Decaying heavy Dirac fermion DM with RHN portals and dark gauge symmetry for PAMELA/AMS02, IceCUBE, KM3-230213A

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KM3-230213A

376 | Nature | Vol 638 | 13 February 2025

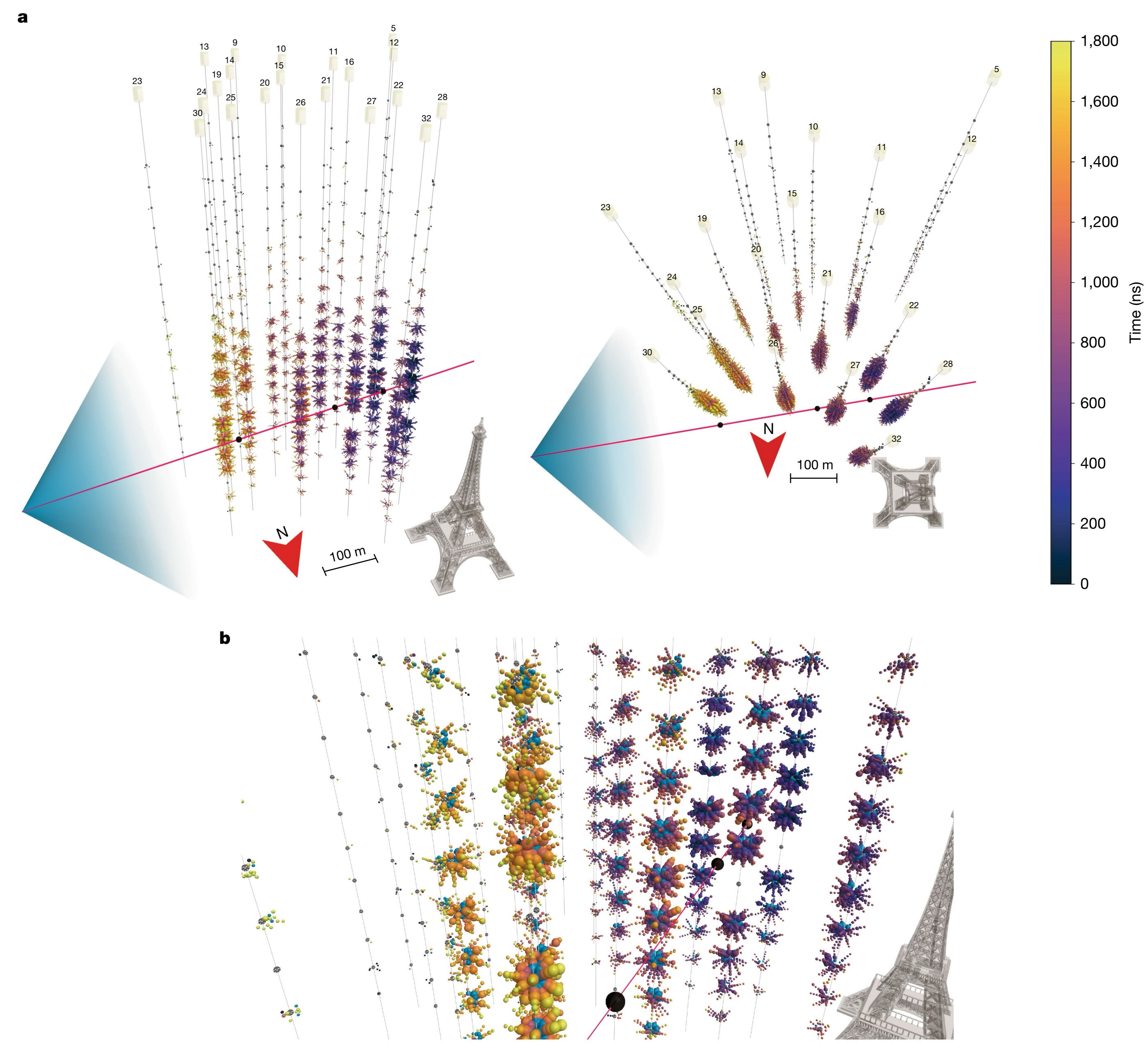

Fig. 1 | Views of the event. a, Side and top views of the event. The reconstructed trajectory of the muon is shown as a red line, along with an artist's representation of the Cherenkov light cone. The hits of individual PMTs are represented by spheres stacked along the direction of the PMT orientations. Only the first five hits on each PMT are shown. As indicated in the legend, the spheres are coloured according to the detection time relative to the first triggered hit. The size of the spheres is proportional to the number of photons detected by the corresponding PMT. The locations of the secondary cascades, discussed in the Supplementary Material, are indicated by the black spheres along the muon trajectory. The north direction is indicated by a red arrow. A 100-m scale and the Eiffel Tower (330 m height, 125 m base width) are shown for size comparison. **b**, Zoomed-in view of the optical modules that are close to the first two observed secondary showers in the event. Here light-blue spheres represent hits that arrive within −5 to 25 ns of the expected Cherenkov arrival times.

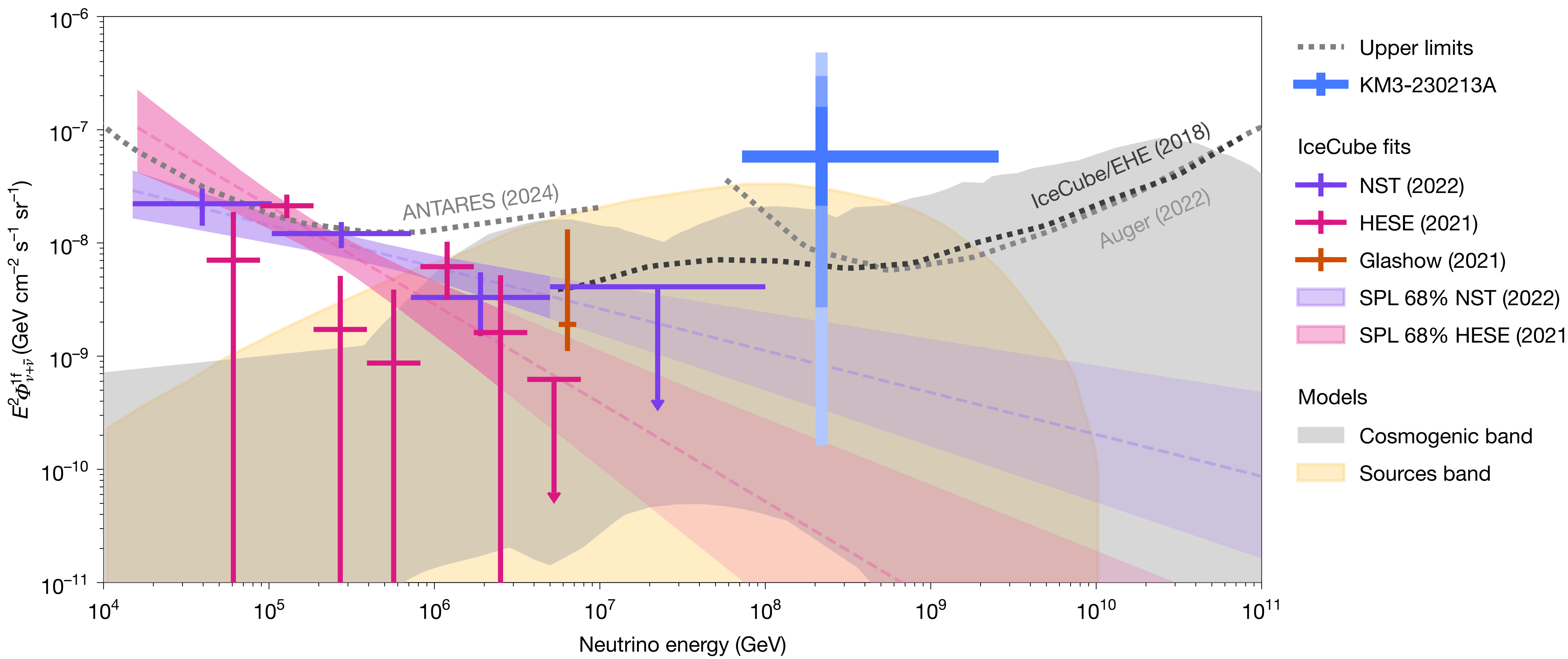

Fig. 5 | Comparison with models and earlier measurements. Shown is the energy-squared per-flavour astrophysical flux derived from the observation of KM3-230213A with measurements and theoretical predictions, assuming equipartition (ν_e:ν_μ:ν_τ = 1:1:1). The blue cross corresponds to the flux needed to achieve one expected event after the track selection described in the text, in the central 90% neutrino energy range associated with KM3-230213A, illustrated with the horizontal span; the vertical bars represent the 1σ, 2σ and 3σ Feldman–Cousins confidence intervals on this estimate. The purple and pink shaded regions represent the 68% confidence level contours of the IceCube single-power-law (SPL) fits (Northern Sky Tracks, NST[5]) and High-Energy Starting Events (HESE)[7], respectively: the darker-shaded regions are the respective 90% central energy range at the best fit (dashed line), whereas the lighter-shaded regions are extrapolations to higher energies. The purple and pink crosses are the piece-wise fit from the same analyses, whereas the orange cross corresponds to the IceCube Glashow resonance event[11]. The dotted lines are upper limits from ANTARES (95% confidence level[47]), Pierre Auger (90% confidence level, for an E^{-2} neutrino spectrum[28], corrected to convert from limits in half-decade to one-decade bins) and IceCube (90% confidence level, estimated assuming an E^{-1} neutrino spectrum in sliding one-decade bins[27]). The grey-shaded band comprises a variety of cosmogenic neutrino expectations following several models of cosmic-ray acceleration and propagation, whereas the yellow-shaded band comprises several scenarios of diffuse transient and variable extragalactic sources, both reported in the Supplementary Material.

KM3-230213A

376 | Nature | Vol 638 | 13 February 2025

- $E_\nu = 220^{+570}_{-110}$ PeV! Wow!
- What is the origin of this event?
- Lorentz violation, BSM, etc..

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We shall propose Heavy Dirac fermion DM decay with the RHN portal for this

What’s new?

- Underlying models are basically the same: Heavy spin-1/2 DM (dark fermion) decays through RHN portals
- A couple of developments during the last ~10 years or so
- Obervation of GW from BH binary merge → GW opens a new window for fundamental physics; dark gauge symmetry breaking predicts GW productions from cosmic strings
- Improved predictions for DM pair annihilations or DM decays into a pair of SM particles using SCET (HDM package by Bauer, Rodd, Webber, 2007.15001 [hep-ph])

Contents

- General Ideas on DM model building along the SM construction
- AMS02 positron excess from decaying fermionic thermal dark matter (P. Ko, Yong Tang,1410.7657, PLB)
- IceCube events from heavy DM decay with RH Neutrino portal (P. Ko and Yong Tang, 1508.02500, PLB)
- Similar idea for the recent KM3-230213A HE neutrino event (2504.16040, with Sarif Khan, Jongkuk Kim)

Dark Matter Model Building along the SM Construction

- Charge/color neutral : no renormalizable int's w/ γ, g
- Eq of State : $\rho \simeq 0$ $(i.e.\ p \simeq 0)$
- $\tau_{\rm DM} \gg \tau$ (Age of the Universe) or ∞

What is the DM mass ?

