KM3-230213A UHE Neutrino event and GW

Pyungwon Ko (KIAS)

Scalars 2025, Sep 22 -25 (2025)

Univ of Warsaw

Dark matter model buildings along the SM construction and KM3 UHE ν Event

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Contents

- Basic properties of DM

- DM model buildings along the SM construction

- Some examples: $U(1)_D \to Z_2$; VDM w/ HP and GC γ ray; $SU(3)_D \to SU(2)_D$; Dark Monopole, VDM and DR; DQCD (WIMP & SIMP), Thermal WIMP in $U(1)_{L_\mu - L_\tau}$ models; Belle II excess in $B^+ \to K^+ \nu \bar{\nu}$; AMS02, KM3NeT; two-component WIMP model free from DD constraints; Higgs-portal assisted Higgs inflation; a simple example of chiral dark sector, etc..

- Summary

Based on

- Reviews: JKPS, 72 (2018) 449-465;
- My talk will be mostly about “MODEL BUILDING”, and not on the detailed DM phenomenology
- Based on a series of works with Seungwon Baek, Wanil Park, Myeonghun Park, Hyun Min Lee, Taeil Hur, Soomin Choi, Alexander Natale, Eibun Senaha, Dongwon Jung, Jinmian Li, Jongkuk Kim, Shu-Yu Ho, Hiroshi Yokoya, Yong Tang, Shu-Yu Ho, Chih-Ting Lu, Yi-Lei Tang, etc.
- Main message: Phenomenology in the presence of massive dark photon can change drastically, w/o and w/ dark Higgs

- 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

General Comments on SM Construction

Current Status of SM

- Only Higgs (~SM) and Nothing Else so far at the LHC
- Yukawa & Higgs self couplings to be measured and tested
- Nature is described by Quantum Gauge Theories
- Unitarity and Gauge Invariance played key roles in development of the SM

Building Blocks of SM

- Lorentz/Poincare Symmetry
- Local Gauge Symmetry : Gauge Group + Matter Representations from Exp's
- Higgs mechanism for masses of weak gauge bosons and SM chiral fermions
- These principles lead to unsurpassed success of the SM in particle physics

Accidental Sym's of SM

- Renormalizable parts of the SM Lagrangian conserve baryon #, lepton # : broken only by dim-6 and dim-5 op's $\longrightarrow$"longevity of proton" and "lightness of neutrinos" becoming Natural Consequences of the SM (with conserved color in QCD)

- QCD and QED at low energy conserve P and C, and flavors

- In retrospect, it is strange that P and C are good symmetries of QCD and QED at low energy, since the LH and the RH fermions in the SM are independent objects

- What is the correct question? "P and C to be conserved or not ?" Or "LR sym or not ?"

How to do Model Building

- Specify local gauge sym, matter contents and their representations w/o any global sym [all the global symmetries are assumed to be accidental like the SM]
- Write down all the operators upto dim-4
- Check anomaly cancellation [Kaon physics & GIM]
- Consider accidental global symmetries
- Look for nonrenormalizable operators that break/conserve the accidental symmetries of the model

- If there are spin-1 particles, extra care should be paid : need an agency which provides mass to the spin-1 object
- Check if you can write Yukawa couplings to the observed fermion
- You may have to introduce additional Higgs doublets with new gauge interaction if you consider new chiral gauge symmetry (Ko, Omura, Yu on chiral U(1)' model for top FB asymmetry)
- Impose various constraints and study phenomenology

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

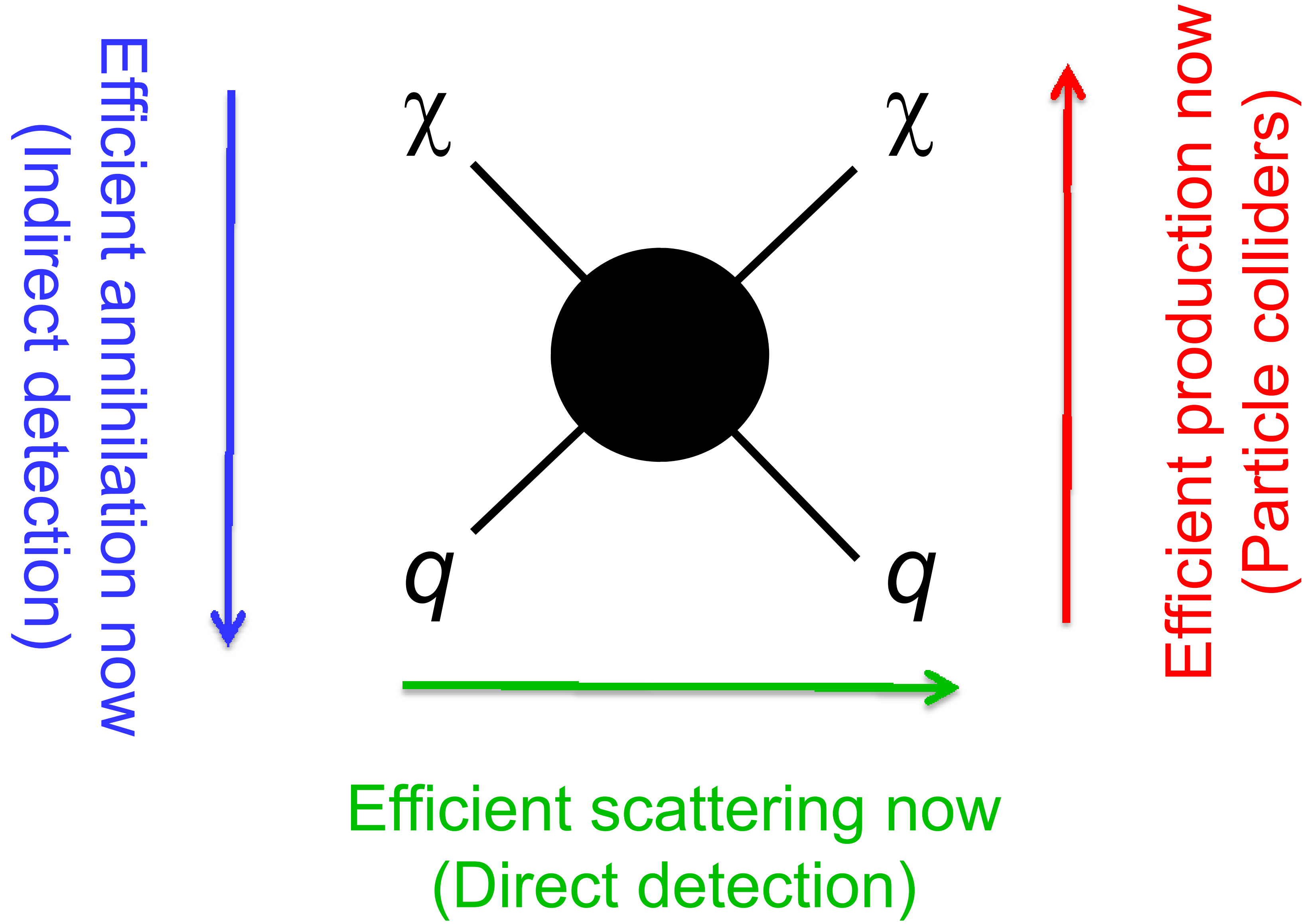
- Dark sector with (excited) dark matter, dark radiation and force mediators might have the same structure as the SM
- "(Chiral) dark gauge theories without any global sym"
- Origin of DM stability/longevity from dark gauge sym, and not from dark global symmetries, as in the SM
- Just like the SM (conservative)

DM Models in literature

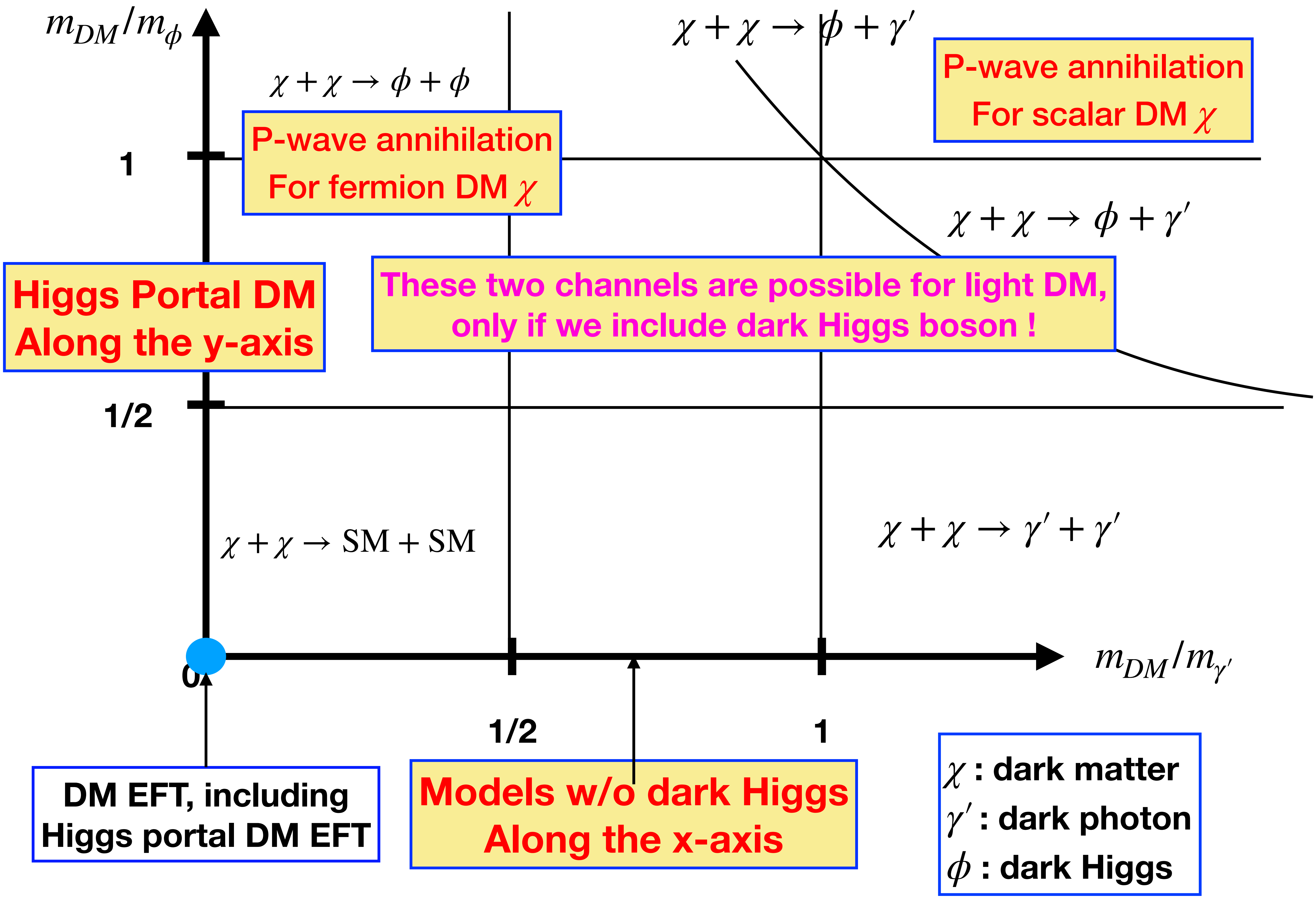
- Top-Down: LSP in SUSY models, LKP in KK models, etc.
- Bottom-Up: ad hoc dark Z_2, Z_3 parities
- Massive dark photon with Stueckelberg mechanism (w/o dark Higgs boson): sometimes could be problematic [see arXiv:2204.04889, for example]
- DM complementarity can be misleading when applied to DM effective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

Crossing & WIMP detection

Correct relic density → Efficient annihilation then



Dark sector parameter space for a fixed m_{DM}



Basic properties of DM

- DM: stable or long-lived ($\tau_{\rm DM} \gg \tau_{\rm universe}$): some exact or accidental 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 ,…) [not in this talk]

In QFT

- DM could be absolutely stable due to unbroken local gauge symmetry (DM with local $U(1)_D \to Z_2, Z_3,$ $SU(3)_D \to SU(2)_D$, etc.) or topology (hidden sector monopole + vector DM + dark radiation)

- Longevity of DM could be due to some accidental symmetries (Strongly interacting hidden sector (DQCD), dark pions and dark baryons : Ko et al (2007))

- Kinematically long-lived if DM is very light (axion, sterile ν_s , etc..) [not covered in this talk]

Dark Gauge Symmetry:
DM Stability/Longevity

Z2 real scalar DM

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

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

- Global Z2 could be broken by gravity effects (higher dim operators)
- e.g. consider Z2 breaking dim-5 op : $\frac{1}{M_{\text{Planck}}} S O_{\text{SM}}^{(4)}$
- 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 Z2 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:

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

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

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

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

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)

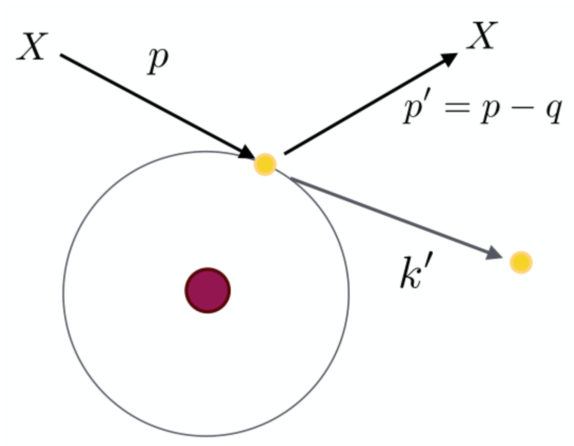
XENON1T Excess

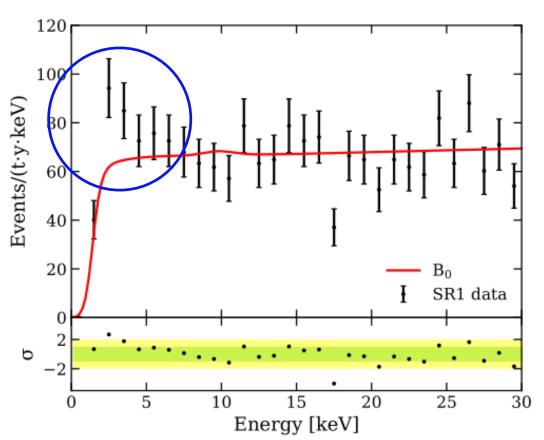
(Scalar XDM, Fermion XDM)

XENON1T Excess

- Excess between 1-7 keV
  - Expectated : 232 ± 15 , Observed : 285
  - Deviation ~ 3.5 σ
- Tritium contamination
  - Long half lifetime (12.3 years)
  - Abundant in atmosphere and cosmogenically produced in Xenon
- Solar axion
  - Produced in the Sun
  - Favored over bkgd @ 3.5 σ
- Neutrino magnetic dipole moment
  - Favored @ 3.2 σ

Electron recoil

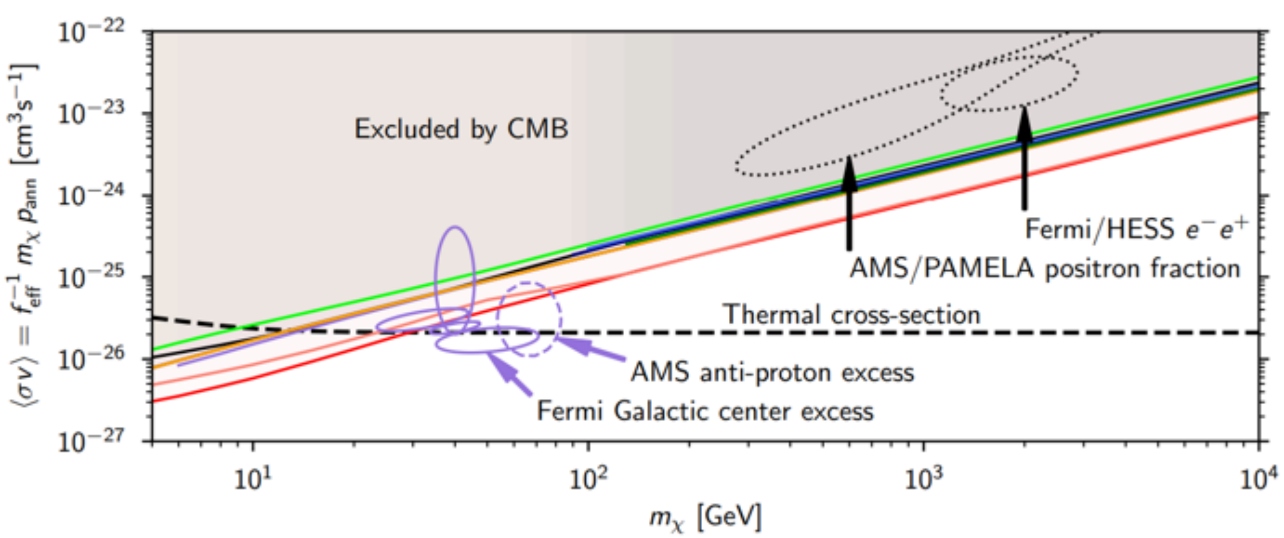


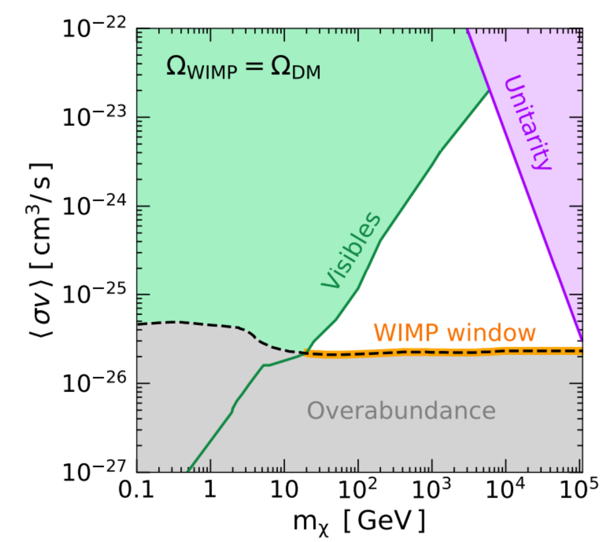


DD/CMB Constraints

- To evade stringent bounds from direct detection expt's : sub GeV DM
- CMB bound excludes thermal DM freeze-out determined by S-wave annihilation : DM annihiliation should be mainly in P-wave $\langle \sigma v \rangle \sim a + bv^2$

Planck 2018
R.K.Leane 35 al, PRD2018





Exothermic DM

- Inelastic exothermic scattering of XDM
- $XDM + e_{\text{atomic}} \rightarrow DM + e_{\text{free}}$ by dark photon exchange + kinetic mixing
- Excess is determined by $E_R \sim \delta = m_{XDM} - m_{DM}$
- Most works are based on effective/toy models where δ is put in by hand, or ignored dark Higgs
- dim-2 op for scalar DM and dim-3 op for fermion DM : soft and explicit breaking of local gauge symmetry), and include massive dark photon as well → theoretically inconsistent !

