Electric dipole moment from a dark sector

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in collaboration with

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Higgs as a Probe of New Physics (HPNP2021)
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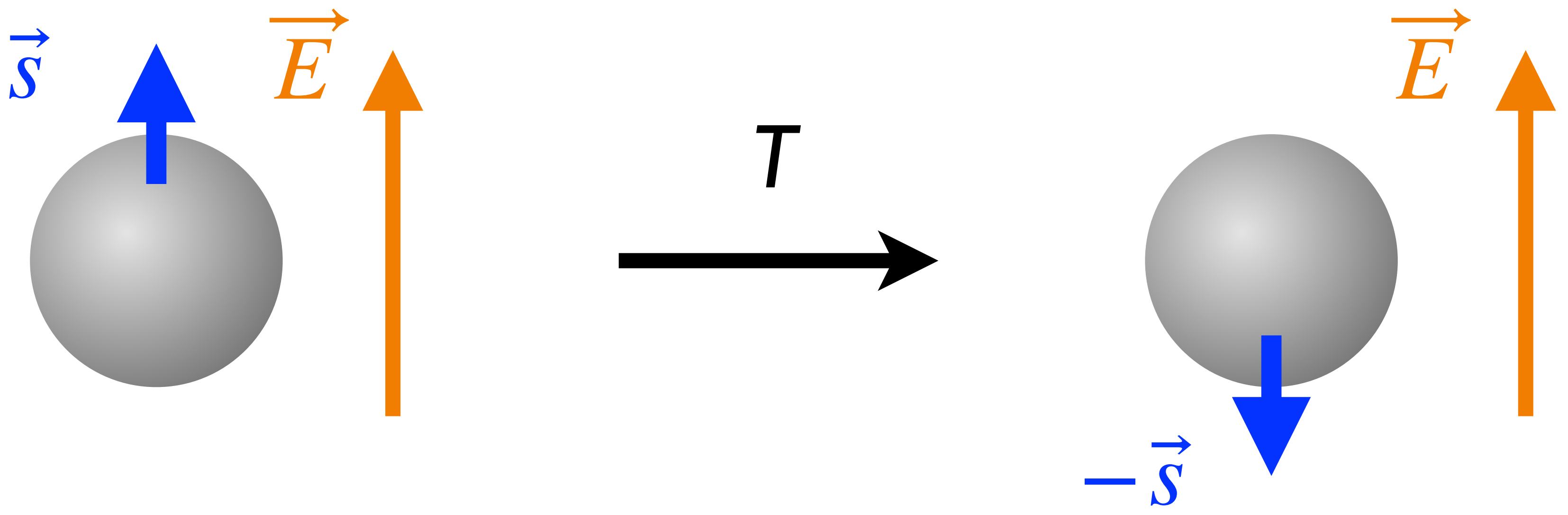
Electric Dipole Moments (EDMs)

$$\mathcal{H} = -d_\psi \, \vec{s} \cdot \vec{E}$$



- ✓ T violating (CP violating)
- ✓ Standard Model contributions suppressed

  e.g.) neutron EDM

  $$(d_n)_{SM} \sim 10^{-32}\, e\mathrm{cm} \ll (d_n)_{\mathrm{exp}} = 3.0 \times 10^{-26}\, e\mathrm{cm}$$

