Centre for
High Energy Physics

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INDIAN INSTITUTE OF SCIENCE
भारतीय विज्ञान संस्थान

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

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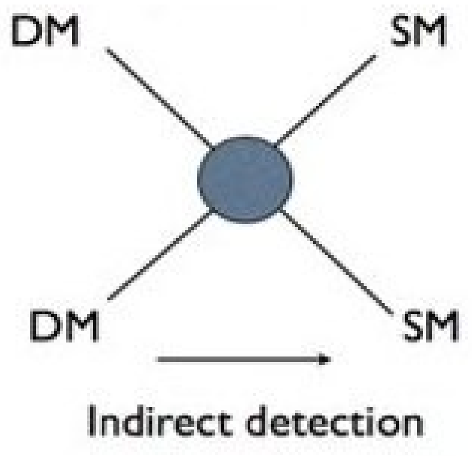
Centre for High Energy Physics
Indian Institute of Science, Bengaluru

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

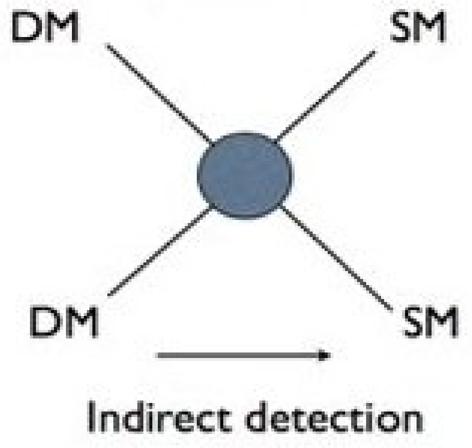
In collaboration with
Tarak Nath Maity, Akash Kumar Saha and Ranjan Laha

Dark Matter Indirect detection

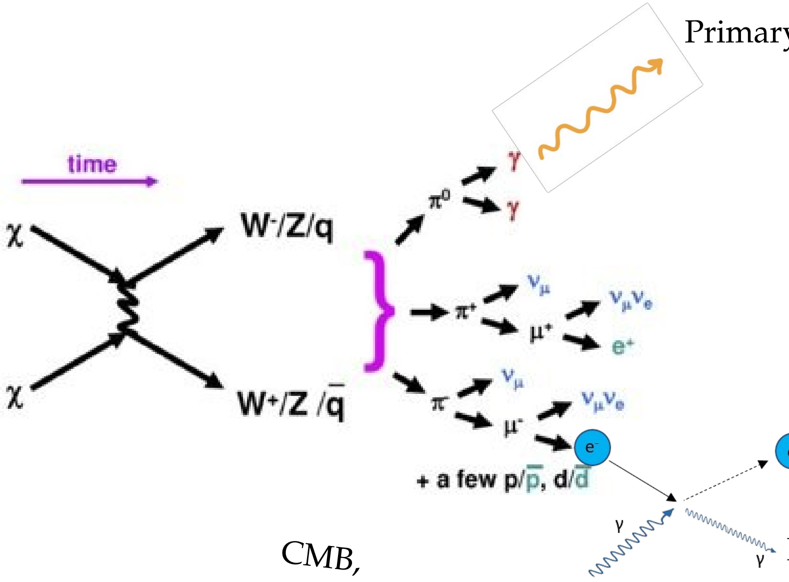


https://particleastro.brown.edu/dark-matter

Dark Matter Indirect detection



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



Primary gamma rays

CMB,

Starlight (SL)+Infrared (IR)

Extragalactic background light (EBL)

Inverse Compton Scattering gamma rays

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 = 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 $\langle\rho^2\rangle \geqslant \langle\rho\rangle^2$), the presence of the subhalos will boost the gamma-ray signatures from dark matter annihilation. It is given by B_{sh} (Boost factor).

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HDMSpectra

DM annihilation

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

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

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

→ Subhalo mass function

Shin'ichiro Ando et al. 2019

Boost factor

Total Luminosity from DM annihilation

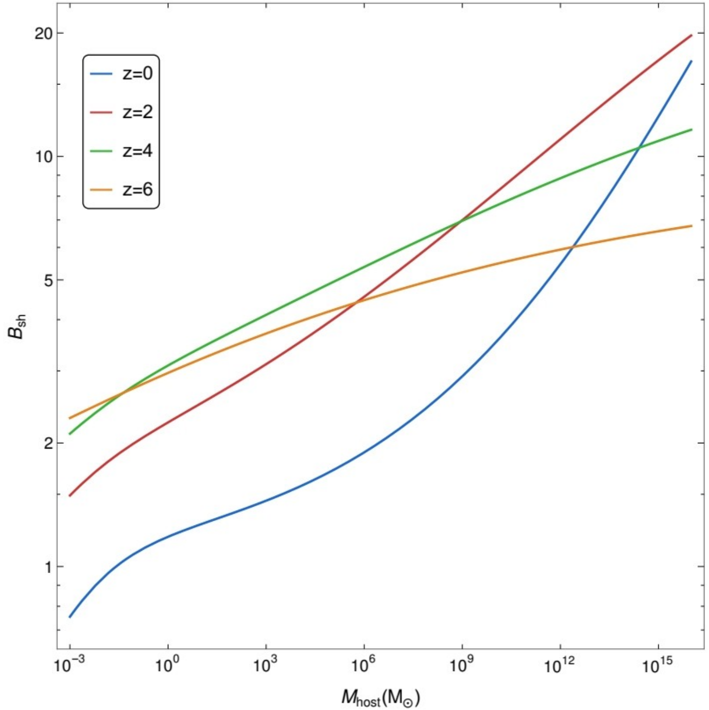
$$\mathrm{L(M)}=[1+B_{\mathrm{sh}}(M)]\,L_{\mathrm{host}}(M)$$

Luminosity from DM annihilation if there is no substructure.

