Electric Dipole Moments From Dark Sectors

Shohei Okawa (U. Victoria)

University of Victoria

Based on work in progress with

Maxim Pospelov (U.Victoria/Perimeter Institute), Adam Ritz (U.Victoria)

Flavor Physics and CP violation (FPCP) 2019 @ Victoria, BC Canada

May 9, 2019

New physics and dark sectors

- The Standard Model confirmed to high precision
  - at both high-energy and intensity frontier experiments
  - but no compelling evidence for new physics so far…

New physics and dark sectors

- The Standard Model confirmed to high precision
  - at both high-energy and intensity frontier experiments
  - but no compelling evidence for new physics so far…

- New physics involving dark sectors
  - empirical evidence for new physics, neutrino mass and dark matter, does not necessarily point to an origin at short distances
  - significant attentions paid to many extensions involving dark sectors (e.g. dark photon, axion(-like) particles, mirror models, etc.)
  - can involve new light degrees of freedom at or below the EW scale

Dark Sectors with light new particles

Dark sector = all new particles are neutral under SM symmetries

- Effective Lagrangian at the EW scale

[Le Dall, Pospelov and Ritz, 1505.01865;
***SO**, Pospelov and Ritz, 1905.xxxxx]*

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{NP}$$

$$\mathcal{L}_{NP} = \mathcal{L}_{IR} + \sum_{d\geq 5} \frac{1}{\Lambda_{UV}^{d-4}} \mathcal{O}_d$$

describes IR new physics involving
light **dark sector particles**

short distance contributions from
possible UV physics

$$\Lambda_{UV} \gg m_W$$

Dark Sectors with light new particles

Dark sector = all new particles are neutral under SM symmetries

- Effective Lagrangian at the EW scale

[Le Dall, Pospelov and Ritz, 1505.01865;
***SO**, Pospelov and Ritz, 1905.xxxxx]*

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{NP}$$

$$\mathcal{L}_{NP} = \mathcal{L}_{IR} + \sum_{d \geq 5} \frac{1}{\Lambda_{UV}^{d-4}} \mathcal{O}_d$$

describes IR new physics involving light **dark sector particles**

short distance contributions from possible UV physics

$$\Lambda_{UV} \gg m_W$$

$$\mathcal{L}_{IR} = \epsilon B^{\mu\nu} F'_{\mu\nu} - (AS + \lambda S^2) H^\dagger H - Y_N \bar{L} H N + \mathcal{L}_{\text{hidden}}$$

possible renormalizable portal interactions

- ✓ *all other interactions*
- ✓ *only neutral particles*
- ✓ *any complex structure allowed*

F' : dark photon

S : singlet scalar

N : neutral lepton (heavy neutrino)

EDMs as a probe of dark sectors

- A good precision observable is Electric Dipole Moments (EDMs)

(cf. 1505.01865 for other precision observables, hadronic flavors and EDMs, LFVs, lepton g-2,…)

$$\mathcal{L}_{EDM} = -i\frac{d_\psi}{2}\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi F_{\mu\nu} \quad \underset{\text{non rel.}}{\longrightarrow} \quad \mathcal{H} = -d_\psi\,\vec{s}\cdot\vec{E}$$

e.g.) recent progress in an electron EDM observation at the ACME experiment

$$d_e \leq 1.1\times 10^{-29}\,\mathrm{ecm} \sim \frac{e}{16\pi^2}\cdot m_e \cdot \left(\frac{100\,\mathrm{TeV}}{\Lambda_{UV}}\right)^2$$

(ACME collaboration, V. Andreev et al., 2018)

SM predicts
$d_e \sim 10^{-38}\,\mathrm{ecm}$

EDMs can probe high-energy scale (UV) physics

EDMs as a probe of dark sectors

- A good precision observable is Electric Dipole Moments (EDMs)

(cf. 1505.01865 for other precision observables, hadronic flavors and EDMs, LFVs, lepton g-2,…)

$$\mathcal{L}_{EDM} = -i\frac{d_\psi}{2}\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi F_{\mu\nu} \quad \xrightarrow[\text{non rel.}]{} \quad \mathcal{H} = -d_\psi\, \vec{s}\cdot\vec{E}$$

e.g.) recent progress in an electron EDM observation at the ACME experiment

$$d_e \leq 1.1\times 10^{-29}\,\text{ecm} \sim \frac{e}{16\pi^2}\cdot m_e \cdot \left(\frac{100\,\text{TeV}}{\Lambda_{UV}}\right)^2$$

(ACME collaboration, V. Andreev et al., 2018)

SM predicts $d_e \sim 10^{-38}\,\text{ecm}$

EDMs can probe high-energy scale (UV) physics

One question:

Can sensitivities of EDM observations be high enough to probe dark sector new physics? In other words, what is a maximum EDM contribution from dark sector new physics?

electron EDM from dark sectors

$$\mathcal{L}_{IR} = \epsilon B^{\mu\nu} F'_{\mu\nu} - (AS + \lambda S^2) H^\dagger H - Y_N \bar{L} H N + \mathcal{L}_{\rm hidden}$$