- ✓ good sensitivity to CP violation in new physics

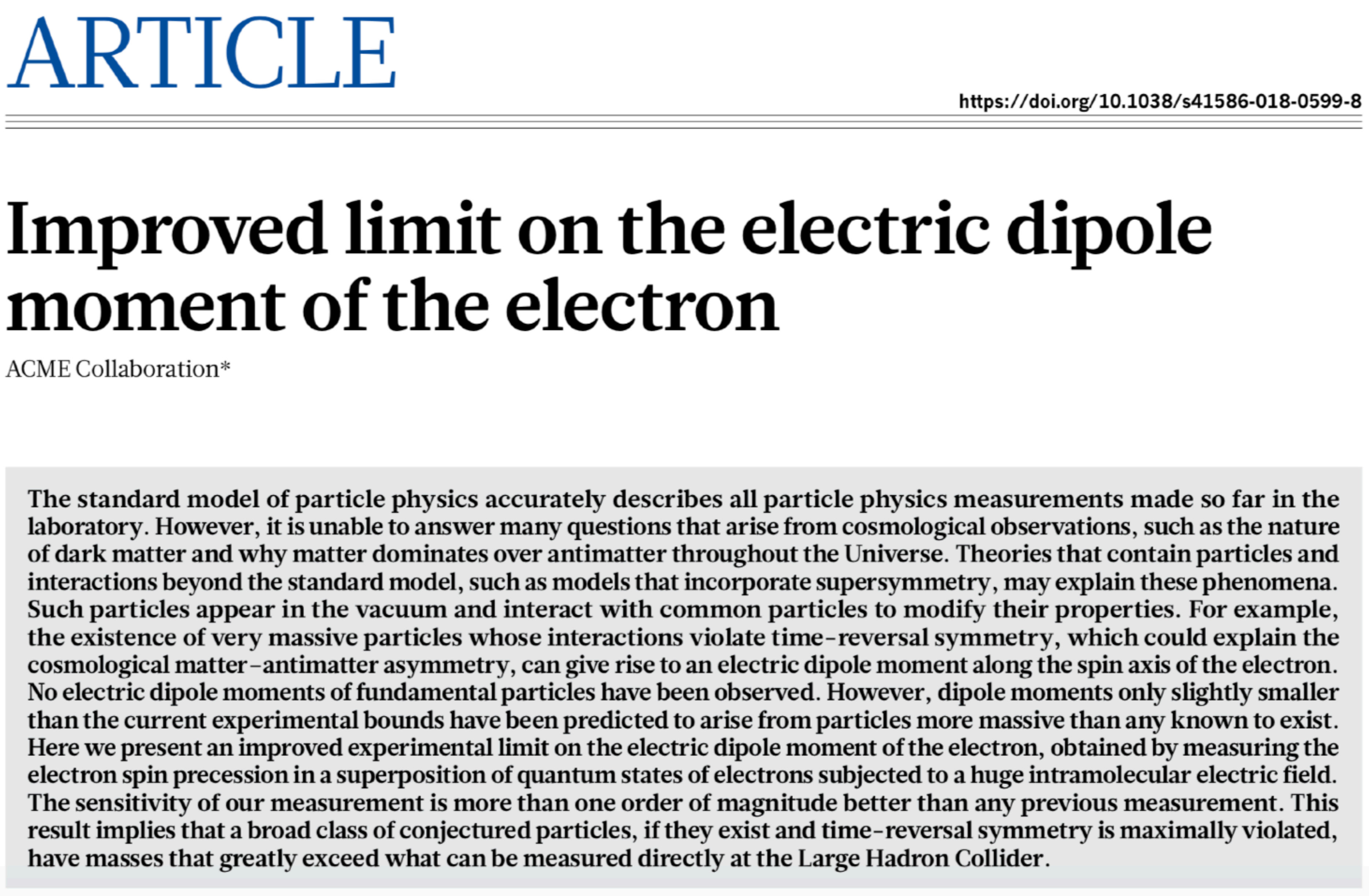
Sensitivity of electron EDM to new physics

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

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

SM value

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



ARTICLE

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Improved limit on the electric dipole moment of the electron

ACME Collaboration*

The standard model of particle physics accurately describes all particle physics measurements made so far in the laboratory. However, it is unable to answer many questions that arise from cosmological observations, such as the nature of dark matter and why matter dominates over antimatter throughout the Universe. Theories that contain particles and interactions beyond the standard model, such as models that incorporate supersymmetry, may explain these phenomena. Such particles appear in the vacuum and interact with common particles to modify their properties. For example, the existence of very massive particles whose interactions violate time-reversal symmetry, which could explain the cosmological matter–antimatter asymmetry, can give rise to an electric dipole moment along the spin axis of the electron. No electric dipole moments of fundamental particles have been observed. However, dipole moments only slightly smaller than the current experimental bounds have been predicted to arise from particles more massive than any known to exist. Here we present an improved experimental limit on the electric dipole moment of the electron, obtained by measuring the electron spin precession in a superposition of quantum states of electrons subjected to a huge intramolecular electric field. The sensitivity of our measurement is more than one order of magnitude better than any previous measurement. This result implies that a broad class of conjectured particles, if they exist and time-reversal symmetry is maximally violated, have masses that greatly exceed what can be measured directly at the Large Hadron Collider.

Sensitivity of electron EDM to new physics

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

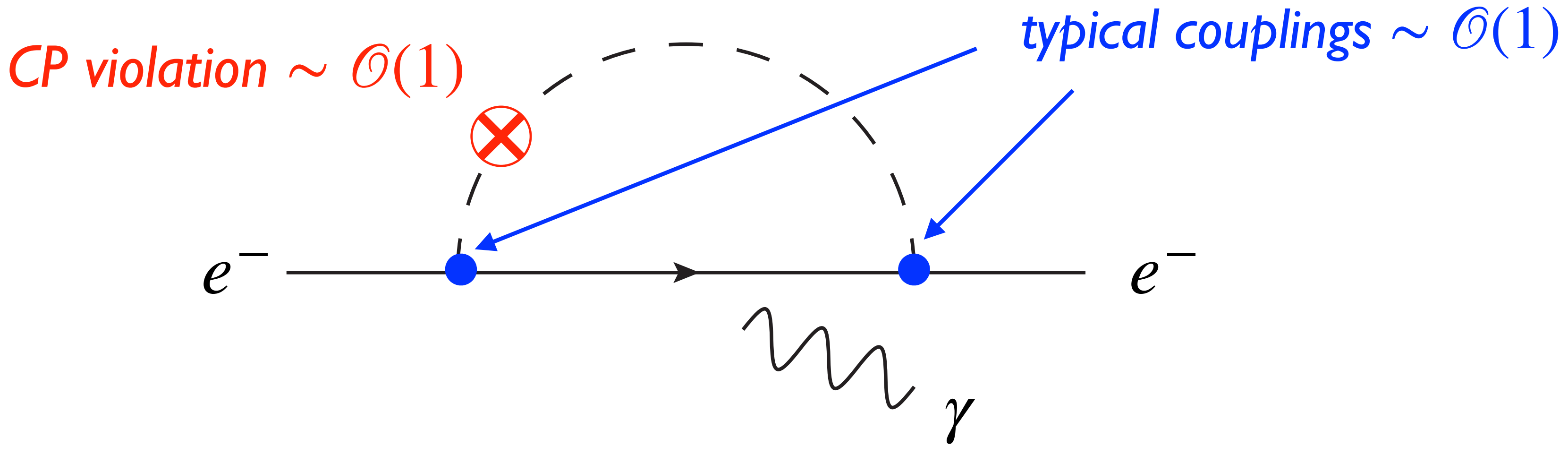
(ACME collaboration, V. Andreev et al., 2018)

