

A Cosmic Microwave Background (CMB) fluctuation map showing temperature variations across the sky. The map is a complex pattern of red, orange, yellow, and blue spots, representing different temperature fluctuations. The background is a dark, mottled red and blue.

The 20 GeV Fermi halo: Evidence for dark matter annihilation?

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戸谷 友則 TOTANI, Tomonori
Dept. Astronomy, Univ. of Tokyo

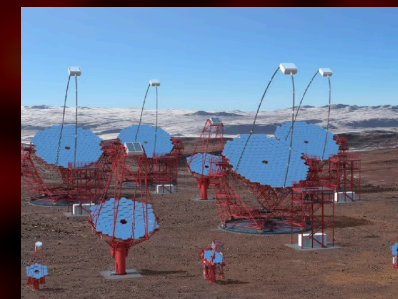
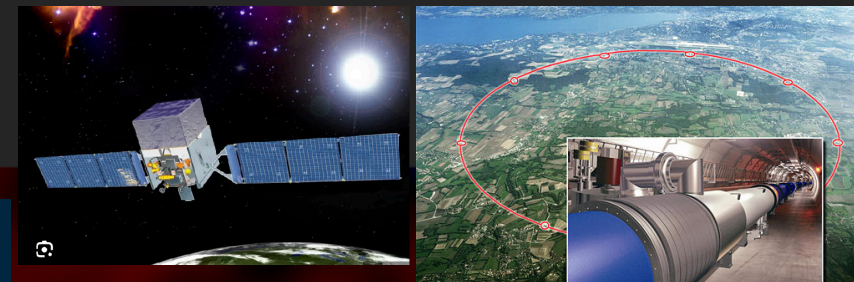
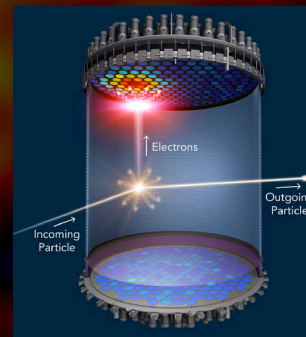
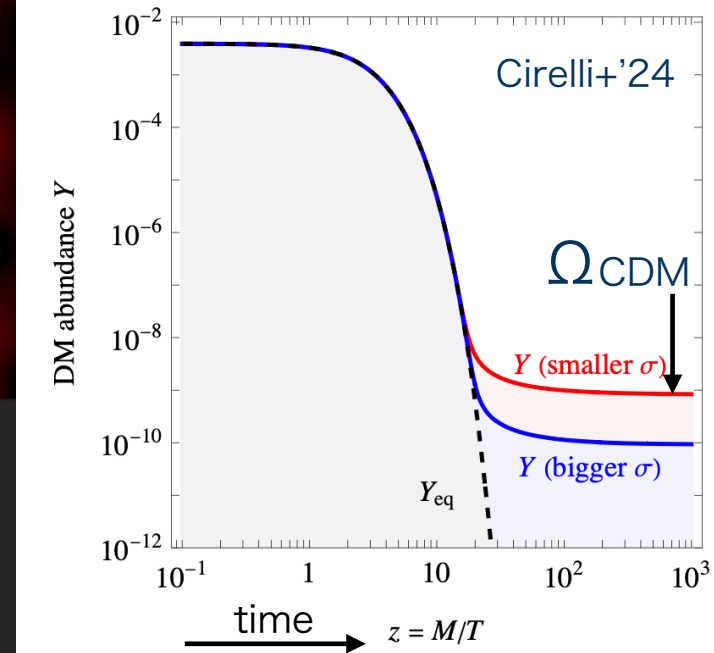
The 16th Particle Physics Phenomenology Workshop
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National Tsing Hua University (NTHU), Taiwan

WIMP as the dark matter

- WIMPs: weakly interacting massive particles
 - mass range 1 GeV - 100 TeV (the electroweak scale)
 - thermal relic from the early universe
 - annihilation cross section to match the observed dark matter density:

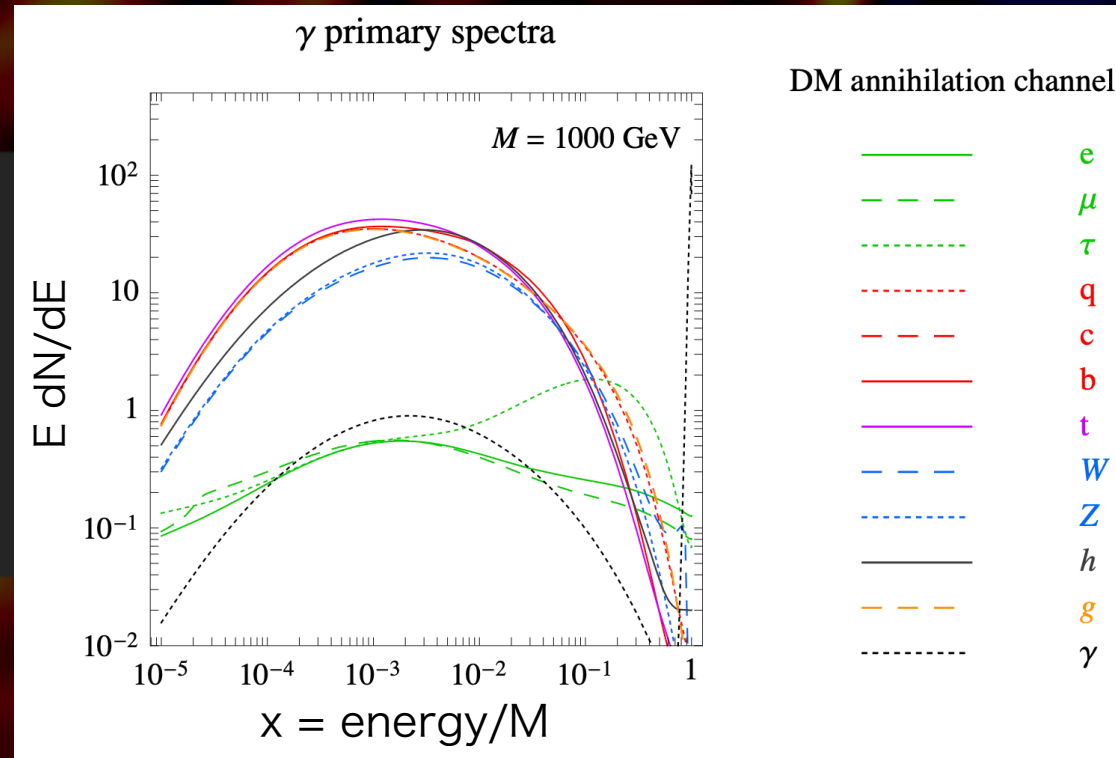
$$\langle \sigma_{\text{ann}} v \rangle_f \approx 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$$

- This is close to the expected cross section for WIMPs around the electroweak scale (the WIMP miracle)
- many well-motivated theoretical candidates (e.g. supersymmetry)
- one of the most popular DM candidates
- can be searched for by:
 - direct detection (underground experiments)
 - indirect detection (annihilation gamma-rays, neutrinos, ...)
 - particle accelerator experiments



Annihilation gamma-rays from WIMPs

- line (monoenergetic) gamma-rays near the WIMP mass energy
 - $\chi\chi \rightarrow \gamma\gamma$ or γZ
 - The branching ratio is likely small and uncertain
- continuum gamma-ray emission
 - cascade from standard particle pairs like bb , W^+W^- , ...
 - produce continuum gamma rays
 - spectral peak typically $\sim 1/10$ of the WIMP mass (in terms of $E^2 dN/dE$)
 - not power-law, unlike many astrophysical sources
 - The branching ratio can be \sim unity
- gamma-ray flux expected by the thermal relic cross section is close to the sensitivity of gamma-ray telescopes
- Many searches done for various targets:
 - Galactic center, dwarf galaxies, galaxy clusters, extragalactic background ...



Cirelli+ '24

Annihilation gamma-rays from Milky-Way halo?

- Our Galaxy (MW) halo (avoiding the very Galactic center, GC) is a good target

- avoiding strong astrophysical flux from GC and disk
- still relatively strong dark matter signal expected

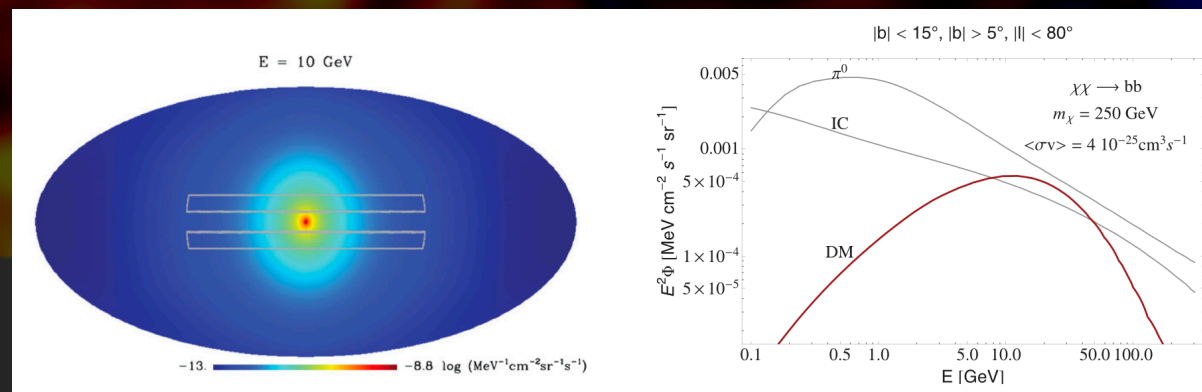
- Not so many papers on MW halo, compared with GC or dwarf galaxies

- Fermi-LAT team's search (Ackermann+'12) using 2-yr Fermi-LAT data

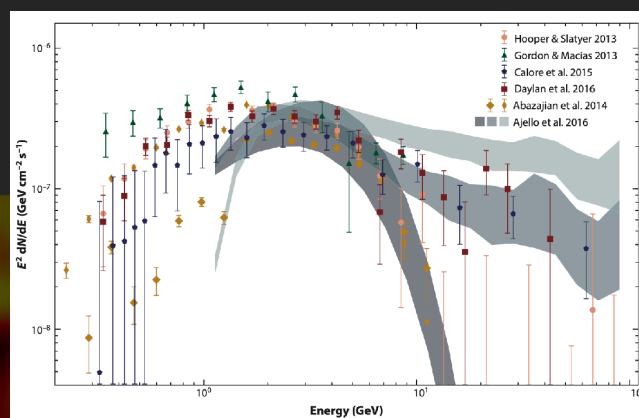
- Possible reasons:

- GeV GC excess peaking at around 2 GeV
 - possibly DM annihilation
 - $\rho \propto r^{-1.25}$, steeper than NFW
 - another strong candidate: milli-second pulsars
- Diffuse structures on the halo scale known
 - Loop I
 - Fermi bubbles

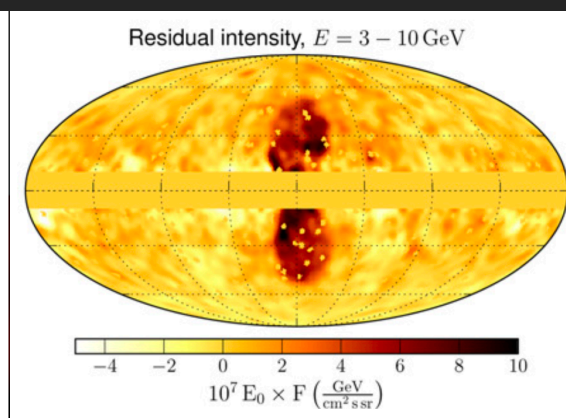
- This work: a new search in the MW halo (without GC/disk) using 15-yr LAT data, with modelings of known diffuse components



halo DM search by Fermi-LAT '12



GC excess spectrum (Murgia+'20)

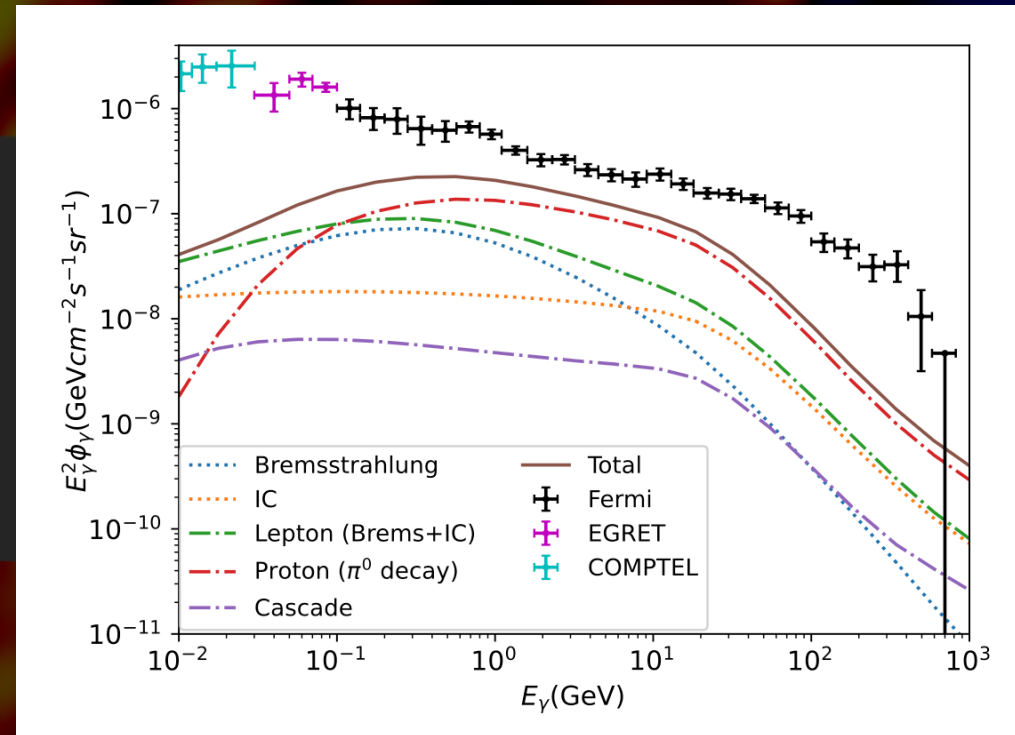


Fermi bubbles (Ackermann+'14)

Why I started this study?

