

Dark multipole vectors below the GeV-scale

Josef Pradler

Particle Physics from Early Universe to Future Colliders

Portorož, Slovenia

April 11 2023



AUSTRIAN
ACADEMY OF
SCIENCES



universität
wien



European Research Council
Established by the European Commission

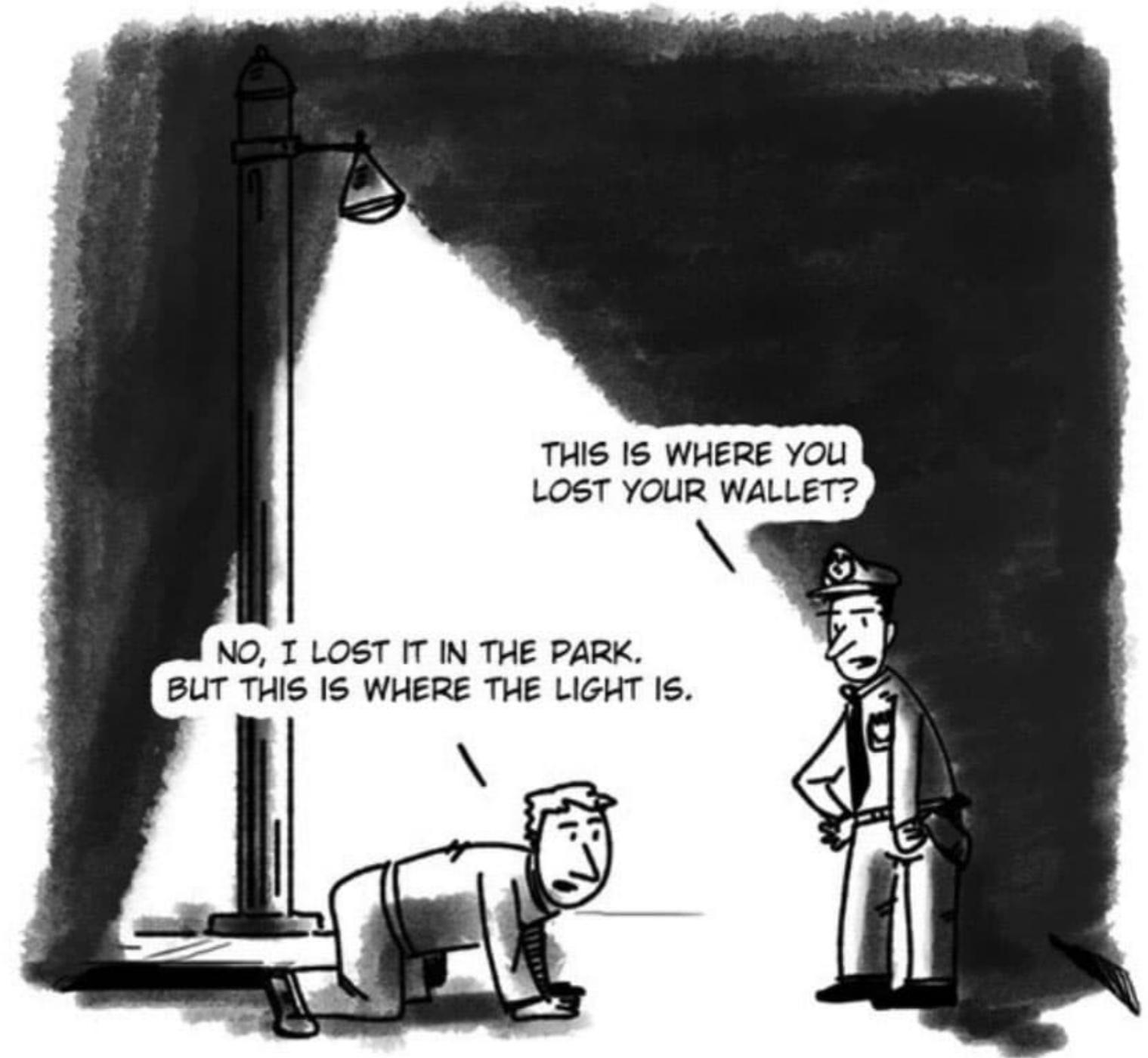
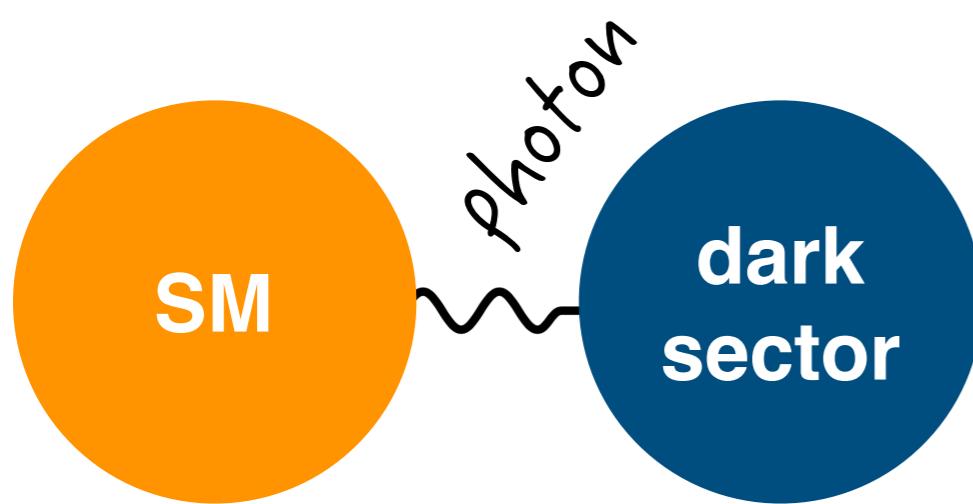
FWF

Der Wissenschaftsfonds.

Lighting New Lampposts for Dark Matter and Beyond the Standard Model

Drunkard search principle

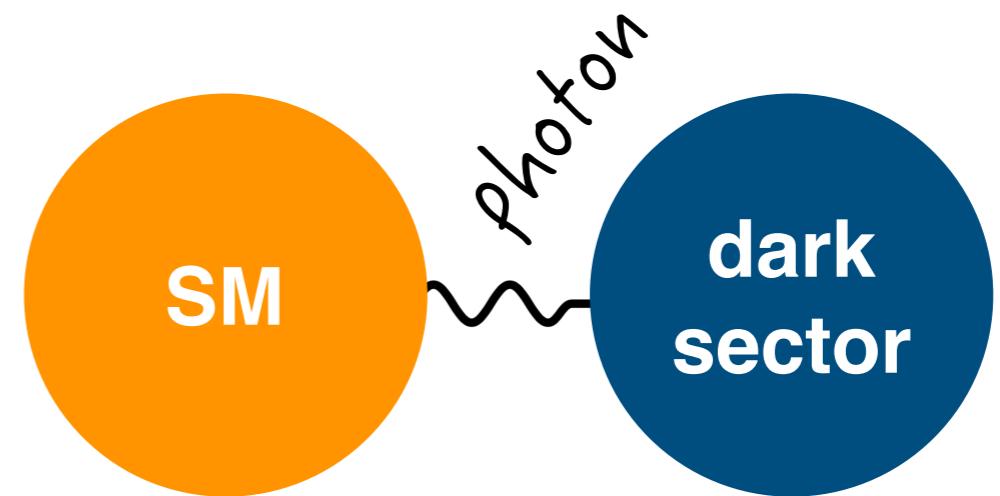
=> let's follow that



Dark states with EM form factors

Photon-portal

Dark Matter obviously needs to be (largely) neutral, but how dark is dark?



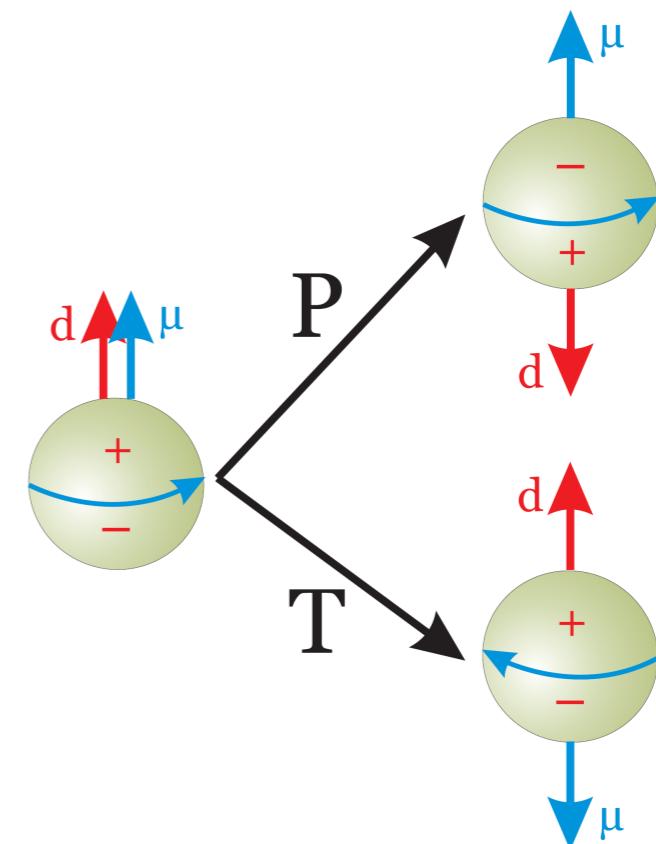
Even perfectly neutral particles can couple to photons

$$H_{\text{MDM}} = -\mu_\chi (\vec{B} \cdot \vec{\sigma}_\chi)$$

magnetic dipole moment (P and T even)

$$H_{\text{EDM}} = -d_\chi (\vec{E} \cdot \vec{\sigma}_\chi)$$

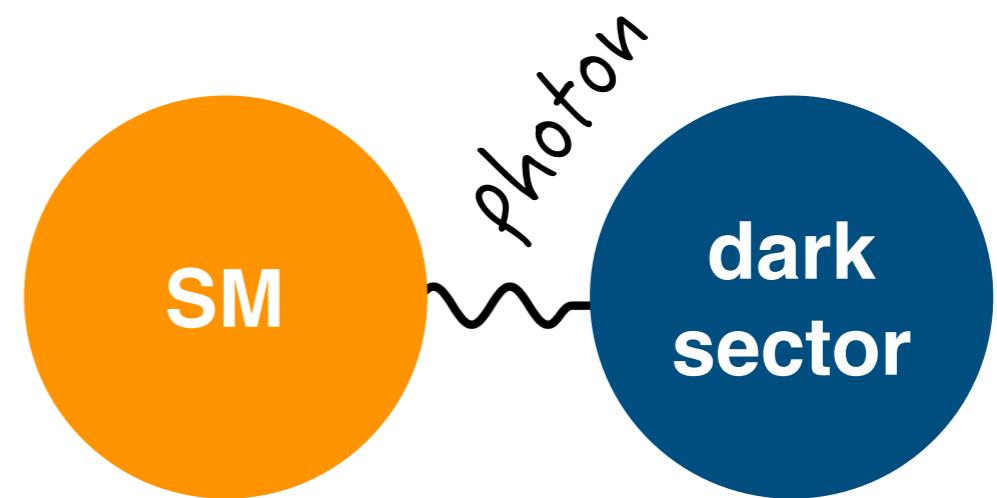
electric dipole (P and T odd => CP violating)



Dark states with EM form factors

Photon-portal

Dark Matter obviously needs to be (largely) neutral, but how dark is dark?



