Rare Invisible Decays and Flavorful Light Dark Matter

Xiao-Gang He
Tsung-Dao Lee Institute
Shanghai Jiao Tong University

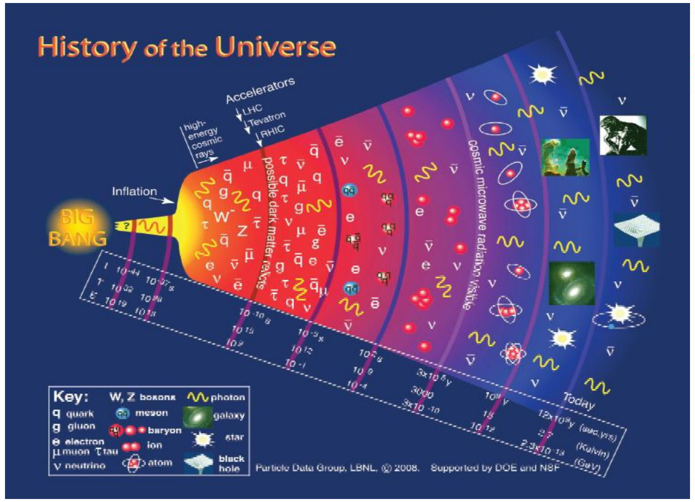
arXive: 2403.12485 (JHEP 07 (2024)168)
XG He, XD Ma, M. Schmidt, G. Valencia, and R. Volkas
arXive:2505.02031(PRD 112(2025) 055025)
XG He, XD Ma, J. Tandean, G. Valencia

AEI 5th (2025)

29/9 - 3/10, 2025

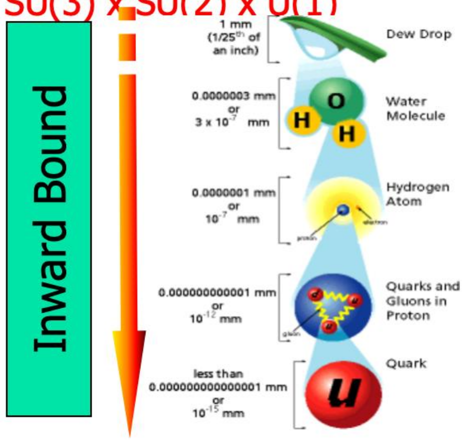
1. A window for a light flavorful dark matter
2. B to K invisible and K to π invisible and DM
3. DM relic density and indirect searches
4. Direct DM searches and Migdal effects
5. Conclusion

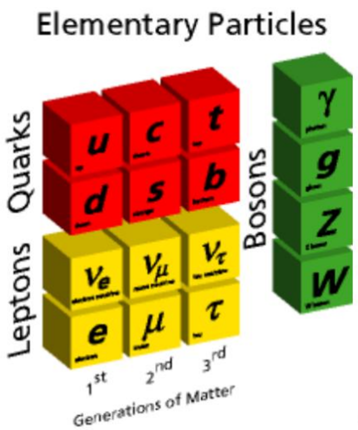
1. A window for a Light Flavorful Dark Matter

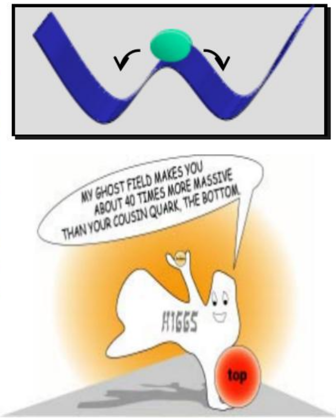


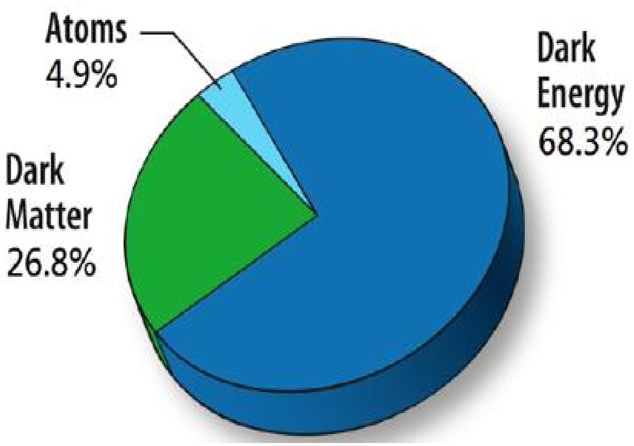
The standard model of electroweak and strong interactions

SU(3) x SU(2) x U(1)









Gravitational effects from cosmology and astrophysics need the existence of Dark Matter! This is new physics beyond the standard model. WIMP is among the best candidates for DM. How it interacts with the SM sector, not known! Just gravity, may be other interactions or it may be specific particle-phlic or particle-phobic.

On the other hand, there are some puzzles or anomalies in particle physics, such as the recently reported excess of B^+ to K^+ vv and room in K^+ to π^+ vv for new physics beyond SM.

DM couplings to SM are flavor dependent

There is the window of a light dark matter for invisible decays!!!

Recent BELLE-II and NA62 results

$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{\mathrm{exp}} = (2.3 \pm 0.7) \times 10^{-5}$$

$$\mathcal{B}(K^+ \to \pi^+ + \not{E})_{\mathrm{exp}} = (13.0^{+3.3}_{-3.0}) \times 10^{-11}$$

The SM predictions

$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{\mathrm{SM}} = (4.43 \pm 0.31) \times 10^{-6}$$

$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})_{\mathrm{SM}} = (8.4 \pm 1.0) \times 10^{-11}$$

There is an excess for B to K vv

There is the $\Delta\mathcal{B}_K = (4.6^{+3.4}_{-3.2}) \times 10^{-11}$ window for something new !

A light flavorful dark matter solution -- DM couplings are flavor dependent

The B^+ -> K^+ invisible is due to B^+ -> K^+ Φ Φ (Φ dark matter). At the quark level due to: b -> s Φ Φ.

The allowed $\Delta\mathcal{B}_K = (4.6^{+3.4}_{-3.2}) \times 10^{-11}$ for K^+ to π^+ Φ Φ is due to, at the quark level: s -> d Φ Φ

$(m_{K^+} - m_{\pi^+})/2 = 177\,\mathrm{MeV}$ in order that the K^+ channel with the DM could occur.

If true, one should also check if the right relic density for DM can be realized.

At the quark level due to: Φ Φ -> dd, uu!

