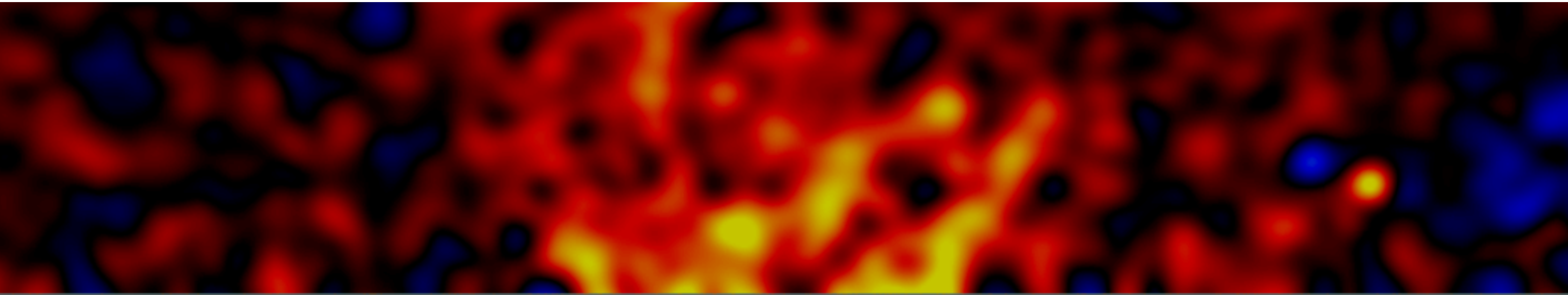

20 GeV halo-like excess of the Galactic diffuse emission: Evidence for dark matter annihilation!?

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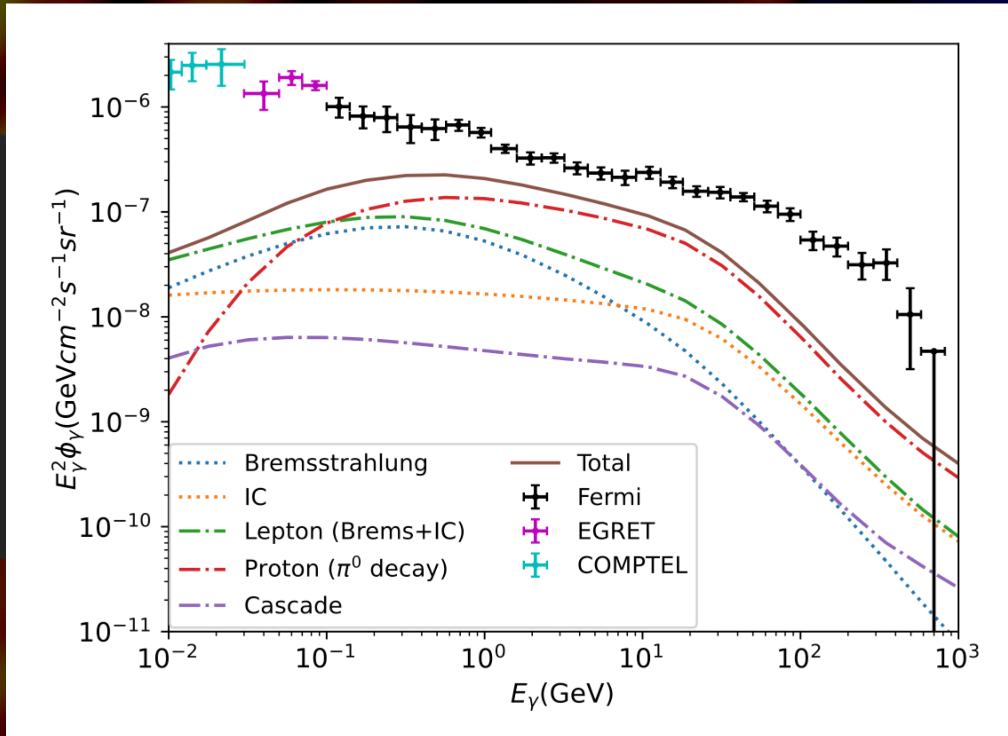
Introduction

- About me:
  - a theoretical astrophysicist working on transients (supernovae, GRBs, FRBs, ⋯), galaxy formation/evolution, cosmology, ⋯
  - No experience with Fermi data analysis!
    - special thanks to Tsunefumi Mizuno for a lot of advice about Fermi data analysis

Extragalactic gamma-ray background from star-forming galaxies



- Why dark matter search now using Fermi data?

Chen+TT '25

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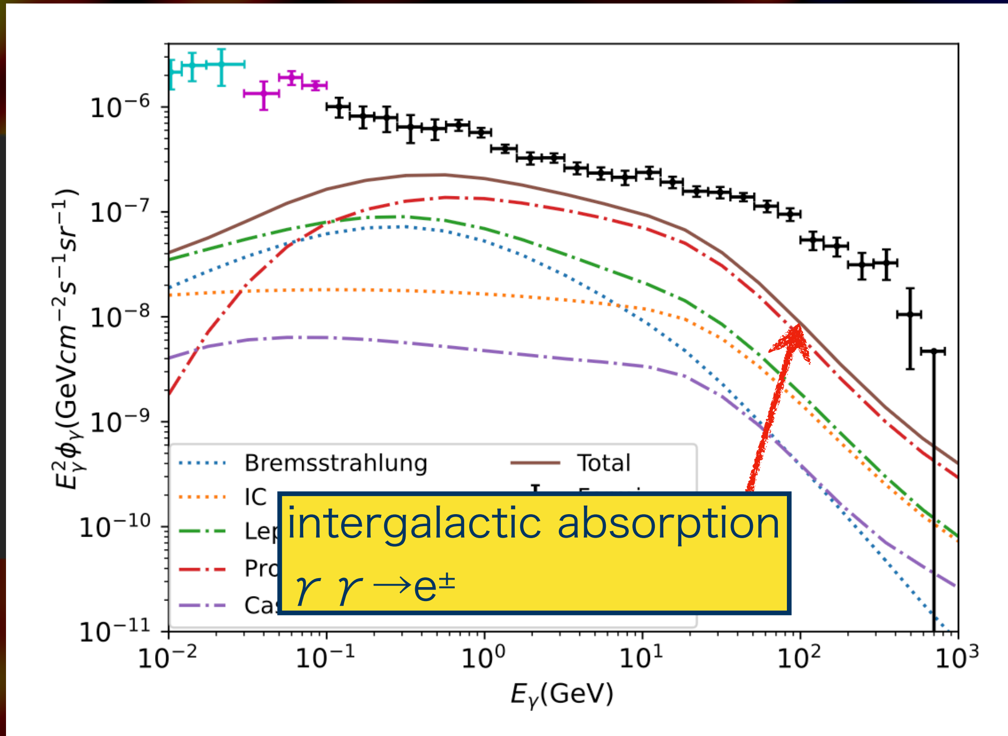

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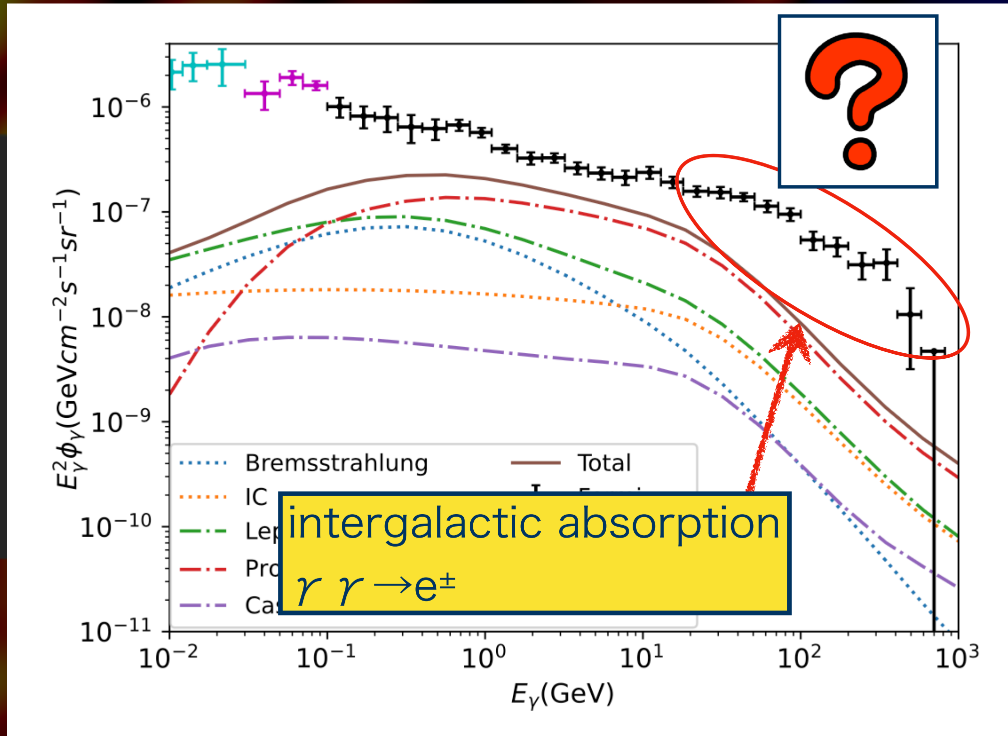

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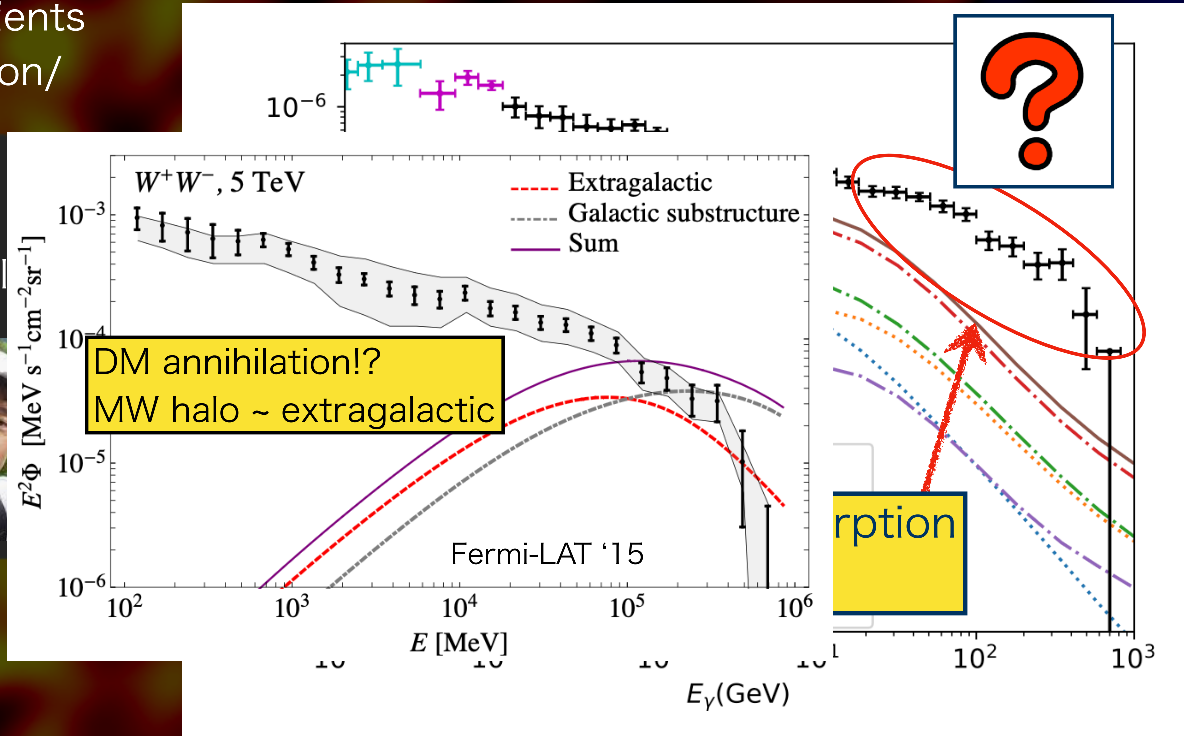

- Why dark matter search now using Fermi data?