SM value

$$d_e \sim 10^{-38}\, e\mathrm{cm}$$

How good is this measurement ?

$$d_e \sim \frac{e}{16\pi^2}\frac{m_e}{M_{UV}^2} \sim 10^{-29}\, e\mathrm{cm} \left(\frac{m_e}{511\,\mathrm{keV}}\right)\left(\frac{70\,\mathrm{TeV}}{M_{UV}}\right)^2$$



⇒ sensitive up to ~70TeV scale new physics

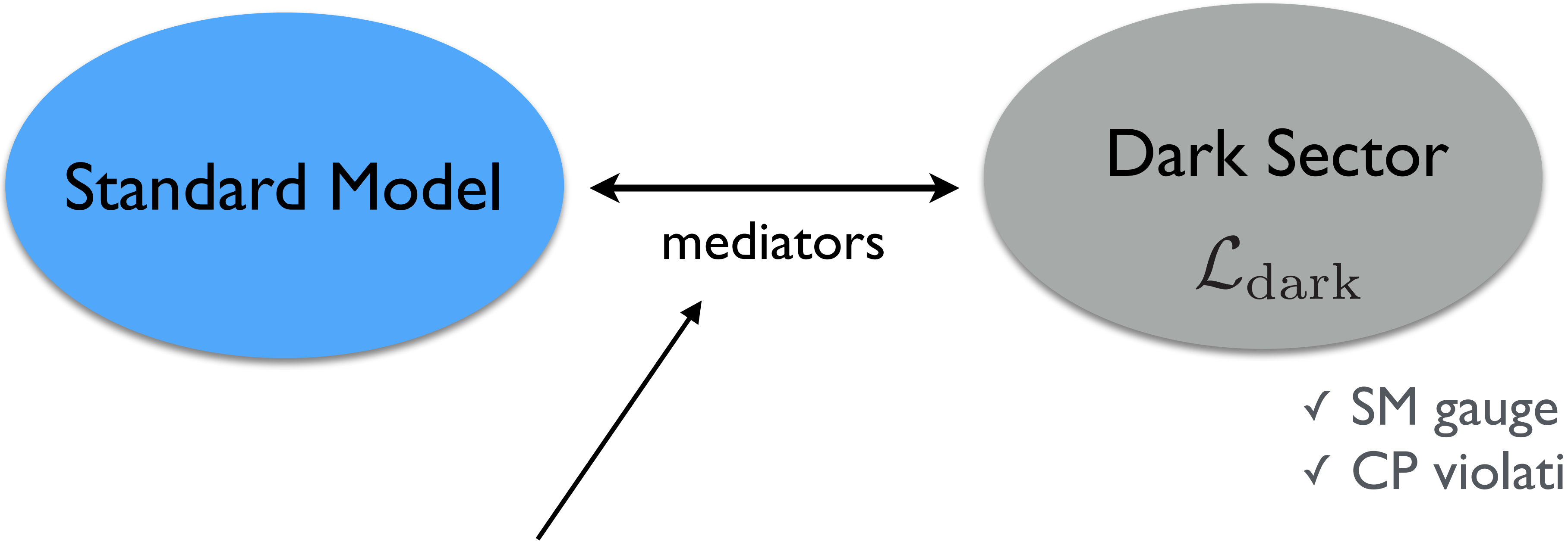
Electron EDM as a probe of dark sectors

- If a nonzero electron EDM is observed near future, it would point to the existence of new physics below ~100TeV
- but is that new physics surely charged under the SM gauge groups?
- In this work, we examine if a large electron EDM can be induced from SM gauge singlet new physics

= Dark Sectors

Dark sector with renormalizable portals

$$\mathcal{L}_{\text{NP}} = \mathcal{L}_{\text{portal}} + \mathcal{L}_{\text{dark}}$$



