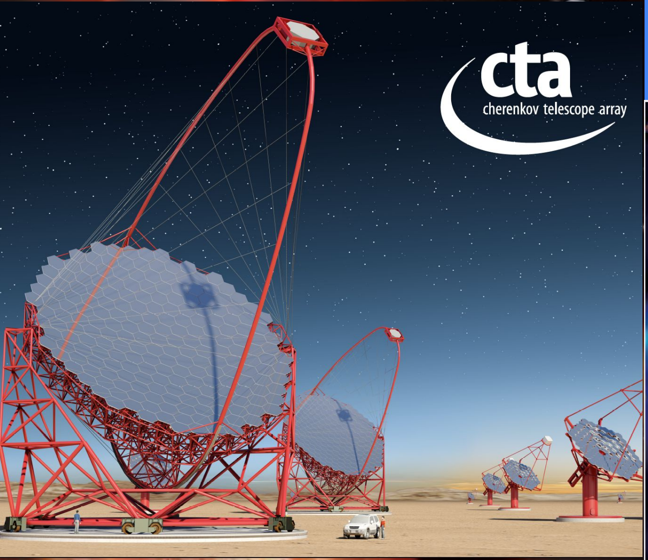
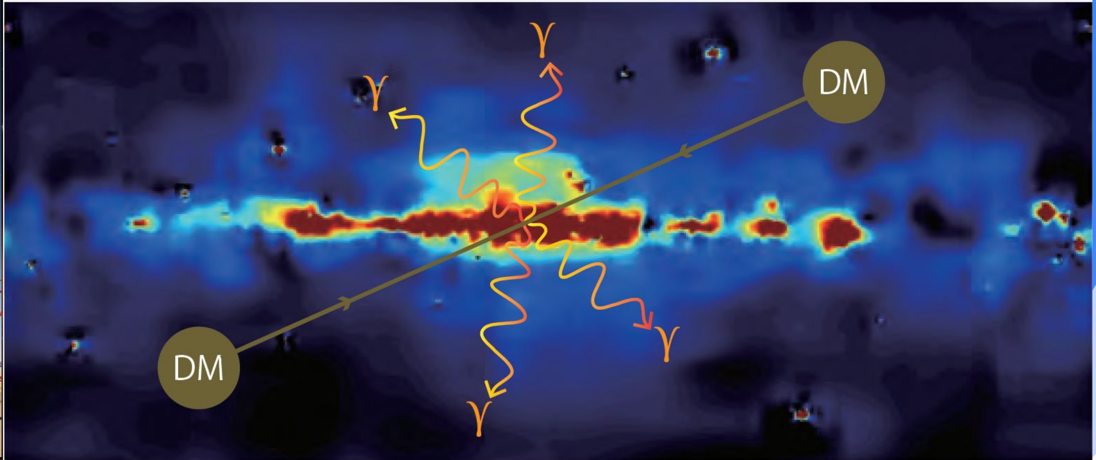
Indirect Search for DM Signal from Galactic Center

T. Mizuno (Hiroshima Univ.)

DMNet Symposium, 2022 Sep. 15th
MPIK





Dark Matter (DM) Search with Gamma-rays

Gamma-rays may encrypt the DM signal

Gamma-ray Flux
(measured by Fermi, CTA)

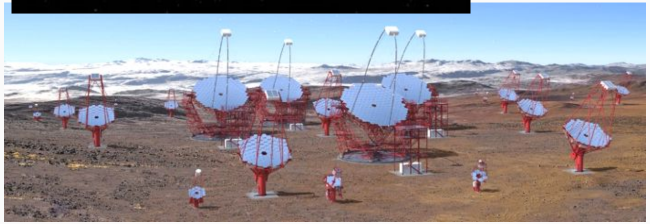
Particle Physics
(photon per annihilation)

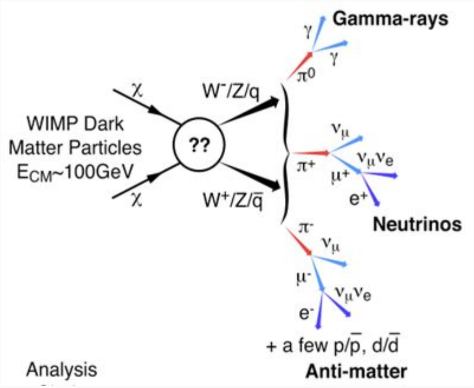
$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f$$

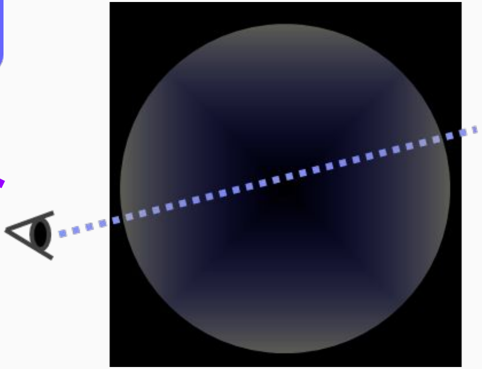
$$\times$$

$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

Astrophysics
(DM distribution)







Dark Matter (DM) Search with Gamma-rays

Gamma-rays may encrypt the DM signal

Gamma-ray Flux **(measured by Fermi, CTA)**

Particle Physics **(photon per annihilation)**

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f$$

$\langle\sigma v\rangle \sim 3\times10^{-26}$ cm^3 s^{-1}
to reproduce the matter density
(if DM is a thermal relic)

$$\times$$

$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))\,dl(r,\phi')$$

(J-factor)

Astrophysics **(DM distribution)**

Indirect search for a DM signal is complementary to direct detection (e.g, distribution of DM)

