Photon portal to MeV dark states and beyond

Josef Pradler

BSM@50 Rencontres du Vietnam

ICISE Quy Nhon

Jan 12 2024

ÖAW AUSTRIAN ACADEMY OF SCIENCES

universität wien

European Research Council
Established by the European Commission

FWF Der Wissenschaftsfonds.

Outline

1. Dark sector below the GeV mass scale coupled to photons

“photon portal” (experiments, astrophysics, cosmology)

(arXiv:1811.04095, arXiv:1908.00553)

arXiv:2303.13643

w/ Xiaoyong Chu, Jui-Lin Kuo, Alejandro Ibarra, Junji Hisano

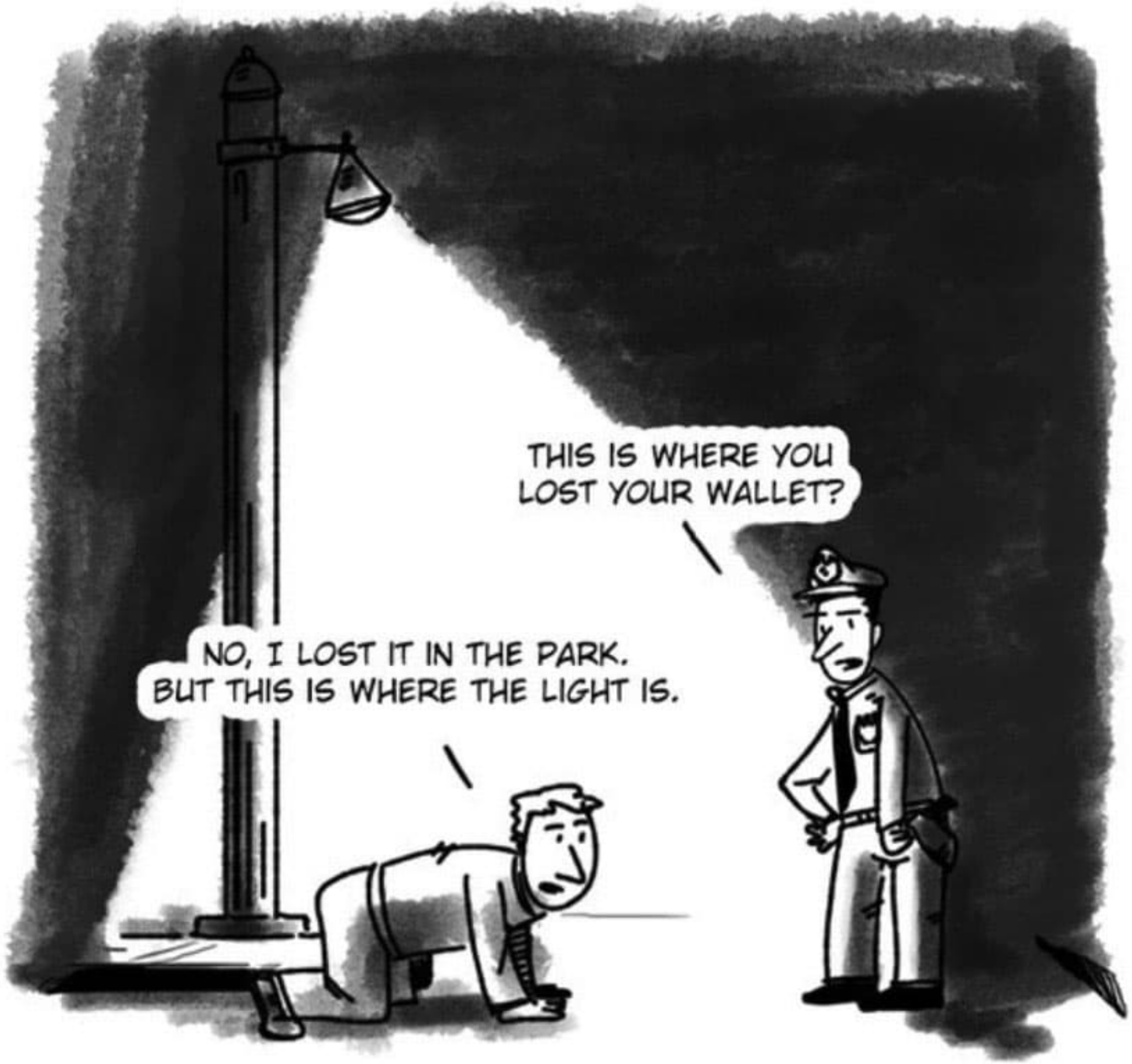
2. remarks on MeV - scale thermal dark matter freeze-out

arXiv:2205.05714
arXiv:2310.06611

w/ Xiaoyong Chu, Jui-Lin Kuo

Philosophy of this talk

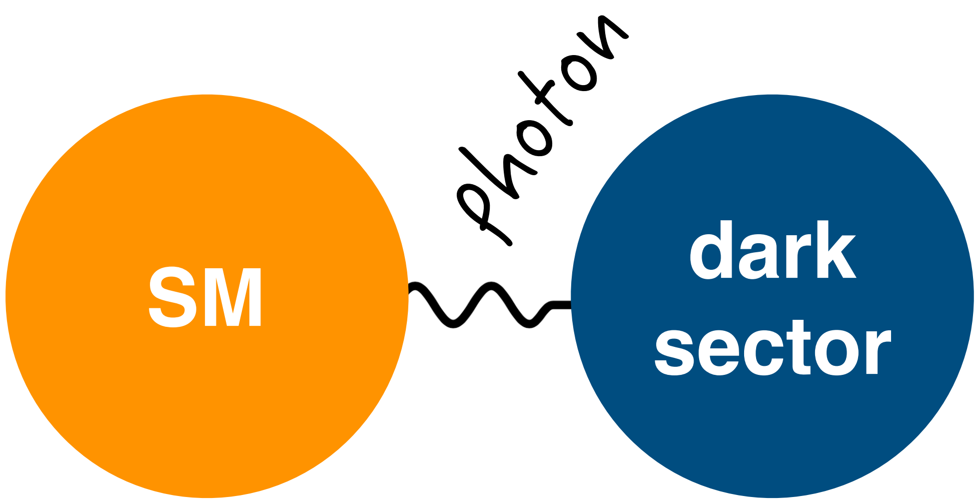
Streetlight effect or Drunkard search principle

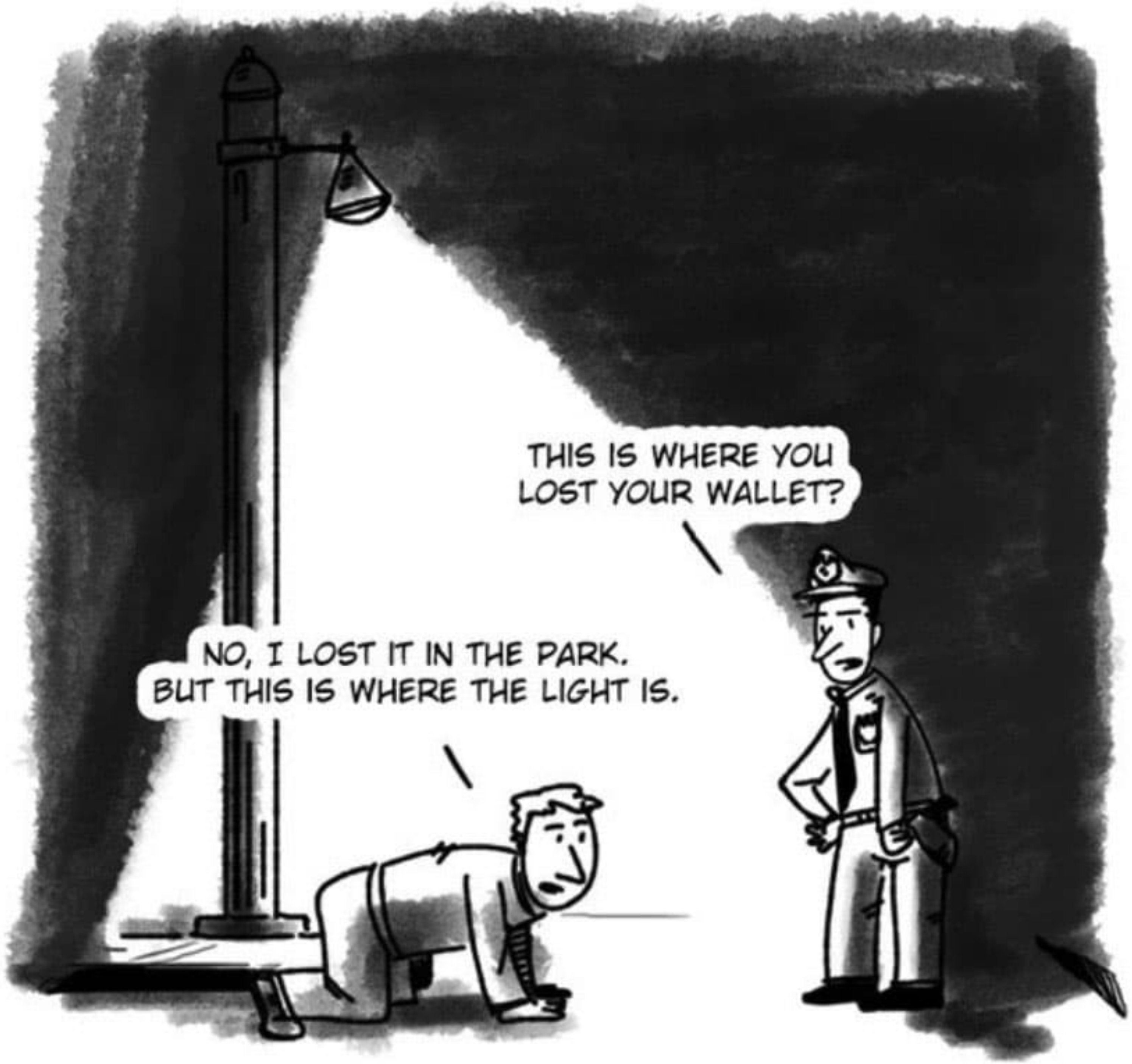


Philosophy of this talk

Streetlight effect or Drunkard search principle

=> let's search under the lamppost

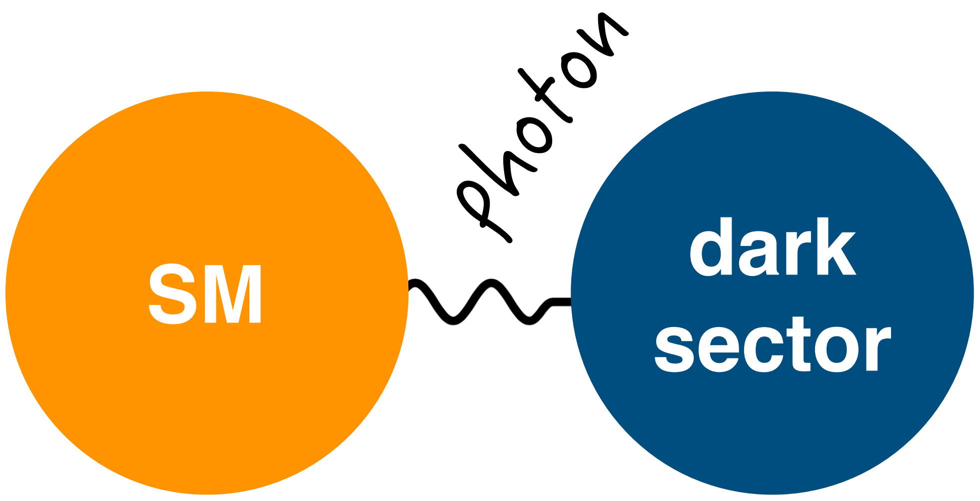




1. Dark states with EM form factors

Photon-portal

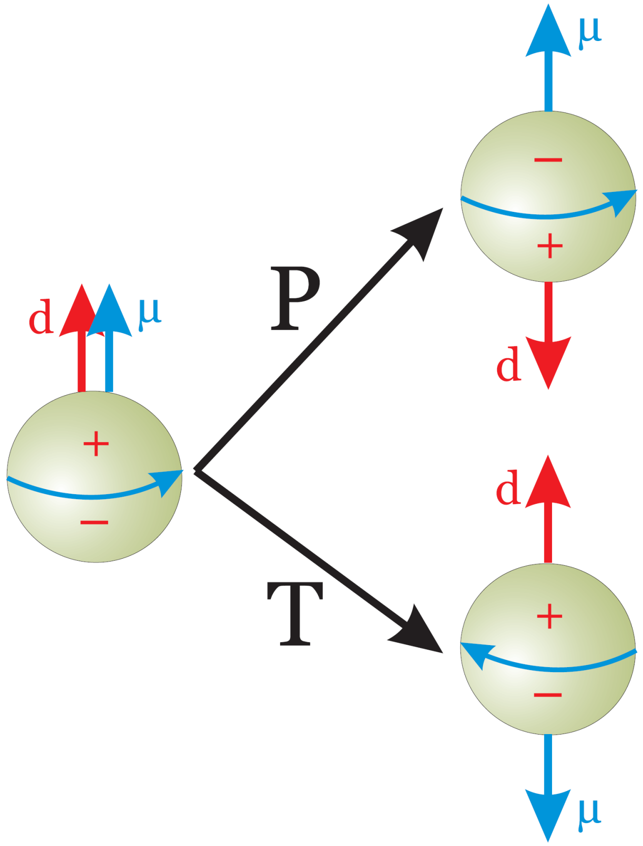
Dark Matter obviously needs to be (largely) neutral, but how dark is dark?



Even perfectly neutral particles can couple to photons

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

magnetic dipole moment (P and T even)



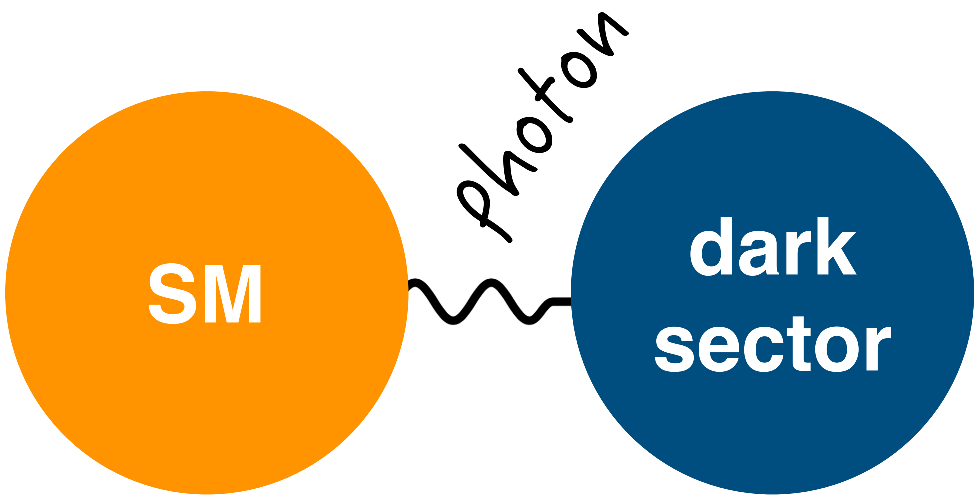
$$H_{\rm EDM} = -d_\chi(\vec{E}\cdot\vec{\sigma}_\chi)$$

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

1. Dark states with EM form factors

Photon-portal

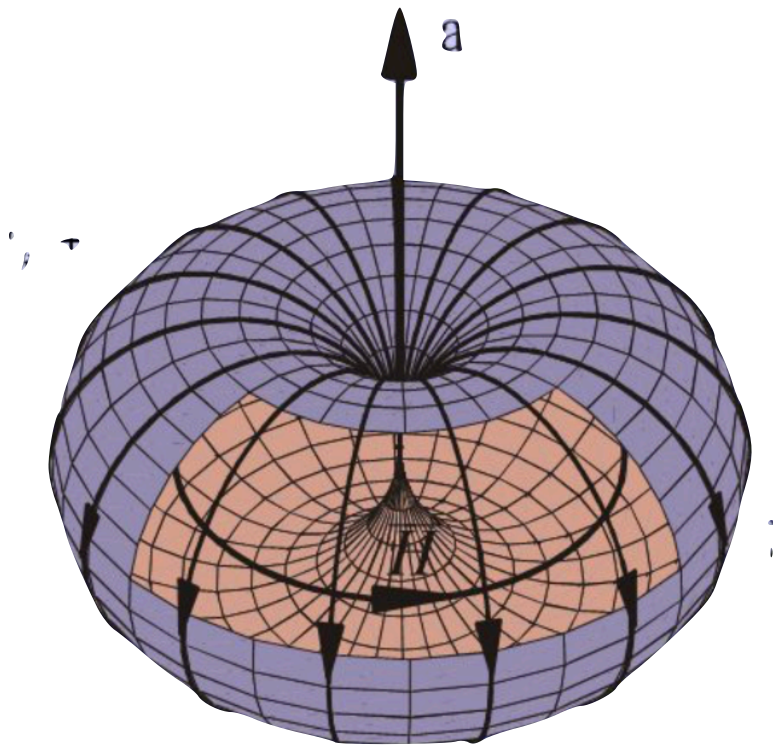
Dark Matter obviously needs to be (largely) neutral, but how dark is dark?



