

Indirect searches for dark matter: gamma-rays and neutrinos

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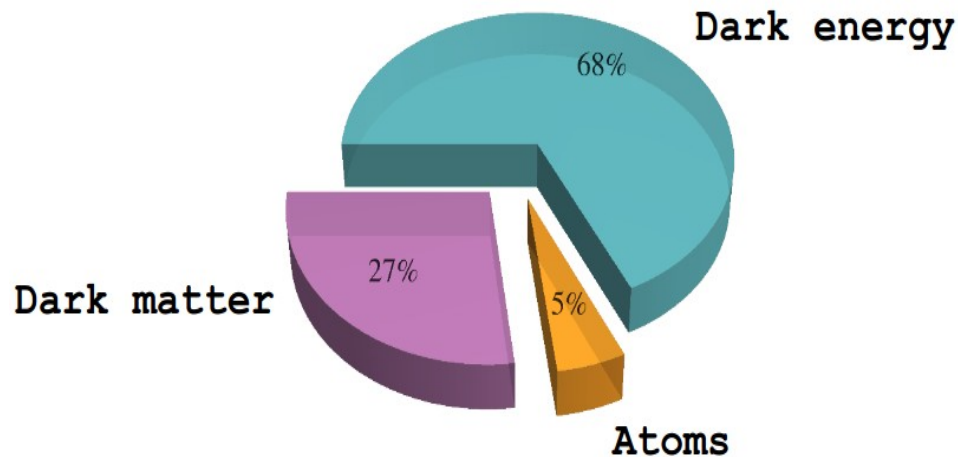
Based on

TNM, A K Saha, A Dubey, R Laha 2105.05680

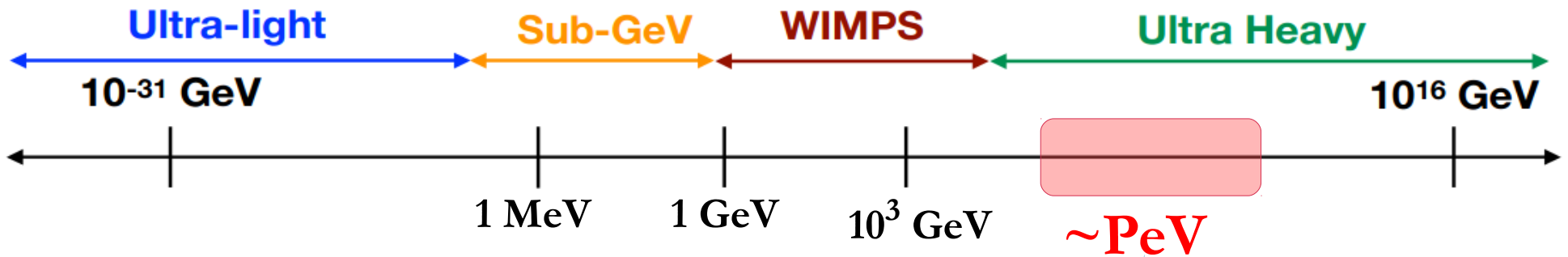
D Bose, TNM, T S Ray 2108.12420



Dark Matter Landscape



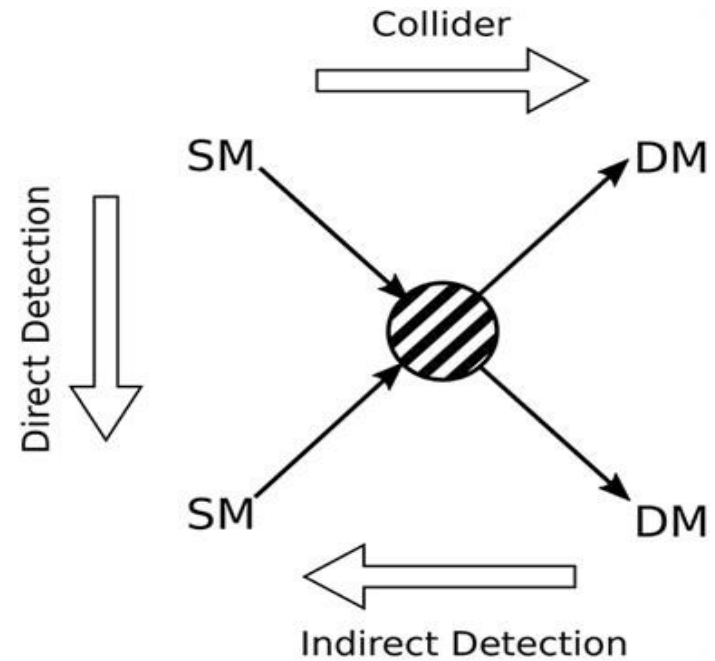
- ✓ Cold : non-relativistic
- ✓ Stable: no decay, very long lived
- ✓ Massive: wide range



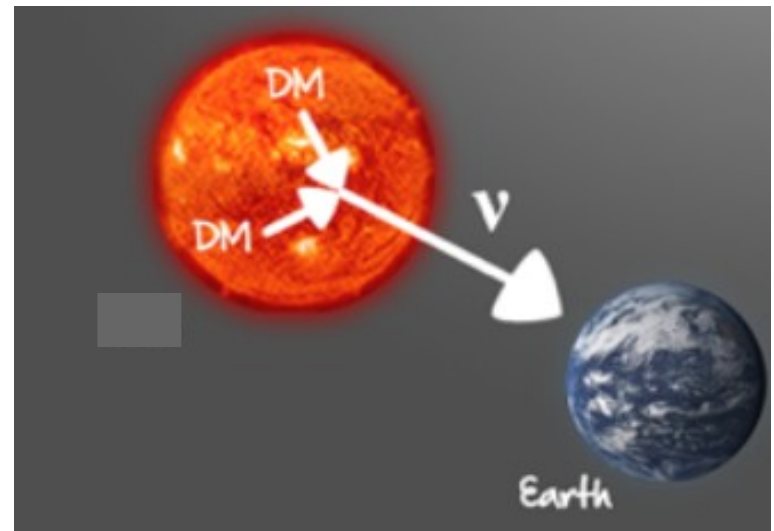
This talk

Heavy DM: Indirect searches

- ✗ Difficult to probe at collider:
kinematically disfavored
- ✗ Direct detection:
very low flux
- ✓ Indirect searches:
extremely useful



Tibet AS γ

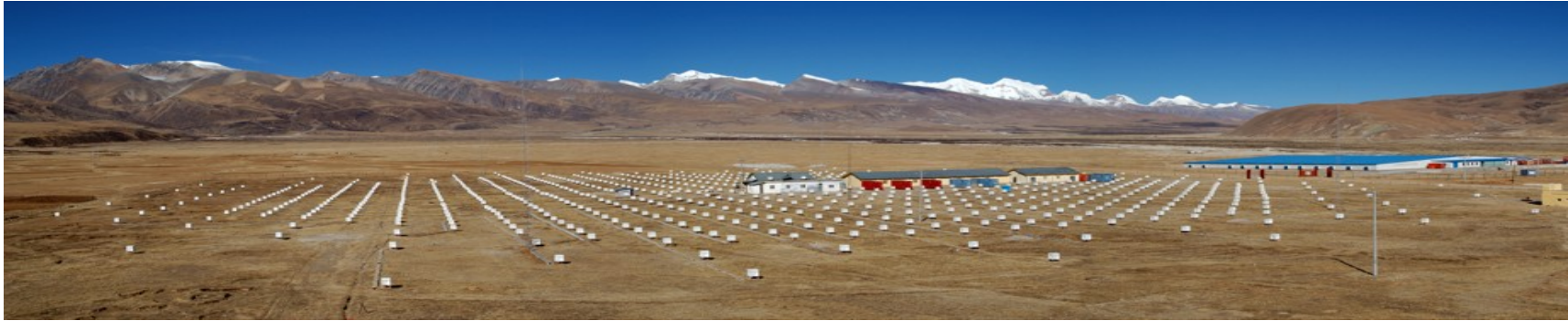


Neutrinos from captured DM

Outline

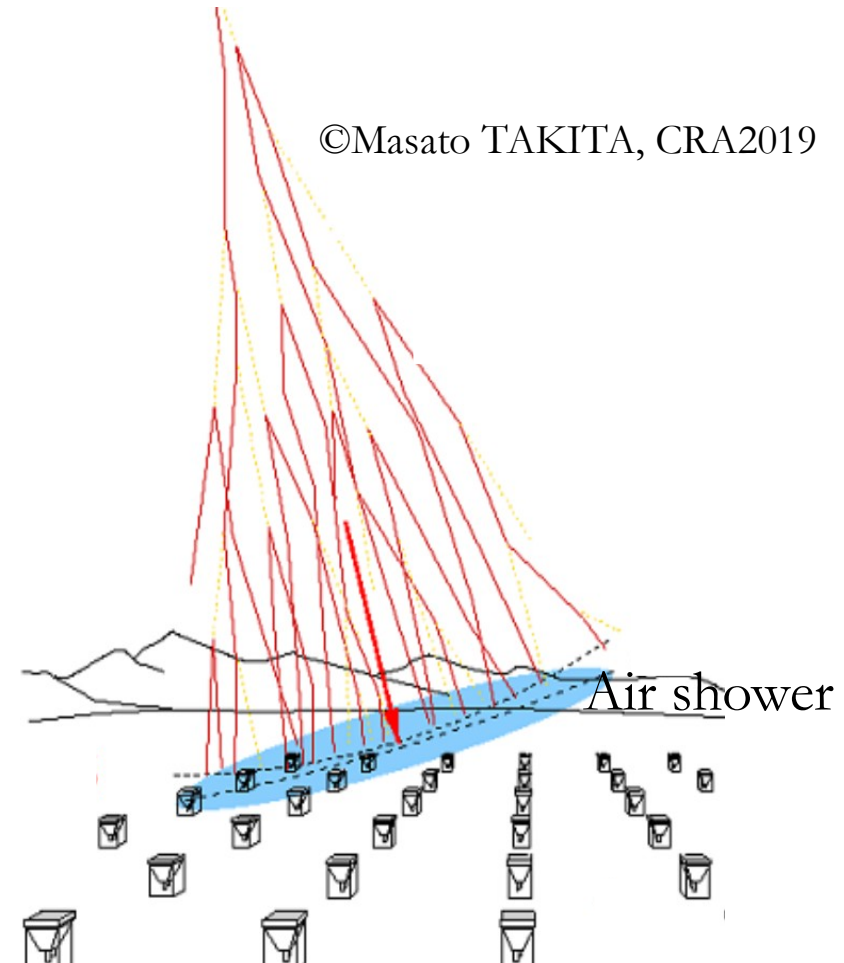
- Tibet AS_γ : gamma rays from decaying DM
 - Theorist's view of Tibet AS_γ
 - New physics: decaying DM
- Neutrinos from captured DM
- Conclusion

Tibet AS_γ



- ✓ 4300 m above sea level
- ✓ Effective area: ~ 0.5 KIAS
- ✓ No. of scintillator detectors: 597
- ✓ Each having area 0.5 m^2