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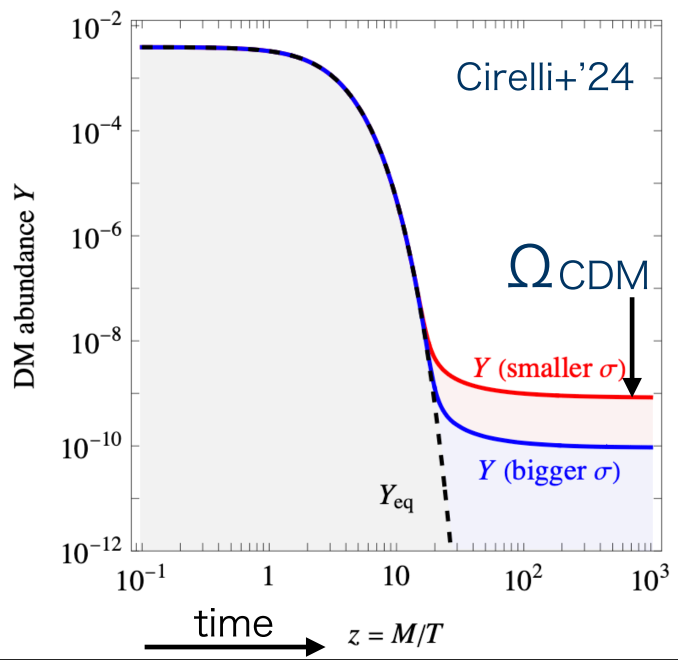
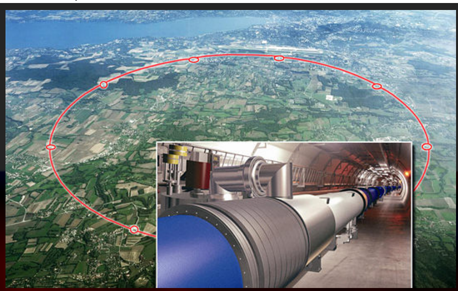
WIMP as the dark matter

- 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:

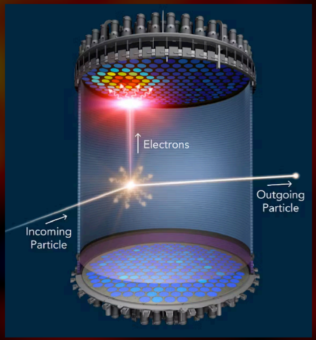
$$\langle \sigma_{\rm ann} v \rangle_f \approx 3 \times 10^{-26}\ {\rm cm}^3\ {\rm s}^{-1}$$

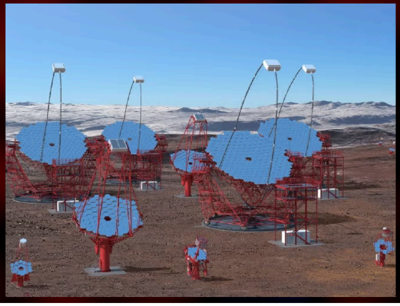
    - This is close to the weak cross section for WIMPs around the electroweak scale (the WIMP miracle)
  - many well-motivated theoretical candidates (e.g. supersymmetry)
  - one of the most popular DM candidates





- can be searched for by:
  - direct detection (underground experiments)
  - indirect detection (annihilation gamma-rays, neutrinos, ⋯)
  - particle accelerator experiments



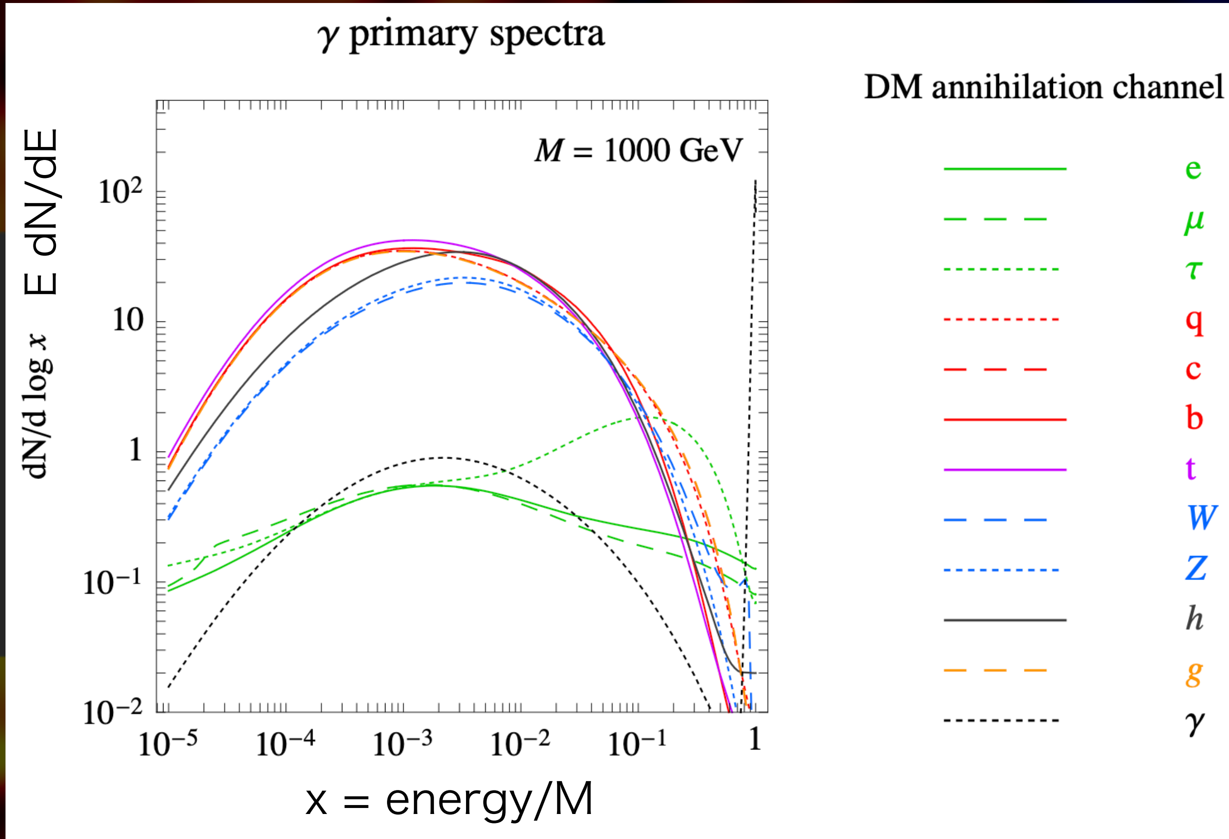


Annihilation gamma-rays from WIMPs

- 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^-, …
  - cascade to continuum gamma rays
  - spectral peak typically ~1/10 of the WIMP mass (in terms of E^2dN/dE)
  - not power-law, unlike many astrophysical sources
  - The branching ratio can be ~unity

- gamma-ray flux expected by the thermal relic cross section is close to the sensitivity of gamma-ray telescopes



Cirelli+ '24

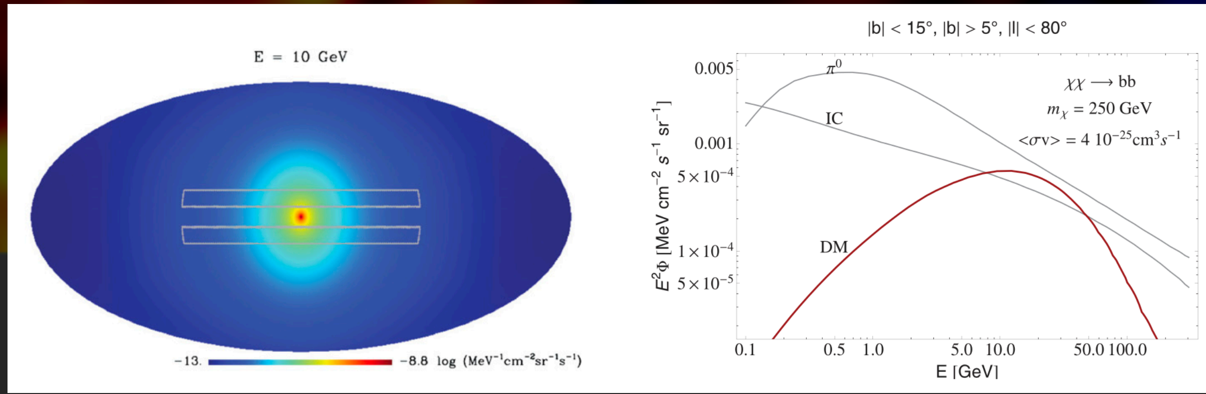
Annihilation gamma-rays from Milky-Way halo?

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

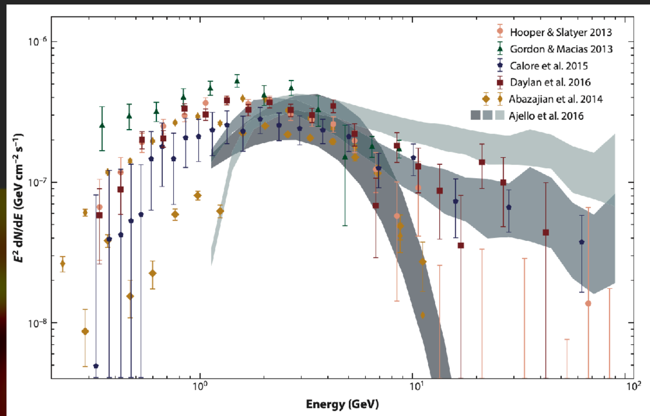
- not so many papers on MW halo (without GC/disk), compared with Galactic center (GC) or dwarf galaxies

- 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

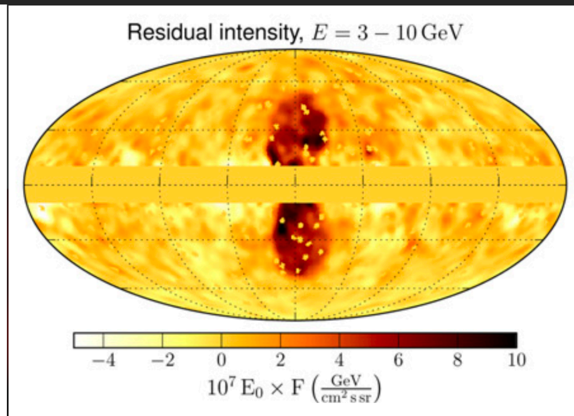
- This work: a new search in the MW halo (without GC/disk) using 15-yr LAT data, with modelings of known diffuse components



halo DM search by Fermi-LAT '12



GC excess spectrum (Murgia+'20)