In a model independnet way, the following minimal interactions terms are needed

$$\mathcal{L}^{\phi\mathrm{LEFT}}_{qq\phi^2} \supset \frac{1}{2}\Big[C^{S,kl}_{d\phi}(\overline{d_k}d_l) + C^{P,kl}_{d\phi}(\overline{d_k}i\gamma_5 d_l) + C^{S,uu}_{u\phi}(\overline{u}u) + C^{P,uu}_{u\phi}(\overline{u}i\gamma_5 u)\Big]\phi^2\,,$$

There are stringent constraints from indirect DM searches, effects on CMB,

and also direct DM search via Migdal effect.

We find that light DM with a mass m_Φ between 110 MeV - 136 MeV is allowed and solves all problems

Light Flavorful Dark Matter Models !

2. B to K invisible and K to π invisible and MD

Combining previous bound,

$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})^{2021}_{\tt exp} = (1.1 \pm 0.4) \times 10^{-5}$$

$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})^{\tt ave}_{\tt exp} = (1.3 \pm 0.4) \times 10^{-5}$$

Room for new physics:

$$\mathcal{B}(B^+ \to K^+ + \text{inv})_{\tt NP} = (0.86 \pm 0.40) \times 10^{-5}$$

Also need to satisfy constraints

$$\mathcal{B}(B^0 \to K^0\nu\bar{\nu}) \leq 2.6 \times 10^{-5}\ (90\%\ \text{c.l.})$$

$$\mathcal{B}(B^+ \to K^{+*}\nu\bar{\nu}) \leq 4.0 \times 10^{-5}\ (90\%\ \text{c.l.})$$

$$\mathcal{B}(B^0 \to K^{0*}\nu\bar{\nu}) \leq 1.8 \times 10^{-5}\ (90\%\ \text{c.l.})$$

The invisible is due to Φ Φ pair in b to s Φ Φ decay induced B to K invisible

$$\mathcal{L}^{\phi\text{LEFT}}_{qq\phi^2} \supset \frac{1}{2}\Big[C^{S,kl}_{d\phi}(\overline{d_k}d_l) + C^{P,kl}_{d\phi}(\overline{d_k}i\gamma_5 d_l) + C^{S,uu}_{u\phi}(\overline{u}u) + C^{P,uu}_{u\phi}(\overline{u}i\gamma_5 u)\Big]\phi^2\,,$$

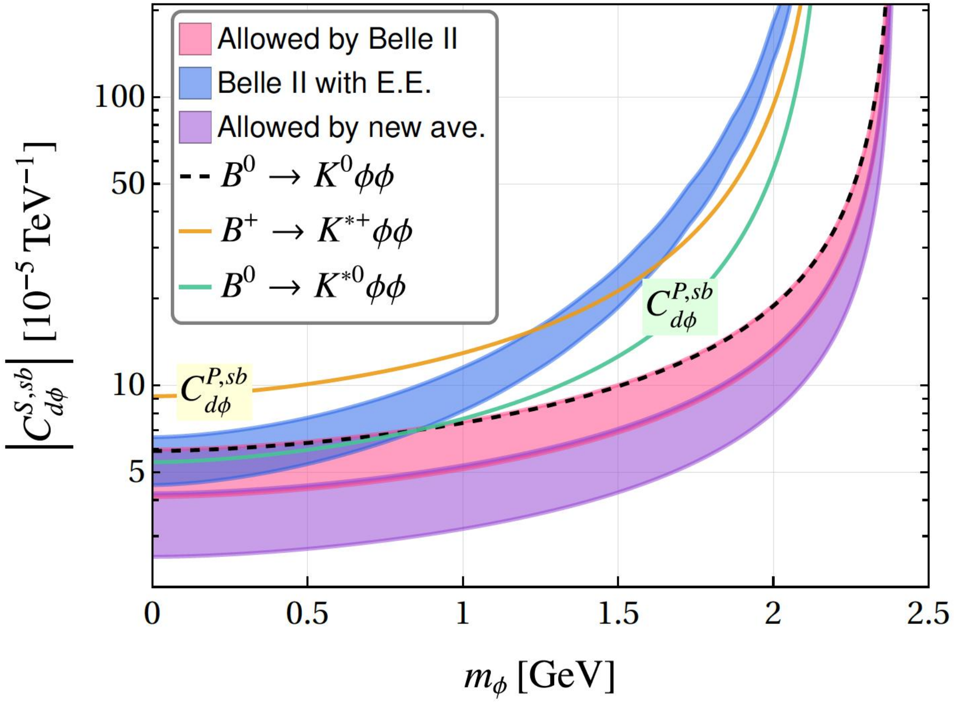
$$\frac{d\Gamma_{B\to K\phi\phi}}{ds_B} = \frac{\left|C_{d\phi}^{S,sb}\right|^2 m_B}{512\pi^3} f_0^2 \frac{(1-x_K)^2\lambda^{\frac{1}{2}}(1,x_K,s_B)\sqrt{1-4x_\phi/x_B}}{(\sqrt{x_b}-\sqrt{x_s})^2},$$

$$\frac{d\Gamma_{B\to K^*\phi\phi}}{ds_B} = \frac{\left|C_{d\phi}^{P,sb}\right|^2 m_B}{512\pi^3} A_0^2 \frac{\lambda^{\frac{3}{2}}(1,x_{K^*},s_B)\sqrt{1-4x_\phi/x_B}}{(\sqrt{x_b}+\sqrt{x_s})^2},$$

$$\lambda(x,y,z) = x^2+y^2+z^2-2xy-2xz-2yz. \qquad q^2 = s_B m_B^2$$

$$x_{K^{(*)}} = m_{K^{(*)}}^2/m_B^2,\ x_\phi = m_\phi^2/m_B^2,\ x_b = m_b^2/m_B^2,\ \text{and}\ x_s = m_s^2/m_B^2.$$

f_0 and A_0 use numerical fitting from “Dispersive analysis of B → K(*) and Bs→ ϕ form factors,” JHEP 12 (2023) 153, arrive:2305.06301 [hep-ph].



$$C_{d\phi}^{S,bs} \in [3,7]/(10^5\,\text{TeV}) \text{ and } m_\phi \in [0.1, 1]\,\text{GeV}$$

A light flavorful DM can solve the Belle-II excess.

Without conflicting bounds from other decay modes!

Can do more?

Figure 2: Preferred parameter space to explain the excess in $B^+ \to K^+ + \text{inv}$ via additional decay channels to DM final states, $B^+ \to K^+\phi\phi$ based on the latest Belle II measurement [1] in red, with an additional reweighted one to account for the selection efficiency in blue, and finally based on the new average in purple [1]. The dashed line indicates the current constraint from $B^0 \to K^0 + \text{inv}$ [4; 5] on $|C_{d\phi}^{S,sb}|$ and the solid orange and green lines the constraints on $|C_{d\phi}^{P,sb}|$ posed by the searches for $B^+ \to K^{+*} + \text{inv}$ and $B^0 \to K^{0*} + \text{inv}$ [4; 5], respectively.