NFW profile usually assumed

$$\rho(r) = \rho_0 \frac{r_0}{r}\frac{(1+r_0/a_0)^2}{(1+r/a_0)^2}$$

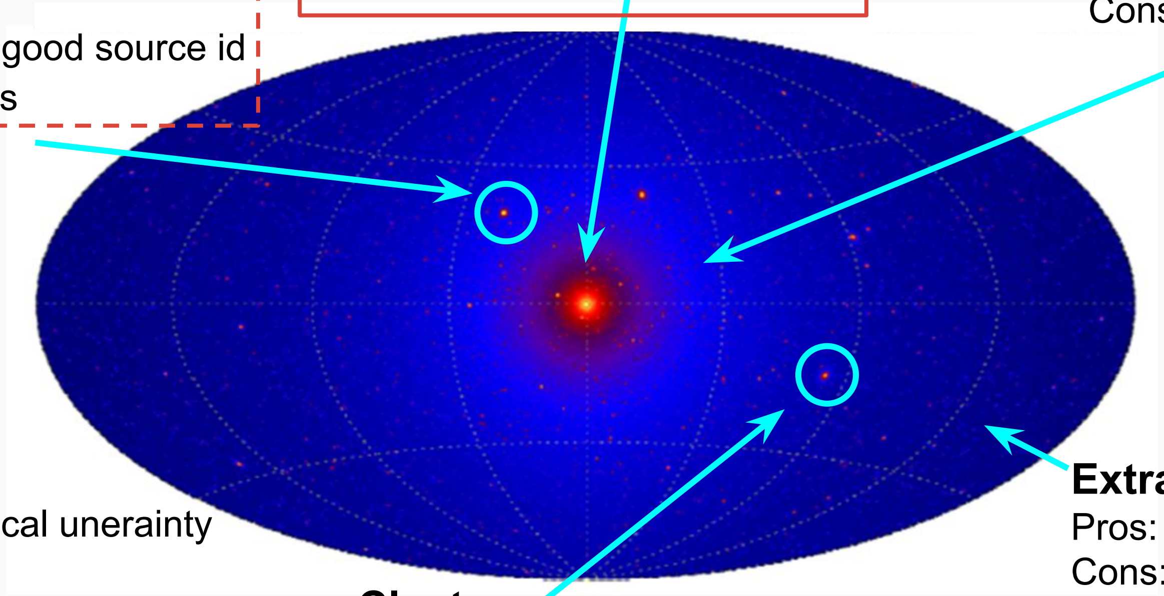
(ρ_0~0.3 GeV cm^{-3}, a_0~20 kpc, r_0~8.5 kpc for the MW)

DM Search Strategies with Gamma-rays

Galactic Center
Pros: good statistics
Cons: diffuse/astrophysical BG

MW halo
Pros: very good statistics
Cons: diffuse BG

Satellites
Pros: low BG and good source id
Cons: low statistics



Spectral lines
Pros: no astrophysical unerainty (smoking gun)
Cons: low statistics, instrumental uncertainties (e.g., PRD 88, 082002 (2013))

Clusters
Pros: low BG and good source id
Cons: low statistics, astrophysical uncertainties

Extragalactic
Pros: very good statistics
Cons: diffuse BG, astrophysical uncertainties

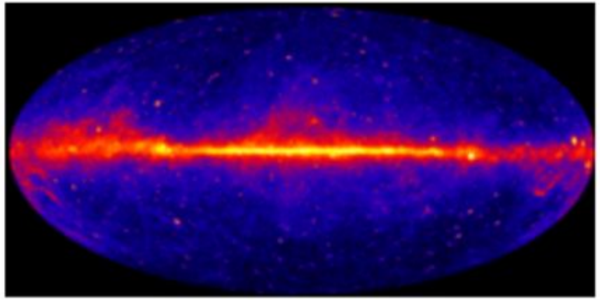
DM Search Strategies with Gamma-rays (Cont'd)

In short, we search for DM signal in gamma-rays by using their spatial and spectral signatures

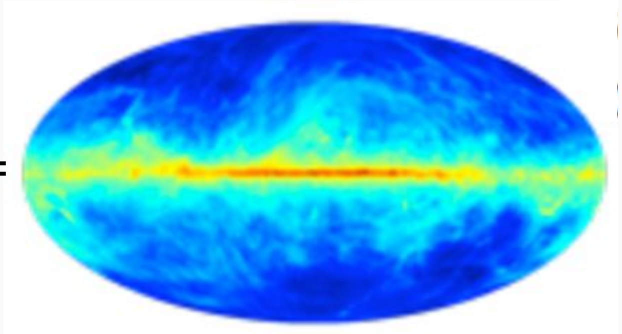
Gamma-ray data

Galactic diffuse, sources, isotropic (+unresolved sources)

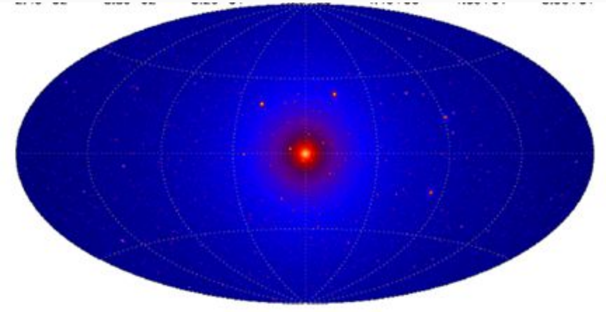
DM signal (e.g., Galactic center)?



=



+



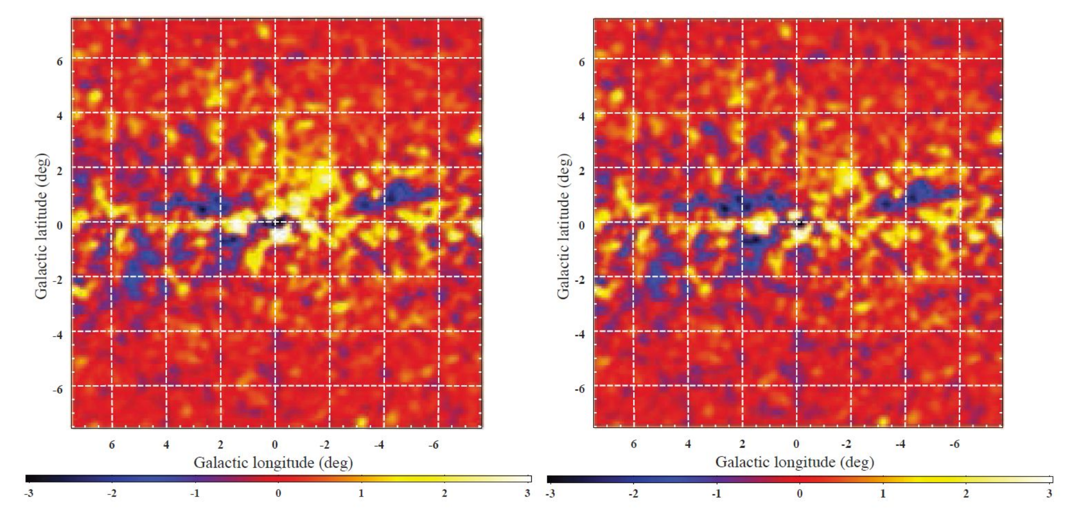
Good understanding of diffuse BG is crucial
Complementary searches from several source types are also important

Galactic Center Excess (GCE)