Amenomori et al 2104.05181 PRL

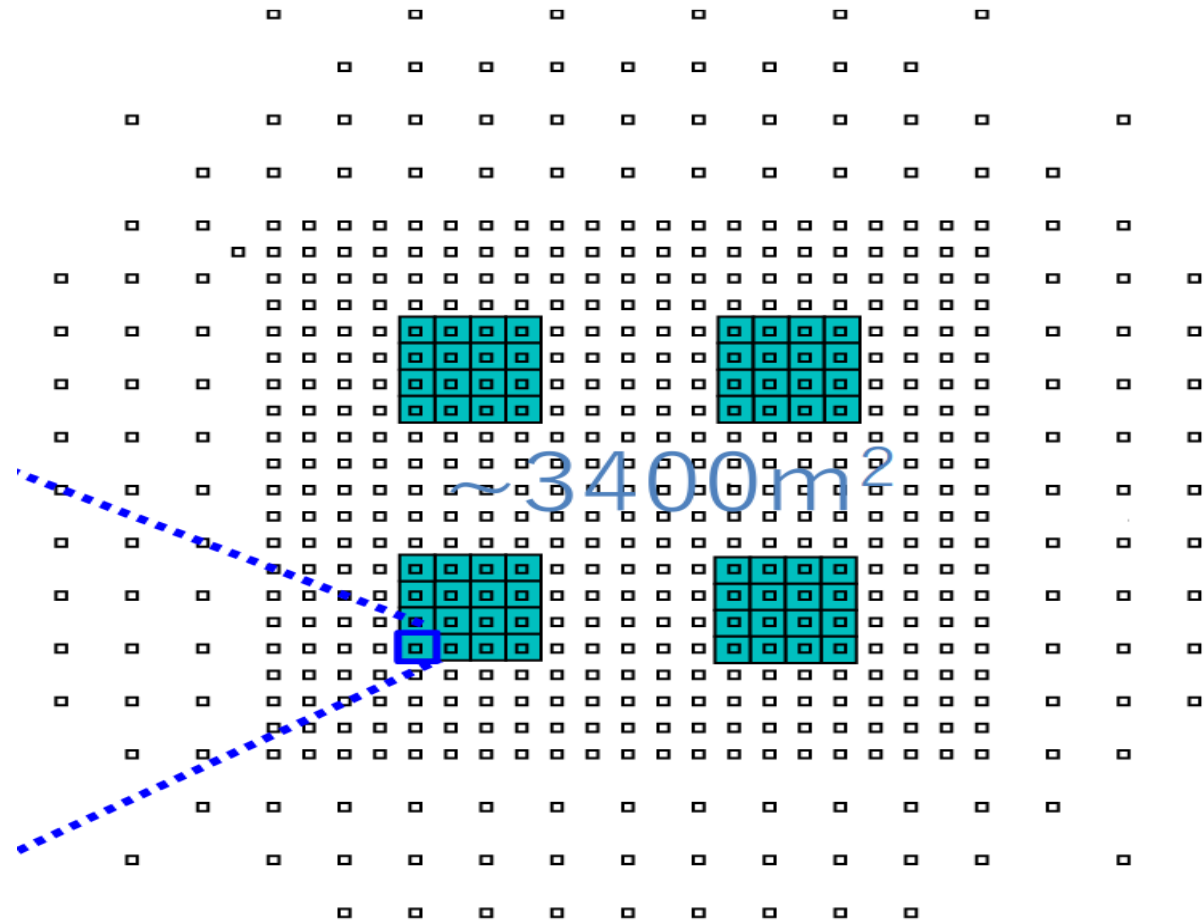


Tibet AS+MD

✓ 2.4m underground

✓ Hybridize with muon detector.

✓ Muon with energy greater than 1 GeV

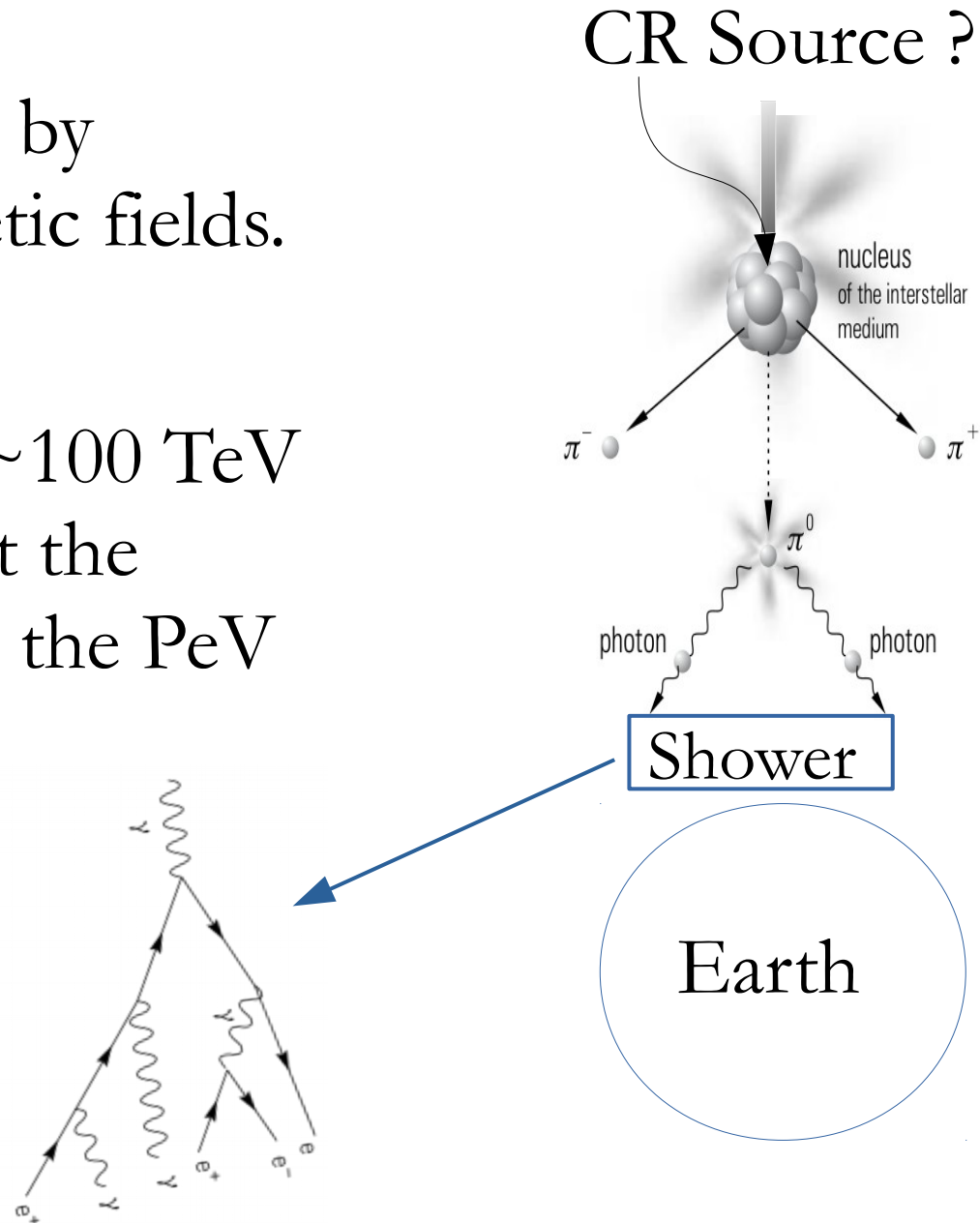


Livetime: 719 days from February 2014 to May 2017

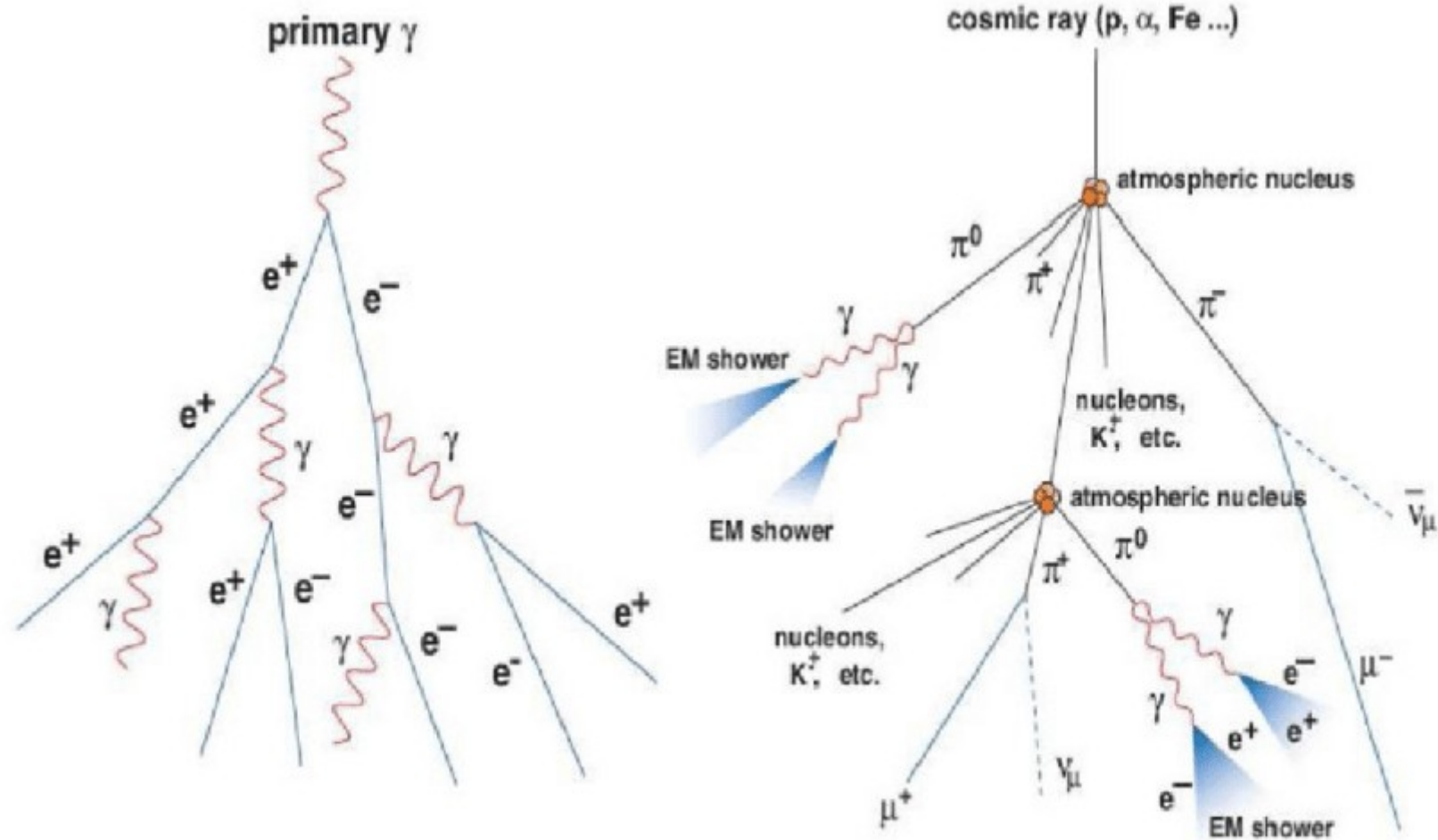
Muon detector: gamma and cosmic ray (CR) discrimination

Gamma ray as messenger

- ✓ Are not deflected by interstellar magnetic fields.
- ✓ Observation of ~ 100 TeV gamma ray predict the Galactic origin of the PeV cosmic ray.

