# EDMs theoretical interest

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FCC Working Group - Experiments with the CERN injectors

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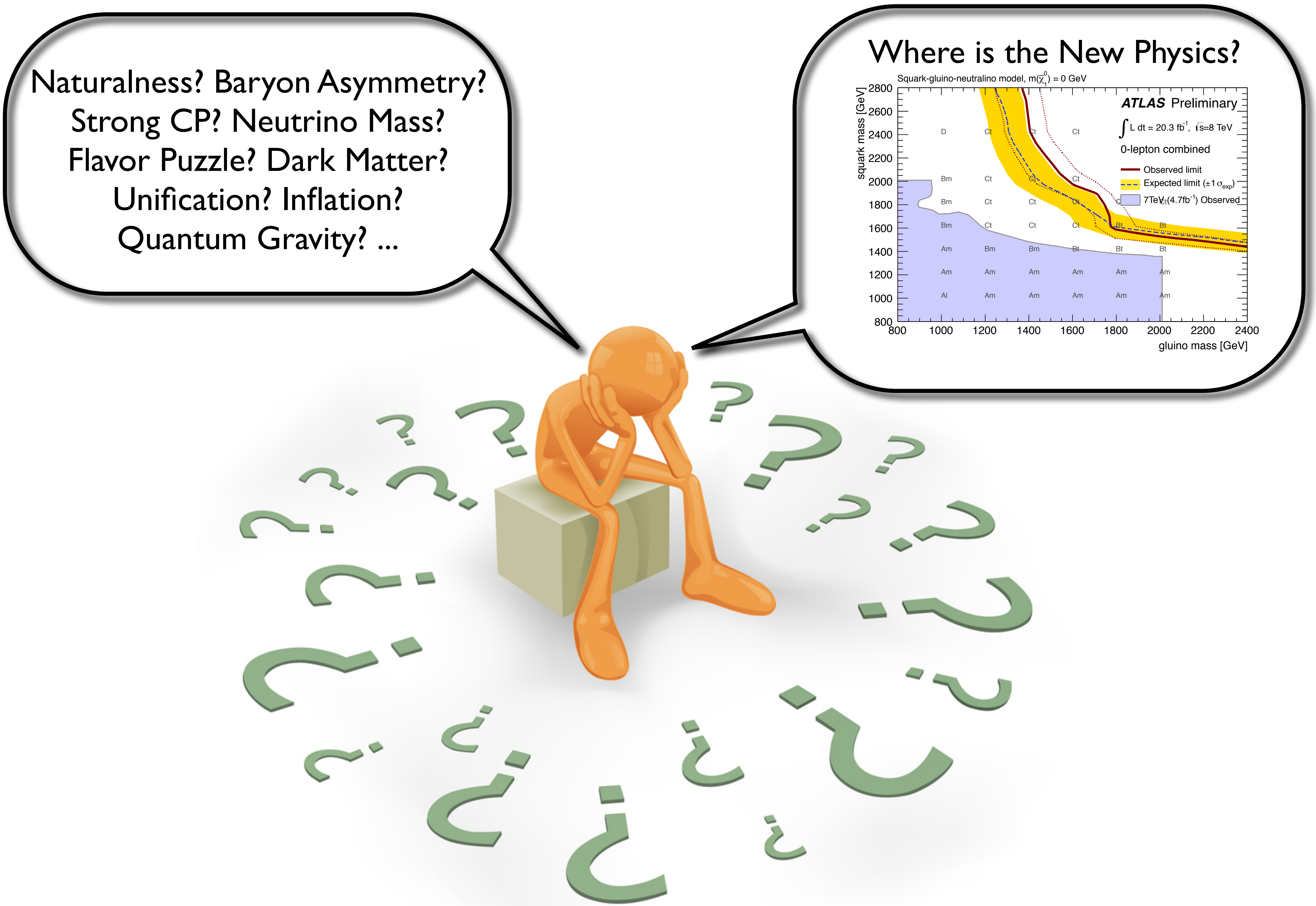

Naturalness? Baryon Asymmetry?
Strong CP? Neutrino Mass?
Flavor Puzzle? Dark Matter?
Unification? Inflation?
Quantum Gravity? ...
Where is the New Physics?
Squark-gluino-neutralino model, m($\tilde{\chi}_1^0$) = 0 GeV
ATLAS Preliminary
$\int L\,dt$ = 20.3 fb$^{-1}$, $\sqrt{s}$=8 TeV
0-lepton combined
Observed limit
Expected limit ($\pm 1\,\sigma_{exp}$)
7TeV (4.7fb$^{-1}$) Observed
squark mass [GeV]
gluino mass [GeV]