Z_2 DM models with dark Higgs

- We solve this inconsistency and unitarity issue with Krauss-Wilczek mechanism

- By introducing a dark Higgs, we have many advantages:

  - Dark photon gets massive

  - Mass gap δ is generated by dark Higgs mechanism

  - We can have DM pair annihilation in P-wave involving dark Higgs in the final states, unlike in other works

Usual Approaches

For example, arXiv:2006.11938

$$V(\phi) = m^2|\phi|^2 + \Delta^2 \left(\phi^2 + \phi^{*2}\right), \qquad (1)$$

This term is problematic

$$\mathcal{L} = g_D A'^{\mu} \left(\chi_1 \partial_\mu \chi_2 - \chi_2 \partial_\mu \chi_1\right) + \epsilon e A'_\mu J^\mu_{\mathrm{EM}},$$

Similarly for the fermion DM case

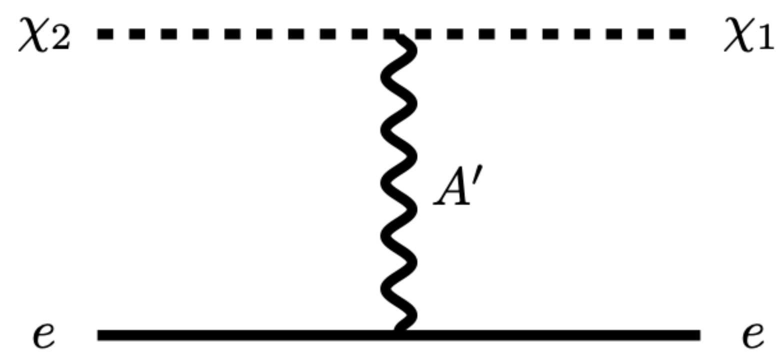


FIG. 1. Inelastic scattering of the heavier DM particle χ_2 off the electron e into the lighter particle χ_1, mediated by the dark photon A'.

- The model is not mathematically consistent, since there is no conserved current a dark photon can couple to in the massless limit
- The second term with Δ^2 breaks $U(1)_X$ explicitly, although softly

Relic Density from

$$XX^{\dagger} \rightarrow Z^{'\,*} \rightarrow f\bar{f}$$

(P-wave annihilation)

For example, arXiv:2006.11938

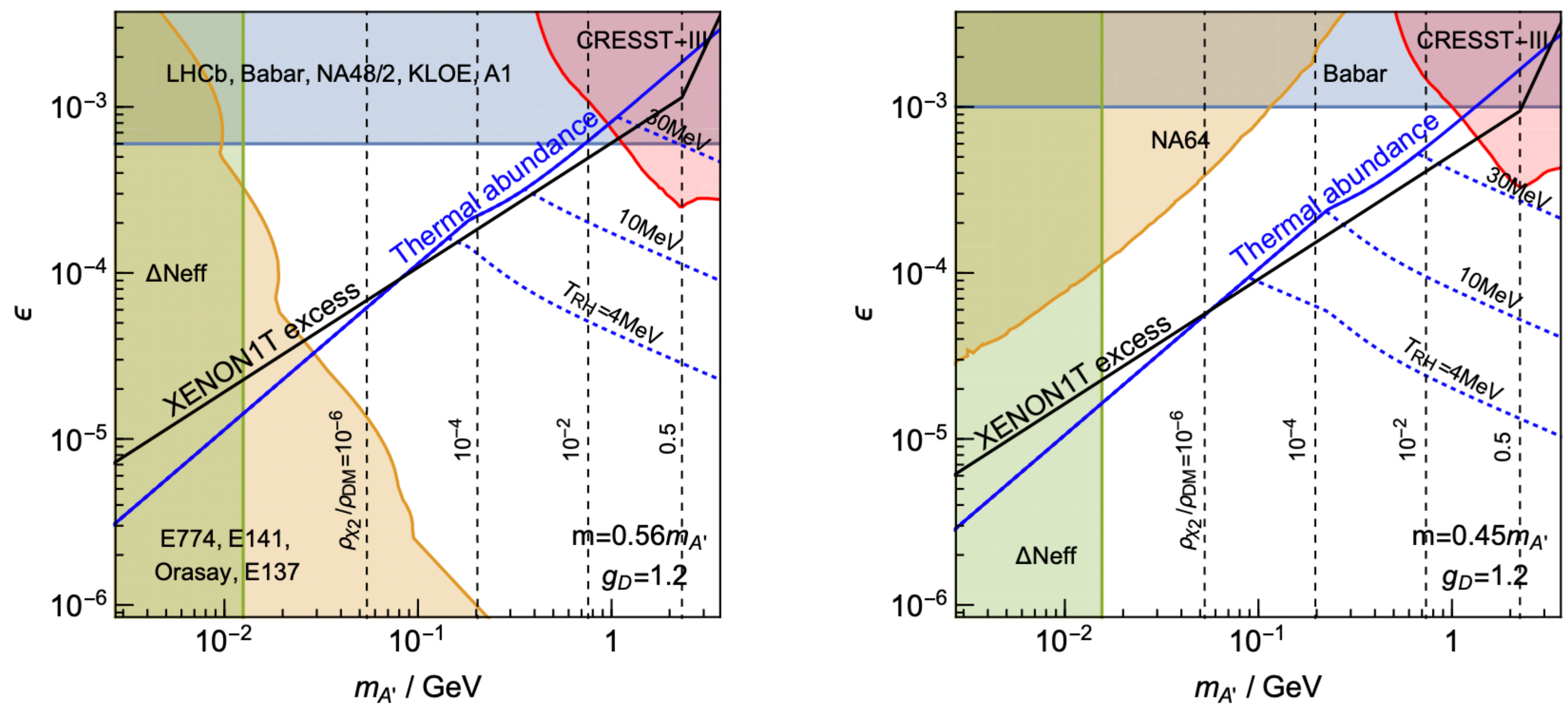


FIG. 4. The required value of ϵ to explain the observed excess of events at XENON1T in terms of the dark photon mass $m_{A'}$ (black solid lines). The left and right panels correspond to the cases of $m > m_{A'}/2$ and $m < m_{A'}/2$ respectively. We assume $g_D = 1.2$ in both cases. The blue lines denote the required value of ϵ to obtain the observed DM abundance by the thermal freeze-out process, discussed in Sec. IV. The solid lines correspond to the case without any entropy production. The dashed lines assume freeze-out during a matter dominated era and the subsequent reheating at $T_{\rm RH}$, which suppresses the DM abundance by a factor of $(T_{\rm RH}/T_{\rm FO})^3$. The black dashed lines denote the mass density of χ_2 normalized by the total DM density. The shaded regions show the constraints from dark radiation and various searches for the dark photon A' which are discussed in Sec. V.

Scalar XDM (X_R & X_I)

Field	ϕ	X	χ
U(1) charge	2	1	1

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} - \frac{1}{2}\sin\epsilon\hat{X}_{\mu\nu}\hat{B}^{\mu\nu} + D^\mu\phi^\dagger D_\mu\phi + D^\mu X^\dagger D_\mu X - m_X^2 X^\dagger X + m_\phi^2\phi^\dagger\phi$$
$$-\lambda_\phi\left(\phi^\dagger\phi\right)^2 - \lambda_X\left(X^\dagger X\right)^2 - \lambda_{\phi X}X^\dagger X\phi^\dagger\phi - \lambda_{\phi H}\phi^\dagger\phi H^\dagger H - \lambda_{HX}X^\dagger X H^\dagger H$$
$$-\mu\left(X^2\phi^\dagger + H.c.\right), \quad (1)$$

$$X = \frac{1}{\sqrt{2}}(X_R + iX_I),$$

$$H = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v_H + h_H) \end{pmatrix}, \quad \phi = \frac{1}{\sqrt{2}}(v_\phi + h_\phi),$$

$$\mathcal{L} \supset \epsilon g_X s_W Z^\mu(X_R\partial_\mu X_I - X_I\partial_\mu X_R) - \frac{g_Z}{2}Z_\mu\overline{\nu}_L\gamma^\mu\nu_L.$$

$$\mathcal{L} \supset g_X Z'^\mu(X_R\partial_\mu X_I - X_I\partial_\mu X_R) - \epsilon\, e c_W Z'_\mu\overline{e}\gamma^\mu e,$$

$U(1) \to Z_2$ by $v_\phi \neq 0 : X \to -X$

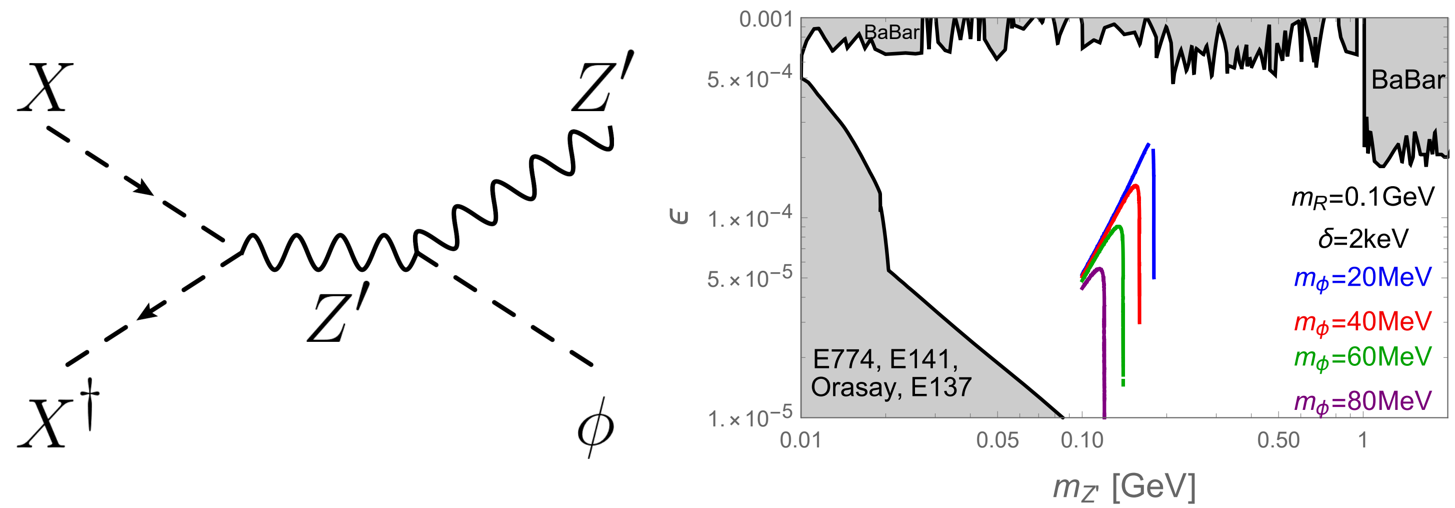


FIG. 1: (*left*) Feynman diagrams relevant for thermal relic density of DM: $XX^\dagger \to Z'\phi$ and (*right*) the region in the $(m_{Z'}, \epsilon)$ plane that is allowed for the XENON1T electron recoil excess and the correct thermal relic density for scalar DM case for $\delta = 2$ keV : (a) $m_{\rm DM} = 0.1$ GeV. Different colors represents $m_\phi = 20, 40, 60, 80$ MeV. The gray areas are excluded by various experiments, from BaBar [61], E774 [62], E141 [63], Orasay [64], and E137 [65], assuming $Z' \to X_R X_I$ is kinematically forbidden.

P-wave annihilation x-sections

Scalar DM : $XX^\dagger \to Z'^* \to Z'\phi$

$$\sigma v \simeq \frac{g_X^4 v^2}{384\pi\, m_X^4 (4m_X^2 - m_{Z'}^2)^2} \left(16 m_X^4 + m_{Z'}^4 + m_\phi^4 + 40 m_X^2 m_{Z'}^2 - 8 m_X^2 m_\phi^2 - 2 m_{Z'}^2 m_\phi^2\right)$$
$$\times \left[\left\{4m_X^2 - (m_{Z'} + m_\phi)^2\right\} \left\{4m_X^2 - (m_{Z'} - m_\phi)^2\right\} \right]^{1/2} + \mathcal{O}(v^4), \quad (10)$$

Fermion XDM (χ_R & χ_I)

$$\mathcal{L} = -\frac{1}{4}\hat{X}^{\mu\nu}\hat{X}_{\mu\nu} - \frac{1}{2}\sin\epsilon\hat{X}_{\mu\nu}B^{\mu\nu} + \overline{\chi}\left(i\not{D} - m_\chi\right)\chi + D_\mu\phi^\dagger D^\mu\phi$$
$$- \mu^2\phi^\dagger\phi - \lambda_\phi|\phi|^4 - \frac{1}{\sqrt{2}}\left(y\phi^\dagger\overline{\chi^C}\chi + \text{h.c.}\right) - \lambda_{\phi H}\phi^\dagger\phi H^\dagger H$$

$$\chi = \frac{1}{\sqrt{2}}(\chi_R + i\chi_I),$$
$$\chi^c = \frac{1}{\sqrt{2}}(\chi_R - i\chi_I),$$
$$\chi_R^c = \chi_R, \quad \chi_I^c = \chi_I,$$

$$\mathcal{L} = \frac{1}{2}\sum_{i=R,I}\overline{\chi_i}\left(i\not{\partial} - m_i\right)\chi_i - i\frac{g_X}{2}(Z'_\mu + \epsilon s_W Z_\mu)\left(\overline{\chi_R}\gamma^\mu\chi_I - \overline{\chi_I}\gamma^\mu\chi_R\right)$$
$$- \frac{1}{2}yh_\phi\left(\overline{\chi_R}\chi_R - \overline{\chi_I}\chi_I\right),$$

$U(1) \to Z_2$ by $v_\phi \neq 0 : \chi \to -\chi$

Without dark Higgs

P.Ko, T.Matsui, Yi-Lei Tang, arXiv:1910.04311, Appendix A

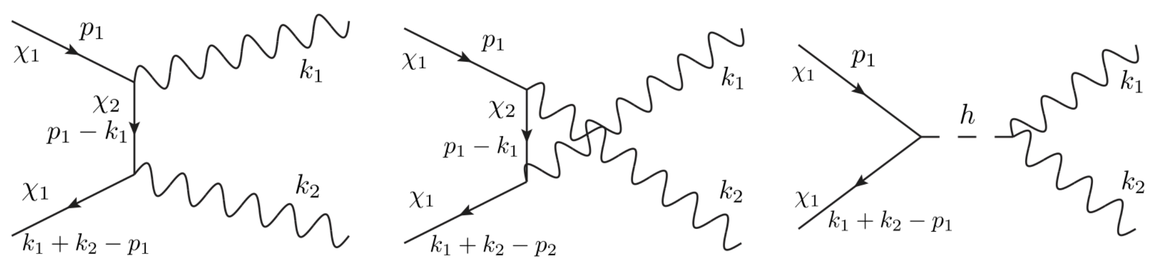


Figure 9: $\chi_1\chi_1 \to \gamma'\gamma'$ diagrams. Compared with the Higgsless soft-breaking model, the third diagram arises in our model

- Only the first two diagrams if the mass gap is given by hand
- The third diagram if the mass gap is generated by dark Higgs mechanism
- Without the last diagram, the amplitude violates unitarity at large $E_{\gamma'}$, or in the limit $m_{\gamma'} \to 0$

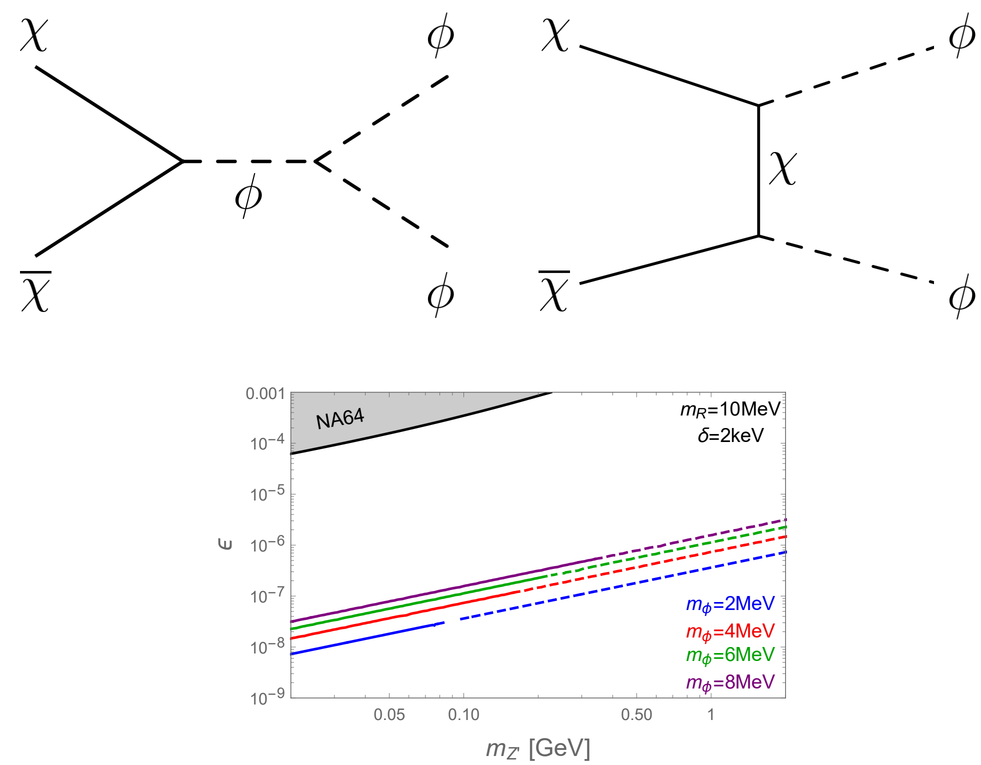


FIG. 2: (*top*) Feyman diagrams for $\chi\bar{\chi} \to \phi\phi$. (*bottom*) the region in the $(m_{Z'}, \epsilon)$ plane that is allowed for the XENON1T electron recoil excess and the correct thermal relic density for fermion DM case for $\delta = 2$ keV and the fermion DM mass to be $m_R = 10$ MeV. Different colors represents $m_\phi = 2, 4, 6, 8$ MeV. The gray areas are excluded by various experiments, assuming $Z' \to \chi_R \chi_I$ is kinematically allowed, and the experimental constraint is weaker in the ϵ we are interested in, compared with the scalar DM case in Fig. 1 (right). We also show the current experimental bounds by NA64 [66].