- If very light, DM is long lived for the kinematical reason
- Axion and light sterile ν's are good examples

- If not, reasonable to assume some conserved quantum #, either exactly or approximately conserved
- Local or global Dark Sym

Local dark gauge symmetry

- Better to use local gauge symmetry for DM stability/ longevity (Baek,Ko,Park,arXiv:1303.4280)

- Success of the Standard Model of Particle Physics lies in "local gauge symmetry" without imposing any internal global symmetries
- Electron stability : U(1)em gauge invariance, electric charge conservation, massless photon
- Proton longevity : baryon # is an accidental sym of the SM
- No gauge singlets in the SM ; all the SM fermions chiral

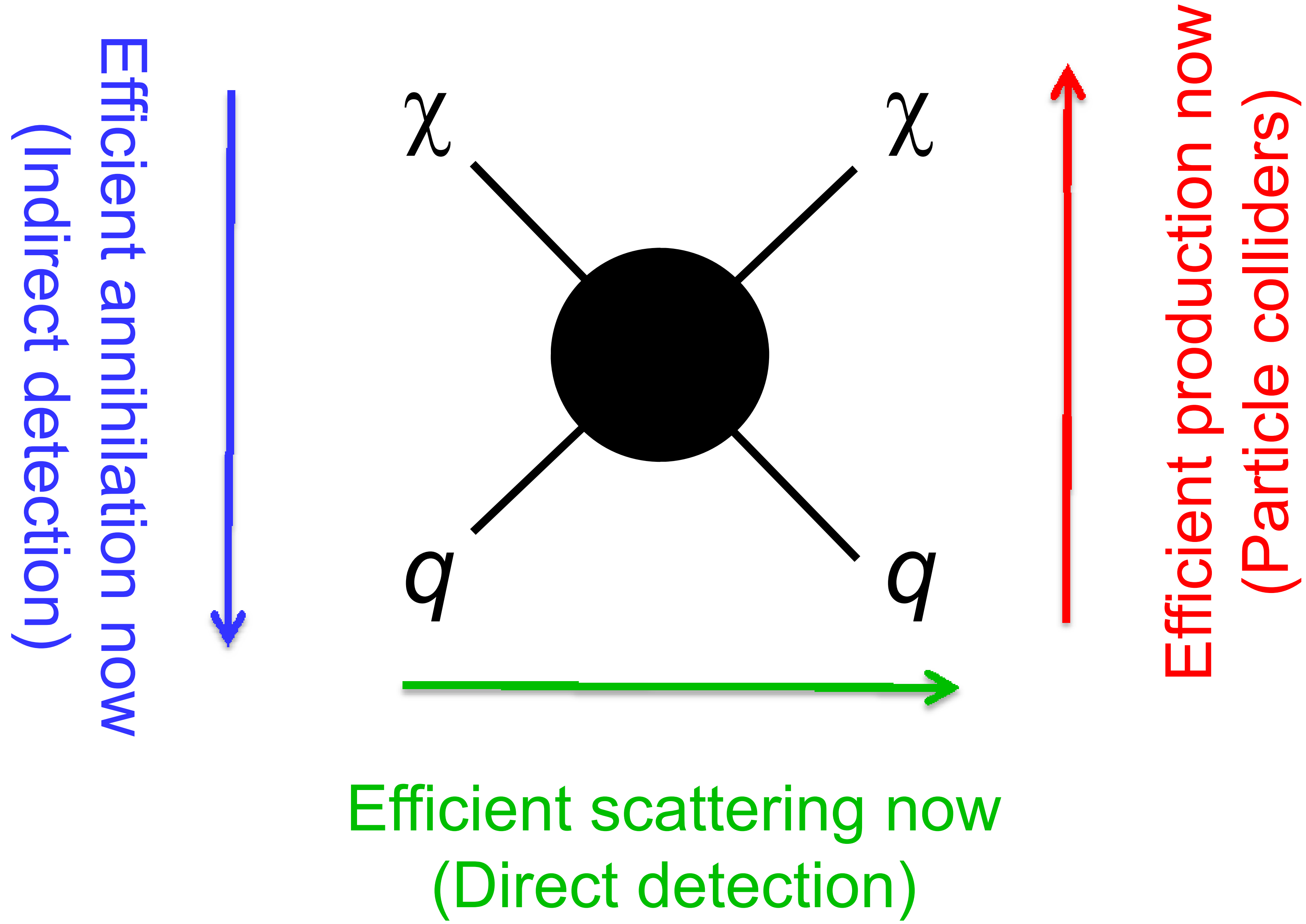
- Dark sector with (excited) dark matter, dark radiation and force mediators might have the same structure as the SM
- "(Chiral) dark gauge theories without any global sym"
- Origin of DM stability/longevity from dark gauge sym, and not from dark global symmetries, as in the SM
- Just like the SM (conservative)

DM Models in literature

- Top-Down: LSP in SUSY models, LKP in KK models, etc.
- Bottom-Up: ad hoc dark Z_2, Z_3 parities
- Massive dark photon with Stueckelberg mechanism (w/o dark Higgs boson): sometimes could be problematic [see arXiv:2204.04889, for example]
- DM complementarity can be misleading when applied to DM effective theory or simplified DM models w/o full SM gauge symmetry (and dark gauge symmetry)

Crossing & WIMP detection

Correct relic density → Efficient annihilation then



Basic properties of DM

- DM: stable or long-lived ($\tau_{\rm DM} \gg \tau_{\rm universe}$): some exact or accidental global symmetry
- No global symmetry from the beginning [like the SM. And it is believed to be generically violated by gravity.]
- Then, there are 3 possibilities within QFT:
  - Stable due to exact gauge symmetries or topological reasons
  - Long-lived due to some accidental sym. (broken @ dim-6)
  - Long-lived since it is very light (axion, ν_s ,…)

Dark Gauge Symmetry:
DM Stability/Longevity

Z2 real scalar DM

- Simplest DM model with Z2 symmetry : $S \to -S$

$$\mathcal{L} = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{\lambda_S}{4!} S^4 - \frac{\lambda_{SH}}{2} S^2 H^\dagger H.$$

- Global Z2 could be broken by gravity effects (higher dim operators)

- e.g. consider Z2 breaking dim-5 op : $\dfrac{1}{M_{\text{Planck}}} S O_{\text{SM}}^{(4)}$

- Lifetime of EW scale mass “S” is too short to be a DM

- Similarly for singlet fermion DM

Fate of CDM with Z2 sym

(Baek,Ko,Park,arXiv:1303.4280)

Consider Z_2 breaking operators such as

$$\frac{1}{M_{\rm Planck}} S O_{\rm SM}$$

keeping dim-4 SM operators only

The lifetime of the Z_2 symmetric scalar CDM S is roughly given by

$$\Gamma(S) \sim \frac{m_S^3}{M_{\rm Planck}^2} \sim (\frac{m_S}{100 {\rm GeV}})^3 10^{-37} GeV$$

- Global Z2 cannot save EW scale DM from decay with long enough lifetime

The lifetime is too short for ~100 GeV DM

Fate of CDM with Z_2 sym

Spontaneously broken local U(1)x can do the job to some extent, but there is still a problem

Let us assume a local $U(1)_X$ is spontaneously broken by $\langle \phi_X \rangle \neq 0$ with

$$Q_X(\phi_X) = Q_X(X) = 1$$

Then, there are two types of dangerous operators:

$$\phi_X^\dagger X H^\dagger H, \quad \text{and} \quad \phi_X^\dagger X O_{\rm SM}^{(dim-4)}$$

Problematic !

Perfectly fine !

Higgs is not good for DM stability/longvity

- These arguments will apply to DM models based on ad hoc symmetries (Z2,Z3 etc.)

- One way out is to implement Z2 symmetry as local U(1) symmetry (arXiv:1407.6588 with Seungwon Baek and Wan-Il Park);

- See a paper by Ko and Tang on local Z3 scalar DM, and another by Ko, Omura and Yu on inert 2HDM with local $U(1)_H$

- DM phenomenology richer and DM stability/longevity on much more solid ground arXiv:1407.6588 w/ WIPark and SBaek

$$Q_X(\phi) = 2, \quad Q_X(X) = 1$$

$$\mathcal{L} = \mathcal{L}_{\rm SM} + -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{1}{2}\epsilon X_{\mu\nu}B^{\mu\nu} + D_\mu\phi_X^\dagger D^\mu\phi_X - \frac{\lambda_X}{4}\left(\phi_X^\dagger\phi_X - v_\phi^2\right)^2 + D_\mu X^\dagger D^\mu X - m_X^2 X^\dagger X$$
$$- \frac{\lambda_X}{4}\left(X^\dagger X\right)^2 - \left(\mu X^2\phi^\dagger + H.c.\right) - \frac{\lambda_{XH}}{4}X^\dagger X H^\dagger H - \frac{\lambda_{\phi_X H}}{4}\phi_X^\dagger\phi_X H^\dagger H - \frac{\lambda_{XH}}{4}X^\dagger X\phi_X^\dagger\phi_X$$

The lagrangian is invariant under $X \to -X$ even after $U(1)_X$ symmetry breaking.

Unbroken Local Z2 symmetry

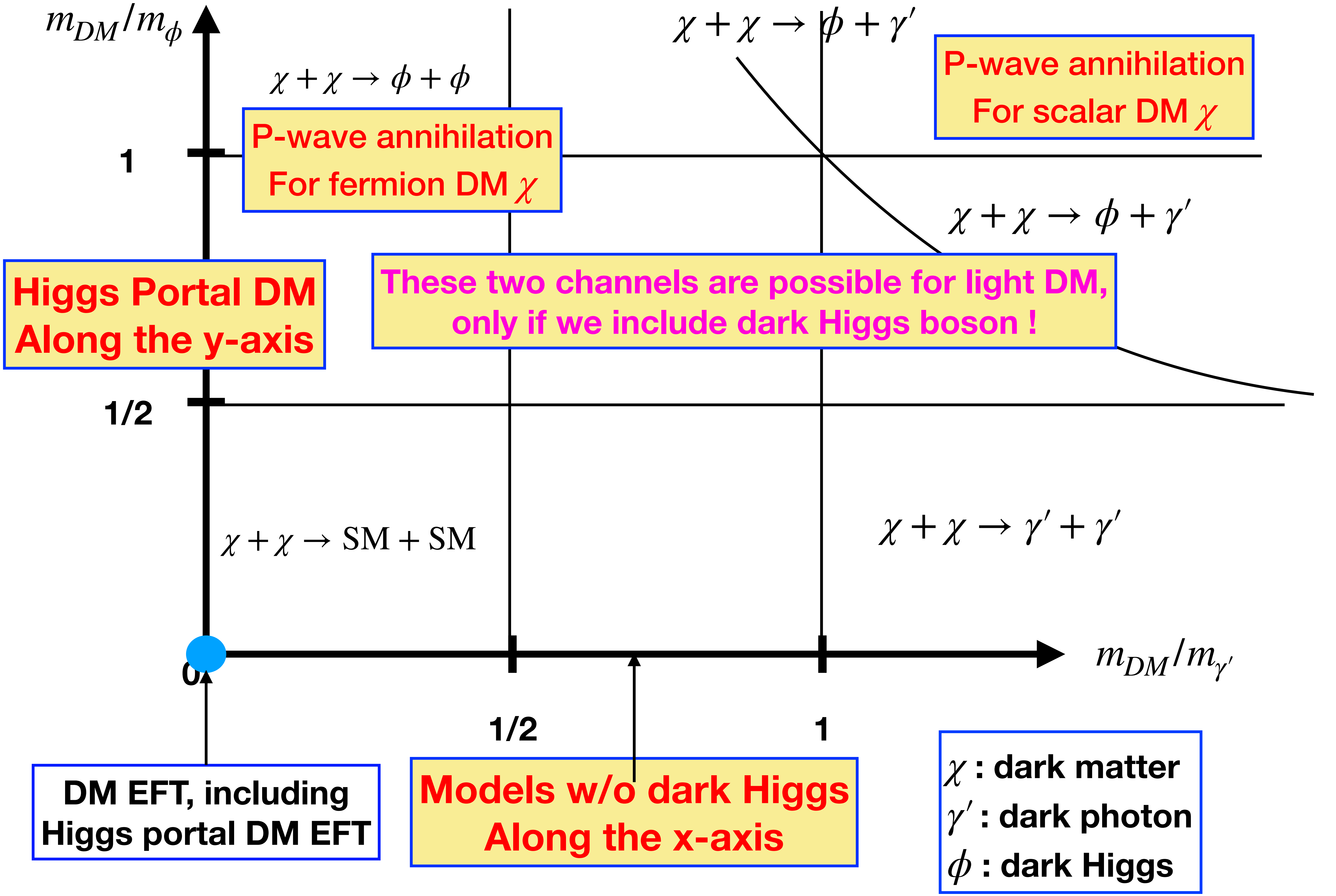
Gauge models for excited DM

$X_R \to X_I \gamma_h^*$ followed by $\gamma_h^* \to \gamma \to e^+e^-$ **etc.**

The heavier state decays into the lighter state

The local Z2 model is not that simple as the usual Z2 scalar DM model (also for the fermion CDM)