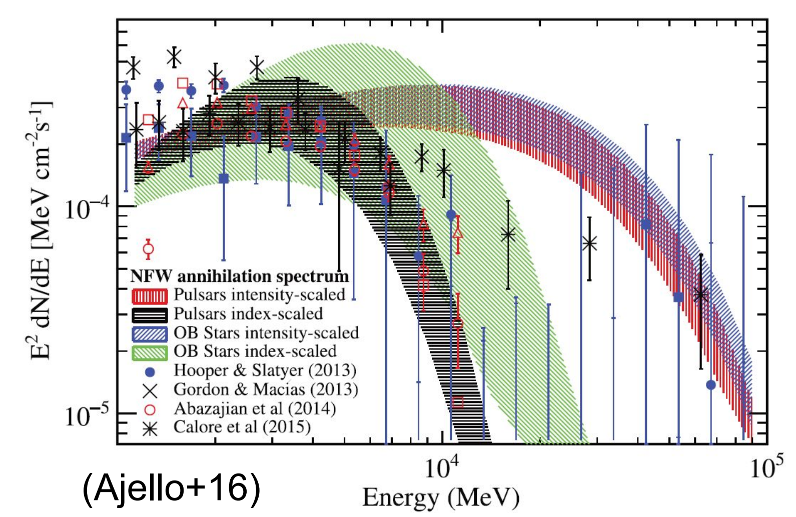
Several groups reported excess emission at a few GeV from Galactic Center (GCE) in Fermi-LAT data that is compatible with DM signal (of M_{WIMP} = a few 10s GeV)

- Spectrum depends on assumed BG model

Residual w/o (left) and w/ (right) GCE template



GCE spectrum



(Ajello+16)

Uncertainty of GCE Energy Spectrum

We started with a sample model and studied uncertainty of GCE spectrum due to BG model

Data/ROI

CR propagation model

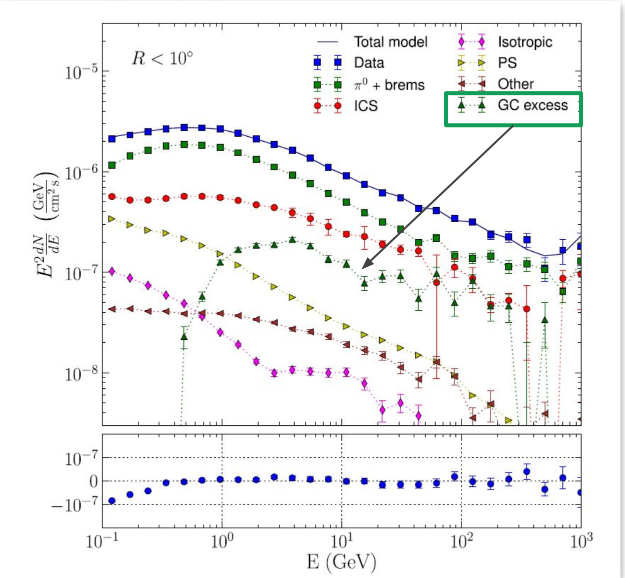
Gas model

CR sources @GC

Fermi bubble

Point sources

Variation	Parameters	Effect on GC excess	Energy range
Choice of the data sample	Clean, UltraCleanVeto, UltraCleanVeto PSF 2 and 3	Minor Slightly larger	All Below 1 GeV
Choice of the ROI	$\|b\|,\ \|\ell\| < 10°$ $\|b\|,\ \|\ell\| < 20°$ $\|b\|,\ \|\ell\| < 30°$	Significantly larger	Below 1 GeV
Tracers of CR sources	OB stars Pulsars and SNRs		
Propagation halo size	$z = 4$ kpc $R = 30$ kpc		
Spin temperature	Optically thin		
IC models	Split in 5 rings Combine all rings and ISRF components		
Gas distribution	*Planck*, GASS surveys SL extinction		
GC CR sources	Bulge electron source CMZ, $z = 2$, 4 kpc CMZ, $z = 8$ kpc		
Fermi bubbles	…		
PS templates within 10°	3FGL, Pointlike Fermipy		
Refit PS within 10°	3FGL, Fermipy, 1FIG Pointlike 3FGL, Pointlike, Fermipy, 1FIG		

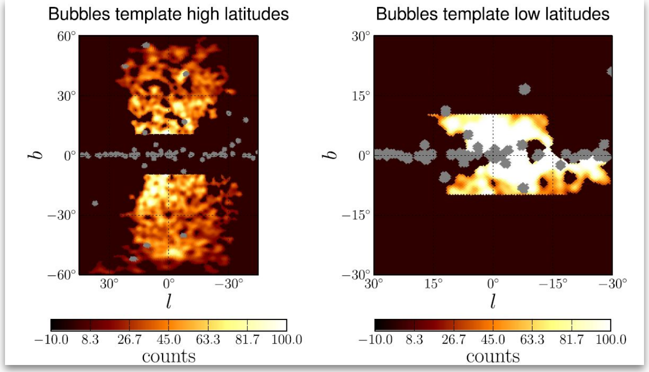


(Ackermann+17)

Uncertainty of GCE Energy Spectrum (Cont'd)

We studied uncertainty of GCE spectrum due to BG model

- Several alternative models appreciably reduce the spectrum (some of them may be too conservative, though)
- Including Fermi bubble (has no "a priori" template and has been omitted in most of past studies) significantly reduces the spectrum



FB template derived using data itself (spectral component analysis proce)

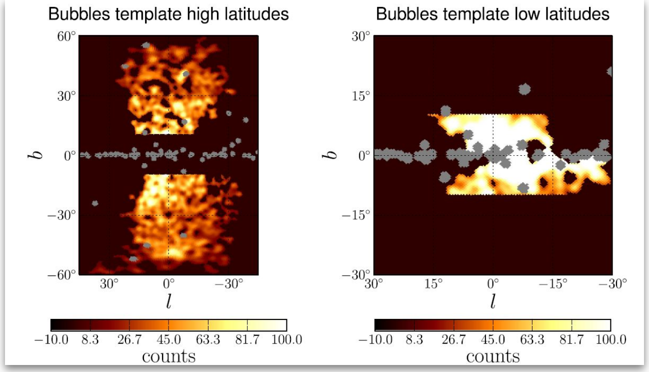
IC models	Split in 5 rings	Smaller	All
	Combine all rings and	…	…
	ISRF components	Smaller	All, especially below a few GeV
Gas distribution	*Planck*, GASS surveys	Slightly smaller	Below 1 GeV
	SL extinction	Larger	Below 1 GeV
GC CR sources	Bulge electron source	Smaller	Between 1 and 10 GeV
	CMZ, $z = 2$, 4 kpc	Minor	All
	CMZ, $z = 8$ kpc	Smaller	Below a few GeV
Fermi bubbles	…	Excess vanishes	Below 1 GeV, above 10 GeV
		Smaller	Between 1 and 10 GeV
PS templates within 10°	3FGL, Pointlike	Slightly larger	Below 1 GeV
	Fermipy	Larger	Below 1 GeV
Refit PS within 10°	3FGL, Fermipy, 1FIG	Larger	Below a few GeV
	Pointlike	Smaller	All, especially below a few GeV
	3FGL, Pointlike, Fermipy, 1FIG	Smaller	Above 10 GeV