Even perfectly neutral particles can couple to photons

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

anapole moment (P odd but CP even)

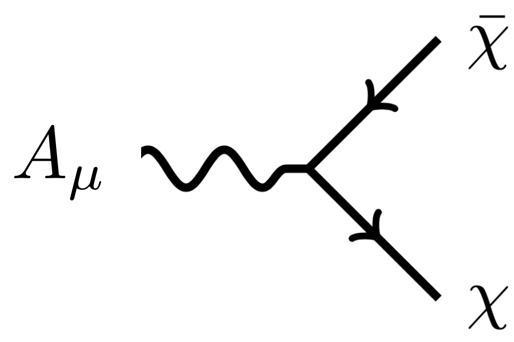


$$H_{\rm CR} = -b_\chi(\vec{\nabla}\cdot\vec{E})$$

charge radius (P and T even)

1. Dark states with EM form factors

Photon-portal



Effective operators

millicharge (ϵQ):	$\epsilon e\,\bar{\chi}\gamma^\mu\chi A_\mu,$	dim 4
magnetic dipole (MDM):	$\frac{1}{2}\mu_\chi\,\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu},$	
electric dipole (EDM):	$\frac{i}{2}d_\chi\,\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi F_{\mu\nu},$	dim5
anapole moment (AM):	$a_\chi\,\bar{\chi}\gamma^\mu\gamma^5\chi\partial^\nu F_{\mu\nu},$	
charge radius (CR):	$b_\chi\,\bar{\chi}\gamma^\mu\chi\partial^\nu F_{\mu\nu}.$	dim6

Vertex

$$\Gamma^\mu(q) = i\sigma^{\mu\nu}q_\nu\left[M(q^2) + iD(q^2)\gamma^5\right] + \left(q^2\gamma^\mu - q^\mu \not{q}\right)\left[V(q^2) - A(q^2)\gamma^5\right]$$

$$\mu_\chi = M(0), \quad d_\chi = D(0), \quad a_\chi = A(0), \quad b_\chi = V(0)$$

1. Dark states with EM form factors

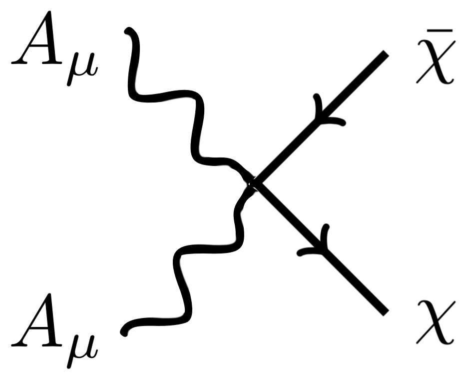
Photon-portal

Rayleigh/Susceptibility ops

$$\bar{\chi}\chi \qquad \qquad F_{\mu\nu}F^{\mu\nu}$$

$$\otimes$$

$$\bar{\chi}\gamma^5\chi \qquad \qquad F_{\mu\nu}\tilde{F}^{\mu\nu}$$



....

dim 7

....

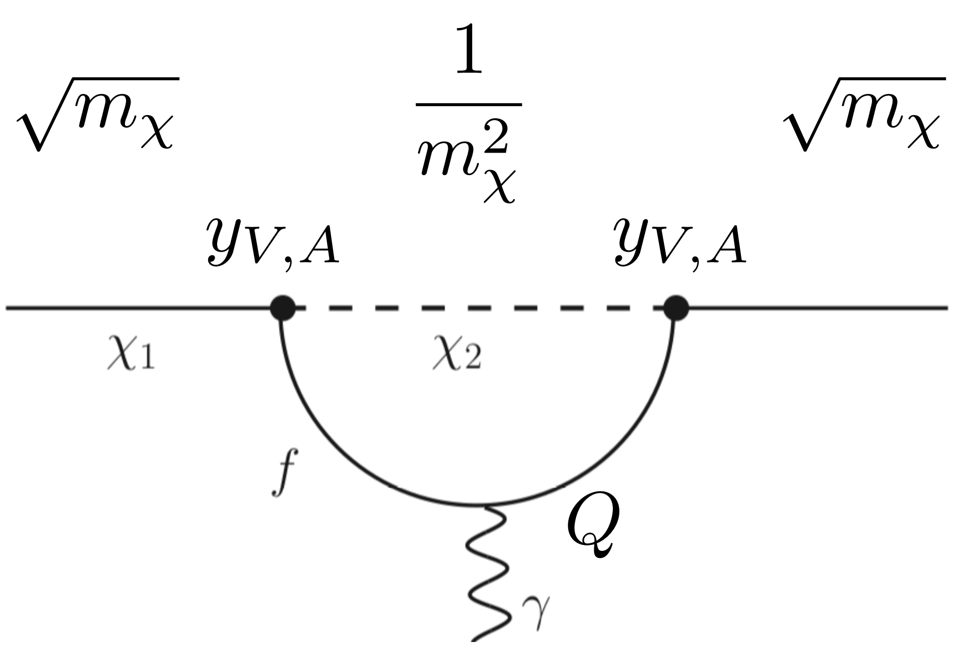
=> different (or loop-suppressed) phenomenology

Complex scalars: dim-6 Rayleigh and charge radius interaction

Vectors: also quadrupole moments exist

1. Dark states with EM form factors

Photon-portal



$$\mu_\chi \sim \frac{Q|y_{A,V}|^2}{m_\chi} \qquad d_\chi \sim \frac{Q\,\mathrm{Im}[\mathrm{y}_\mathrm{V}\mathrm{y}_\mathrm{A}^*]}{m_\chi}$$

$$a_\chi,\ b_\chi \sim \frac{Q|y_{A,V}|^2}{M^2}$$

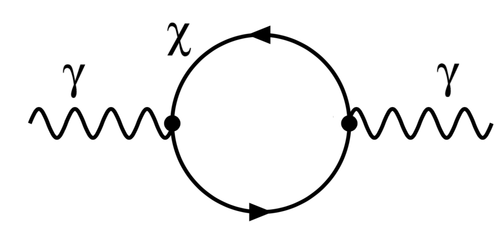
or $$a_\chi,\ b_\chi \sim \frac{Q|y_{A,V}|^2}{m_\chi} \times \frac{1}{\Delta m}$$

e.g. Bagnasco, Dine, Thomas 1994; Foadi, Frandsen, Sannino 2009; Antipin, Redi, Strumia, and Vigiani 2015; Kavanagh, Panci, Ziegler 2018

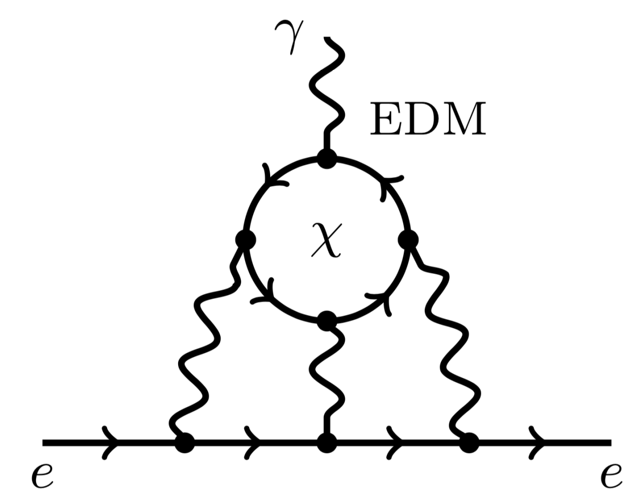
1. Dark states with EM form factors

Photon-portal

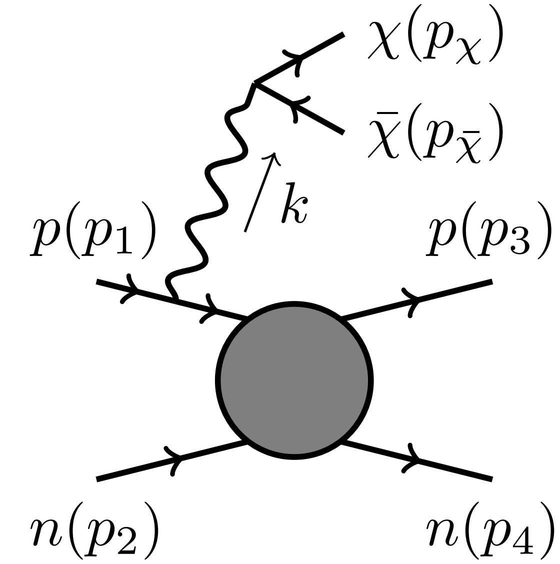
Tinkering with the photon may affect many known phenomena



- 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?



Muon g-2

- Muon g-2 puzzle: (3-4)σ tension between SM prediction and measurement

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (290 \pm 90) \times 10^{-11}$$

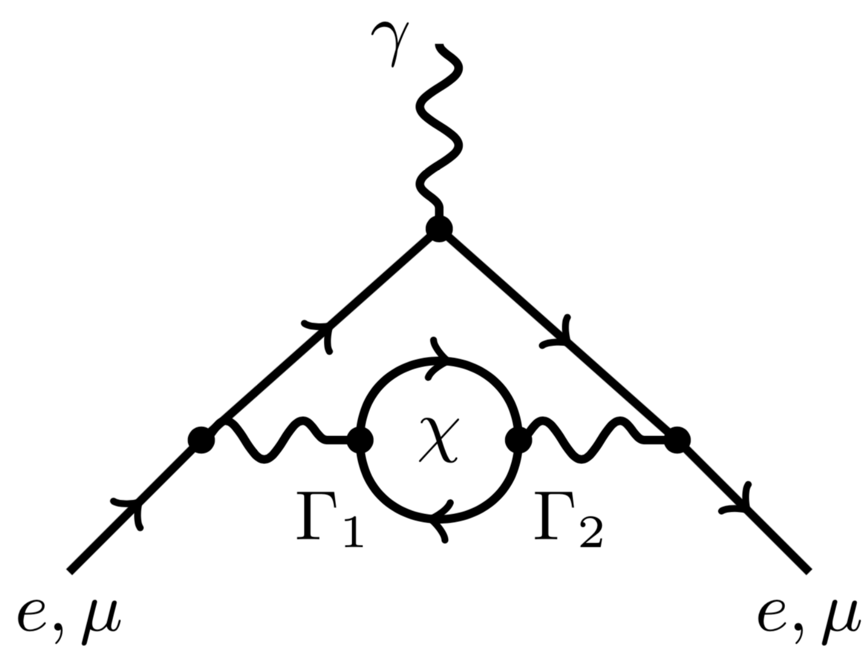
- For form-factor interactions, contributions enter through the vacuum polarization

e.g. use dispersion relation + unitarity

$$\Delta a_\mu = \frac{1}{4\pi^3} \int_{4m_\chi^2} ds\, \sigma_{e^+e^- \to \chi\bar{\chi}}(s) K(s)$$

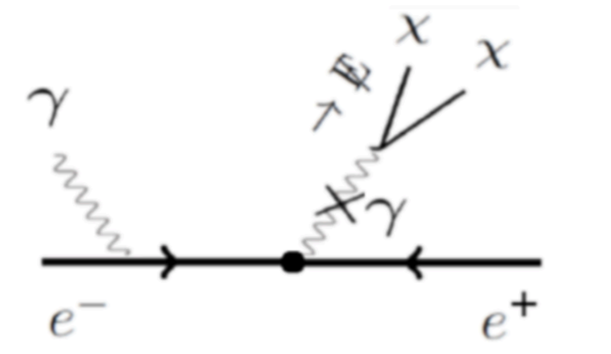
solution to g-2 for

$$|\mu_\chi|,\ |d_\chi| \sim \text{few} \times 10^{-3} \mu_{\rm B}$$

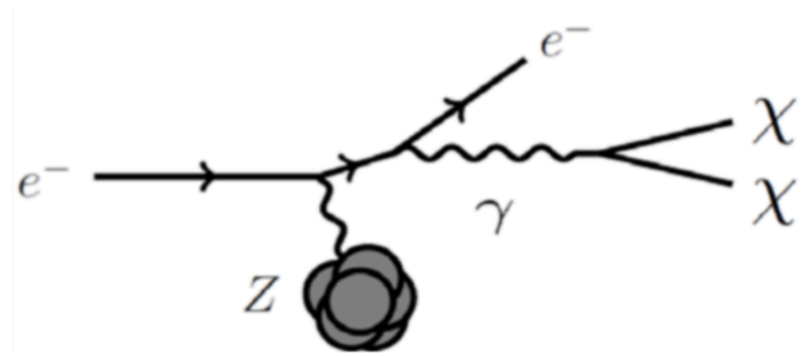


sub-GeV states:
a target for intensity frontier

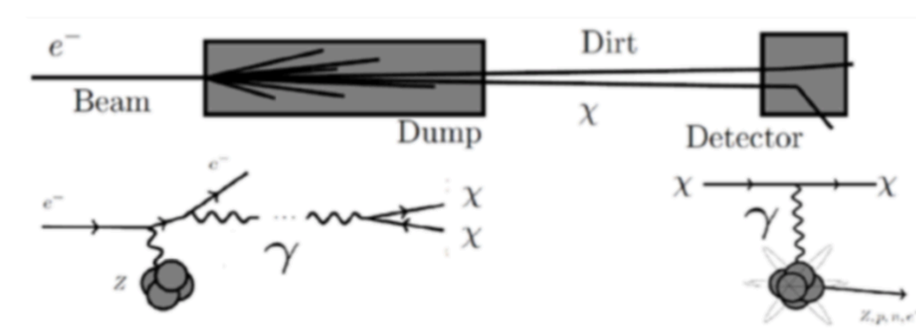
missing momentum



missing energy



direct search



BaBar:
- CM energy: 10 GeV
- Luminosity: 28/19 fb^{-1}

Belle II (projected)**:**
- Luminosity: 50 ab^{-1}

Main Backgrounds:
- $e^+e^- \to \gamma\gamma$
- $e^+e^- \to \gamma\gamma\gamma$
- $e^+e^- \to \gamma\, e^+e^-$

NA64:
- Beam energy: 100 GeV
- Lead Target
- EOT: 10^{10}

LDMX (projected)**:**
- Beam energy: 4/8 GeV
- Tungsten/Aluminum Target
- EOT: 10^{14} / 10^{15}

