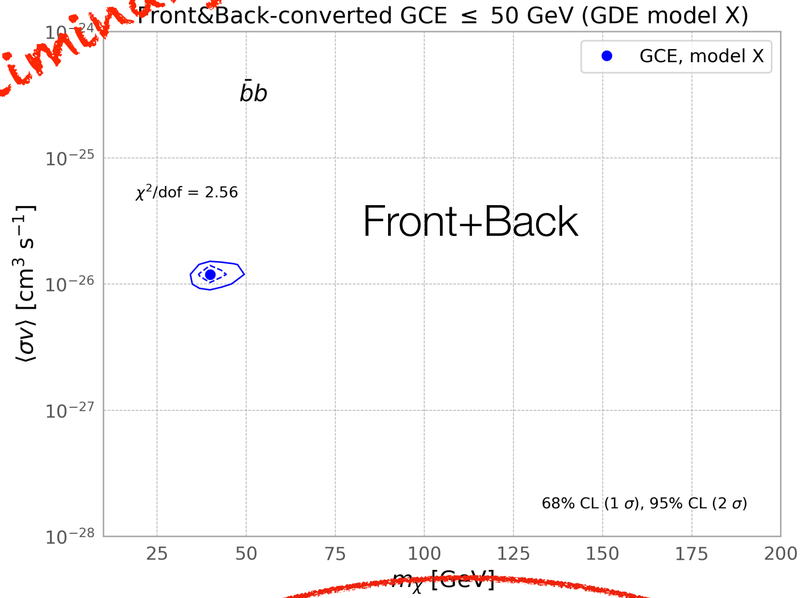
12 thin tungsten foils (front)
4 thick tungsten foils (back)

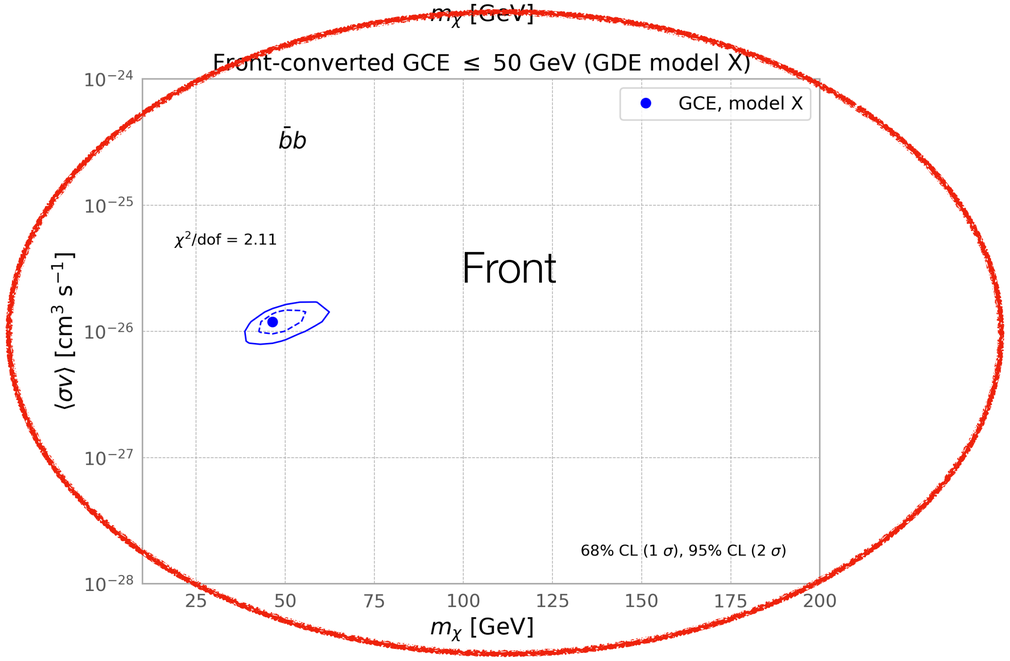
Data analysis

Model X

Preliminary

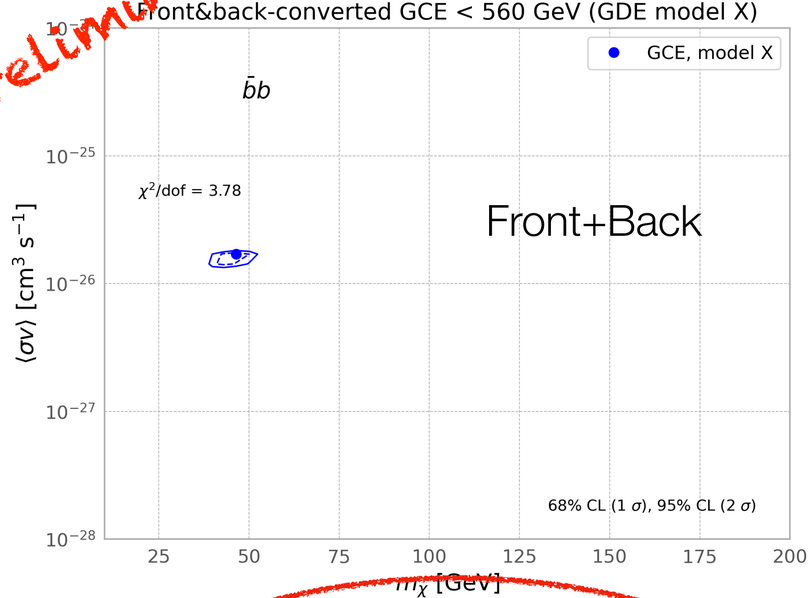
Up to 50 GeV bin

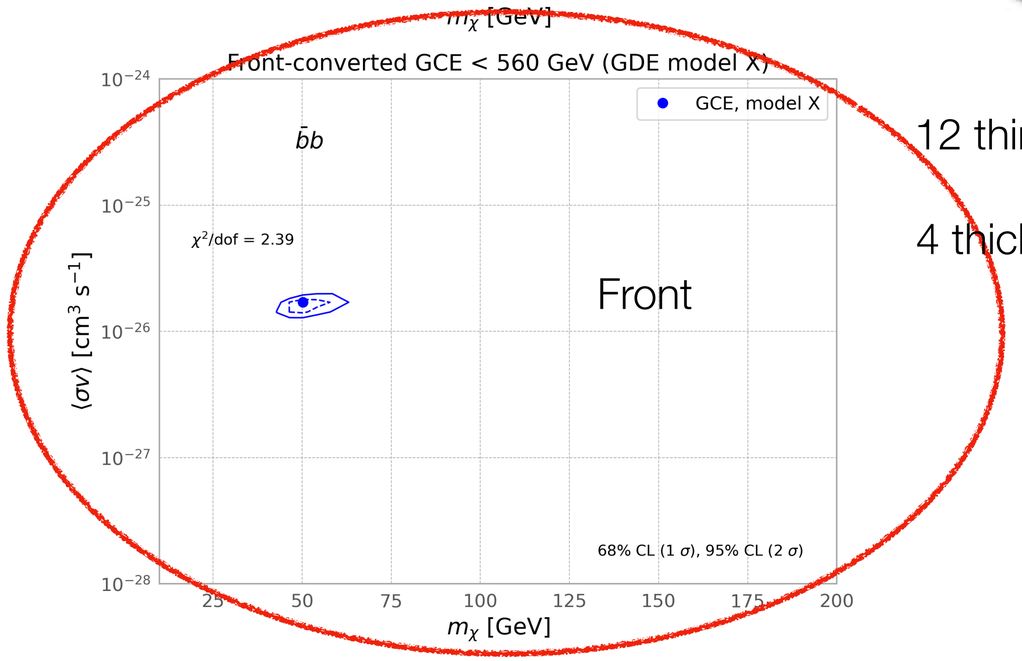


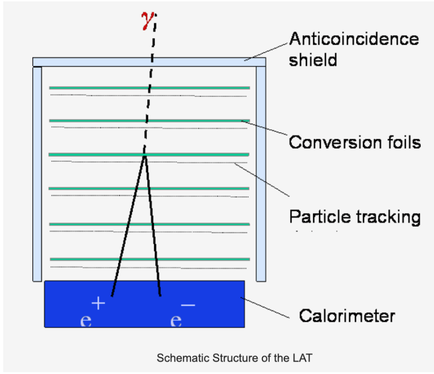


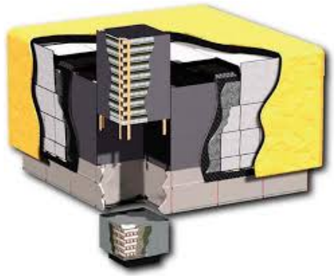
Preliminary

Up to 560 GeV bin









12 thin tungsten foils (front)
4 thick tungsten foils (back)

Test of the GCE from the 16 years of dSphs bound collected in Fermi-LAT

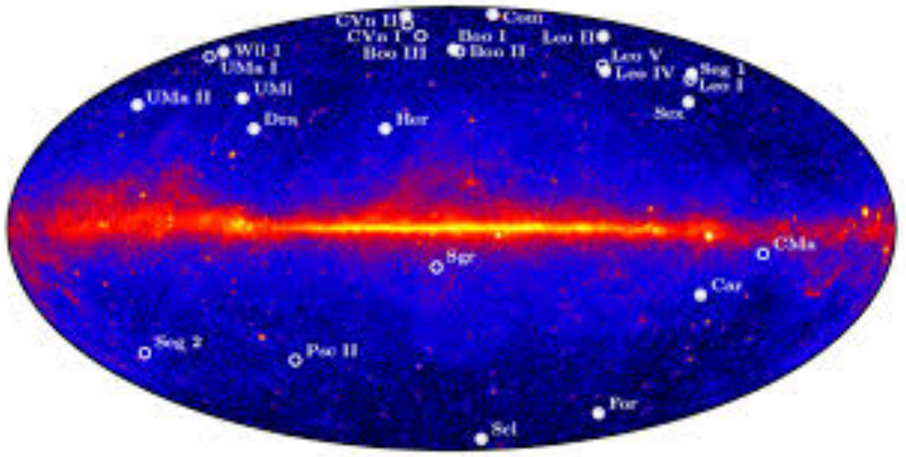
- DM prompt annihilation for GCE: unavoidable bounds by the γ-ray observation coming from the dwarf spheroidal galaxies (dSphs).

- We collect data from the 30 dSphs with well established J-factors and find log likelihood from null hypothesis following the reference:

McDaniel, Ajello, Karwin, Di Mauro, Drlica-Wagner, Sanchez-Conde, arXiv:2311.04982

- In our work, the bonds on the 4-body final state channels are obtained from the raw data analysis.

Data categorized with the directional reconstruction qualities:
DFS0, DFS1, DFS2, DFS3



Joint likelihood function

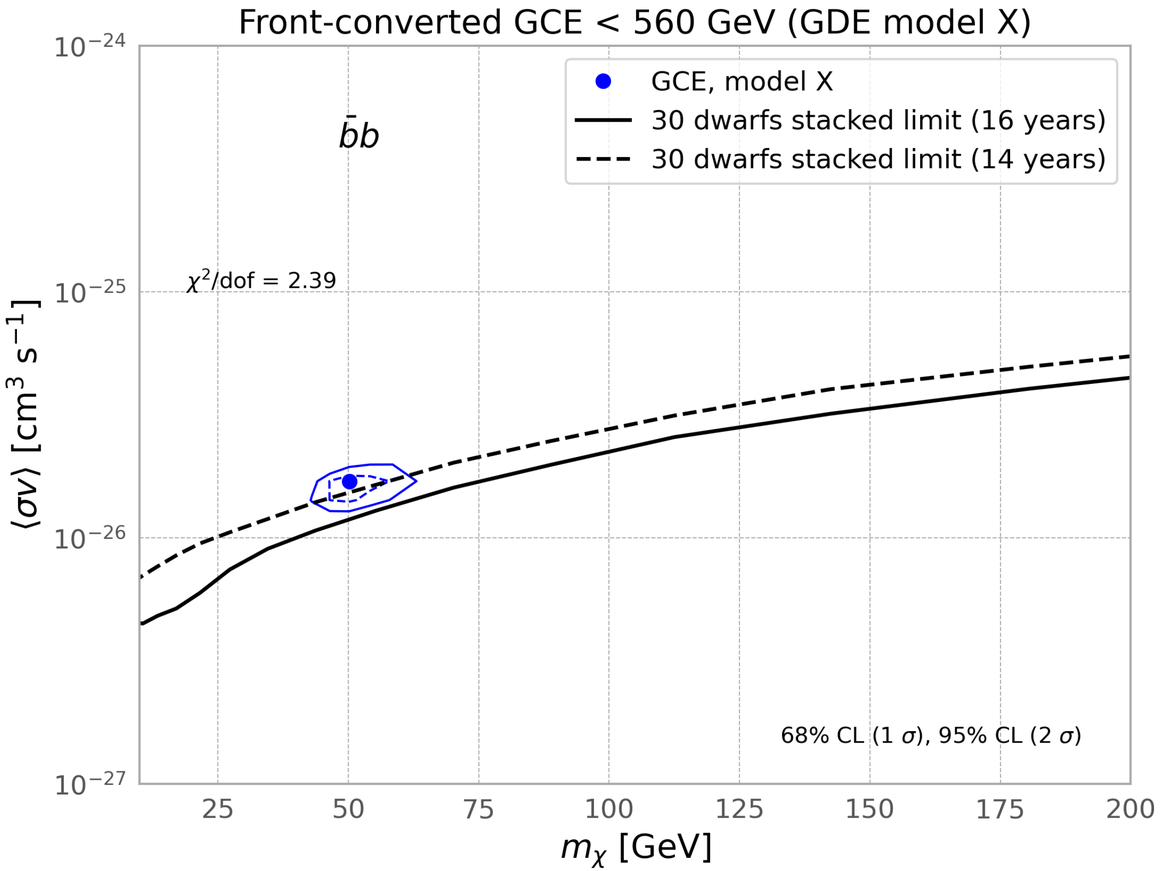
$$\log \mathcal{L} = \sum_{i=0}^{3} \log \mathcal{L}_{\mathrm{PSF}i}$$

Energy range: 0.5 GeV - 1 TeV (26 logarithmic bins)

ROI: 10°×10° around the source

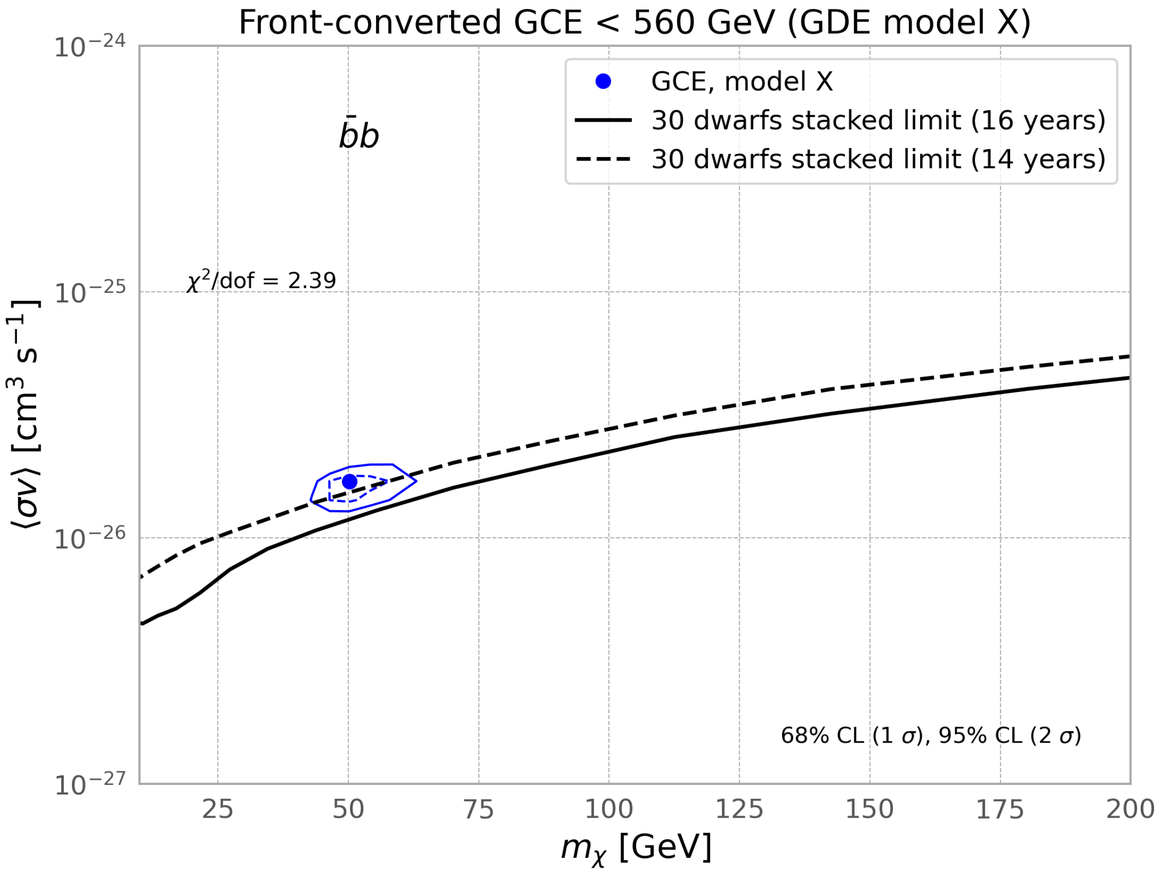
fermipy v1.2.0 & fermitools v2.2.0

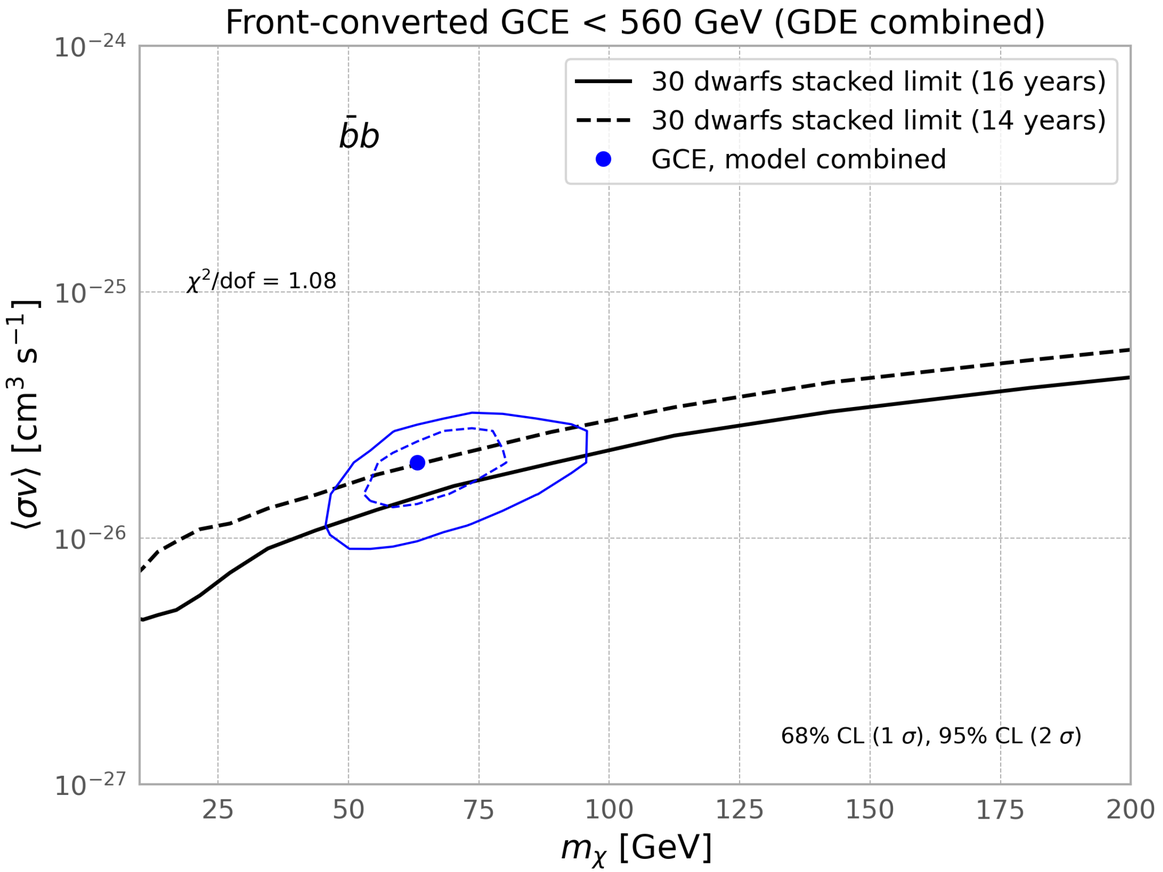
GCE with dSphs bounds



The new dSphs bound excludes the $\chi\chi \to bb$ interpretation.

