ベクトル暗黒物質多極子の直接探索

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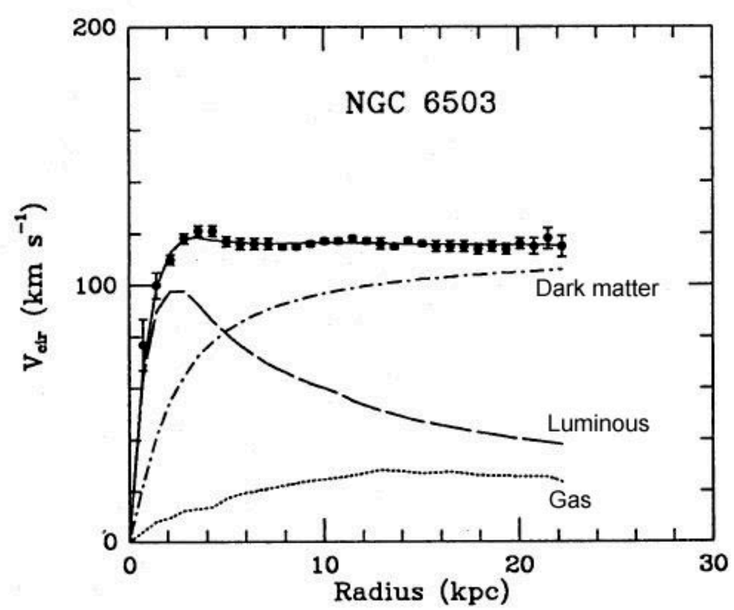
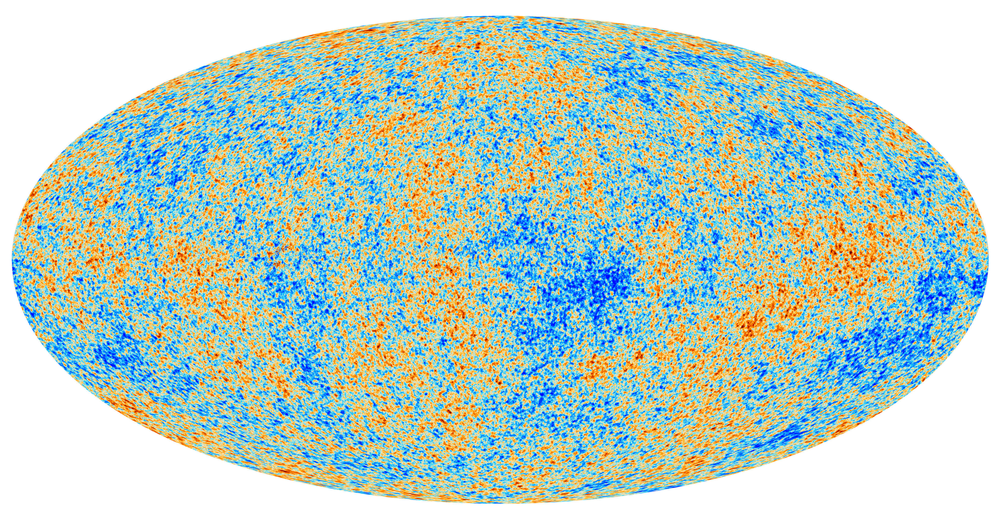
素粒子物理学の進展 2020

暗黒物質の存在証拠



Begeman et. al. (1991)

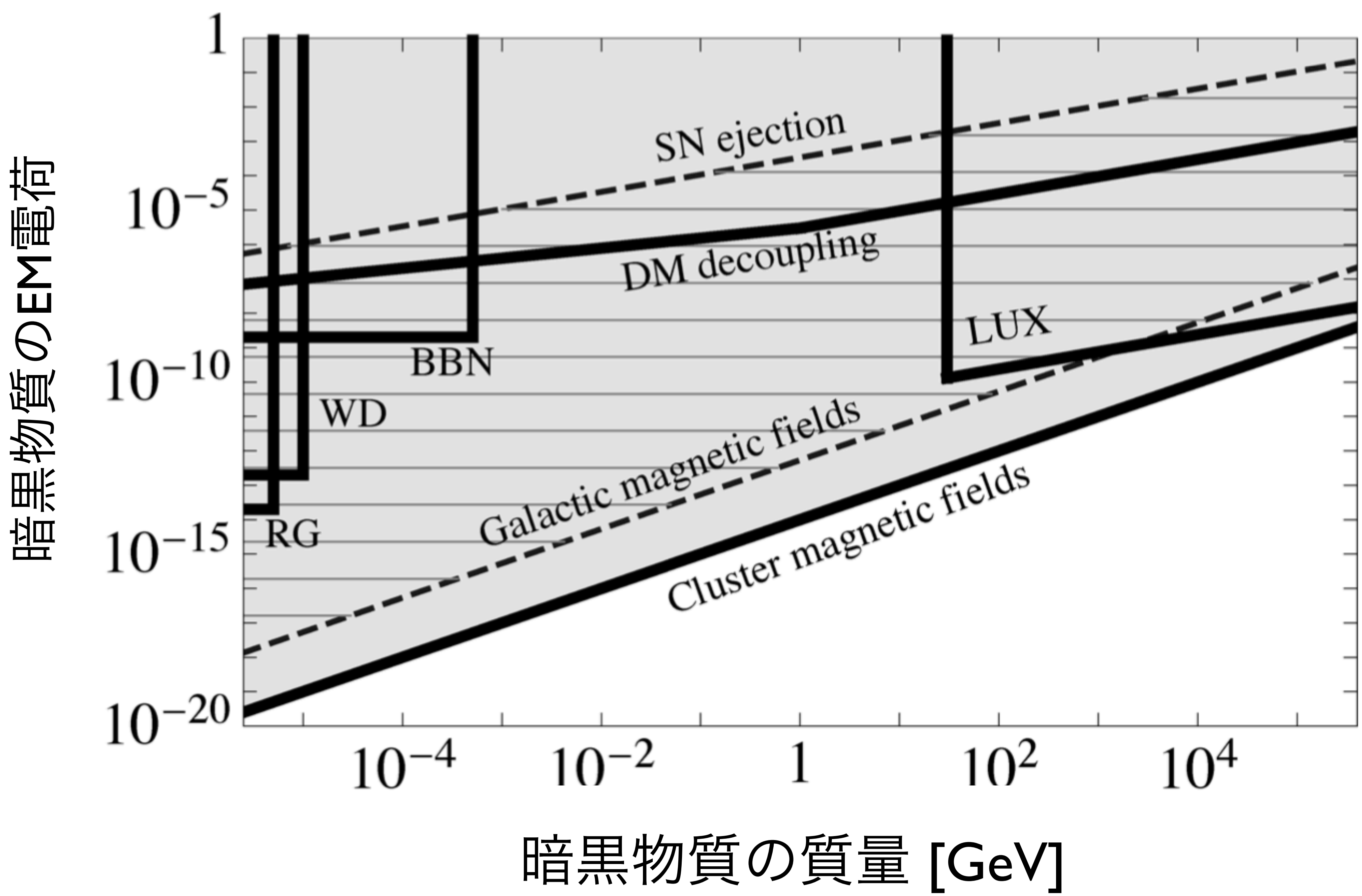
Clowe et. al. (2006)



Plank (2013)

Dark matter must be "dark".

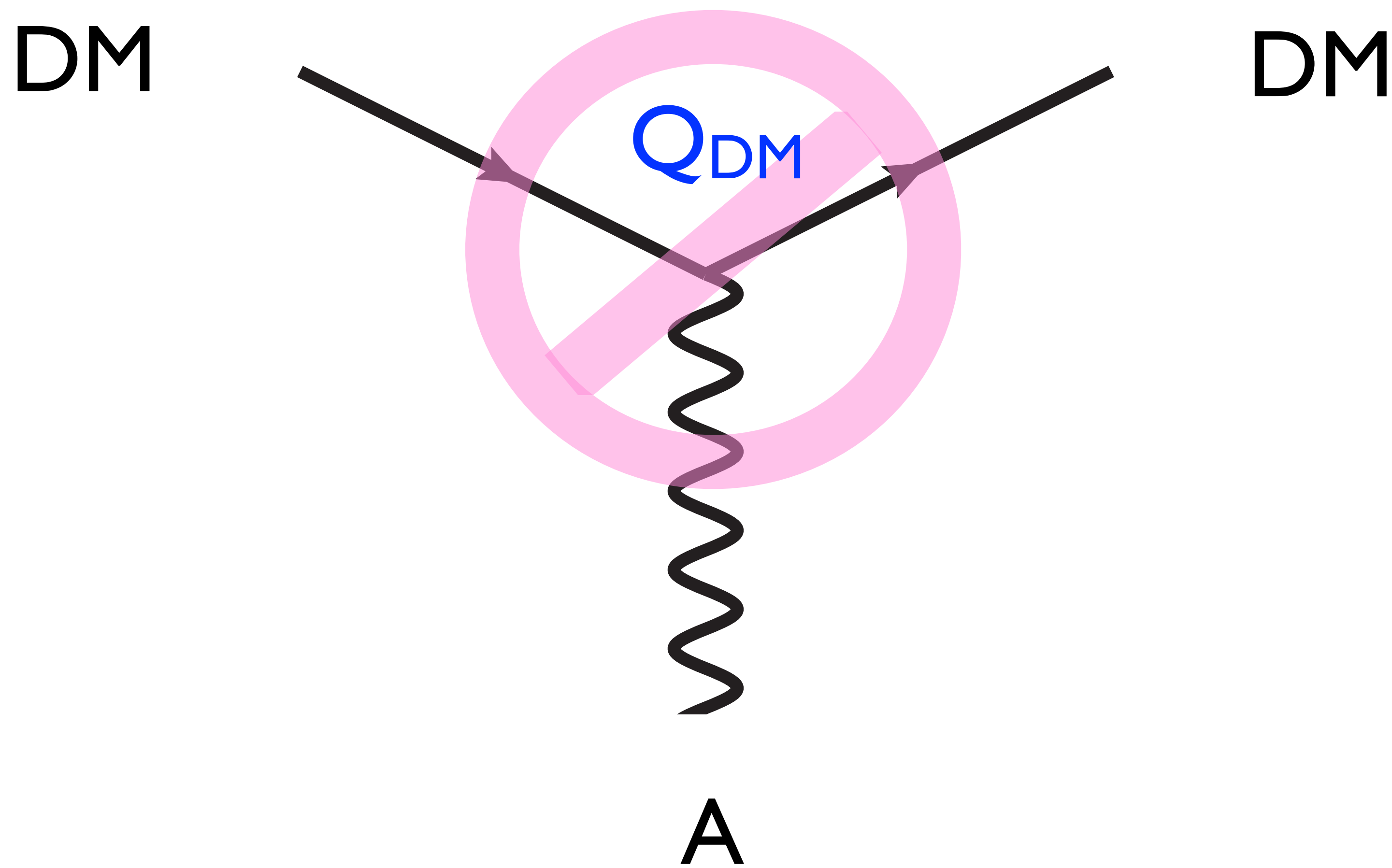
暗黒物質は”暗い”



Kadota-Sekiguchi-Tashiro (2016)

