15th International Workshop on the Identification of Dark Matter 2024, L'Aquila (Italy)

Search for dark matter decay and annihilation using γ ray observation by Tibet AS$_\gamma$

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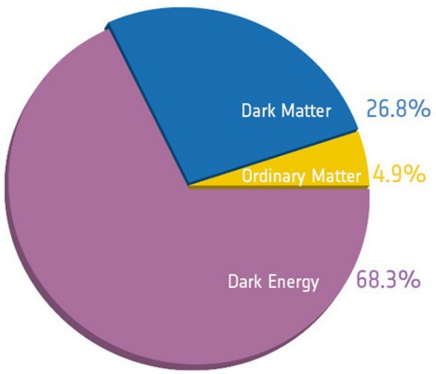
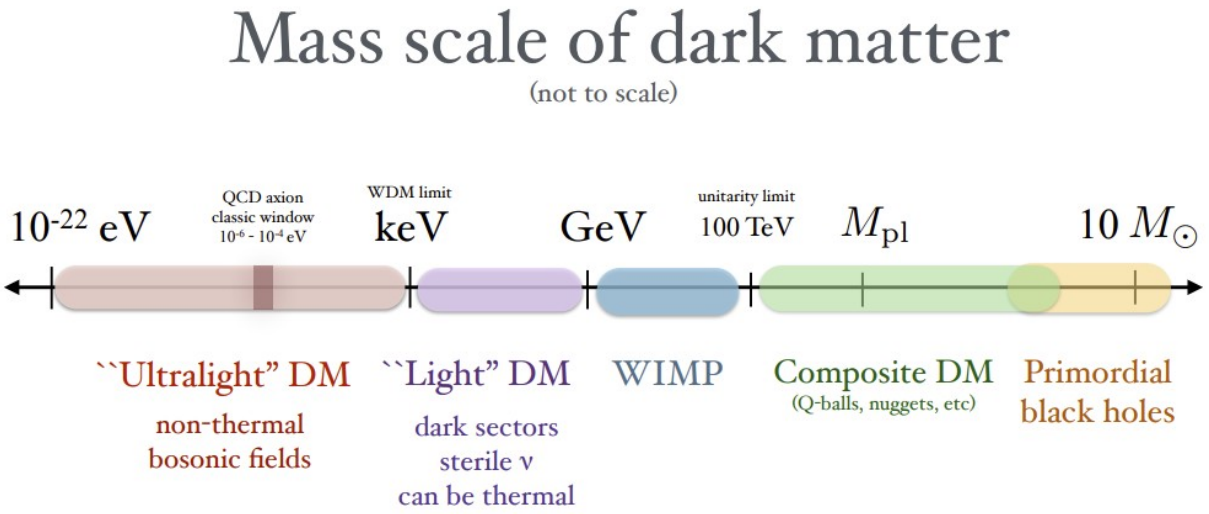
Based on arXiv:2105.05680 (PRD Letter) & Dubey et al (In Prep.)

In collaboration with
Tarak Nath Maity, Akash Kumar Saha and Ranjan Laha

Dark Matter (DM)



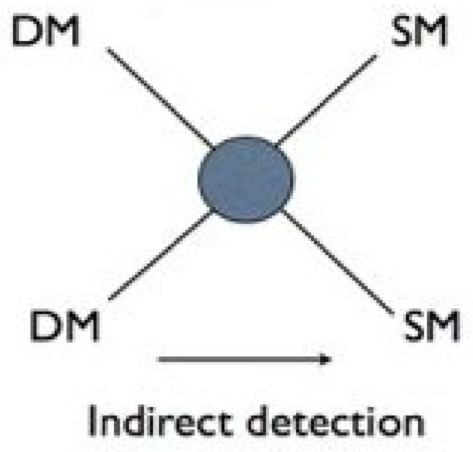
- No electric charge
- No or very little baryonic interactions
- Long-lived or stable



https://darkmatterdarkenergy.com/2013/06/18/more-dark-matter-first-planck-results/

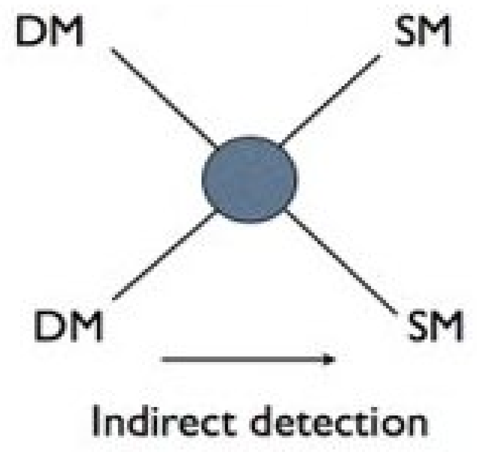
http://abyss.uoregon.edu/~js/21st_century_science/lectures/lec23.html

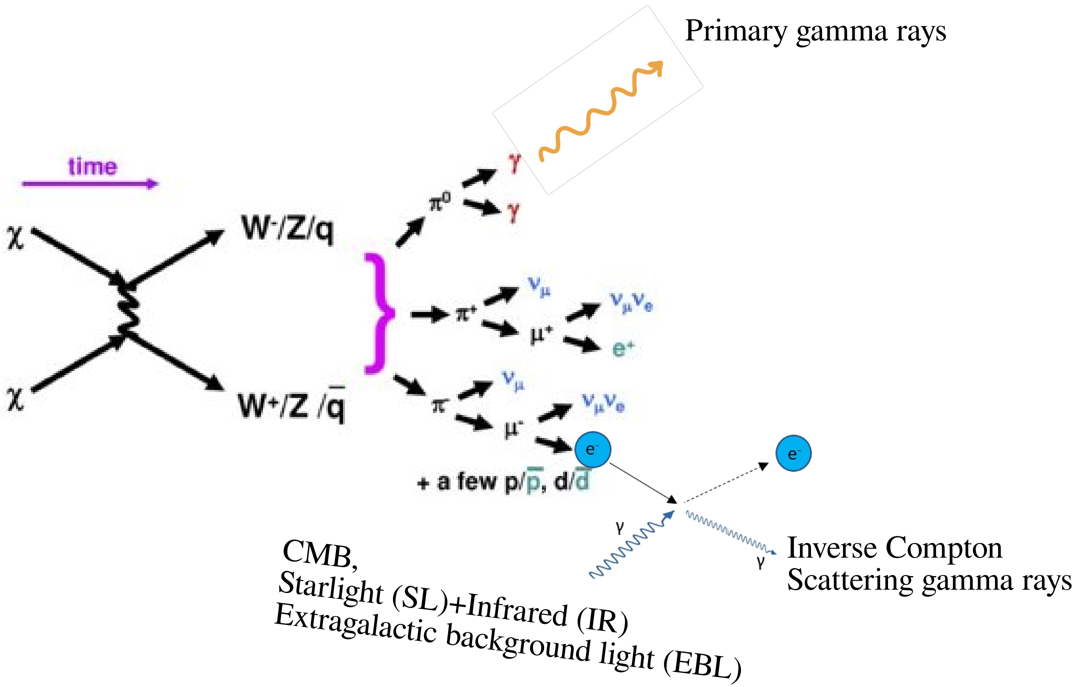
Dark Matter Indirect detection



https://particleastro.brown.edu/dark-matter

Dark Matter Indirect detection





https://particleastro.brown.edu/dark-matter

https://conferences.pa.ucla.edu/ATI-2018/talks/weniger.pdf

Flux of gamma rays from DM decay/annihilation

DM decay

$$\frac{d\Phi^G}{dE_\gamma} = \frac{1}{4\pi m_\chi \tau_\chi} \frac{dN}{dE_\gamma} \int_0^\infty ds \rho(s,b,l) e^{-\tau_{\gamma\gamma}(E_\gamma,s,b,l)}$$

HDMSpectra

m_χ = DM mass, τ_χ = DM lifetime,
E_γ, E_e = energy of the prompt photons and prompt electrons/positron
ρ= DM density profile, which we have taken as NFW profile
s = line-of-sight distance taken for our galaxy, b, l are Galactic latitude and longitude
$\tau_{\gamma\gamma}$ = optical depth of photons due to CMB, SL+IR and EBL

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HDMSpectra

DM annihilation

$$\frac{d\Phi^G}{dE_\gamma} = \frac{\langle\sigma v\rangle}{8\pi m_\chi^2}\frac{dN}{dE_\gamma}\int_0^\infty ds\rho^2(s,b,l)B_{sh}(s,b,l)e^{-\tau_{\gamma\gamma}(E_\gamma,s,b,l)}$$

Since the annihilation rate depends on the dark matter density squared (and $\langle\varrho^2\rangle \geq \langle\varrho\rangle^2$), the presence of the subhalos will boost the gamma-ray signatures from dark matter annihilation. It is given by B_{sh} (Boost factor).