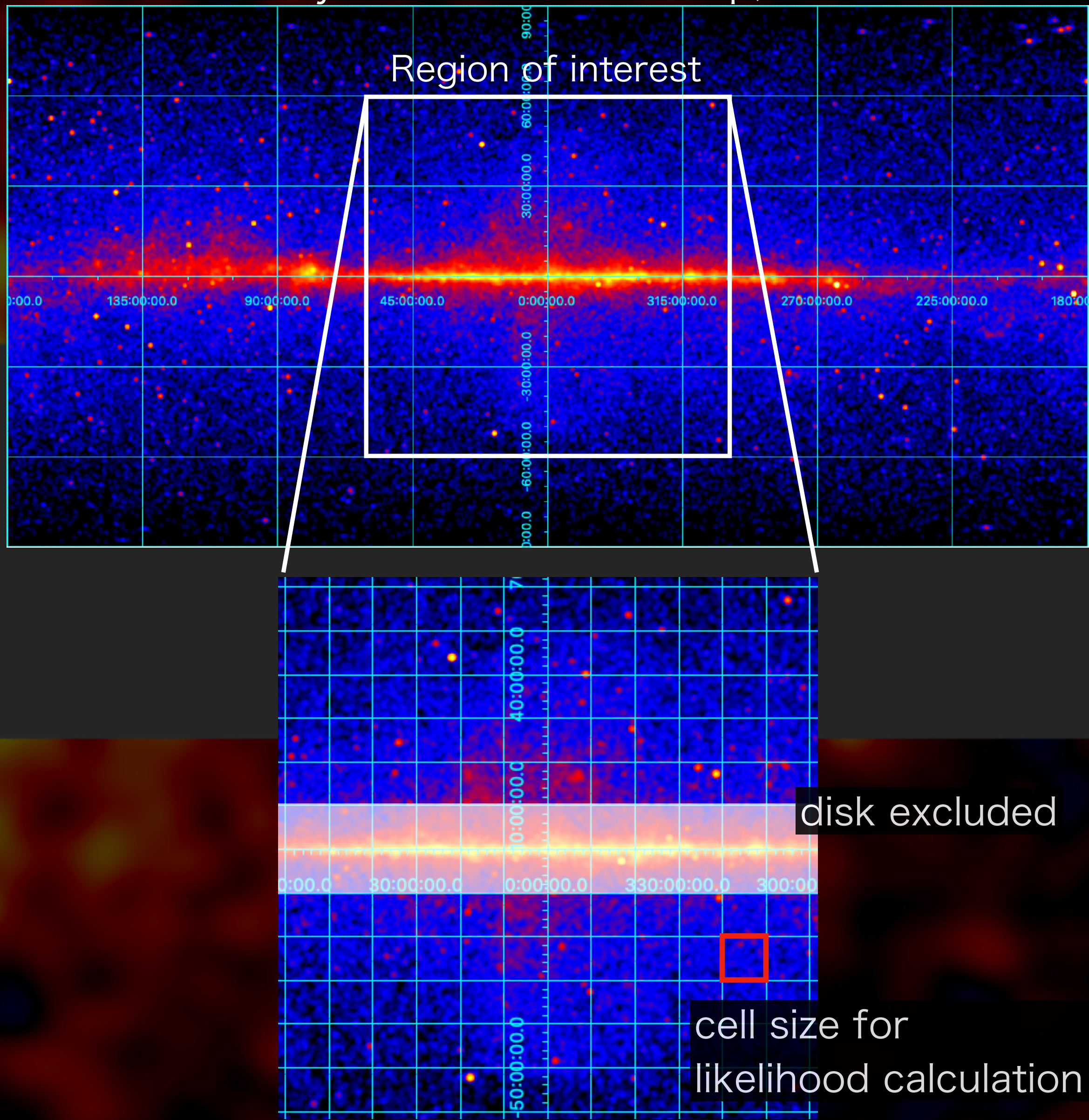


Fermi bubbles (Ackermann+'14)

The Fermi data and analysis

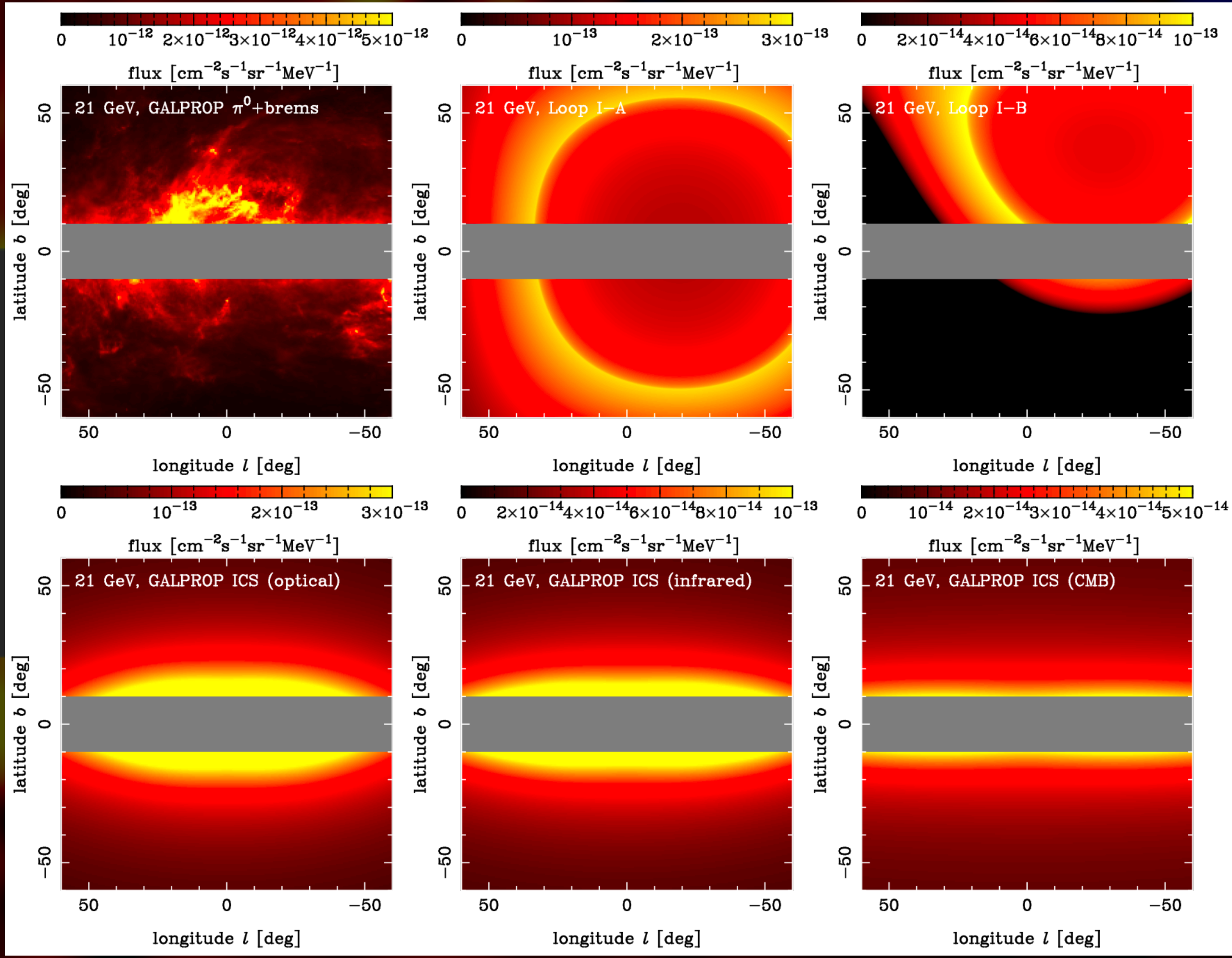
- The public Fermi data used:
  - 15-yr (2008-2023), Pass 8 UltraClean
  - zenith angle cut θ < 100 deg
  - 1.5-810 GeV, 19 bin (log-spaced)
  - Cartesian coordinates
  - pixel scale: 0.125 deg
- Region of interest (ROI)
  - $|\, l \,| < 60$ deg
  - $10 < |\, b \,| < 60$ deg
- Likelihood calculation: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

all-sky smoothed count map, 21 GeV



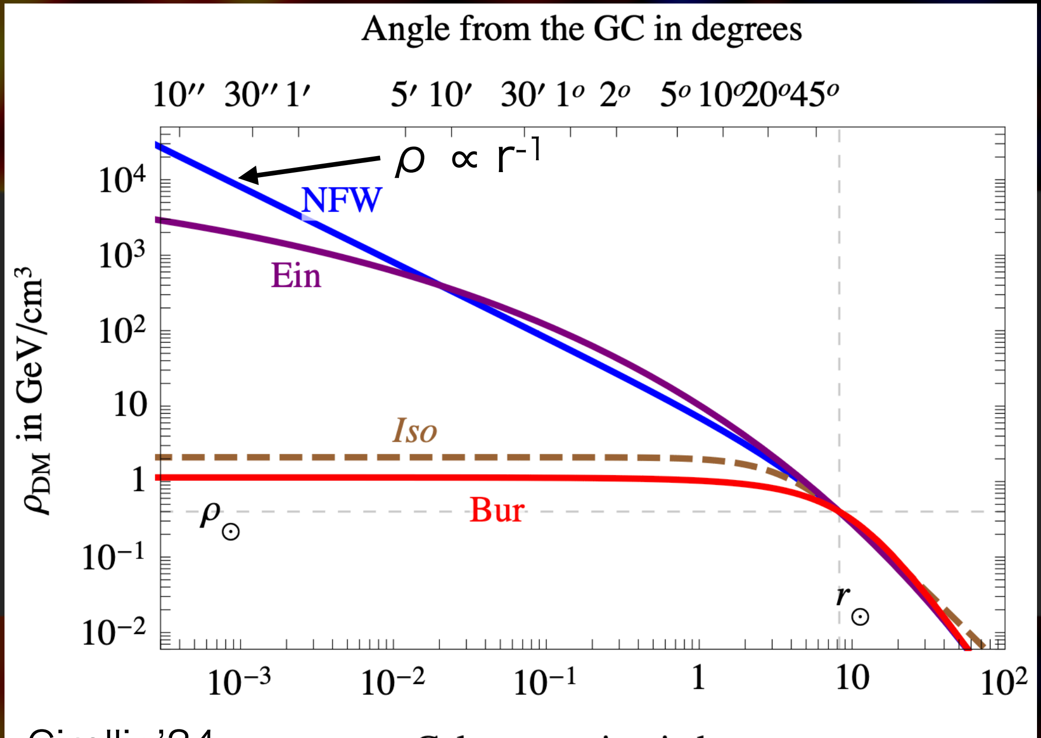
Model map templates

- 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: 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 for NFW with $\varepsilon_\gamma \propto \rho^{2.5}$