GCE with dSphs bounds

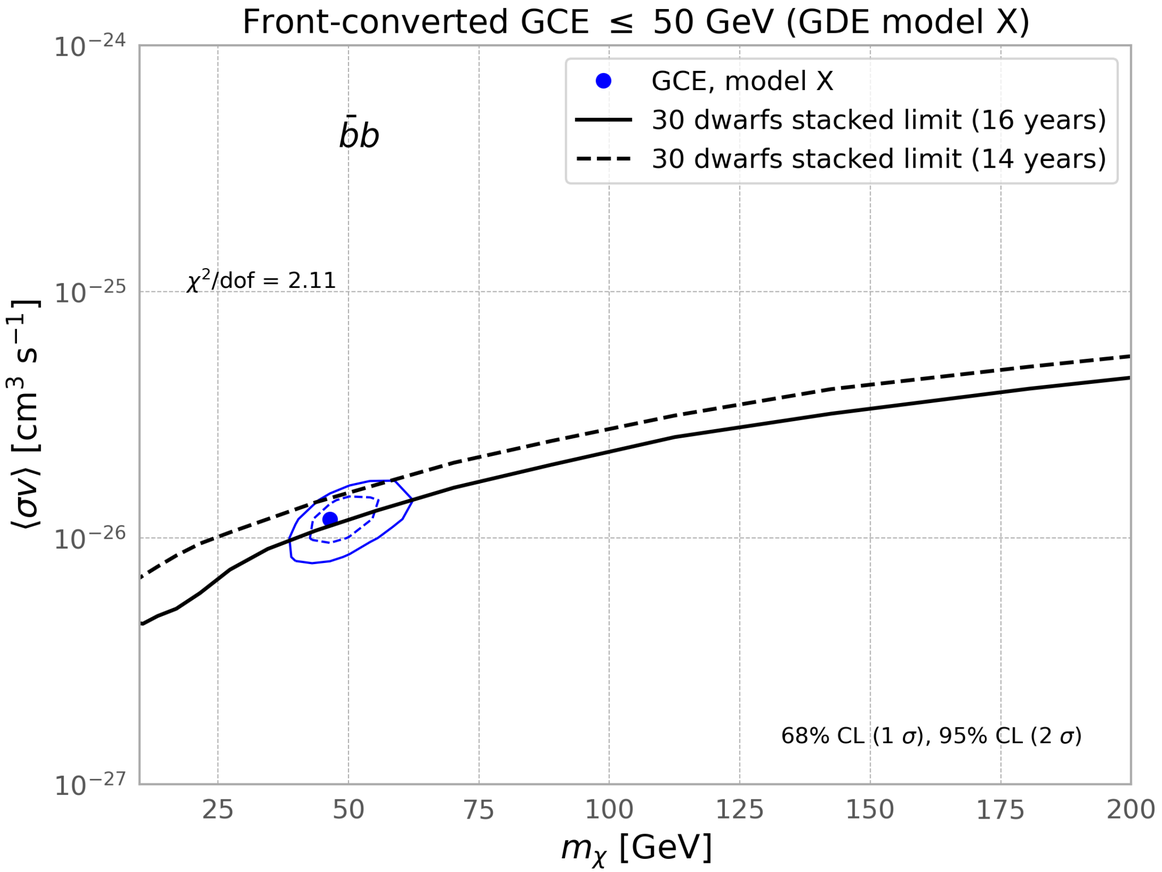


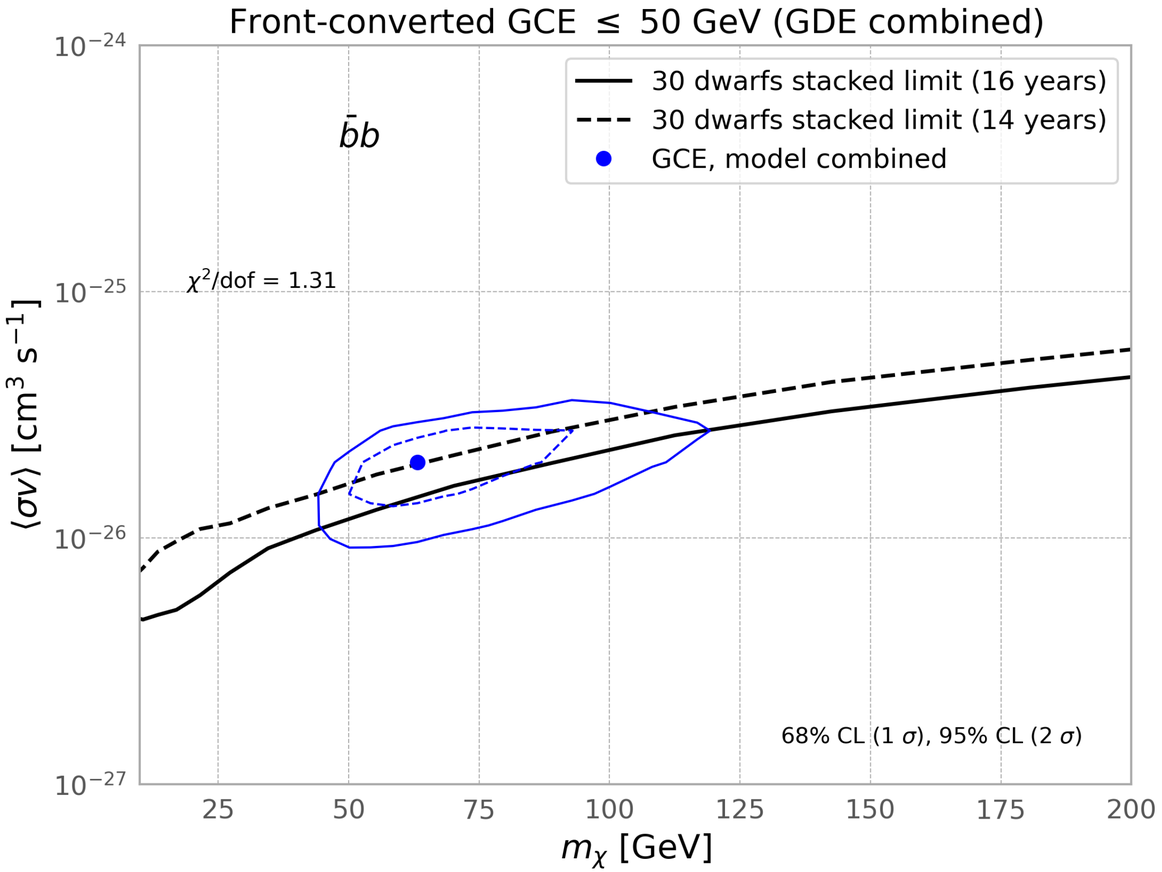


The new dSphs bound excludes the $\chi\chi \to bb$ interpretation.

GDE model uncertainties are included: χ^2 range larger

GCE with dSphs bounds





The new dSphs bound may allow the $\chi\chi \to bb$ interpretation.

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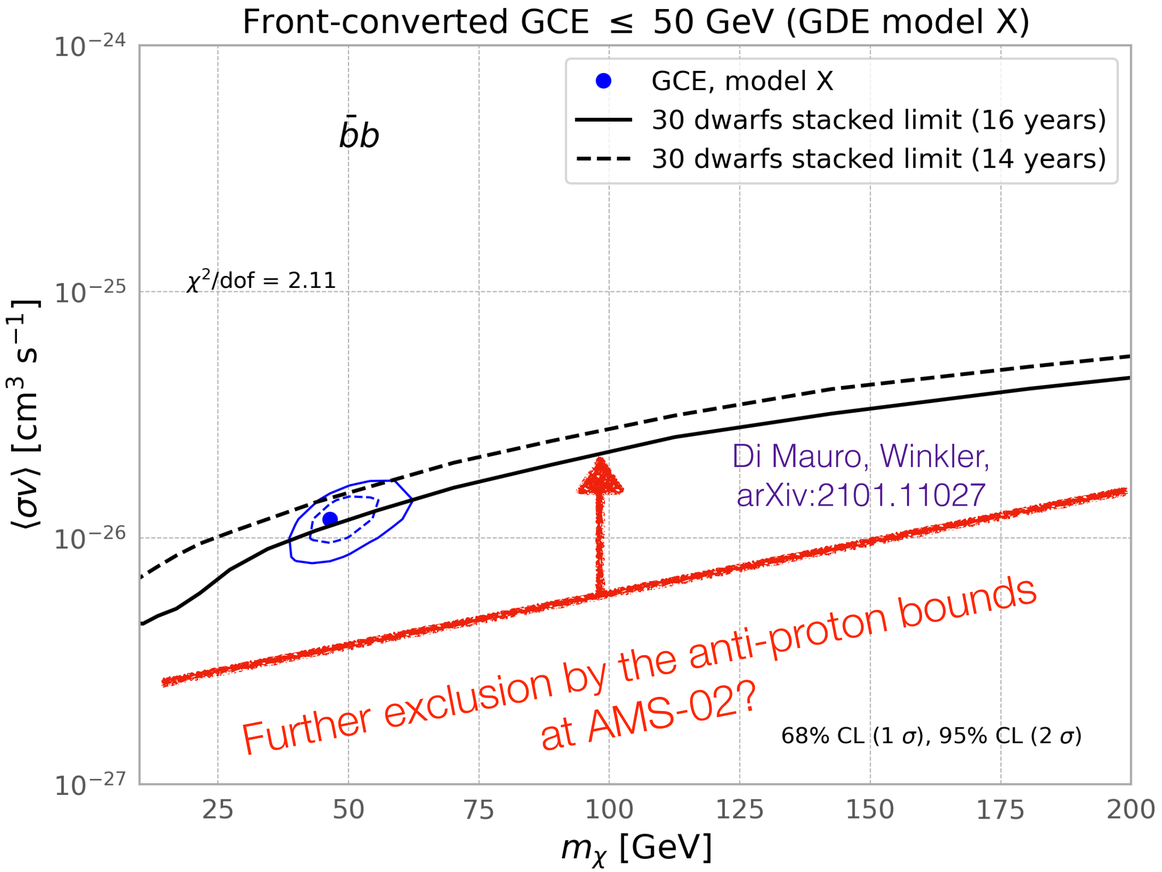
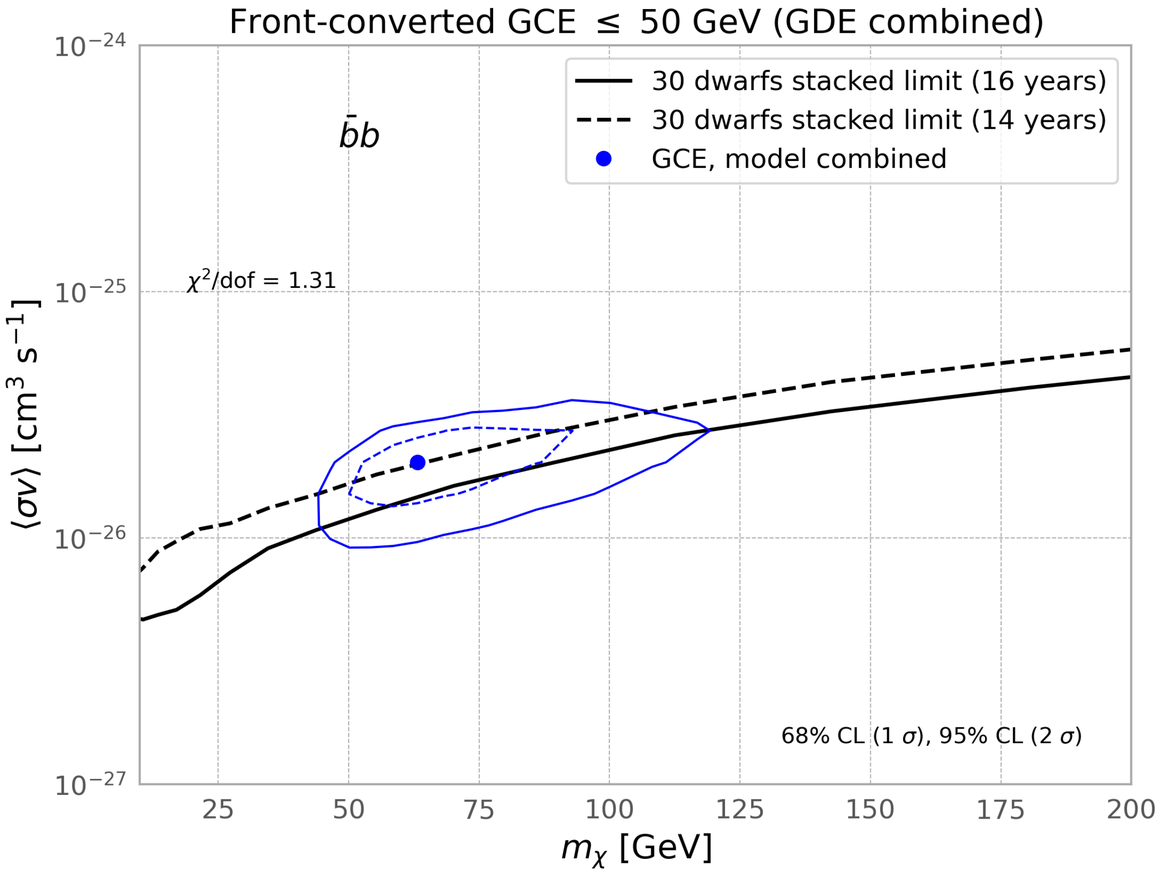
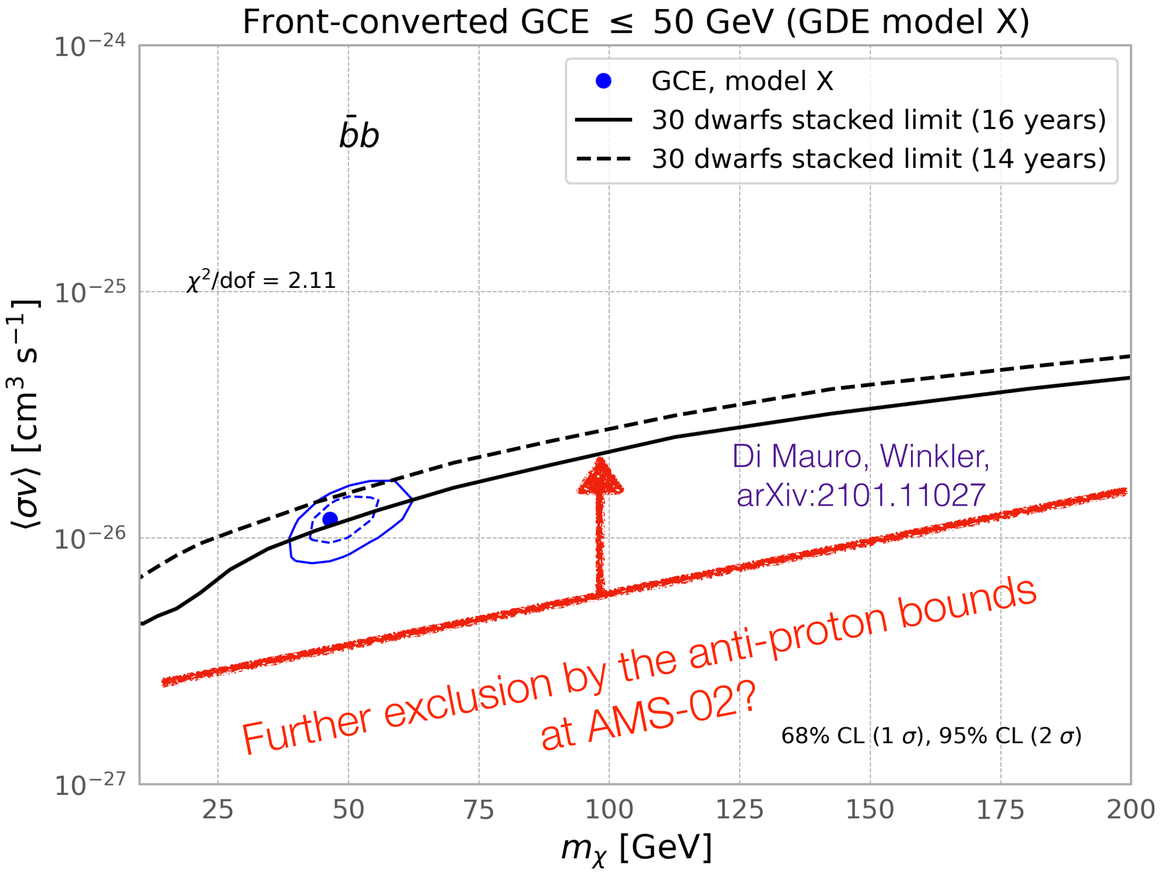