P-wave annihilation x-sections

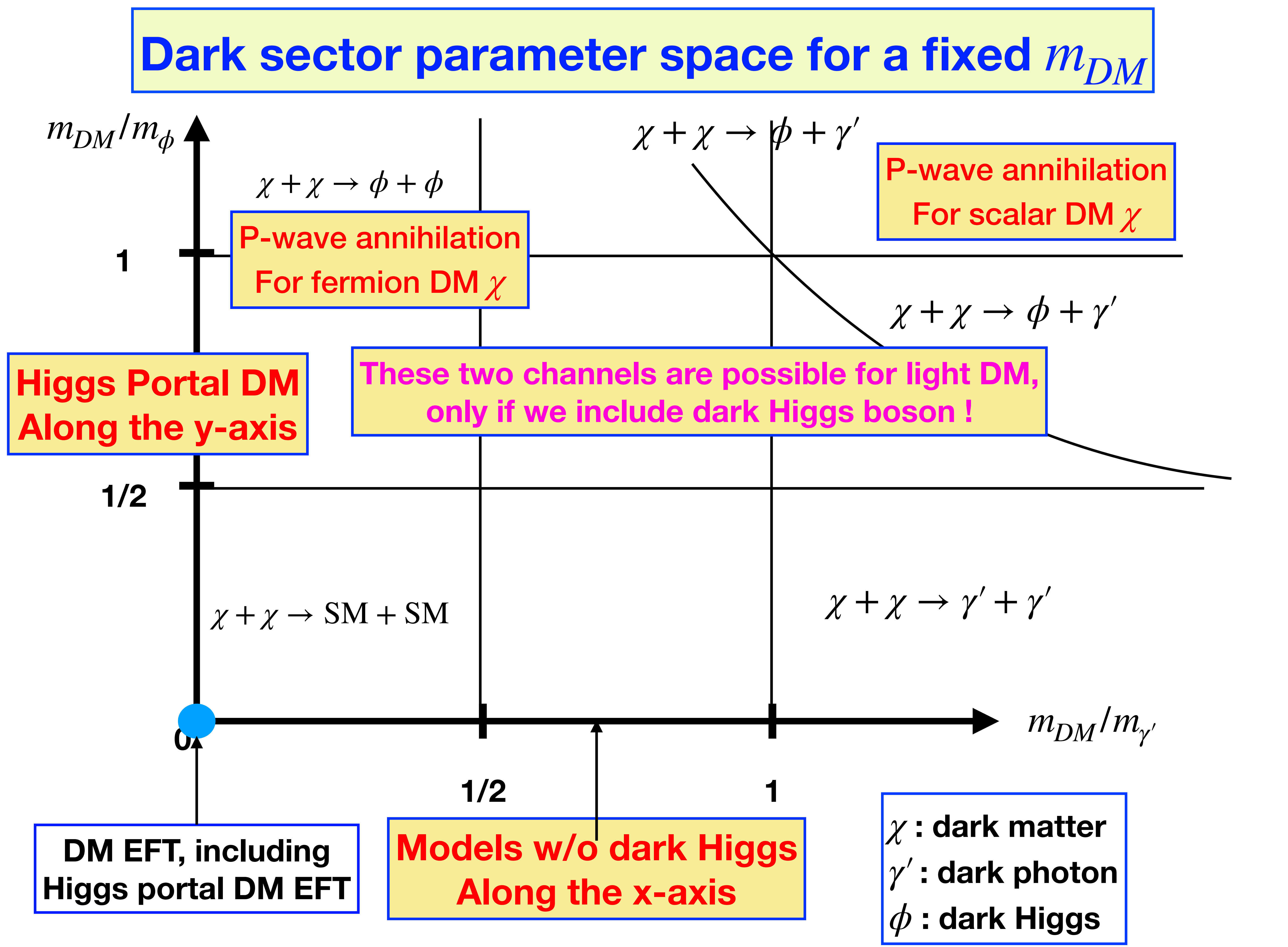
Scalar DM : $XX^{\dagger} \rightarrow Z'^{*} \rightarrow Z'\phi$

$$\sigma v \simeq \frac{g_X^4 v^2}{384\pi\, m_X^4 (4m_X^2 - m_{Z'}^2)^2} \left(16m_X^4 + m_{Z'}^4 + m_\phi^4 + 40m_X^2 m_{Z'}^2 - 8m_X^2 m_\phi^2 - 2m_{Z'}^2 m_\phi^2\right) \times \left[\left\{4m_X^2 - (m_{Z'} + m_\phi)^2\right\}\left\{4m_X^2 - (m_{Z'} - m_\phi)^2\right\}\right]^{1/2} + \mathcal{O}(v^4), \quad (10)$$

Fermion DM : $\chi\bar{\chi} \rightarrow \phi\phi$

$$\sigma v = \frac{y^2 v^2 \sqrt{m_\chi^2 - m_\phi^2}}{96\pi m_\chi} \left[\frac{27\lambda_\phi^2 v_\phi^2}{(4m_\chi^2 - m_\phi^2)^2} + \frac{4y^2 m_\chi^2 (9m_\chi^4 - 8m_\chi^2 m_\phi^2 + 2m_\phi^4)}{(2m_\chi^2 - m_\phi^2)^4}\right] + \mathcal{O}(v^4), \quad (28)$$

Crucial to include “dark Higgs” to have DM pair annihilation in P-wave



Dark sector parameter space for a fixed m_{DM}
m_{DM}/m_{ϕ}
$\chi + \chi \to \phi + \phi$
$\chi + \chi \to \phi + \gamma'$
P-wave annihilation
For scalar DM χ
1
P-wave annihilation
For fermion DM χ
$\chi + \chi \to \phi + \gamma'$
Higgs Portal DM
Along the y-axis
These two channels are possible for light DM,
only if we include dark Higgs boson !
1/2
$\chi + \chi \to \mathrm{SM} + \mathrm{SM}$
$\chi + \chi \to \gamma' + \gamma'$
0
$m_{DM}/m_{\gamma'}$
1/2
1
DM EFT, including
Higgs portal DM EFT
Models w/o dark Higgs
Along the x-axis
χ : dark matter
γ' : dark photon
ϕ : dark Higgs

EWSB and CDM from Strongly Interacting Hidden Sector

All the masses (including CDM mass) from hidden sector strong dynamics, and CDM long lived by accidental sym

Hur, Jung, Ko, Lee : 0709.1218, PLB (2011)
Hur, Ko : arXiv:1103.2517,PRL (2011)
Proceedings for workshops/conferences during 2007-2011 (DSU,ICFP,ICHEP etc.)

Nicety of QCD

- Renormalizable
- Asymptotic freedom : no Landau pole
- QM dim transmutation :
- Light hadron masses from QM dynamics
- Flavor & Baryon # conservations : accidental symmetries of QCD (pion is stable if we switch off EW interaction; proton is stable or very long lived)

h-pion & h-baryon DMs

- In most WIMP DM models, DM is stable due to some ad hoc Z_2 symmetry
- If the hidden sector gauge symmetry is confining like ordinary QCD, the lightest mesons and the baryons could be stable or long-lived >> Good CDM candidates
- If chiral sym breaking in the hidden sector, light h-pions can be described by chiral Lagrangian in the low energy limit

Key Observation

- If we switch off gauge interactions of the SM, then we find
- Higgs sector ~ Gell-Mann-Levy's linear sigma model which is the EFT for QCD describing dynamics of pion, sigma and nucleons
- One Higgs doublet in 2HDM could be replaced by the GML linear sigma model for hidden sector QCD

- Potential for H_1 and H_2

$$V(H_1, H_2) = -\mu_1^2(H_1^\dagger H_1) + \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 - \mu_2^2(H_2^\dagger H_2) + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3(H_1^\dagger H_1)(H_2^\dagger H_2) + \frac{a v_2^3}{2}\sigma_h$$

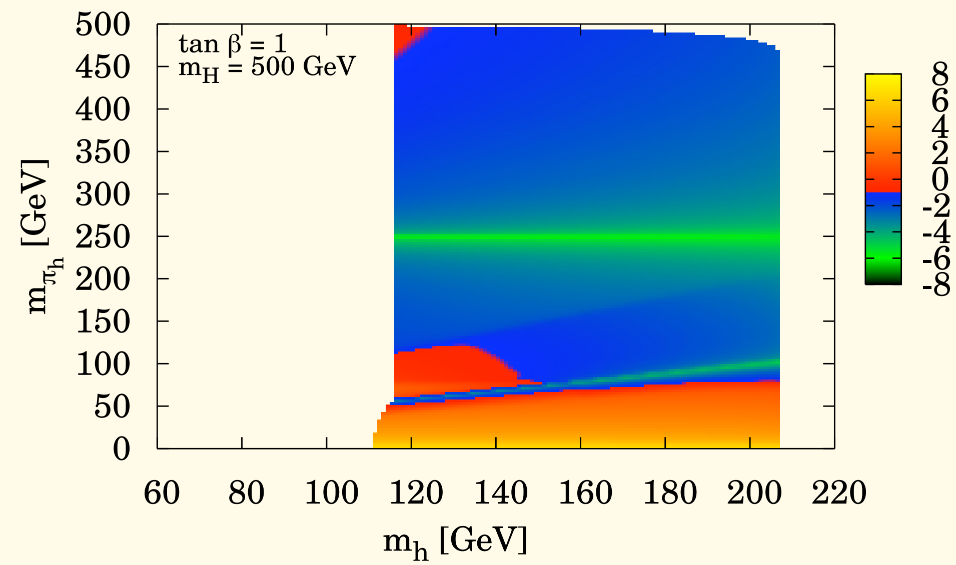
Not present in the two-Higgs Doublet model

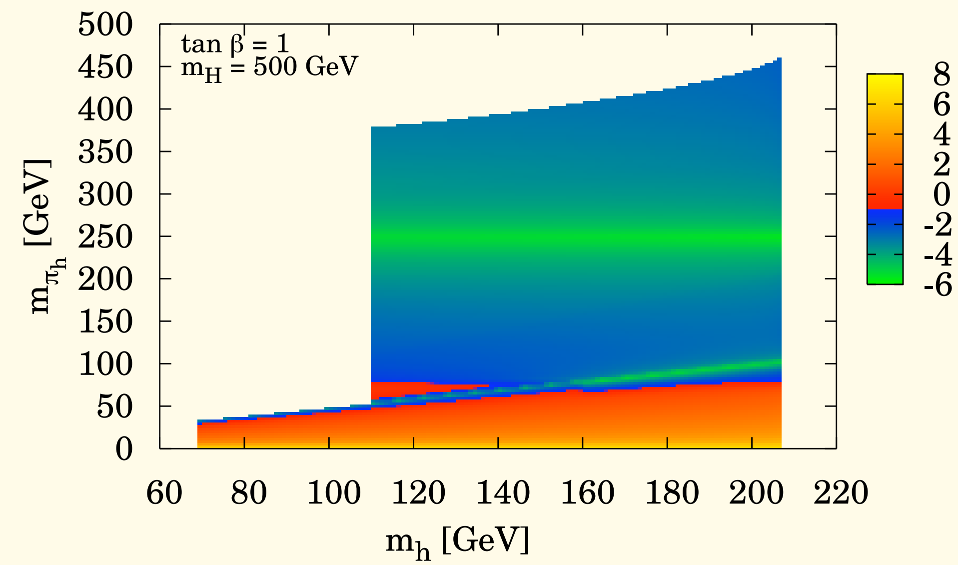
- Stability : $\lambda_{1,2} > 0$ and $\lambda_1 + \lambda_2 + 2\lambda_3 > 0$
- Consider the following phase:

$$H_1 = \begin{pmatrix} 0 \\ \frac{v_1 + h_{\rm SM}}{\sqrt{2}} \end{pmatrix}, \qquad H_2 = \begin{pmatrix} \pi_h^+ \\ \frac{v_2 + \sigma_h + i\pi_h^0}{\sqrt{2}} \end{pmatrix}$$

- Correct EWSB : $\lambda_1(\lambda_2 + a/2) \equiv \lambda_1 \lambda_2' > \lambda_3^2$

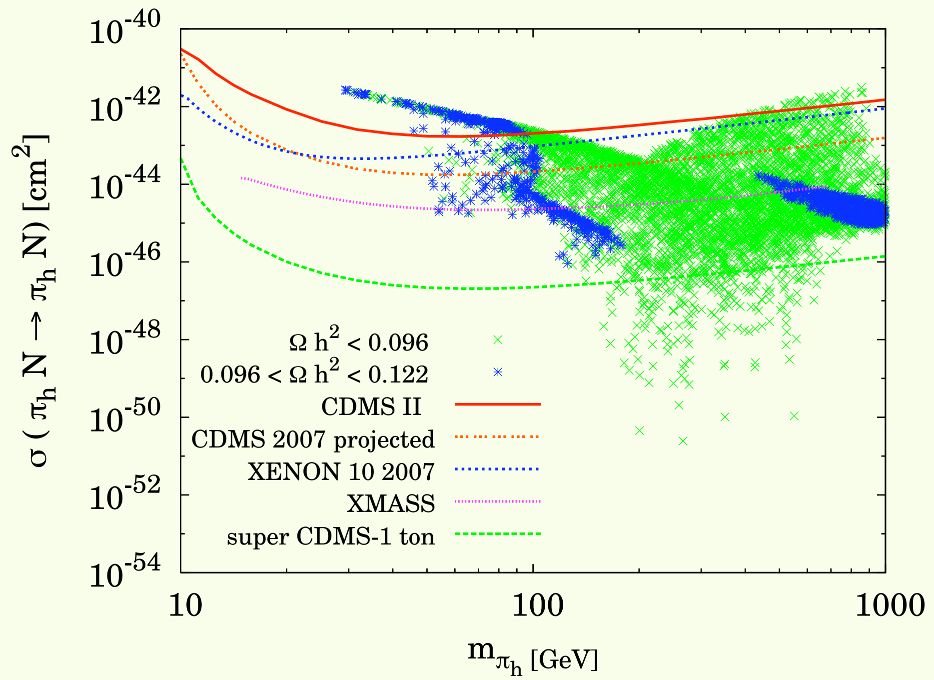
Relic Density

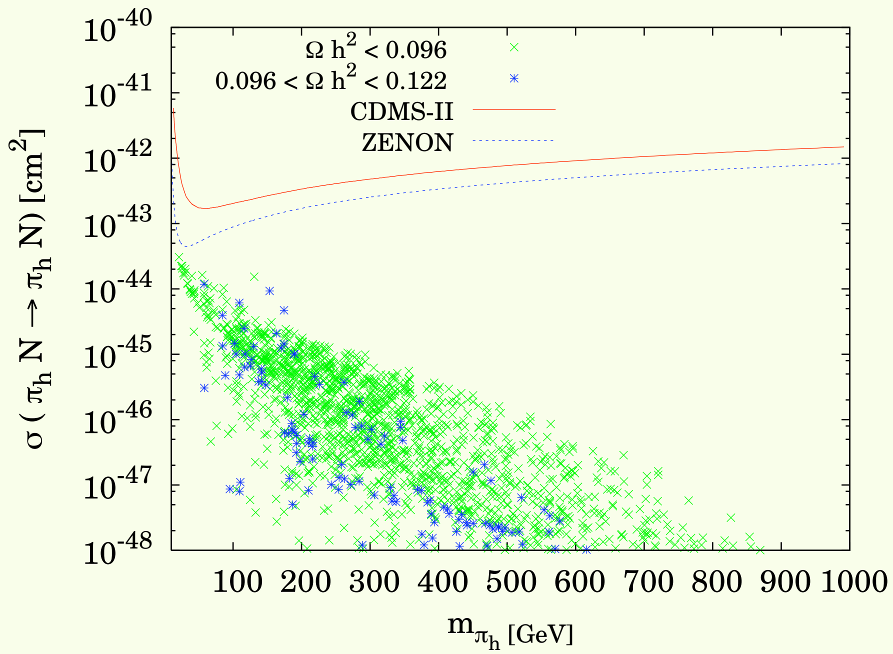




- $\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for $\tan\beta = 1$ and $m_H = 500$ GeV
- Labels are in the $\log_{10}$
- Can easily accommodate the relic density in our model

Direct detection rate

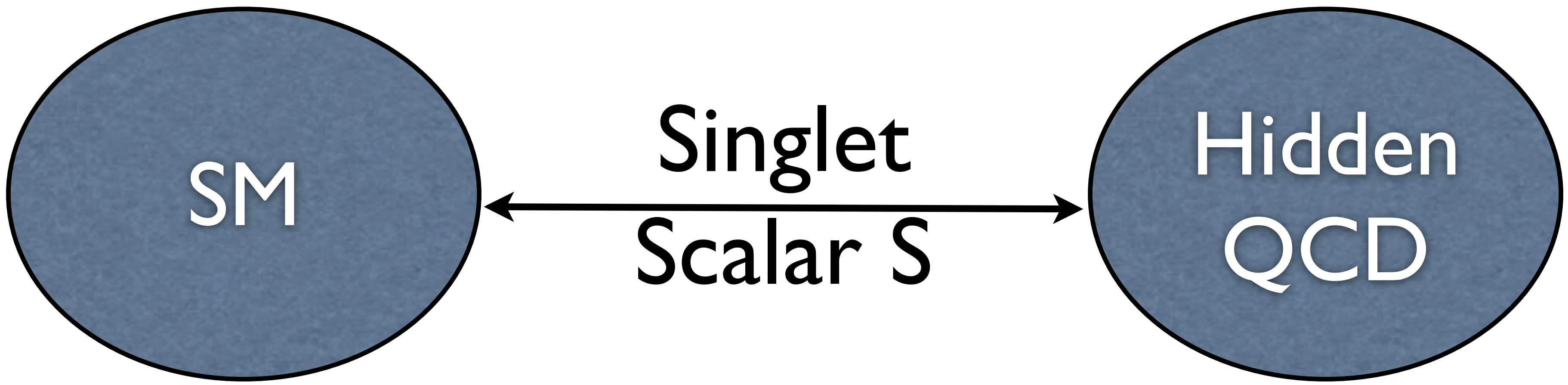




- $\sigma_{SI}(\pi_h p \to \pi_h p)$ as functions of m_{π_h} for $\tan\beta = 1$ and $\tan\beta = 5$.
- σ_{SI} for $\tan\beta = 1$ is very interesting, partly excluded by the CDMS-II and XENON 10, and als can be probed by future experiments, such as XMASS and super CDMS
- $\tan\beta = 5$ case can be probed to some extent at Super CDMS

Model I (Scalar Messenger)

Hur, Ko, PRL (2011)



- SM - Messenger - Hidden Sector QCD
- Assume classically scale invariant lagrangian --> No mass scale in the beginning
- Chiral Symmetry Breaking in the hQCD generates a mass scale, which is injected to the SM by "S"

Scale invariant extension of the SM with strongly interacting hidden sector

Modified SM with classical scale symmetry

$$\begin{aligned}\mathcal{L}_{\rm SM} &= \mathcal{L}_{\rm kin} - \frac{\lambda_H}{4}\,(H^\dagger H)^2 - \frac{\lambda_{SH}}{2}\,S^2\,H^\dagger H - \frac{\lambda_S}{4}\,S^4 \\ &+ \Big(\overline{Q}^i H Y_{ij}^D D^j + \overline{Q}^i \tilde{H} Y_{ij}^U U^j + \overline{L}^i H Y_{ij}^E E^j \\ &+ \overline{L}^i \tilde{H} Y_{ij}^N N^j + S N^{iT} C Y_{ij}^M N^j + h.c.\Big)\end{aligned}$$