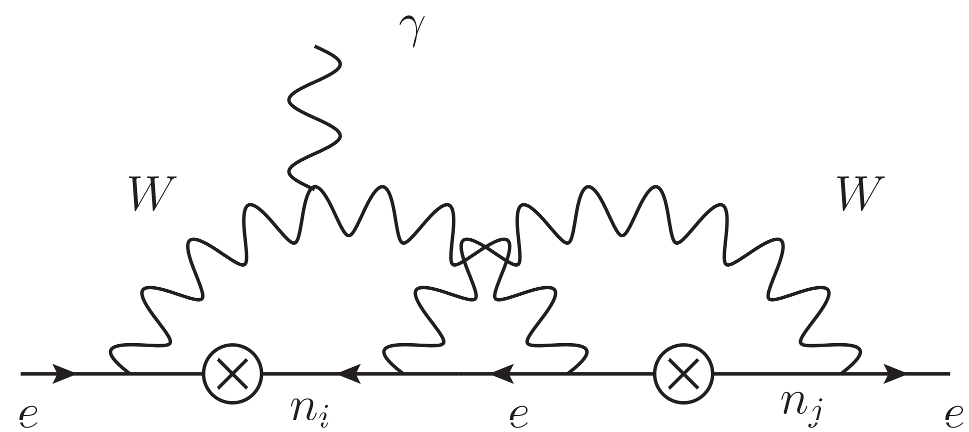
electron EDM from dark sectors

$$\mathcal{L}_{IR} = \epsilon B^{\mu\nu} F'_{\mu\nu} - (AS + \lambda S^2) H^\dagger H - Y_N \bar{L} H N + \mathcal{L}_{\text{hidden}}$$

- Neutrino portal
  - appears only for *Majorana* neutrino

$$\mathcal{L}_{\text{hidden}} = M_N \bar{N}^c N + h.c.$$

$$\Rightarrow \quad d_e \lesssim 10^{-33}\, e \cdot \text{cm}$$



[Archambault, Czarnecki and Pospelov, 0406089; Le Dall, Pospelov and Ritz, 1505.01865; Ng and Ng, 9510306]

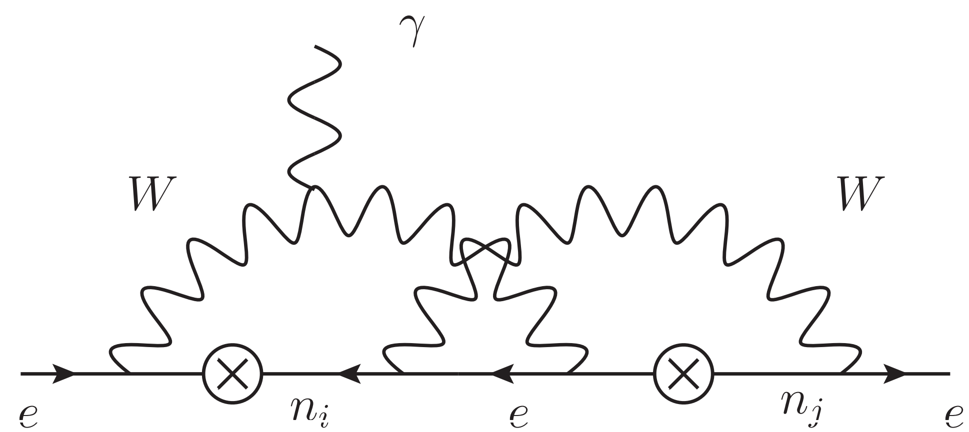
electron EDM from dark sectors

$$\mathcal{L}_{IR} = \epsilon B^{\mu\nu} F'_{\mu\nu} - (AS + \lambda S^2) H^\dagger H - Y_N \bar{L} H N + \mathcal{L}_{\text{hidden}}$$

- Neutrino portal
  - appears only for *Majorana* neutrino

$$\mathcal{L}_{\text{hidden}} = M_N \bar{N}^c N + h.c.$$

$$\Rightarrow \quad d_e \lesssim 10^{-33}\, e \cdot \text{cm}$$

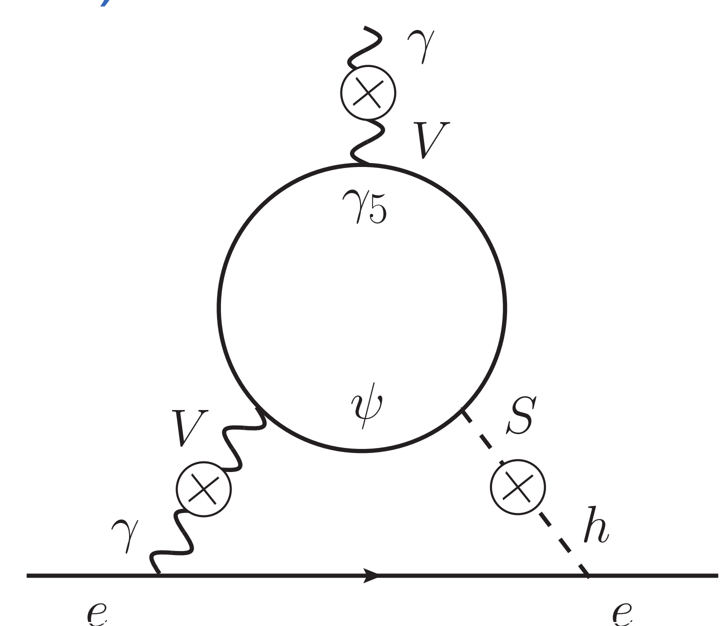


[Archambault, Czarnecki and Pospelov, 0406089; Le Dall, Pospelov and Ritz, 1505.01865; Ng and Ng, 9510306]

- Vector and scalar portal (Dark Barr-Zee mechanism)
  - $\mathcal{L}_{\text{hidden}} = Y_S\, S \bar{\psi} i \gamma_5 \psi$ (ψ : dark fermion)
  - electron EDM induced via "dark EDM"