(Ackermann+17)

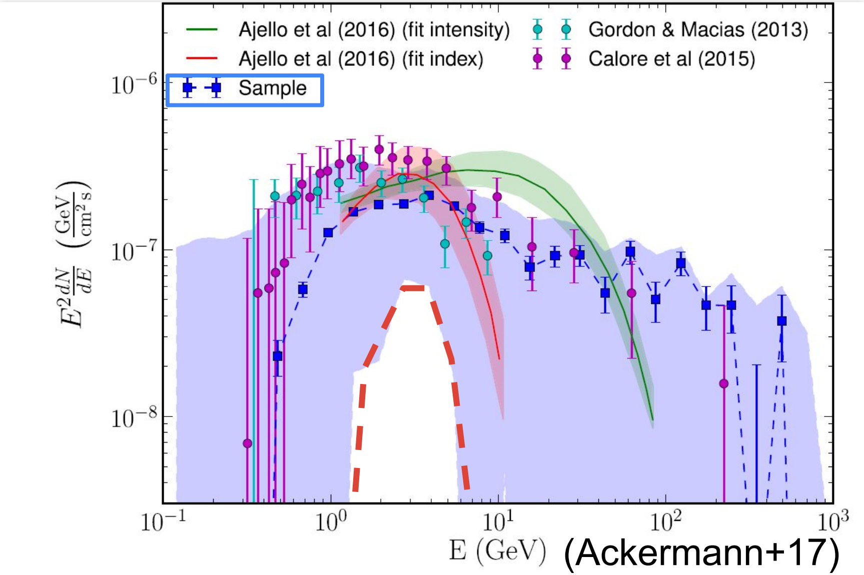
Energy Spectrum of GCE

We studied uncertainty of GCE spectrum due to BG model

- Several alternative models (e.g, that w/ FB) appreciably affects the spectrum
- An excess around a few GeV is always statistically significant, but can be much smaller than that with sample model and most of those reported in the past



FB template derived using data itself
(NB sources are masked)

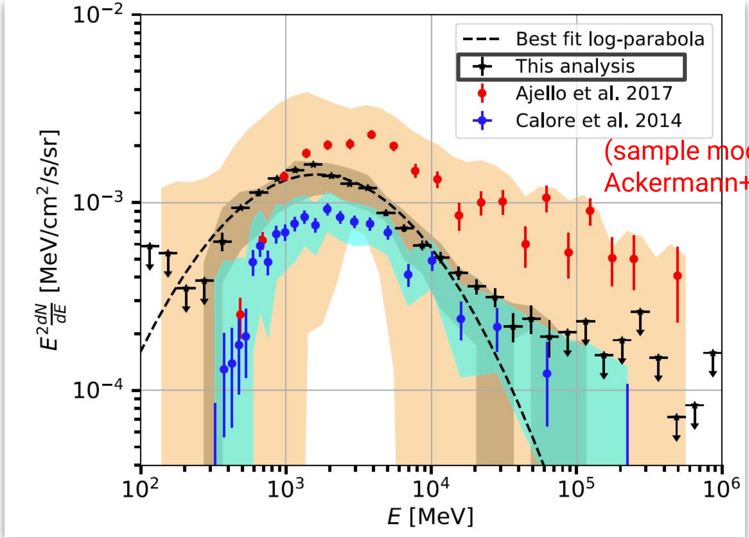


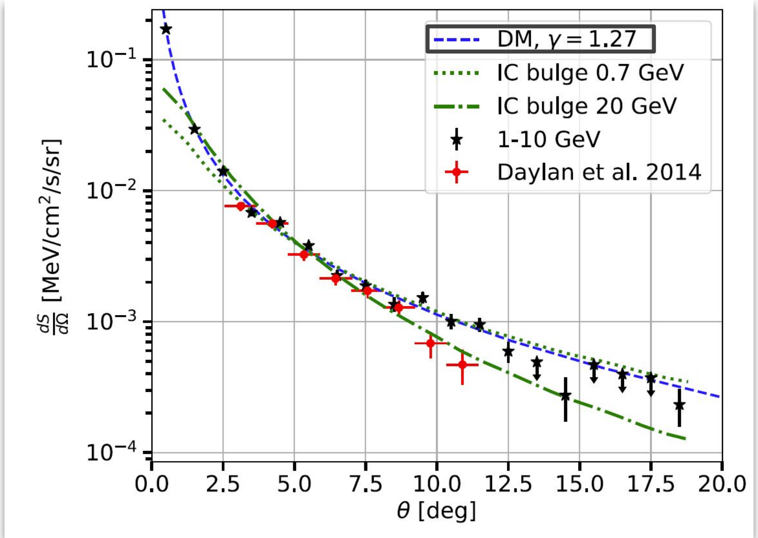
(Ackermann+17)

Morphology of GCE

Di Mauro 2021 examined GCE properties in detail w/ updated analysis (data and # of sources doubled, sources not masked)

- Confirmed (reduced) spectrum
- An excess is spherically symmetric and compatible with gNFW profile of γ~1.25
  - Millisecond pulsar (MSP) scenario can also explain the data (e.g., Eckner+18)





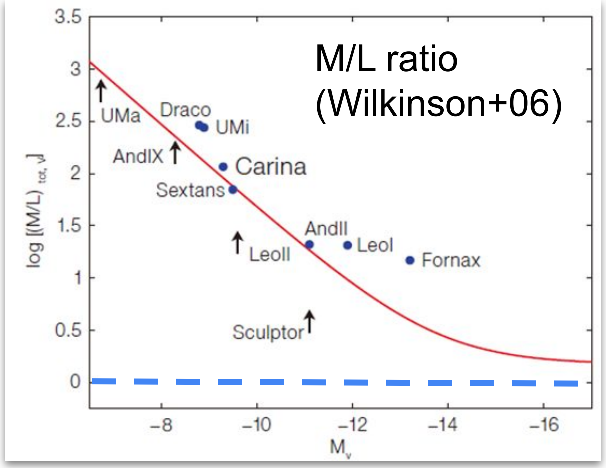
(Di Mauro 2021)