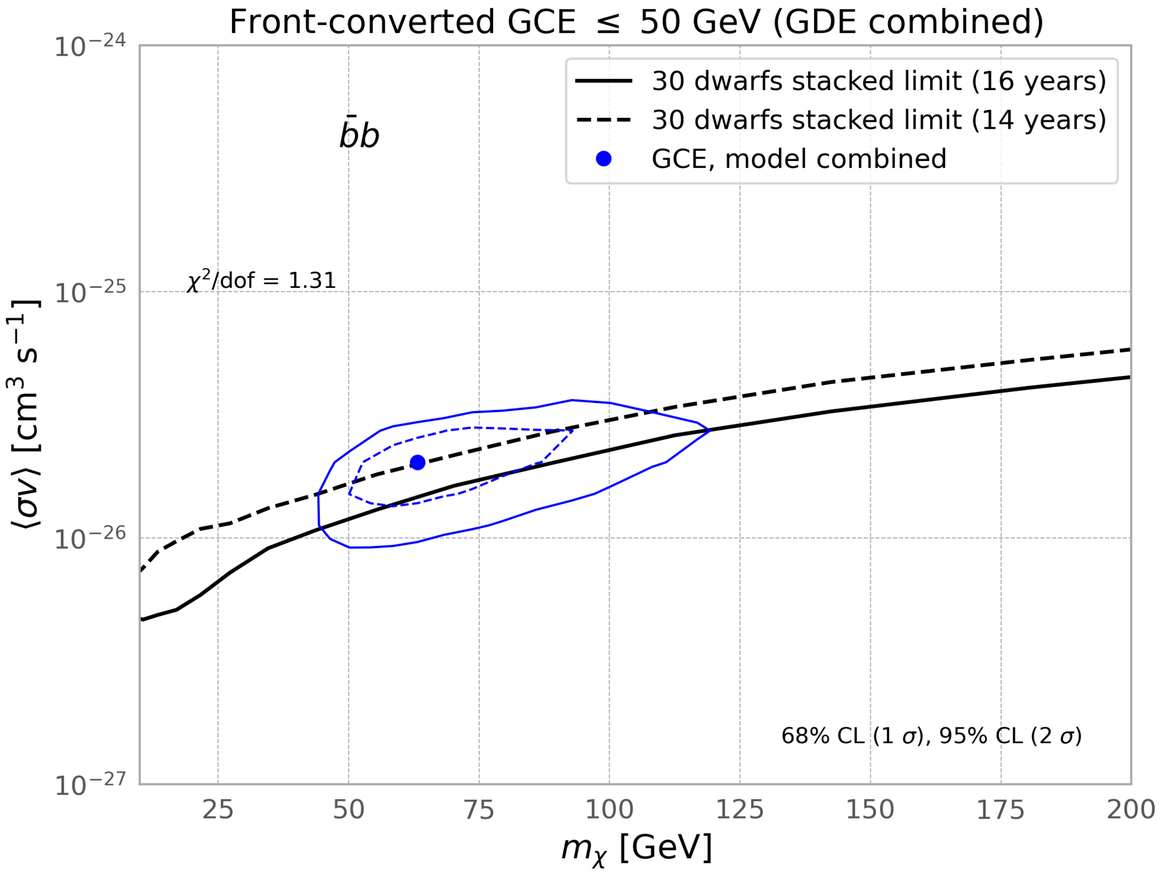


The new dSphs bound may allow the $\chi\chi \to bb$ interpretation.

GCE with dSphs bounds

Our own dedicated analysis on anti-proton needed since the bounds heavily rely on the density and GDE model





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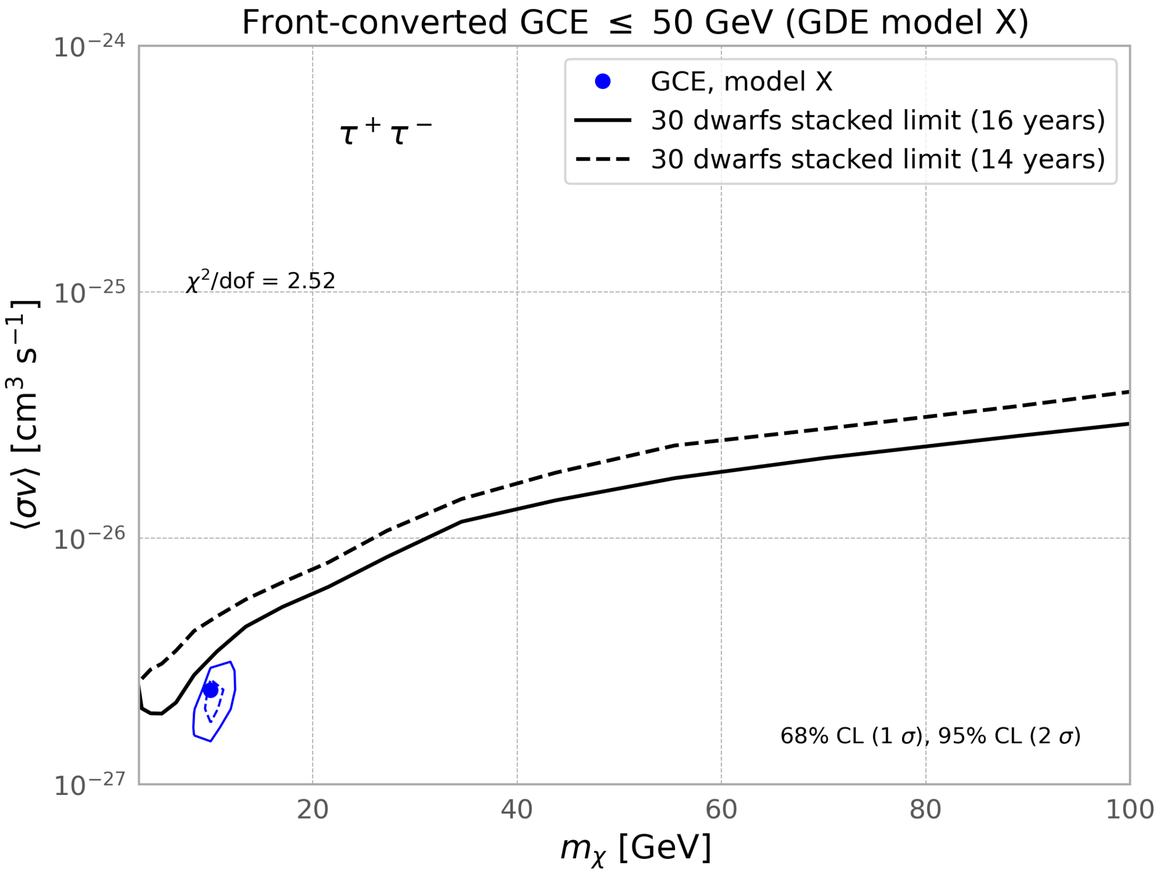
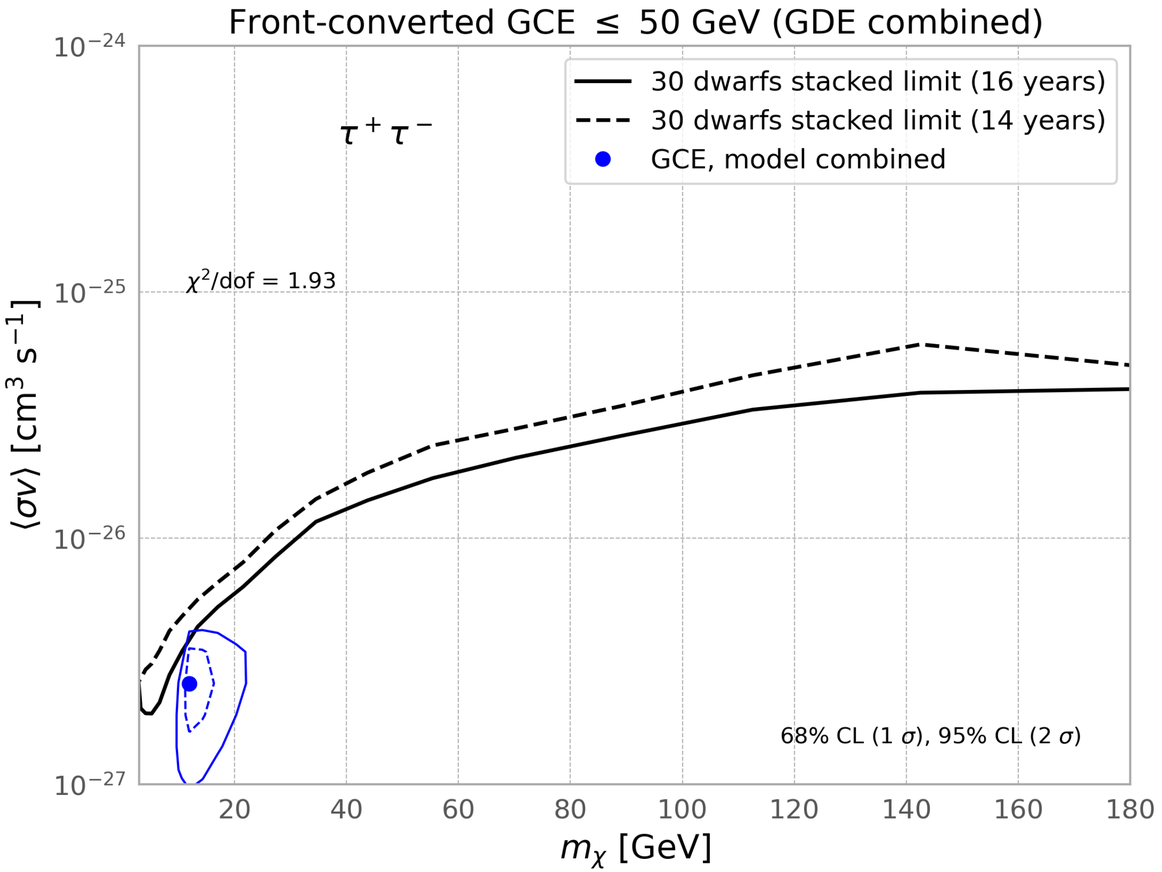
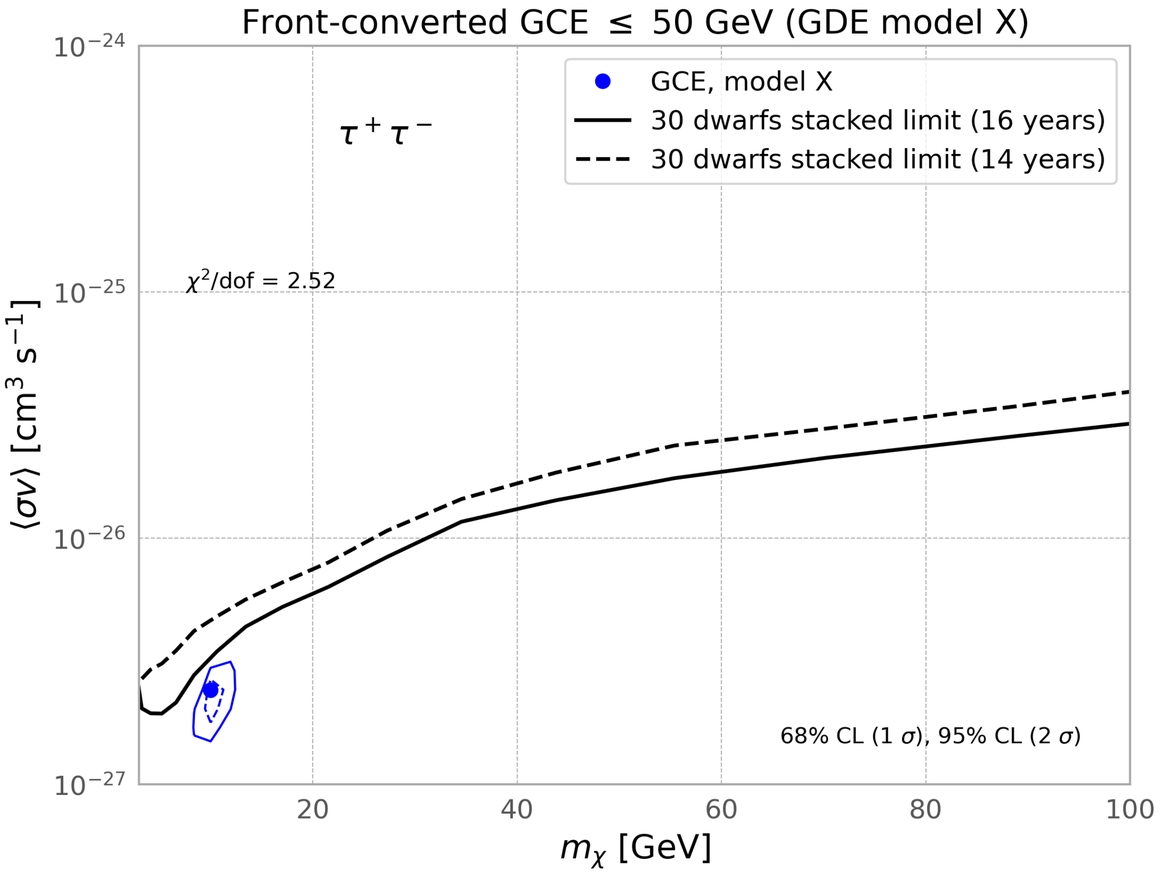
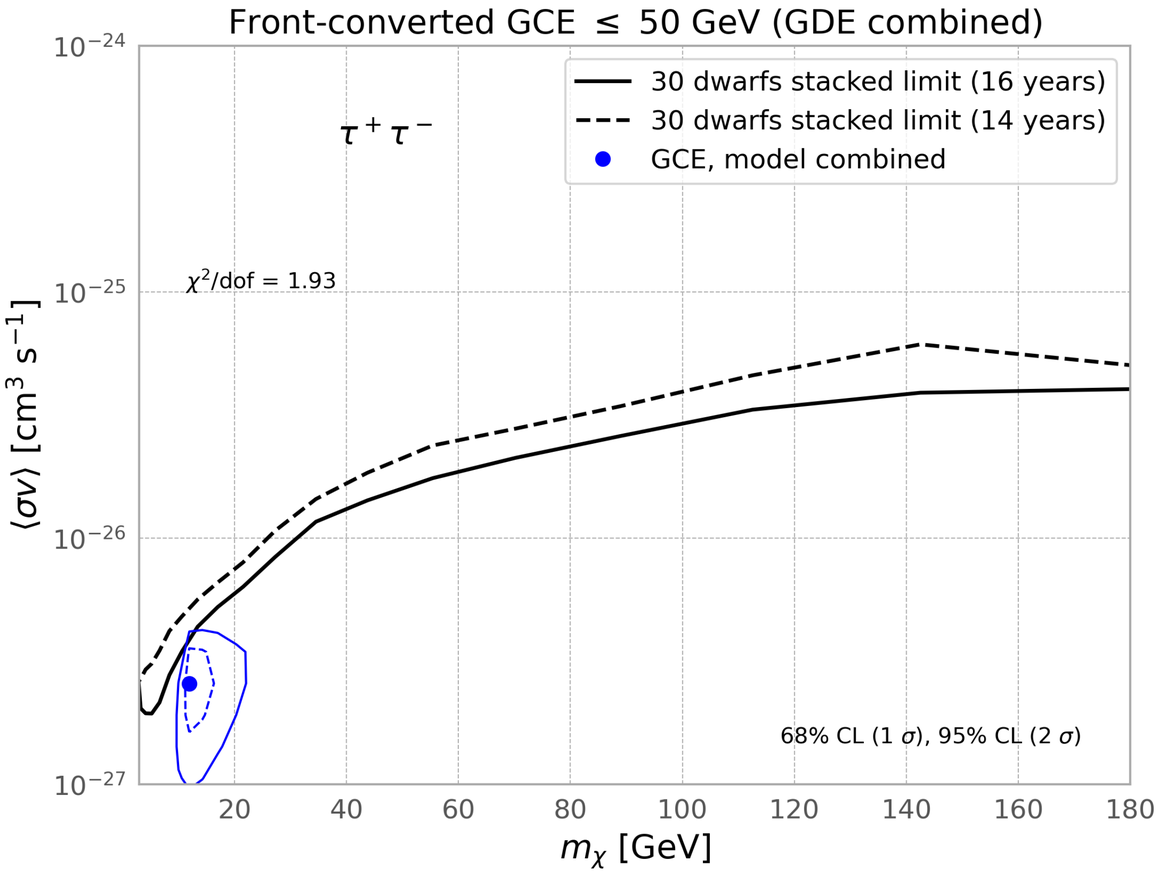




The new dSphs bound still allows the $\chi\chi\to\tau\tau$ interpretation.

