CP Violation and the Search for Electric Dipole Moments

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Outline

1. CP Violation in the SM and Beyond

2. CP Violation and Baryogenesis at the Weak Scale

3. CP Violation in the Strong Force and Axions

CPV in the SM and Beyond

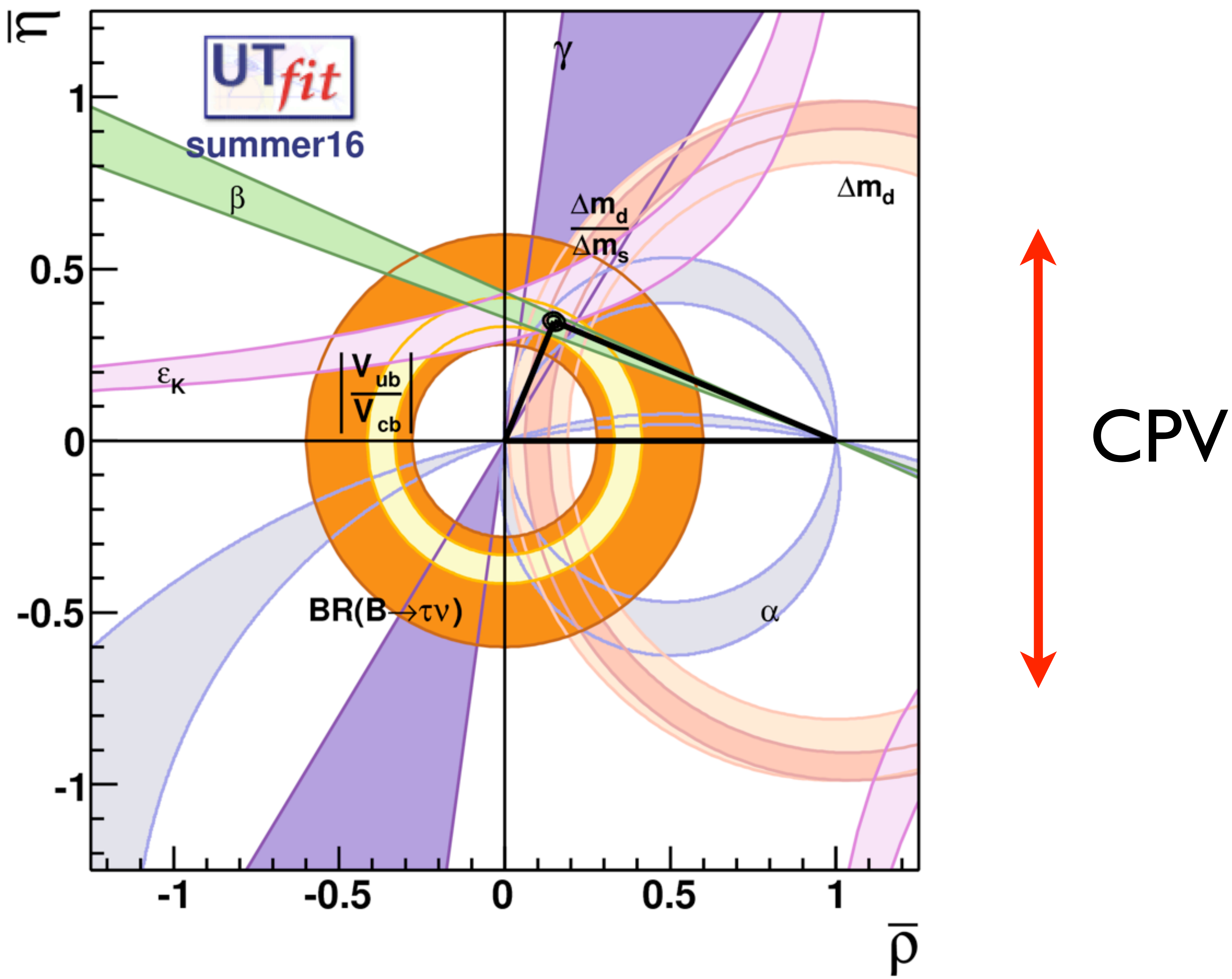
Flavor and CP in the SM

- All here:

$$\mathcal{L} \supset (\bar{u},\, \bar{c},\, \bar{t})\, \gamma^\mu P_L \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{= V_{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix} W_\mu^+ \;+\; (h.c.)$$

- V_{CKM} = Cabbibo-Kobayashi Maskawa matrix
  - unitary
  - one physical CP violating phase with 3 generations
  - need at least 3 generations for CPV!

Flavor and CP in the SM



SM CPV and EDMs

- CP violation in the SM only produces small EDMs:

$$d_e^{CKM} \simeq 10^{-38}\, e\,\mathrm{cm}$$ [Ng, Ng 1996]

$$d_n^{CKM} \simeq (1-6) \times 10^{-32}\, e\,\mathrm{cm}$$ [Seng 2015]

$$d_{^{199}\mathrm{Hg}}^{CKM} \simeq 10^{-35}\, e\,\mathrm{cm}$$ [Dmitriev, Senkov 2003]

- Current experimental bounds:

$$|d_e| < 9.7 \times 10^{-29}\, e\,\mathrm{cm}$$ [ACME 2014]

$$|d_n| < 3.6 \times 10^{-26}\, e\,\mathrm{cm}$$ [Pendlebury *et al.* 2015]

$$|d_{^{199}\mathrm{Hg}}| < 7.4 \times 10^{-30}\, e\,\mathrm{cm}$$ [Graner *et al.* 2016]

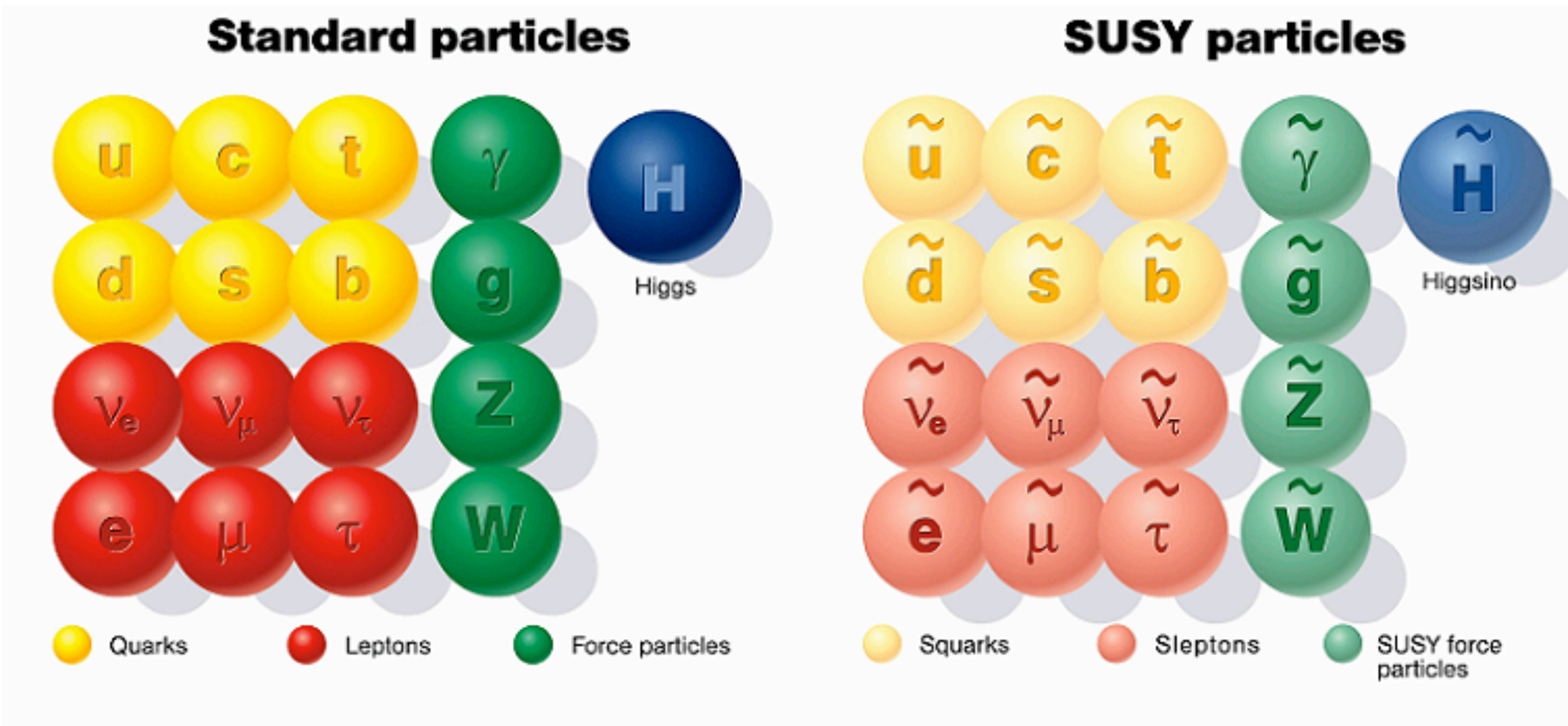
CPV Beyond the Standard Model

- Many reasons for new physics beyond the SM:
  - electroweak hierarchy problem
  - dark matter
  - baryon asymmetry

- Theories of new physics can introduce new CPV!
- CP is not a good symmetry of the SM, so there is no reason to expect it to be a symmetry in extensions of it.
- EDM searches are sensitive to these new sources.