- ✓ SM gauge singlet fields
- ✓ CP violation

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

Kinetic mixing — Higgs portal — Neutrino portal

F' : dark photon

S : singlet scalar

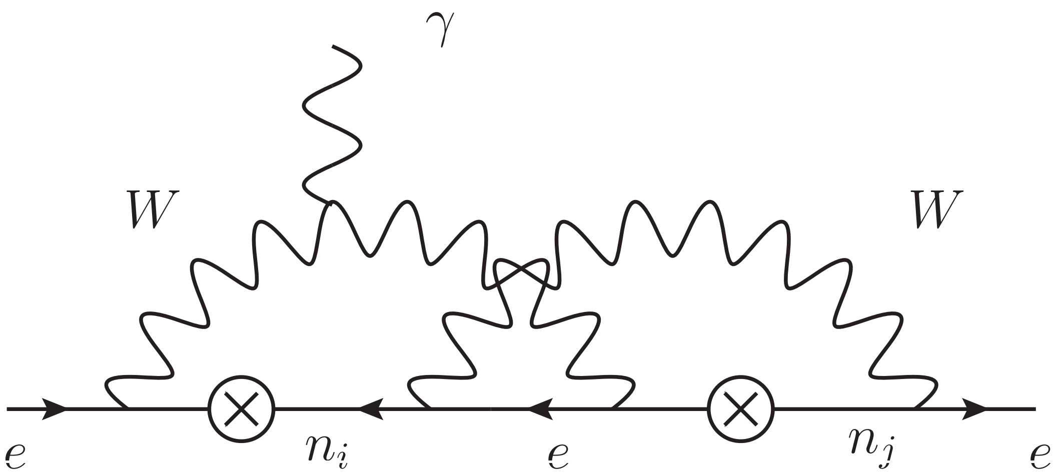
N : heavy neutral lepton

Electron EDM from dark sectors

- **Neutrino portal** Archambault, Czarnecki, Pospelov (2004); Ng, Ng (1995)

$$\mathscr{L}_{\rm NP} = -Y_N \bar{L} H N - M_N \overline{N^c} N$$

$$\Rightarrow \boxed{d_e \lesssim 10^{-33}\, e\cdot\mathrm{cm}}$$



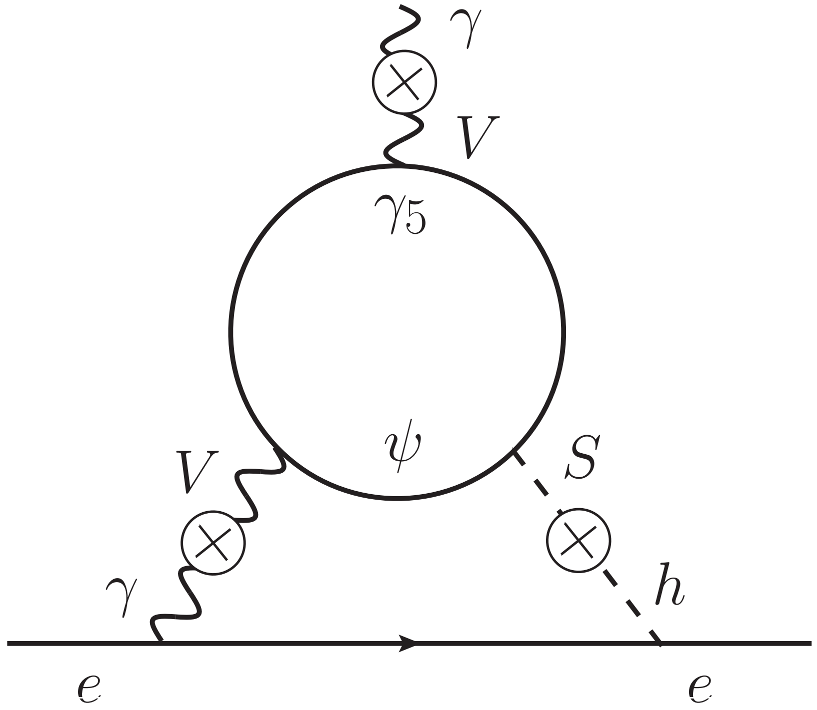
- **Vector and scalar portal** Le Dall, Pospelov, Ritz (2015)

$$\mathscr{L}_{\rm NP} = \epsilon B^{\mu\nu} F'_{\mu\nu} - AS|H|^2 - Y_S S \bar{\psi} i \gamma_5 \psi \quad (\psi : \text{dark fermion})$$

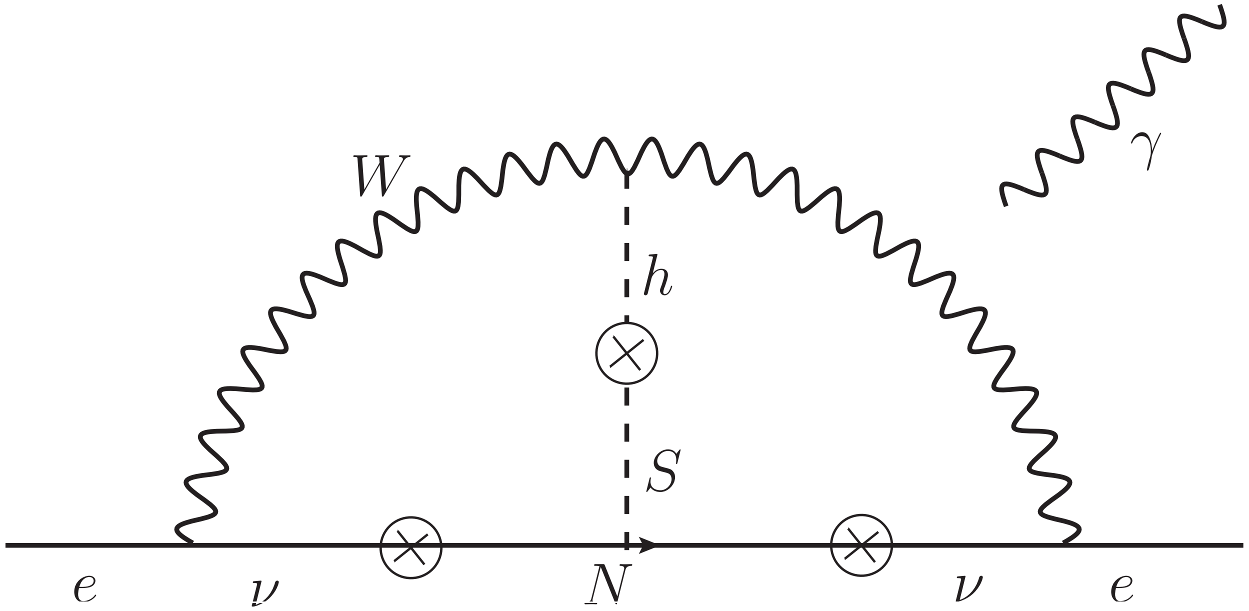
  - electron EDM induced via "dark EDM"