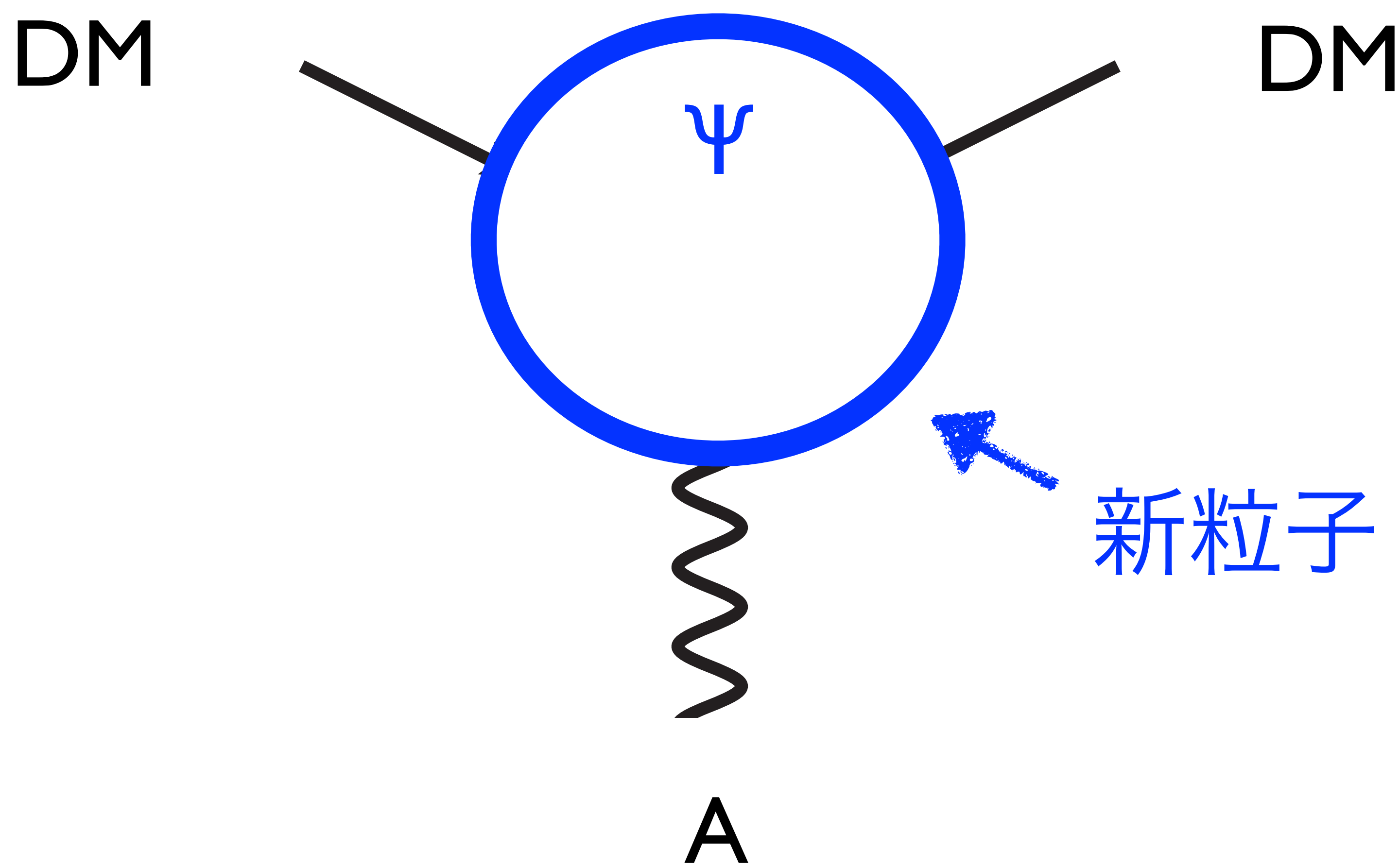
暗黒物質は"暗い"

暗黒物質は電気的に**中性**としましょう。



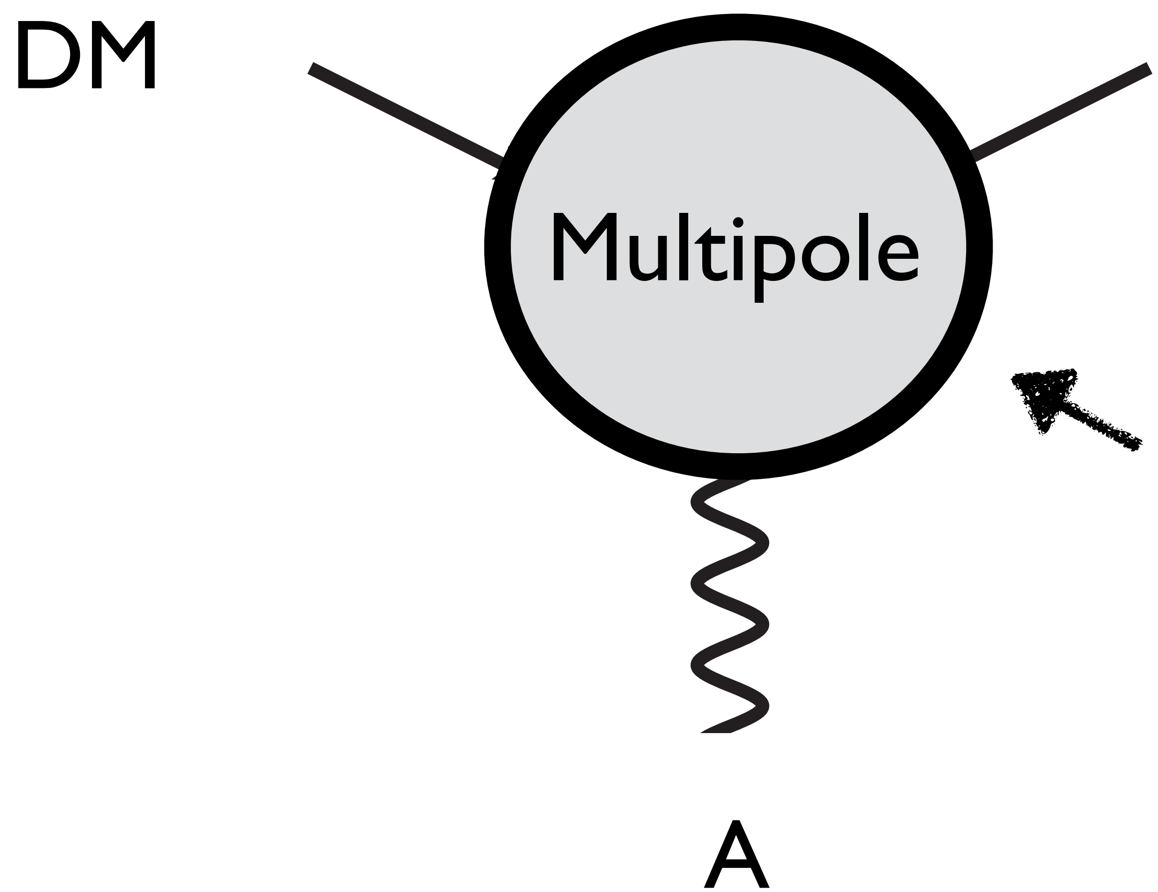
暗黒物質と光子

中性だとしても、**光子と相互作用**する。



暗黒物質と光子

中性だとしても、**光子と相互作用**する。



Charge radius

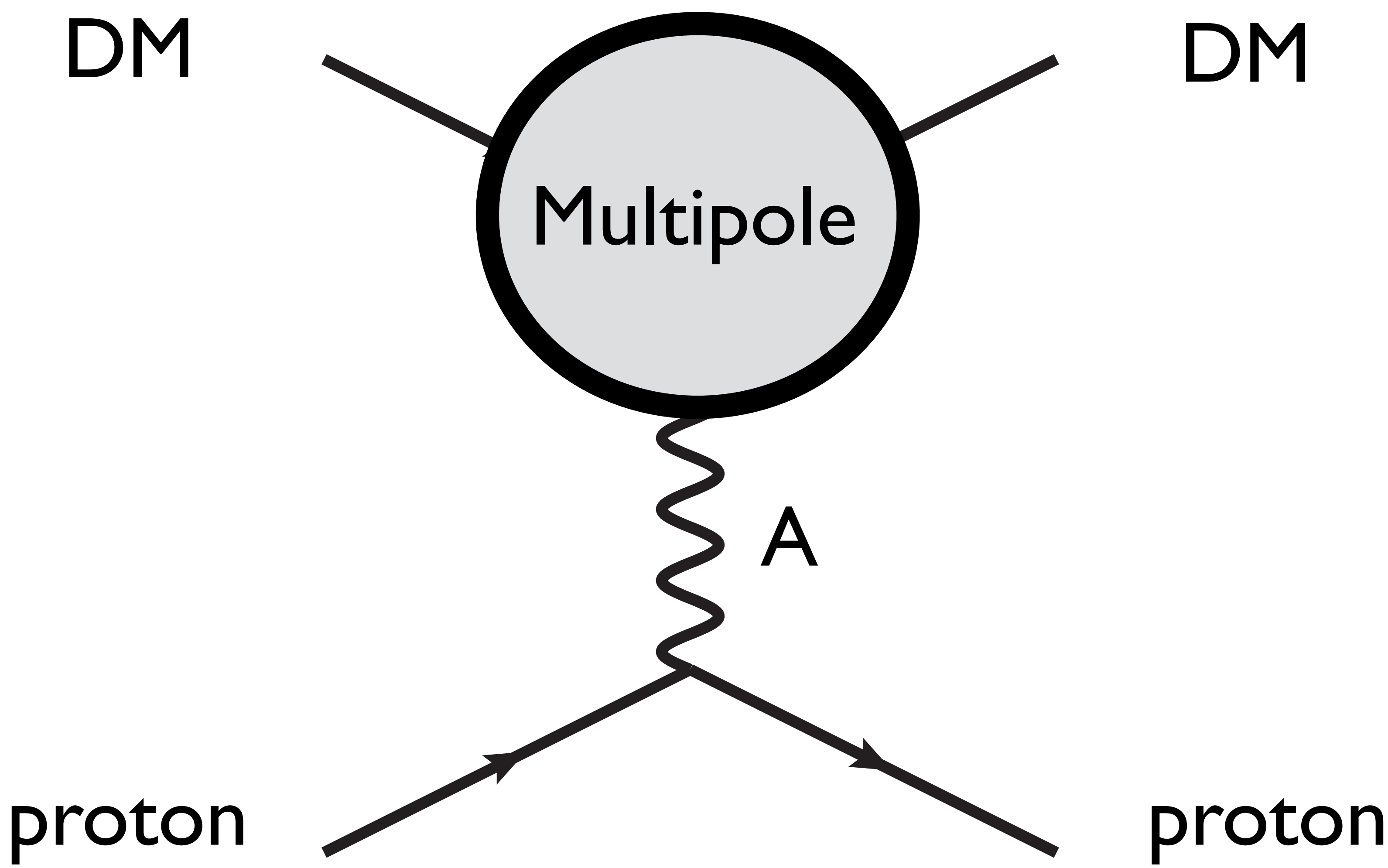
Dipole

Quadrupole

…..