Hidden sector lagrangian with new strong interaction

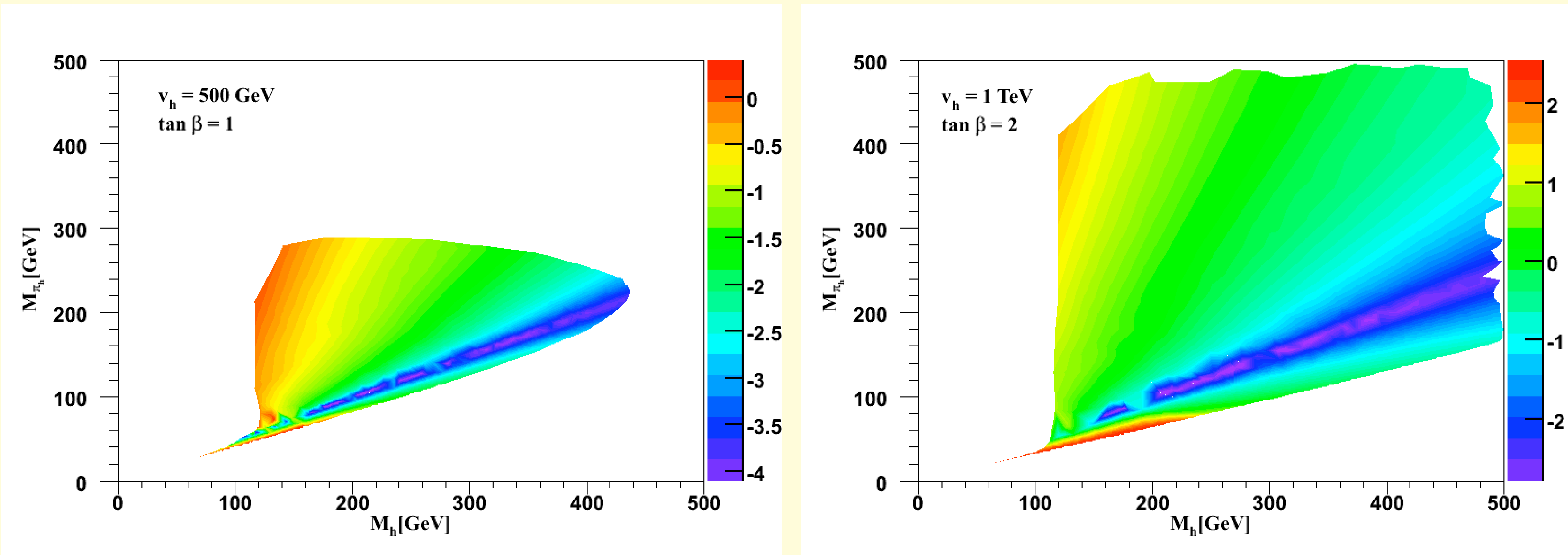
$$\mathcal{L}_{\rm hidden} = -\frac{1}{4}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu} + \sum_{k=1}^{N_{HF}} \overline{\mathcal{Q}}_k (i\mathcal{D}\cdot\gamma - \lambda_k S)\mathcal{Q}_k$$

3 neutral scalars : h, S and hidden sigma meson
Assume h-sigma is heavy enough for simplicity

Effective lagrangian far below $\Lambda_{h,\chi} \approx 4\pi\Lambda_h$

$$\begin{aligned}
\mathcal{L}_{\rm full} &= \mathcal{L}^{\rm eff}_{\rm hidden} + \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm mixing} \\
\mathcal{L}^{\rm eff}_{\rm hidden} &= \frac{v_h^2}{4}{\rm Tr}[\partial_\mu \Sigma_h \partial^\mu \Sigma_h^\dagger] + \frac{v_h^2}{2}{\rm Tr}[\lambda S \mu_h (\Sigma_h + \Sigma_h^\dagger)] \\
\mathcal{L}_{\rm SM} &= -\frac{\lambda_1}{2}(H_1^\dagger H_1)^2 - \frac{\lambda_{1S}}{2} H_1^\dagger H_1 S^2 - \frac{\lambda_S}{8} S^4 \\
\mathcal{L}_{\rm mixing} &= -v_h^2 \Lambda_h^2 \left[\kappa_H \frac{H_1^\dagger H_1}{\Lambda_h^2} + \kappa_S \frac{S^2}{\Lambda_h^2} + \kappa_S' \frac{S}{\Lambda_h} \right. \\
&+ \left. O(\frac{S H_1^\dagger H_1}{\Lambda_h^3}, \frac{S^3}{\Lambda_h^3}) \right] \\
&\approx -v_h^2 \left[\kappa_H H_1^\dagger H_1 + \kappa_S S^2 + \Lambda_h \kappa_S' S \right]
\end{aligned}$$

Relic density

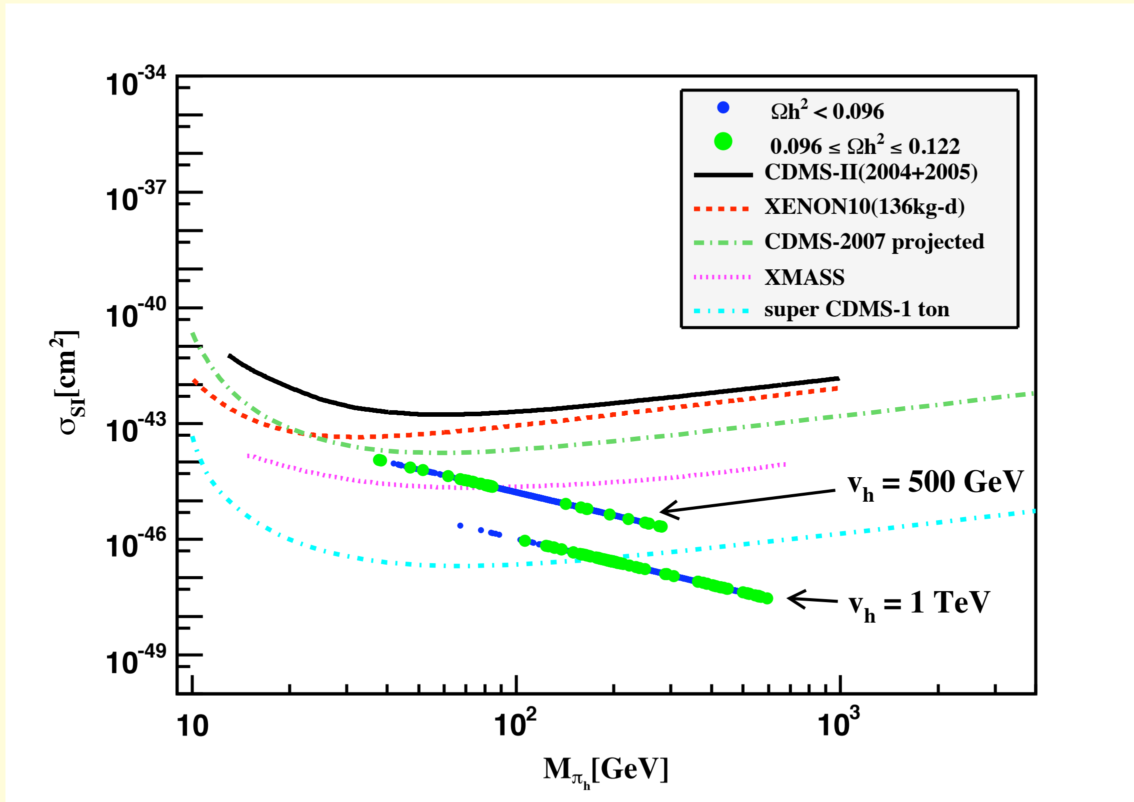


$\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for

(a) $v_h = 500$ GeV and $\tan\beta = 1$,

(b) $v_h = 1$ TeV and $\tan\beta = 2$.

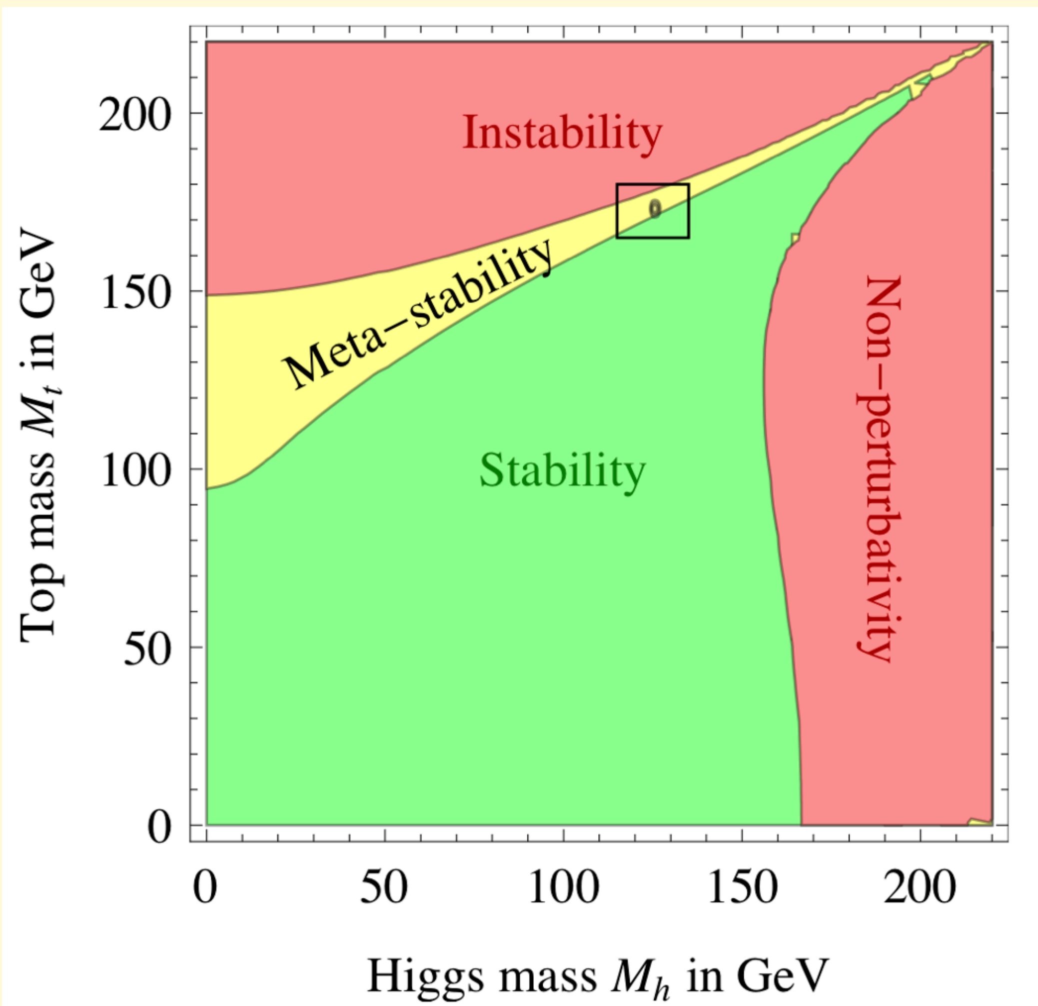
Direct Detection Rate



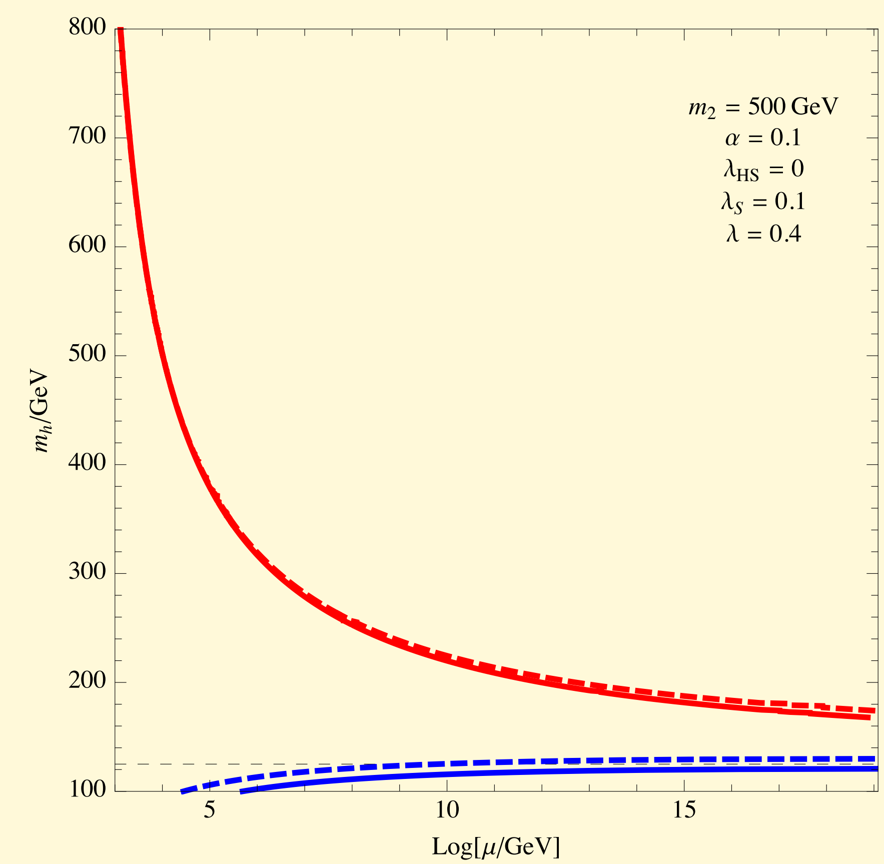
$\sigma_{SI}(\pi_h p \to \pi_h p)$ as functions of m_{π_h}.
the upper one: $v_h = 500$ GeV and $\tan\beta = 1$,

the lower one: $v_h = 1$ TeV and $\tan\beta = 2$.

Vacuum Stability Improved by the singlet scalar S



A. Strumia, Moriond EW 2013



Baek, Ko, Park, Senaha (2012)

Low energy pheno.

- Universal suppression of collider SM signals

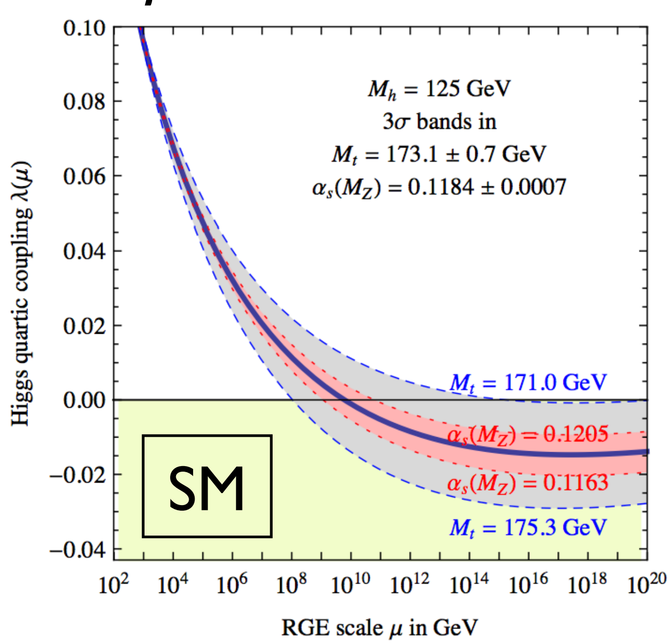
[See 1112.1847, Seungwon Baek, P. Ko & WIP]

- If "$m_h > 2\, m_\phi$", non-SM Higgs decay!

- Tree-level shift of $\boldsymbol{\lambda}_{H,SM}$ (& loop correction)

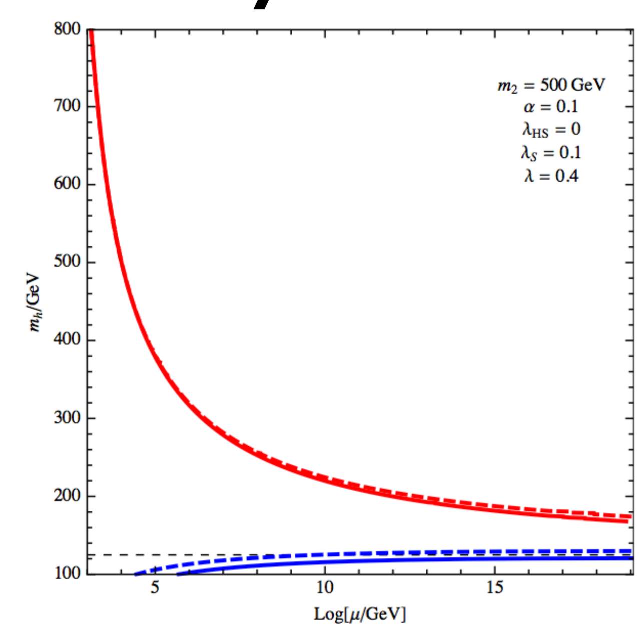
$$\lambda_{\Phi H} \Rightarrow \lambda_H = \left[1 + \left(\frac{m_\phi^2}{m_h^2} - 1\right)\sin^2\alpha\right]\lambda_H^{\rm SM}$$

If "$m_\phi > m_h$", vacuum instability can be cured.



[G. Degrassi et al., 1205.6497]

α



[S. Baek, P. Ko, WIP & E. Senaha, JHEP(2012)]

Comparison w/ other model

- Dark gauge symmetry is unbroken (DM is long-lived because of accidental flavor symmetry), but confining like QCD (No long range dark force and no Dark Radiation)
- DM : composite hidden hadrons (mesons and baryons)
- All masses including CDM masses from dynamical sym breaking in the hidden sector
- Singlet scalar is necessary to connect the hidden sector and the visible sector
- Higgs Signal strengths : universally reduced from one

- Similar to the massless QCD with the physical proton mass without finetuning problem
- Similar to the BCS mechanism for SC, or Technicolor idea
- Eventually we would wish to understand the origin of DM and RH neutrino masses, and this model is one possible example
- Could consider SUSY version of it

More issues to study

- DM : strongly interacting composite hadrons in the hidden sector >> self-interacting DM >> can solve the small scale problem of DM halo
- TeV scale seesaw : TeV scale leptogenesis, or baryogenesis from neutrino oscillations
- Wess-Zumino term: 3 > 2 possible (e.g. Hochberg, Kuflik, Murayam, Volansky, Wacker for Sp(N) case)
- Another approach for hQCD ? (For example, Kubo, Lindner et al use NJL approach; and AdS/QCD approach with H.Hatanaka, D.W.Jung@KIAS)

SIMP Scenario in Dark QCD

SIMP paradigm

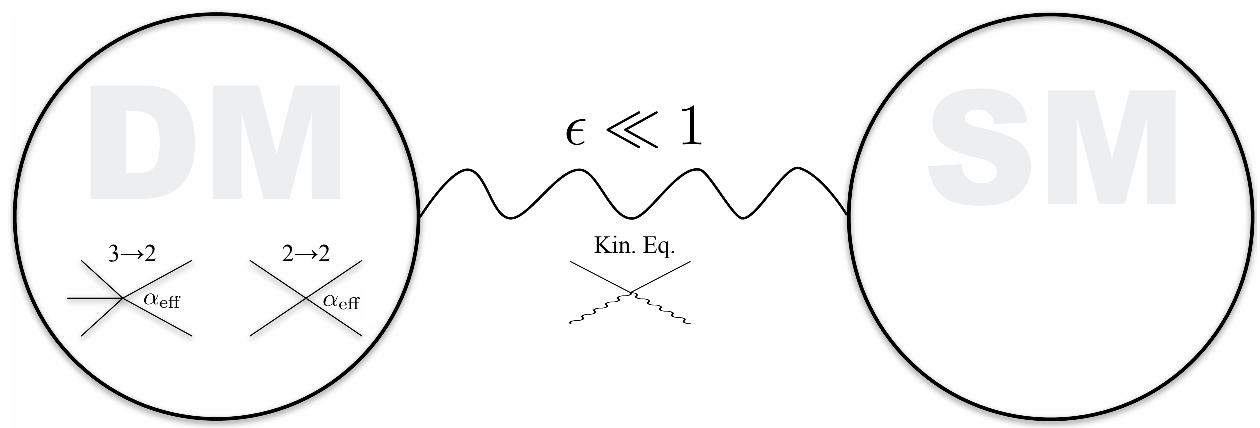


FIG. 1: A schematic description of the SIMP paradigm. The dark sector consists of DM which annihilates via a $3 \to 2$ process. Small couplings to the visible sector allow for thermalization of the two sectors, thereby allowing heat to flow from the dark sector to the visible one. DM self interactions are naturally predicted to explain small scale structure anomalies while the couplings to the visible sector predict measurable consequences.

