Electric dipole moments and Higgs funnel annihilating dark matter in CPV MSSM

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and its update

§ Charge Parity (CP) Symmetry

A symmetry between particle and anti-particle

Left-handed electron

C

Left-handed positron

P

Right-handed positron

§ § Electric dipole moment (EDM)

- EDM: vector, bias of charge (q)
- Only proper vector = The spin ***s***
- EDM:
  - $\boldsymbol{d} = q\,\boldsymbol{s} \underset{C}{\longrightarrow} (-q)\,\boldsymbol{s} \underset{P}{\longrightarrow} (-q)(-\boldsymbol{s}) = q\,\boldsymbol{s}$ if CP is not violated
  - $H_{EDM} = -d\,\left({}^{\boldsymbol{s}}/_{|\boldsymbol{s}|}\right)\cdot\boldsymbol{E}$
- **Why do we measure EDM?**
  - Direct measurement of CP violation
  - Search for **new sources** of CP violation
    - **SUSY, BSM**

Discovery of CP Violation

CP violation in Kaon system

- $K_L^0 \rightarrow \pi^+\pi^-$ is forbidden unless CP is violated.
- This decay was discovered indeed. [Christenson, Cronin, Fitch and Turlay (1964)].
- K^0 - $\overline{K^0}$ mixing

- Difference between B^0 decay and $\overline{B^0}$ decay was also discovered [Belle (2001), Babar (2001)] .

§ § Electric dipole moment

- Relevant terms in the effective Lagrangian

$$\mathcal{L} \supset -d_f \frac{i}{2} \bar{f} \sigma^{\mu\nu} \gamma_5 f F_{\mu\nu} - g_s d_q^C \frac{i}{2} \bar{q} \sigma^{\mu\nu} \gamma_5 q G_{\mu\nu} - \omega \frac{1}{6} f^{abc} G^a_{\mu\nu} G^{b\nu}{}_{\rho} G^c_{\alpha\beta} \epsilon^{\rho\mu\alpha\beta},$$

  - EDM of fermion: d_f
  - chromo EDM (cEDM): $d_q{}^C$
  - Wilson coefficient of Weinberg operator: ω
    - Always negligible for our studies

§ § Electric dipole moment

- Energy evolution

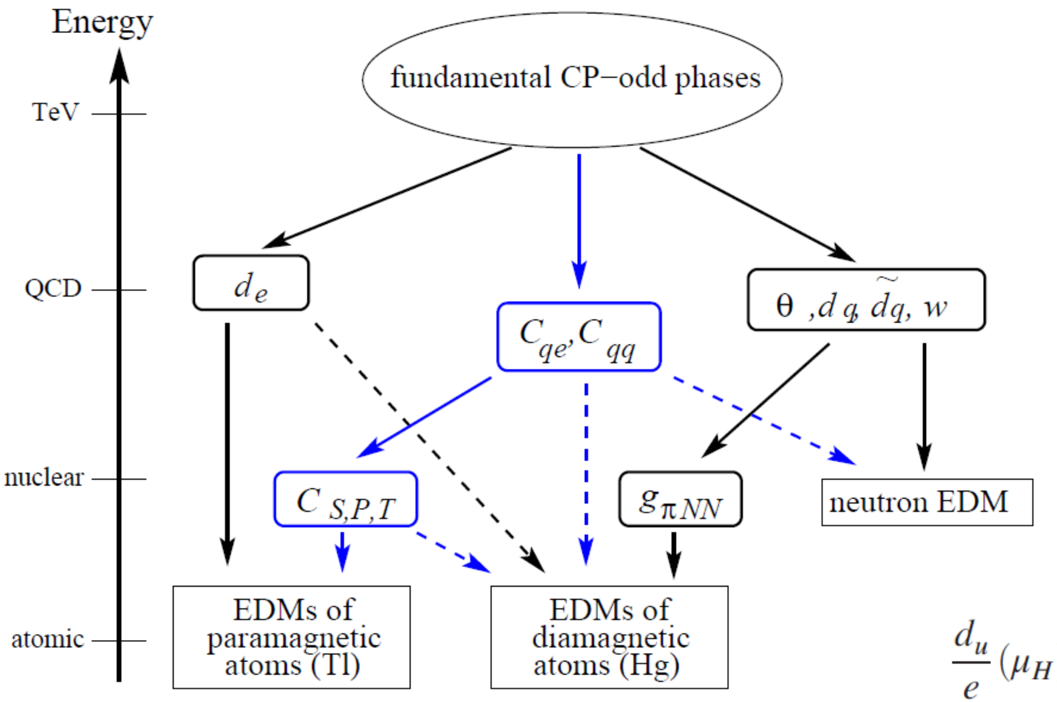


Fig from [Pospelov and Ritz (2005)]

Example

$$\frac{d_u}{e}(\mu_H) = 0.35\frac{d_u}{e}(\mu_W) - 0.17 g_s(\mu_W) d_u^C(\mu_W) - (9.24874 \times 10^{-5}\ \mathrm{GeV})\omega(\mu_W), \qquad (3.2)$$

$$d_u^C(\mu_H) = 0.34 g_s(\mu_W) d_u^C(\mu_W) + (0.00031\ \mathrm{GeV})\omega(\mu_W), \qquad (3.3)$$

Old view of EDM in SUSY

1. New sources of flavor mixing and/or CP violation
   - SUSY CP problem

$$\frac{d_n}{e} \sim \left(\frac{300\ \mathrm{GeV}}{M_{\mathrm{SUSY}}}\right)^2 \sin\phi\, 10^{-24}\ \mathrm{cm} \quad < 10^{-26}\ \mathrm{cm\ (by\ exp.)}$$

§ SUSY dark matter

MSSM with R-parity conservation

⇒ stable DM candidate

1. Neutralino
   Neutral gaugino + neutral Higgsino
2. LH Sneutrino
   Excluded
3. Others (in beyond the MSSM):
   RH sneutrino, Gravitino, Axino, …

Neutralino dark matter

Bino-like neutralino interacts too weakly

⇒ tends to be overabundant

Wayout

1. Higgsino-like, or Wino-like [Nagata and Shirai (2015)]

   SU(2) interaction

2. Co-annihilation with NLSP little phase allowed

   Stau, Stop, …

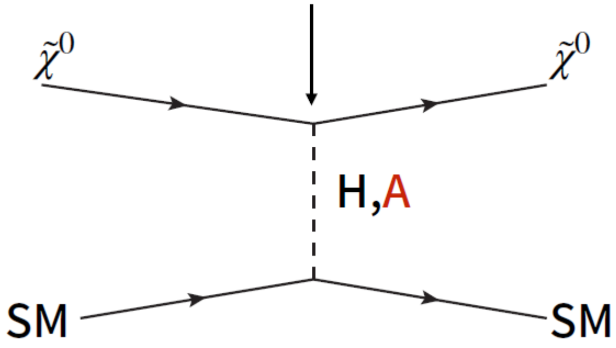
3. Rapid annihilation through resonances ←

   Heavy Higgs bosons (H, A)

We study this case!