Almost no Backgrounds:
- Active veto system
- Cuts on search region

mQ:
- Beam energy: 30 GeV
- Tungsten Target
- EOT: 10^{19}

BDX (projected)**:**
- Beam energy: 11 GeV
- Aluminum Target
- EOT: 10^{22}

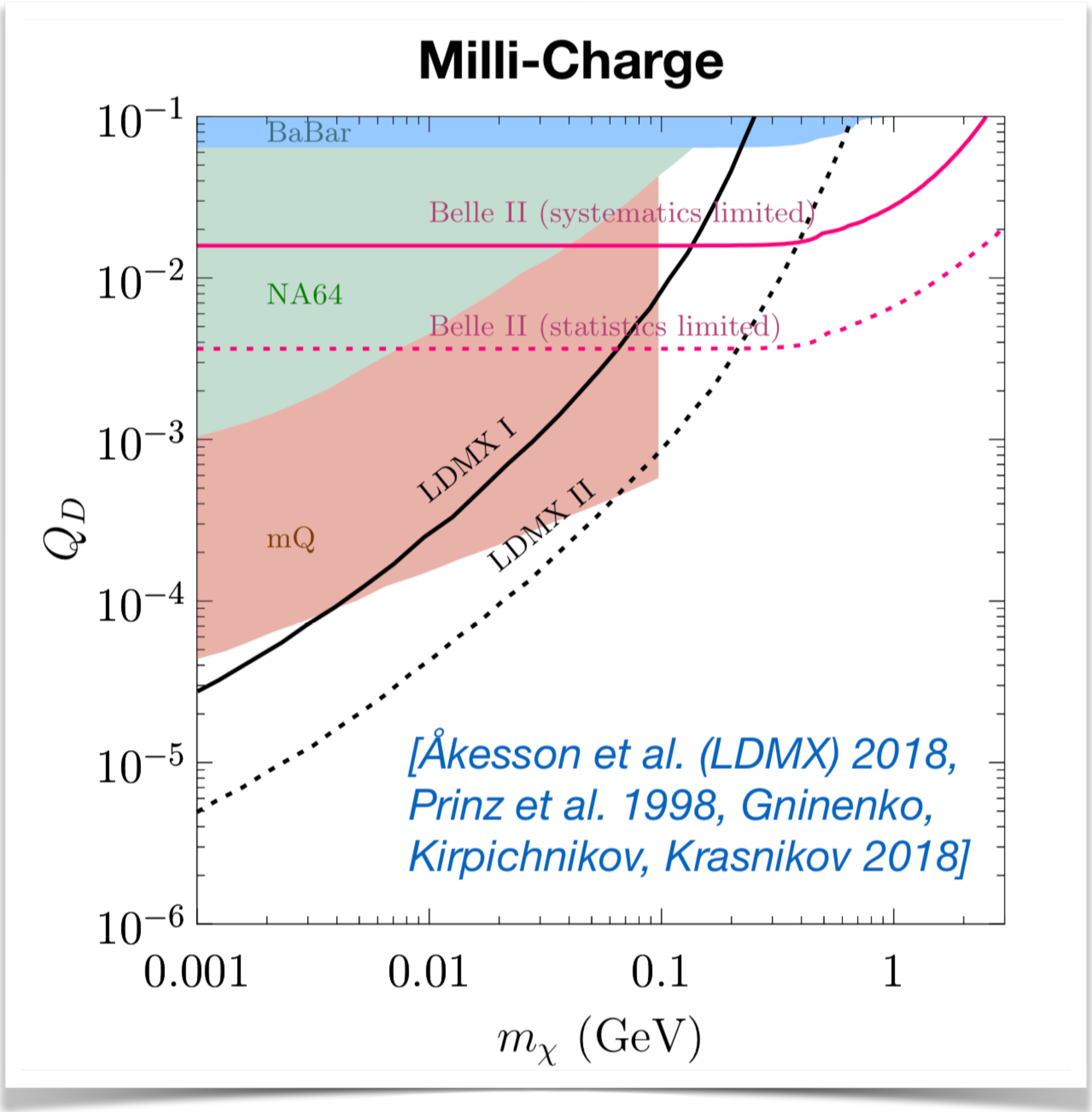
Main Backgrounds:
- High energy neutrinos

Dark states with EM form factors

Photon-portal

MeV-GeV mass bracket

Chu, JP, Semmelrock 2019
Chu, Kuo, JP 2020

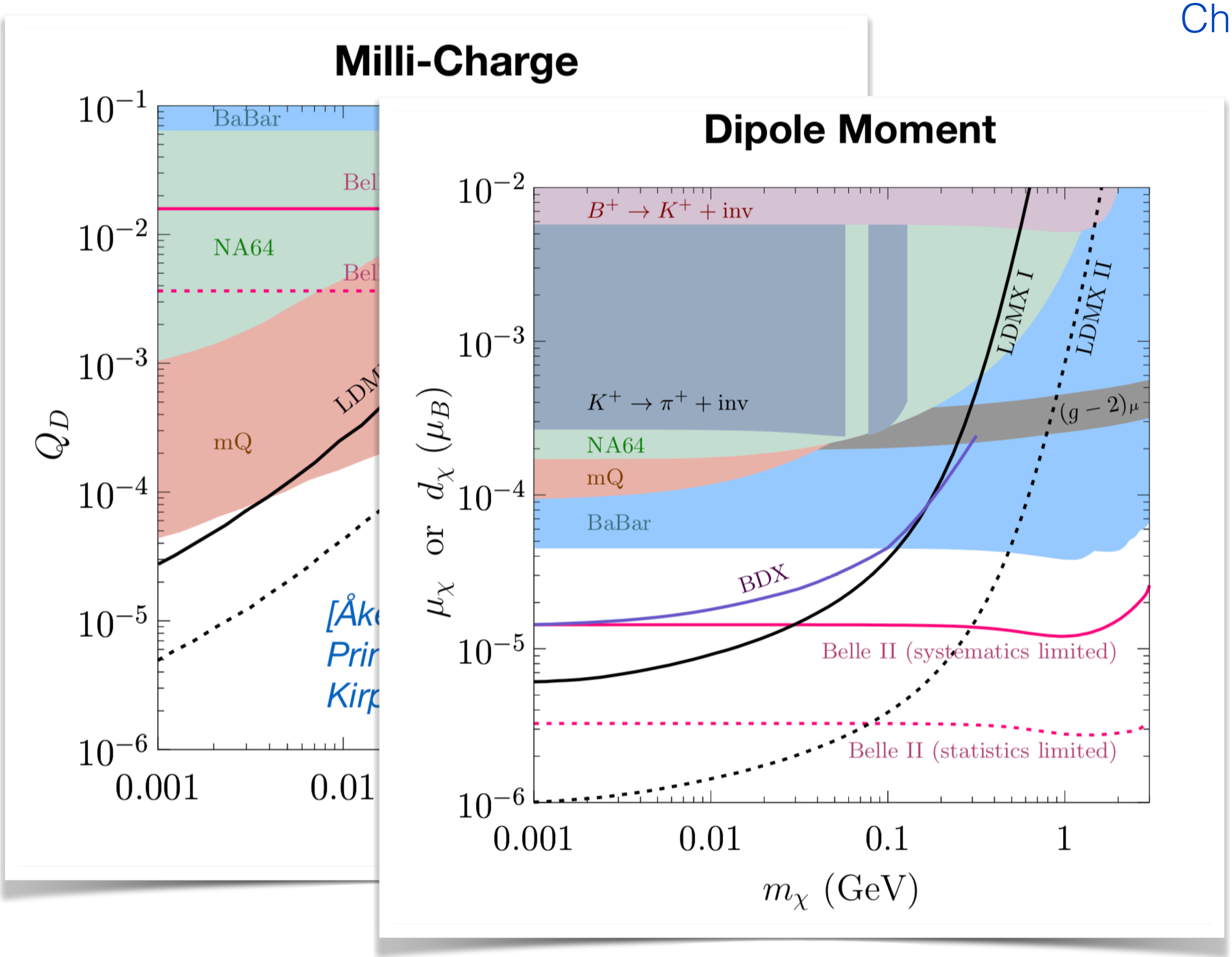


Dark states with EM form factors

Photon-portal

MeV-GeV mass bracket

Chu, JP, Semmelrock 2019
Chu, Kuo, JP 2020

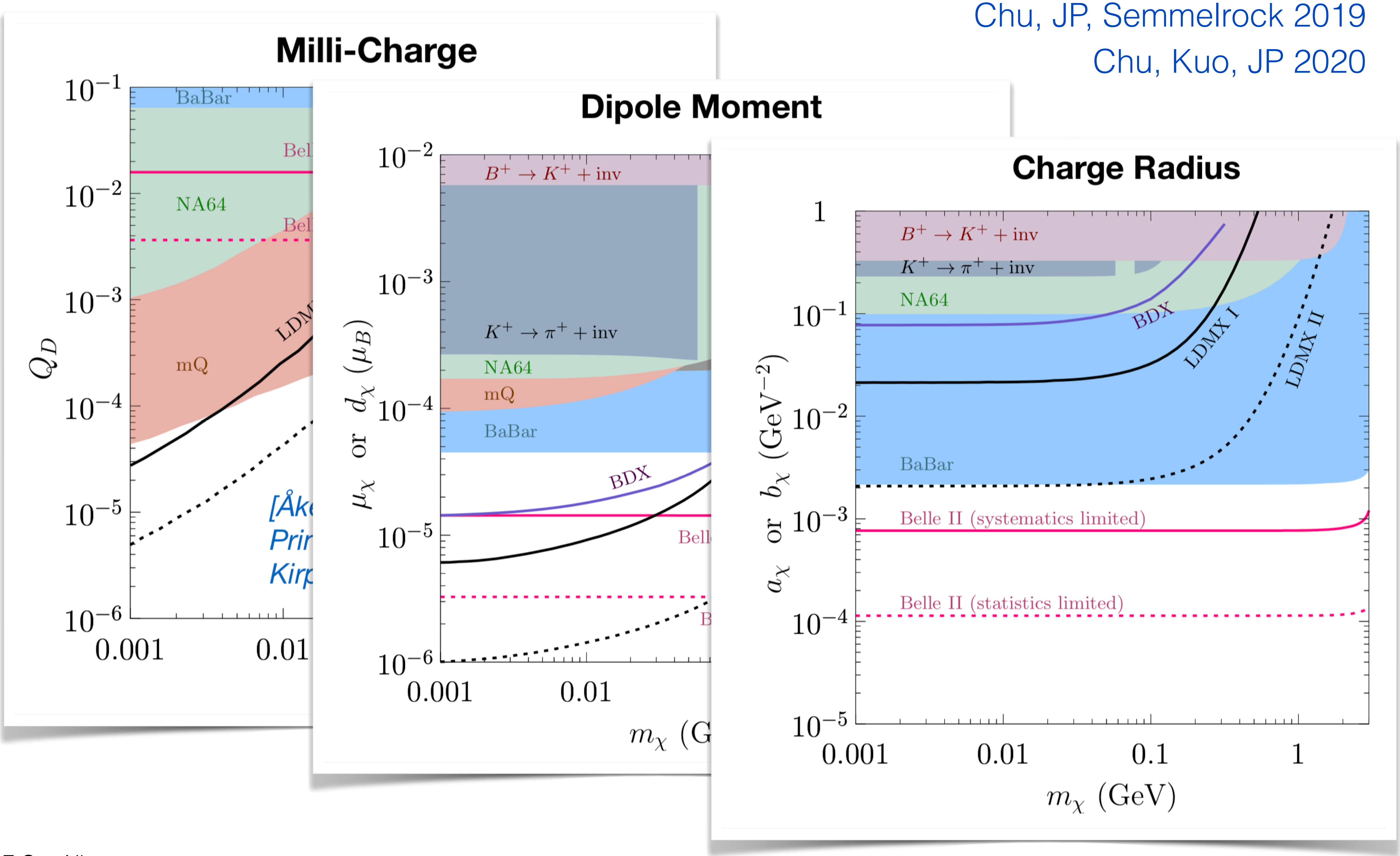


Dark states with EM form factors

Photon-portal

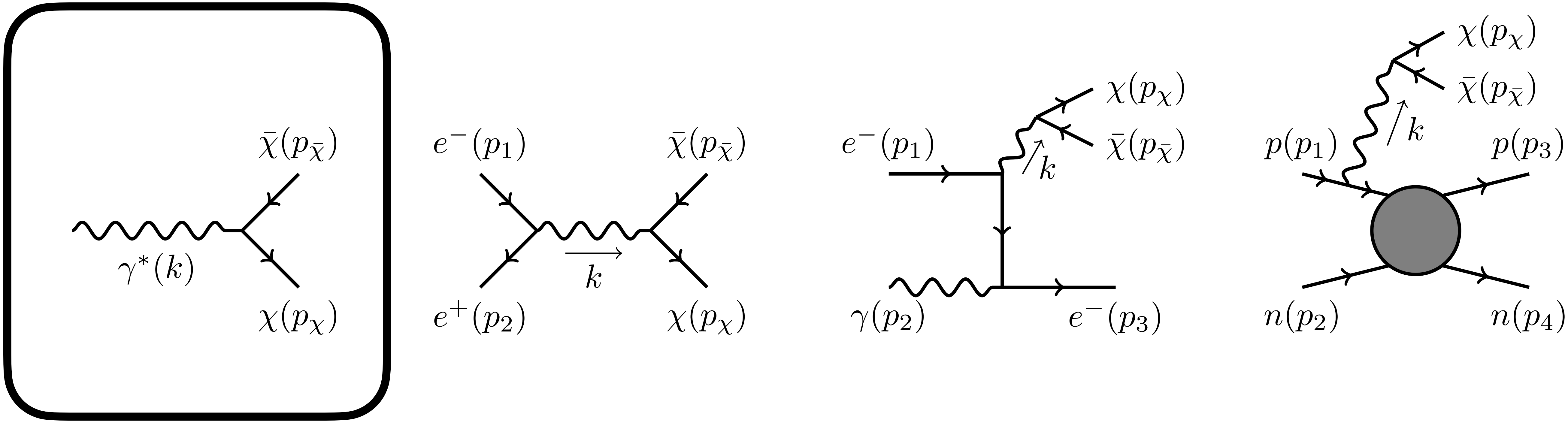
MeV-GeV mass bracket

Chu, JP, Semmelrock 2019
Chu, Kuo, JP 2020



Energy loss in dark states

Stellar probes of dark sector - photon interactions



T/L "Plasmon" decay

(all)

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

Energy loss in dark states

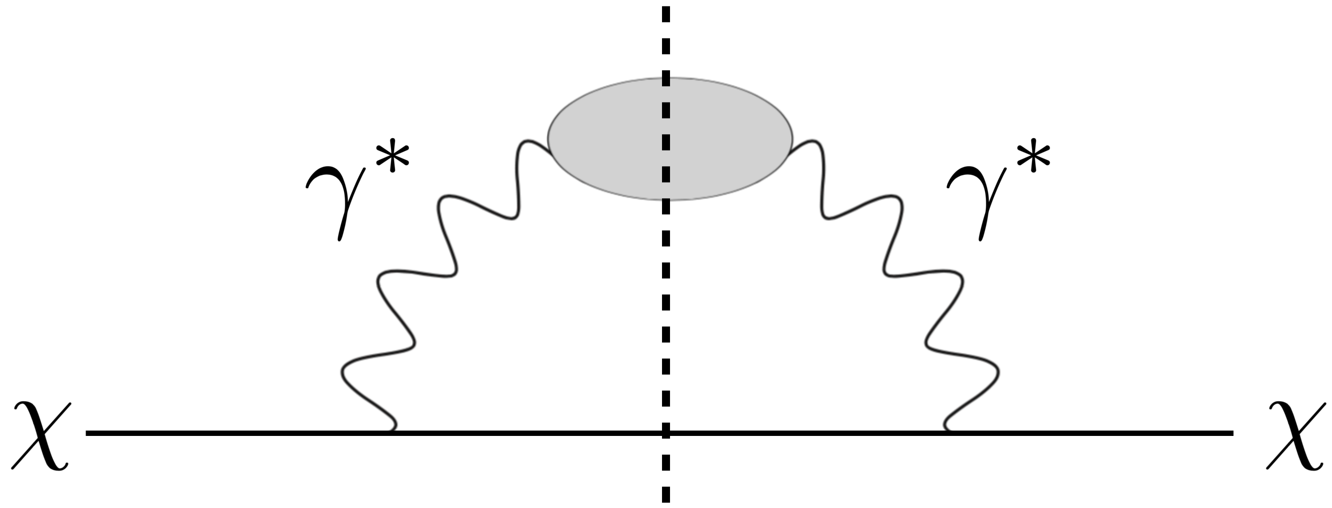
Unifying formula for pair emission

$$\dot{N}_\chi = -\int \frac{d^3\vec{p}_\chi}{(2\pi)^3} \frac{1}{(e^{E_\chi/T}+1)} \frac{\mathrm{Im}\,\Pi_\chi(E_\chi,\vec{p}_\chi)}{E_\chi}$$

Finite-T optical theorem: rate with which a particle comes into thermal equilibrium is given by the discontinuity of the self energy

$$\mathrm{Im}\,\Pi_\chi(E_\chi,\vec{p}_\chi) = \bar{u}(p_\chi)\Sigma(E_\chi,\vec{p}_\chi)u(p_\chi)$$

Weldon 1983



Energy loss in dark states

Unifying formula for pair emission

$$\frac{d\dot{N}_\chi}{ds_{\chi\bar{\chi}}} = -\sum_{i=\mathrm{T,L}} g_i \int \frac{d^3\vec{k}}{(2\pi)^3} \frac{1}{(e^{\omega/T}-1)} \frac{\mathrm{Im}\,\Pi_i(\omega,\vec{k})}{\omega} \times \frac{f(s_{\chi\bar{\chi}})}{16\pi^2|s_{\chi\bar{\chi}}-\Pi_i|^2}\sqrt{1-\frac{4m_\chi^2}{s_{\chi\bar{\chi}}}}$$

In this version (derived from works on dilepton-production in hot matter) the imaginary part of the *photon self-energy* enters

$$\Pi^{\mu\rho} = (\epsilon^\mu_{\mathrm{T},1}\epsilon^\rho_{\mathrm{T},1} + \epsilon^\mu_{\mathrm{T},2}\epsilon^\rho_{\mathrm{T},2})\,\Pi_\mathrm{T} + \epsilon^\mu_\mathrm{L}\epsilon^\rho_\mathrm{L}\,\Pi_\mathrm{L}$$

=> leading contribution from the pole $s_{\chi\bar{\chi}} = \mathrm{Re}\,\Pi_{\mathrm{L,T}}$
recover plasmon-decay rate