# Why Electric Dipole Moments?

## EDMs from CKM:

- CKM contribution to quark, electron EDMs contribution is tiny
  - Requires exchange of three generations of quarks to "see" CP violating phase ~ several loops, Jarlskog Invariant is small ~ $10^{-5}$

- In atoms, molecules, long distance contributions dominate, but still several orders of magnitude below experimental sensitivity

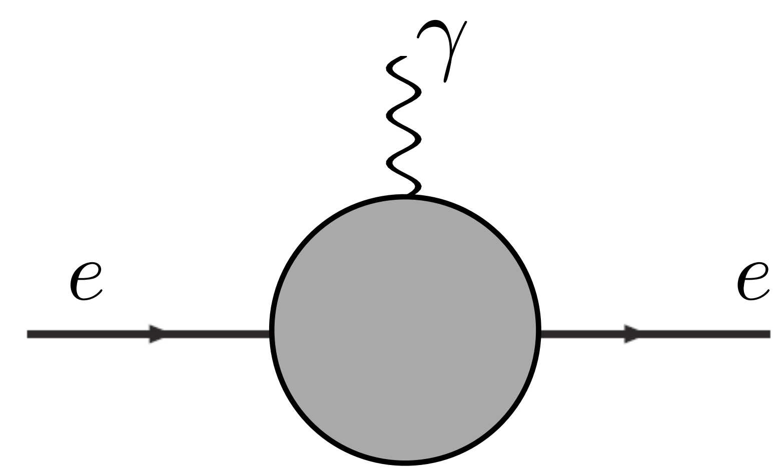
EDMs provide "background free" probe of New Physics

# Why Electric Dipole Moments?

## EDMs from New Physics:

$$\mathcal{L}^{(6)} \supset -\frac{e^{i\phi}}{\sqrt{2}\Lambda^2}\bar{L}_L\sigma^{\mu\nu}e_R\, H\, B_{\mu\nu} + \text{h.c.}$$

$$\supset -d_e\,\frac{i}{2}\,\bar{e}\,\sigma^{\mu\nu}\gamma^5 e\, F_{\mu\nu}$$




$$d_e = c_W \sin\phi \frac{v}{\Lambda^2}$$

$$\sim 8.7\times 10^{-29}\,\text{e cm} \times \sin\phi \left(\frac{4\times 10^5\,\text{TeV}}{\Lambda}\right)^2$$

ACME limit

New physics scale

EDMs indirectly probe scales much higher than direct searches at the LHC!

# Why Electric Dipole Moments?

$$\mathcal{L}^{(6)} \supset -\frac{e^{i\phi}}{\sqrt{2}\Lambda^2}\bar{L}_L \sigma^{\mu\nu} e_R\, H\, B_{\mu\nu} + \text{h.c.}$$

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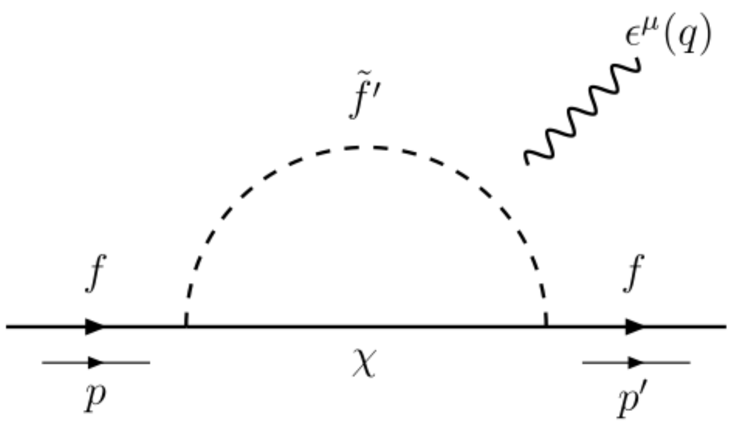



Perturbative, flavor-safe, 1-loop new physics contribution:

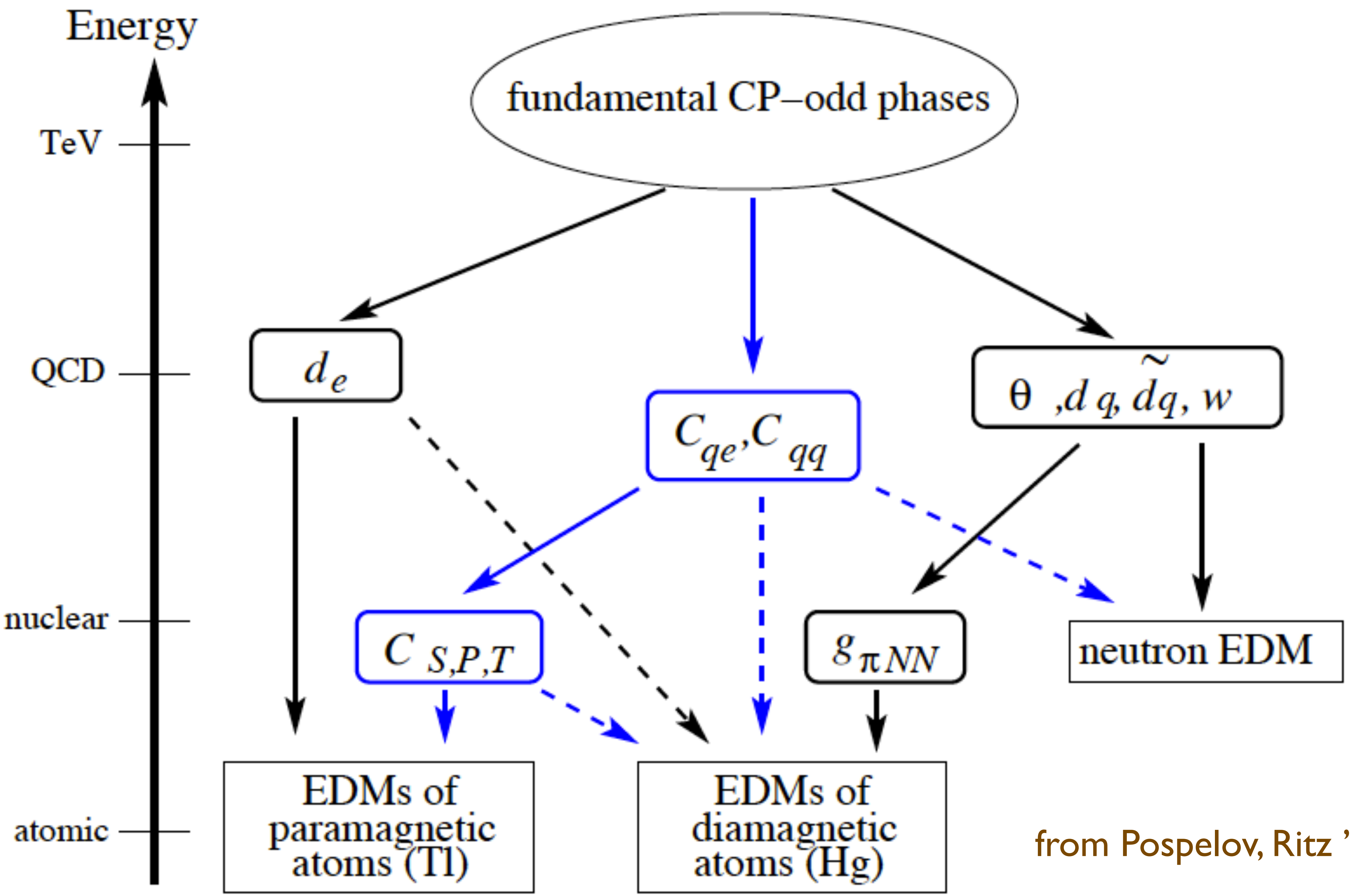
$$\frac{1}{\Lambda^2} \sim y_e g' \frac{g^2}{16\pi^2}\frac{1}{M^2}$$

$$d_e \sim e \sin\phi \frac{g^2}{16\pi^2}\frac{m_e}{M^2}$$

$$\sim 8.7 \times 10^{-29}\, \text{e cm} \times \sin\phi \left(\frac{20\,\text{TeV}}{M}\right)^2$$

