Nikhef

Radboud Universiteit

ELECTRIC DIPOLE MOMENTS AND BARYOGENESIS

Marieke Postma
Madrid June 2023

PLAN

1. Electric dipole moments
2. Implications for electroweak baryogenesis

MAGNETIC AND ELECTRIC DIPOLE MOMENTS

Hamiltonian for non-relativistic particle with spin

$$H = -d_m \vec{S} \cdot \vec{B} - d_e \vec{S} \cdot \vec{E}$$

magnetic dipole moment

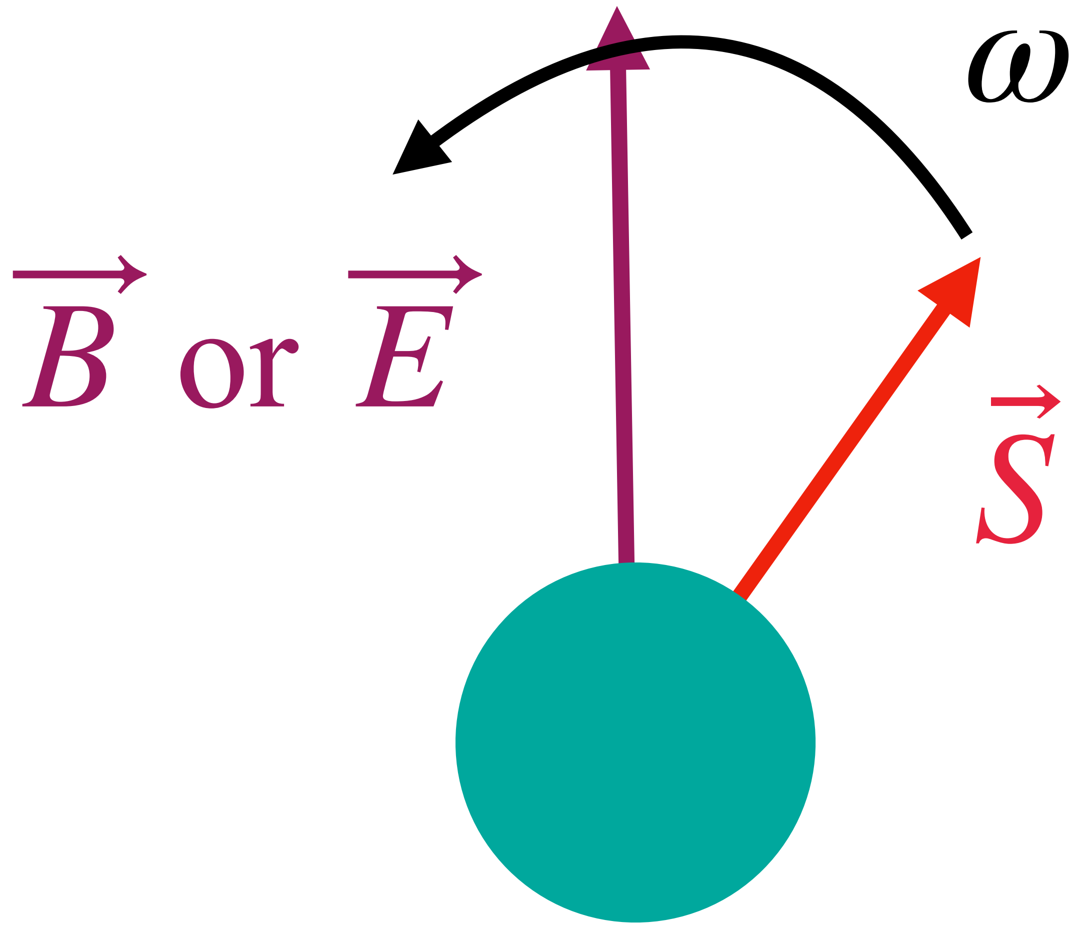
electric dipole moment

MAGNETIC AND ELECTRIC DIPOLE MOMENTS

Hamiltonian for non-relativistic particle with spin

$$H = -d_m \vec{S} \cdot \vec{B} - d_e \vec{S} \cdot \vec{E}$$

spin procession



magnetic dipole $\omega = d_m B \sin\theta$

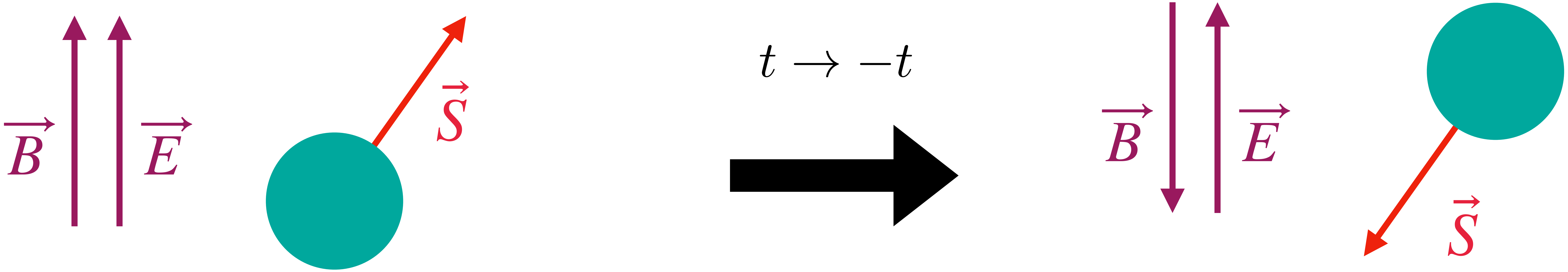
electric dipole $\omega = d_e E \sin\theta$