NA62 experiment has measured the rarest SM decay K to π νν process

$$\mathcal{B}(K^+ \to \pi^+ + \not{E})_{\rm exp} = \left(13.0^{+3.3}_{-3.0}\right) \times 10^{-11} \qquad \mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})_{\rm SM} = (8.4 \pm 1.0) \times 10^{-11}$$

There is a gap between central values

$$\Delta\mathcal{B}_K = \left(4.6^{+3.4}_{-3.2}\right) \times 10^{-11}$$

Allow, s to d Φ Φ decay, induced K to π invisible. Theoretical calculations

Chiral realization

For such low-mass DM, we can deal with $K \to \pi\phi\phi$ and the DM annihilation into light hadrons brought about by the LEFT operators in Eq. (1) by means of chiral perturbation theory. This leads to the ϕ interactions with light mesons given by

$$\begin{aligned}\mathcal{L}_{\phi P} \supset \frac{B_0}{2}\phi^2 \Bigg\{ & \left(C^{S,uu}_{u\phi} + C^{S,dd}_{d\phi}\right)\left(\pi^+\pi^- + \frac{1}{2}\pi^0\pi^0\right) + \left(C^{S,uu}_{u\phi} + C^{S,ss}_{d\phi}\right)K^+K^- \\ & + \left(C^{S,dd}_{d\phi} + C^{S,ss}_{d\phi}\right)K^0\bar{K}^0 + \frac{1}{6}\left(C^{S,uu}_{u\phi} + C^{S,dd}_{d\phi} + 4C^{S,ss}_{d\phi}\right)\eta^2 + \frac{1}{\sqrt{3}}\left(C^{S,uu}_{u\phi} - C^{S,dd}_{d\phi}\right)\pi^0\eta \\ & + \left[C^{S,sd}_{d\phi}\left(\pi^-K^+ - \frac{1}{\sqrt{2}}\pi^0K^0 - \frac{1}{\sqrt{6}}\eta K^0\right) + \mathrm{H.c.}\right]\Bigg\}, \end{aligned} \tag{2}$$

$$\frac{d\Gamma_{K^+\to\pi^+\phi\phi}}{dq^2} = \frac{\lambda^{1/2}(m^2_{K^+}, m^2_{\pi^+}, q^2)\,\lambda^{1/2}(m^2_\phi, m^2_\phi, q^2)\,B_0^2}{512\pi^3\, m^3_{K^+}\, q^2}\left|C^{S,sd}_{d\phi}\right|^2,$$

$$\frac{d\Gamma_{K_L\to\pi^0\phi\phi}}{dq^2} = \frac{\lambda^{1/2}(m^2_{K^0}, m^2_{\pi^0}, q^2)\,\lambda^{1/2}(m^2_\phi, m^2_\phi, q^2)\,B_0^2}{512\pi^3\, m^3_{K^0}\, q^2}\left(\mathrm{Re}\, C^{S,sd}_{d\phi}\right)^2,$$

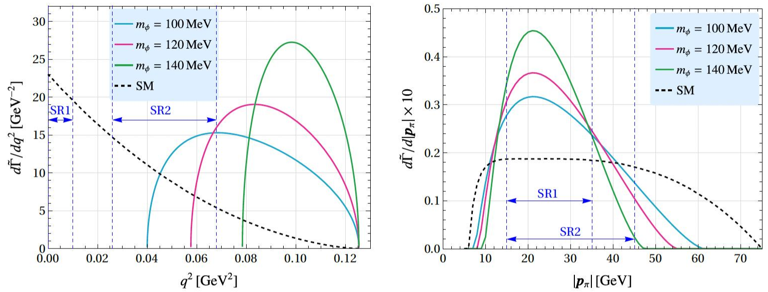


FIG. 2. The normalized distribution of the rate, Γ, of $K^+ \to \pi^+ + \not{E}$ against q^2 (left) and the π^+-momentum $|\boldsymbol{p}_\pi|$ (right) for several benchmark masses of the DM particle. The labels of the vertical axes are $d\tilde{\Gamma}/dq^2 \equiv (1/\Gamma)d\Gamma/dq^2$ and $d\tilde{\Gamma}/d|\boldsymbol{p}_\pi| \equiv (1/\Gamma)d\Gamma/d|\boldsymbol{p}_\pi|$, respectively.

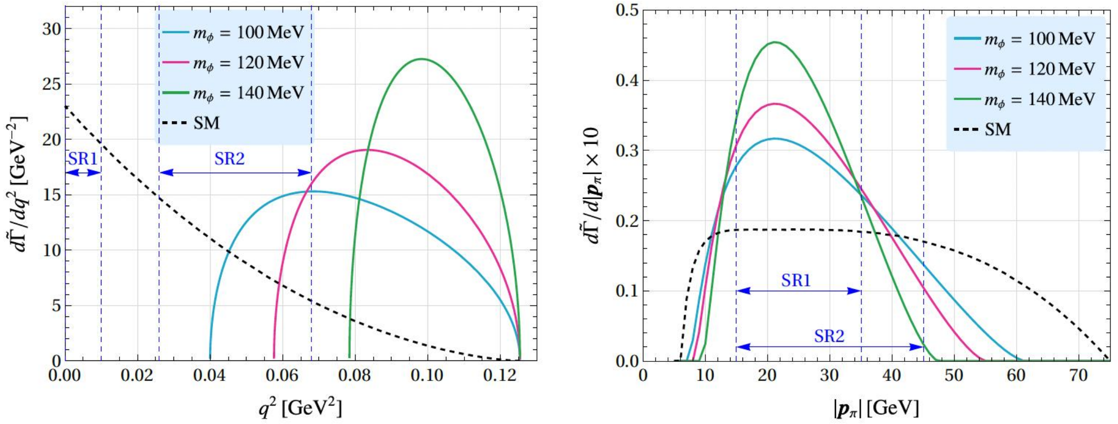


FIG. 2. The normalized distribution of the rate, Γ, of $K^+ \to \pi^+ + \not{E}$ against q^2 (left) and the π^+-momentum $|\boldsymbol{p}_\pi|$ (right) for several benchmark masses of the DM particle. The labels of the vertical axes are $d\tilde{\Gamma}/dq^2 \equiv (1/\Gamma)d\Gamma/dq^2$ and $d\tilde{\Gamma}/d|\boldsymbol{p}_\pi| \equiv (1/\Gamma)d\Gamma/d|\boldsymbol{p}_\pi|$, respectively.