- Why dark matter search now, after so many papers on DM search using Fermi data?
 - My background: theoretical modeling of extragalactic gamma-ray background from AGNs, star-forming galaxies, ...
 - Special thanks to Tsunefumi Mizuno for a lot of advice about Fermi data analysis

Extragalactic gamma-ray background from star-forming galaxies

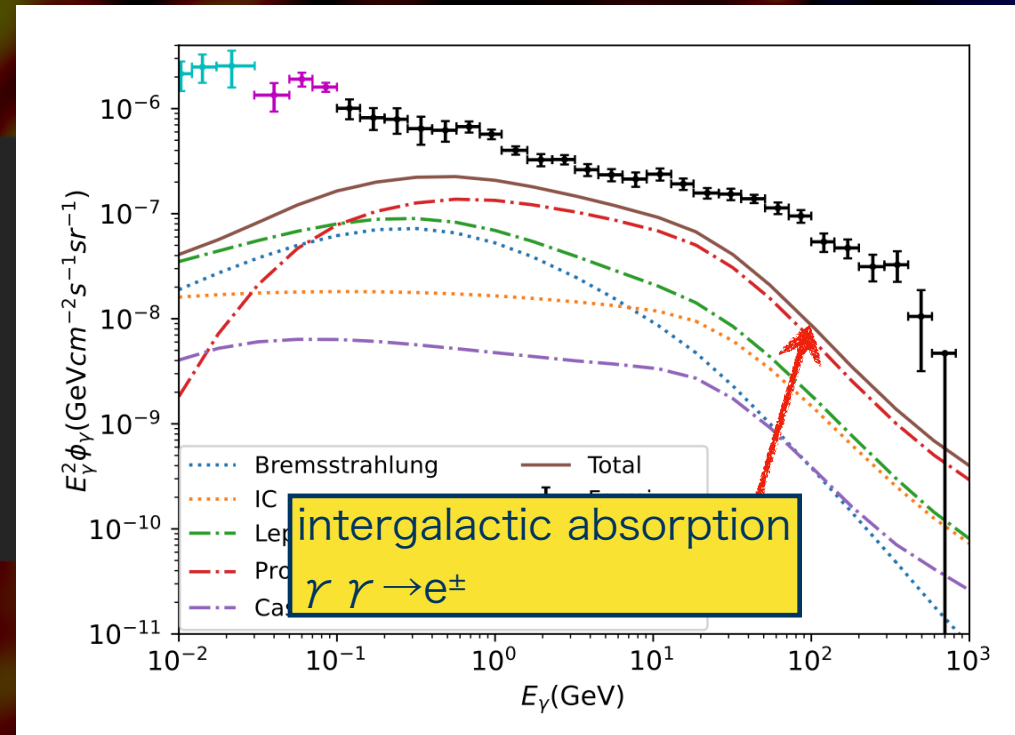


Chen+TT '25

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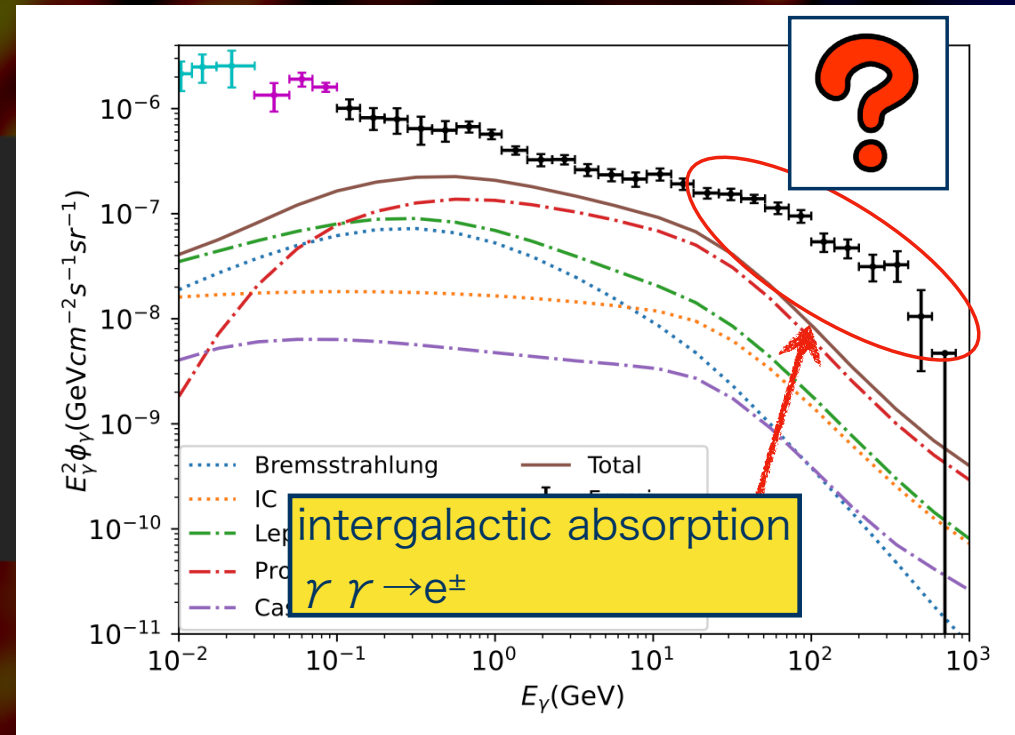


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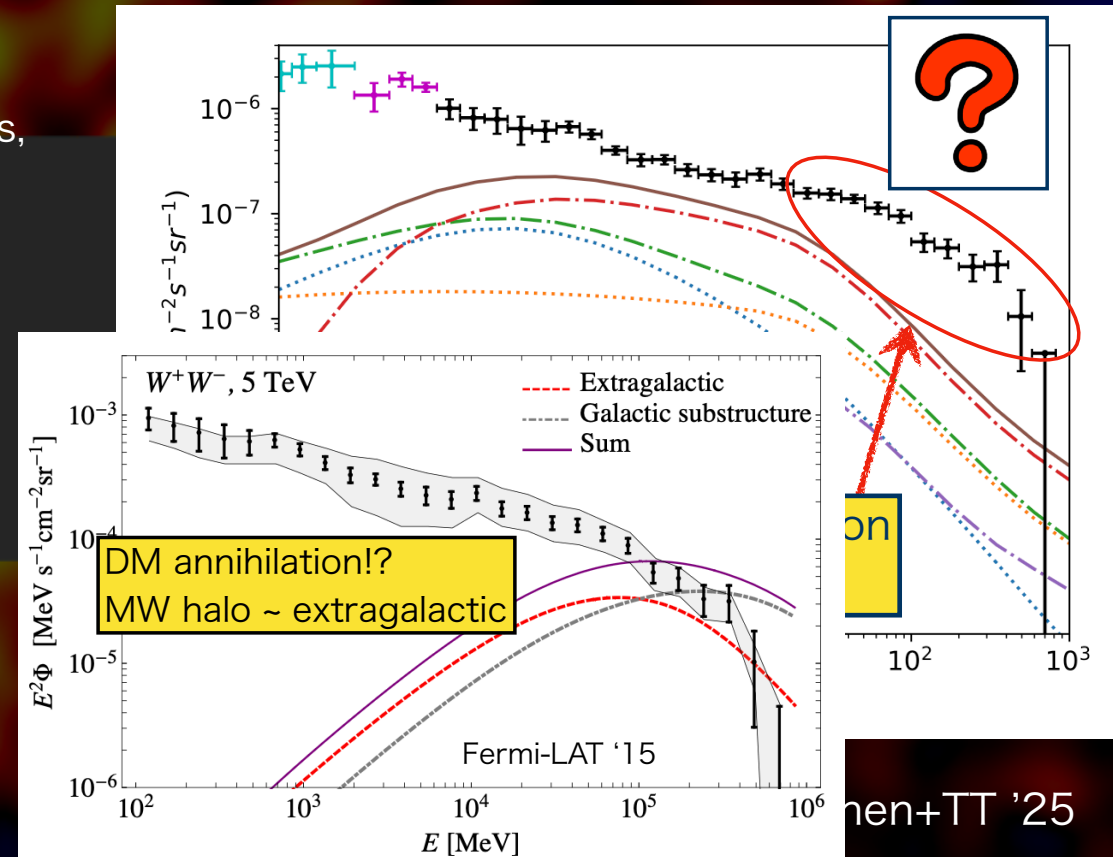


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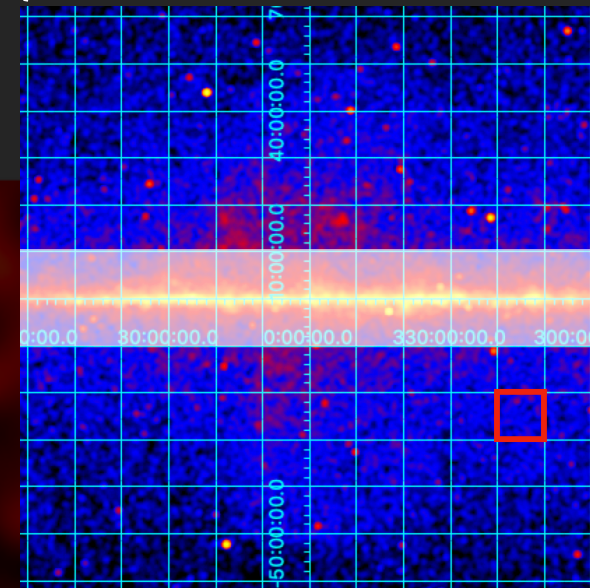
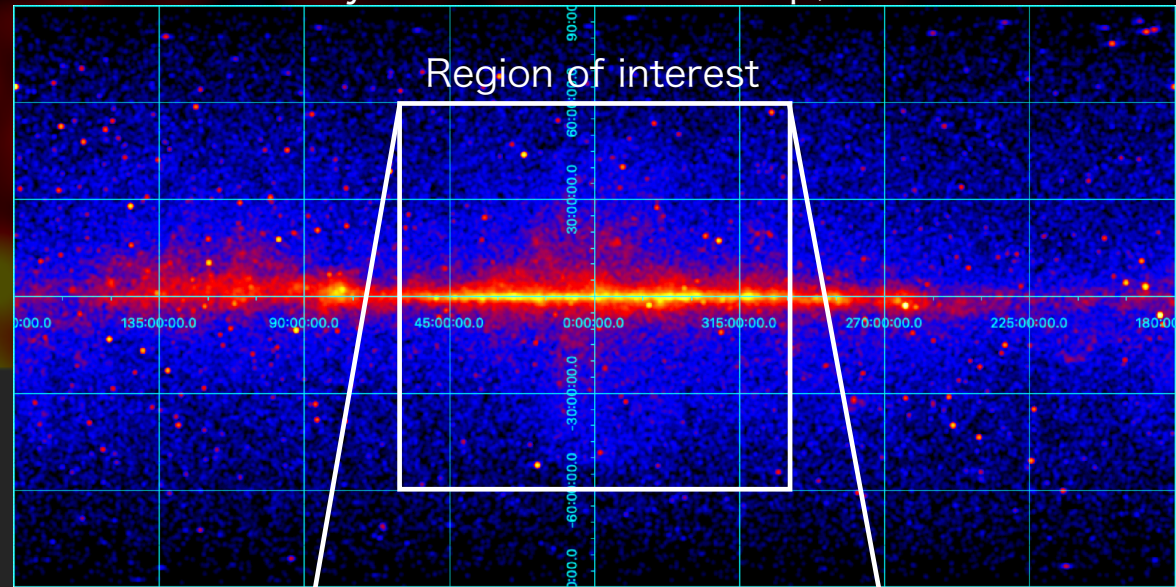
Extragalactic gamma-ray background from star-forming galaxies



The Fermi data and analysis

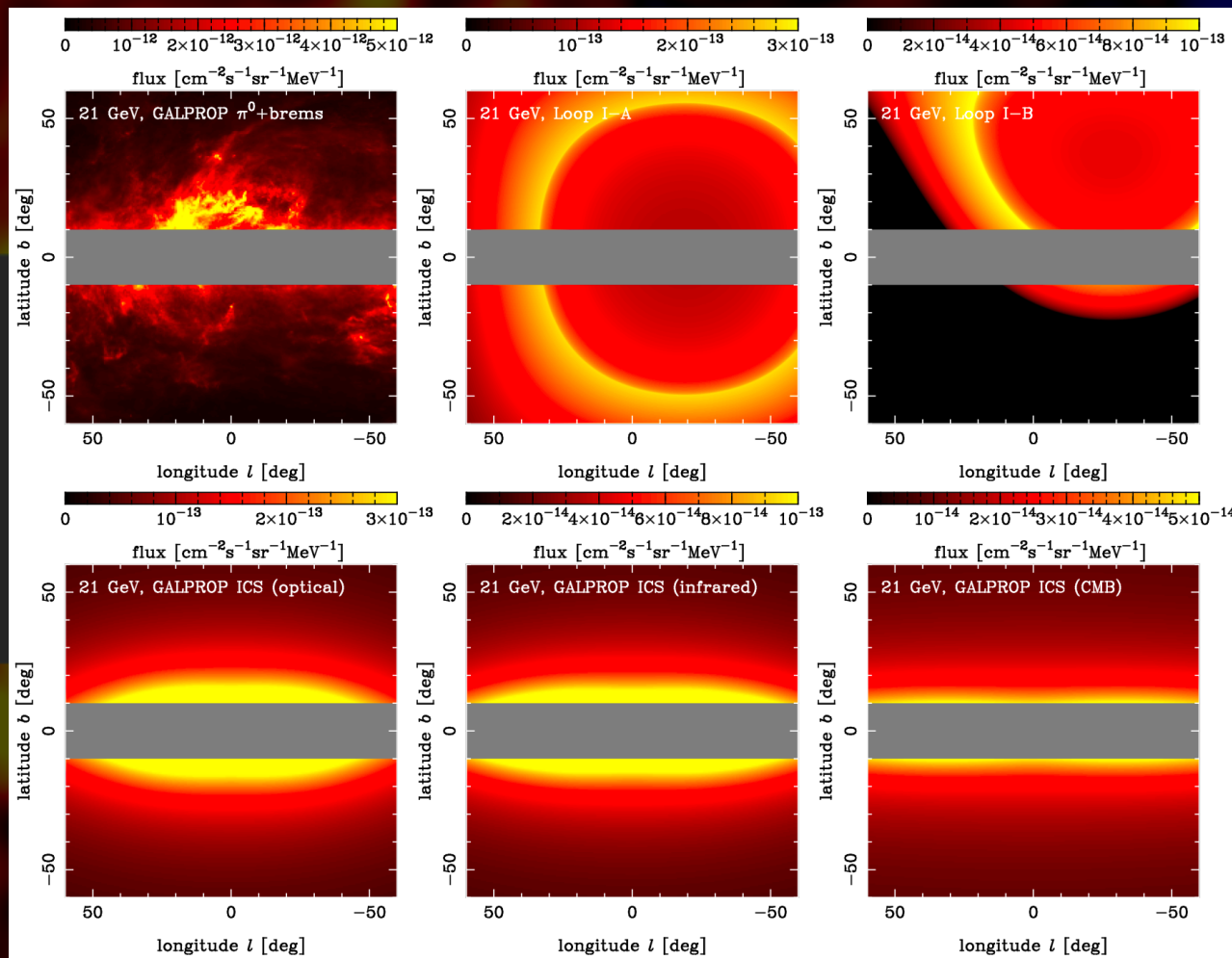
- The public Fermi data used:
 - 15-yr (2008-2023), Pass 8 UltraClean
 - zenith angle cut $\theta < 100$ deg
 - 1.5-810 GeV, 19 bin (log-spaced)
 - Cartesian coordinates
 - pixel scale: 0.125 deg
- Region of interest (ROI)
 - longitude: $|l| < 60$ deg
 - latitude: $10 < |b| < 60$ deg
- Likelihood calculation:
 - 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