暗黒物質と光子

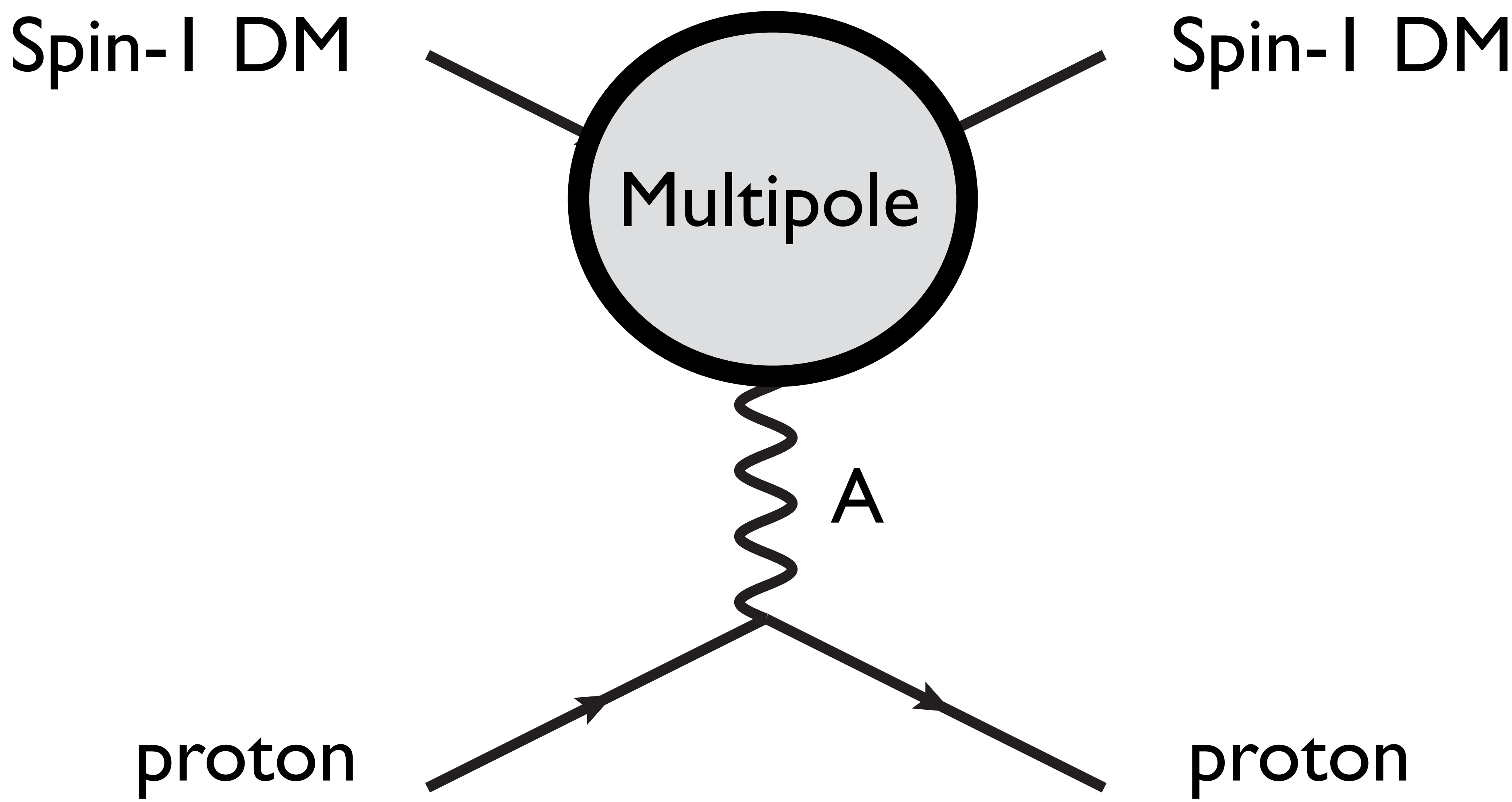
直接探索で調べられるのでは？



今日のトーク

スピン1暗黒物質の多極子直接探索

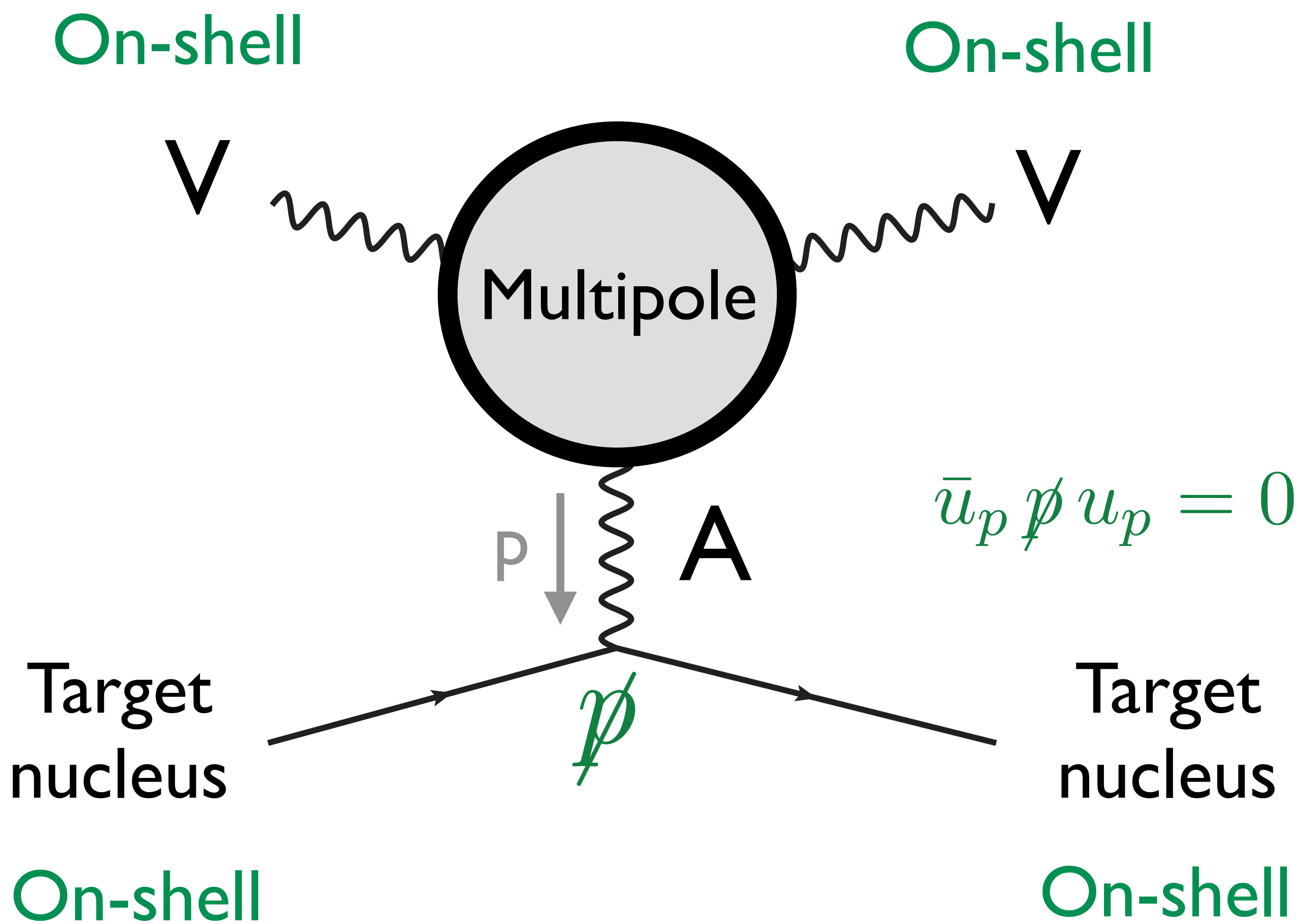
cf: フェルミオンについて： Hisano-**Nagai**-Nagata (2018), …



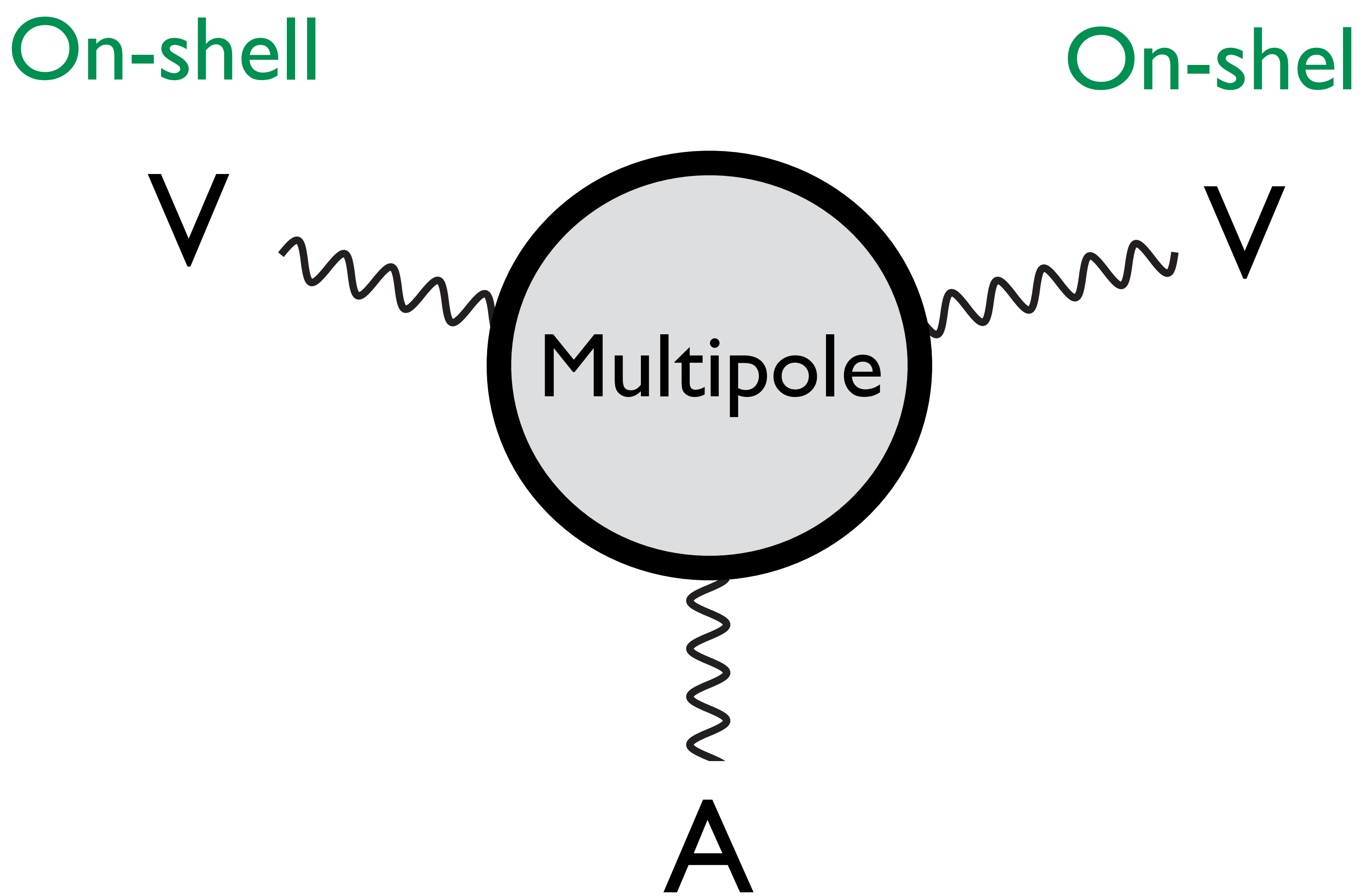
今日のトーク

- 一般論
- 模型の例

VVA vertex

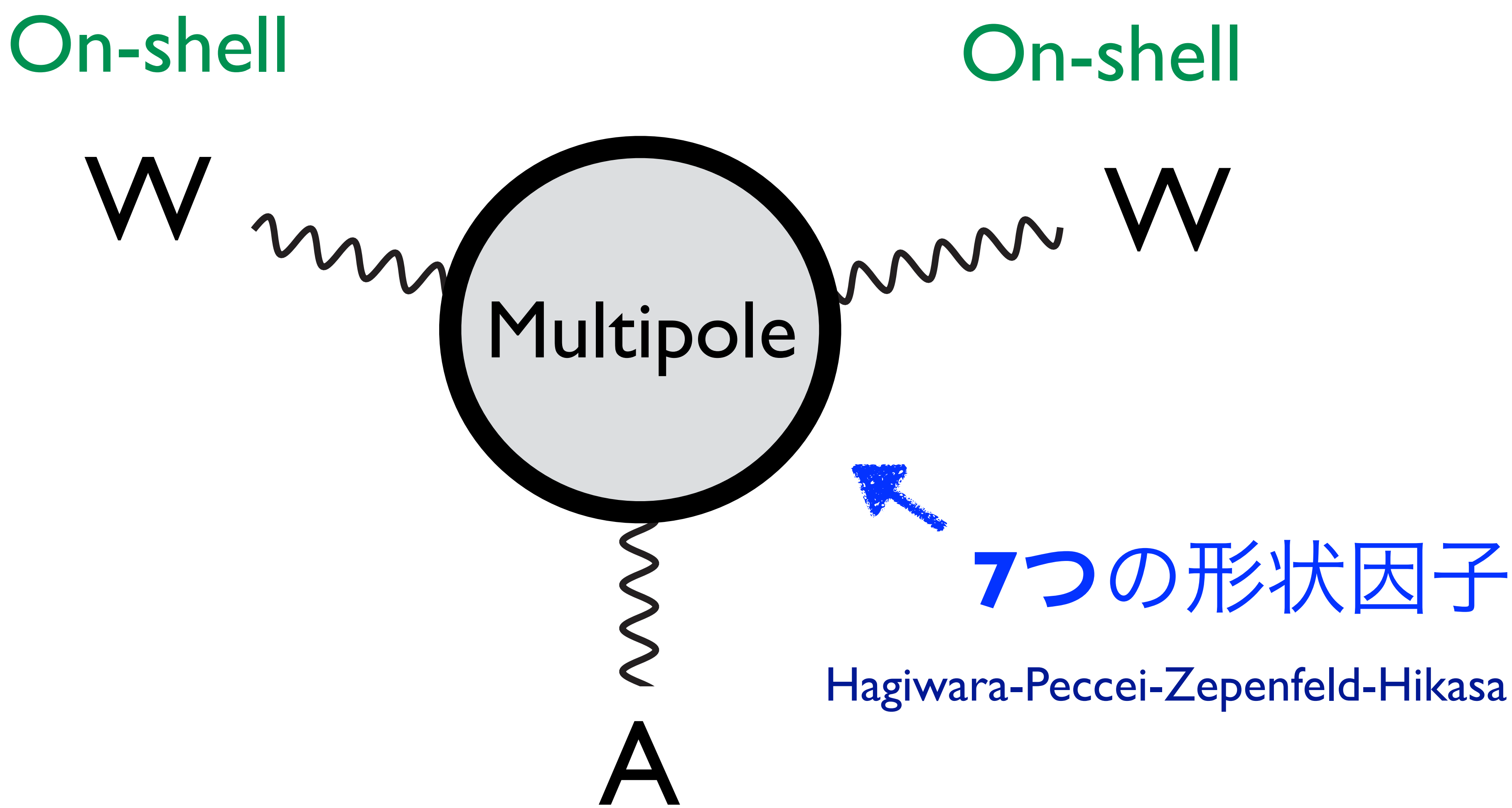

On-shell
On-shell
V
V
Multipole
p
A
$\bar{u}_p \not{p} u_p = 0$
Target nucleus
Target nucleus
$\not{p}$
On-shell
On-shell