Example: Supersymmetry

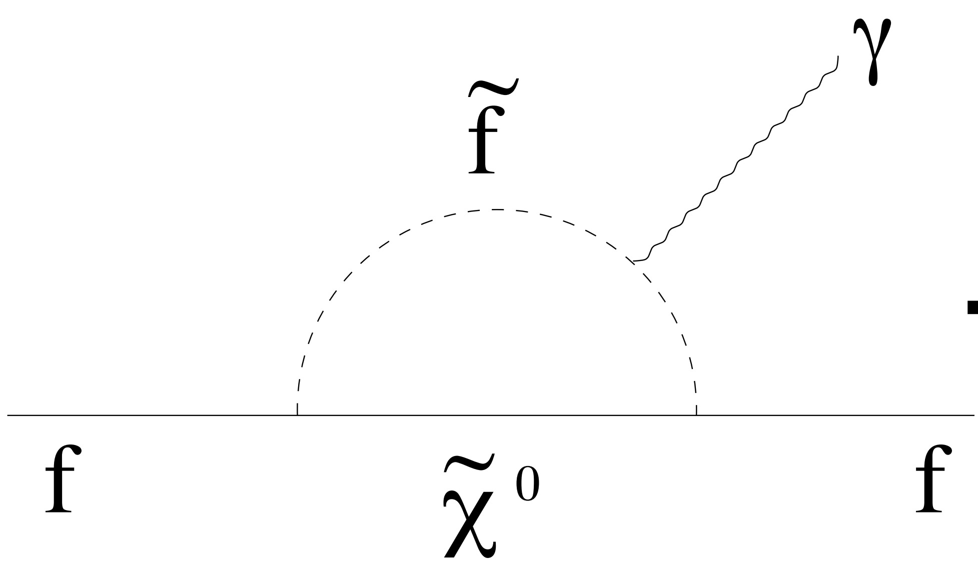
- Every SM particle has a superpartner:



- SUSY must be broken to explain heavier superpartners.
- SUSY breaking terms can have lots of new CPV phases!

Example: Supersymmetry

- New SUSY breaking phases contribute to EDMs in loops:



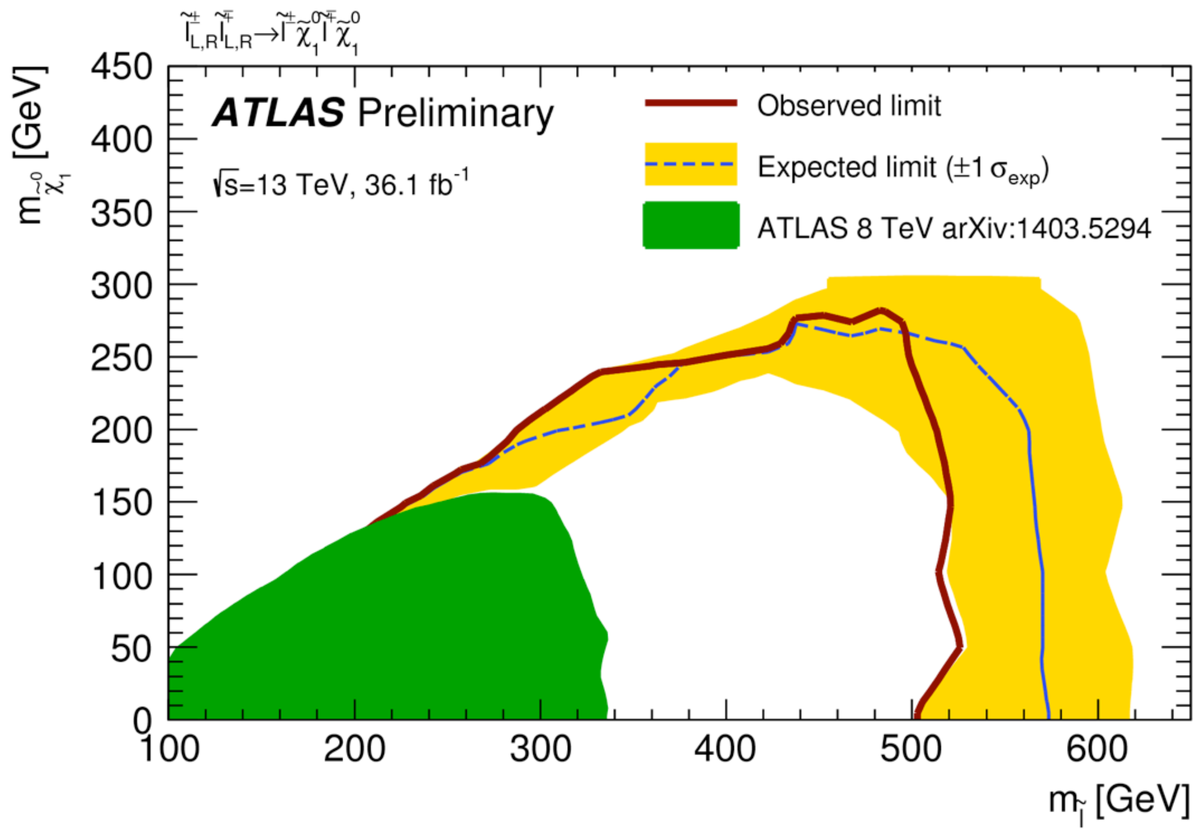
$$\longrightarrow \quad d_f$$

$$d_f \;\sim\; (10^{-25}\, e\,\mathrm{cm})\, \frac{m_f}{\mathrm{MeV}}\, \sin\phi \left(\frac{1\,\mathrm{TeV}}{m_{\tilde f}}\right)^2$$

[Pospelov, Ritz 2005]

Example: Supersymmetry

- Current electron EDM bound exceeds LHC direct slepton searches for $\sin\phi \sim 1$.



$$d_f \;\sim\; \left(10^{-25}\, e\, \mathrm{cm}\right)\, \frac{m_f}{\mathrm{MeV}}\, \sin\phi \left(\frac{1\,\mathrm{TeV}}{m_{\tilde{f}}}\right)^2$$

[Pospelov, Ritz 2005]

CPV Beyond the SM

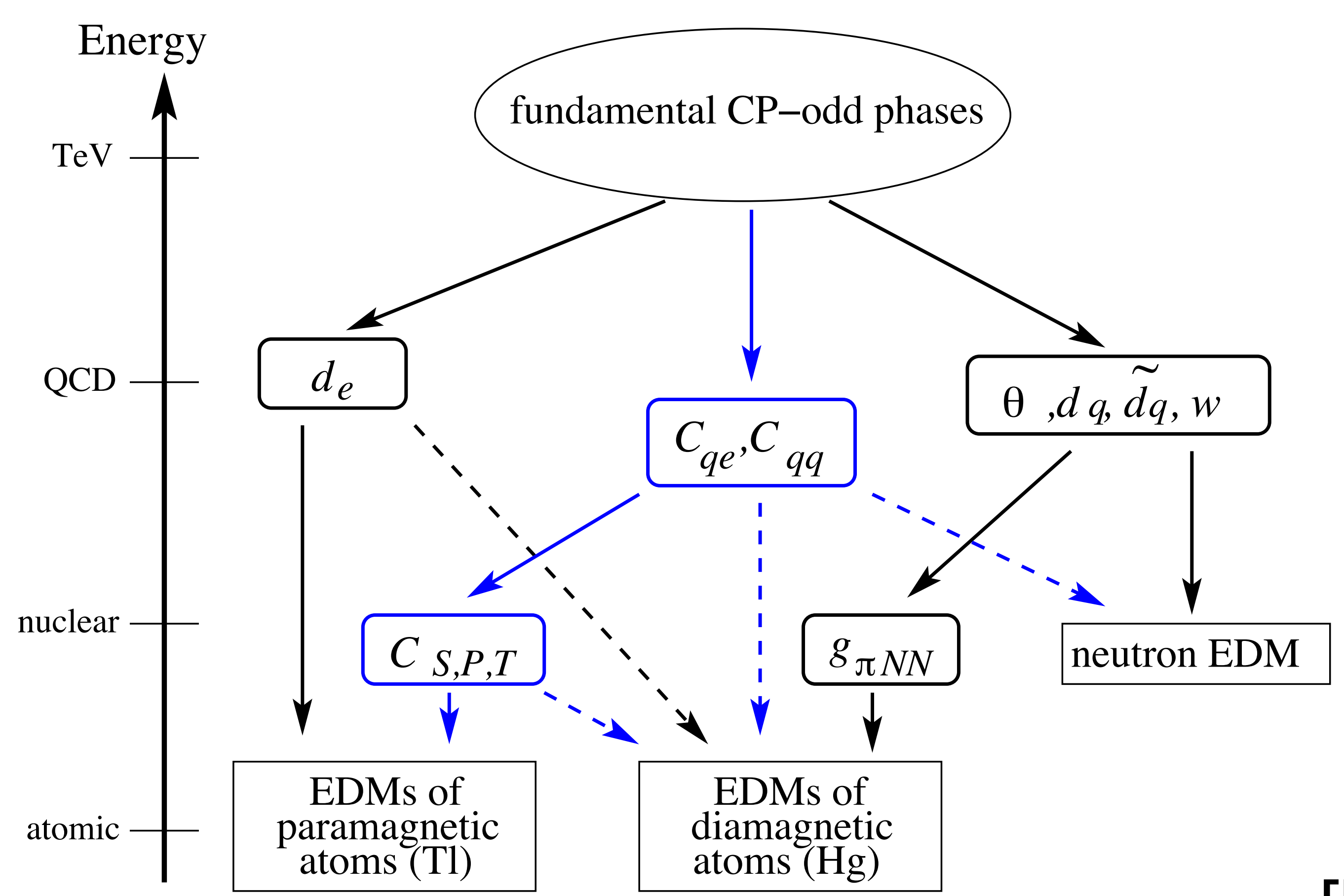
- General Result:

$$\Delta d_i,\ \Delta C_i \ \sim\ (10^{-22}\, e\,\mathrm{cm})\ L\ \sin\phi \left(\frac{m_i}{\mathrm{MeV}}\right)\left(\frac{1\,\mathrm{TeV}}{\Lambda}\right)^2$$

loop factor

CPV phase

mass of new physics



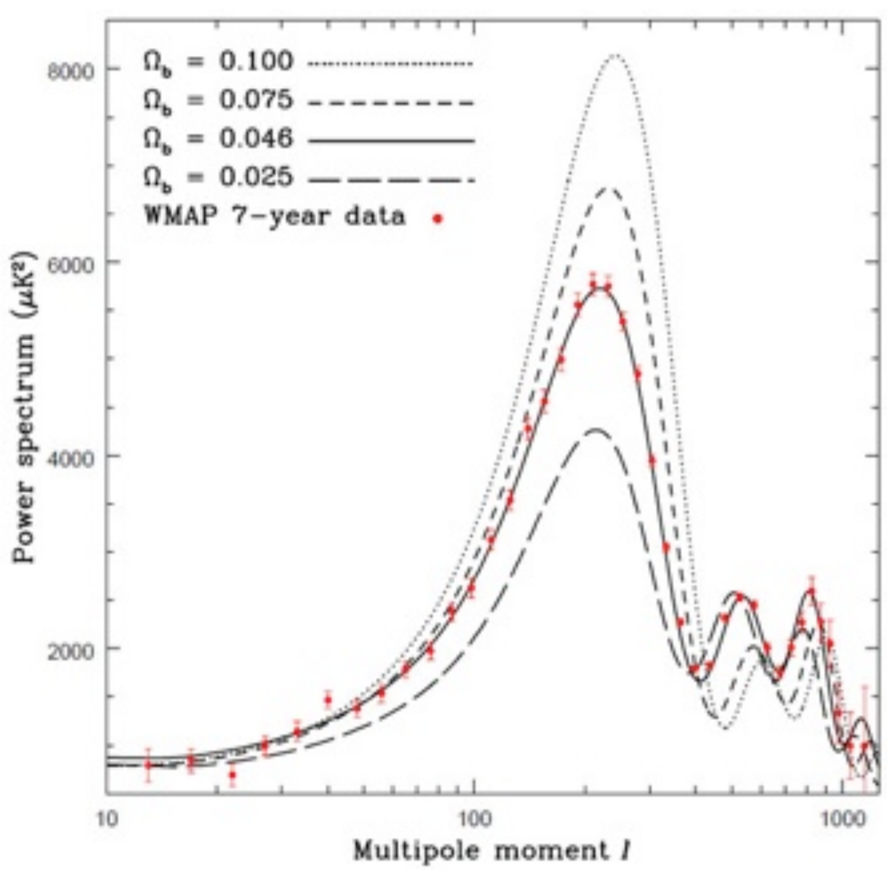
[Pospelov, Ritz 2005]

More CPV:
Baryogenesis

Baryons in the Universe

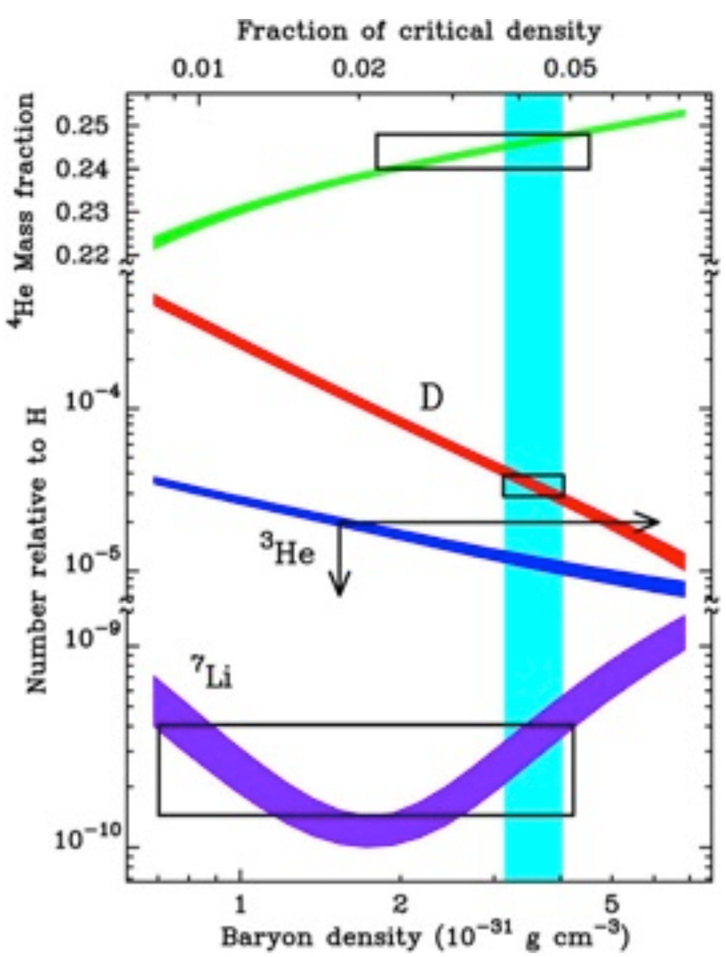
- "Regular" matter is mostly baryons, $\rho_B/\rho_{tot} \simeq 5\%$.
- It consists almost entirely of baryons, not antibaryons.
- Why: Baryogenesis.

CMB



[Garrett+Duda 2010]

BBN



[Cyburt *et al.* 1997]

Baryogenesis Ingredients [Sakharov '67]

1. Baryon Number Violation:
   $|B = 0\rangle \;\; \to \;\; |B \neq 0\rangle$ requires B violation.

2. C and CP Violation:
   Without both, B violation makes just as many baryons as anti-baryons.

3. Departure from Equilibrium
   $\langle B \rangle \; = \; \text{constant}$ in equilibrium.

All three are present in the Standard Model!

Baryogenesis Ingredients [Sakharov ’67]

Ingredients are not enough.

$+$

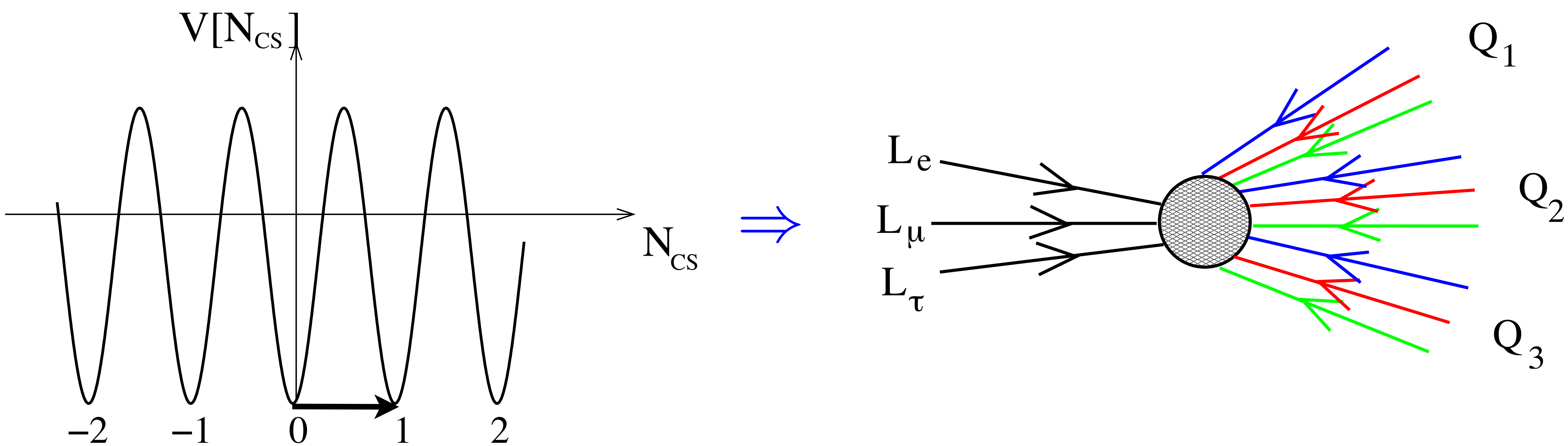
$\neq$

A mechanism for baryogenesis is needed.