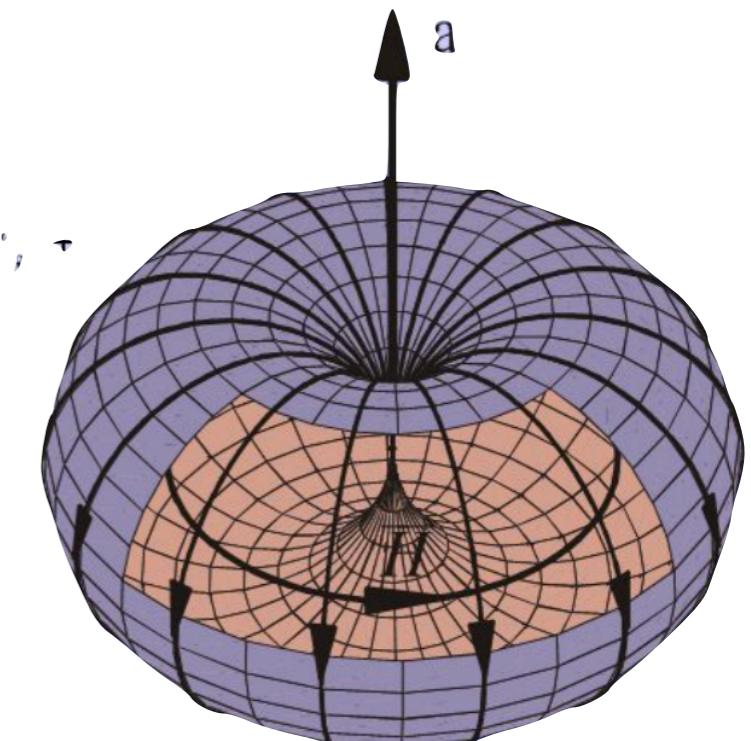
Even perfectly neutral particles can couple to photons

$$H_{\text{AM}} = -a_\chi (\vec{J} \cdot \vec{\sigma}_\chi)$$

anapole moment (P odd but CP even)

$$H_{\text{CR}} = -b_\chi (\vec{\nabla} \cdot \vec{E})$$

charge radius (P and T even)

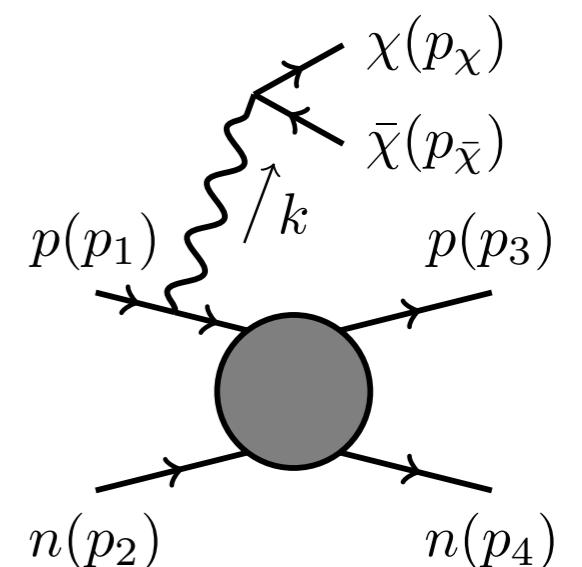
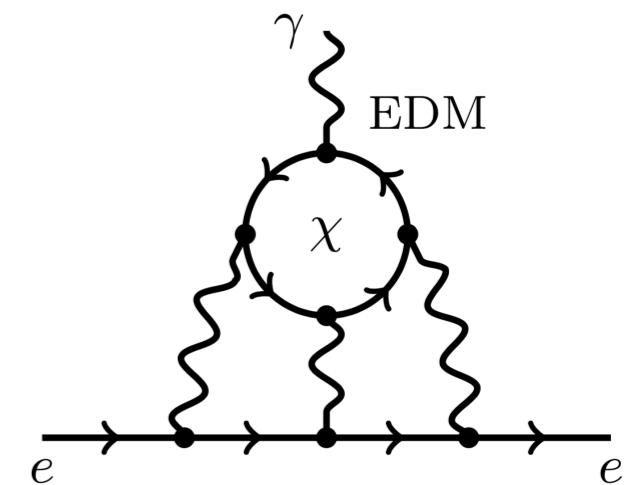
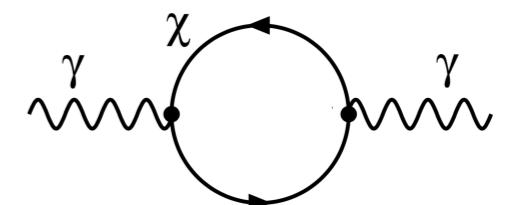


Dark states with EM form factors

Photon-portal

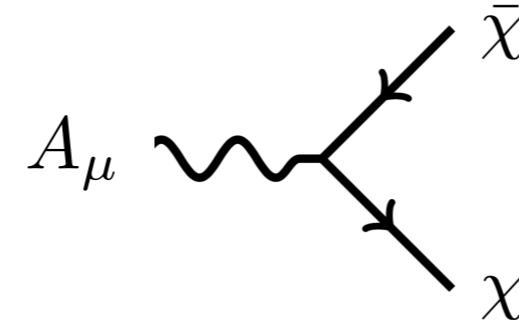
Tinkering with the photon may affect many known phenomena

- changes the strength of the EM interaction at various energy scales
- affects SM precision observables, e.g. g-2
- provides new photon-mediated decay channels of particles
- can we produce those “dark states” in the laboratory?
- can we have a “theory of dark matter” through the photon coupling?
- implications for astrophysics? is it cosmologically viable?



Dark states with EM form factors

SPIN 1/2 case is familiar



Effective operators

millicharge (ϵQ):

$$\epsilon e \bar{\chi} \gamma^\mu \chi A_\mu, \quad \text{dim 4}$$

magnetic dipole (MDM):

$$\frac{1}{2} \mu_\chi \bar{\chi} \sigma^{\mu\nu} \chi F_{\mu\nu}, \quad \dots \dots \dots$$

electric dipole (EDM):

$$\frac{i}{2} d_\chi \bar{\chi} \sigma^{\mu\nu} \gamma^5 \chi F_{\mu\nu}, \quad \text{dim5}$$

anapole moment (AM):

$$a_\chi \bar{\chi} \gamma^\mu \gamma^5 \chi \partial^\nu F_{\mu\nu}, \quad \dots \dots \dots$$

charge radius (CR):

$$b_\chi \bar{\chi} \gamma^\mu \chi \partial^\nu F_{\mu\nu}. \quad \text{dim6}$$

Rich history of studies: [Pospelov and T. ter Veldhuis (2000); Sigurdson et al (2004); Ho and Scherrer (2013), ...; **Chu et al (2019, 2020a,b)**, Chang et al (2021), ...]

=> SPIN 1 case has comparatively received much less attention

Vector Dark States

Chu, Ibarra, Hisano, Kuo, JP
2303.13643

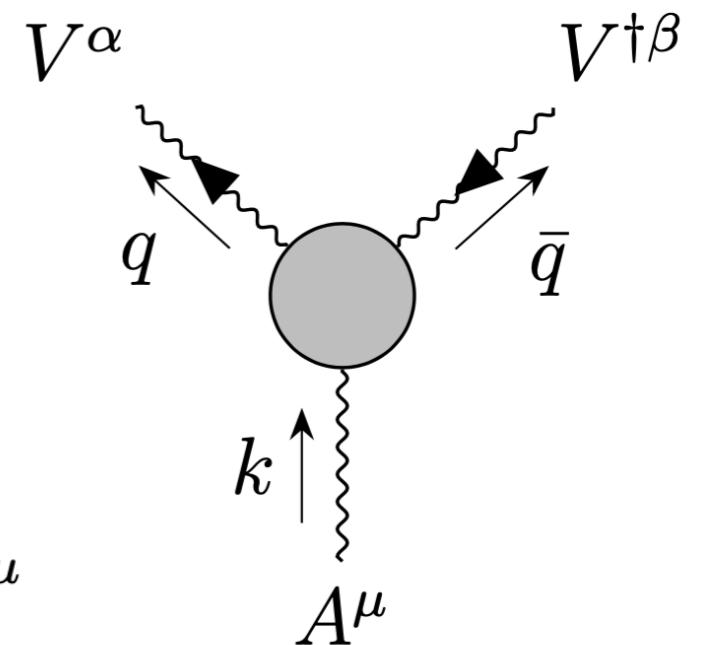
SPIN1 case: construction

Consider all possible Lorentz structures

=> yields 9 structures

$$i\Gamma_{VV^\dagger\gamma}^{\alpha\beta\mu}(q, \bar{q}, k) =$$

$$\begin{aligned} \Gamma_{VV^\dagger\gamma}^{\alpha\beta\mu} &= c_1(k^2) p^\mu g^{\alpha\beta} + c_2(k^2) k^\alpha g^{\beta\mu} + c_3(k^2) k^\beta g^{\alpha\mu} \\ &+ c_4(k^2) k_\lambda \epsilon^{\mu\alpha\beta\lambda} + c_5(k^2) p_\lambda \epsilon^{\mu\alpha\beta\lambda} \\ &+ c_6(k^2) k^\alpha k^\beta p^\mu \\ &+ c_7(k^2) p^\mu [kp]^{\alpha\beta} + c_8(k^2) k^\alpha [kp]^{\beta\mu} + c_9(k^2) k^\beta [kp]^{\mu\alpha} \end{aligned}$$



$$p = q - \bar{q} \quad \partial_\mu V^\mu = 0$$

$$[kp]^{\mu\nu} = \epsilon^{\mu\nu\rho\sigma} k_\rho p_\sigma$$

Hagiwara, Peccei, Zeppenfeld 1987
Ibarra, Hisano, Ryo 2022

Vector Dark States

Chu, Ibarra, Hisano, Kuo, JP
2303.13643

SPIN1 case: construction

Consider all possible Lorentz structures

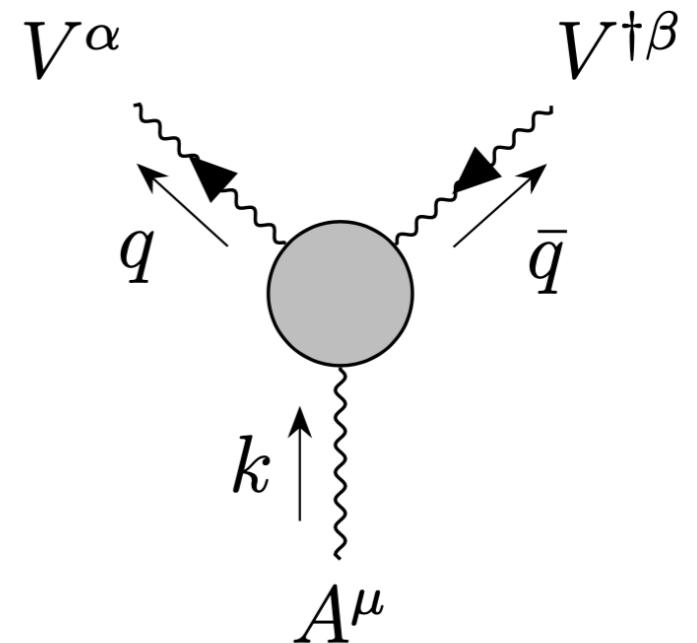
=> yields 9 structures

no rank-5 completely antisymmetric tensor exists in four dimensions

only seven out of the nine helicity states of the V pair can be reached by s-channel vector boson exchange ($J = 1$ channel)

=> 7 independent structures

$$\begin{aligned} \Gamma_{VV^\dagger\gamma}^{\alpha\beta\mu}/e &= f_1^A(k^2)p^\mu g^{\alpha\beta} - \frac{f_2^A(k^2)}{m_V^2}p^\mu k^\alpha k^\beta + f_3^A(k^2)(k^\alpha g^{\mu\beta} - k^\beta g^{\mu\alpha}) \\ &\quad + i f_4^A(k^2)(k^\alpha g^{\mu\beta} + k^\beta g^{\mu\alpha}) + i f_5^A(k^2)\epsilon^{\mu\alpha\beta\rho}p_\rho \\ &\quad - f_6^A(k^2)\epsilon^{\mu\alpha\beta\rho}k_\rho - \frac{f_7^A(k^2)}{m_V^2}p^\mu [kp]^{\alpha\beta}. \end{aligned}$$