ACME limit

New physics scale




from Pospelov, Ritz ’05

# Current EDM limits and future experimental benchmarks

Paramagnetic

$d_{\mathrm{para}}(d_e, C_{eeqq})$

Nucleons

$d_{\mathrm{n,p}}(\bar{\theta}, d_q, \tilde{d}_q, w, C_{qqqq})$

Diamagnetic

$d_{\mathrm{dia}}(\bar{\theta}, d_q, \tilde{d}_q, w, C_{qqqq})$

| System | Present 90% C.L. Limit ($e$ fm)[a] | Sensitivity goal[b] | Group |
|---|---|---|---|
| Cs | $1.2 \times 10^{-10}$ | | [169] |
| Tl | $9.5 \times 10^{-12}$ | | [170] |
| YbF[d] | $10.5 \times 10^{-15}$ | | [152] |
| ThO[d] | – | $10^{-15} \to 10^{-17}$ | |
| $n$ | $2.7 \times 10^{-13}$ | | [171] |
| $n$ | | $(1-3) \times 10^{-14}$ | CryoEDM |
| $n$ | | $4 \times 10^{-15}$ | nEDM/SNS |
| $n$ | | $5 \times 10^{-14}$ | nEDM/PSI |
| $n$ | | $5 \times 10^{-15}$ | n2EDM/PSI |
| $n$ | | $2 \times 10^{-15}$ | nedm/FRM-II Munich |
| $n$ | | $10^{-14} - 10^{-15}$ | TRIUMF |
| $p$ | | $10^{-16}$ | srEDM |
| $^{199}$Hg | $2.6 \times 10^{-16}$ | $(2.6-5) \times 10^{-17}$ | [172] |
| $^{225}$Ra | | $(10-100) \times 10^{-15}$ | Argonne |
| $^{221/223}$Rn | | $1.3 \times 10^{-14}$ | TRIUMF |
| $^{221/223}$Rn | | $2 \times 10^{-15}$ | FRIB |
| $^{129}$Xe | $5.5 \times 10^{-14}$ | | [173] |

Engel et al. 2013

Complementarity: different systems probe different combinations of underlying CPV parameters

# Strong CP problem

CPV QCD theta term:

$$\mathcal{L} \supset \frac{g_3^2}{32\pi^2}\,\overline{\theta}\,G_{\mu\nu}^{A}\widetilde{G}^{\mu\nu A}$$

$$\overline{\theta} = \theta + \arg\det(Y_u Y_d)$$

Neutron EDM:

$$d_n \sim \frac{e m_q^*}{m_N^2} \sim 10^{-17} e\,\mathrm{cm} \times \overline{\theta}$$

Experimental Bound:

$$d_n^{\mathrm{exp}} \lesssim 10^{-26}\, e\,\mathrm{cm}$$

$$\overline{\theta} \lesssim 10^{-9}$$

Strong CP Problem:
Why so small?

# Baryon Asymmetry of the Universe

- We observe matter, but not antimatter! $n_B \gg n_{\overline{B}}$
- Initial conditions? CMB anisotropies support inflation, early universe dominated by vacuum - matter produced via reheating

➡ Need for baryogenesis!