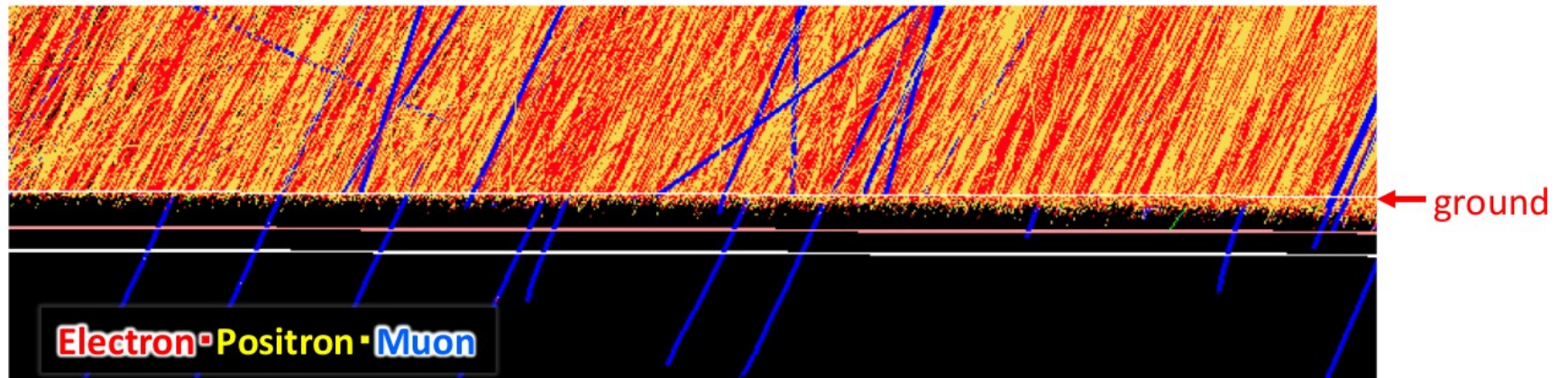


Photon and Proton Shower

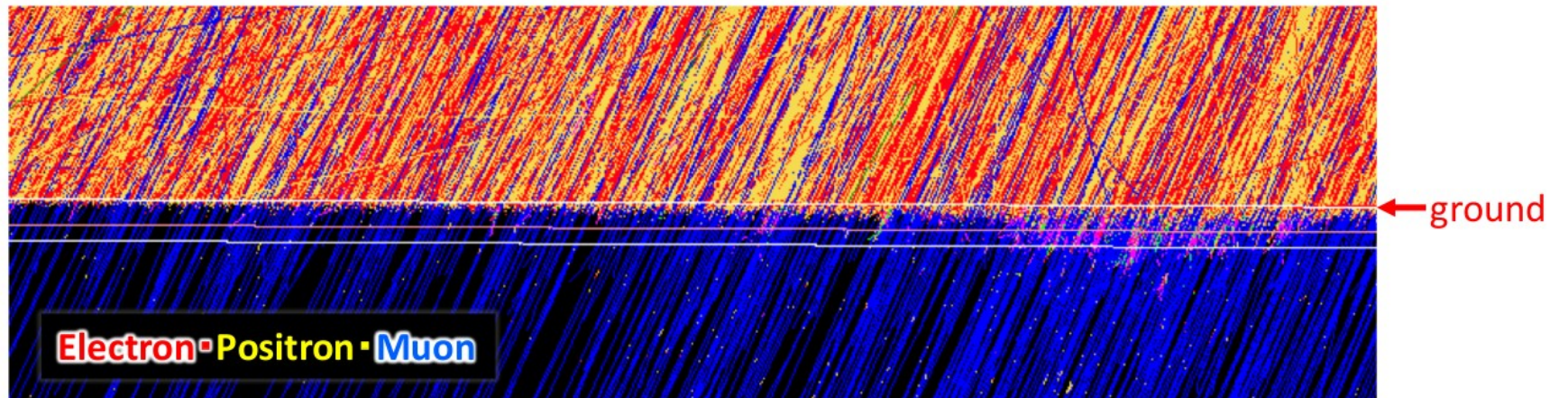


Occasional γ -p interaction gives rises shower similar to hadronic shower

Photon and Proton Shower



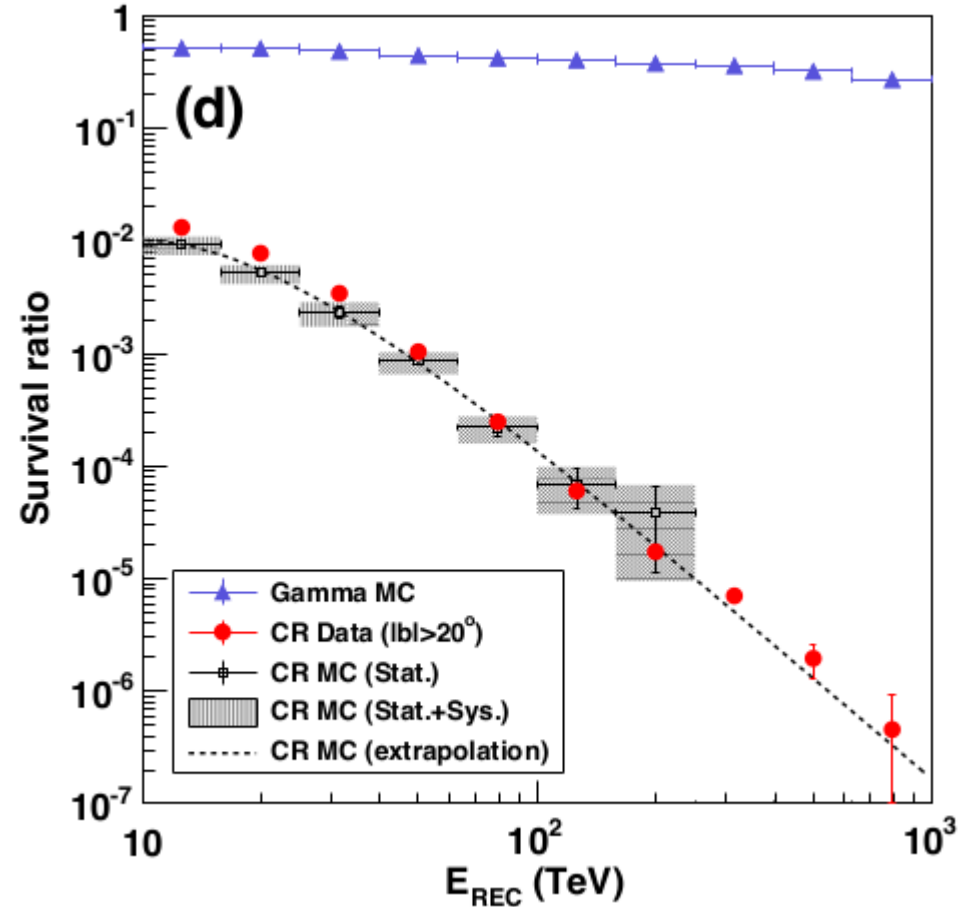
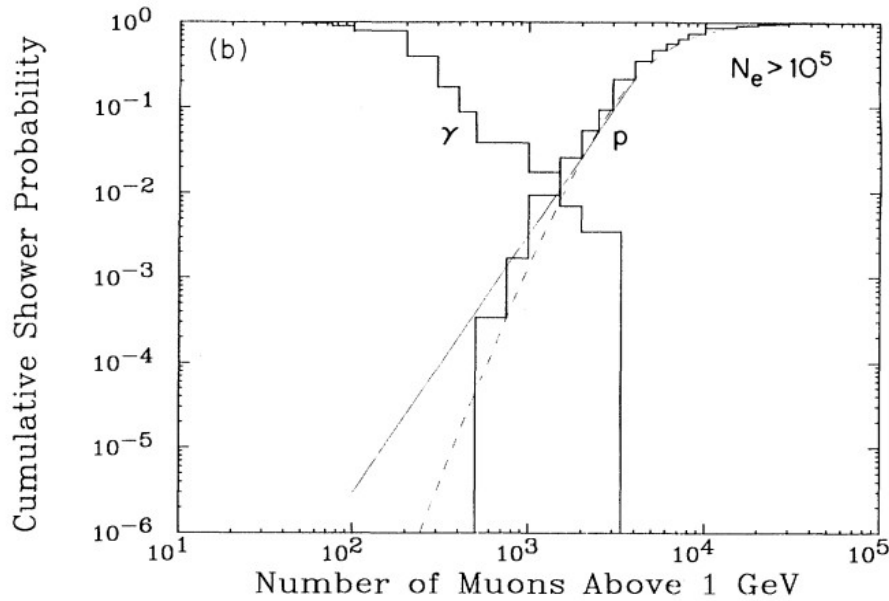
200TeV Gamma-ray induced AS



200TeV Proton induced AS

Photon Proton Shower: Tibet AS γ

After muon cut

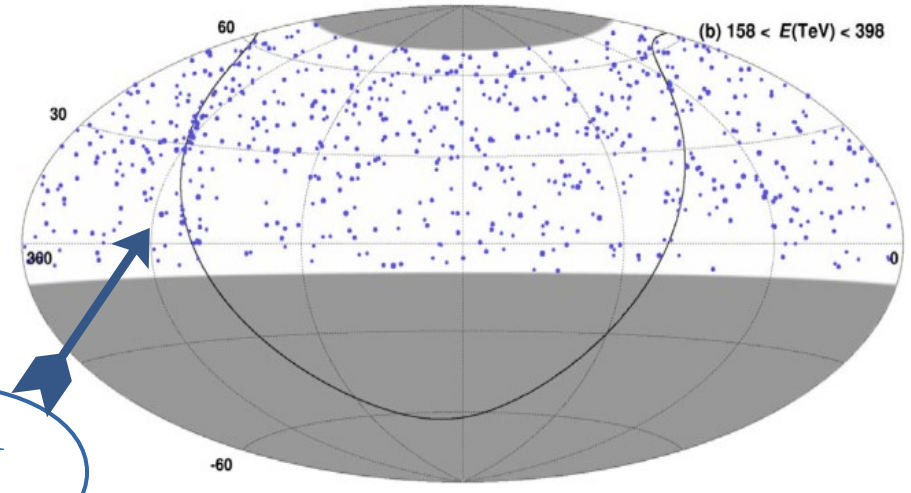
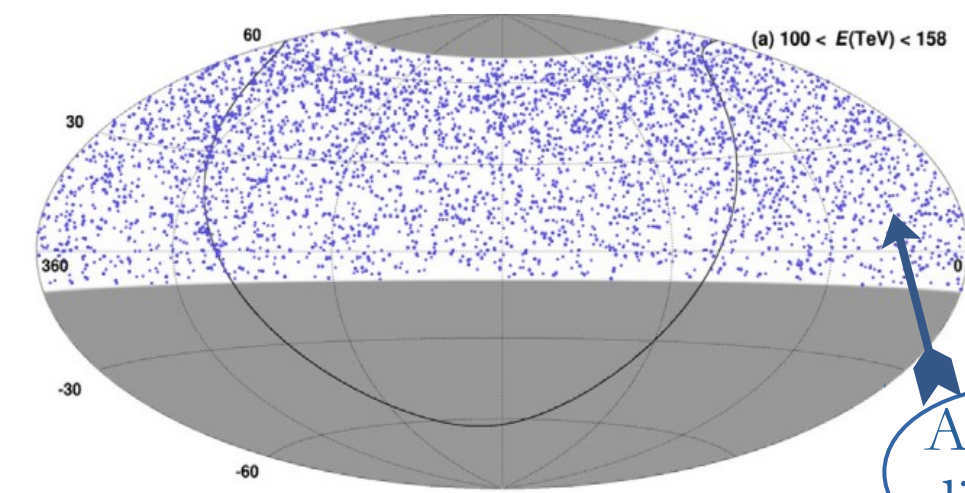