Hagiwara, Peccei, Zeppenfeld 1987
Ibarra, Hisano, Ryo 2022

Vector Dark States

Chu, Ibarra, Hisano, Kuo, JP
2303.13643

SPIN1 case: construction

Consider all possible Lorentz structures

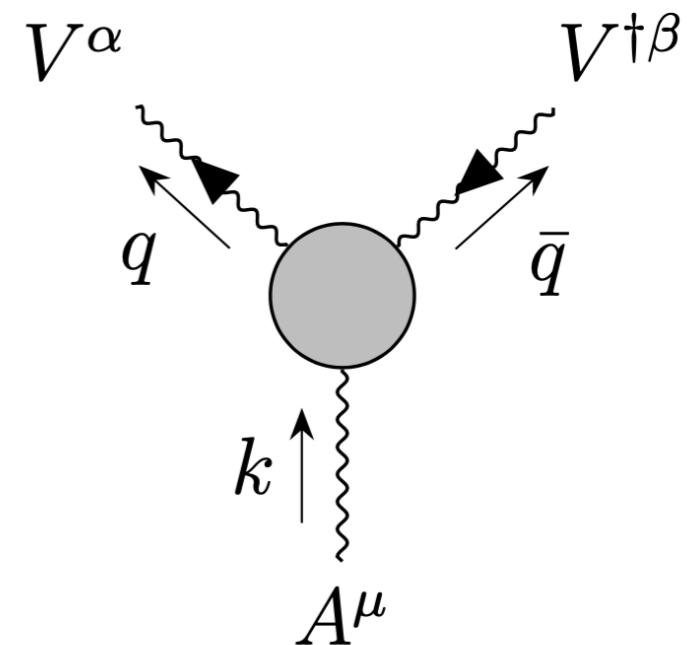
=> yields 9 structures

=> 7 independent structures

neutrality of V and gauge invariance of A require

=> $f_{1,4,5}^A(0) = 0$

$$i\Gamma_{VV^\dagger\gamma}^{\alpha\beta\mu}(q, \bar{q}, k) =$$



~~$$f_1^A(k^2) = f_1^A(0) + \frac{k^2}{2\Lambda^2} [g_1^A(k^2) + \lambda_A(k^2)]$$~~

~~$$f_4^A(k^2) = f_4^A(0) + \frac{k^2}{\Lambda^2} g_4^A(k^2)$$~~

~~$$f_5^A(k^2) = f_5^A(0) + \frac{k^2}{\Lambda^2} g_5^A(k^2)$$~~

$$f_2^A(k^2) = \lambda_A(k^2)$$

$$f_3^A(k^2) = \kappa_A(k^2) + \lambda_A(k^2)$$

$$f_6^A(k^2) = \tilde{\kappa}_A(k^2) - \tilde{\lambda}_A(k^2)$$

$$f_7^A(k^2) = -\frac{1}{2} \tilde{\lambda}_A(k^2)$$

Hagiwara, Peccei, Zeppenfeld 1987
Ibarra, Hisano, Ryo 2022

Vector Dark States

Chu, Ibarra, Hisano, Kuo, JP
2303.13643

SPIN1 case: construction

Matched onto the following effective Lagrangian

$$\begin{aligned}\frac{\mathcal{L}}{e} = & \frac{ig_1^\Lambda}{2\Lambda^2} \left[(V_{\mu\nu}^\dagger V^\mu - V^{\dagger\mu} V_{\mu\nu}) \partial_\lambda F^{\lambda\nu} - V^{\dagger\mu} V^\nu \square F_{\mu\nu} \right] \\ & + \frac{g_4^\Lambda}{\Lambda^2} V_\mu^\dagger V_\nu (\partial^\mu \partial_\rho F^{\rho\nu} + \partial^\nu \partial_\rho F^{\rho\mu}) \\ & + \frac{g_5^\Lambda}{\Lambda^2} \epsilon^{\mu\nu\rho\sigma} \left(V_\mu^\dagger \overleftrightarrow{\partial}_\rho V_\nu \right) \partial^\lambda F_{\lambda\sigma} \\ & + i\kappa_\Lambda V_\mu^\dagger V_\nu F^{\mu\nu} + \frac{i\lambda_\Lambda}{\Lambda^2} V_{\lambda\mu}^\dagger V^\mu_\nu F^{\nu\lambda} \\ & + i\tilde{\kappa}_\Lambda V_\mu^\dagger V_\nu \tilde{F}^{\mu\nu} + \frac{i\tilde{\lambda}_\Lambda}{\Lambda^2} V_{\lambda\mu}^\dagger V^\mu_\nu \tilde{F}^{\nu\lambda},\end{aligned}$$

Vector Dark States

Chu, Ibarra, Hisano, Kuo, JP
2303.13643

SPIN1 case: construction

Matched onto the following effective Lagrangian

$$\frac{\mathcal{L}}{e} = \frac{ig_1^\Lambda}{2\Lambda^2} [(V_{\mu\nu}^\dagger V^\mu -$$

$$+ \frac{g_4^\Lambda}{\Lambda^2} V_\mu^\dagger V_\nu (\partial^\mu \partial_\rho F^{\rho\nu}) -$$

$$+ \frac{g_5^\Lambda}{\Lambda^2} \epsilon^{\mu\nu\rho\sigma} (V_\mu^\dagger \overleftrightarrow{\partial}_\rho V_\nu) F^{\rho\sigma} + i\kappa_\Lambda V_\mu^\dagger V_\nu F^{\mu\nu} + i\tilde{\kappa}_\Lambda V_\mu^\dagger V_\nu \tilde{F}^{\mu\nu} + \dots]$$

interaction type	coupling	C	P	CP
magn. dipole	$\mu_V = \frac{e}{2m_V} (\kappa_\Lambda + \frac{m_V^2}{\Lambda^2} \lambda_\Lambda)$	+1	+1	+1
elec. dipole	$d_V = \frac{e}{2m_V} (\tilde{\kappa}_\Lambda + \frac{m_V^2}{\Lambda^2} \tilde{\lambda}_\Lambda)$	+1	-1	-1
magn. quadrupole	$Q_V = -\frac{e}{m_V^2} (\kappa_\Lambda - \frac{m_V^2}{\Lambda^2} \lambda_\Lambda)$	+1	+1	+1
elec. quadrupole	$\tilde{Q}_V = -\frac{e}{m_V^2} (\tilde{\kappa}_\Lambda - \frac{m_V^2}{\Lambda^2} \tilde{\lambda}_\Lambda)$	+1	-1	-1
charge radius	$g_1^A/m_V^2 = g_1^\Lambda/\Lambda^2$	+1	+1	+1
toroidal moment	$g_4^A/m_V^2 = g_4^\Lambda/\Lambda^2$	-1	+1	-1
anapole moment	$g_5^A/m_V^2 = g_5^\Lambda/\Lambda^2$	-1	-1	+1

Vector Dark States

Vertex factor

Consider all possible Lorentz structures

$$i\Gamma_{VV^\dagger\gamma}^{\alpha\beta\mu}(q, \bar{q}, k) =$$

$$i\Gamma^{\mu\alpha\beta}(k, p) = -\frac{ieg_1^A}{2m_V^2} k^2 p^\mu g^{\alpha\beta}$$

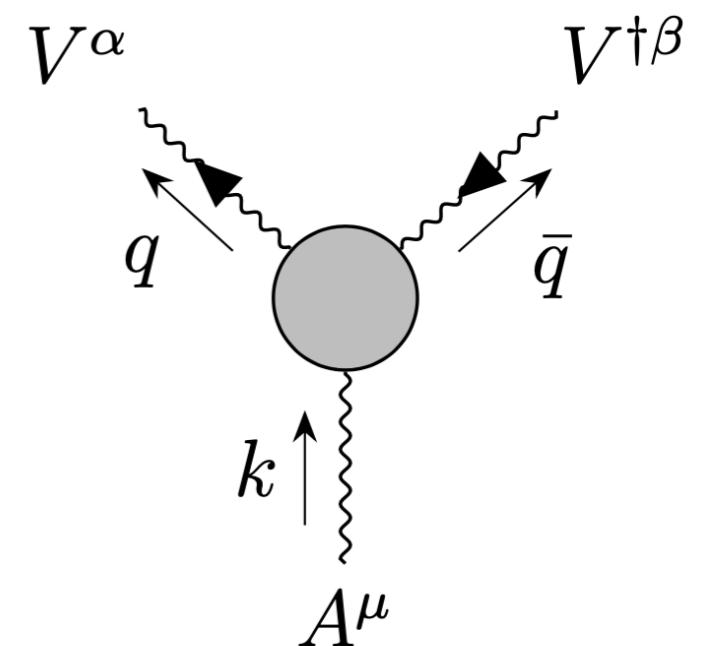
$$-\frac{eg_4^A}{m_V^2} k^2 (k^\alpha g^{\mu\beta} + k^\beta g^{\mu\alpha}) - \frac{eg_5^A}{m_V^2} k^2 \epsilon^{\mu\alpha\beta\rho} p_\rho$$

$$-2im_V\mu_V \left[k^\alpha g^{\mu\beta} - k^\beta g^{\mu\alpha} + \frac{1}{4m_V^2} (k^2 g^{\alpha\beta} p^\mu - 2k^\alpha k^\beta p^\mu) \right]$$

$$-\frac{iQ_V}{4} (k^2 g^{\alpha\beta} p^\mu - 2k^\alpha k^\beta p^\mu)$$

$$-\frac{id_V}{2m_V} p^\mu [kp]^{\alpha\beta} - \frac{i\tilde{Q}_V}{4} \left(p^\mu [kp]^{\alpha\beta} + 4m_V^2 \epsilon^{\mu\alpha\beta\rho} k_\rho \right),$$

=> interactions grouped by their CP properties and familiar nomenclature; defined such that m_V is the only explicit scale



Vector Dark States

Chu, Ibarra, Hisano, Kuo, JP
2303.13643

Universal description of V-pair production

Spin-summed matrix element of VV production

$$\sum_{\lambda, \lambda'} |\mathcal{M}^{\lambda\lambda'}|^2 = D_{\mu\nu}(k) D_{\rho\sigma}^*(k) \mathcal{T}_{\text{SM}}^{\mu\rho} \mathcal{T}_{\text{DM}}^{\nu\sigma}$$

any SM-current producing $\gamma^*(k)$
 (can receive medium corrections)

interaction type	$f(s)$
magnetic dipole	$\frac{\mu_V^2 s (s - 4m_V^2)(16m_V^2 + 3s)}{12m_V^2}$
electric dipole	$\frac{d_V^2 s (s - 4m_V^2)^2}{6m_V^2}$
magnetic quadrupole	$\frac{Q_V^2 s^2 (s - 4m_V^2)}{16}$
electric quadrupole	$\frac{\tilde{Q}_V^2 s^2 (s + 8m_V^2)}{24}$
charge radius	$\frac{e^2 (g_1^A)^2 s^2 (s - 4m_V^2)(12m_V^4 - 4m_V^2 s + s^2)}{48m_V^8}$
toroidal moment	$\frac{e^2 (g_4^A)^2 s^3 (s - 4m_V^2)}{3m_V^6}$
anapole moment	$\frac{e^2 (g_5^A)^2 s^2 (s - 4m_V^2)^2}{3m_V^6}$