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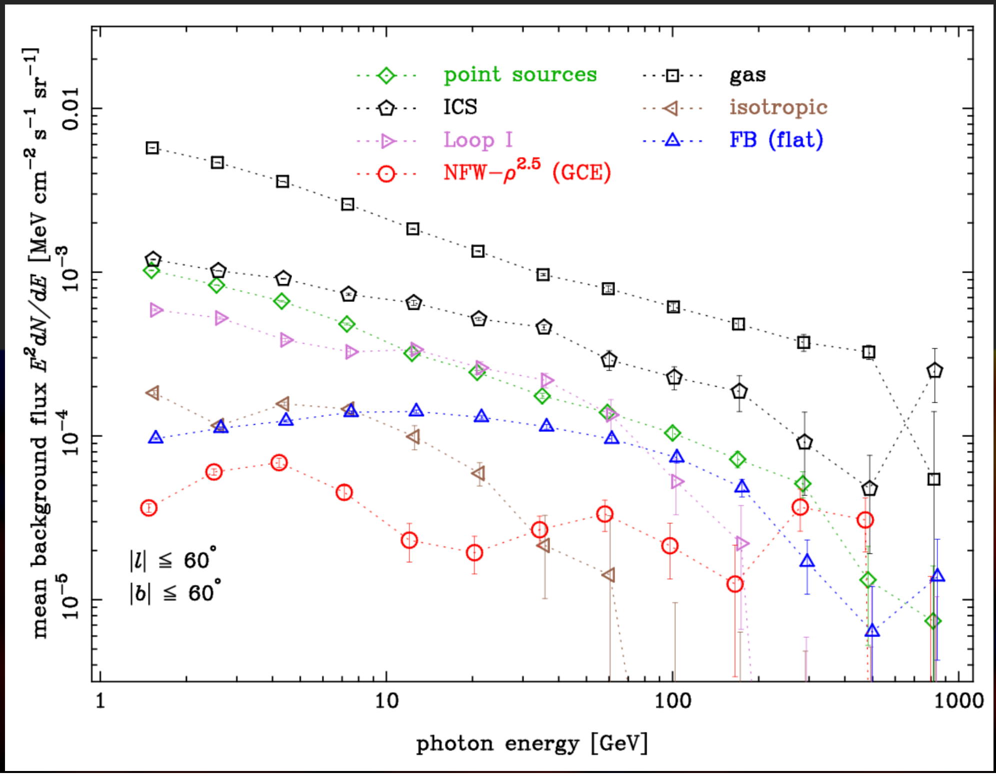
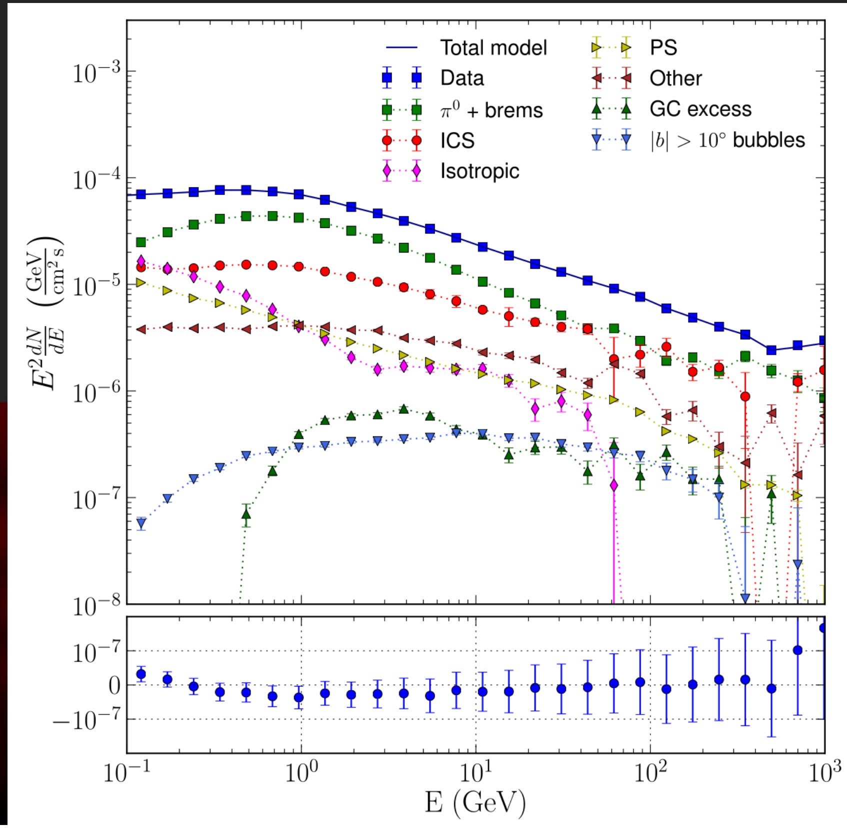
Model map templates: Fermi bubbles

- Fermi bubble templates are created in this work
- starting from the simple flat FB template
- fit the observed map by model templates, including flat FB and GC excess
  - fit including the disk region
  - independent fits in each energy bin
- similar results to the past Fermi-LAT papers

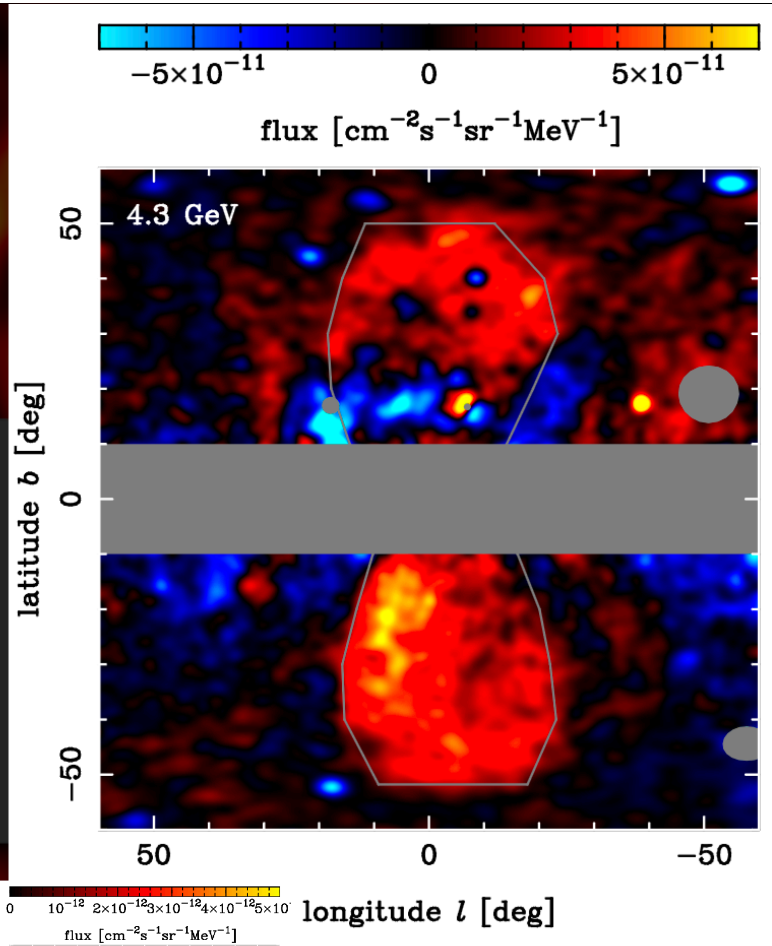


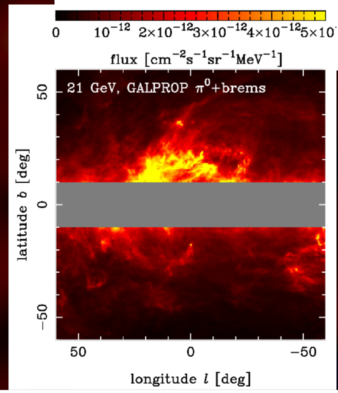
Fermi-LAT collab. ’17



Model map templates: Fermi bubbles

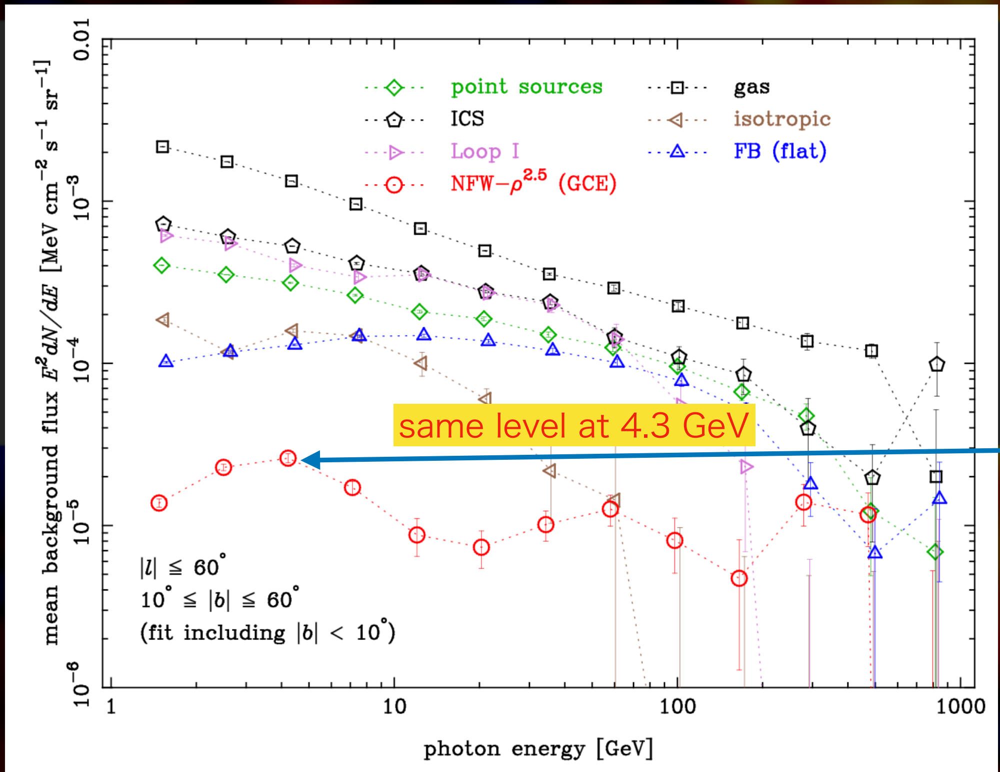
- Fermi bubble image (flat FB template + residual) at 4.3 GeV bin
- positive flux regions dominated by FB, but there are some negative regions, correlated with the GALPROP gas map
- our approach to search for a halo-like excess:
  - add the positive (FB) and negative residual maps as two independent model templates
    - map @4.3 GeV bin as the energy-independent template for all 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



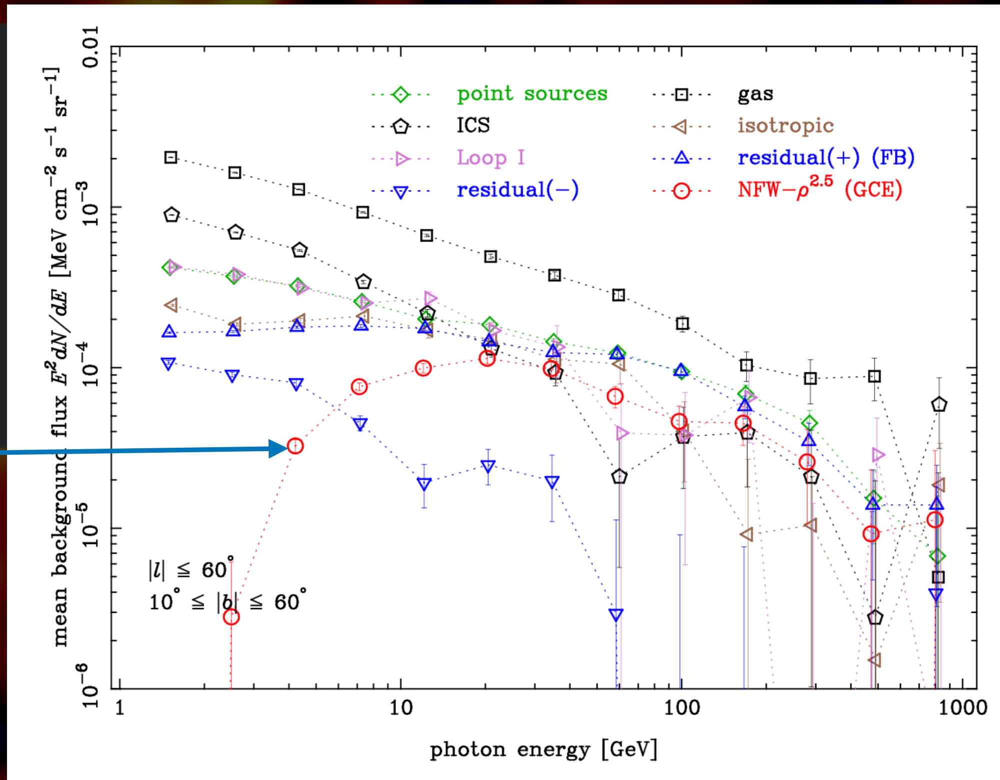


Fit with a halo component

- fit with NFW-$\rho^{2.5}$ (GC excess) excluding the disk region (right figure)
- no change at 4.3 GeV from the previous fit (including disk), as it should be
- 10 times higher halo flux than the fit including the disk, at 20 GeV!
- implying the significant halo component around 20 GeV, with a profile shallower than GC excess