No known mechanism works in the Standard Model.

Aside: B Violation in the SM

- B violation in the SM is induced by transitions between different $SU(2)_L$ vacua.

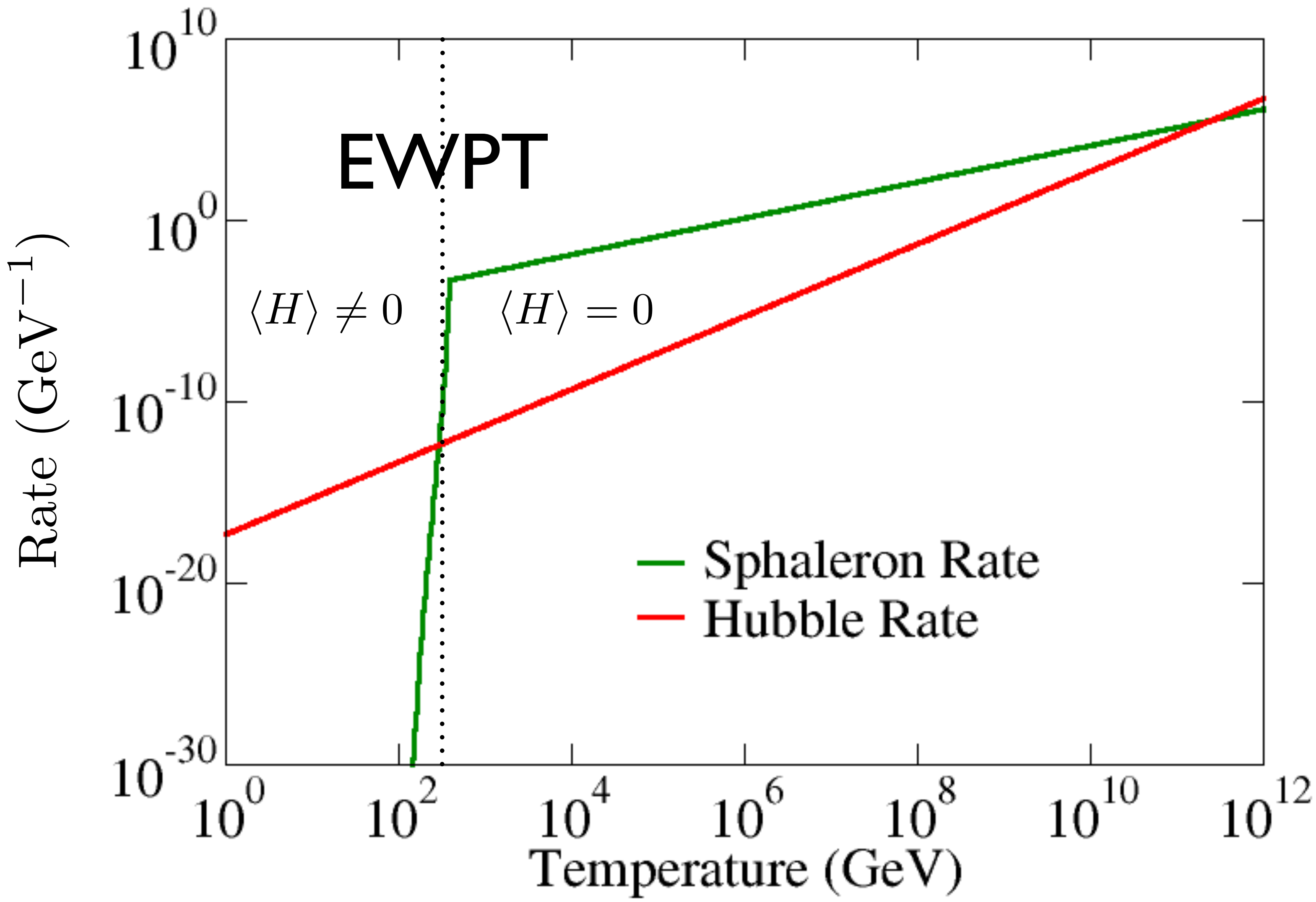


[Cline '06]

- Each transition violates (B+L) by 3 units.

Aside: B Violation in the SM

- Rate of (SM) B violation in the early Universe:



- Electroweak transition: $\langle H \rangle = 0 \quad \rightarrow \quad \langle H \rangle \sim 174\,\mathrm{GeV}$.

Electroweak Baryogenesis

[Kuzmin, Rubakov, Shaposhnikov '87]

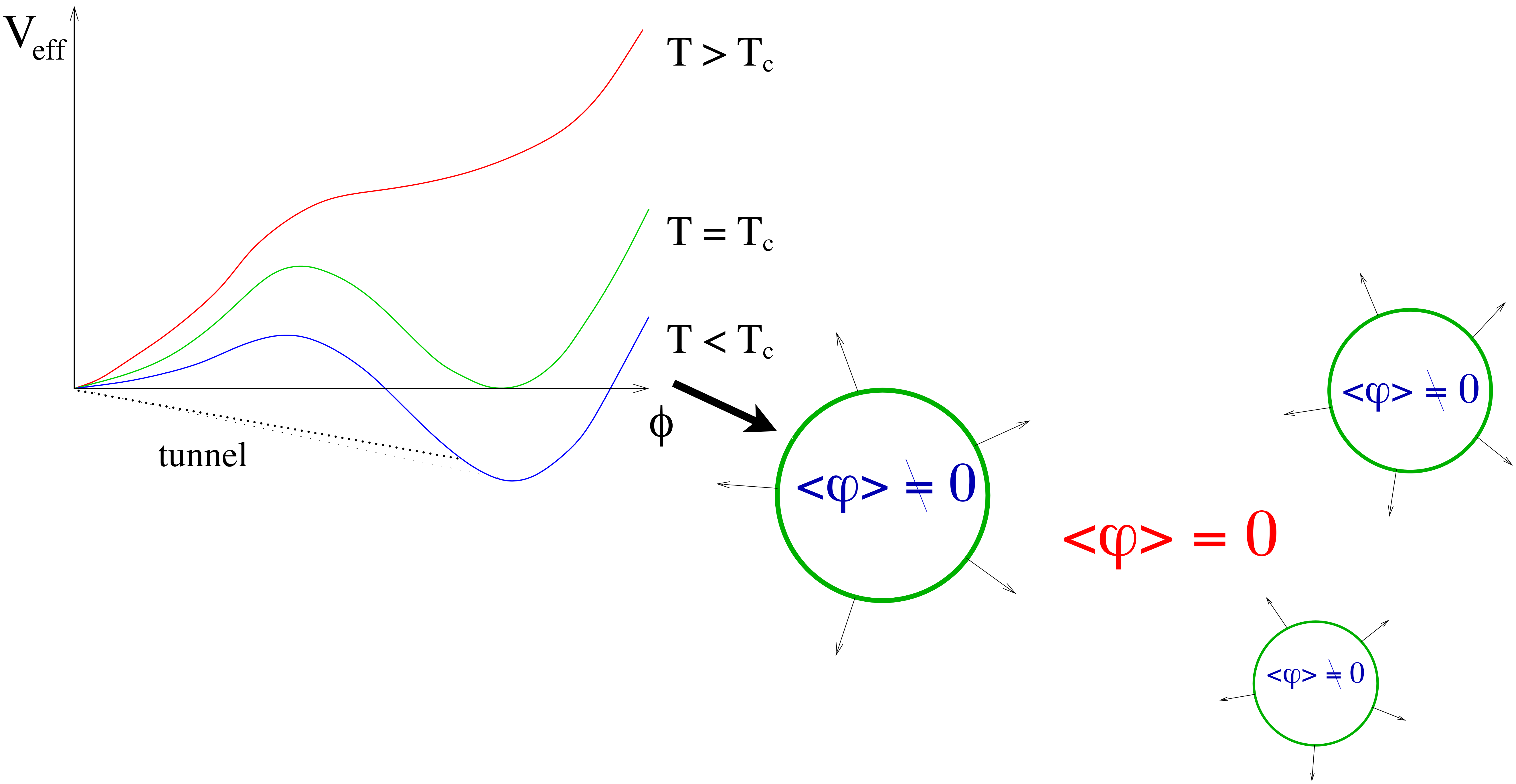
[Cohen, Kaplan, Nelson '90-'95]

Three Steps:

1. First-order EW phase transition makes "Higgs" bubbles.
2. C and CP violation near the bubble walls induce chiral asymmetries.
3. Electroweak sphalerons convert this to a baryon charge.