all-sky smoothed count map, 21 GeV



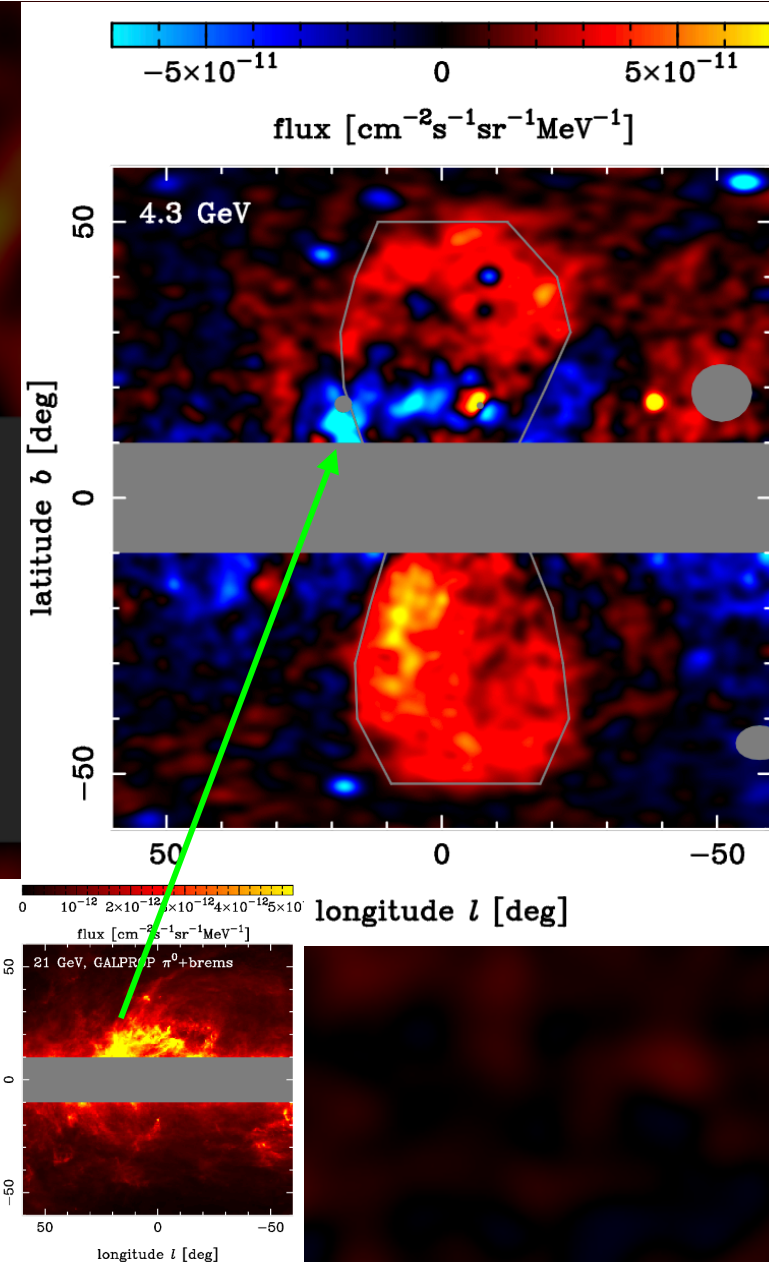
Model map templates

- 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



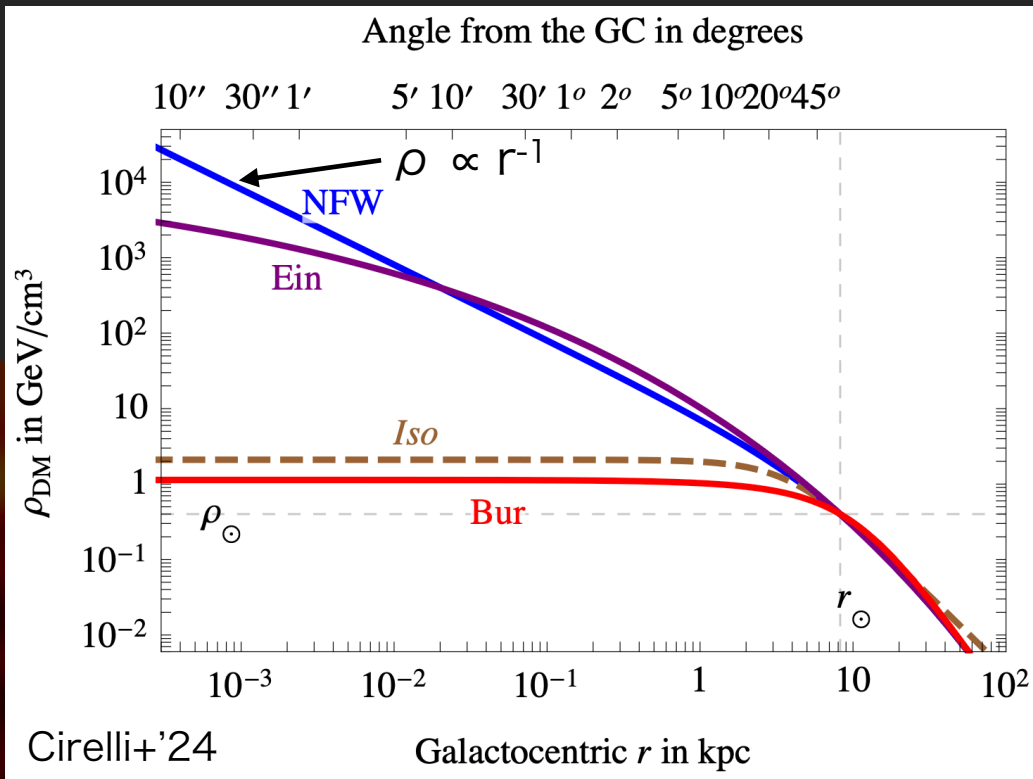
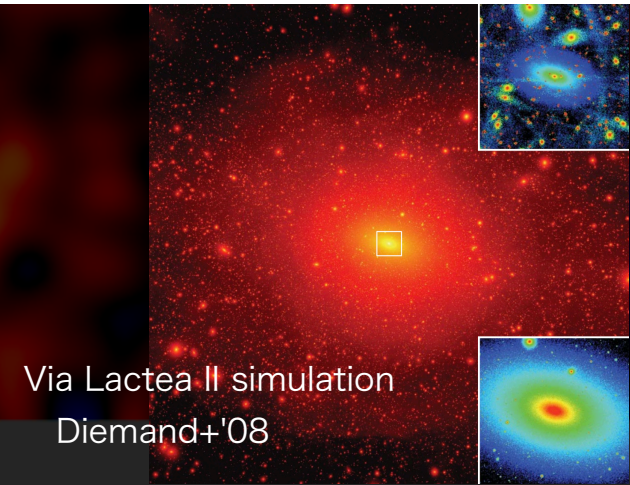
Model map templates: Fermi bubbles

- 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



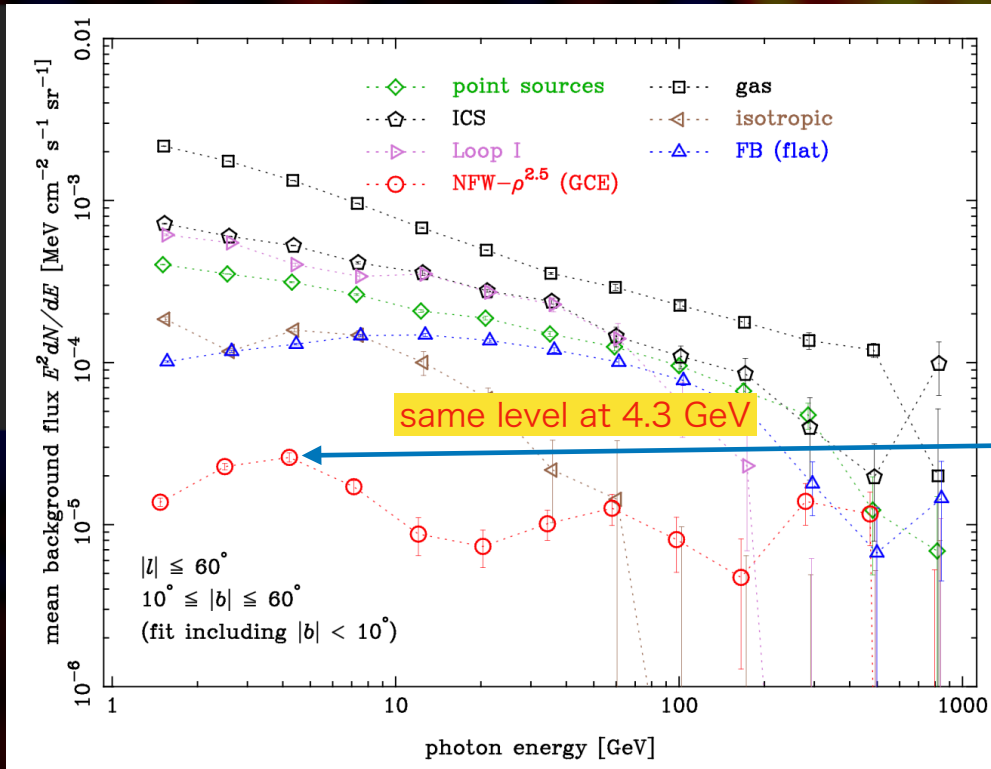
Model map templates: DM halo of MW

- the NFW profile assumed
 - parameters from the Via Lactea II simulation (Kuhlen+'08)
- volumetric gamma-ray emissivity ϵ_γ
 - NFW- ρ^2 : $\epsilon_\gamma \propto \rho^2$
 - annihilation with smooth density profile
 - NFW- ρ^1 : $\epsilon_\gamma \propto \rho^1$
 - sub-structure/subhalo dominant annihilation
 - decaying DM rather than annihilation
 - NFW- $\rho^{2.5}$: $\epsilon_\gamma \propto \rho^{2.5}$
 - GC GeV excess
 - $\rho \propto r^{-1.25}$ favored from GC analysis
 - same emissivity profile as NFW with $\epsilon_\gamma \propto \rho^{2.5}$