Search for a Galactic DM Substructure

In the standard cosmological model, structures form from bottom up; numerical simulations predict that the MW should be surrounded by smaller structures

Optically observed Dwarf Spheroidal (dSph) galaxies are the most attractive candidates

- known position and mass (stellar velocity dispersion), high M/L ratio
- Low astrophysical background (complementary to GCE)

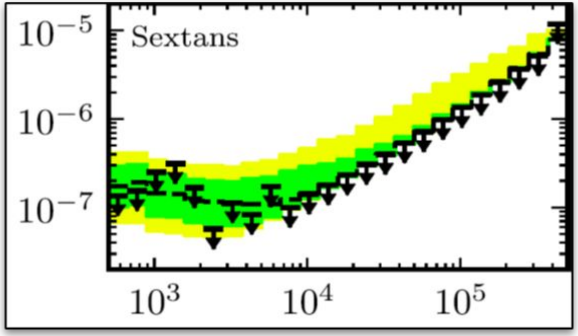


1x M_{Sun}/L_{Sun}

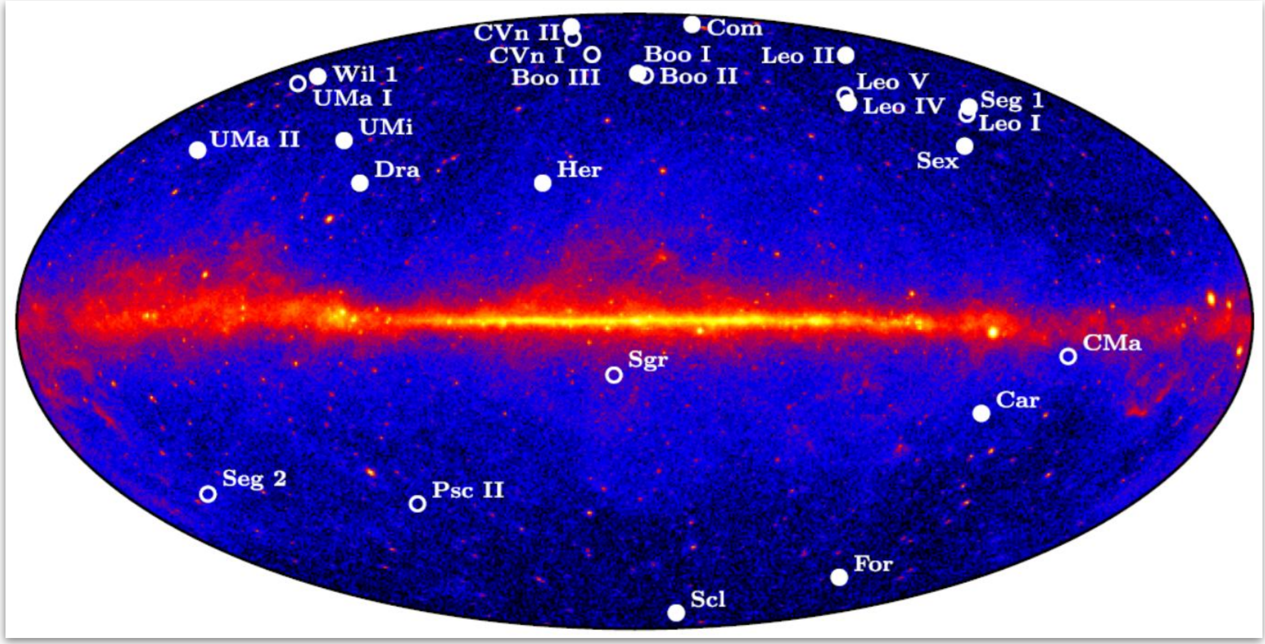
Fermi-LAT Study of dSphs

We investigated 25 dSphs and found no significant gamma-ray emission

- => combined analysis using 15 “well behaved” samples



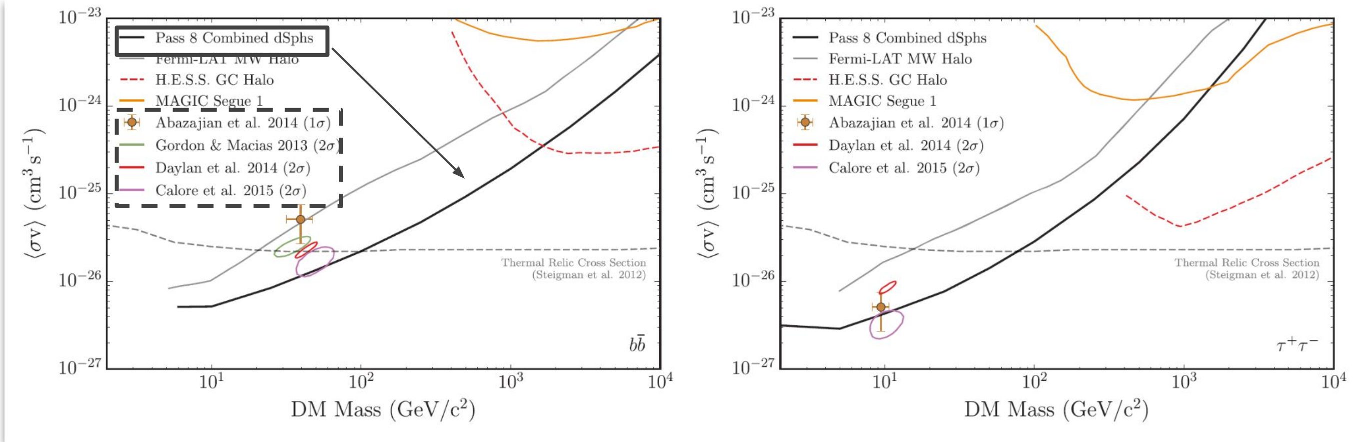
(Ackermann+14)

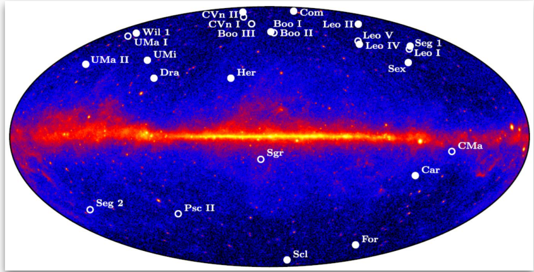


Fermi-LAT Study of dSphs (Cont'd)