VVA vertex



$$\partial_\mu A^\mu = 0$$

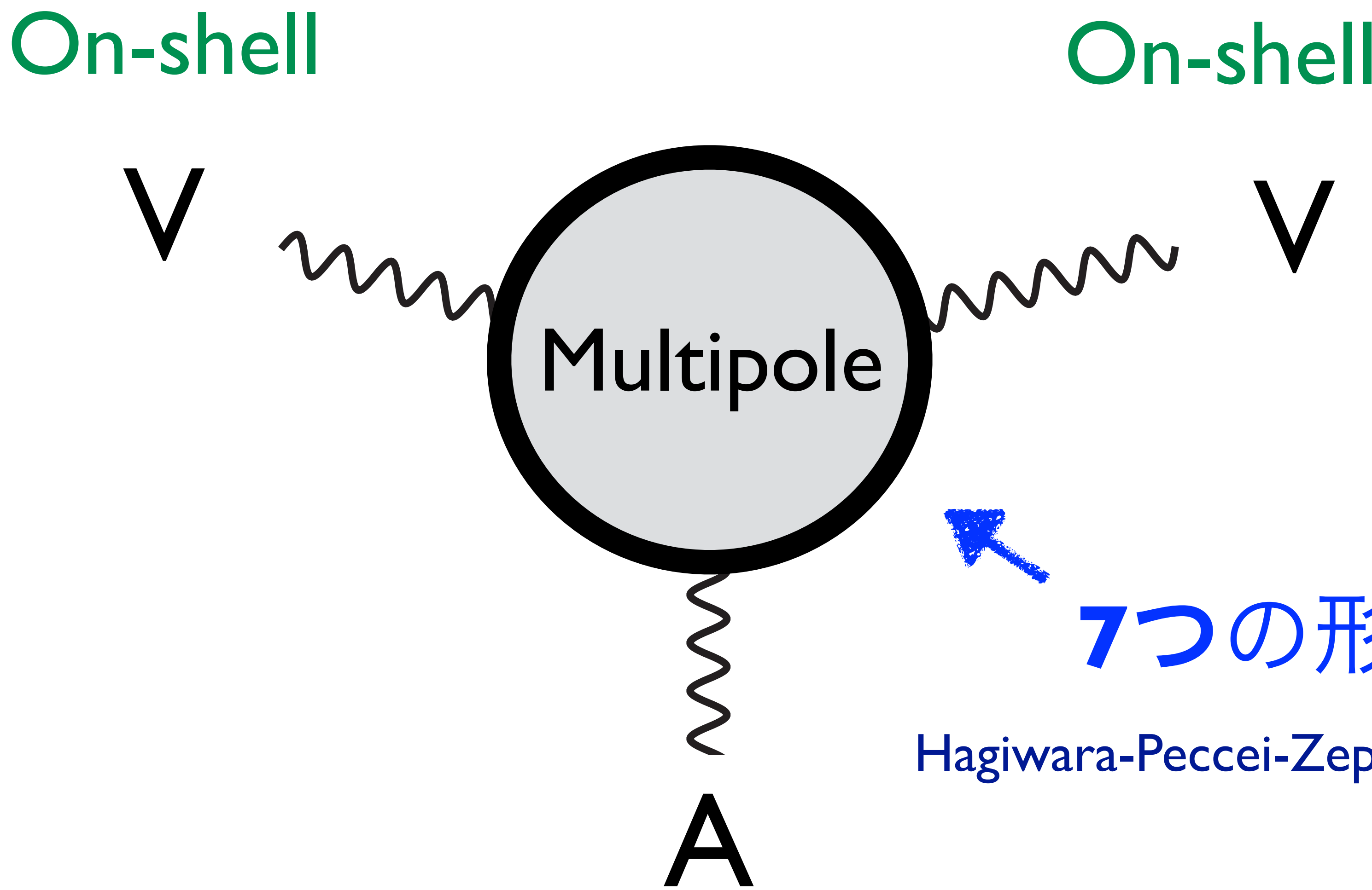
VVA vertex



Hagiwara-Peccei-Zepenfeld-Hikasa (1986)

$$\partial_\mu A^\mu = 0$$

VVA vertex



7つの形状因子

Hagiwara-Peccei-Zepenfeld-Hikasa (1986)

$$\partial_\mu A^\mu = 0$$

VVA vertex

$$\mathcal{L} = \frac{ie}{2m_V^2} g_1^A \Big[(V^\dagger_{\mu\nu} V^\mu - V^{\dagger\mu} V_{\mu\nu}) \partial_\lambda F^{\lambda\nu} - V^{\dagger\mu} V^\nu \Box F_{\mu\nu} \Big]$$

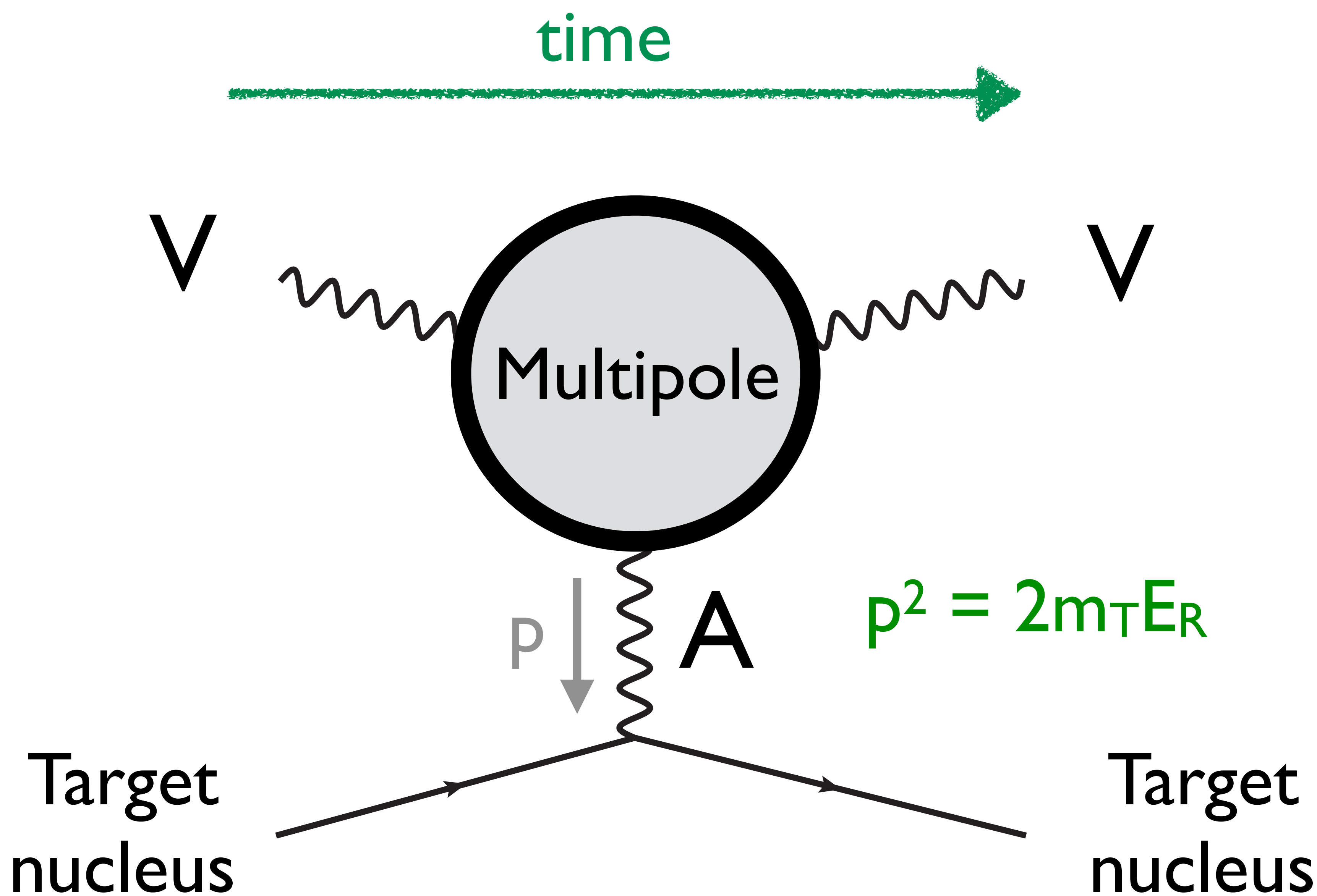
$$+ \frac{e}{m_V^2} g_4^A V^\dagger_\mu V_\nu (\partial^\mu \partial_\rho F^{\rho\nu} + \partial^\nu \partial_\rho F^{\rho\mu})$$

$$+ \frac{e}{m_V^2} g_5^A \epsilon^{\mu\nu\rho\sigma} (V^\dagger_\mu \overleftrightarrow{\partial}_\rho V_\nu) \partial^\lambda F_{\lambda\sigma}$$

$$+ ie\kappa_A V^\dagger_\mu V_\nu F^{\mu\nu} + \frac{ie}{m_V^2} \lambda_A V^\dagger_{\lambda\mu} V_\nu{}^\mu F^{\nu\lambda}$$

$$+ ie\tilde{\kappa}_A V^\dagger_\mu V_\nu \tilde{F}^{\mu\nu} + \frac{ie}{m_V^2} \tilde{\lambda}_A V^\dagger_{\lambda\mu} V_\nu{}^\mu \tilde{F}^{\nu\lambda}$$

Direct detection



Direct detection

$$\frac{d\sigma}{dE_R} = \frac{Z^2e^2}{6\pi m_T}F_Z^2(E_R)\left[\left(\frac{m_T}{E_R}+\frac{m_T^2-4m_Vm_T-2m_V^2}{4m_V^2v^2}\right)(\mu_V)^2+\frac{m_T}{E_Rv^2}(d_V)^2\right.$$
$$+\frac{3m_T^2}{16v^2}(Q_V)^2+\frac{m_T^2}{8}(\tilde{Q}_V)^2+\frac{3e^2m_T^2}{4m_V^4v^2}(g_1^A)^2+\frac{2e^2m_T^2}{m_V^4}(g_5^A)^2$$
$$\left.+\frac{m_T^2}{4m_Vv^2}\mu_VQ_V+\frac{3em_T^2}{2m_V^3v^2}\mu_Vg_1^A+\frac{em_T^2}{4m_V^2v^2}Q_Vg_1^A+\frac{m_T^2}{2m_Vv^2}d_V\tilde{Q}_V\right]$$
$$+\frac{e^2}{12\pi m_T}F_D^2(E_R)\left(\frac{\bar{\mu}_T}{\mu_N}\right)^2\left[\frac{2}{v^2}(\mu_V)^2+(d_V)^2\right]$$

$$\mu_V=\frac{e}{2m_V}(\lambda_V+\kappa_V)\,,\quad Q_V=\frac{e}{m_V^2}(\lambda_V-\kappa_V)\,,\quad d_V=\frac{e}{2m_V}(\tilde{\lambda}_V+\tilde{\kappa}_V)\,,\quad \tilde{Q}_V=\frac{e}{m_V^2}(\tilde{\lambda}_V-\tilde{\kappa}_V)\,.$$

- O(E_R/M, v^2) は無視した.　　(M : reduced mass)

Direct detection

$$\frac{d\sigma}{dE_R} = \frac{Z^2e^2}{6\pi m_T}F_Z^2(E_R)\left[\left(\frac{m_T}{E_R} + \frac{m_T^2 - 4m_V m_T - 2m_V^2}{4m_V^2 v^2}\right)(\mu_V)^2 + \frac{m_T}{E_R v^2}(d_V)^2\right.$$

Magnetic dipole   Electric dipole

$$+\frac{3m_T^2}{16v^2}(Q_V)^2 + \frac{m_T^2}{8}(\tilde{Q}_V)^2 + \frac{3e^2m_T^2}{4m_V^4v^2}(g_1^A)^2 + \frac{2e^2m_T^2}{m_V^4}(g_5^A)^2$$

Electric quadrupole   Magnetic quadrupole   Charge radius   Anapole

$$\left. + \frac{m_T^2}{4m_V v^2}\mu_V Q_V + \frac{3em_T^2}{2m_V^3v^2}\mu_V g_1^A + \frac{em_T^2}{4m_V^2v^2}Q_V g_1^A + \frac{m_T^2}{2m_V v^2}d_V\tilde{Q}_V\right]$$

$$\mu_V = \frac{e}{2m_V}(\lambda_V + \kappa_V)\,, \quad Q_V = \frac{e}{m_V^2}(\lambda_V - \kappa_V)\,, \quad d_V = \frac{e}{2m_V}(\tilde{\lambda}_V + \tilde{\kappa}_V)\,, \quad \tilde{Q}_V = \frac{e}{m_V^2}(\tilde{\lambda}_V - \tilde{\kappa}_V)\,.$$

- $O(E_R/M, v^2)$ は無視した.　　(M : reduced mass)
- g_4^A の寄与 ~ $O(E_R/M)$

Direct detection

	C	P
MDM (μ_V)	$+$	$+$
MQM (Q_V)	$+$	$-$
EDM (d_V)	$+$	$-$
EQM $(\tilde{Q}_V)$	$+$	$+$
CR (g_1^A)	$+$	$+$
AM (g_5^A)	$-$	$+$