=> further contributions to chi-pair production found from identifying the contributions to the photon self-energy

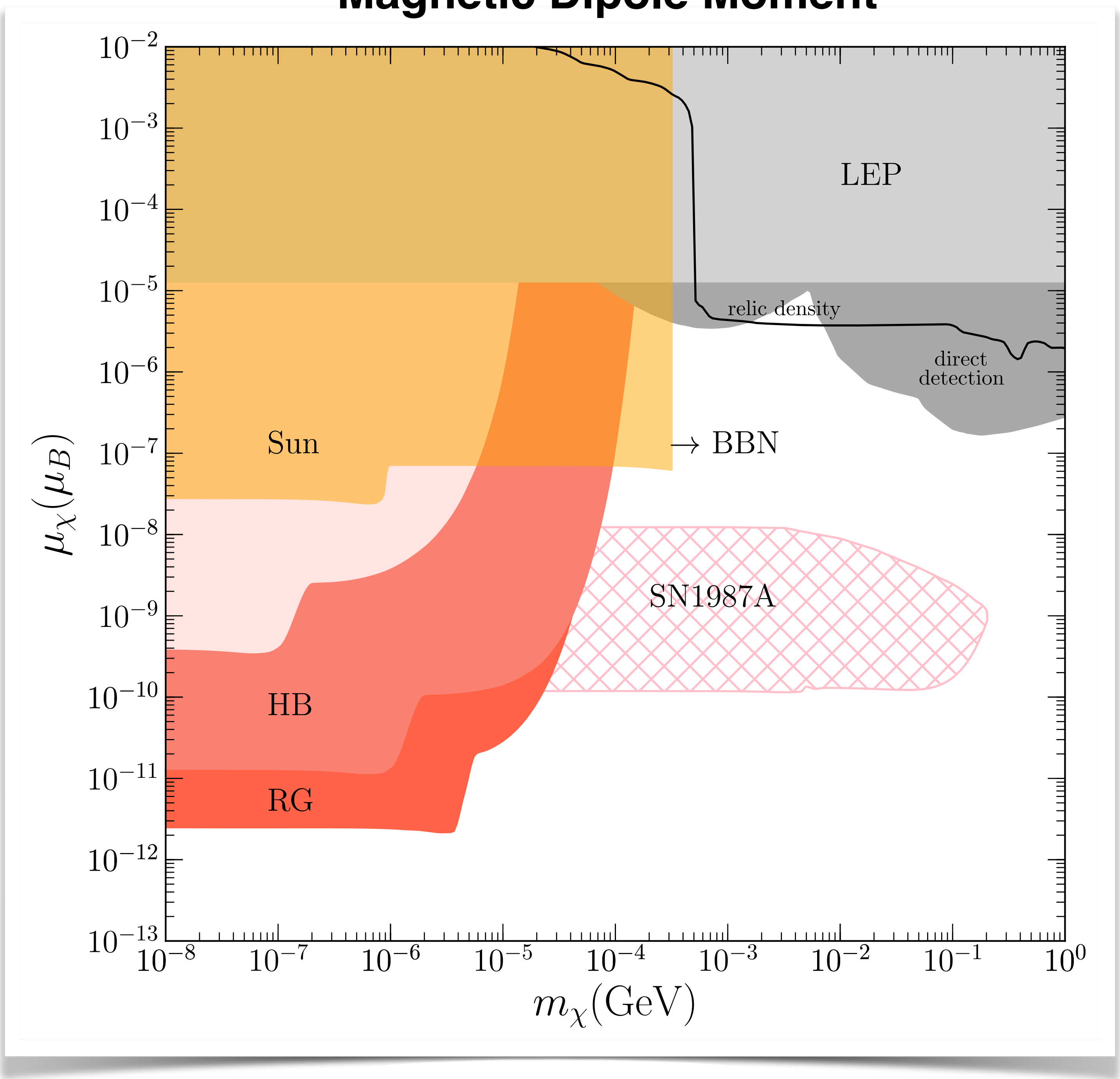
Application 1

keV-MeV mass bracket

Photon-portal

Chu, Kuo, JP, Semmelrock 2019

Magnetic Dipole Moment



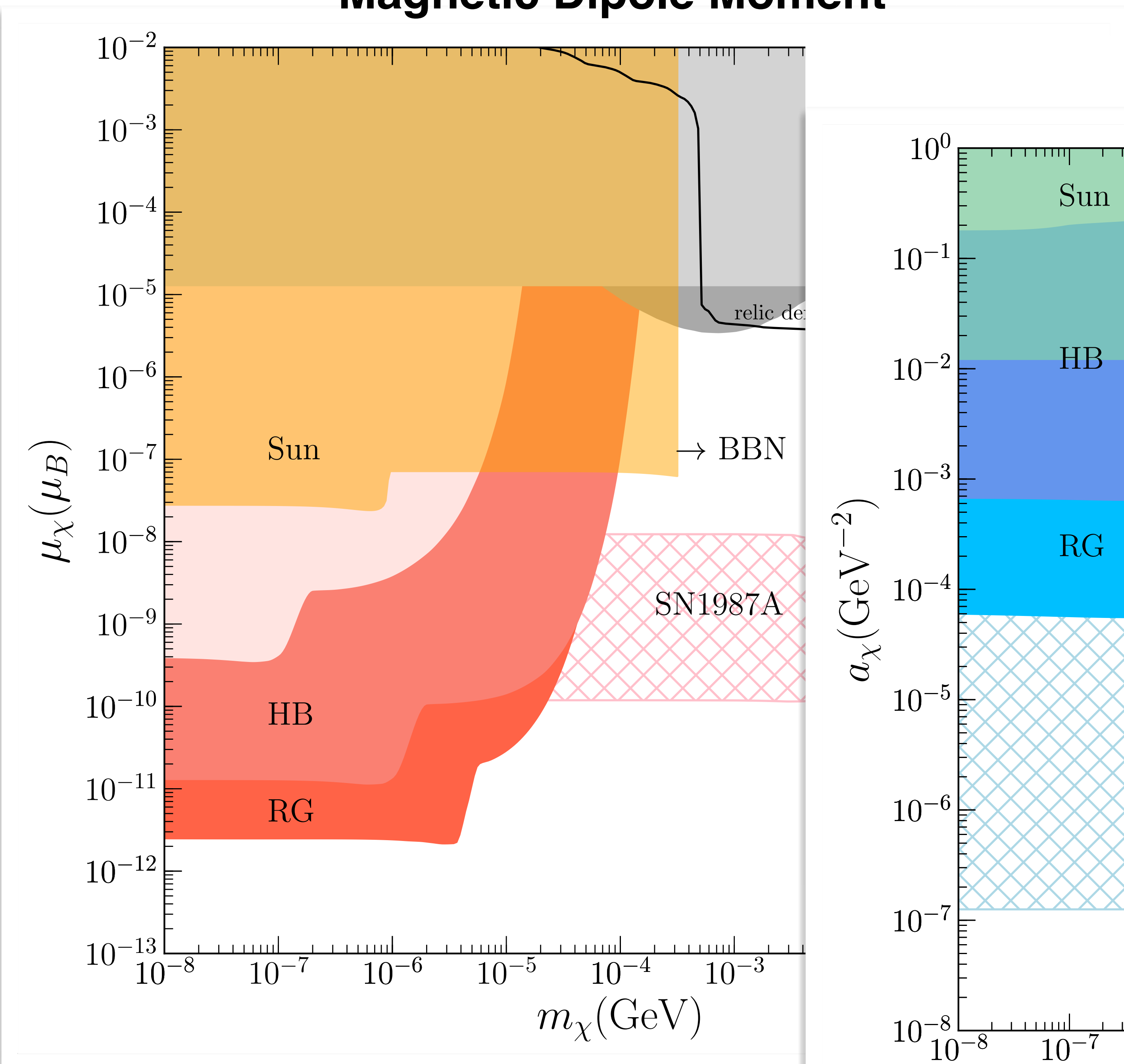
Application 1

keV-MeV mass bracket

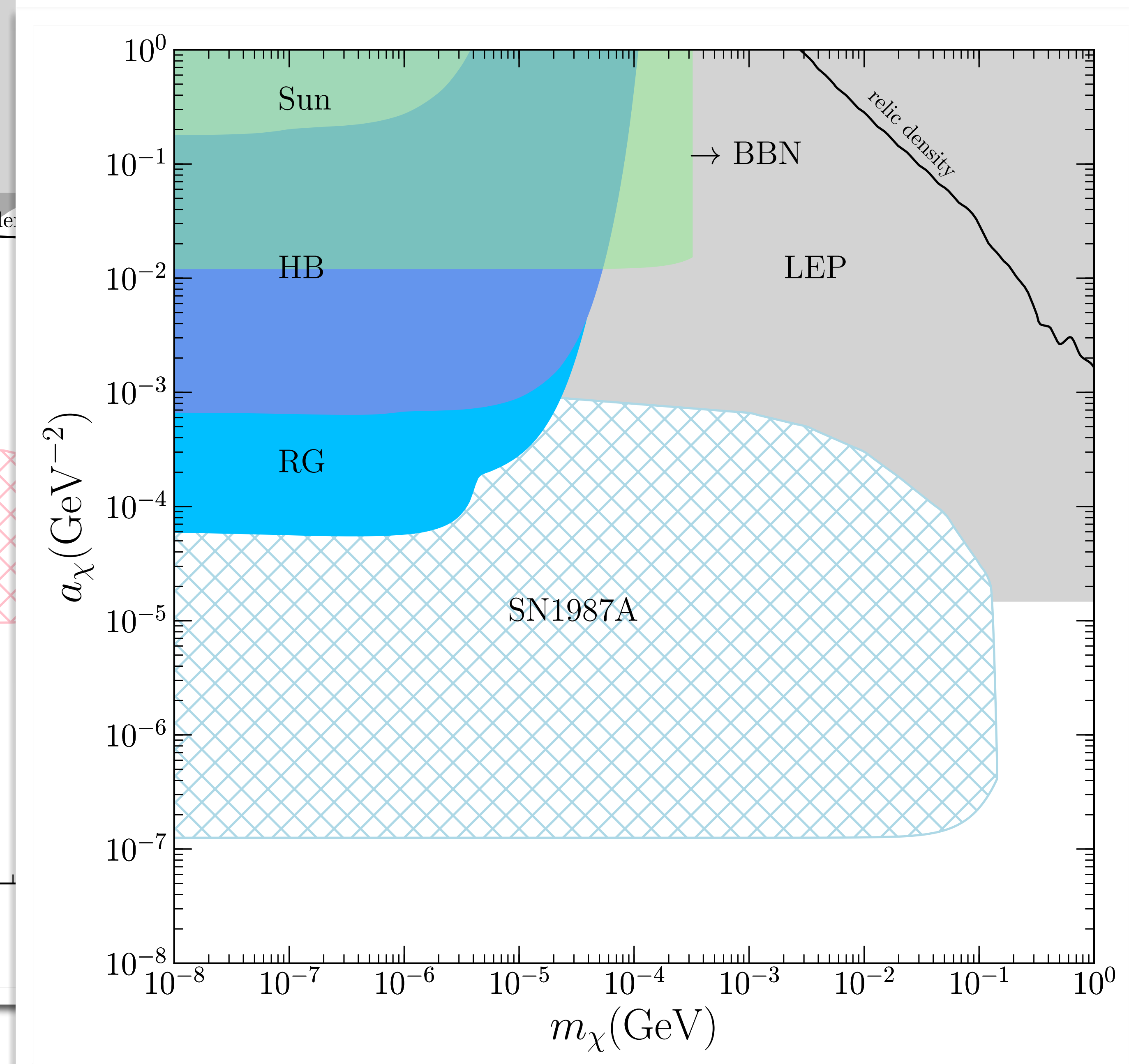
Photon-portal

Chu, Kuo, JP, Semmelrock 2019

Magnetic Dipole Moment

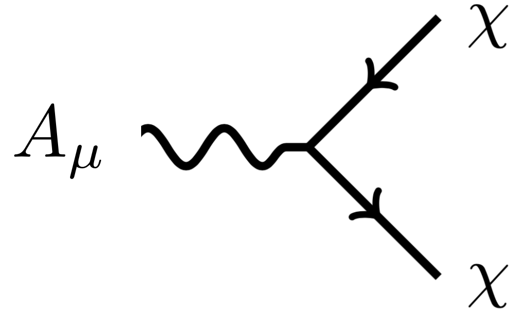


Anapole Moment



Dark states with EM form factors

SPIN 1/2 case is now familiar ✓



Effective operators

millicharge (ϵQ):	$\epsilon e\, \bar{\chi}\gamma^\mu\chi A_\mu,$	dim 4
		....
magnetic dipole (MDM):	$\frac{1}{2}\mu_\chi\, \bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu},$	
electric dipole (EDM):	$\frac{i}{2}d_\chi\, \bar{\chi}\sigma^{\mu\nu}\gamma^5\chi F_{\mu\nu},$	dim5
		....
anapole moment (AM):	$a_\chi\, \bar{\chi}\gamma^\mu\gamma^5\chi\partial^\nu F_{\mu\nu},$	
charge radius (CR):	$b_\chi\, \bar{\chi}\gamma^\mu\chi\partial^\nu F_{\mu\nu}.$	dim6

=> SPIN 1 case has comparatively received much less attention

Vector Dark States

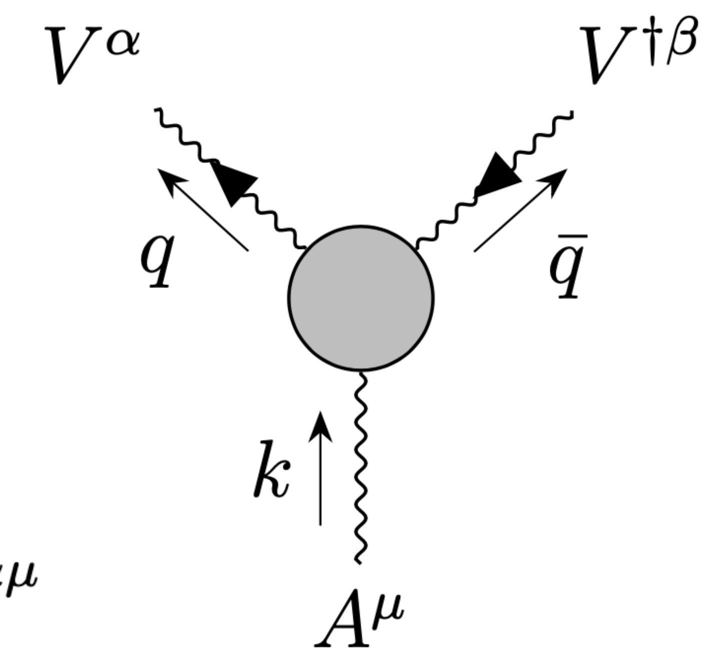
Chu, Ibarra, Hisano, Kuo, JP
2303.13643

SPIN1 case: construction

Consider all possible Lorentz structures

=> yields 9 structures

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



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

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

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

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

Vector Dark States

Chu, Ibarra, Hisano, Kuo, JP
2303.13643

SPIN1 case: construction

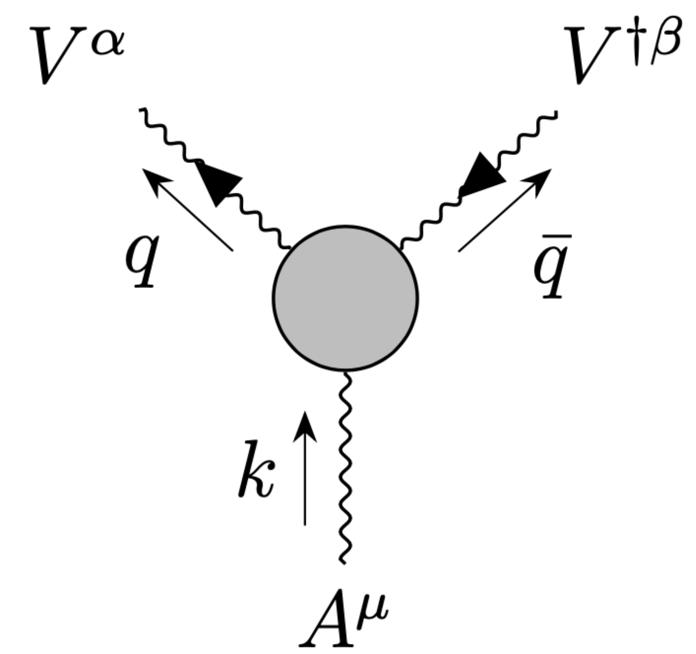
Consider all possible Lorentz structures