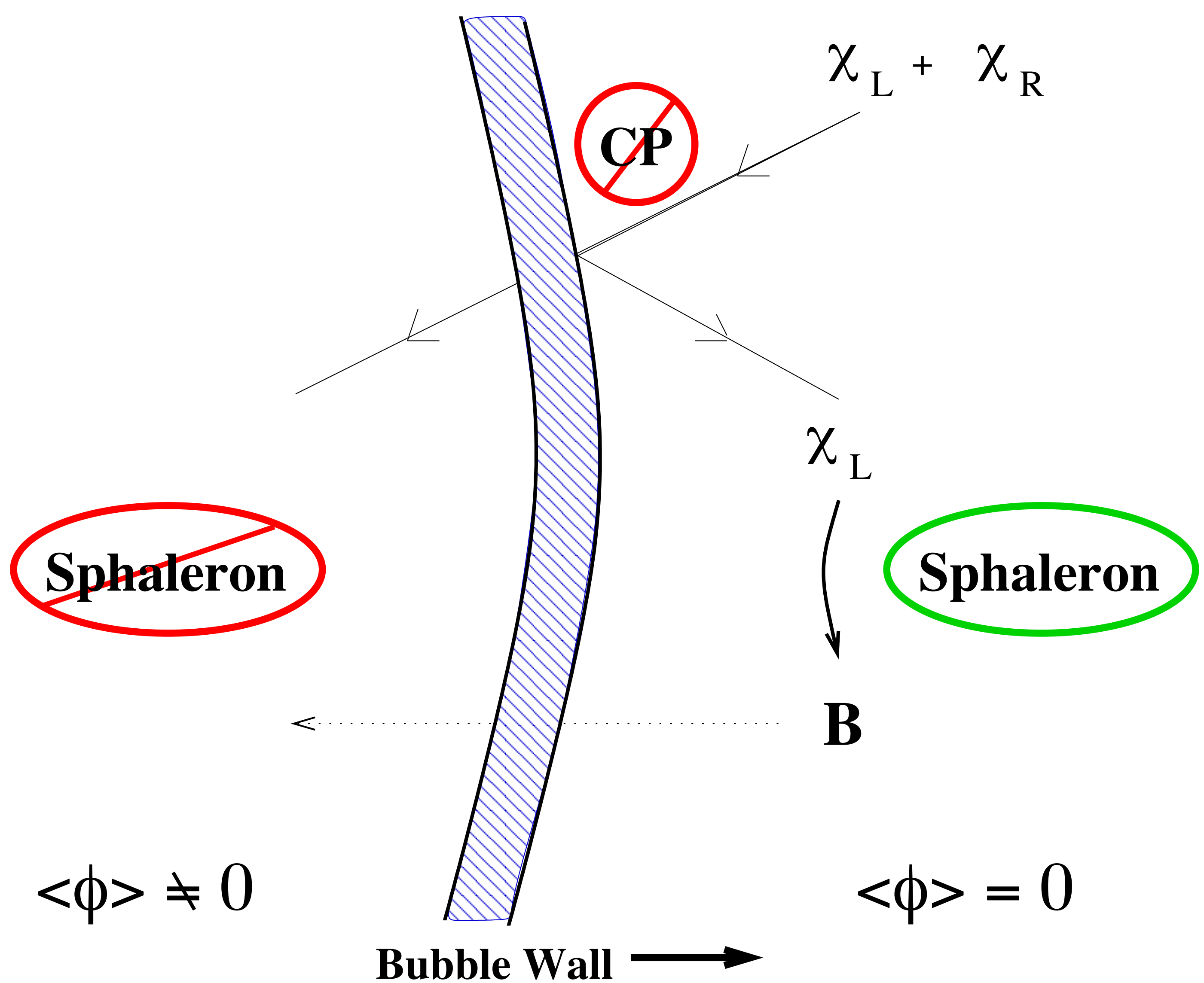
EWBG Step 1: Electroweak Bubbles

- First-order electroweak breaking phase transition:



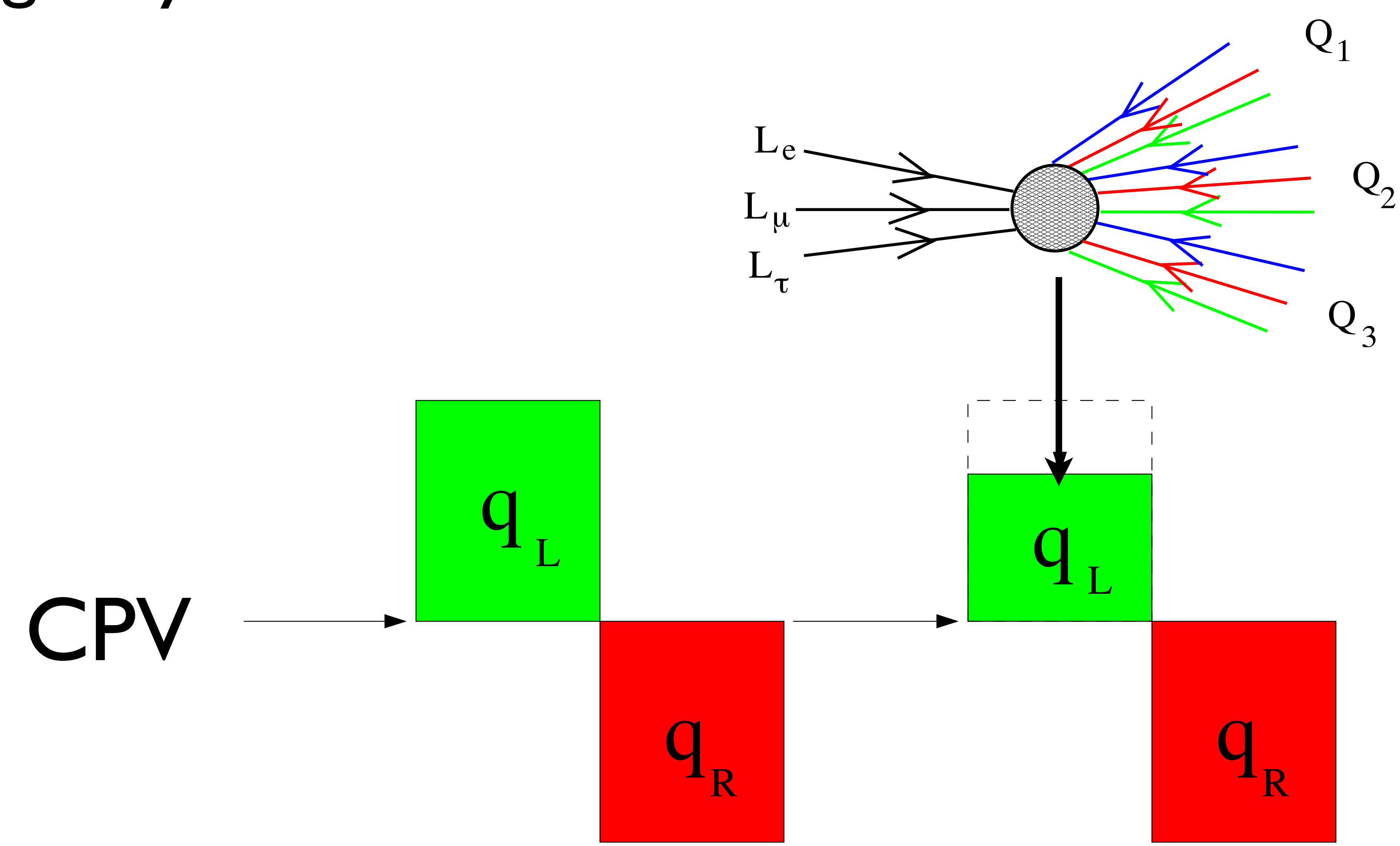
EWBG Step 2: Particle Asymmetries

- Particles in the plasma scatter off the bubbles. C+CP violation can lead to charge asymmetries.



EWBG Step 3: Sphaleron Transitions

- Sphaleron transitions are active outside the bubbles. Charge asymmetries bias them to make more baryons.



- Baryons are swept up by bubbles where they are stable.