MAGNETIC AND ELECTRIC DIPOLE MOMENTS

Hamiltonian for non-relativistic particle with spin

$$H = -d_m \vec{S} \cdot \vec{B} - d_e \vec{S} \cdot \vec{E}$$

$$H = -d_m \vec{S} \cdot \vec{B} + d_e \vec{S} \cdot \vec{E}$$

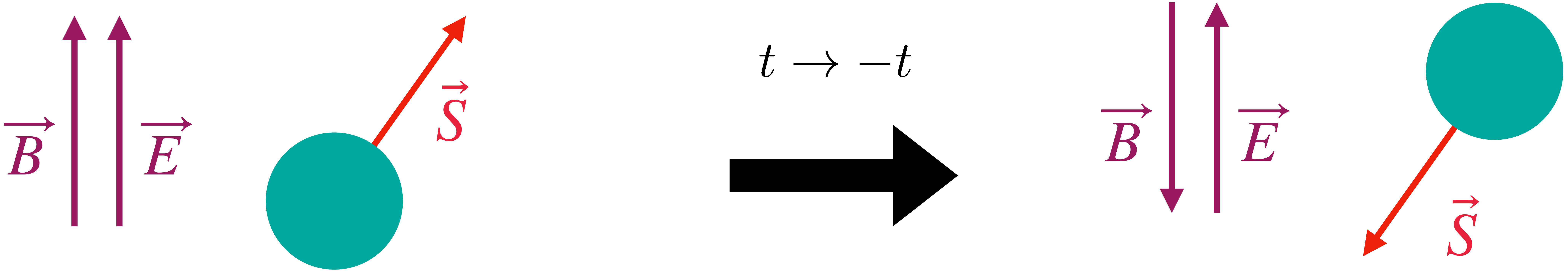


MAGNETIC AND ELECTRIC DIPOLE MOMENTS

Hamiltonian for non-relativistic particle with spin

$$H = -d_m \vec{S} \cdot \vec{B} - d_e \vec{S} \cdot \vec{E}$$