=> yields 9 structures

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

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



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

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

Vector Dark States

Chu, Ibarra, Hisano, Kuo, JP
2303.13643

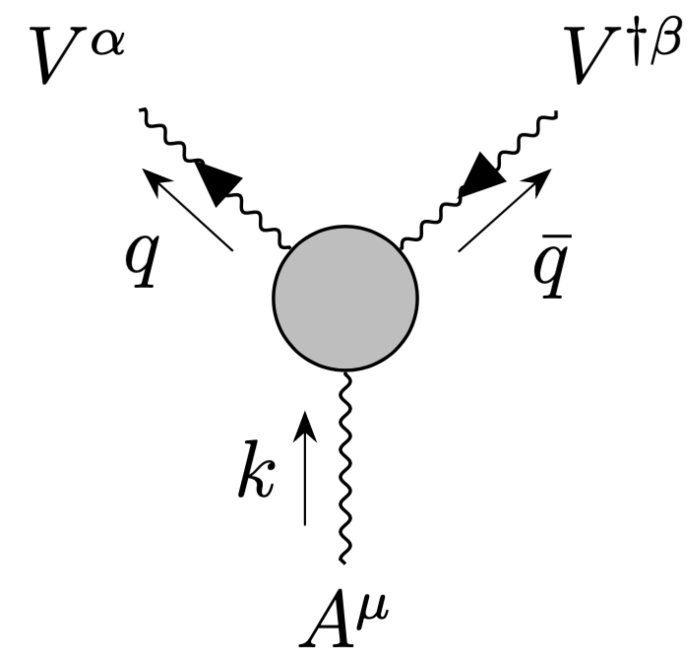
SPIN1 case: construction

Consider all possible Lorentz structures

=> yields 9 structures

=> 7 independent structures

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



neutrality of V and gauge invariance of A require

=> $f^A_{1,4,5}(0) = 0$

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

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

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

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

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

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

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

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

$$
\begin{aligned}
\frac{\mathcal{L}}{e} = & \frac{i g_1^{\Lambda}}{2\Lambda^2}\left[\left(V^{\dagger}_{\mu\nu}V^{\mu} - V^{\dagger\mu}V_{\mu\nu}\right)\partial_{\lambda}F^{\lambda\nu} - V^{\dagger\mu}V^{\nu}\Box F_{\mu\nu}\right] \\
& + \frac{g_4^{\Lambda}}{\Lambda^2}V^{\dagger}_{\mu}V_{\nu}\left(\partial^{\mu}\partial_{\rho}F^{\rho\nu} + \partial^{\nu}\partial_{\rho}F^{\rho\mu}\right) \\
& + \frac{g_5^{\Lambda}}{\Lambda^2}\epsilon^{\mu\nu\rho\sigma}\left(V^{\dagger}_{\mu}\overleftrightarrow{\partial}_{\rho}V_{\nu}\right)\partial^{\lambda}F_{\lambda\sigma} \\
& + i\kappa_{\Lambda}V^{\dagger}_{\mu}V_{\nu}F^{\mu\nu} + \frac{i\lambda_{\Lambda}}{\Lambda^2}V^{\dagger}_{\lambda\mu}V^{\mu}{}_{\nu}F^{\nu\lambda} \\
& + i\tilde{\kappa}_{\Lambda}V^{\dagger}_{\mu}V_{\nu}\tilde{F}^{\mu\nu} + \frac{i\tilde{\lambda}_{\Lambda}}{\Lambda^2}V^{\dagger}_{\lambda\mu}V^{\mu}{}_{\nu}\tilde{F}^{\nu\lambda}\,,
\end{aligned}
$$

Vector Dark States

Chu, Ibarra, Hisano, Kuo, JP
2303.13643

SPIN1 case: construction

Matched onto the following effective Lagrangian

$$\frac{\mathcal{L}}{e} = \frac{i g_1^\Lambda}{2\Lambda^2} \left[\left(V^\dagger_{\mu\nu} V^\mu - \right. \right.$$

$$+ \frac{g_4^\Lambda}{\Lambda^2} V^\dagger_\mu V_\nu \left(\partial^\mu \partial_\rho F \right.$$

$$+ \frac{g_5^\Lambda}{\Lambda^2} \epsilon^{\mu\nu\rho\sigma} \left(V^\dagger_\mu \overleftrightarrow{\partial_\rho} V \right.$$

$$+ i\kappa_\Lambda V^\dagger_\mu V_\nu F^{\mu\nu} + \frac{i}{\ }$$

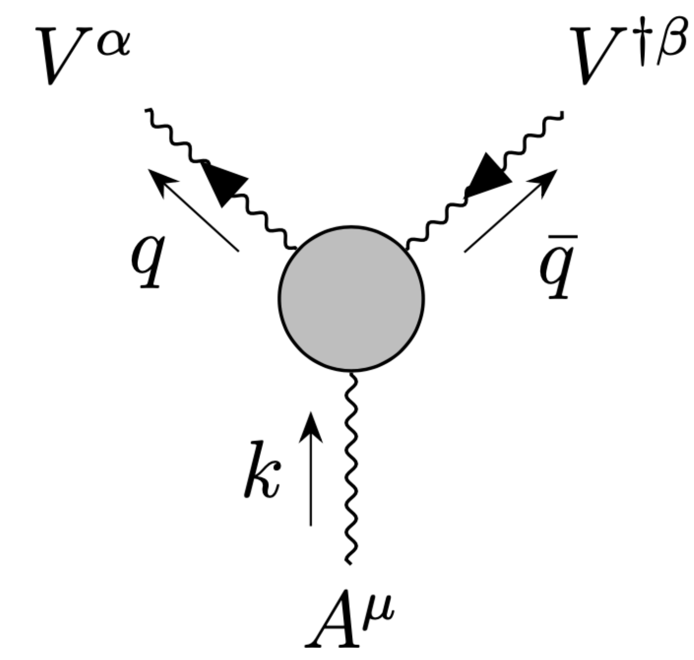
$$+ i\tilde{\kappa}_\Lambda V^\dagger_\mu V_\nu \tilde{F}^{\mu\nu} + \frac{i}{\ }$$

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



$$
\begin{aligned}
i\Gamma^{\mu\alpha\beta}(k,p) = &-\frac{ieg_1^A}{2m_V^2}k^2 p^\mu g^{\alpha\beta} \\
&-\frac{eg_4^A}{m_V^2}k^2(k^\alpha g^{\mu\beta}+k^\beta g^{\mu\alpha}) - \frac{eg_5^A}{m_V^2}k^2\epsilon^{\mu\alpha\beta\rho}p_\rho \\
&-2im_V\mu_V\left[k^\alpha g^{\mu\beta}-k^\beta g^{\mu\alpha}+\frac{1}{4m_V^2}\left(k^2 g^{\alpha\beta}p^\mu - 2k^\alpha k^\beta p^\mu\right)\right] \\
&-\frac{iQ_V}{4}\left(k^2 g^{\alpha\beta}p^\mu - 2k^\alpha k^\beta p^\mu\right) \\
&-\frac{id_V}{2m_V}p^\mu\,[kp]^{\alpha\beta} - \frac{i\tilde{Q}_V}{4}\left(p^\mu\,[kp]^{\alpha\beta}+4m_V^2\epsilon^{\mu\alpha\beta\rho}k_\rho\right)\,,
\end{aligned}
$$

=> interactions grouped by their CP properties and familiar nomenclature; defined such that mV 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

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

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

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

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	$\frac{e^2(g_5^A)^2 s^2(s-4m_V^2)^2}{3m_V^6}$

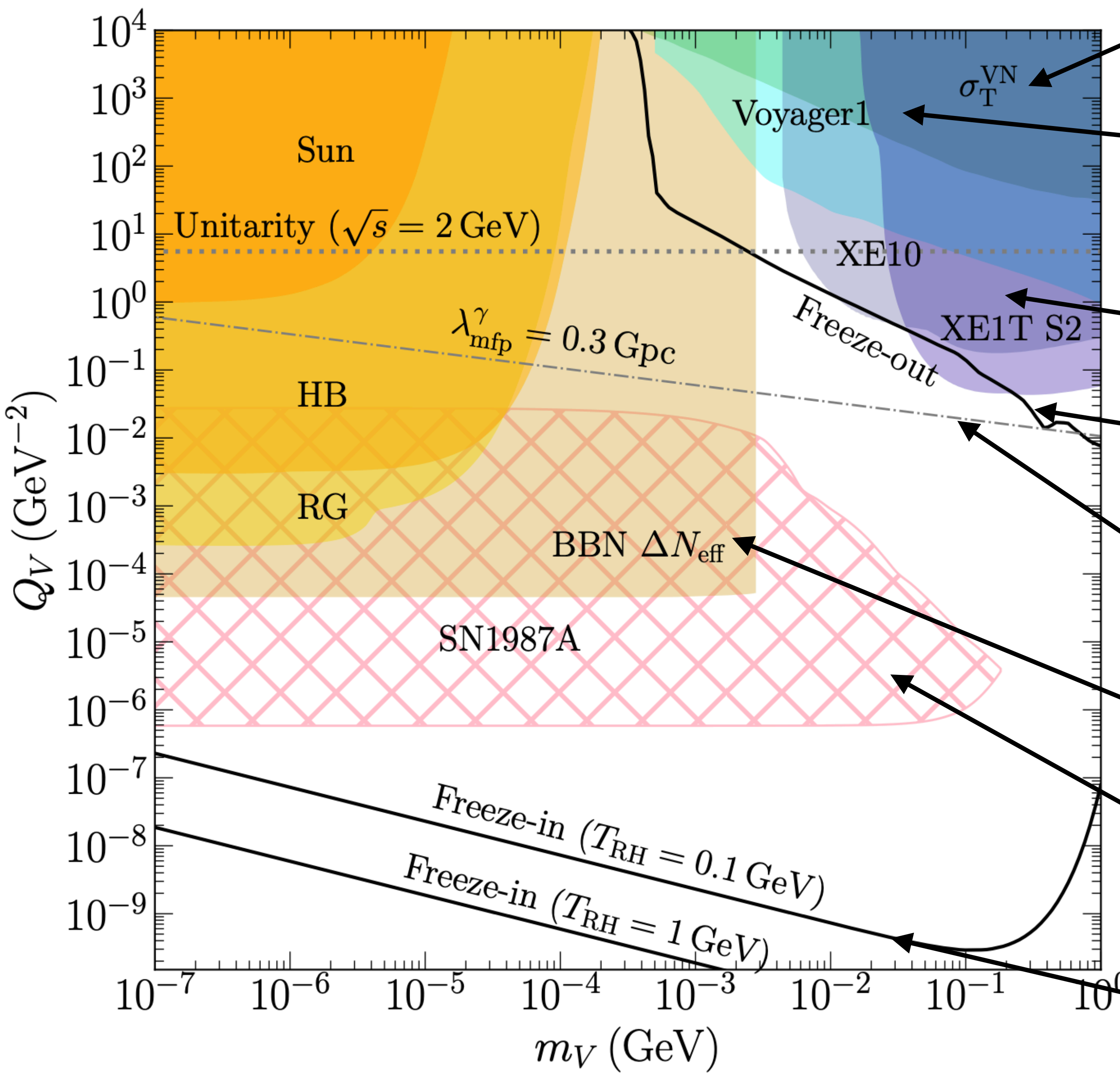
f(s) with mass-dimension 2 summarizes all effective interactions when VV phase space can be integrated

Vector DM

Chu, Ibarra, Hisano, Kuo, JP
2303.13643

Mass vs. coupling plane

electric quadrupole



modification of matter power spectrum

indirect detection limit by annihilation (weak because of velocity suppression)

direct detection DM-e scattering

annihilation into e^+e^- and $\gamma\,\gamma$ (typically p- or d-wave)