## Sakharov conditions:

1. Baryon number violation
2. C and CP violation
3. Departure from thermal equilibrium

# Baryon Asymmetry of the Universe

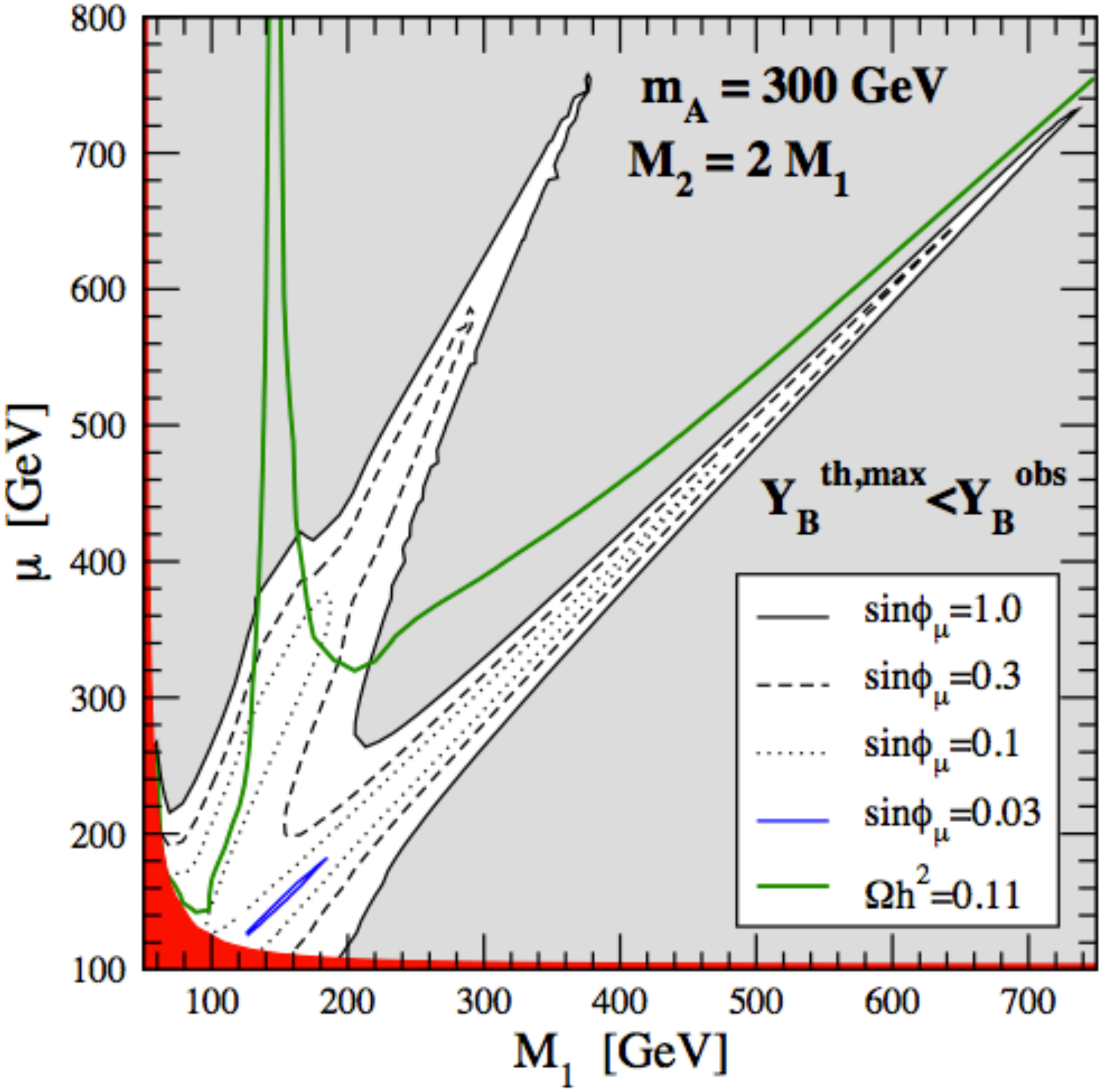
- In principle, Sakharov conditions satisfied in the Standard Model
    - Sphalerons, CKM phase, EW phase transition
- However, in practice EW baryogenesis doesn't work in the SM:
    - CP violation too small
    - 125 GeV Higgs - absence of 1st order EW phase transition

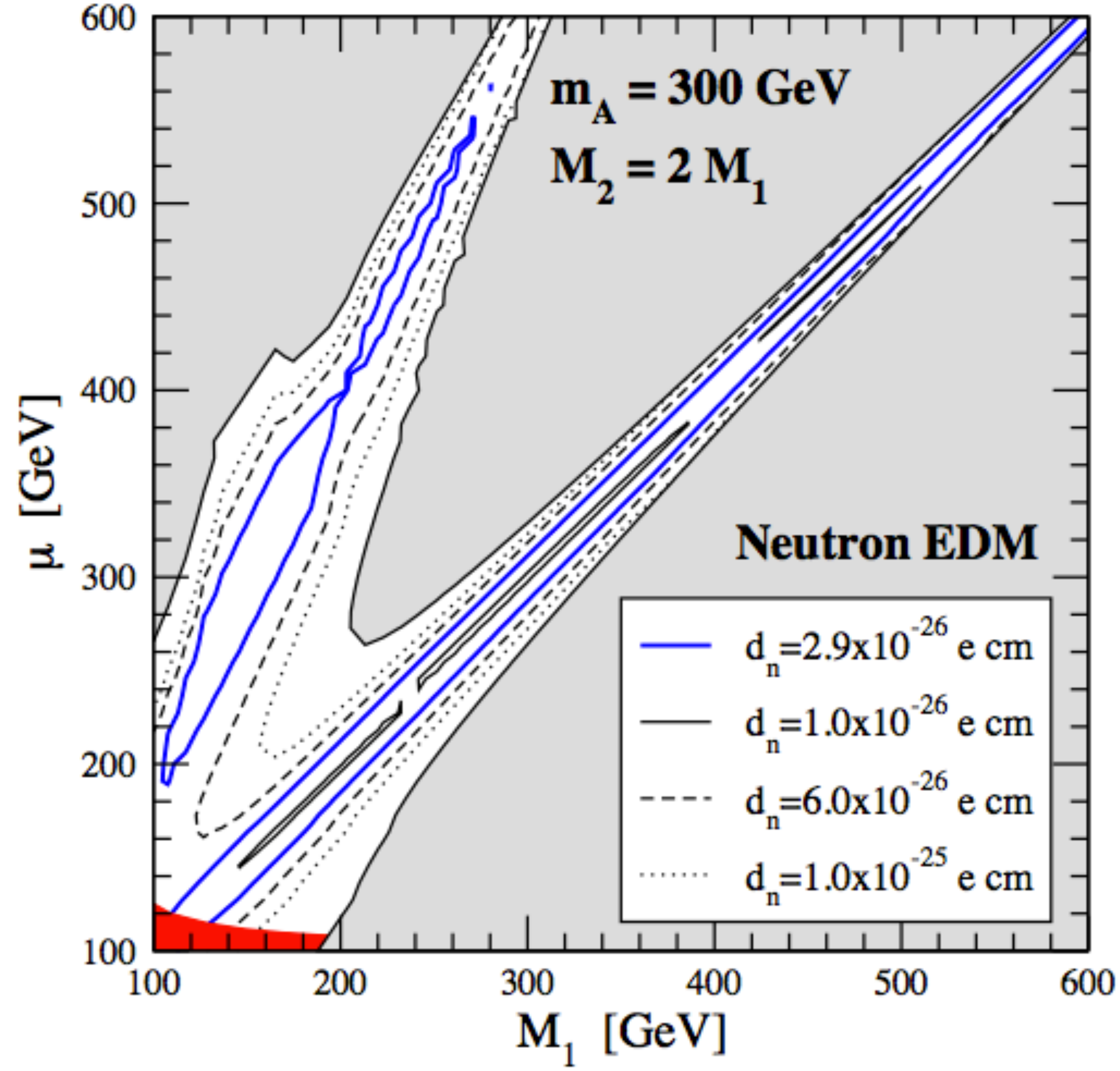
New dynamics and sources of CP violation needed to account for the baryon asymmetry!