No significant emission found => combined analysis using well behaved samples

- 18 dSphs w/ kinematically determined J-factors
- 15 "non overlapping" sources used for the combined analysis (filled circles in image)
  - (again) no detection; gave upper limit
- M_{WIMP}<=100 GeV not favored
- DM scenario for nominal GCE not completely excluded, but in tension with obtained limit
- (Updated analyses by Albert+17 and Di Mauro+21 confirmed the conclusions)





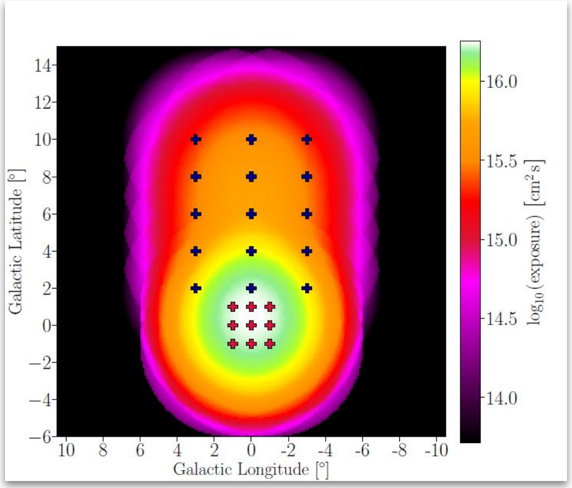
(Ackermann+15)

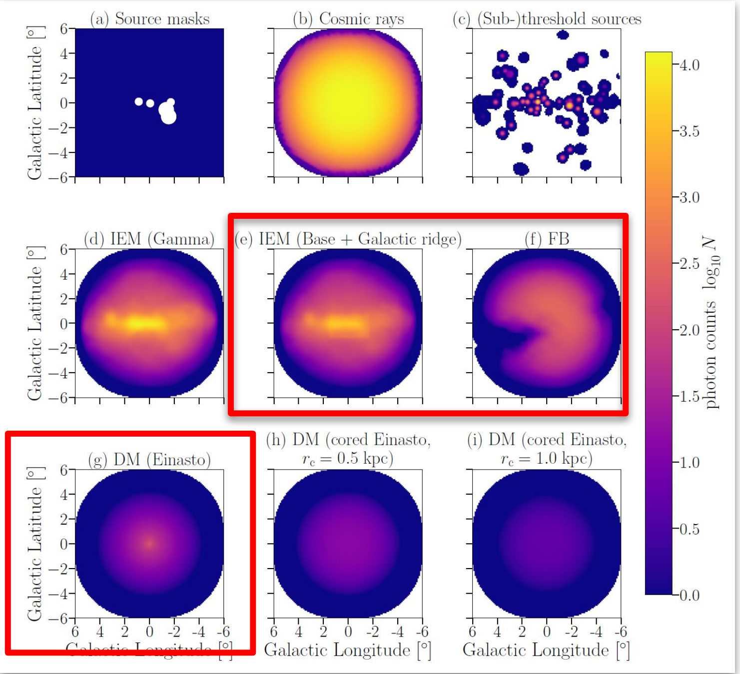
CTA Search for DM from GC

Issues for nominal GCE (M_{WIMP} = a few 10s GeV)

Possible signal in larger M_{WIMP} will be explored w/ more data (Fermi) and Cherenkov Telescopes Array (CTA)

Planned exposure (left)
Signal/BG templates (right)
(Acharya+21)



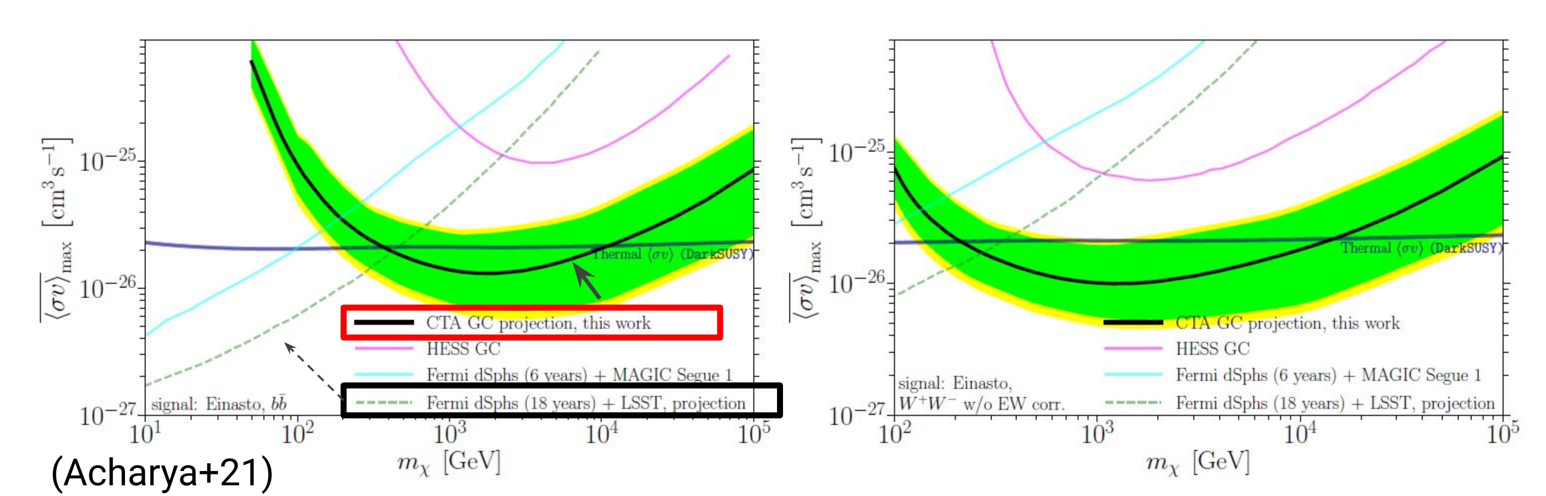


Expected Sensitivity w/ CTA

Expected sensitivity studied by realistic MC simulations (astrophysical BG, instrumental systematics) N_{err}=1%, l_s=0.1deg (~PSF size)

Mean projected sensitivity reaches thermal <σv> in a few 100s GeV - 10 TeV

With a factor of 3 improvement of Fermi (more exposure and dSphs), M_{WIMP} in 0.01-10 TeV will be covered with sensitivity at thermal <σv>