Flux of gamma rays from DM decay/annihilation

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HDMSpectra

DM annihilation

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Since the annihilation rate depends on the dark matter density squared (and $\langle\varrho^2\rangle \geq \langle\varrho\rangle^2$), the presence of the subhalos will boost the gamma-ray signatures from dark matter annihilation. It is given by B_{sh} (Boost factor) and $\langle\delta^2\rangle$ (Clumping factor in case for Extragalcatic gamma rays flux)

In our analysis, we have taken both primary and inverse Compton scattering gamma ray flux from Galactic and Extragalactic domain into consideration.

Boost factor

Total Luminosity from DM annihilation ← $\mathrm{L(M)}=[1+B_{\rm sh}(M)]\,L_{\rm host}(M)$ ← Luminosity from DM annihilation if there is no substructure.

$$B_{\rm sh}\,(M)=\frac{1}{L_{\rm host}(M)}\int dm\frac{dN}{dm}L_{\rm sh}(m)\,[1+B_{\rm ssh}\,(m)]$$

→ Subhalo mass function

Shin'ichiro Ando et al. 2019

Boost factor

Total Luminosity from DM annihilation ← $\mathrm{L(M)}=[1+B_{\rm sh}(M)]\,L_{\rm host}(M)$ ← Luminosity from DM annihilation if there is no substructure.

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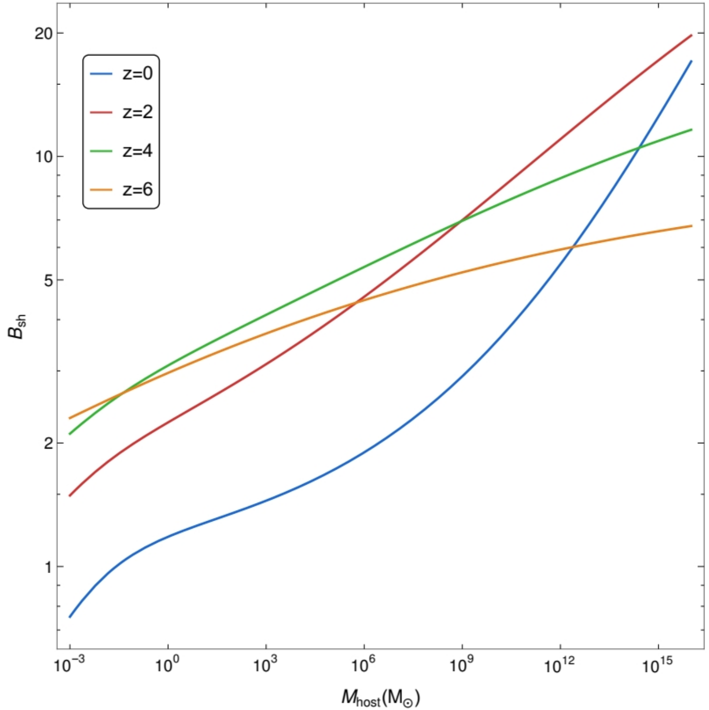
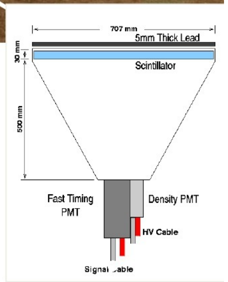
Shin'ichiro Ando et al. 2019

Subhalo mass function



Tibet Air Shower Array



- Site: Tibet (90.522°E, 30.102°N) 4,300 m a.s.l.

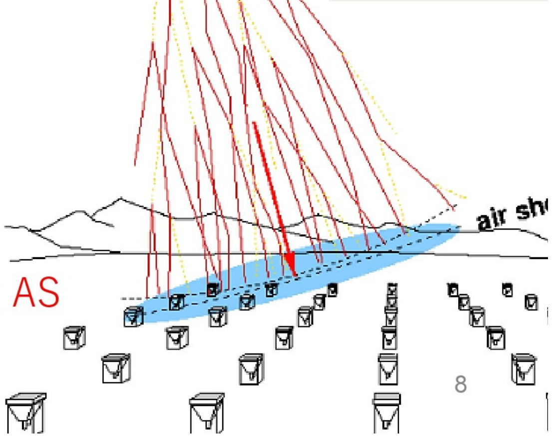
<u>Present Performance</u>

◻ # of detectors	0.5 m^2 x 597
◻ Effective area	~65,700 m^2
◻ Angular resolution	~0.5° @10TeV
	~0.2° @100TeV
◻ Energy resolution	~40%@10TeV γ
	~20%@100TeV γ

→Observation of secondary (mainly $e^{+/-}$, γ) in AS

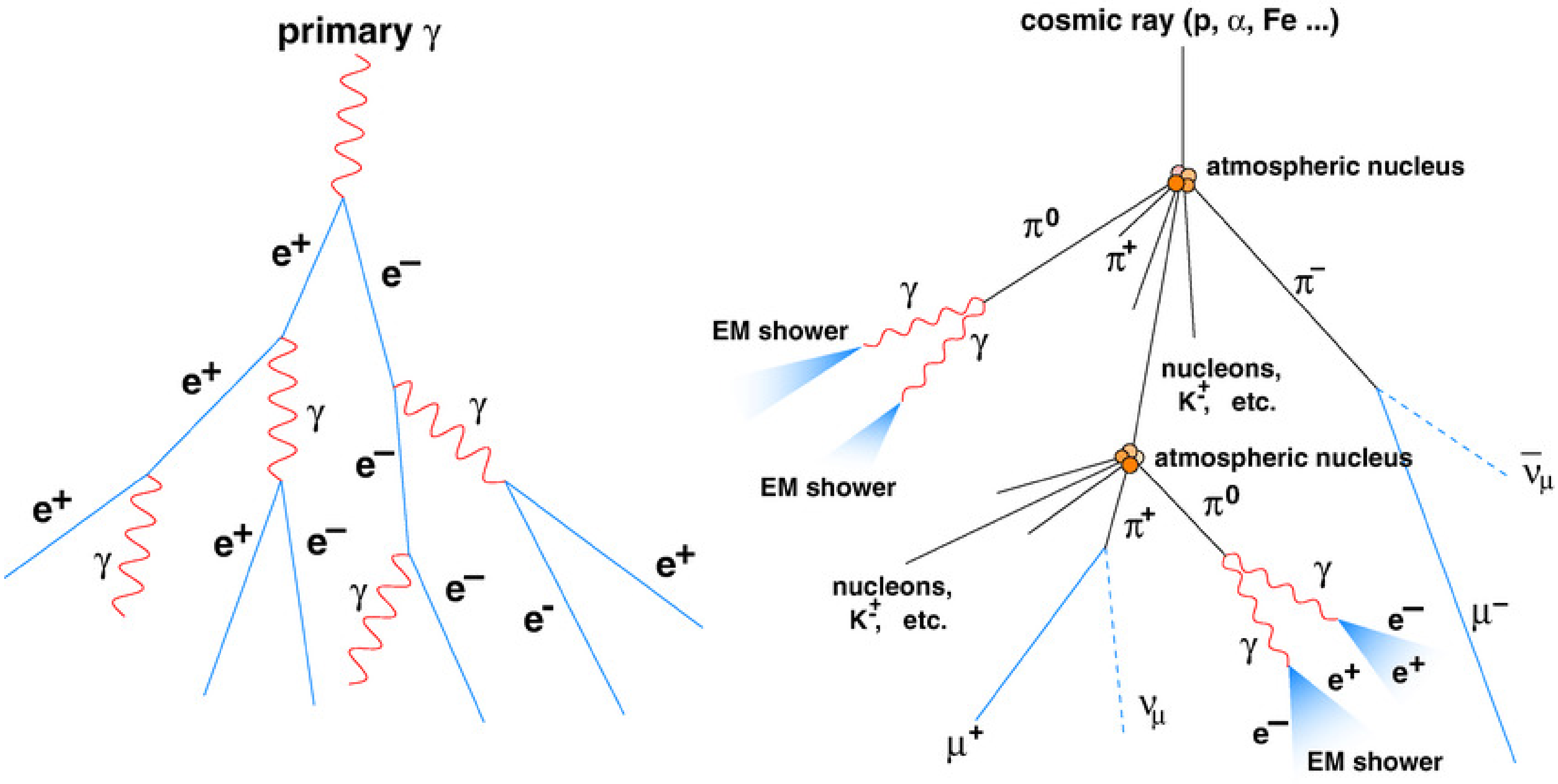
Primary energy : 2^{nd} particle densities

Primary direction : 2^{nd} relative timings



https://agenda.infn.it/event/28874/contributions/170169/attachments/94543/129448/ICHEP2022_takita_20220709_presentation.pdf