EWBG in the Standard Model

- It does not work for two reasons:

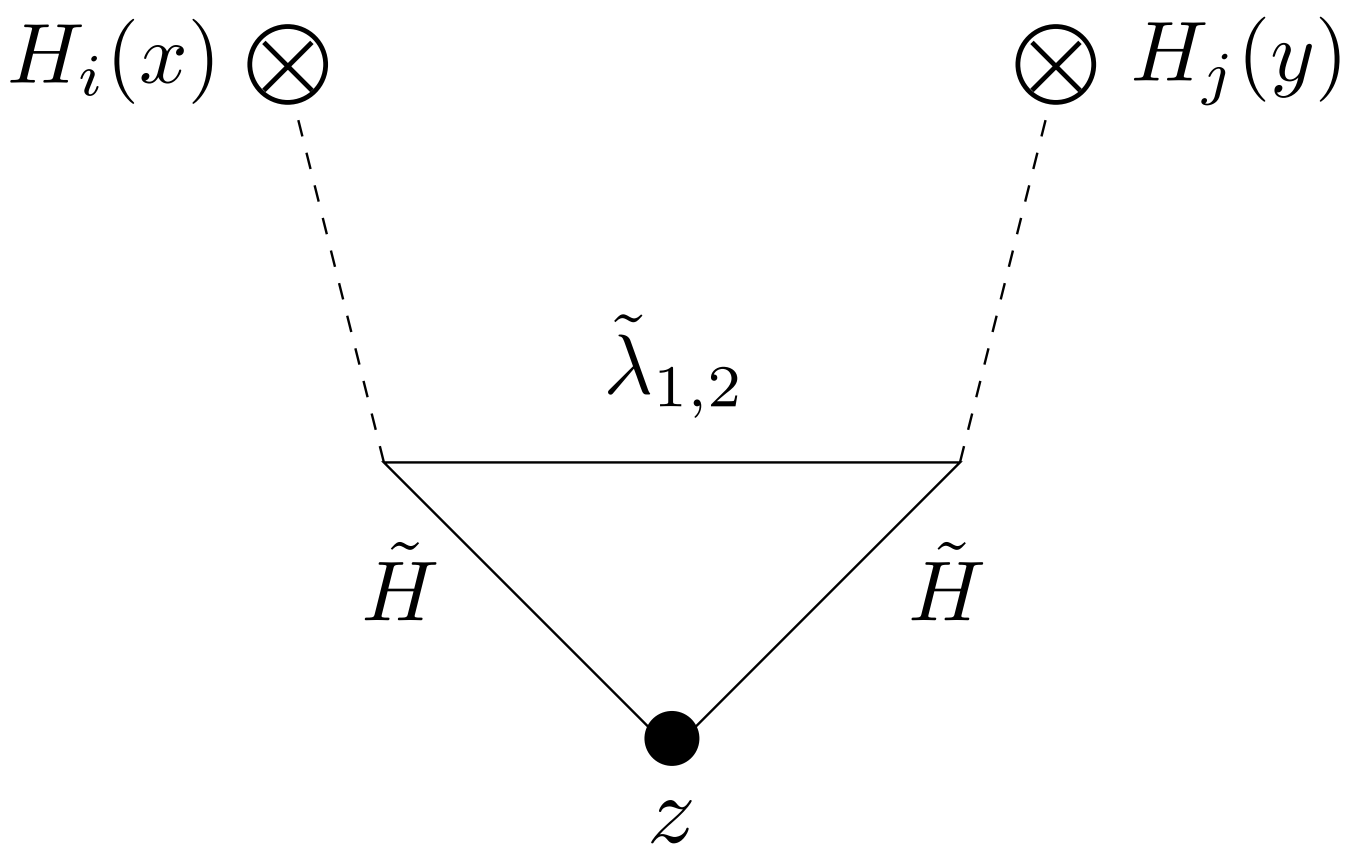
  1. The EW PT is not first order for m_h = 125 GeV.
     [Kajantie, Laine, Rummukainen, Shaposhnikov '98]

  2. Not enough effective CP violation.
     [Gavela, Hernandez, Orloff, Pene'94; Huet + Sather '95]

- EWBG could work with new physics.
  e.g. Minimal Supersymmetric Standard Model (MSSM)

CP Violating Sources

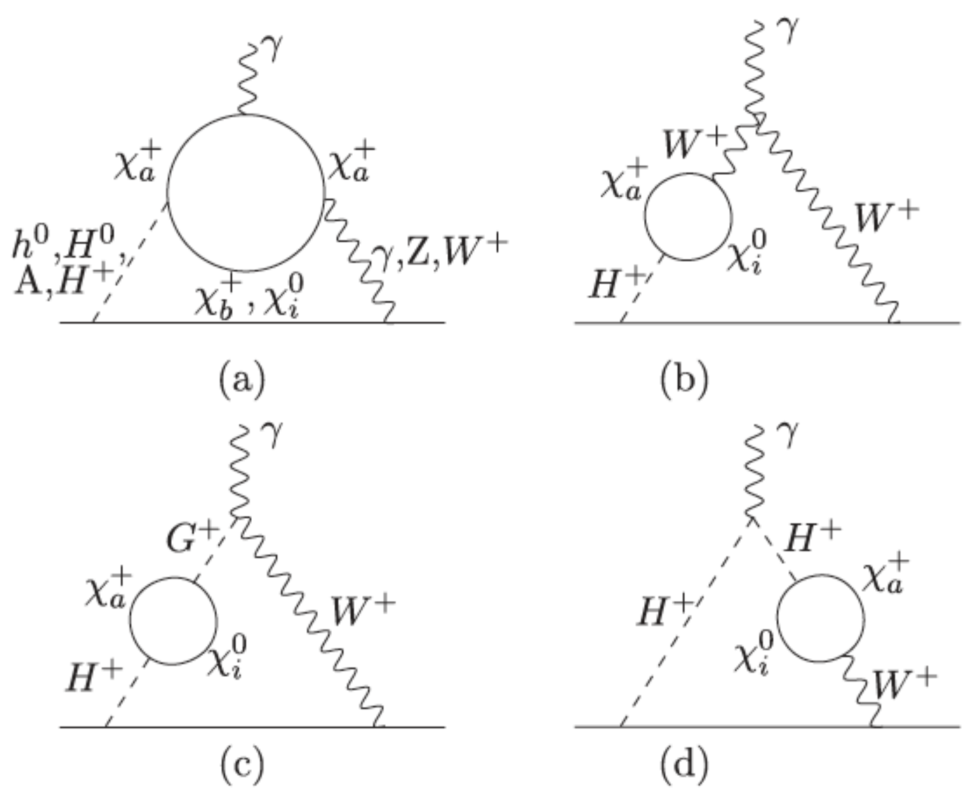
MSSM: Charginos and Neutralinos $(\widetilde{H}_u, \widetilde{H}_d, \widetilde{W}^a, \widetilde{B}^0)$



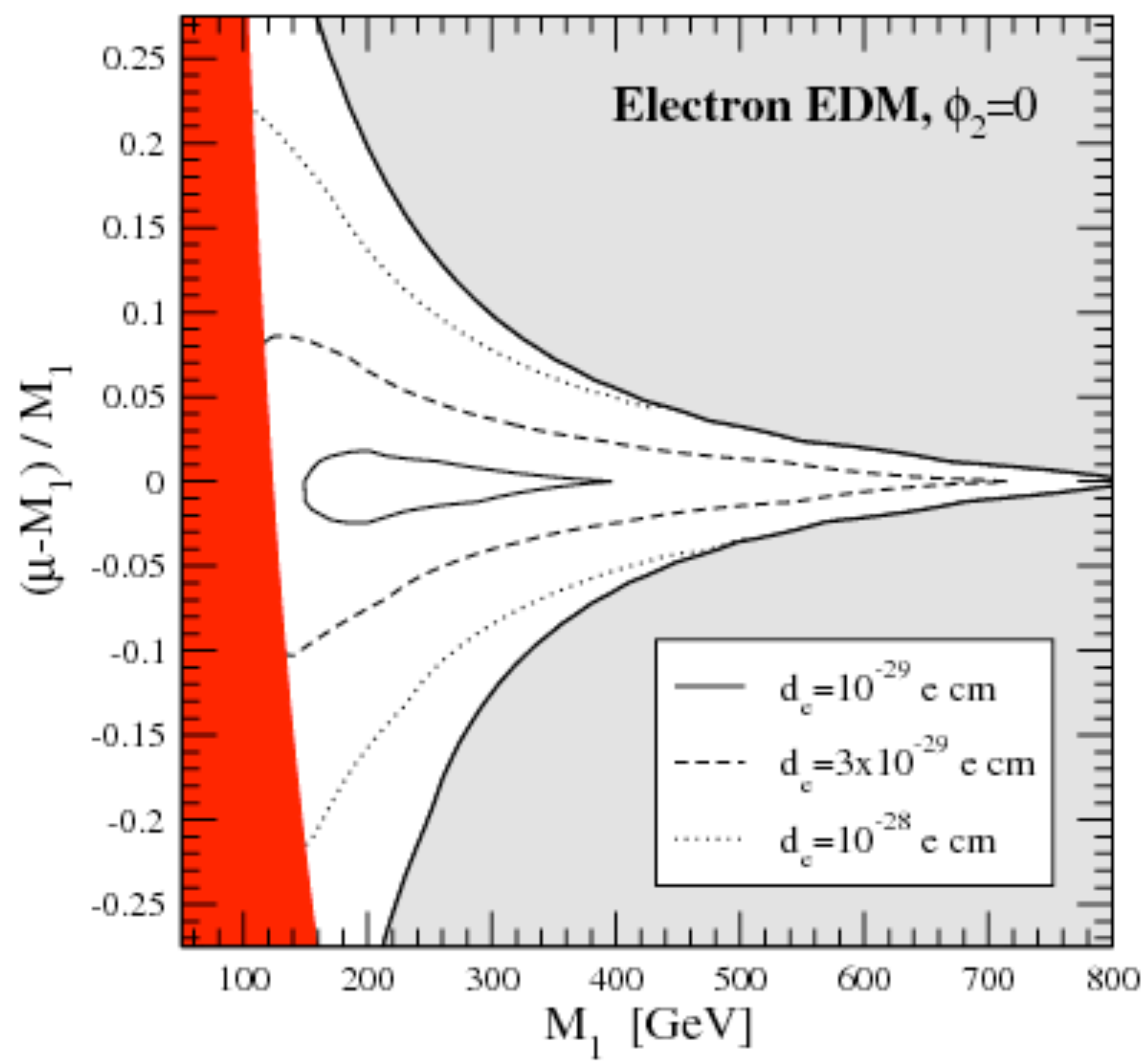
$$
\begin{aligned}
S_{CPV}^{\tilde{H}} &= \partial_0 J_{\tilde{H}}^0(z) \\
&\propto Im(\mu\, M_i)\, \partial_z f(v_u(z), v_d(z))
\end{aligned}
$$

Electric Dipole Moments (EDM)

- Two loop:
  [Chang, Keung, Pilaftsis '98; ...]