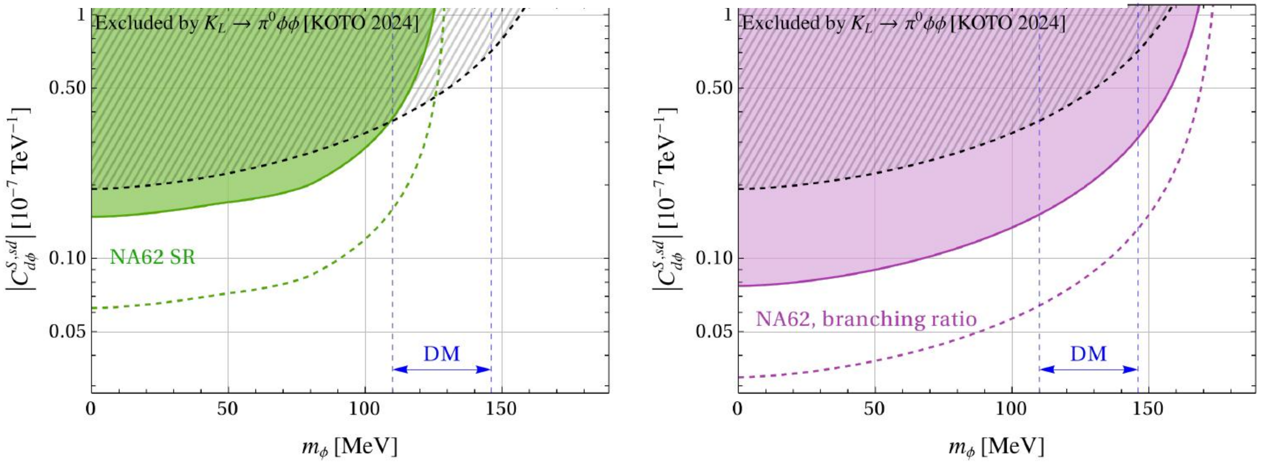
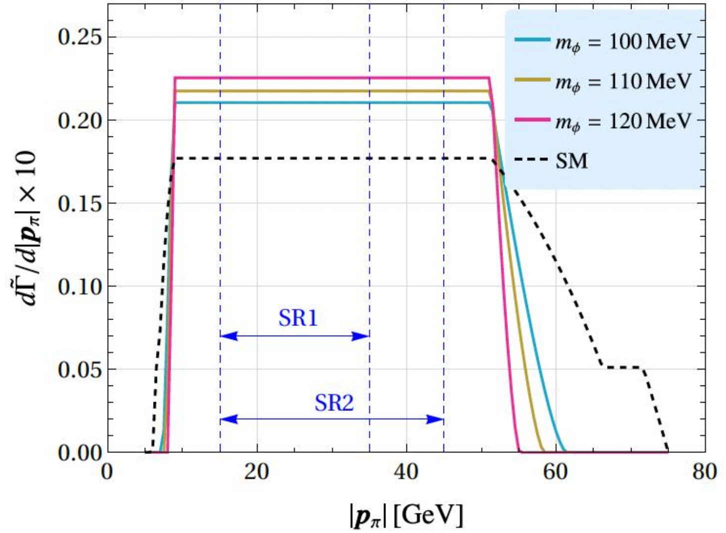


FIG. 1. Left: the green-shaded region represents the $|C_{d\phi}^{S,sd}|$ versus m_ϕ parameter space excluded by the latest NA62 [1] measurement of $K^+ \to \pi^+ + \not{E}$. The unshaded region between the solid and dashed green curves is where the new-physics window $\Delta\mathcal{B}_K$ can be populated by $K^+ \to \pi^+\phi\phi$. Only the $m_\phi \in [110, 146]$ MeV range, as indicated, is permitted by the DM relic density requirement. The hatched region is excluded by the recent KOTO [51] search for $K_L \to \pi^0 + \not{E}$ if $C_{d\phi}^{S,sd}$ is purely real. Right: the same as the left panel but using only the branching-ratio value reported by NA62 [1] and without regard to its signal regions.



There is room for light DM to contribute to K^+ to π^+ Φ Φ

A light flavorful DM allowed!

Refined spectrum measurement for K^+ to π^+ νν will test the scenario proposed here

Koto experiment to provide more information.

3. DM relic density and indirect seaches

DM relic density: Φ Φ -> uu, dd -> $\pi^+\pi^+$, $\pi^0\pi^0$ for m_ϕ <177 MeV for hadronic annihilation

also possible to photonic and leptonic finall states. there are some problems!

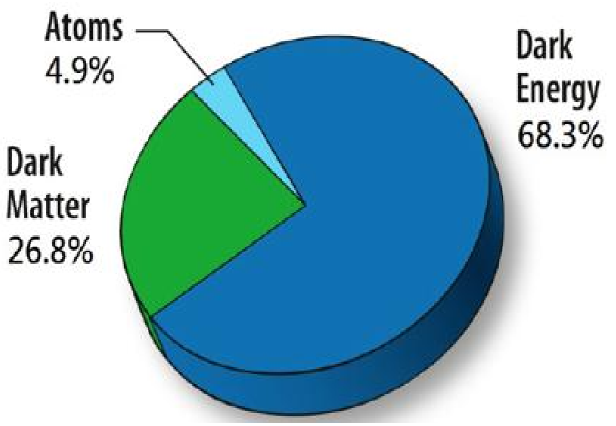
$$\mathcal{L} \ni \mathcal{L}_{\rm QCD} - [\overline{q_R}(s+ip)q_L + \text{ h.c. }] \qquad s = -\frac{1}{2}\begin{pmatrix} C_{u\phi}^{S,uu} & 0 & 0 \\ 0 & C_{d\phi}^{S,dd} & C_{d\phi}^{S,ds} \\ 0 & C_{d\phi}^{S,sd} & C_{d\phi}^{S,ss} \end{pmatrix}\phi^2, \quad p = \frac{1}{2}\begin{pmatrix} C_{u\phi}^{P,uu} & 0 & 0 \\ 0 & C_{d\phi}^{P,dd} & C_{d\phi}^{P,ds} \\ 0 & C_{d\phi}^{P,sd} & C_{d\phi}^{P,ss} \end{pmatrix}\phi^2 .$$