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

Shin'ichiro Ando et al. 2019

Subhalo mass function



High Energy γ ray detectors

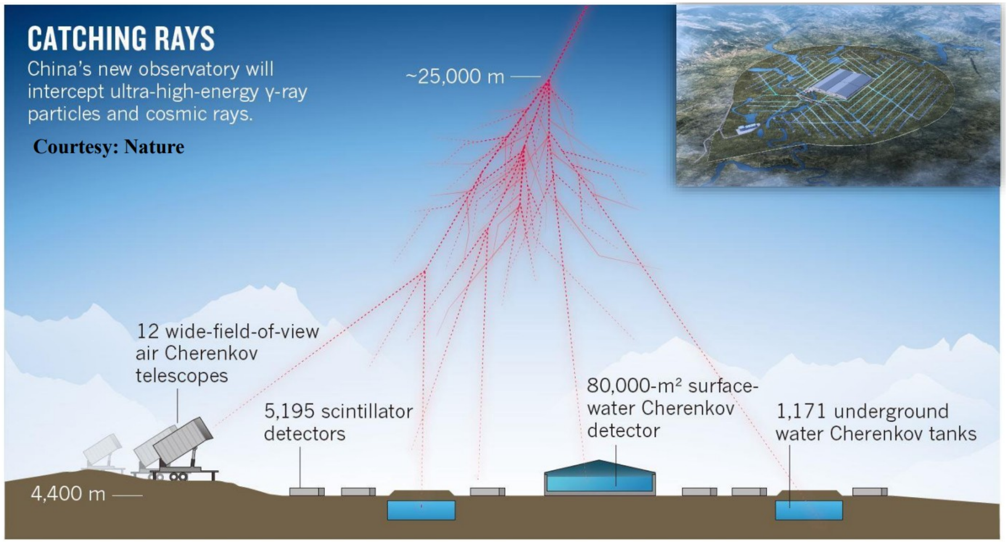
Tibet AS$_\gamma$

Present Performance

☐	# 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

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

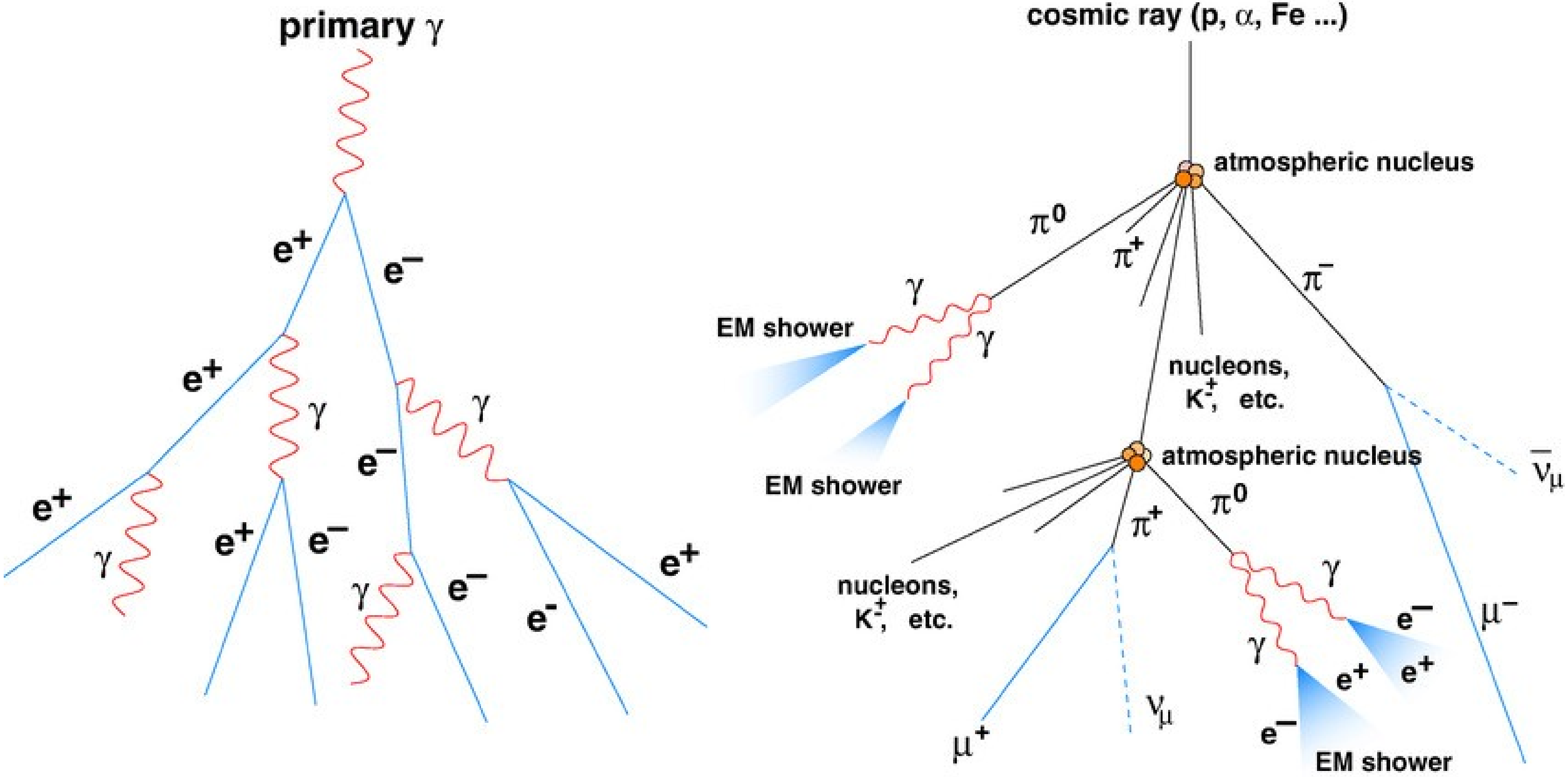
LHAASO



Pointing accuracy	~0.1°
Angular resolution	~0.3°
Energy resolution	<20%@6TeV

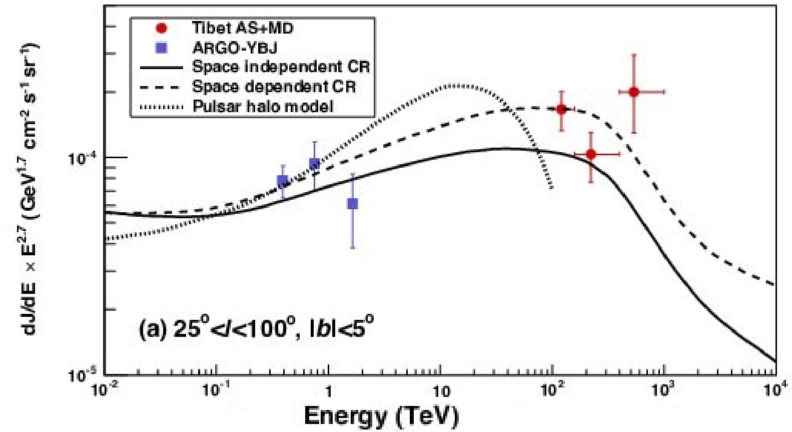
https://indico-tdli.sjtu.edu.cn/event/43/contributions/400/attachments/179/300/20191129LHAASOmultimsg.pdf

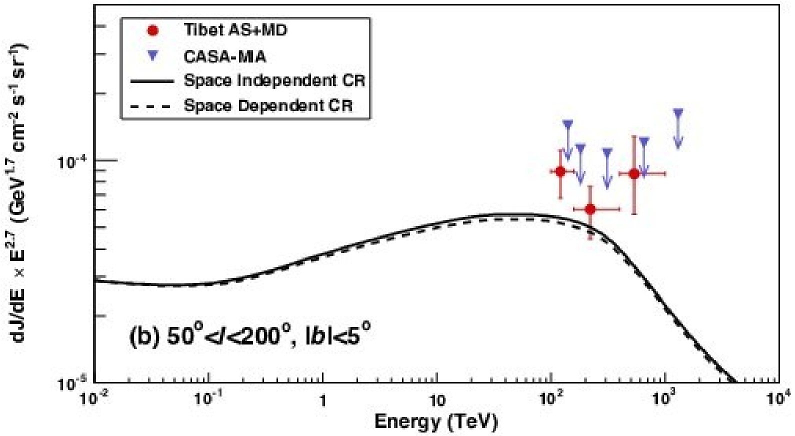
Photon vs Cosmic ray shower



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

Sub-PeV diffuse Gamma rays from the Galactic disk





First detection of sub PeV diffuse γ rays by Tibet AS$_\gamma$

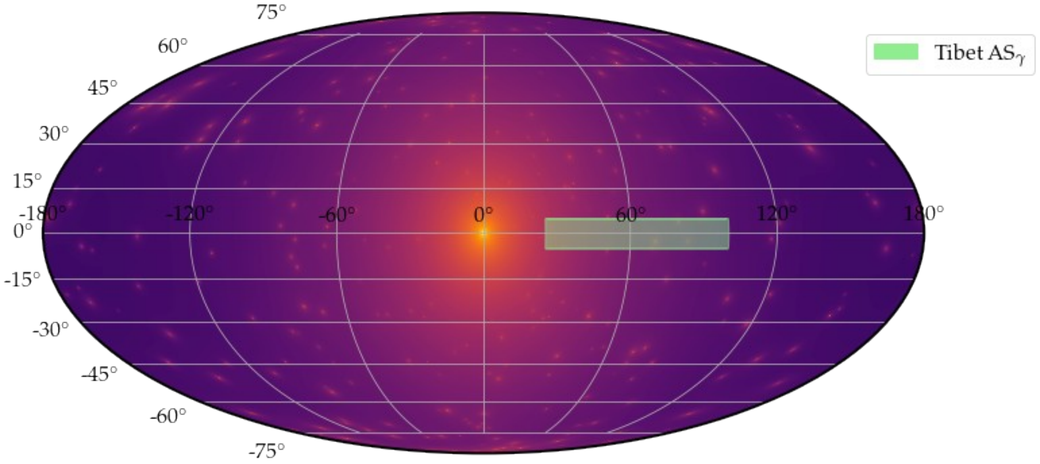
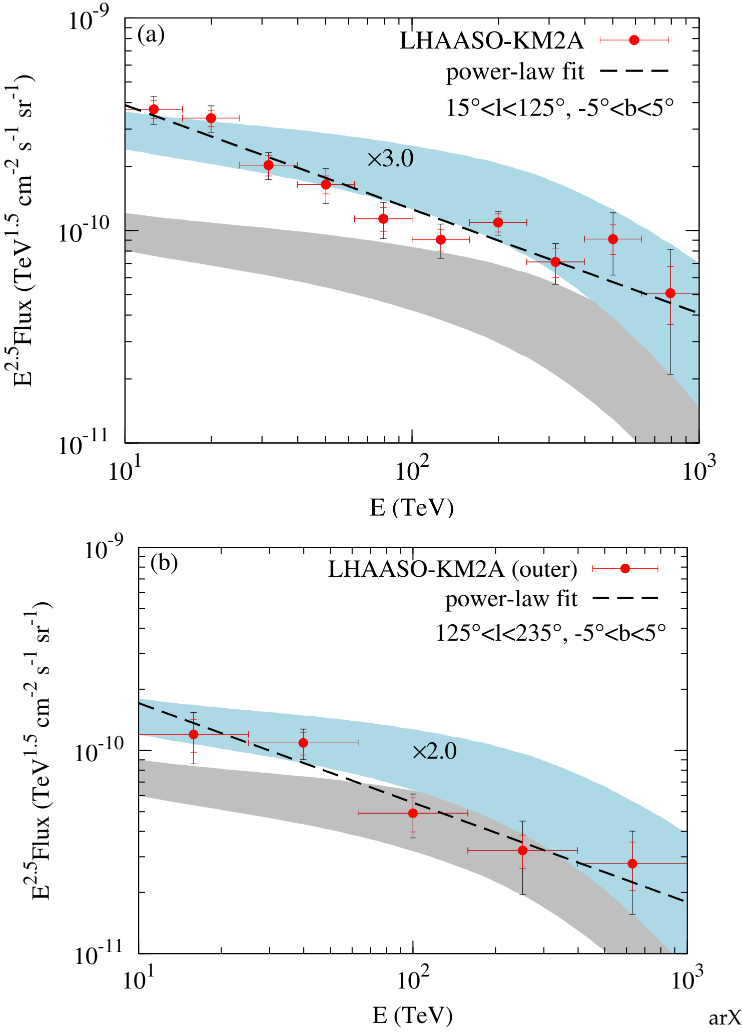