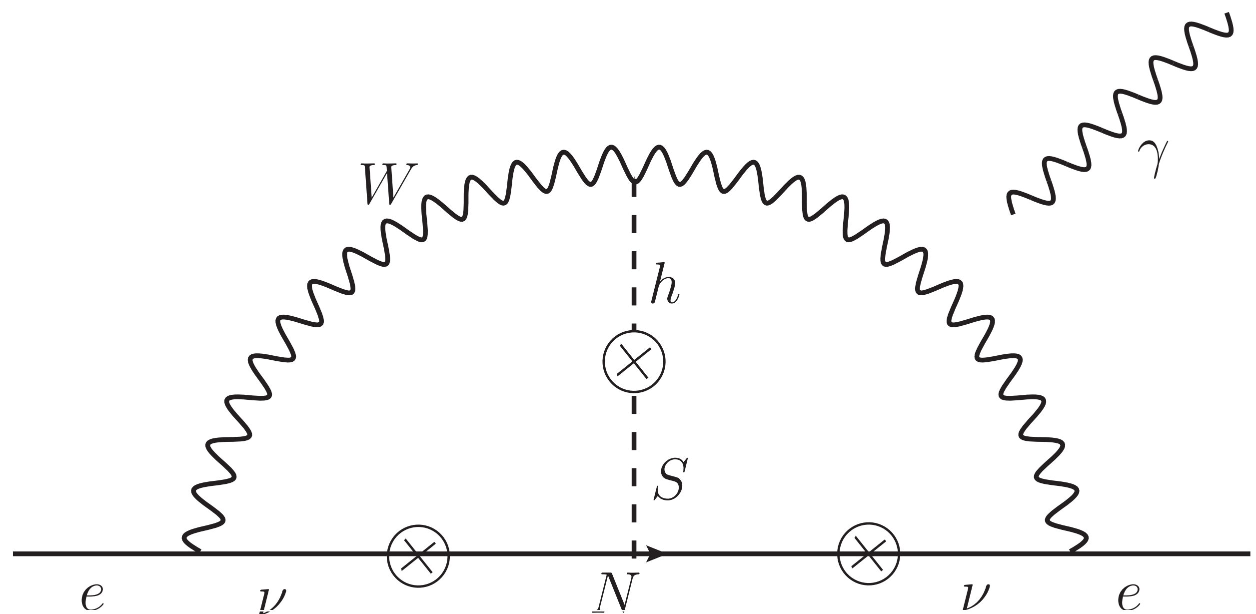
$$\bar{e}\sigma^{\mu\nu}\gamma_5 e F'_{\mu\nu} \to \bar{e}\sigma^{\mu\nu}\gamma_5 e \frac{\Box F_{\mu\nu}}{m_{A'}^2}$$

$$\Rightarrow \quad d_e \sim 4 \times 10^{-33}\, e \cdot \text{cm} \left(\frac{1\,\text{GeV}}{m_\psi}\right) \left(\frac{\epsilon}{10^{-4}}\right)^2 \left(\frac{\theta_h}{10^{-3}}\right)$$



[Le Dall, Pospelov and Ritz, 1505.01865]

new!



$$-\mathcal{L}_{IR} = ASH^\dagger H + Y_N \bar{L} H N + \lambda_N S \bar{N} i\gamma_5 N$$

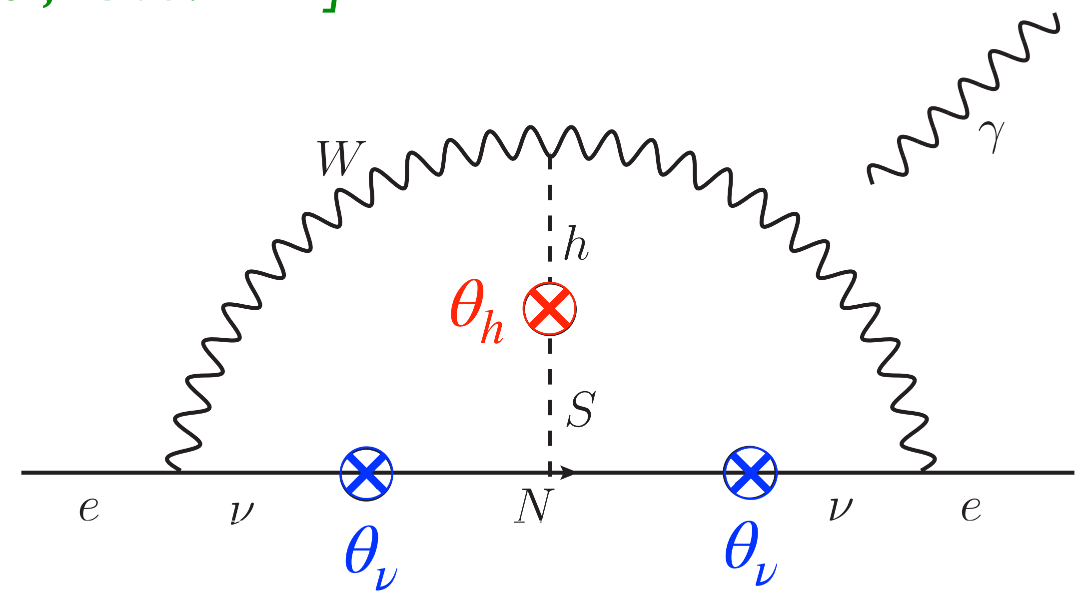
[**SO**, Pospelov and Ritz, 1905.xxxxx]

New contribution

[**SO**, Pospelov and Ritz, 1905.xxxxx]

$$-\mathcal{L}_{IR} = ASH^\dagger H + Y_N \bar{L} H N + \lambda_N S \bar{N} i\gamma_5 N$$

(* assume Dirac neutrino)



