20 GeV halo-like excess of the Galactic diffuse emission: evidence for dark matter annihilation?

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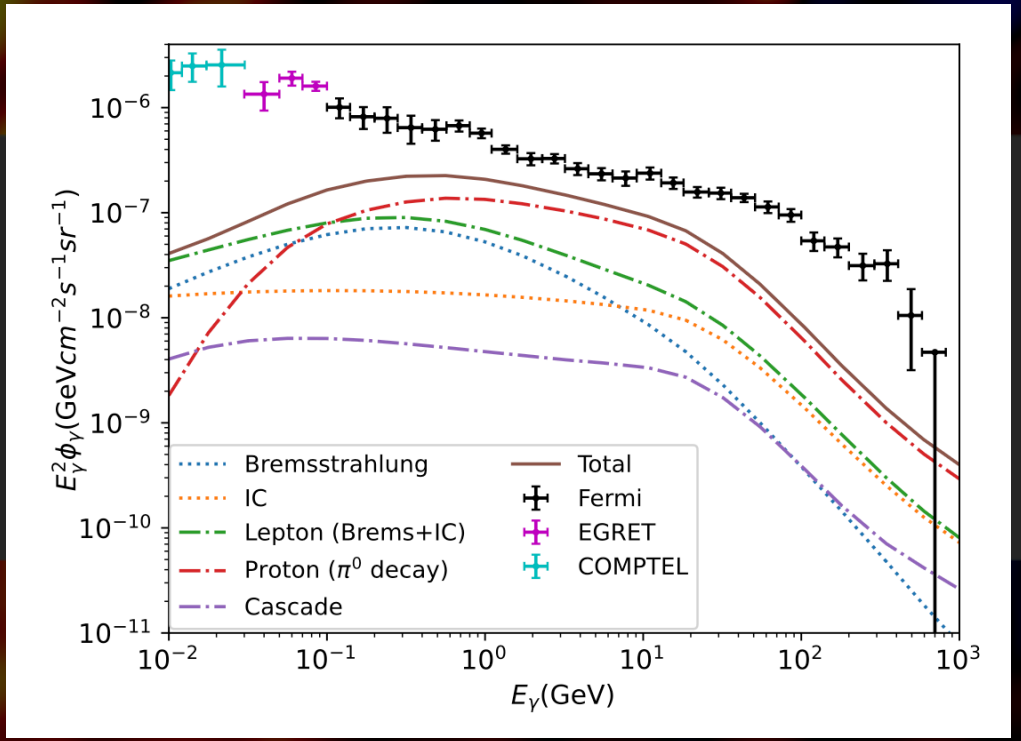
Introduction

- The Milky Way (MW) halo is a good region to search for annihilation gamma-rays from dark matter
  - avoiding strong astrophysical radiation in the Galactic Center (GC) and disk
- But not so many activities using Fermi-LAT
  - Fermi-LAT '12 using only 2-yr LAT data
  - Reasons?
    - GC GeV excess may be dark matter annihilation?
      - But it can also be explained by e.g., millisecond pulsars
    - Known diffuse structures (cosmic-rays, Fermi bubbles, Loop I, ⋯)
- This work presents a search using 15-yr LAT data
  - examination of a halo-like component in the diffuse map, in addition to the known components

Why I started this study?

- My background:
  - Theoretical modeling of extragalactic gamma-ray background from AGNs, star-forming galaxies, ⋯
  - No experience with Fermi data analysis!
    - special thanks to Tsunefumi Mizuno for a lot of advice about Fermi data analysis
- Why dark matter search now using Fermi data?

Extragalactic gamma-ray background from star-forming galaxies



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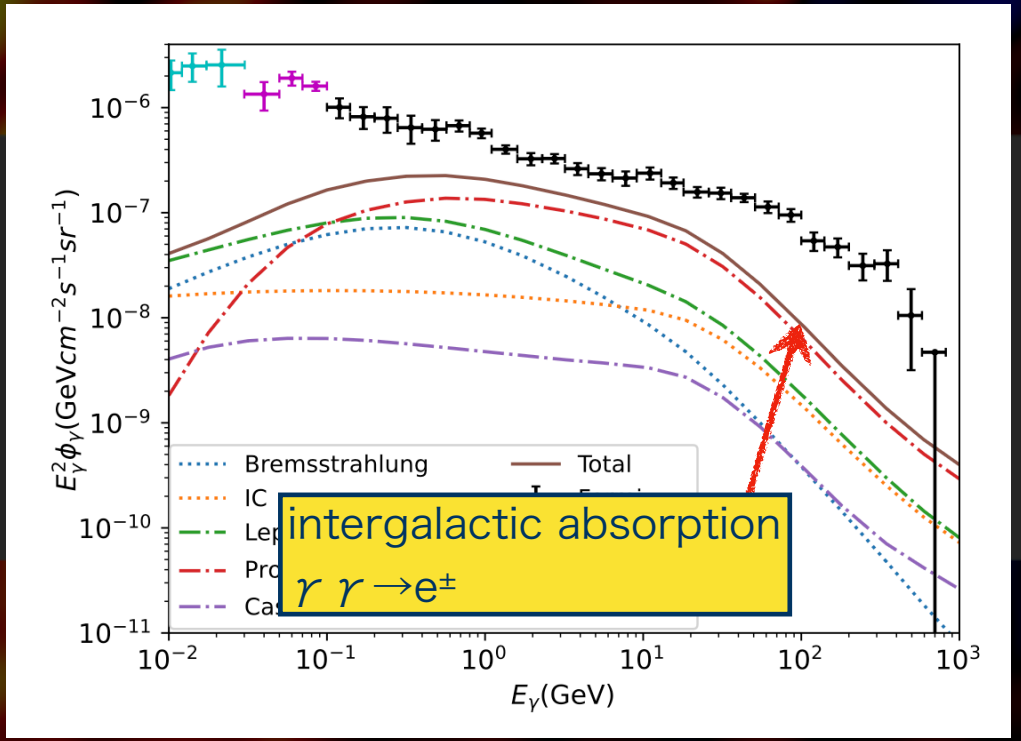

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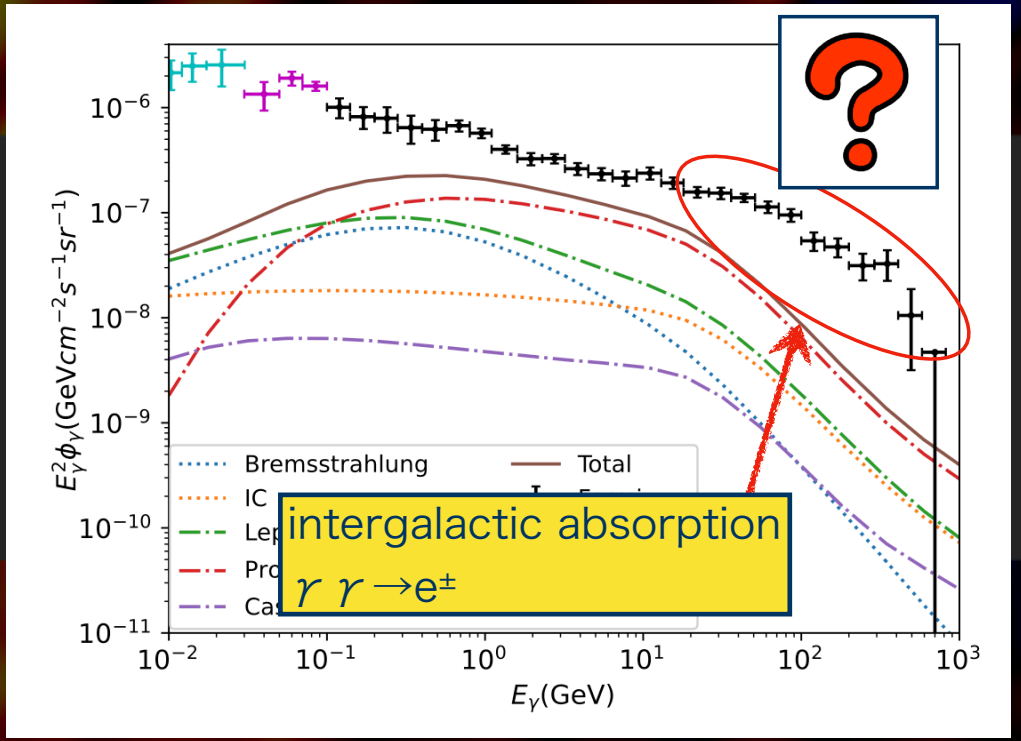

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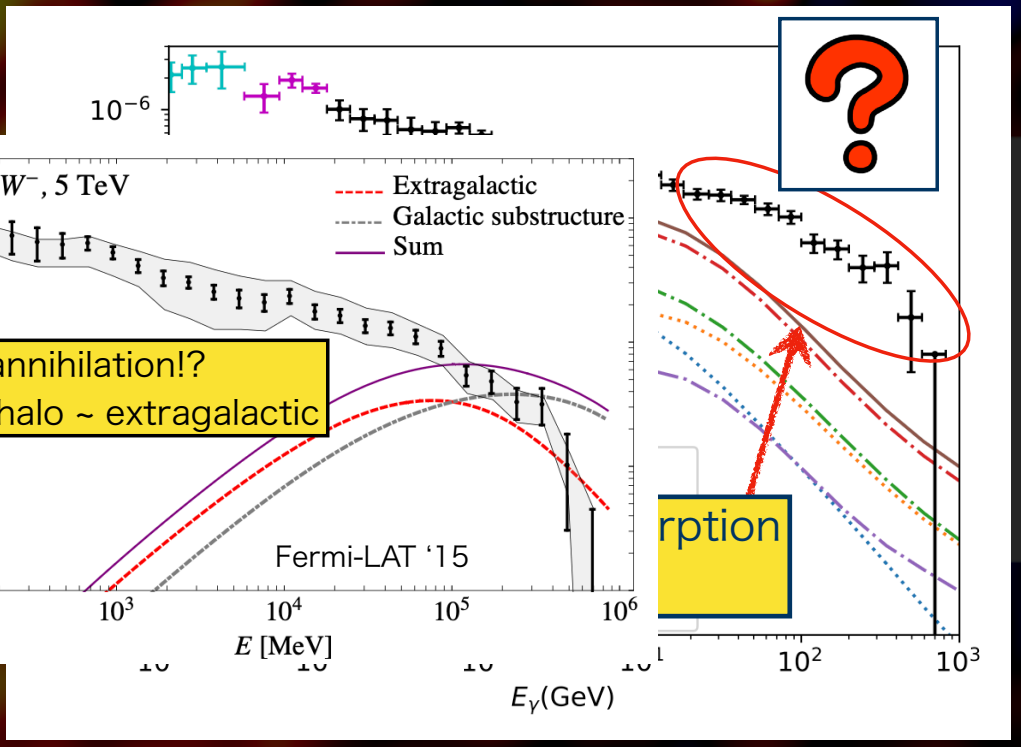

