Indirect searches for dark matter: gamma-rays and neutrinos

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CHEP, IISc Bangalore

Based on

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

D Bose, TNM, T S Ray 2108.12420

LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

INDIAN INSTITUTE OF SCIENCE

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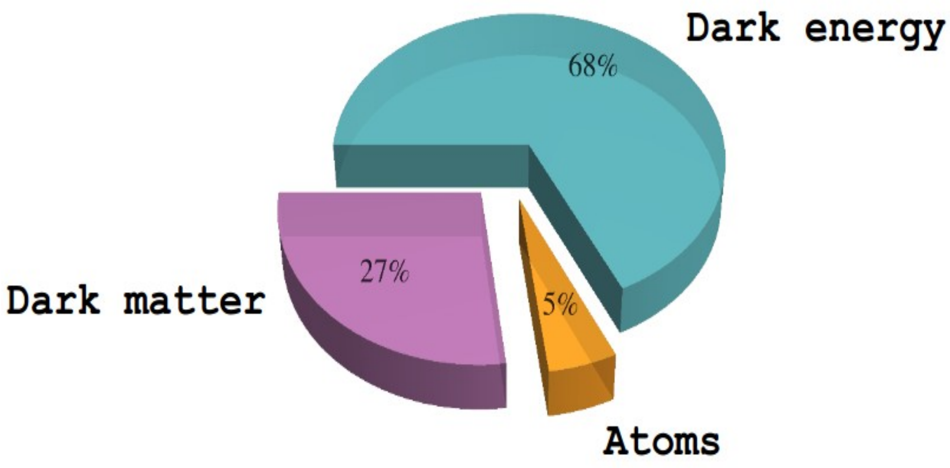
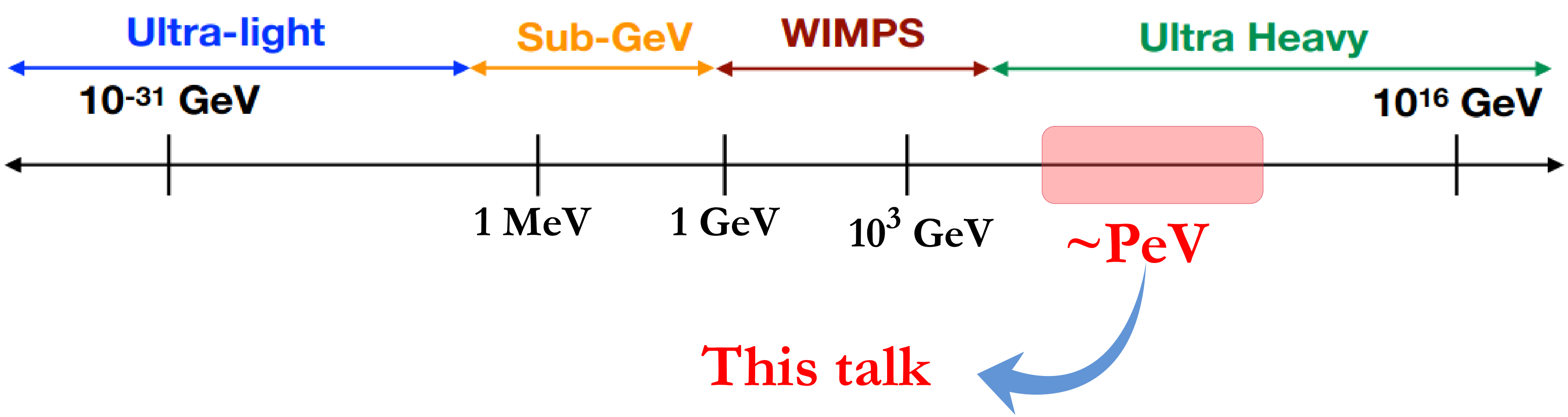
Dark Matter Landscape