- Let's estimate the expected EDM

$$\mathcal{L}_{\rm EDM} = -i\frac{d_e}{2}\,\bar{e}\sigma^{\mu\nu}\gamma_5 e F^{\mu\nu}$$

$$d_e \sim \frac{e}{(16\pi^2)^2}\cdot\theta_h\theta_\nu^2\cdot\frac{m_e}{m_{NP}^2}\cdot\lambda_N \sim 4\cdot 10^{-29}\, e\cdot{\rm cm}\times\left(\frac{\theta_h\theta_\nu^2}{10^{-3}}\right)\left(\frac{100\,{\rm GeV}}{m_{NP}}\right)^2\left(\frac{\lambda_N}{1}\right)$$

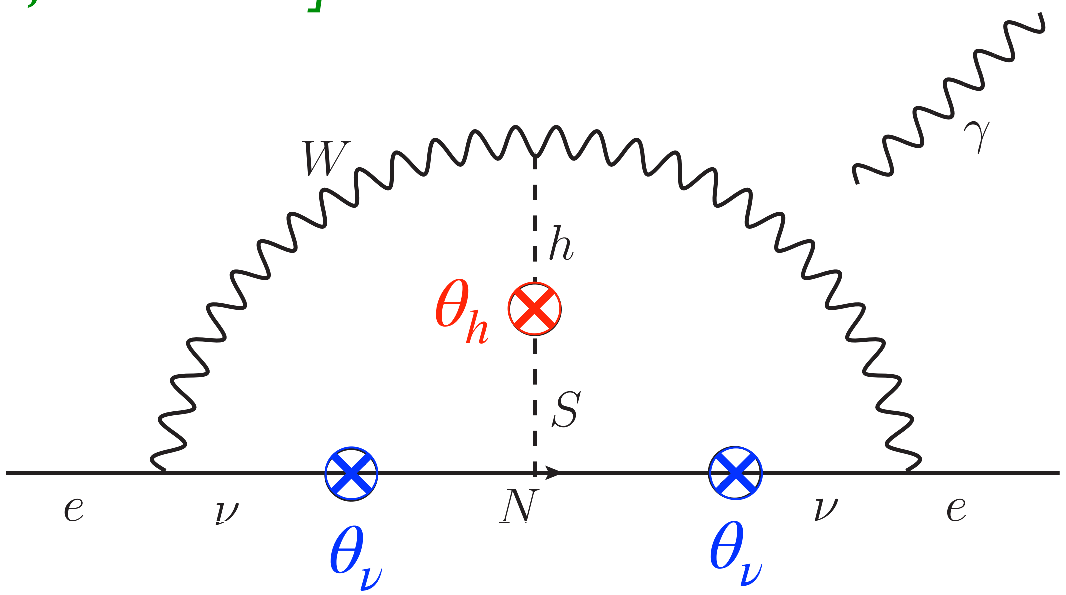
It is close to the current bound: $d_e \leq 1.1\times 10^{-29}\,{\rm ecm}$ @ ACME

New contribution

[**SO**, Pospelov and Ritz, 1905.xxxxx]

$$-\mathcal{L}_{IR} = ASH^\dagger H + Y_N \bar{L} H N + \lambda_N S \bar{N} i\gamma_5 N$$

(* assume Dirac neutrino)



- Let's estimate the expected EDM

$$\mathcal{L}_{\rm EDM} = -i\frac{d_e}{2}\bar{e}\sigma^{\mu\nu}\gamma_5 e F^{\mu\nu}$$

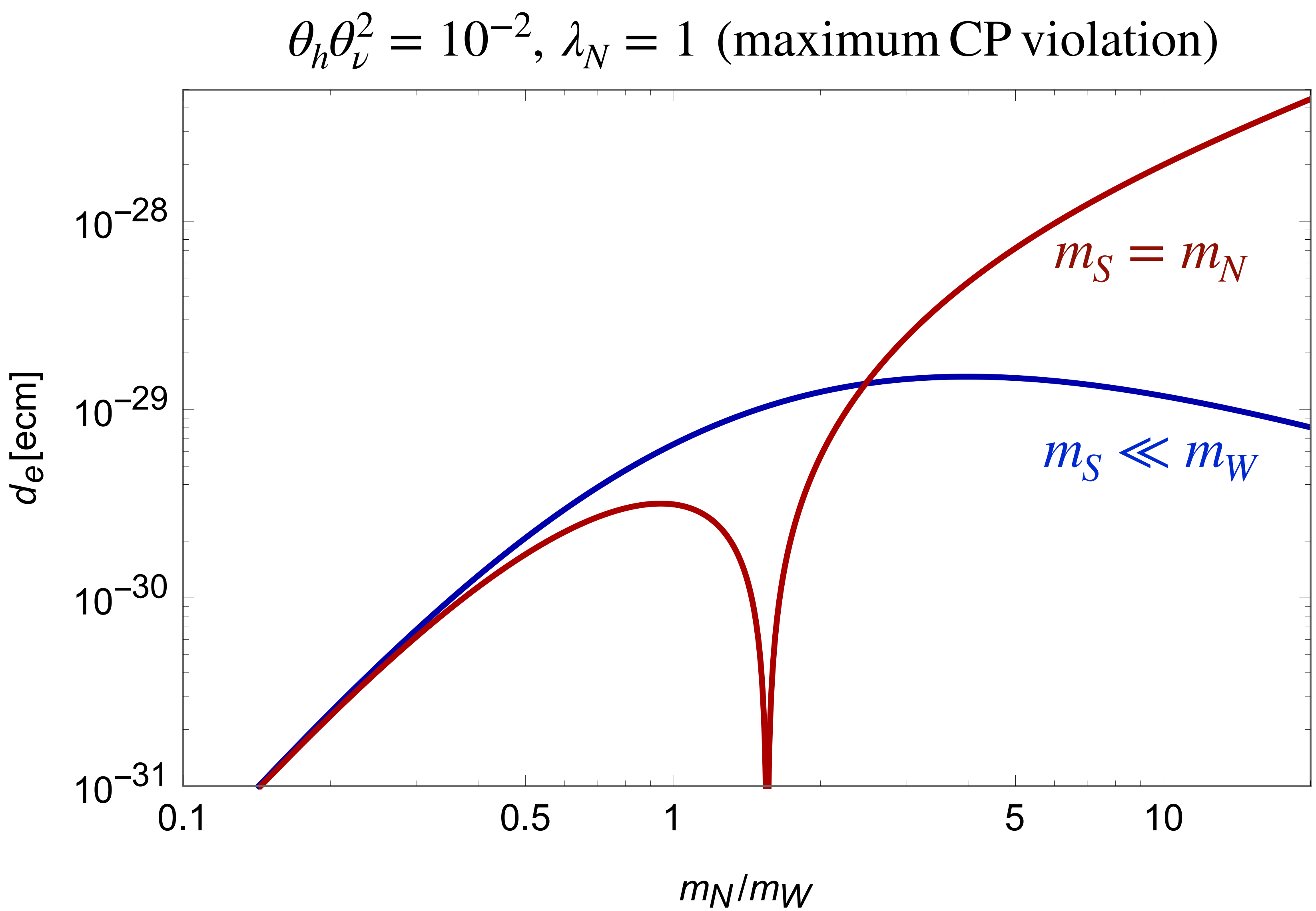
$$d_e \sim \frac{e}{(16\pi^2)^2} \cdot \theta_h\theta_\nu^2 \cdot \frac{m_e}{m_{NP}^2} \cdot \lambda_N \sim 4\cdot 10^{-29}\, e\cdot {\rm cm} \times \left(\frac{\theta_h\theta_\nu^2}{10^{-3}}\right)\left(\frac{100\,{\rm GeV}}{m_{NP}}\right)^2\left(\frac{\lambda_N}{1}\right)$$