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

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



new!



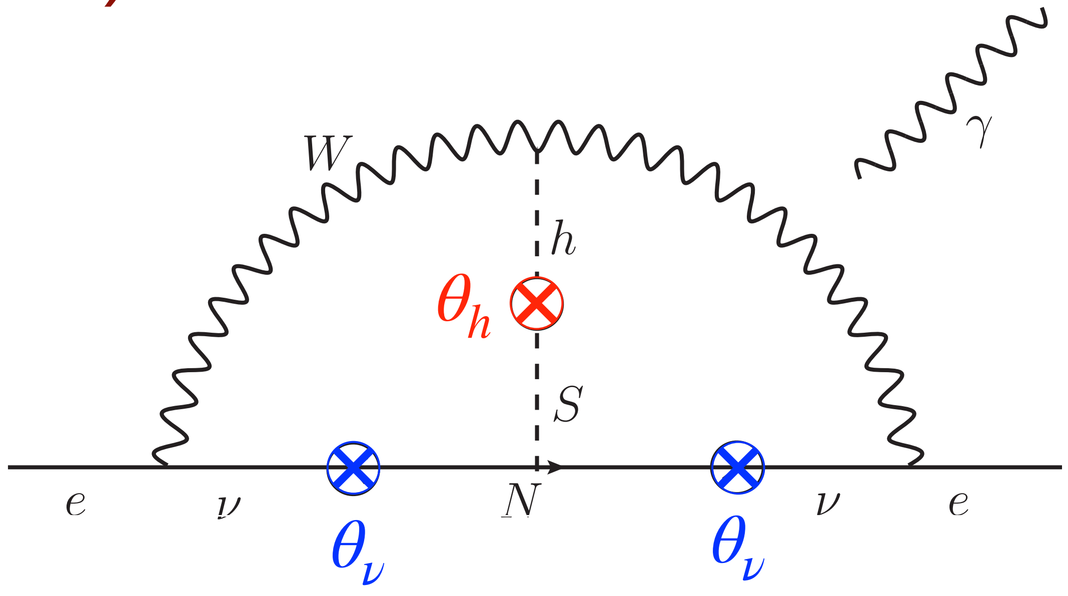
$$-\mathcal{L}_{\rm NP} = ASH^\dagger H + Y_N \overline{L} H N + \lambda_N S \overline{N} i\gamma_5 N$$

[**SO**, Pospelov and Ritz, 1905.05219]

New contribution (singlet portal)

$$-\mathcal{L}_{\rm NP} = ASH^\dagger H + Y_N \overline{L} H N + \lambda_N S \overline{N} i\gamma_5 N + m_N \overline{N} N$$

CP violating



- Consider Dirac neutrino
  - no seesaw relation
  - sizable neutrino mixing is allowed