Fig. γ rays observed by Tibet AS$_\gamma$ in Galactic plane in the regions of $|b| < 5^\circ$, $25^\circ < l < 100^\circ$

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

Sub-PeV diffuse Gamma rays from the Galactic disk



Diffuse γ rays observed by LHAASO

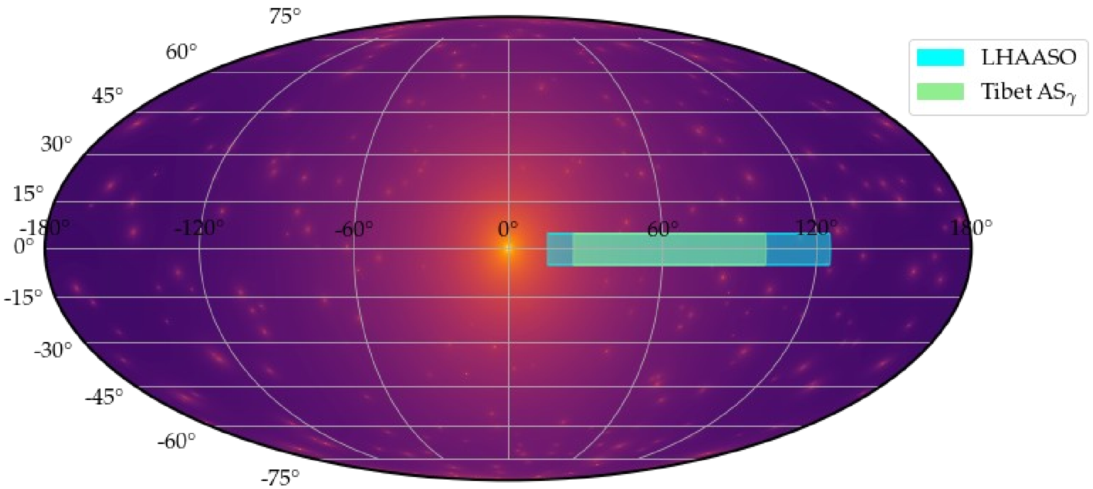


Fig. γ rays observed by LHAASO in inner Galaxy plane region of $|b| < 5^\circ$, $15^\circ < l < 125^\circ$ and Tibet AS$_\gamma$ in the regions of $|b| < 5^\circ$, $25^\circ < l < 100$

arXiv:2305.05372 (LHAASO Collaboration) 2023

Limit on high Galactic latitude PeV γ-ray flux from Tibet AS$_\gamma$

Due to the better sensitivity of Tibet-AS$_\gamma$ 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$_\gamma$ observations can be used to constrain the γ ray flux from the sky outside the Galactic plane (|b| > 20 deg.).

Neronov et al. 2021

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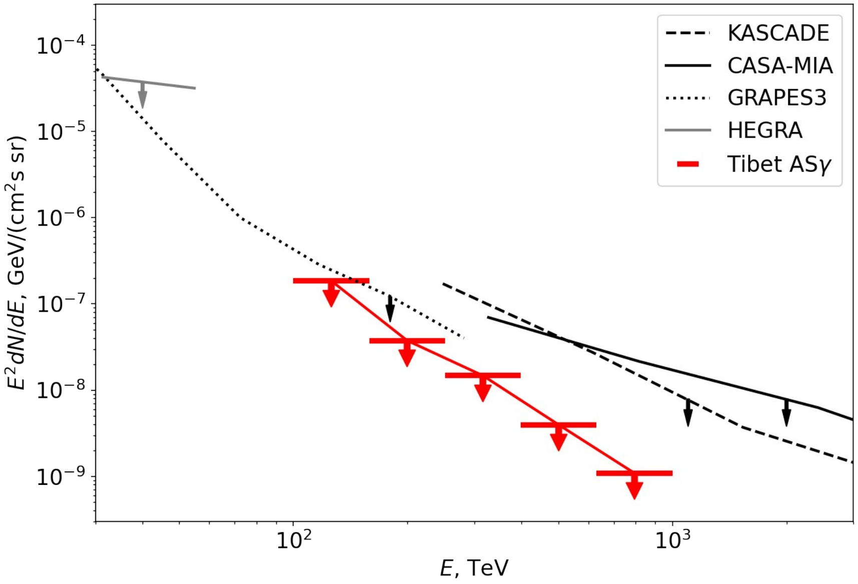
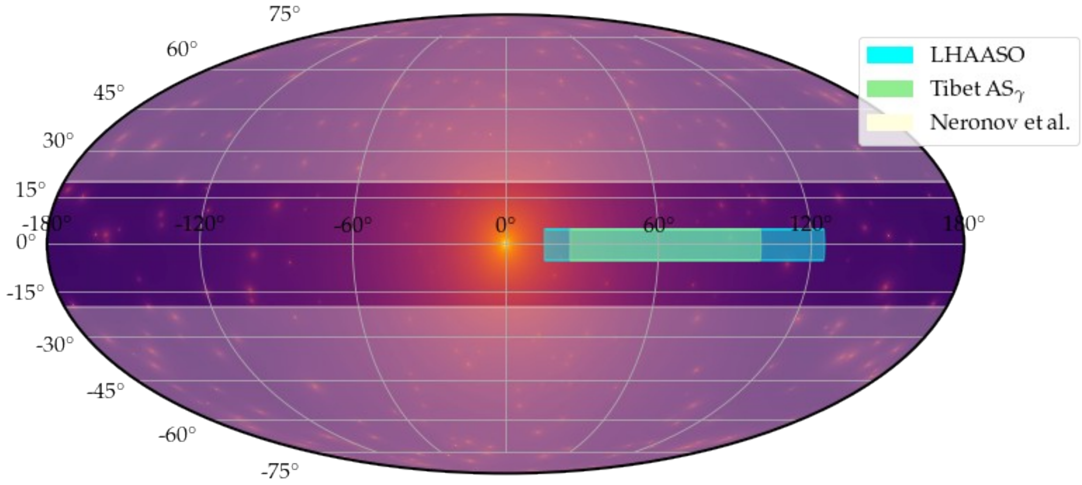
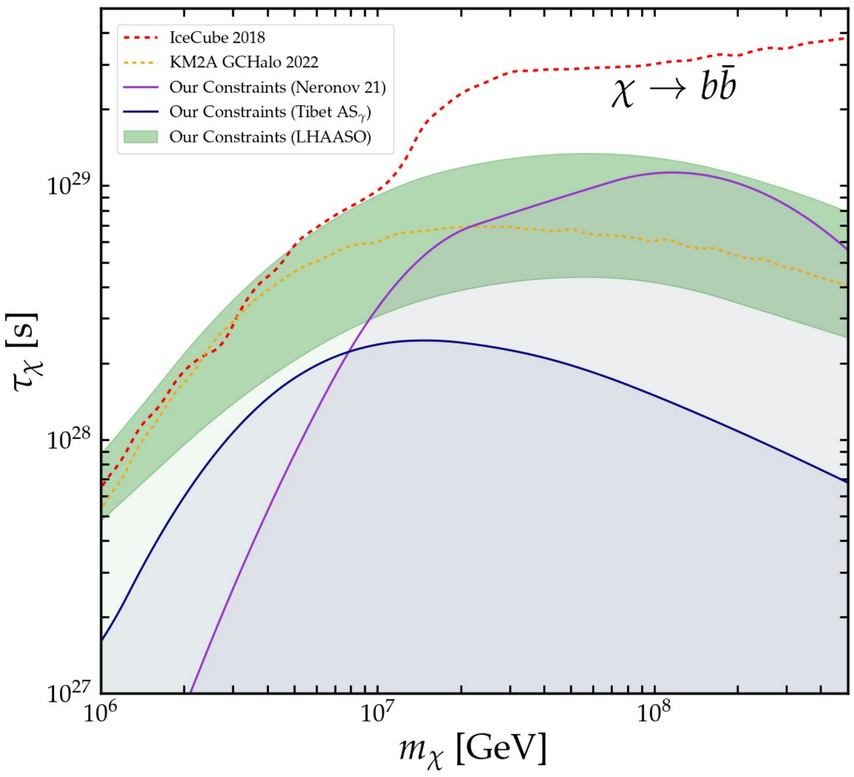