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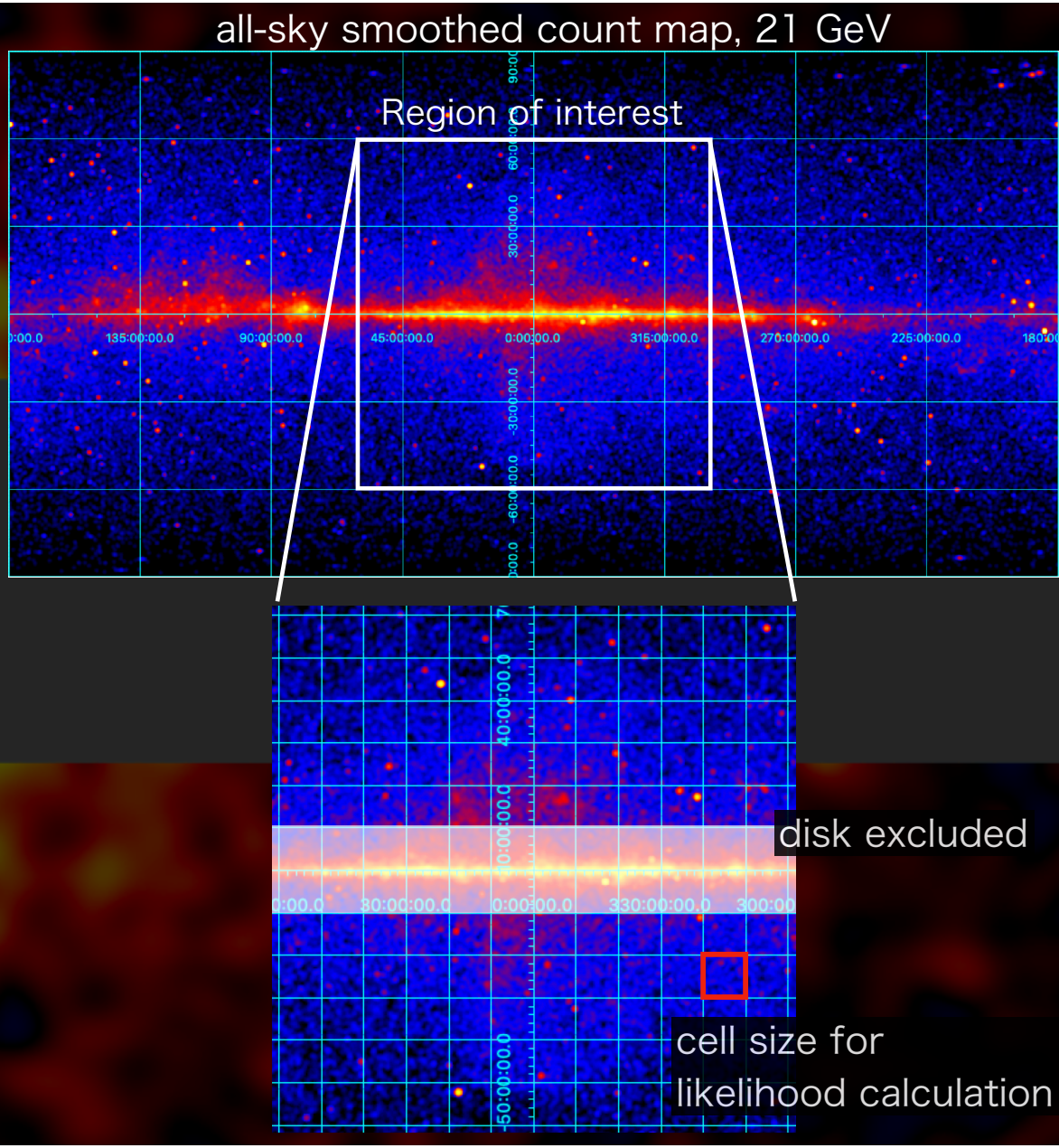
The Fermi data and analysis

- The public Fermi data used:
  - 15-yr (2008-2023), Pass 8 UltraClean
  - zenith angle cut θ < 100 deg
  - 1.5-810 GeV, 19 bin (log-spaced)
  - Cartesian coordinates
  - pixel scale: 0.125 deg

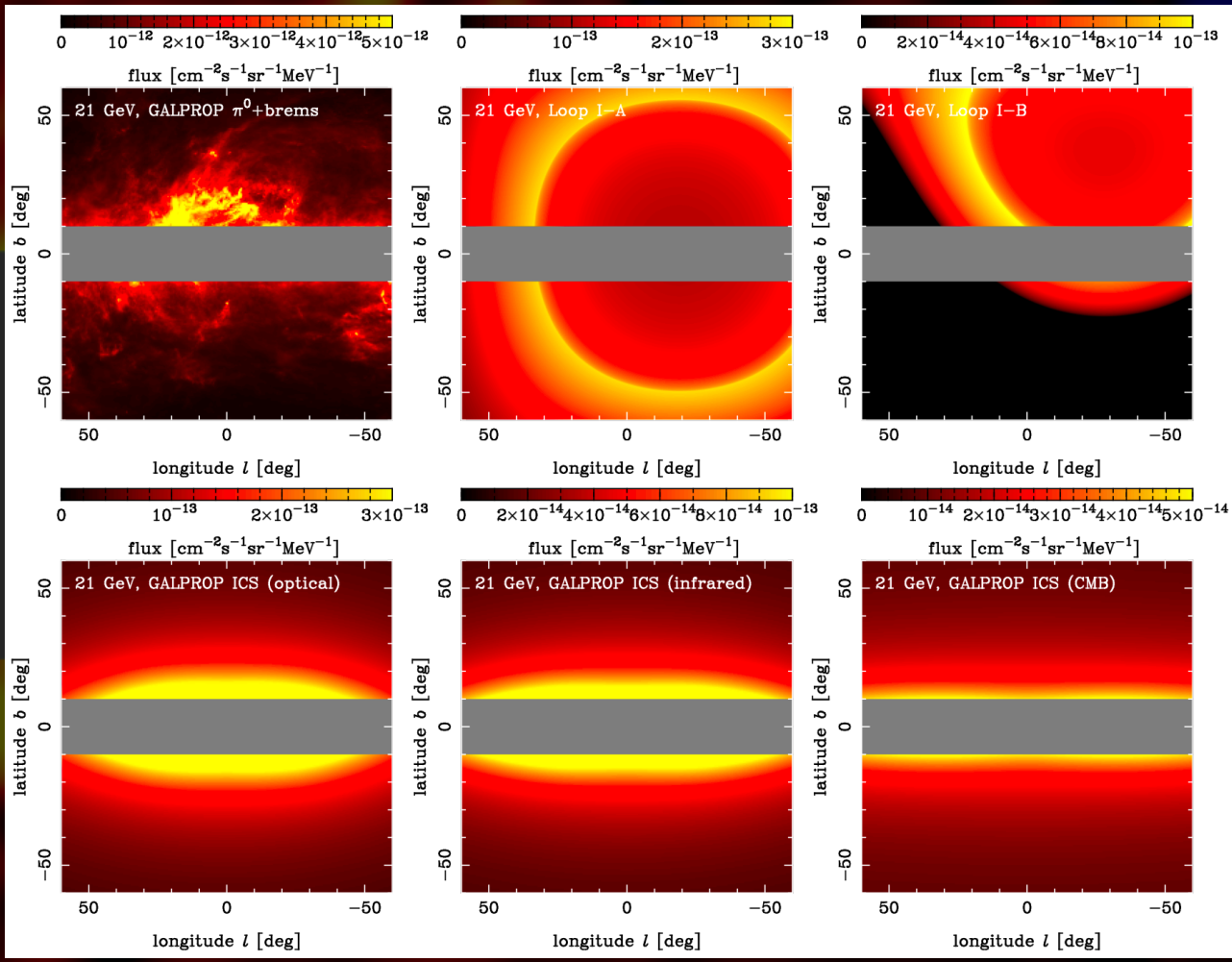
- Region of interest (ROI)
  - $|l| < 60$ deg
  - $10 < |b| < 60$ deg

- Likelihood calculation:
  - photon counts in each cell of 10 deg x 10 deg
  - DM halo annihilation signal is expected to be smooth on this scale
  - save computing time than pixel-scale calculation
  - pixel-scale model-data mismatch smoothed out



Model map templates

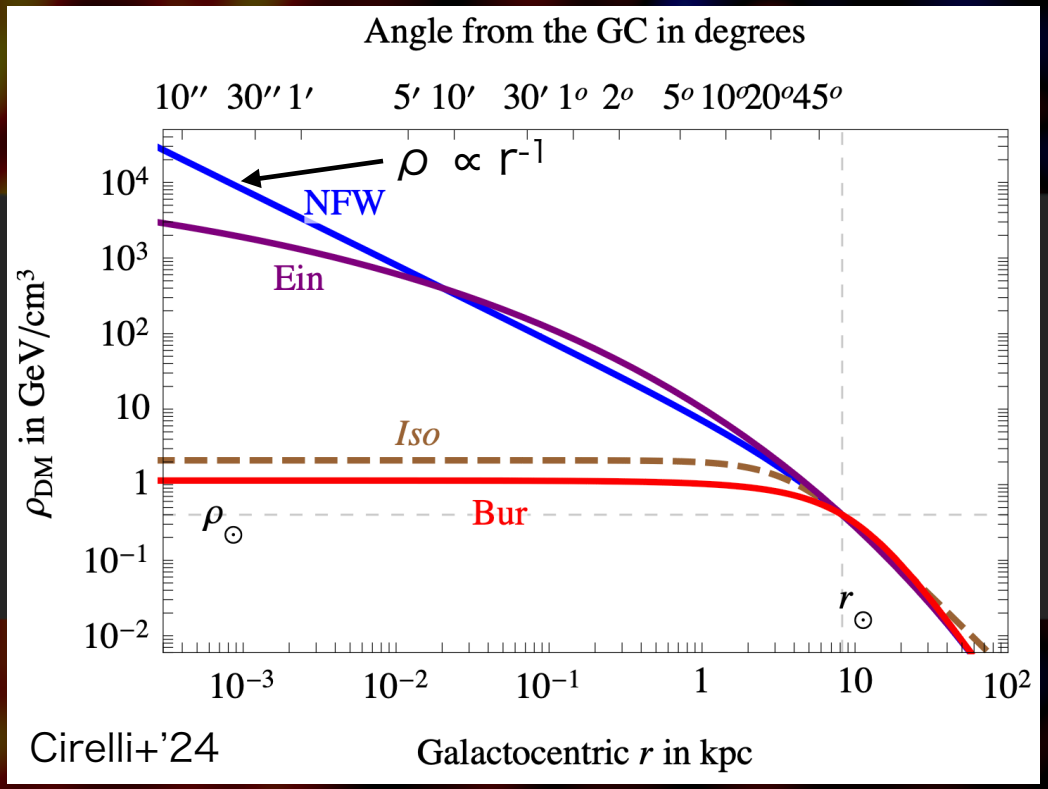
- known sources:
  - point sources: subtracted using the Fermi PS catalog
  - extended sources: masked
- diffuse emission by cosmic-ray interactions:
  - GALPROP model
    - gas (pion-decay + bremsstrahlung)
    - inverse-Compton scattering (ICS)
- Loop I
  - giant diffuse structure in radio bands
  - the geometric model including two emission shells (Wolleben '07)
- isotropic background



Model map templates: DM halo of MW

- the NFW profile assumed
  - parameters from the Via Lactea II simulation (Kuhlen+'08)

- volumetric gamma-ray emissivity ε_γ
  - NFW-ρ^2: $\varepsilon_\gamma \propto \rho^2$
    - annihilation with smooth density profile
  - NFW-ρ^1: $\varepsilon_\gamma \propto \rho^1$
    - sub-structure/subhalo dominant
    - decaying DM rather than annihilation
  - NFW-$\rho^{2.5}$: $\varepsilon_\gamma \propto \rho^{2.5}$
    - GC GeV excess
    - $\rho \propto r^{-1.25}$ favored from GC analysis
    - same emissivity profile as NFW with $\varepsilon_\gamma \propto \rho^{2.5}$