- Unfortunately we don't know the scale associated with this dynamics
    - GUT baryogenesis, Leptogenesis, Electroweak baryogenesis, ...

can lead to observable EDMs

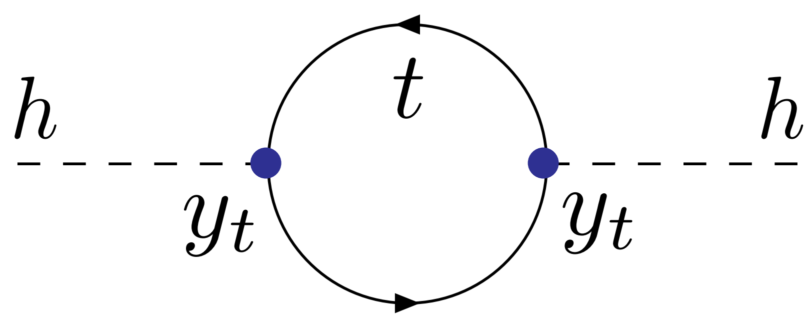
# EDMs probe baryogenesis in the MSSM




Cirigliano et al '09

# Naturalness and the Weak Scale




$$\delta m_h^2 = -\frac{3y_t^2}{8\pi^2}\Lambda^2$$

( $\Lambda$ ~ scale of new physics)

Very naively we expect

$$|\delta m_h^2| \lesssim m_h^2 = (125\,\mathrm{GeV})^2$$

$\Rightarrow$ $\boxed{\Lambda \lesssim 650\,\mathrm{GeV}}$

or else we start to tune...

Suggests new dynamics at 100 GeV - 1 TeV!

# Naturalness and the New Physics CP problem

- Theories addressing hierarchy problem scale typically introduces many new CP violating parameters

- Strong constraints from EDMS for ~ TeV scale SUSY

$$\phi \lesssim 0.001 - 0.1$$

- SUSY baryogenesis prefers order one phases.

① Example: MSSM

$$m_1 \tilde{B}\tilde{B} + m_2 \tilde{W}\tilde{W} + m_3 \tilde{g}\tilde{g}$$
$$+\mu \tilde{H}_u \tilde{H}_d + B\mu H_u H_d$$

$\rightarrow$ 5 phases

$$m_Q^2 \tilde{Q}_L^\dagger \tilde{Q}_L + m_U^2 \tilde{U}_R^\dagger \tilde{U}_R + m_D^2 \tilde{D}_R^\dagger \tilde{D}_R$$
$$+m_L^2 \tilde{L}_L^\dagger \tilde{L}_L + m_E^2 \tilde{E}_R^\dagger \tilde{E}_R$$