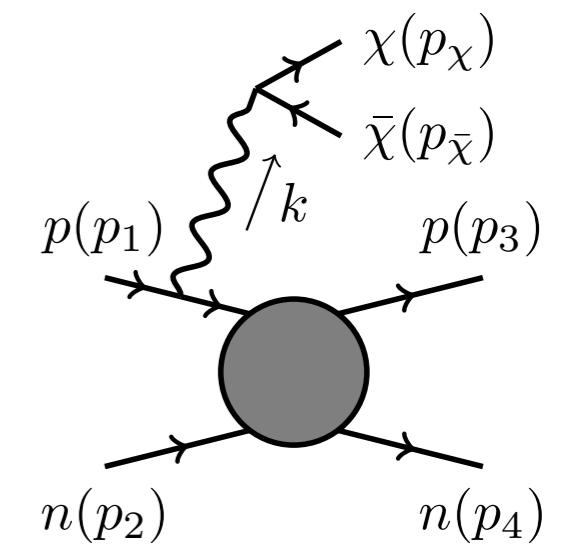
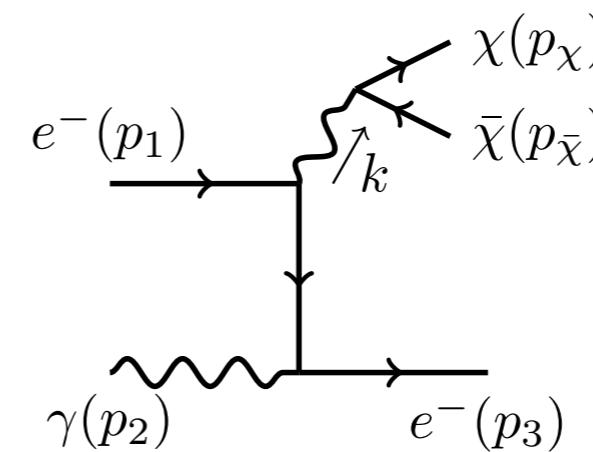
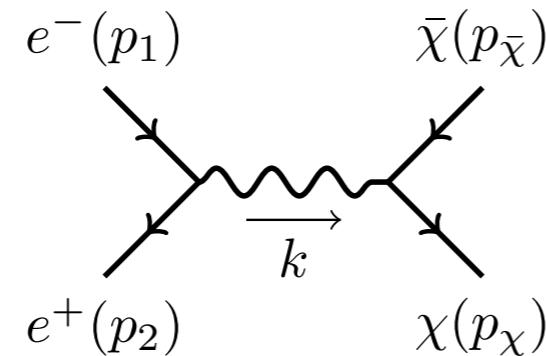
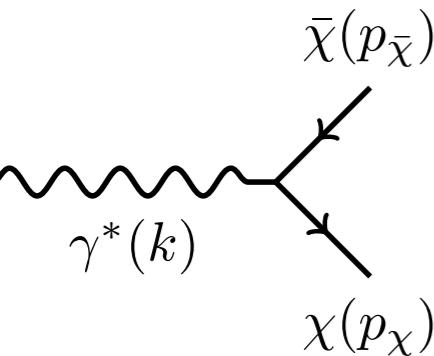
$$\int d\Phi_2 \mathcal{T}_{\text{DM}}^{\nu\sigma} = \frac{1}{8\pi} \sqrt{1 - \frac{4m_V^2}{s}} f(s) \left(-g^{\nu\sigma} + \frac{k^\nu k^\sigma}{s} \right)$$

$f(s)$ with mass-dimension 2 summarizes
 all effective interactions when VV phase
 space can be integrated

Stellar production

Various, in part overlapping production channels

$$\chi = V, \bar{\chi} = V^\dagger$$



e.g. T/L “Plasmon” decay

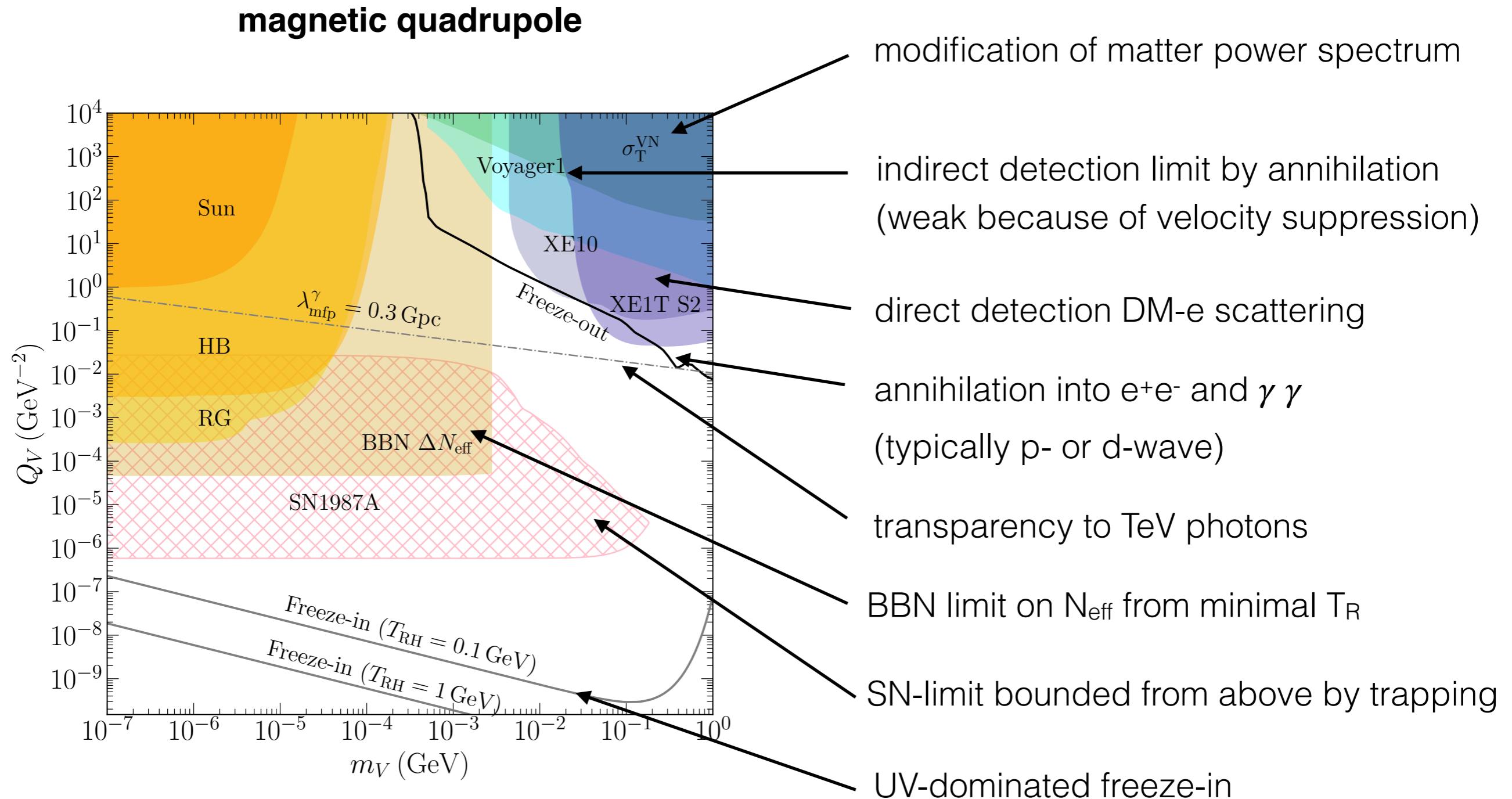
(all)

$$\omega_p \sim \begin{cases} 0.3 \text{ keV} & \text{Sun's core} \\ 2.6 \text{ keV} & \text{HB's core} \\ 8.6 \text{ keV} & \text{RG's core} \\ 17.6 \text{ MeV} & \text{SN's core} \end{cases}$$

Vector DM

Chu, Ibarra, Hisano, Kuo, JP
[2303.13643](#)