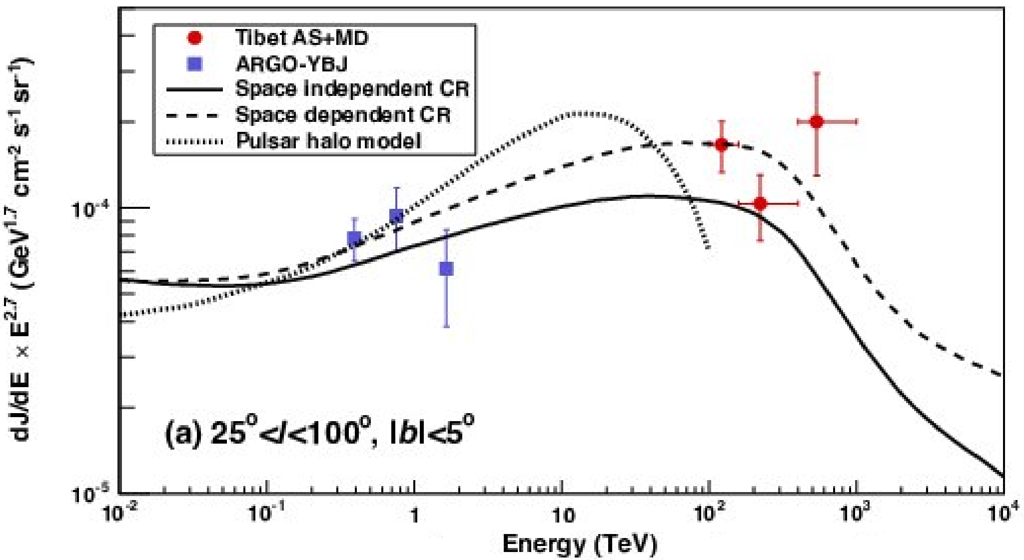
Photon vs Cosmic ray shower

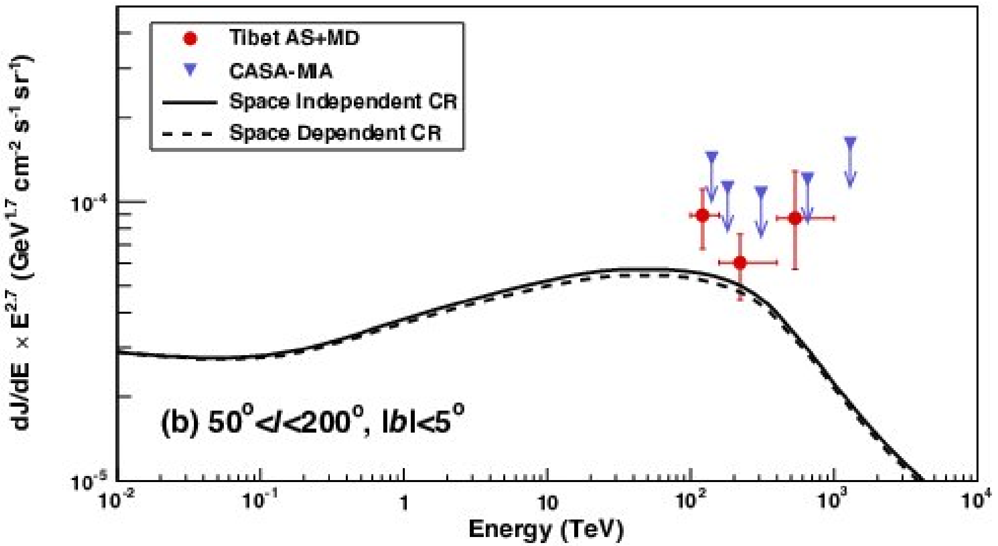


hhttps://www.researchgate.net/figure/Schematic-representation-of-two-atmospheric-showers-initiated-by-a-photon-left-or-by-a_fig9_1901518

First detection of sub-PeV diffuse Gamma rays from the Galactic disk

M. Amenomori et al. (Tibet AS$_\gamma$ Collaboration) 2021



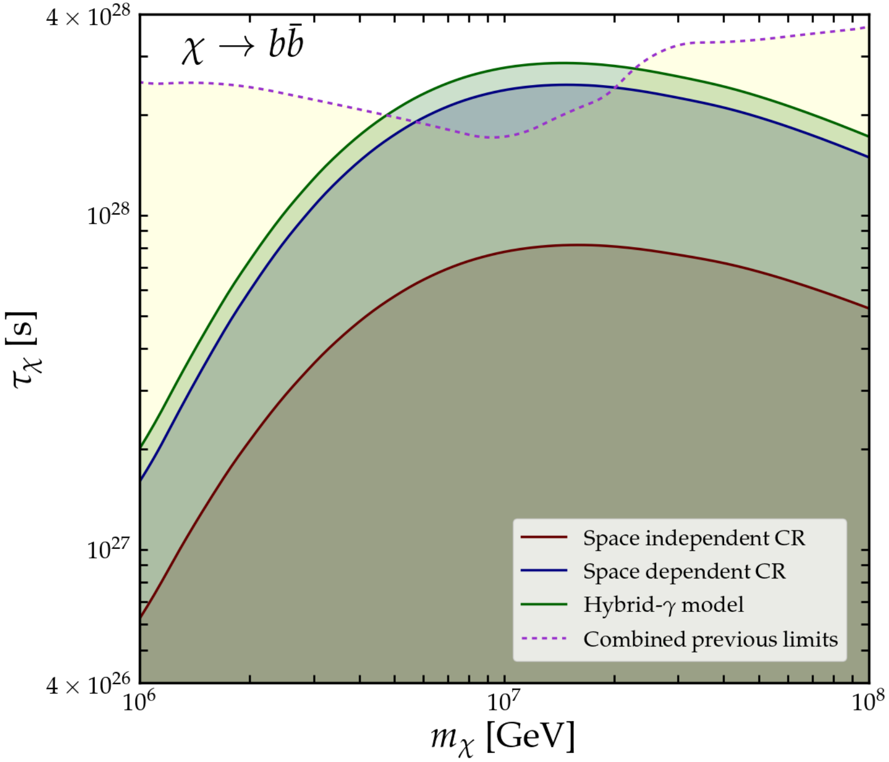


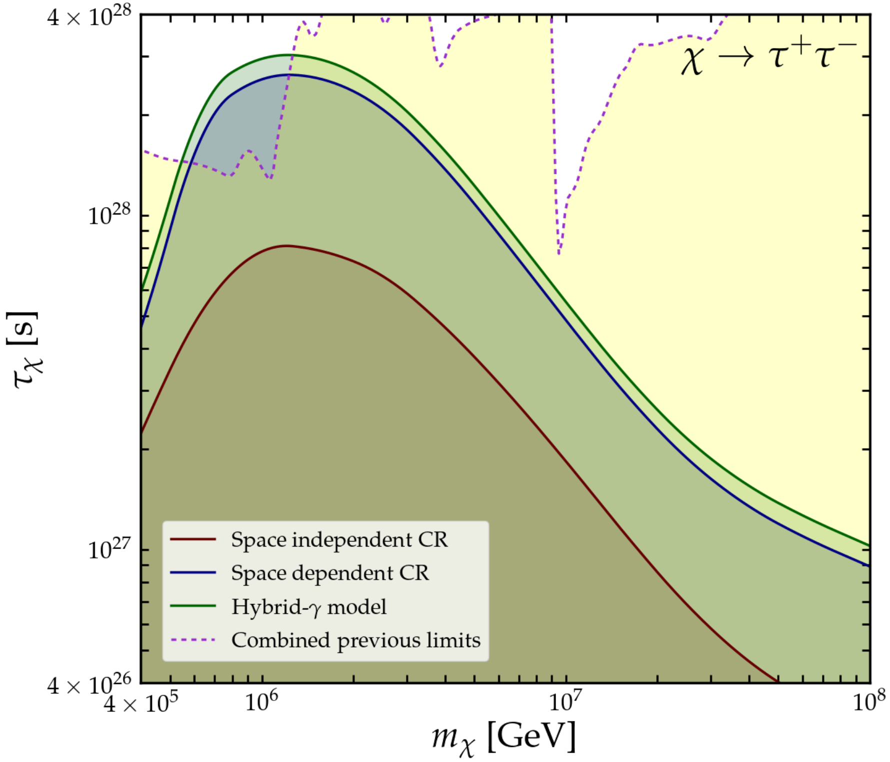
Results also observed by LHAASO!!!