Dark sector parameter space for a fixed m_{DM}



AMS02 positron excess from decaying fermionic thermal DM

P. Ko, Yong Tang,1410.7657, PLB

Decaying DM for PAMELA/AMS02

$$\delta\mathcal{L} = \lambda_{\rm eff}\bar{\chi}\phi\nu, \quad \text{with} \quad \lambda_{\rm eff} \sim 10^{-26}$$

Hamaguchi, Shirai, Yanagida et al. with $\phi = h$

arXiv:0812.2374 [hep-ph]

If we use the SM Higgs for ϕ, strong constraints from gamma ray and antiproton flux data

Can we make use of light dark Higgs instead ?

YES !

Model

Ko and Tang, 1404.0236
Published in PLB

We consider a local dark gauge symmetry $U(1)_X$ with dark Higgs Φ and two different Dirac fermions in the dark sector, χ and ψ. Assign $U(1)_X$ charges to the dark fields as follows:

$$(Q_\chi, Q_\psi, Q_\Phi) = (2, 1, 1),$$

we can write down the possible renormalizable interactions including singlet right-handed neutrinos N for the model,

$$\begin{aligned}\mathcal{L} =&\mathcal{L}_{\rm SM} + \frac{1}{2}\bar{N}_I i\partial\!\!\!/ N_I - \left(\frac{1}{2}m_{NI}\bar{N}_I^c N_I + y_{\alpha I}\bar{L}HN_I + h.c\right) \\ & - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{1}{2}\sin\epsilon X_{\mu\nu}F_Y^{\mu\nu} + \left(D_\mu\Phi\right)^\dagger D^\mu\Phi - V(\phi, H) \\ & + \bar{\chi}\left(iD\!\!\!\!/ - m_\chi\right)\chi + \bar{\psi}\left(iD\!\!\!\!/ - m_\psi\right)\psi - \left(f\bar{\chi}\Phi\psi + g_I\bar{\psi}\Phi N_I + h.c\right), \end{aligned} \quad (2.1)$$

with Higgs portal interactions

$$V = \lambda_H\left(H^\dagger H - \frac{v_H^2}{2}\right)^2 + \lambda_{\phi H}\left(H^\dagger H - \frac{v_H^2}{2}\right)\left(\Phi^\dagger\Phi - \frac{v_\phi^2}{2}\right) + \lambda_\phi\left(\Phi^\dagger\Phi - \frac{v_\phi^2}{2}\right)^2.$$

Feynman Diagrams

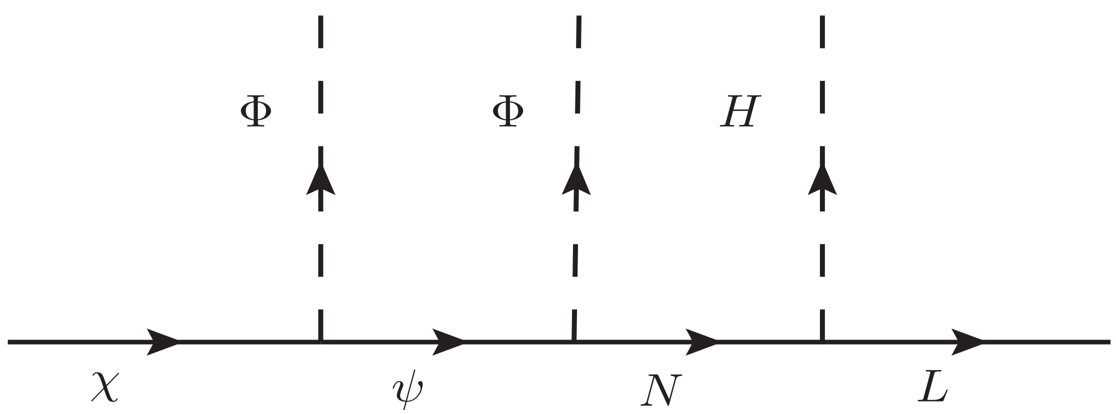


FIG. 1: Feynman diagram that generates the effector operator $\bar{\chi}\Phi\Phi\tilde{H}L$.

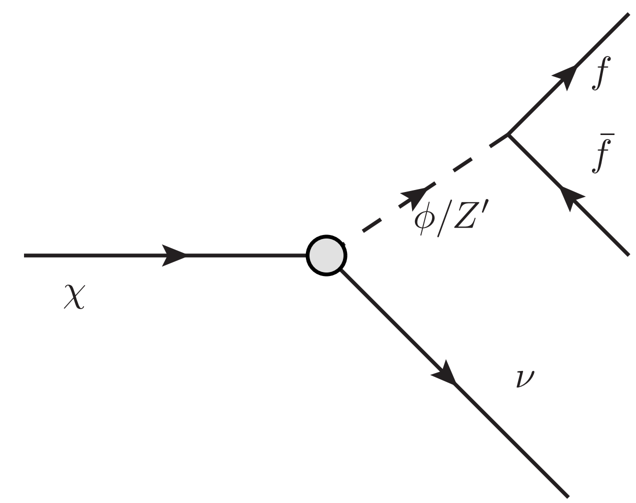


FIG. 2: Dominant decaying process.

In this model, we can estimate

$$\lambda_{\text{eff}} \sim \frac{yfg}{4\sqrt{2}}\frac{v_\phi}{m_\psi}\frac{v_H}{m_N} \sim 10^{-26}.$$

This can be easily achieved if we chose the parameters as

$$v_\phi \sim O(100)\text{MeV},\ m_N \sim m_\chi \sim 10^{14}\text{GeV},\ yfg \sim 1.$$

$$Br(\chi \to \phi\nu) : Br(\chi \to Z'\nu) = 1 : 1$$

$$\tau_\chi \sim 10^{26}\text{sec}$$

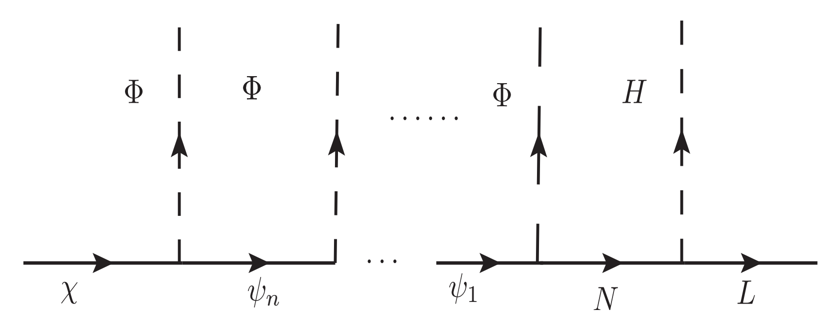


FIG. 4: Feynman diagram that generates the effector operator $\bar{\chi}\Phi^{n+1}\tilde{H}L$.

$$Br(\chi \to \phi\nu) : Br(\chi \to Z'\nu) = n^2 : 1.$$

$$(Q_\chi, Q_{\psi_n}, ..., Q_{\psi_1}, \Phi) = (n+1, n, ..., 1, 1)$$

Integrating out ψ and N, we get $\frac{yfg}{m_\psi m_N}\bar{\chi}\Phi\Phi\tilde{H}L$

After gauge sym breaking, these operators are generated

$$\text{dim-3}: \frac{v_\phi^2 v_H}{m_\psi m_N}\bar{\chi}\nu \; ,$$

omitting the common factor $\frac{yfg}{4\sqrt{2}}$.

$$\text{dim-4}: \frac{v_\phi^2}{m_\psi m_N}\bar{\chi}h\nu \; , \quad \frac{2v_\phi v_H}{m_\psi m_N}\bar{\chi}\phi\nu,$$

$$\text{dim-5}: \frac{v_H}{m_\psi m_N}\bar{\chi}\phi\phi\nu \; , \quad \frac{2v_\phi}{m_\psi m_N}\bar{\chi}\phi h\nu,$$

$$\text{dim-6}: \frac{1}{m_\psi m_N}\bar{\chi}\phi\phi h\nu \; .$$

Then $\bar{\chi}\phi\nu$ is dominant over $\bar{\chi}h\nu$ for $m_\phi \ll m_H$!

Fit to the data

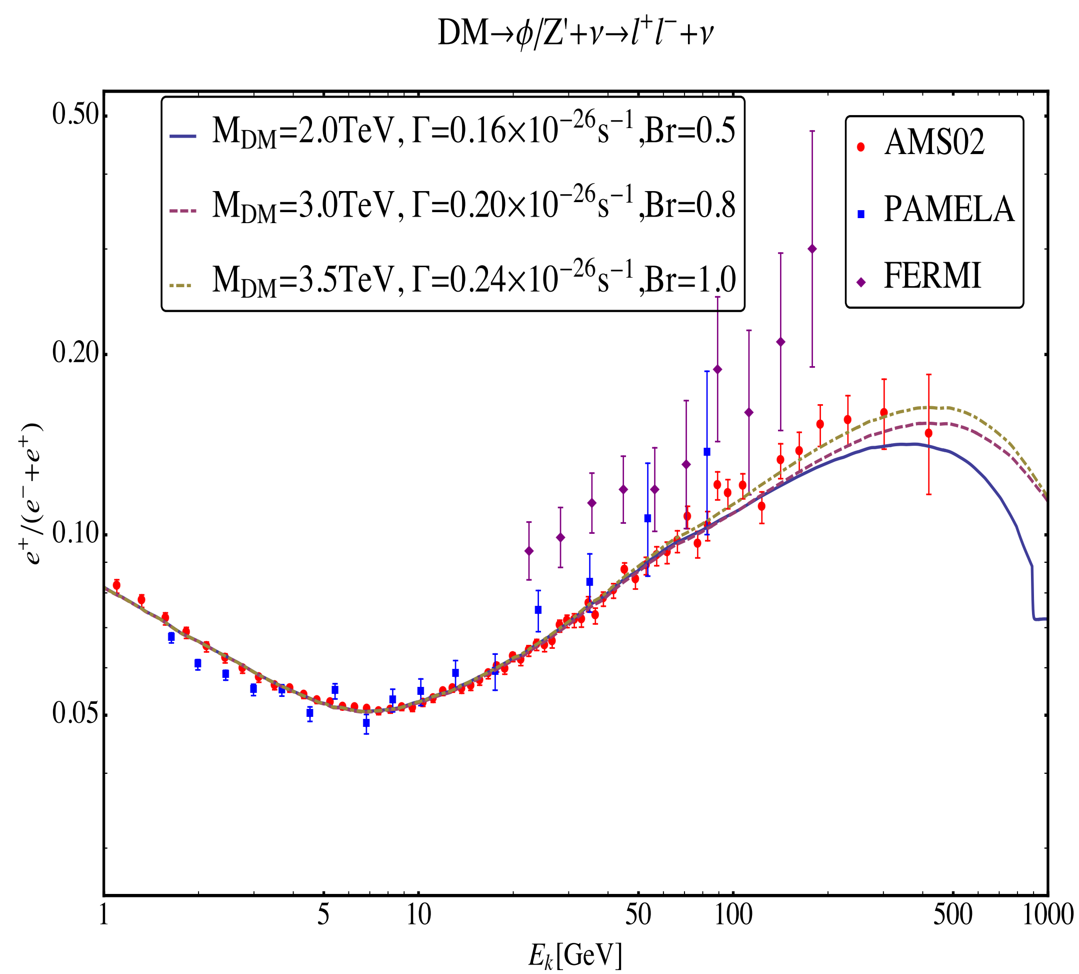


FIG. 5: Positron fraction in three different sets of parameters. $M_{\rm DM}$ and total decay width Γ are chosen to visually match the positron fraction data. Data are extracted from Ref. [58].