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

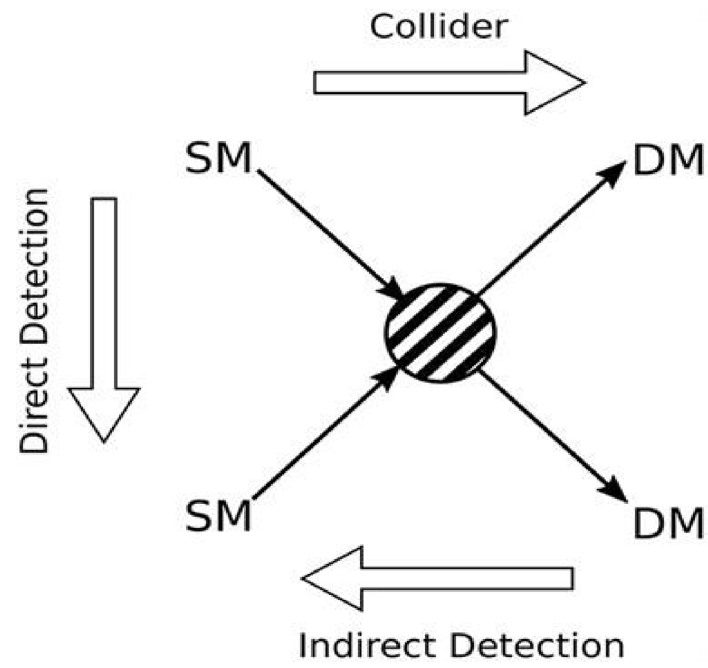


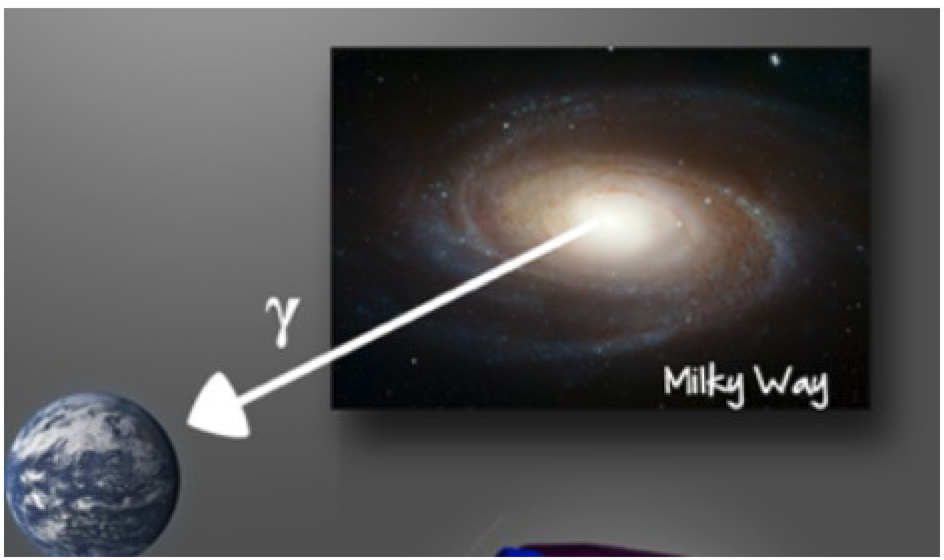
Heavy DM: Indirect searches

✗ Difficult to probe at collider:
kinematically disfavored

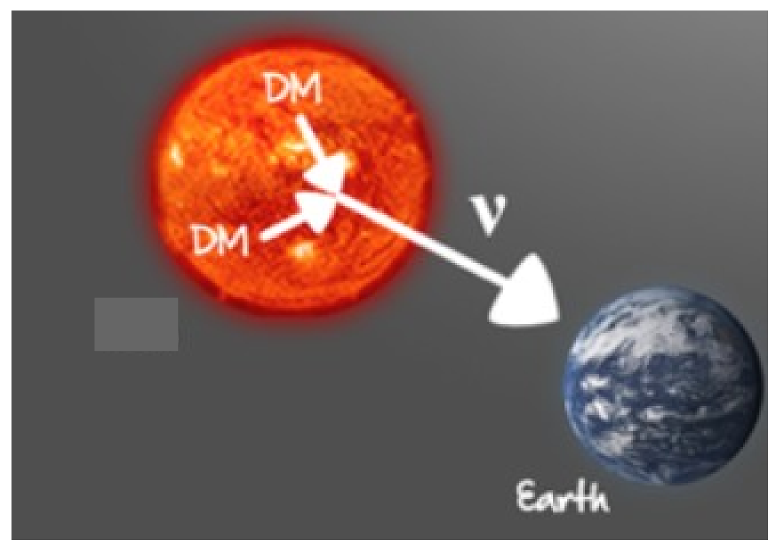
✗ Direct detection:
very low flux

✔ Indirect searches:
extremely useful





Tibet AS$_\gamma$

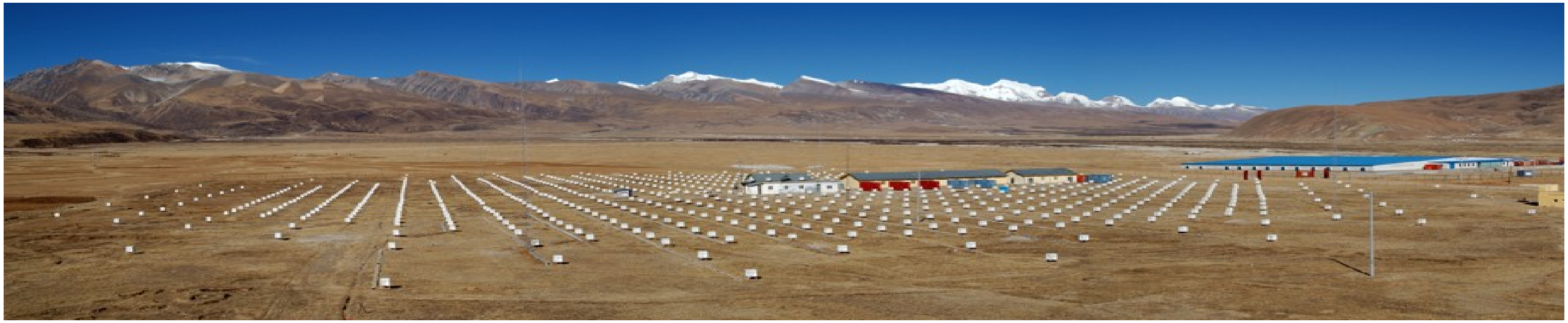


Neutrinos from captured DM

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 ASγ



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

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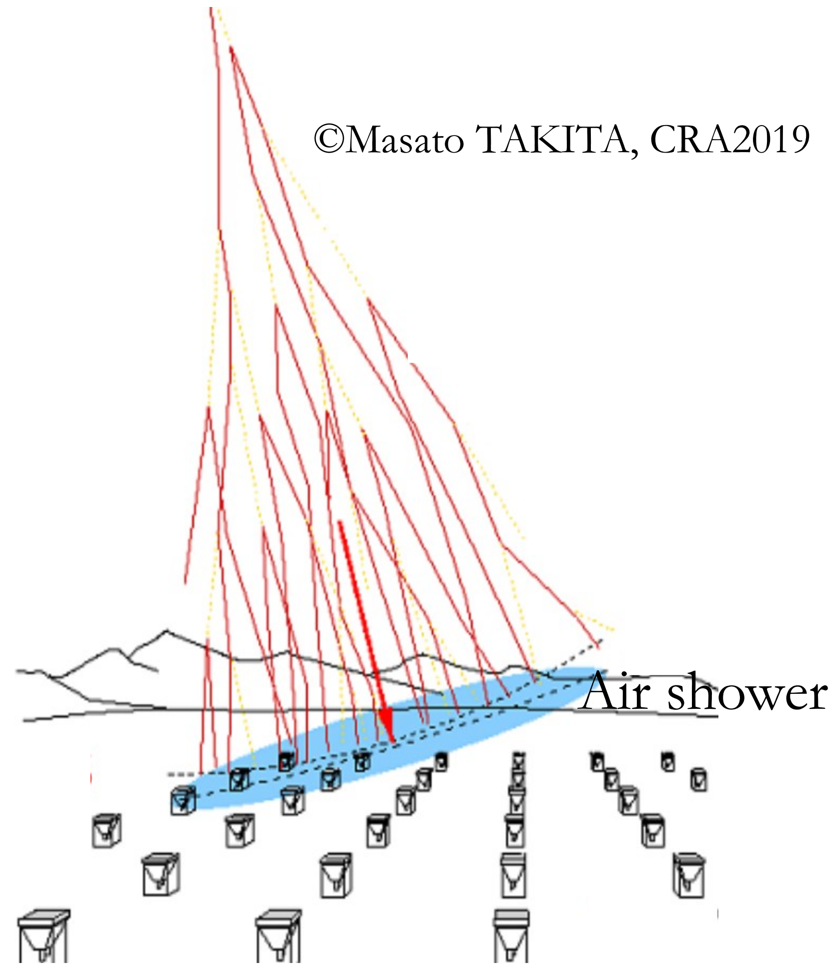


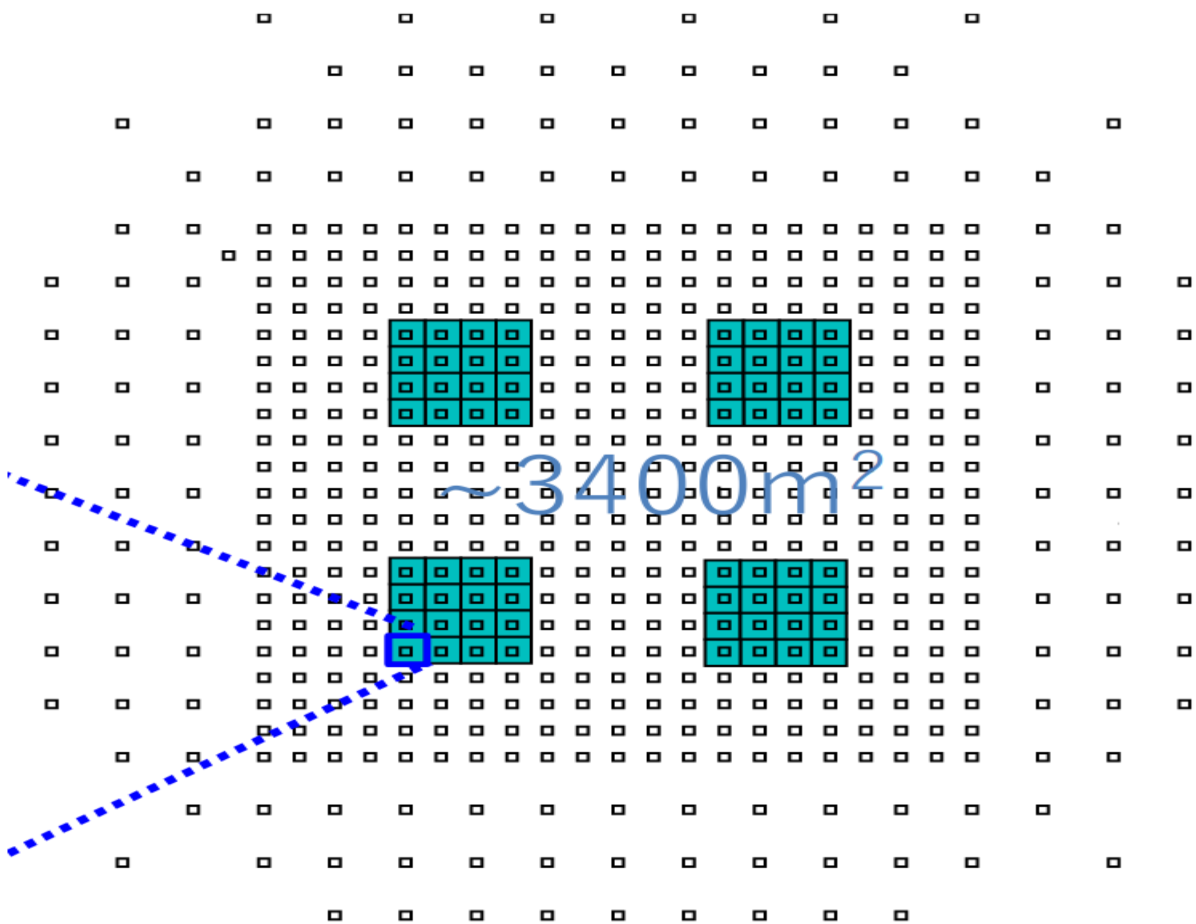
Amenomori et al 2104.05181 PRL

Tibet AS+MD

✔2.4m underground

✔ Hybridize with muon detector.

✔ Muon with energy greater than 1 GeV



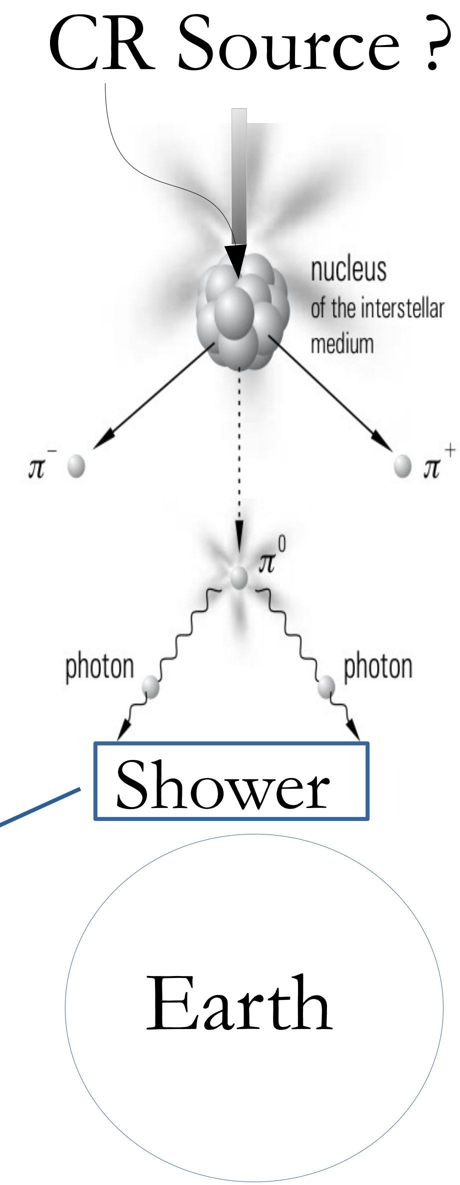
Livetime: 719 days from February 2014 to May 2017

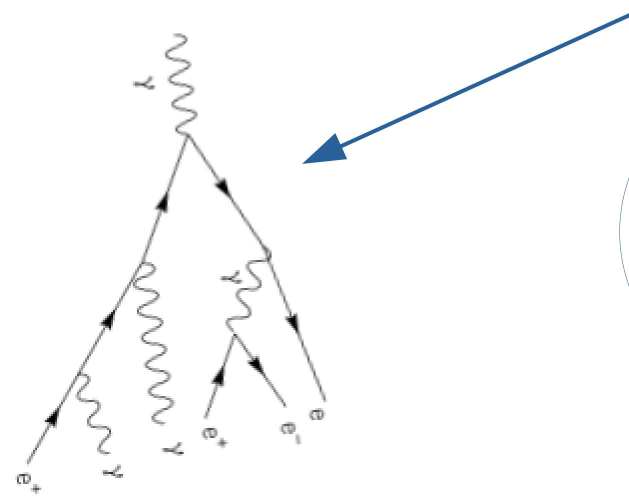
Muon detector: gamma and cosmic ray (CR) discrimination