§ MSSM with CPV

- CP phases affect
  - EDMs
    - electron, mercury, neutron
  - spin-independent cross section
    - Pseudo scalar coupling is strongly suppressed in non-relativistic limit



- CP phases hardly affect
  - Neutralino Annihilation cross section

§ § CP phases in MSSM

- Soft SUSY breaking terms

$$
\begin{aligned}
\mathcal{L}_{\text{soft}} = & -\frac{M_1}{2}\tilde{B}\tilde{B} - \frac{M_2}{2}\tilde{W}^\alpha\tilde{W}^\alpha - \frac{M_3}{2}\tilde{G}^A\tilde{G}^A \\
& - m_{H_1}^2 H_{1a}^* H_1^a + m_{H_2}^2 H_{2a}^* H_2^a - \tilde{q}_{iLa}^* (M_{\tilde{q}}^2)_{ij} \tilde{q}_{jL}^a - \tilde{\ell}_{iLa}^* (M_{\tilde{\ell}}^2)_{ij} \tilde{\ell}_{jL}^a \\
& - \tilde{u}_{iR} (M_{\tilde{u}}^2)_{ij} \tilde{u}_{jR}^* - \tilde{d}_{iR} (M_{\tilde{d}}^2)_{ij} \tilde{d}_{jR}^* - \tilde{e}_{iR} (M_{\tilde{e}}^2)_{ij} \tilde{e}_{jR}^* \\
& - \epsilon_{ab}\left[(T_e)_{ij} H_1^a \tilde{\ell}_{iL}^b \tilde{e}_{jR} + (T_d)_{ij} H_1^a \tilde{q}_{iL}^b \tilde{d}_{jR} + (T_u)_{ij} H_2^a \tilde{q}_{iL}^b \tilde{u}_{jR} + m_3^2 H_1^a H_2^b + \text{h.c.}\right]
\end{aligned}
$$

  - Trilinear $(T_u)_{33} = A_\tau y_t$, $(T_d)_{33} = A_\tau y_b$, and $(T_e)_{33} = A_\tau y_\tau$

- Phases can be rotated out and physical quantities can be described by

$$
\arg(M_i M_j^*)\ , \quad \arg(M_i A_t^*)\ , \quad \arg(\mu M_i)\ , \quad \arg(\mu A_t)\ , \quad (i, j = 1, 2, 3)
$$

§ § Benchmark scenarios

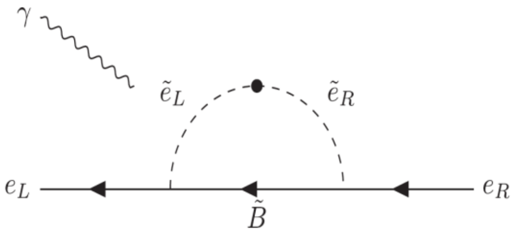
- Favor mixings in sfermion are ignored
- Fixed parameters
  - $m_{H^\pm} = 2\,M_1$ (~resonance)
  - $M_{\tilde{Q}_3} = M_{\tilde{t}} = 7$ TeV
  - $A_t = 10$ TeV
  - $\phi_{A_t} = 0$ (for simplicity)
  - $\tan\beta = 30$
  - $|M_3| = 10$ TeV
  - $\phi_{M_3} = 0$ (unphysical phase fixing)
  - $M_{\text{other sfermions}} = 100$ TeV
  - Other A-terms $= 0$

$m_h = 125$ GeV

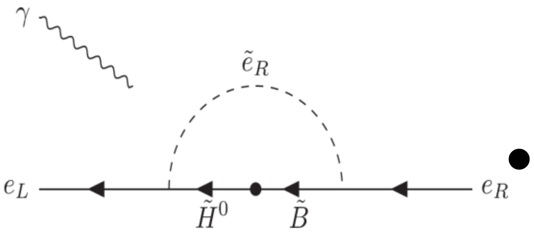
- Input parameters
  - M_1 ($\cong m_{DM}$)
  - ϕ_μ
  - ϕ_{M_1}
  - ϕ_{M_2}
  - $|M_2| \gg |M_1|$
  - $|\mu|$ ($\Omega h^2 = 0.1$)

§ § EDM in MSSM – 1 loop

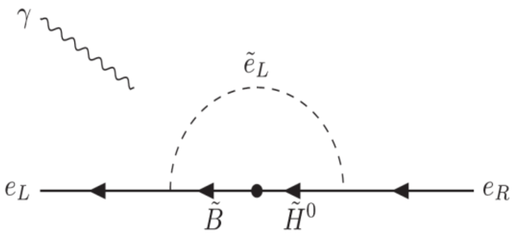
- Quickly decoupled for heavy sfermions



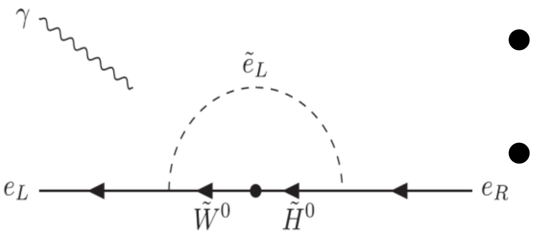
(N1)



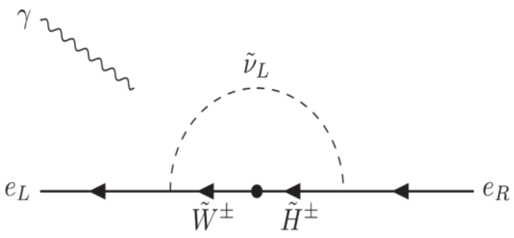
(N2)



(N3)



(N4)