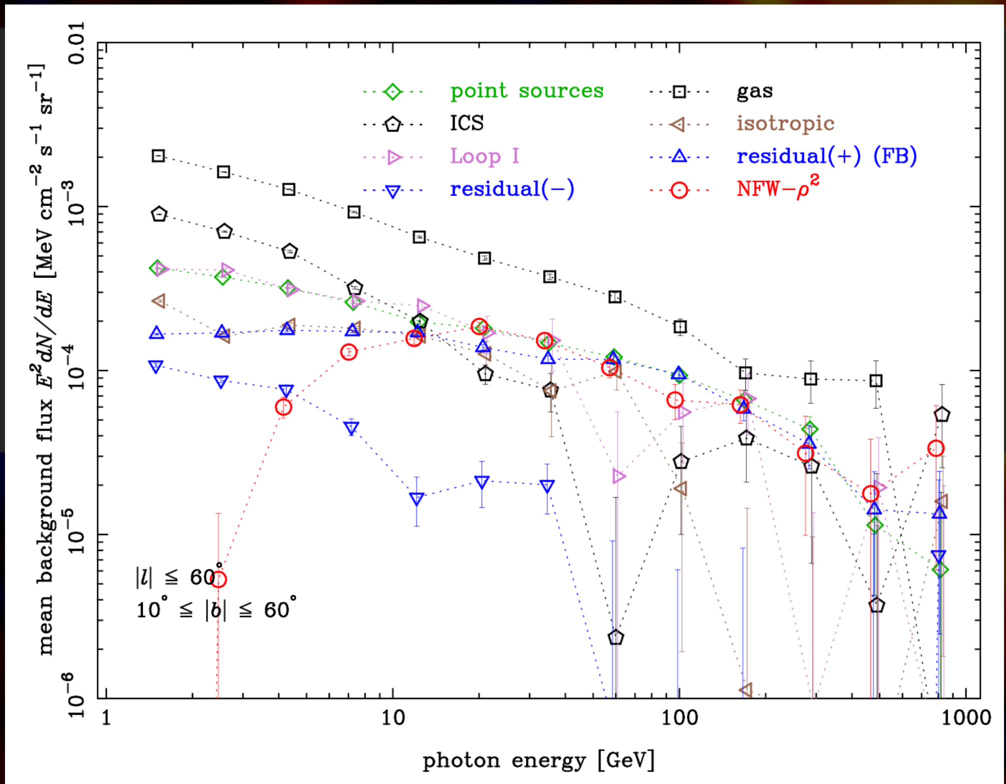
fit including the disk



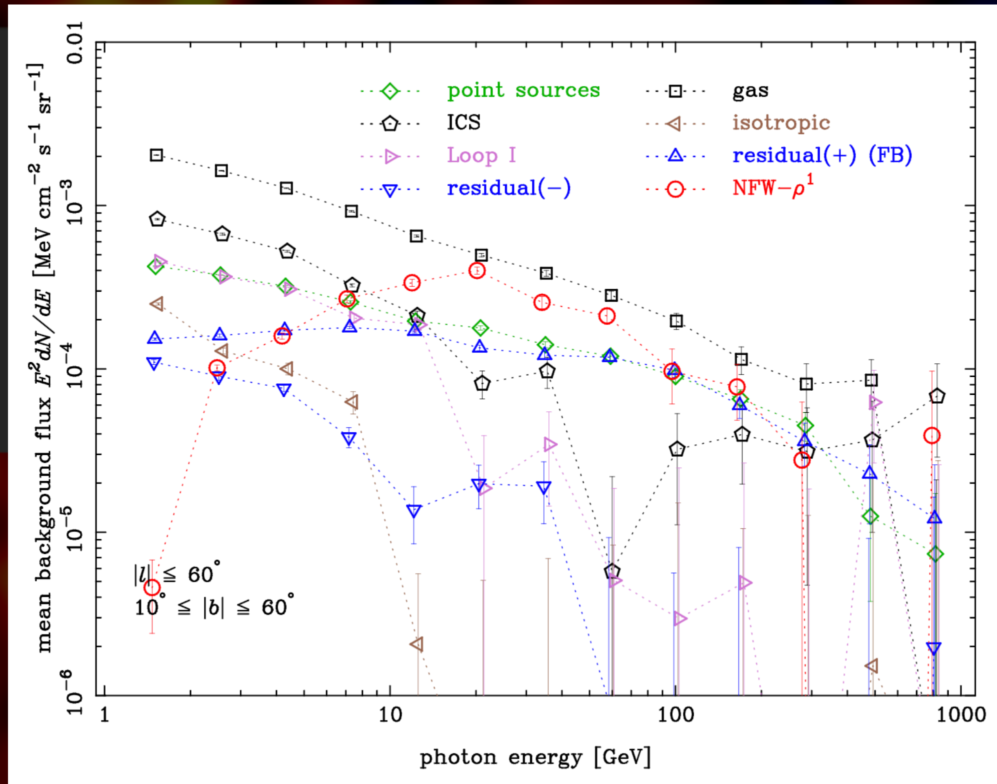
fit excluding the disk

Fit with a halo component

- 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



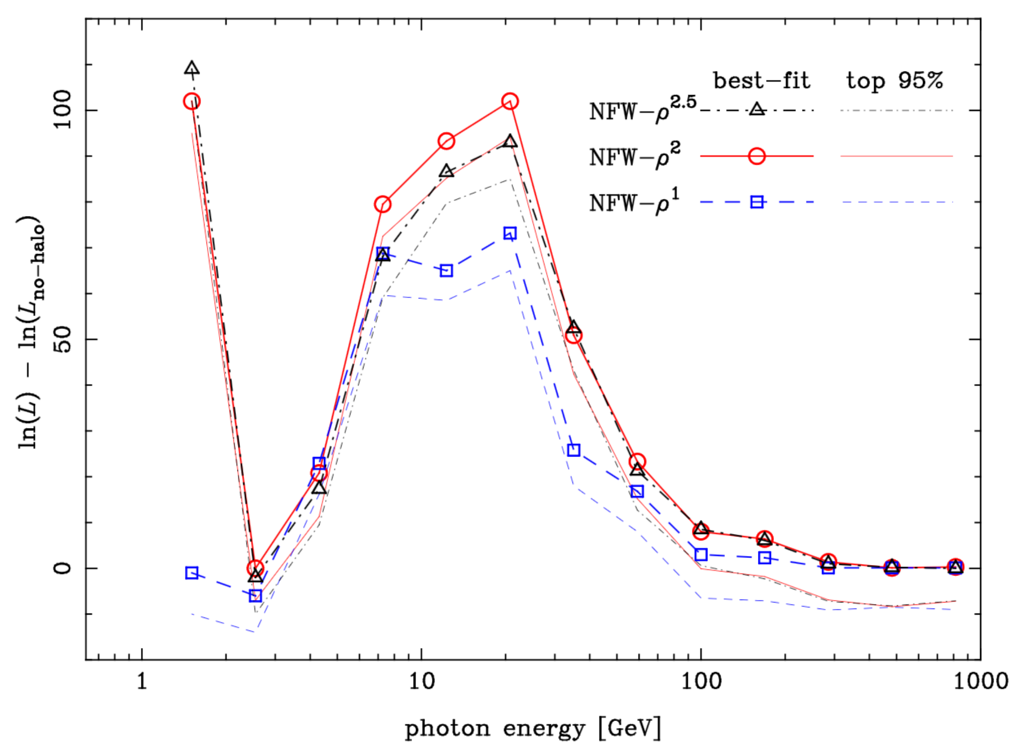
fit with NFW-ρ^2

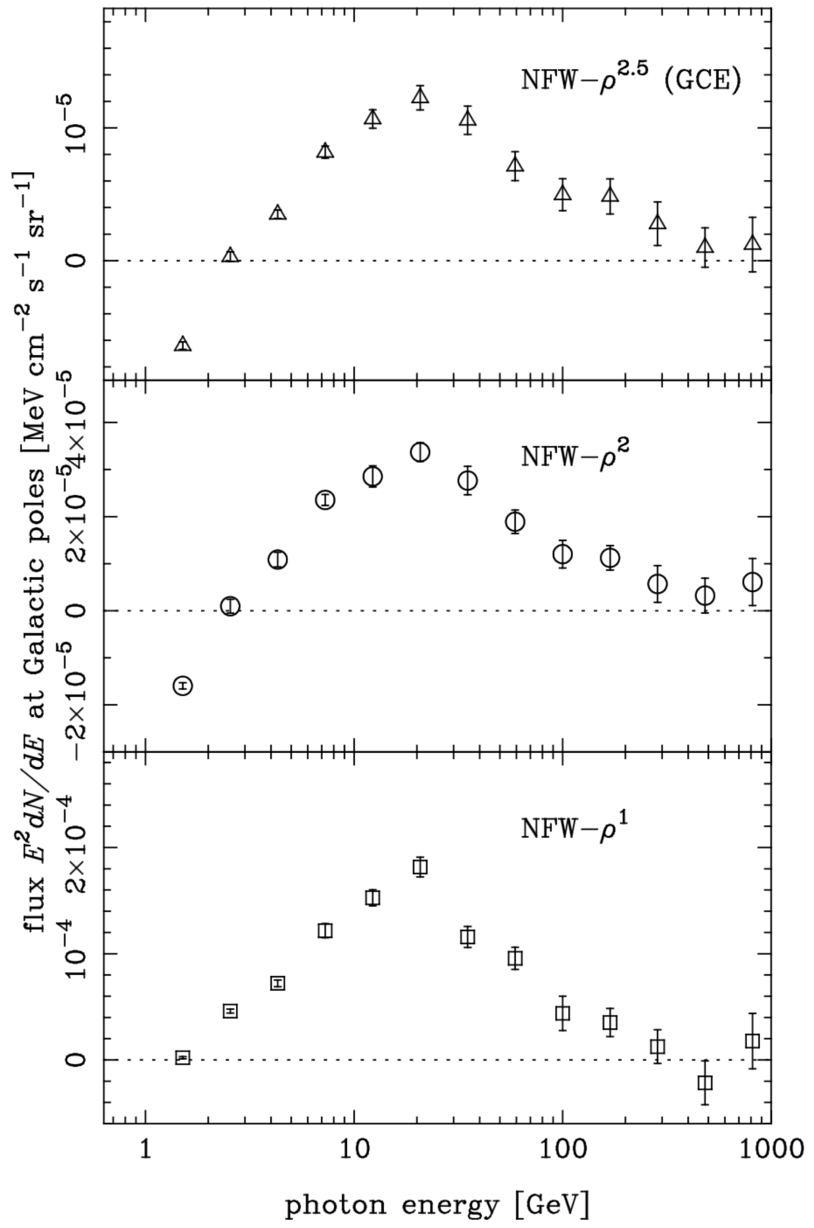


fit with NFW-ρ^1

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



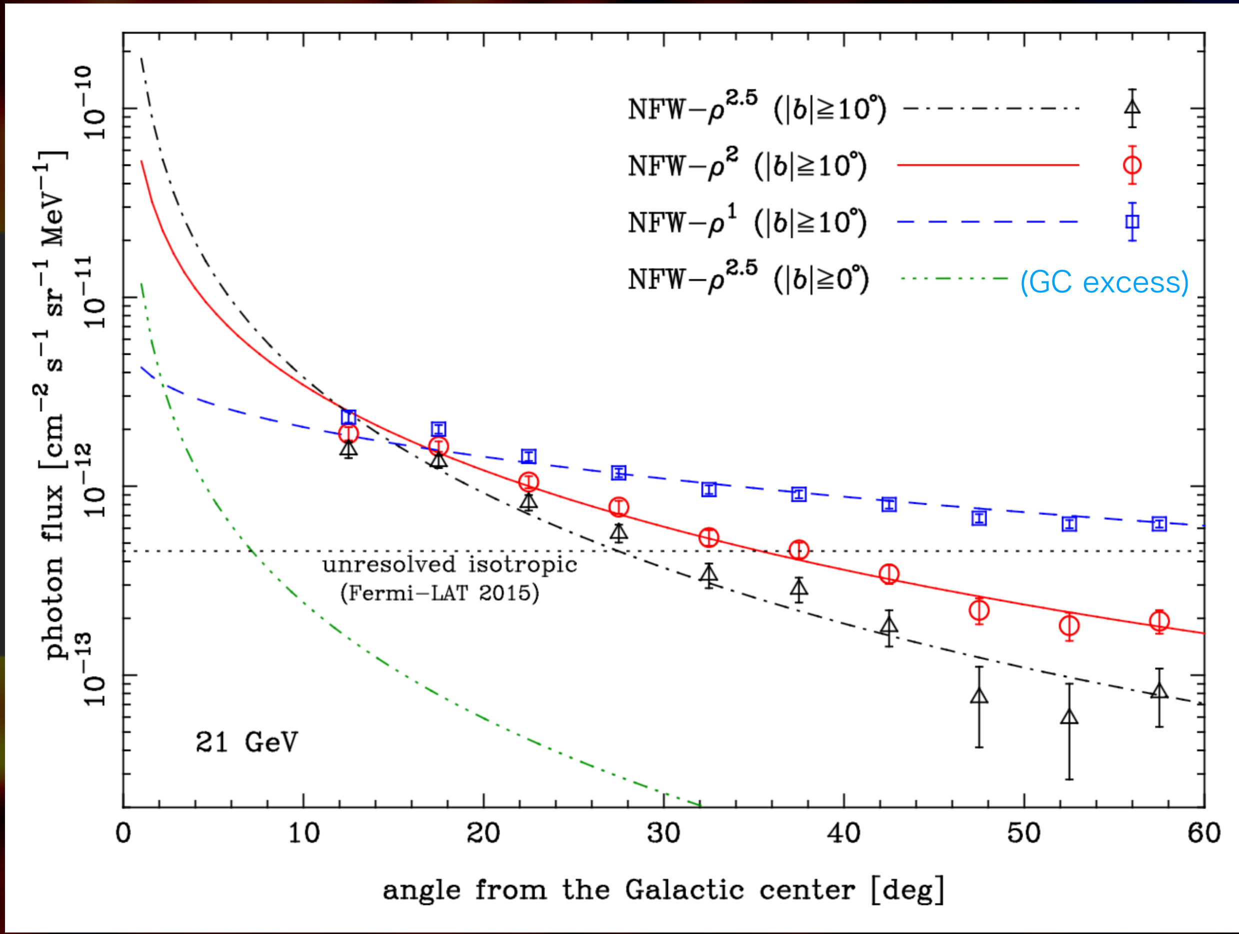


Radial angular profiles at 21 GeV