$$2m_\mu < m_{\phi,Z'} < 2m_{\pi^0}:$$

No constraint from anti-p, and χ : SIDM

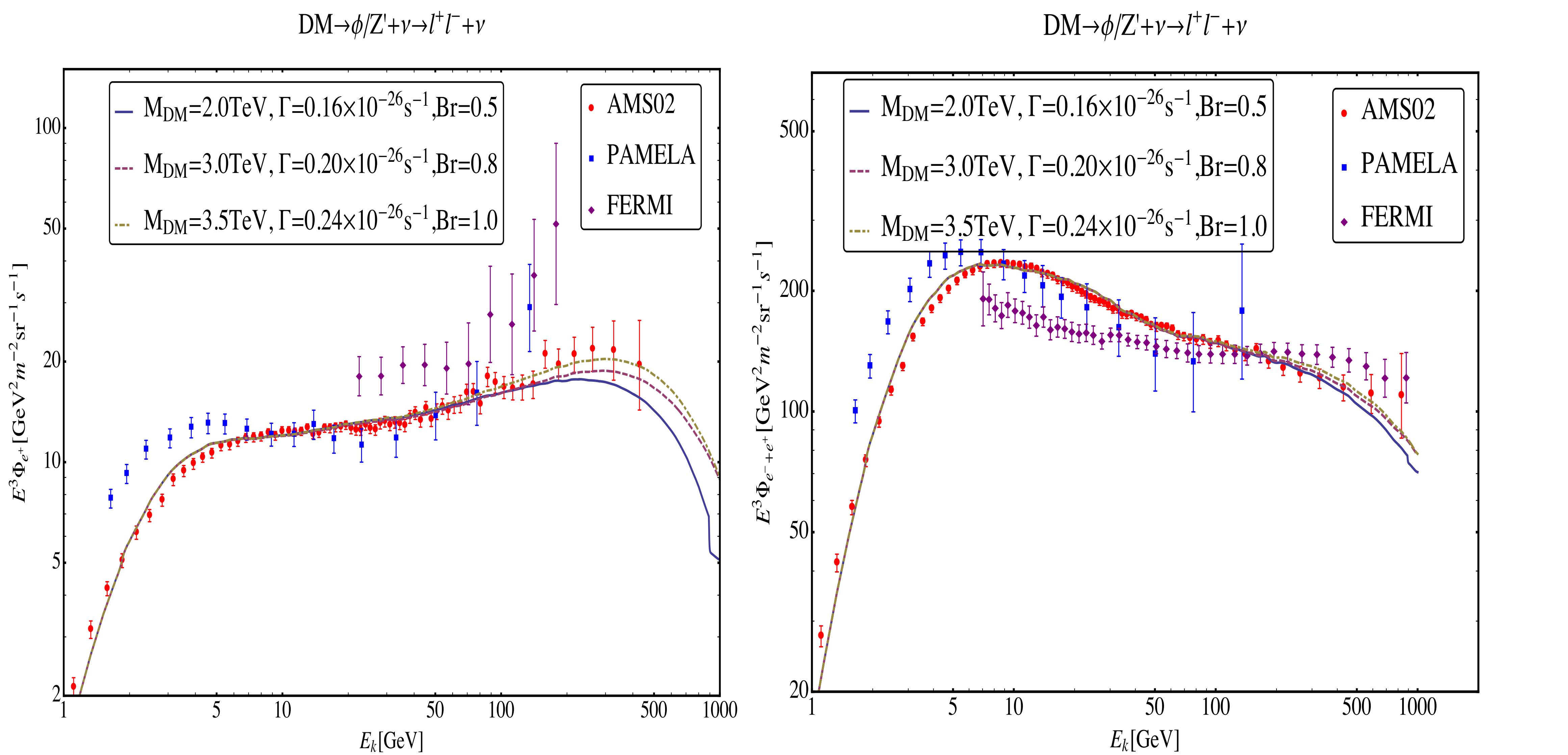


FIG. 6: Positron flux (left) and electron+positron flux (right) [59–61] for three different sets of parameters described in the text, Eqs. (5.6)-(5.8).

Both absolute fluxes and the ratio could be fit in a reasonable way

IceCube events from heavy DM decay with RH neutrino portal

P. Ko and Yong Tang,
1508.02500, PLB (2015)

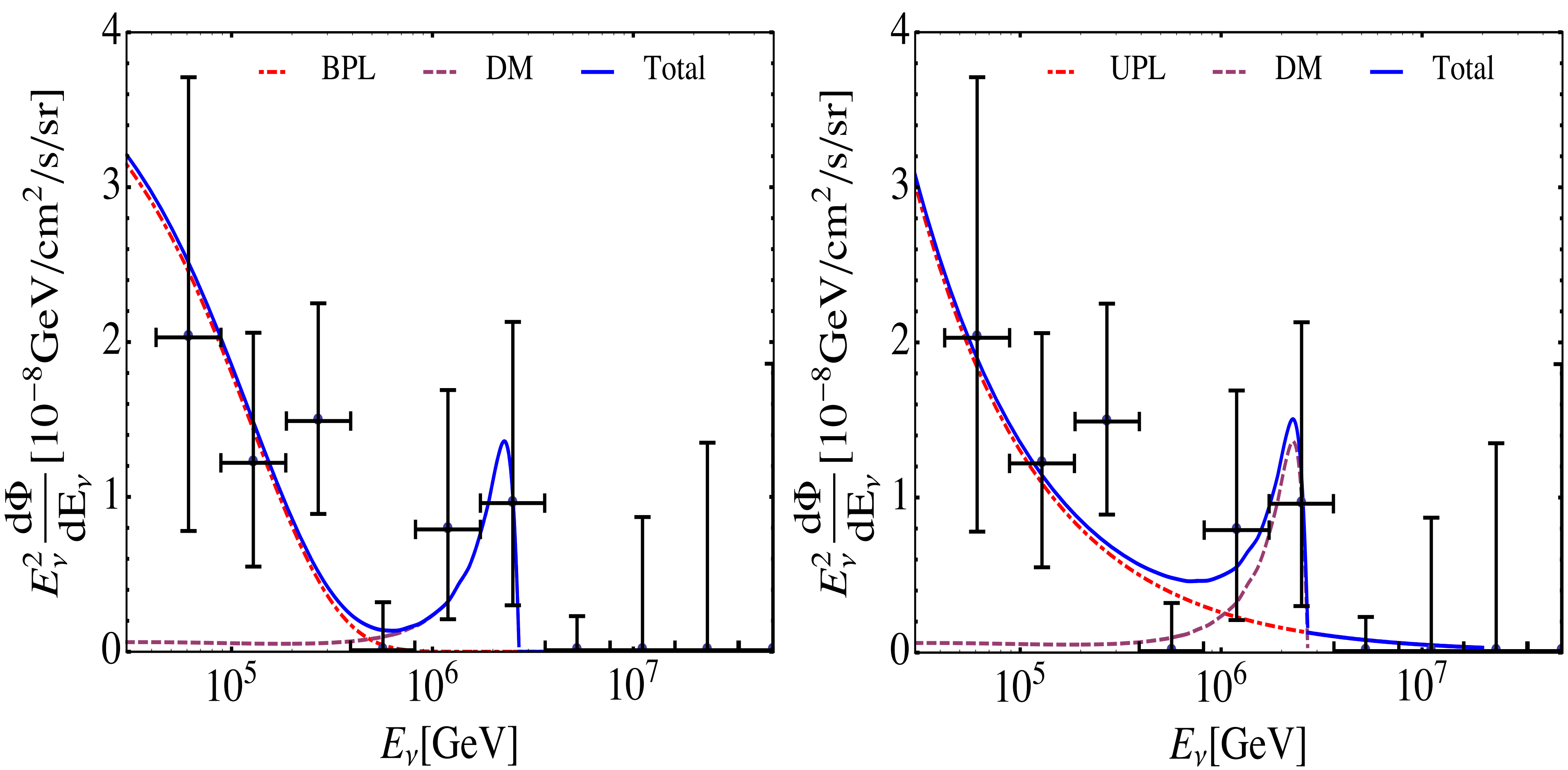


FIG. 2. Neutrino flux from DM χ's decay with $m_\chi \sim 5$PeV and lifetime $\tau_\chi = 1/\Gamma \sim 2 \times 10^{28}$s and IceCube Data [1]. The left (right) panel used a broken (unbroken) power law (BPL) for astrophysical neutrino flux with a red dot-dashed curve. DM's contributions and total flux are labeled with purple dashed and blue solid curves, respectively. See details in the text.

We consider a dark sector with a dark Higgs field Φ and a Dirac fermion DM χ associated $U(1)_X$ gauge symmetry. Their $U(1)_X$ charges are assigned as follows [2]:

$$(Q_\Phi, Q_\chi) = (1, 1).$$

We begin with the following renormalizable and gauge invariant Lagrangian including just one singlet right-handed (RH) neutrino N and one lepton flavor (more Ns and/or flavors can be easily generalized):

$$\begin{aligned}\mathcal{L} =& \mathcal{L}_{\rm SM} + \frac{1}{2}\bar{N} i\partial\!\!\!/ N - \left(\frac{1}{2} m_N \bar{N}^c N + y \bar{L}\widetilde{H} N + \text{h.c.}\right) - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{1}{2}\sin\epsilon X_{\mu\nu} F_Y^{\mu\nu} \\ &+ D_\mu \Phi^\dagger D^\mu \Phi - V(\Phi, H) + \bar{\chi}\left(i D\!\!\!\!/ - m_\chi\right)\chi - \left(f \bar{\chi}\Phi N + \text{h.c.}\right),\end{aligned} \tag{2.1}$$

$$V = \lambda_H \left(H^\dagger H - \frac{v_H^2}{2}\right)^2 + \lambda_{\phi H}\left(H^\dagger H - \frac{v_H^2}{2}\right)\left(\Phi^\dagger \Phi - \frac{v_\phi^2}{2}\right) + \lambda_\phi \left(\Phi^\dagger\Phi - \frac{v_\phi^2}{2}\right)^2,$$

Integrating out the RH neutrino, we get

$$\frac{yf}{m_N}\bar{\chi}\Phi H^\dagger L + h.c.,$$

After EW and DG SB, we get

$$\frac{v_\phi v_H}{m_N}\bar{\chi}\nu,\ \frac{v_\phi}{m_N}\bar{\chi}h\nu,\ \frac{v_H}{m_N}\bar{\chi}\phi\nu,\ \frac{1}{m_N}\bar{\chi}\phi h\nu,$$

$$\chi \to Z'\nu, Z\nu, W^{\mp}l^{\pm} \sim v_H^2 : v_\phi^2 : 2v_\phi^2$$

$$\chi \to h\nu, \phi\nu \sim v_\phi^2 : v_H^2$$

$$\chi \to \phi\nu, Z'\nu \sim 1 : 1$$

Therefore, all the decay branching ratios are basically calculable and completely fixed in this model [4]. Note that the decay modes with Z' or ϕ are unique features of DM models with dark gauge symmetries [5].