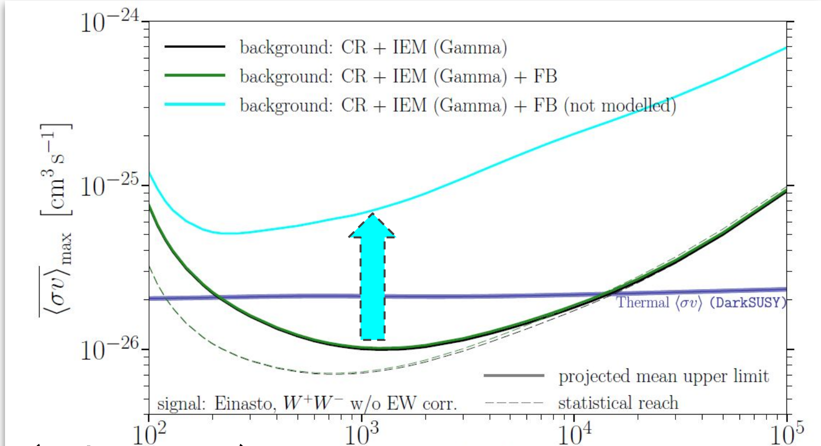
(Acharya+21)

Path to Achieve the Sensitivity

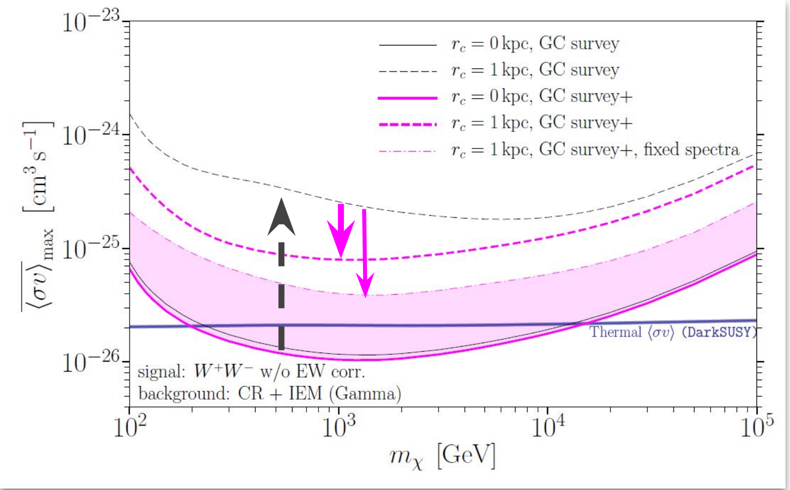
W/ Fermi and CTA, M_{WIMP} in 0.01-10 TeV will be covered with sensitivity at thermal <σv>

Two major sources of uncertainty:

- FB morphology in TeV not known (Herold+19 suggests similar profile in TeV)
- DM profile may be less peaked (extended GC survey mitigates the effects)



(Acharya+21)



Summary

Indirect search for DM signal using gamma-rays is complementary to direct detection (e.g., distribution of DM)

GC (and dSphs) are promising targets. Fermi & CTA will cover M_{WIMP} in 0.01-10 TeV

Fermi GCE (at a few GeV) is statistically significant and compatible with gNFW

- Spectrum is significantly affected by astrophysical sources toward GC. MSP can explain the GCE as well

CTA GC observation will cover M_{WIMP}>=300 GeV

- Preparing good templates for FB and DM profile is key to success

Thank you for your attention

References

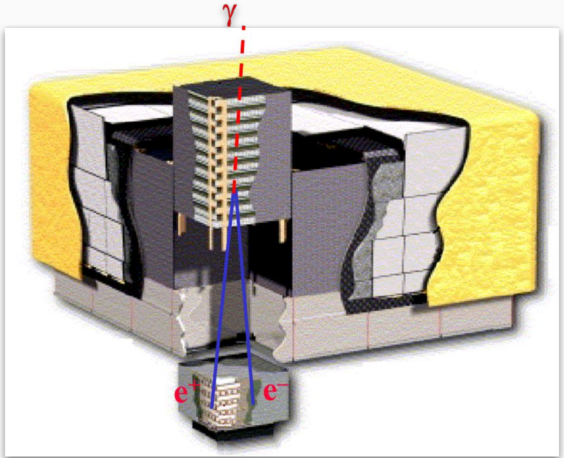
- Atwood et al. 2009, ApJ 687, 1071
- Ackermann et al. 2013, PRD 88, 082002
- Ajello et al. 2016, ApJ 819, 44
- Ackermann et al. 2017, ApJ 840, 43
- Di Mauro 2021, PRD 103, 063029
- Eckner et al. 2018, ApJ 862, 79
- Ackermann et al. 2014, PRD 89, 2001
- Ackermann et al. 2015, PRL 115, 231301
- Albert et al. 2017, ApJ 834, 110
- Di Mauro et al. 2021, PRD 103, 123005
- Acharya et al. 2021, JCAP 1, 57
- Herold et al. 2019, A&A 625, 110

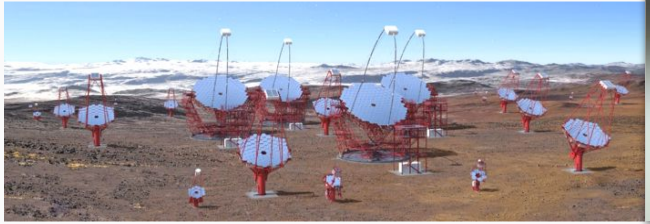
Backup Slide

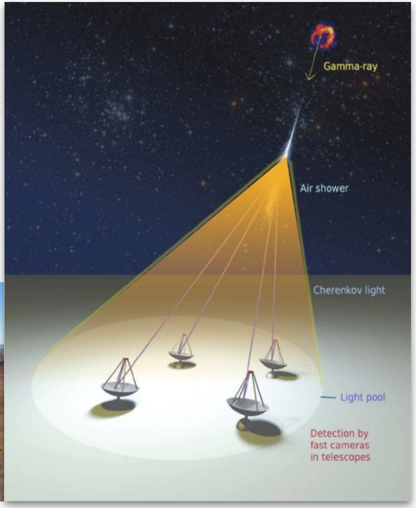
Fermi & CTA

Fermi-LAT: Space-borne gamma-ray telescope (pair-conversion type) consists of Si Tracker, CsI calorimeter and anti-coincidence detector (20 MeV to >300 GeV)

CTA: Ground-based gamma-ray telescope (imaging atmospheric Cherenkov telescope) consists of LST (large-sized telescope), MST (medium sized) and SST (small-sized) (20 GeV to 300 TeV)