Direct detection

$$\frac{d\sigma}{dE_R} = \frac{Z^2e^2}{6\pi m_T}F_Z^2(E_R)\left[\left(\frac{m_T}{E_R} + \frac{m_T^2 - 4m_V m_T - 2m_V^2}{4m_V^2 v^2}\right)(\mu_V)^2 + \frac{m_T}{E_R v^2}(d_V)^2\right.$$

Magnetic dipole　　Electric dipole

$$+\frac{3m_T^2}{16v^2}(Q_V)^2 + \frac{m_T^2}{8}(\tilde{Q}_V)^2 + \frac{3e^2m_T^2}{4m_V^4v^2}(g_1^A)^2 + \frac{2e^2m_T^2}{m_V^4}(g_5^A)^2$$

Electric quadrupole　　Magnetic quadrupole　　Charge radius　　Anapole

$$\left.+\frac{m_T^2}{4m_V v^2}\mu_V Q_V + \frac{3em_T^2}{2m_V^3 v^2}\mu_V g_1^A + \frac{em_T^2}{4m_V^2 v^2}Q_V g_1^A + \frac{m_T^2}{2m_V v^2}d_V\tilde{Q}_V\right]$$

$$\mu_V = \frac{e}{2m_V}(\lambda_V + \kappa_V)\,, \quad Q_V = \frac{e}{m_V^2}(\lambda_V - \kappa_V)\,, \quad d_V = \frac{e}{2m_V}(\tilde{\lambda}_V + \tilde{\kappa}_V)\,, \quad \tilde{Q}_V = \frac{e}{m_V^2}(\tilde{\lambda}_V - \tilde{\kappa}_V)\,.$$

- $O(E_R/M, v^2)$ は無視した.　　(M : reduced mass)
- g_4^A の寄与 ~ $O(E_R/M)$

Direct detection

$$\frac{d\sigma}{dE_R} = \frac{Z^2e^2}{6\pi m_T} F_Z^2(E_R) \left[\left(\frac{m_T}{E_R} + \frac{m_T^2 - 4m_V m_T - 2m_V^2}{4m_V^2 v^2} \right) (\mu_V)^2 + \frac{m_T}{E_R v^2} (d_V)^2 \right.$$

Magnetic dipole　Electric dipole

$$+ \frac{3m_T^2}{16v^2}(Q_V)^2 + \frac{m_T^2}{8}(\tilde{Q}_V)^2 + \frac{3e^2m_T^2}{4m_V^4 v^2}(g_1^A)^2 + \frac{2e^2m_T^2}{m_V^4}(g_5^A)^2$$

Electric quadrupole　Magnetic quadrupole　Charge radius　Anapole

$$\left. + \frac{m_T^2}{4m_V v^2}\mu_V Q_V + \frac{3em_T^2}{2m_V^3 v^2}\mu_V g_1^A + \frac{em_T^2}{4m_V^2 v^2} Q_V g_1^A + \frac{m_T^2}{2m_V v^2} d_V \tilde{Q}_V \right]$$

$$\mu_V = \frac{e}{2m_V}(\lambda_V + \kappa_V)\,, \quad Q_V = \frac{e}{m_V^2}(\lambda_V - \kappa_V)\,, \quad d_V = \frac{e}{2m_V}(\tilde{\lambda}_V + \tilde{\kappa}_V)\,, \quad \tilde{Q}_V = \frac{e}{m_V^2}(\tilde{\lambda}_V - \tilde{\kappa}_V)\,.$$

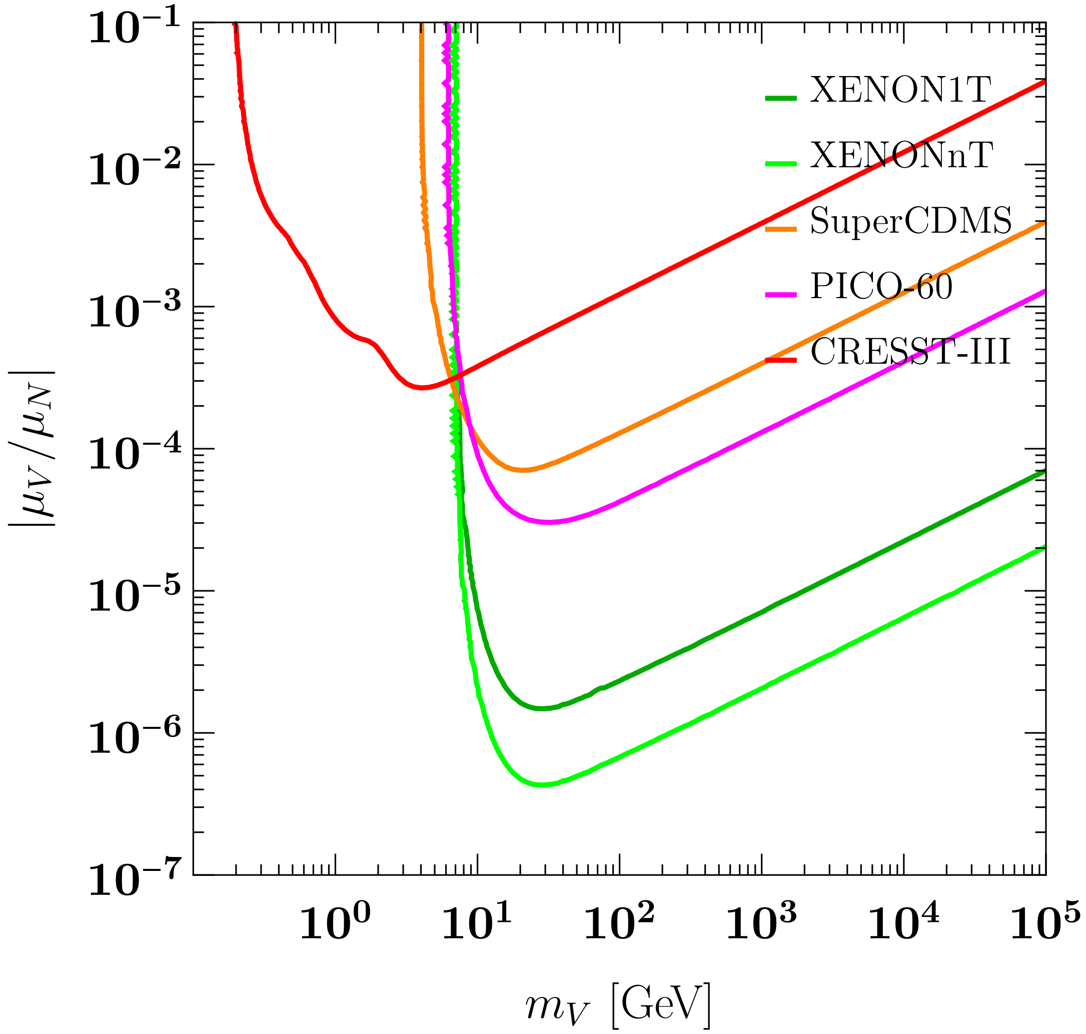
- $O(E_R/M, v^2)$ は無視した.　(M : reduced mass)
- g_4^A の寄与 ~ $O(E_R/M)$

Direct detection

	$\mathbf{C}$	$\mathbf{P}$	Enhancement
MDM (μ_V)	$+$	$+$	$1/E_R$
MQM (Q_V)	$+$	$-$	—
EDM (d_V)	$+$	$-$	$1/(E_R v^2)$
EQM $(\tilde{Q}_V)$	$+$	$+$	$1/v^2$
CR (g_1^A)	$+$	$+$	$1/v^2$
AM (g_5^A)	$-$	$-$	—