GCE with dSphs bounds



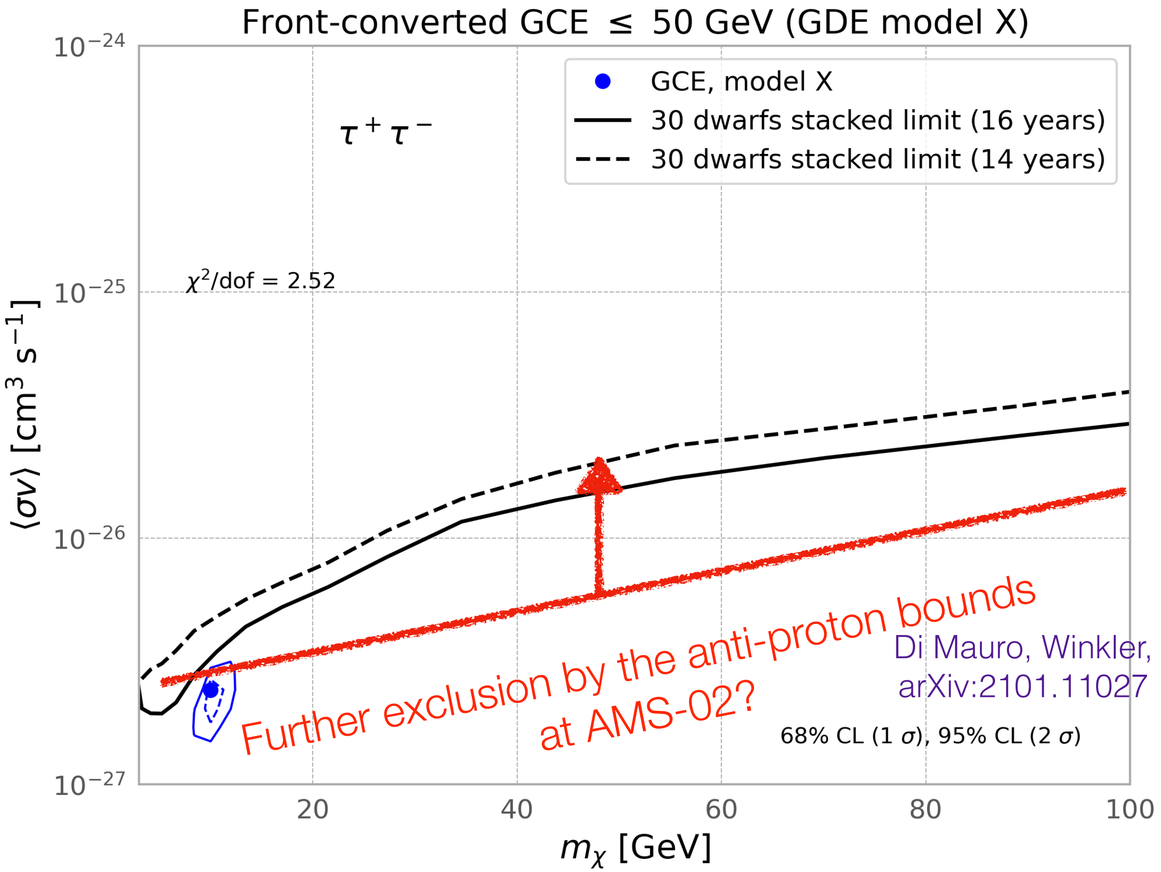


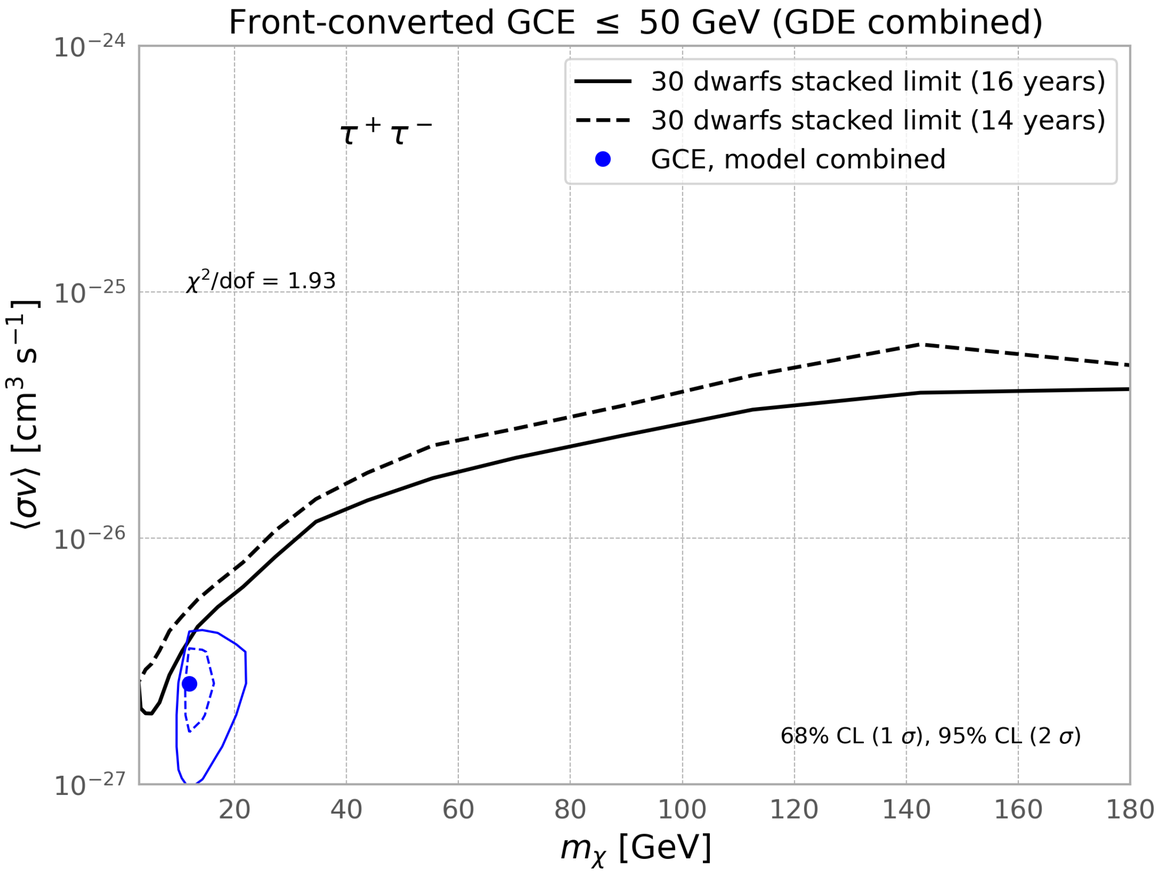
The new dSphs bound still allows the $\chi\chi\to\tau\tau$ interpretation.

Maybe the contribution by $\pi^0\to\gamma\gamma$ and leptons can easily fit the GCE with smaller $\langle\sigma v\rangle$ values?

GCE with dSphs bounds

Some GCE region is safe even from anti-proton bound?





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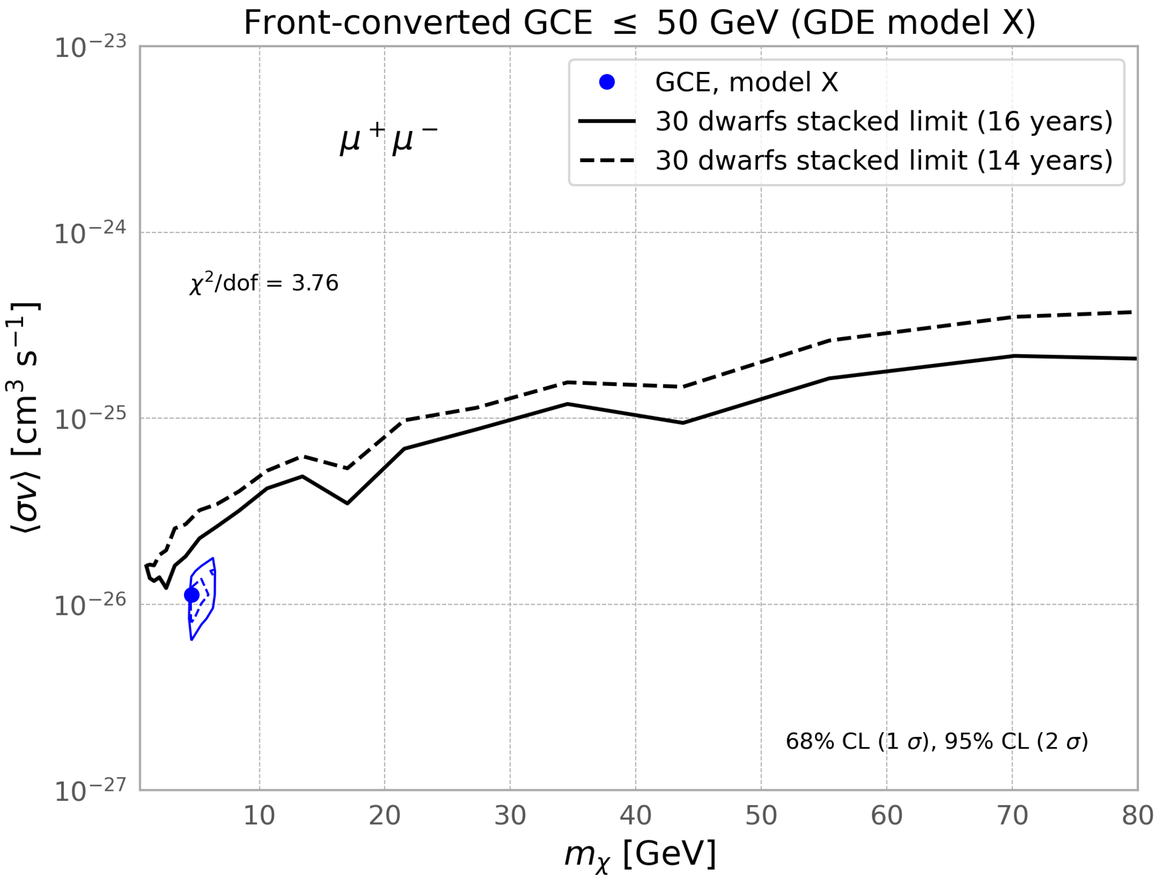

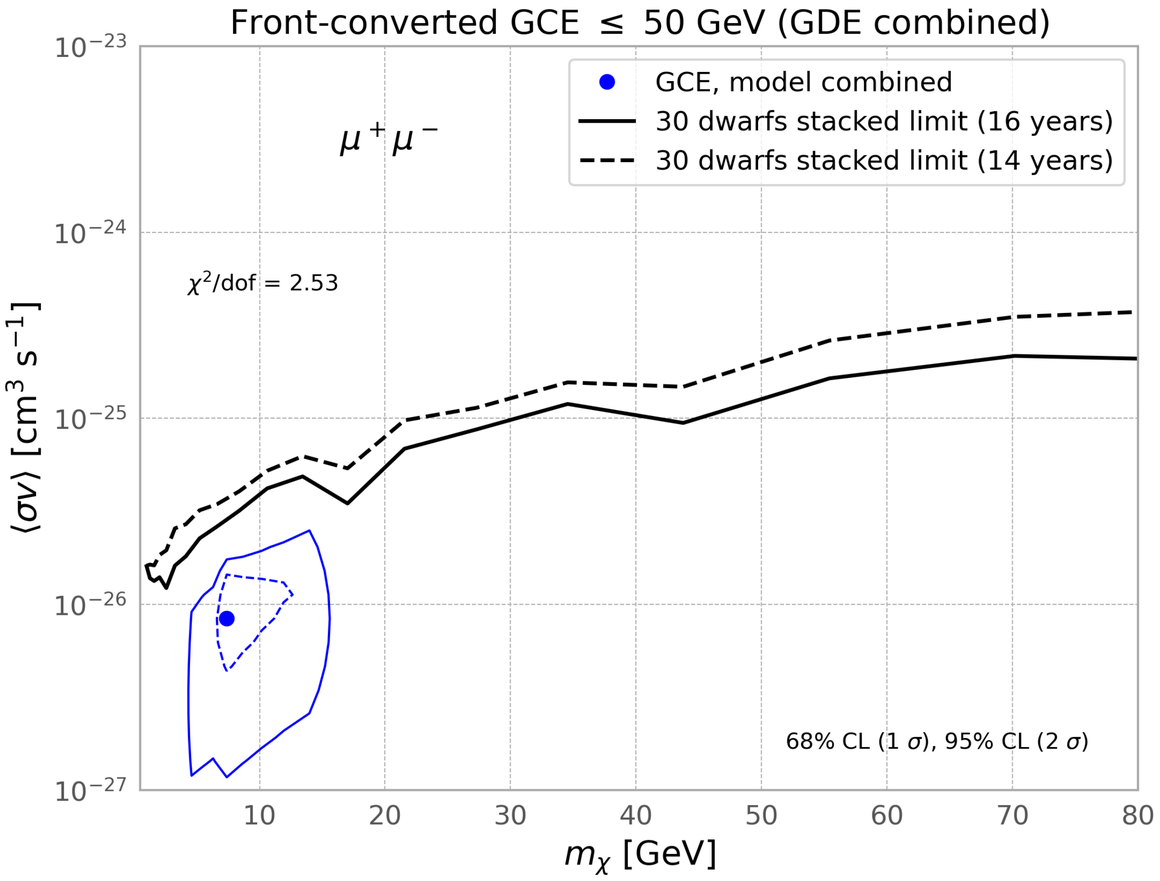

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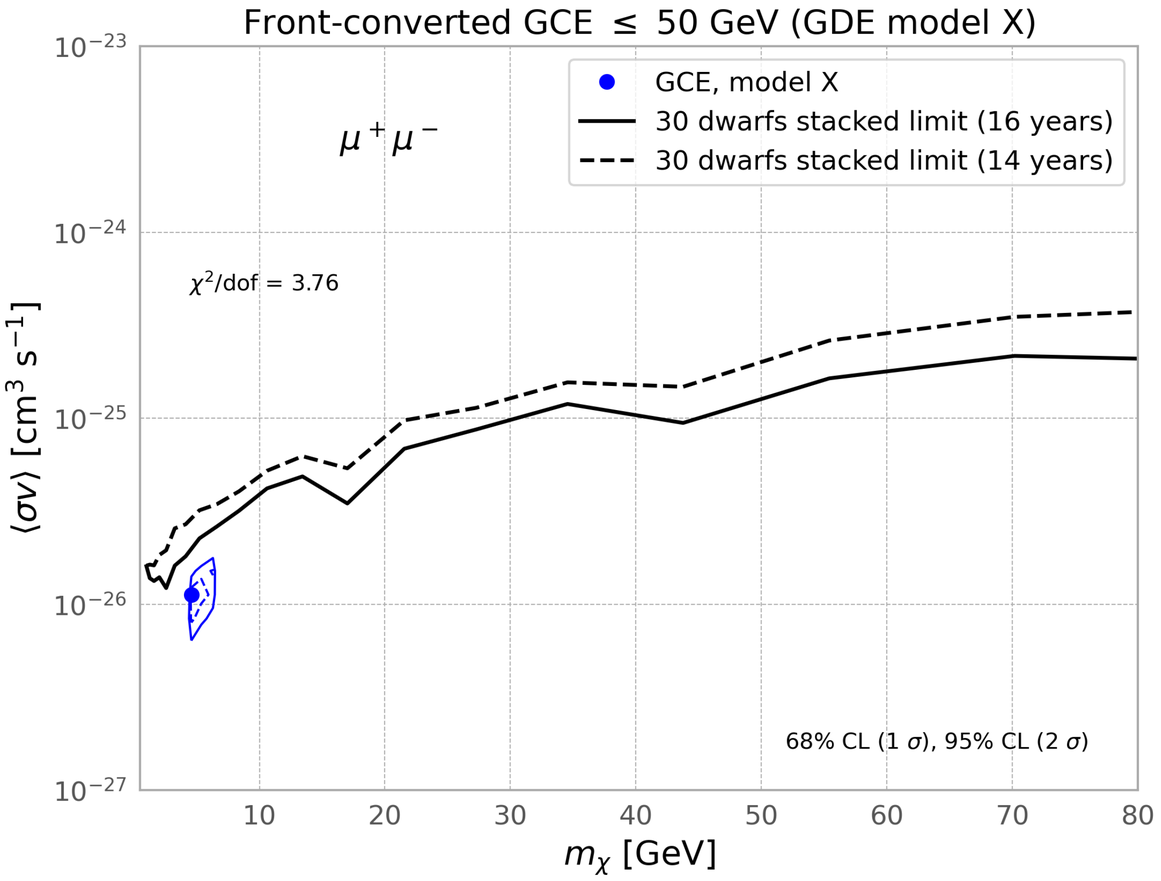
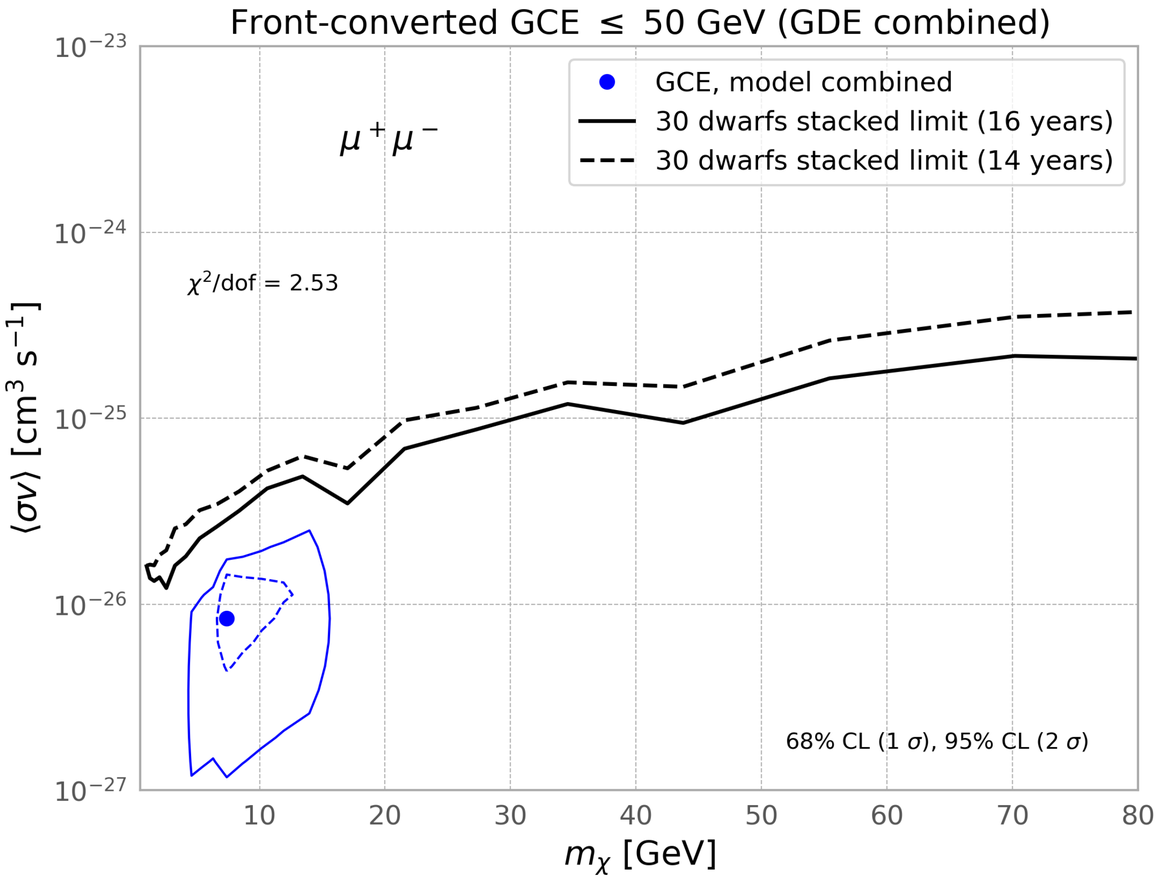
GCE with dSphs bounds

Free from the anti-proton bound but challenged by the e^+ bound !!!