Mass vs. coupling plane

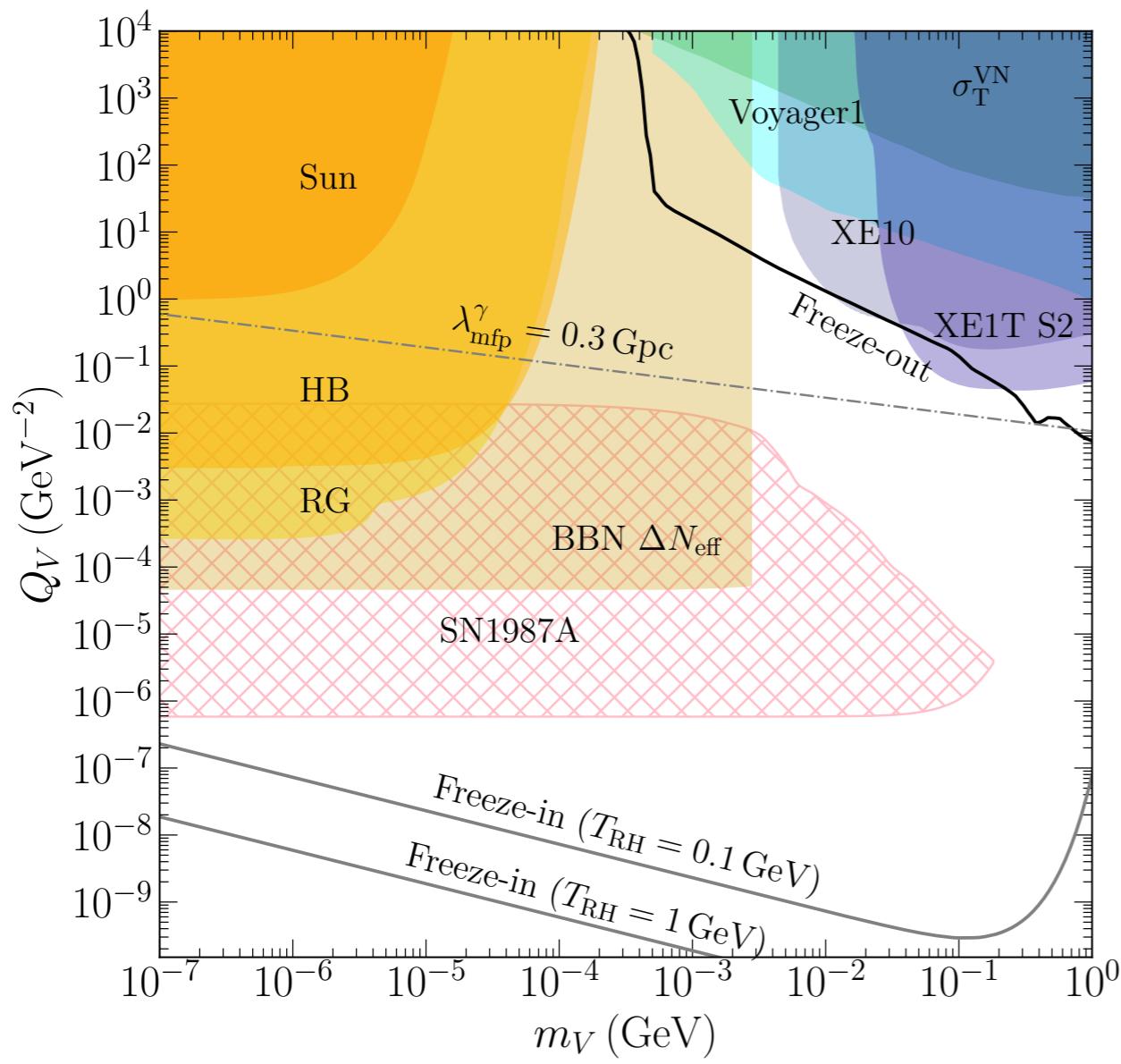


Vector DM

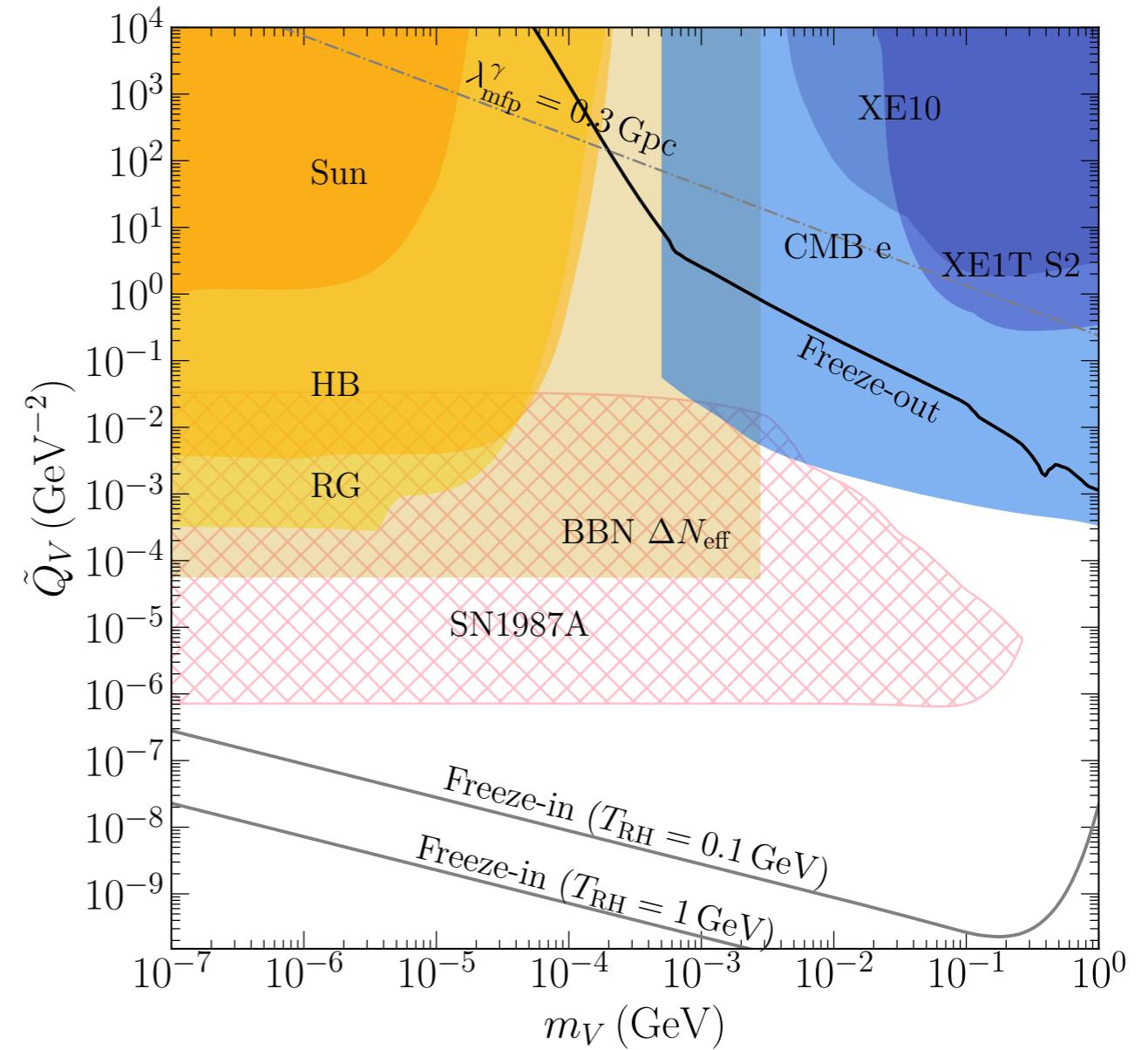
Chu, Ibarra, Hisano, Kuo, JP
[2303.13643](#)

Mass vs. coupling plane

magnetic quadrupole



electric quadrupole

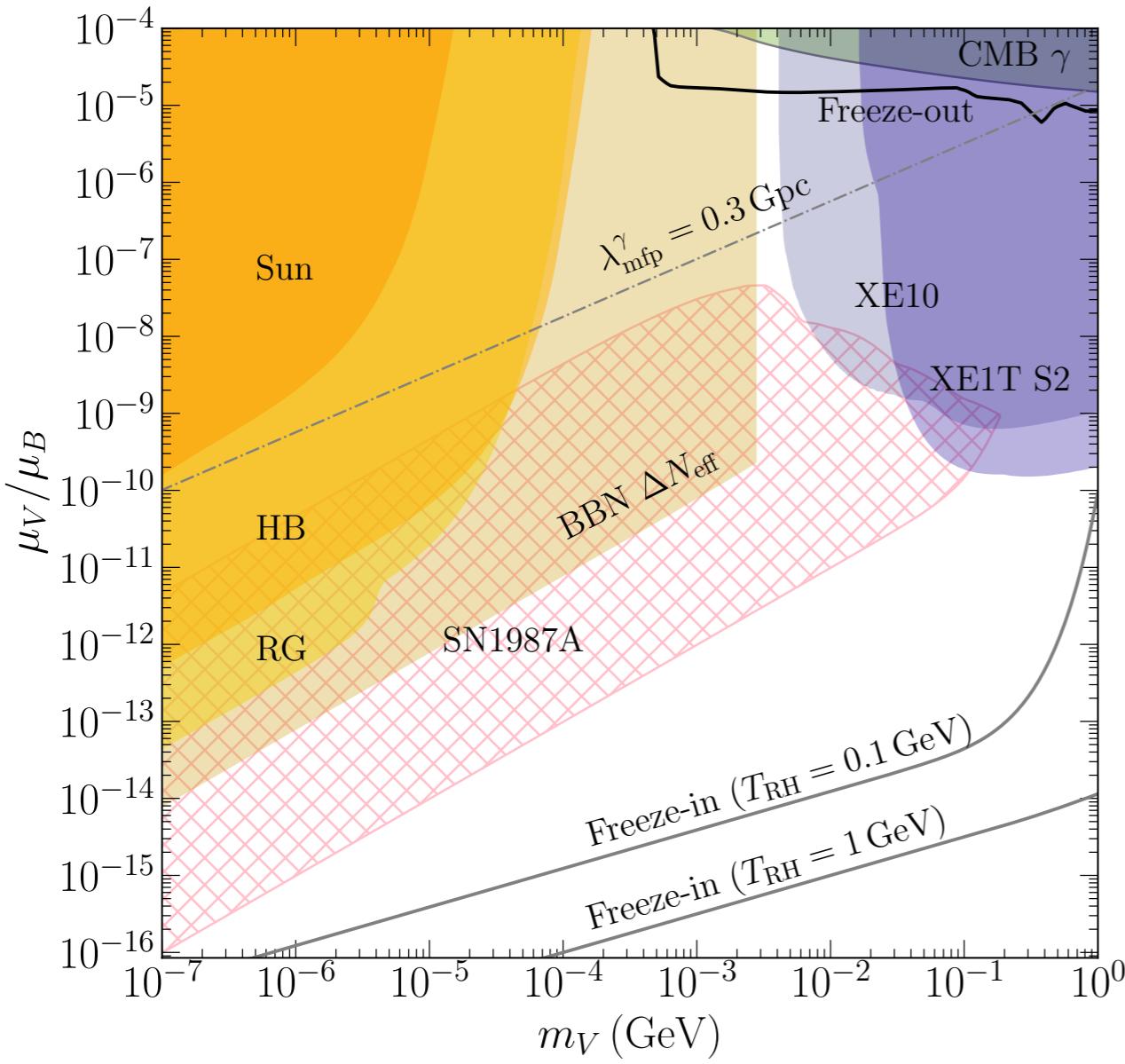


Vector DM

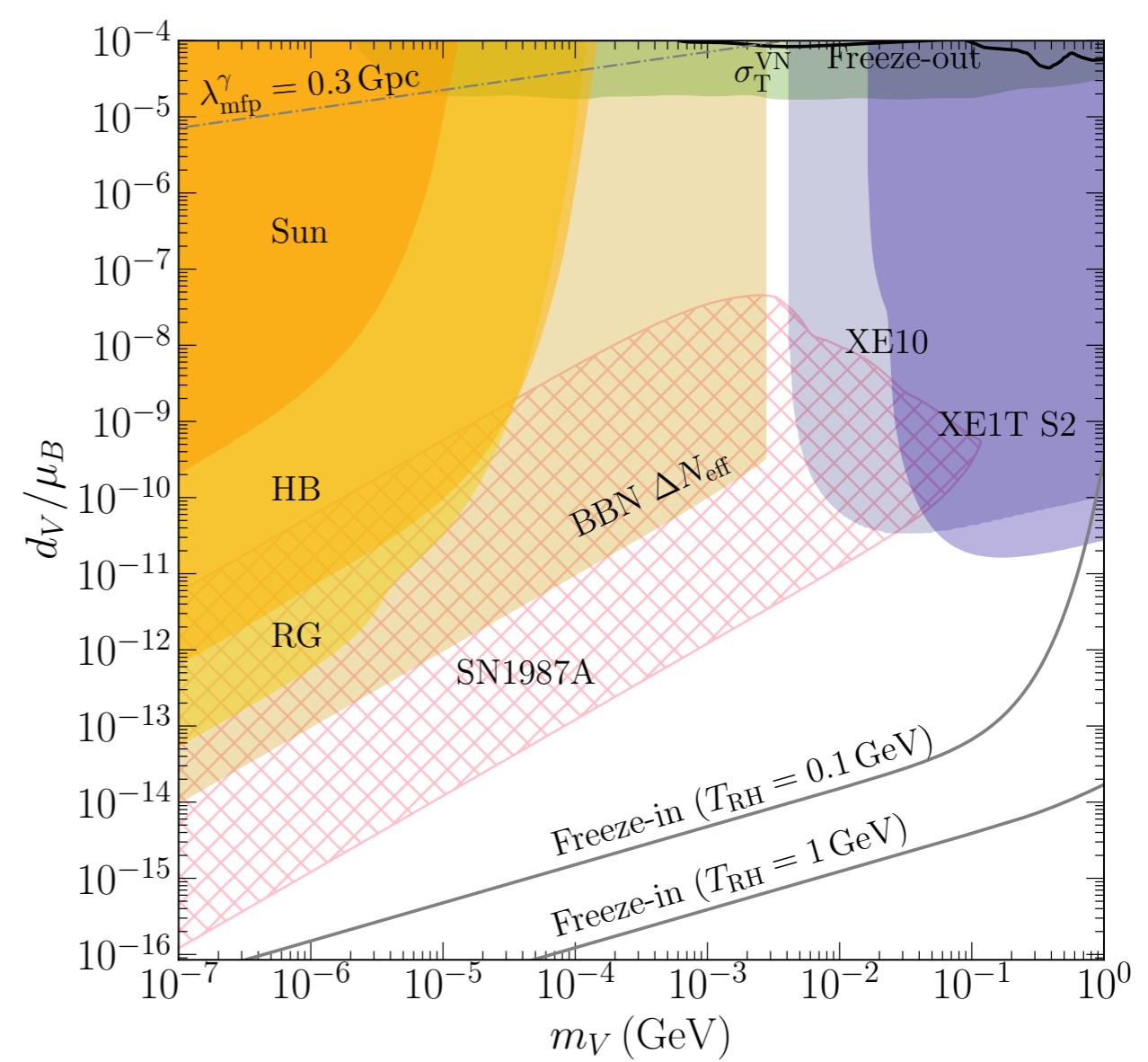
Chu, Ibarra, Hisano, Kuo, JP
[2303.13643](#)