Chiral realization

$$\begin{aligned}\mathcal{L}_{\phi P} \ni \frac{B}{2}\phi^2 \Big\{ & \left(C_{u\phi}^{S,uu} + C_{d\phi}^{S,dd}\right)\left(\pi^+\pi^- + \frac{1}{2}\pi^0\pi^0\right) + \left(C_{u\phi}^{S,uu} + C_{d\phi}^{S,ss}\right)K^+K^- \\ & + (C_{d\phi}^{S,dd} + C_{d\phi}^{S,ss})K^0\bar{K}^0 + \frac{1}{6}\left(C_{u\phi}^{S,uu} + C_{d\phi}^{S,dd} + 4C_{d\phi}^{S,ss}\right)\eta^2 + \frac{1}{\sqrt{3}}\left(C_{u\phi}^{S,uu} - C_{d\phi}^{S,dd}\right)\pi^0\eta \\ & + \left[C_{d\phi}^{S,ds}\left(\pi^+K^- - \frac{1}{\sqrt{2}}\pi^0\bar{K}^0 - \frac{1}{\sqrt{6}}\eta\bar{K}^0\right) + \text{h.c.}\right]\Big\} .\end{aligned}$$

$$\sigma(\phi\phi \to \pi^+\pi^-/\pi^0\pi^0) = \frac{1}{\mathcal{S}}\frac{B_0^2\left|C_{u\phi}^{S,uu} + C_{d\phi}^{S,dd}\right|^2}{16\pi\hat{s}}\sqrt{\frac{\hat{s}-4m_\pi^2}{\hat{s}-4m_\phi^2}},$$

$\mathcal{S} = 1$ and 2 for the $\pi^+\pi^-$ and $\pi^0\pi^0$ channels.



DM relic density: Thermal averaged annihilation interaction rate

$$\langle\sigma v\rangle(\phi\phi \to \pi^+\pi^-/\pi^0\pi^0) = \frac{1}{\mathcal{S}}\frac{B_0^2\left|C_{u\phi}^{S,uu} + C_{d\phi}^{S,dd}\right|^2\tilde{\eta}(x,z_\pi)}{64\pi m_\phi^2}, \qquad x \equiv m_\phi/T$$

$$\tilde{\eta}(x,z) \equiv \frac{4x}{K_2^2(x)}\int_{\epsilon_{\rm th}}^{\infty} d\epsilon\, \frac{\sqrt{\epsilon}\sqrt{1+\epsilon-z}}{\sqrt{1+\epsilon}}K_1(2x\sqrt{1+\epsilon}) \qquad \epsilon_{\rm th} \equiv \max(0, z_\pi - 1), \quad z_\pi \equiv m_\pi^2/m_\phi^2$$

K_i standing for the modified Bessel function of order i

To produce the DM relic density, Ω h^2 = 0.12

$$\langle\sigma v\rangle \simeq 2.4\times10^{-26}\,\frac{\rm cm^3 s^{-1}}{(\hbar c)^2 c} = 2.2\times10^{-9}\,\text{GeV}^{-2}$$

Various Indirect DM effect constraints

$m_\phi < 177$ MeV the DM annihilates mostly into pion pairs, $\Phi\ \Phi \rightarrow \pi^+\pi^+,\ \pi^0\pi^0$.

The neutral pions emit photons ($\pi^0 \rightarrow \gamma\gamma$) and the charged ones produce them radiatively or via the inverse Compton scattering of their secondary electrons/positrons off the background photons.

These processes can take place within the DM halo of the Milky Way galaxy.The DM couplings are subject to constraints from astrophysical X-ray and gamma-ray observations (from telescopes such as INTEGRAL, XMM-Newton, Fermi-LAT, etc).

When DM annihilation occurs during the epoch of CMB, $\Phi\ \Phi \rightarrow \pi^+\pi^+,\ \pi^0\pi^0$ formation in the early Universe, the energy injected into the cosmic fluid from the annihilation products can alter the CMB anisotropy spectrum.

Therefore, measurements of CMB temperature and polarization anisotropies also imply restrictions on the annihilation processes.

Among indirect effects, CBM anisotropy spectrum gives a better constraint!

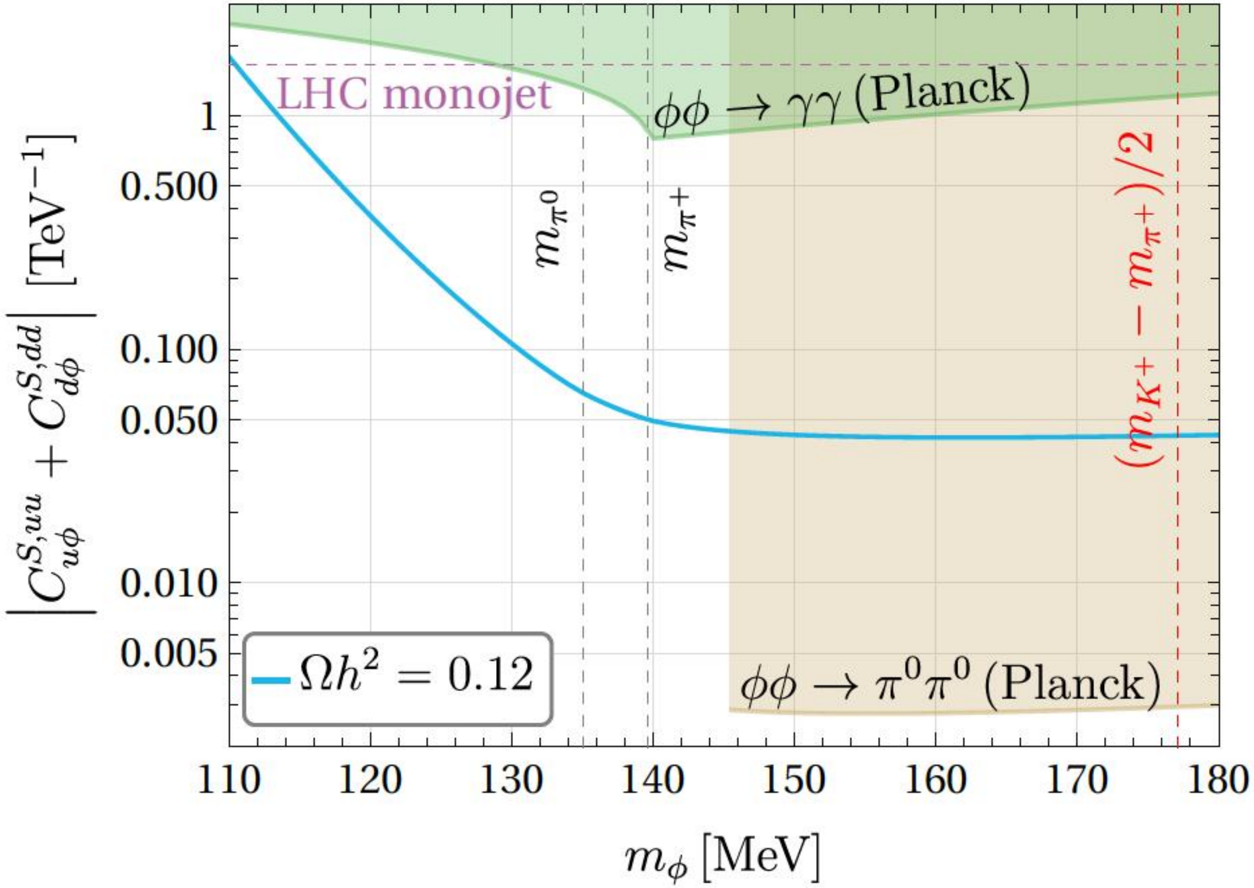
Indirect processes from effective interaction in the model