Energy bin (TeV)	Representative E (TeV)	Flux ($25^\circ < l < 100^\circ$, $\lvert b \rvert < 5^\circ$) ($\mathrm{TeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}}$)	Flux ($50^\circ < l < 200^\circ$, $\lvert b \rvert < 5^\circ$) ($\mathrm{TeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}}$)
100 – 158	121	$(3.16 \pm 0.64) \times 10^{-15}$	$(1.69 \pm 0.41) \times 10^{-15}$
158 – 398	220	$(3.88 \pm 1.00) \times 10^{-16}$	$(2.27 \pm 0.60) \times 10^{-16}$
398 – 1000	534	$(6.86\ ^{+3.30}_{-2.40}) \times 10^{-17}$	$(2.99\ ^{+1.40}_{-1.02}) \times 10^{-17}$

Results

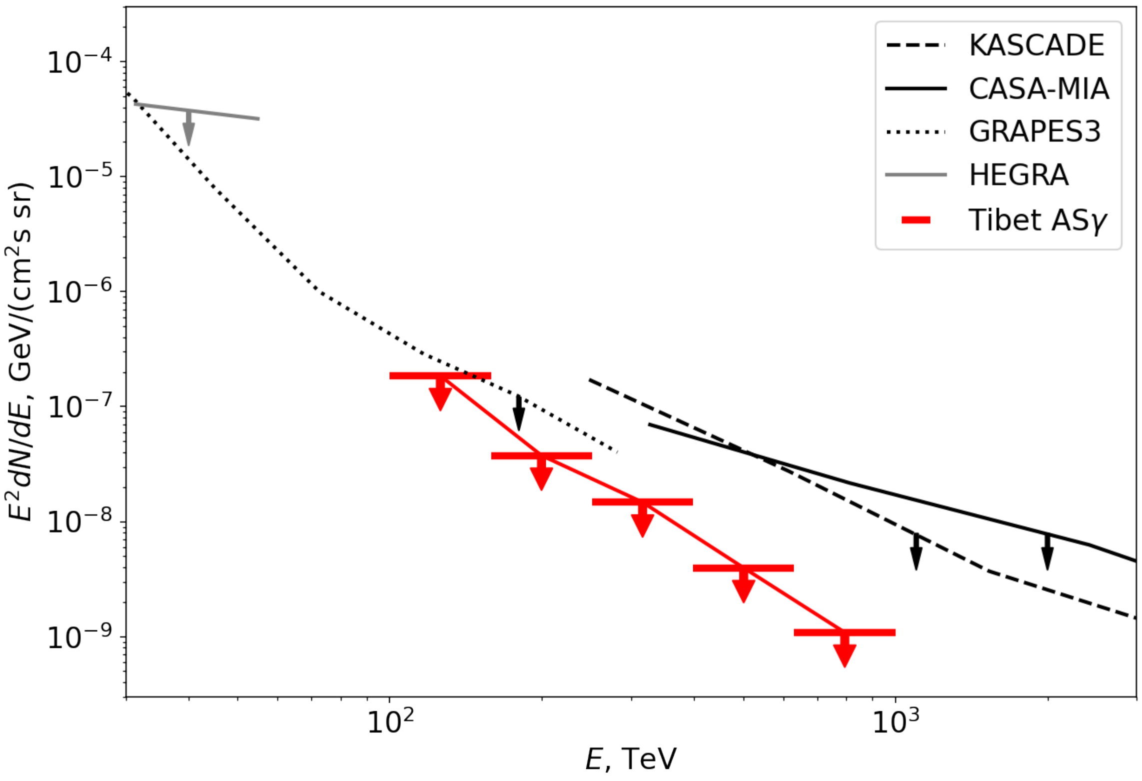
arXiv:2105.05680 **(PRD Letter)**





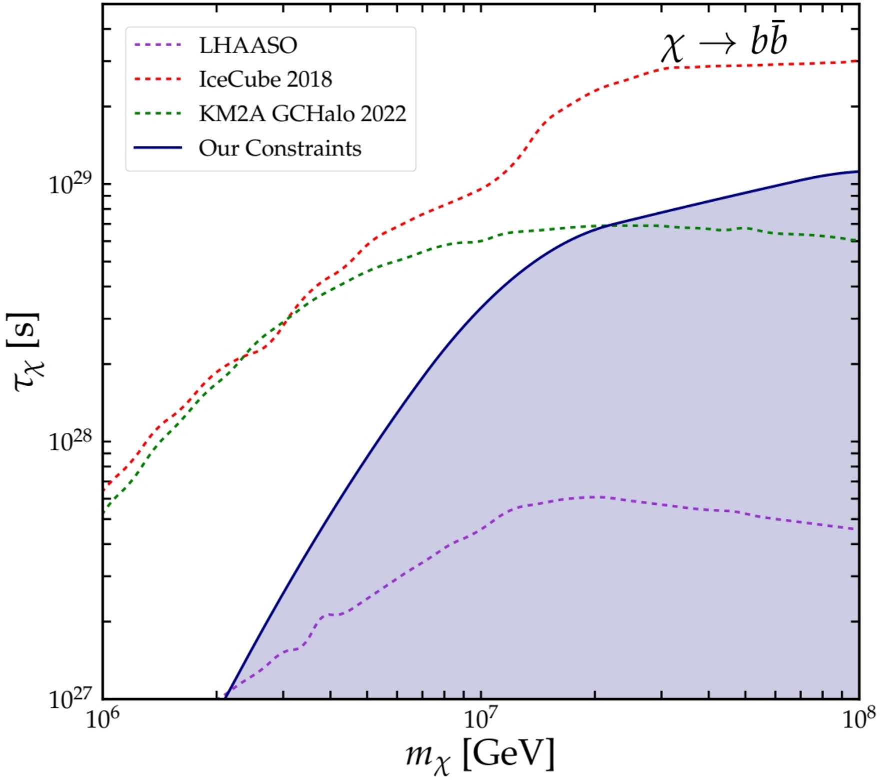
Limit on high Galactic latitude PeV γ-ray flux from Tibet AS_γ

Due to the better sensitivity of Tibet-AS_γ and higher energy reach compared to MILAGRO, HAWC, and ARGO-YBJ and also more efficient suppression of background EAS produced by protons and atomic nuclei, Tibet-AS_γ observations can be used to constrain the γ ray flux from the sky outside the Galactic plane (|b| > 20 deg.).

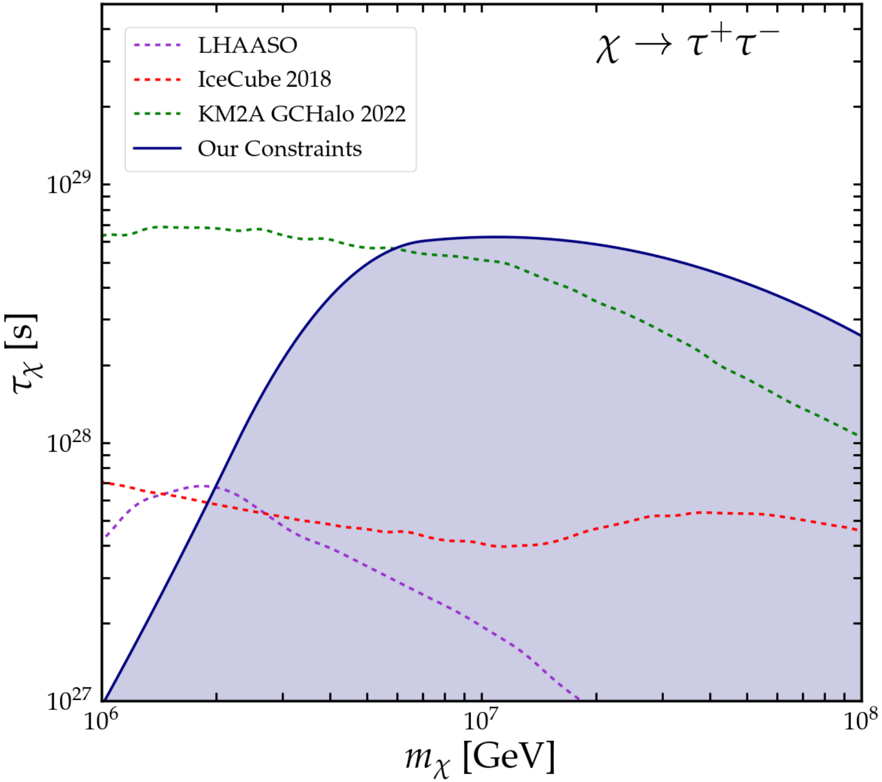


Neronov et al. 2021

Results



Dubey et al. (In Prep.)