transparency to TeV photons

BBN limit on N_{eff} from minimal T_R

SN-limit bounded from above by trapping

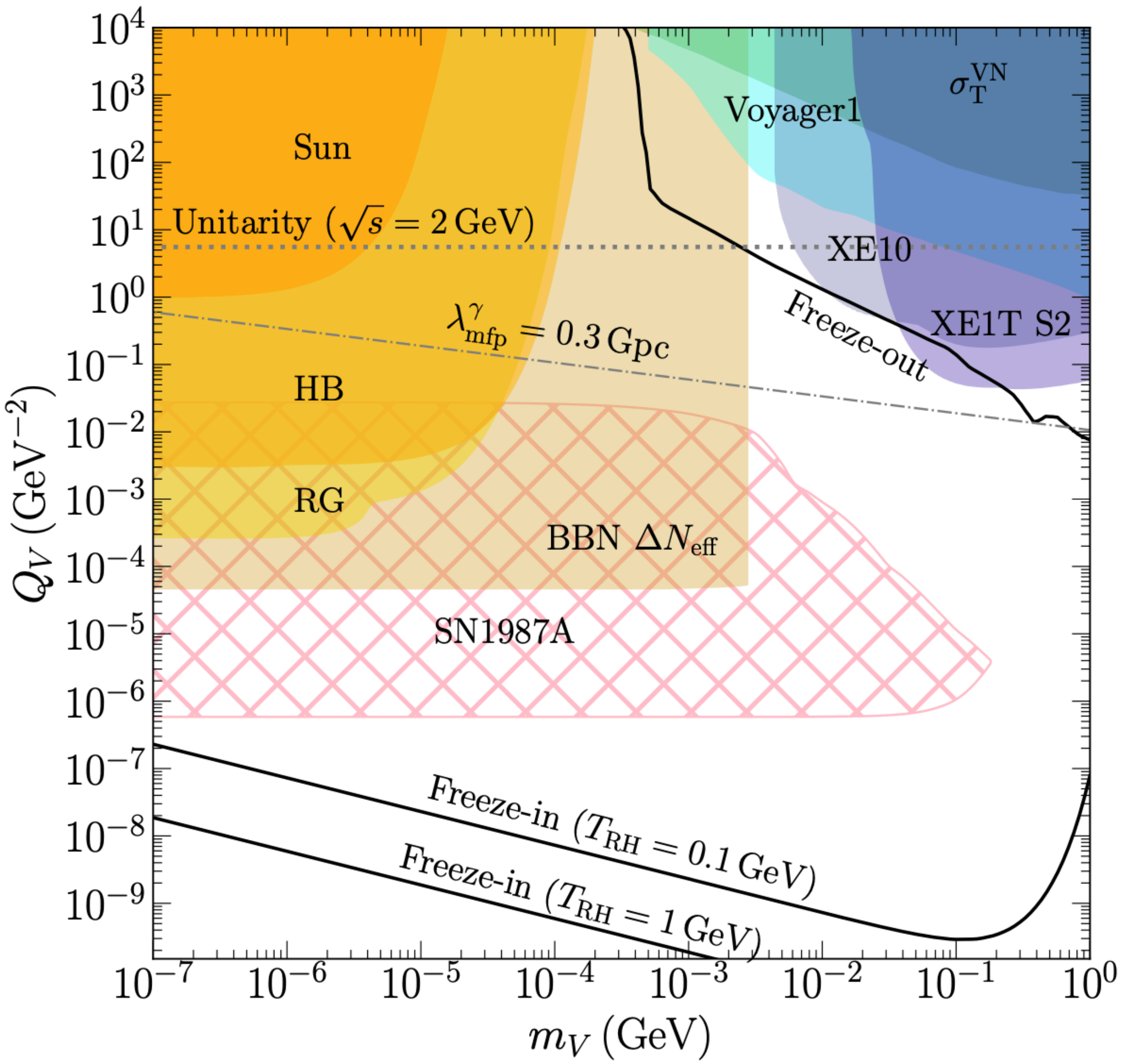
UV-dominated freeze-in

Vector DM

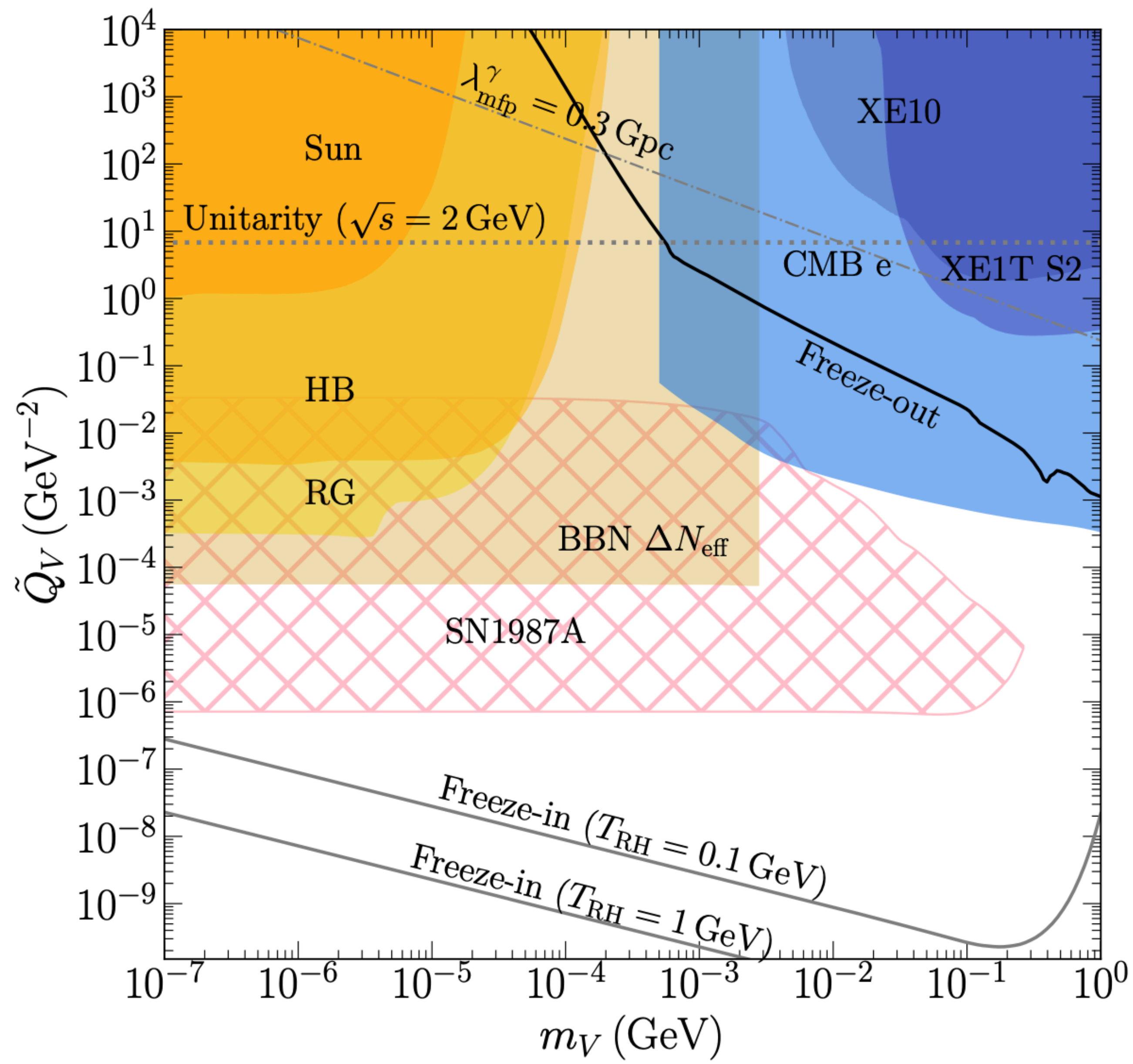
Chu, Ibarra, Hisano, Kuo, JP
2303.13643

Mass vs. coupling plane

electric quadrupole



magnetic quadrupole

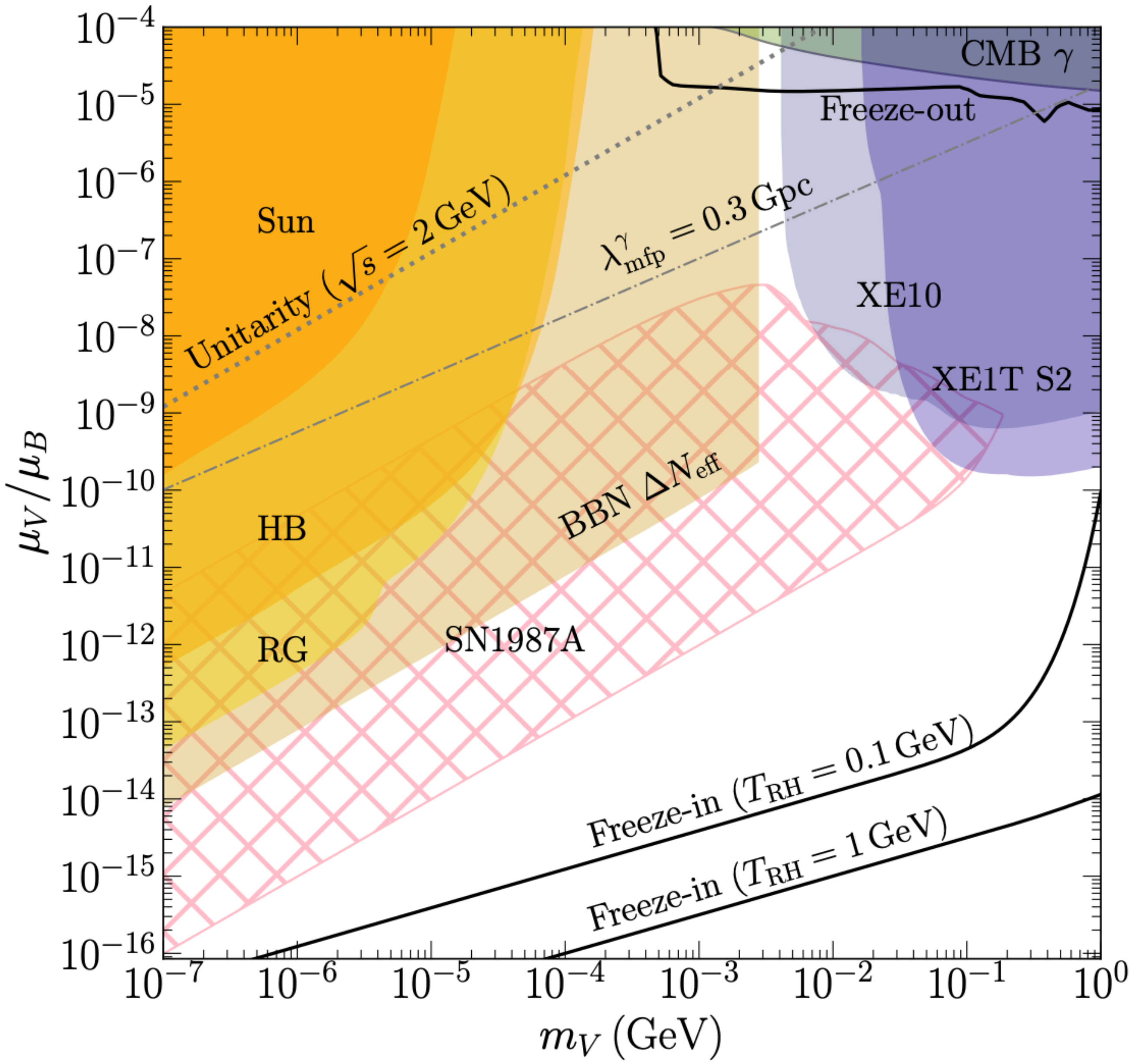


Vector DM

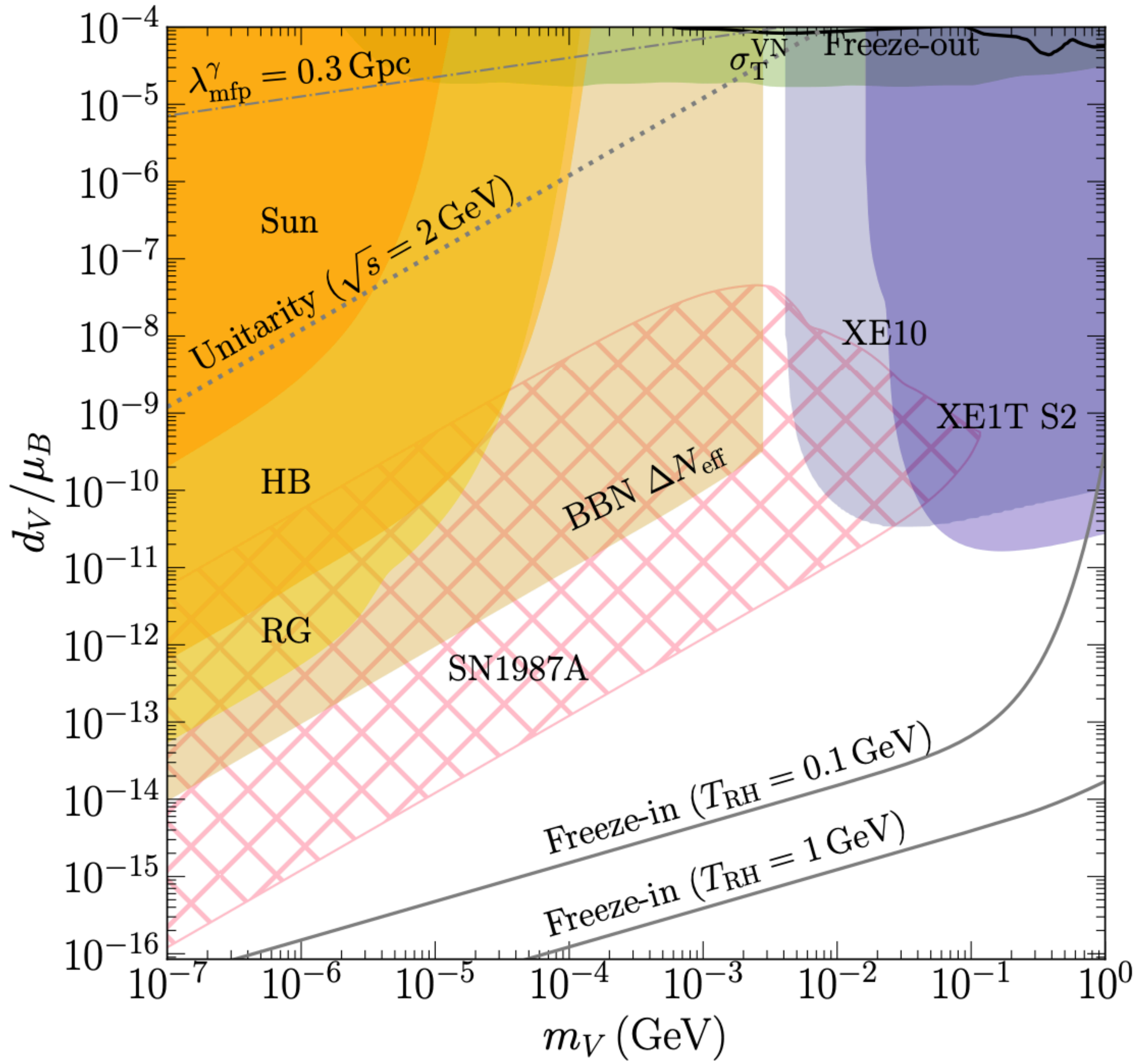
Chu, Ibarra, Hisano, Kuo, JP
2303.13643

Mass vs. coupling plane

magnetic dipole



electric dipole



Vector DM

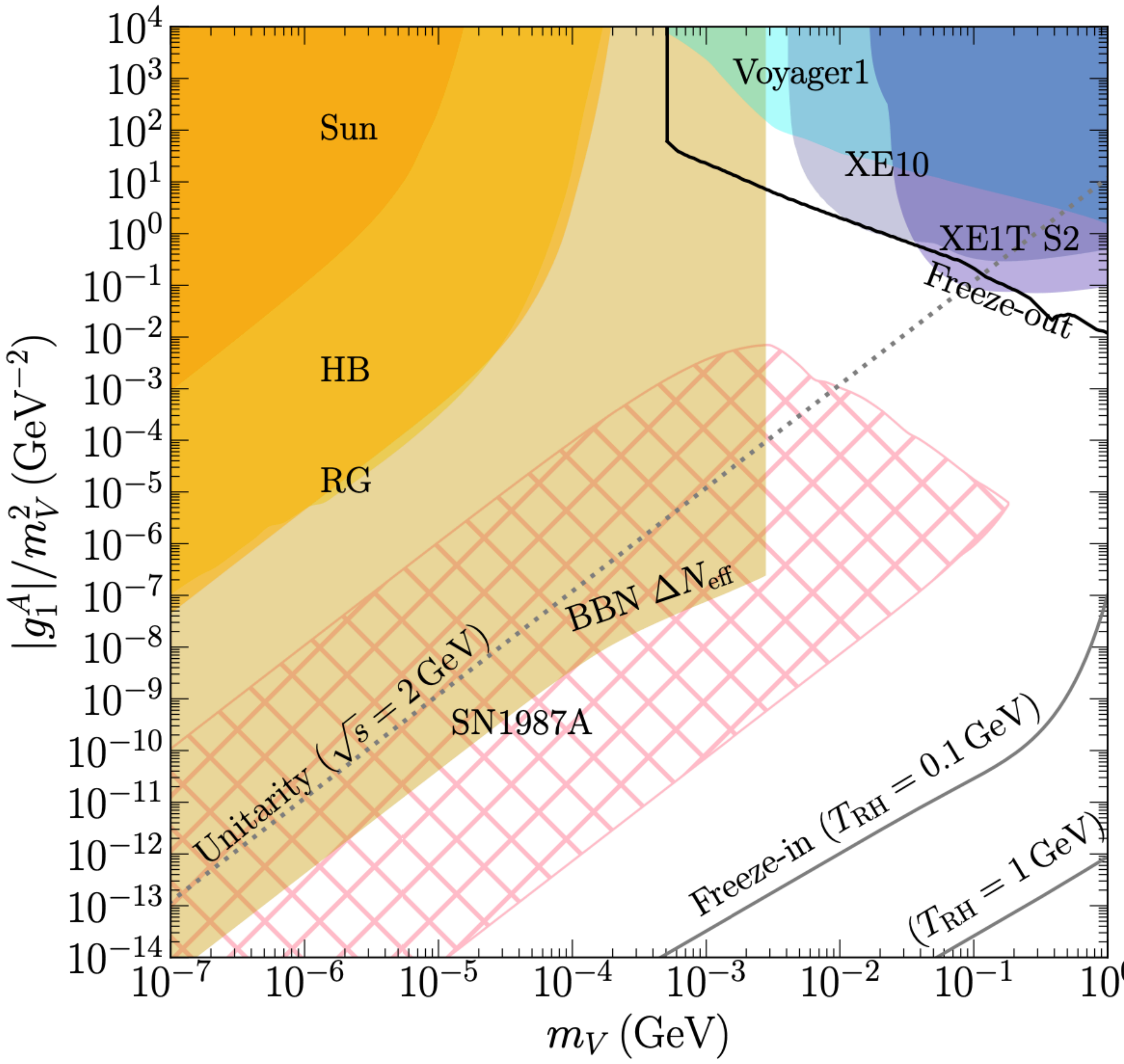
Chu, Ibarra, Hisano, Kuo, JP
2303.13643

Validity of the effective approach?