It is close to the current bound: $d_e \leq 1.1\times 10^{-29}\,{\rm ecm}$ @ACME

In our calculation,

- take weak decoupling limit, *i.e.* utilize only Goldstone bosons
- 't Hooft - Feynman gauge

Size of the induced electron EDM



$$\theta_h = Av/(m_S^2 - m_h^2)$$

$$\theta_\nu \simeq \frac{Y_\nu v}{m_N} \simeq \frac{m_\nu}{m_N}$$

$$d_e \leq 1.1 \times 10^{-29}\,\text{ecm}$$

(ACME collaboration, V. Andreev et al., 2018)

- two regimes: $m_S \ll m_W$ and $m_S = m_N$
- mild decoupling as $m_N \to \infty$, like top quark non-decoupling in FCNCs
- significant suppressions for $m_N \ll m_W$ in both cases
- resonant behavior for $m_S = m_N$

Sensitivity plots

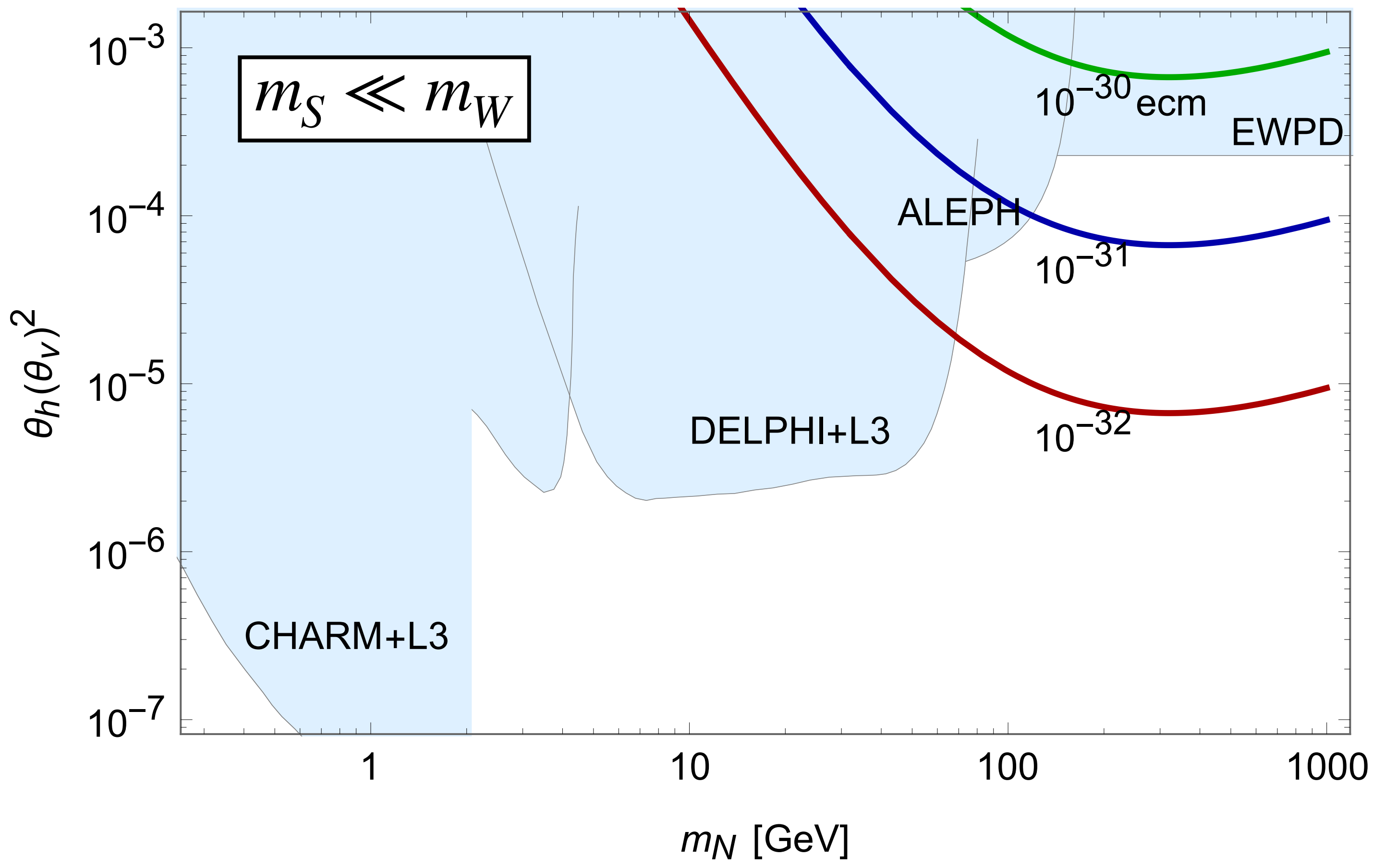
- maximum CP violation assumed
- current bound:

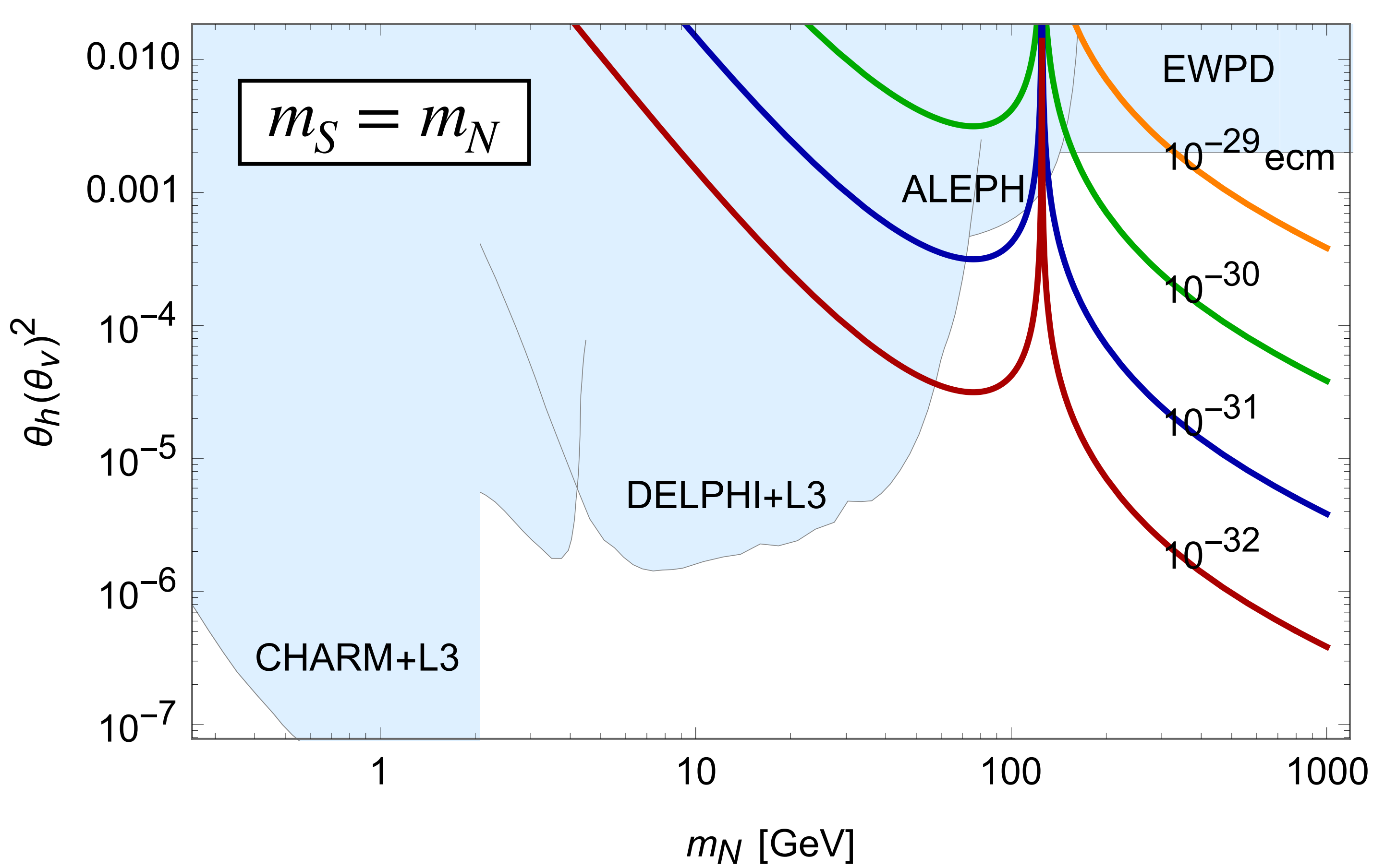
$$d_e \leq 1.1 \times 10^{-29}\,\mathrm{ecm}$$

(ACME collaboration, V. Andreev et al., 2018)