	$N_\mu < 75$	$N_\mu < 100$	$N_\mu < 200$	$N_\mu < 300$
Percentage of γ -ray signals retained	10%	20%	60%	83%
Level of cosmic-ray background				
Solid line fit	10^{-5}	1.5×10^{-5}	4×10^{-5}	10^{-4}
Dashed line fit	$< 10^{-7}$	10^{-7}	6.6×10^{-7}	4×10^{-6}

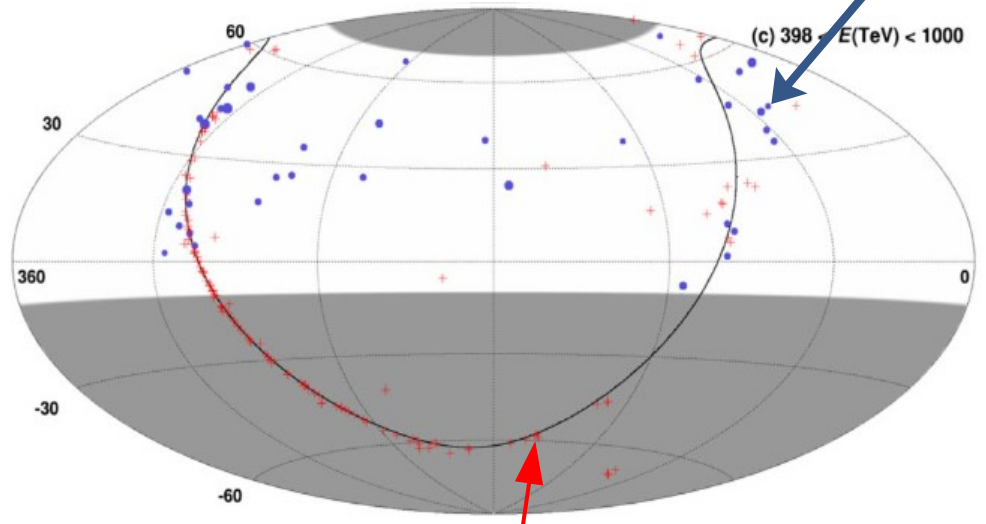
Gaisser et al PRD '91

Amenomori et al 2104.05181 PRL

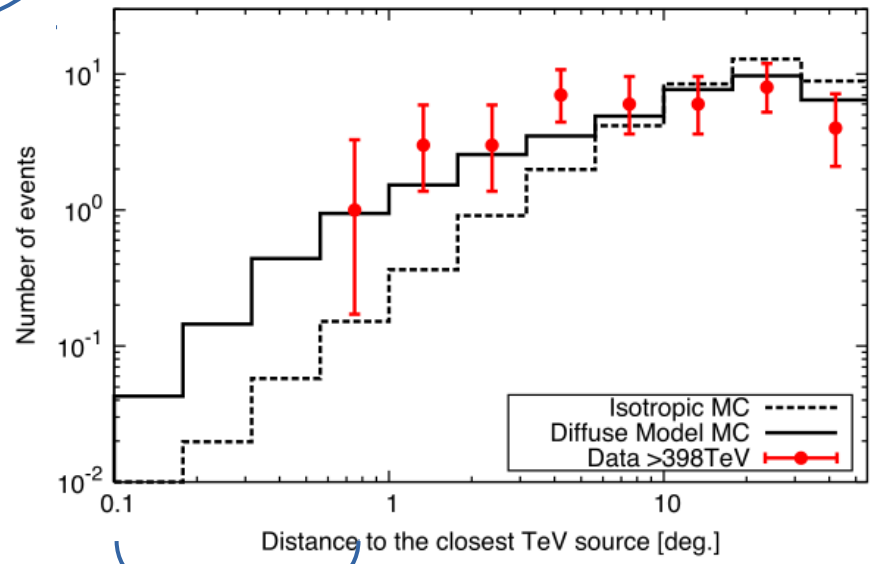
Tibet AS γ



Arrival direction

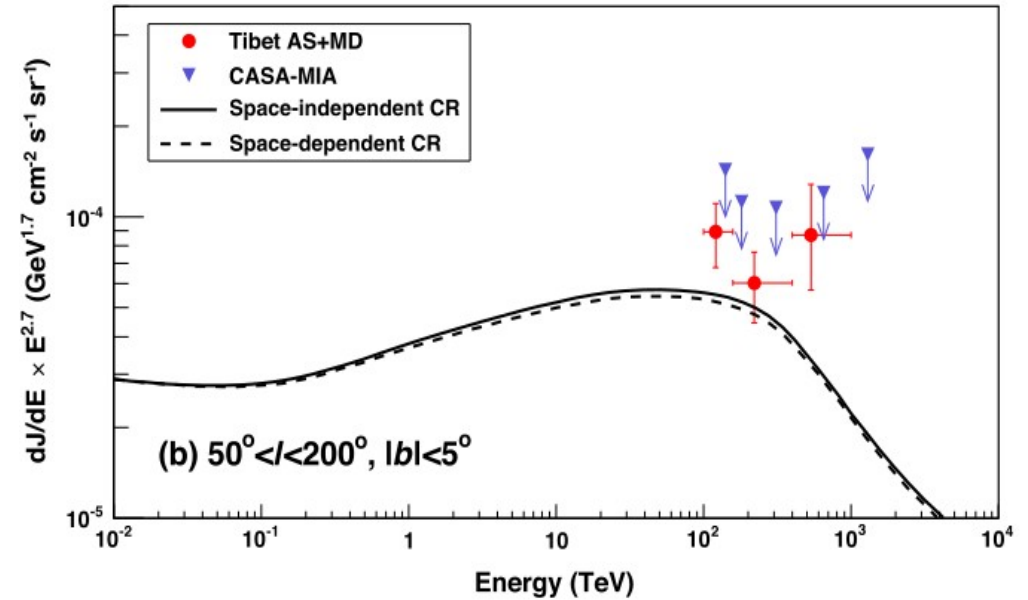
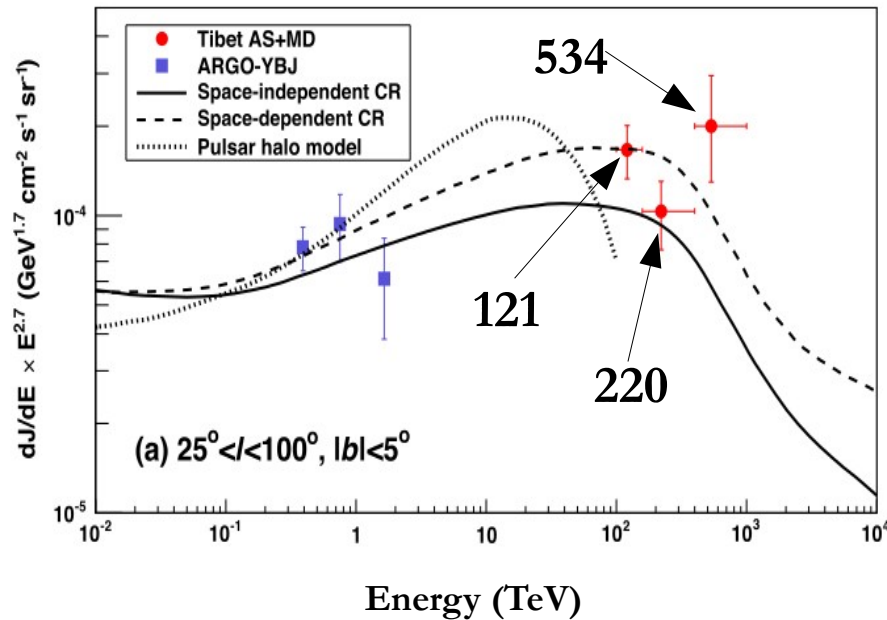


Known TeV sources



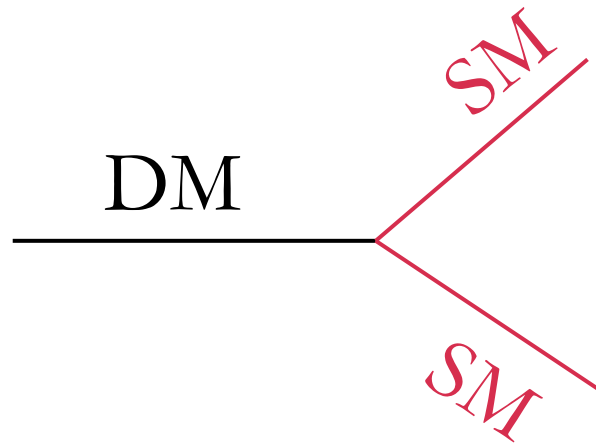
Diffuse gamma ray event

Observed Flux



- ✓ First detection of sub-PeV diffuse gamma rays.
- ✓ Space dependent and space independent cosmic ray model seems to fit well with data, proposed in 1804.10116
- ✓ Several recent proposals e.g., see 2104.09491, 2104.03729, 2104.05609

Observed Flux: whether this observation could be used for detection of dark matter?



Ko & Tang 1508.02500

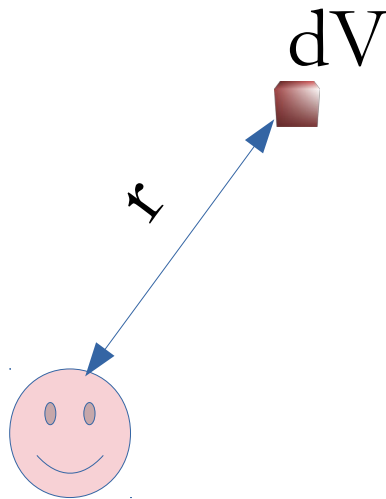
Chun & Park 1506.07522

Baek, Ko, Park 1407.6588

Ko & Tang 1504.03908 ...