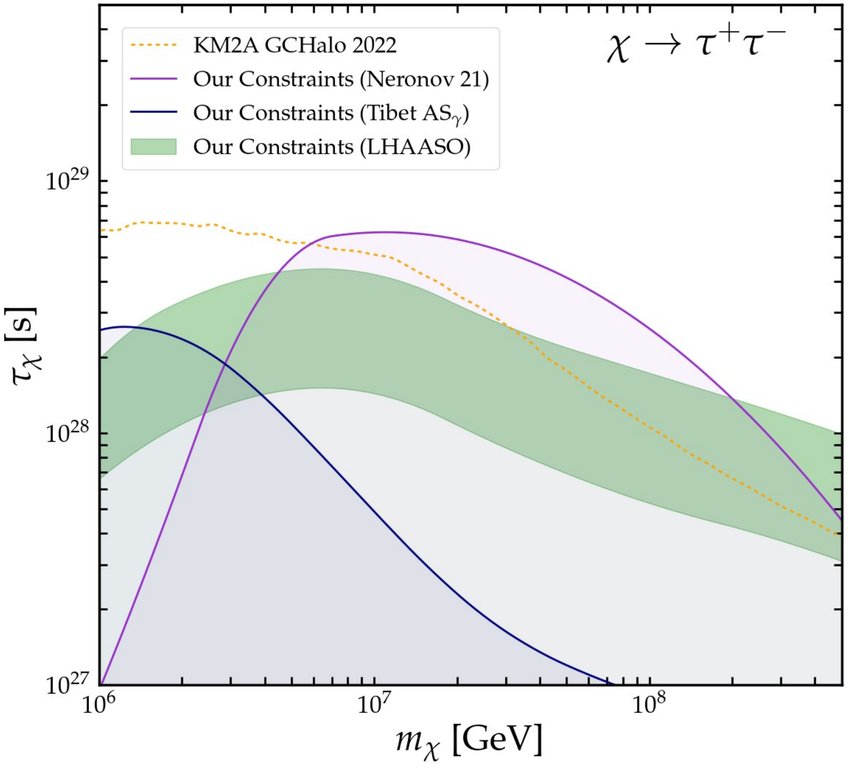


Neronov et al. 2021

Results

arXiv:2105.05680 **(PRD Letter)** + Dubey et al. (In Prep.)





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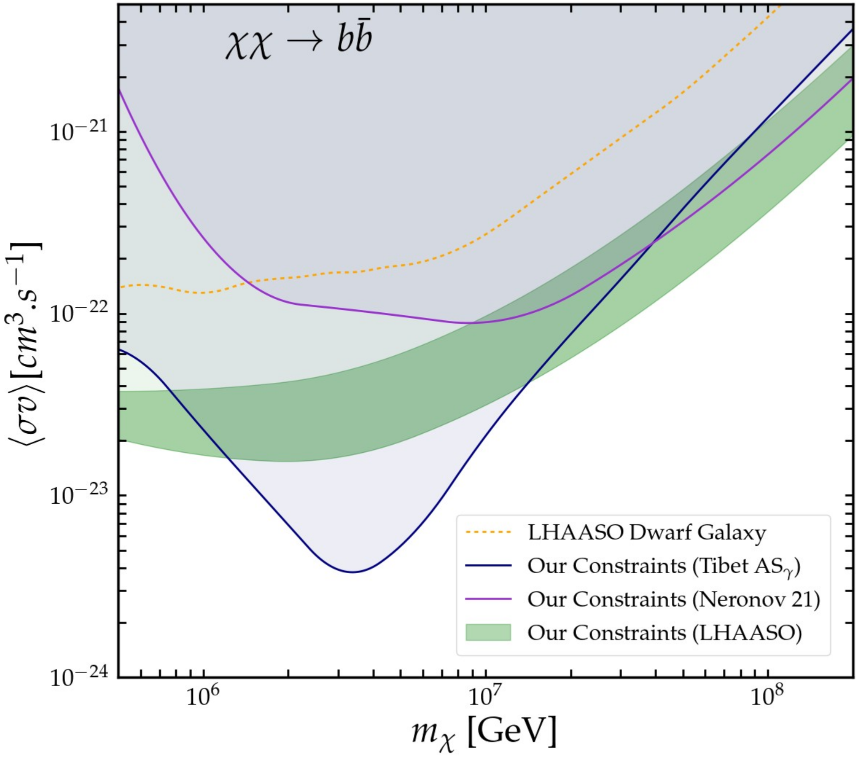
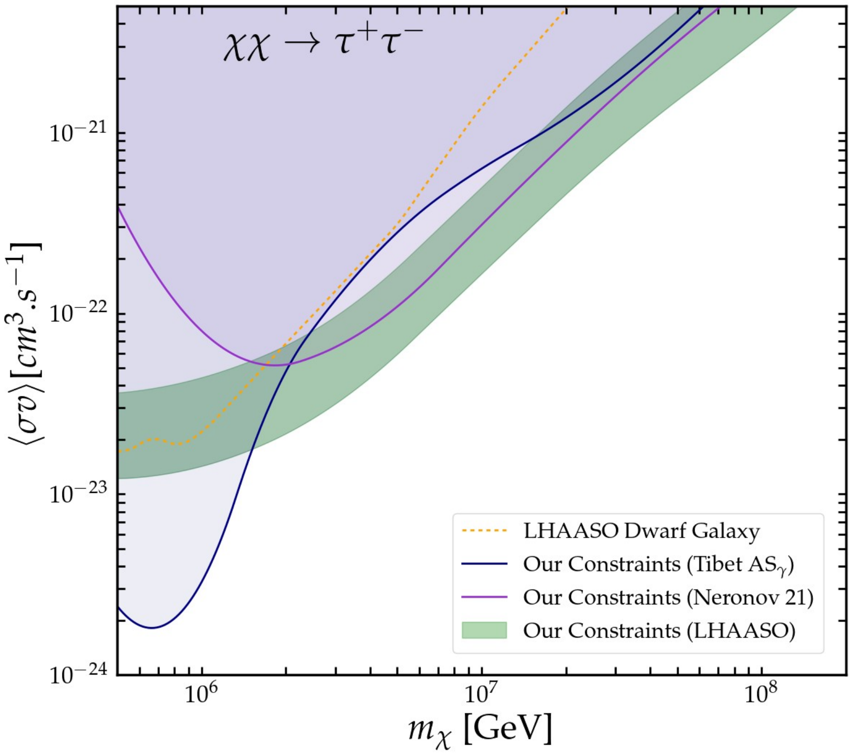
Dubey et al. (In Prep.)





Conclusions

- We have obtained constraints on Dark Matter lifetime and annihilation cross section for different final states using Tibet AS$_\gamma$ and LHAASO 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.