Dipole moment

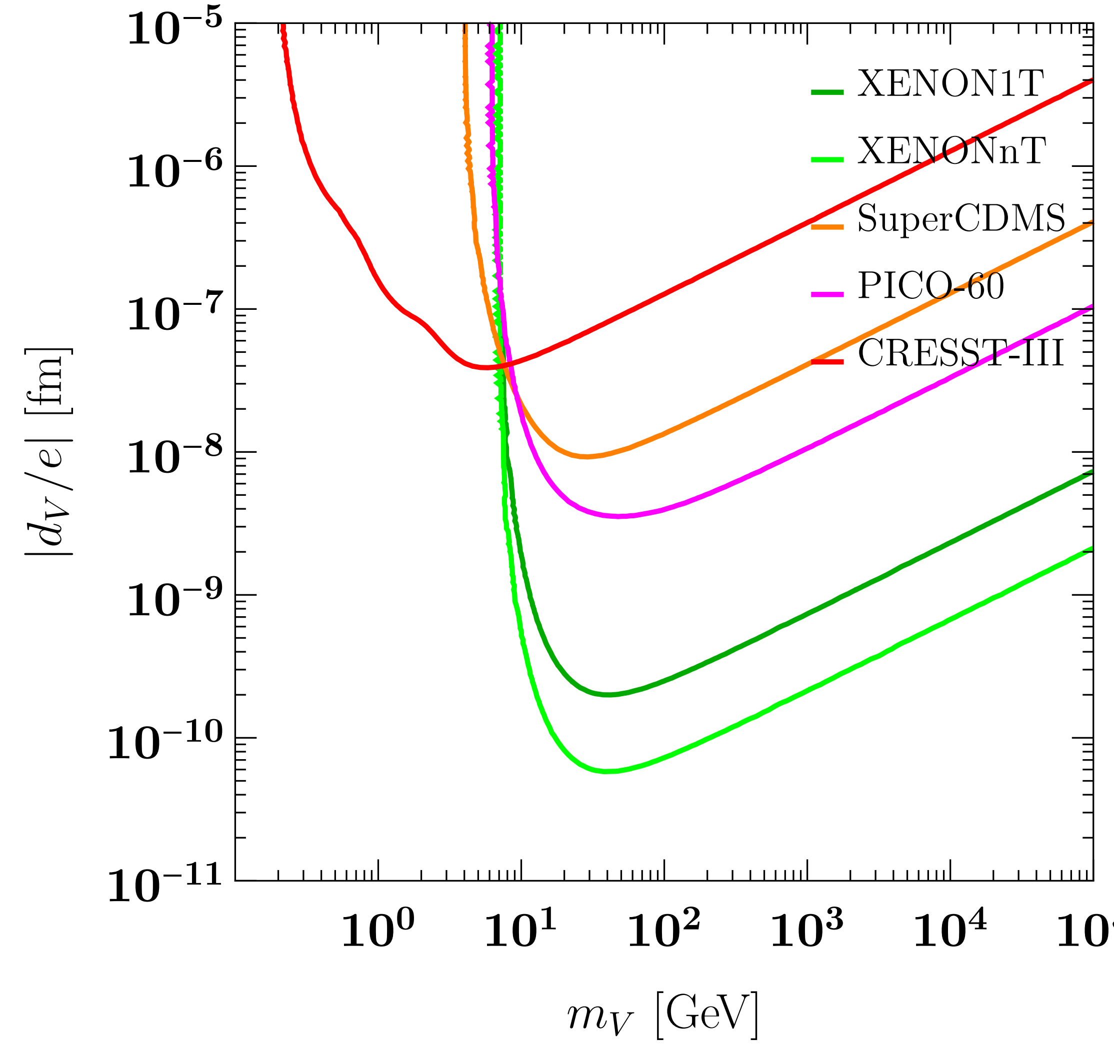
MDM



$\lesssim 2 \times 10^{-6} \mu_N$

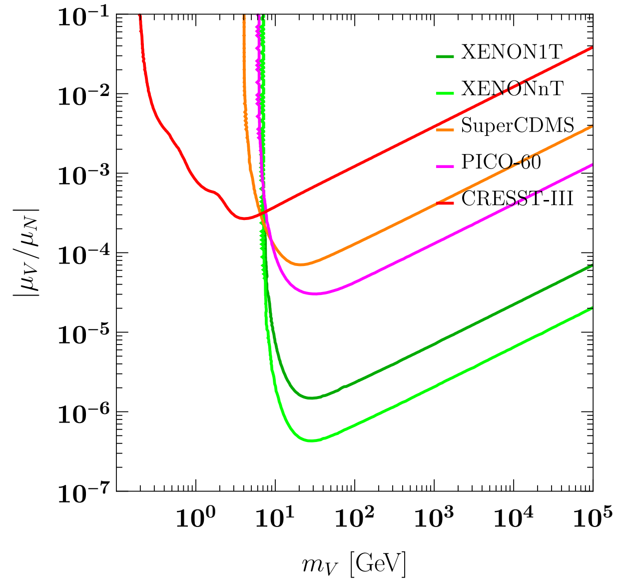
Nuclear magneton

EDM

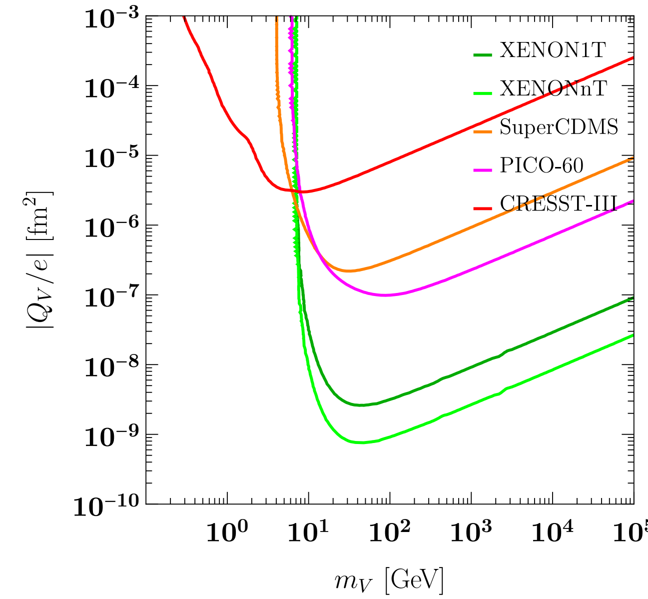


$\lesssim 2 \times 10^{-10} e\,\mathrm{fm}$

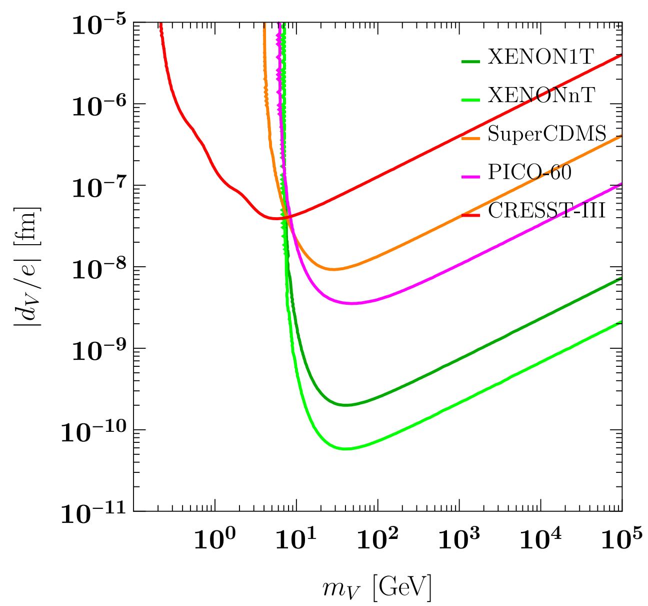
MDM



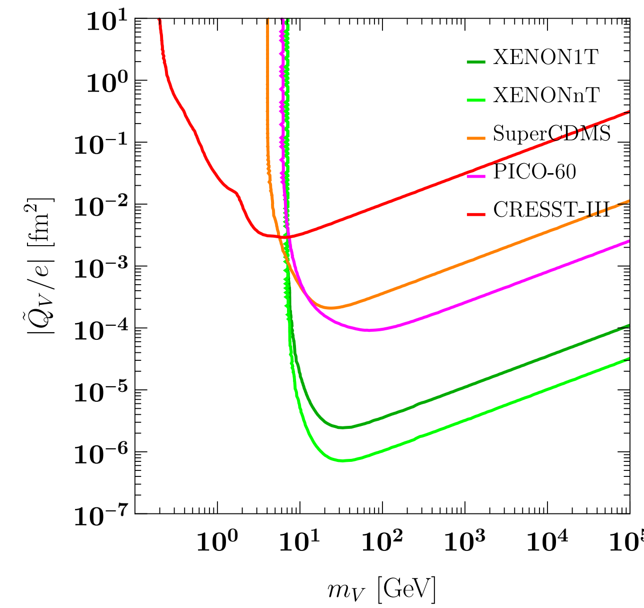
MQM



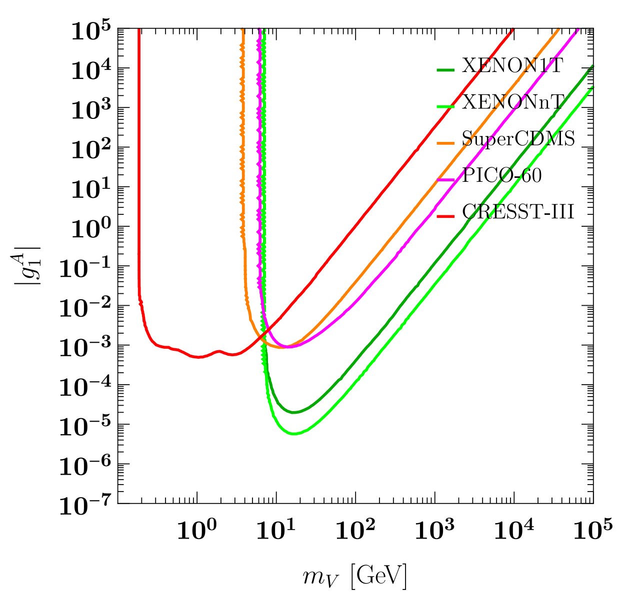
EDM



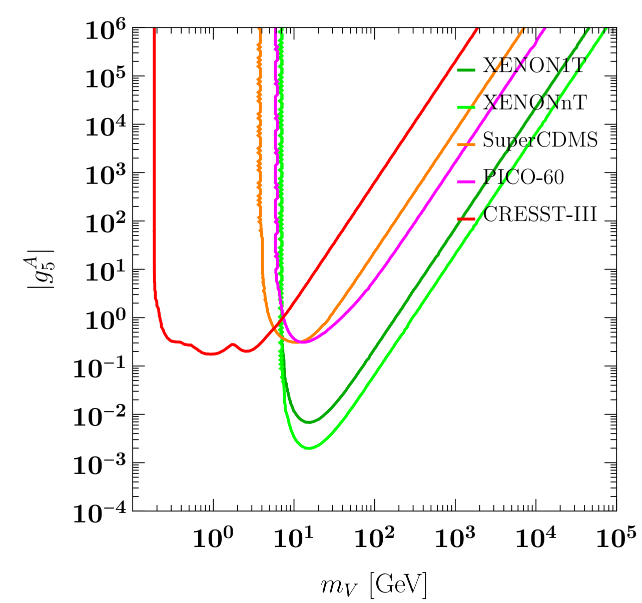
EQM



CR



AM



Direct detection

	$\mathbf{C}$	$\mathbf{P}$	Upper limit (m$_{DM}$ ~ 30GeV)
MDM (μ_V)	$+$	$+$	$2\times10^{-6}\mu_N$
MQM (Q_V)	$+$	$-$	$3\times10^{-9}e\,\mathrm{fm}^2$
EDM (d_V)	$+$	$-$	$2\times10^{-10}e\,\mathrm{fm}$
EQM $(\tilde{Q}_V)$	$+$	$+$	$3\times10^{-6}e\,\mathrm{fm}^2$
CR (g_1^A)	$+$	$+$	3×10^{-5}
AM (g_5^A)	$-$	$-$	8×10^{-3}

今日のトーク

- 一般論
- 模型の例

Recipe

３つの要素

1) 非可換ゲージ対称性の自発的破れ

→ 新たなベクトル場

2) U(1) 対称性 → 安定性, 複素場

3) 新たな物質場 (DMとphoton, どちらとも結合する)

→ 多極子

A simple model

- SM-like "dark" SSB :

$$SU(2)_D \times U(1)_X \rightarrow U(1)_D$$

global   global

$$V = \mu_D^2(\Phi_D^\dagger \Phi_D) + \frac{\lambda_D}{4}(\Phi_D^\dagger \Phi_D)^2 + \frac{\lambda_{DH}}{4}(\Phi_D^\dagger \Phi_D)(H^\dagger H)$$

"dark" Higgs
($SU(2)_D$ doublet)

for simplicity

A simple model

- SM-like "dark" SSB :

$$SU(2)_D \times U(1)_X \rightarrow U(1)_D$$

global　　　global

$$V = \mu_D^2(\Phi_D^\dagger \Phi_D) + \frac{\lambda_D}{4}(\Phi_D^\dagger \Phi_D)^2 + \frac{\lambda_{DH}}{4}(\Phi_D^\dagger \Phi_D)(H^\dagger H)$$

- 3つのゲージボソン　$W_D^+, \quad W_D^-, \quad W_D^0$

U(1)D charged

A simple model

- 物質場を導入

	$SU(2)_D$	$U(1)_X$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
Ψ_l	$\mathbf{2}$	$-1/2$	$\mathbf{1}$	$\mathbf{1}$	-1
Ψ_e	$\mathbf{1}$	-1	$\mathbf{1}$	$\mathbf{1}$	-1

$$-\mathcal{L}_{\rm mass} = m_{\Psi_l}\bar{\Psi}_l P_L \Psi_l + m_{\Psi_e}\bar{\Psi}_e P_L \Psi_e$$

$$+\bar{\Psi}_l \Phi_D \left(\lambda_L P_L + \lambda_R P_R\right)\Psi_e + y\bar{\Psi}_l (i\tau^2 \Phi_D^*) l_R + \text{h.c.}$$

A simple model

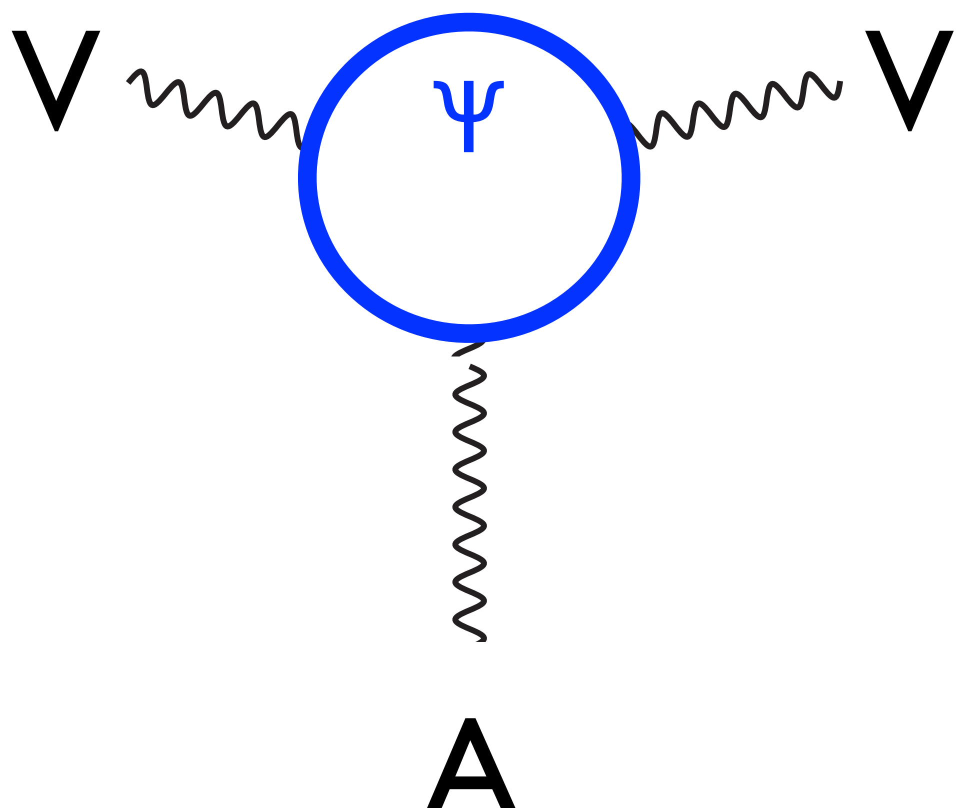
	Mass	$U(1)_{\rm D}$	$U(1)_{\rm EM}$
W_D^+	m_{W_D}	$+1$	0
W_D^-	m_{W_D}	-1	0
W_D^0	m_{W_D}	0	0
Ψ_N	m_N	0	-1
Ψ_{E_1}	m_{E_1}	-1	-1
Ψ_{E_2}	m_{E_2}	-1	-1