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

- data points differ by the three models
  - degeneracy with the isotropic background
  - isotropic flux of the NFW-ρ^2 fit 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 from the likelihood result

- 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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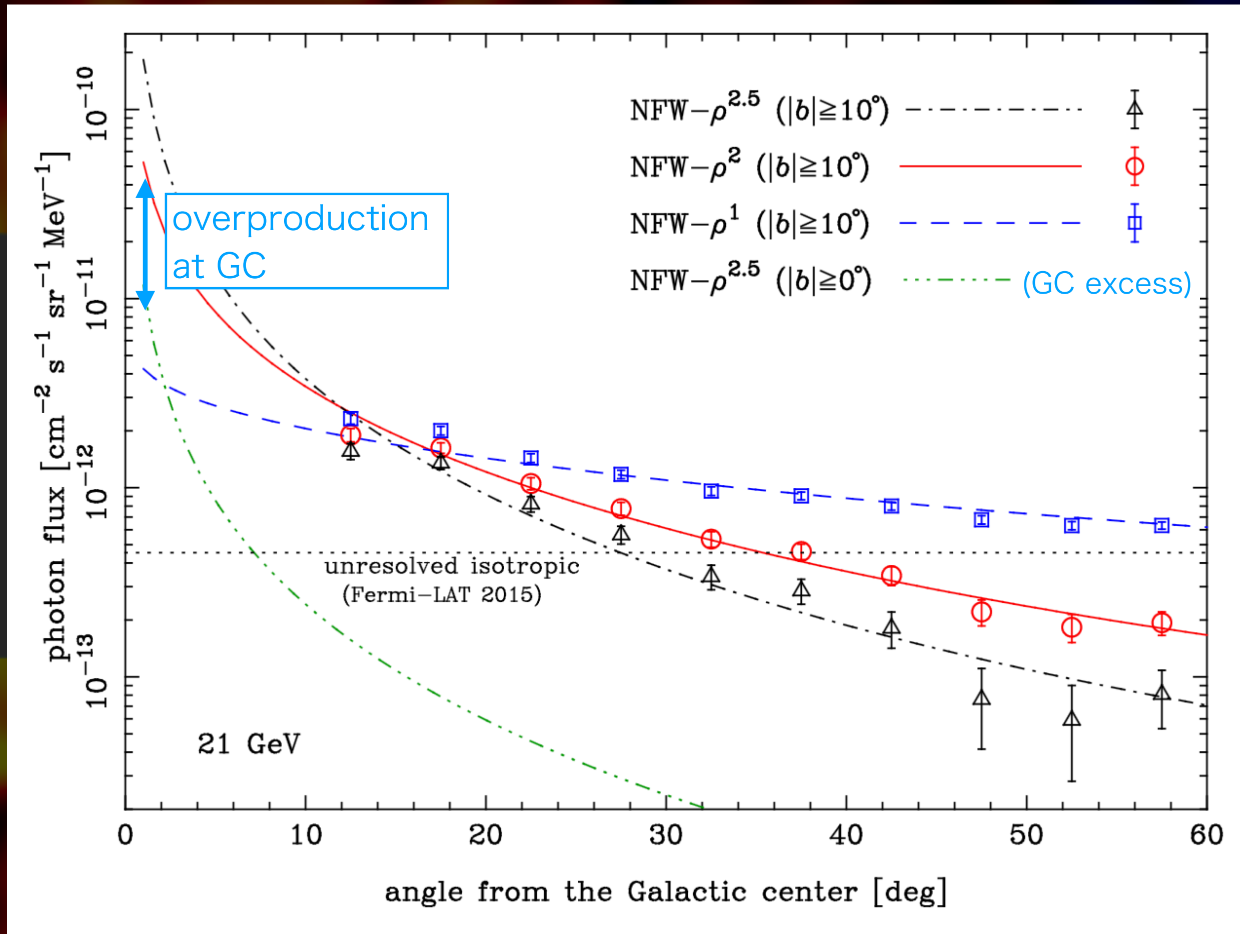
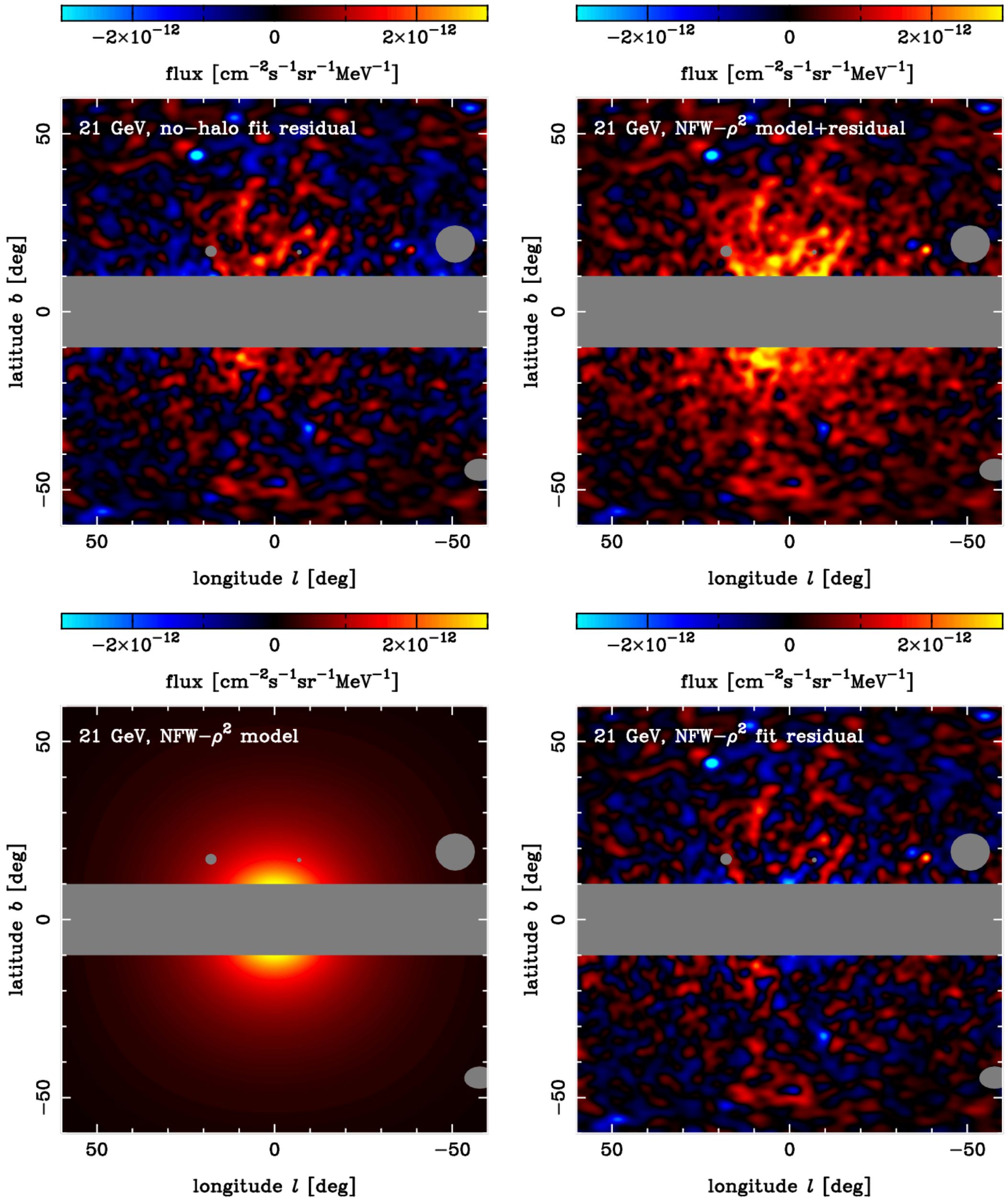
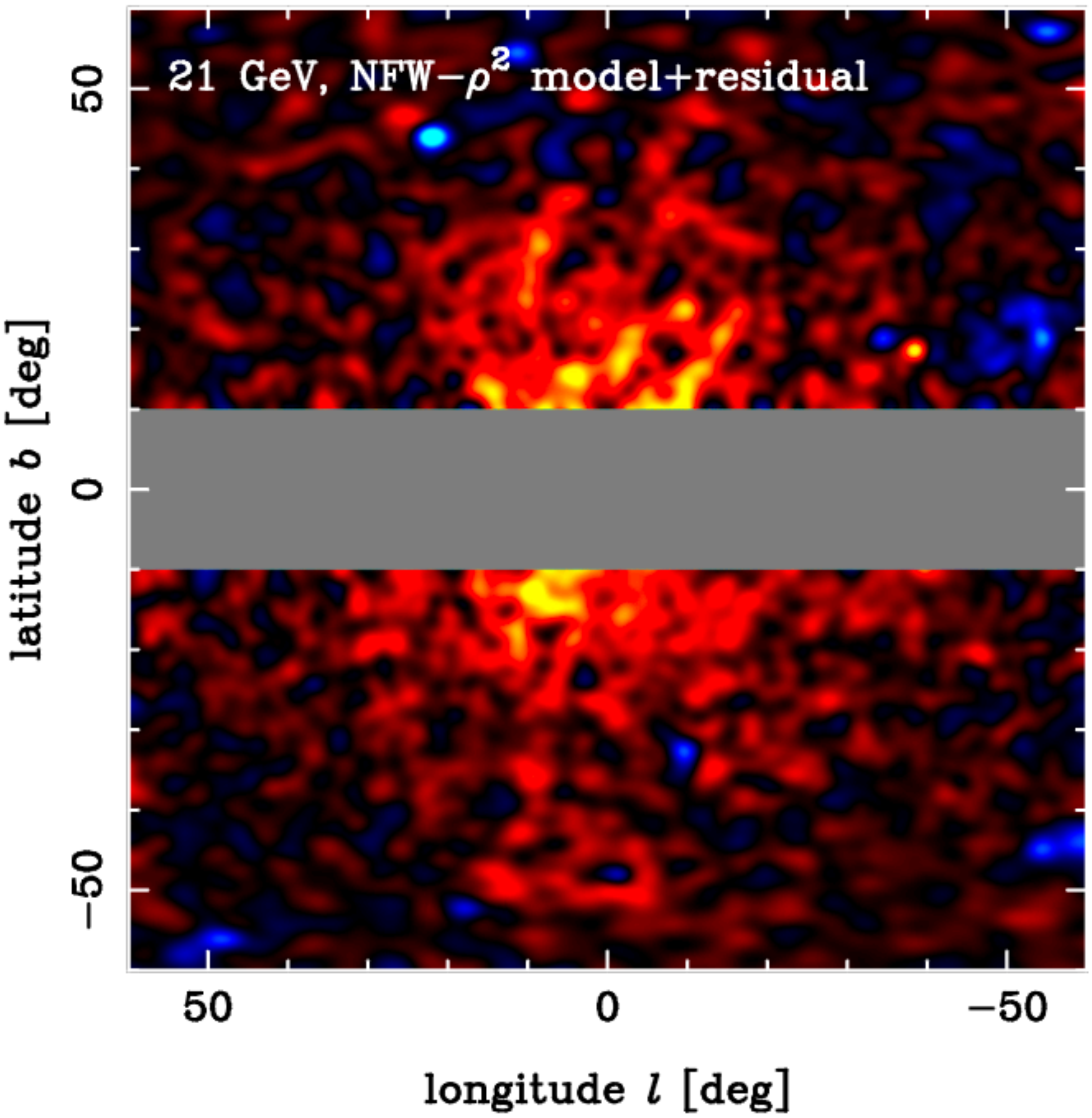


