Electric Dipole Moments in supersymmetry

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DESY

Outline :

1. What are EDMs

2. EDMs in SUSY

3. Fundamental sources of $\not{CP}$

4. Prospects

Introduction to EDMs

Interaction H :

$$\boxed{H_{\text{nonrel.}} = -d\,\vec{S}\cdot\vec{E}}$$

$\vec{E}$ = el. field , $\vec{S}$ = spin vector

Measurement :

$$\boxed{\frac{d\vec{S}}{dt} = \vec{\mu}\times\vec{B} + \vec{d}\times\vec{E}}$$

$$\Delta\omega_{\text{Larmor}} \propto |\vec{d}\times\vec{E}|$$

Experimental results:

all negative ...

$d_{Tl} < 9 \times 10^{-25}$ e·cm (90% CL)

$d_{Hg} < 2 \times 10^{-28}$ e·cm (95% CL)

$d_n < 6 \times 10^{-26}$ e·cm (90% CL)

Note:

SM predictions are very small,

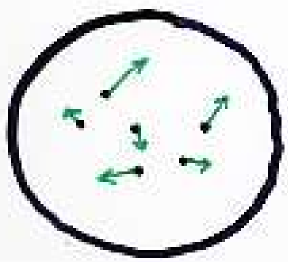
$d_n \sim 10^{-32}$ e·cm

...

EDMs of complex systems

Schiff theorem:

$$d_{system} \overset{\text{nonrel.}}{=} 0$$



$\rightarrow \vec{E}_{net} = 0$,

no net EDM.

However :

does not apply to relativistic / non-point-like particles

E.g. $d_{param.\,atom} / d_e \sim 10\, Z^3 \alpha^2$,

for d_{Tl} the enhancement ~ 585 .

Relativistic EDMs

$$H_{\text{non-rel.}} = -d\,\vec{S}\cdot\vec{E}$$

$$\Downarrow$$

$$\boxed{\mathcal{L}_{\text{rel.}} = -\frac{i}{2}\, d\, \bar{\Psi}\,(F\sigma)\,\gamma_5\,\Psi}$$

$$\begin{cases} F_{\mu\nu} = \text{photon field strength} \\ \Psi = \text{fermion} \end{cases}$$

For composite objects (n, atoms, ...) also relevant

$$\mathcal{L} = \frac{g^2}{32\pi^2}\,\Theta\, G_{\mu\nu}\,\tilde{G}^{\mu\nu} + \frac{w}{3} f^{abc}\, G_a \tilde{G}_b G_c$$

$$- \frac{i}{2}\,\tilde{d}\;\bar{\Psi}\, g\,(G\sigma)\,\gamma_5\,\Psi$$

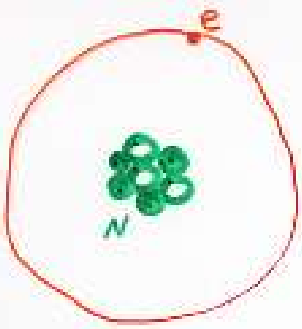
$$+ \sum_{ij} C_{ij}\,(\bar{\Psi}_i \Psi_i)(\bar{\Psi}_j\, i\gamma_5 \Psi_j)\,.$$

$$\begin{cases} G_{\mu\nu} = \text{gluon field strength} \\ \Theta = \text{QCD } \Theta\text{-term} \\ w = \text{Weinberg operator} \\ \tilde{d} = \text{colour EDM} \end{cases}$$

$$\text{EDM} = f(\theta, w, d, \tilde{d}, C_{ij})$$

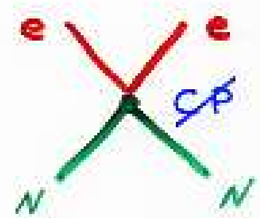
<u>**Example :**</u>

Tl atom



$\mathcal{L} \sim \bar{e}\, i\gamma_5 e\, \bar{N} N$

$\Downarrow$



Deforms the atom $\rightarrow$ EDM

$$d_{Tl} \simeq -585\, d_e - C_S \cdot 43\, e \cdot \text{GeV}$$

$\searrow \mathcal{L} \sim C_S\, \bar{e}\, i\gamma_5 e\, \bar{N} N$

C_S can be more important than d_e (e.g. heavy superpartners)