Hochberg, Kuflik, Tolansky, Wacker, arXiv:1402.5143
Phys. Rev. Lett. 113, 171301 (2014)

SIMP Conditions

Freeze-out :

$$\Gamma_{3\to 2} = n_{DM}^2 \langle \sigma v^2 \rangle_{3\to 2} \sim H(T_F)$$

$$\langle \sigma v^2 \rangle_{3\to 2} = \frac{\alpha_{\rm eff}^3}{m_{\rm DM}^5}$$

$$\alpha_{\rm eff} = 1 - 30 \to m_{\rm DM} \sim 10{\rm MeV} - 1{\rm GeV}$$

2->2 Self scattering :

$$\frac{\sigma_{\rm scatter}}{m_{\rm DM}} = \frac{a^2 \alpha_{\rm eff}^2}{m_{\rm DM}^3}$$

with a~O(1)

$$\frac{\sigma_{\rm scatter}}{m_{\rm DM}} \lesssim 1 \ {\rm cm}^2/{\rm g}$$

Dark QCD + WZW

- Dark flavor symmetry G=SU(N_f)$_L$ x SU(N_f)$_R$ is SSB into diagonal H=SU(N_f)$_V$ by dark QCD condensation

- Effective Lagrangian for NG bosons (dark pions) contain 5-point self interaction : WZW term for π_5 (G/H) = Z (Nf > 2)

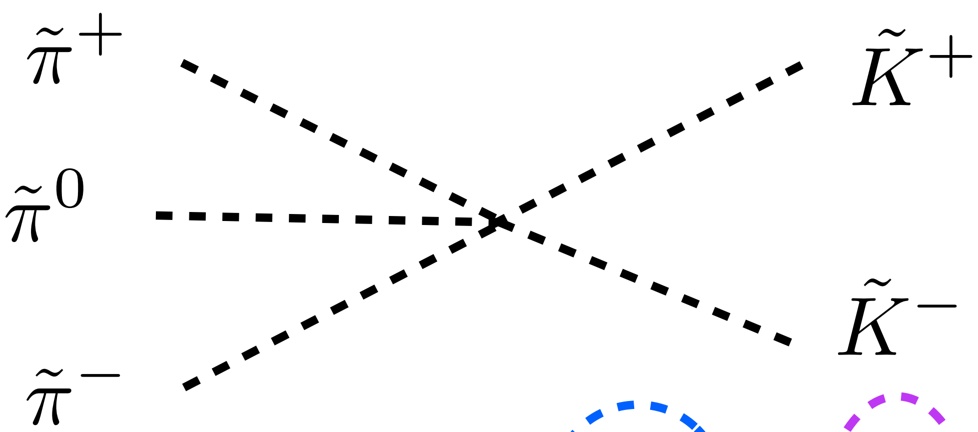
$$\Gamma_{\mathrm{WZ}} = C \int_{M^5} d^5x \ \mathrm{Tr}(\alpha^5) \qquad \text{with} \quad \alpha = dUU^\dagger.$$

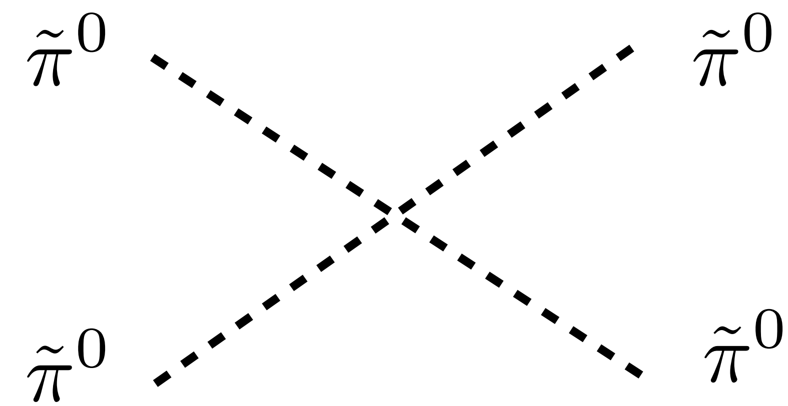
$$U = e^{2i\pi/F}$$

$$C = -i\frac{N_c}{240\pi^2}$$

in the absence of external gauge fields

SIMP Dark Mesons





~const

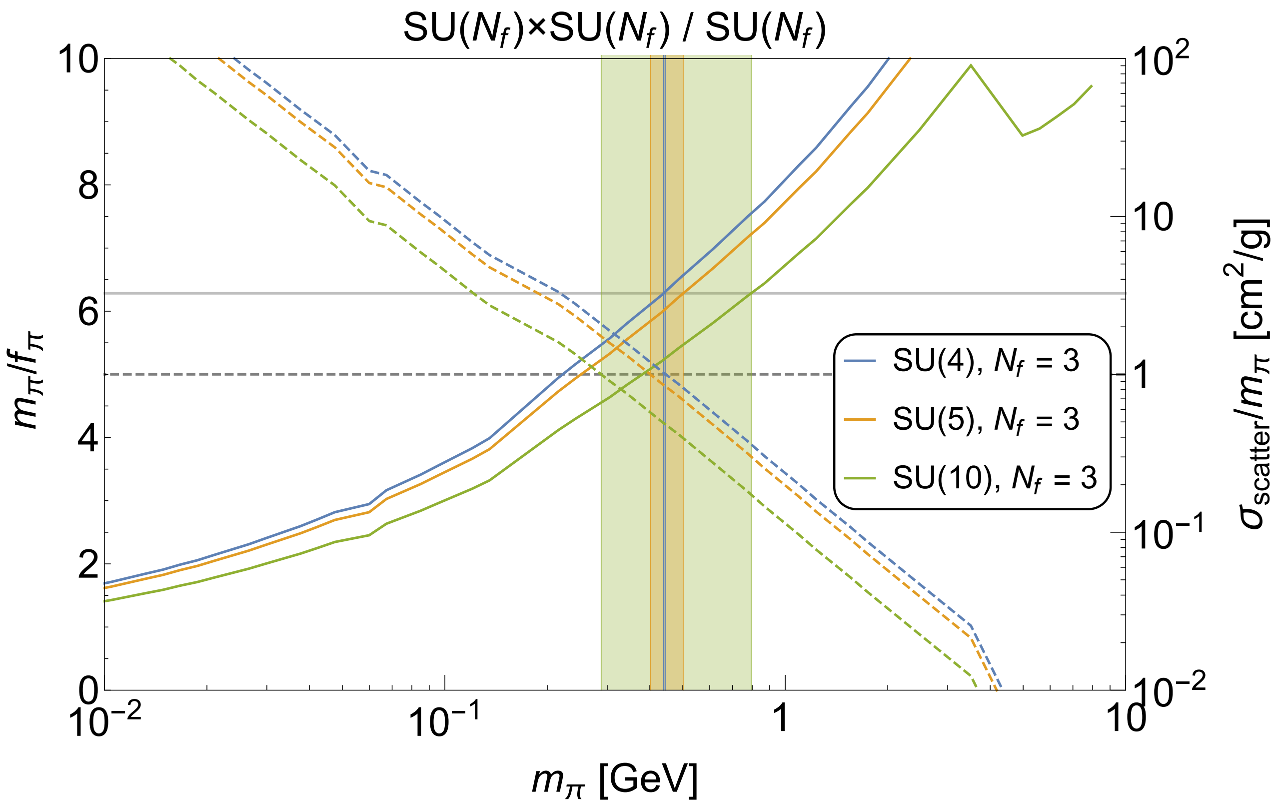
~const

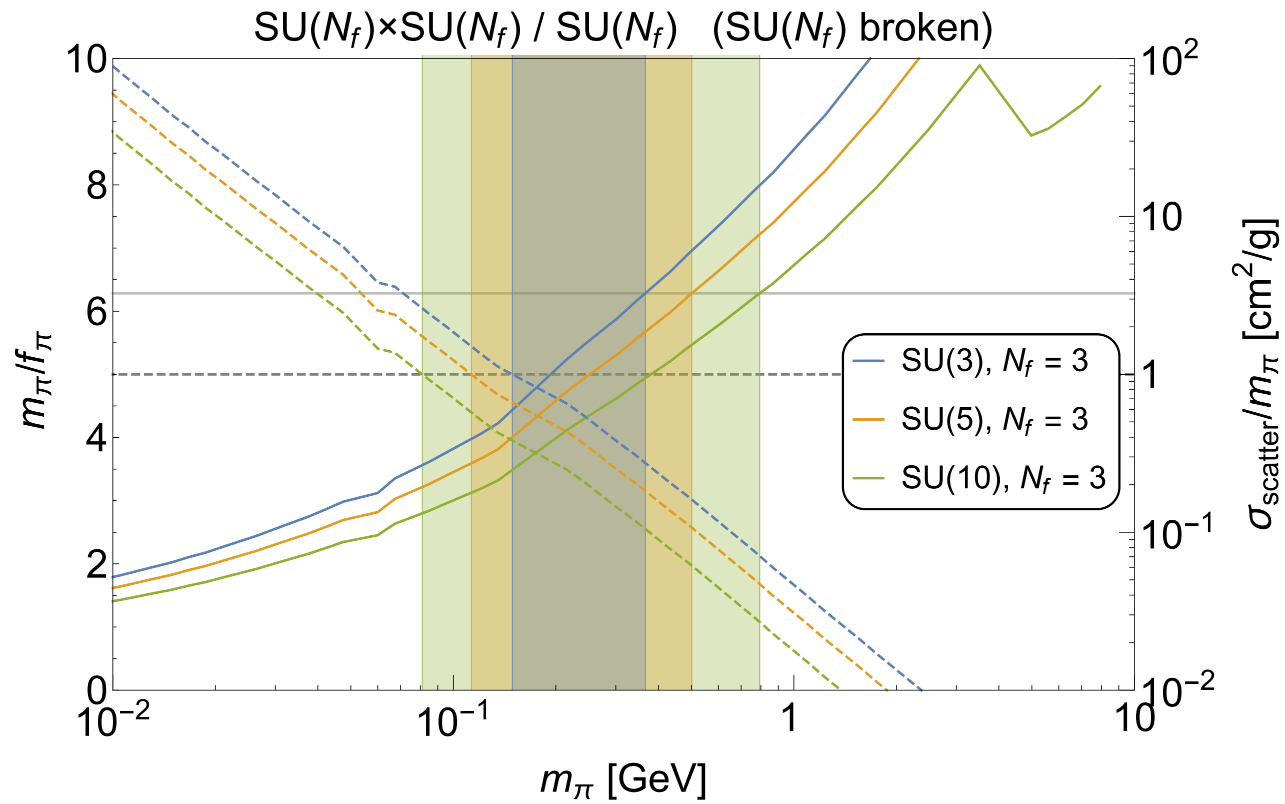
$$\langle\sigma v^2\rangle_{3\to2} = \frac{5\sqrt{5}N_c^2 m_\pi^5}{2\pi^5 F^{10}}\frac{t^2}{N_\pi^3}\left(\frac{T_F}{m_\pi}\right)^2, \qquad \sigma_{\rm self} = \frac{m_\pi^2}{32\pi F^4}\frac{a^2}{N_\pi^2}$$

G_c	G_f/H	N_π	t^2	$N_f^2 a^2$
$SU(N_c)$	$\frac{SU(N_f)\times SU(N_f)}{SU(N_f)}$ $(N_f \geq 3)$	$N_f^2 - 1$	$\frac{4}{3}N_f(N_f^2-1)(N_f^2-4)$	$8(N_f-1)(N_f+1)(3N_f^4-2N_f^2+6)$
$SO(N_c)$	$SU(N_f)/SO(N_f)$ $(N_f \geq 3)$	$\frac{1}{2}(N_f+2)(N_f-1)$	$\frac{1}{12}N_f(N_f^2-1)(N_f^2-4)$	$(N_f-1)(N_f+2)(3N_f^4+7N_f^3-2N_f^2-12N_f+24)$
$Sp(N_c)$	$SU(2N_f)/Sp(2N_f)$ $(N_f \geq 2)$	$(2N_f+1)(N_f-1)$	$\frac{2}{3}N_f(N_f^2-1)(4N_f^2-1)$	$4(N_f-1)(2N_f+1)(6N_f^4-7N_f^3-N_f^2+3N_f+3)$

[Hochberg, Kuflik, Murayama, Volansky, Wacker, 1411.3727, PRL (2015)]

SIMP Parameter Space





Hochberg, Kuflik, Murayama, Volansky, Wacker, 1411.3727, PRL

- DM self scattering : $\sigma_{\rm self}/m_{\rm DM} < 1\,{\rm cm}^2/{\rm g}$

Large Nc > 3

- Validity of ChPT : $m_\pi/f_\pi < 2\pi$

More serious in NNLO ChPT
Sannino et al, 1507.01590

Issues in the SIMP w/ hQCD

- Dark flavor sym is not good enough to stabilize dark pion (We have to assume dim-5 operator is highly suppressed)

- Dark baryons can make additional contribution to DM of the universe (It could produce additional diagrams for SIMP)

- Validity region of ChPT : need to include resonances (dark rho meson, dark sigma meson, etc.)

- How to achieve Kinetic equilibrium with the SM ? (Dark sigma meson or adding singlet scalar S may help. Or lifting the mass degeneracy of dark pions can help.)

SIMP + VDM

With Soo Min Choi, Hyun Min Lee, Alexander Natale,
arXiv:1801.07726, PRD (2018)

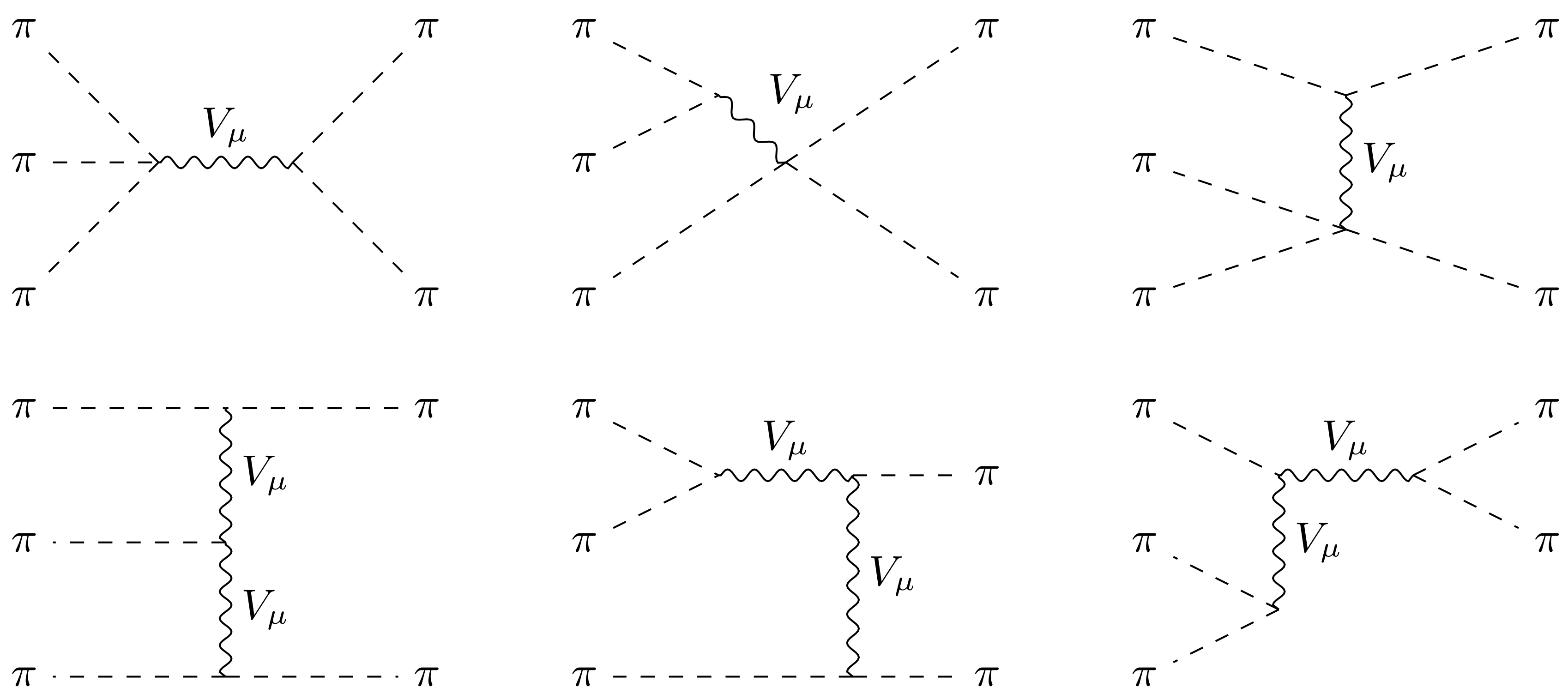


FIG. 1: Feynman diagrams contributing to $3 \to 2$ processes for the dark pions with the vector meson interactions.