Results

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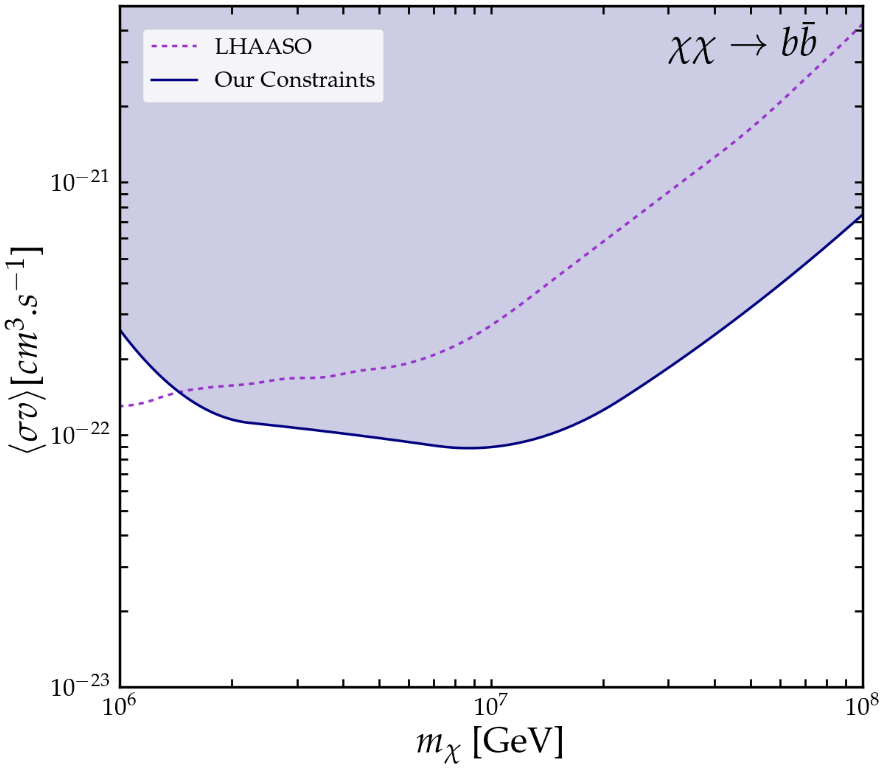
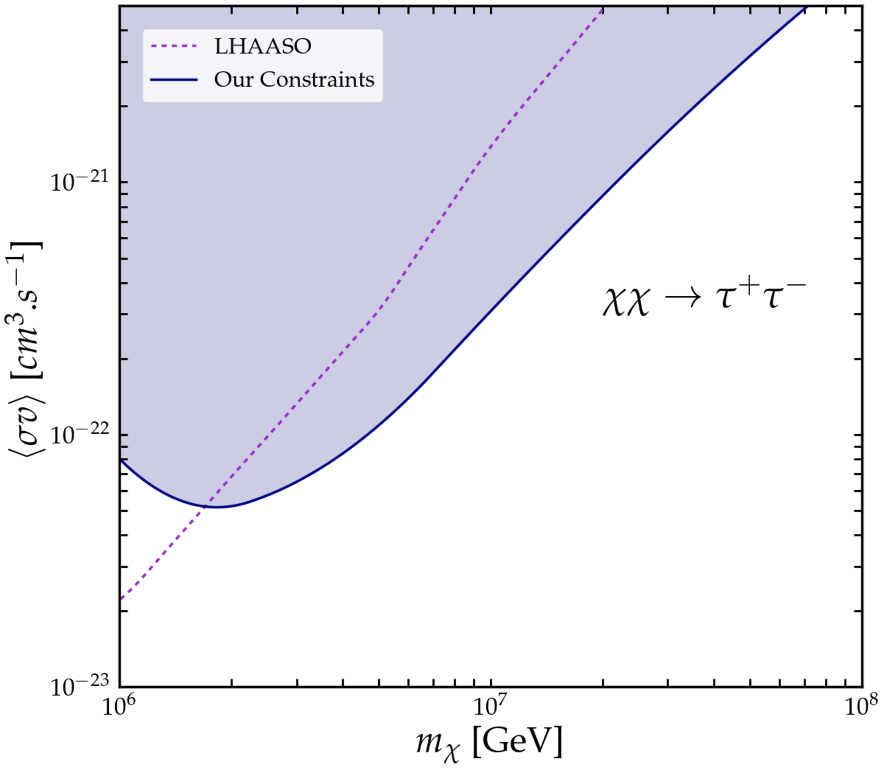




Conclusions

- We have obtained constraints on Dark Matter lifetime and annihilation cross section for different final states using Tibet AS_γ observation.

- We have studied the effect of inverse Compton scattering and dark matter substructure which helps put better constrain dark matter parameters.

- We get the most stringent constraints in large region of parameter space for both dark matter decay and annihilation.

Thank You

Email: abhishekd1@iisc.ac.in

Backup

Cosmic Ray measurement by Tibet ASγ

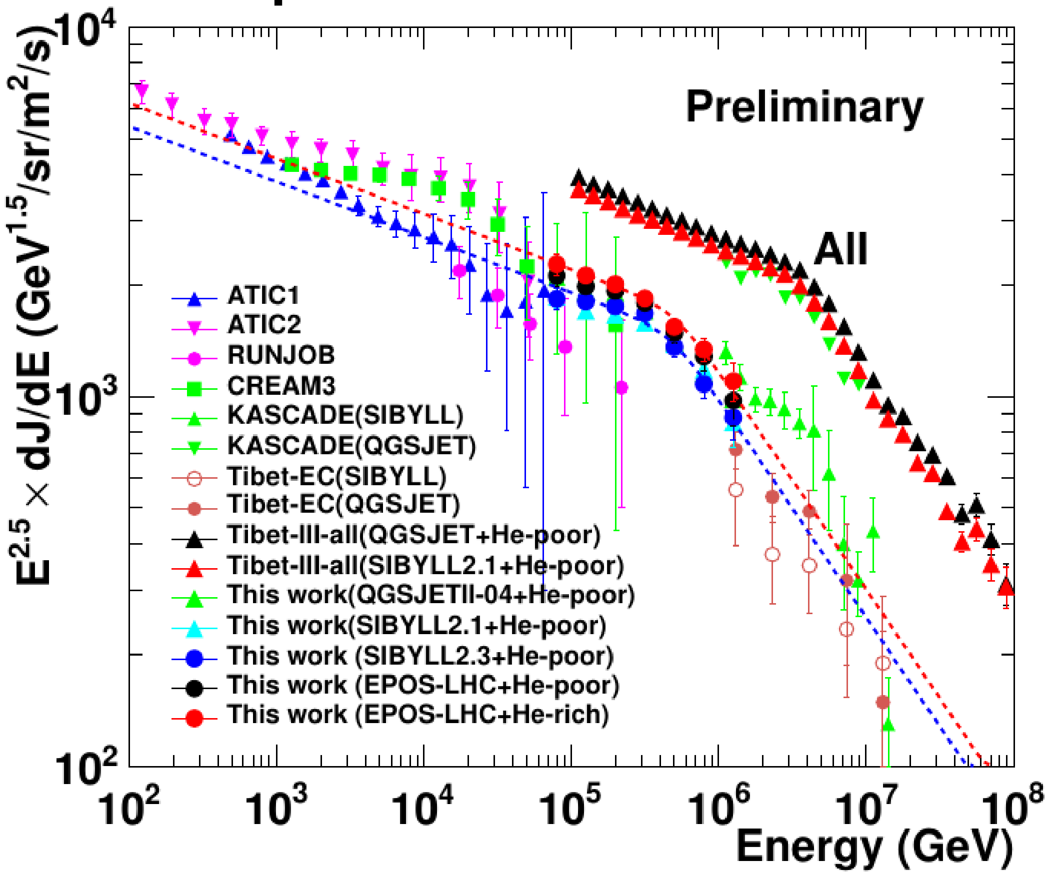
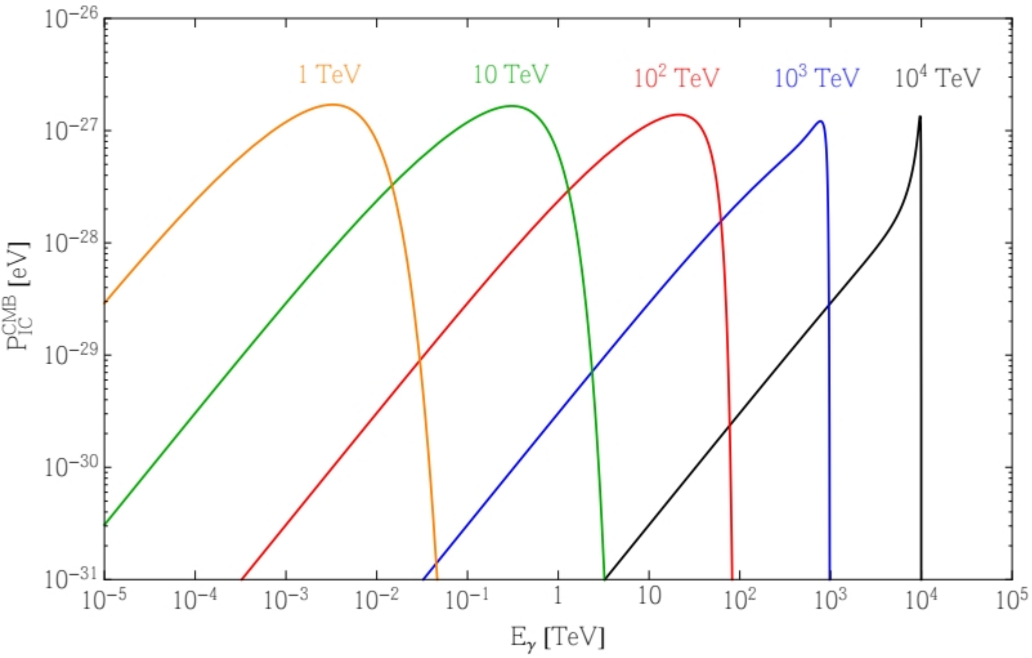
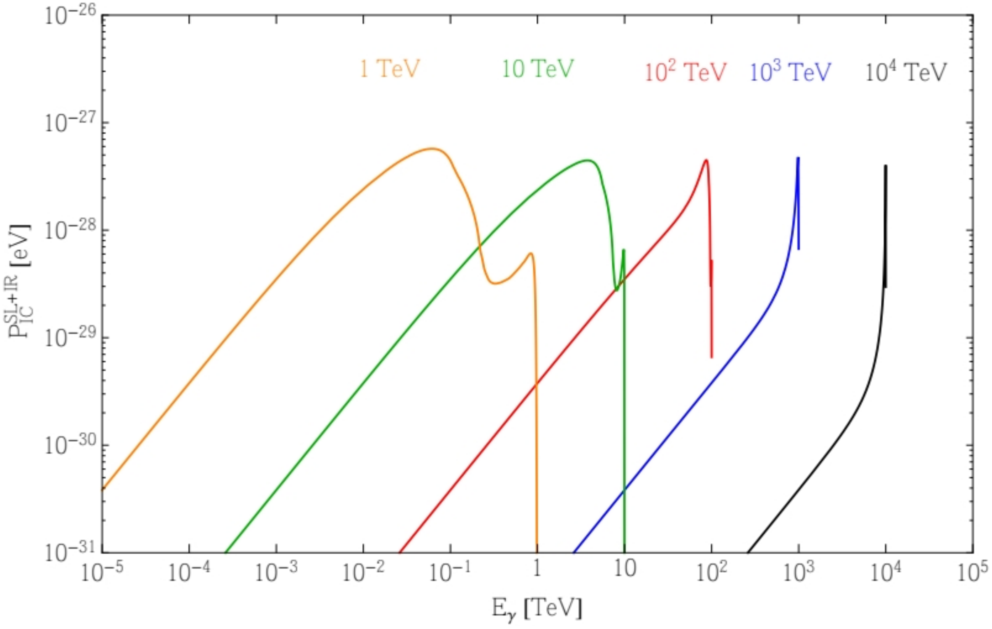