Morphologies of the halo excess at 21 GeV bin

- residual of no-halo fit
  - a halo-like excess can be seen
- the best-fit NFW-ρ^2 model + residual
  - the halo-like excess clearly seen
- residual of the fit with NFW-ρ^2 model
  - no significant residuals within the region of interest
  - The fit by “known components plus the halo” is successful in describing the data

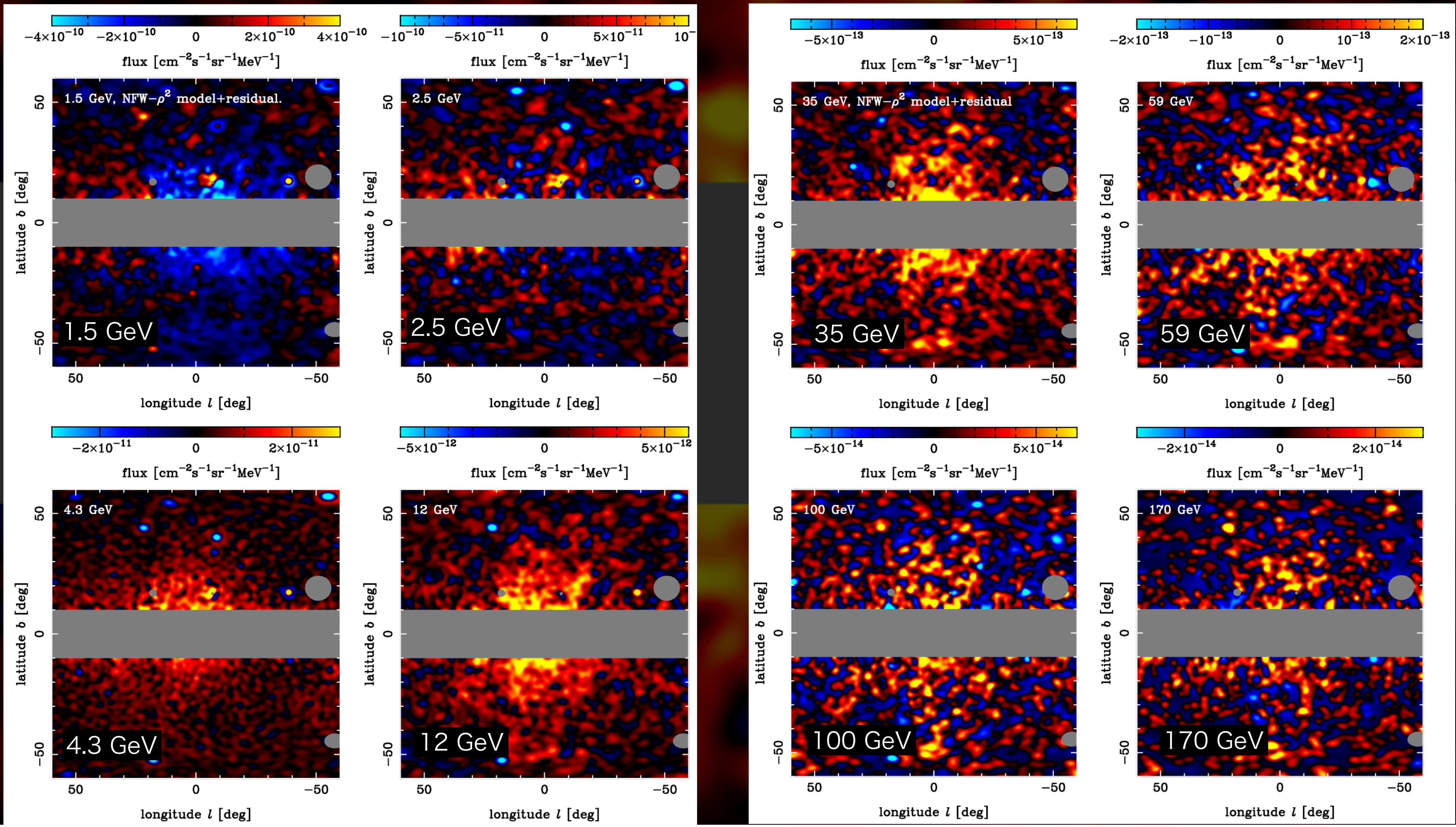




21 GeV, NFW-ρ^2 model+residual
50
0
−50
latitude b [deg]
50
0
−50
longitude l [deg]

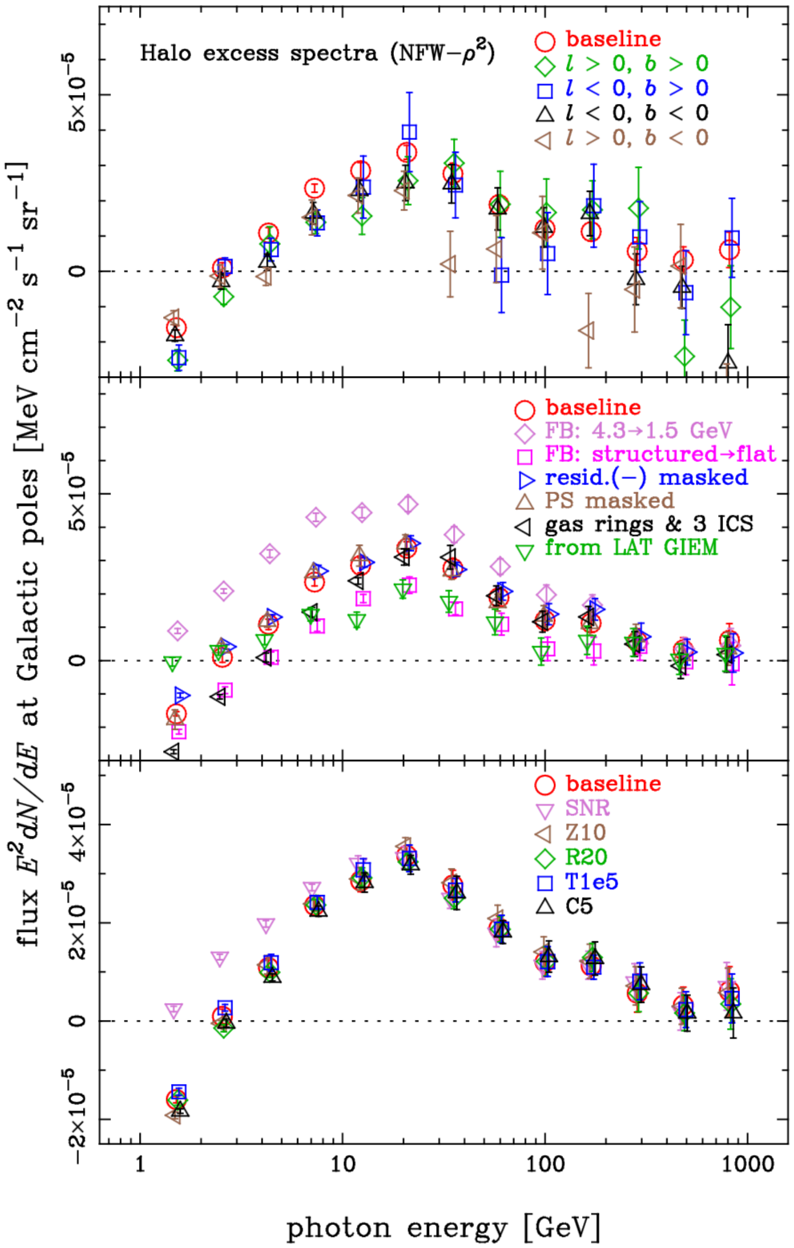
Morphologies of the halo excess

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



Examination of systematics

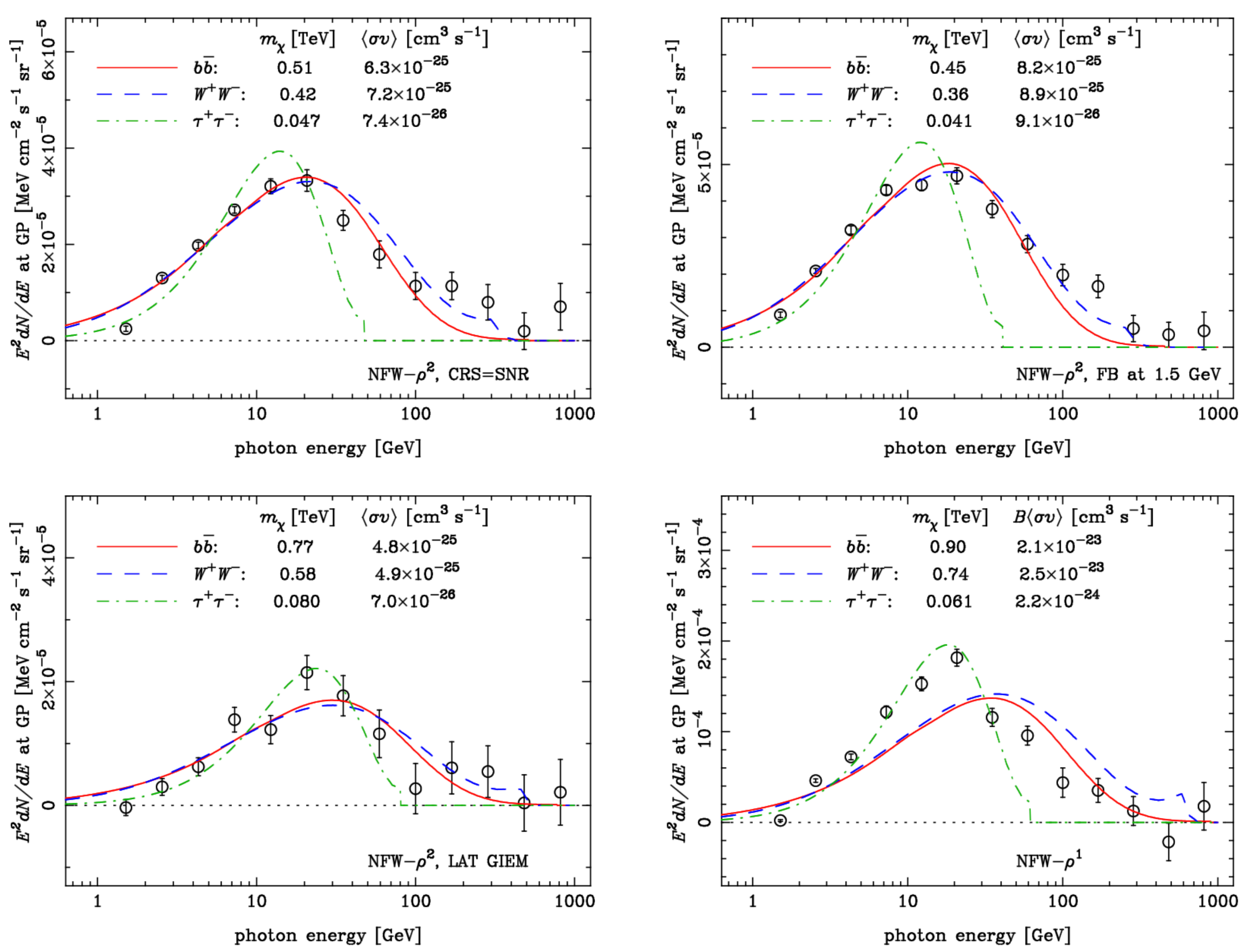
- divided into four quadrants around GC
- FB template modeling:
  - change the energy bin 4.3 → 1.5 GeV
  - structured → flat FB template
  - negative residual region masked
- halo excess against the LAT GIEM (Galactic interstellar emission model)
  - LAT standard background model recommended for point-source 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

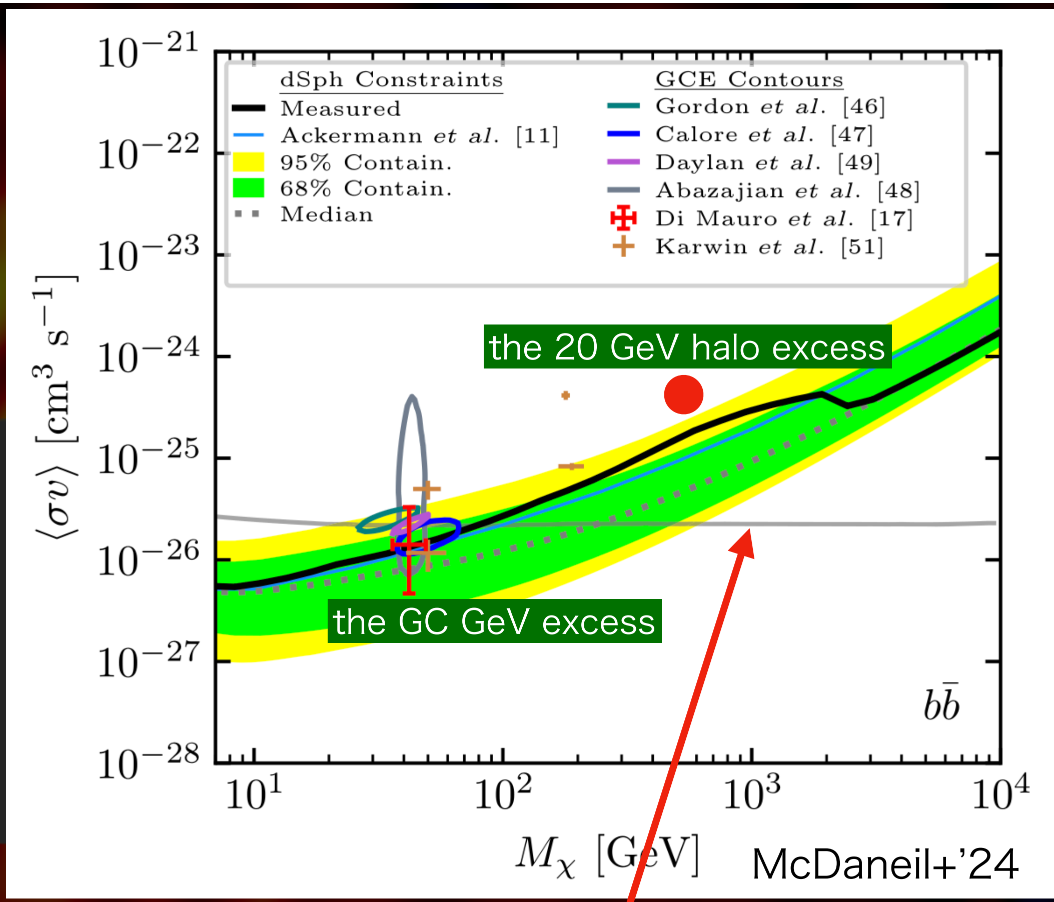
- annihilation gamma-ray spectrum (PPPC4DMID) fit to:
  - three cases of NFW-ρ^2
    - not negative at ~ 1 GeV
  - baseline case of NFW-ρ^1

- 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



Discussion on WIMP parameters

- Comparison with other constraints
  - 〈σv〉 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 halo DM density
      - density profile function
      - density around the Solar System
    - uncertainty also in dSph analysis
  - A similar level of tension exists for the GC GeV excess



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