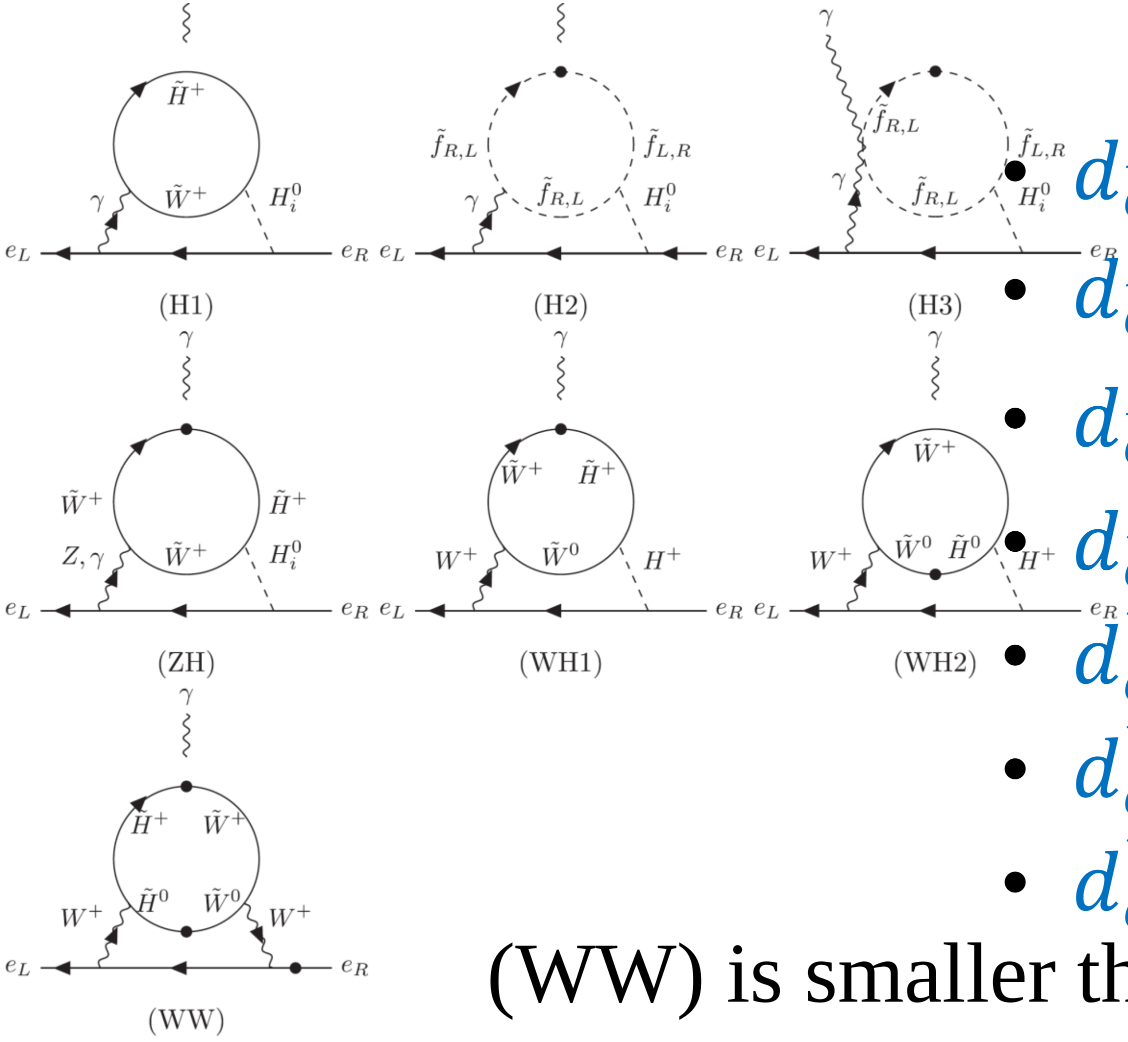
(C)

- $d_e^{N1} \propto \mathrm{Im}(M_{eLR}^2 M_1)$
- $d_e^{N2} \propto \mathrm{Im}(\mu M_1)$
- $d_e^{N3} \propto \mathrm{Im}(\mu M_1)$
- $d_e^{N4} \propto \mathrm{Im}(\mu M_1)$
- $d_e^{C} \propto \mathrm{Im}(\mu M_2)$

$$M_{eLR}^2 = A_e^* m_e - \mu m_e \tan\beta$$

§ § EDM in MSSM – 2 loop

- Dominant for heavy sfermions

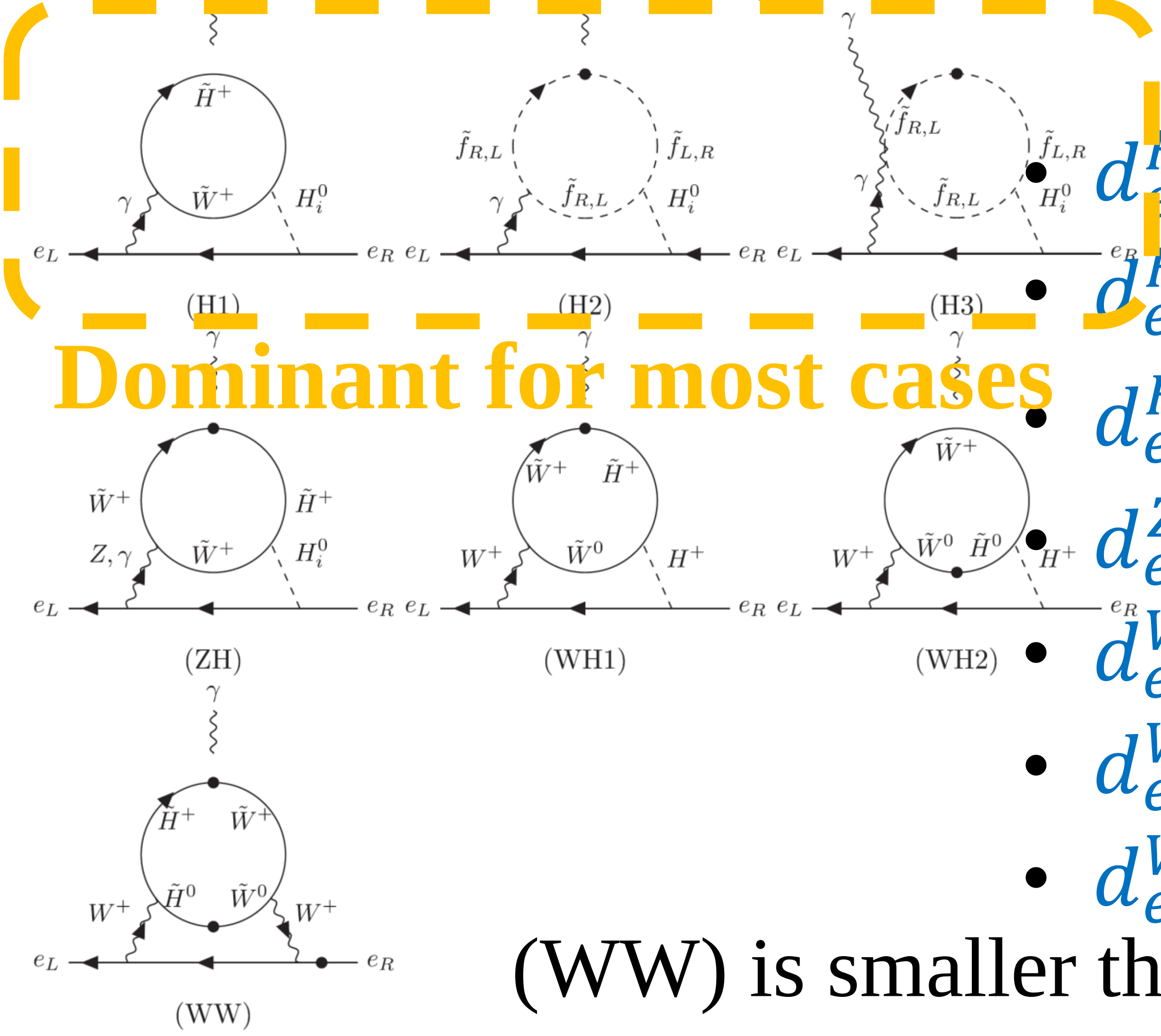


- $d_e^{H1} \propto \mathrm{Im}(\mu M_2)$
- $d_e^{H2} \propto \mathrm{Im}(M_{fLR}^{2*}\mu)$
- $d_e^{H3} \propto \mathrm{Im}(M_{fLR}^{2*}\mu)$
- $d_e^{ZH} \propto \mathrm{Im}(\mu M_2)$
- $d_e^{WH1} \propto \mathrm{Im}(\mu M_2)$
- $d_e^{WH2} \propto \mathrm{Im}(\mu M_2)$
- $d_e^{WW} \propto \mathrm{Im}(\mu M_2)$

(WW) is smaller than the others.