Amenomori et al 2104.05181 PRL

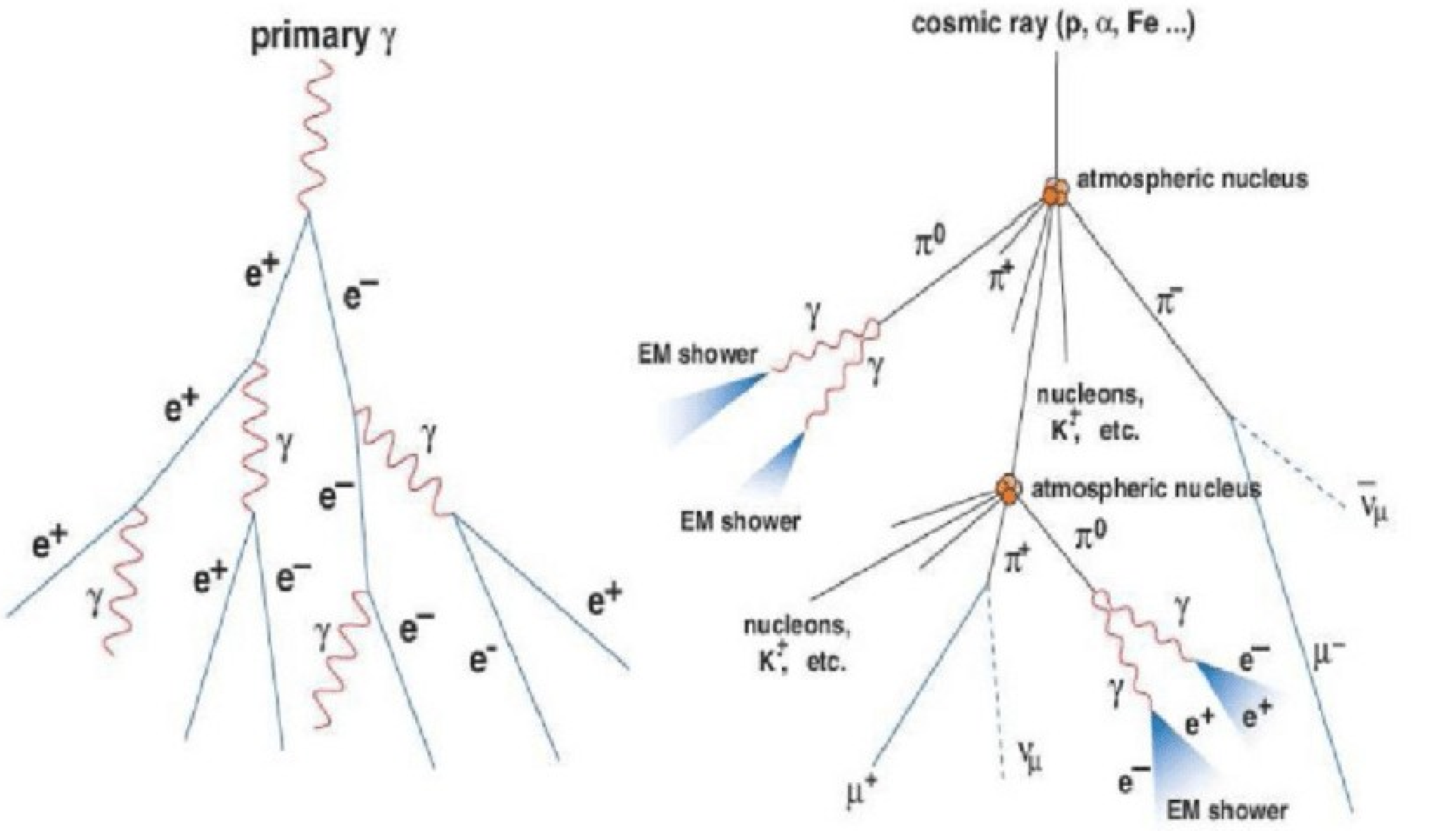
Gamma ray as messenger

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



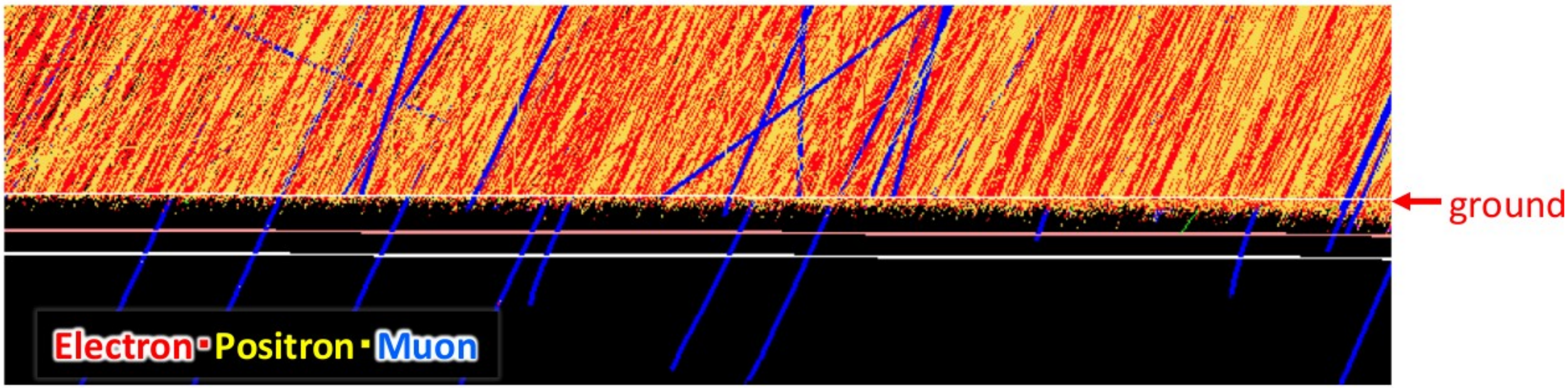


Photon and Proton Shower

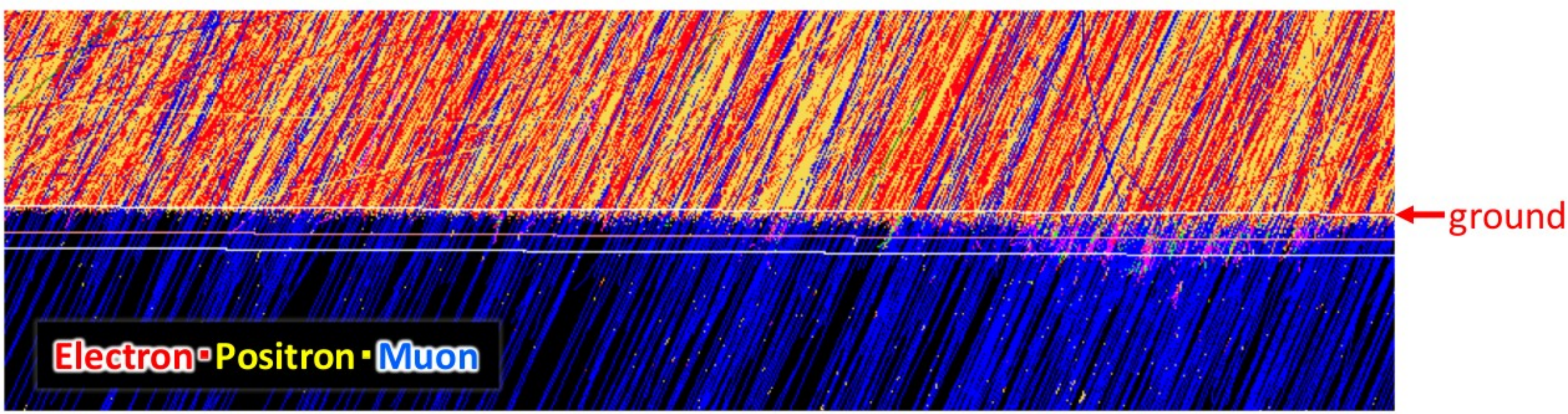


Occasional γ-p interaction gives rises shower similar to hadronic shower

Photon and Proton Shower

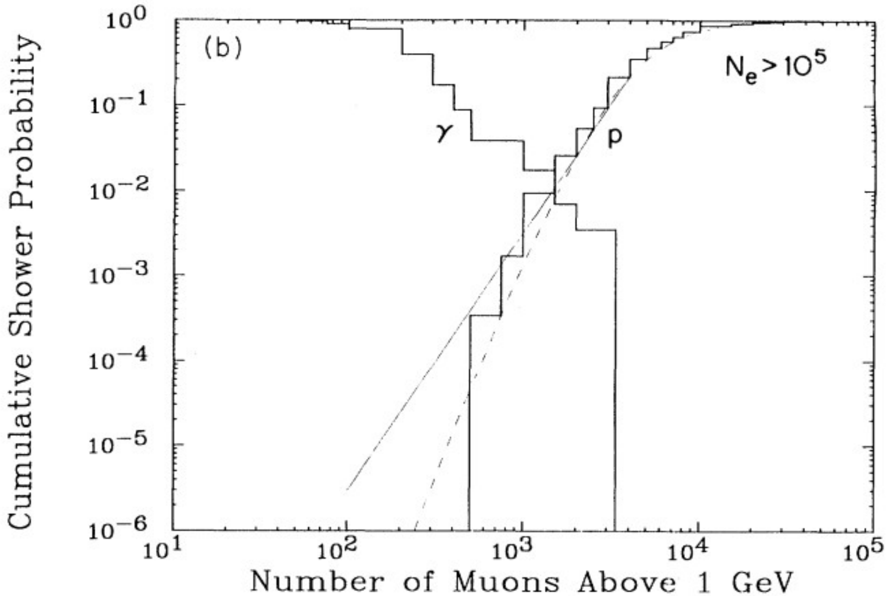


200TeV Gamma-ray induced AS



200TeV Proton induced AS

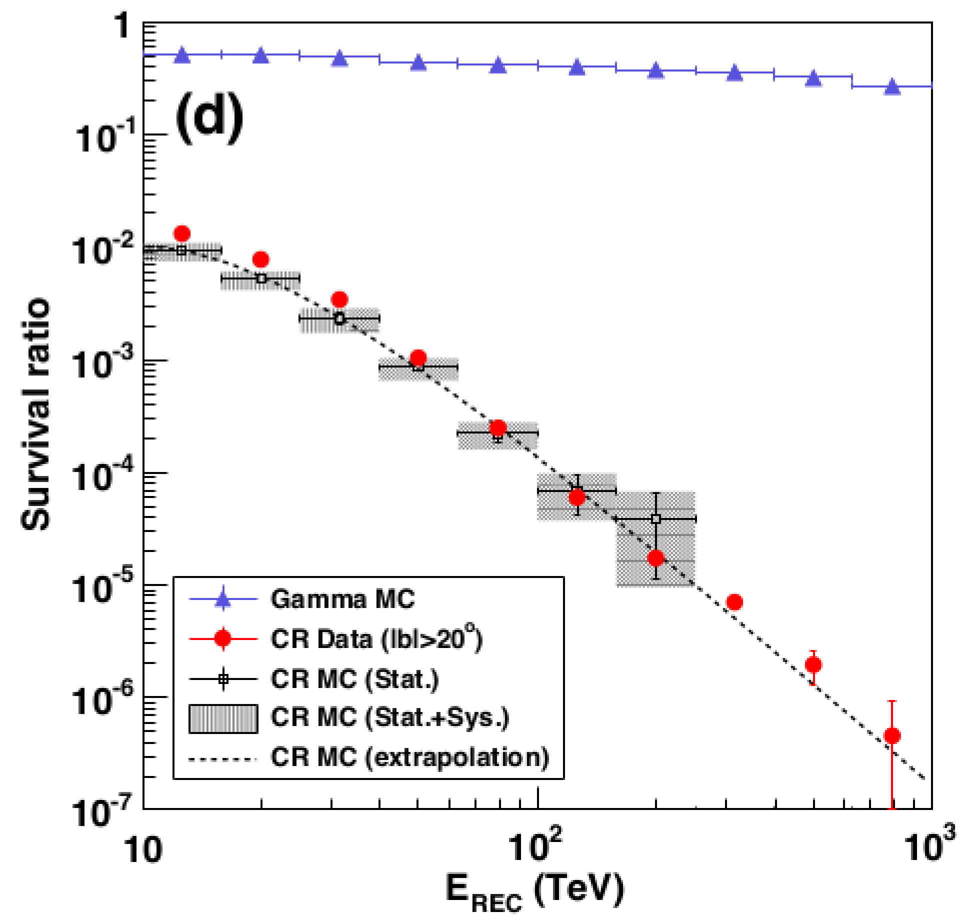
Photon Proton Shower: Tibet ASγ



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

After muon cut



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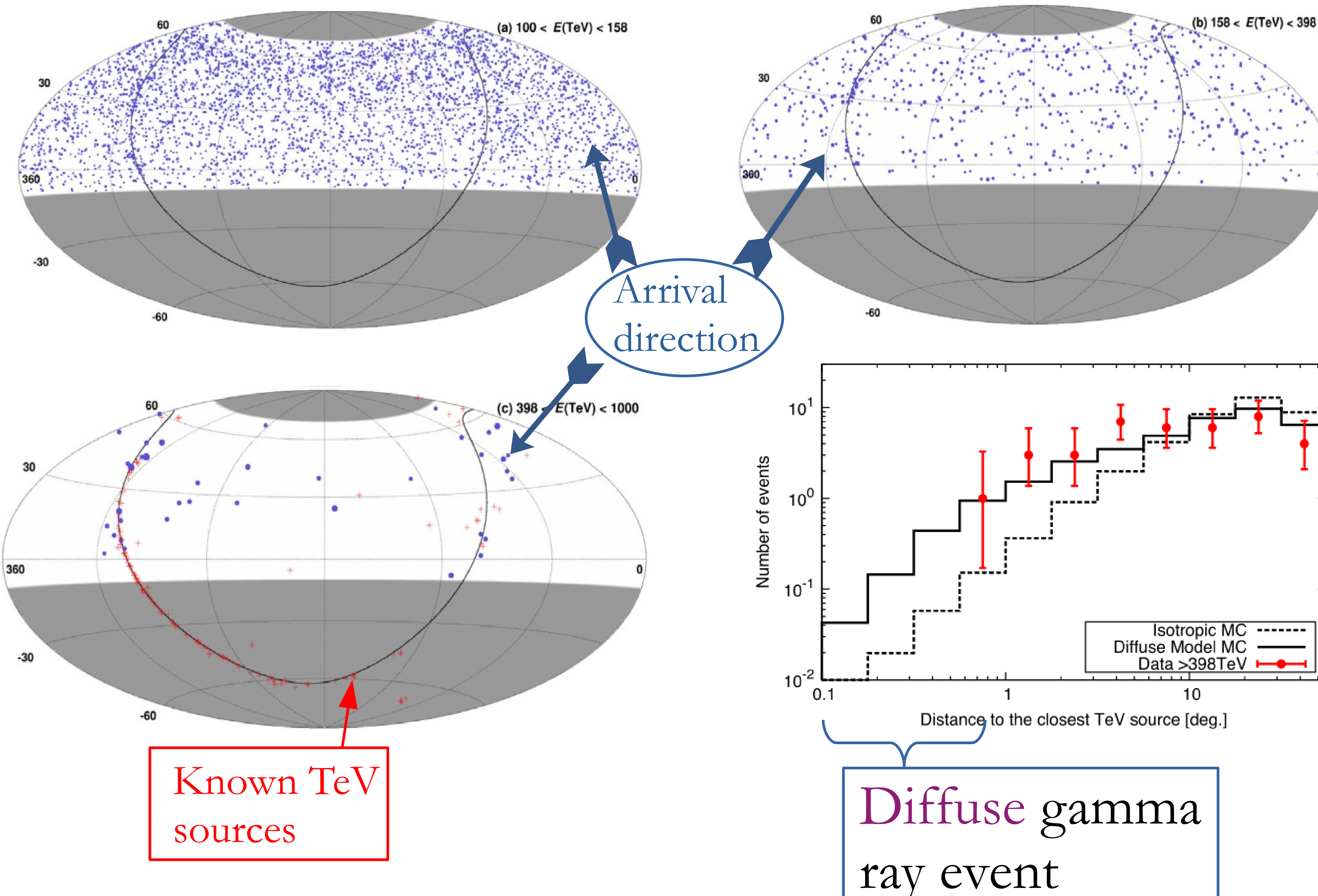
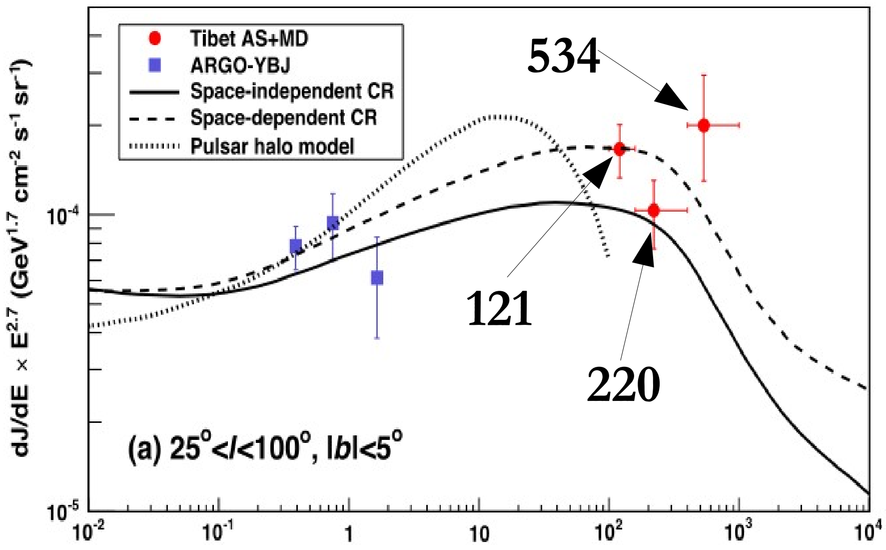
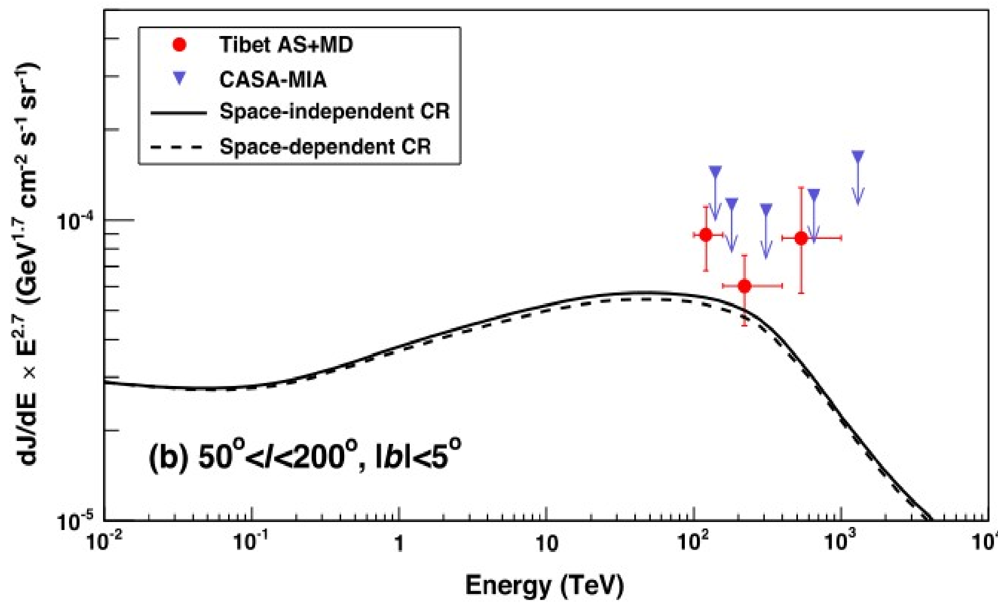
Tibet ASγ



Amenomori et al 2104.05181 PRL

Observed Flux