Mass vs. coupling plane

magnetic dipole



electric dipole



Vector DM

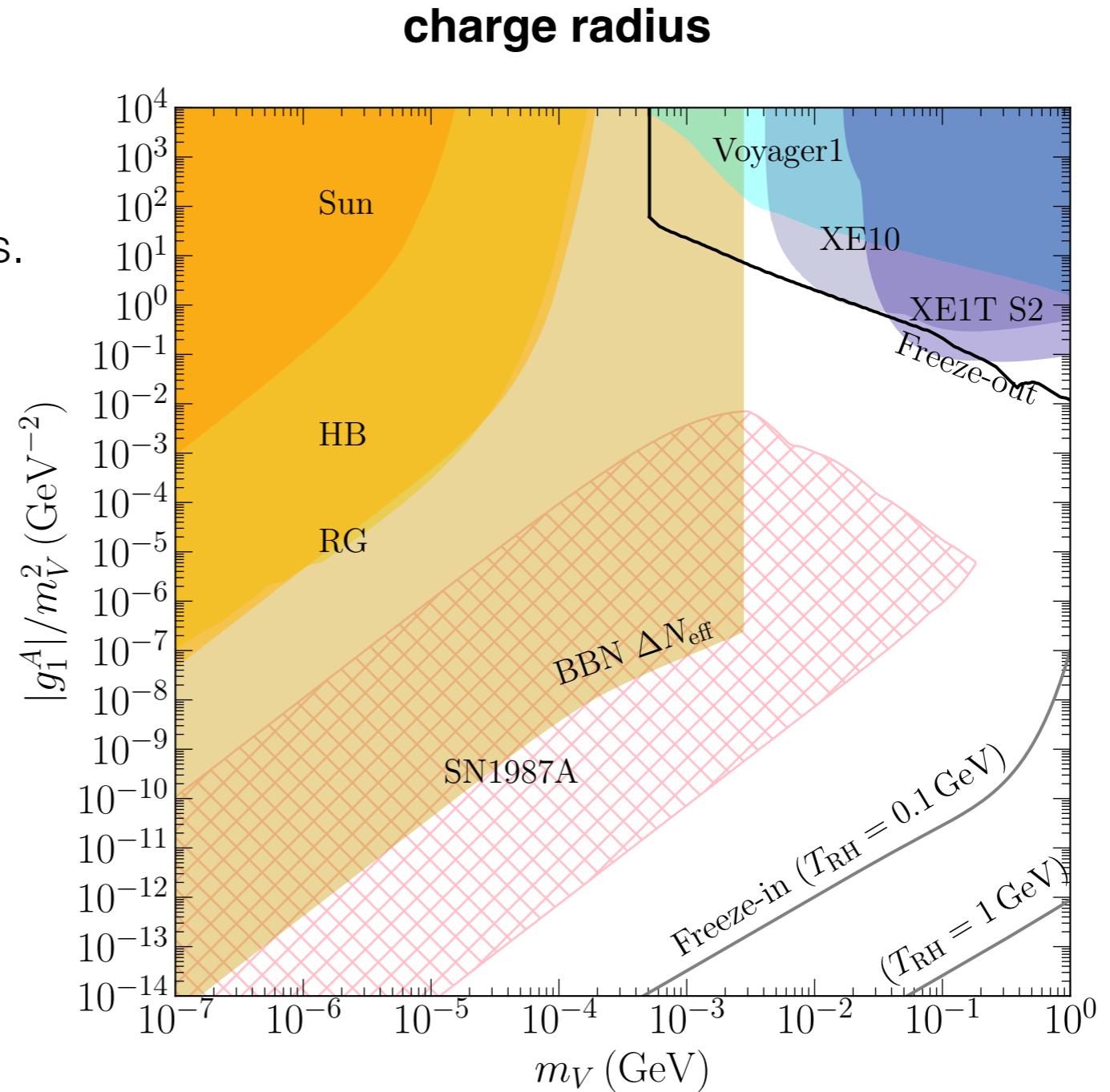
Chu, Ibarra, Hisano, Kuo, JP
[2303.13643](#)

Validity of the effective approach?

$m_V \rightarrow 0$ limit appears worrisome for most of the effective interactions.

Appears as if rates diverge in the zero mass limit.

$\sqrt{s} \lesssim v_D$ must hold as otherwise contributions from the dark Higgs will enter.



Vector DM

Chu, Ibarra, Hisano, Kuo, JP
2303.13643

Expected scaling of rates from naive dimensional analysis

Production rates should scale according to their transverse (T) and longitudinal (V) polarity as

$$\dot{Q}_{\lambda\lambda'} \propto \begin{cases} g_D^4/m_V^4 & \lambda\lambda' = LL, \\ g_D^4/m_V^2 & \lambda\lambda' = LT, \\ g_D^4 & \lambda\lambda' = TT. \end{cases} \quad \text{for } \sqrt{s}/m_V \gg 1 \quad (\text{high-energy limit})$$
$$\epsilon_L = \left(\frac{p}{m_V}, 0, 0, \frac{E}{m_V} \right), \quad \epsilon_T^\pm = \left(0, \frac{1}{\sqrt{2}}, \pm \frac{i}{\sqrt{2}}, 0 \right)$$

For example, in the UV-picture $m_V \sim g_D v_D$

$$\dot{Q}_{LL} \propto |(g_D \epsilon_{L,1})(g_D \epsilon_{L,2})|^2 \propto \frac{g_D^4}{m_V^4} \propto \frac{1}{v_D^4}$$

FINITE, independent of gauge coupling
(Goldstone boson equivalence thm.)

BUT: even effective operators that do NOT permit LL mode (e.g. electric dipole) show same scaling

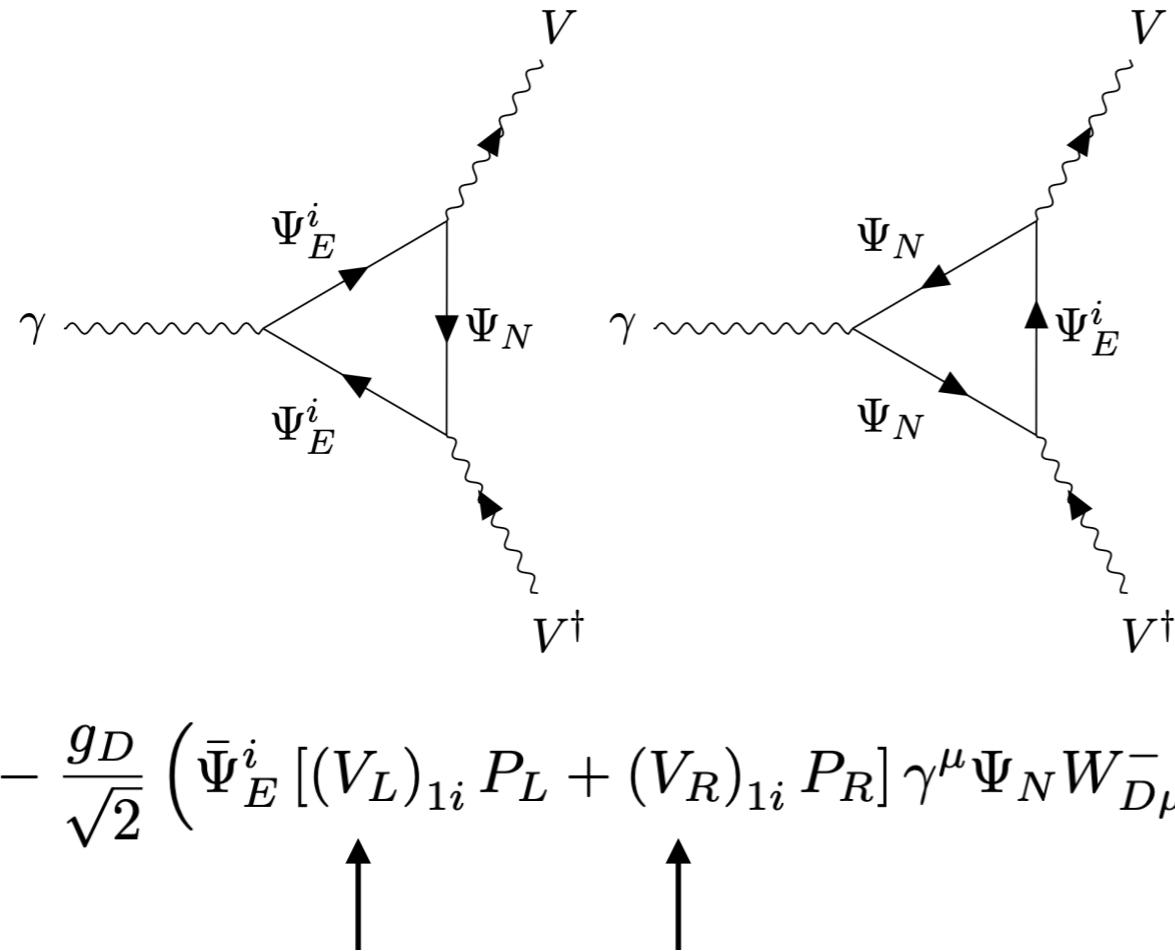
=> resolution in the UV-picture

Vector DM

UV-completion

Dark $SU(2)_D \times \text{global } U(1)_X$ with a vector triplet W_D^a , dark fermions Ψ , Higgsed by Φ_D
=> six of the seven operators radiatively induced

Ibarra, Hisano, Ryo (2020)



$$\langle \Phi_D \rangle = v_D / \sqrt{2}$$

$$m_{W_D} = g_D v_D / 2$$

$$\mathcal{L}_{\text{int}} = -\frac{g_D}{\sqrt{2}} \left(\bar{\Psi}_E^i [(V_L)_{1i} P_L + (V_R)_{1i} P_R] \gamma^\mu \Psi_N W_{D\mu}^- + \text{h.c.} \right) - e \Psi_N \gamma^\mu \Psi_N A_\mu - e \bar{\Psi}_E^i \gamma^\mu \Psi_E^i A_\mu.$$

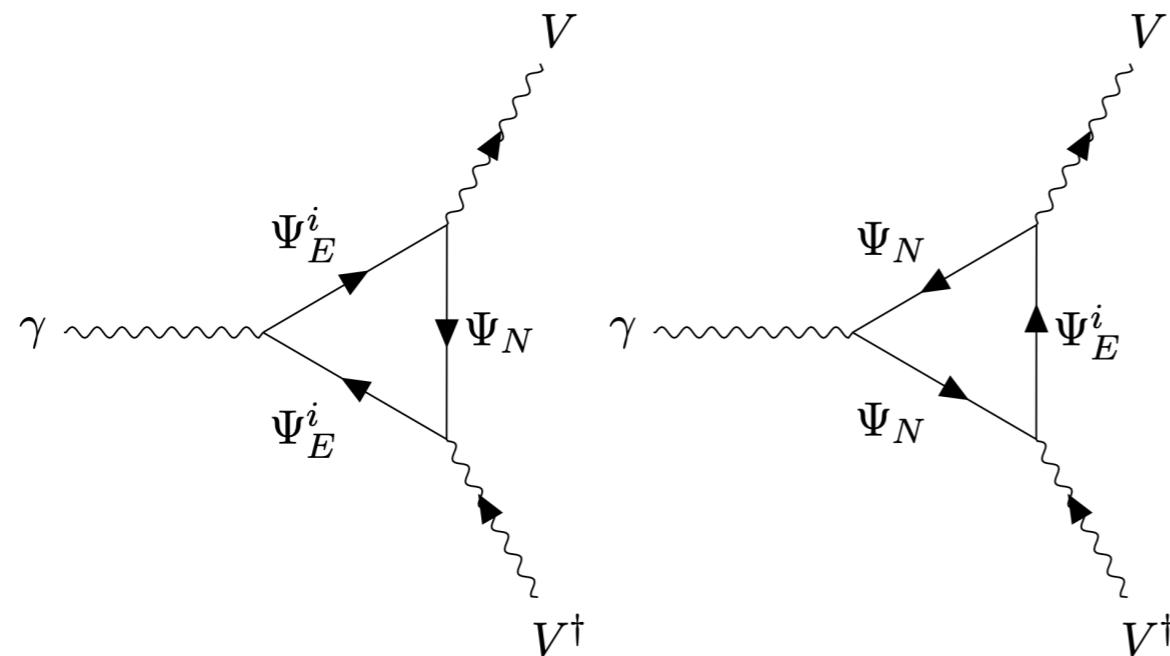
V 's diagonalize Ψ' 's after SSB

Vector DM

UV-completion

Dark $SU(2)_D \times \text{global } U(1)_X$ with a vector triplet W_D^a , dark fermions Ψ , Higgsed by Φ_D
=> six of the seven operators radiatively induced