Esmaili, Serpico 2105.01826

Decaying DM: Flux



τ_χ : DM lifetime

$$\text{Decay rate/time} = \frac{n_\chi(r) dV}{\tau_\chi}$$

@ One obs.
particle/decay

A: detector area

$$\frac{dN}{dt} = \frac{A}{4\pi r^2} \frac{n_\chi(r) dV}{\tau_\chi}$$

$$\frac{dN}{dt} = A \frac{\rho_\chi(\vec{r})}{m_\chi \tau_\chi} \frac{d\Omega}{4\pi} dr$$

@ Energy does not change
between production and reception

Line of sight integration

$$\frac{1}{A} \frac{dN}{dt} = \frac{1}{4\pi m_\chi \tau_\chi} \underbrace{\int \rho_\chi(\vec{r}) d\Omega dr}_{\sim J_{\text{decay}}}$$

Decaying DM: Flux

τ_χ : DM lifetime

$$\text{Decay rate/time} = \frac{n_\chi(r)dV}{\tau_\chi}$$

dV

@ One obs.
particle/decay

$$\frac{dN}{dE}$$

A: detector area

$$\frac{dN}{dEdt} = \frac{A}{4\pi r^2} \frac{n_\chi(r)dV}{\tau_\chi} \frac{dN}{dE}$$

$$\frac{dN}{dEdt} = A \frac{\rho_\chi(\vec{r})}{m_\chi \tau_\chi} \frac{dN}{dE} \frac{d\Omega}{4\pi} dr$$

@ Energy does not
change between
production and
reception

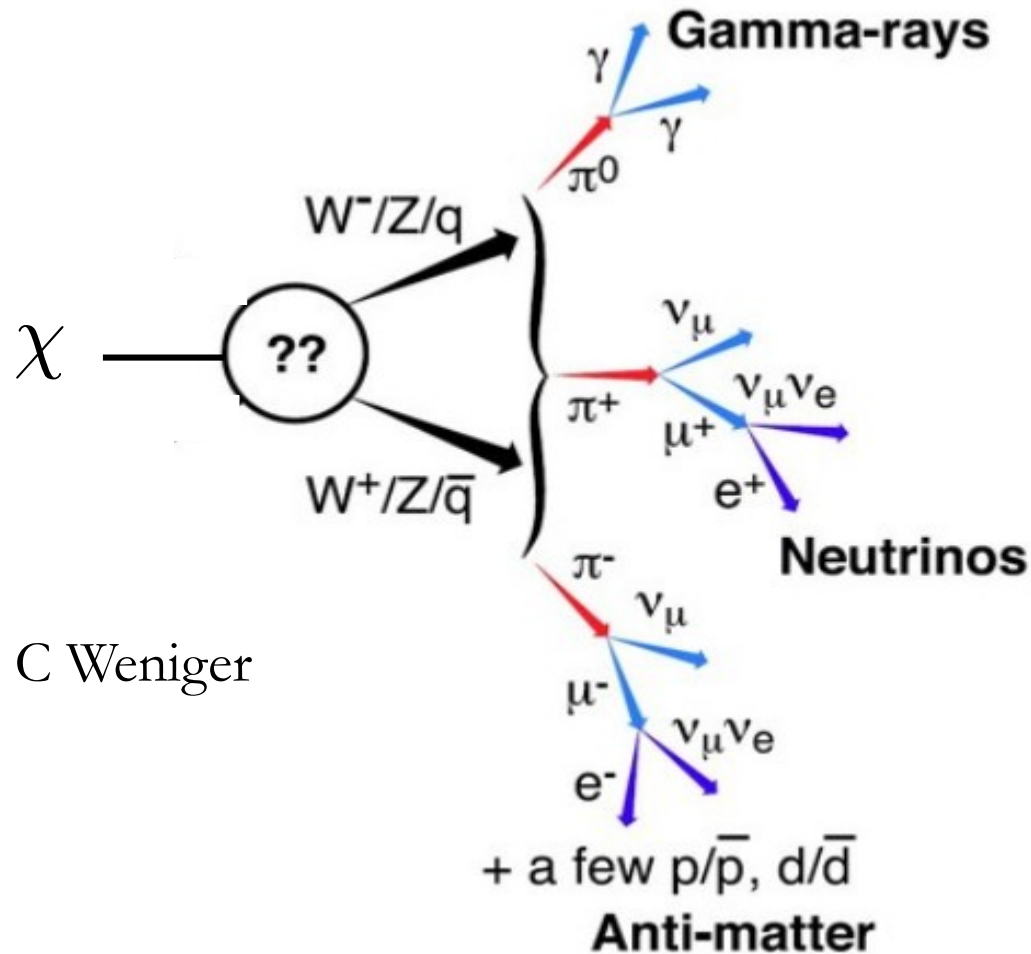
Attenuation
etc.

Line of sight integration

$$\frac{1}{A} \frac{dN}{dEdt} = \frac{1}{4\pi m_\chi \tau_\chi} \frac{dN}{dE} \int \rho_\chi(\vec{r}) e^{-\tau(E_\gamma, \vec{r})} d\Omega dr$$

Decaying DM: gamma-ray spectrum

$$\frac{dN}{dE}$$



PPPC

Cirelli et al 1012.4515

HDMSpectra

Bauer et al 2007.15001

© C Weniger

Decaying DM: Attenuation

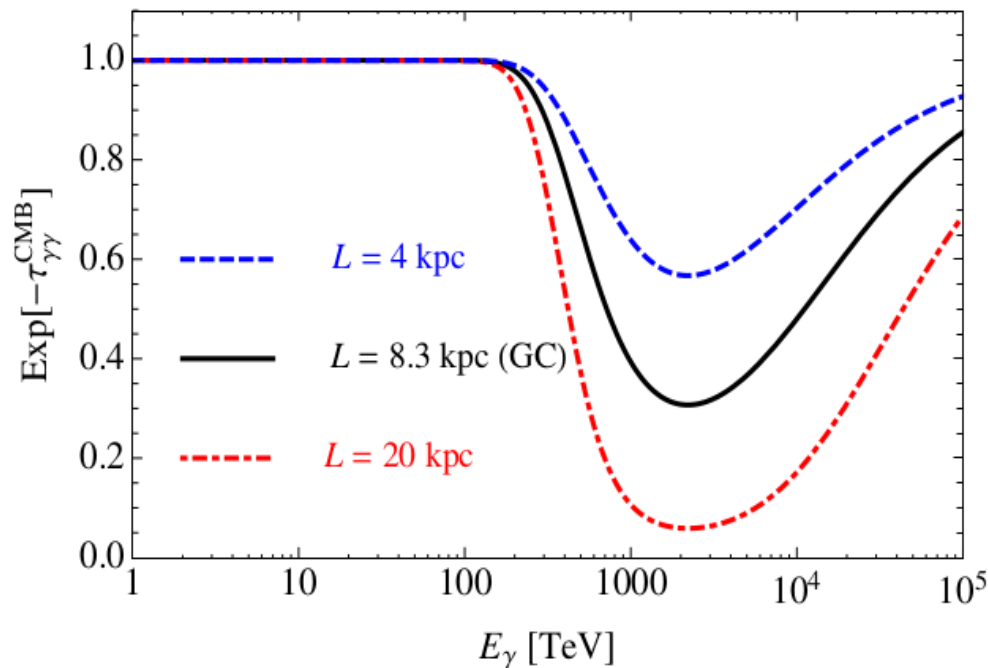
Pair production: $\gamma + \gamma_b \rightarrow e^+ e^-$

γ_b { CMB
Starlight
Infrared

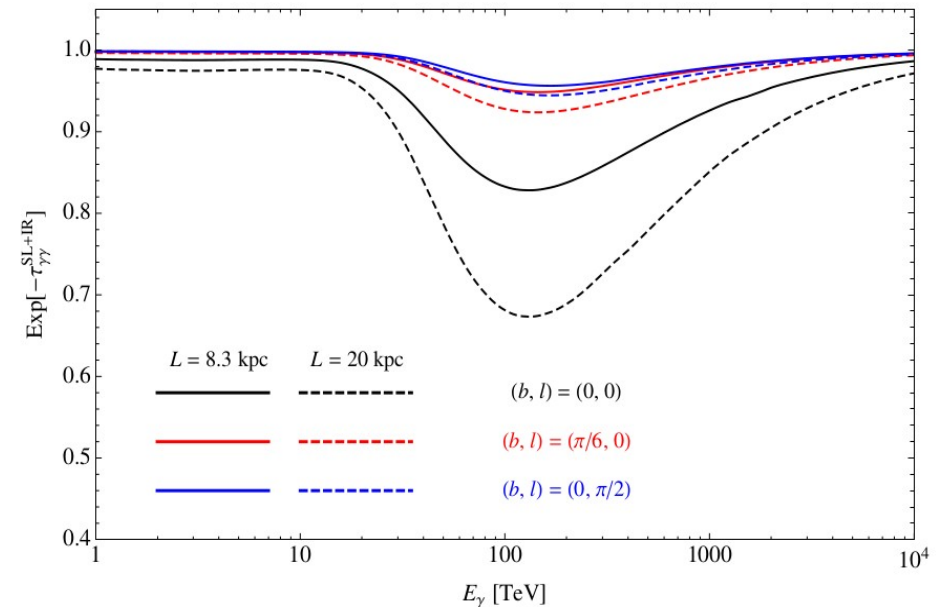
Attenuation $\sim e^{(-L/\lambda)}$

Mean free path $\lambda = 1/n_b \sigma_{\gamma\gamma}$

CMB



SL+IR



✓ A 100 TeV photon must originate from our galaxy.

Decaying DM + Background < Data

DM Flux

$$\frac{d^2 \phi_\gamma}{dE_\gamma d\Omega}(E_\gamma) = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} d\Omega \frac{1}{4\pi m_\chi \tau_\chi} \frac{dN_\gamma}{dE_\gamma}(E_\gamma)$$

$$\int_0^{s_{\max}} \rho_\chi(s, b, l) e^{-\tau_{\gamma\gamma}(E_\gamma, s, b, l)} ds$$

NFW ← (points to $\rho_\chi(s, b, l)$)

↓ (points from $e^{-\tau_{\gamma\gamma}(E_\gamma, s, b, l)}$)

Attenuation

Background

Different cosmic ray models

- Space dependent CR, 1804.10116
- Space independent CR, 1804.10116
- Hybrid gamma-model, 2104.09491