[Cirigliano, Li, Profumo, Ramsey-Musolf '09]



- Does not decouple!
- ACME (2013): $d_e < 8.7 \times 10^{-29}\,\mathrm{e\ cm}$

More CPV:
Strong CP and the Axion

Strong CP

- An allowed term in the QCD Lagrangian is:

$$\mathcal{L}_{QCD} \supset \Theta \frac{\alpha_s}{16\pi} \epsilon^{\mu\nu\alpha\beta} G^a_{\mu\nu} G^a_{\alpha\beta}$$
$$\sim \Theta \frac{\alpha_s}{16\pi} \vec{E}^a \cdot \vec{B}^a$$

- Non-zero Θ breaks P and T explicitly.

- Implication:

$$d_n \simeq \Theta\,(1.0 \times 10^{-16})\,\mathrm{e\,cm}$$

[Shindler, Luu, de Vries 2015]

- Strong CP problem: why is Θ so small?

Strong CP and the Axion

- Axion = new pseudo-Nambu-Goldstone boson

$$\mathcal{L}_{eff} \supset \left(\Theta + \frac{a}{f_a}\right) \frac{\alpha_s}{16\pi} \epsilon^{\mu\nu\alpha\beta} G^a_{\mu\nu} G^a_{\alpha\beta}$$

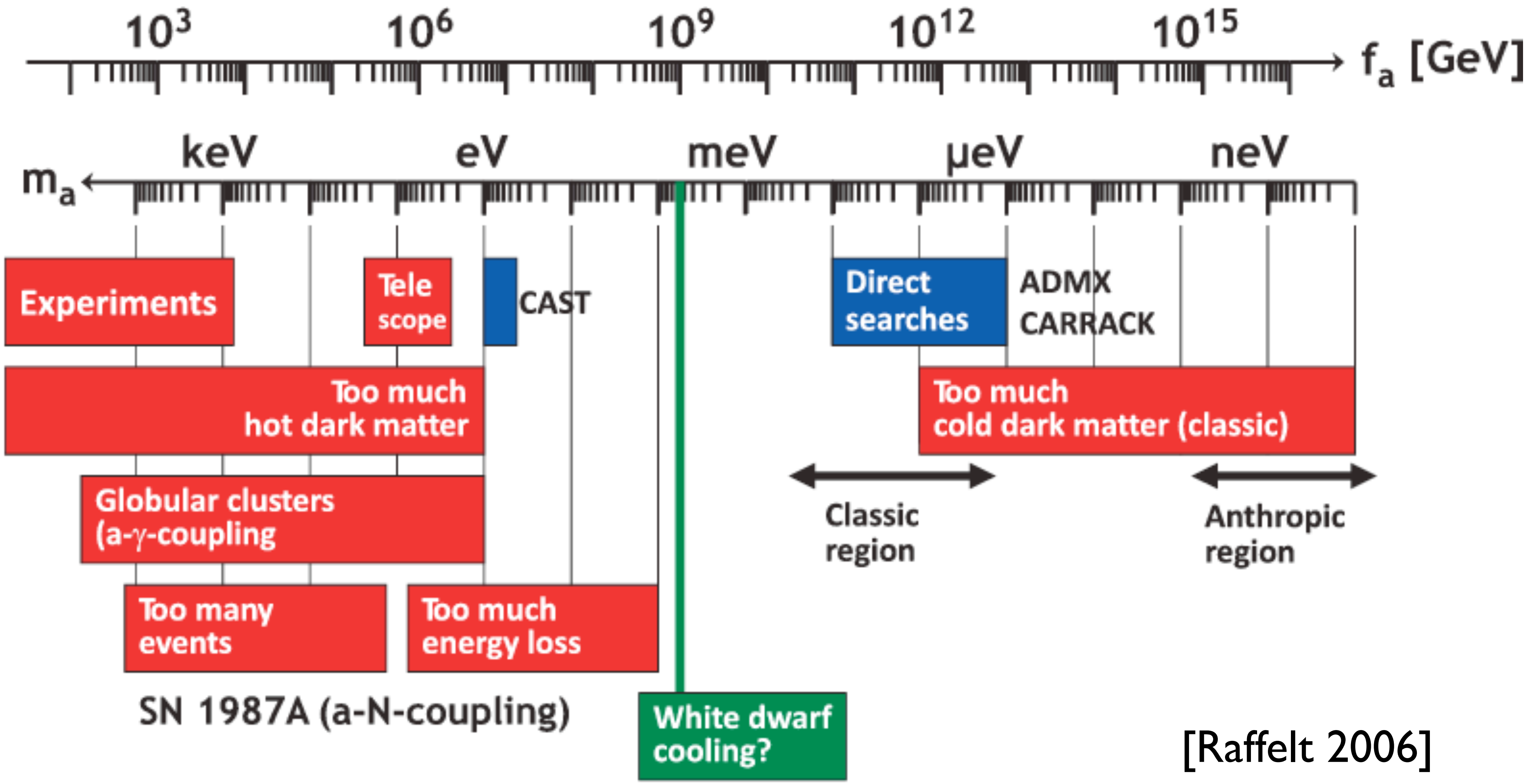
f_a = axion decay constant

- QCD confinement generates a potential

$$V_{eff}(a) \sim \Lambda^4_{QCD} \left[1 - \cos(\Theta + a/f_a)\right]$$

Minimized with $\Theta_{eff} = (\Theta + a/f_a) \to 0\,!$

Axion Bounds



[Raffelt 2006]

- Axion window: $$f_a \in [10^9, 10^{12}]\,\mathrm{GeV}$$ $$m_a \in [10^{-6}, 10^{-3}]\,\mathrm{eV}$$

Axion Corrections and the nEDM

- Axion theories usually rely on global symmetries. These are expected to be broken by quantum gravity. e.g.

$$\Delta V_{eff}(a) \;\sim\; \lambda \frac{a^{n+4}}{M_{\rm Pl}^n}$$

- These ruin the axion cancellation: [Holman *et al.* 1992]

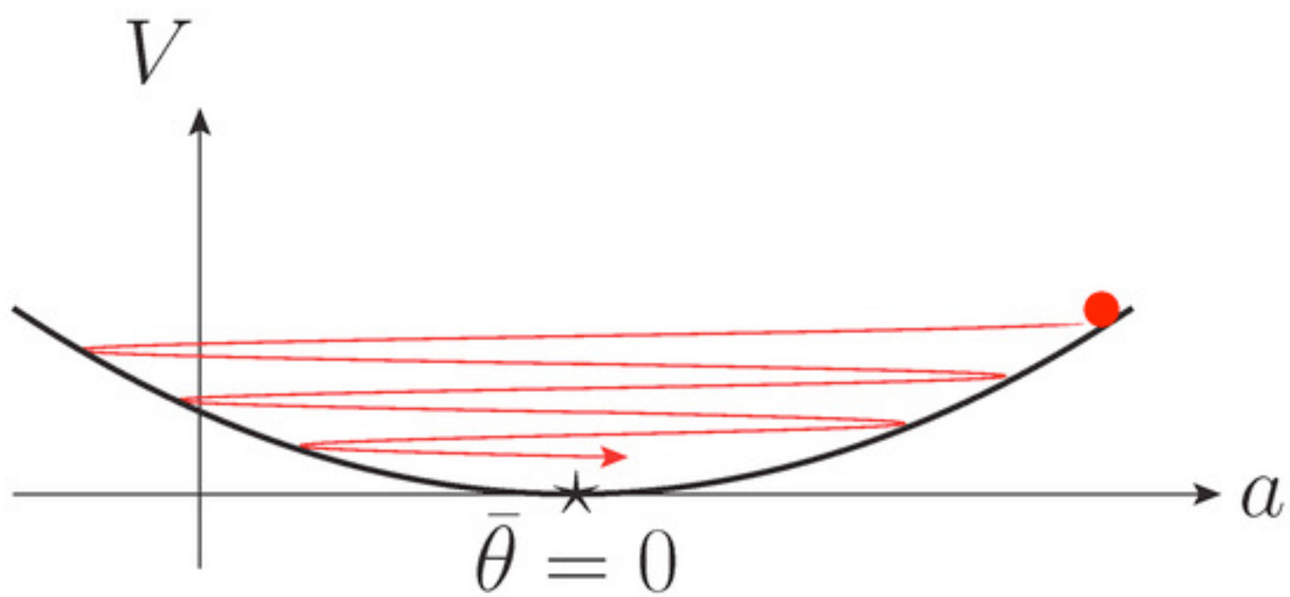
$$\Theta_{eff} \;=\; \langle \Theta + a/f_a \rangle$$

$$\to\; (10^{48})\,\lambda\,\Theta\left(\frac{f_a}{10^{11}\,\mathrm{GeV}}\right)^4\left(\frac{f_a}{M_{\rm Pl}}\right)^n$$

- Improving limits on Θ_{eff} via d_n constrains axion theories.