Neutron EDM

a) Naive dimensional analysis

$$d_n \simeq \frac{4}{3} d_d - \frac{1}{3} d_u$$

$$d_q \equiv \eta\, d_q^E + \tilde{\eta}\, \frac{e}{4\pi}\, \tilde{d}_q^C + \dots$$

Arnowitt, Lopez, .. '90

$$\boxed{d_n^{NDA} \sim 2 d_d - 0.5 d_u + e(0.4 \tilde{d}_d - 0.1 \tilde{d}_u) + + 0.3\ \mathrm{GeV} \cdot eW}$$

Here $d_q, \tilde{d}_q$ at EW scale

b) QCD sum rules

Pospelov, Ritz '01

$$\boxed{d_n^{SR} \simeq 2 d_d - 0.5 d_u + e\left(\tilde{d}_d + 0.5 \tilde{d}_u\right) + + 0.1\ \mathrm{GeV} \cdot eW}$$

4-fermion operators = small

c) ...

Thallium EDM :

Liu, Kelly '92
Bouchiat '75

$$d_{Tl} = -585\, d_e - C_S \cdot 43\ e\cdot\mathrm{GeV},$$

$$\mathcal{L} \sim C_S\, \bar{e}\, i\gamma_5\, e\, \bar{N} N$$

Hence, a bound on de :

$$d_e < 1.5 \times 10^{-27}\ e\ \mathrm{cm}$$

Mercury EDM

Flambaum, Dmitriev, Senkov '03, Pospelov '01

$$d_{Hg} \simeq 7\cdot 10^{-3}\, e\,(\tilde{d}_u - \tilde{d}_d) + \underbrace{\ldots}_{\text{4-fermion, } \ldots}$$

This is from:

⇒ nucleus Shiff moment

EDMs in SUSY

Induced by new CP phases:

$$\Delta \mathcal{L} = \mu \, \overline{\psi}_{H_1} \psi_{H_2} + B\mu \, H_1 H_2 + h.c.$$

$$+ \frac{1}{2} \left(m_3 \overline{\lambda}_3 \lambda_3 + m_2 \overline{\lambda}_2 \lambda_2 + m_1 \overline{\lambda}_1 \lambda_1 \right)$$

$$+ A^d_{ij} H_1 \tilde{q}_{L_i} \tilde{q}^*_{R_j} + \dots$$

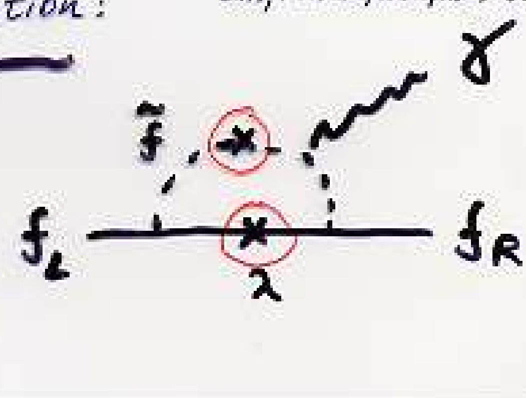
$(\dots)$ = complex

2 phases eliminated by $U(1)_R$, $U(1)_{PQ}$

Physical phases: $\mathrm{Arg}(m_i^* A)$, $\mathrm{Arg}(B^* A)$, ...

Typical EDM contribution:

Ellis, Ferrara, Nanopoulos '82



$\varphi_{SUSY} \sim 10^{-2} \Leftarrow$

(CP problem)

The CP problem appears already in the minimal SUSY scenario

mSUGRA :

μ, A = complex !

(unlike the FCNC problem)

Suppression of EDMs:

1. small phases
2. decoupling
3. off diagonal $\cancel{CP}$

(+ accidental cancellations)

① Small phases

E.g. phase alignment

$$\varphi_M = \varphi_A = -\varphi_\mu$$

$$\Downarrow$$

$$\varphi(M^* A) = \varphi(\mu A) = .. = 0$$

(dilaton domination + Giudice - Masiero)

② Decoupling

Nath '91

Kizukuri, Oshimo '92

$$\sim \; 1/m^2_{\tilde q_{1,2}} \xrightarrow{\sim 10\text{ TeV}} 0$$

③ off diagonal $\not{CP}$

$$\left.\begin{array}{l} A = A^+ \\ \mu = \mu^+ \\ .. \end{array}\right\} \text{ by symmetry} \begin{array}{l} \nearrow LR \\ \searrow \text{flavour} \end{array}$$