§ § EDM in MSSM – 2 loop

- Dominant for heavy sfermions



Dominant for most cases

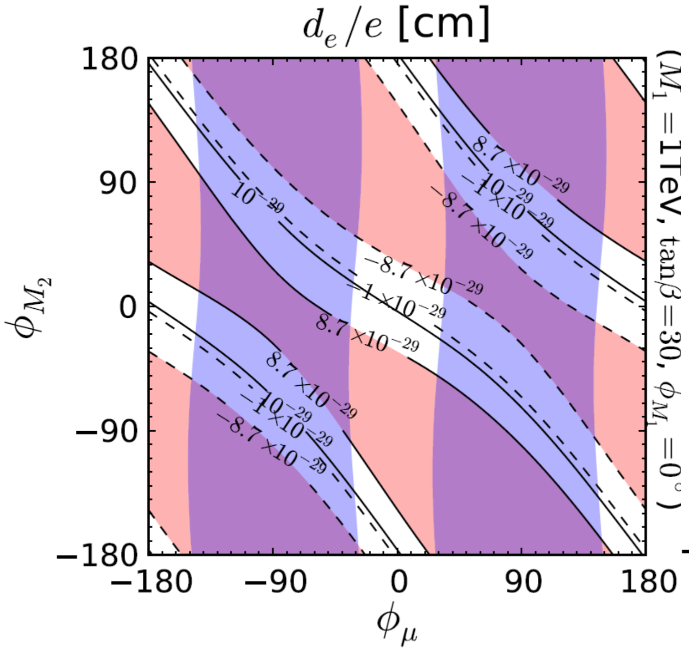
- $d_e^{H1} \propto \mathrm{Im}(\mu M_2)$
- $d_e^{H2} \propto \mathrm{Im}(M_{fLR}^{2*} \mu)$
- $d_e^{H3} \propto \mathrm{Im}(M_{fLR}^{2*} \mu)$
- $d_e^{ZH} \propto \mathrm{Im}(\mu M_2)$
- $d_e^{WH1} \propto \mathrm{Im}(\mu M_2)$
- $d_e^{WH2} \propto \mathrm{Im}(\mu M_2)$
- $d_e^{WW} \propto \mathrm{Im}(\mu M_2)$

(WW) is smaller than the others.

Numerical results : EDM

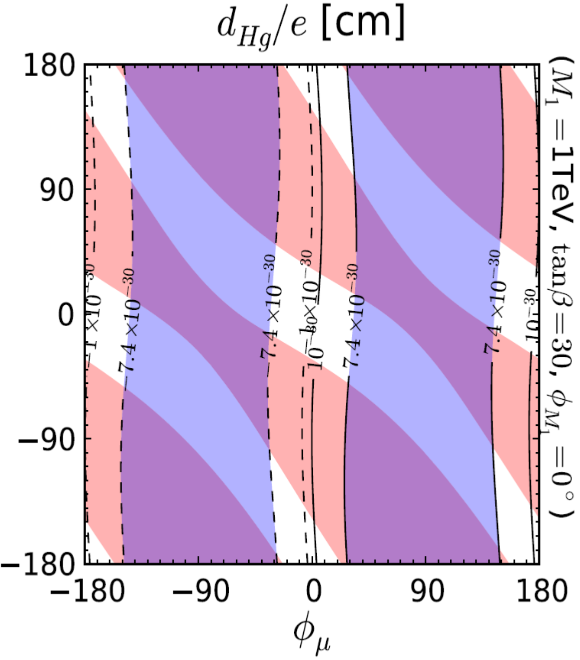
$M_1 = 1\ \mathrm{TeV}, \phi_{M_1} = 0^\circ, M_2 = 10\ \mathrm{TeV}$

electron


d_e/e [cm]

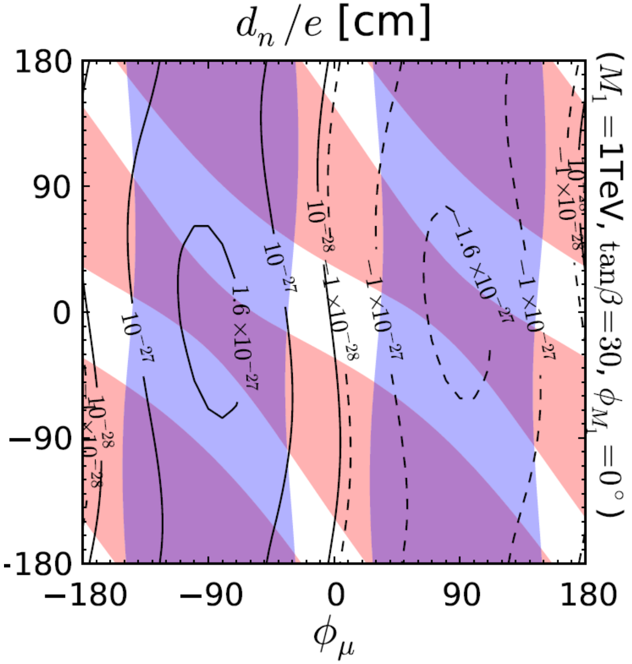
$< 8.7 \times 10^{-29}$

mercury


d_{Hg}/e [cm]