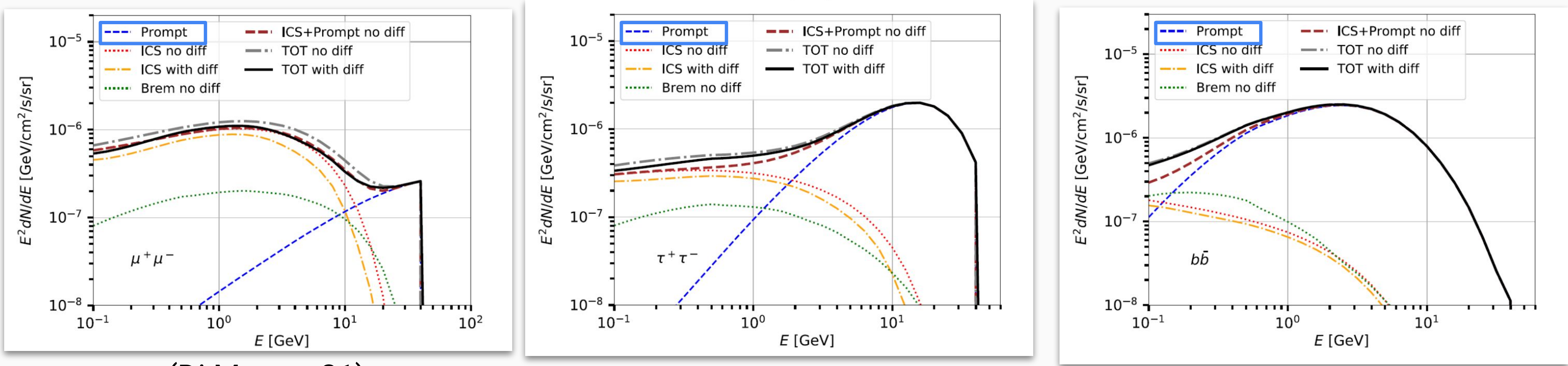




DM Annihilation Signal in Gamma-Rays

Expected gamma-ray signal from DM (M=50 GeV) annihilation into $\mu^+\mu^-$ (left), $\tau^+\tau^-$ (middle) and b b-bar (right) for GC

- Contribution from secondary (Inverse Compton) is minor for b b-bar (and $\tau^+\tau^-$)



(Di Mauro+21)

FB in Energies up to 1 TeV

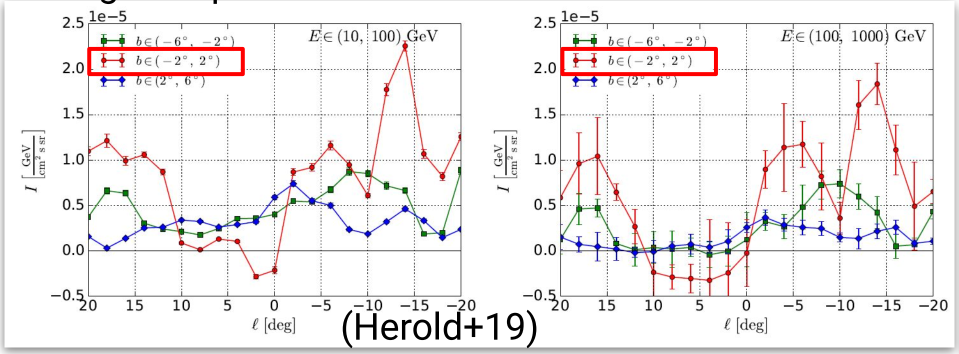
Herold+19 employed several methods to study gamma-ray emission at the base of FB (low-latitude FB) in high E

- (Empirical) rectangles-model of FB + background based on low-E data, or subtract (physical) background model based on Galprop

Low-latitude FB is shifted to the west and is extended >= 500 GeV

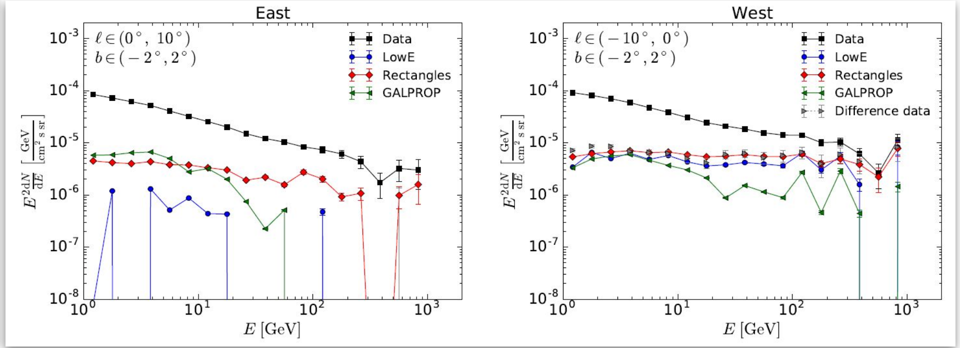
- (Supermassive black-hole scenario not favored)
- Supports using FB template of Ackermann+17 for CTA sensitivity study

Longitude profile



(Herold+19)

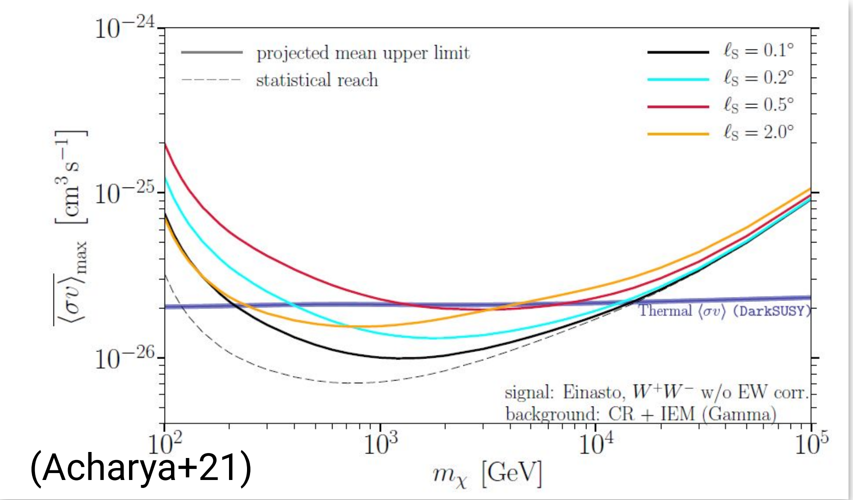
Spectrum



Effect of Instrumental Systematics and Background Model

Effects on sensitivity from instrumental systematics (left) and assumed background model (right) are examined and confirmed to be small

Several choices of spatial correlation length l_s (with 1% overall normalization error)



(Acharya+21)

Several choices of background model