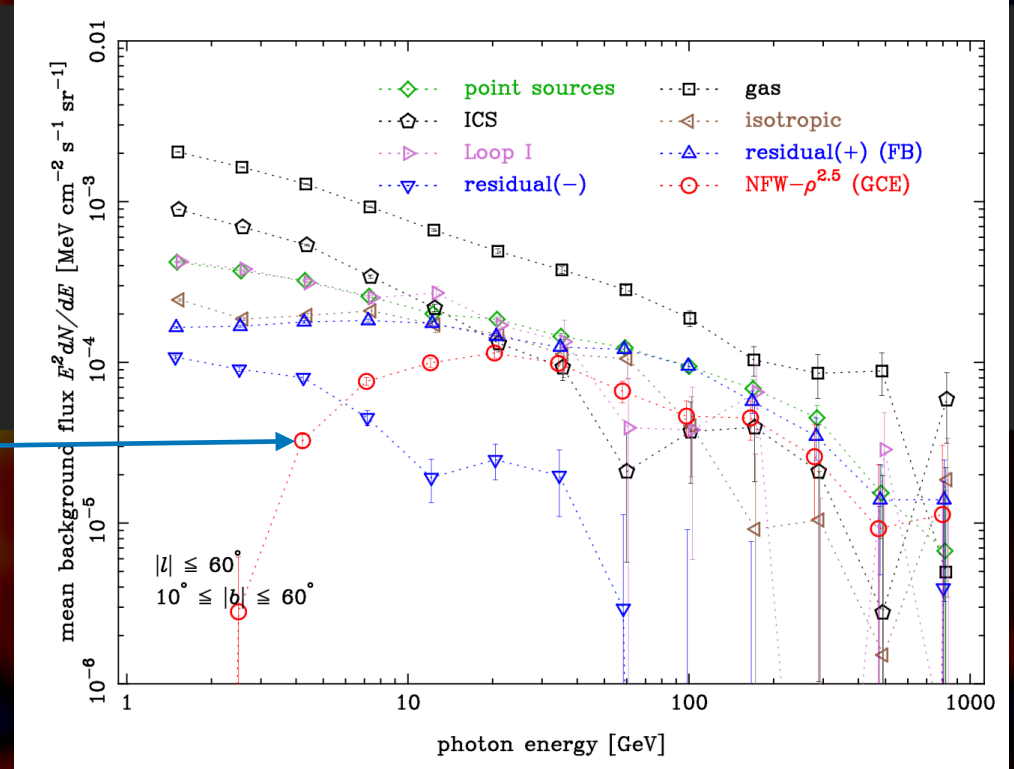


Fit by known components + GC GeV excess

- 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



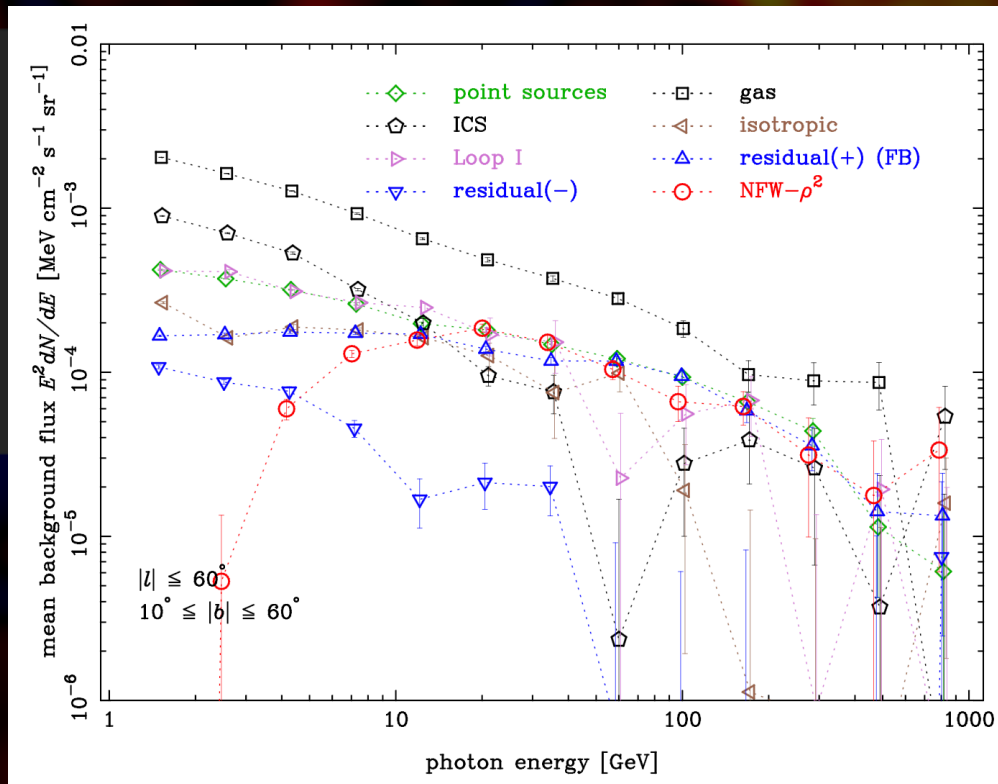
fit including the disk



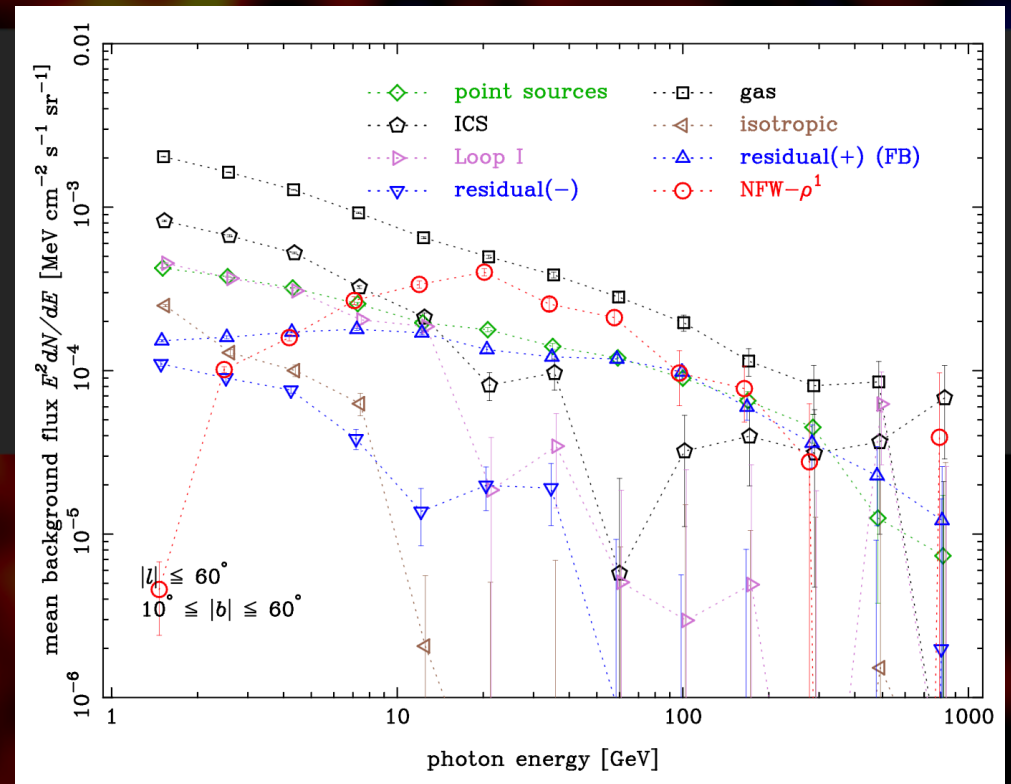
fit excluding the disk ($|b| < 10$ deg)

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



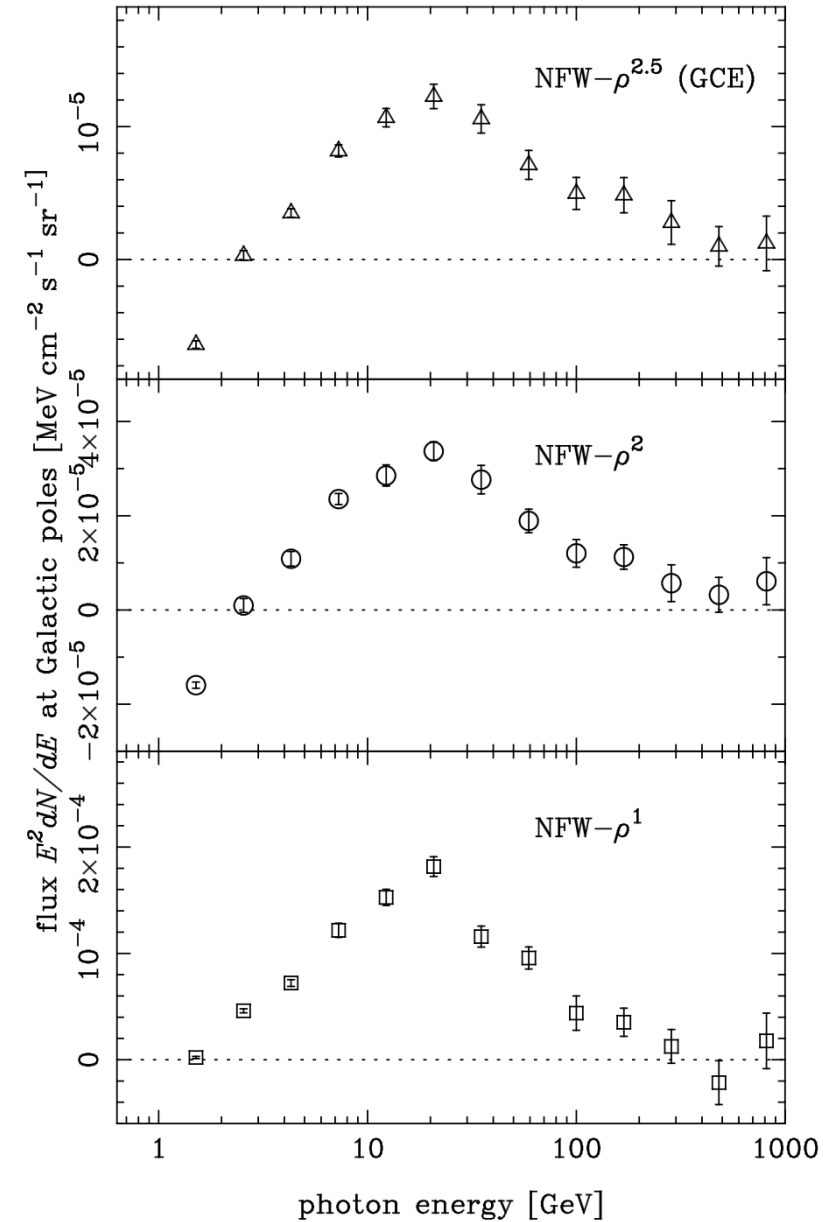
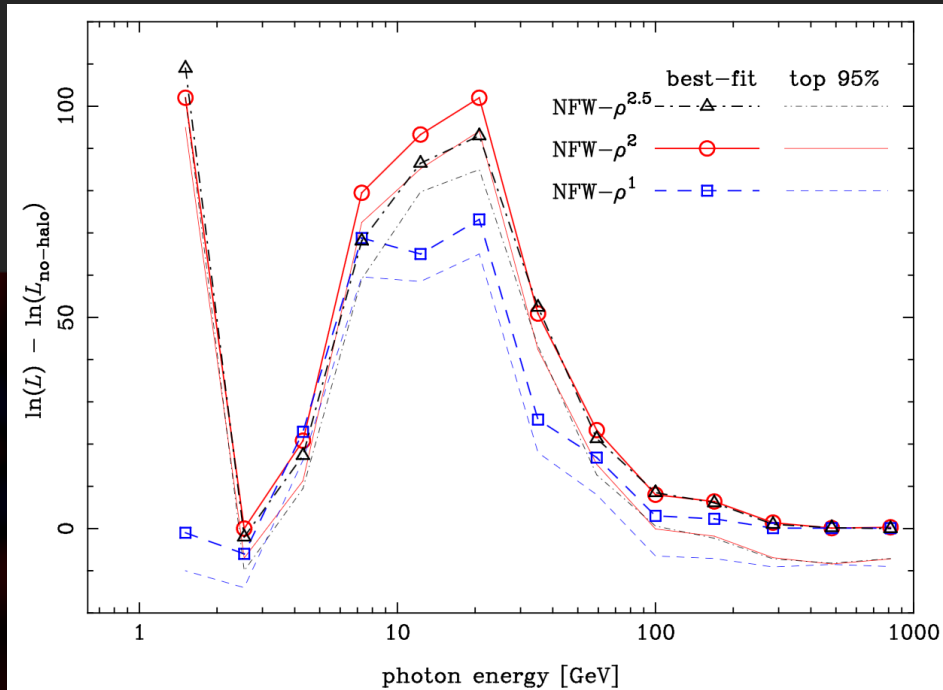
fit with NFW- ρ^2



fit with NFW- ρ^1

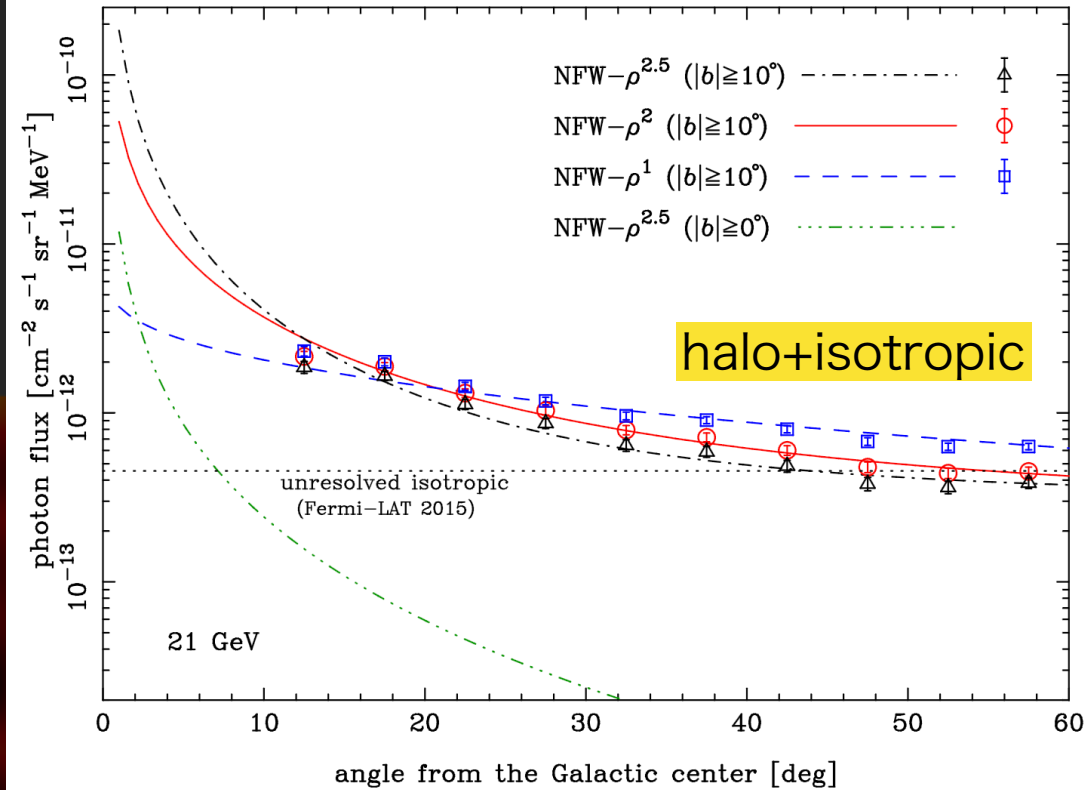
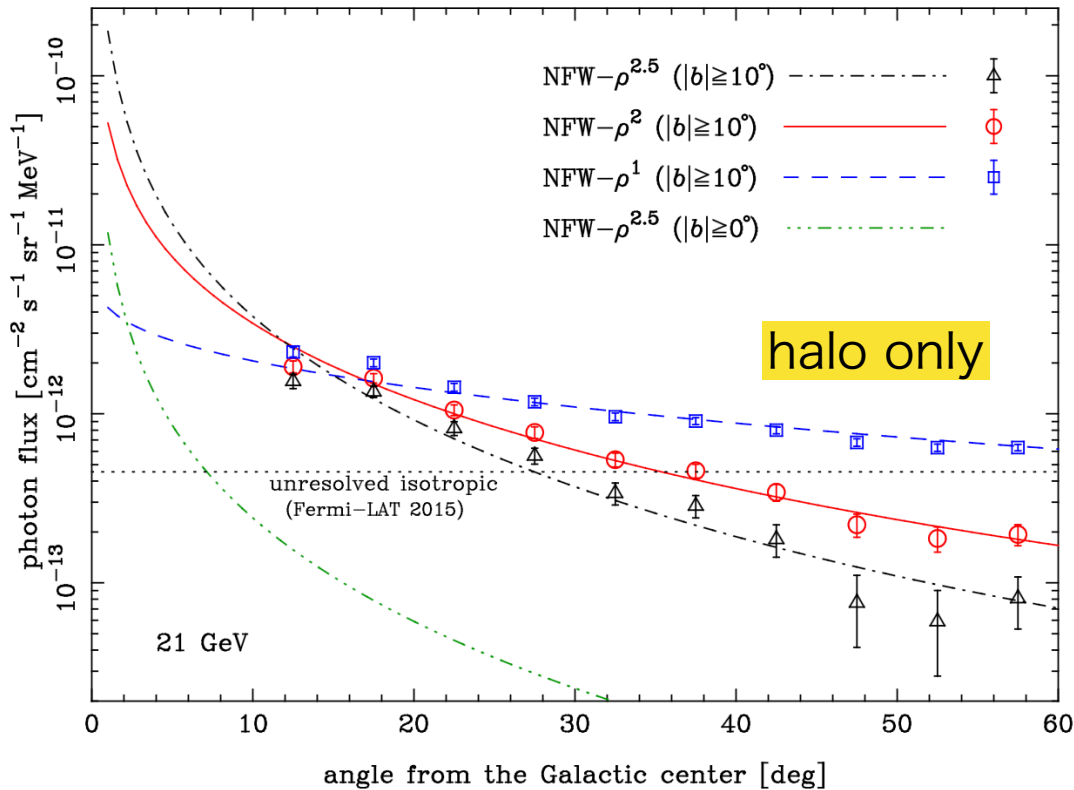
The halo excess spectra & likelihood

- 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 around 20 GeV
 - likelihood “dip” at 3 GeV because best-fit halo flux is zero