$< 7.4 \times 10^{-30}$

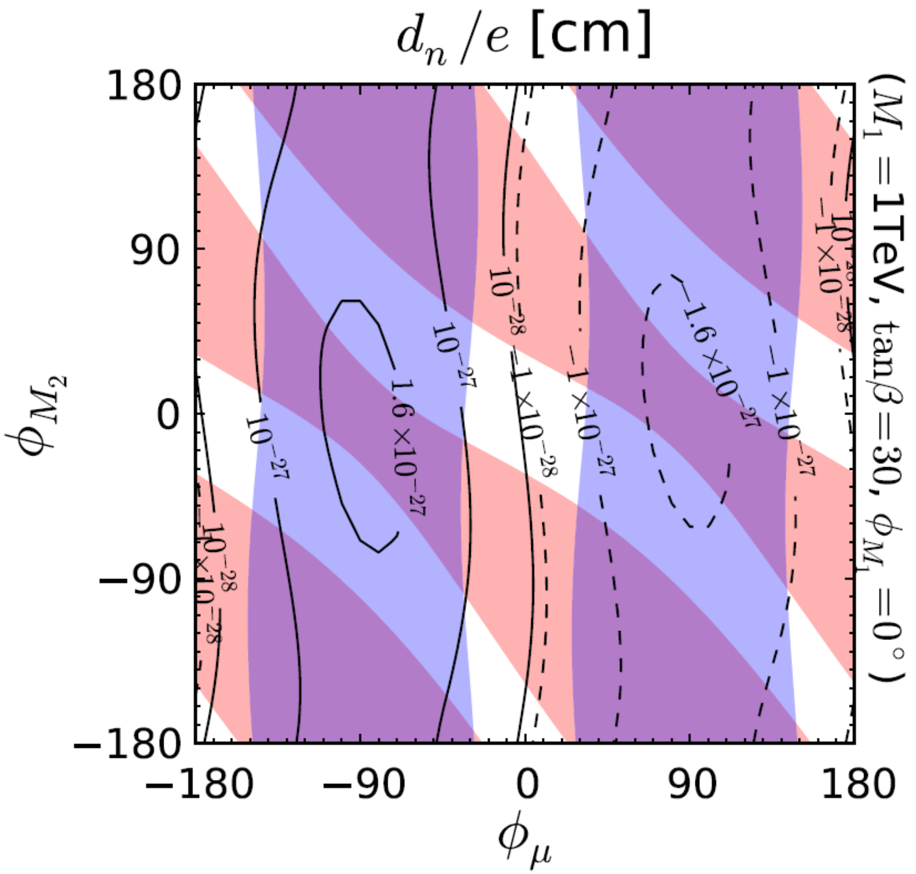
neutron

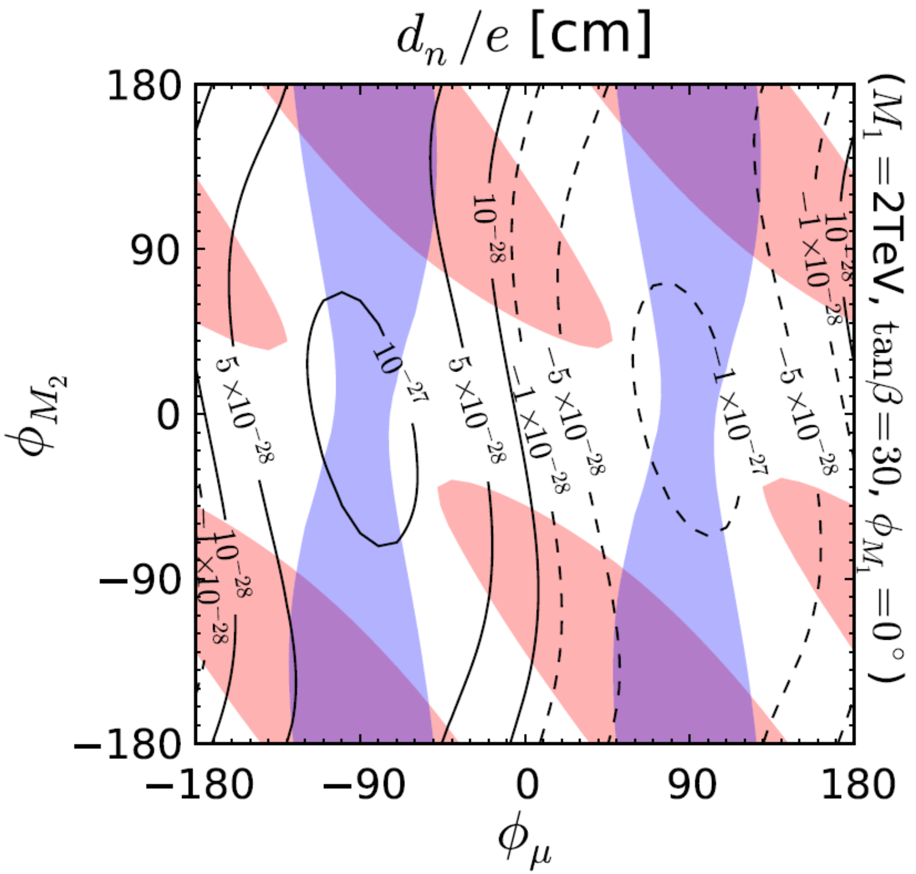

d_n/e [cm]

$< 2.9 \times 10^{-26}$

Numerical results : EDM

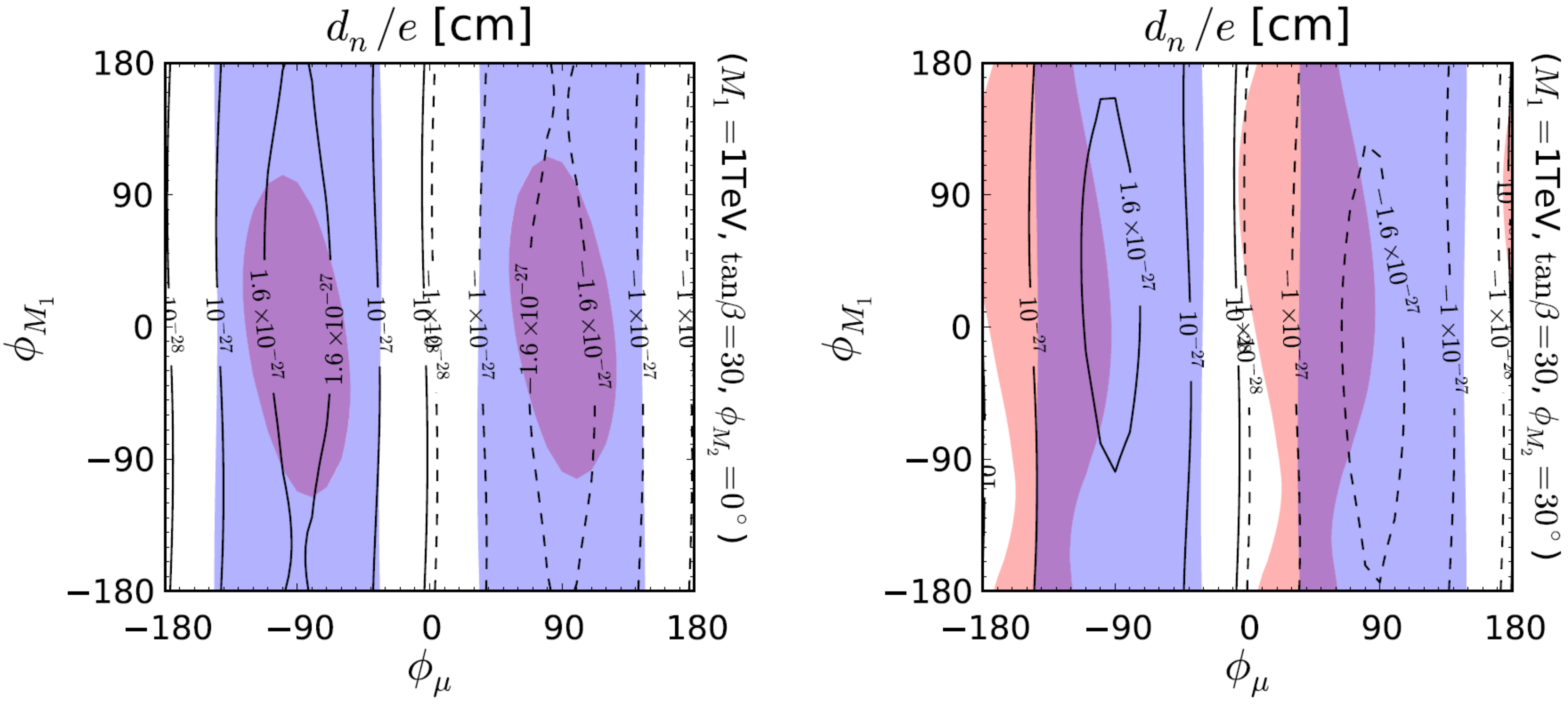
$M_1 = 1\ \text{TeV} \rightarrow 2\ \text{TeV}, \phi_{M_1} = 0^{\circ}, M_2 = 10\ \text{TeV}$