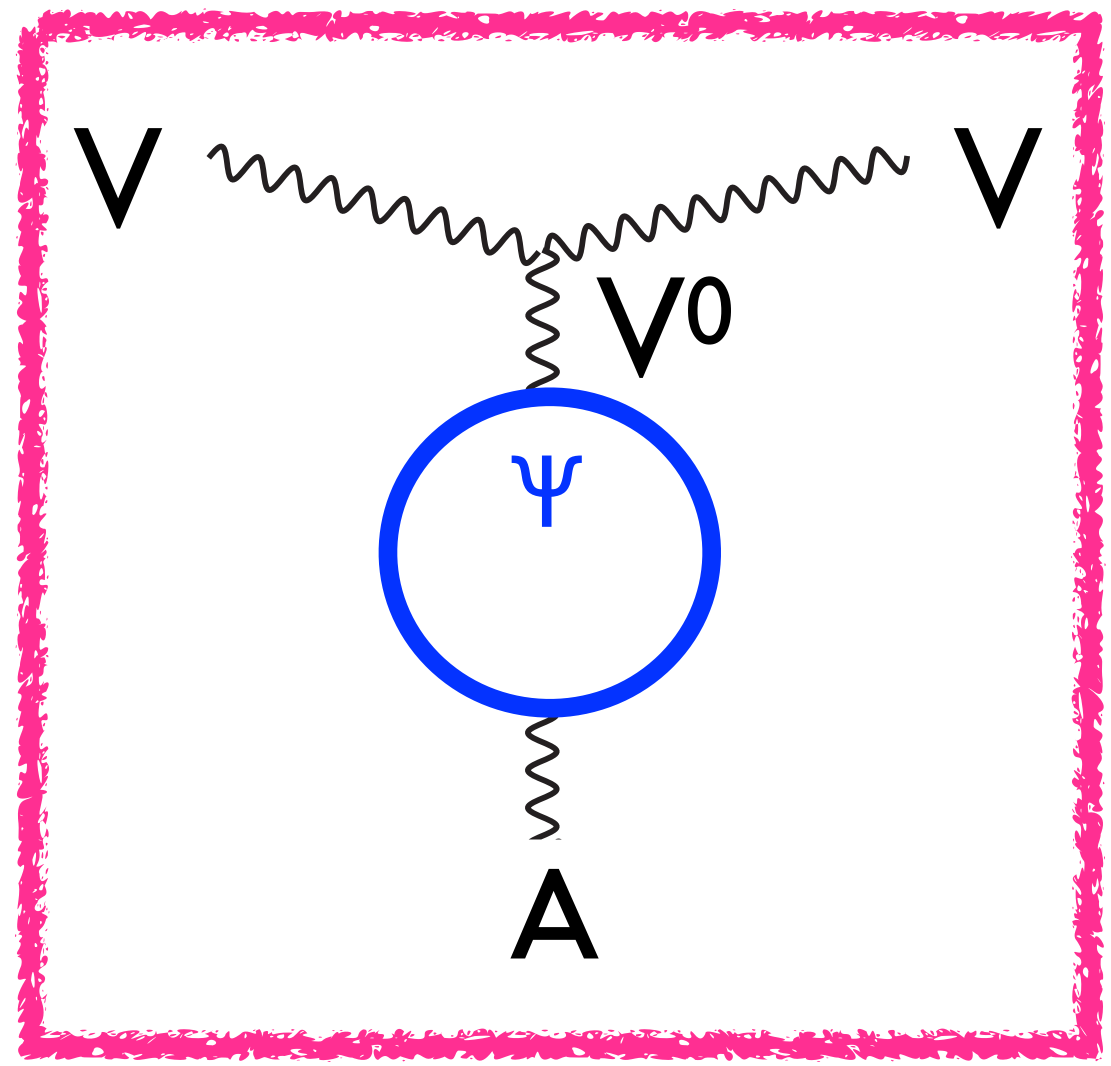
→ DM ($W_D^\pm$)

→ Multipoles (Ψ_N, Ψ_{E_1}, Ψ_{E_2})

- $m_{W_D} < m_{E_1,E_2}$ を仮定

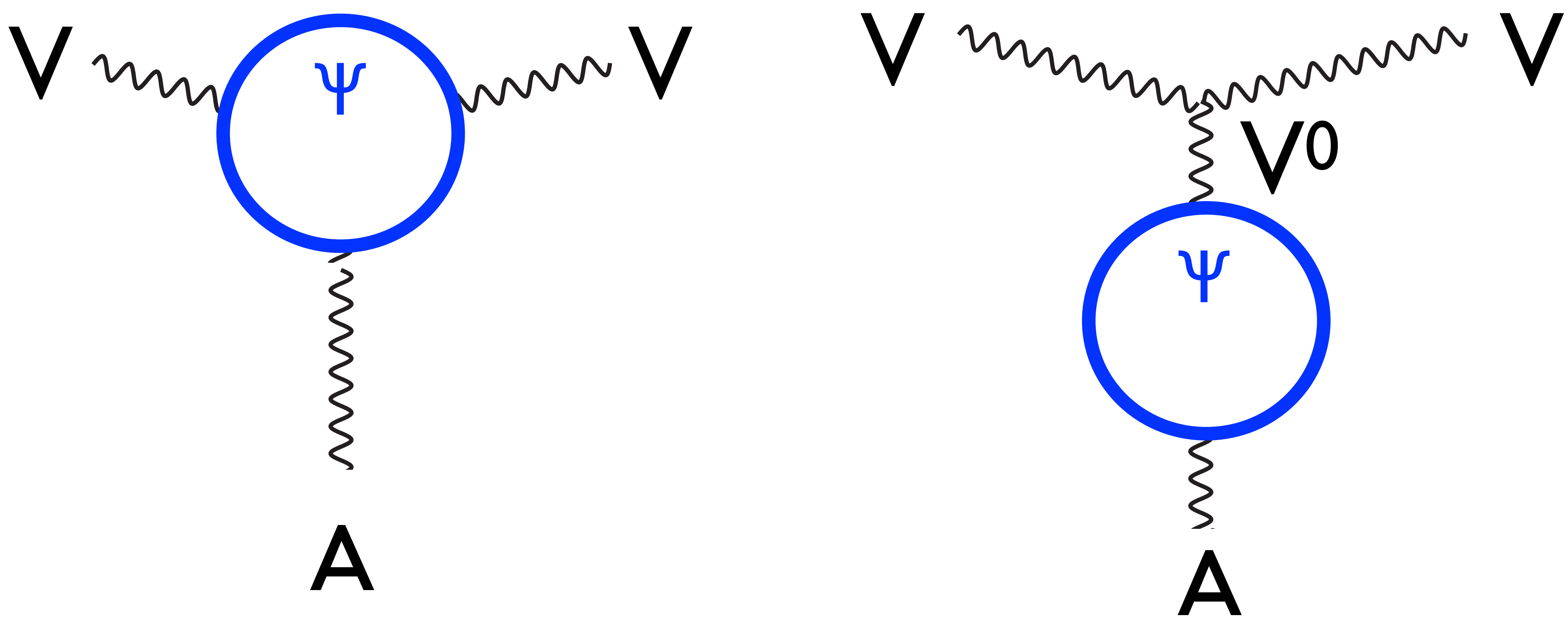
Dark multipoles





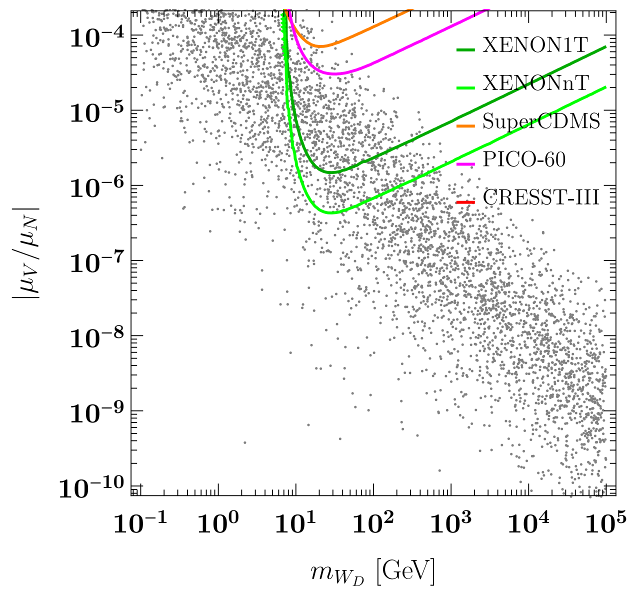
→ Charge radius

Dark multipoles

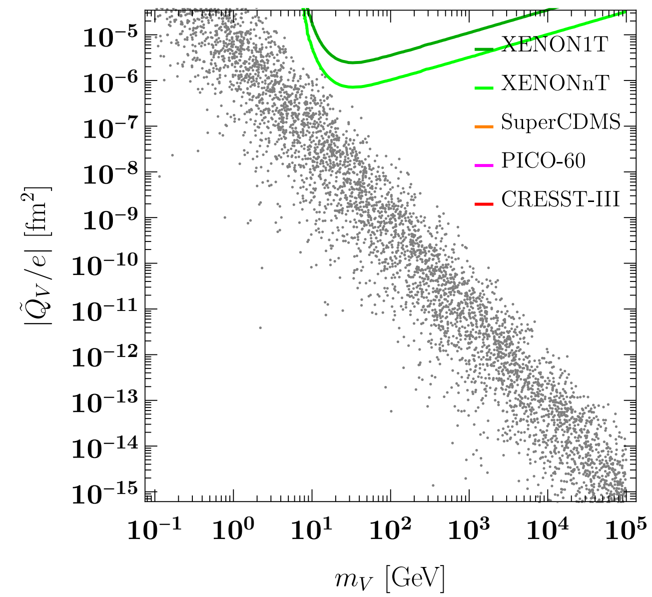


Parameters: $\mathbf{m_V}$, $\mathbf{m_\Psi}$, $\mathbf{g_D}$, **Ψ-mixing** (~ Yukawa)