$$\theta_\nu \simeq \frac{Y_N v}{m_N} \ : \text{neutrino mixing}$$

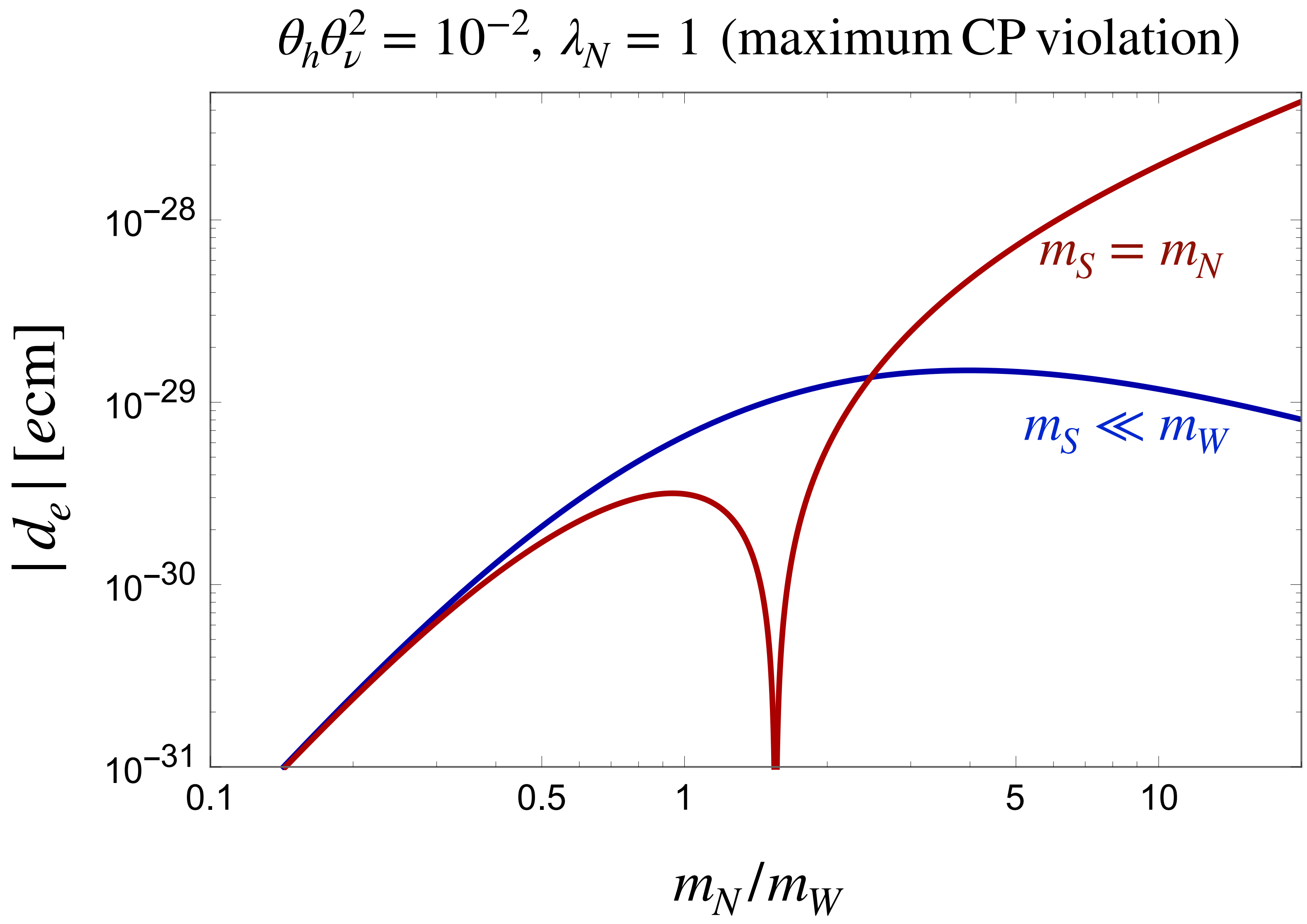
$$\theta_h \simeq \frac{Av}{m_S^2 - m_h^2} \ : \ \text{Higgs} - \text{singlet mixing}$$

- Naive estimate

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

close to the current sensitivity

Size of the induced electron EDM



$$A S H^\dagger H \simeq \frac{\theta_h (m_S^2 - m_h^2)}{v} S H^\dagger H$$

$$Y_N \bar{L} H N \simeq \frac{\theta_\nu m_N}{v} \bar{L} H N$$

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

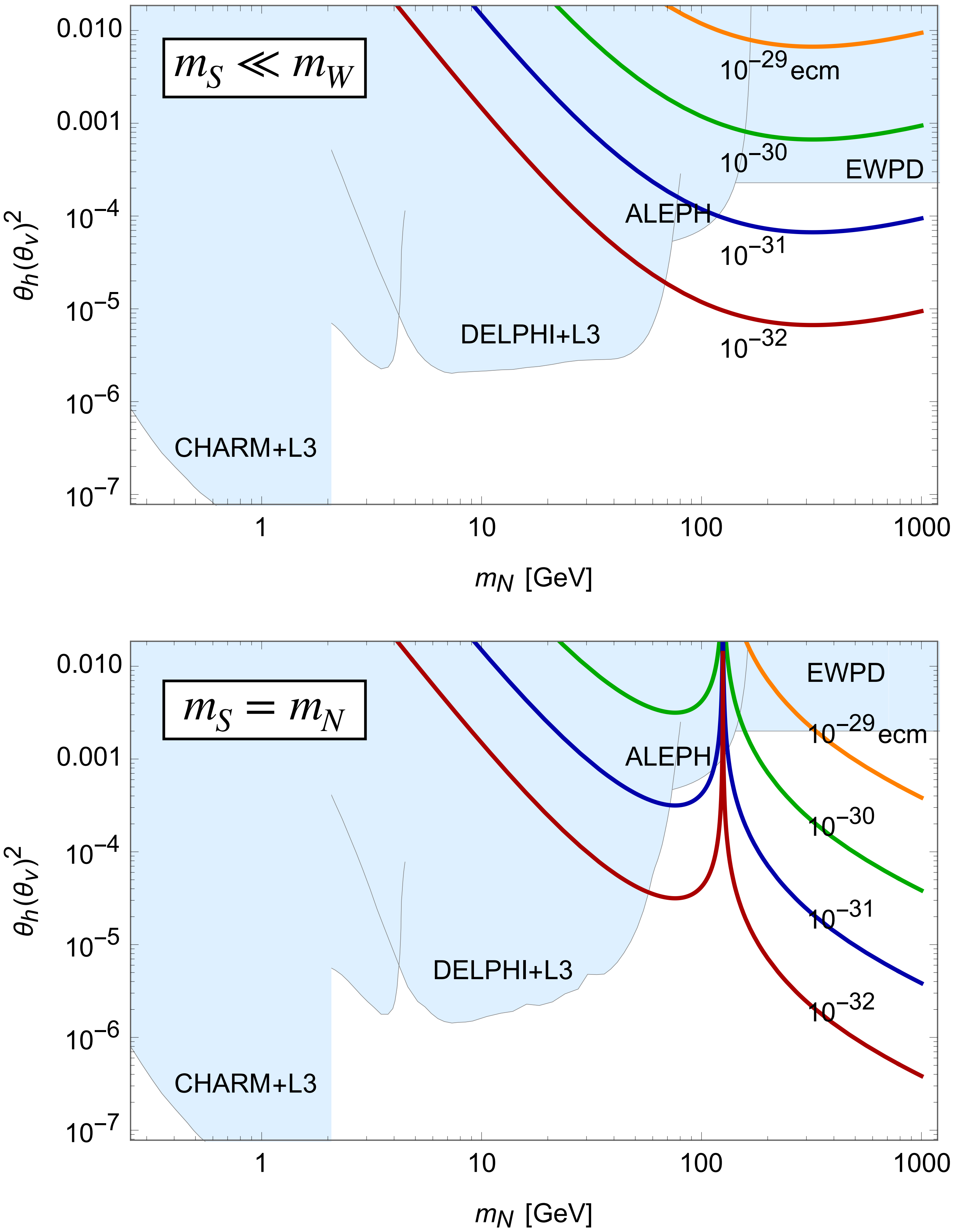
(ACME collaboration, V. Andreev et al., 2018)