Ibarra, Hisano, Ryo (2020)



$$\langle \Phi_D \rangle = v_D / \sqrt{2}$$

$$m_{W_D} = g_D v_D / 2$$

For example:

$$\mu_V = -e \frac{g_D^2}{64\pi^2} \frac{1}{m_V} \sum_{i=1}^2 (1 - x_i^2) \left[\left(\left| (V_L)_{1i}^2 \right|^2 + \left| (V_R)_{1i}^2 \right|^2 \right) \times \text{loop function} \right]$$

$$d_V = e \frac{g_D^2}{64\pi^2} \frac{1}{m_V} \sum_{i=1}^2 \text{Im} \left((V_L)_{1i}^* (V_R)_{1i}^* \right) \times \text{loop function}$$

Vector DM

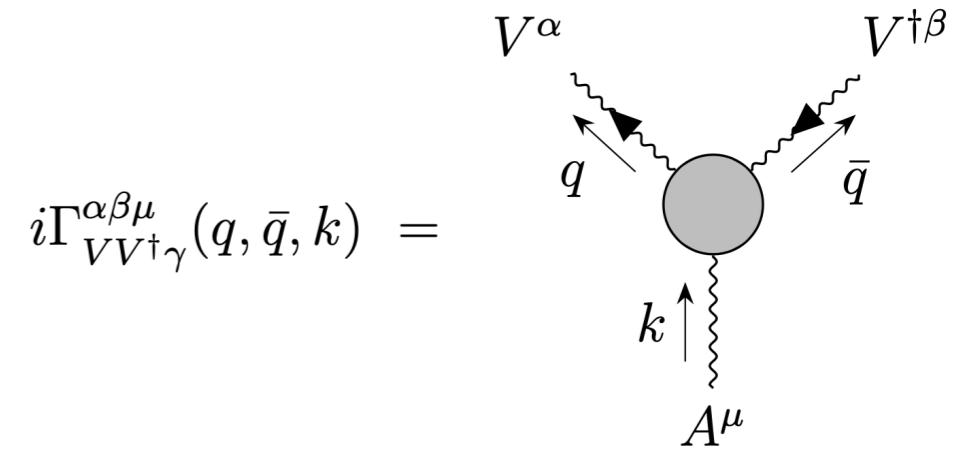
proper high energy limit

Coupl.	UV model	$\dot{Q} \propto f(s)$	$\dot{Q} _{m_V \rightarrow 0}$	pol.
μ_V	$\frac{g_D^2}{m_V} \propto \frac{g_D}{v_D}$	$\frac{\mu_V^2}{m_V^2} \propto \frac{1}{v_D^4}$	finite	all
d_V	$\frac{g_D^2}{m_V} \propto \frac{g_D}{v_D}$	$\frac{d_V^2}{m_V^2} \propto \frac{1}{v_D^4}$	finite	TT

From the UV perspective, multipole moments are not independent, emission rate probes $i\Gamma^{\alpha\beta\mu}$

magn. dipole	$\mu_V = \frac{e}{2m_V} (\kappa_\Lambda + \frac{m_V^2}{\Lambda^2} \lambda_\Lambda)$
elec. dipole	$d_V = \frac{e}{2m_V} (\tilde{\kappa}_\Lambda + \frac{m_V^2}{\Lambda^2} \tilde{\lambda}_\Lambda)$

=> switch basis



	κ_Λ	λ_Λ	g_1^A
UV	g_D^2	$\frac{g_D^2 \Lambda^2}{m_N^2}$	$\frac{g_D^2 m_V^2}{m_N^2}$
C,P			$(+, +)$
\dot{Q}_{LL}		$\frac{\kappa_\Lambda^2}{m_V^4} \propto \frac{g_D^4}{m_V^4}$	
\dot{Q}_{LT}		$\frac{\kappa_\Lambda^2}{m_V^2} \propto \frac{g_D^4}{m_V^2}$	
\dot{Q}_{TT}		$\left(\frac{\lambda_\Lambda}{\Lambda^2} + \frac{g_1^A}{m_V^2}\right)^2 \propto g_D^4$	

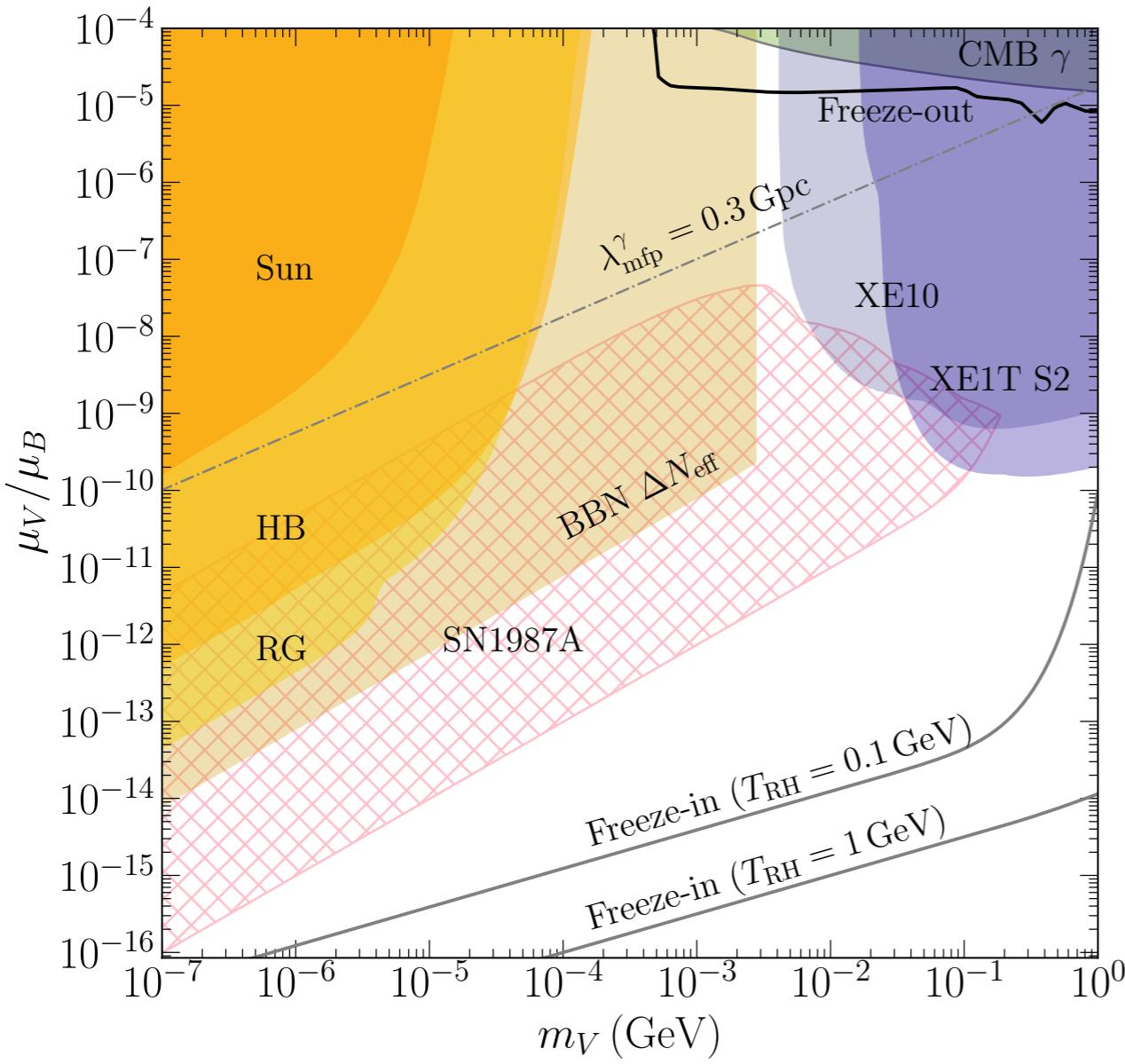
=> when all operators that share C,P properties are considered jointly, rates scale precisely as NDA suggests!

Vector DM

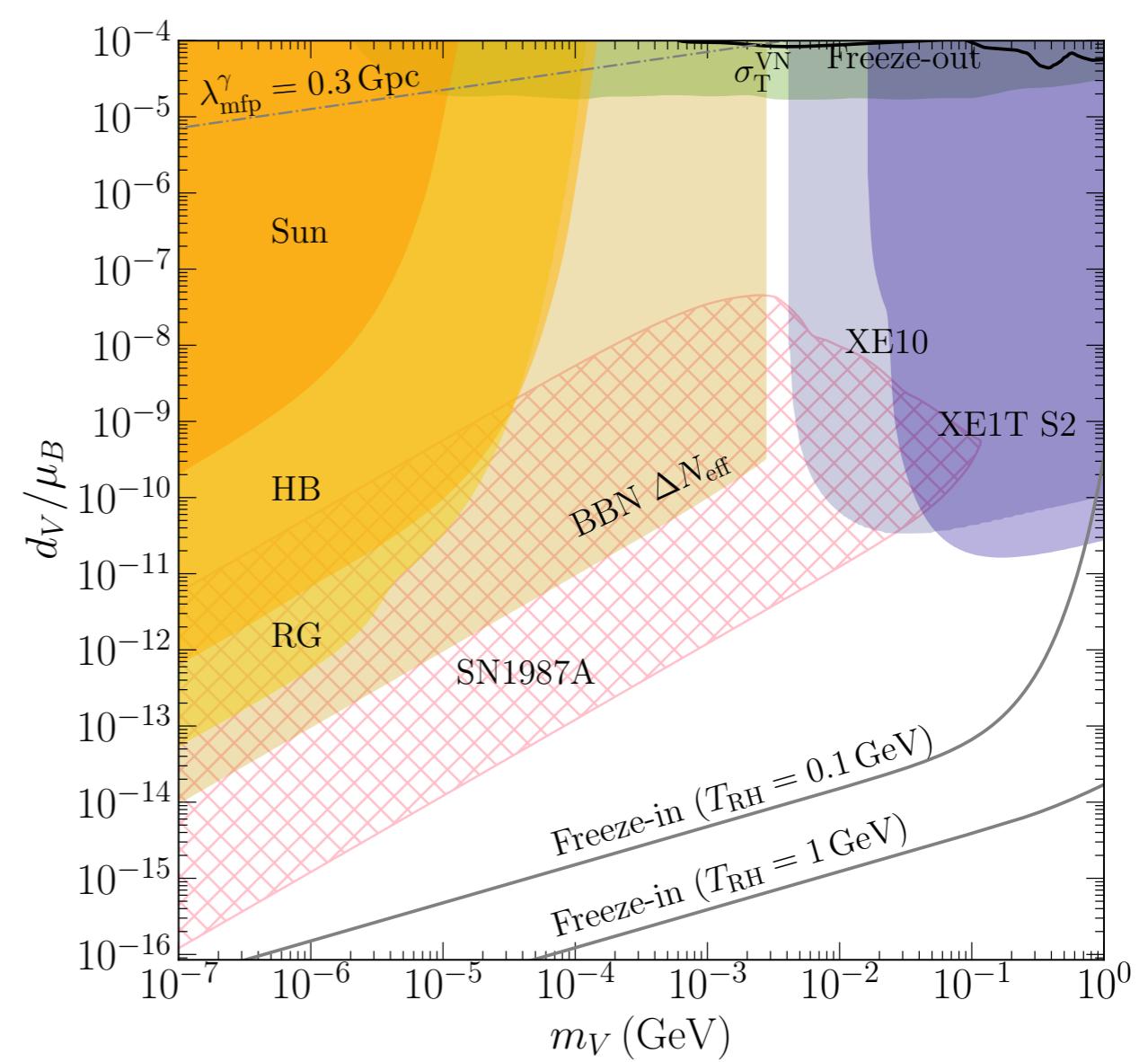
Chu, Ibarra, Hisano, Kuo, JP
[2303.13643](#)