$\rightarrow$ 15 flavor mixing angles + 15 phases

$$A_u \, H_u \tilde{Q}_L^\dagger \tilde{U}_R + A_d \, H_d \tilde{Q}_L^\dagger \tilde{D}_R + A_\ell \, H_d \tilde{L}_L^\dagger \tilde{E}_R$$

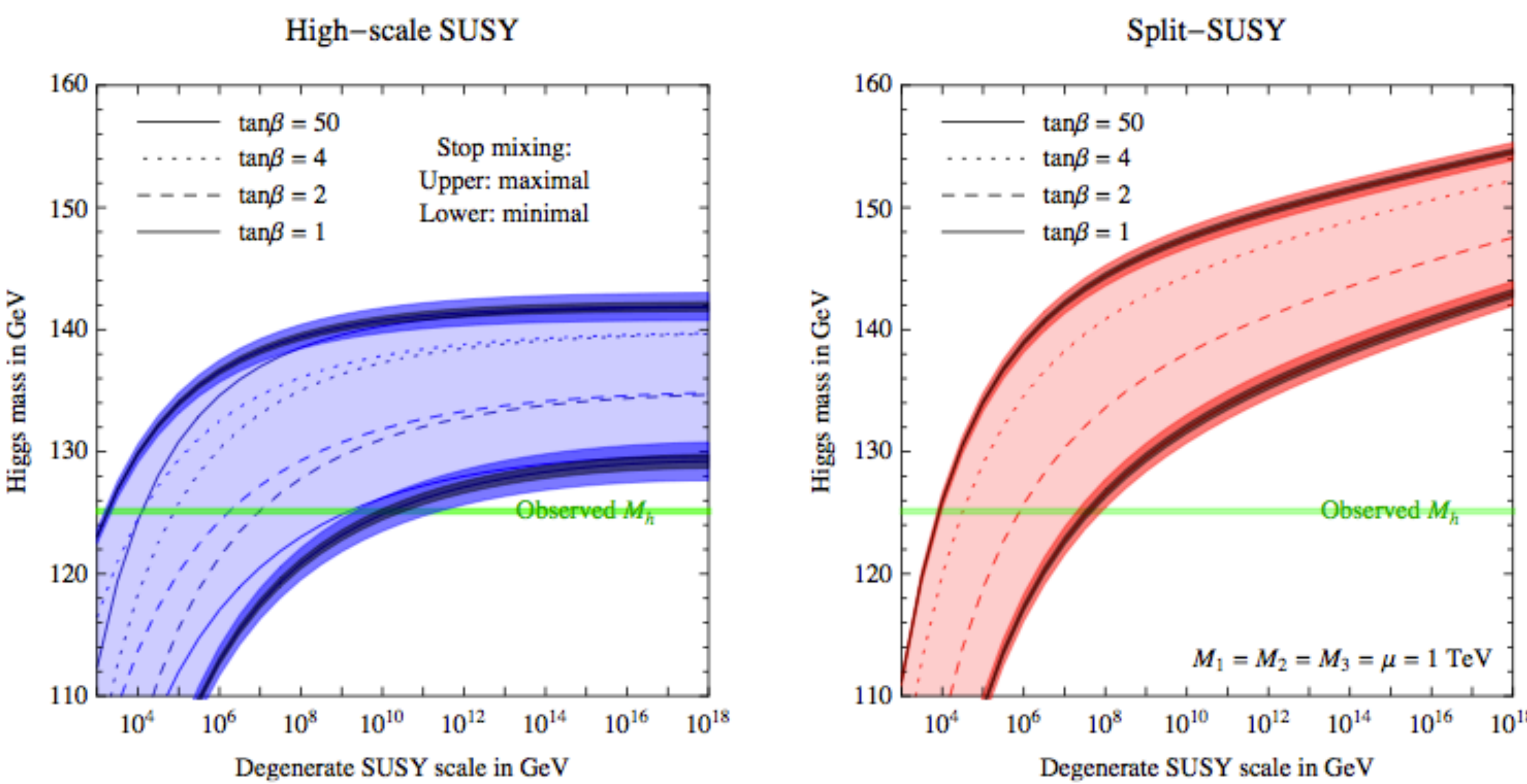
$\rightarrow$ 18 flavor mixing angles + 27 phases

2 phases can be rotated away...