SIMP + VM

New diagrams involving dark vector mesons

$$\pi^+\pi^-\pi^0 \to \omega \to K^+K^-(K^0\overline{K^0})$$

$$\gamma = \frac{m_V \Gamma}{9m_\pi^2}, \text{ and } \epsilon = \frac{m_V^2 - 9m_\pi^2}{9m_\pi^2}$$ **(for 3 pi resonance case)**

We choose a small epsilon [say, 0.1 (near resonance)]
and a small gamma (NWA)

Results

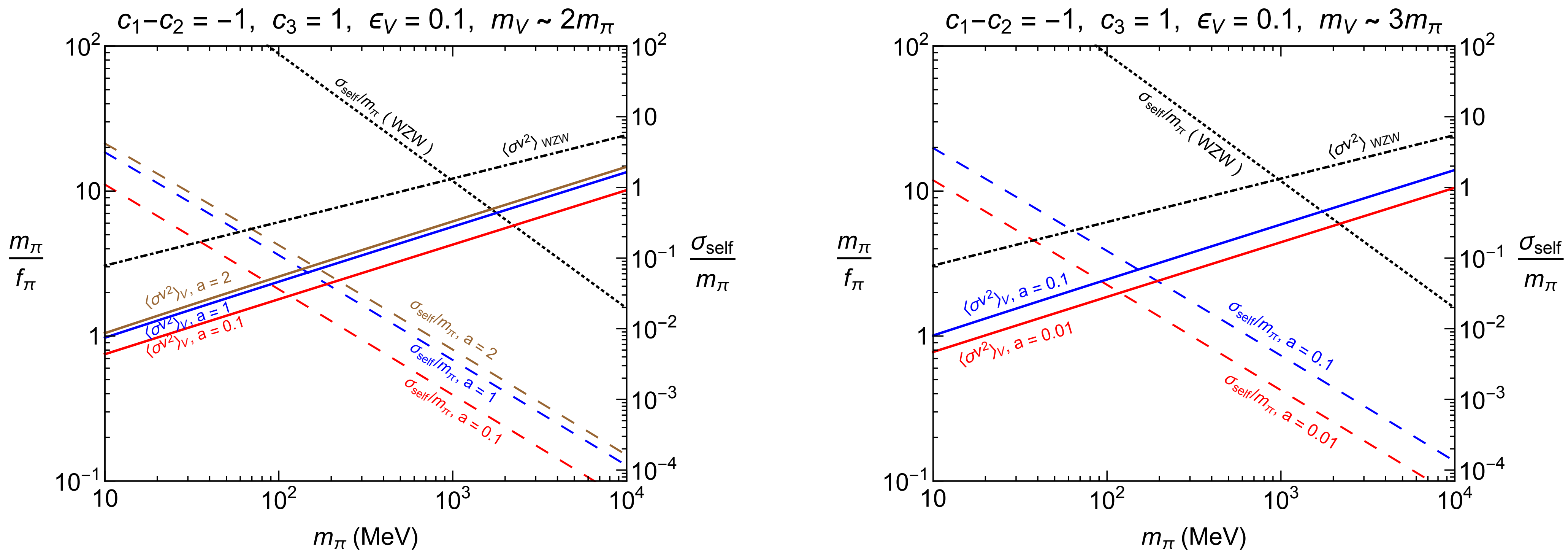


FIG. 2: Contours of relic density ($\Omega h^2 \approx 0.119$) for m_π and m_π/f_π and self-scattering cross section per DM mass in cm^2/g as a function of m_π. The case without and with vector mesons are shown in black lines and colored lines respectively. We have imposed the relic density condition for obtaining the contours of self-scattering cross section. Vector meson masses are taken near the resonances with $m_V = 2(3)m_\pi\sqrt{1+\epsilon_V}$ on left(right) plots. In both plots, $c_1 - c_2 = -1$ and $\epsilon_V = 0.1$ are taken.

- The allowed parameter space is in a better shape now, especially for 2 pi resonance case

Conclusion

- Hidden (dark) QCD models make an interesting possibility to study the origin of EWSB, (C)DM

- WIMP scenario is still viable, and will be tested to some extent by precise measurements of the Higgs signal strength and by discovery of the singlet scalar, which is however a formidable task unless we are very lucky

- SIMP scenario using 3->2 scattering via WZW term is interesting, but there are a few issues which ask for further study (dark resonance could play an important role for thermal relic and kinetic contact with the SM sector)

AMS02 positron excess from decaying fermionic thermal DM

P. Ko, Yong Tang,1410.7657, PLB

Decaying DM

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

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,

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

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

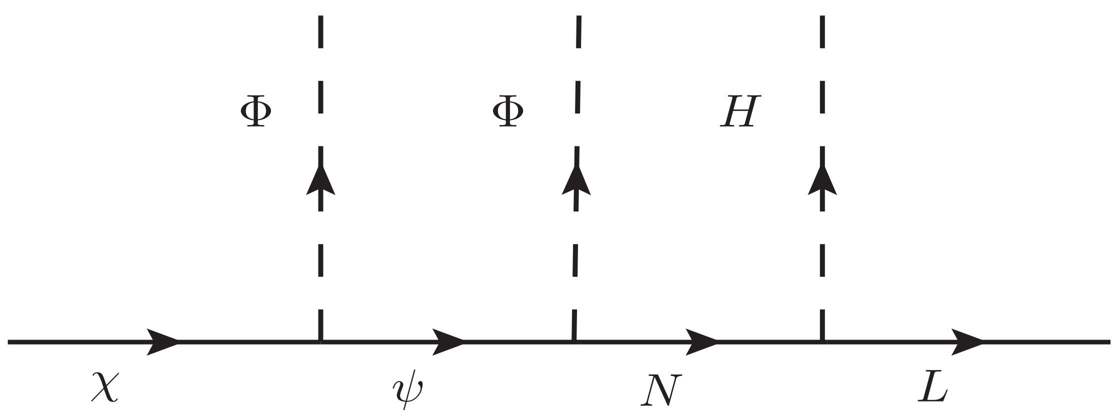


FIG. 1: Feynman diagram that generates the effector operator $\bar{\chi}\Phi\Phi\tilde{H}L$.

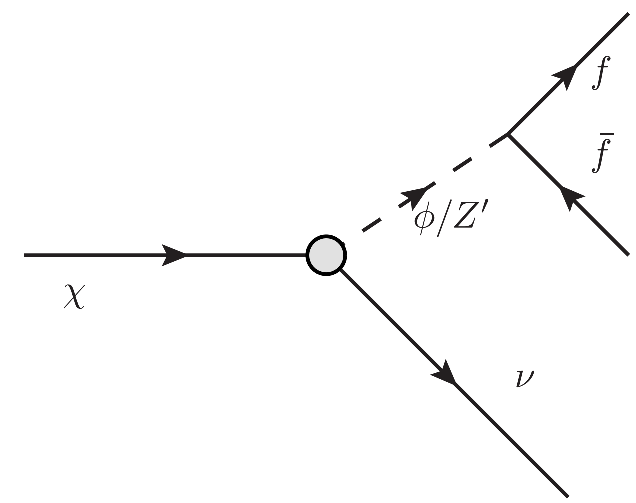


FIG. 2: Dominant decaying process.

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

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

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

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

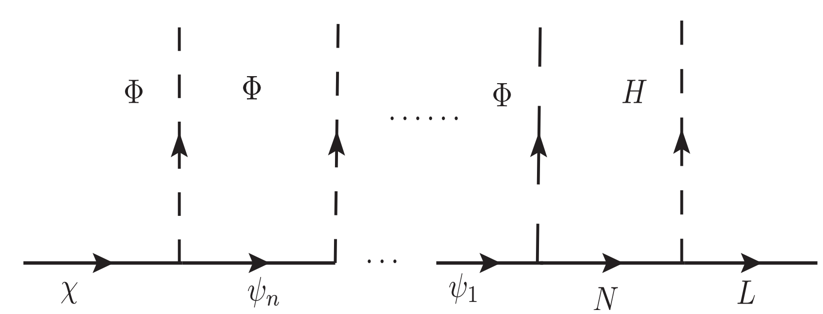


FIG. 4: Feynman diagram that generates the effector operator $\bar{\chi}\Phi^{n+1}\tilde{H}L$.

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

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

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

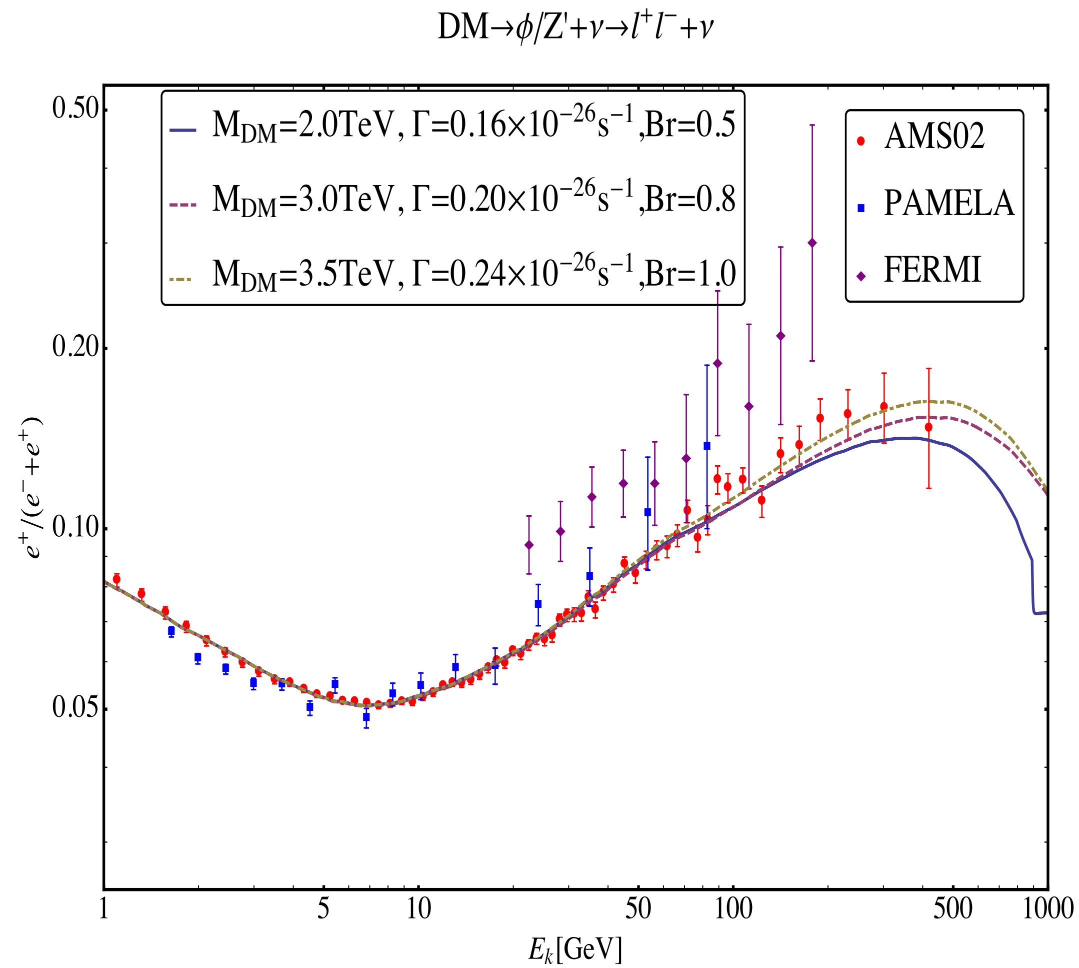


FIG. 5: Positron fraction in three different sets of parameters. M_{DM} and total decay width Γ are chosen to visually match the positron fraction data. Data are extracted from Ref. [58].

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

No constraint from anti-p, and χ : SIDM

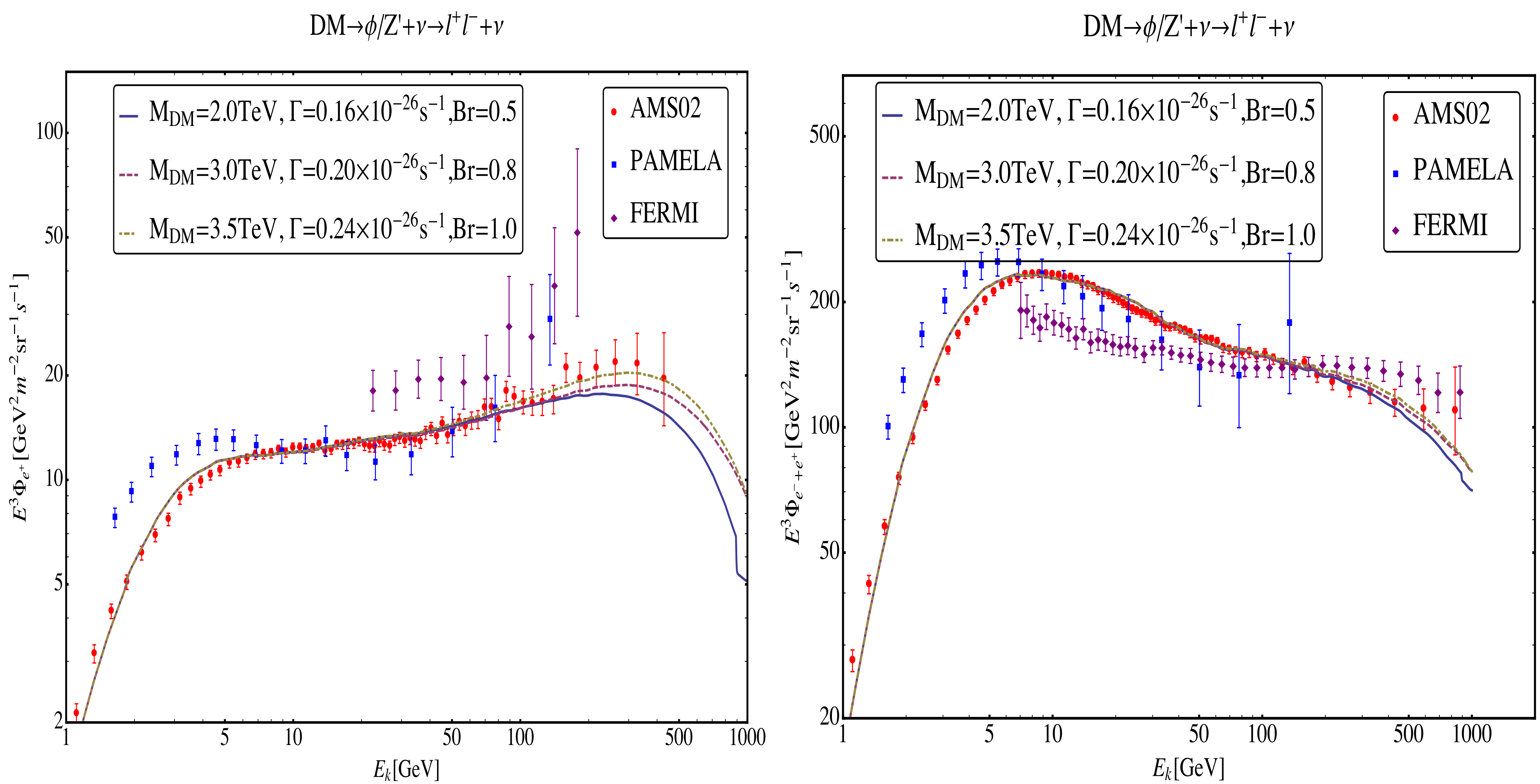


FIG. 6: Positron flux (left) and electron+positron flux (right) [59–61] for three different sets of parameters described in the text, Eqs. (5.6)-(5.8).

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)

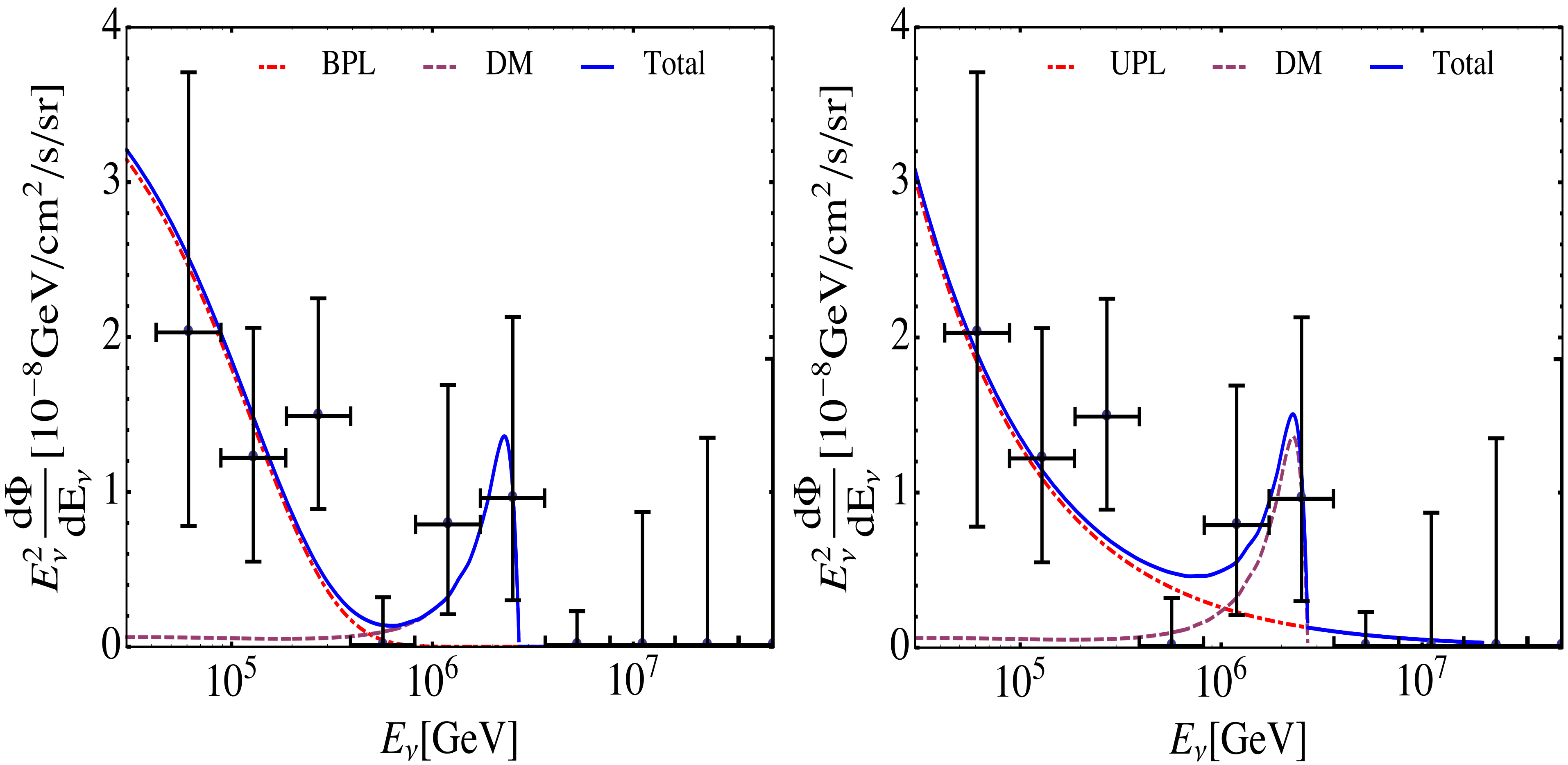


FIG. 2. Neutrino flux from DM χ's decay with $m_\chi \sim 5$PeV and lifetime $\tau_\chi = 1/\Gamma \sim 2 \times 10^{28}$s and IceCube Data [1]. The left (right) panel used a broken (unbroken) power law (BPL) for astrophysical neutrino flux with a red dot-dashed curve. DM's contributions and total flux 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 $m_\chi \gg v_\phi$:

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

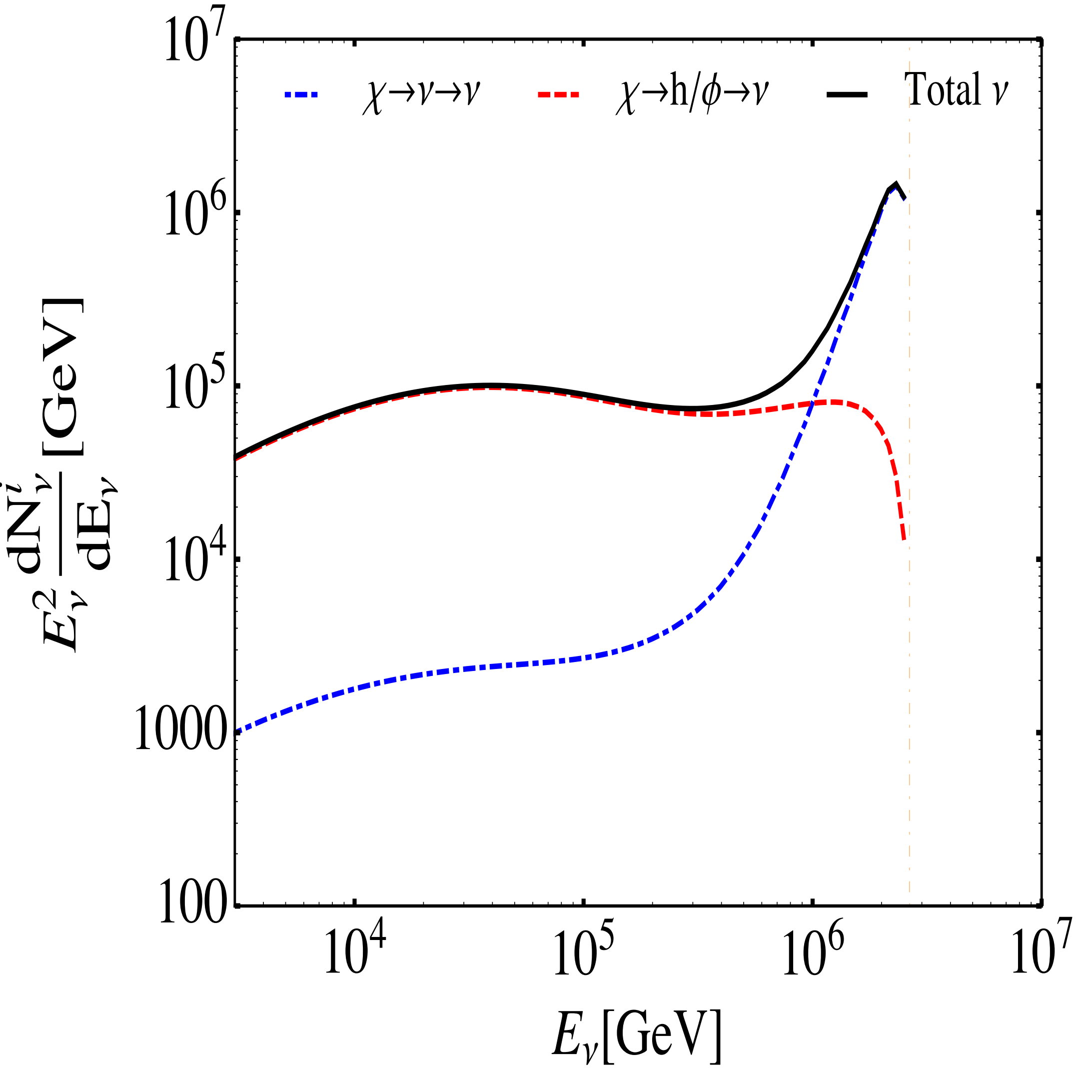
since we actually have an enhancement from heavy m_χ even though there is a phase space suppression from three-body final states. There are another three-body decay channels that are equally important:

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

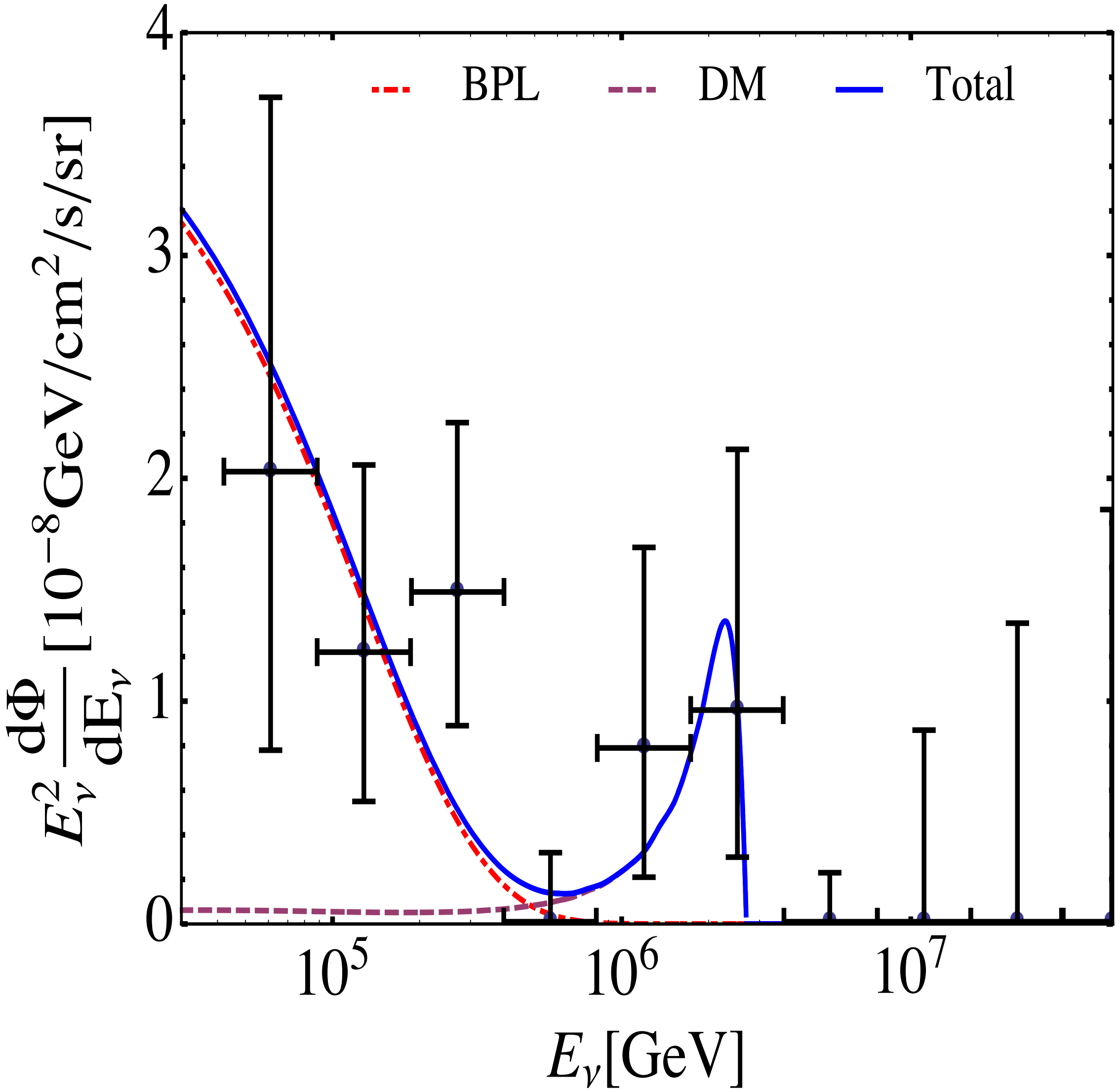
with branching ratios 1 : 1 : 2 due to the Goldstone boson equivalence theorem. In the following, if not otherwise stated explicitly, we use $\chi \to \phi h \nu$ to represent all these channels and in numerical calculations we take all of them into account.

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,

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



χ→ν→ν
χ→h/ϕ→ν
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]

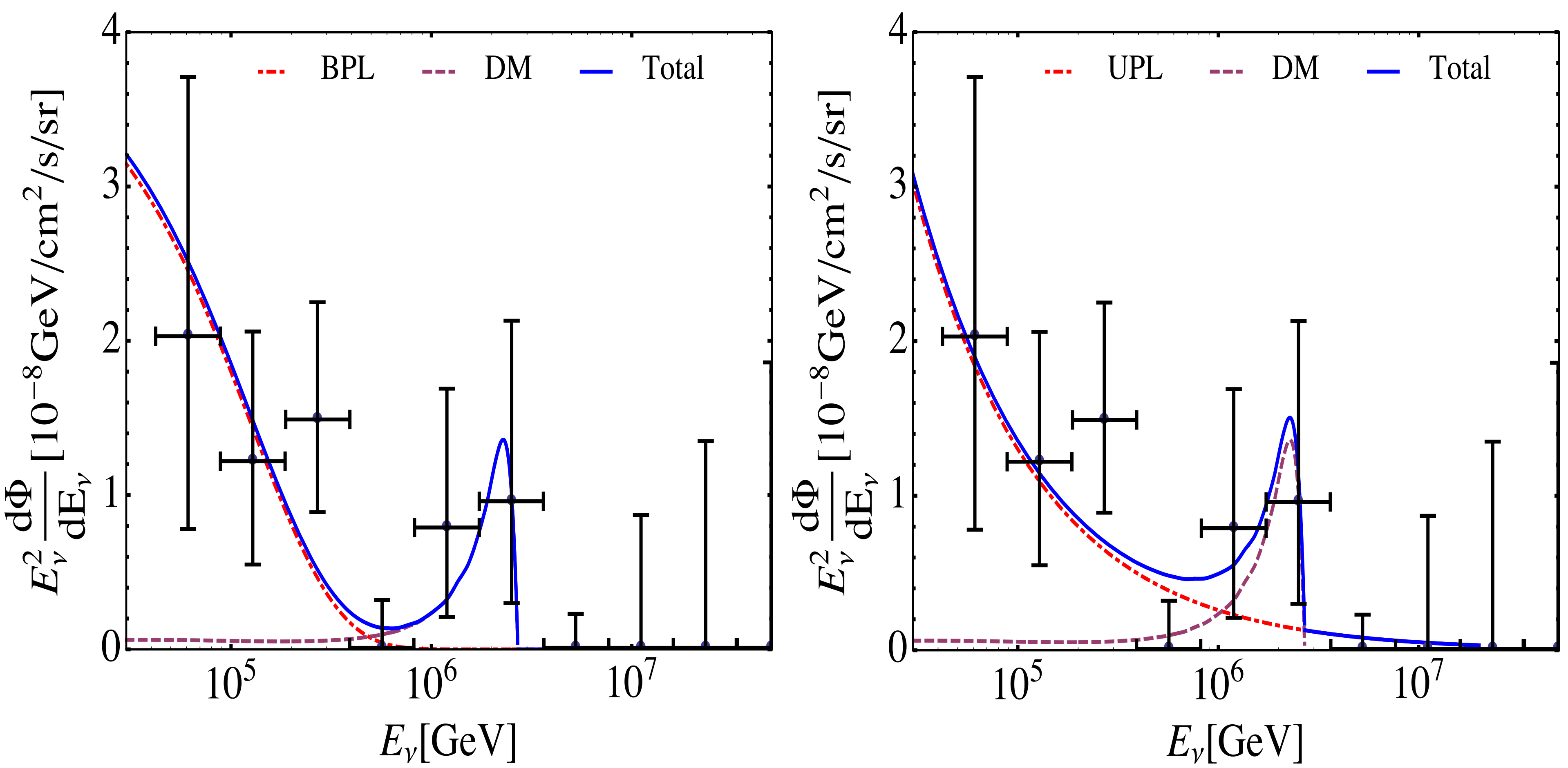


FIG. 2. Neutrino flux from DM χ's decay with $m_\chi \sim 5$PeV and lifetime $\tau_\chi = 1/\Gamma \sim 2 \times 10^{28}$s and IceCube Data [1]. The left (right) panel used a broken (unbroken) power law (BPL) for astrophysical neutrino flux with a red dot-dashed curve. DM's contributions and total flux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

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,

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

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

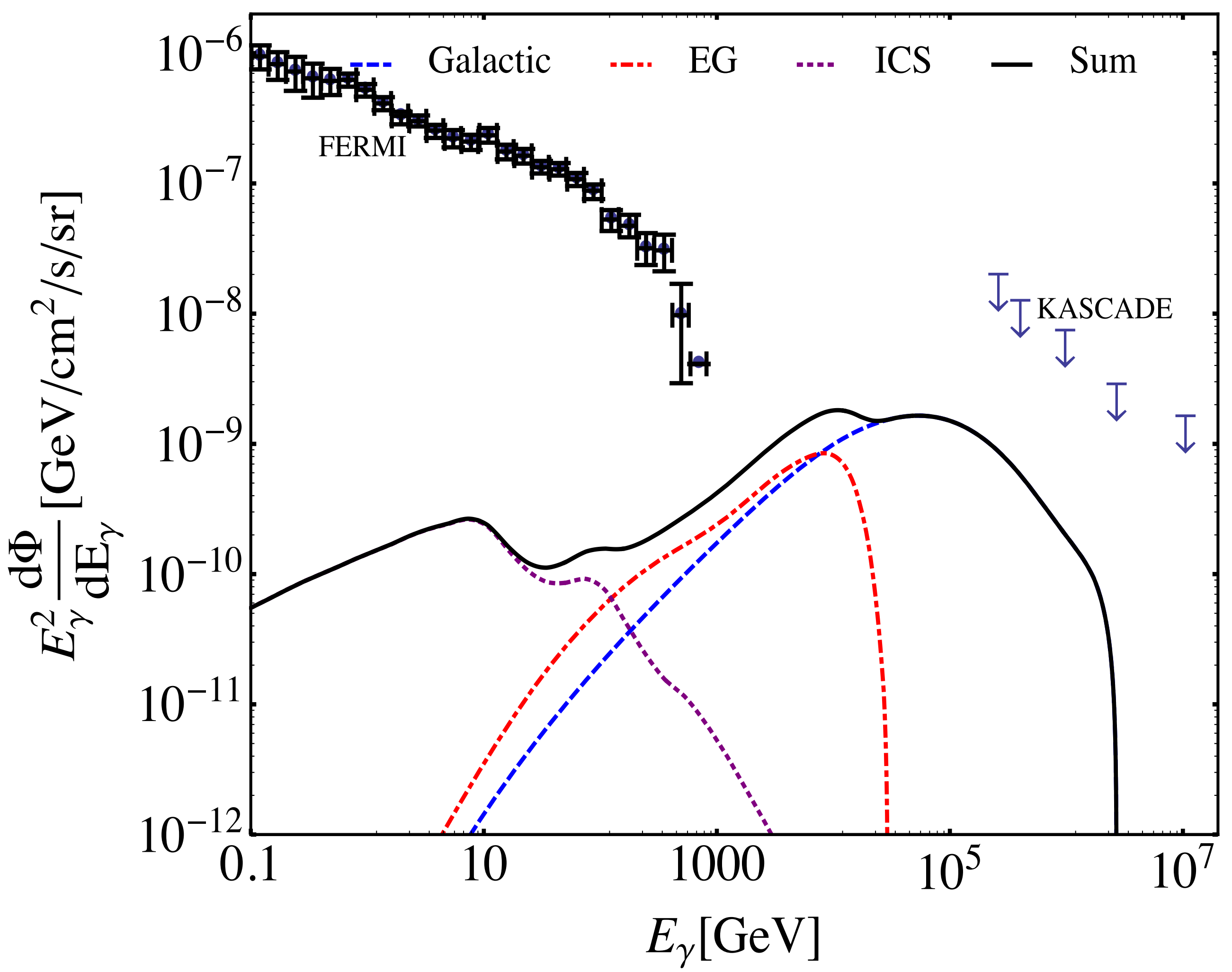


FIG. 5. The gamma-ray flux from DM decay with $m_\chi \sim 5$PeV and lifetime $\tau_\chi \sim 2 \times 10^{28}$s, confronted with constraints from Fermi-LAT [67] and KASCADE [68] data.

KM3NeT HE ν (KM3-230213A)

2504.16040 [hep-ph]

With Sarif Khan, Jongkuk Kim

KM3-230213A

376 | Nature | Vol 638 | 13 February 2025

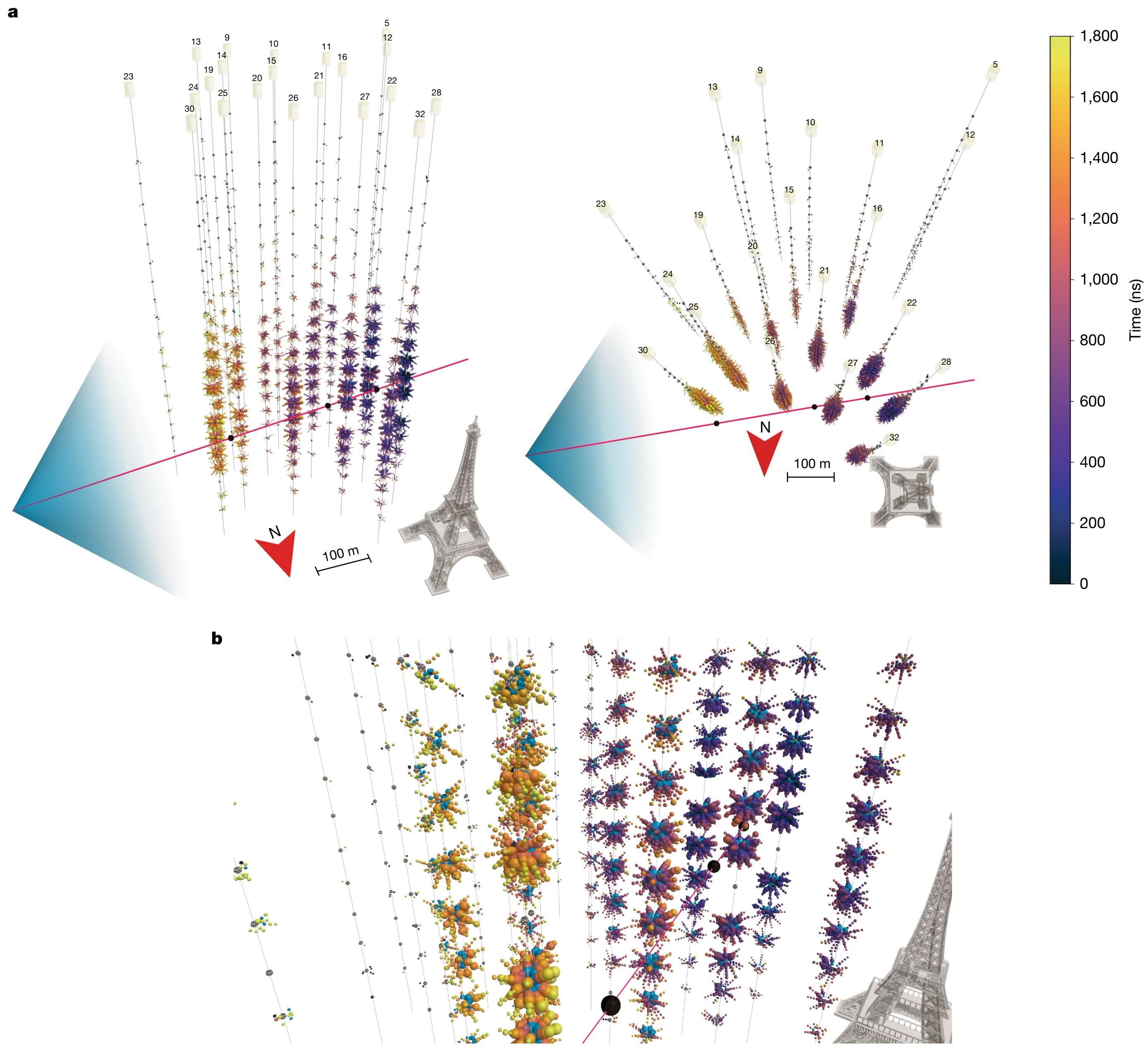


Fig. 1 | Views of the event. a, Side and top views of the event. The reconstructed trajectory of the muon is shown as a red line, along with an artist's representation of the Cherenkov light cone. The hits of individual PMTs are represented by spheres stacked along the direction of the PMT orientations. 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.