- neutrino mixing bound - CHARM, DELPHI, ALEPH, EWPD
- scalar mixing bound - L3

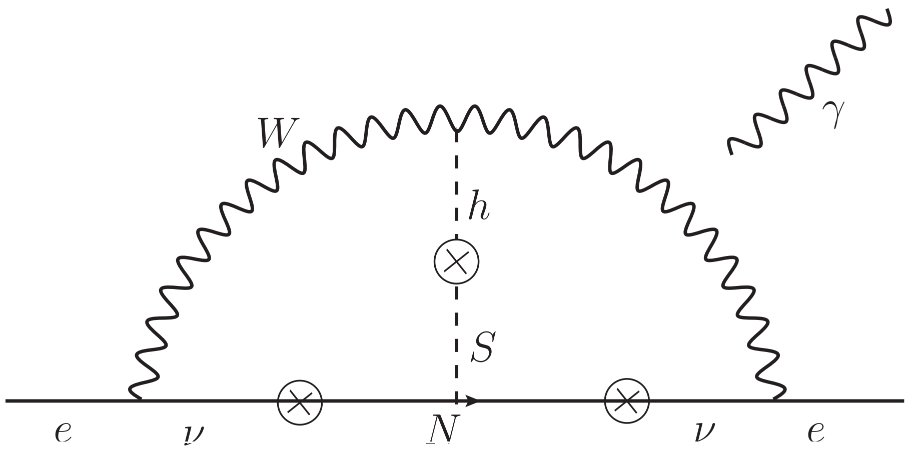
The EDM observation at the ACME already provides the best sensitivity to neutrino mixing for large m_N





Summary and Conclusion

- examine (electron) EDMs from dark sectors
  - several mediation channels
  - arise @ 2-loop or more
  - largest contribution from ***singlet portal***



- singlet portal contribution:
  - a combined mediation by a heavy neutrino and a singlet scalar
  - never considered so far
  - maximum value: $d_e \sim 10^{-29}\, e \cdot \mathrm{cm}$
  - a good sensitivity to neutrino mixing for large singlet masses

Thanks a lot for your attention!!

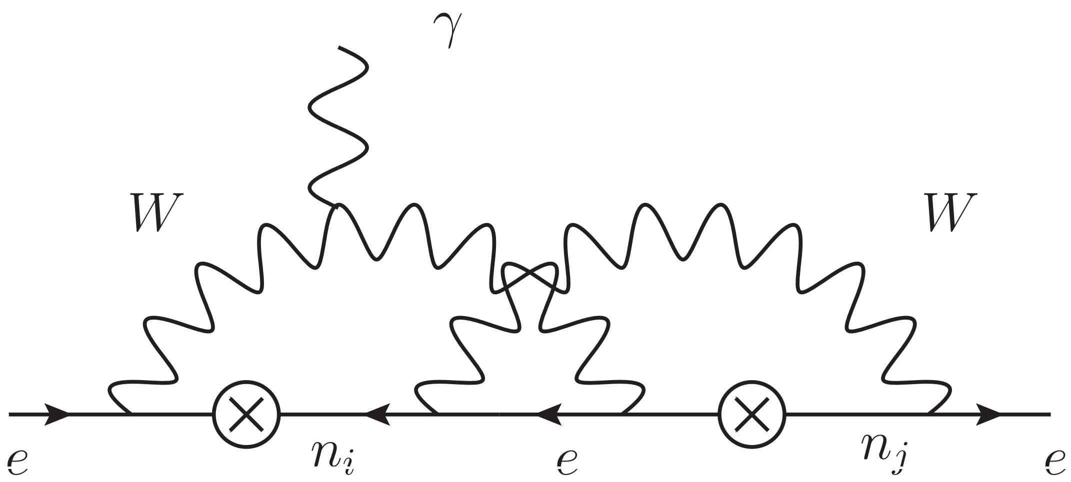
Back up

EDM via neutrino portal

- a minimal seesaw model

$$\mathcal{L}_{IR} = Y_{D_i}\bar{L}HN_i - M^{ij}\bar{N}_i^c N_j + h.c.$$

  - *Majorana* neutrino
  - mass matrix for (ν, N_1, N_2)



[Archambault, Czarnecki and Pospelov, 0406089; Le Dall, Pospelov and Ritz, 1505.01865; Ng and Ng, 9510306]

$$\mathcal{M} = \begin{pmatrix} 0 & m_{D_1} & m_{D_2} \\ m_{D_1} & M_1 & \epsilon \\ m_{D_2} & \epsilon & M_2 \end{pmatrix}$$

m_{D_i} : Dirac masses, M_i : Majorana masses

$m_{D_i}, \epsilon \ll M_{1,2}$

$$d_e \sim (3 \cdot 10^{-35}\, e \cdot \mathrm{cm}) \frac{m_{D_1}^2 m_{D_2}^2}{M^4} \frac{M_1^2 - M_2^2}{\mathrm{GeV}^2}$$

$$m_\nu \simeq \frac{m_{D_1}^2 - m_{D_2}^2}{M}$$

$$M = (M_1 + M_2)/2$$

$$\theta_\nu \simeq m_{D_i}/M$$

If we allow considerable tuning, it reaches a maximum value

de ~ 10^{-33} ecm

EDM by dark Barr-Zee mechanism

$$\mathcal{L}_{IR} = \epsilon B^{\mu\nu} F'_{\mu\nu} - ASH^\dagger H - Y_S\, S\bar{\psi} i\gamma_5 \psi$$

[Le Dall, Pospelov and Ritz, 1505.01865]

- Topology of the diagram is well studied
  - EDM is generated via "dark EDM" operator