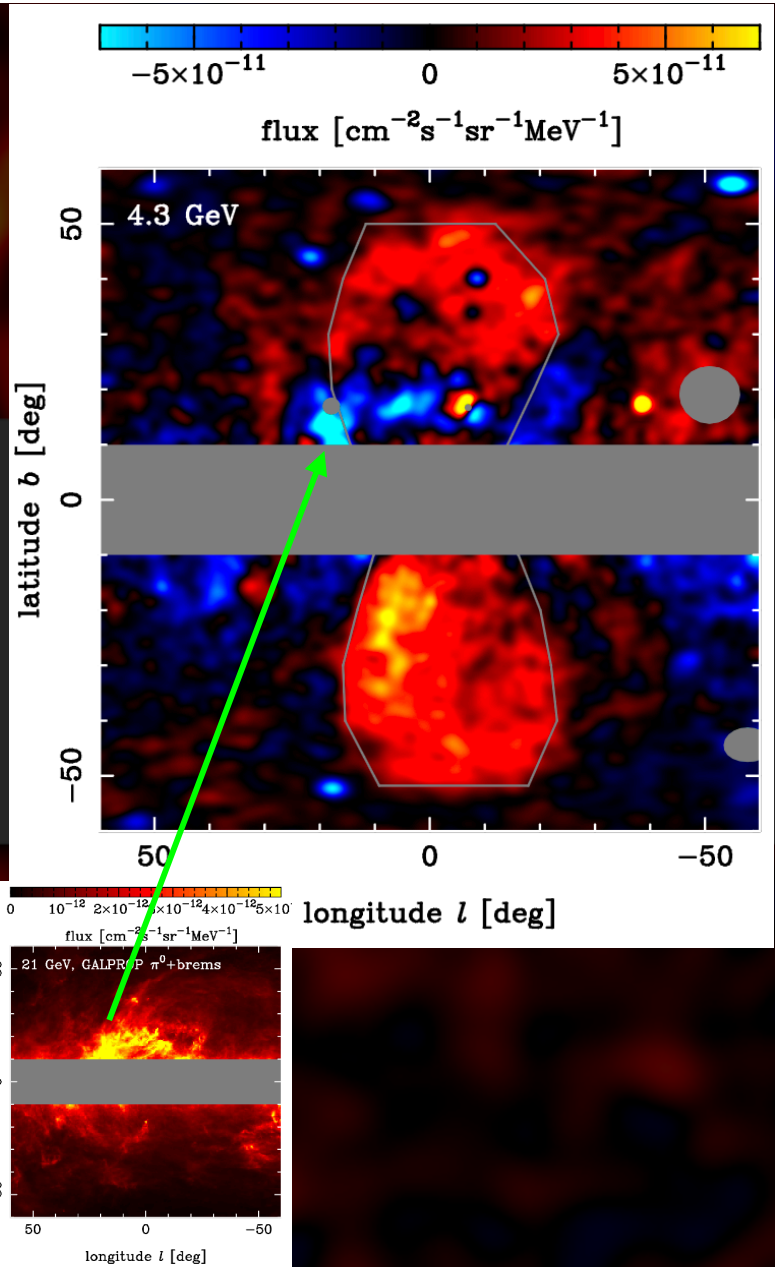


Model map templates: Fermi bubbles

- Fermi bubble image (flat FB template + residual) at 4.3 GeV bin

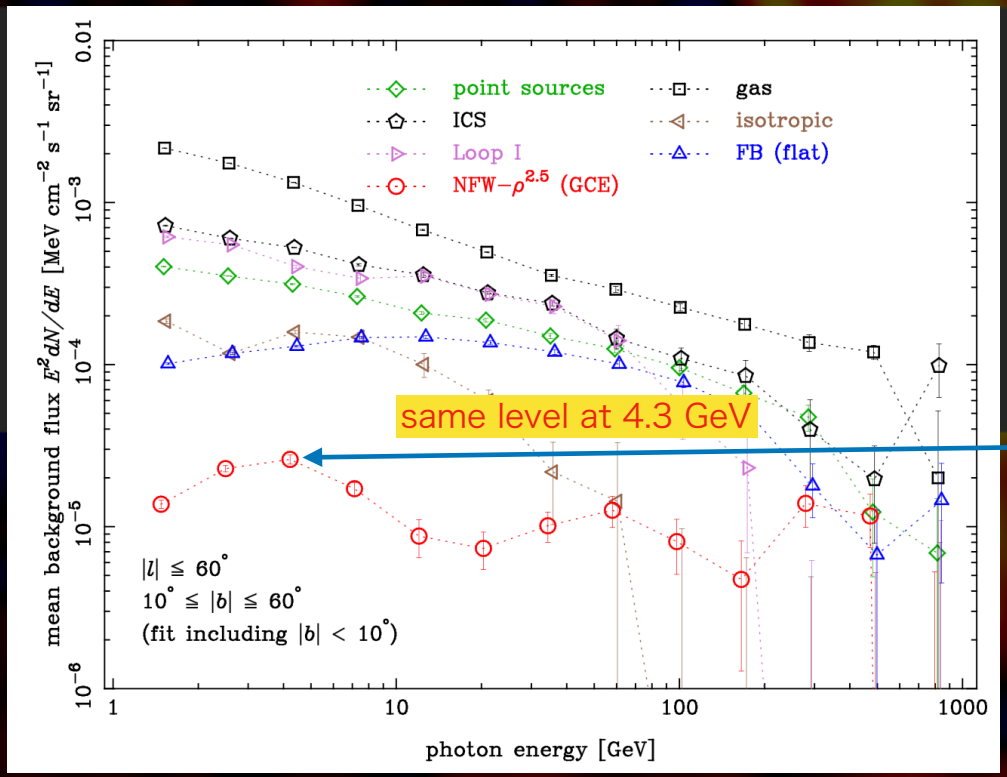
- positive flux regions dominated by FB, but there are some negative regions, correlated with the GALPROP gas map (~5% level of the model)

- our approach to search for a halo-like excess:
  - add the positive (FB) and negative residual maps at 4.3 GeV as two independent model templates, for all photon energy bins
  - At 4.3 GeV, the fit should be successful without any additional component
  - If there is a halo-like component with strong energy dependence, positive or negative halo excess will appear in other energy bins

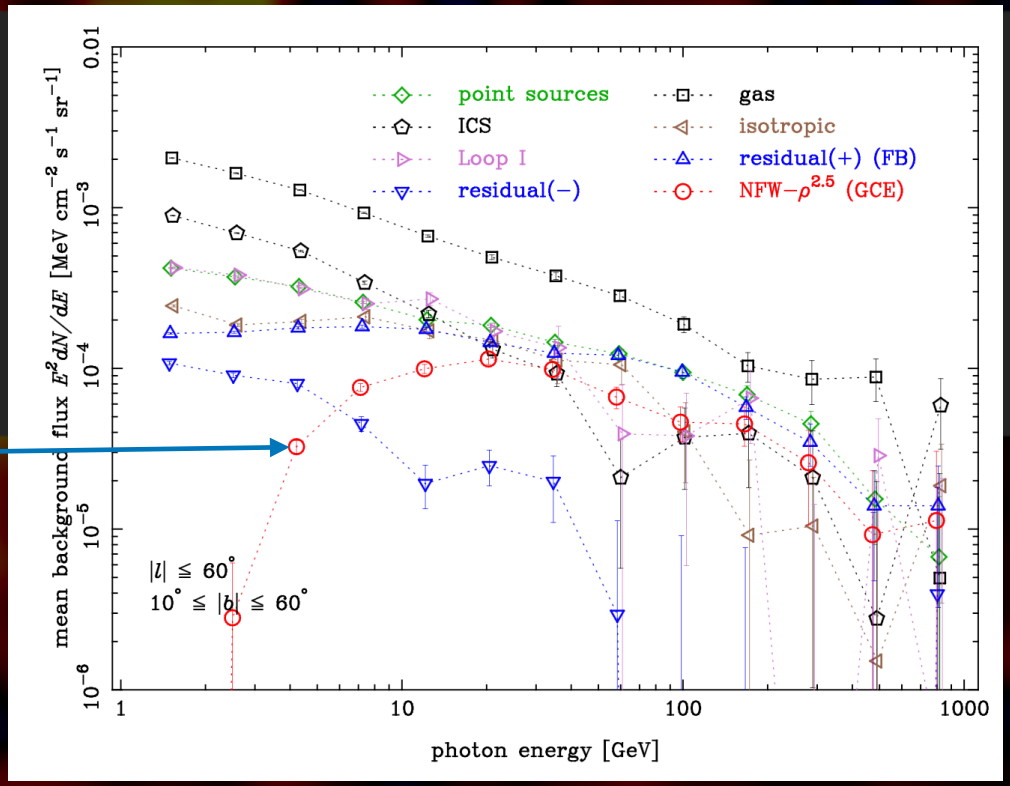


Fit by known components + GC GeV excess

- fit including NFW-$\rho^{2.5}$ halo (GC excess), independently for all energy bins
- GC GeV excess is seen in the fit including the disk, consistent with the literature
- excluding the disk from the fit: no change at 4.3 GeV (as it should be)
- But at 20 GeV, the halo flux becomes x10 by excluding the disk
- implying the significant halo component around 20 GeV, with a profile shallower than GC excess