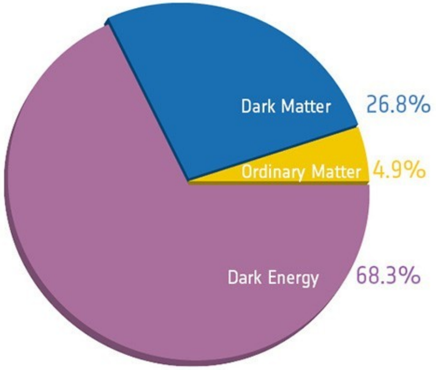
Thank You

Email: abhishekd1@iisc.ac.in

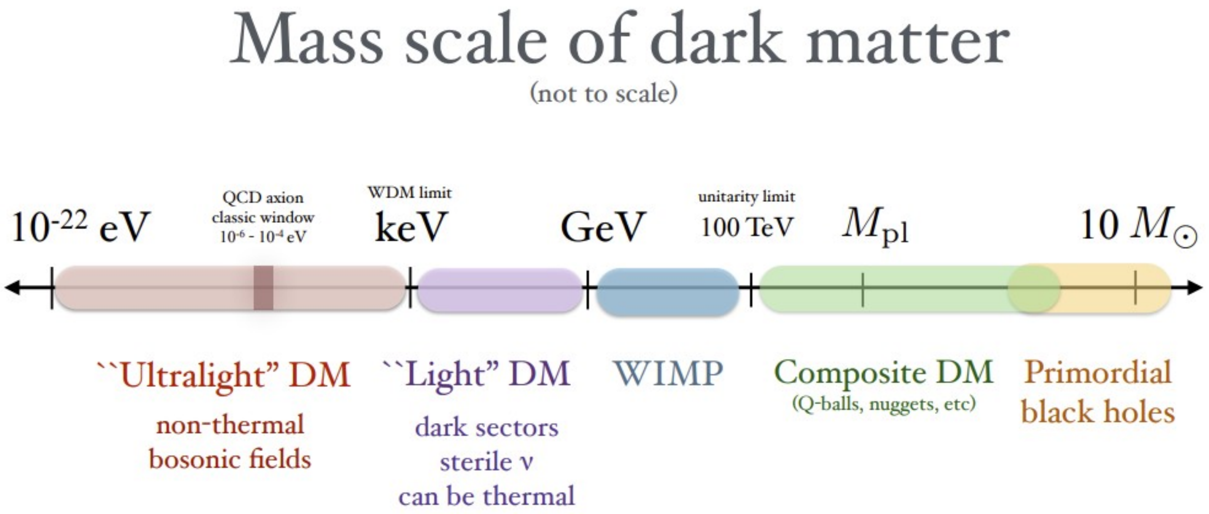
Backup

Dark Matter (DM)

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



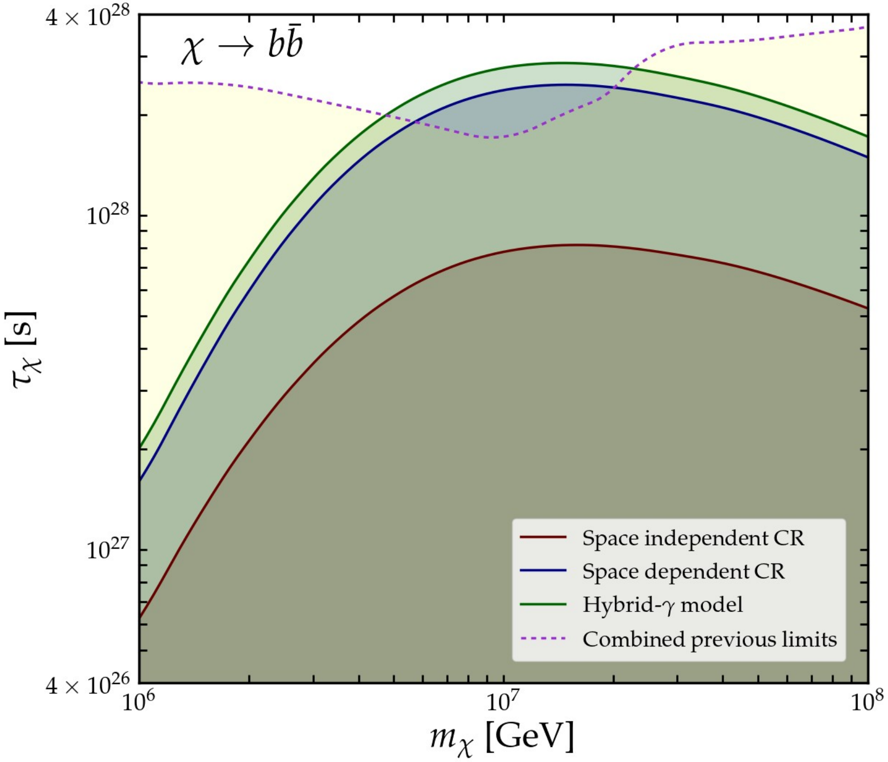
https://darkmatterdarkenergy.com/2013/06/18/more-dark-matter-first-planck-results/