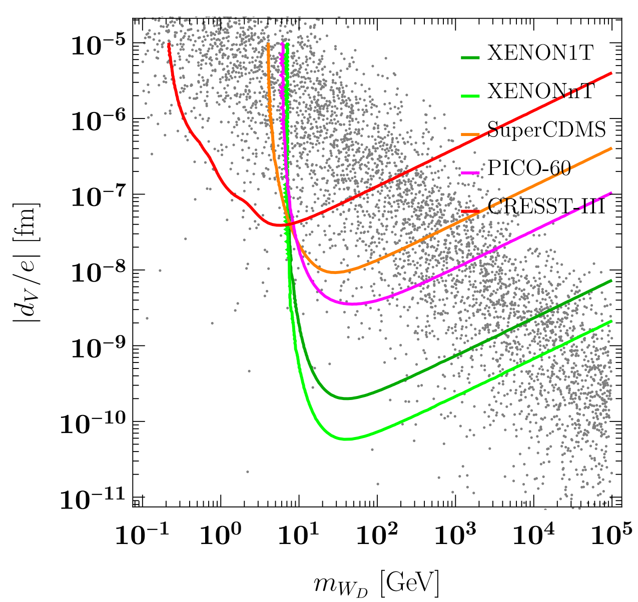
MDM



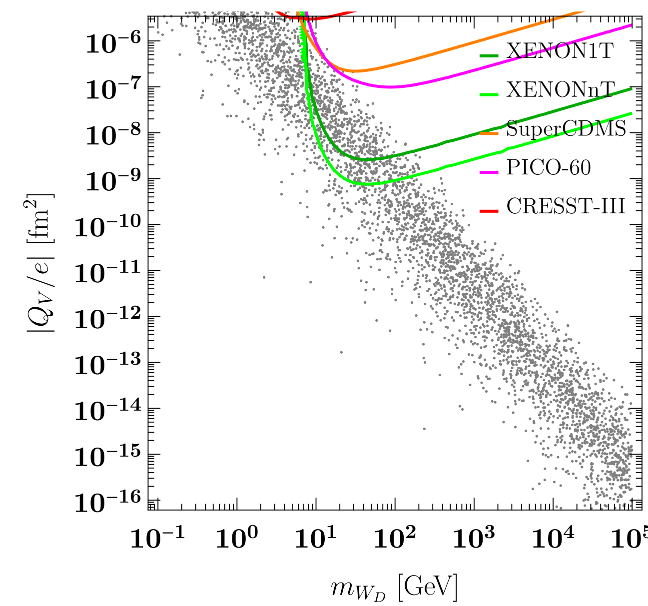
MQM



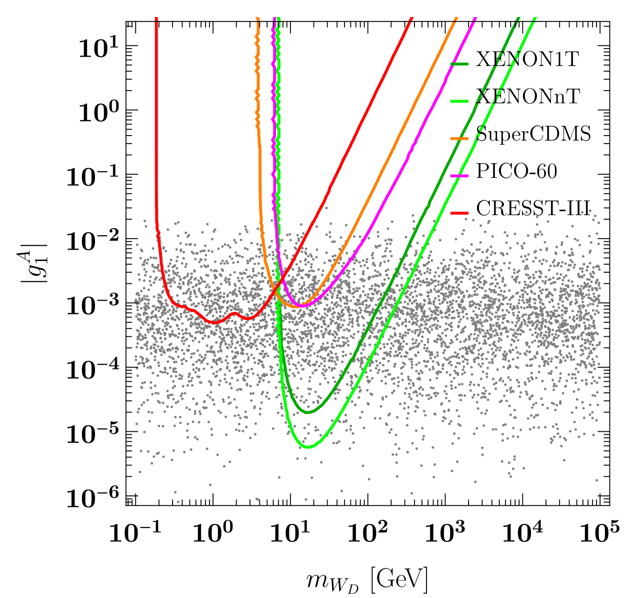
EDM



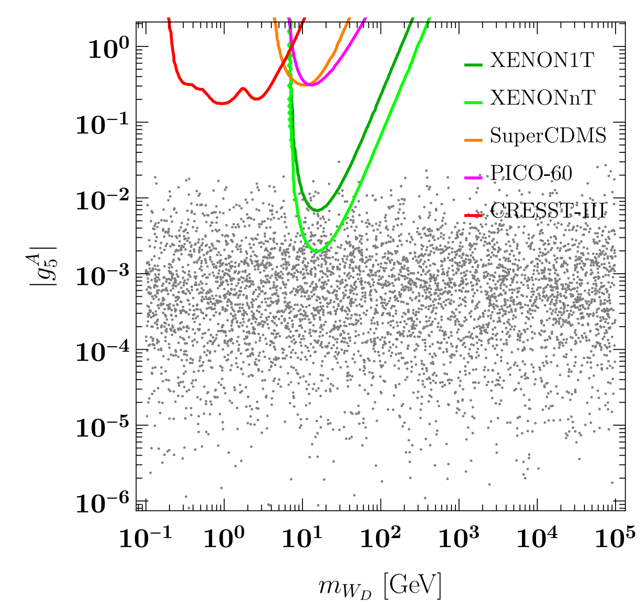
EQM



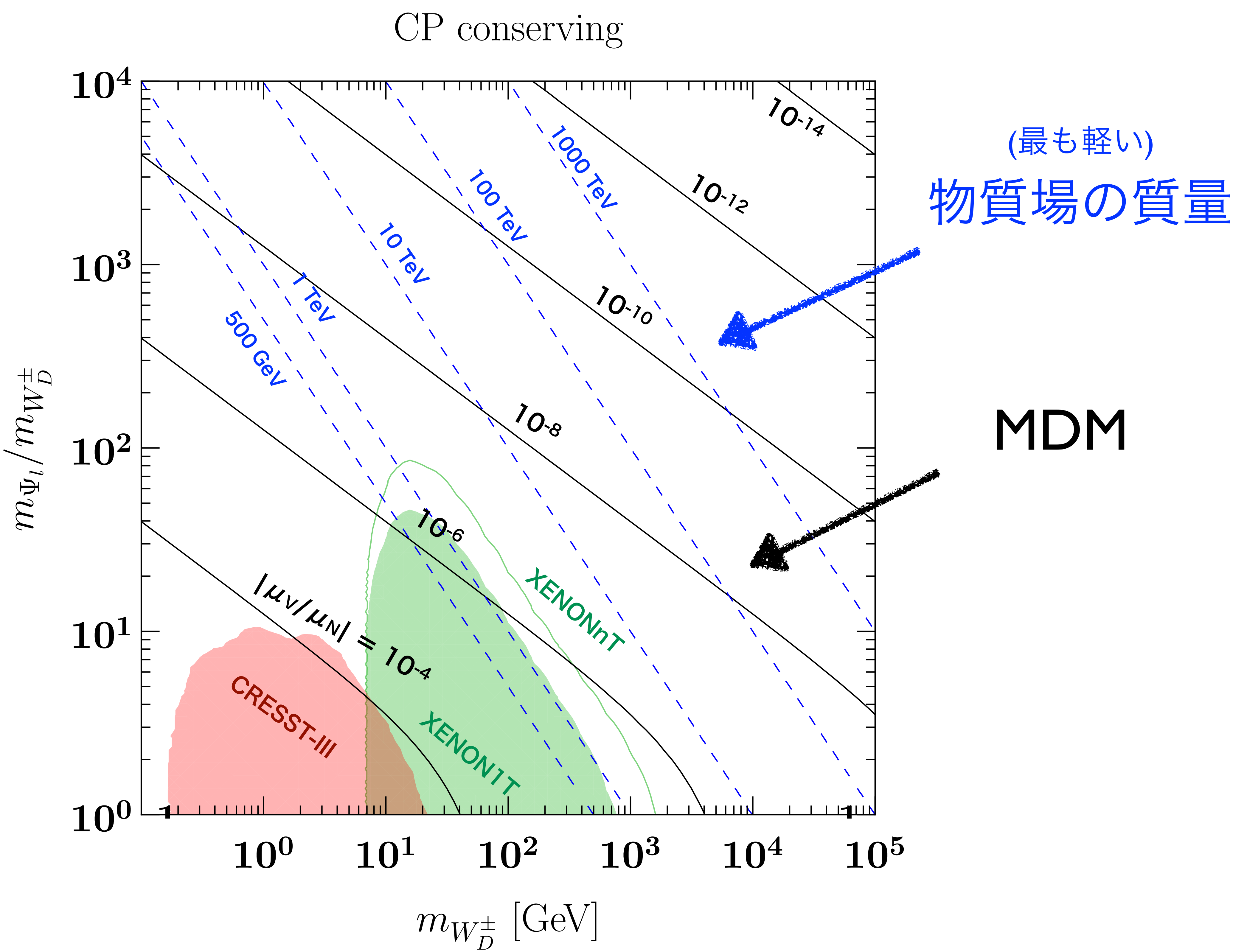
CR



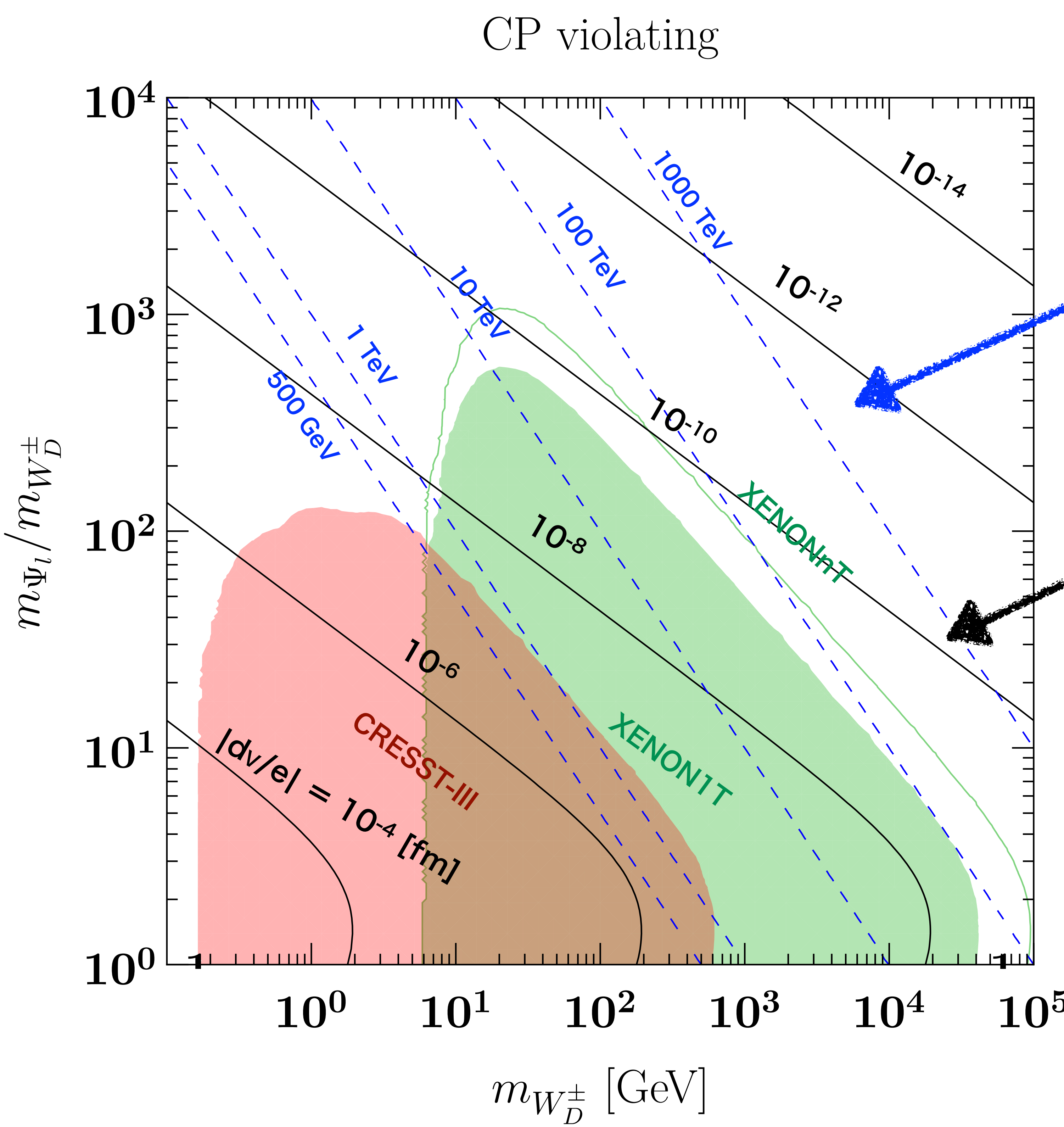
AM



Direct detection: CPC



Direct detection: CPV

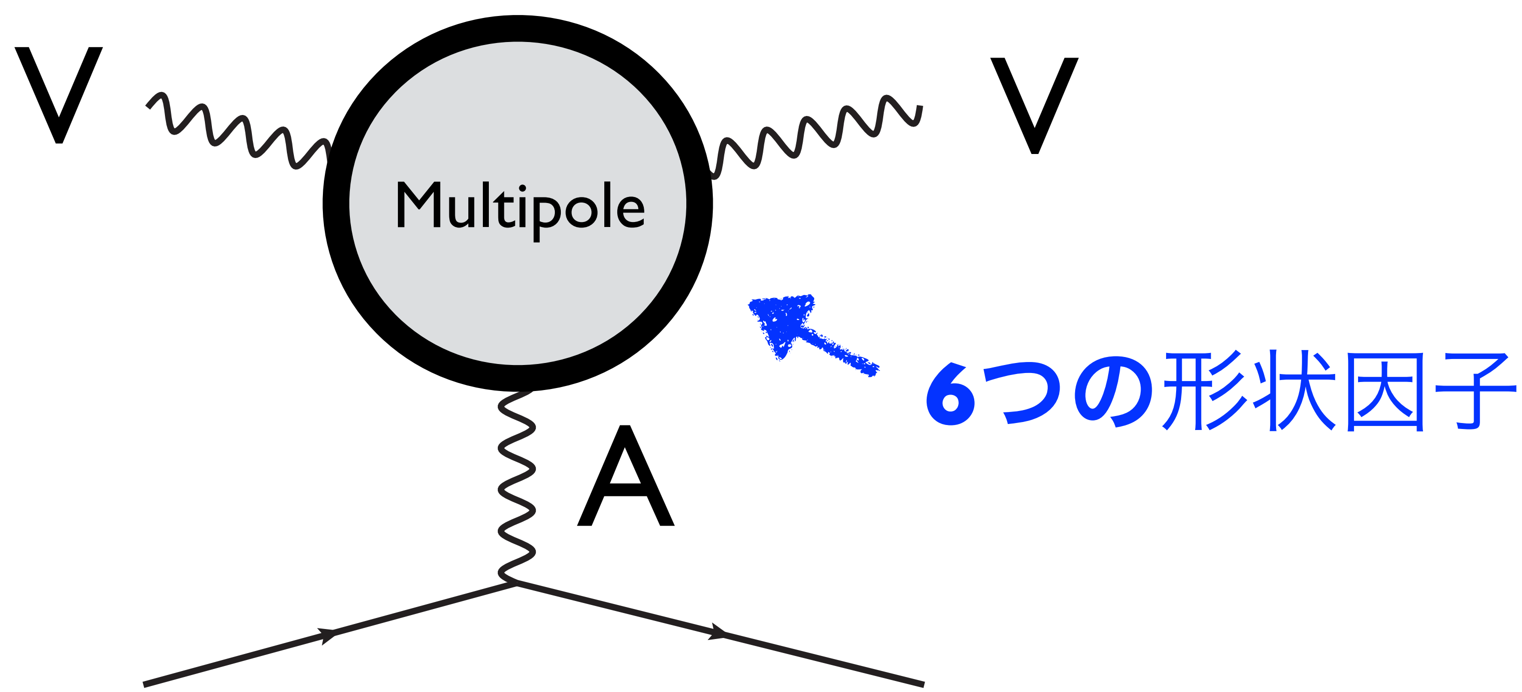


(最も軽い)
物質場の質量

EDM

まとめ

スピン1暗黒物質の多極子直接探索



Despite the loop suppression, the dark multipoles can lead to detectable rate in the direct detections.