Fig: Amenomori et al., EPJ Web of Conferences 208, 03001 (2019)

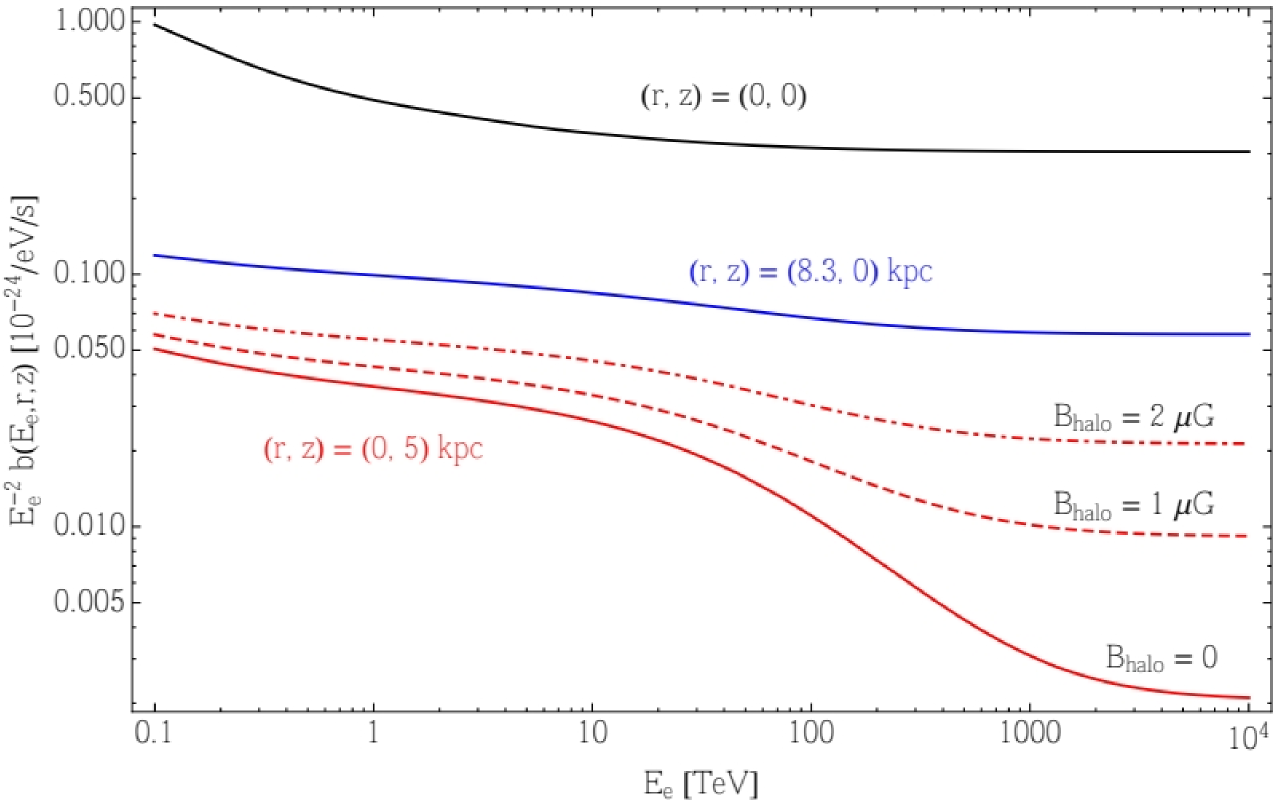
P_{IC} and Energy Loss for ICS and Synchrotron





Esmaili & Serpico 2015

P_{IC} and Energy Loss for ICS and Synchrotron



Esmaili & Serpico 2015

Does cosmic ray measurement by Tibet ASγ tell us anything about the diffuse gamma ray at this sky region ($|b| > 20$ deg.) ?

YES

!

It can give an upper limit on the diffuse gamma rays

Implication of Muon Cut for Tibet ASγ

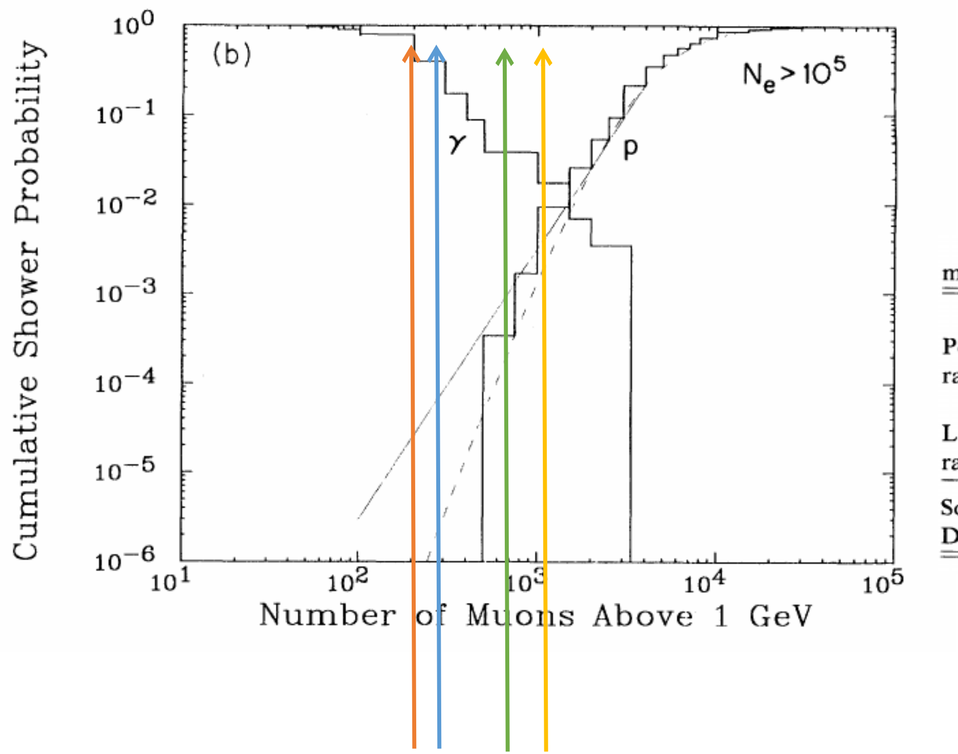
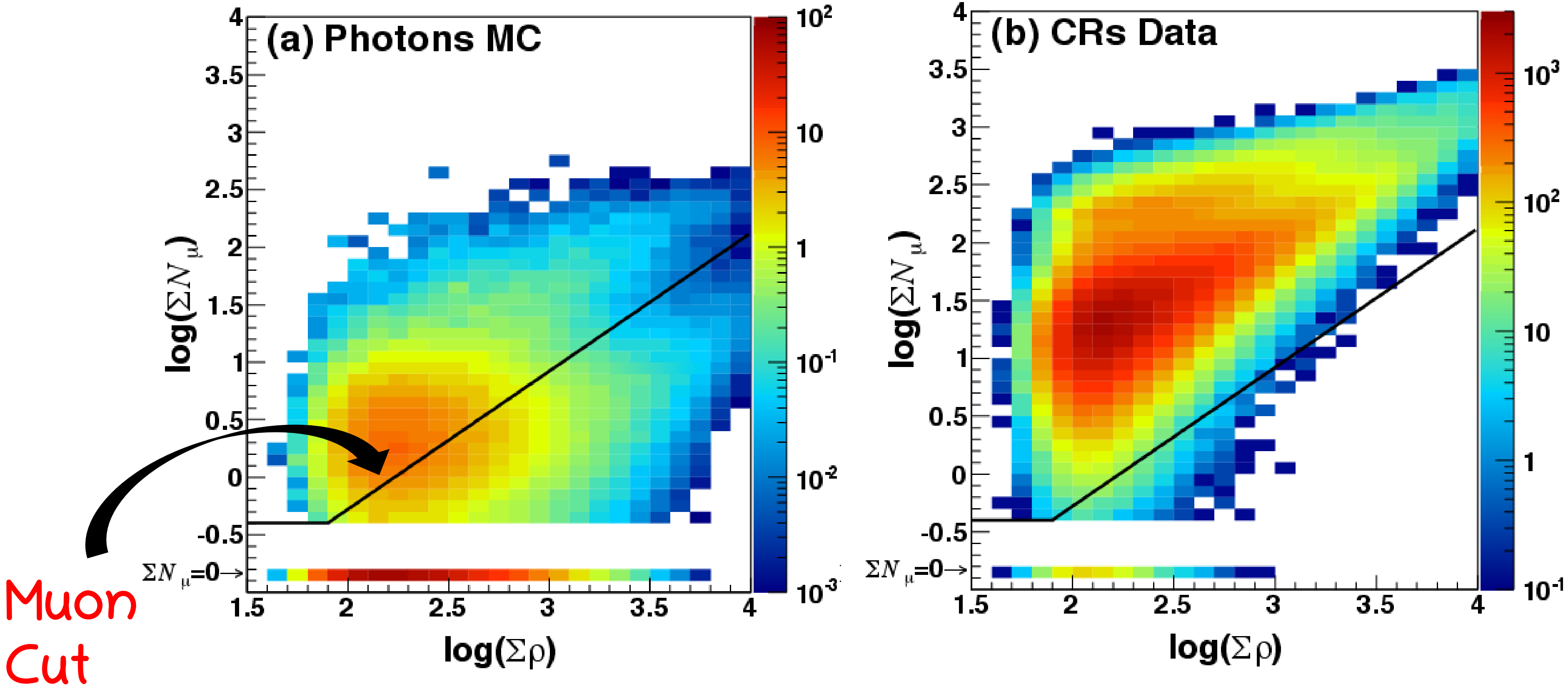