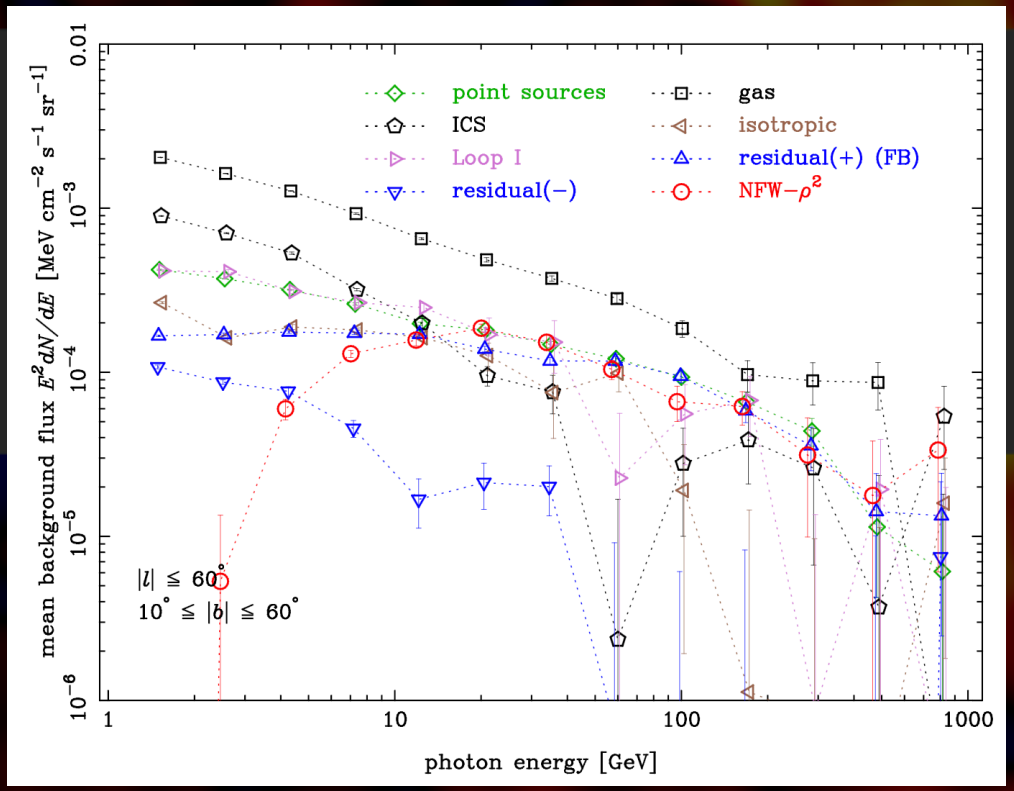
fit including the disk



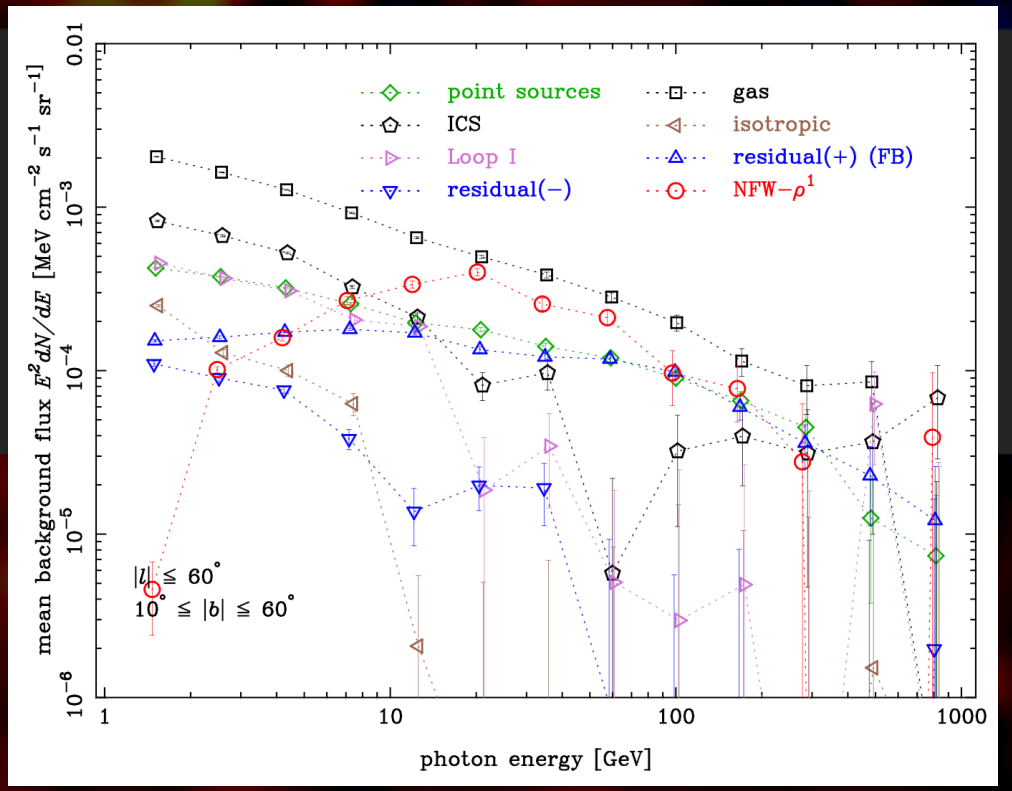
fit excluding the disk (|b| < 10 deg)

Fit with shallower halo models

- fit with shallower profiles than GC excess:
  - NFW-ρ^2 (annihilation from smooth density profile)
  - NFW-ρ^1 (annihilation from subhalos, or decaying DM)
- The halo excess with a peak at 20 GeV in all cases



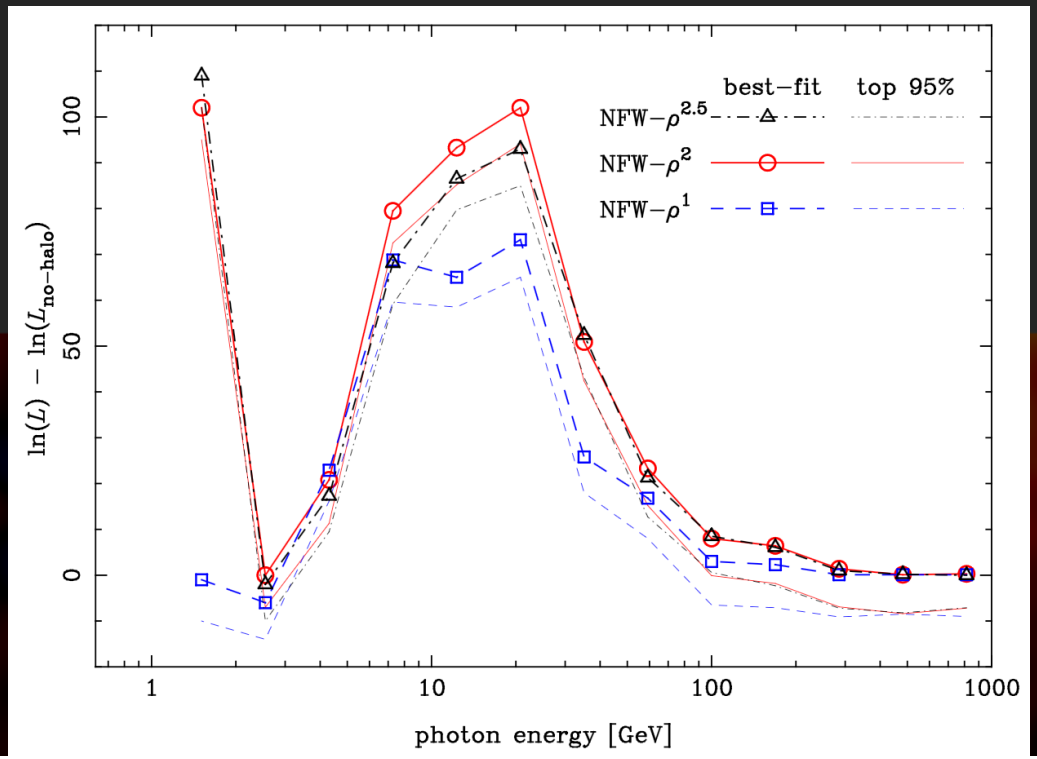
fit with NFW-ρ^2

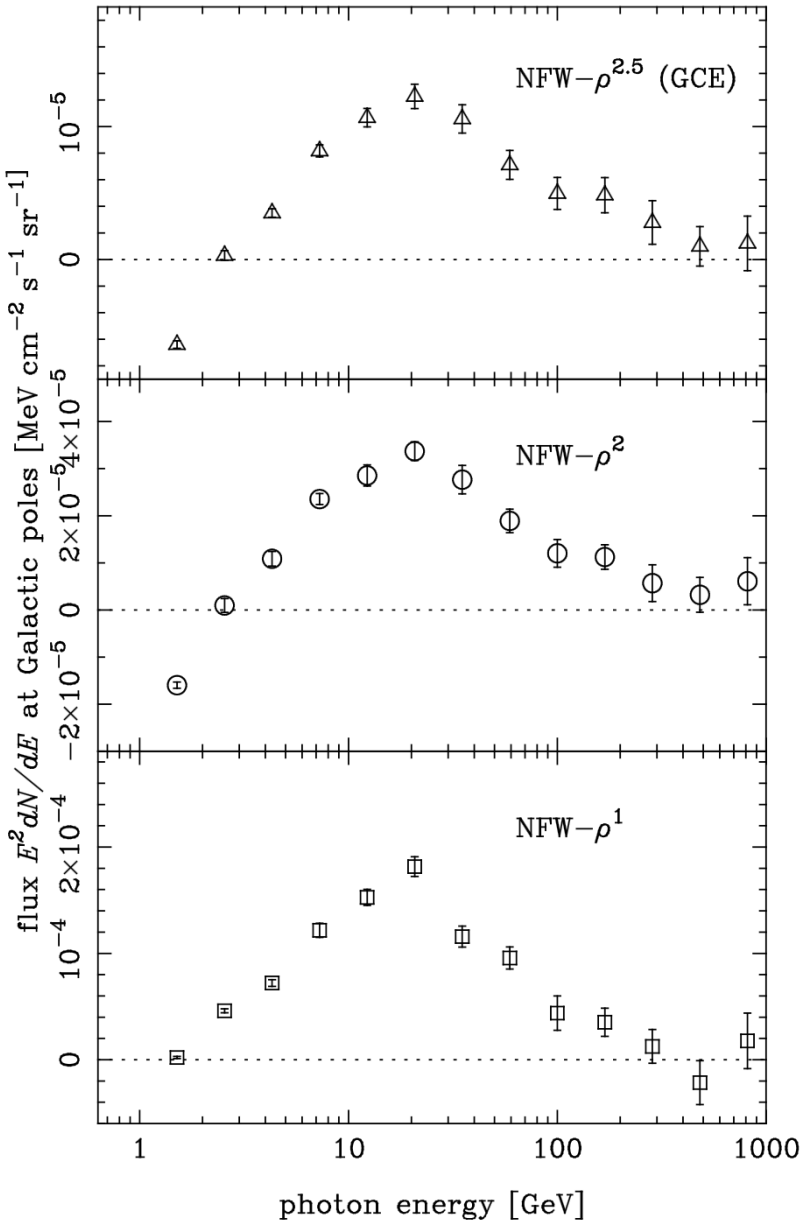


fit with NFW-ρ^1

The halo excess spectra & likelihood

- halo excess spectra in linear plot for the three models
  - sharp rise from 1 to 20 GeV, and then rapid decay in all cases
  - negative at the lowest energy (~ 1 GeV), possibly because the FB residual maps were created at 4.3 GeV
- likelihood values indicate that NFW-ρ^2 best fits at 2σ or more