Another interesting phenomenon in this model is that three body decay channel $\chi \to \phi h \nu$ is dominant over all other channels when $m_\chi \gg v_\phi$:

$$\frac{\Gamma_3\left(\chi \to \phi h \nu\right)}{\Gamma_2\left(\chi \to h\nu, \phi\nu\right)} \simeq \frac{1}{16\pi^2}\frac{m_\chi^2}{v_\phi^2 + v_H^2} \gg 1, \tag{2.10}$$

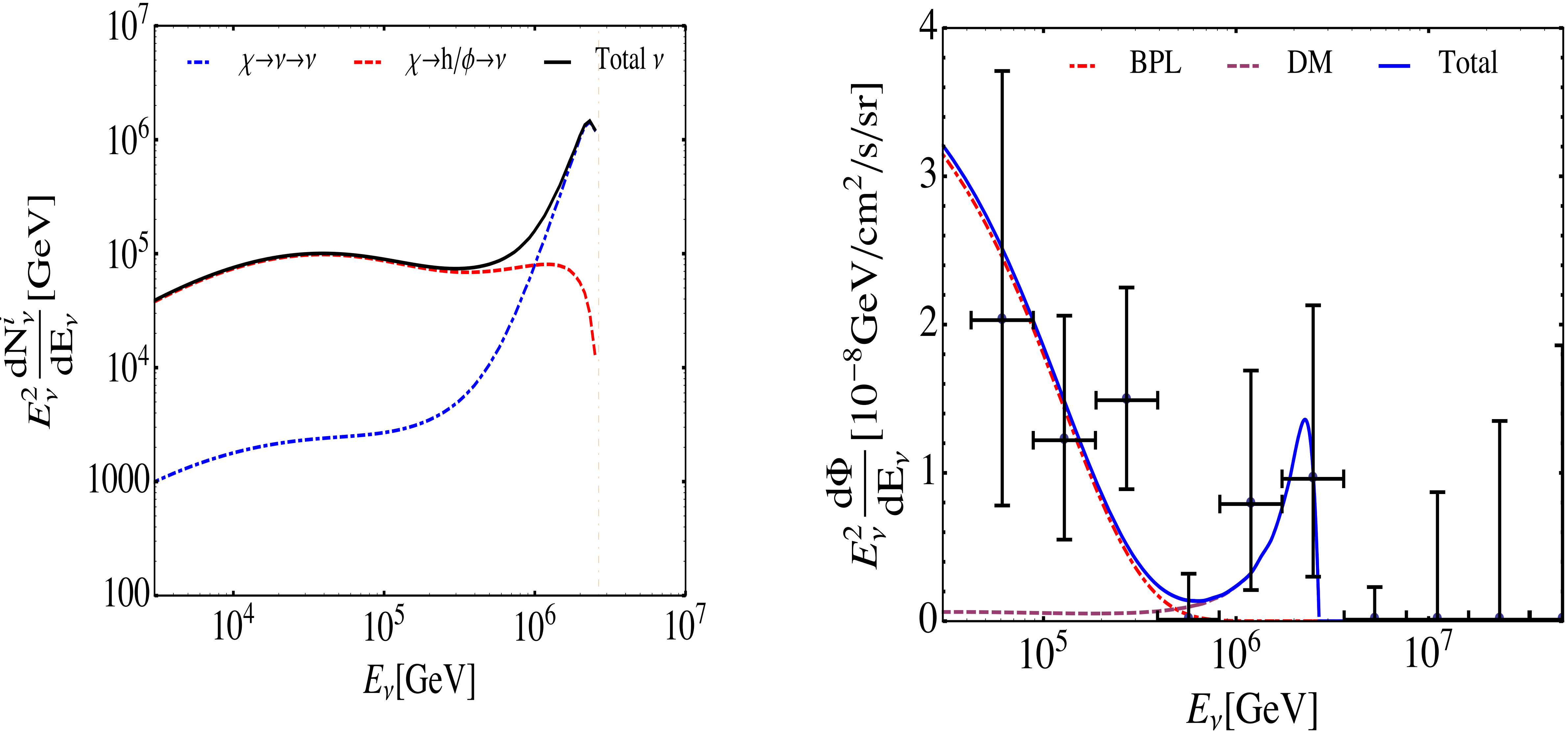
since we actually have an enhancement from heavy m_χ even though there is a phase space suppression from three-body final states. There are another three-body decay channels that are equally important:

$$\chi \to \phi/Z' + h + \nu,\ \phi/Z' + Z + \nu,\ \phi/Z' + W^\pm + l^\mp,$$

with branching ratios 1 : 1 : 2 due to the Goldstone boson equivalence theorem. In the following, if not otherwise stated explicitly, we use $\chi \to \phi h \nu$ to represent all these channels and in numerical calculations we take all of them into account.

There are some crucial differences between our model and some others in the literature. For example, the authors in Ref. [23, 29] considered the effective operator, $y\bar{L}\widetilde{H}\chi$ with $y \sim 10^{-30}$, which induces mainly two-body decay of DM χ,

$$\chi \to \nu h,\ \nu Z,\ l^\pm W^\mu.$$



$\chi\to\nu\to\nu$
$\chi\to h/\phi\to\nu$
Total ν
$E_\nu^2 \frac{dN_\nu^i}{dE_\nu}$ [GeV]
E_ν[GeV]
BPL
DM
Total
$E_\nu^2 \frac{d\Phi}{dE_\nu}$ [10^{-8}GeV/cm^2/s/sr]
E_ν[GeV]

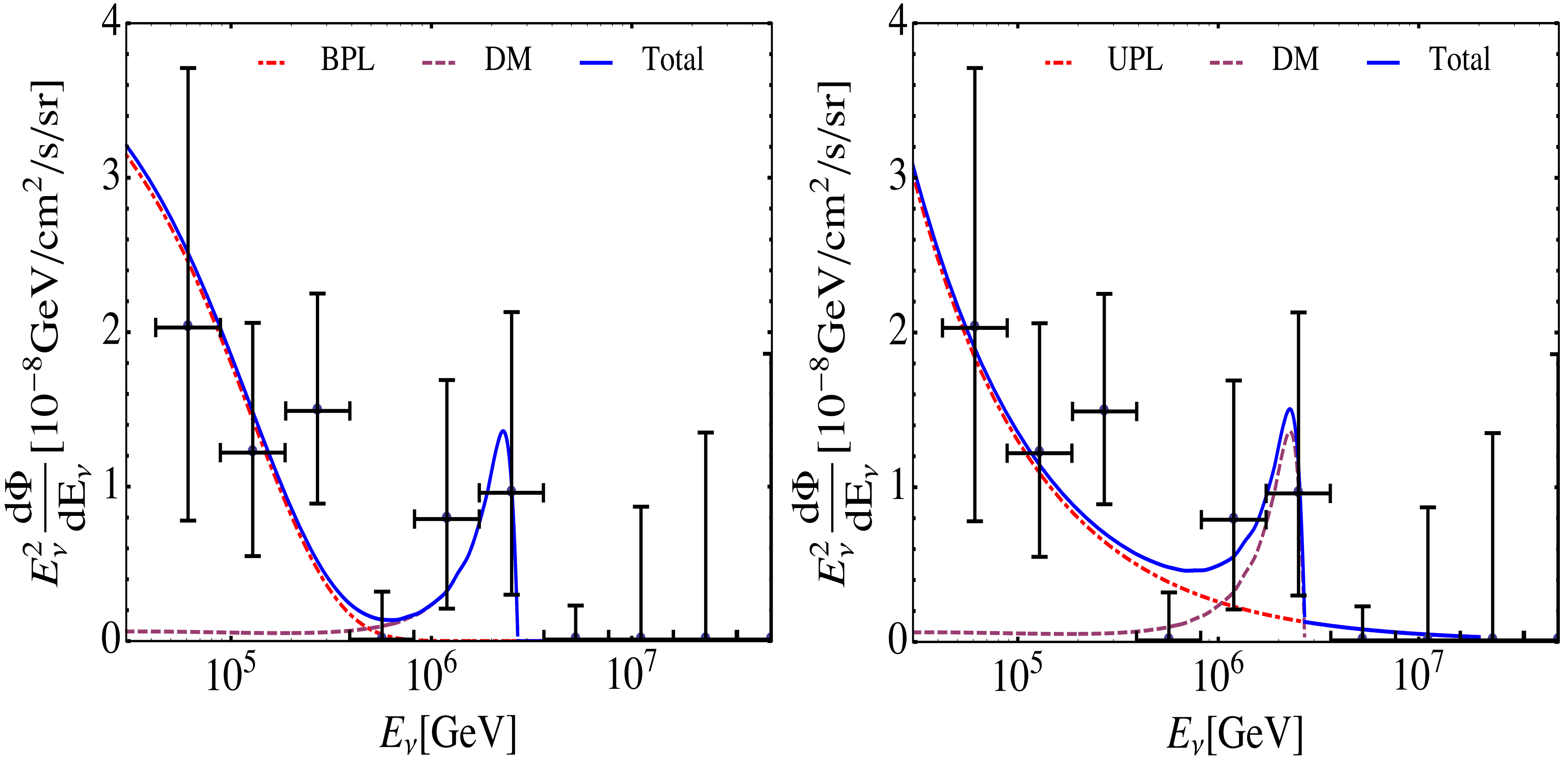


FIG. 2. Neutrino flux from DM χ's decay with $m_\chi \sim 5$PeV and lifetime $\tau_\chi = 1/\Gamma \sim 2 \times 10^{28}$s and IceCube Data [1]. The left (right) panel used a broken (unbroken) power law (BPL) for astrophysical neutrino flux with a red dot-dashed curve. DM's contributions and total flux are labeled with purple dashed and blue solid curves, respectively. See details in the text.

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$$\chi \to \nu h,\ \nu Z,\ l^{\pm} W^{\mu}.$$

In this scenario, the neutrino spectrum shows that there should be no gap between 400 TeV $\sim$ 1 PeV [26]. Our model predicts that the dominant decay mode are

$$\chi \to \phi/Z' + h + \nu,\ \phi/Z' + Z + \nu,\ \phi/Z' + W^{\pm} + l^{\mp},$$

which is a consequence of $U(1)_X$ dark gauge symmetry and the dark charge assignments of the dark Higgs and dark matter fermion χ. The neutrino spectra from primary χ decay and the secondary decays of h and ϕ have different shapes and could account for the possible gap. However, we should note that the current data can not favor one over another yet due to its low statistics. Also the neutrino flux in our model is softer than the one predicted in Ref. [23, 29], for example.