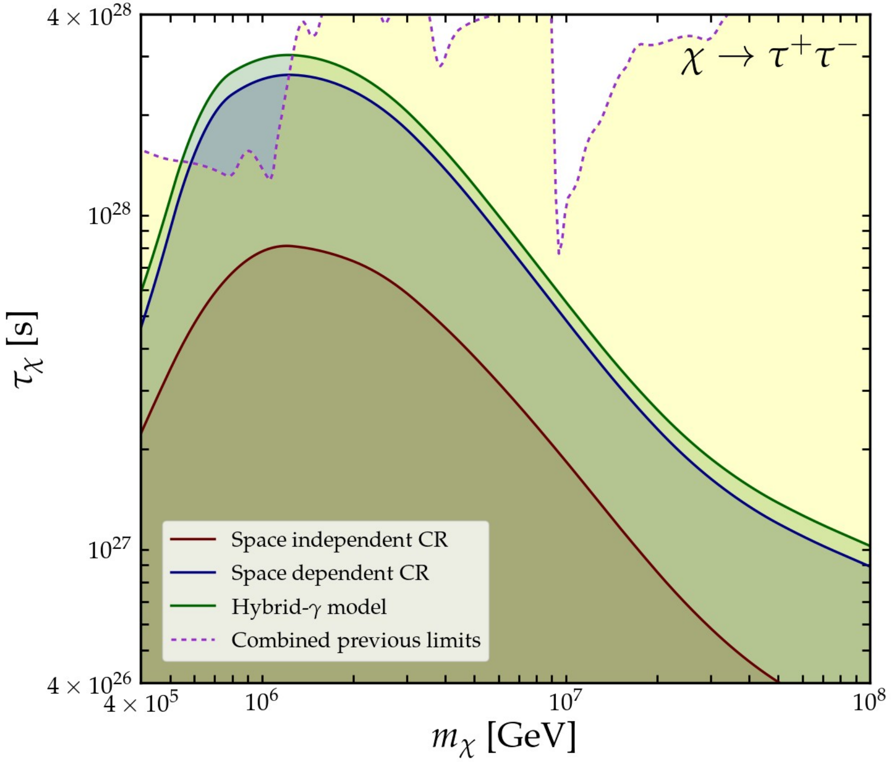


http://abyss.uoregon.edu/~js/21st_century_science/lectures/lec23.html

Results

arXiv:2105.05680 **(PRD Letter)**





Cosmic Ray measurement by Tibet ASγ

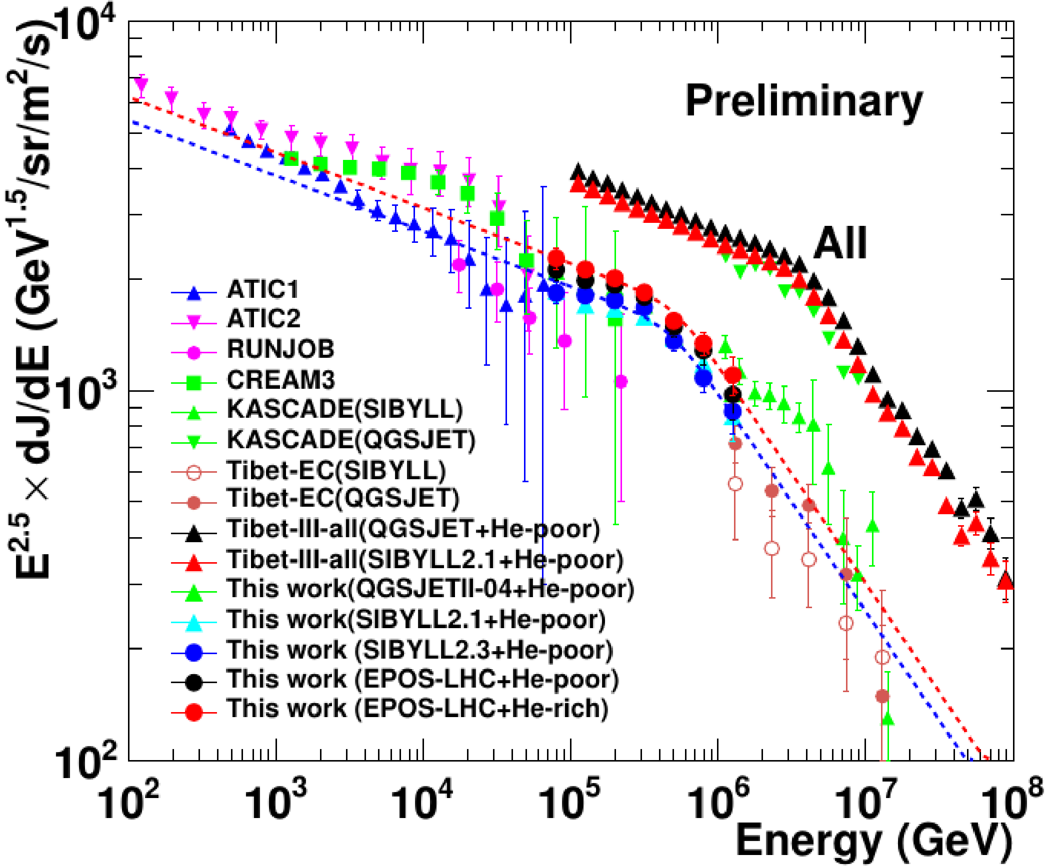
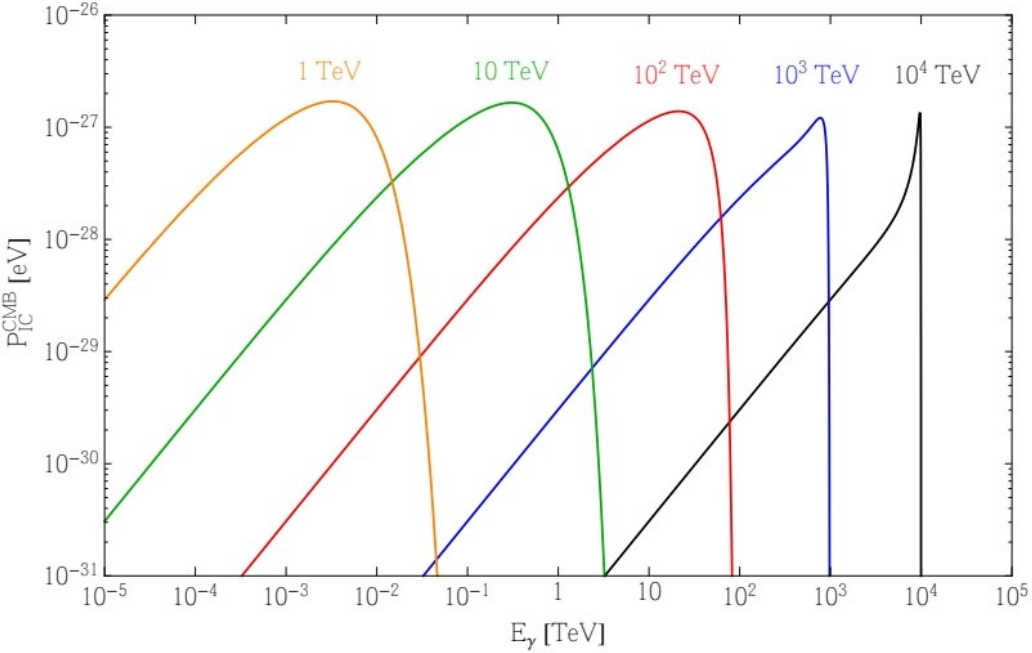
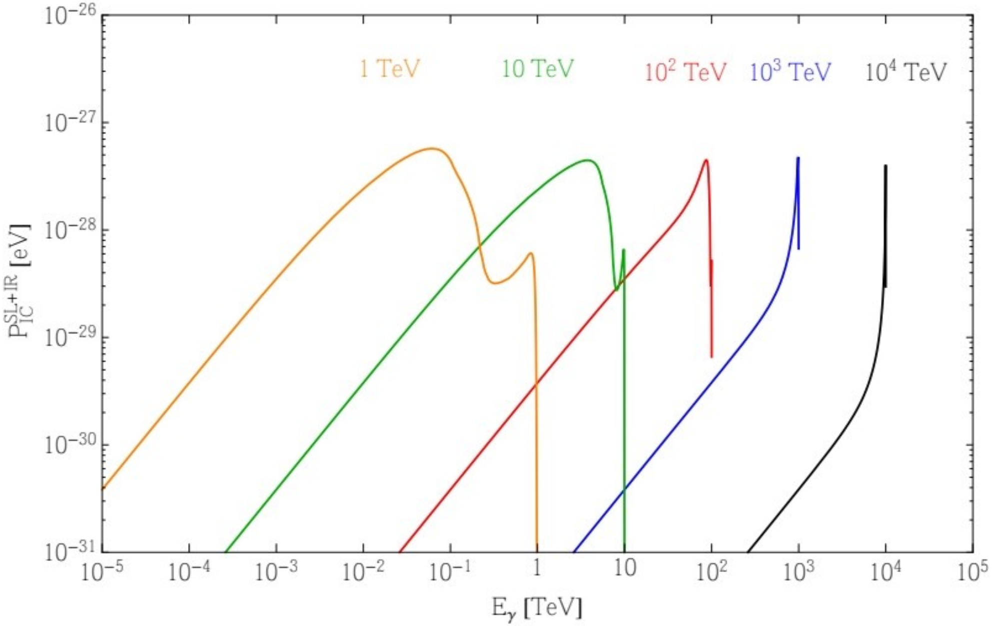


Fig: Amenomori et al., EPJ Web of Conferences 208, 03001 (2019)

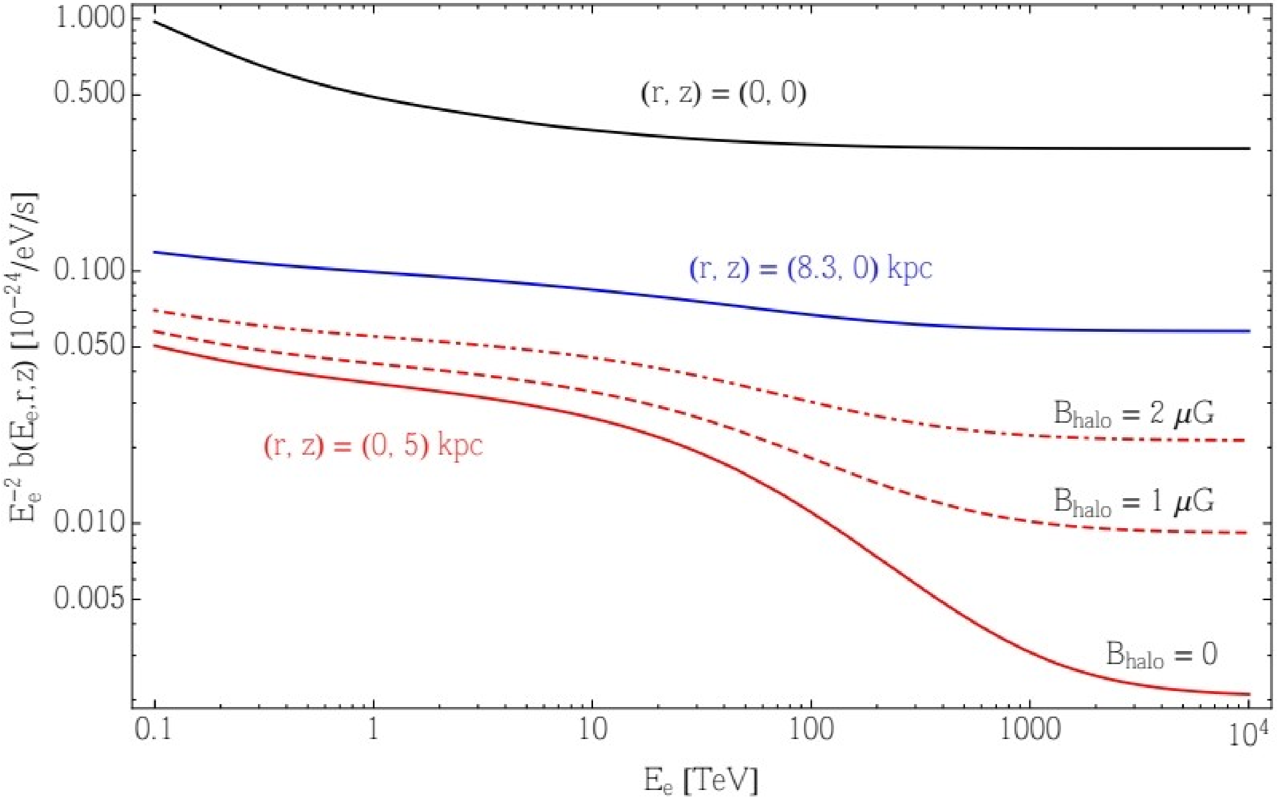
P_{IC} and Energy Loss for ICS and Synchrotron