Axion Oscillations and Dark Matter

- Coherent axion oscillations act as dark matter.



- Result: $\Theta_{eff} \;=\; (\Theta + a/f_a)$ oscillates!

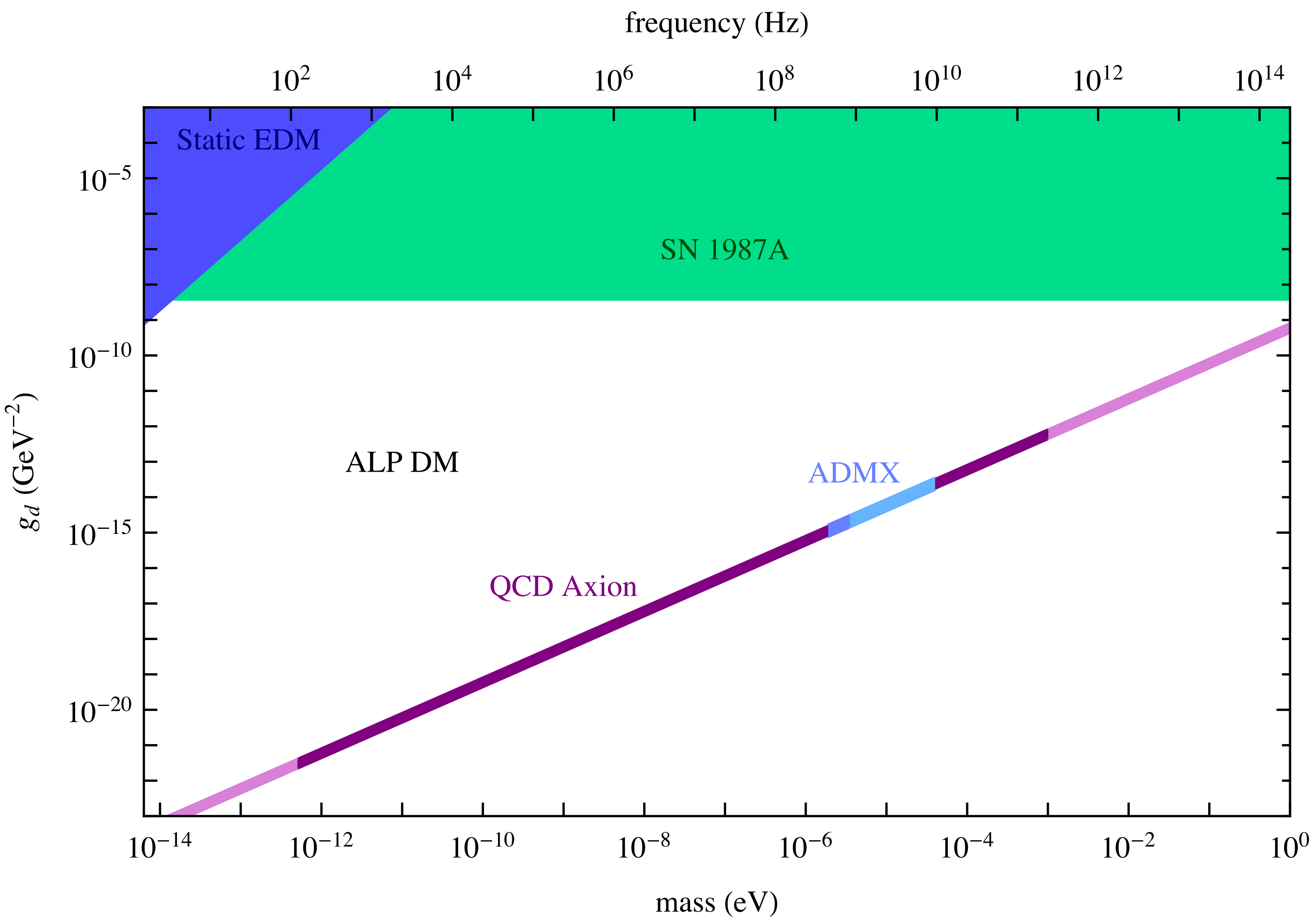
- For axion DM,

$$d_n \;\simeq\; (9 \times 10^{-35}\, e\,\mathrm{cm})\; \cos(m_a t)$$

[Graham, Rajendran 2013]

Axion Oscillations and Dark Matter

- Landscape of possibilities:



[Graham, Rajendran 2013]

Summary

- Known CP violation only produces small EDMs.
- EDM searches can probe new CP violating physics up to masses beyond the reach of the LHC.
- New sources of CP violation are needed to explain the matter asymmetry of the universe.
- EDM searches are already testing weak-scale BG mechanism.
- QCD seems to contain an overly large source of CPV.
- An axion can fix this, with interesting consequences...

Extra Slides

CKM Mixing

- Suggestive:

$$|V_{CKM}| \simeq \begin{pmatrix} 0.9748 & 0.226 & 0.0041 \\ 0.220 & 0.995 & 0.042 \\ 0.0082 & 0.040 & 1.0 \end{pmatrix} .$$

- Hierarchical structure hints at underlying theory of flavor!

- Note - CKM CPV is not small:

$$\delta = (65.9 \pm 0.2)^\circ$$

But the hierachical flavor structure suppresses flavor-conserving CPV observables like EDMs.

Baryogenesis at the Weak Scale?

- B-violating transitions occur by quantum tunnelling:

$$\Gamma/V \;\propto\; e^{-16\pi^2/g_W^2} \;\sim\; 10^{-320}$$

- At finite temperature, transitions can also occur via thermal "sphaleron" fluctuations over the barrier.

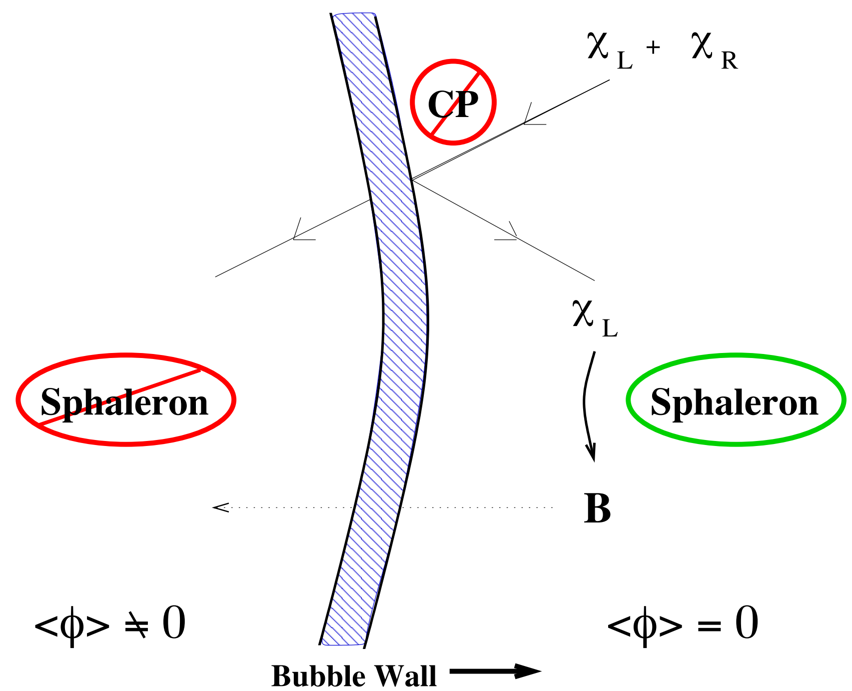
$$\Gamma/V \sim \begin{cases} (\alpha_w T)^4 & \langle H \rangle = 0 \;\; \text{(fast)} \\ T^4 \exp(-8\pi\langle H \rangle/g_w T) & \langle H \rangle \neq 0 \;\; \text{(slow)} \end{cases}$$

- $\langle H \rangle$ = Higgs expectation value ($m_W = g_W \langle H \rangle/\sqrt{2}$)

A Strong Phase Transition

- Electroweak PT must be "strongly" first order to prevent sphaleron washout of B within the broken phase.

$$\Gamma/V \ \sim \ T^4 \exp(-8\pi\langle H\rangle/g_w T)$$



- For bubble nucleation close to the critical temperature,

$$\frac{``\langle H_c\rangle"}{T_c} \gtrsim 1.0 \ .$$

[Bochkarev, Kuzmin, Shaposhnikov '91; Patel, Ramsey-Musolf '11]