In Ref. [32], leptophilic three-body decay induced by dimension-six $\bar{L}_\alpha l_\beta \bar{L}_\gamma \chi$ was considered with global $U(1)$ or A_4 flavor symmetries. Besides the neutrino spectrum difference, our model involves an additional gauge boson which mediates the DM-nucleon scattering, and could be tested by DM direct searches.

Our scenario is also different from those in which DM decay is also responsible for the low-energy flux [24]. The DM lifetime in Ref. [24] should be around 2×10^{27}s, as mainly determined by the low energy part of events. This is partly due to the reason that the branching ratio into neutrinos and $b\bar{b}$ there should be about 10% and 90%, respectively, to account for the possible gap. On the other hand, in our scenario 1/2 of the decay channels have prompt neutrinos. Another main difference is that three-body-decay usually gives broader spectra at PeV range than two-body-decay considered in Ref. [24], but more data is required in order to discriminate this difference.

Relic density of χ

- $m_\chi \sim O(1-10)\ \mathrm{PeV}$: above the Unitarity bound for thermal DM
- Nonthermal productions (freeze-in), gravitational productions, etc..
- See the paper for an explicit example

γ ray flux from DM decay

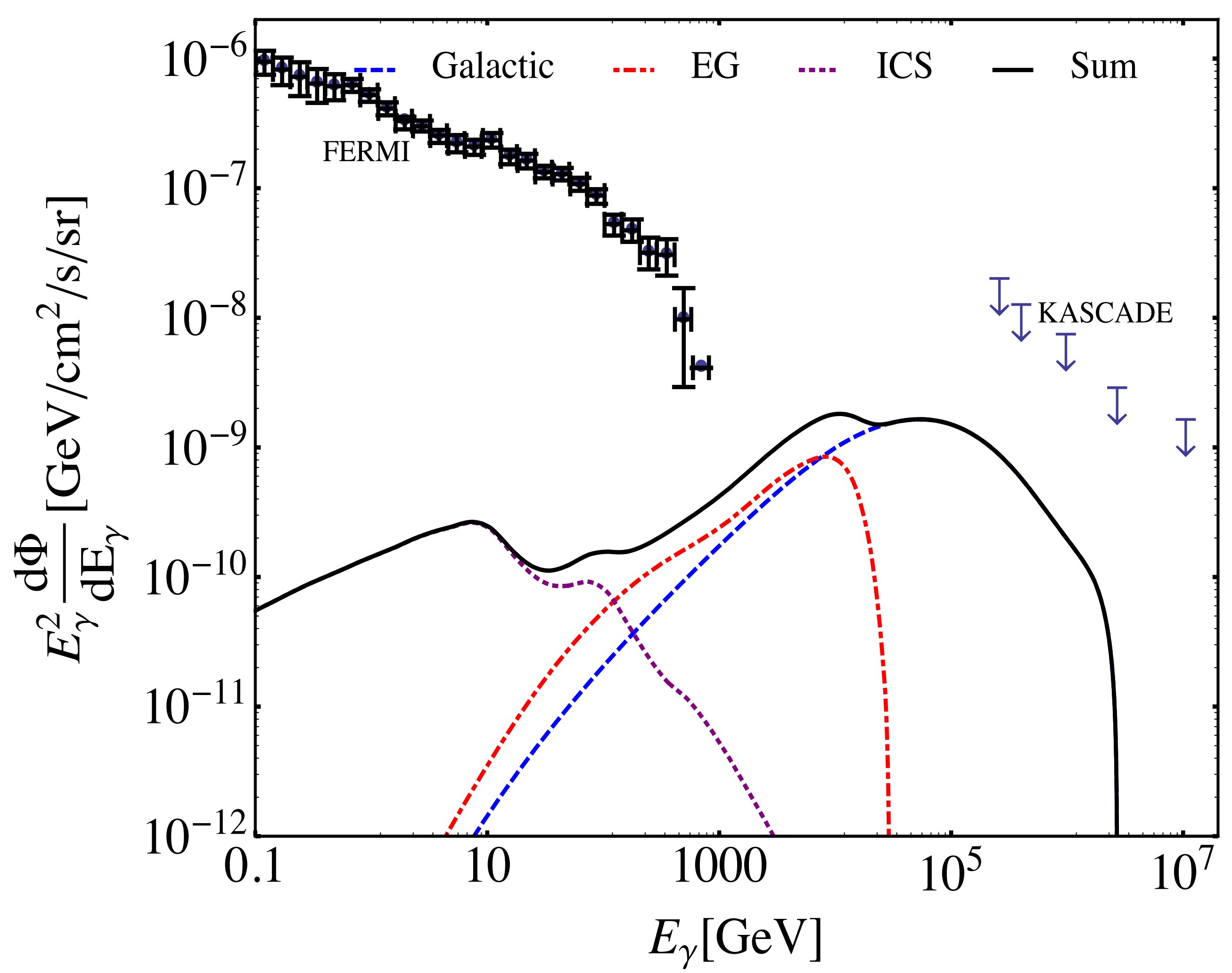

FIG. 5. The gamma-ray flux from DM decay with $m_\chi \sim 5$PeV and lifetime $\tau_\chi \sim 2 \times 10^{28}$s, confronted with constraints from Fermi-LAT [67] and KASCADE [68] data.

KM3NeT HE ν
(KM3-230213A)

2504.16040 [hep-ph]

With Sarif Khan, Jongkuk Kim

KM3-230213A

376 | Nature | Vol 638 | 13 February 2025

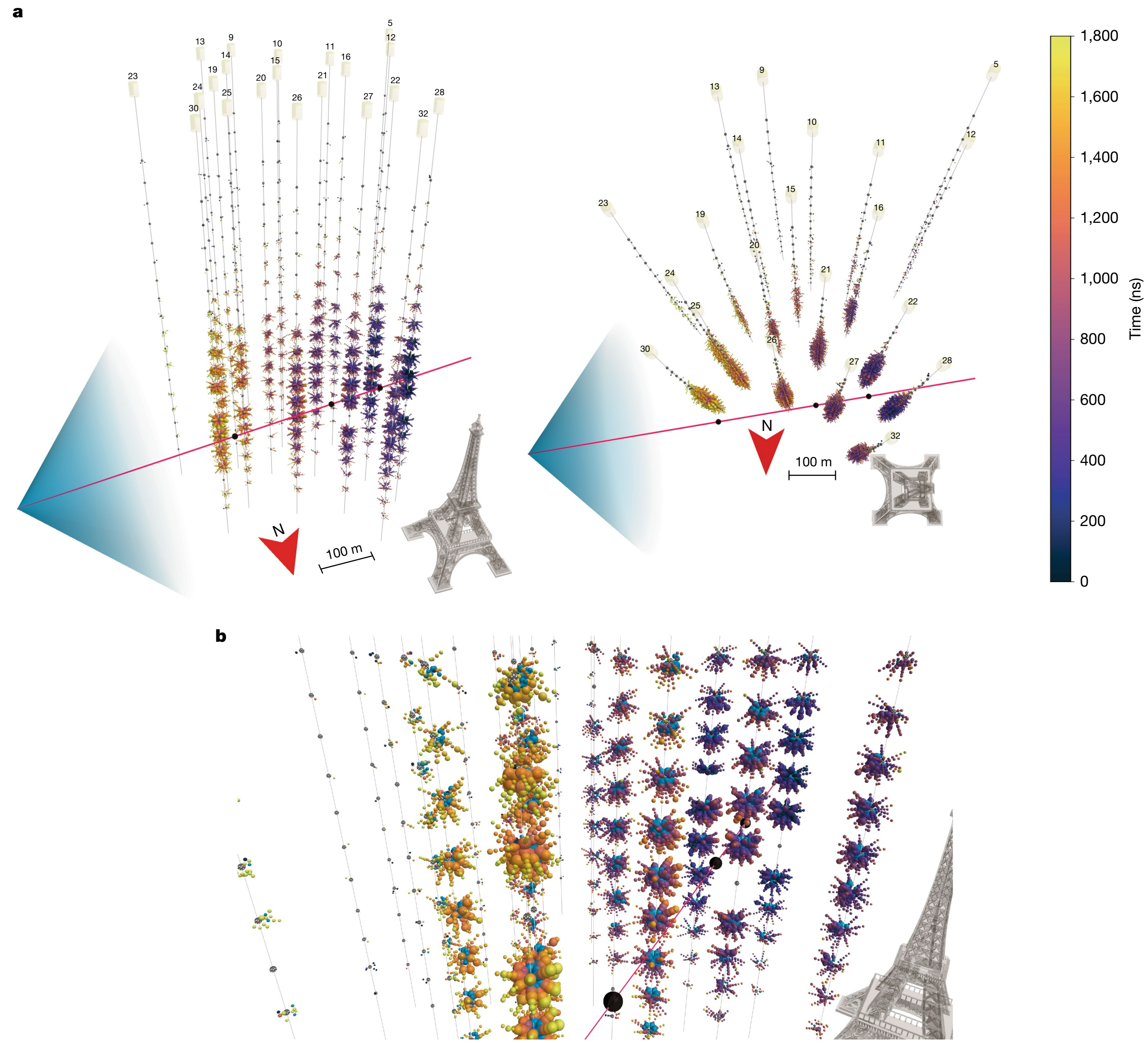

Fig. 1 | Views of the event. a, Side and top views of the event. The reconstructed trajectory of the muon is shown as a red line, along with an artist's representation of the Cherenkov light cone. The hits of individual PMTs are represented by spheres stacked along the direction of the PMT orientations. Only the first five hits on each PMT are shown. As indicated in the legend, the spheres are coloured according to the detection time relative to the first triggered hit. The size of the spheres is proportional to the number of photons detected by the corresponding PMT. The locations of the secondary cascades, discussed in the Supplementary Material, are indicated by the black spheres along the muon trajectory. The north direction is indicated by a red arrow. A 100-m scale and the Eiffel Tower (330 m height, 125 m base width) are shown for size comparison. **b**, Zoomed-in view of the optical modules that are close to the first two observed secondary showers in the event. Here light-blue spheres represent hits that arrive within −5 to 25 ns of the expected Cherenkov arrival times.