$$\langle \sigma v \rangle (\phi\phi \to \pi^+\pi^-/\pi^0\pi^0)_{\text{I.D.}} \approx \frac{1}{\mathcal{S}} \frac{B_0^2 \left| C_{u\phi}^{S,uu} + C_{d\phi}^{S,dd} \right|^2}{32\pi m_\phi^2} \sqrt{1 - \frac{m_\pi^2}{m_\phi^2}},$$

"I.D." indicates that the quantity has been derived for DM indirect searches

$$\langle \sigma v \rangle (\phi\phi \to \gamma\gamma)_{\text{I.D.}} \approx \frac{B_0^2 \left| C_{u\phi}^{S,uu} + C_{d\phi}^{S,dd} \right|^2}{64\pi m_\phi^2} \frac{8\alpha_{\text{em}}^2 m_\phi^4}{\pi^2 m_{\pi^+}^4} |F(\rho_\pi)|^2 .$$

$$F(\rho_\pi) = \frac{-1}{\rho_\pi} \left(\frac{1}{\rho_\pi} \ln^2 \frac{\sqrt{\rho_\pi - 4} - \sqrt{\rho_\pi}}{\sqrt{\rho_\pi - 4} + \sqrt{\rho_\pi}} + 1 \right), \qquad \rho_\pi = \frac{2q_1 \cdot q_2}{m_{\pi^+}^2} \approx \frac{4m_\phi^2}{m_{\pi^+}^2} .$$



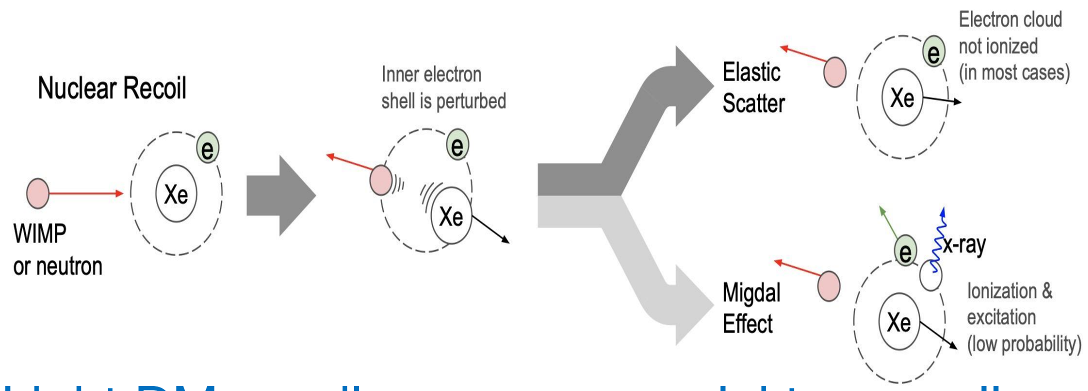
LHC monojet production DM limit is also shown in the figurehe model

Very strongly constrain parameter space and also allowed DM mass range, but DM window allowed!!!

4. Direct DM searches and Migdal effects

The Migdal effects and light DM constraints

Threshold of electron too recoil for Xenon experiment: ~ 100 eV



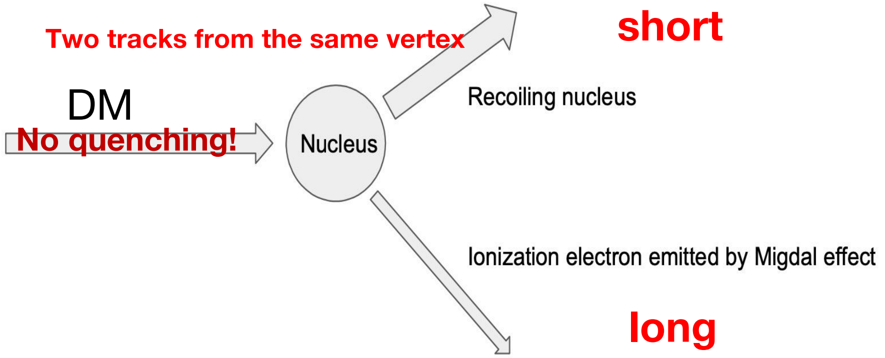
$$B_q^N \equiv \frac{\langle N(\boldsymbol{k},r)|\bar{q}q|N(\boldsymbol{k},r)\rangle}{2m_N} = \frac{m_N}{m_q} f_{Tq}^{(N)} ;$$

$$f_{Tu}^{(p)} = 0.018(5)\,, \quad f_{Td}^{(p)} = 0.027(7)\,, \quad f_{Ts}^{(p)} = 0.037(17)$$

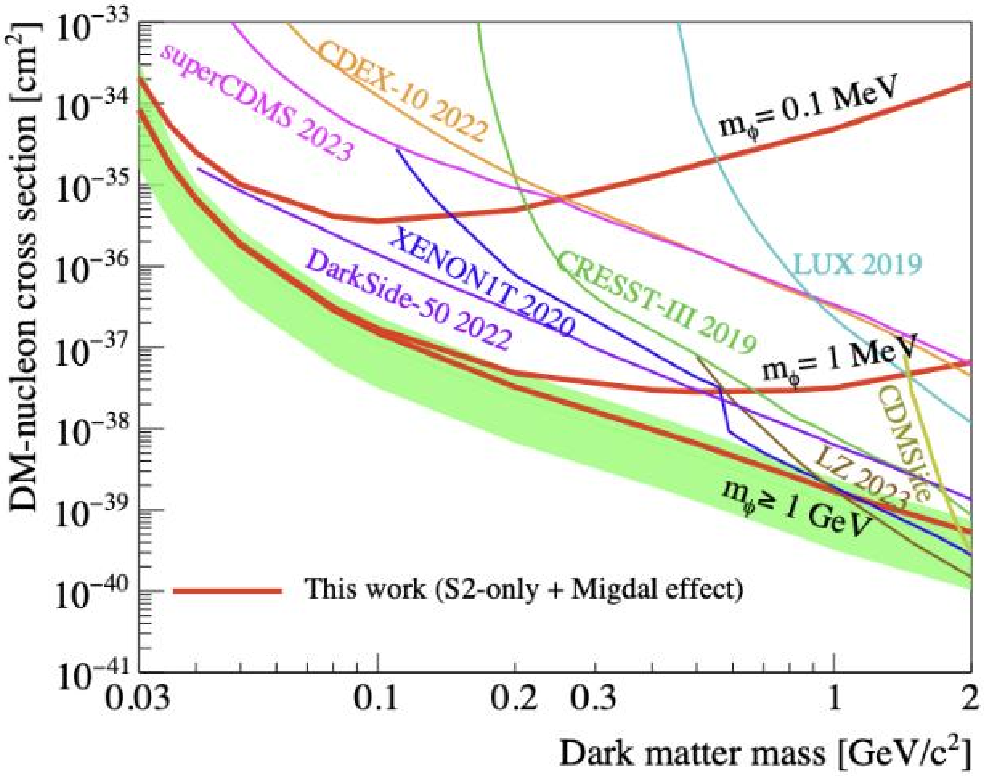
$$f_{Tu}^{(n)} = 0.013(3)\,, \quad f_{Td}^{(n)} = 0.040(10)\,, \quad f_{Ts}^{(n)} = 0.037(17)$$