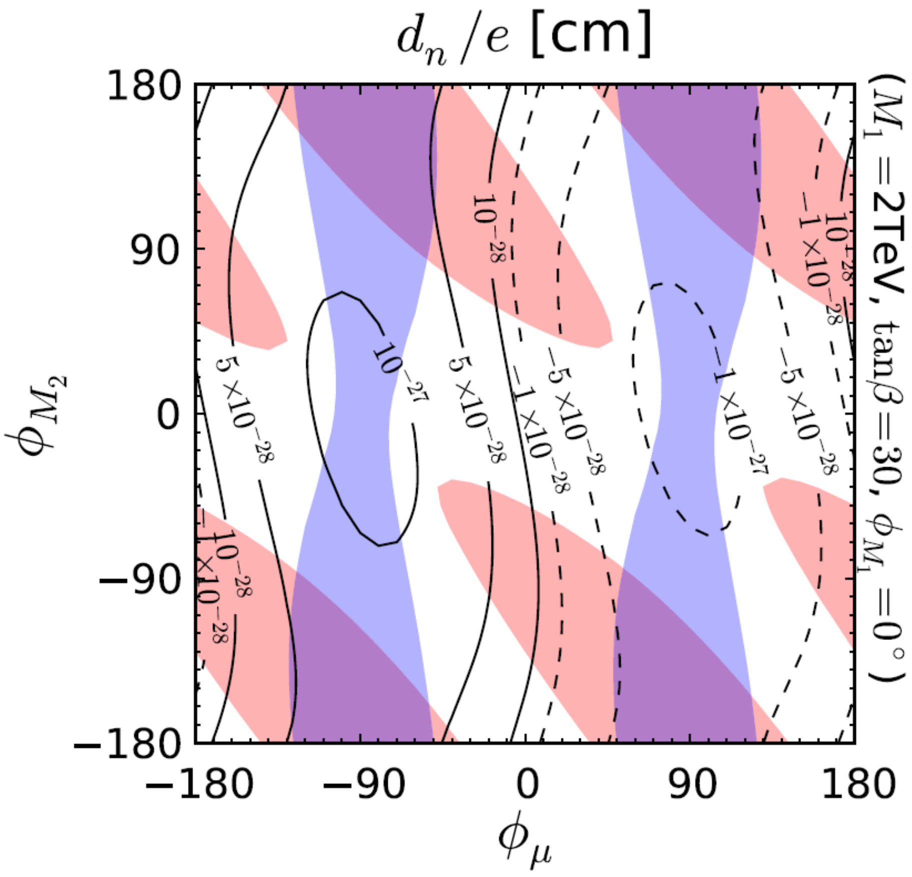
Numerical results : EDM

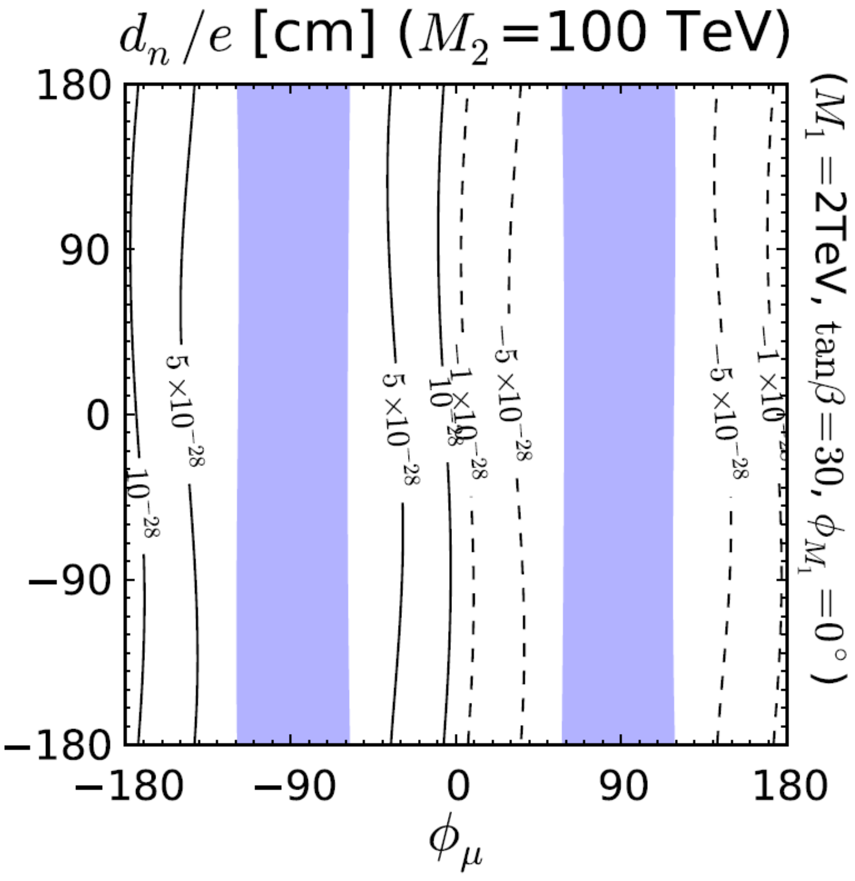
$M_1 = 1\ \text{TeV}, \phi_{M_1} = 0^\circ \rightarrow \phi_{M_2} = \{0^\circ, 30^\circ\}, M_2 = 10\ \text{TeV}$