- mild or non-decoupling behavior as $m_N \to \infty$
- significant suppressions for $m_N \ll m_W$ in both cases
- resonant behavior at $m_S = m_h$ for a massive scalar

Sensitivity plots

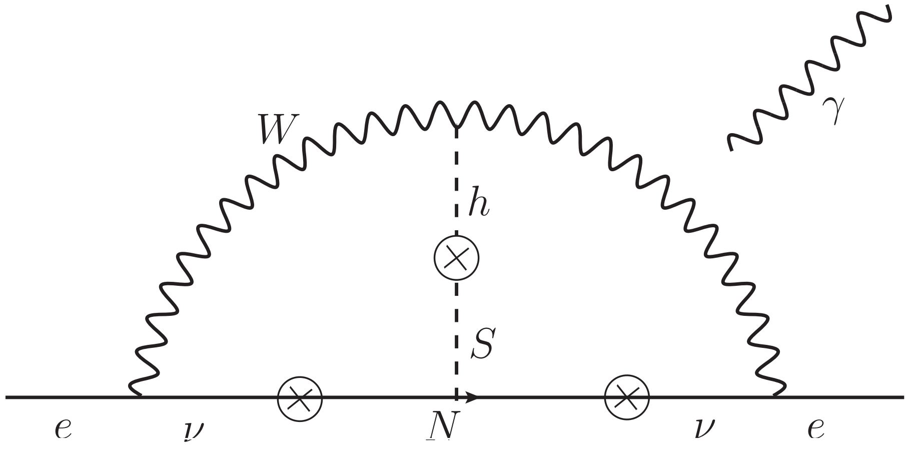
- maximum CP violation assumed
- $d_e \leq 1.1 \times 10^{-29}\, e\mathrm{cm}$ (ACME)
- limit on neutrino mixing
  - CHARM: N from D meson decay
  - DELPHI: $Z \to N\nu$
  - ALEPH: $e^+e^- \to N\nu \to 2\ell 2\nu$
  - Electroweak precision data
- limit on scalar mixing
  - L3: $e^+e^- \to Z^*S$

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



Summary and Conclusion

- examine electron EDMs induced from dark sectors
  - several mediation channels
  - @ 2-loop level or more
  - largest contribution = ***singlet portal***



- singlet portal contribution
  - a combined mediation by a heavy neutrino and a singlet scalar
  - never considered so far
  - a 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

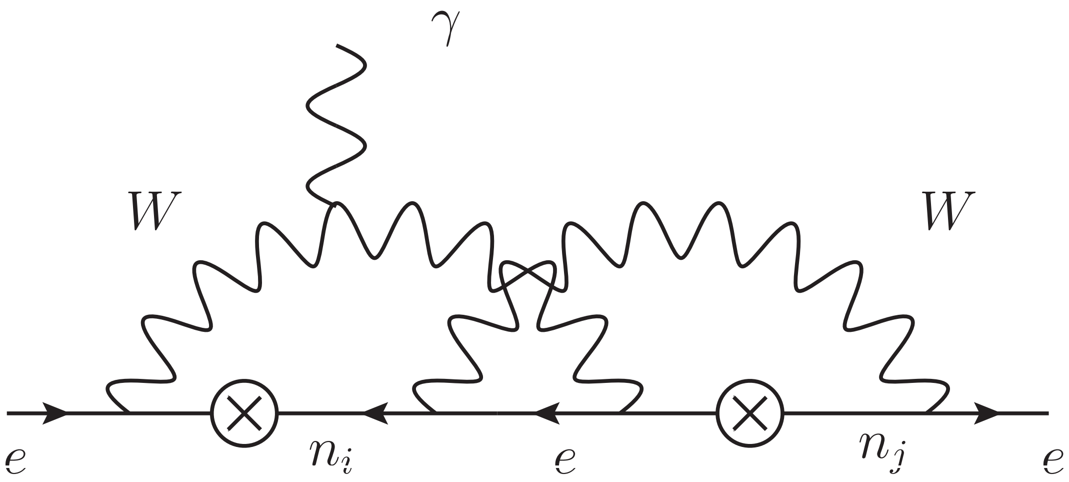
EDM via neutrino portal

- 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)