$$H = -d_m \vec{S} \cdot \vec{B} + d_e \vec{S} \cdot \vec{E}$$



CPT theorem: T-violation ↔ CP violation

MAGNETIC AND ELECTRIC DIPOLE MOMENTS

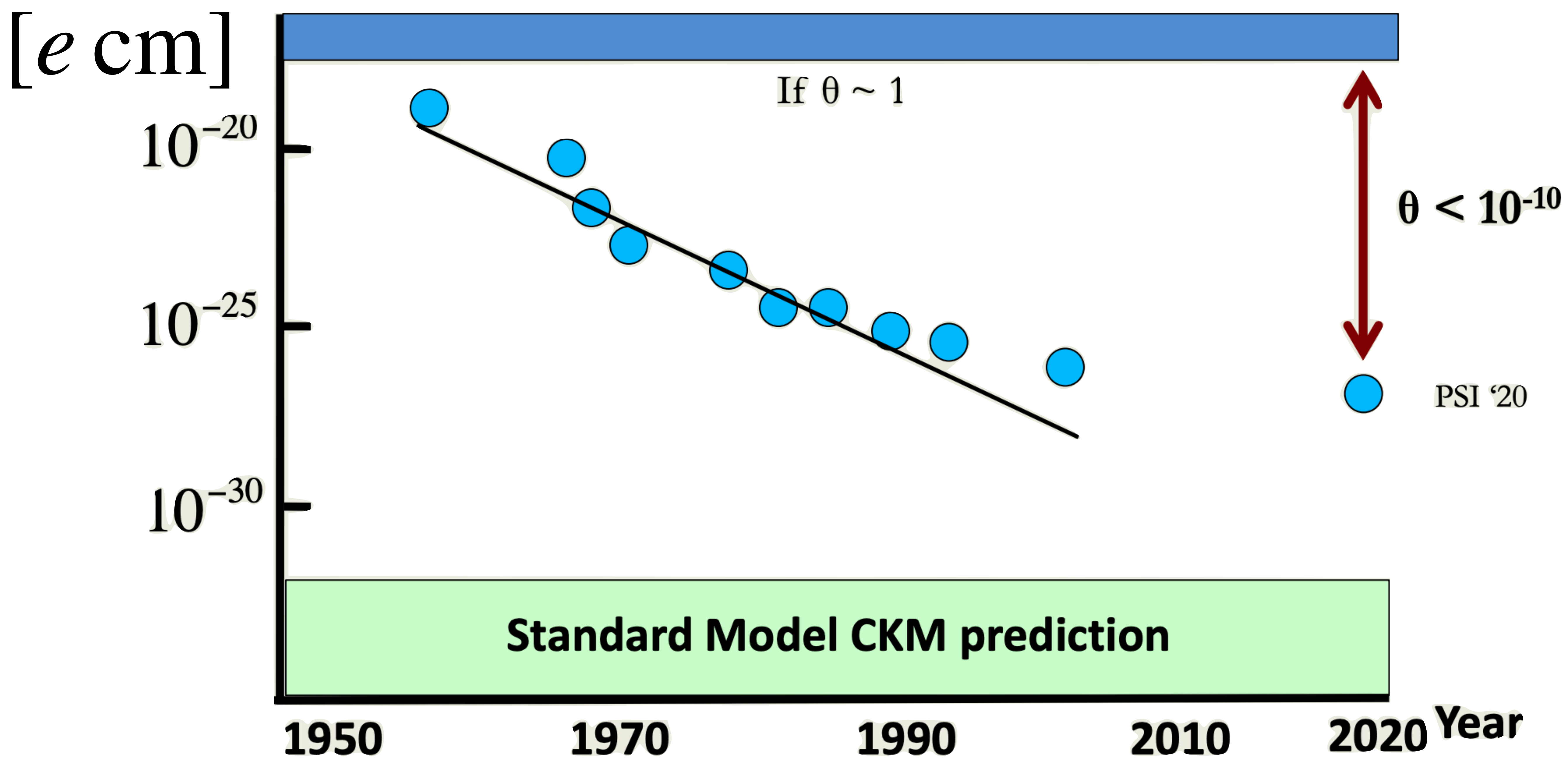
Hamiltonian for non-relativistic particle with spin

$$H = -\underset{\substack{\uparrow \\ (g-2)}}{d_m}\vec{S}\cdot\vec{B} - \underset{\substack{\nwarrow \\ \text{EDM}}}{d_e}\vec{S}\cdot\vec{E}$$

$$\mathcal{L} = -d\frac{i}{2}\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi F_{\mu\nu}$$