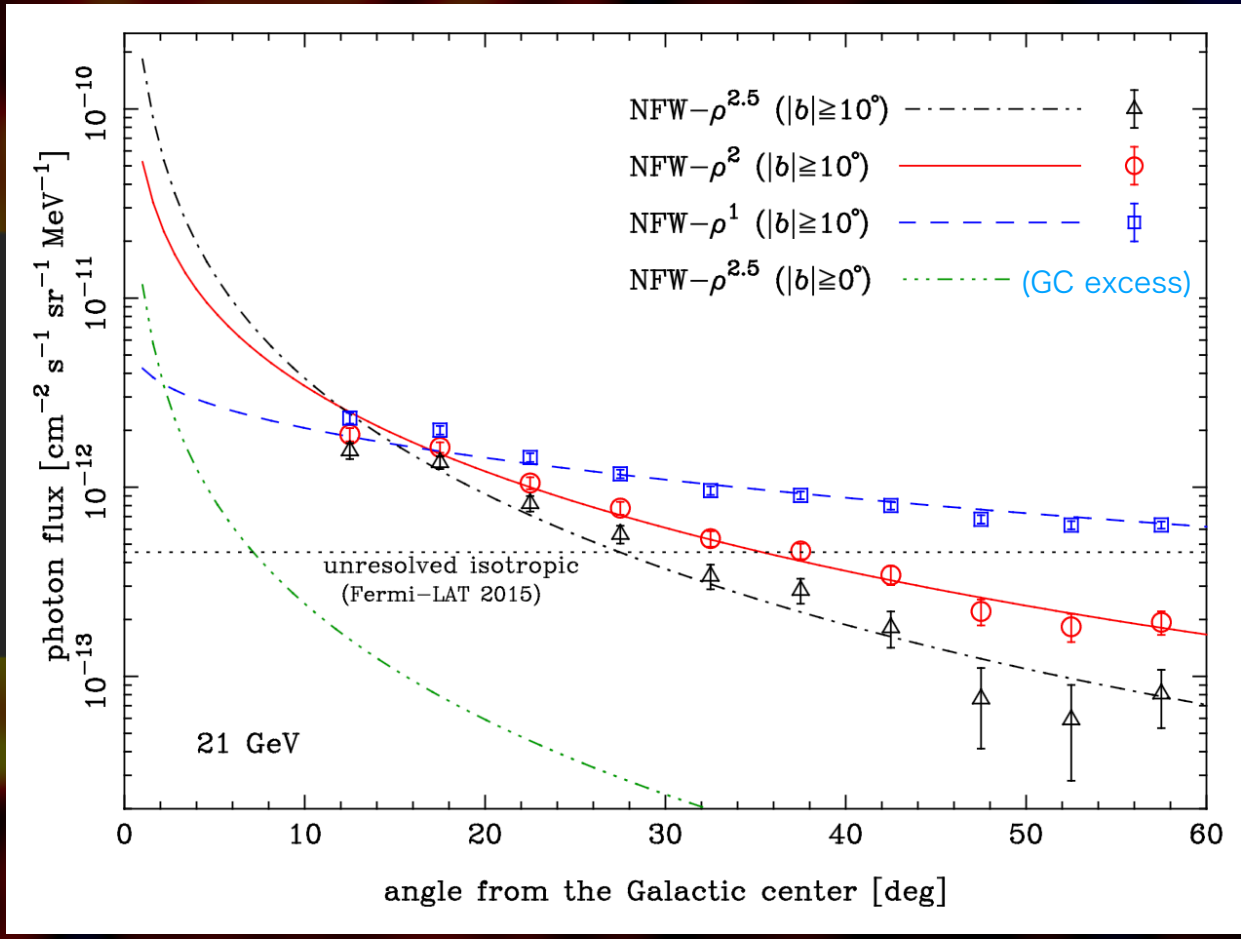


Radial angular proflies at 21 GeV

- data points: halo model + fit residual
- curves: halo model

- data points differ by the three halo models
  - degeneracy with the isotropic background
  - isotropic background flux of the NFW-ρ^2 fit is consistent with that reported by Fermi-LAT team
  - no room for isotropic background in the fit of NFW-ρ^1
    - NFW-ρ^1 is not favored, independent argument from the likelihood value

- NFW-ρ^2 best-fit overproduces the data when extrapolated to GC by a factor of ~4
  - a profile shallower than NFW-ρ^2 around GC?



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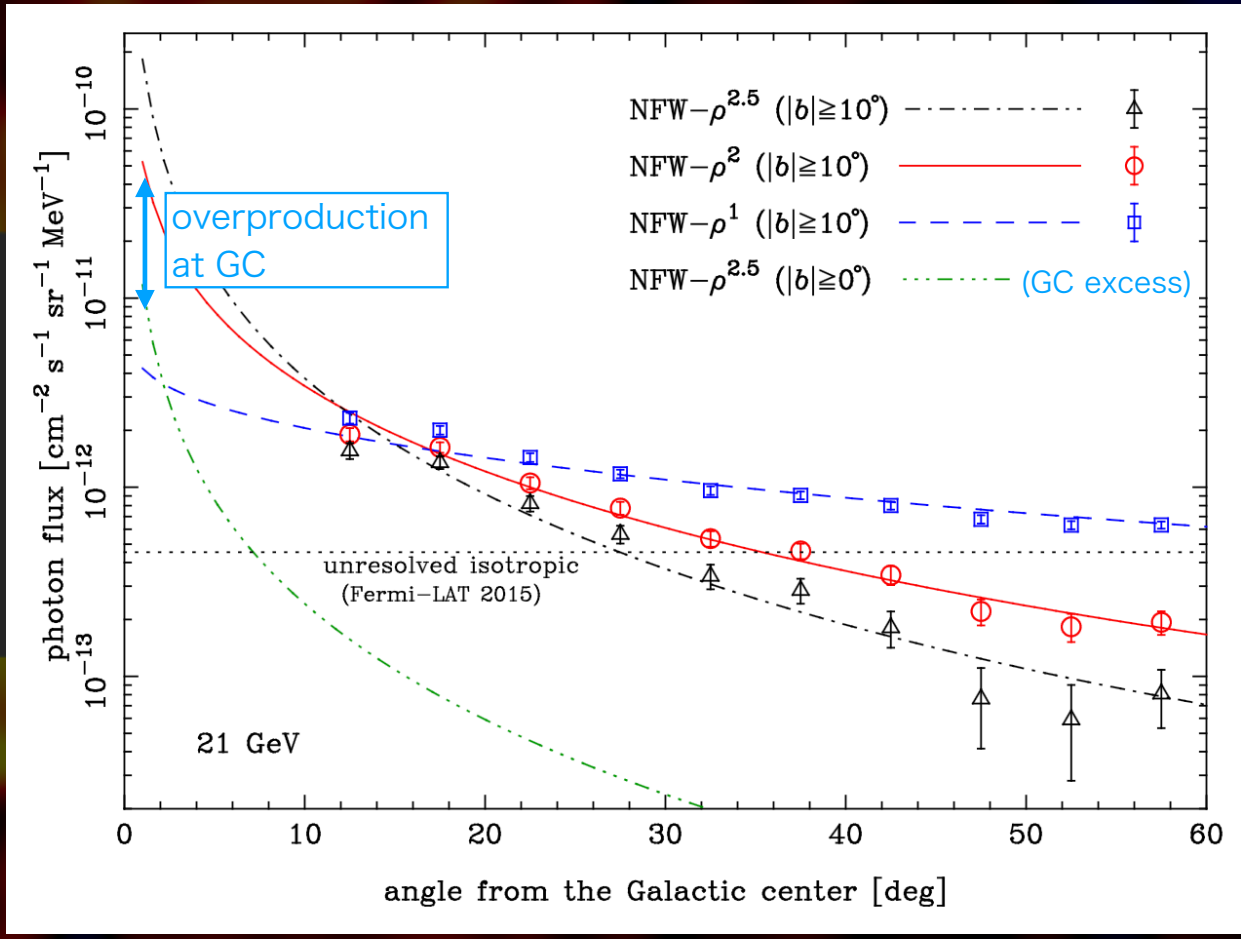
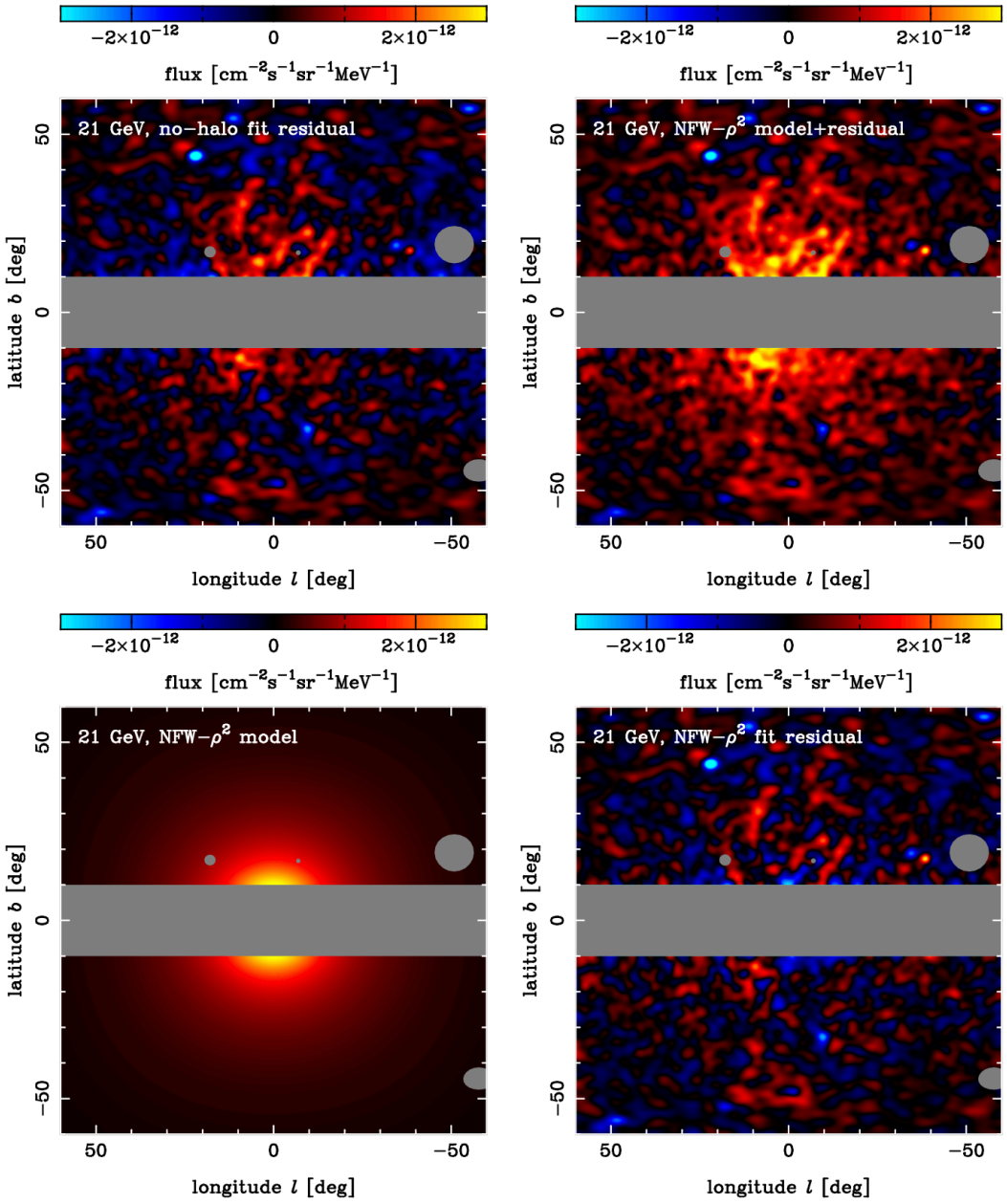


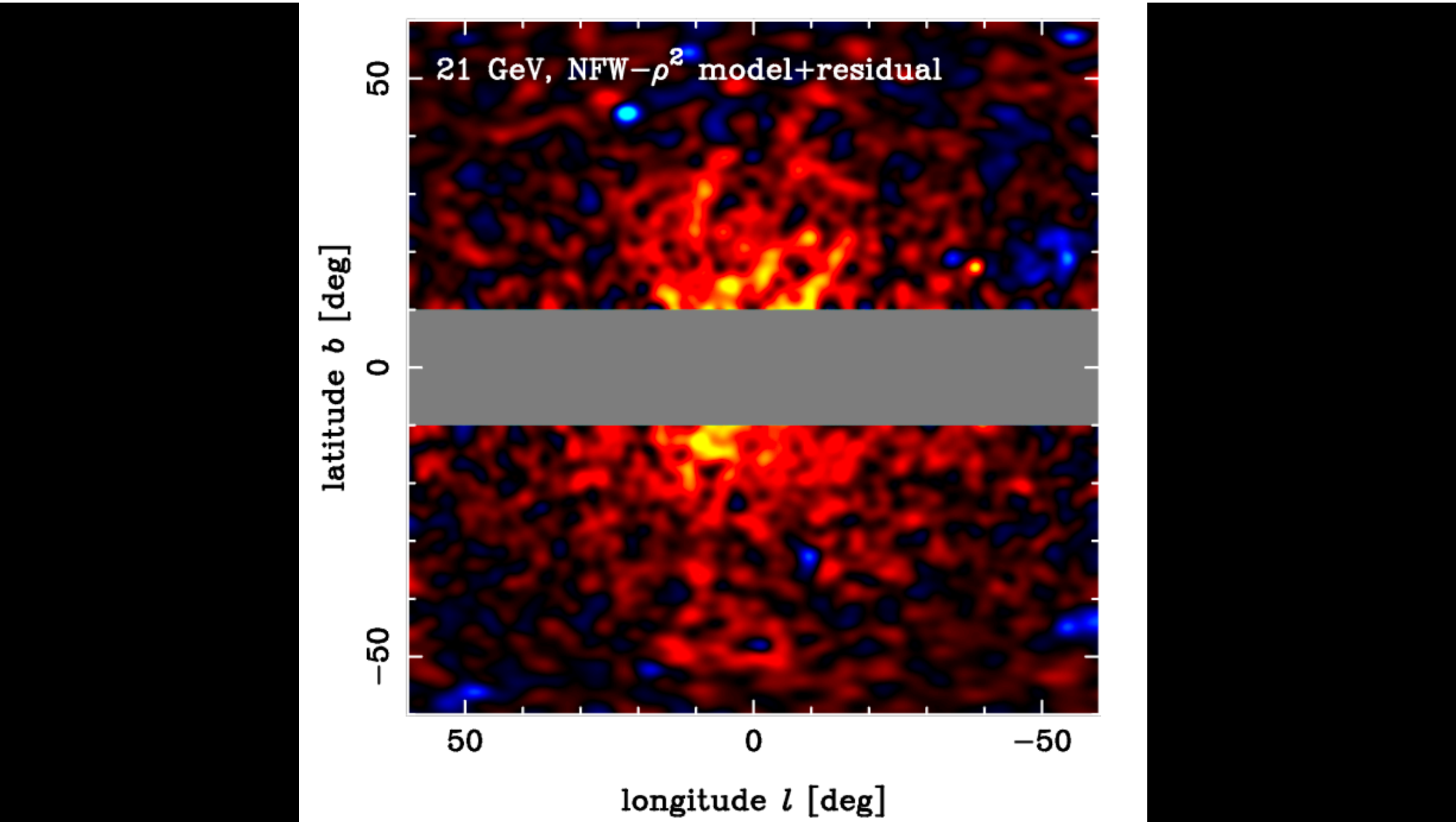
Morphologies of the halo excess at 21 GeV bin