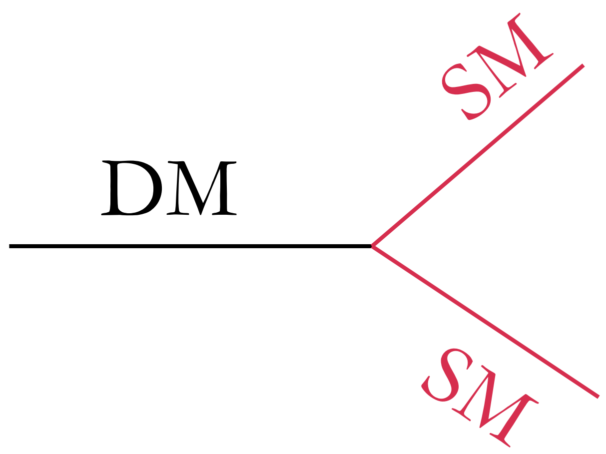
✔ **First detection of sub-PeV diffuse gamma rays.**

✔ 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

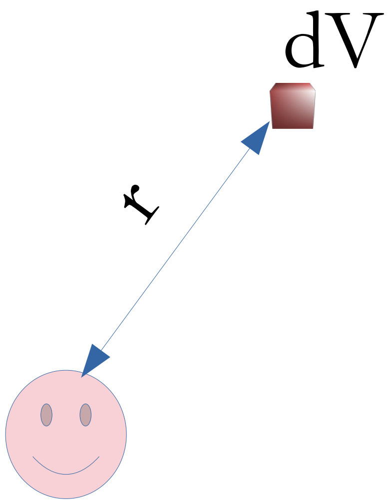
Amenomori et al 2104.05181 PRL

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



Cirelli et al 0912.0663, 1205.5283, 1307.7152 …
Lefranc et al 1608.00786
Esmaili, Serpico 2105.01826

Decaying DM: Flux



τ_χ : DM lifetime

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

@ 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

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

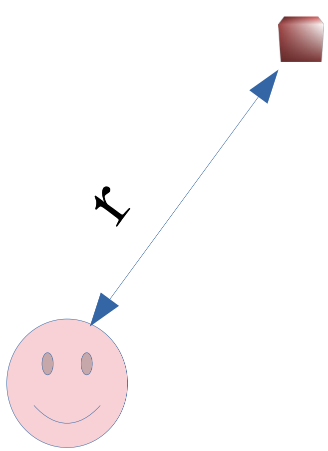
Slatyer 1710.05137

Decaying DM: Flux

τ_χ: DM lifetime

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

dV



@ One obs. particle/decay → $\dfrac{dN}{dE}$

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.