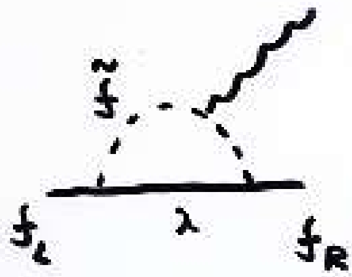
Mohapatra, Senjanovich

Abel, Bailin, Khalil, OL

Like in the SM, small EDMs.

Classes of EDM contributions

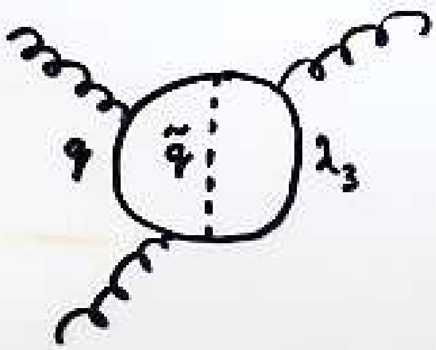
(1)



→ typically the most important contributions

(2) Weinberg operator

Weinberg '89
Dai et al. '90



→ $\Delta\mathcal{L} \sim G\tilde{G}G$;

non-zero d_n

It dominates when 1,2^{d} generation sfermions are decoupled:

$$m_{\tilde{q}_{1,2}} \longrightarrow \infty$$

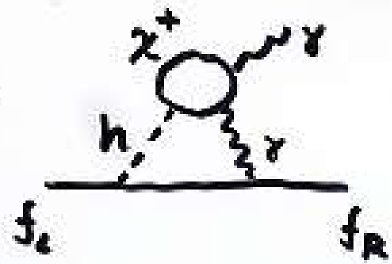
Barr, Zee '90

③ Barr-Zee-type contributions

Chang Keung Pilaftsis '99

→ subleading to the Weinberg op., induces $d_n, d_e, \dots$

Chang Chang Keung '02 Pilaftsis '02

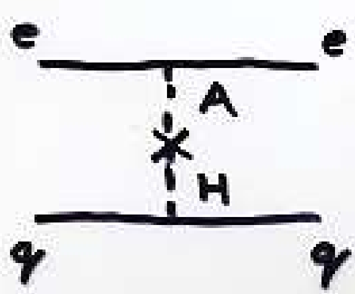


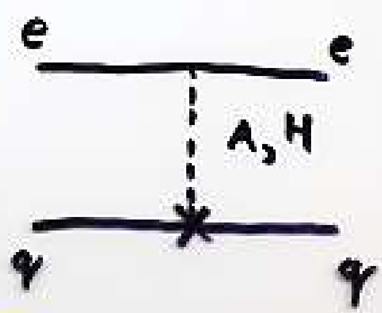
→ survives when sfermions decouple

Dominates in split SUSY.

④ 4-fermion operators

Barr '92 OL, Pospelov '02





→ $\Delta\mathcal{L} \sim \bar{e} i\gamma_5 e \cdot \bar{N}N$

→ $d_{Tl}, d_{Hg}, \dots$

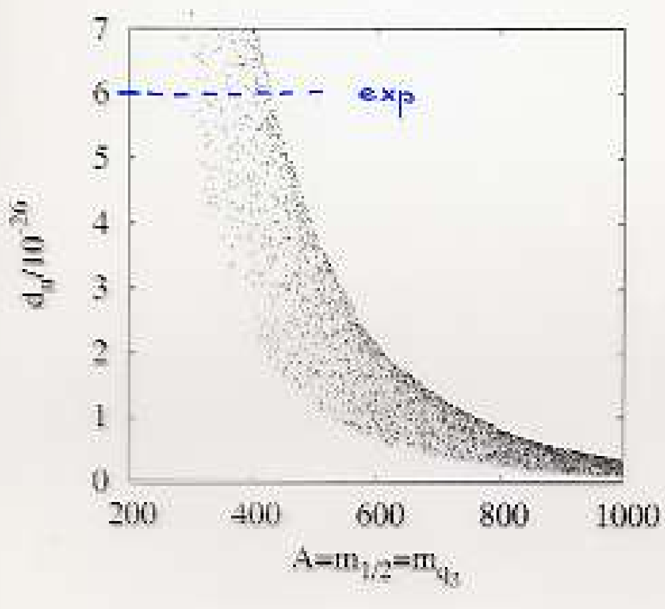
Dominates when all SUSY particles are decoupled. Also at large $\tan\beta$.

nEDM due to the Weinberg op.