Data

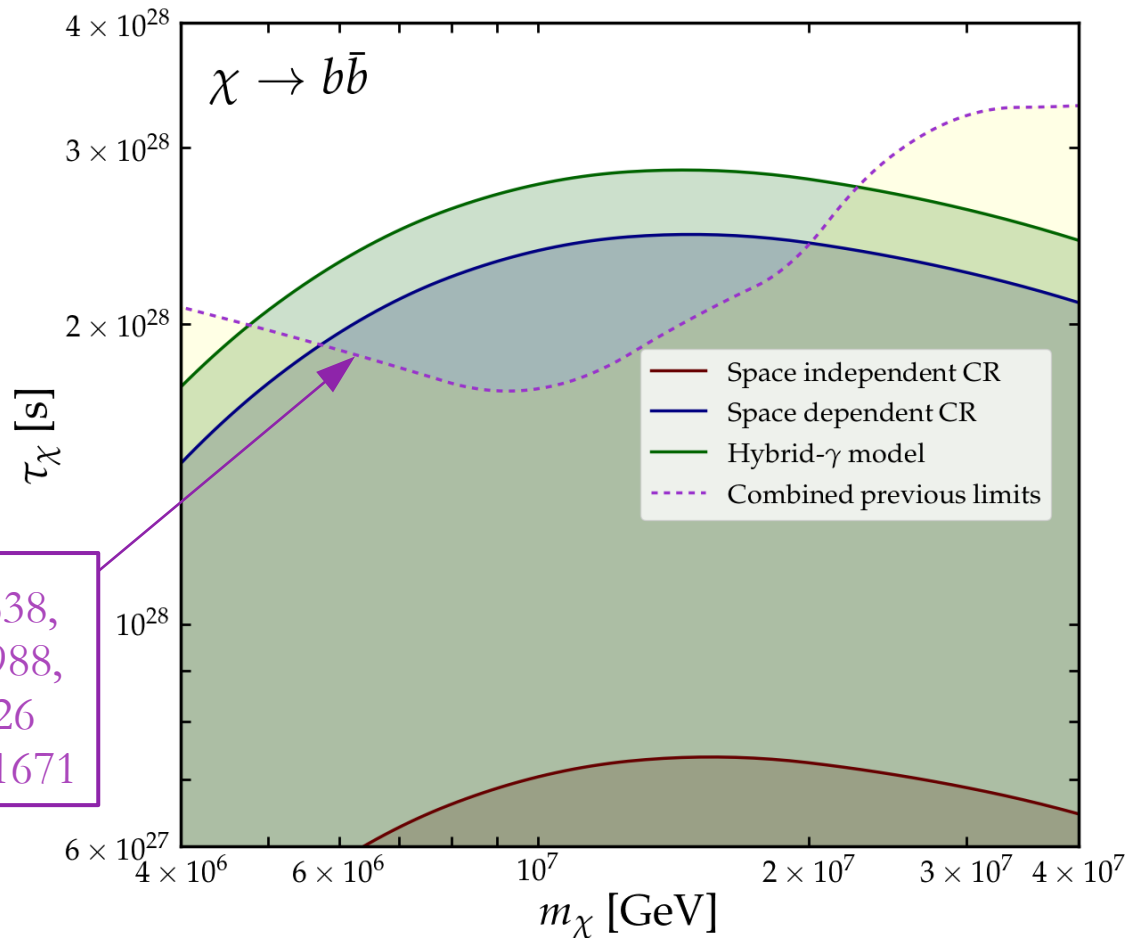
TABLE S2. Galactic diffuse gamma-ray fluxes measured by the Tibet AS+MD array.

Energy bin (TeV)	Representative E (TeV)	Flux ($25^\circ < l < 100^\circ, b < 5^\circ$) ($\text{TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$)	Flux ($50^\circ < l < 200^\circ, b < 5^\circ$) ($\text{TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$)
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	$(6.86^{+3.30}_{-2.40}) \times 10^{-17}$	$(2.99^{+1.40}_{-1.02}) \times 10^{-17}$

Amenomori et al 2104.05181 PRL

Decaying DM: Limits

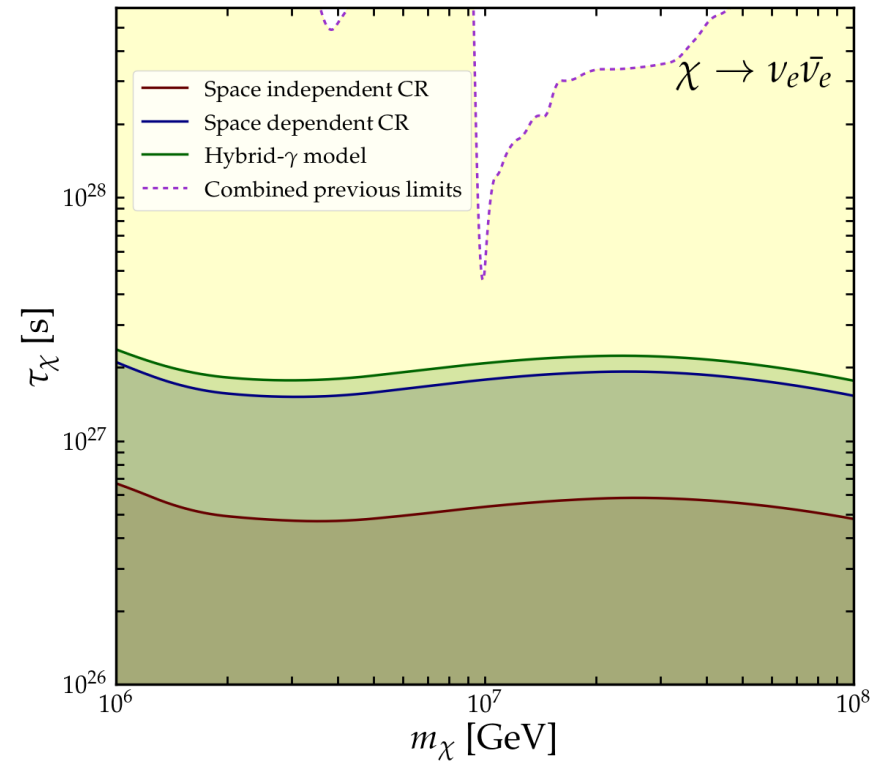
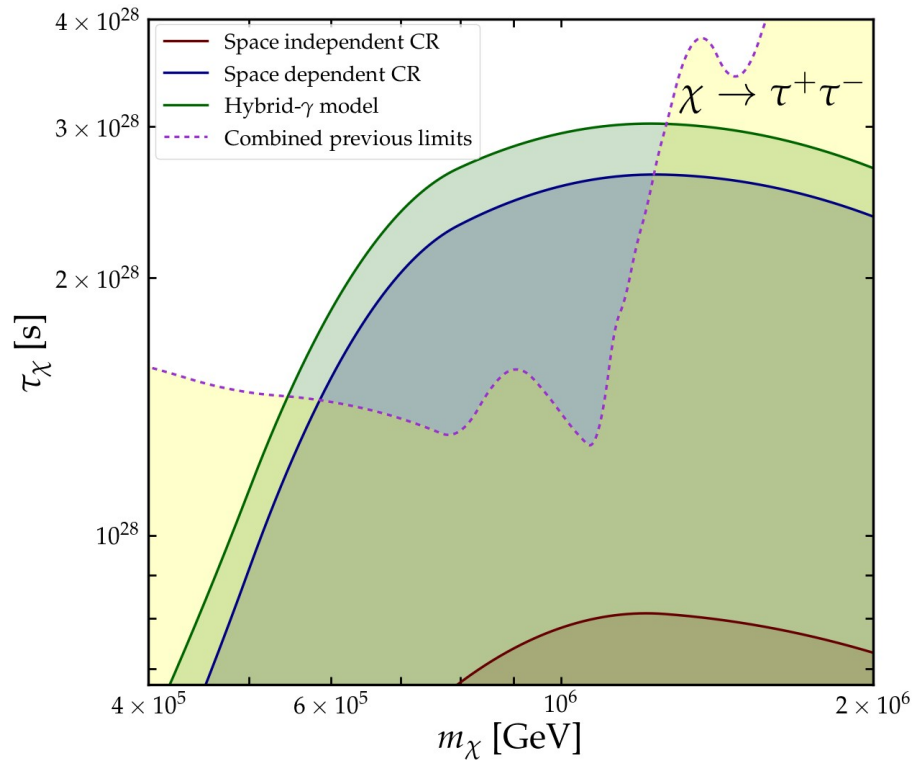
✓ We have done a χ^2 analysis to set the limits.



TNM, Saha, Dubey,
Laha 2105.05680

Cohen et al 1612.05638,
Blanco et al 1811.05988,
Bhatt. et al 1903.12626
Ishiwata et al 1907.11671

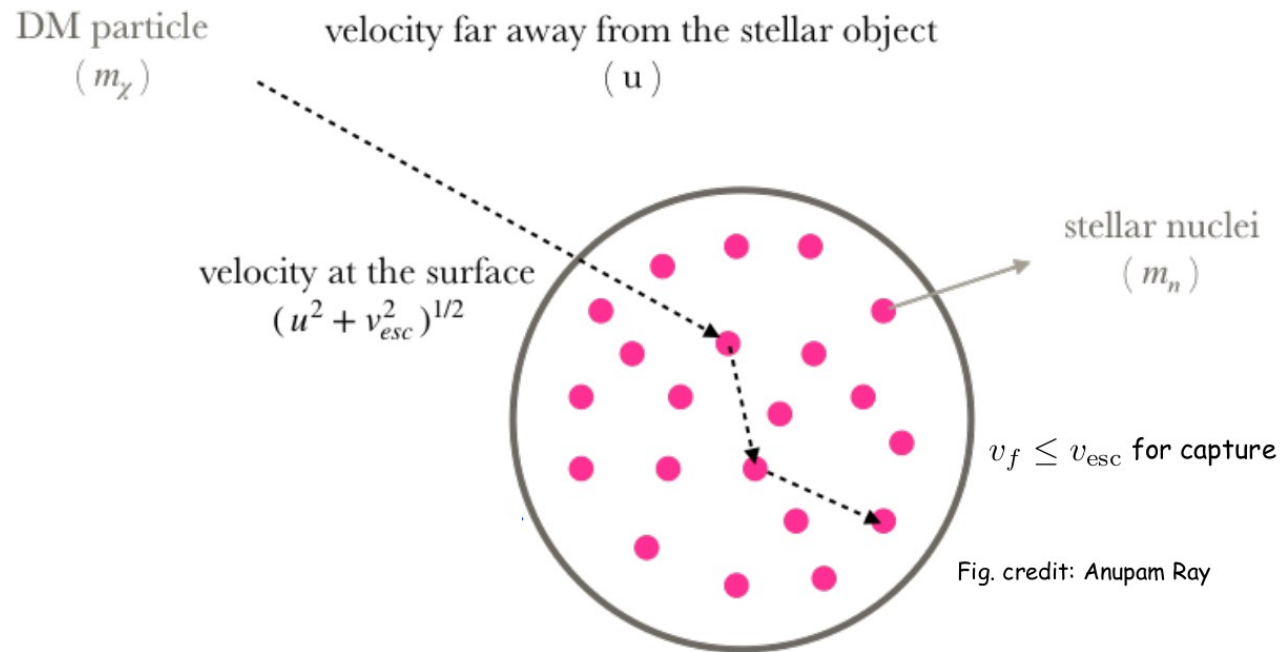
Decaying DM: Limits



- ✓ For **most of the channels** (except first two generations of leptons) our bounds are **stronger** than previous limits.
- ✓ Our limits are **robust**, does not depend on choice of **DM density profile**.

Neutrinos from captured DM annihilation

DM capture in neutron star



$$C \simeq \frac{\rho_\chi}{m_\chi} \int \frac{f(u) du}{u} (u^2 + v_{esc}^2) \min(\sigma_{\chi n}, \sigma_{\chi n}^{sat}) N_n g(w)$$

DM flux
DM-nucleon cross section
No. of targets
Capture probability

Goldman et al PRD 89 ...

Bramante et al 1703.04043 ...