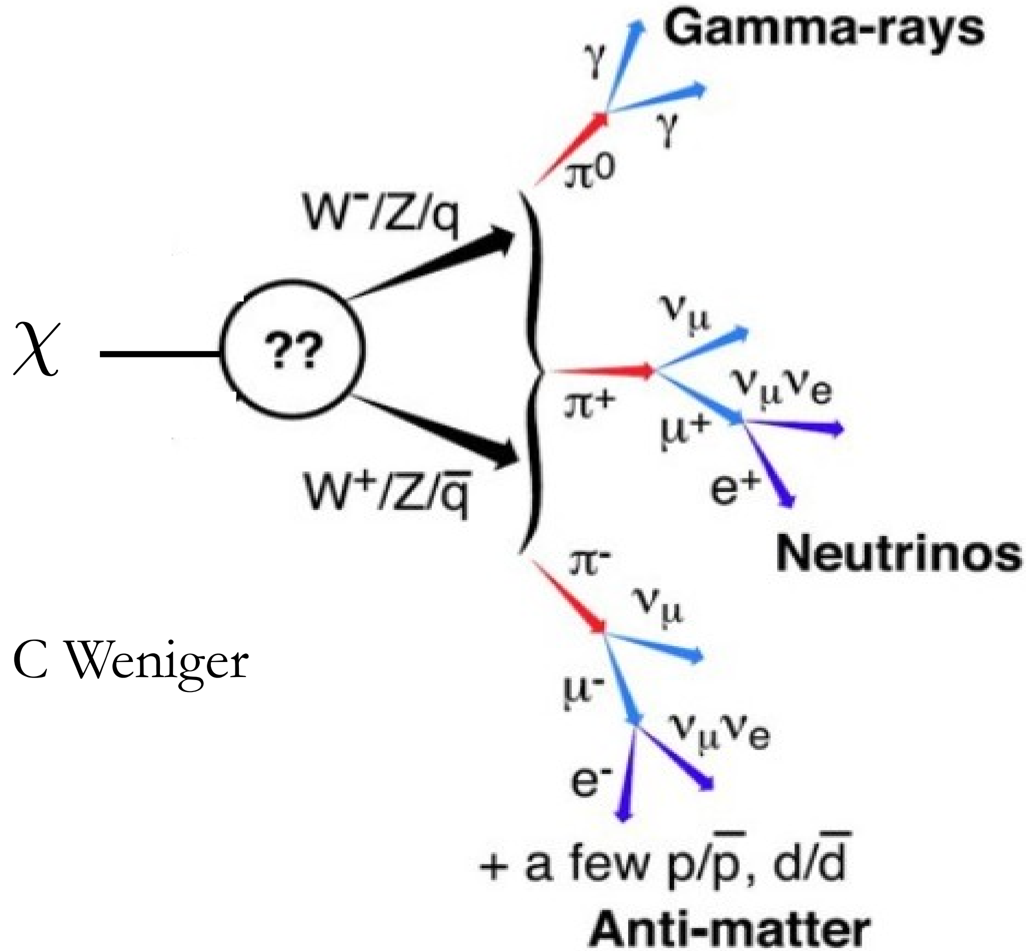
Line of sight integration

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

Slatyer 1710.05137

Decaying DM: gamma-ray spectrum

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



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PPPC

Cirelli et al 1012.4515

HDMSpectra

Bauer et al 2007.15001

Decaying DM: Attenuation

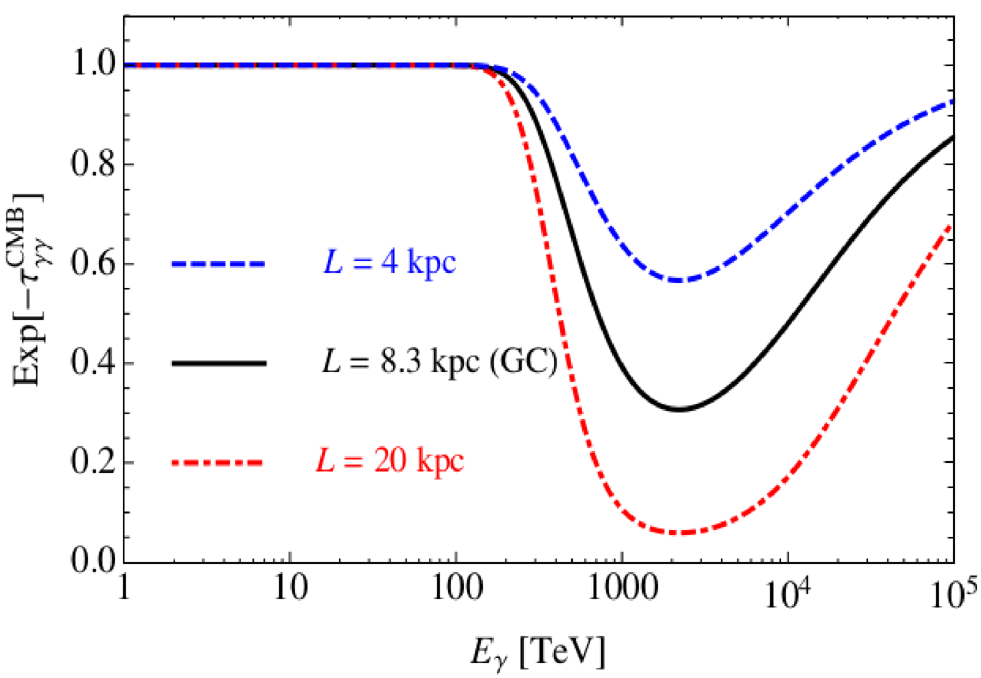
Pair production: $\gamma + \gamma_b \rightarrow e^+ e^-$

γ_b { CMB, Starlight, Infrared

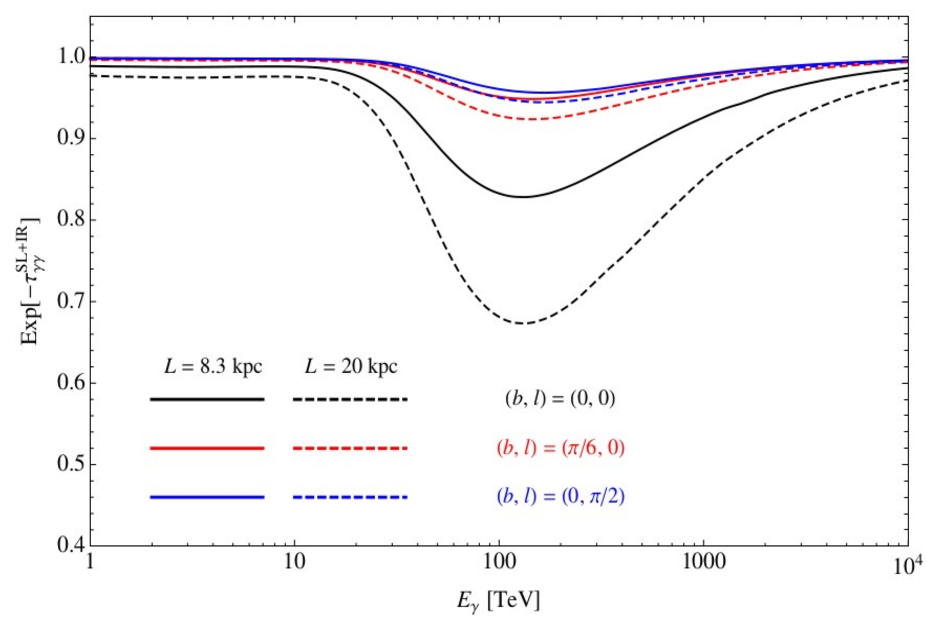
Attenuation $\sim e^{(-L/\lambda)}$

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

CMB



SL+IR



✔ A 100 TeV photon must originate from our galaxy.

Esmaili, Serpico 1505.06486

Decaying DM + Background < Data

DM Flux

$$\frac{d^2\phi_\gamma}{dE_\gamma d\Omega}(E_\gamma) = \frac{1}{\Delta\Omega}\int_{\Delta\Omega} d\Omega \frac{1}{4\pi m_\chi \tau_\chi}\frac{dN_\gamma}{dE_\gamma}(E_\gamma)\int_0^{s_{\max}} \rho_\chi(s,b,l)\, e^{-\tau_{\gamma\gamma}(E_\gamma,s,b,\ell)}\, ds$$

NFW ← $\rho_\chi(s,b,l)$

Attenuation ← $e^{-\tau_{\gamma\gamma}(E_\gamma,s,b,\ell)}$

Background

Different cosmic ray models:
- Space dependent CR, 1804.10116
- Space independent CR, 1804.10116
- Hybrid gamma-model, 2104.09491

Data

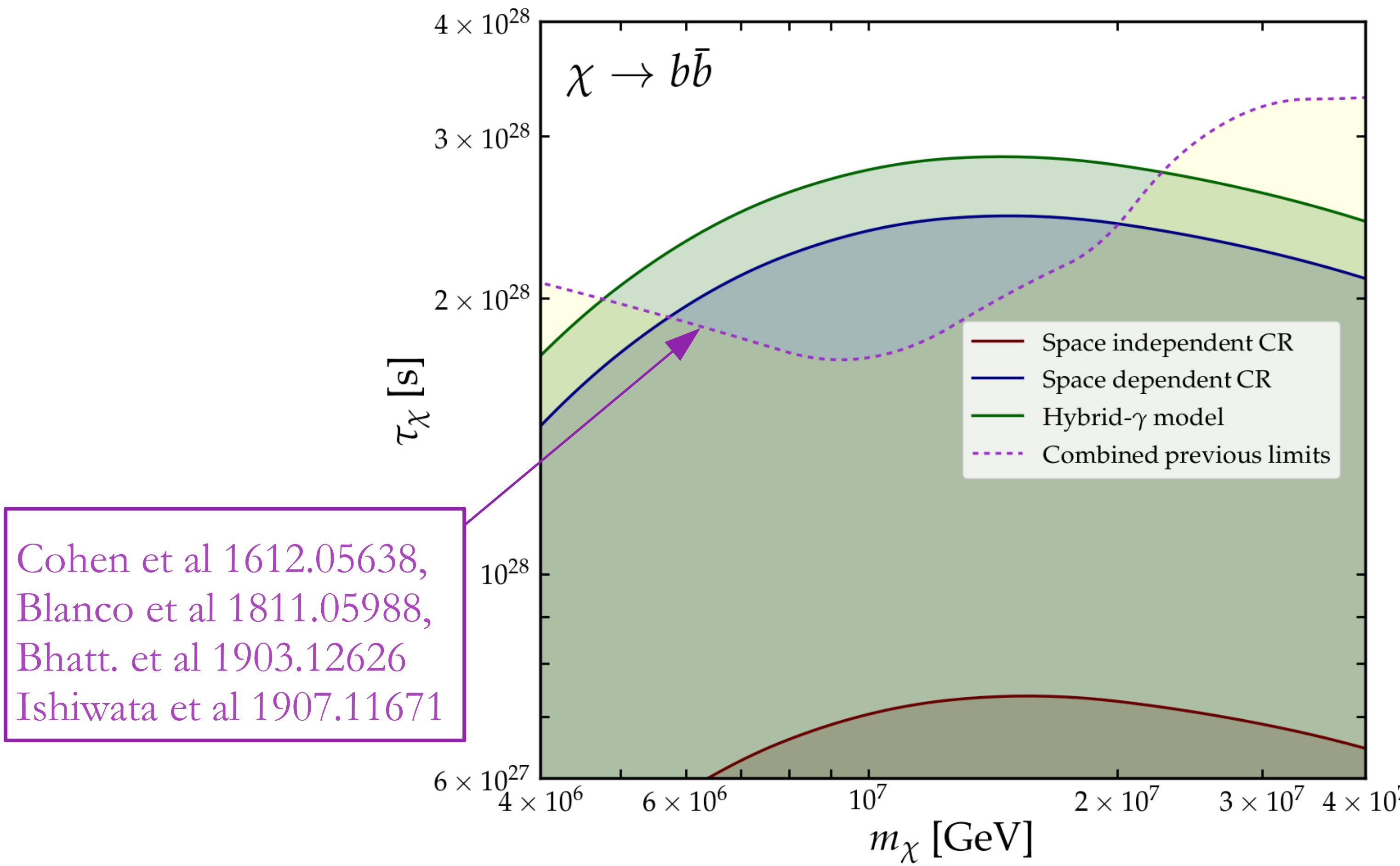
TABLE S2. Galactic diffuse gamma-ray fluxes measured by the Tibet AS+MD array.