$m_V \to 0$ 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.

charge radius



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

$$\dot{Q}_{\lambda\lambda'} \propto \begin{cases} g_D^4/m_V^4 & \lambda\lambda' = \text{LL}, \\ g_D^4/m_V^2 & \lambda\lambda' = \text{LT}, \\ g_D^4 & \lambda\lambda' = \text{TT}. \end{cases}$$

for $\sqrt{s}/m_V \gg 1$ (high-energy limit)

$$\epsilon_{\text{L}} = \left(\frac{p}{m_V}, 0, 0, \frac{E}{m_V}\right), \quad \epsilon_{\text{T}}^{\pm} = \left(0, \frac{1}{\sqrt{2}}, \pm\frac{i}{\sqrt{2}}, 0\right)$$

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

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

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 $SU(2)_D$ x global $U(1)_X$ with a vector triplet W_D^a, dark fermions Ψ , Higgsed by Φ_D

Charge assignment such that two of the W's are protected from decay

Ibarra, Hisano, Ryo (2020)

$$V = W^-,\ V^\dagger = W^+,\ m_V = m_{W_D}$$

global quantum number

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

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

$W_D^0,\ \Psi'\mathrm{s}$ unprotected and decay to SM (W^0 via radiatively induced kinetic mixing)

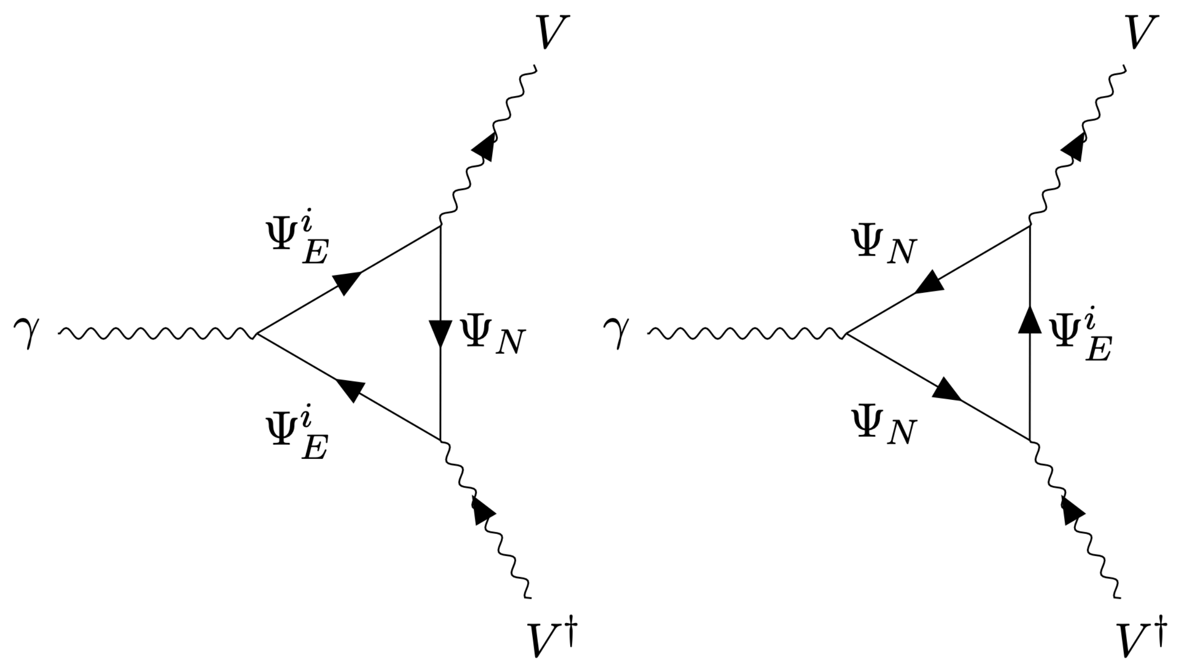
Vector DM

UV-completion

Dark SU(2)D x global U(1)X with a vector triplet W^a_D, dark fermions Ψ , Higgsed by Φ_D

=> six of the seven operators radiatively induced

Ibarra, Hisano, Ryo (2020)



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

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

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

V's diagonalize Ψ's after SSB

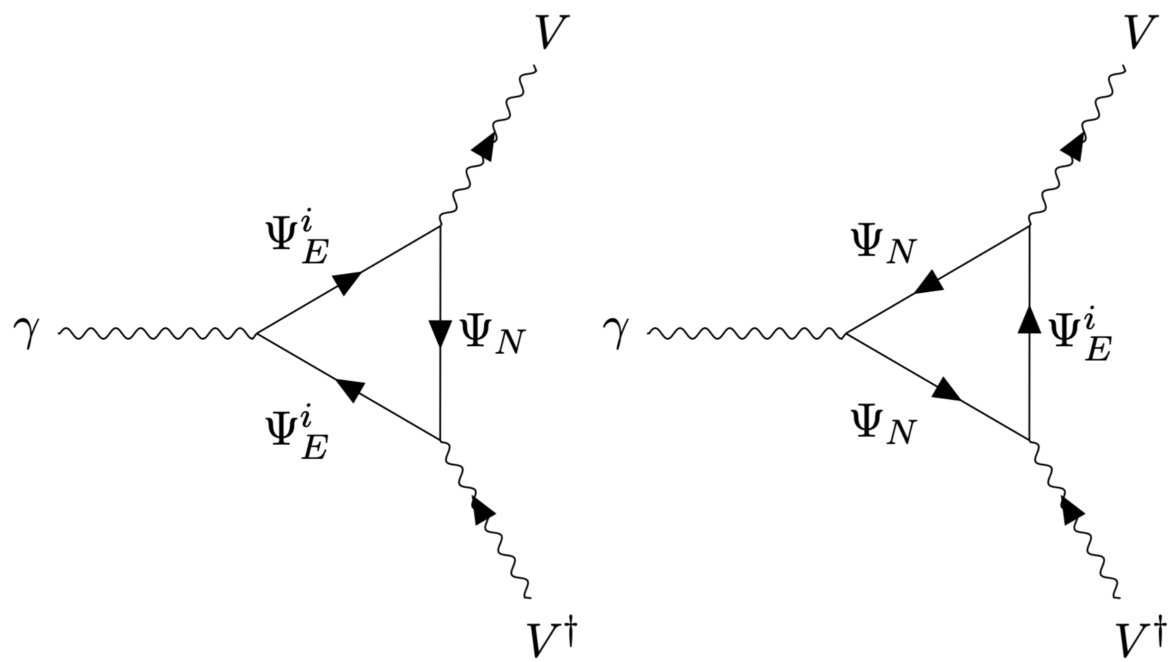
Vector DM

UV-completion

Dark SU(2)$_D$ x 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:

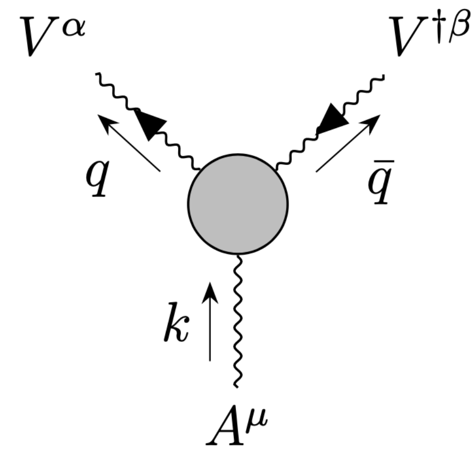
$$\mu_V = -e\frac{g_D^2}{64\pi^2}\frac{1}{m_V}\sum_{i=1}^{2}(1-x_i^2)\left[\left(\left|(V_L)_{1i}^2\right|^2 + \left|(V_R)_{1i}^2\right|^2\right)\right.$$ x loop function

$$d_V = e\frac{g_D^2}{64\pi^2}\frac{1}{m_V}\sum_{i=1}^{2}\mathrm{Im}\left((V_L)_{1i}^\star\,(V_R)_{1i}^\star\right)$$ x loop function

Vector DM

proper high energy limit

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



Coupl.	UV model	$\dot{Q} \propto f(s)$	$\dot{Q}\vert_{m_V\to 0}$	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	$d_V = \frac{e}{2m_V}(\tilde{\kappa}_\Lambda + \frac{m_V^2}{\Lambda^2}\tilde{\lambda}_\Lambda)$

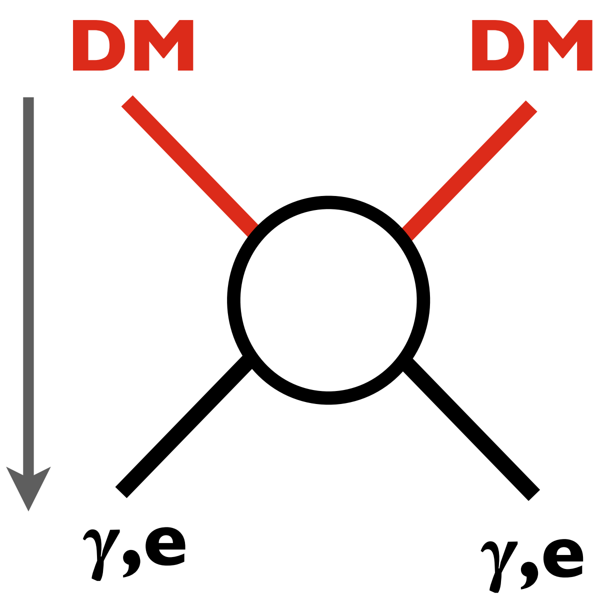
=> switch basis

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

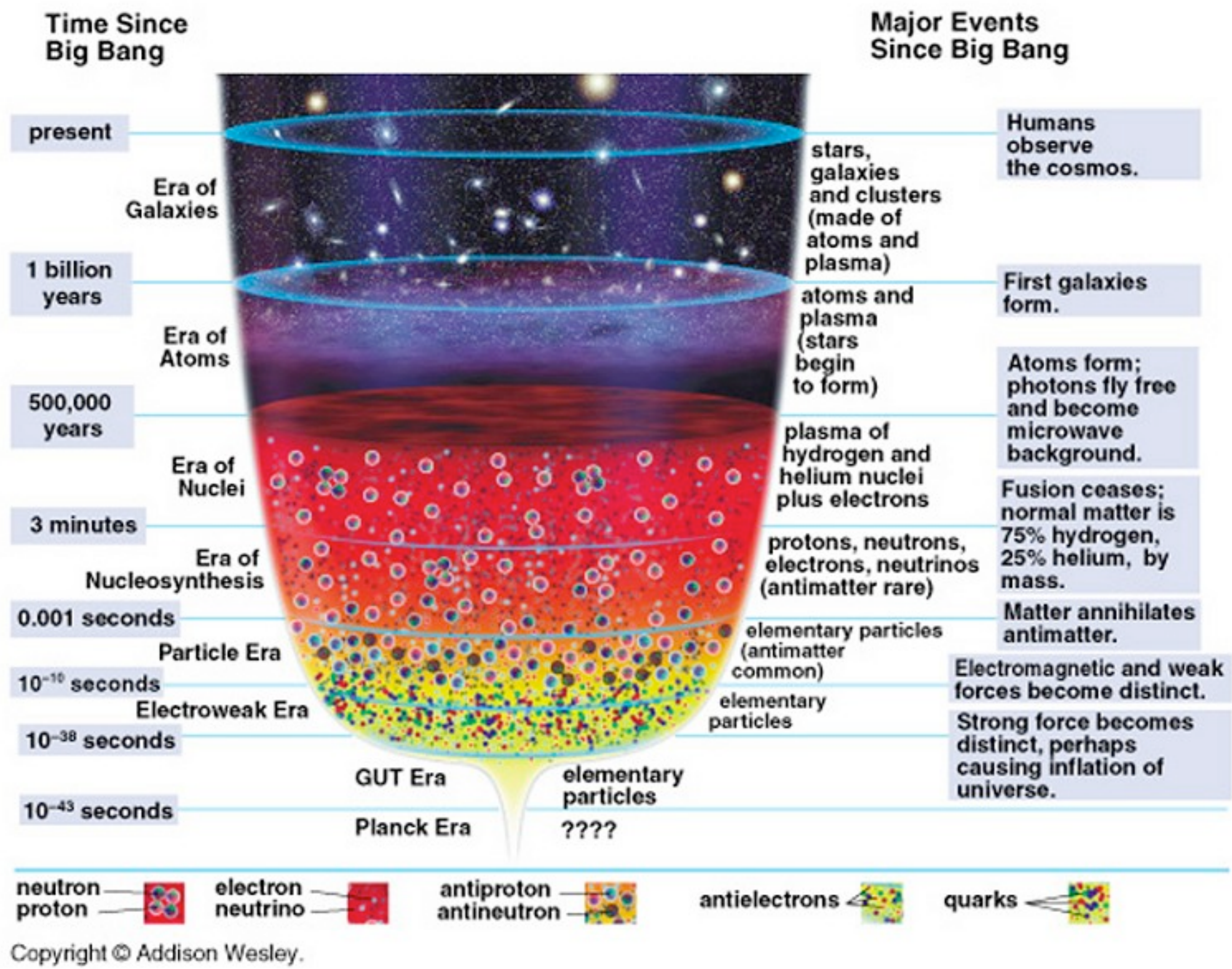
=> when all operators that share C,P properties are considered jointly, rates scale precisely as NDA suggests!

2. Thermal MeV DM

OR: what is the lightest thermal DM mass?



freeze out T ~ m/20



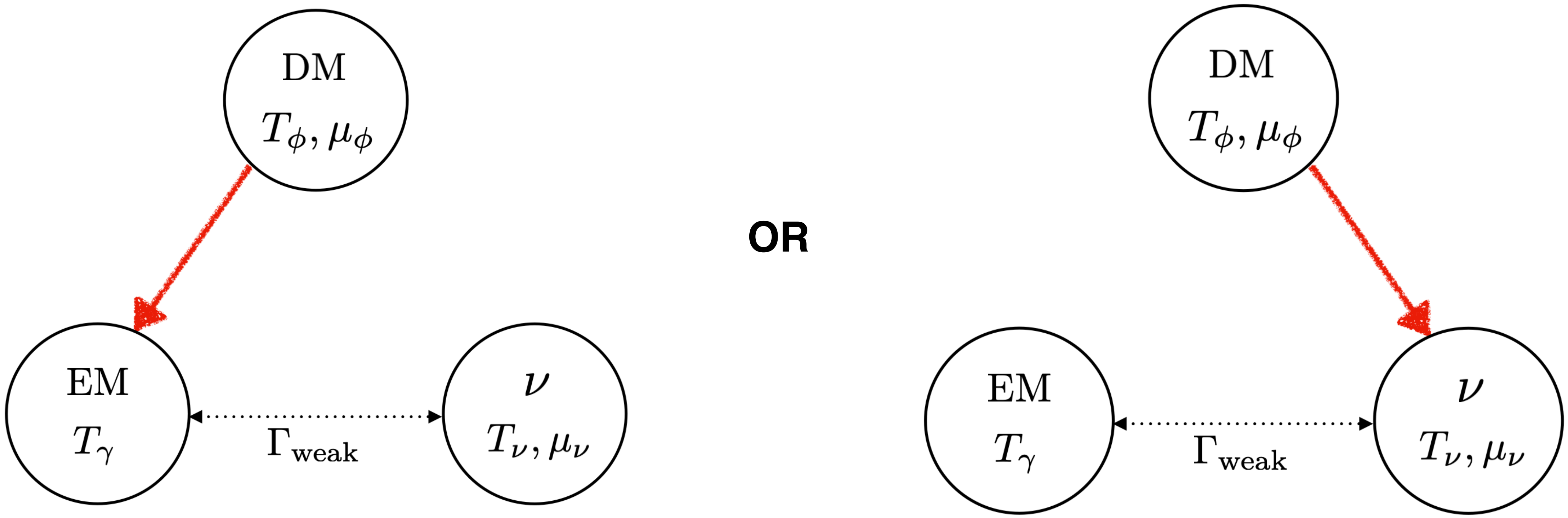
2. Thermal MeV DM

Chu, Kuo, JP, PRD 2022
Chu, JP arXiv:2310.06611

OR: 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:



2. Thermal MeV DM

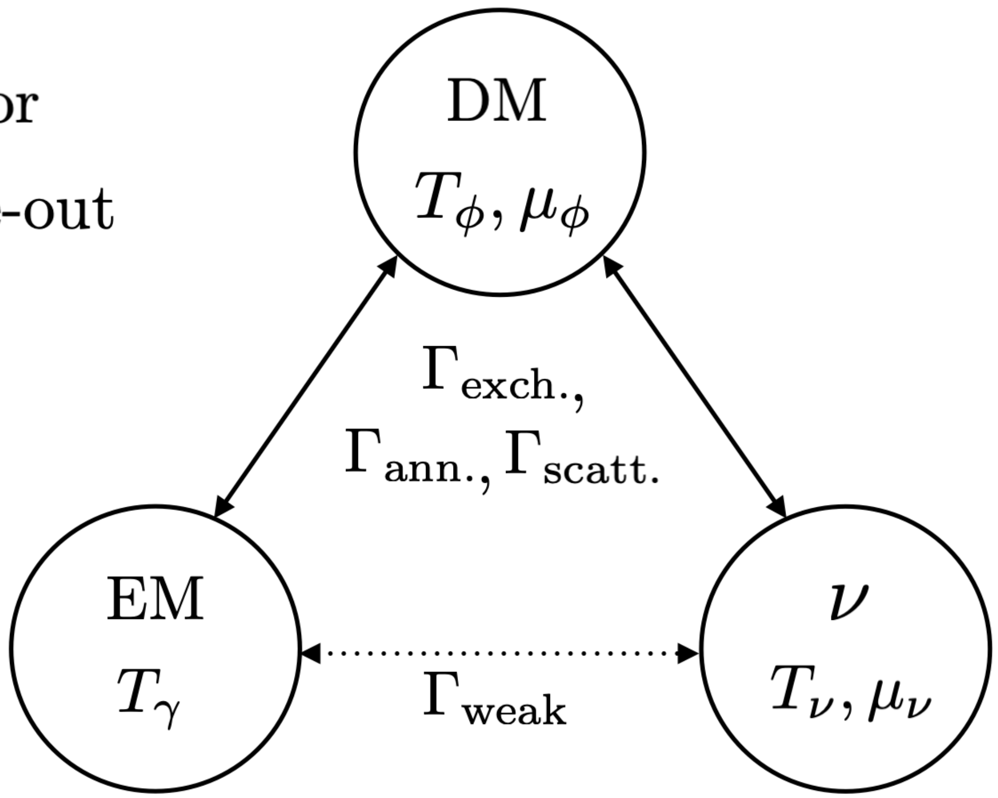
Chu, Kuo, JP, PRD 2022
Chu, JP arXiv:2310.06611