Mass vs. coupling plane

magnetic dipole



electric dipole

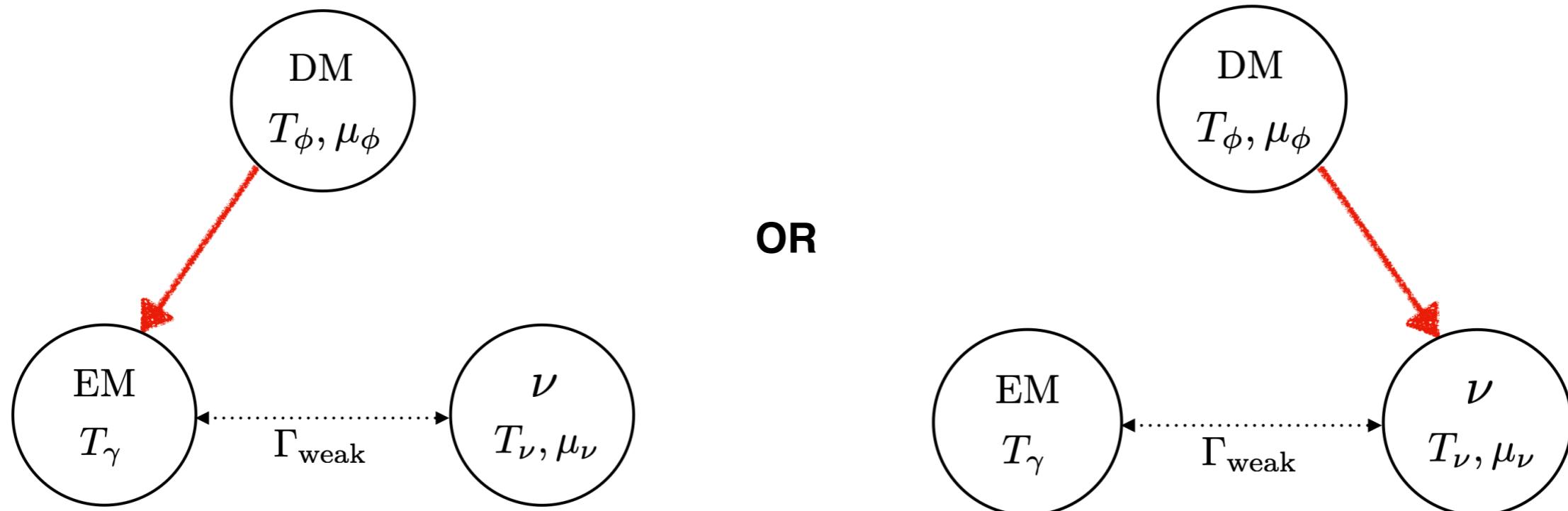


Light DM freeze out

What is the lightest thermal DM mass?

Well known that MeV-DM subject to Neff bound from heating by annihilation

Previous treatments had to assume a branching either into EM-sector OR neutrinos:



Light DM freeze out

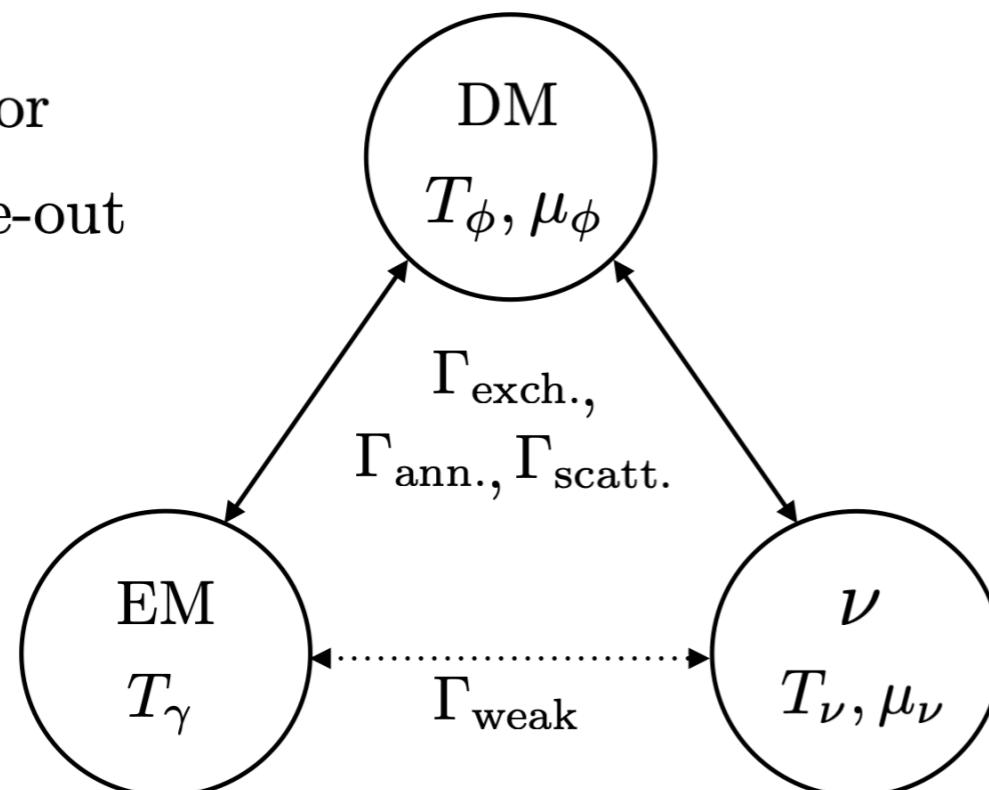
What is the lightest thermal DM mass?

Well known that MeV-DM subject to Neff bound from heating by annihilation

In the full picture, joint treatment of the three coupled sectors is necessary

three-sector

DM freeze-out



$$\begin{aligned}\Gamma_{\text{weak}} &\equiv n_e G_F^2 T_\gamma^2 , \\ \Gamma_{\text{ann.}} &\equiv n_\phi \langle \sigma_{\text{ann.}} v \rangle , \\ \Gamma_{\text{exch.},i} &\equiv n_\phi^2 \langle \sigma_{\text{ann.},i} v \delta E \rangle / \rho_i , \\ \Gamma_{\text{scatt.},i} &\equiv n_i \langle \sigma_{\text{scatt.}}^{\phi i} v \rangle .\end{aligned}$$

=> we are the first to be able to treat a relative branching AND to include energy transfer from elastic scattering

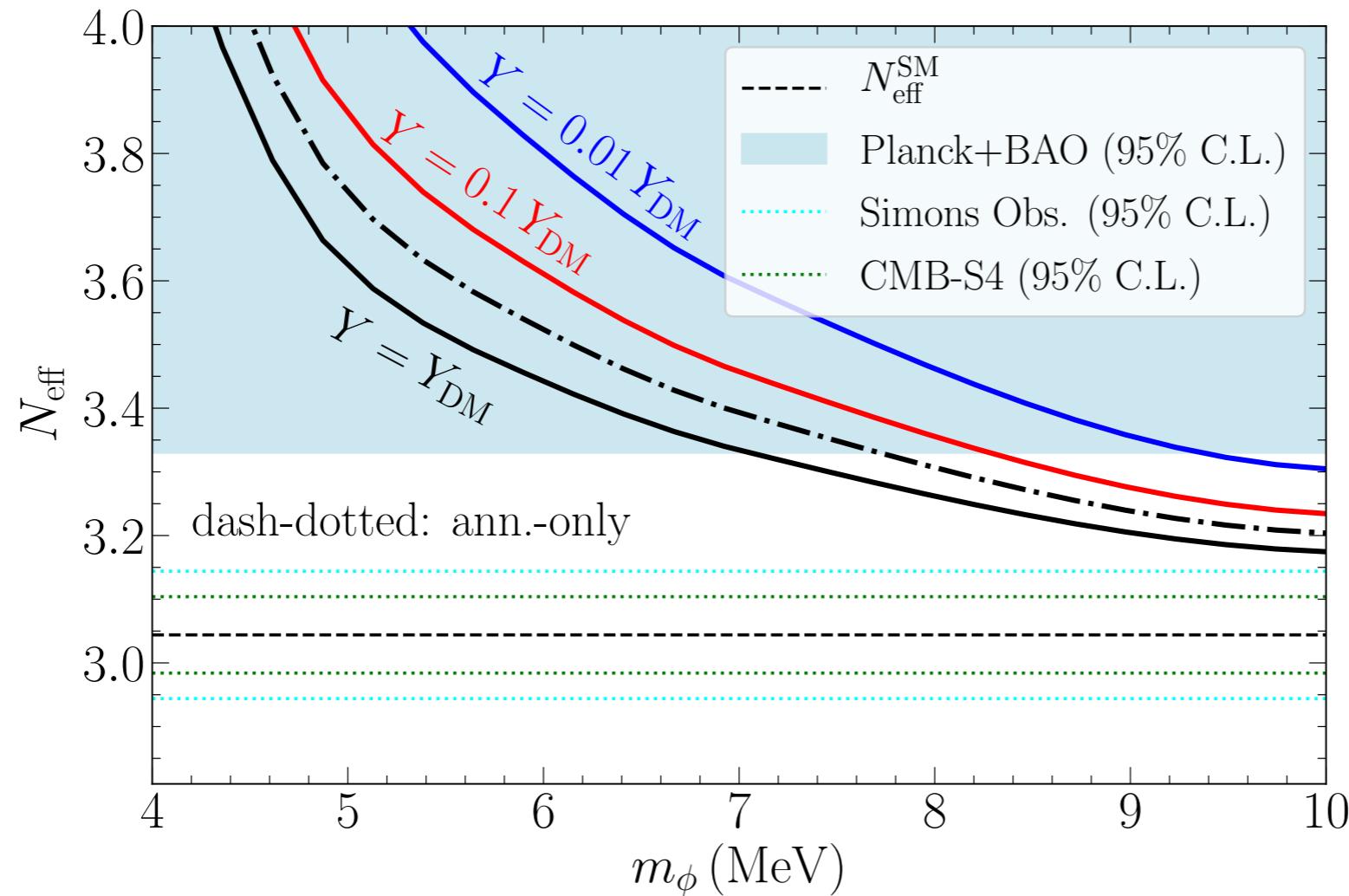
=> allows to track DM temperature (feeds into efficiency of annihilation for p-, d- ... wave)

=> allows for a precision prediction of Neff and to derive a lower bound on the DM mass

Light DM freeze out

What is the lightest thermal DM mass?

Example: flavor-blind Z' mediated p-wave annihilation (approximate equal branchings to ν and e)



Chu, Kuo, JP (2022)

Positive contribution to N_{eff} , unless $\text{Br}(\text{neutrinos}) < 10^{-4}$!

Chu, Kuo, JP (in preparation)

Fine tuned point that escapes the N_{eff} constraint; requires $\text{Br}(\text{neutrinos}) < 10^{-4}$

Summary

sub-GeV dark state phenomenology

- neutral dark vector particles can couple to the photon through higher dimensional electromagnetic moment interactions. Spin-1 particles have many
 - thermal freeze-out excluded by direct detection and indirect detection constraints (exceptions are anapole and toroidal moment interactions)
 - thermal freeze-in line is never touched by any considered probes, but dark state parameter space otherwise severely constrained by astrophysical limits
-
- A comprehensive assessment of thermal MeV-scale DM necessitates a three-sector treatment of vastly changing rates => found a systematic formulation