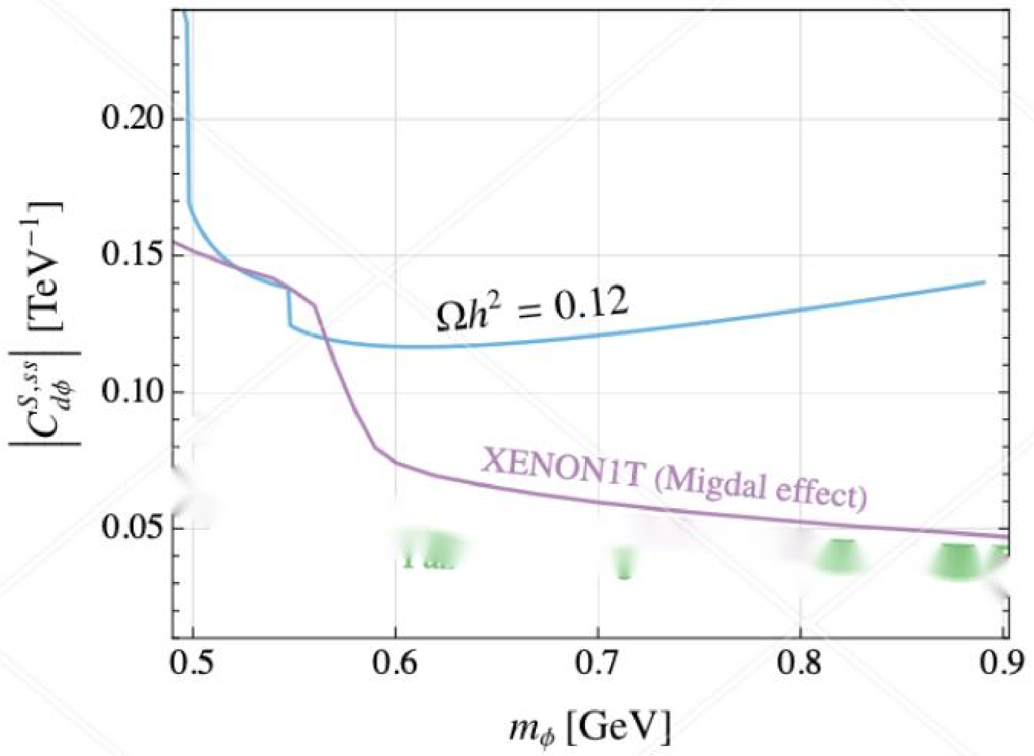
Light DM recoil energy on nuclei too small, not sensitive.

But sensitive to electron reciol energy from Migdal effect



$$\frac{d\langle\sigma_{n,l}v\rangle}{d\ln E_e} = \frac{\bar{\sigma}_n}{8\mu_n^2}[f_p Z + f_n(A-Z)]^2 \int dq\, \left[q|F_N(q)|^2 \times |F_{\rm DM}(q)|^2 |f_{nl}^{\rm ion}(p_e,q_e)|^2 \eta(v_{\rm min}(q,\Delta E_{n,l}))\right]$$





Left figure, m_ϕ is mediator mass, not the dark mass.

Problem: If only a non-zero $|C_{d\phi}^{S,ss}|$, ruled out by PandaX4T data

similarly for only $C^{S,uu}$ and $C^{S,dd}$ ruled out by data. Also even if only uu, dd together and allow cancellations, also ruled out.

But include uu, dd and ss all togheter, possible to have suviving regions!!

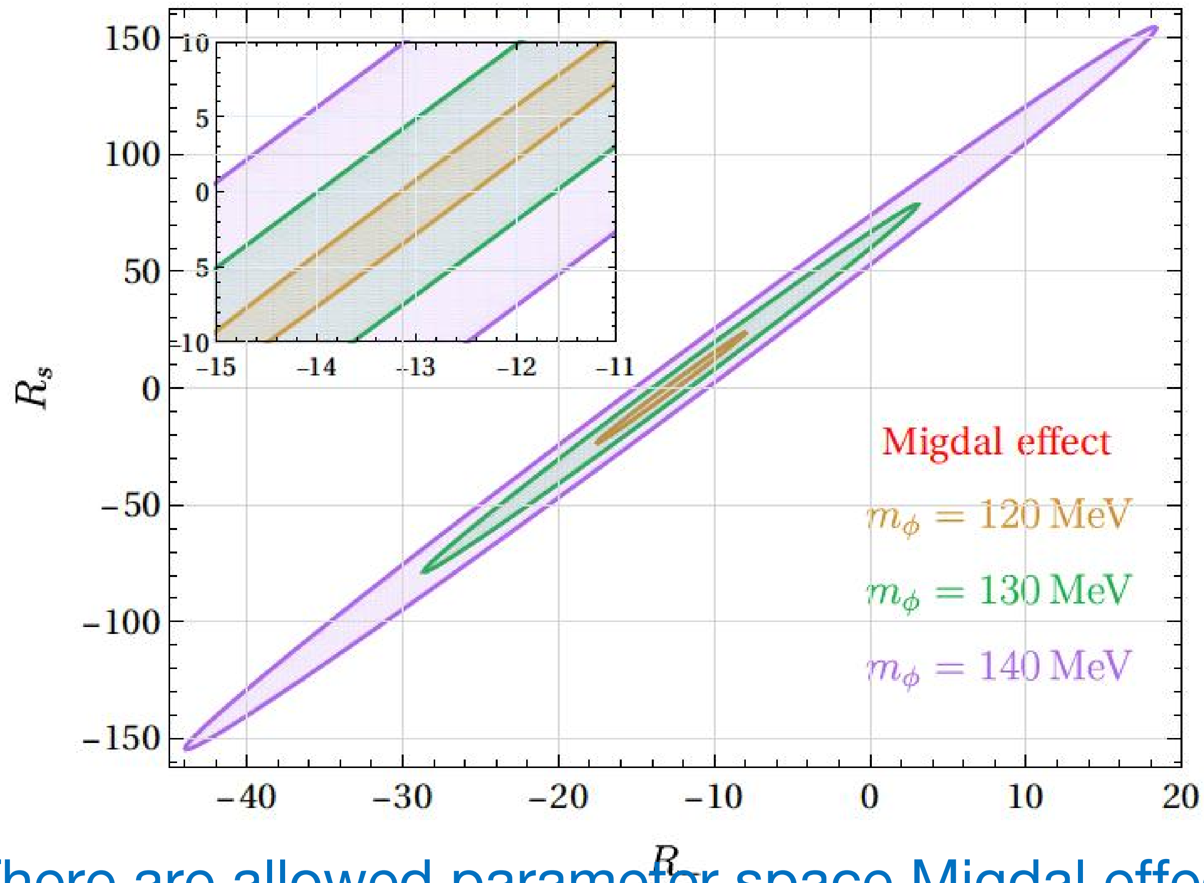
$$\frac{d\langle\sigma_{n,l}v\rangle}{d\ln E_e} = \frac{\bar{\sigma}_n}{8\mu_n^2}[f_p Z + f_n(A-Z)]^2 \int dq\ [q|F_N(q)|^2 \times |F_{\rm DM}(q)|^2 |f_{nl}^{\rm ion}(p_e,q_e)|^2 \eta(v_{\rm min}(q,\Delta E_{n,l}))]$$