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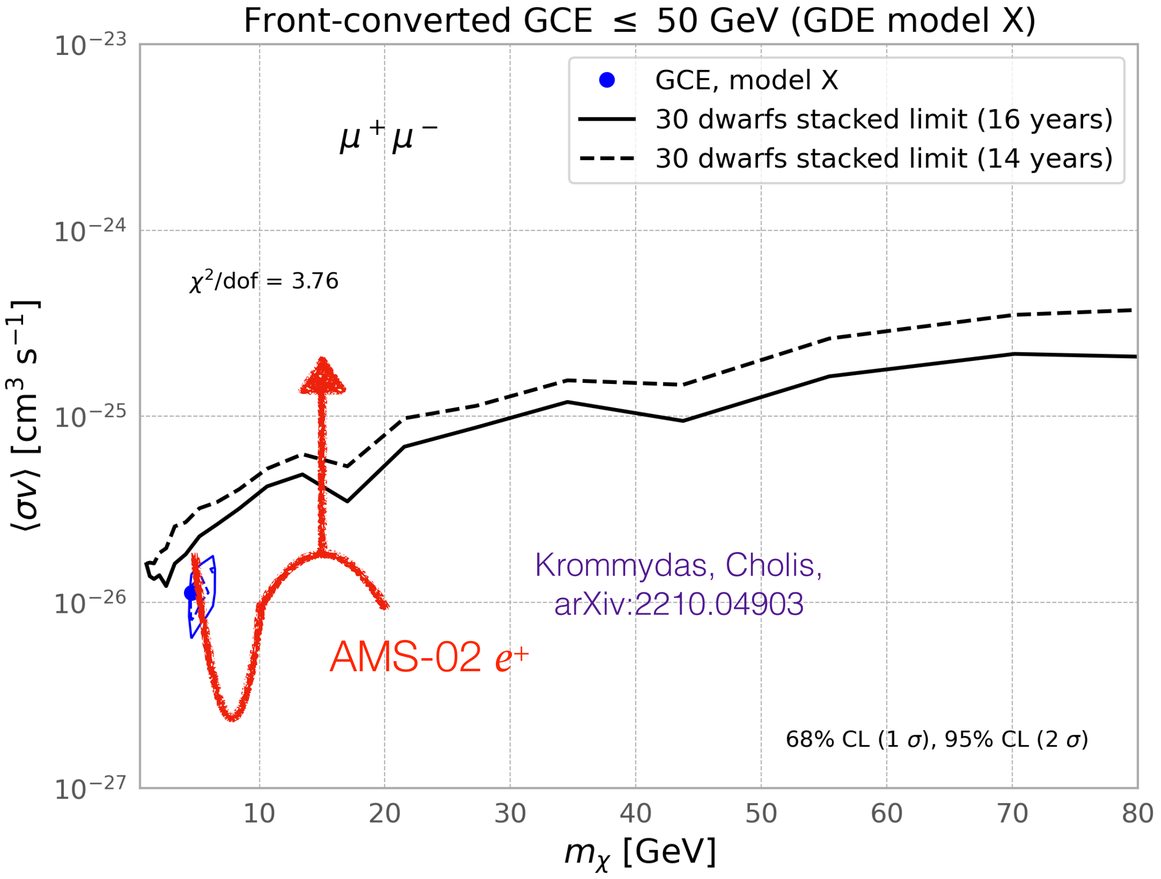

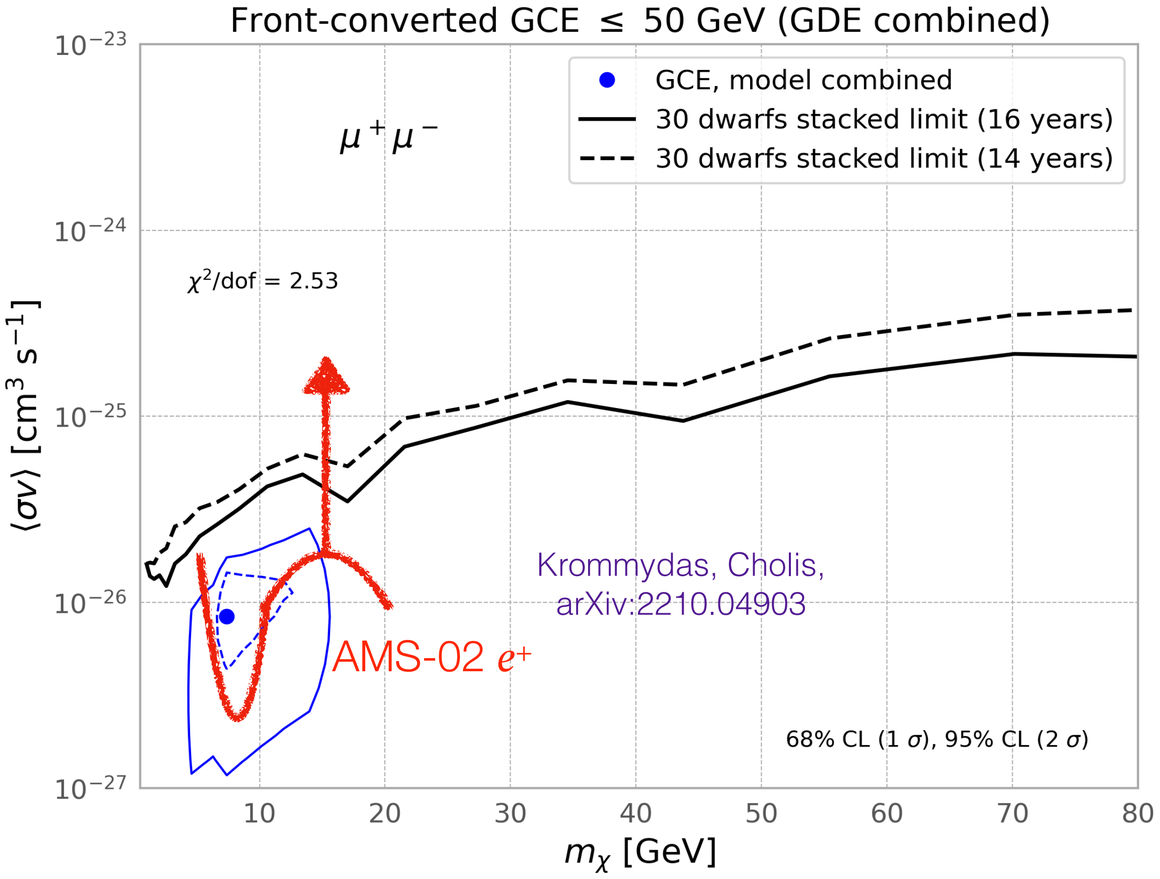

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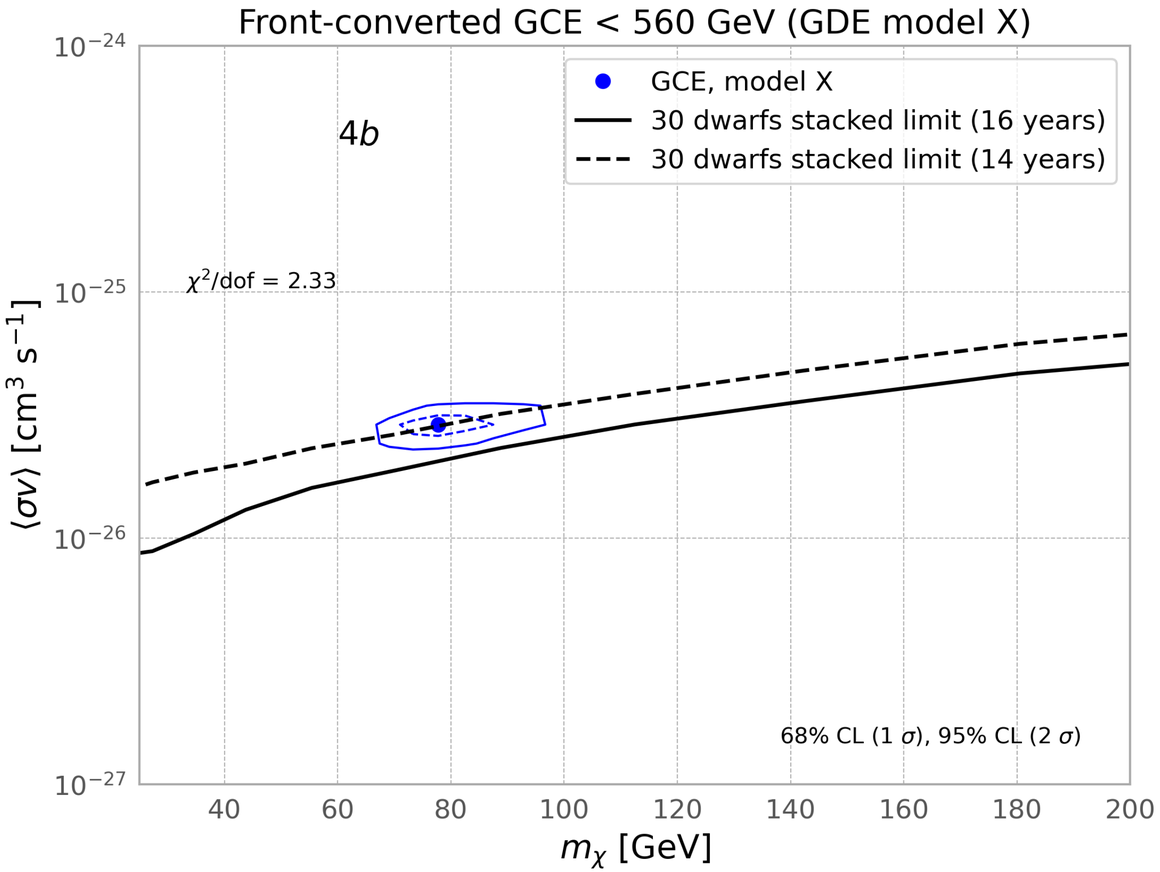
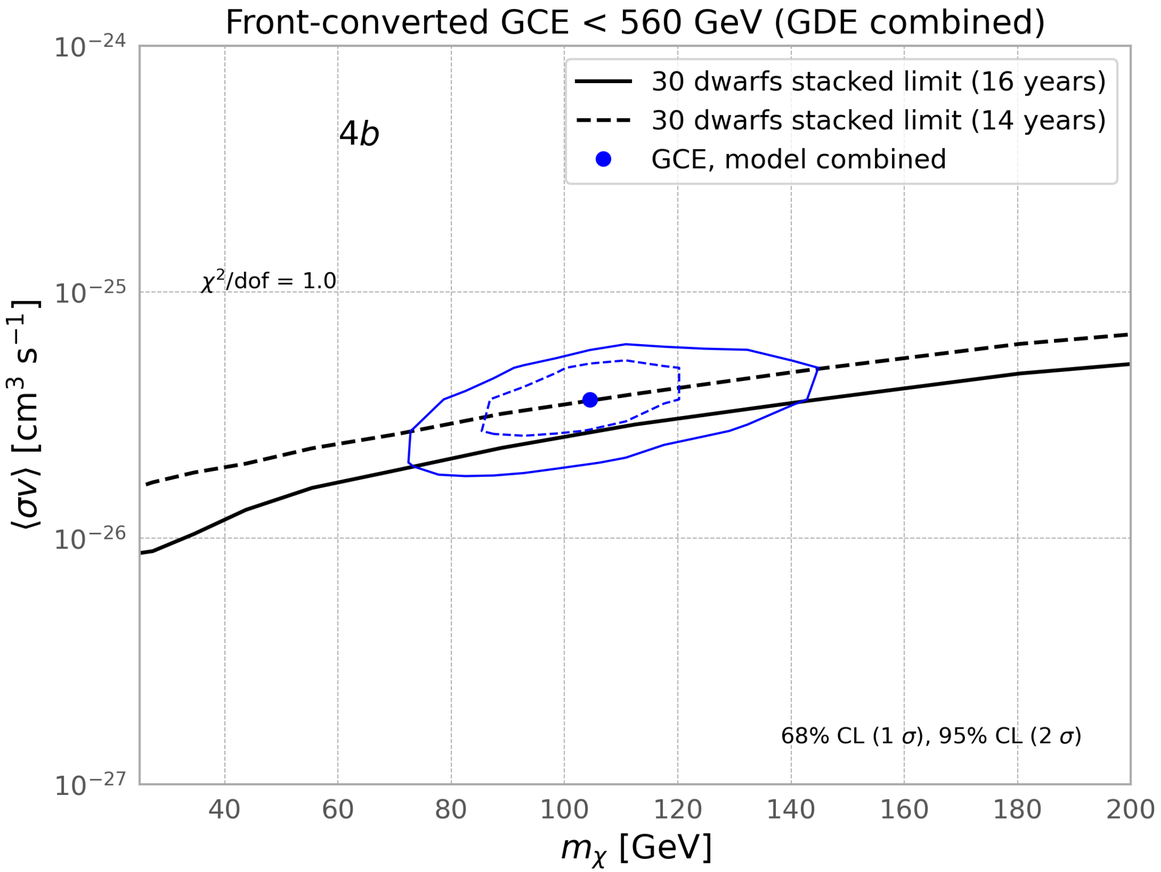
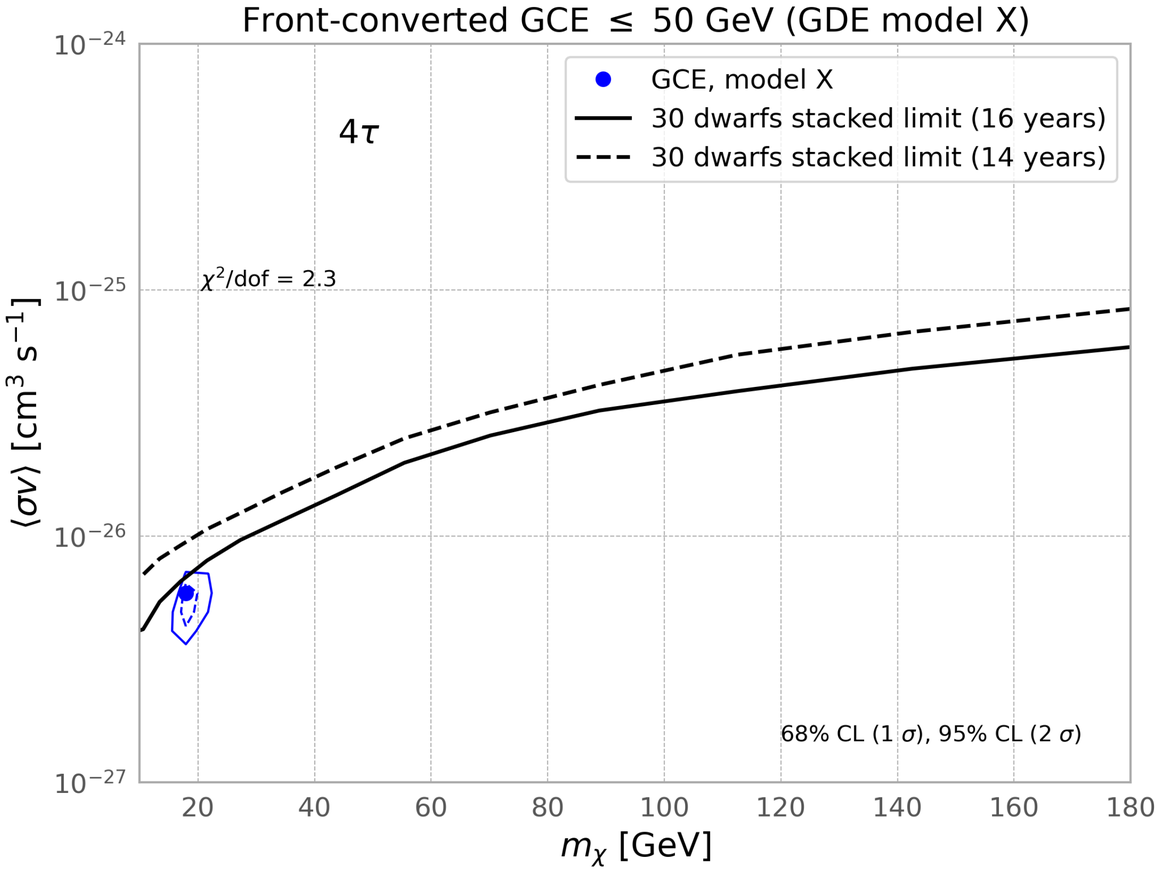


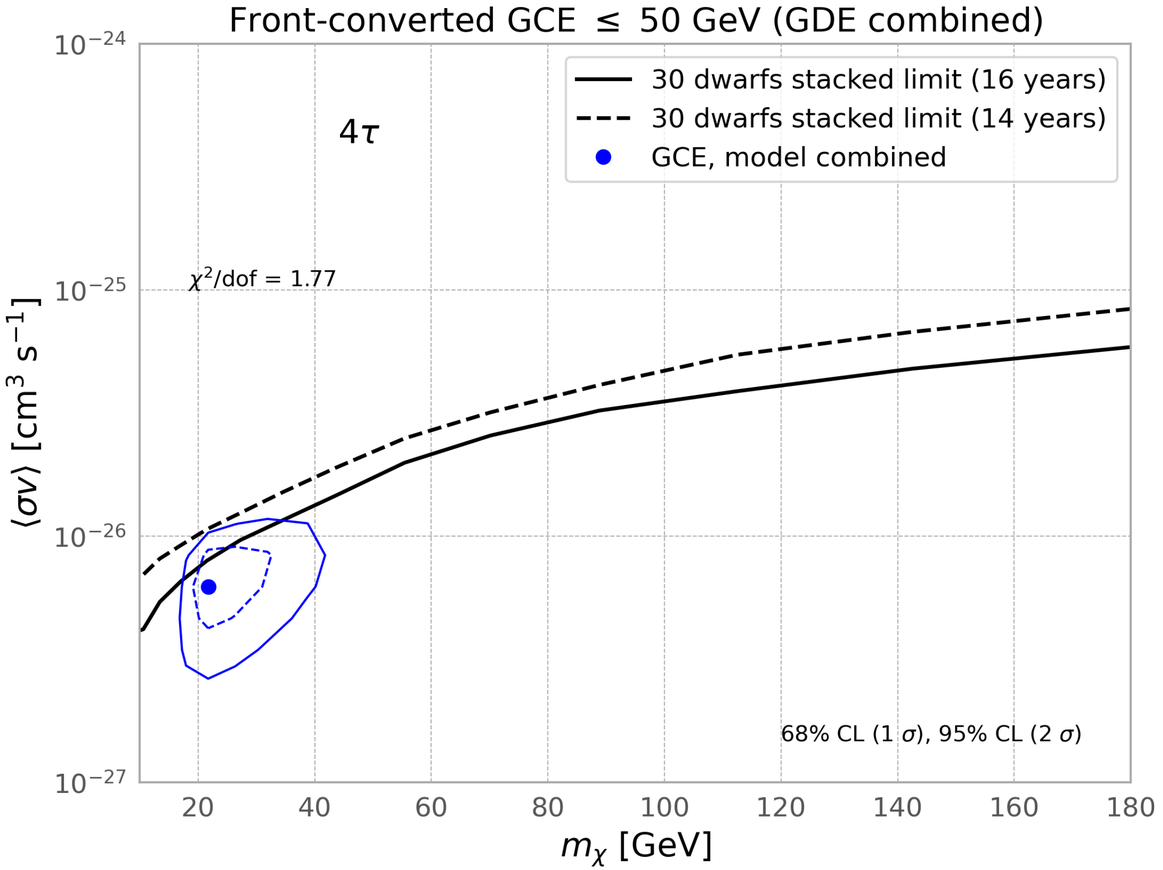
The new dSphs bound excludes the $\chi\chi\to 4b$ interpretation.