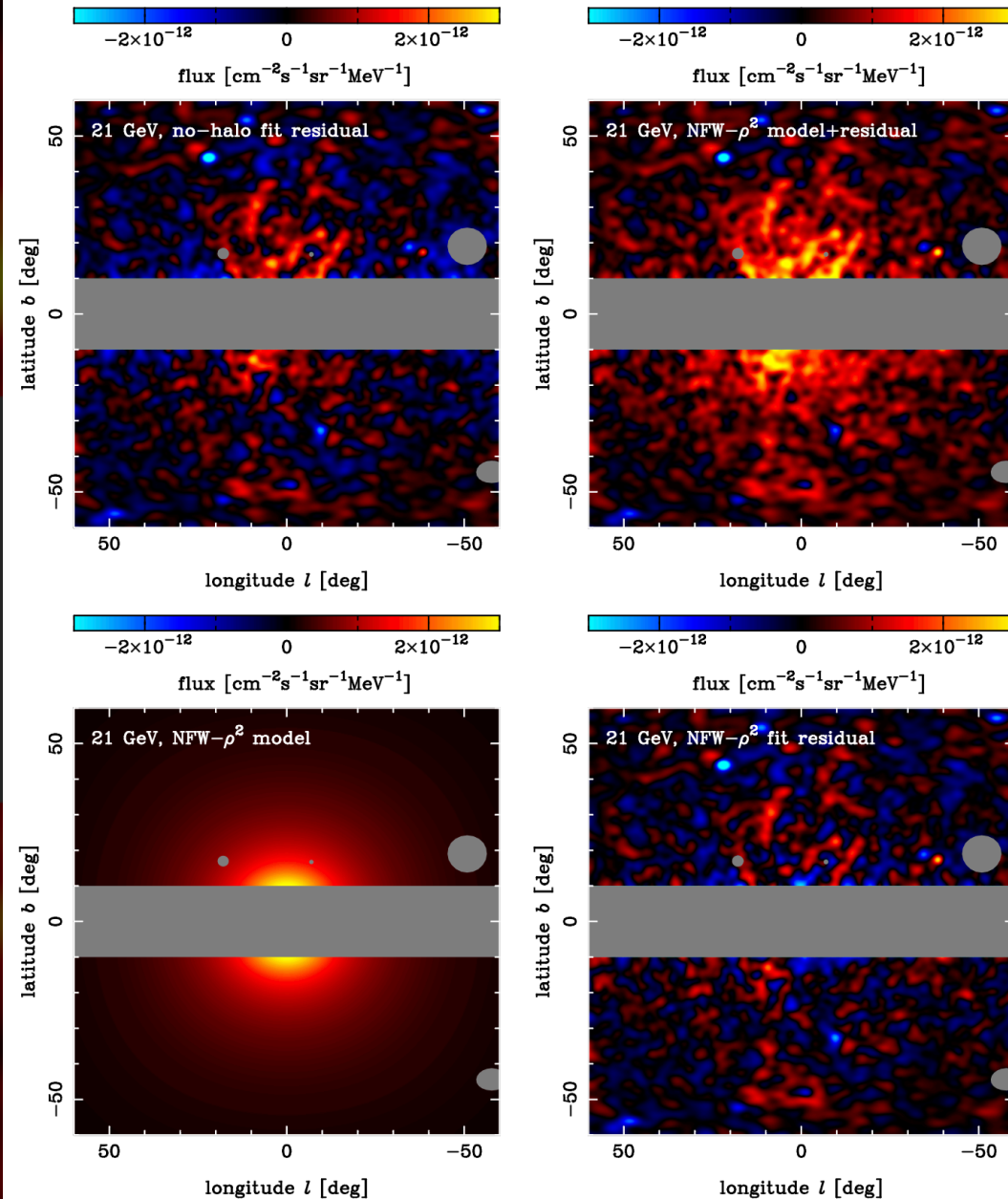
Radial angular profiles at 21 GeV

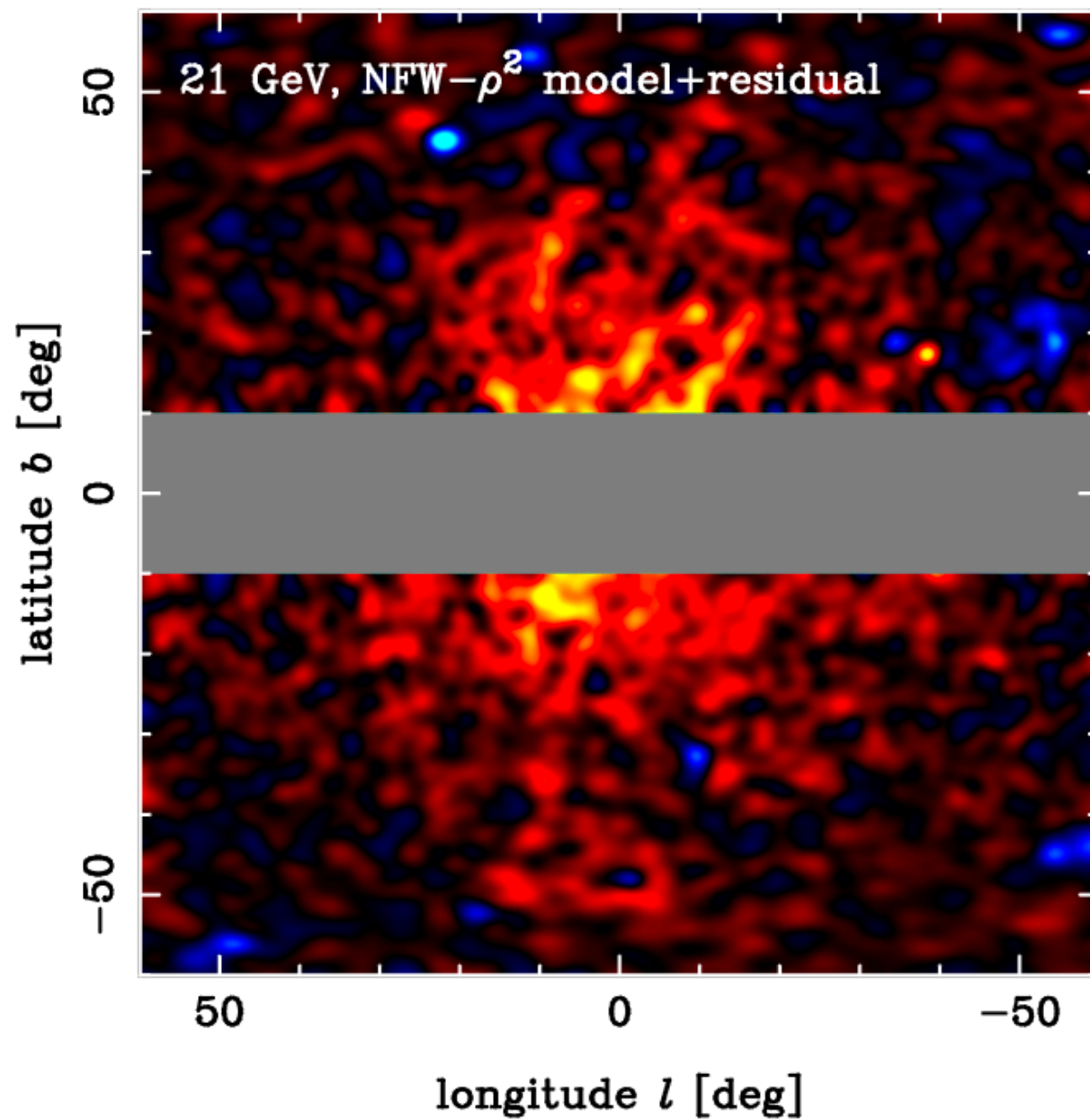
- curves: best-fit halo model data points: halo model + fit residual
- data points differ among the three halo models
 - degeneracy with the isotropic background (around the halo tail)
 - the isotropic flux of the NFW- ρ^2 fit is consistent with that reported by Fermi-LAT team
 - no room for isotropic in the fit of NFW- ρ^1 : disfavored, independently from likelihood

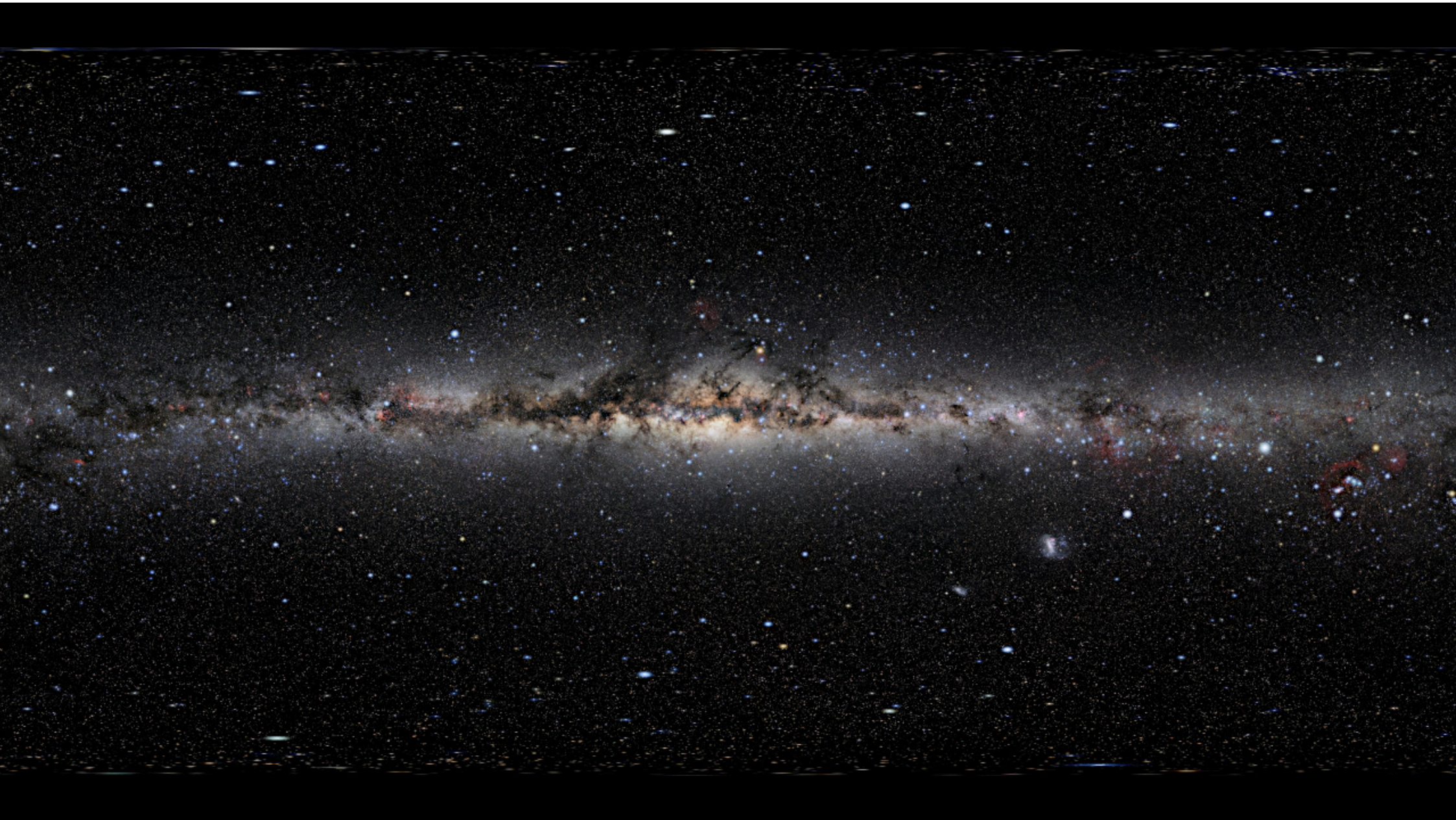


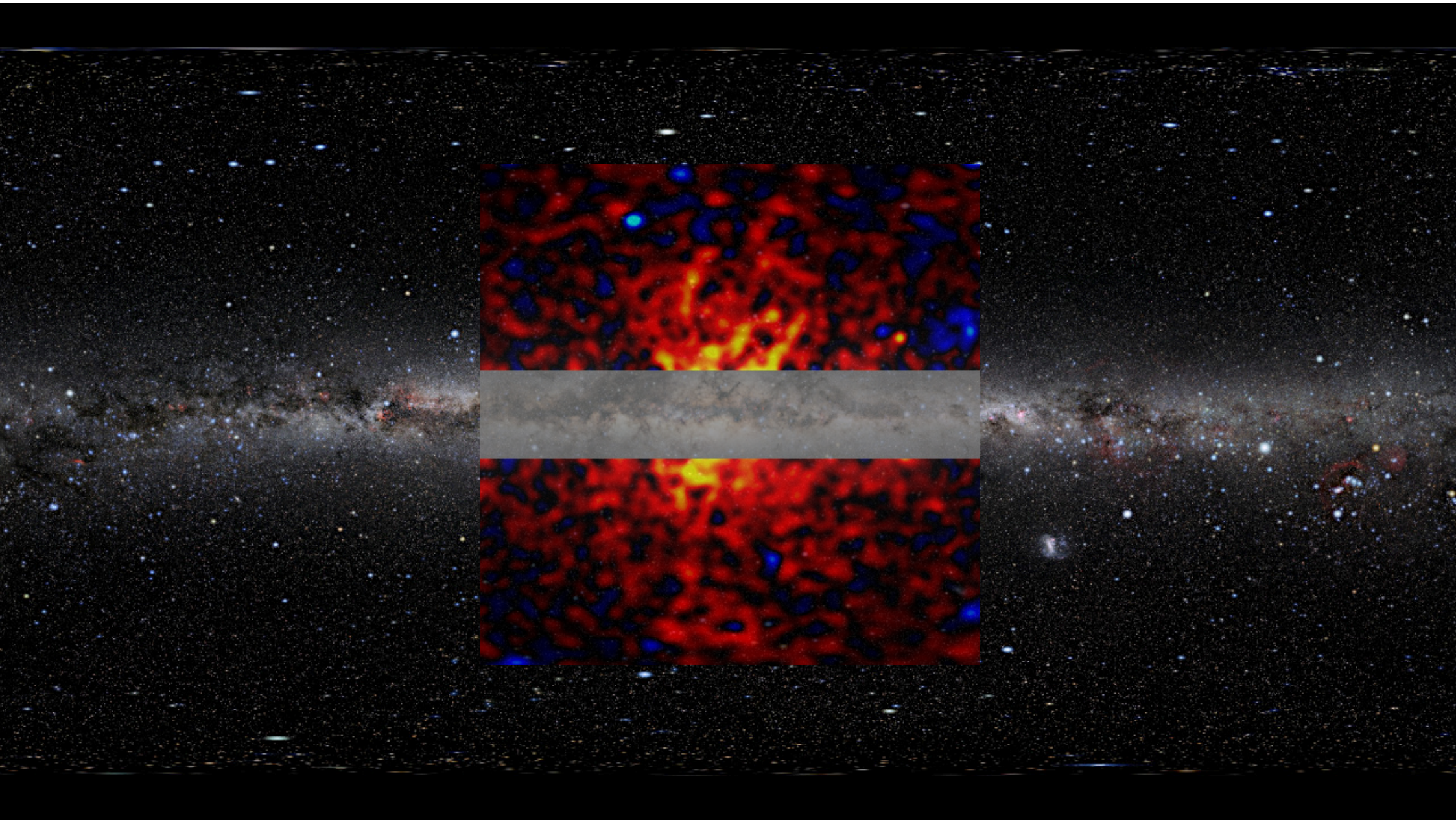
Morphologies of the halo excess at 21 GeV bin

- residual of no-halo fit
 - a halo-like excess can be seen, implying that a halo component physically exists
- the best-fit NFW- ρ^2 model + residual
 - the spherical halo-like excess clearly seen
 - likelihood significantly improved than the no-halo case ($>\sim 10$ sigma)
- 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