from talk by W. Altmanshoffer

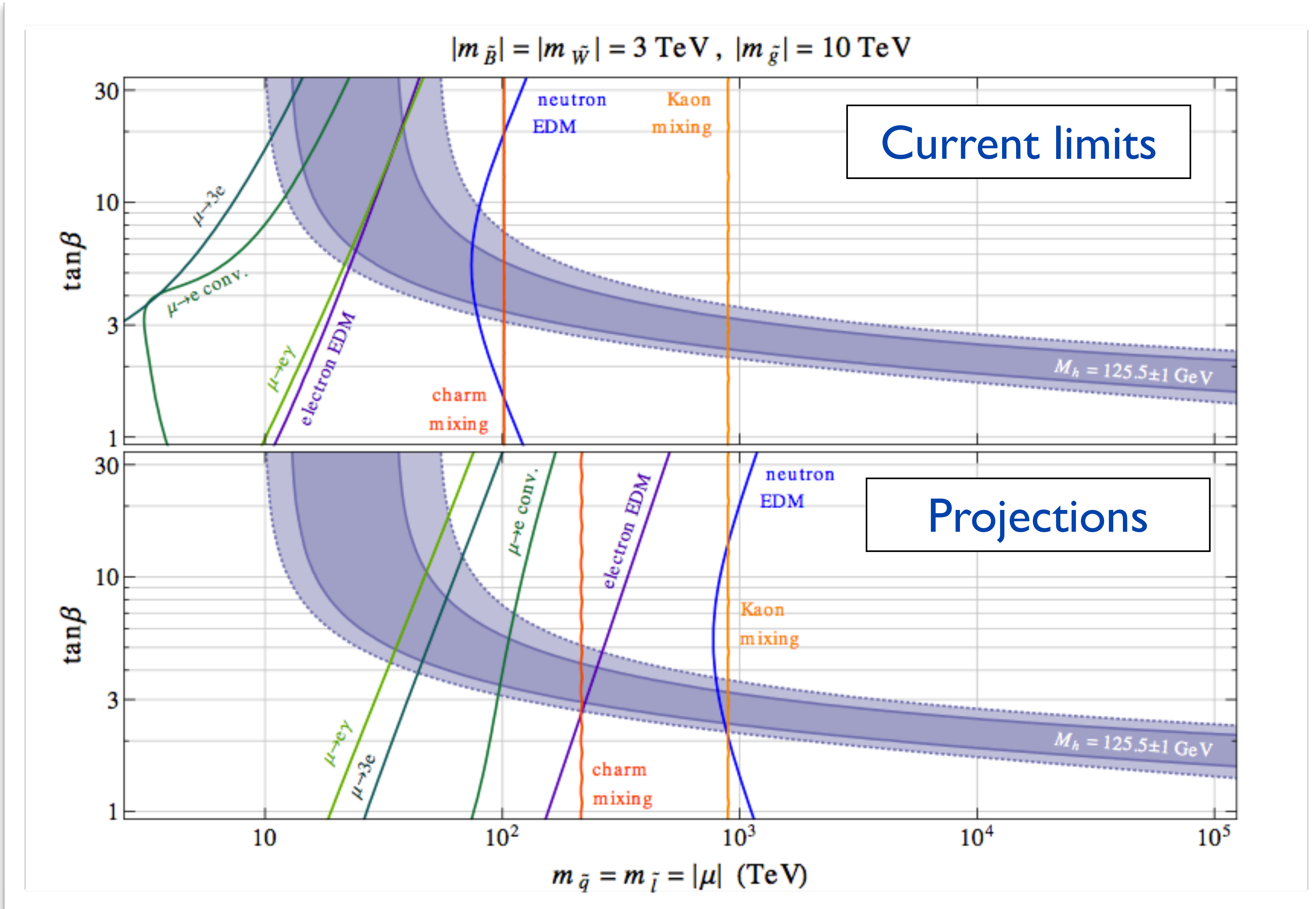
# Maybe SUSY is a bit heavier than expected?

- No signs of superpartners in Run 1
- SUSY flavor, CP problems ameliorated
- 125 GeV Higgs mass points towards heavy scalars




Bagnaschi et al. 2014

# EDMs and other indirect tests probe heavy SUSY




Altmanshoffer, Harnik, Zupan

# Summary

- We know there is new physics, but so far we haven't found it!
- With no direct evidence for new physics from the LHC, we need to pursue a broad program to test the SM and go beyond
- EDMs are a cruical component of this program!
  - Strong CP problem, Baryogenesis, Hierarchy problem are all good reasons to probe for new sources of CP violation
  - Allow indirect access to very high scales of order 1-1000 TeV!
- It is worthwhile to consider how CERN can contribute to this program!