The $\chi\chi\to 4b$ interpretation is allowed with the inclusion of GDE model uncertainties.

GCE with dSphs bounds





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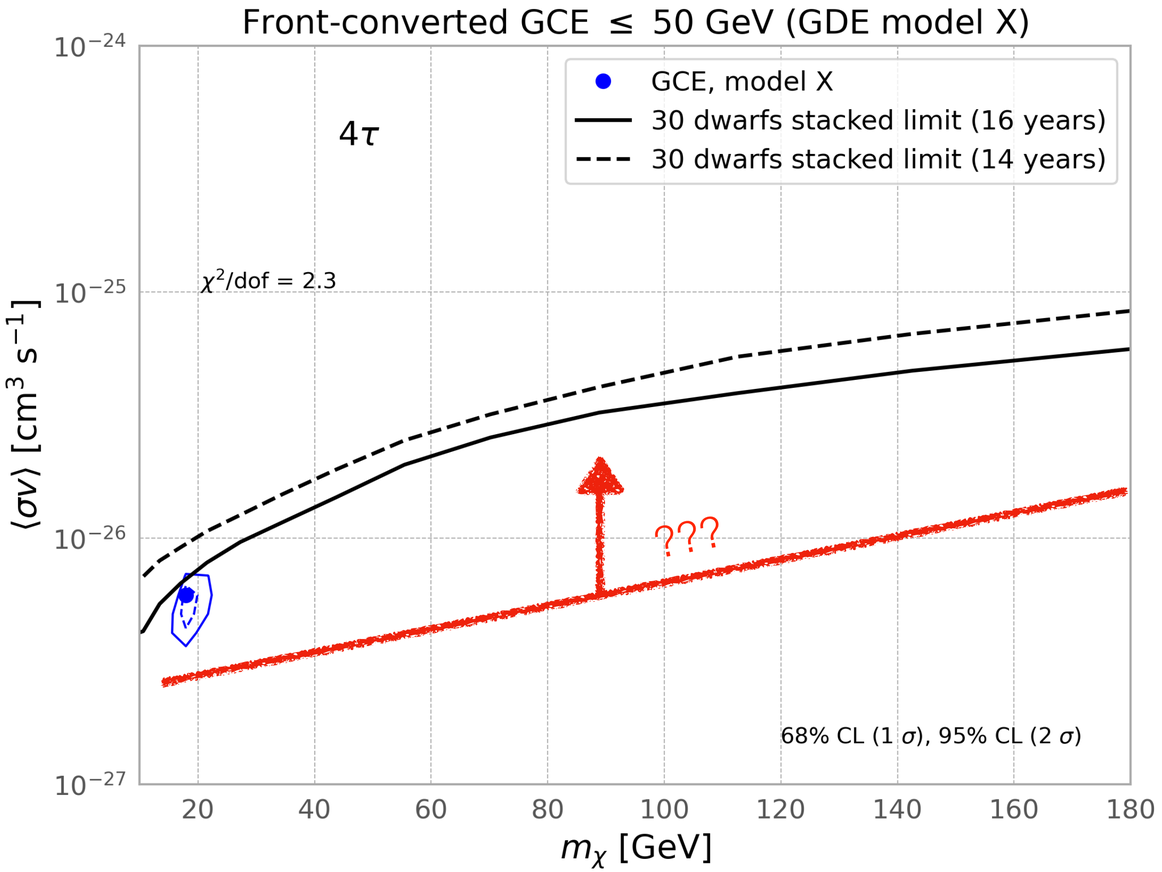
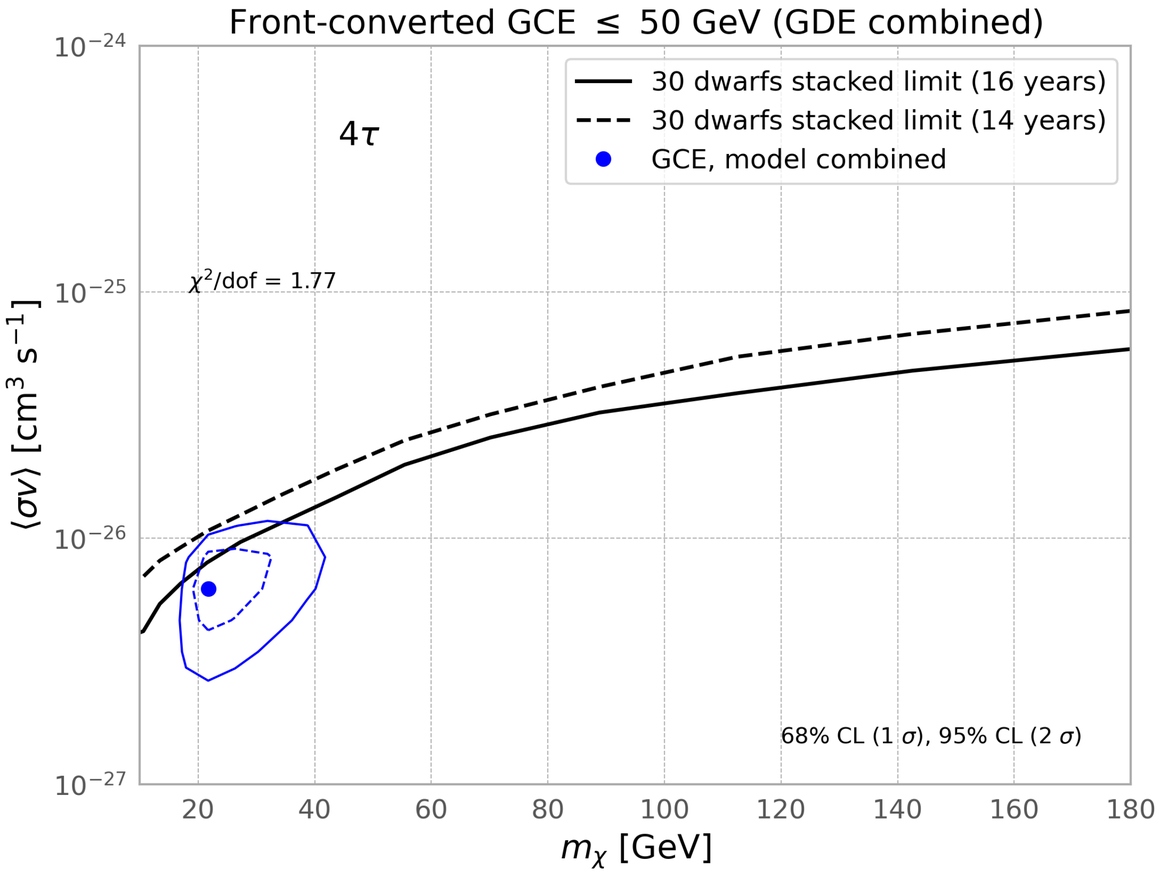
Maybe the contribution by $\pi^0 \to \gamma\gamma$ and leptons can easily fit the GCE with smaller $\langle \sigma v \rangle$ values?

GCE with dSphs bounds

Our own dedicated analysis on anti-proton needed.





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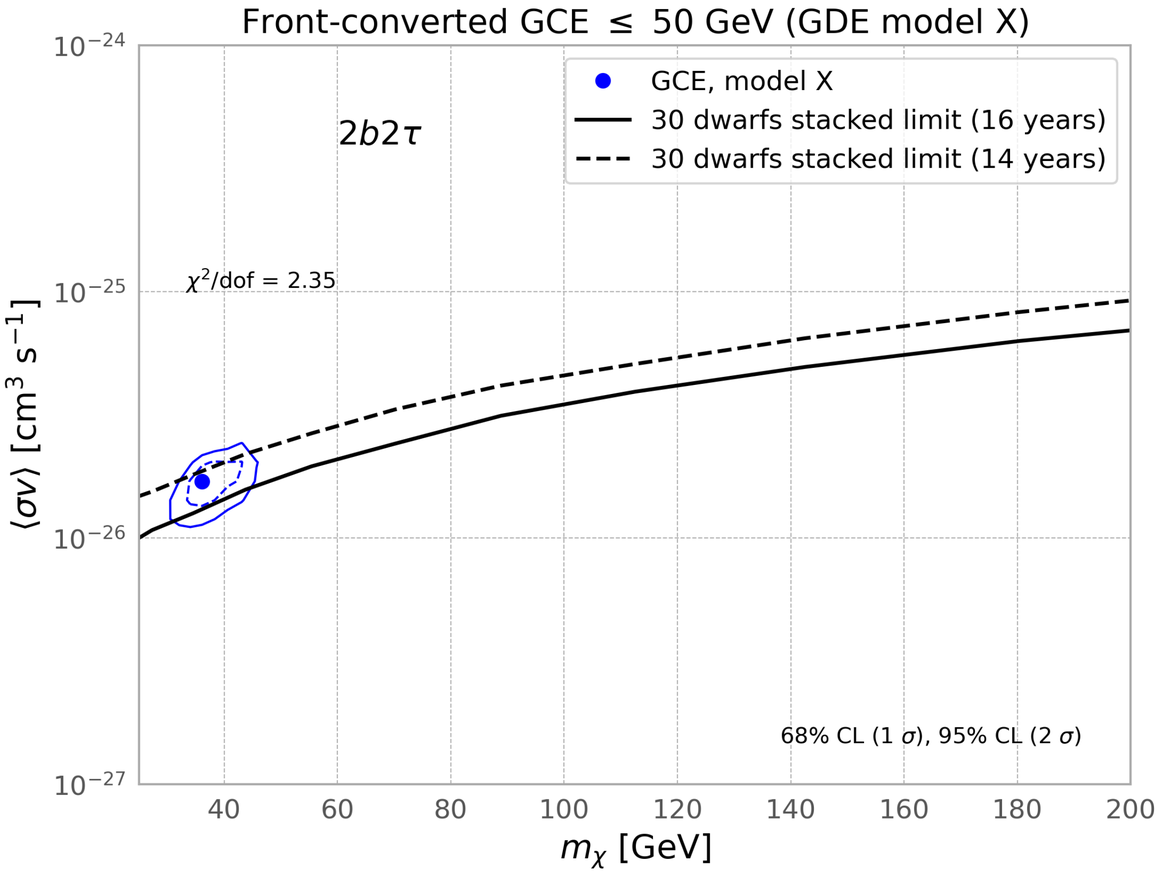
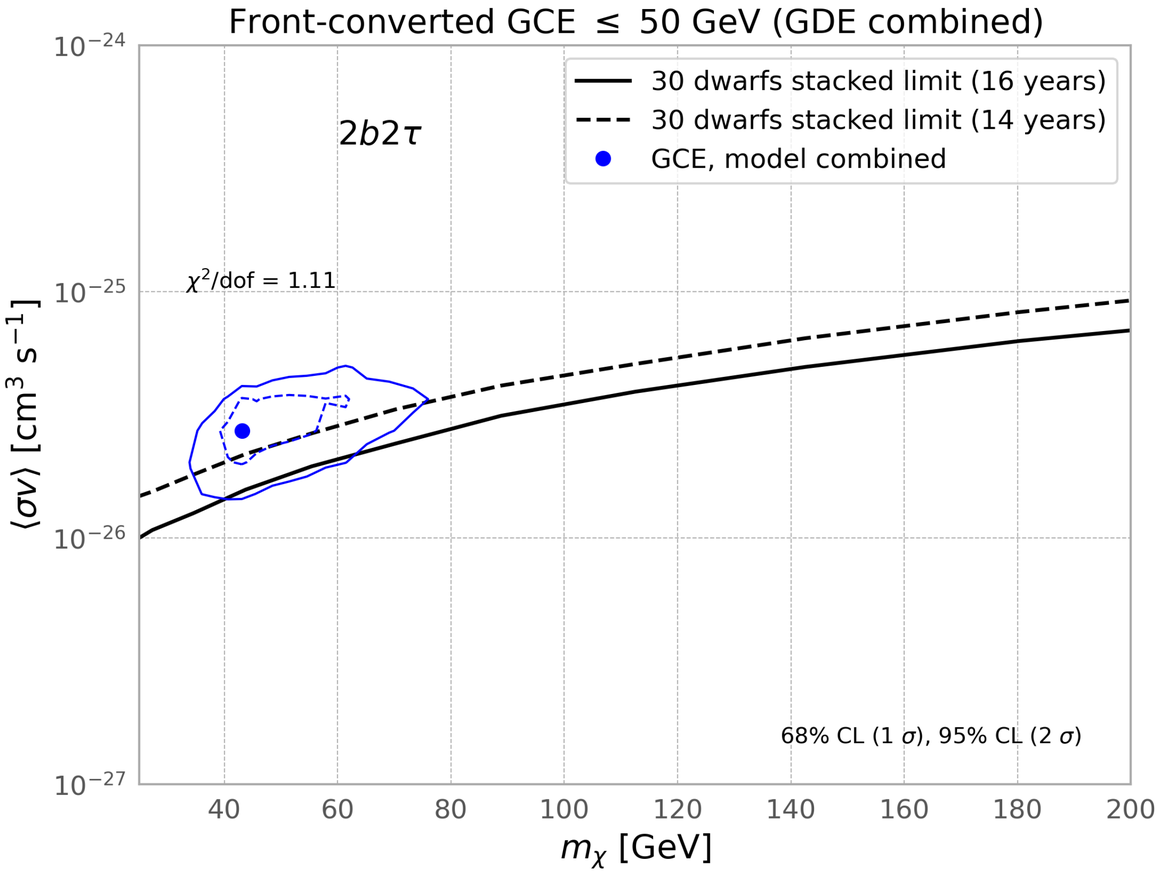
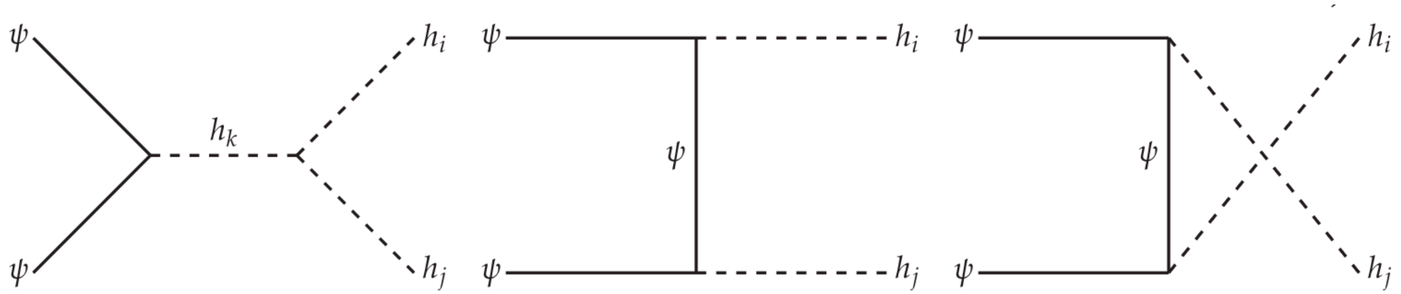
GCE with dSphs bounds





The new dSphs bound does not favor the $\chi\chi\to 2b2\tau$ interpretation.