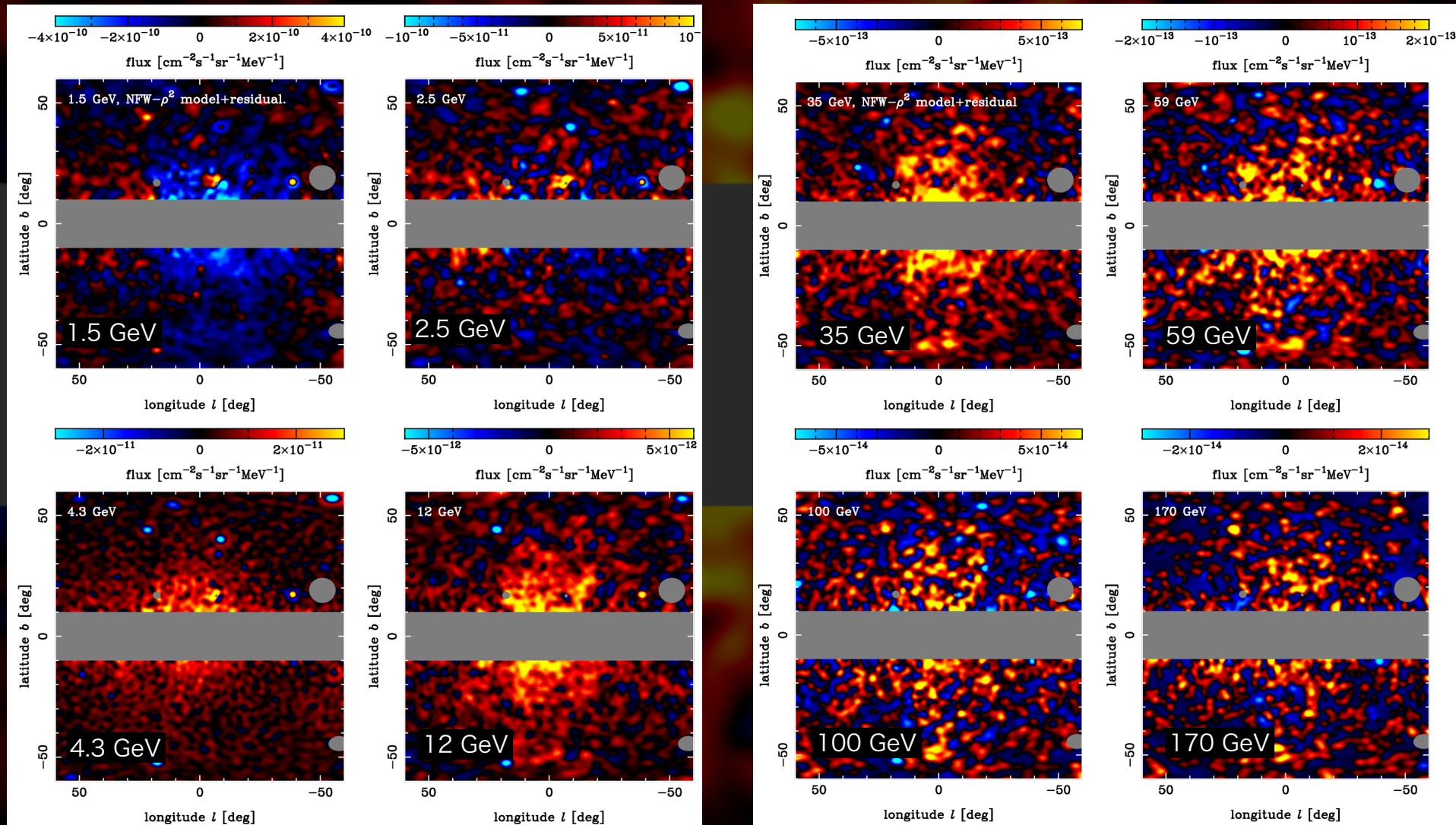






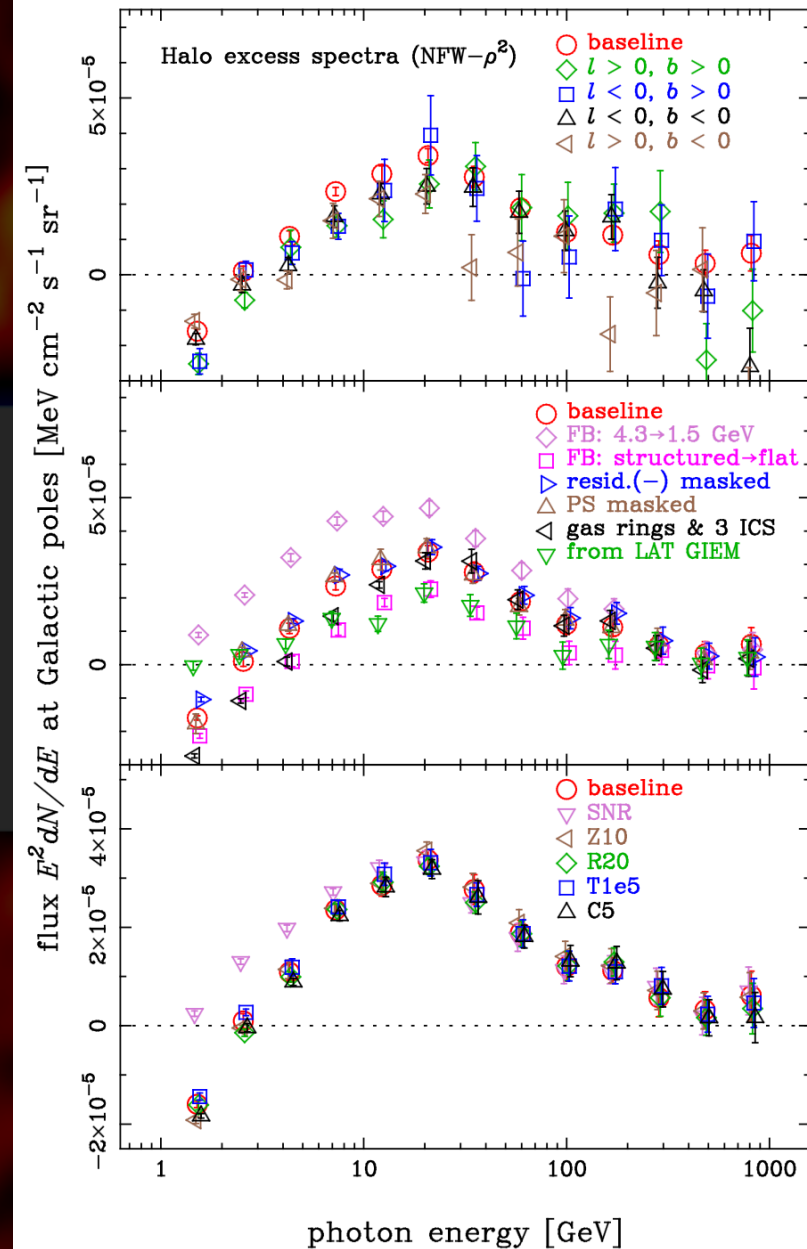
Morphologies of the halo excess in different energy bins

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



Examination of systematics

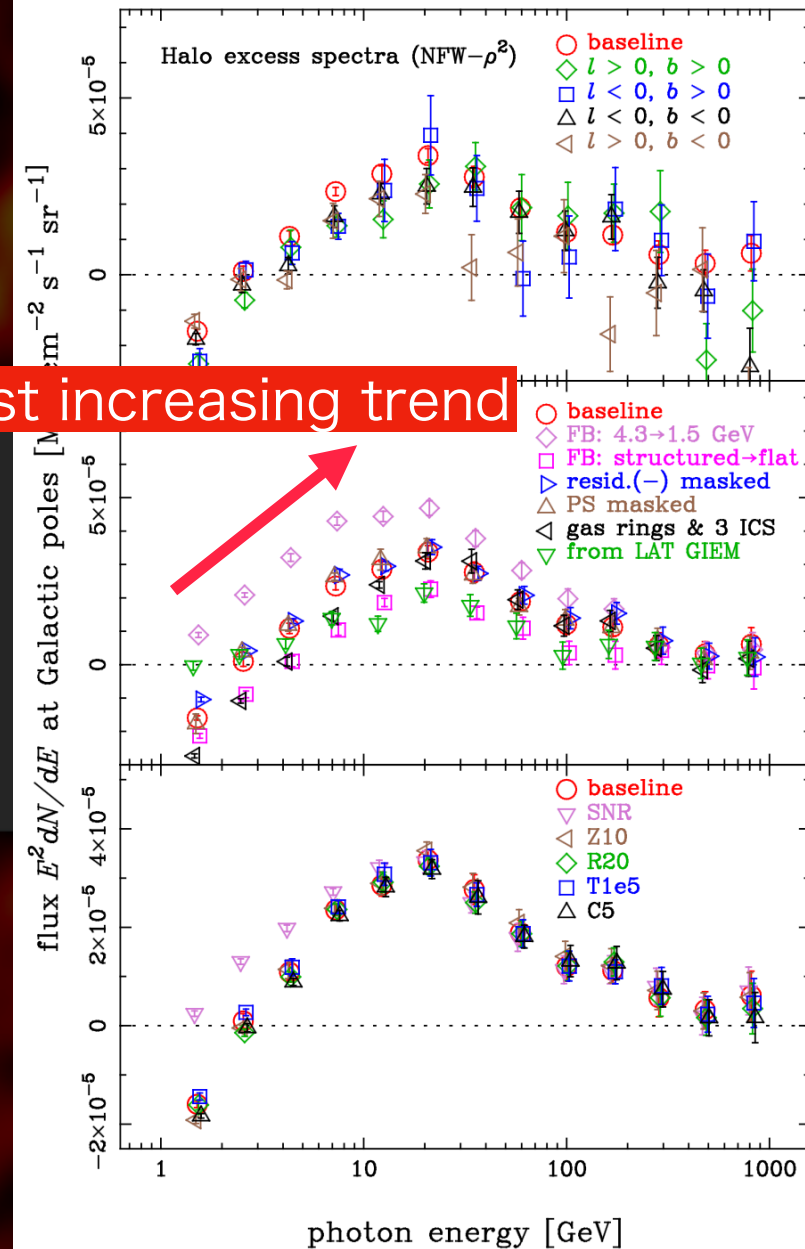
- divided into four quadrants around GC
- FB template modeling:
 - change the energy bin 4.3 → 1.5 GeV
 - structured → flat FB template
 - negative residual region masked
- halo excess against the LAT GIEM (Galactic interstellar emission model)
 - LAT standard background model recommended for point-source analyses
 - includes non-template patch adjusted to fit residuals
 - to erase FB, GC excess, Loop I, and any ...
 - the patch assumes a power-law spectrum above 3 GeV
 - 20 GeV halo excess may still remain
 - changing GALPROP parameters
 - the robust increasing trend always from 1 to 20 GeV



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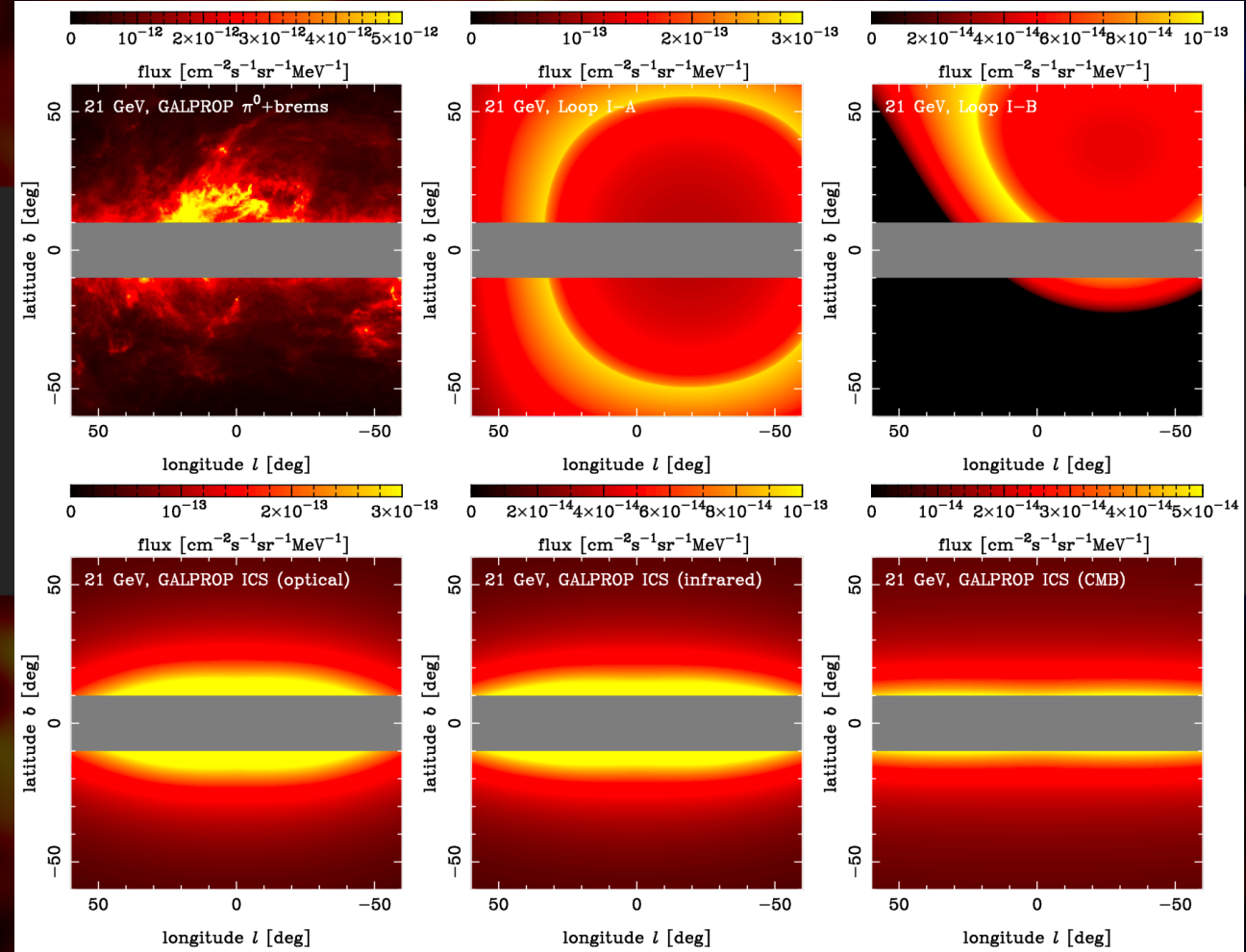
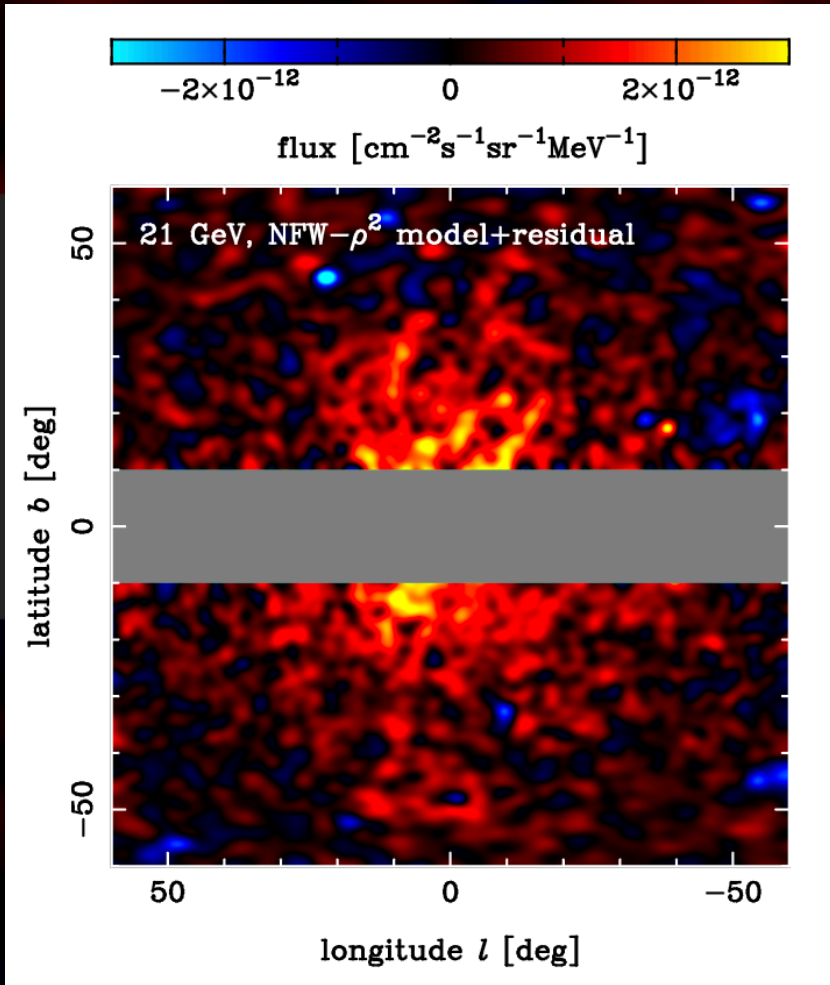
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robust increasing trend



Comparison of the model template maps

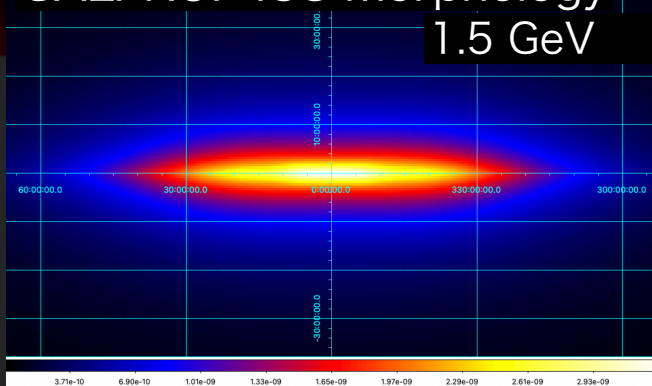
- The shapes of the known components differ significantly from the halo.