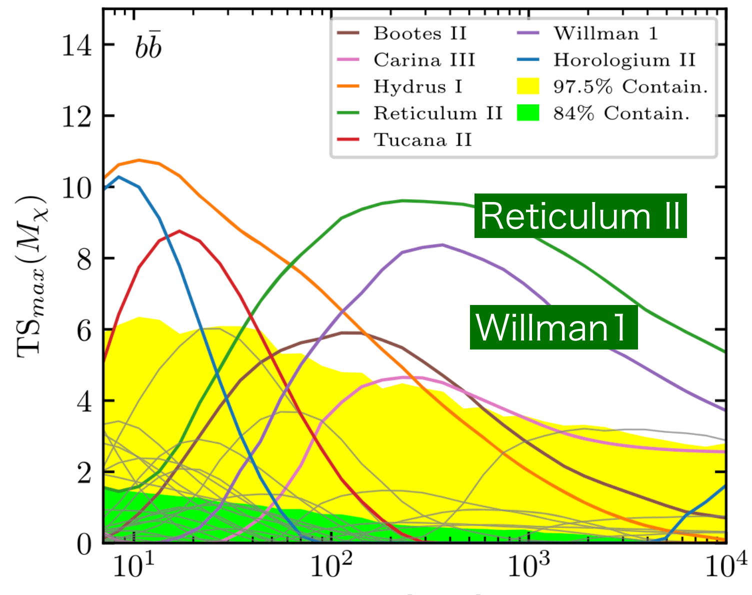
- Comparison with theoretical expectation?
  - 〈σv〉 from the halo excess is more than 10 times larger than the canonical thermal relic value
  - many possibilities of σ enhancement in particle physics theory, e.g. the Sommerfeld correction
  - uncertainty in MW halo DM density

Prospects for future verification

- dwarf galaxy observation:
  - A modest improvement in near future should lead to detection
    - with the same energy spectrum as the halo excess
  - Some dSph are already showing interesting excess
    - the largest excess: Reticulum II (2-3σ)
    - preferred DM mass (0.2-0.6 TeV) is consistent with the MW halo excess!

- line gamma-rays expected around DM mass (~0.5 TeV)
  - ground air-Cherenkov telescopes
    - CTAO will achieve a great sensitivity improvement in near future
  - depends on branching ratio into line gamma-ray production

- Neutrinos?
  - The present IceCube upper limit toward GC (W^+W^-) is about 20 times larger than ⟨σv⟩ of the 20 GeV halo excess
  - Can this sensitivity be achieved by detectors in the future?



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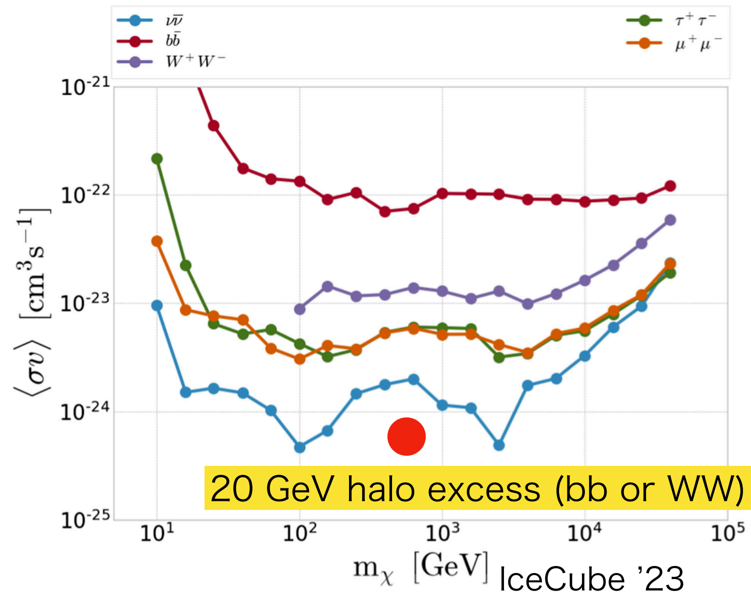

IceCube '23

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, in addition to the known components (cosmic-ray interactions, Loop I, Fermi bubbles, …)
- Radial angular profile matches well the NFW profile, assuming annihilation with a smooth density profile (no substructure)
- The 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, $\langle \sigma v \rangle$ ~ 6×10^{-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)
- Future verification is possible, especially by dwarf spheroidal galaxy observations