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

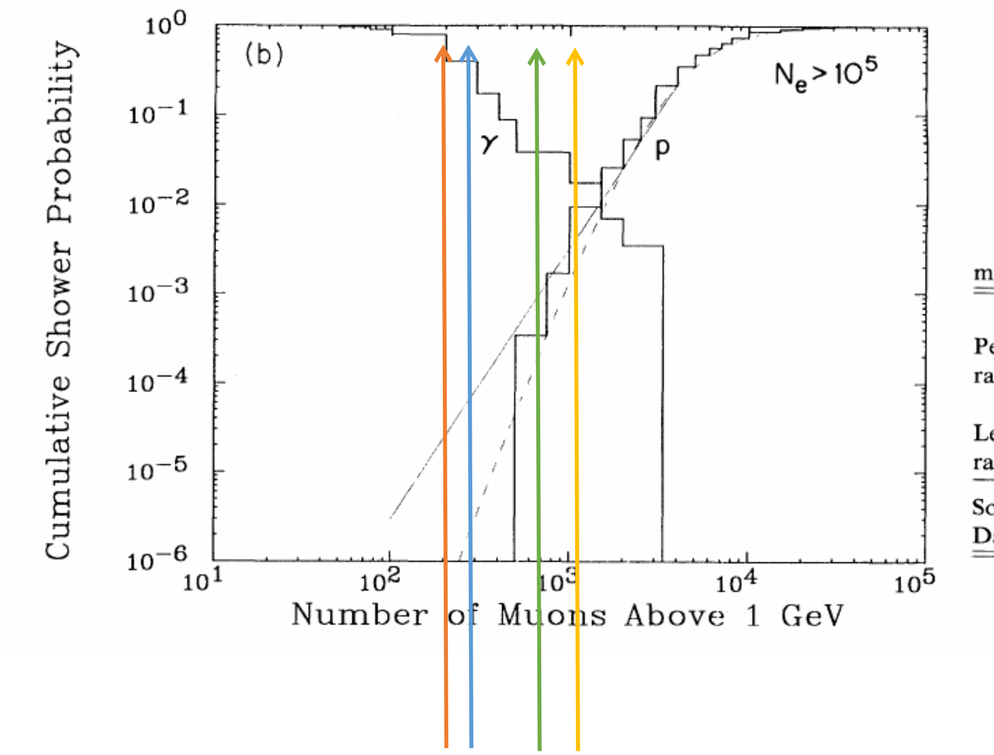


Fig : Gaisser et al., 1991

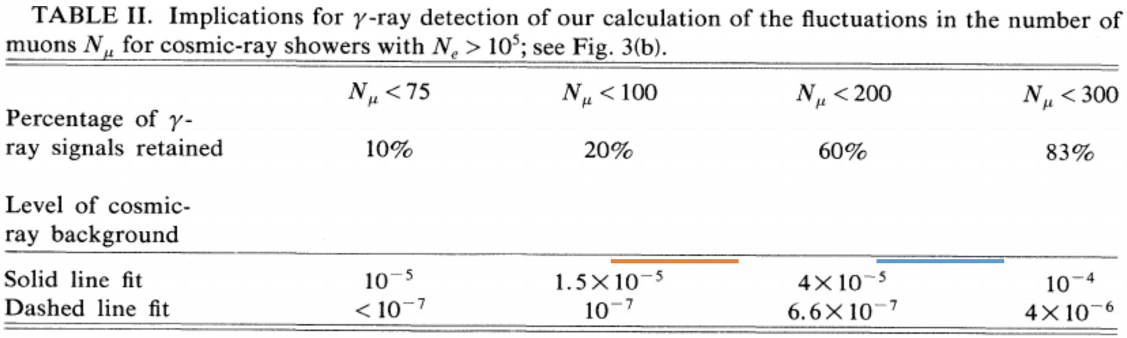
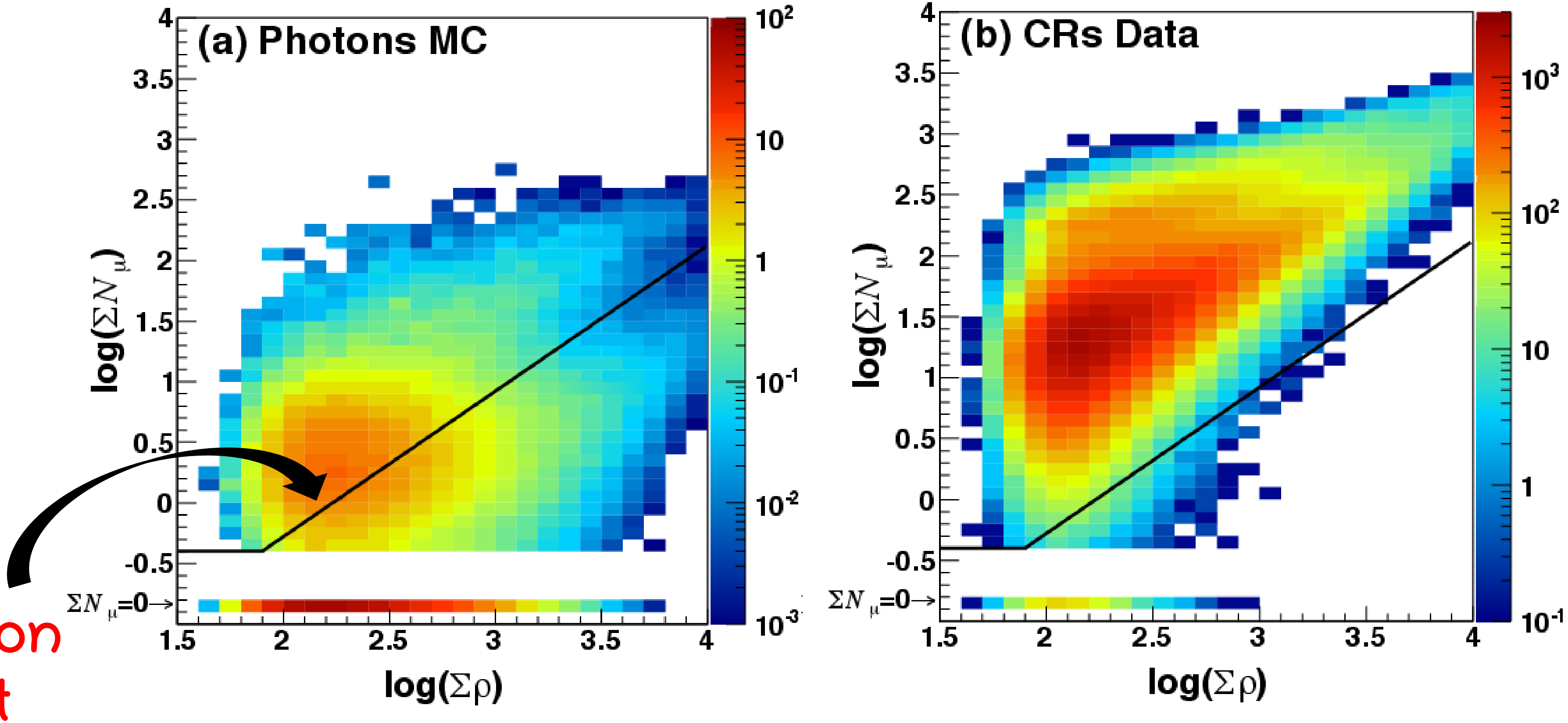


TABLE II. Implications for γ-ray detection of our calculation of the fluctuations in the number of muons N_μ for cosmic-ray showers with $N_e > 10^5$; see Fig. 3(b).