$$\frac{2m_N^2}{m_s} f_{T_s}^{(N)} \left(C_{u\phi}^{S,uu} + C_{d\phi}^{S,dd}\right)\left(r_+^N + r_-^N R_- + R_s\right)$$

$$f_{T_q}^{(N)} = (m_q/m_N)\langle N|\bar{q}q|N\rangle.$$

$$r_\pm^N = \frac{1}{2}\left[\frac{f_{T_u}^{(N)} m_s}{f_{T_s}^{(N)} m_u} \pm \frac{f_{T_d}^{(N)} m_s}{f_{T_s}^{(N)} m_d}\right]$$

$$R_- = \frac{C_{u\phi}^{S,uu} - C_{d\phi}^{S,dd}}{C_{u\phi}^{S,uu} + C_{d\phi}^{S,dd}}, \qquad R_s = \frac{C_{d\phi}^{S,ss}}{C_{u\phi}^{S,uu} + C_{d\phi}^{S,dd}}.$$



Including Migdal effects from uu, dd, ss inside nuclei, there are parameter space to have DM mass below 177 MeV

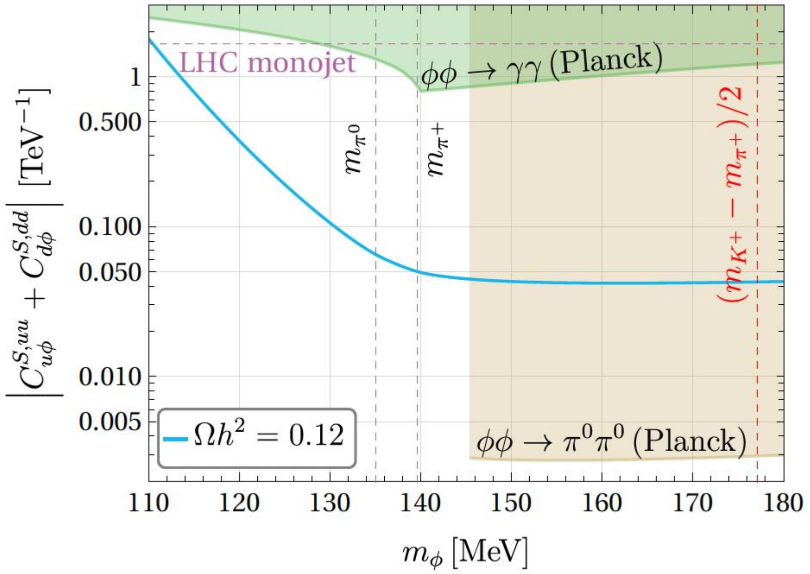
There are allowed parameter space Migdal effect constraints can be envaded.

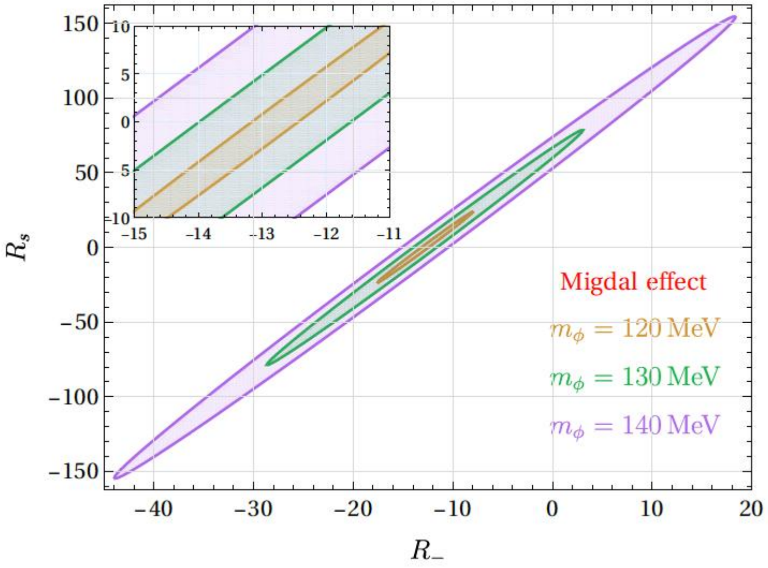
A light DM window of mass below 177 MeV exist!

5. Conclusion

It is viable to construct flavorful dark matter model in the window from recent NA62 result from K to π invisible satisfying:

DM relic density, indirect and direct detections for DM in the range 110 – 130 MeV





Further test of such models: Using another Nuclear target, such as CDEX data ([68]Ge…) carry out a similar ananlysis!!

Reniormalzable model? Heavy vector quark fermion (arXiv: 2403.12458 (JHEP07(2024)168), or Two Higgs doblet models (arXiv: 2502.09603) possible.

Dark Matter to be fermion or vector types, under investigations.

Thank you for Listening