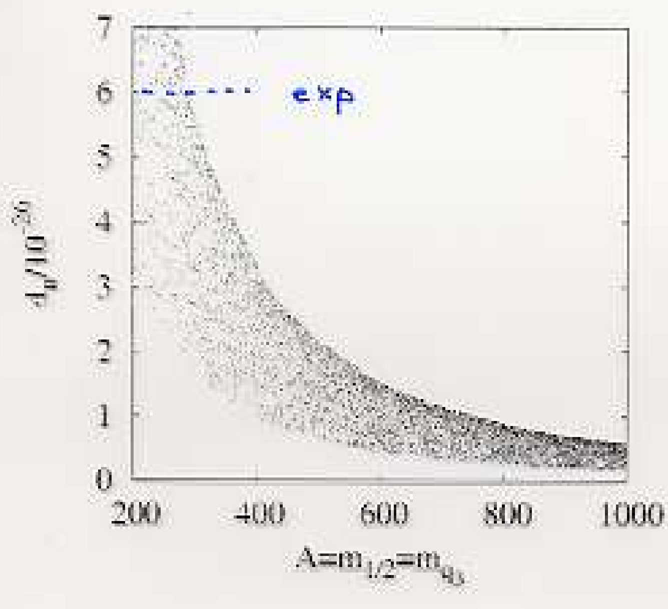
$$\left. \begin{array}{l} m_{1,2} \to \infty \; ; \quad A = m_{1/2} = m_3 \\ \tan\beta = 5 \end{array} \right|_{GUT}$$

$$\begin{cases} \varphi_A = 0 \\ \varphi_\mu \in [\pi/10 \, , \pi/2] \end{cases}$$

Abel, OL '05



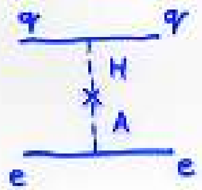
$$\begin{cases} \varphi_A \in [\pi/10 \,,\, \pi/2] \\ \varphi_\mu = 0 \end{cases}$$



Abel, OL'05

d_{Tl} due to 4-fermion interactions

m1 :