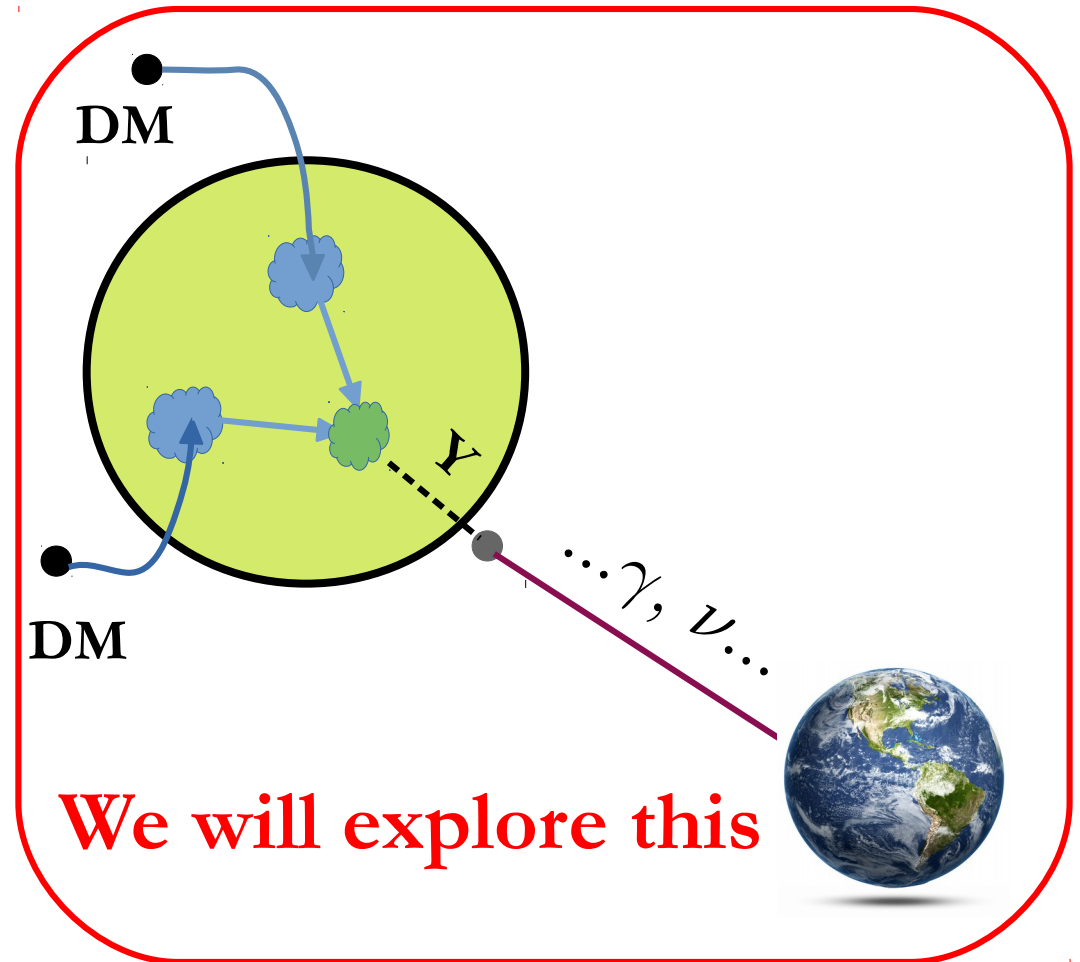
Bell et al 2004.14888 ...

Annihilating DM capture in neutron star: signatures

Heating



© 1707.09442



We will explore this

Goldman et al PRD 89 ...
Baryakhtar et al 1704.01577 ...
Acevedo et al 1911.06334
Bell et al 2004.14888 ...
Leane and Smirnov 2010.00015 ...
TNM, Queiroz 2104.02700 ...

Tarak Nath Maity

Silk et al PRL 85 ...
Pospelov, Ritz 0810.1502 ...
Leane et al 1703.04629, 2101.12213...
Bell et al 2103.16794 ...
Leane, Linden 2104.02068 ...

Galactic neutron stars: DM capture and annihilation to neutrinos

We consider DM capture in the galactic population of neutron stars.

Generozov et al 1804.01543

$$\chi \chi \rightarrow YY \rightarrow 2 (\text{SM } \bar{\text{SM}}) \rightarrow \dots, \nu, \dots$$

DM Long lived
 Mediator

Pospelov et al 0711.4866
Batell et al 0910.1567

Time evolution: $\frac{dN_\chi}{dt} \approx C_{\text{tot}} - C_{\text{ann}} N_\chi^2$

↓ Equilibrium

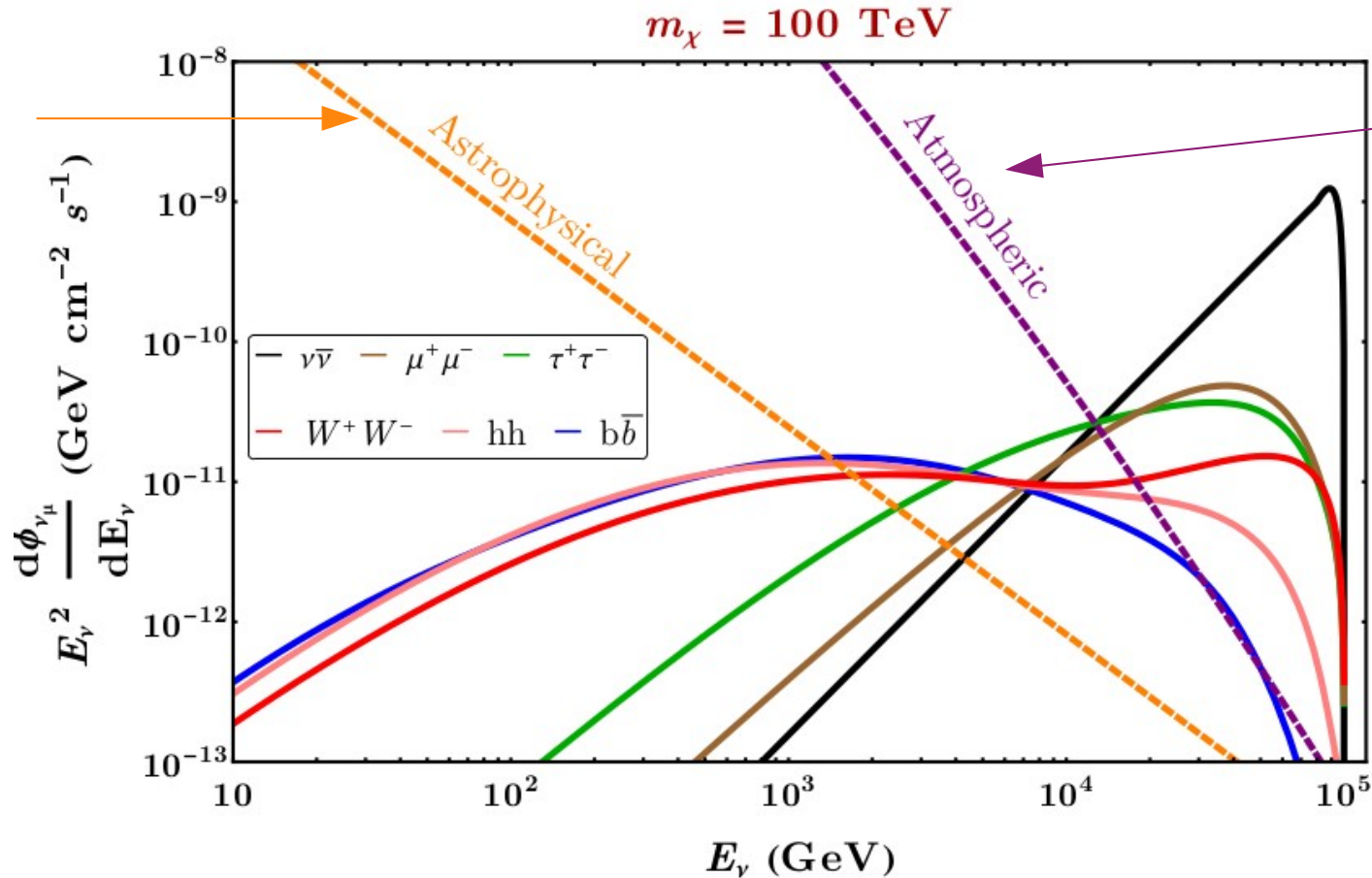
Annihilation rate: $\Gamma_{\text{ann}} = \frac{1}{2} C_{\text{ann}} N_\chi^2 = \frac{1}{2} C_{\text{tot}}$

Neutrino flux

$$\frac{d\phi}{dE_\nu} = \frac{\Gamma_{\text{ann}}}{4\pi D^2} \text{Br}(Y \rightarrow \text{SM S}\bar{\text{M}}) \frac{dN_\nu}{dE_\nu} \underbrace{\left(e^{-\frac{R}{\eta c\tau_Y}} - e^{-\frac{D}{\eta c\tau_Y}} \right)}_{\text{Survival ratio}}$$