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



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

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

$$d_e \sim 10^{-33}\, e \cdot \mathrm{cm}$$

Dark Barr-Zee mechanism (vector&scalar portal)

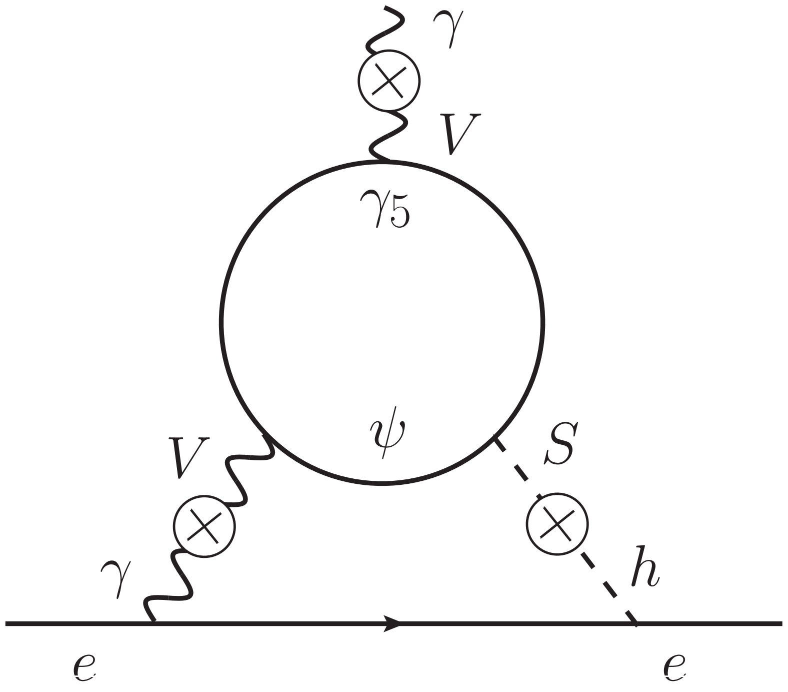
$$\mathcal{L}_{IR} = \epsilon B^{\mu\nu} F'_{\mu\nu} - ASH^\dagger H - Y_S\, S\bar{\psi} i\gamma_5\psi$$

[Le Dall, Pospelov and Ritz, 1505.01865]

- "dark EDM" operator

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

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



- EDM "radius"

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

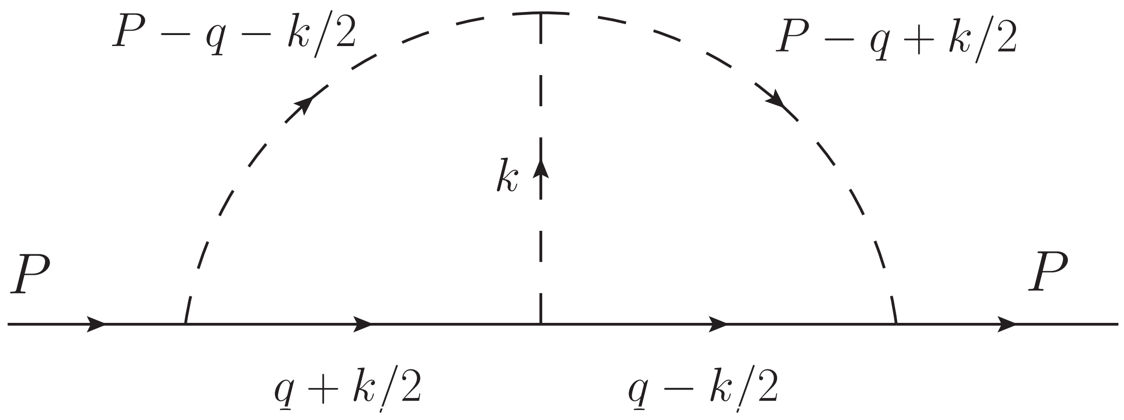
$$r_d^2 \simeq \frac{|e|\alpha' Y_S}{16\pi^3 v m_\psi m^2_{A'}} \times \epsilon^2\theta_h \ln(m_\psi^2/m_S^2)$$

($m_{A'} \ll m_S \ll m_\psi$)

- the effective EDM radius translates to eEDM by
  1. identifying the corresponding scale with a K-shell radius: $\Box \to (Z\alpha m_e)^2$
  2. $m_{A'} \gtrsim (Z\alpha m_e),\ q_\psi = 1,\ \alpha' = \alpha$ and $Y_S = 1$

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

Calculation procedure



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

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

3. 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

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

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

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