	$N_\mu < 75$	$N_\mu < 100$	$N_\mu < 200$	$N_\mu < 300$
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}

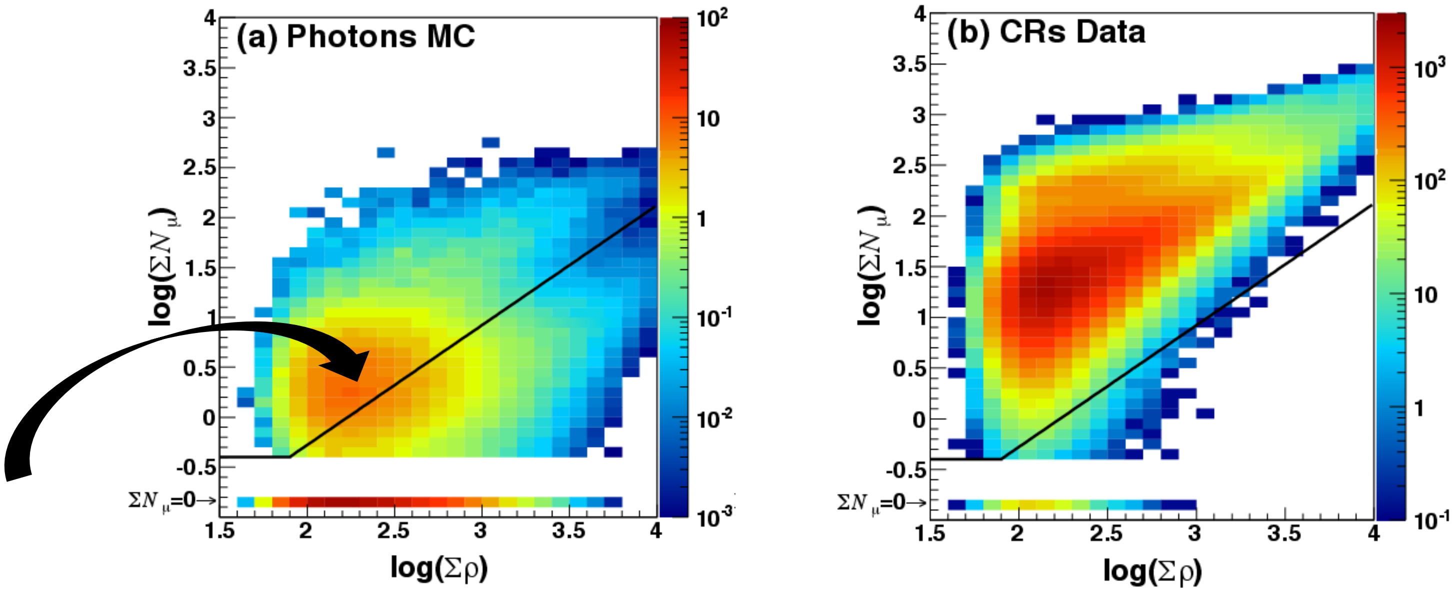
Implication of Muon Cut for Tibet ASγ



Muon Cut

Amenomori et al,. PRL, 2019

Implication of Muon Cut for Tibet ASγ



Muon Cut

Amenomori et al,. PRL, 2019

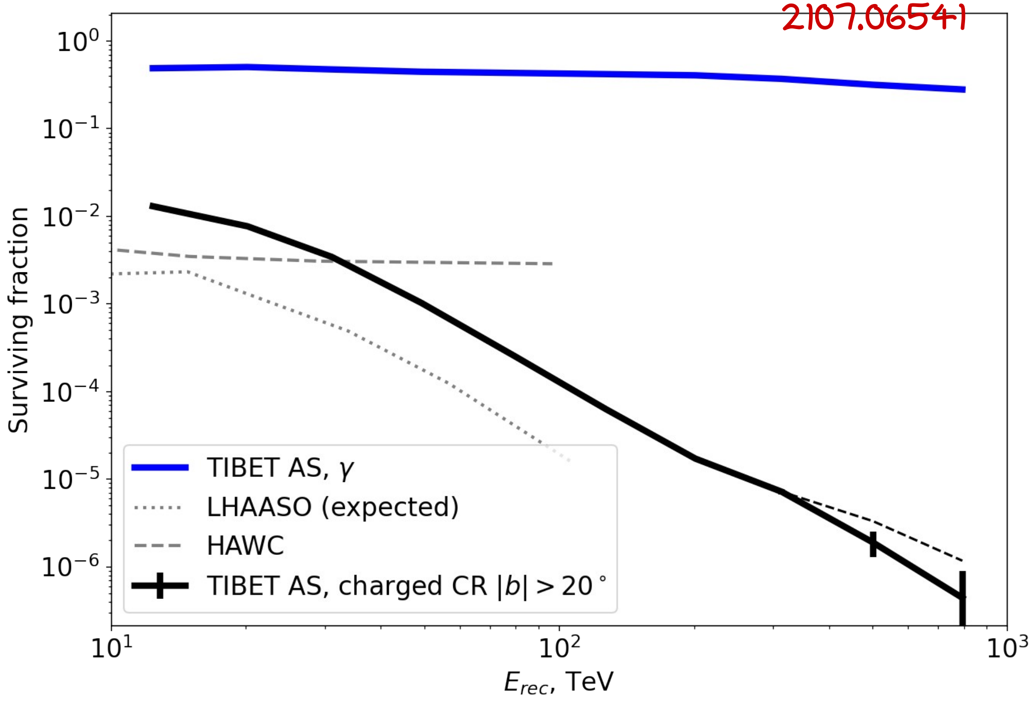
Choose a Muon Cut

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

$$\text{Upper limit on gamma ray flux} = \frac{\text{Cosmic Ray flux measured} \times \text{Surviving event fraction of Hadronic EAS}}{\text{Efficiency of the selection of Gamma ray EAS}}$$

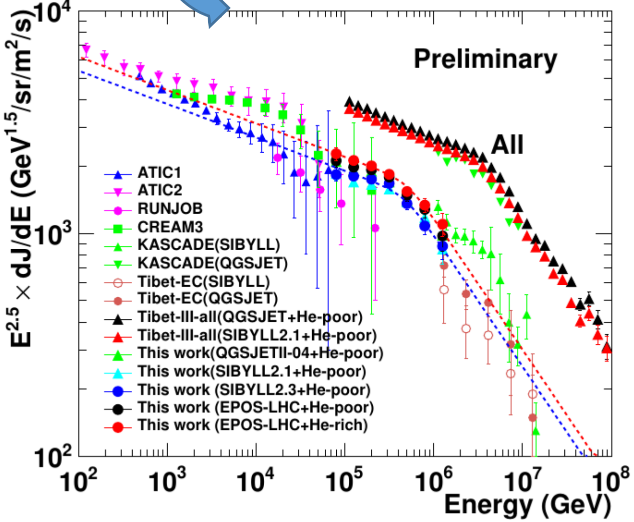


Fig: Amenomori et al., EPJ Web of Conferences 208, 03001 (2019)

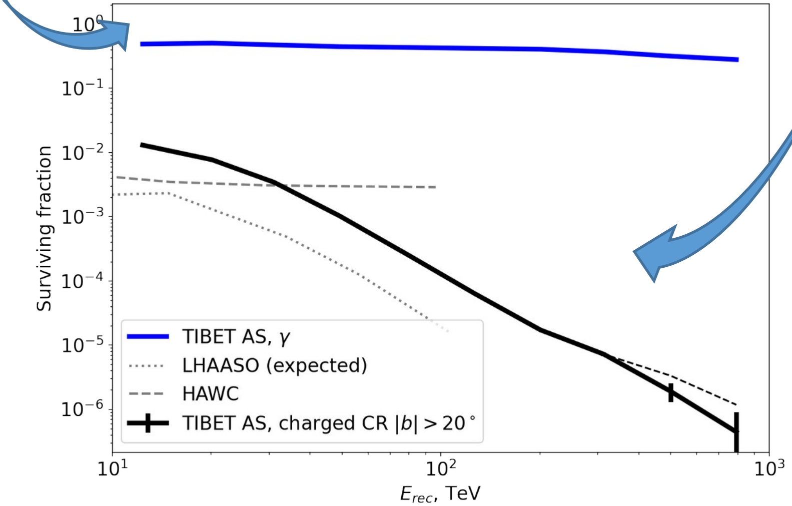


Fig: 2107.06541

Flux of gamma rays from DM decay

ray flux of direct production from DM decay

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

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

HDMSpectra

m = DM mass, = DM lifetime,

E , 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

= optical depth of photons due to CMB, SL+IR and EBL

ray flux of Inverse compton production from DM decay

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

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

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

P$_{\mathrm{IC}}$ is ICS radiative power and b$_{\mathrm{IC}}$ is the energy loss of electrons/positrons due to ICS and Synchrotron radiation.

Flux of gamma rays from DM annihilation

ray flux of direct production from DM annihilation

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

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

ray flux of inverse Compton production from DM annihilation

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

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

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

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

Boost factor and Clumping factor

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

Hiroshima, et al. 2018

→ Halo mass funtion