OR: 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



$$\Gamma_{\rm weak} \equiv n_e G_F^2 T_\gamma^2 \,,$$
$$\Gamma_{\rm ann.} \equiv n_\phi \langle \sigma_{\rm ann.} v \rangle \,,$$
$$\Gamma_{{\rm exch.},i} \equiv n_\phi^2 \langle \sigma_{{\rm ann.},i} v \delta E \rangle / \rho_i \,,$$
$$\Gamma_{{\rm scatt.},i} \equiv n_i \langle \sigma^{\phi i}_{\rm scatt.} v \rangle \,.$$

=> 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)

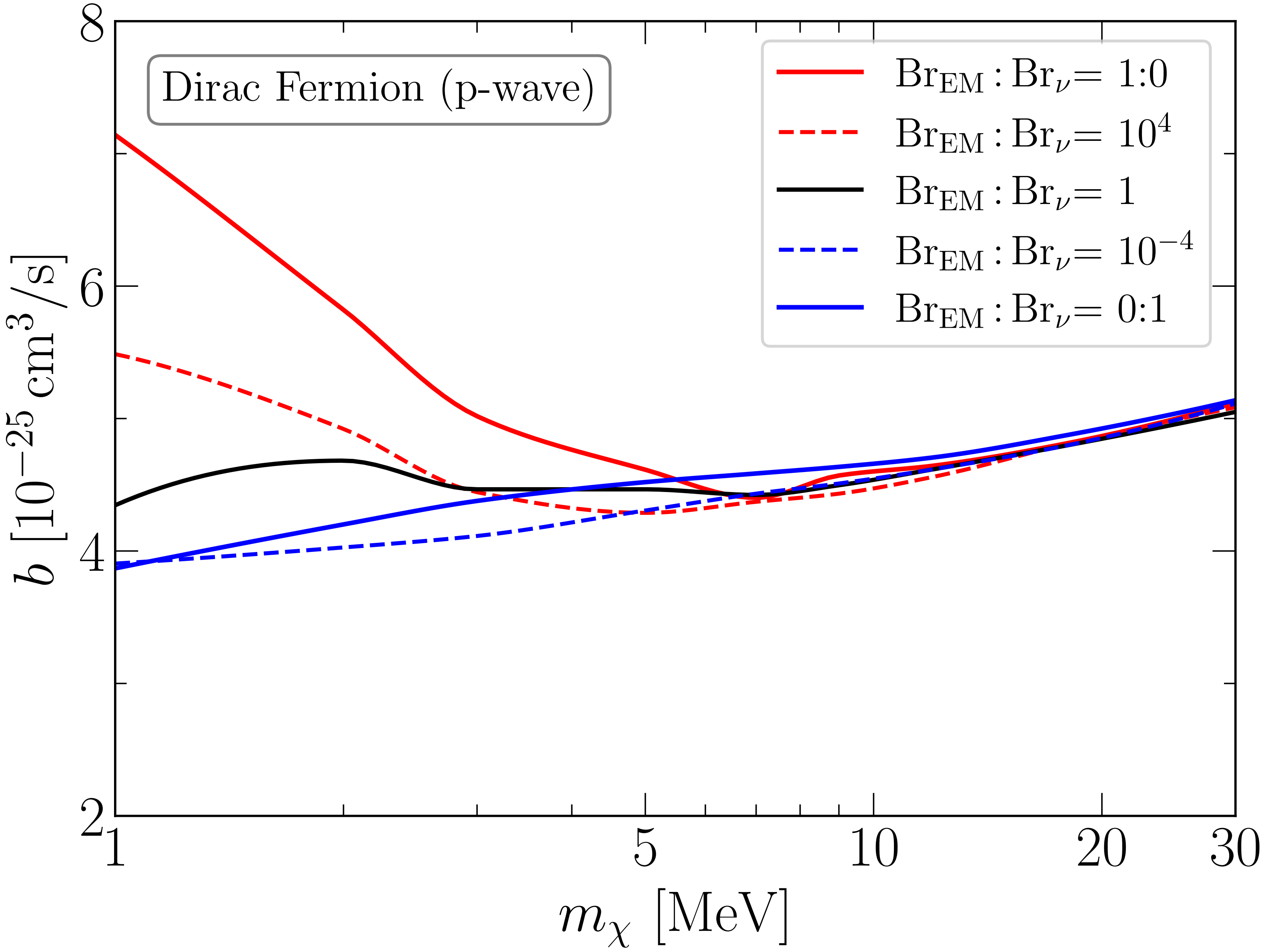
=> allows for a precision prediction of Neff and to derive a lower bound on the DM mass

Chu, JP arXiv:2310.06611

Light DM freeze out

Thermal cross section

$$\sigma_{\text{ann}} v_M = a + b v_{\text{rel}}^2 + \mathcal{O}(v_{\text{rel}}^4)$$

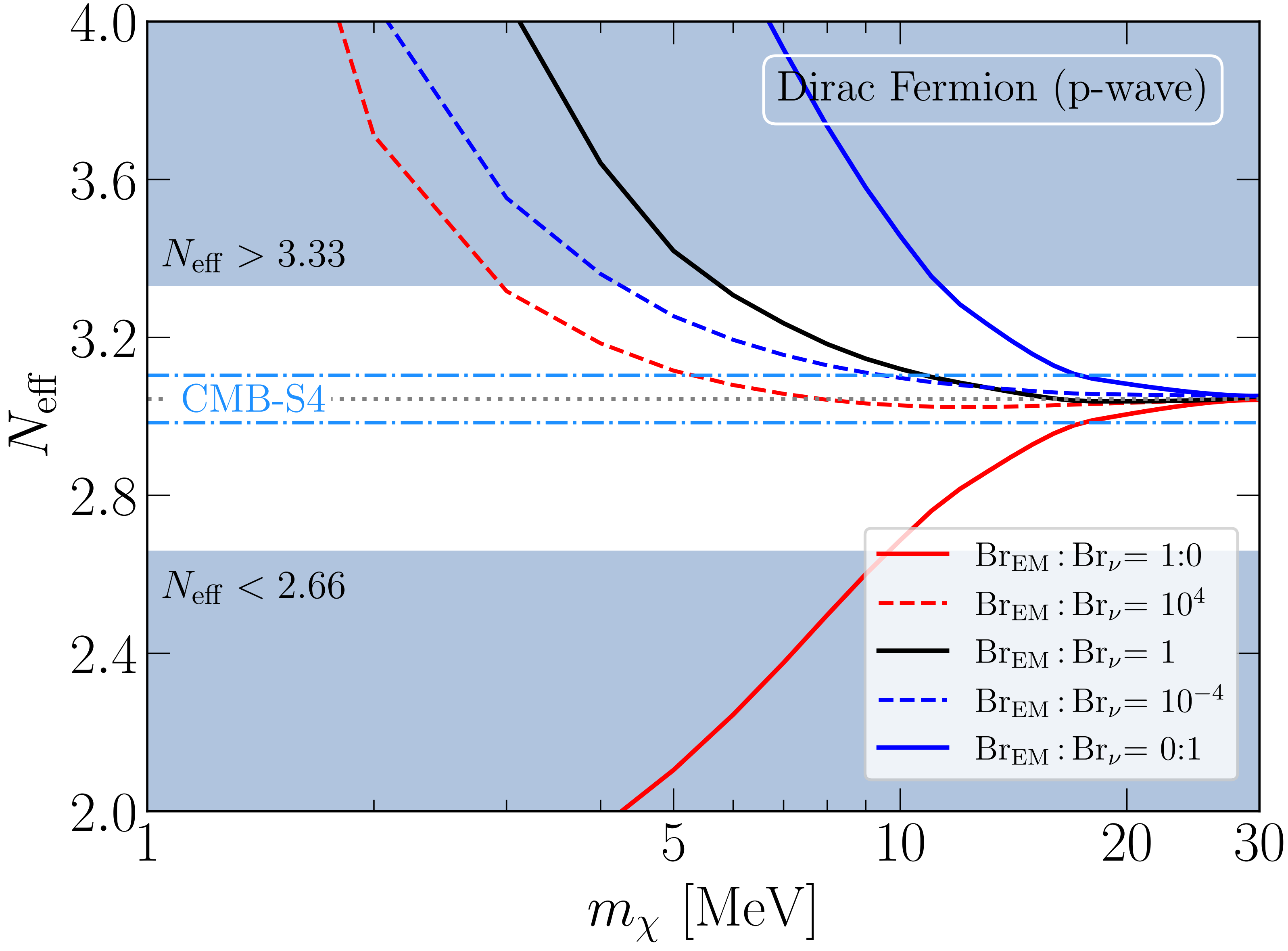


Example: p-wave annihilation

Light DM freeze out

Chu, JP arXiv:2310.06611

What is the lightest thermal DM mass?

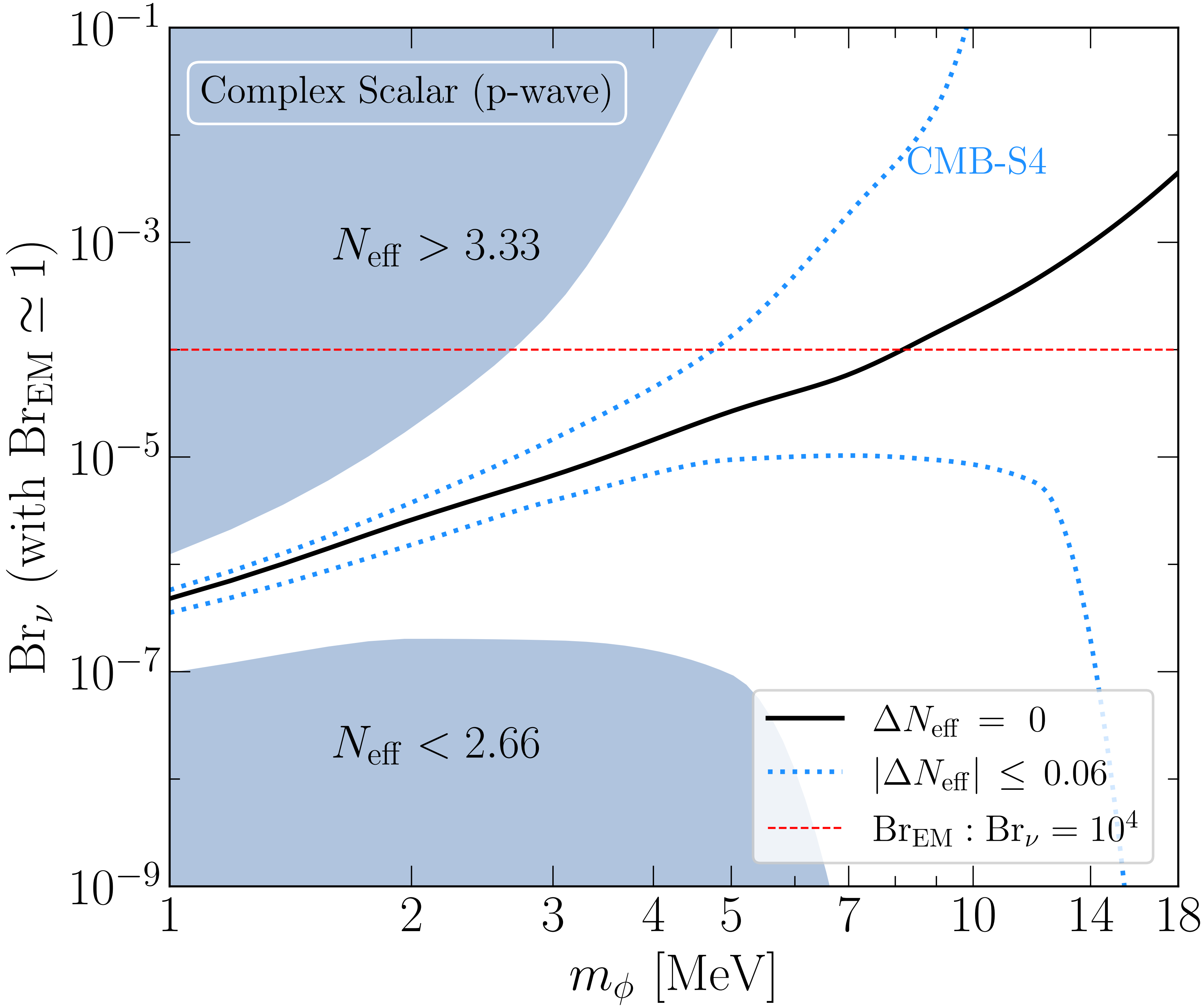


Example: p-wave annihilation

Chu, JP arXiv:2310.06611

Evading Neff bound

OR: How low can you go?

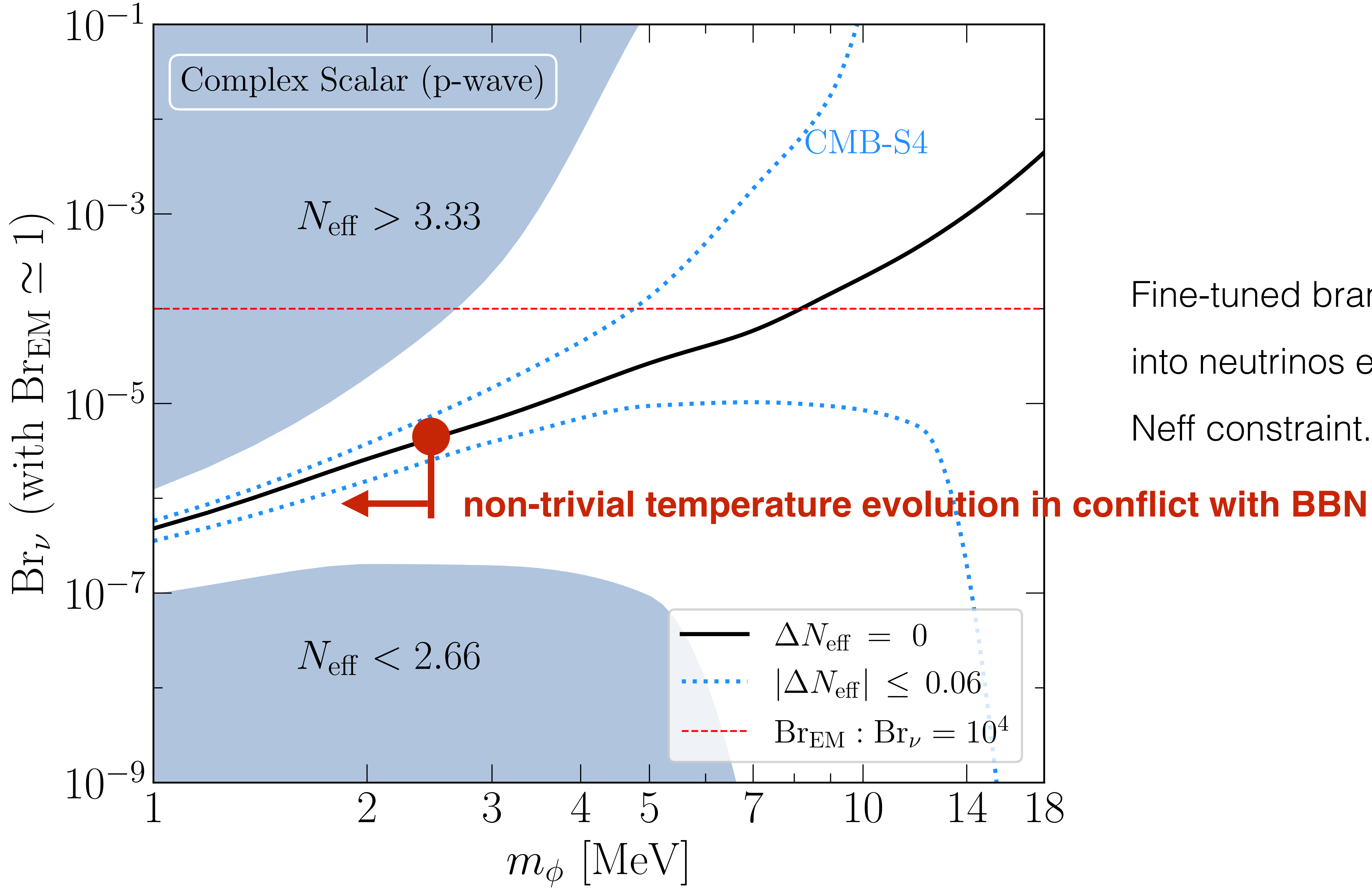


Fine-tuned branching into neutrinos evades Neff constraint.

Evading Neff bound

Chu, JP arXiv:2310.06611

OR: How low can you go?



Fine-tuned branching into neutrinos evades Neff constraint.

Summary

sub-GeV dark state phenomenology

- neutral dark particles can couple to the photon through higher dimensional electromagnetic moment interactions. Spin-1/2 and 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