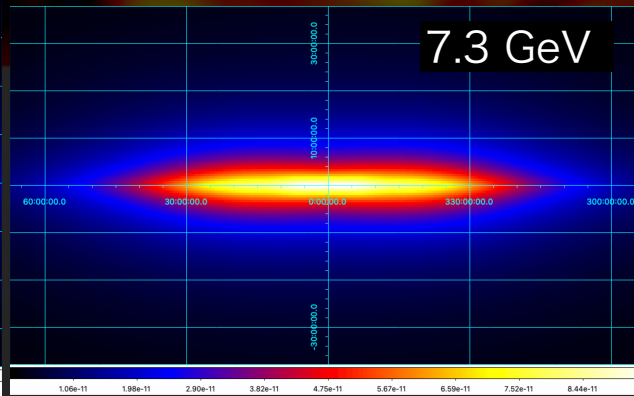
Inverse-Compton scattering maps

- Could changes in ICS morphology dependent on photon energy be confused with the halo signal?
- The halo signal comparable with ICS at 20 GeV, but negligible at 1 GeV
- significant ICS morphological change from 1 to 20 GeV required, to explain the halo signal

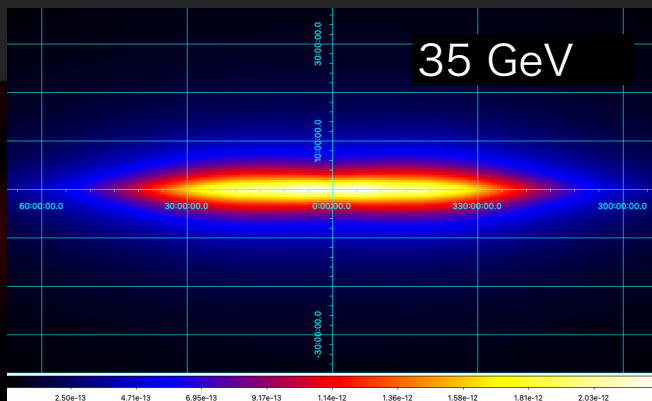
GALPROP ICS morphology
1.5 GeV



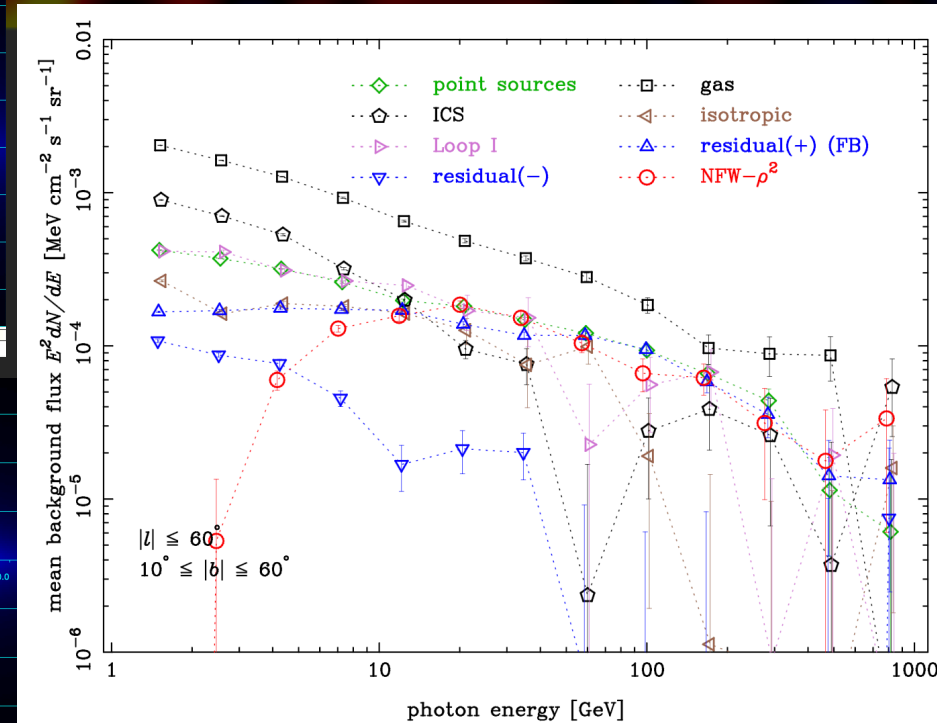
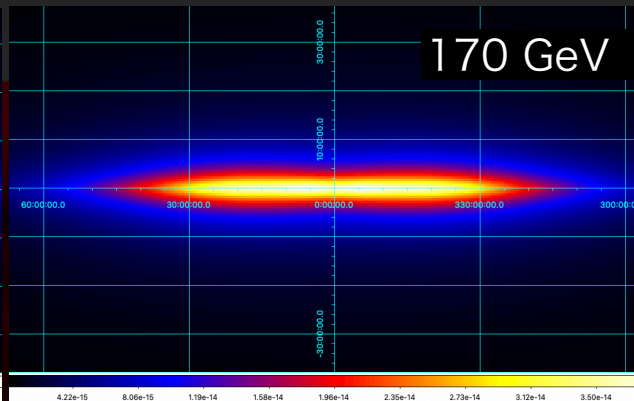
7.3 GeV



35 GeV

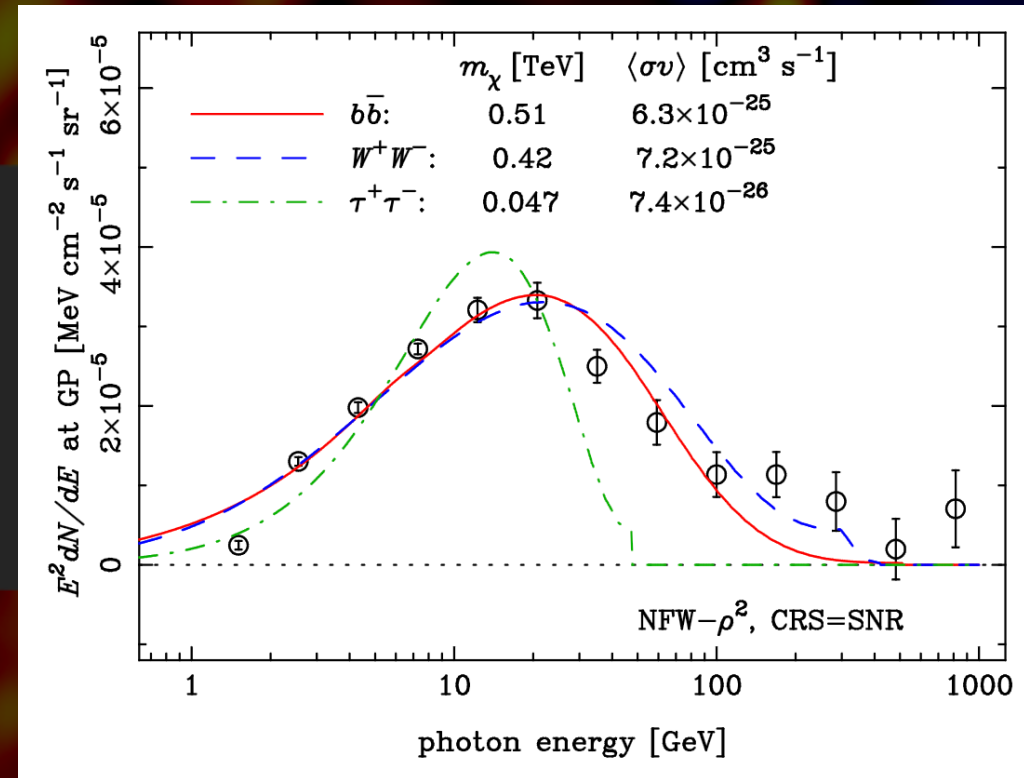


170 GeV



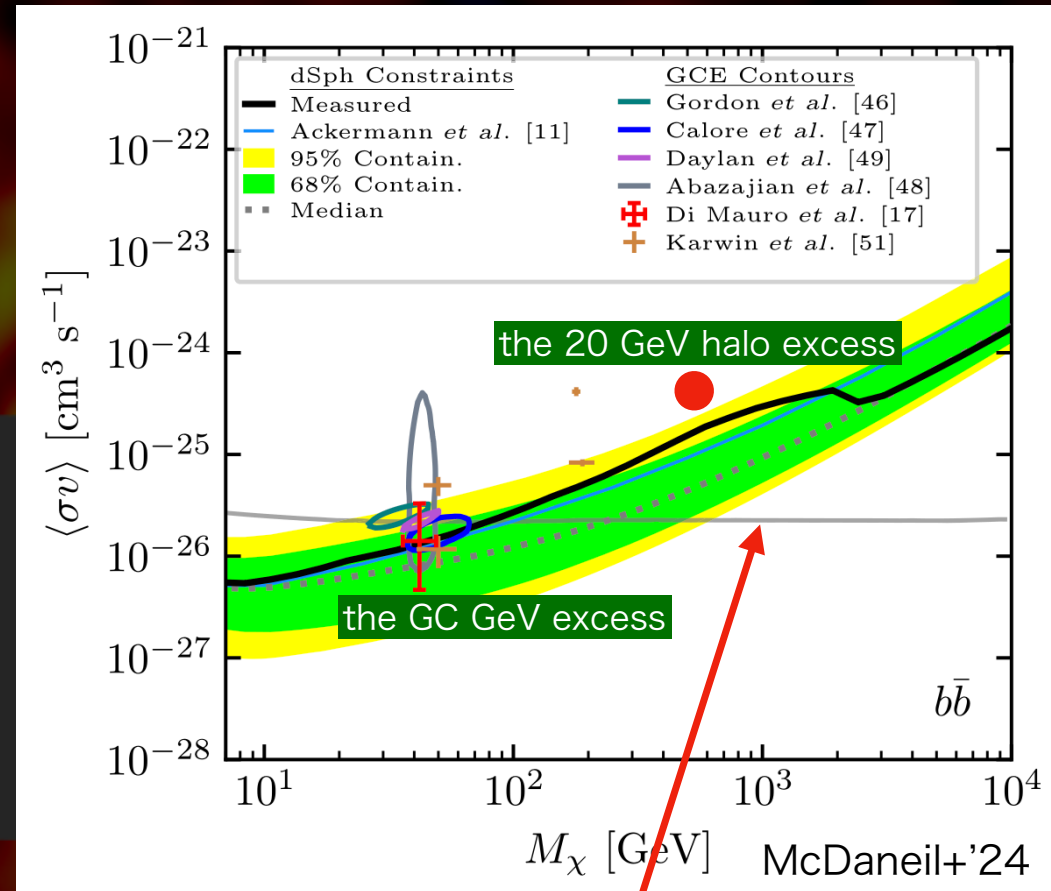
Interpretation by dark matter annihilation

- 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 $b\bar{b}$ or W^+W^- channels
 - mass ~ 0.5 TeV
 - velocity-averaged cross section $\langle\sigma v\rangle \sim 6 \times 10^{-25} \text{ cm}^3/\text{s}$
- The $\tau^+\tau^-$ channel fits worse



Discussion on WIMP parameters

- Comparison with theoretical expectation?
 - $\langle \sigma v \rangle$ from the halo excess is more than 10 times larger than the canonical thermal relic value
 - DM substructure definitely reduces the true $\langle \sigma v \rangle$
 - many possibilities of σ enhancement by $\times 10^{1-2}$ in particle physics theory, e.g. the Sommerfeld correction
- A tension with dwarf galaxy constraints
 - a factor of a few above the upper limit
 - but not an immediate discrepancy:
 - uncertainty in MW DM density profile/ substructures
 - uncertainty also in dSph analysis
 - relative substructure boost factor?
 - ~several to more than 10 for MW
 - ~1 for dwarfs (Gao+'12; Hiroshima+'18)