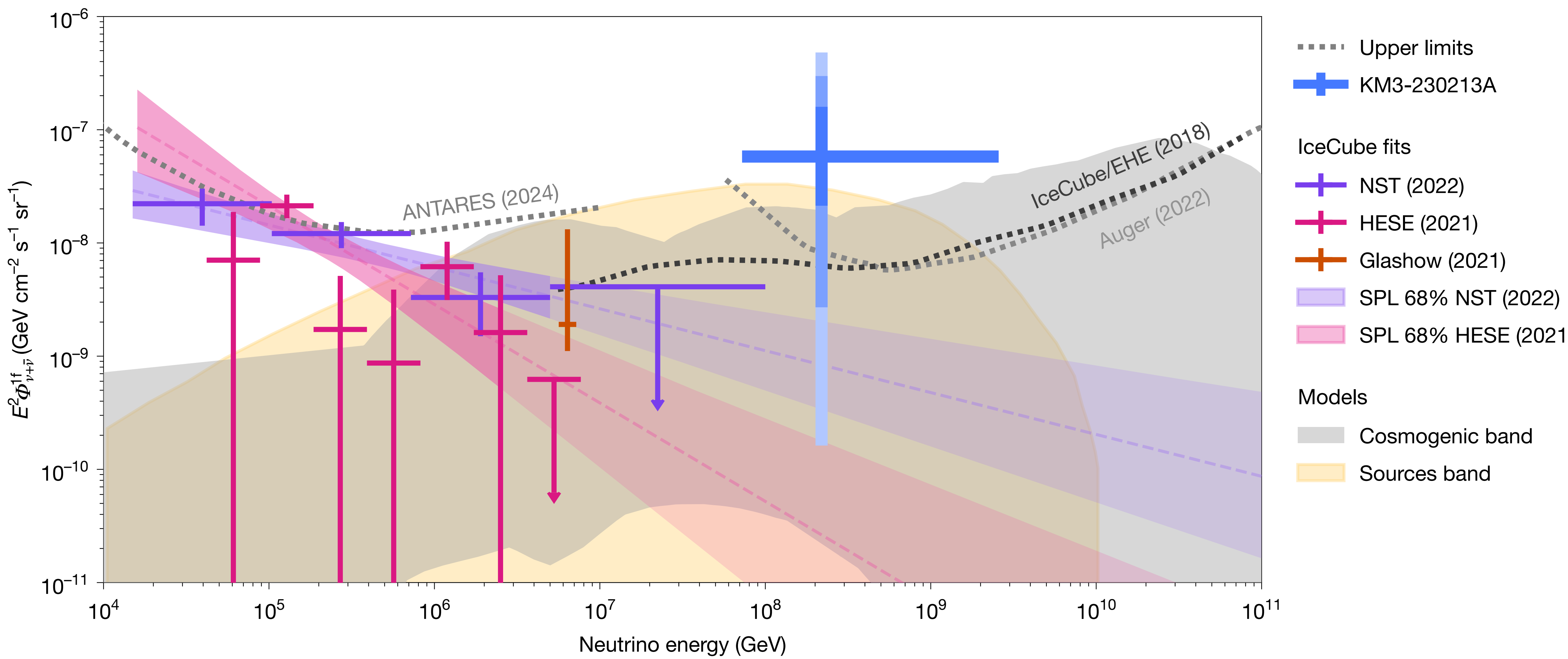


Fig. 5 | Comparison with models and earlier measurements. Shown is the energy-squared per-flavour astrophysical flux derived from the observation of KM3-230213A with measurements and theoretical predictions, assuming equipartition (ν_e:ν_μ:ν_τ = 1:1:1). The blue cross corresponds to the flux needed to 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..

Model

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

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

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

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

$\chi \to Z'\nu, Z\nu, W^\mp l^\pm,$ 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 $\to$ only single peak in the neutrino energy spectrum in practice

Results

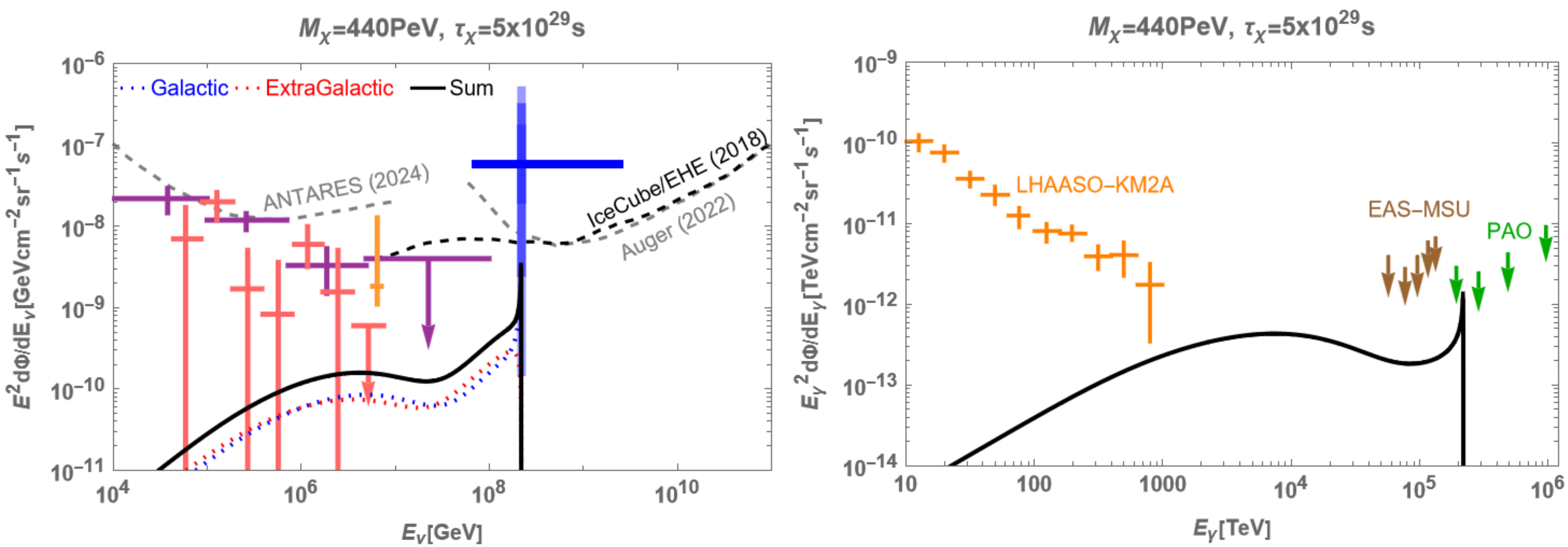


Figure 1. Neutrino (left-panel) and Gamma-ray (right-panel) spectra from DM χ decay with $M_\chi = 440$PeV and lifetime $\tau_\chi = 1/\Gamma = 5 \times 10^{29}$s. In the left panel, bounds come from IceCube [43, 44]. Blue cross corresponds to KM3NeT with 3σ C.L [1]. It presents the galactic (blue dotted 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

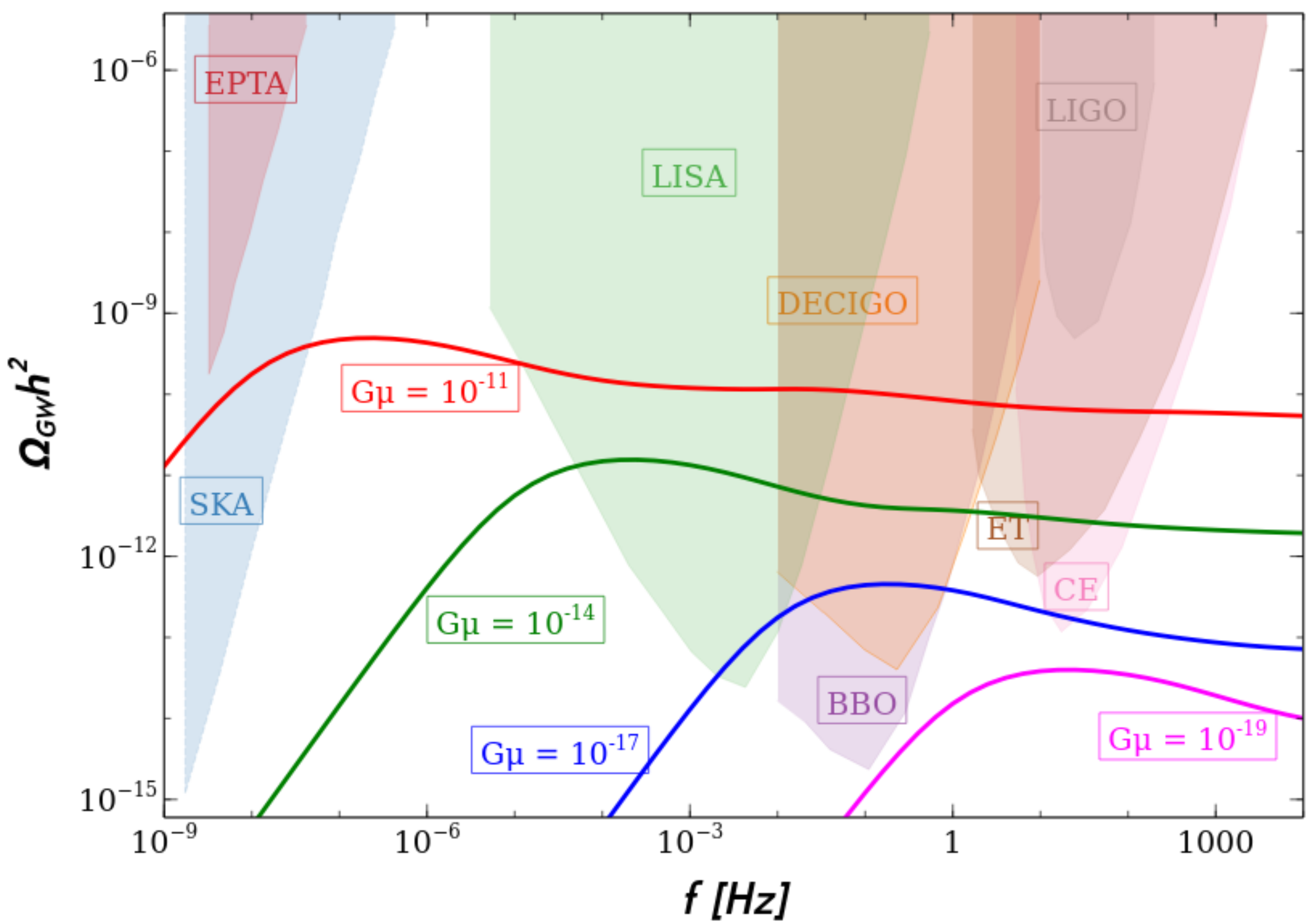


Figure 2. Variation of relic GW density with frequency for different values of string tension. Different colours represent the sensitivity prospects of various future GW detectors. EPTA data excludes cosmic string tensions $G\mu > 2 \times 10^{-11}$.

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

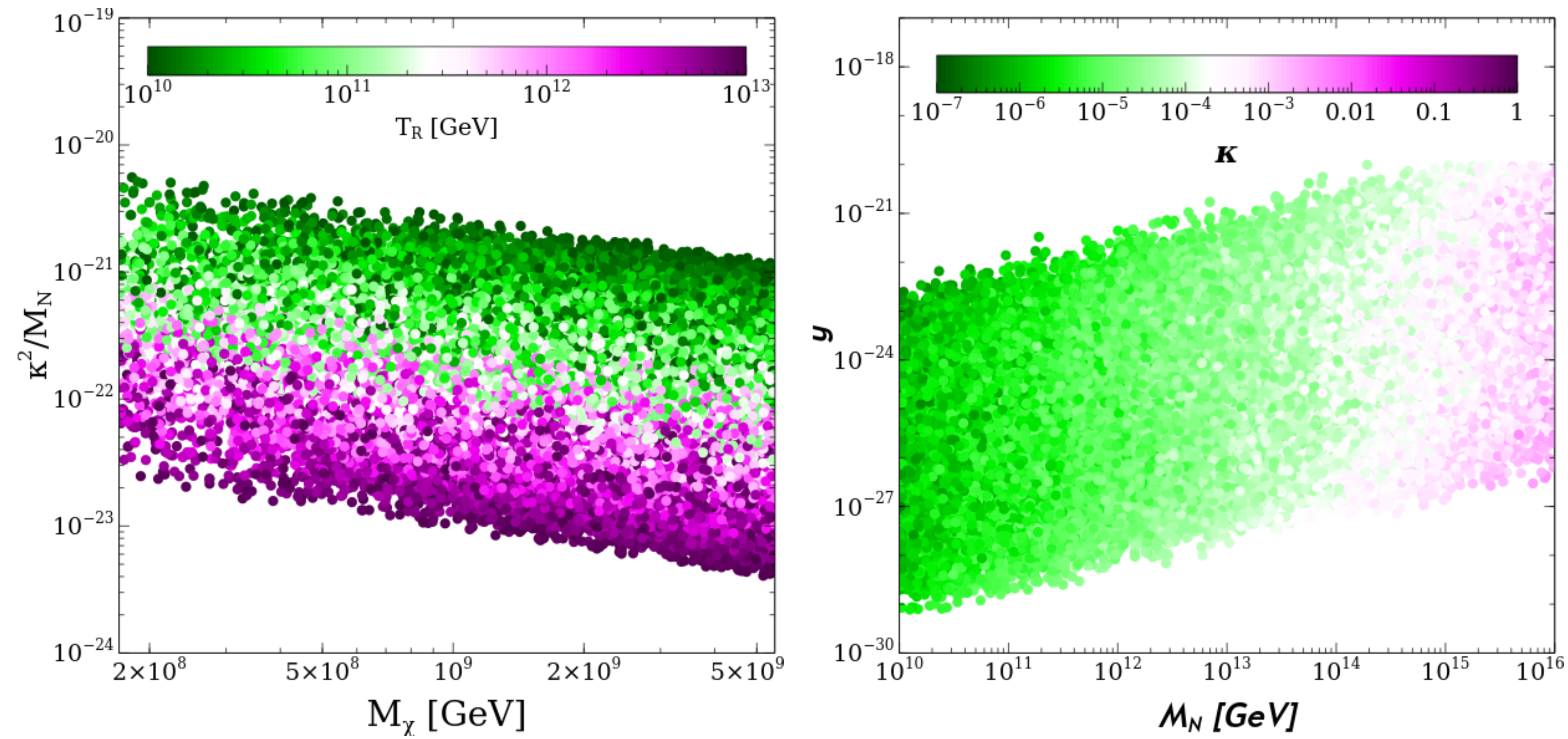


Figure 3. In the left panel (LP), we show the scatter plot in the $(M_\chi,\ \frac{\kappa^2}{M_N})$ plane, whereas the right panel (RP) displays the scatter plot in the $(M_N,\ y)$ plane. The color gradient in the LP represents different values of the reheating temperature T_R, while in the RP, it corresponds 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

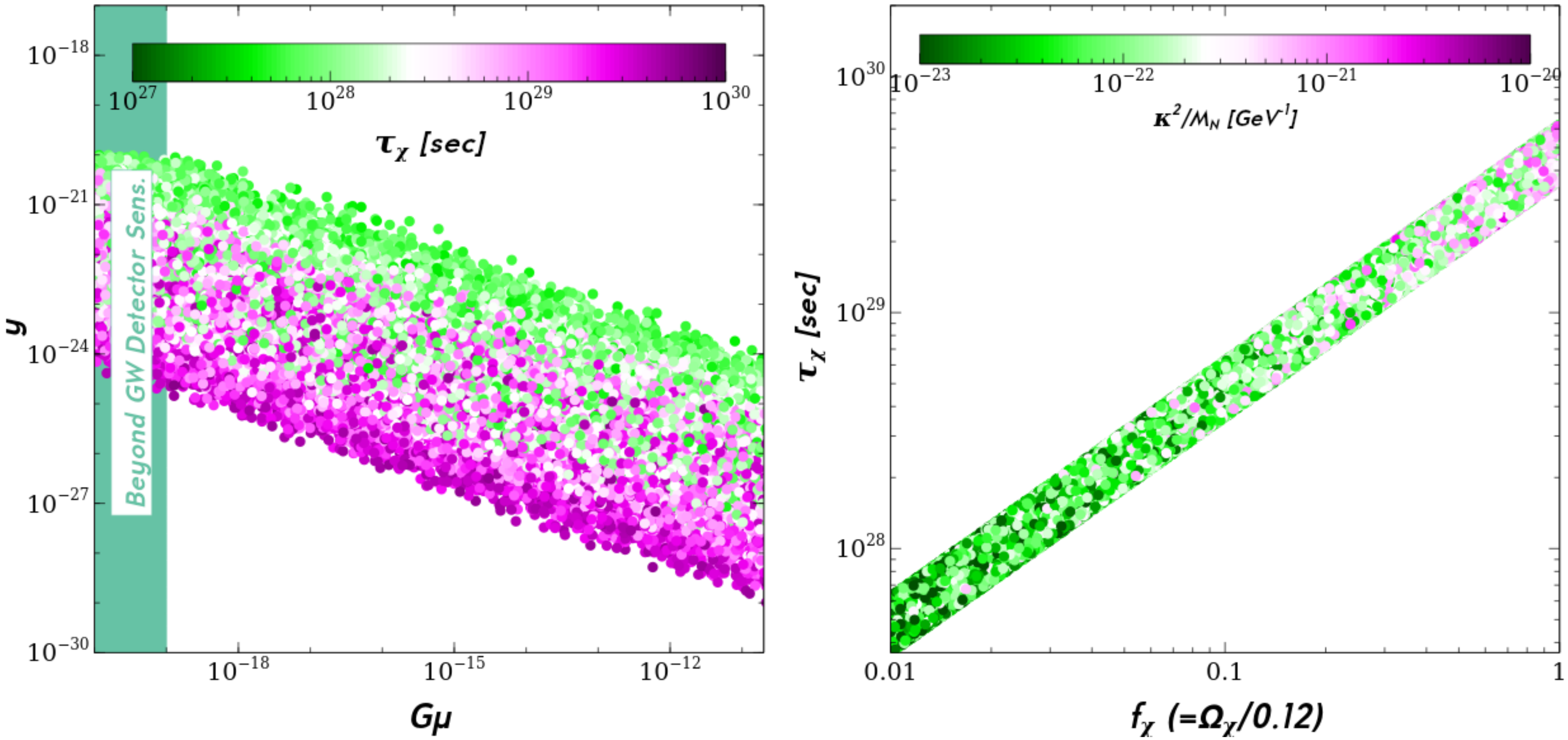


Figure 4. The LP and RP show scatter plots in the $(G\mu,\ y)$ and $(f_\chi,\ \tau_\chi)$ planes, respectively. In the LP, the color gradient represents different values of τ_χ, while in the RP, it corresponds to values of κ^2/M_N.

$T_R \sim 10^{10}$ 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

Old Wine in a New Bottle

- Following the SM construction, I discussed dark gauge symmetry to accommodate absolutely stable or long-lived EW mass scale DM particles
- Mathematically consistent models (nothing under the rug)
- Inelastic DM with dark Higgs boson (XENON1T excess)
- DQCD w/ scale sym: EWSB and CDM from DQCD sector
- Decaying heavy spin-1/2 DM for AMS02, IceCUBE, KM3
- Chiral dark sector (750GeV diphoton excess=dark Higgs)
- These anomalies are all gone, but the underlying models may be useful in the future