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

Amenomori et al 2104.05181 PRL

Decaying DM: Limits

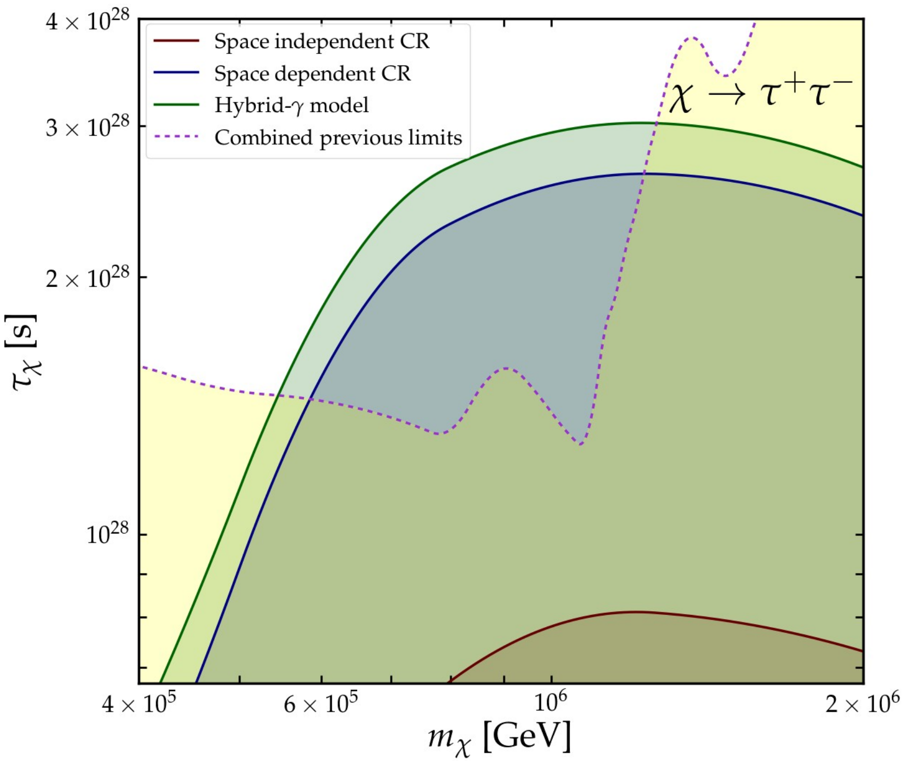
✔ We have done a χ^2 analysis to set the limits.

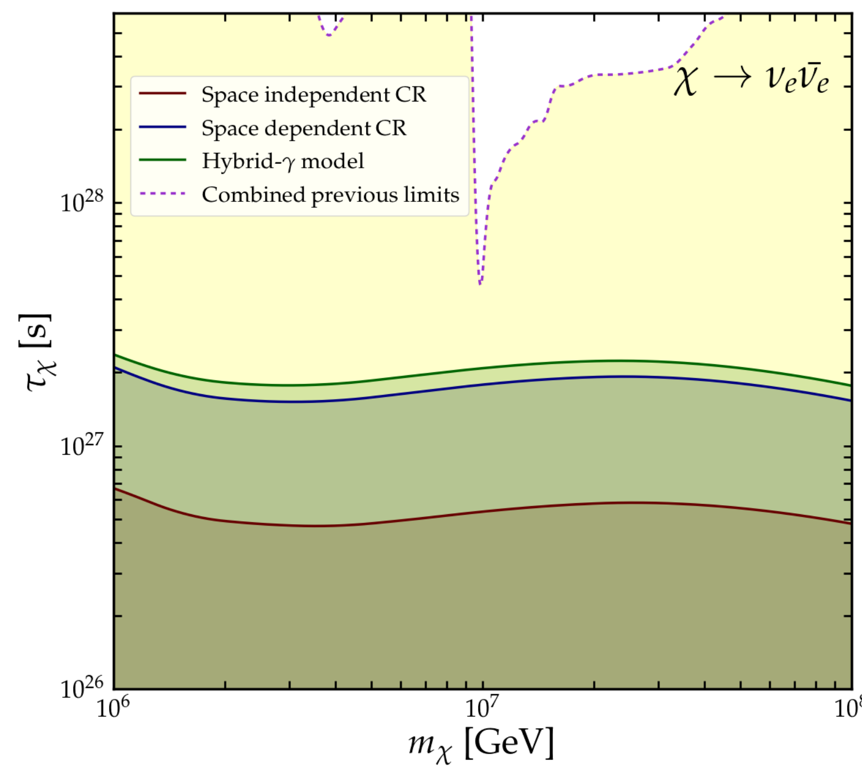


TNM, Saha, Dubey, Laha 2105.05680

Related work: Esmaili, Serpico 2105.01826

Decaying DM: Limits



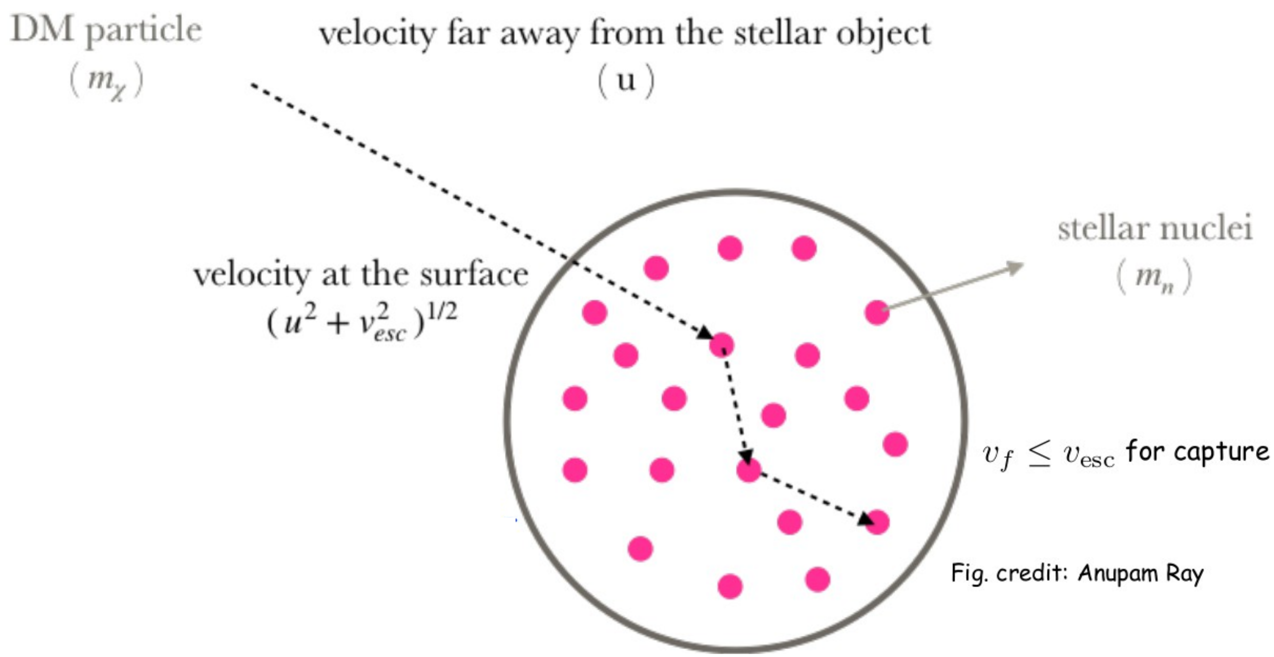


✔ For most of the channels (except first two generations of leptons) our bounds are stronger than previous limits.

✔ Our limits are robust, does not depend on choice of DM density profile.

Neutrinos from captured DM annihilation

DM capture in neutron star



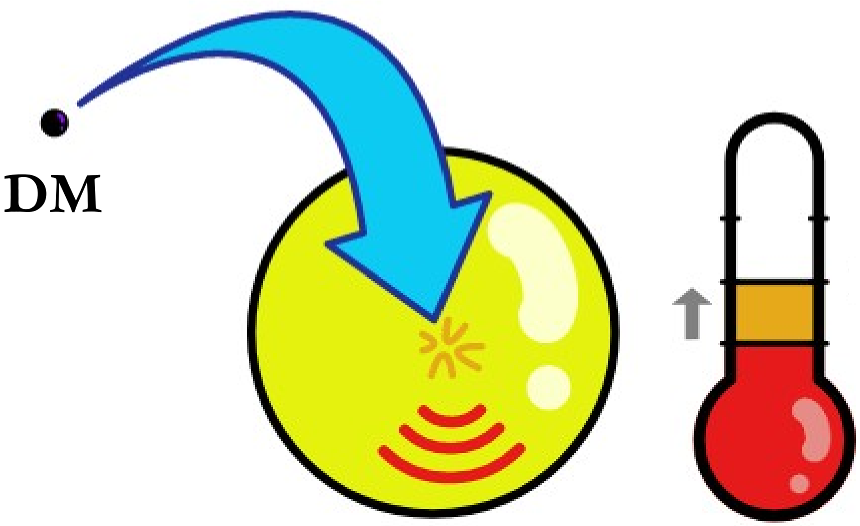
$$C \simeq \frac{\rho_\chi}{m_\chi} \int \frac{f(u)du}{u}(u^2 + v_{\rm esc}^2) \min(\sigma_{\chi n}, \sigma_{\chi n}^{\rm sat}) N_n \, g(w)$$

- $\frac{\rho_\chi}{m_\chi} \int \frac{f(u)du}{u}(u^2 + v_{\rm esc}^2)$: DM flux
- $\min(\sigma_{\chi n}, \sigma_{\chi n}^{\rm sat})$: DM-nucleon cross section
- N_n: No. of targets
- $g(w)$: 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



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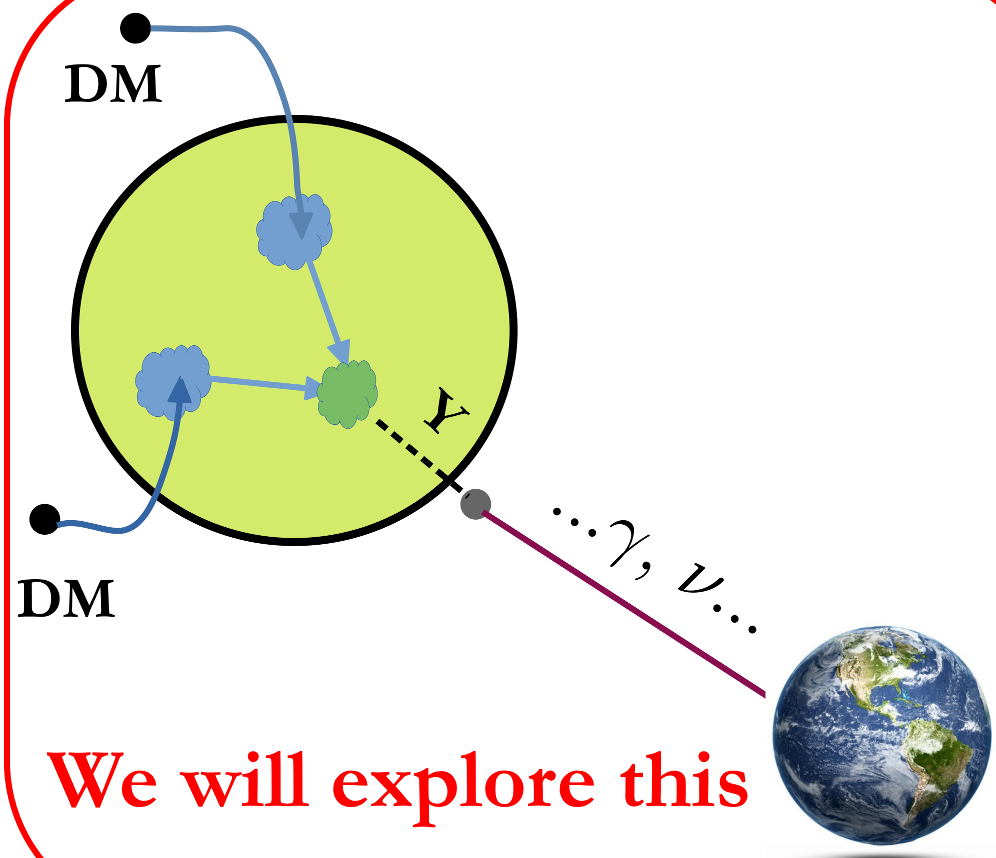