4-body final states from secluded DM scenarios



Y.G. Kim, K.Y. Lee, C.B. Park, **SS**, Phys. Rev. D93, 075023 (2016) [arXiv:1601.05089]

- Effect of the mediator mass: if the mediator mass ≪ DM mass, all the final states are boosted toward the Earth direction
→ photon energy spectrum is shifted toward high energy direction and the bounds can be different

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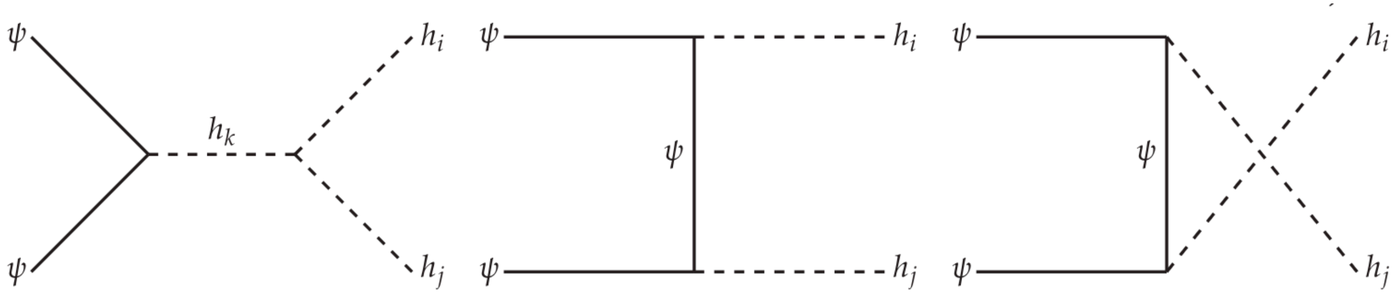

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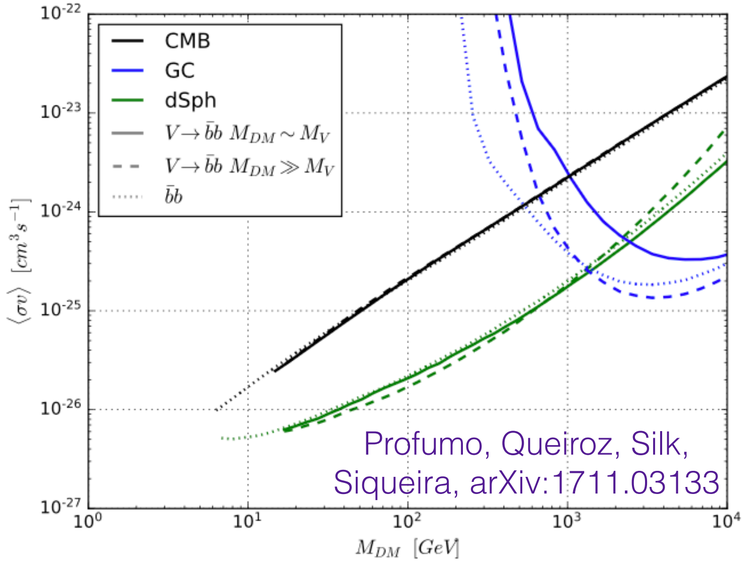

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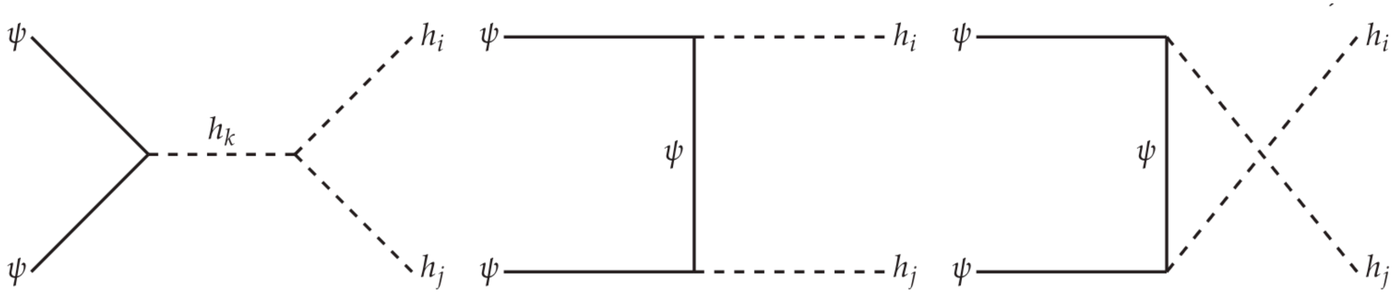

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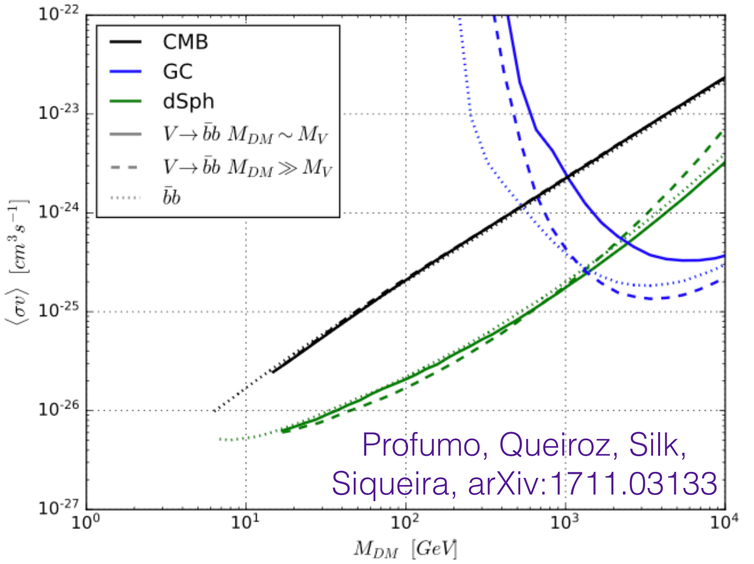
- The mediator mass effect also depends on the final states, e.g., not significant for τ due to neutrinos.

- More dedicated analysis underway.



Conclusions

- The origin of the GCE is not conclusive: DM annihilation, MSP, CR outburst, …

- We revisit the DM annihilation into 2-body and 4-body final states for GCE from the most up-to-date 16 years of data of Fermi-LAT including the update of the point source catalogue and test those with other observations: dSphs.

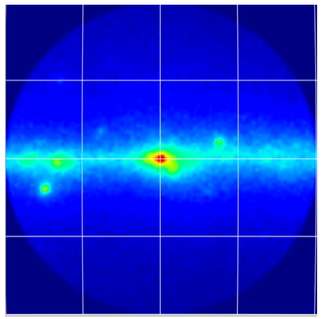
- Bounds from dSphs observed by Fermi-LAT, in particular the 4-body channel, are imposed directly from data.

- The GCE fit by DM annihilation to the b-quark involved final states are strongly constrained by the updated dSphs bound, while the τ or μ final states are still available. But τ (μ) final states possibly constrained by the anti-proton (e^+) observations.

- The dedicated analysis on the anti-proton bounds, e^+ bounds, and the mediator mass effects for the 4-body final states (in secluded DM scenarios) are needed.

Backup: Gamma-ray observation at Fermi-LAT

All sky map, E = 1.6 GeV, 16 years of data



Center: 40°×40°
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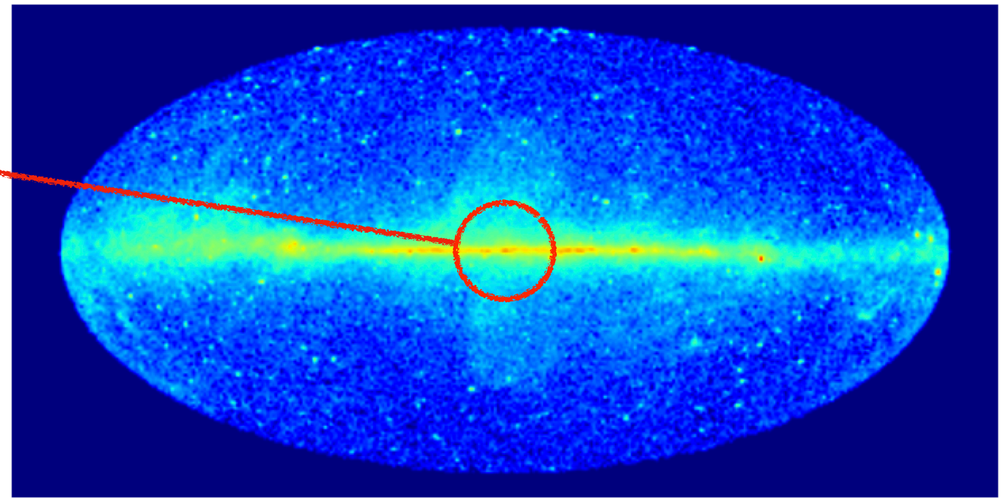

More than 80% of the photons: diffuse emission

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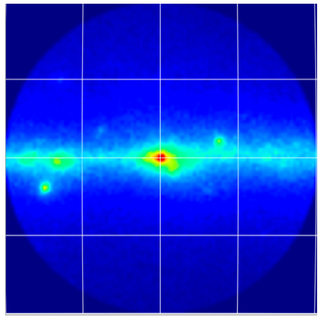

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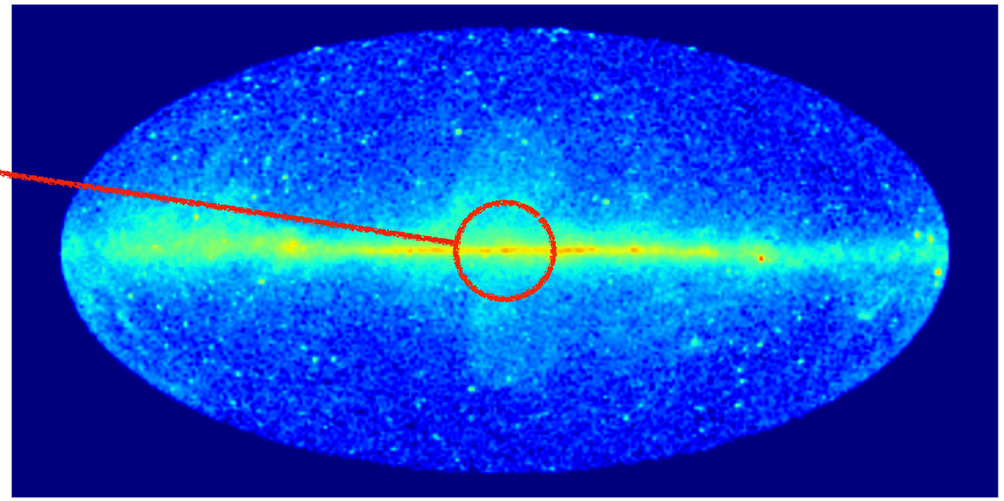

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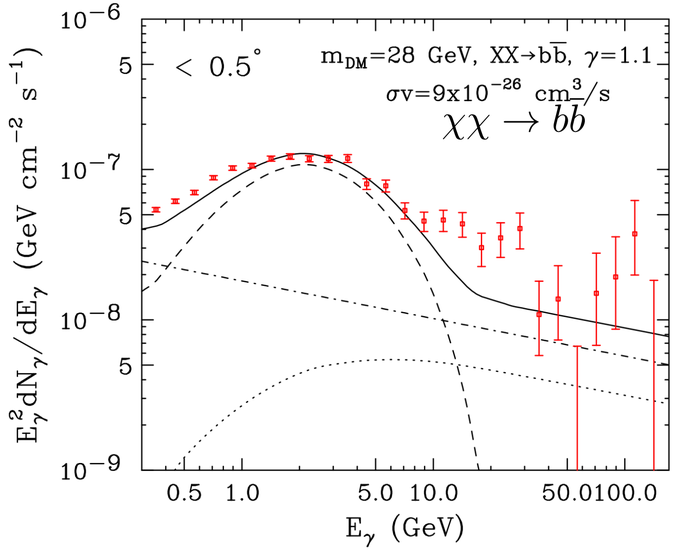
Excess is first reported by HEP/Astro theorists



Goodenough, Hooper, arXiv:0910.2998

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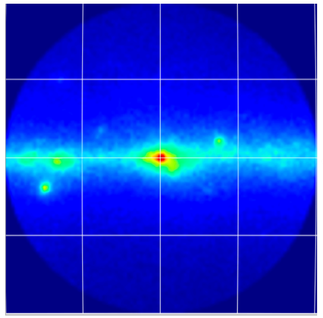

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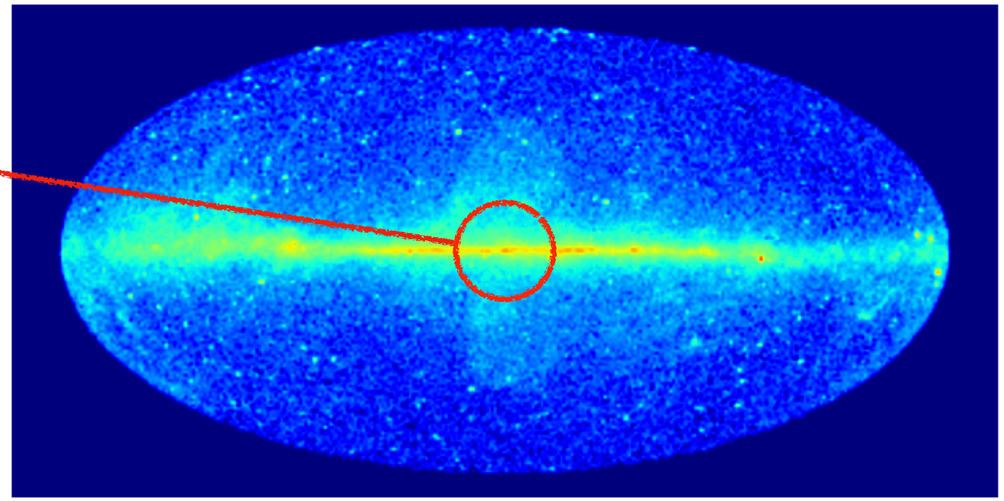

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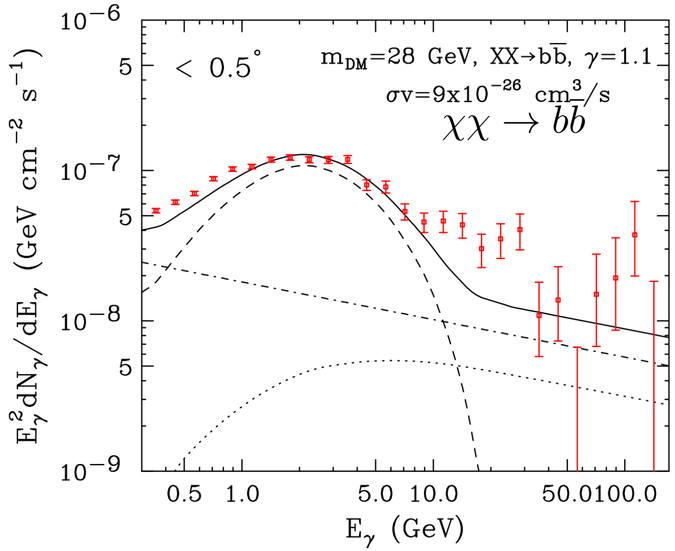

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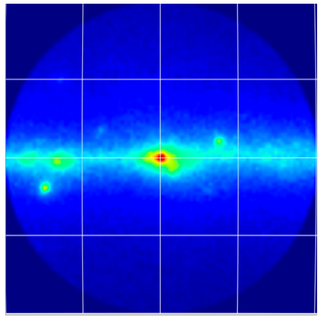

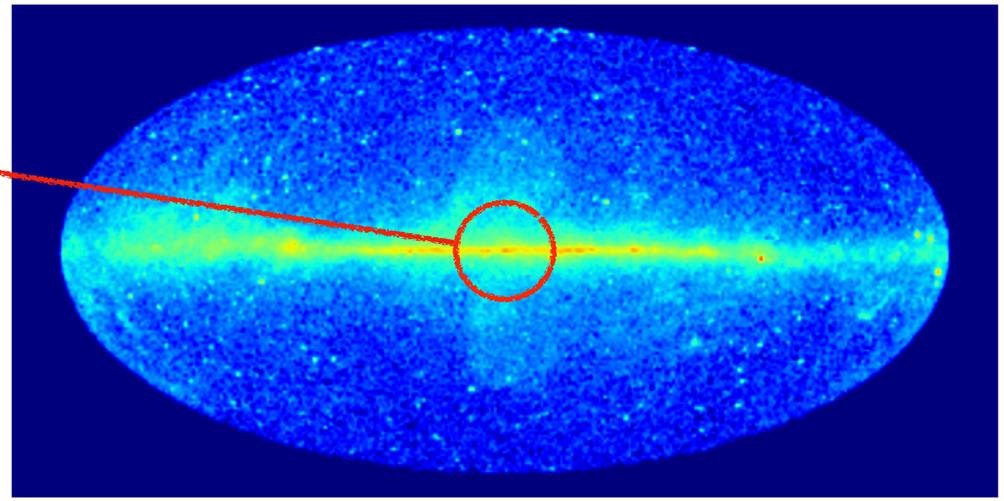

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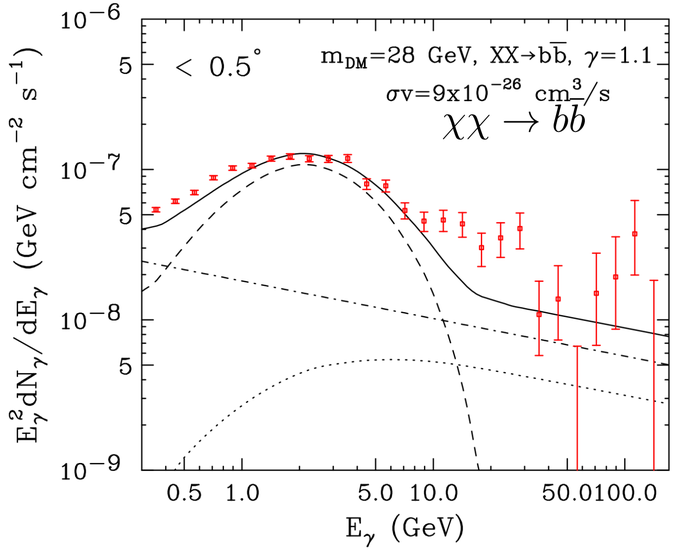

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Fermi-LAT, arXiv:1511.02938

1-100 GeV, 15°×15°,
~1kpc from the GC

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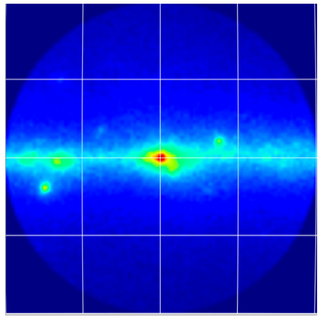

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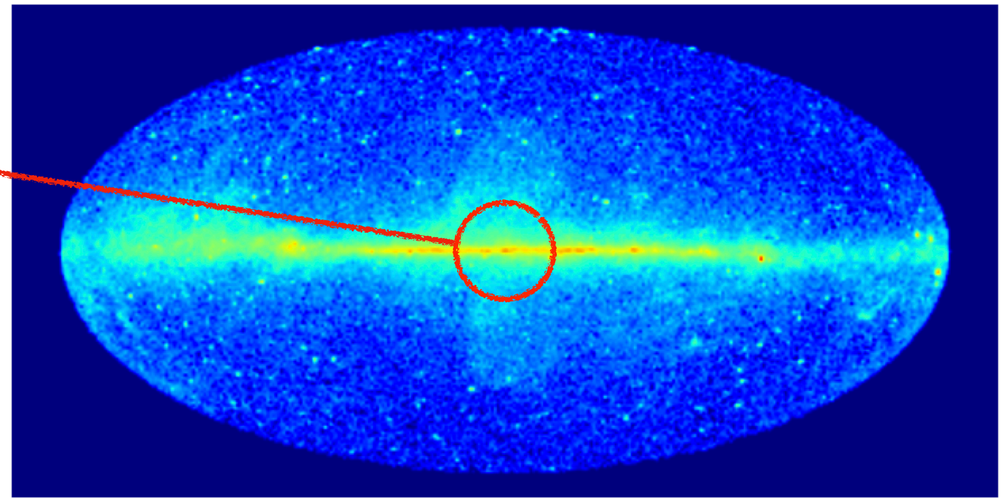

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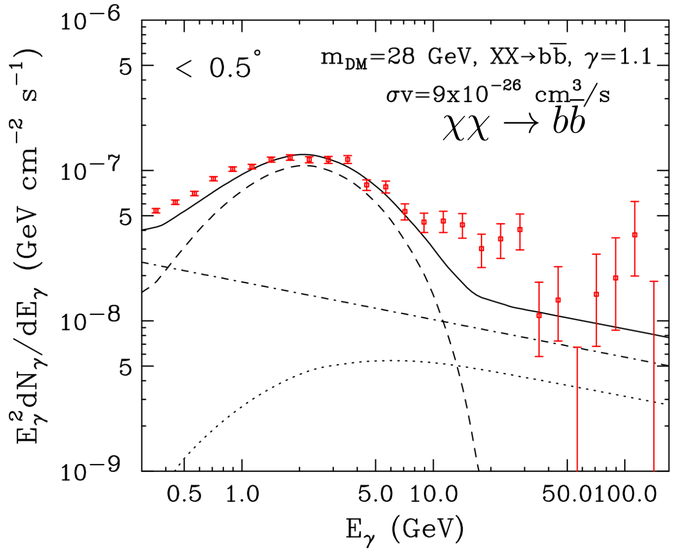

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Improved diffuse emission model templates by CR observations prefer DM.