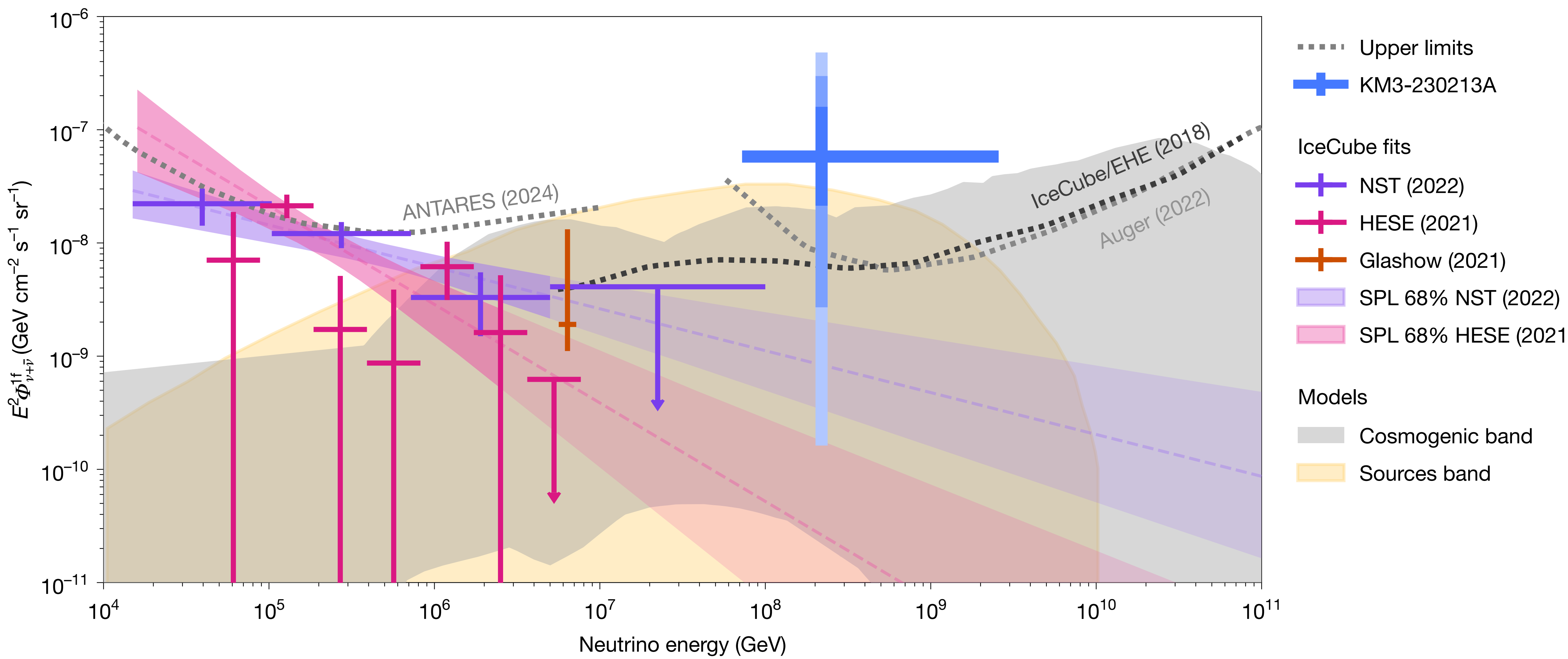

Fig. 5 | Comparison with models and earlier measurements. Shown is the energy-squared per-flavour astrophysical flux derived from the observation of KM3-230213A with measurements and theoretical predictions, assuming equipartition (ν_e:ν_μ:ν_τ = 1:1:1). The blue cross corresponds to the flux needed to achieve one expected event after the track selection described in the text, in the central 90% neutrino energy range associated with KM3-230213A, illustrated with the horizontal span; the vertical bars represent the 1σ, 2σ and 3σ Feldman–Cousins confidence intervals on this estimate. The purple and pink shaded regions represent the 68% confidence level contours of the IceCube single-power-law (SPL) fits (Northern Sky Tracks, NST[5]) and High-Energy Starting Events (HESE)[7], respectively: the darker-shaded regions are the respective 90% central energy range at the best fit (dashed line), whereas the lighter-shaded regions are extrapolations to higher energies. The purple and pink crosses are the piece-wise fit from the same analyses, whereas the orange cross corresponds to the IceCube Glashow resonance event[11]. The dotted lines are upper limits from ANTARES (95% confidence level[47]), Pierre Auger (90% confidence level, for an E^{-2} neutrino spectrum[28], corrected to convert from limits in half-decade to one-decade bins) and IceCube (90% confidence level, estimated assuming an E^{-1} neutrino spectrum in sliding one-decade bins[27]). The grey-shaded band comprises a variety of cosmogenic neutrino expectations following several models of cosmic-ray acceleration and propagation, whereas the yellow-shaded band comprises several scenarios of diffuse transient and variable extragalactic sources, both reported in the Supplementary Material.

KM3-230213A

376 | Nature | Vol 638 | 13 February 2025

- $E_\nu = 220^{+570}_{-110}$ PeV! Wow!
- What is the origin of this event?
- Lorentz violation, BSM, etc..

We shall propose Heavy Dirac fermion DM decay with the RHN portal for this

Model

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\bar{N}i\partial\!\!\!/ N - \left(\frac{1}{2}m_N\bar{N}^cN + y\bar{L}\widetilde{H}N + \text{h.c.}\right) - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{1}{2}\sin\epsilon X_{\mu\nu}F_Y^{\mu\nu}$$
$$+D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi, H) + \bar{\chi}\left(i\not{D} - m_\chi\right)\chi - (\kappa\bar{\chi}\Phi N + \text{h.c.})\,, \qquad (2.1)$$

- Dark U(1) gauge symmetry with $(Q_\chi, Q_\Phi) = (1{,}1)$
- Integrate out the RHN when $m_N \gg m_\chi$, obtaining

$$\frac{y\kappa}{m_N}\bar{\chi}\Phi H^\dagger L + h.c.$$

$$\frac{y\kappa}{2}\frac{v_\phi v_H}{m_N}\bar{\chi}\nu,\ \ \frac{y\kappa}{2}\frac{v_\phi}{m_N}\bar{\chi}h\nu,\ \ \frac{y\kappa}{2}\frac{v_H}{m_N}\bar{\chi}\phi\nu,\ \ \frac{y\kappa}{2}\frac{1}{m_N}\bar{\chi}\phi h\nu.$$

$\chi \to Z'\nu, Z\nu, W^\mp l^\pm,$ W/ Br $\sim v_H^2 : v_\phi^2 : 2v_\phi^2.$

Different HE ν peaks

- $\chi \to \phi\nu, Z'\nu, h\nu, Z\nu, etc.$
- $E_\nu = (M_\chi^2 - m_\phi^2)/2M_\chi$ for $\chi \to \phi\nu$: We have E_ν peaks for different $m_\phi, m_{Z'}, etc.$ Note that $m_h, m_Z \sim 0$
- $M_\chi \sim O(500) TeV$
- Fixed relative Br's $\propto v_h^2 : v_h^2 : v_\phi^2 : v_\phi^2$
- Need $v_\phi \gg m_\chi$: to have the SM 2-body decays be dominant → only single peak in the neutrino energy spectrum in practice

Results

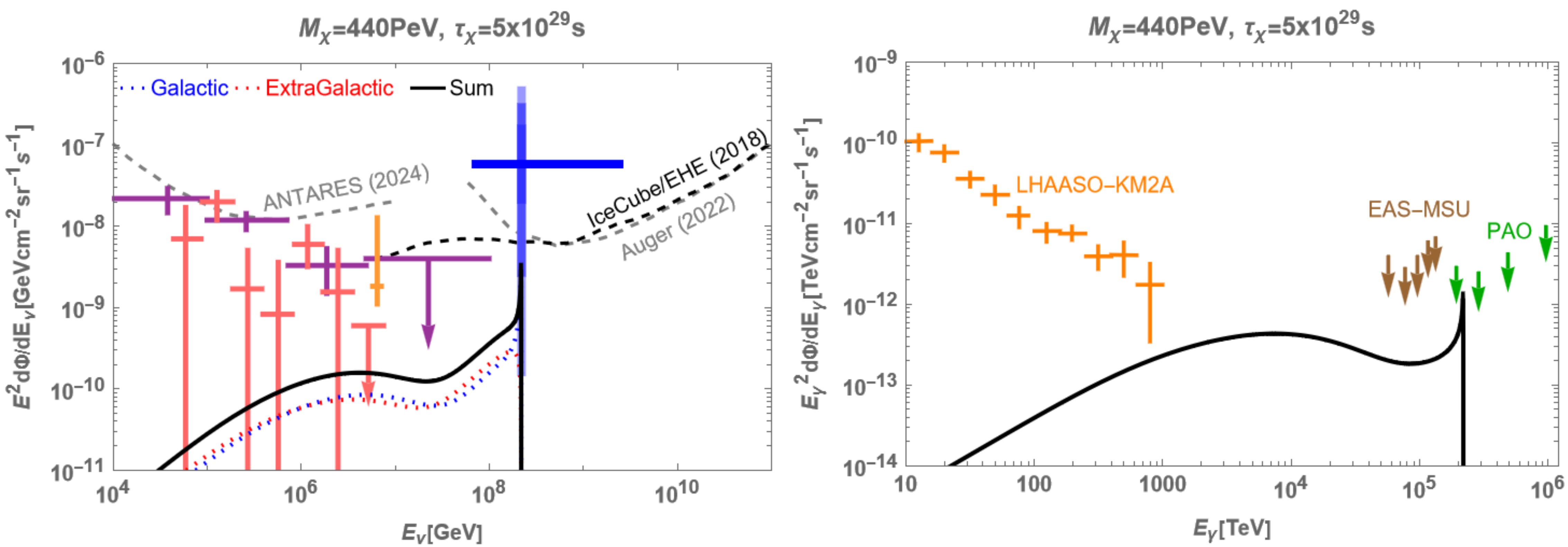

Figure 1. Neutrino (left-panel) and Gamma-ray (right-panel) spectra from DM χ decay with $M_\chi = 440$PeV and lifetime $\tau_\chi = 1/\Gamma = 5 \times 10^{29}$s. In the left panel, bounds come from IceCube [43, 44]. Blue cross corresponds to KM3NeT with 3σ C.L [1]. It presents the galactic (blue dotted curve) and extragalactic (red dotted curve) neutrino flux. In the right panel, orange crosses correspond to gamma-ray constraints from LHAASO-KM2A [45] whereas EAS-MSU [46] and PAO [47] limits are shown in brown and green arrows, respectively.