Numerical results : EDM

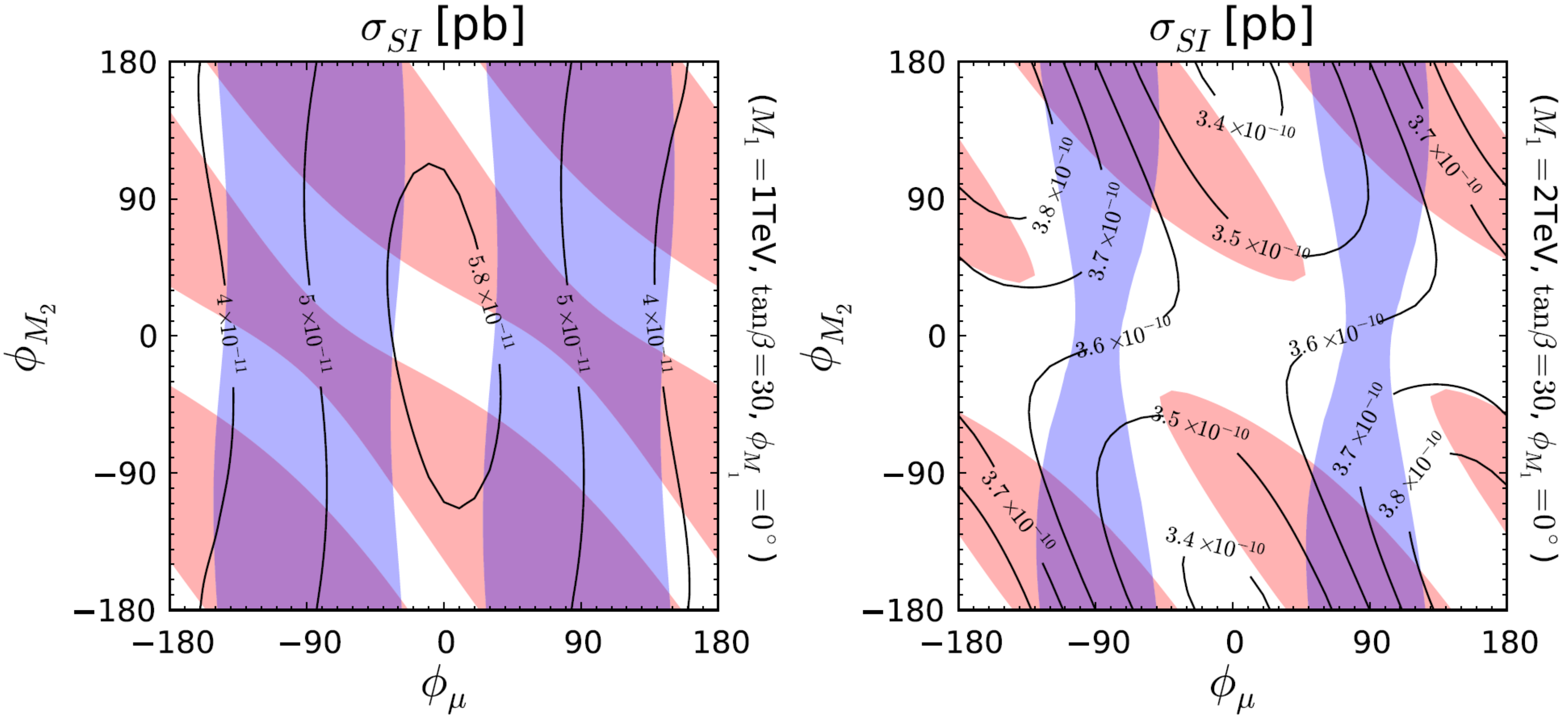
$M_1 = 2\ \mathrm{TeV}, \phi_{M_1} = 0^\circ, M_2 = 10\ \mathrm{TeV} \rightarrow 100\ \mathrm{TeV}$





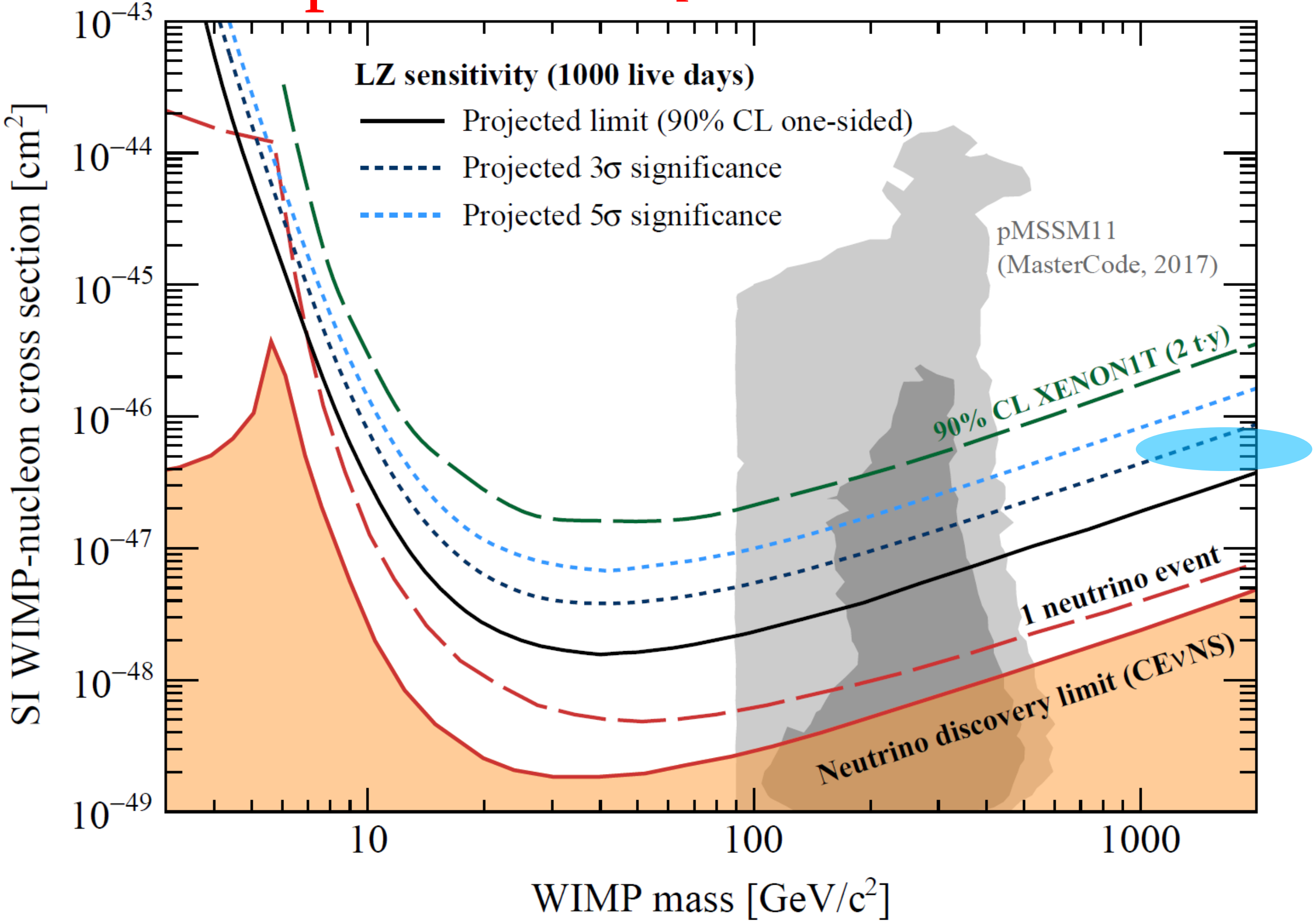
Numerical results : SI cross section

$M_1 = 1\text{TeV} \rightarrow 2\text{ TeV}, \phi_{M_1} = 0^{\circ}, M_2 = 10\text{ TeV}$