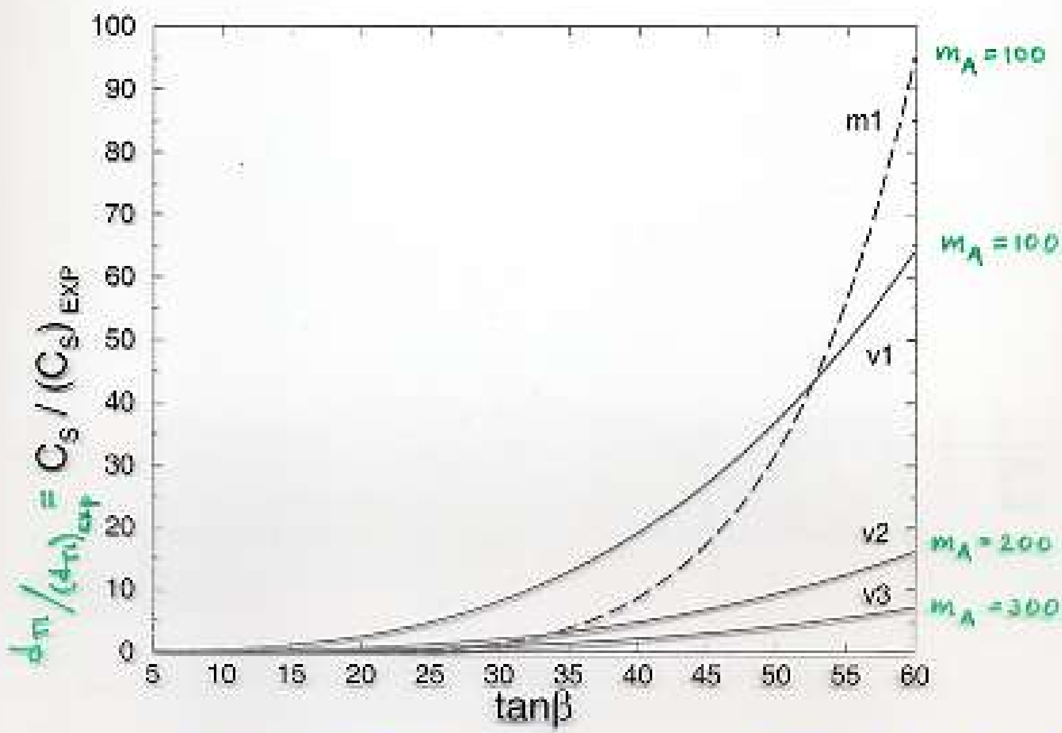


$\sim \tan^6\beta$

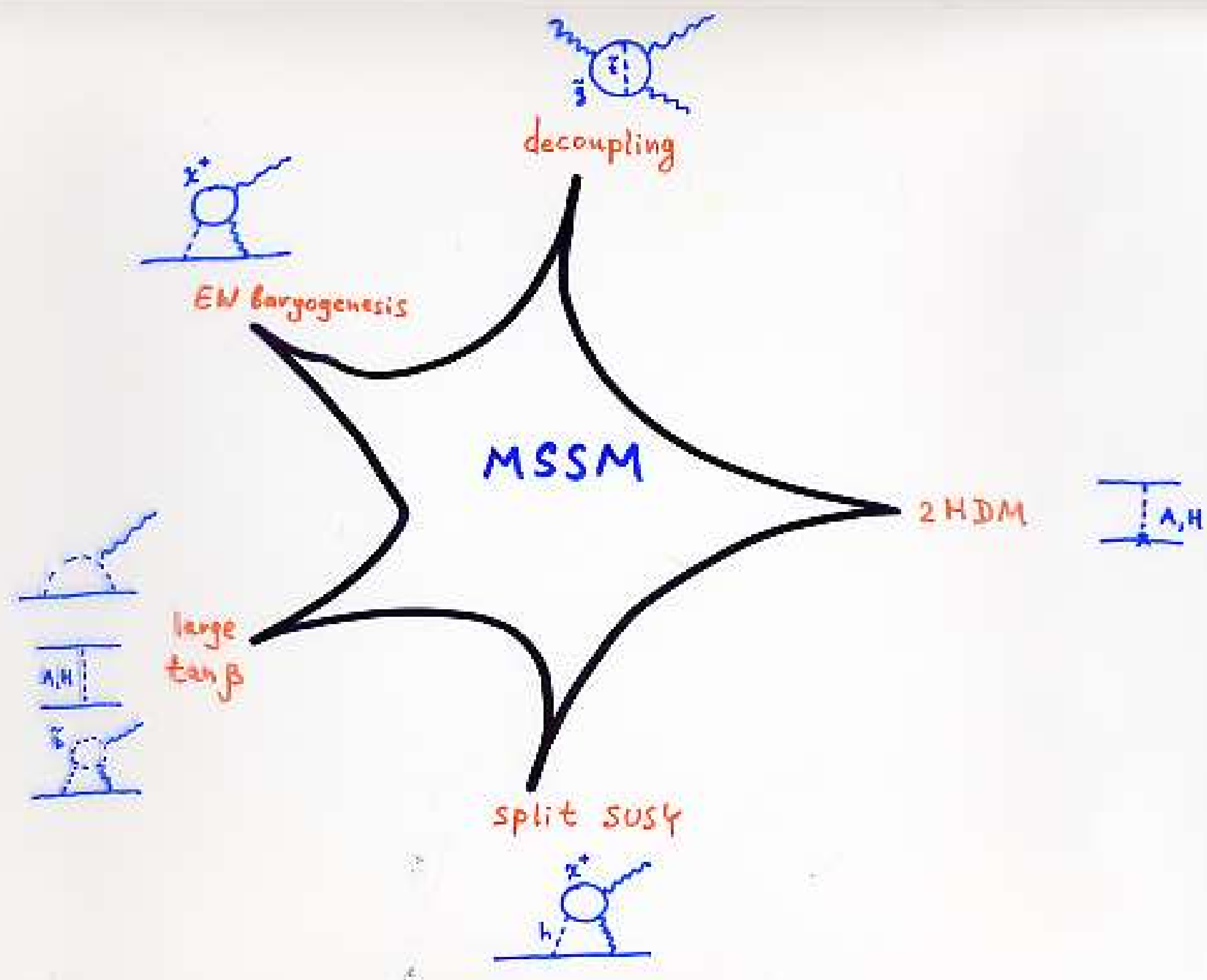
vi :