TABLE II. Implications for γ-ray detection of our calculation of the fluctuations in the number of muons N_μ for cosmic-ray showers with $N_e > 10^5$; see Fig. 3(b).

	$N_\mu < 75$	$N_\mu < 100$	$N_\mu < 200$	$N_\mu < 300$
Percentage of γ-ray signals retained	10%	20%	60%	83%
Level of cosmic-ray background				
Solid line fit	10^{-5}	1.5×10^{-5}	4×10^{-5}	10^{-4}
Dashed line fit	$<10^{-7}$	10^{-7}	6.6×10^{-7}	4×10^{-6}

Fig : Gaisser et al., 1991

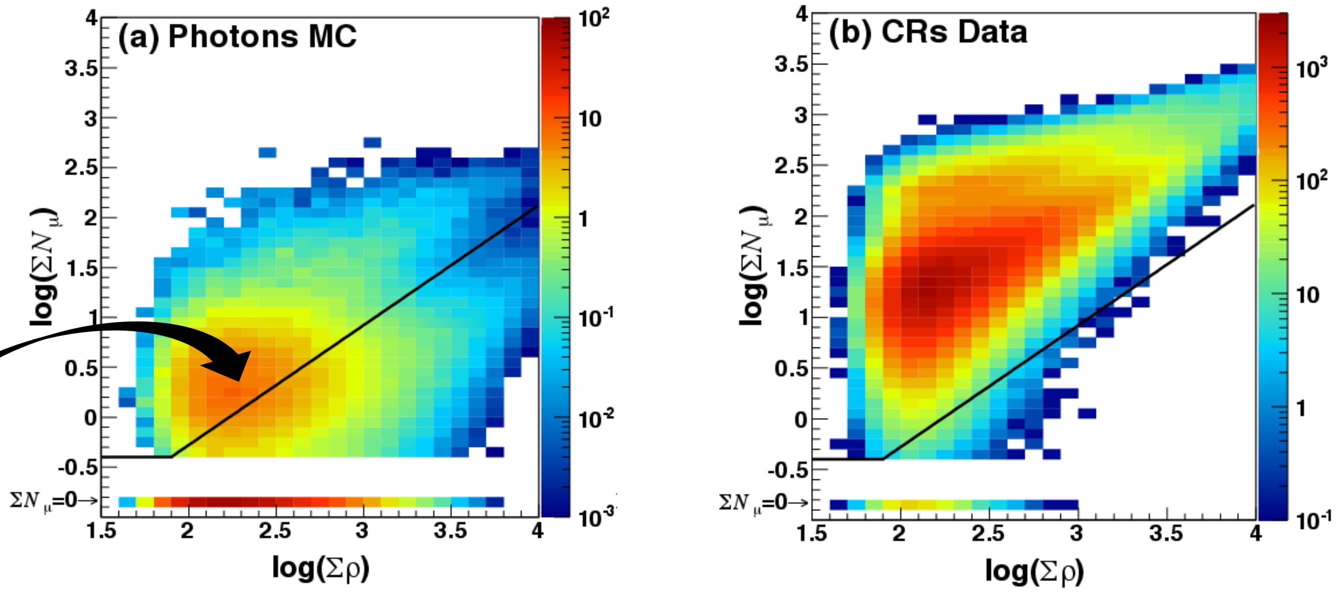
Implication of Muon Cut for Tibet ASγ



Amenomori et al,. PRL, 2019

Implication of Muon Cut for Tibet ASγ

Muon Cut



Amenomori et al,. PRL, 2019

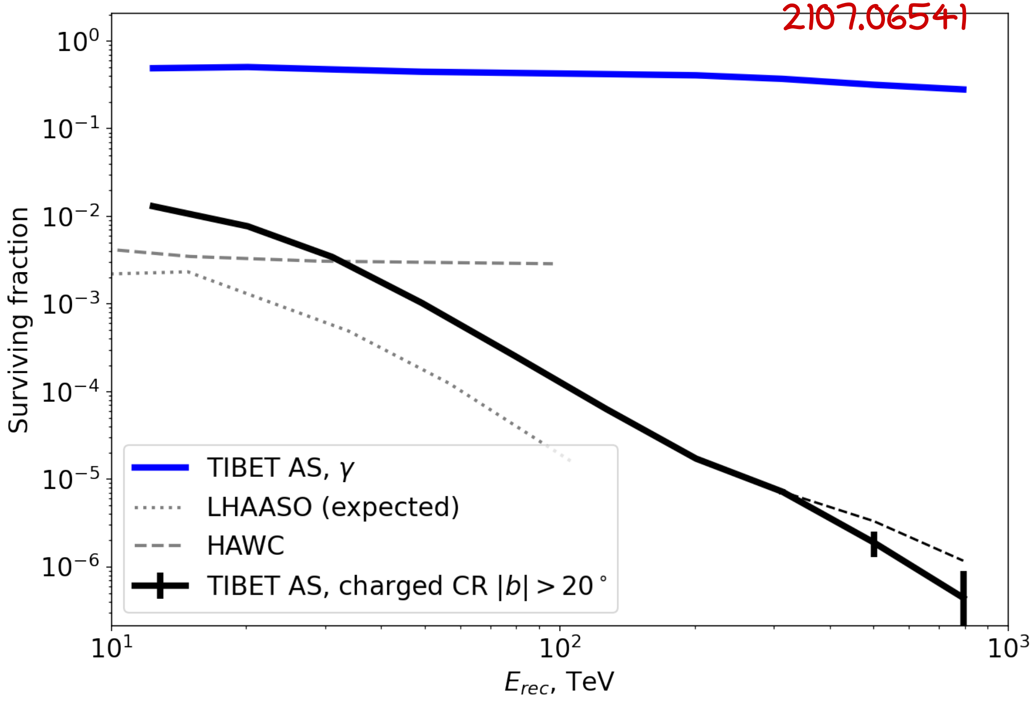
Choose a Muon Cut

Take into account majority of photon induced events

Discard most of the background (CR induced) events

Our detector is not perfect ! Even after the tight muon cut some CR induced shower will get in