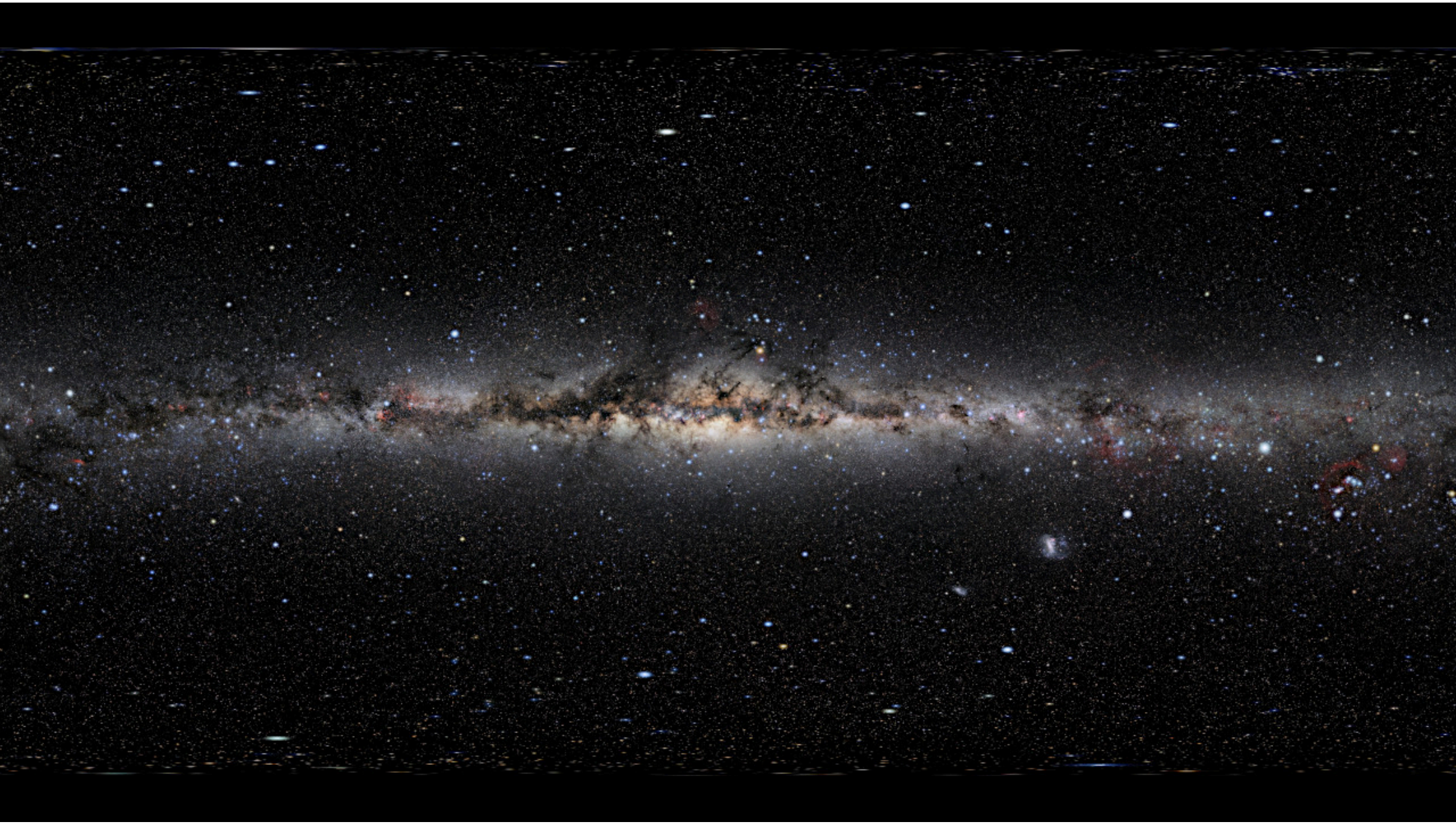
- residual of no-halo fit
  - a halo-like excess can be seen, implying that a halo component exists

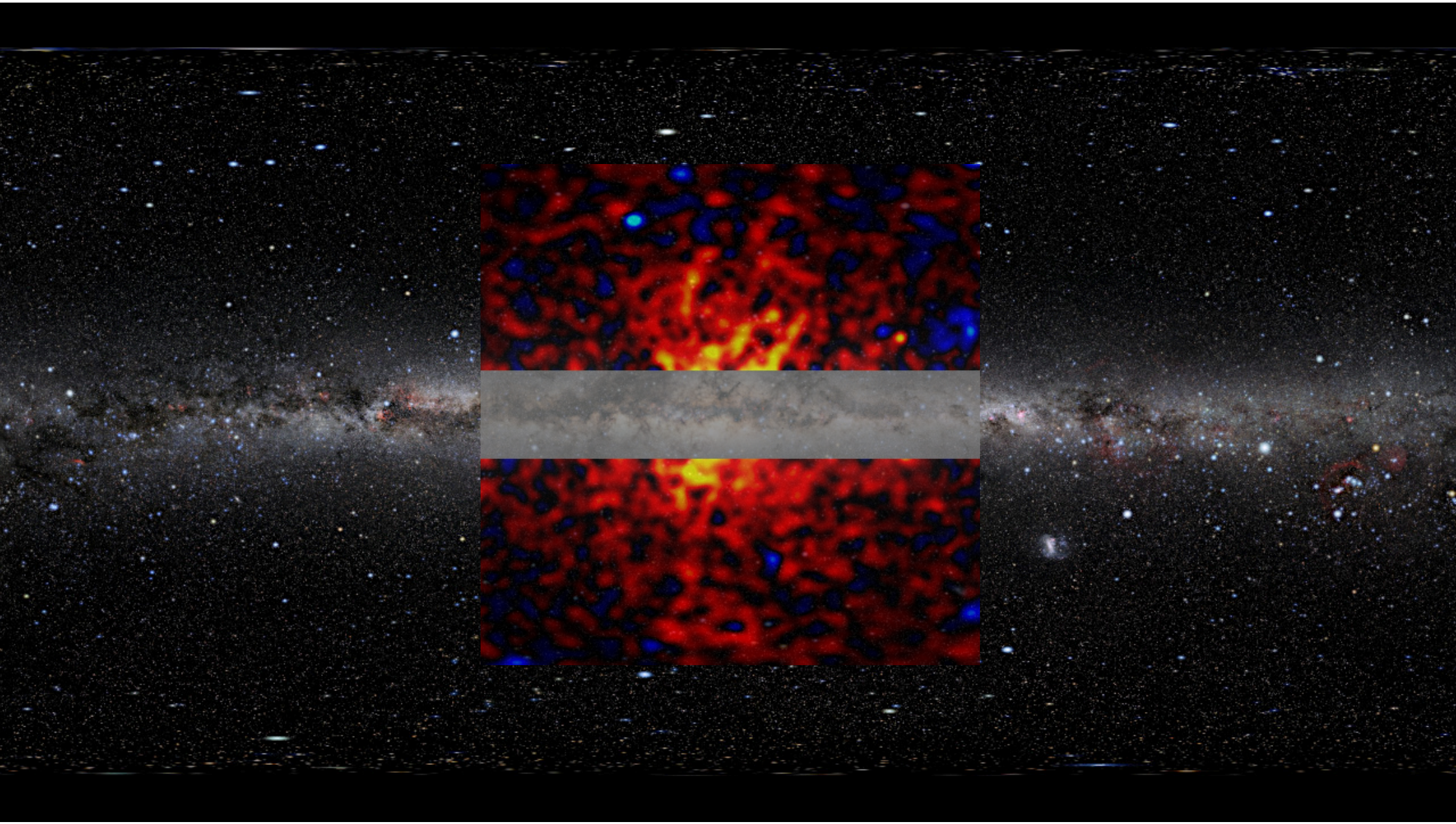
- the best-fit NFW-ρ^2 model + residual
  - the spherical halo-like excess clearly seen

- No significant residuals in the fit with NFW-ρ^2 model within the region of interest
  - The fit by “known components + the halo” is successful in describing the data