$m_\chi, \sigma_{\chi n}$

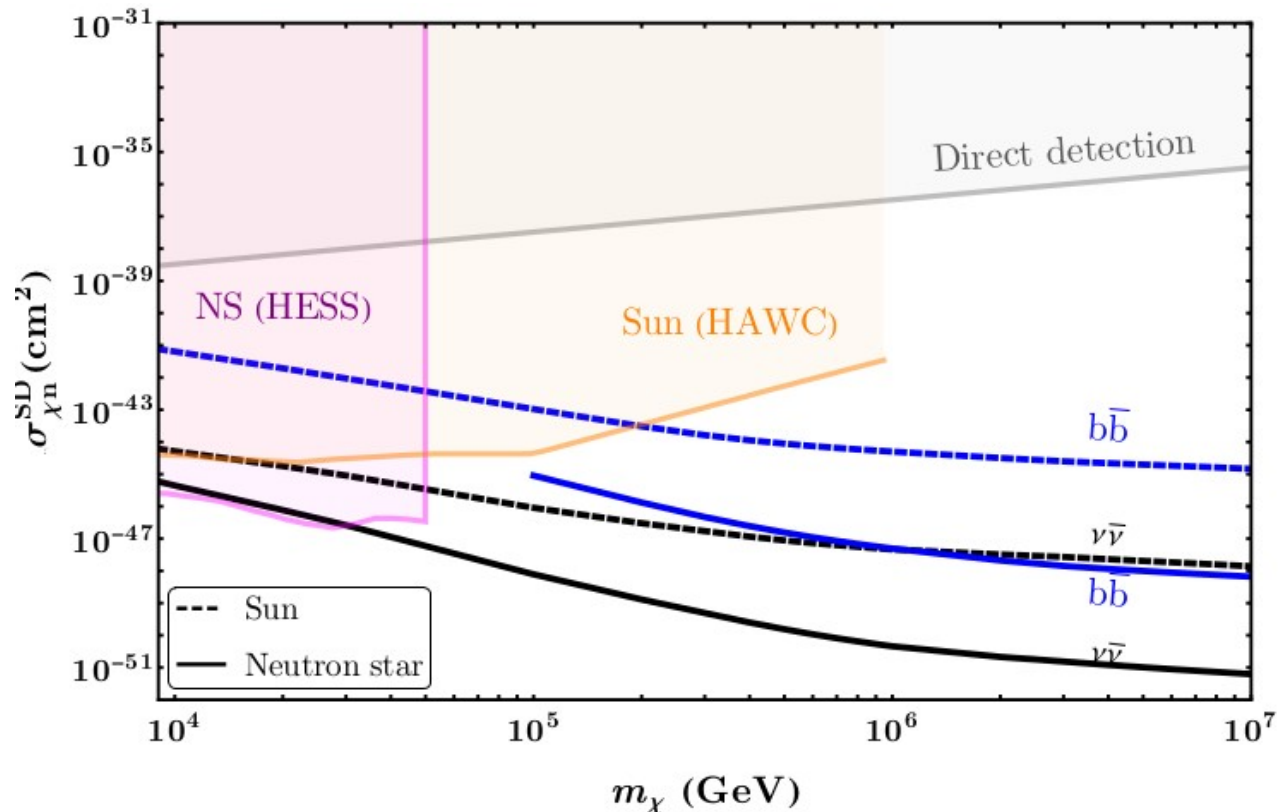
Stettner
1908.09551



Honda et al
1502.03916

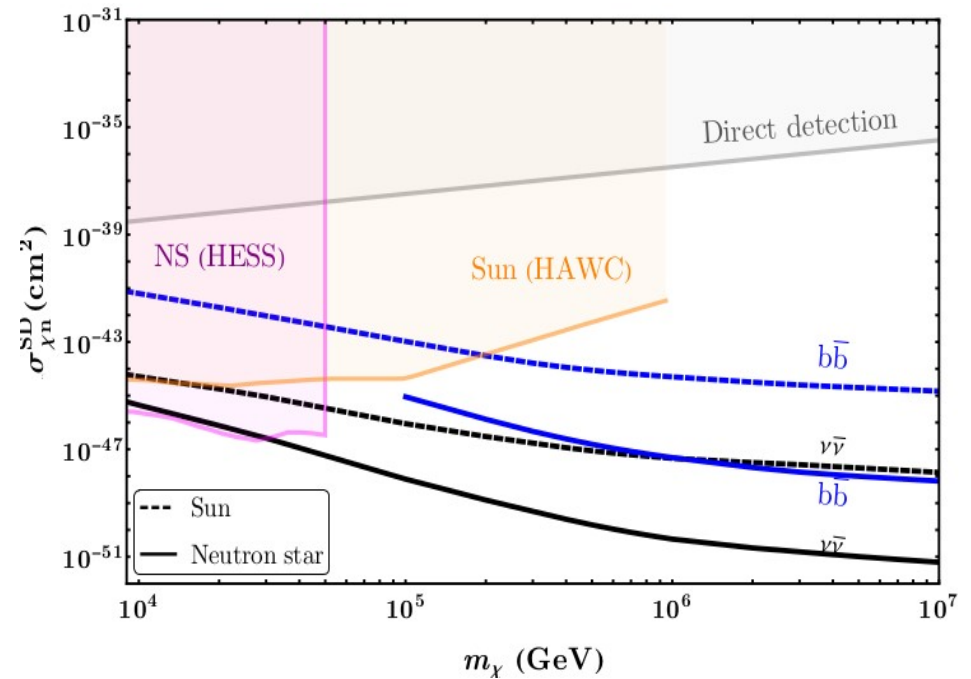
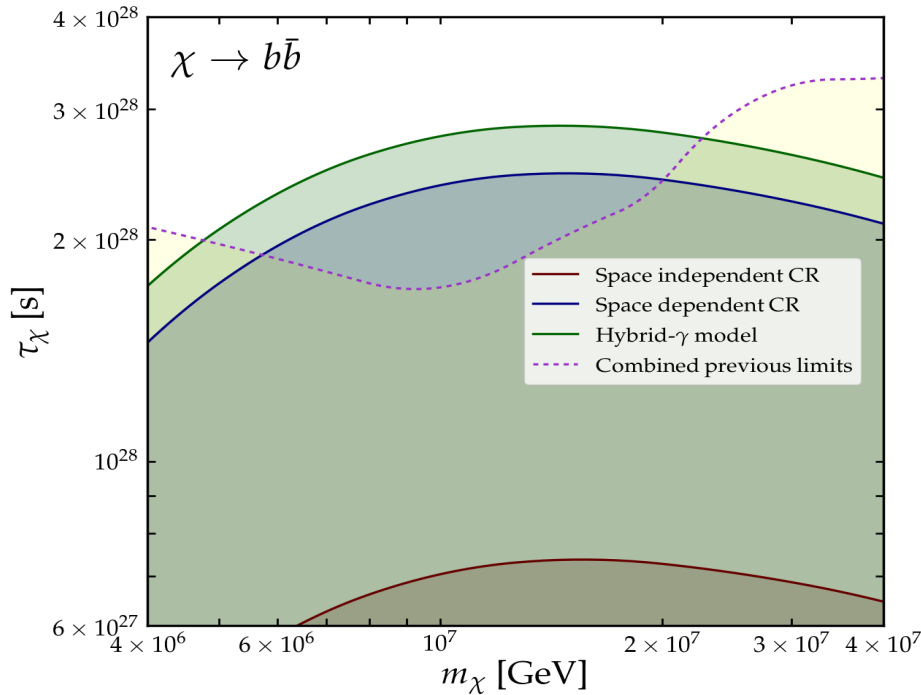
Prospect of gigaton detector

$$\frac{dN_\mu}{dE_\mu} \simeq N_A \rho V T \frac{1}{1-y} \left[\frac{d\phi_{\nu\mu}}{dE_\nu}(E_\nu) \sigma_{CC}(E_\nu) \right]_{E_\nu = \frac{E_\mu}{1-y}} e^{-\tau(E_\nu)}$$



- ✓ Limits are obtained by equating DM events to astrophysical and atmospheric neutrinos

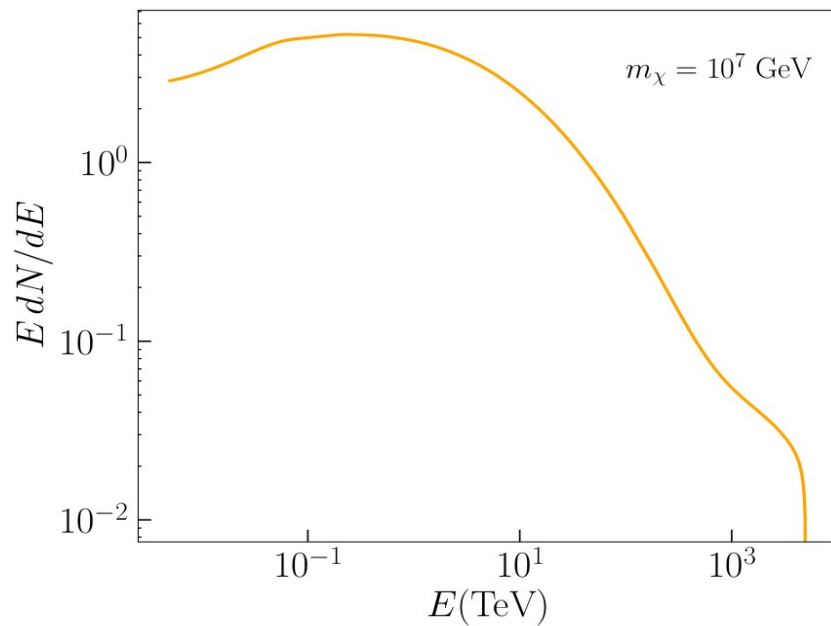
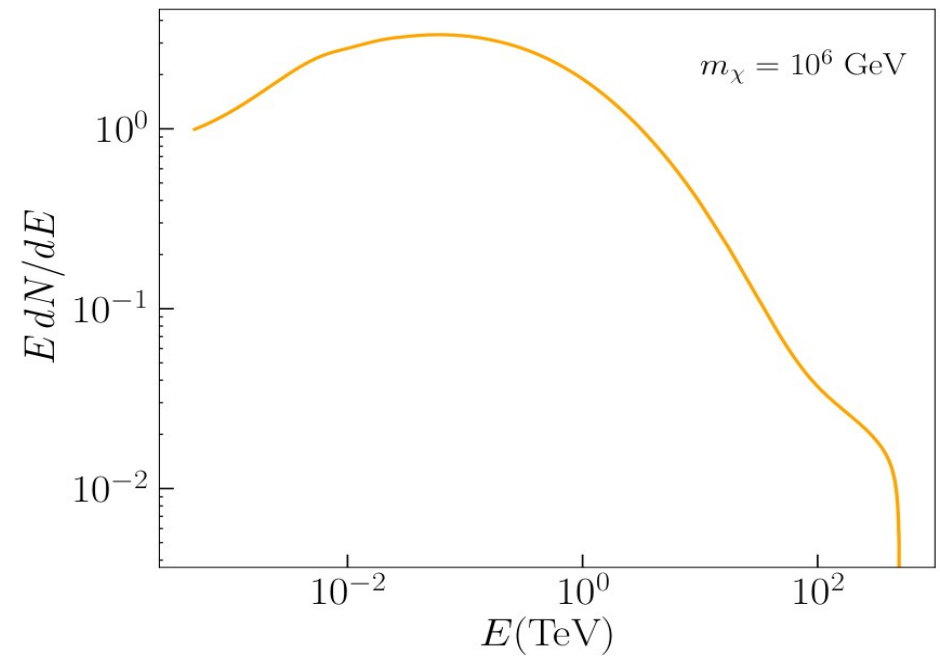
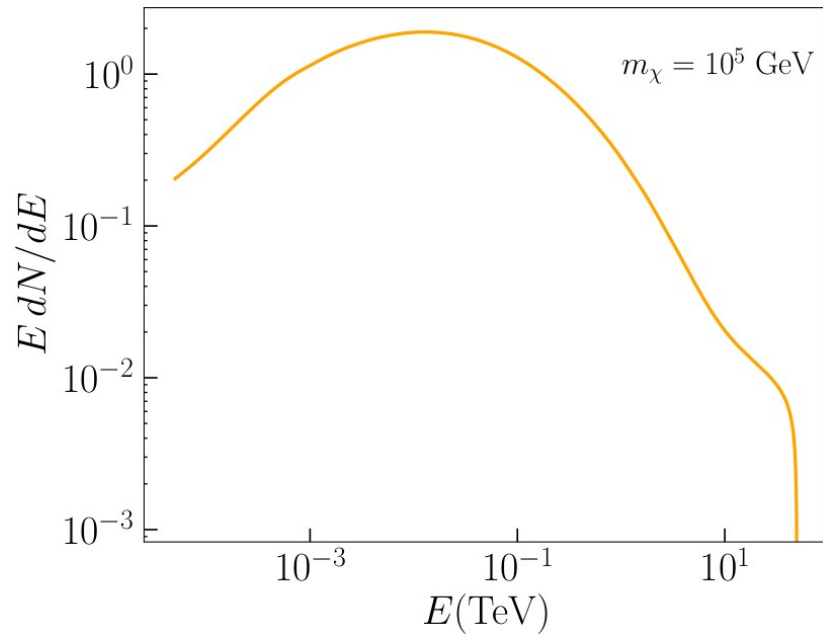
Conclusions



- ✓ Indirect searches for heavy DM through gamma rays and neutrinos.
- ✓ We explored new regions of the DM parameter space.

Gamma-ray spectrum

$$\chi \rightarrow b\bar{b} \rightarrow \gamma$$



- ✓ Utilizing HDMSpectra
- ✓ Set the DM mass range