We will explore this

Goldman et al PRD 89 …
Baryakhtar et al 1704.01577 ...
Bell et al 2004.14888 ...
TNM, Queiroz 2104.02700…

Silk et al PRL 85 …
Pospelov, Ritz 0810.1502 …
Baratella et al PPPC 1312.6408
Bell, Petraki 1102.2958
Leane et al 1703.04629, 2101.12213…
Bell et al 2103.16794

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

$$\chi\,\chi \to Y Y \to 2\,(\mathrm{SM}\,\bar{\mathrm{SM}}) \to \ldots, \nu, \ldots$$

DM

Long lived Mediator

Pospelov et al 0711.4866
Batell et al 0910.1567

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

↓ Equilibrium

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

Bose, TNM, Ray 2108.12420

Neutrino flux

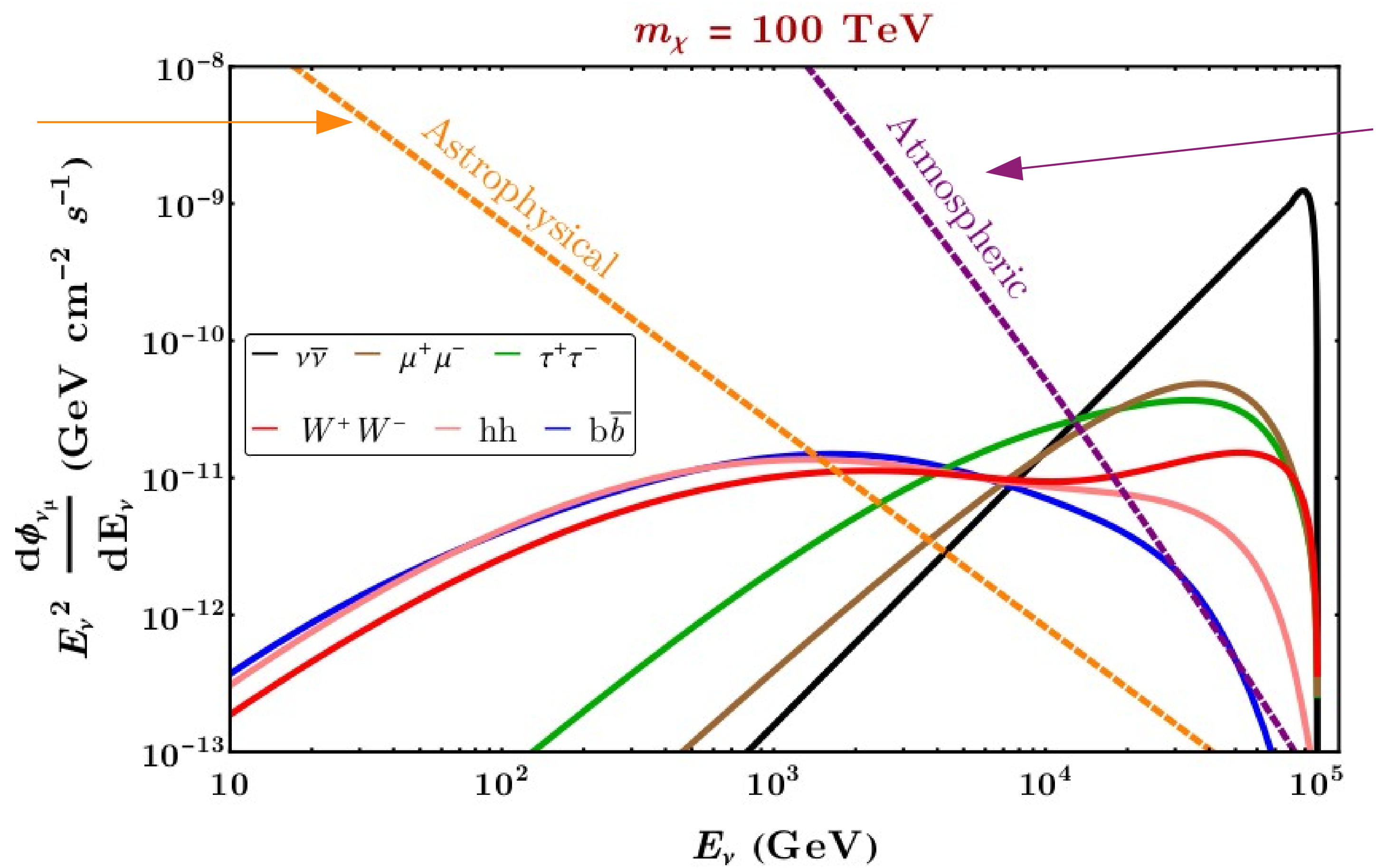
$$\frac{d\phi}{dE_\nu} = \frac{\Gamma_{\rm ann}}{4\,\pi\,D^2}\,{\rm Br}({\rm Y} \to {\rm SM}\,\bar{\rm SM})\,\frac{dN_\nu}{dE_\nu}\,\left(e^{-\frac{R}{\eta c \tau_Y}} - e^{-\frac{D}{\eta c \tau_Y}}\right)$$

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

Survival ratio

Stettner 1908.09551

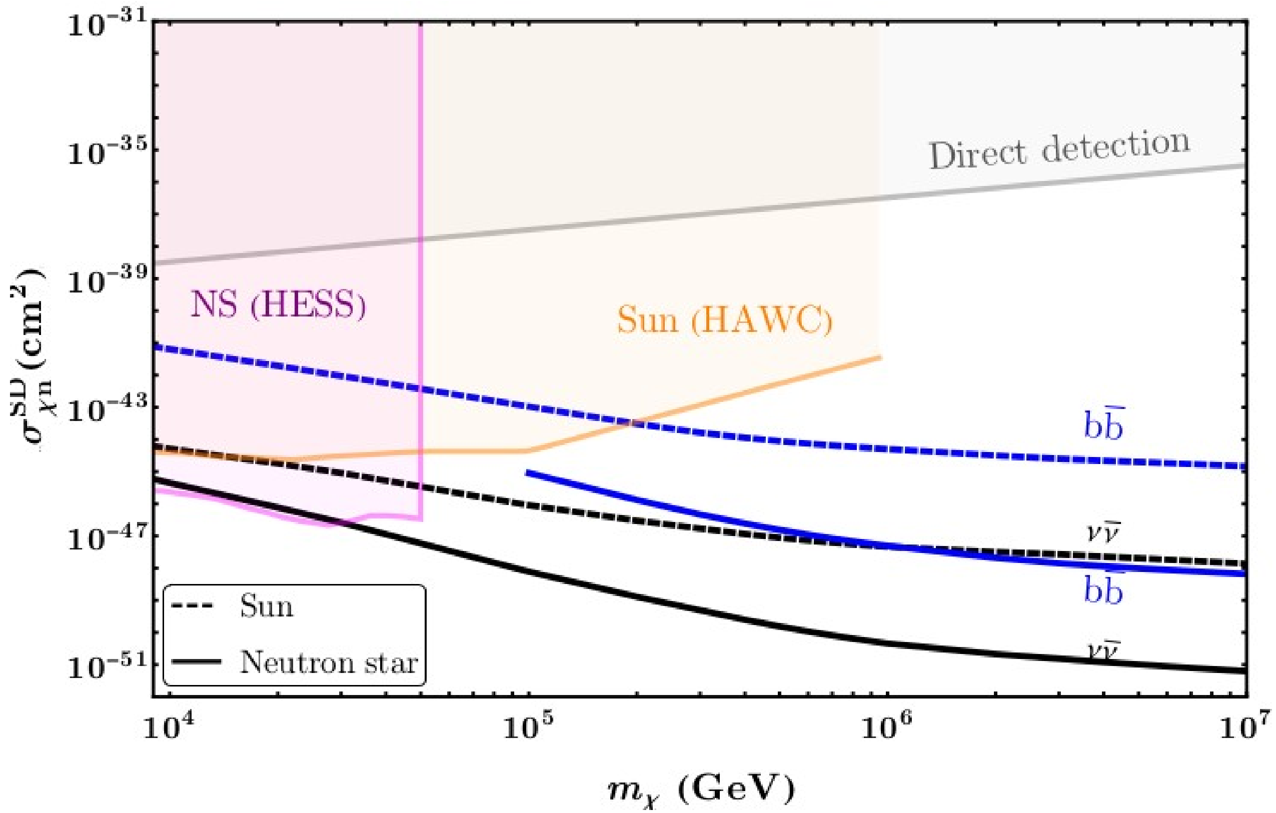
Honda et al 1502.03916



Bose, TNM, Ray 2108.12420

Prospect of gigaton detector

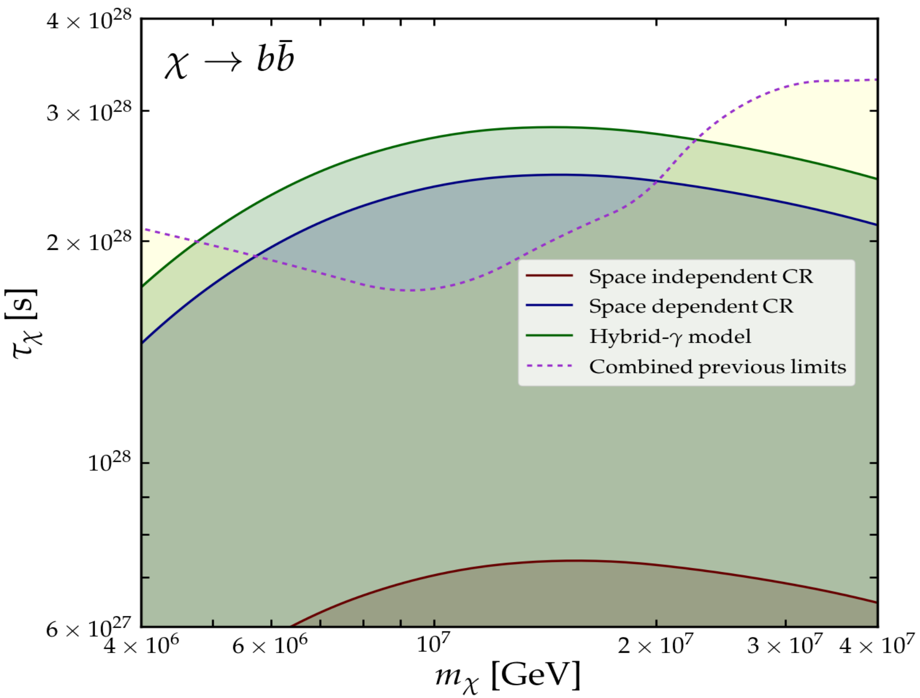
$$\frac{dN_\mu}{dE_\mu} \simeq N_A\,\rho\,V\,T\,\frac{1}{1-y}\left[\frac{d\phi_{\nu_\mu}}{dE_\nu}(E_\nu)\,\sigma_{\rm CC}(E_\nu)\right]_{E_\nu=\frac{E_\mu}{1-y}} e^{-\tau(E_\nu)}$$