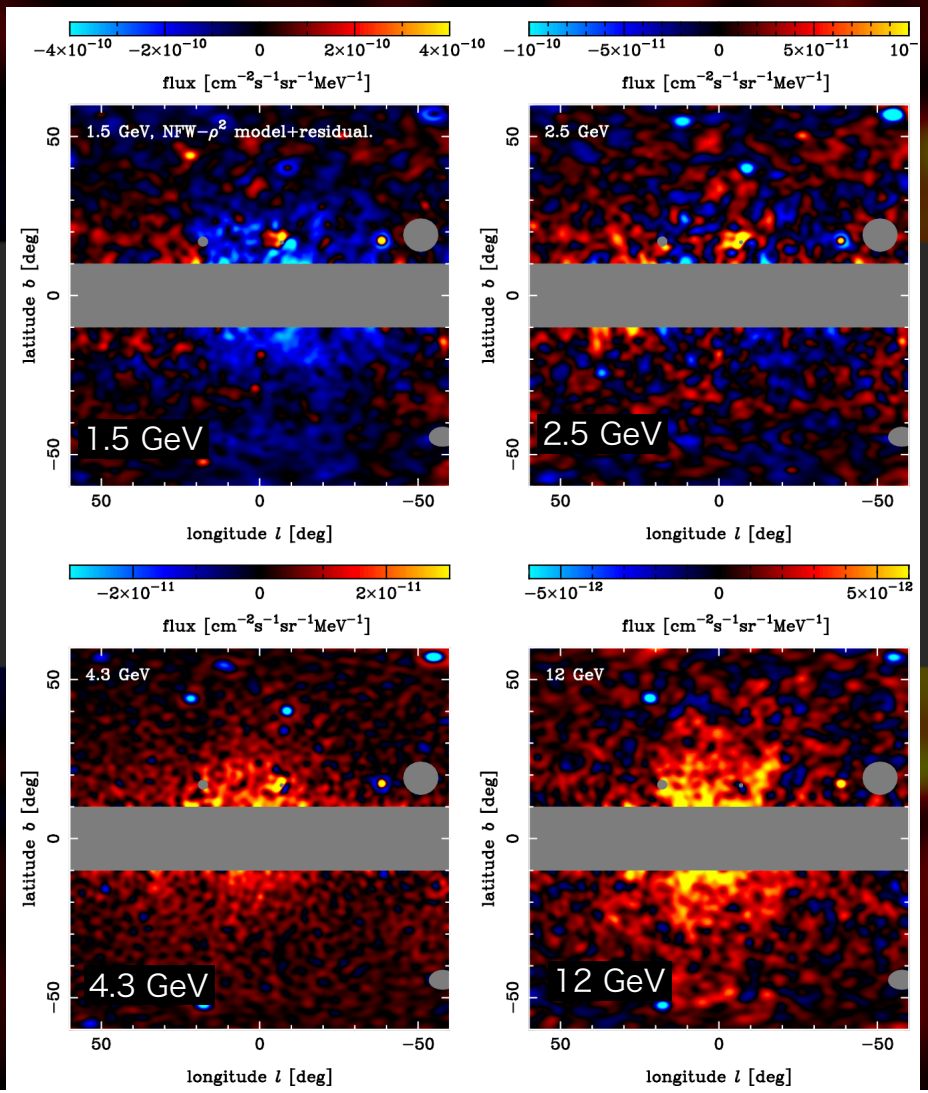

21 GeV, NFW−ρ^2 model+residual
50
0
−50
latitude b [deg]
50
0
−50
longitude l [deg]

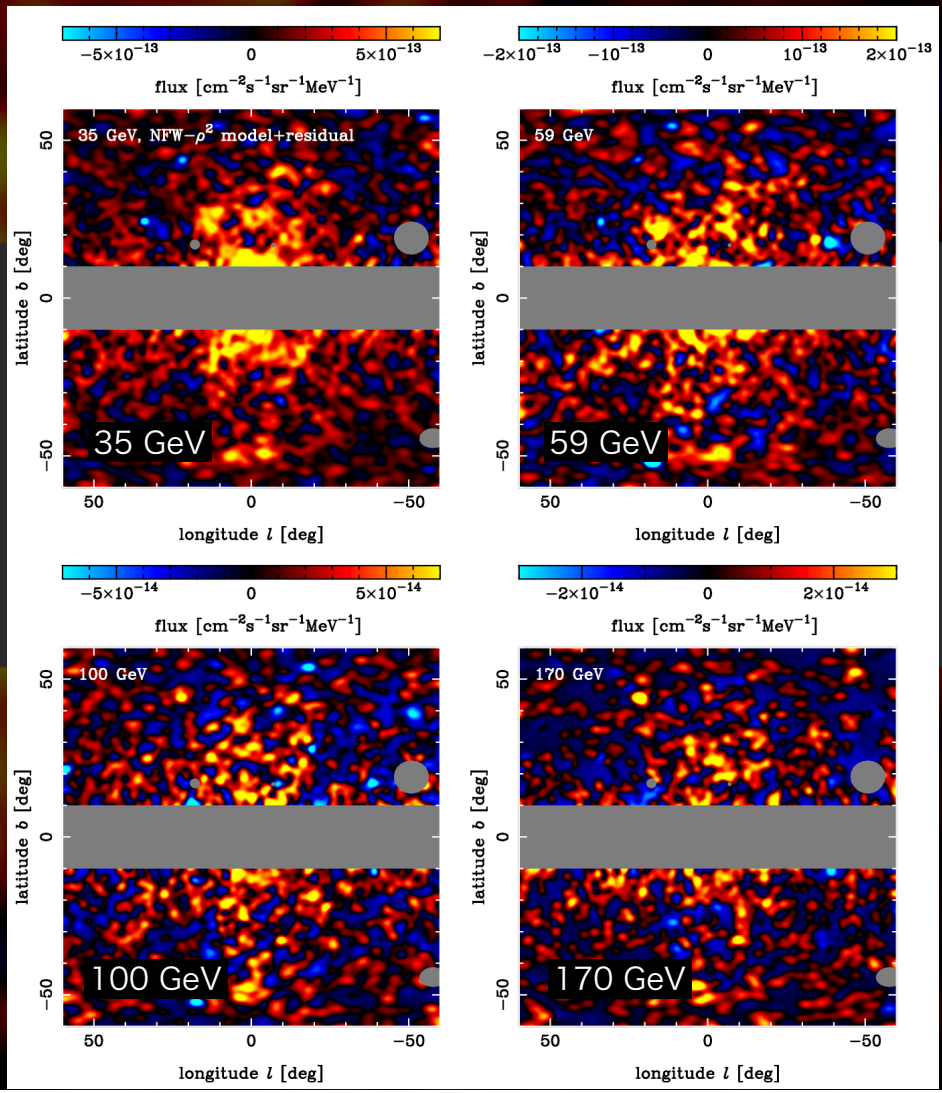




Morphologies of the halo excess

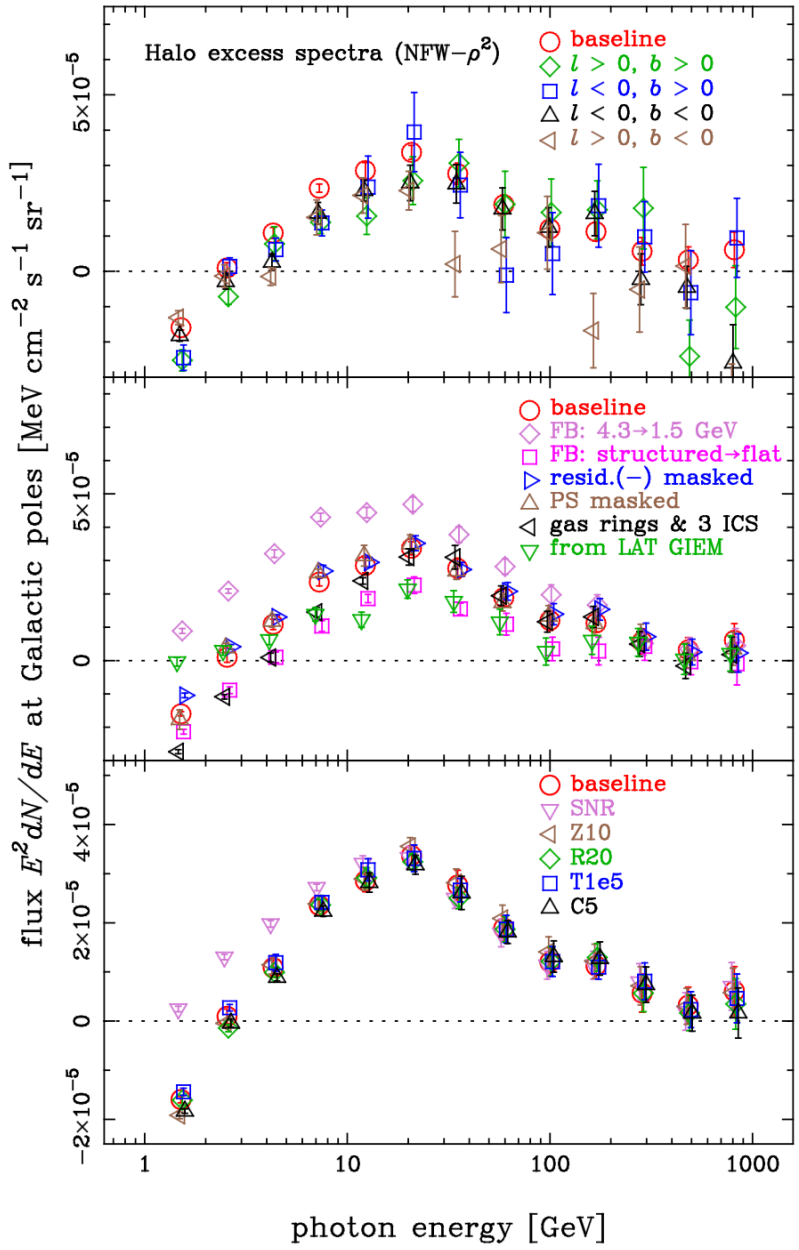
- halo excess (NFW-ρ^2 model + residual) in 8 energy bins other than 21 GeV





Examination of systematics

- divided into four quadrants around GC
- FB template modeling:
  - change the energy bin 4.3 → 1.5 GeV
  - structured → flat FB template
  - negative residual region masked
- halo excess against the LAT GIEM (Galactic interstellar emission model)
  - LAT standard background model recommended for point-source analyses
  - includes non-template patch adjusted to fit residuals
    - to erase FB, GC excess, Loop I, ⋯
  - the patch assumes a power-law spectrum above 3 GeV
    - 20 GeV halo excess may still remain
- changing GALPROP parameters

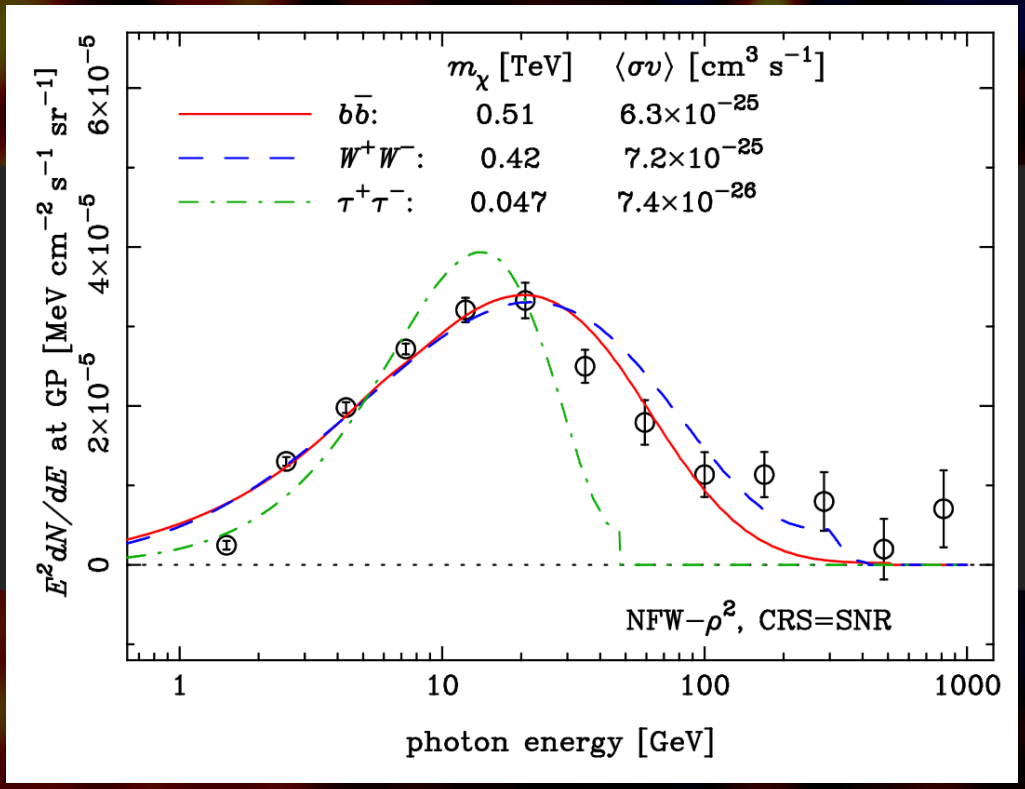


Interpretation by dark matter annihilation

- Annihilation gamma-ray spectrum (PPPC4DMID) is fit to the NFW-ρ^2 halo excess (smooth NFW)