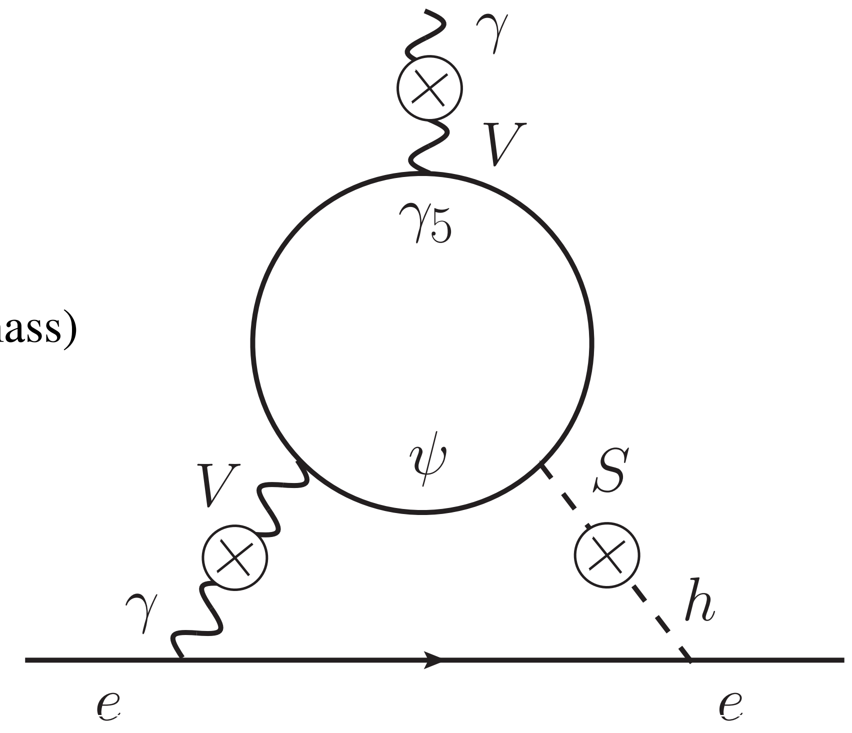
$$\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi F'_{\mu\nu} \rightarrow \bar{\psi}\sigma^{\mu\nu}\gamma_5\psi \frac{\Box F_{\mu\nu}}{m^2_{A'}}$$

($m_{A'}$: dark photon mass)

  - EDM "radius" (or Schiff moment)

$$\mathcal{L}_{\rm eff} = r_d^2\, \frac{i}{2} \bar{\psi}\sigma^{\mu}\gamma_5\psi \Box F_{\mu\nu}$$

$$r_d^2 \simeq \frac{|e|\alpha' Y_S}{16\pi^3 v m_\psi m^2_{A'}} \times \epsilon^2 \theta_h \ln(m^2_\psi / m^2_S)$$



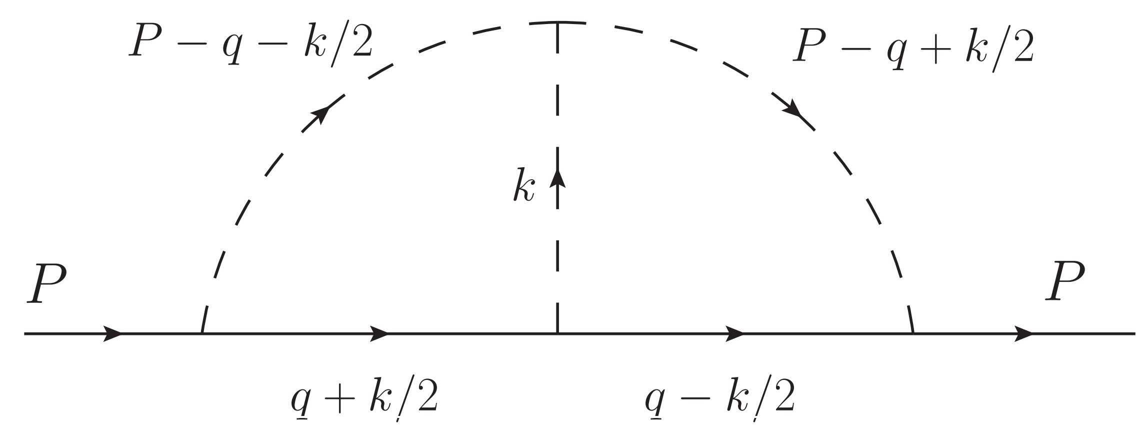
m_ψ : dark fermion mass m_S : singlet scalar mass
ϵ : gauge kinetic mixing θ_h : scalar mixing

Assuming α'=α and YS=1, the effective EDM radius translates to the electron EDM:

$$d_e \sim (Z\alpha m_e)^2 r_d^2 \simeq 4 \cdot 10^{-33}\, e\cdot {\rm cm} \times \left(\frac{1\,{\rm GeV}}{m_\psi}\right)\left(\frac{\epsilon}{10^{-4}}\right)^2 \left(\frac{\theta_h}{10^{-3}}\right)$$

Calculation procedure

- calculate the electron self-energy in a general EM background field
- expand its CP-violating part in terms of a electron covariant derivative $P_\mu = p_\mu + eA_\mu$



$$\mathcal{M} = \bar{\psi}_e \Sigma(P) \psi_e$$

- extract the EDM contributions using the following relations:

$$[P_\mu, P_\nu] = ieF_{\mu\nu} \qquad P^2 = \not{P}\not{P} + \frac{1}{2}e(F\cdot\sigma) \qquad \not{P}\psi_e(P) = m_e\psi_e(P)$$

In the end, we obtain

$$\mathcal{M} = -\frac{i}{2} d_e^{\rm scale}\, \bar{\psi}_e (F\cdot\sigma)\gamma_5\psi_e \times \int \frac{d^4k d^4q}{\pi^4} f(k,q)$$

$$d_e = d_e^{\rm scale} \times \int \frac{d^4k d^4q}{\pi^4} f(k,q)$$

$$d_e^{\rm scale} = \frac{e}{(16\pi^2)^2}\cdot\theta_h\theta_\nu^2\cdot\frac{2m_e m_N}{v^3} \simeq 4\cdot 10^{-29}\, e\cdot{\rm cm}\times\left(\frac{\theta_h\theta_\nu^2}{10^{-2}}\right)\times\frac{m_N}{m_W}$$