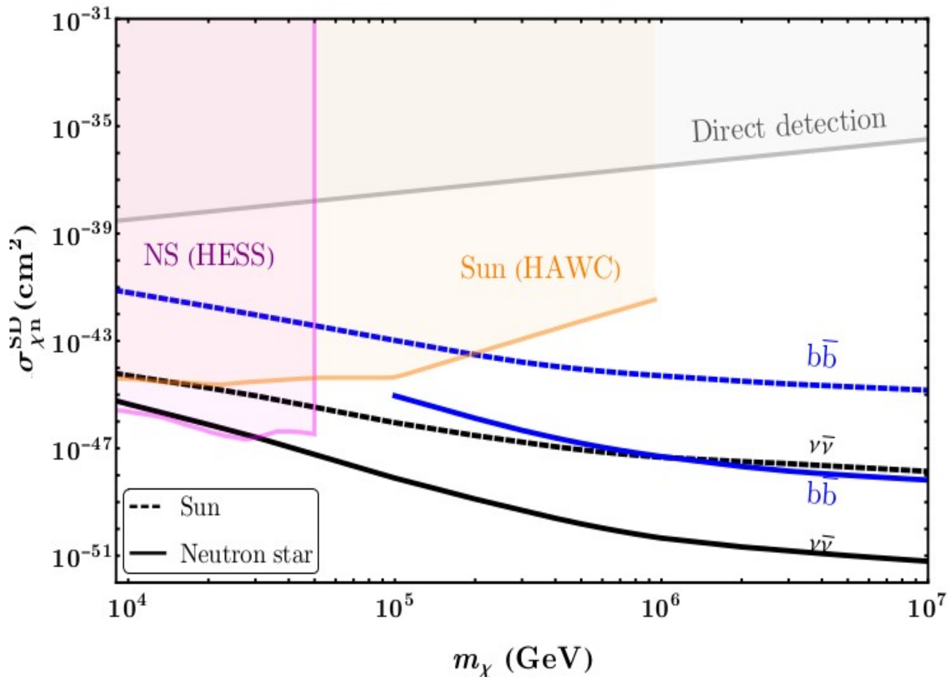


✔ Limits are obtained by equating DM events to astrophysical and atmospheric neutrinos

Bose, TNM, Ray 2108.12420

Conclusions





✔ Indirect searches for heavy DM through gamma rays and neutrinos.

✔ We explored new regions of the DM parameter space.

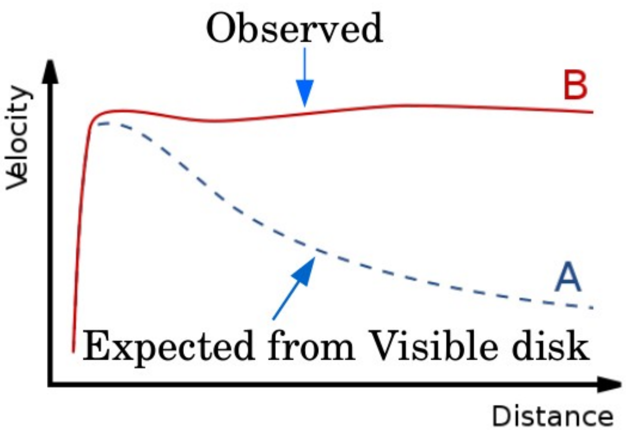
TNM, Saha, Dubey, Laha 2105.05680

Bose, TNM, Ray 2108.12420

email: tarak.maity.physics@gmail.com

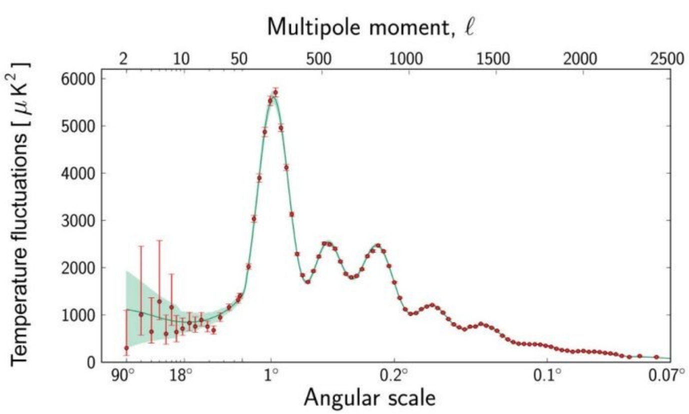
Thank you

Why Dark Matter?



Galaxy Rotational curve

Gravitational lensing



CMB

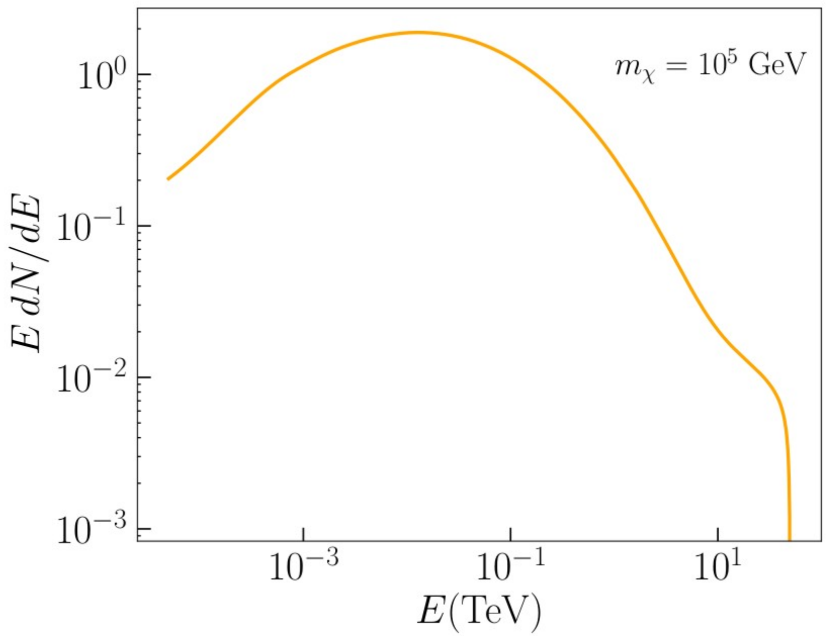
$$\Omega h^2 = 0.120 \pm 0.001$$

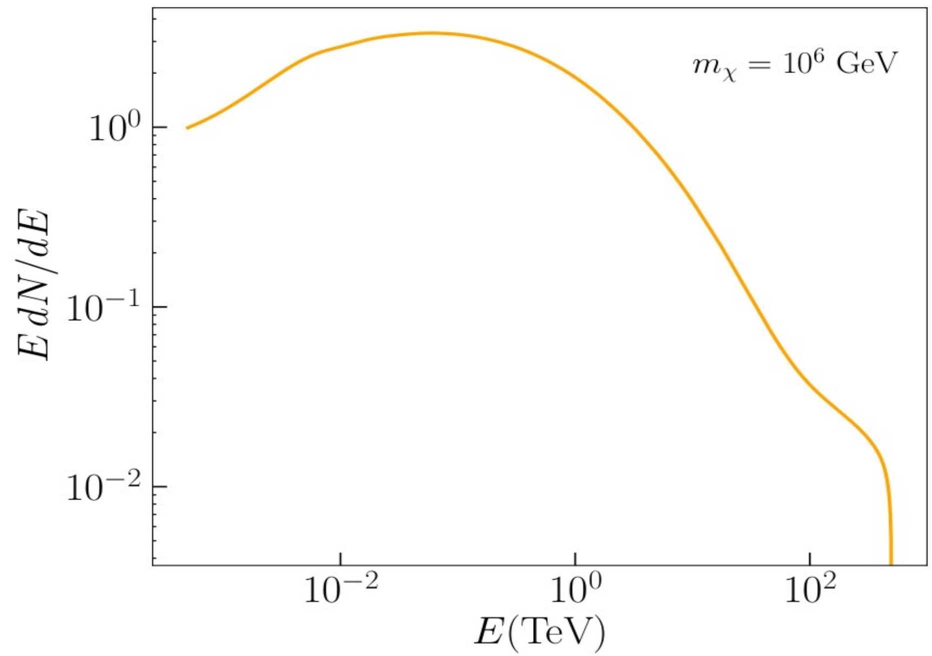
Hard fact : DM exists

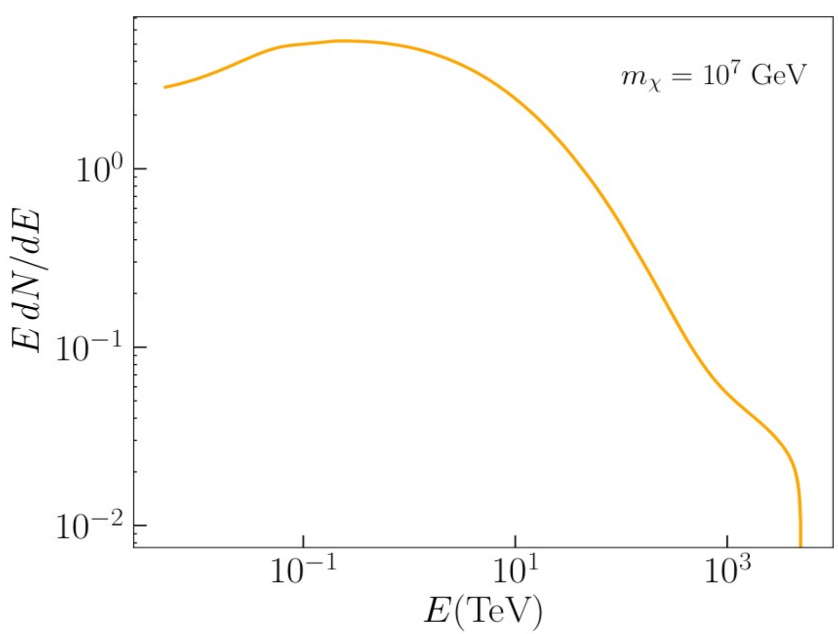
Nature of DM ?

Gamma-ray spectrum

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







✔ Utilizing HDMSpectra

✔ Set the DM mass range