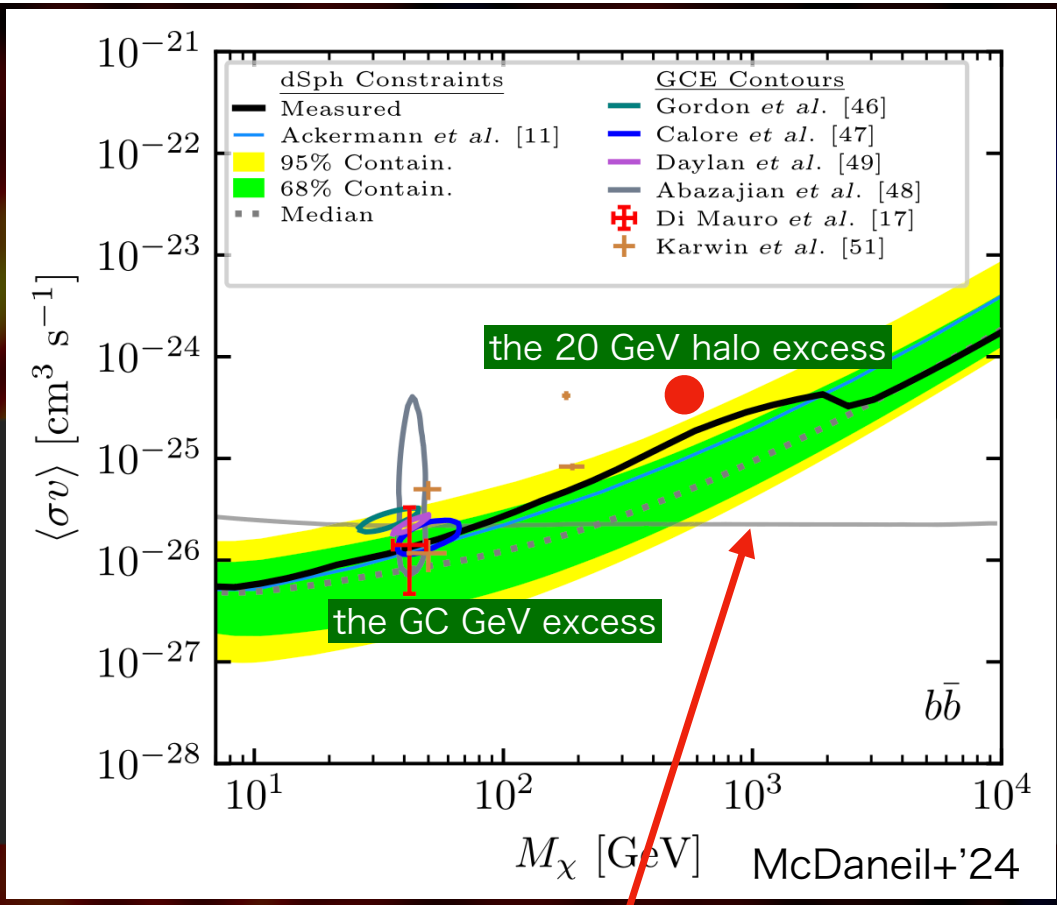
- The halo spectrum can be fit with the popular bb or W^+W^- channels
  - mass ~ 0.5 TeV
  - velocity-averaged cross section $\langle \sigma v \rangle$ ~ 6×10^{-25} cm^3/s

- The $\tau^+\tau^-$ channel fits worse



Discussion on WIMP parameters

- $\langle \sigma v \rangle$ from the halo excess is a factor of 2-3 larger than the upper limits from dwarf galaxies
  - A tension, but not immediate discrepancy:
    - a large uncertainty in MW DM density profile
    - uncertainty also in dSph analysis
  - A similar level of tension exists for the GC GeV excess
  - gamma-ray excess (2-3 σ) reported from some dwarf galaxies!
    - e.g. Reticulum II favors the same WIMP mass as the MW halo excess!



- Comparison with theoretical expectation?
  - $\langle \sigma v \rangle$ from the halo excess is more than 10 times larger than the canonical thermal relic value
  - many possibilities of σ enhancement in particle physics theory, e.g. the Sommerfeld correction
  - uncertainty in MW DM density profile

canonical thermal relic cross section

$$\langle \sigma_{\rm ann} v \rangle_f \approx 3 \times 10^{-26}\ {\rm cm}^3\ {\rm s}^{-1}$$

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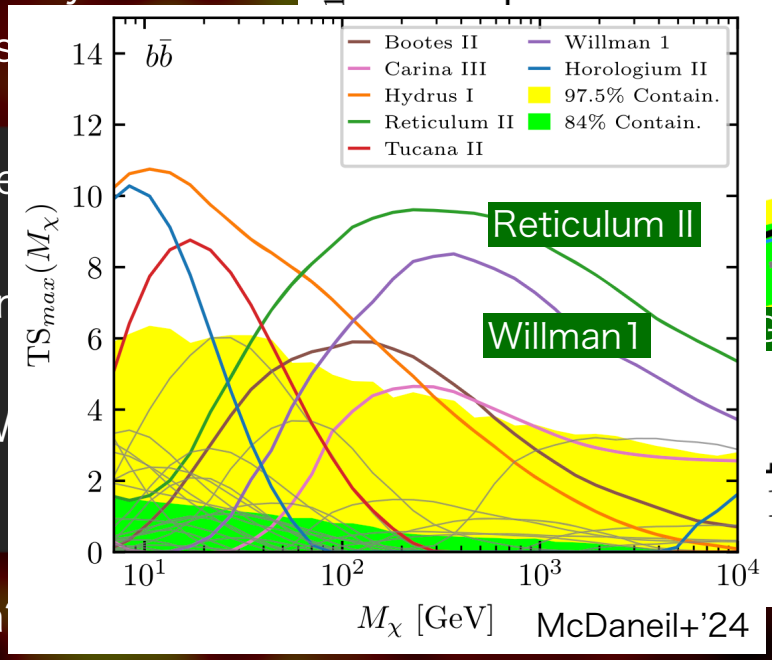

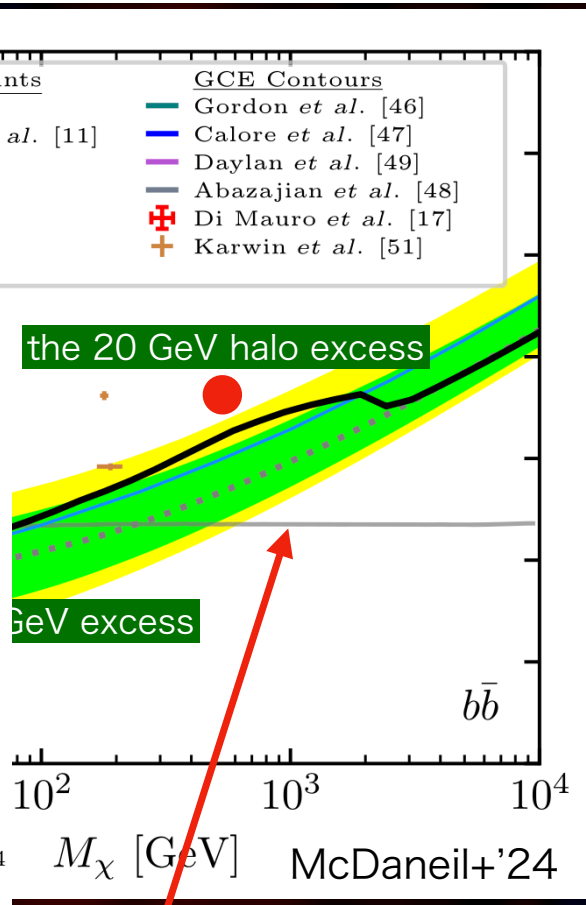

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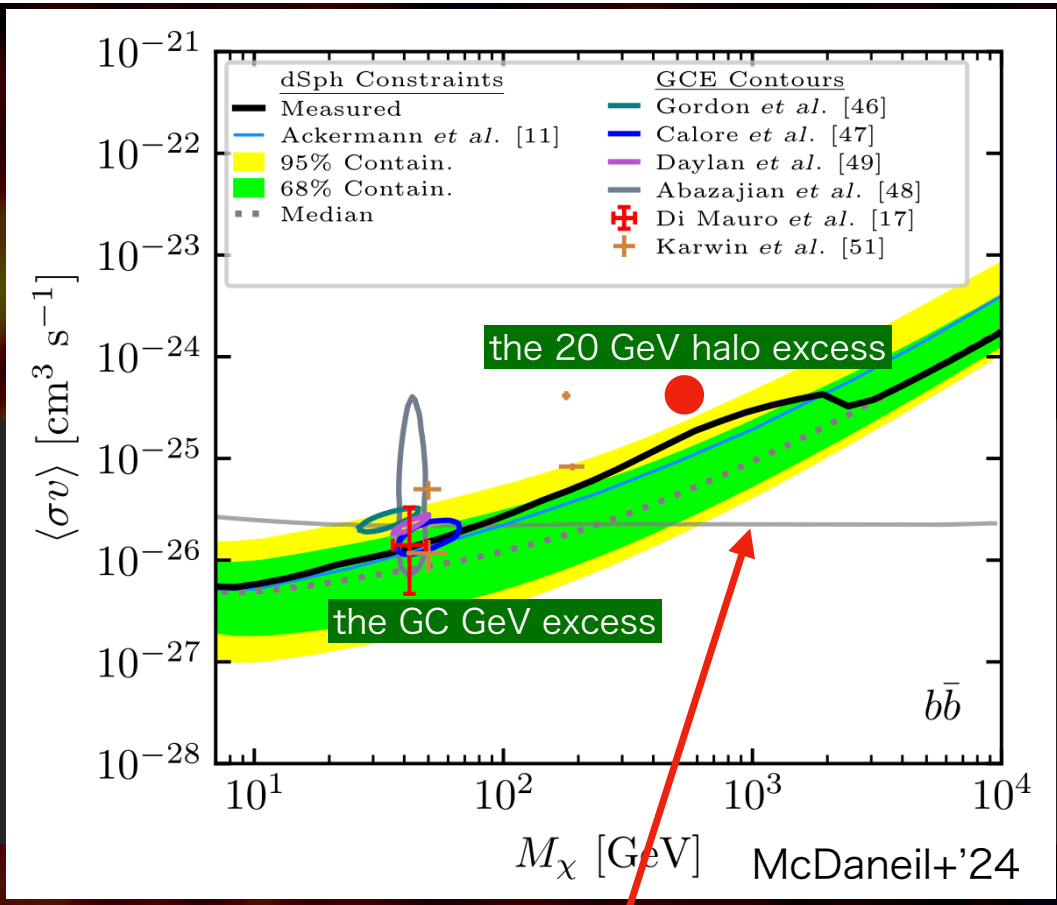

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Conclusions

- DM annihilation gamma-rays were searched towards the MW halo region (excluding disk), using Fermi-LAT 15-yr data
- Statistically significant (>10σ at a few energy bins) halo-like excess is found around 20 GeV
- Radial angular profile matches the annihilation with the NFW profile
- Map morphology of the halo excess is consistent with a spherical halo-like emission
- DM annihilation spectrum by the popular bb or W^+W^- channels is in agreement with the halo-excess
  - DM mass ~ 0.5 TeV, $\langle \sigma v \rangle \sim 6 \times 10^{-25}$ cm^3/s
- Tension with the dwarf galaxy constraints and the canonical thermal relic cross section, but the DM interpretation is viable, considering various uncertainties (e.g., MW halo density profile)
- Future verification is possible, especially by dwarf spheroidal galaxy observations