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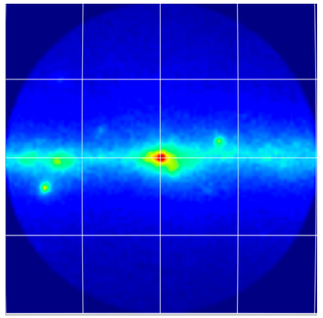

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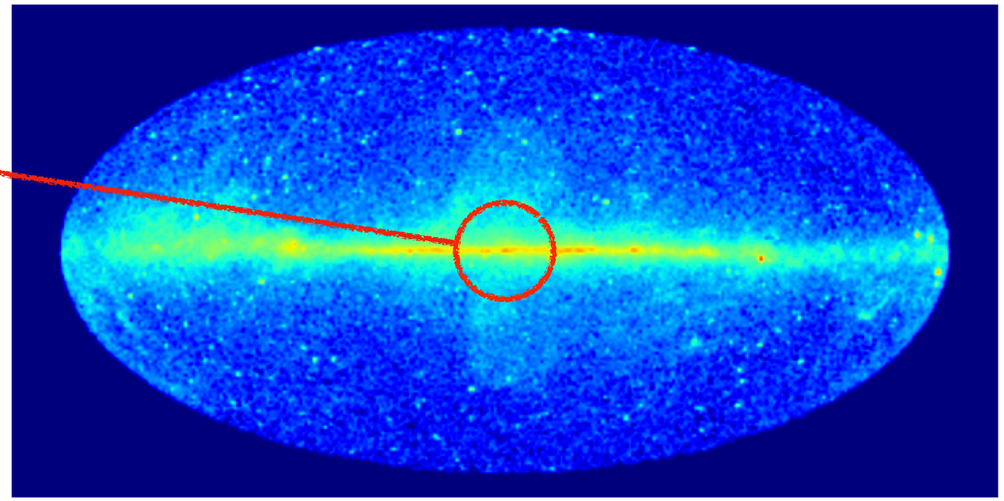
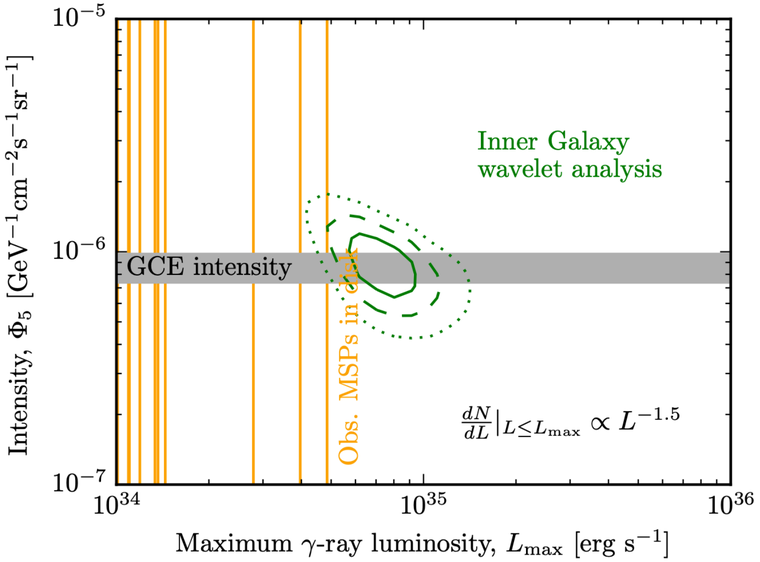


Point-like source contribution also gives a good fit.



Bartels, Krishnamurthy, Weniger, arXiv:1506.05104

Lee, Lisanti, Said, Slatyer, Xue, arXiv:1506.05124

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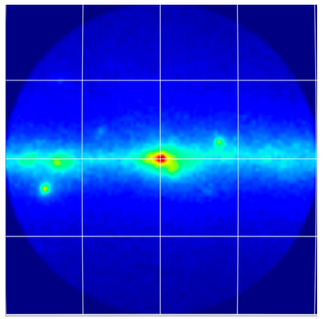

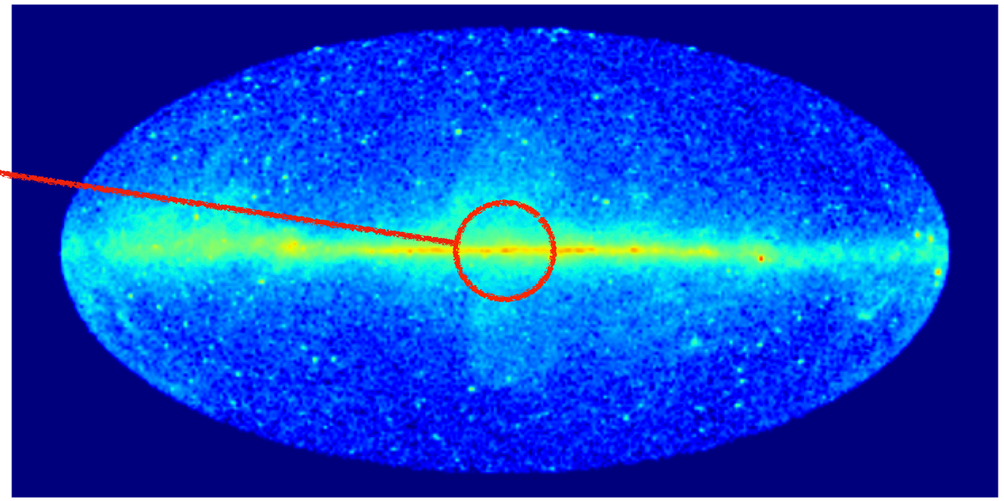

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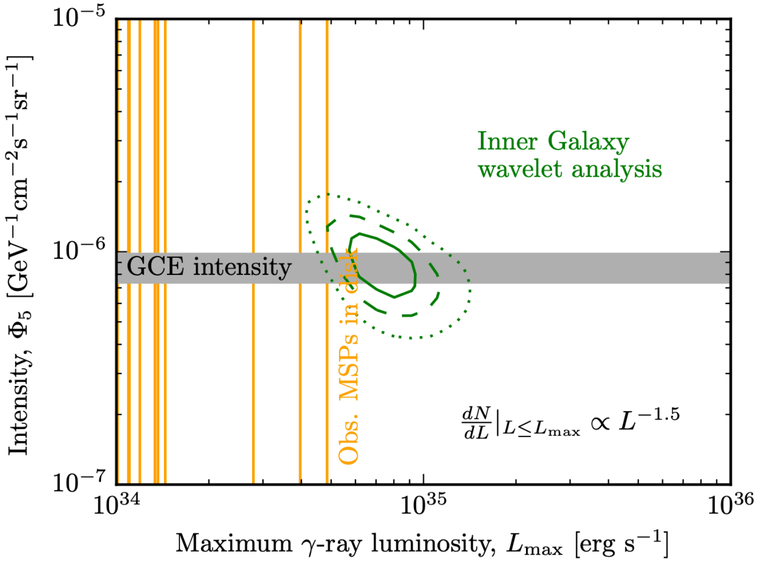

Bartels, Krishnamurthy, Weniger, arXiv:1506.05104

Lee, Lisanti, Said, Slatyer, Xue, arXiv:1506.05124

Identification of MSP

- Update of the luminosity function: comparison with the known pulsars

Hooper, Cholis, Linden, Siegal-Gaskins, Slatyer, arXiv:1305.0830

Cholis, Hooper, Linden, arXiv:1407.5625

- GW from the energy loss of MSP

Miller, Zhao, arXiv:2301.10239

- Morphology study with another updated diffuse emission model templates (interstellar model, statistical fitting): bulge morphology fits better (MSP inside it)?

Bartels, Strom, Weniger, Calore, arXiv:1711.04778

Ploeg, Gordon, Crocker, Macias, arXiv:2008.10821

Manconi, Calore, Donata, arXiv:2402.04733

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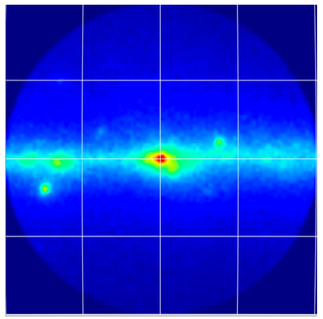
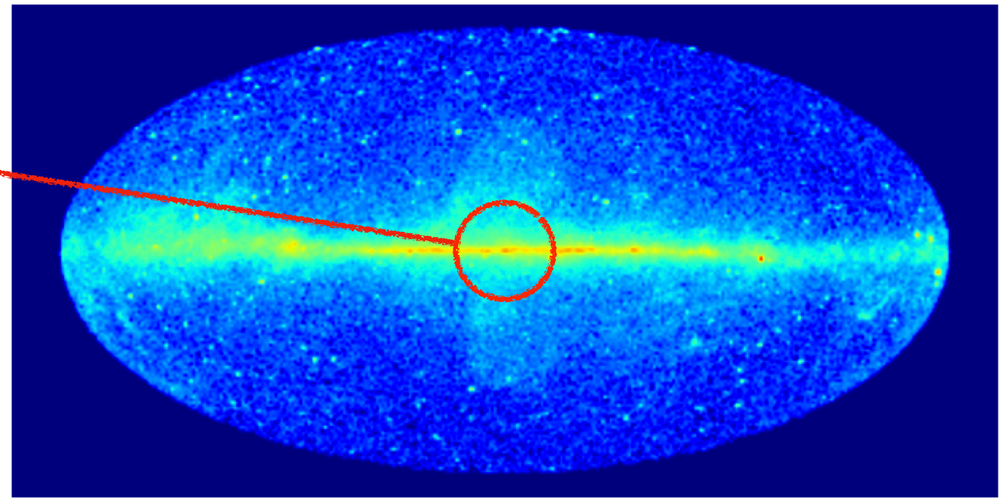


Center: 40°×40°
(white line 10°)



Here, focus on the DM annihilation.

Identification of MSP

- Update of the luminosity function: comparison with the known pulsars

Hooper, Cholis, Linden, Siegal-Gaskins, Slatyer, arXiv:1305.0830

Cholis, Hooper, Linden, arXiv:1407.5625

- GW from the energy loss of MSP

Miller, Zhao, arXiv:2301.10239

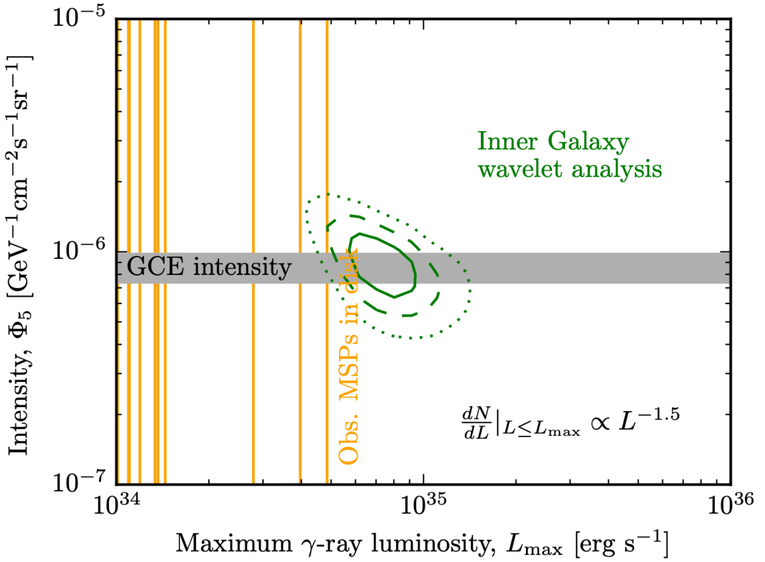
- Morphology study with another updated diffuse emission model templates (interstellar model, statistical fitting): bulge morphology fits better (MSP inside it)?

Bartels, Strom, Weniger, Calore, arXiv:1711.04778

Ploeg, Gordon, Crocker, Macias, arXiv:2008.10821

Manconi, Calore, Donata, arXiv:2402.04733

Point-like source contribution also gives a good fit.



Bartels, Krishnamurthy, Weniger, arXiv:1506.05104

Lee, Lisanti, Said, Slatyer, Xue, arXiv:1506.05124

Backup: Data analysis

- GCE is a subdominant component in the total γ-ray observations.
- The uncertainties of the astrophysical models affect the significance of the GCE signal.
- Uncorrelated uncertainties would overestimate the GCE: include the correlated errors across the energy bins and pixels.

Covariance matrix from different ROIs: 22 ROIs (other than GC) centered at $20° \leq |l| \leq 70°$ in steps of 5° for $b = 0°$

Cholis, Zhong, McDermott, Surdutovich, arXiv:2112.09706

$$\Delta_{ij} = \left\langle E_i^2 E_j^2 \frac{dN}{dE_i} \frac{dN}{dE_j} \right\rangle - \left\langle E_i^2 \frac{dN}{dE_i} \right\rangle \left\langle E_j^2 \frac{dN}{dE_j} \right\rangle$$

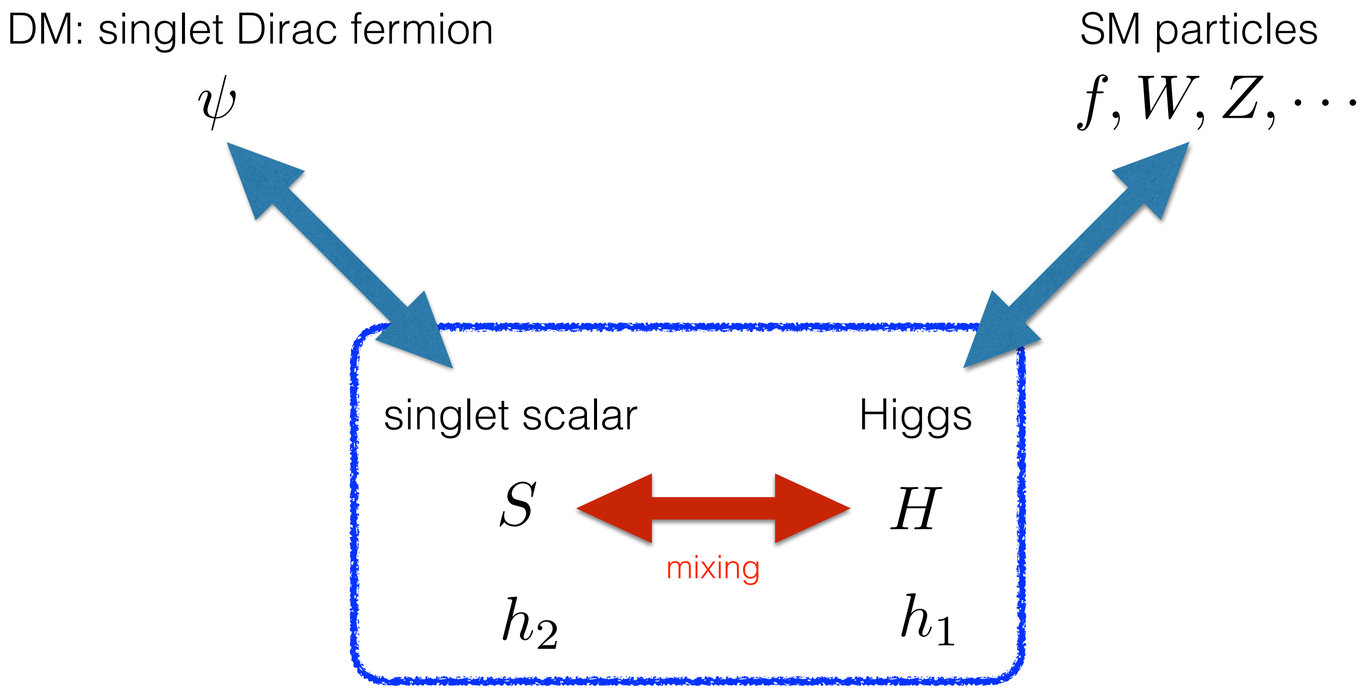
$\frac{dN}{dE_i}$: the best-fit GCE like flux from the ith energy bin

averaged over the 22 different ROIs

$$\chi^2 = \sum_{i,j} \left(E_i^2 \frac{d\bar{N}}{dE_i} [m_\chi, \langle \sigma v \rangle] - E_i^2 \frac{dN}{dE_i} \right) \Delta_{ij}^{-1} \left(E_j^2 \frac{d\bar{N}}{dE_j} [m_\chi, \langle \sigma v \rangle] - E_j^2 \frac{dN}{dE_j} \right)$$

Backup: Singlet Fermionic Dark Matter (SFDM)

As a reference model checking our result, we choose singlet fermionic dark matter model:



Y.G. Kim, K.Y. Lee, **SS**, JHEP 0805, 100 [arXiv:0803.2932]

Technically, we use the secluded SFDM to explain the GCE: extension with a pseudoscalar dark Yukawa interaction.

Y.G. Kim, K.Y. Lee, C.B. Park, **SS**, Phys. Rev. D93, 075023 (2016) [arXiv:1601.05089]

$$-\mathcal{L}_{\rm int}^{\rm dark} = g_S \cos\xi \, s\bar{\psi}\psi + g_S \sin\xi \, s\bar{\psi} i\gamma^5 \psi,$$