GW production from string

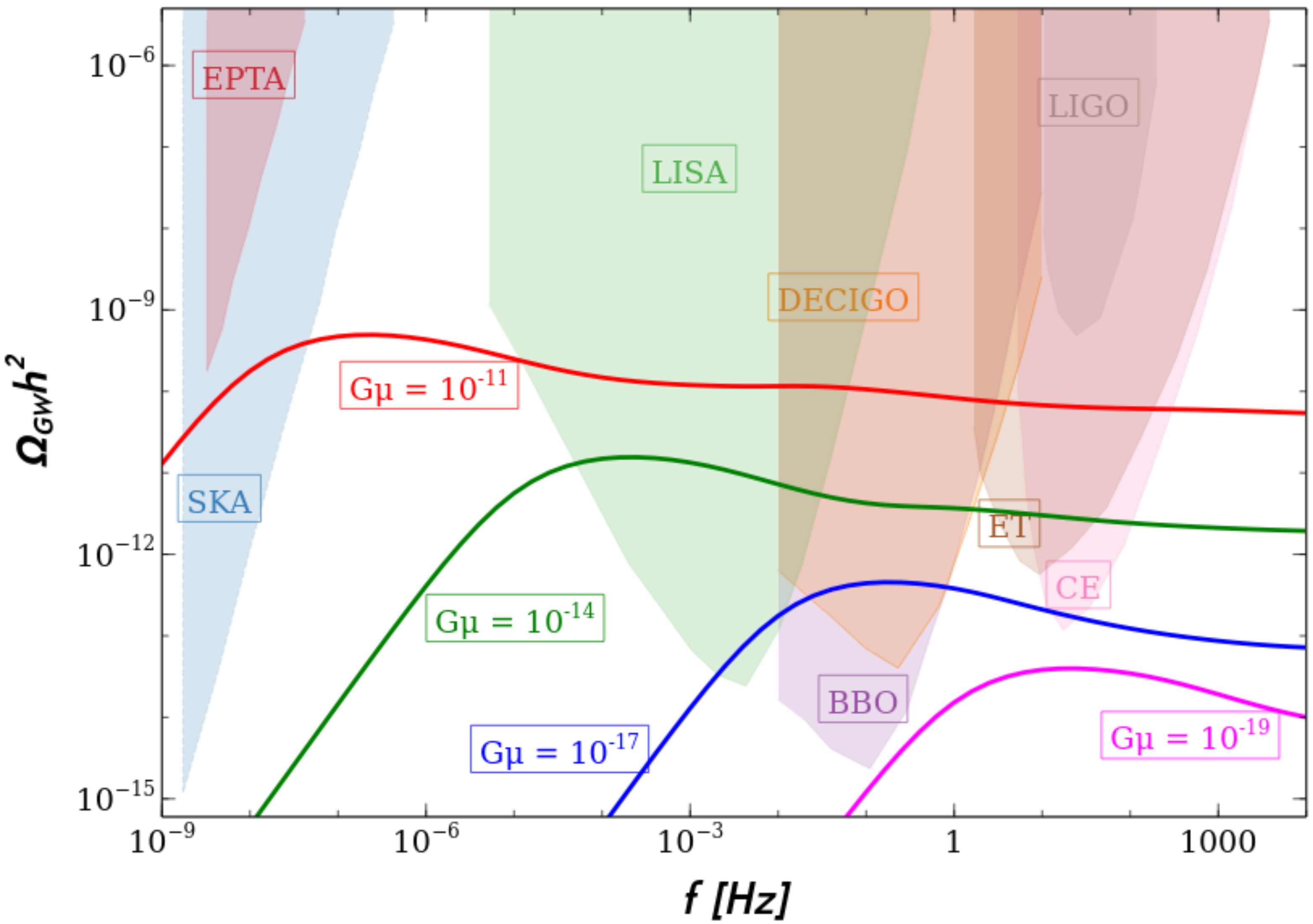

Figure 2. Variation of relic GW density with frequency for different values of string tension. Different colours represent the sensitivity prospects of various future GW detectors. EPTA data excludes cosmic string tensions $G\mu > 2 \times 10^{-11}$.

$\Omega_\chi h^2$ by UV freeze-in

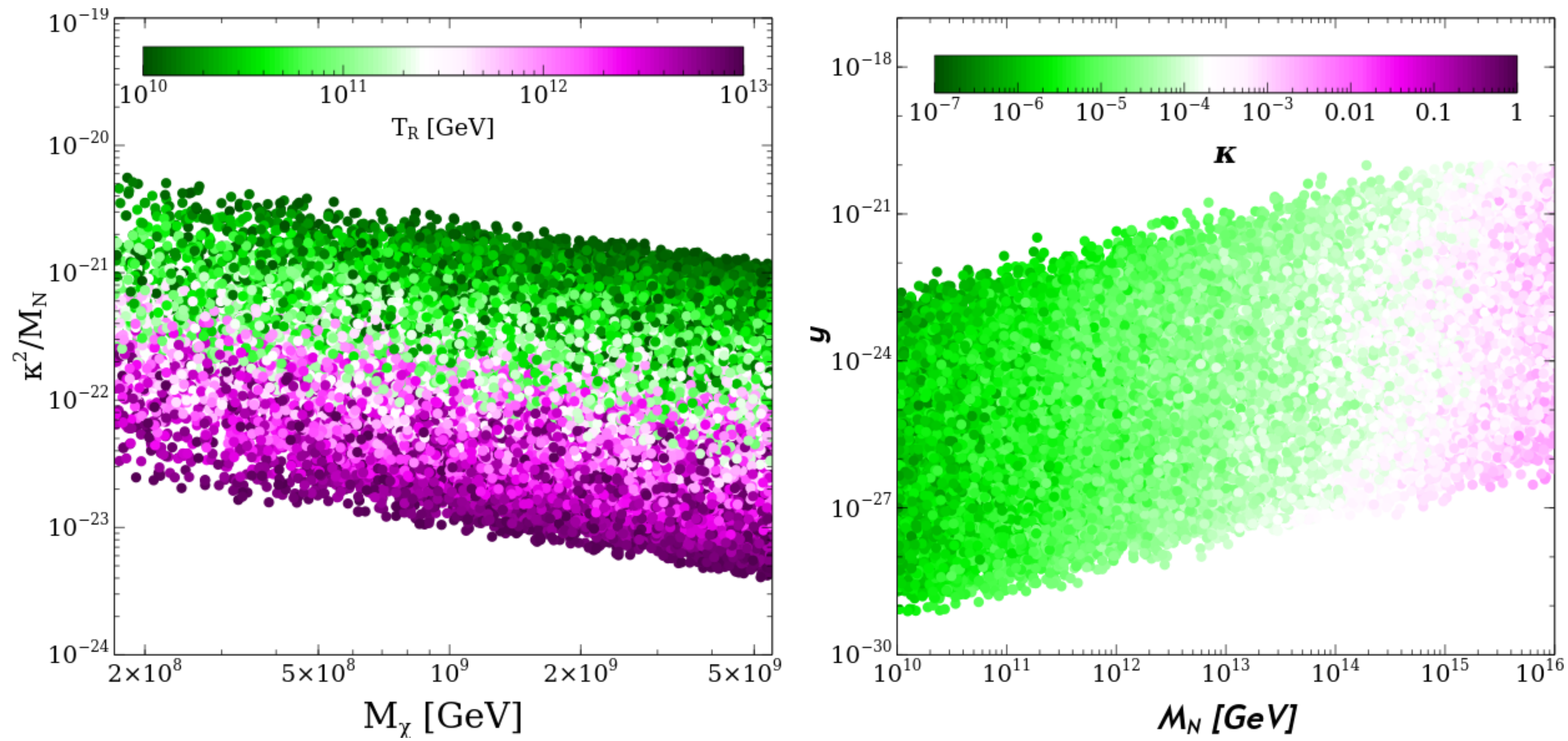

Figure 3. In the left panel (LP), we show the scatter plot in the $(M_\chi,\ \frac{\kappa^2}{M_N})$ plane, whereas the right panel (RP) displays the scatter plot in the $(M_N,\ y)$ plane. The color gradient in the LP represents different values of the reheating temperature T_R, while in the RP, it corresponds to different values of the coupling κ. The other parameters, which are not shown, have been varied as listed in Eq.(5.10).

$$\sigma_{\phi\phi\to\chi\bar{\chi}} = \frac{1}{8\pi}\left(\frac{2\kappa^2}{M_N}\right)^2$$

More plots

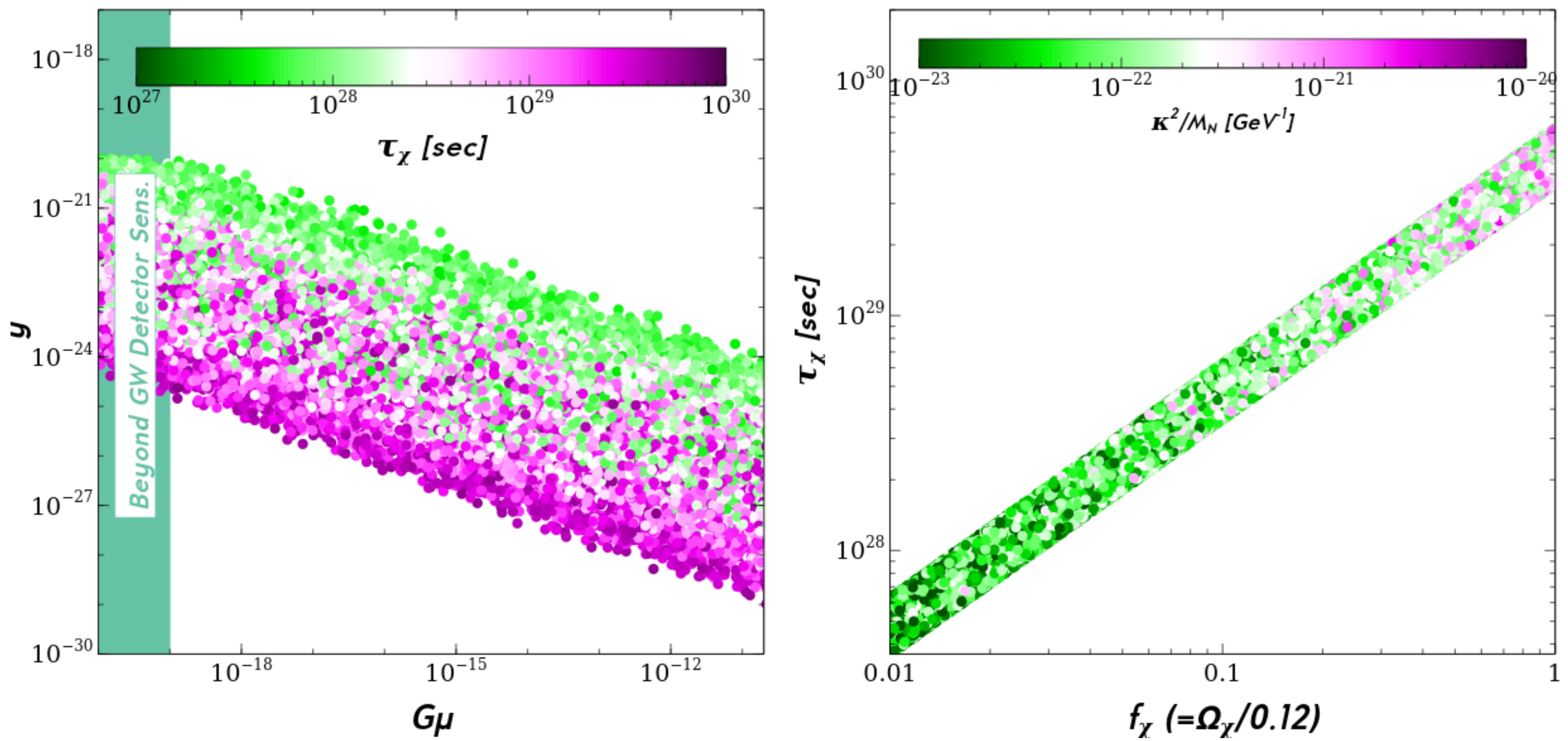

Figure 4. The LP and RP show scatter plots in the $(G\mu,\ y)$ and $(f_\chi,\ \tau_\chi)$ planes, respectively. In the LP, the color gradient represents different values of τ_χ, while in the RP, it corresponds to values of κ^2/M_N.

$T_R \sim 10^{10}$ GeV, $\kappa \sim 10^{-4}$, $M_N \sim 10^{12}$, $v_\phi = 10^{13}$ GeV and $y \sim 10^{-20}$.

Conclusion

- Heavy spin-1/2 decaying DM with RHN portals can accommodate AMS02/PAMELA positron excess, IceCUBE, and KM3-230213A HE neutrino events thanks to 2-body or 3-body decays involving (dark) Higgs boson and/or dark photon, depending on $v_\phi >=< m_\chi$

- For KM3, assuming $v_\phi \gg m_\chi$, the dominant decay channels are $\chi \to h\nu, Z\nu, W^\pm l^\mp$, all in the SM particles

- Interesting GW from string networks with $10^{-19} < G\mu < 10^{-11}$, $(10^{10}\ \mathrm{GeV} < v_\phi < 10^{14}\ \mathrm{GeV})$, which is in the sensitivity ranges of current/future GW detectors

- It is important to impose dark gauge symmetry and dark Higgs boson for correct phenomenology