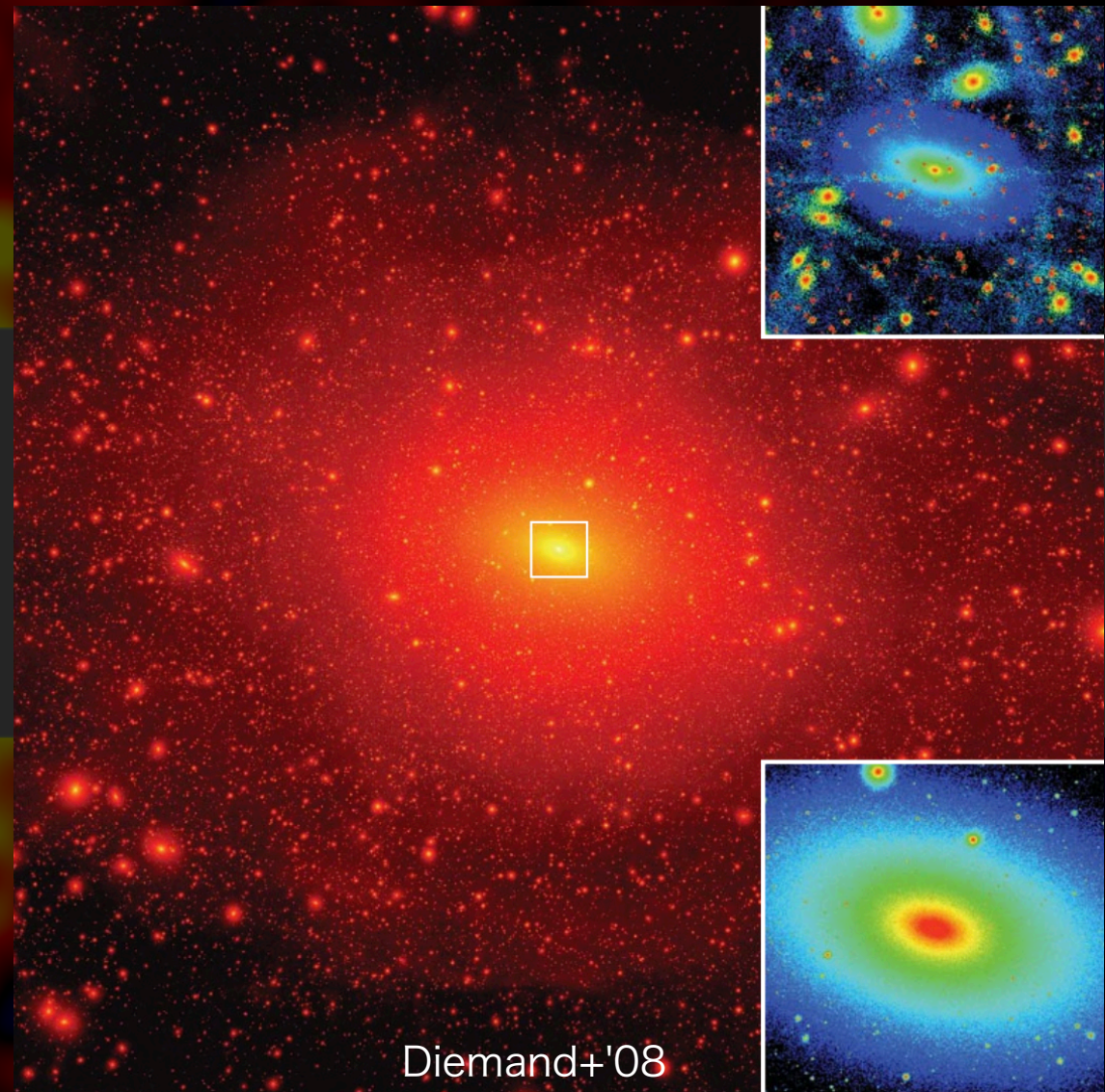


canonical thermal relic cross section

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

Substructures in dark halos

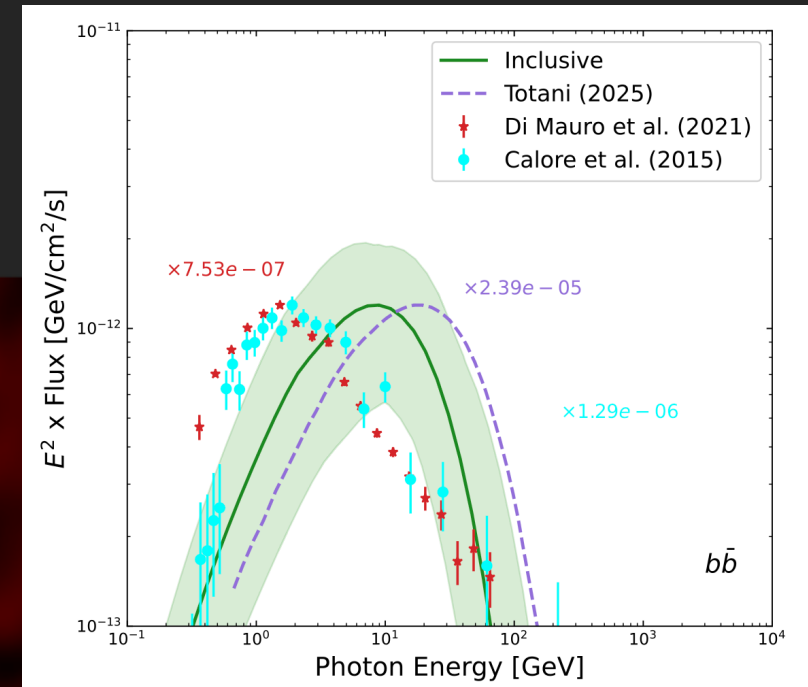
- hierarchical structure formation by “cold dark matter”
 - Smaller halos form earlier, followed by mergers to create larger halos
 - Rich substructures and sub-halos in a halo



MW halo 20 GeV excess vs. dwarf galaxies

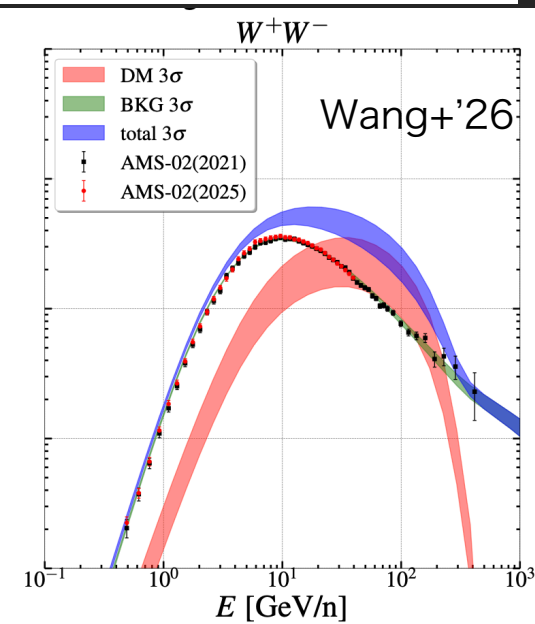
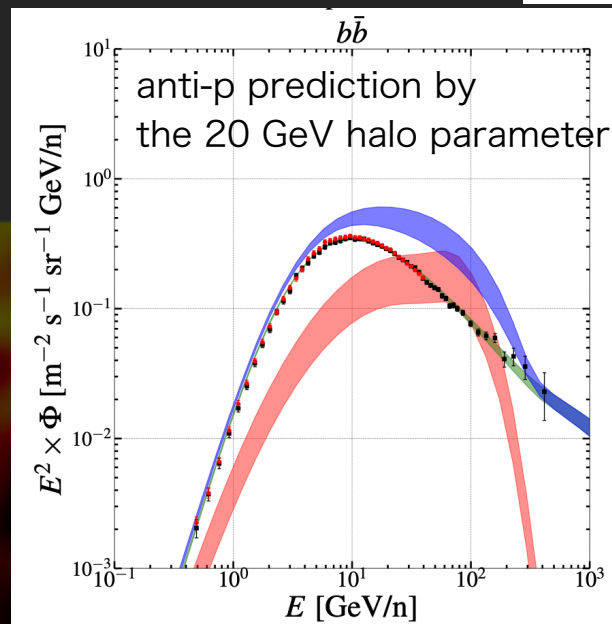
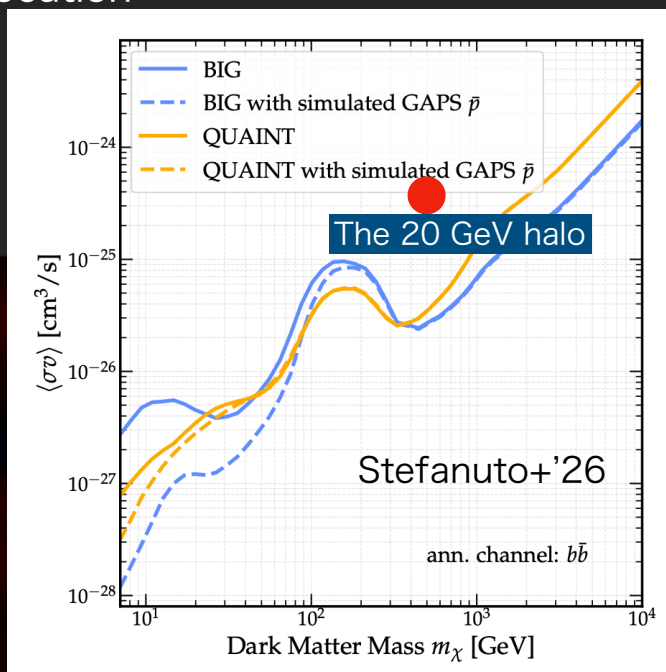
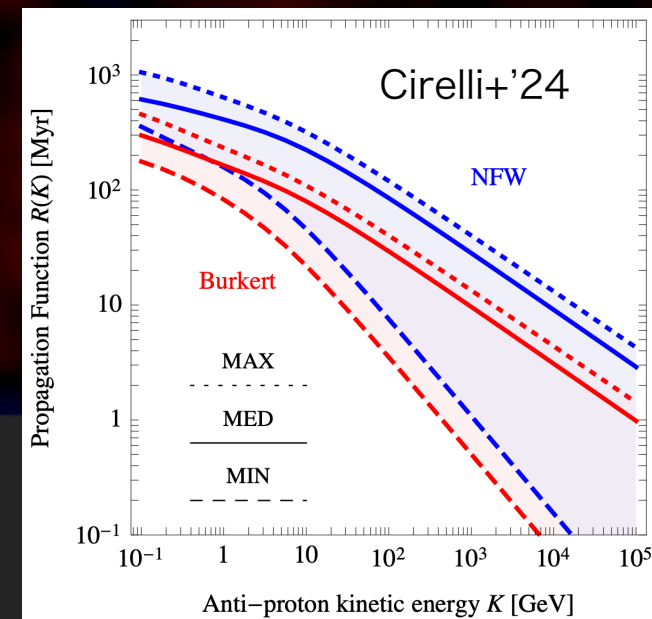
- the latest Fermi dwarf galaxy analysis reports 3σ preference for DM annihilation (Circiello+'26)
 - dwarf galaxies of $M_{\text{DM}} \sim 10^6\text{-}10^9 M_{\text{sun}}$ ($M_{\text{star}} \sim 10^3\text{-}10^7 M_{\text{sun}}$)
 - spectrum consistent with MW halo 20 GeV signal
 - but also with GC excess
 - $\langle\sigma v\rangle \sim 5e26 \text{ cm}^3/\text{s}$ for $M_{\text{WIMP}} \sim 500 \text{ GeV}$, about ~ 10 times smaller than the 20 GeV halo excess
- MW halo & dwarf galaxies can be consistent if:
 - relative substructure boost factor of several to 10 is reasonable between MW halo and dwarfs
 - $\langle\sigma v\rangle$ also approaches the thermal relic value
- high energy tail of the DM spectrum can be tested by CTA!

$b\bar{b}$ channel				
Sample	M_χ [GeV]	$\langle\sigma v\rangle$ [$\text{cm}^3 \text{s}^{-1}$]	p_{local}	p_{global}
Measured	112.5	1.08×10^{-26}	5.8×10^{-2} (1.6σ)	2.7×10^{-1} (0.6σ)
Benchmark	142.5	1.37×10^{-26}	6.9×10^{-3} (2.5σ)	5.0×10^{-2} (1.6σ)
Inclusive	180.5	1.73×10^{-26}	9.0×10^{-5} (3.7σ)	1.6×10^{-3} (3.0σ)
$\tau^+\tau^-$ channel				
Sample	M_χ [GeV]	$\langle\sigma v\rangle$ [$\text{cm}^3 \text{s}^{-1}$]	p_{local}	p_{global}
Measured	17.0	2.65×10^{-27}	8.3×10^{-2} (1.4σ)	3.1×10^{-1} (0.5σ)
Benchmark	34.5	4.24×10^{-27}	5.8×10^{-3} (2.5σ)	4.7×10^{-2} (1.7σ)
Inclusive	34.5	4.24×10^{-27}	1.2×10^{-4} (3.7σ)	2.3×10^{-3} (2.8σ)



Comparison with anti-proton constraints

- Constraint on $\langle\sigma v\rangle$ by anti-p is ~ 10 times lower than the 20 GeV halo
- Large uncertainties in cosmic-ray propagation
 - obviously simplified calculation (diffusion equation with constant diffusion coefficient, homogeneous source injection, ...) compared with reality
 - propagation paths can be different for astrophysical CR and DM anti-p
- DM substructures in MW must be taken into account
 - gamma-ray from the halo will be enhanced
 - anti-p may be reduced around the solar neighborhood, depending on its location



Practical particle physics models?

- The simplest SM extension to explain the 20 GeV halo excess
- inelastic scattering to avoid the constraints from direct detection experiments
 - “inert doublet dark matter”

Electroweak Doublet Dark Matter for a Galactic Halo Gamma-Ray Excess

Yasunori Nomura^{1,2,3,4} and Tomonori Totani^{5,6}

¹*Leinweber Institute for Theoretical Physics, Department of Physics,
University of California, Berkeley, CA 94720, USA*

²*Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

³*RIKEN Center for Interdisciplinary Theoretical and Mathematical Sciences (iTHEMS), RIKEN, Wako 351-0198, Japan*

⁴*Kavli Institute for the Physics and Mathematics of the Universe (WPI),
UTIAS, The University of Tokyo, Kashiwa, Chiba 277-8583, Japan*

⁵*Department of Astronomy, School of Science, The University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan*

⁶*Research Center for the Early Universe, School of Science,
The University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan*

Weakly interacting massive particles provide a well-motivated framework for dark matter, naturally reproducing the observed relic abundance through thermal freeze-out. A recent claim of an indirect-detection signal from the Galactic halo, consistent with dark matter annihilation in the mass range 400–800 GeV, motivates a reexamination of minimal models that can account for such a signal while remaining consistent with existing constraints. In this paper, we analyze the simplest extensions of the Standard Model capable of explaining the signal. We show that electroweak doublet dark matter with Higgs-portal interactions provides a natural and economical explanation. The model predicts annihilation predominantly into longitudinal gauge bosons with characteristic branching fractions and allows for inelastic dark matter with a mass splitting of order 100 keV, intriguingly consistent with a recent direct-detection anomaly. Possible enhancements of the present-day annihilation rate relative to the thermal value are also discussed, including a simple extension with a light scalar field, whose mass can be chosen such that the enhancement is suppressed in dwarf galaxies.

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Conclusions

- DM annihilation gamma-rays were searched towards the MW halo region, using Fermi-LAT 15-yr data
- Statistically significant ($>10\sigma$ at a few energy bins) halo-like excess is found around 20 GeV
- Map morphology of the halo excess is consistent with a spherical halo-like emission
- Radial angular profile matches the annihilation with the NFW profile
- DM annihilation spectrum by the popular bb or W^+W^- channels is in agreement with the halo-excess
 - DM mass ~ 0.5 TeV, $\langle\sigma v\rangle \sim 6\times 10^{-25}$ cm³/s
 - Assuming smooth NFW profile (no substructure at all): real $\langle\sigma v\rangle$ should be lower
- Tension with the dwarf galaxy / anti-p constraints and the canonical thermal relic cross section, but the DM interpretation is viable, considering various uncertainties
- Future verification is possible, especially by dwarf galaxy observations