SI cross section

The predicted cross section is within the reach of near future experiments. [Akerib et al. arXiv:1802.06039]



§ In light of recent new results

[ACME Collaboration (2018)]

ARTICLE

https://doi.org/10.1038/s41586-018-0599-8

Improved limit on the electric dipole moment of the electron

ACME Collaboration*

Results and conclusions

The result of this second-generation EDM measurement using ThO is $\omega^{\mathcal{N}\mathcal{E}} = -510 \pm 373_{\text{stat}} \pm 310_{\text{syst}}\ \mu\text{rad s}^{-1}$. Using $d_e = -\hbar\omega^{\mathcal{N}\mathcal{E}}/\mathcal{E}_{\text{eff}}$ and[16,17] $\mathcal{E}_{\text{eff}} \approx 78\ \text{GV cm}^{-1}$ results in

$$d_e = (4.3 \pm 3.1_{\text{stat}} \pm 2.6_{\text{syst}}) \times 10^{-30} e\ \text{cm} \tag{4}$$

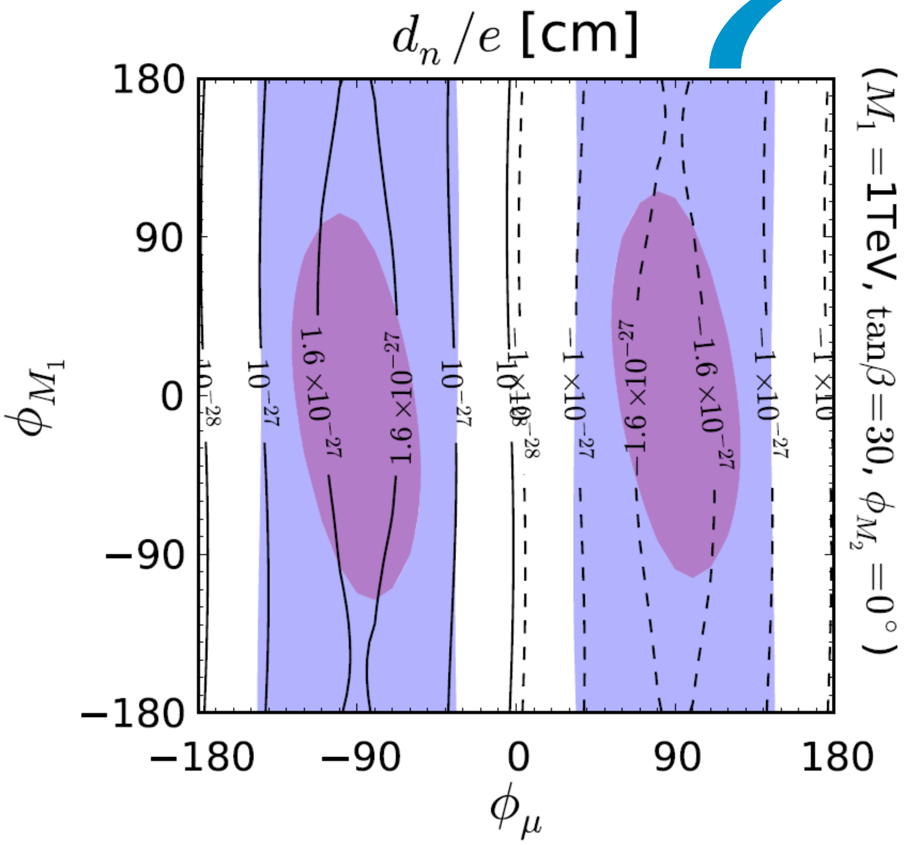
where the combined statistical and systematic uncertainty, $\sigma_{d_e} = 4.0 \times 10^{-30} e\ \text{cm}$, is a factor of 12 smaller than the previous best result, from ACME I[1,9].

An upper limit on $|d_e|$ is computed by applying the Feldman–Cousins prescription[9,33] to a folded normal distribution, which yields

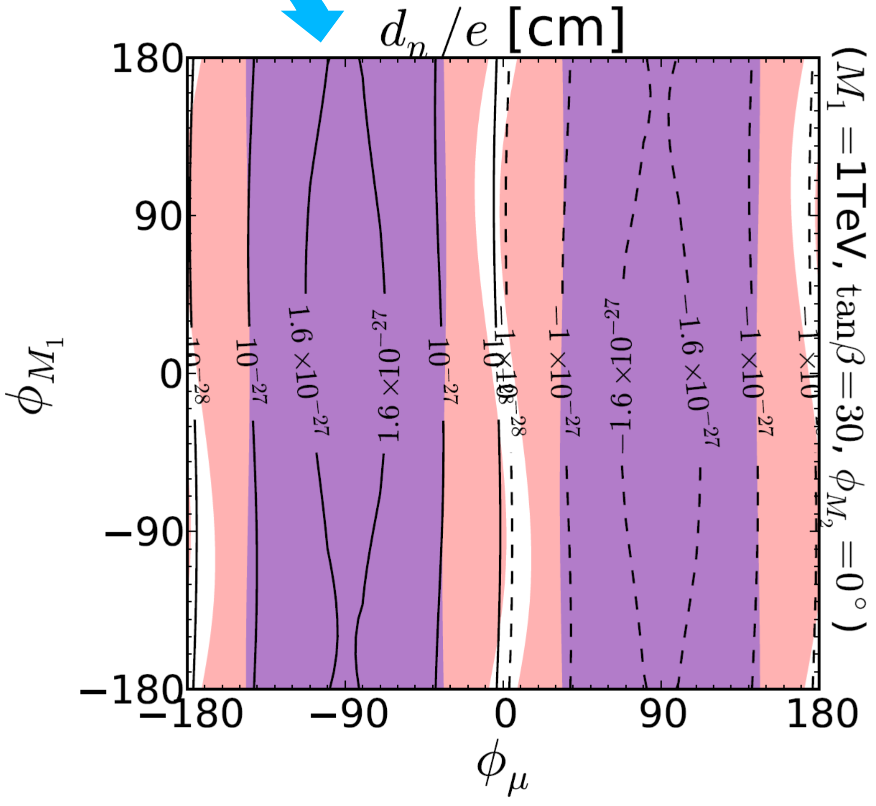
$$|d_e| < 1.1 \times 10^{-29} e\ \text{cm} \tag{5}$$

Before and After

$M_1 = 1\ \mathrm{TeV}, \phi_{M_2} = 0^\circ, M_2 = 10\ \mathrm{TeV}$



$< 8.7 \times 10^{-29}$



$< 1.1 \times 10^{-29}$

§ Summary

- We consider Bino-like Higgs funnel DM in CPV MSSM.

- EDM experiments are powerful tool to explore this scenario
  - “<Several tens degrees” → “< Ten degrees”
- SI cross section weakly depends on CP phases and varies by a factor.