$\sim \tan^3\beta$

OL, Pospelov '02



$Arg(A\mu) = \pi/2$; $A_{t,b} = \mu = 1$ TeV ; $m_{\tilde{q}_3} = 600$ GeV



MSSM
decoupling
EW Baryogenesis
2HDM
A,H
large
tan β
A,H
split SUSY
h

Fundamental sources of SUSY $\not{CP}$

MSSM = low energy limit of supergravity

SUSY breaking

F-terms

SUSY conserving

Yukawas

dangerous CP-phases

① SUSY breaking F-terms

Gaugino masses:

$$m_i \sim F^n \partial_n f_i$$

gauge kinetic function

μ-term:

$$\mu \sim F^n \partial_n Z + \ldots$$

Giudice - Masiero function

...

Leads to flavour-independent phases

$$\mathrm{Arg}(m_i^* m_j) \quad , \mathrm{Arg}(\mu m_i), \ldots$$

(+ possibly flavour-dependent phases in the A-terms)

② SUSY conserving quantities

E.g. Yukawas Y_{ij} are complex

Induce large EDMs through flavour-dependent A-terms.

Abel, Khalil, OL '02

$$A_{ij} \sim F^m \left[Y_{ij} + \underline{\underline{\partial_m Y_{ij}}} + \dots \right]$$

$$\Rightarrow \quad A_{ij} \not\propto Y_{ij}$$

$\Rightarrow$ A_{ij} and Y_{ij} are not diagonalizable simultaneously

$$\begin{cases} Y_{diag} = V_L^+ \, Y \, V_R \\ A' = V_L^+ \, A \, V_R \neq \text{diag} \end{cases}$$

$$A' = \begin{pmatrix} a'_{11} & \dots \\ \dots & \dots \end{pmatrix} \; ; \; \text{Arg}\, a'_{11} \sim O(1)$$

$\rightarrow$ **large EDMs**

What if $\mathcal{L}_{soft}$ is real ?

$$\mathcal{L} = \underline{m_i}\, \bar{\lambda}_i \lambda_i + \underline{A_{ij}}\, \tilde{q}^*_{L_i} \tilde{q}_{R_j} H + \underline{\ldots}$$

all real

Does not help. What matters is

$$A\Big|_{SCKM} = \underline{V_L^+}\, A\, \underline{V_R}$$

order one phases!

Another view: real is basis-dependent!

OL'02

$$\text{SUSY Jarlskog} = \operatorname{Im} \operatorname{Tr} \left\{ Y_u Y_u^+ ,\ Y_d Y_d^+ ,\ A_u A_u^+ \right\}_{\text{antisym.}}$$

$$\vdots$$

Vanishes if $A_u \sim Y_u$, ...

Prospects

EDM predictions :

1. small phases $\rightarrow$?

2. decoupling $\rightarrow \begin{cases} d_n \sim 10^{-26}\ e\,cm \\ d_e \gtrsim 10^{-28}\ e\,cm \end{cases}$

   split SUSY $\rightarrow \begin{cases} d_n \lesssim 10^{-27}\ e\,cm \\ d_e \lesssim 10^{-28}\ e\,cm \end{cases}$

3. off diag. $\cancel{CP}$ $\rightarrow$?

$$\left.\begin{array}{ll} \text{Imperial, Yale} & \rightarrow d_e \sim 10^{-29}, 10^{-30}\ e\,cm \\ \text{ILL} & \rightarrow d_n \sim 10^{-26}\ e\,cm \end{array}\right\} 2006$$

Los Alamos : much better bounds by 2009

BNL : d_D, d_μ

Conclusions

1. EDMs probe CP/flavour of fundamental theories (e.g. SUGRA, string, ...)

2. CP-problem is rather difficult, but possible to avoid

3. Probe solutions in the next 1-4 years