Fig: 2107.06541



Upper limits on diffuse gamma ray flux

Upper limit on gamma ray flux

Cosmic Ray flux measured × Surviving event fraction of Hadronic EAS

=

Efficiency of the selection of Gamma ray EAS

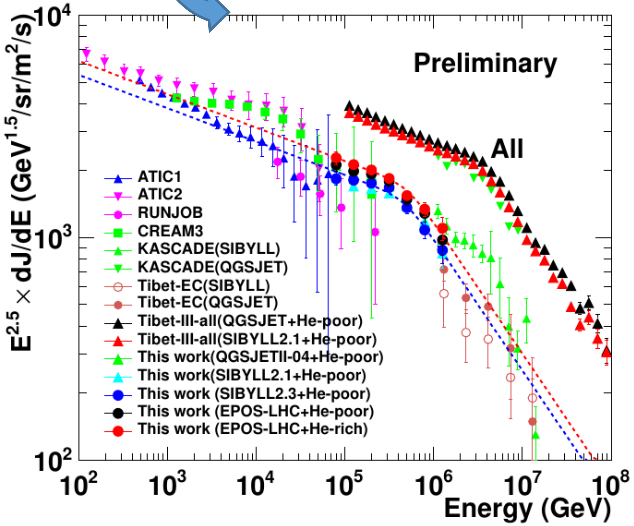


Fig: Amenomori et al., EPJ Web of Conferences 208, 03001 (2019)

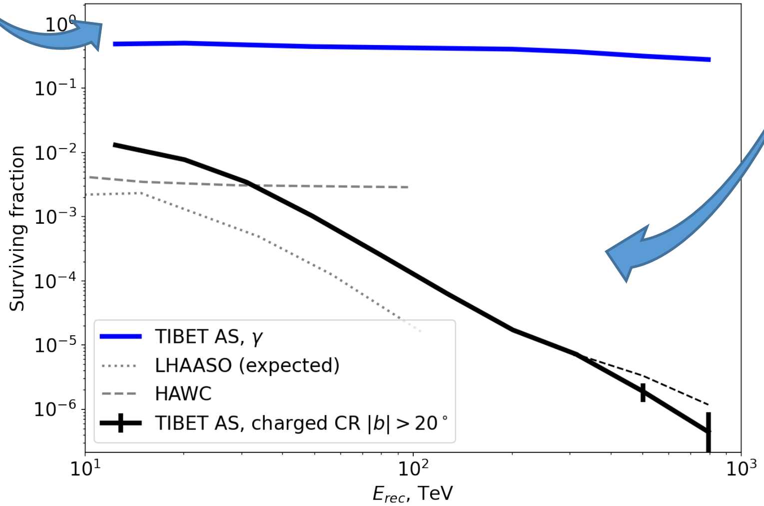


Fig: 2107.06541

Flux of gamma rays from DM decay

γ ray flux of direct production from DM decay

$$\frac{d\Phi^G}{dE_\gamma} = \frac{1}{4\pi m_\chi \tau_\chi}\frac{dN}{dE_\gamma}\int_0^\infty ds\rho(s,b,l)e^{-\tau_{\gamma\gamma}(E_\gamma,s,b,l)}$$

$$\frac{\mathrm{d}\phi_\gamma^{\mathrm{EG}}}{\mathrm{d}E_\gamma} = \frac{\Omega_{\mathrm{DM}}\rho_{\mathrm{cr}}}{4\pi m_\chi \tau_\chi}\int \frac{\mathrm{d}z}{H(z)}\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}\bigg|_{E'_\gamma=E_\gamma(1+z)} e^{-\tau_{\gamma\gamma}(E_\gamma,z)}$$

m_χ = DM mass, τ_χ = DM lifetime,
E_γ, E_e = energy of the prompt photons and prompt electrons/positron
ρ= DM density profile, which we have taken as NFW profile
s = line-of-sight distance taken for our galaxy, b, l are Galactic latitude and longitude
$\tau_{\gamma\gamma}$ = optical depth of photons due to CMB, SL+IR and EBL

HDMSpectra

γ ray flux of Inverse compton production from DM decay

$$\frac{d\Phi_{\mathrm{IC}\gamma}}{dE_\gamma d\Omega} = \frac{2}{E_\gamma}\frac{1}{4\pi m_\chi \tau_\chi}\int_{m_e}^{m_\chi/2} dE_{\mathrm{s}}\frac{dN_e}{dE_e}(E_{\mathrm{s}})\int_{\mathrm{l.o.s.}} ds\,(\rho(s,b,l))\int_{m_e}^{E_{\mathrm{s}}} dE\frac{\sum_i \mathcal{P}_{\mathrm{IC}}^i(E_\gamma,E,s,b,l)}{b(E,s,b,l)} I(E,E_{\mathrm{s}},s,b,l)\,,$$

$$\frac{d\Phi_{\mathrm{EG}\gamma}}{dE_\gamma}(E_\gamma,z) = c\frac{1}{E_\gamma}\int_z^\infty dz'\frac{1}{H(z')(1+z')}\left(\frac{1+z}{1+z'}\right)^3 j_{\mathrm{EG}\gamma}(E'_\gamma,z')\,e^{-\tau(E_\gamma,z,z')}.$$

$$j_{\mathrm{EG}\gamma}^{\mathrm{IC}}(E'_\gamma,z') = \frac{2}{\tau_\chi}\frac{\bar\rho(z')}{m_\chi}\int_{m_e}^{m_\chi/2}\mathrm{d}E_e\frac{\mathcal{P}_{\mathrm{IC}}^{\mathrm{CMB}}(E'_\gamma,E_e,z')}{b_{\mathrm{IC}}^{\mathrm{CMB}}(E_e,z')}\int_{E_e}^{m_\chi/2}\mathrm{d}\tilde{E}_e\frac{\mathrm{d}\tilde{N}_e}{\mathrm{d}\tilde{E}_e}$$

P_{IC} is ICS radiative power and b_{IC} is the energy loss of electrons/positrons due to ICS and Synchrotron radiation.

Flux of gamma rays from DM annihilation

γ ray flux of direct production from DM annihilation

$$\frac{d\Phi^G}{dE_\gamma} = \frac{\langle\sigma v\rangle}{8\pi m_\chi^2}\frac{dN}{dE_\gamma}\int_0^\infty ds\rho^2(s,b,l)B_{sh}(s,b,l)e^{-\tau_{\gamma\gamma}(E_\gamma,s,b,l)}$$

$$\frac{\mathrm{d}\phi_\gamma^{\mathrm{EG}}}{\mathrm{d}E_\gamma} = \frac{\langle\sigma v\rangle\Omega_{\mathrm{DM}}^2\rho_{\mathrm{cr}}^2}{8\pi m_\chi^2}\int\frac{\mathrm{d}z}{H(z)}\left\langle\delta^2(z)\right\rangle(1+z)^3\left.\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}\right|_{E'_\gamma=E_\gamma(1+z)} e^{-\tau_{\gamma\gamma}(E_\gamma,z)}$$

γ ray flux of inverse Compton production from DM annihilation

$$\frac{d\Phi_{\mathrm{IC}\gamma}}{dE_\gamma d\Omega} = \frac{2}{E_\gamma}\frac{\langle\sigma v\rangle}{4\pi m_\chi^2}\int_{m_e}^{m_\chi/2} dE_{\mathrm{s}}\frac{dN_e}{dE_e}(E_{\mathrm{s}})\int_{\mathrm{l.o.s.}} ds\frac{1}{2}B_{sh}(s,b,l)\left(\rho(s,b,l)\right)^2\int_{m_e}^{E_{\mathrm{s}}} dE\frac{\sum_i \mathcal{P}_{\mathrm{IC}}^i(E_\gamma,E,s,b,l)}{b(E,s,b,l)}I(E,E_{\mathrm{s}},s,b,l),$$

$$\frac{d\Phi_{\mathrm{EG}\gamma}}{dE_\gamma}(E_\gamma,z) = c\frac{1}{E_\gamma}\int_z^\infty dz'\frac{1}{H(z')(1+z')}\left(\frac{1+z}{1+z'}\right)^3 j_{\mathrm{EG}\gamma}(E'_\gamma,z')\,e^{-\tau(E_\gamma,z,z')}.$$

$$j_{\mathrm{EG}\gamma}^{\mathrm{IC}}(E'_\gamma,z') = 2\left\langle\delta^2(z)\right\rangle\frac{1}{2}\langle\sigma v\rangle\left(\frac{\bar\rho(z')}{m_\chi}\right)^2\int_{m_e}^{m_\chi/2}\mathrm{d}E_e\frac{\mathcal{P}_{\mathrm{IC}}^{\mathrm{CMB}}(E'_\gamma,E_e,z')}{b_{\mathrm{IC}}^{\mathrm{CMB}}(E_e,z')}\int_{E_e}^{m_\chi/2}\mathrm{d}\tilde E_e\frac{\mathrm{d}\tilde N_e}{\mathrm{d}\tilde E_e}$$

B_{sh} and $<\delta^2>$ are Boost factor and Clumping factor due to dark matter substructure. Since the annihilation rate depends on the dark matter density squared (and $<\rho^2> \geq <\rho>^2$), the presence of the subhalos will boost the gamma-ray signatures from dark matter annihilation.

Boost factor and Clumping factor

$$\langle \delta^2 \rangle = \left(\frac{1}{\Omega_m \rho_c} \right)^2 \int dM \frac{dn(M,z)}{dM} \left[1 + B_{\rm sh}(M) \right] \times \int dV \rho_{\rm host}^2 \left(r \mid M \right)$$

Hiroshima, et al. 2018

Halo mass funtion