ELECTRIC DIPOLE MOMENT OF NEUTRON

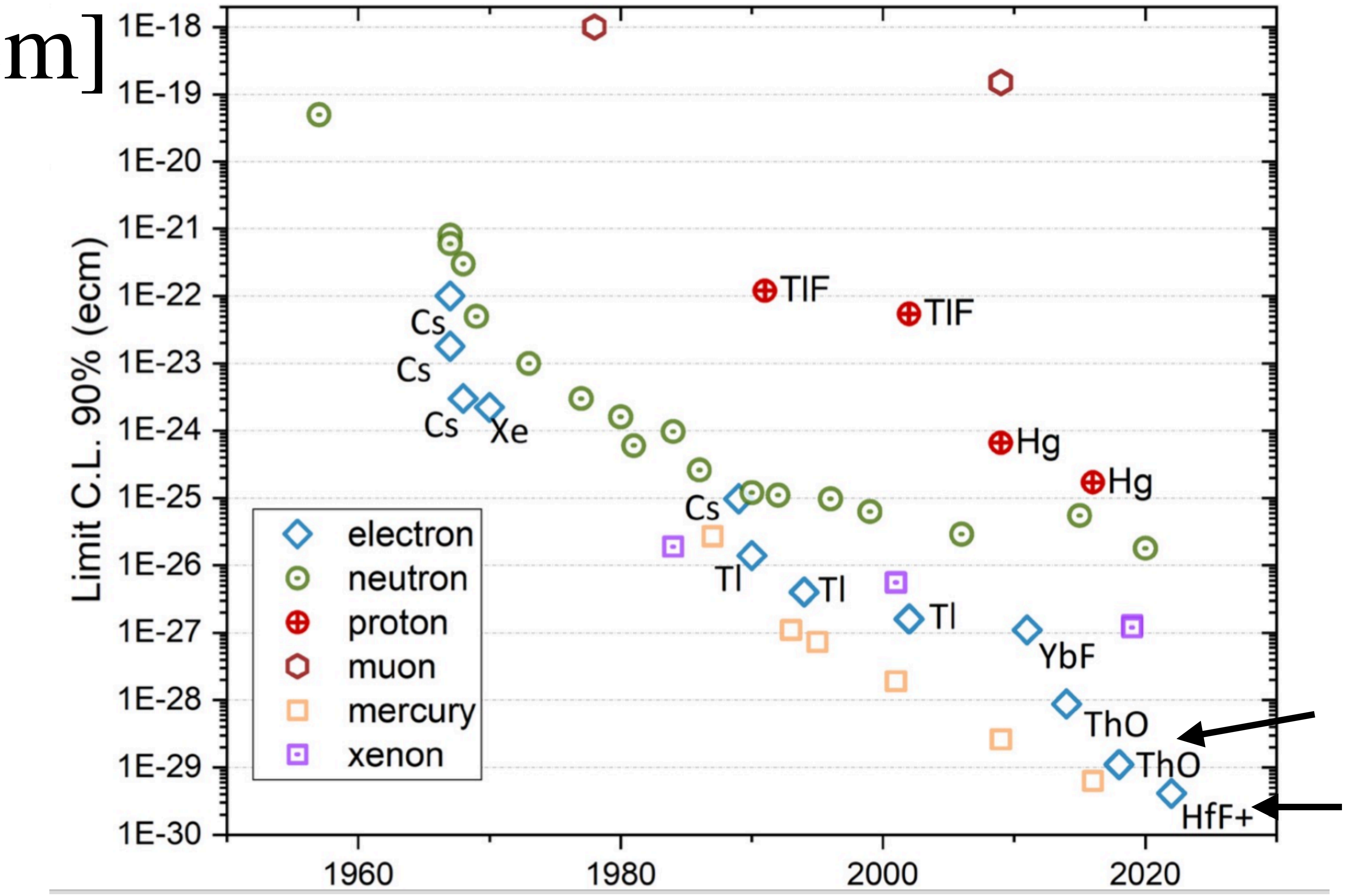
CP violation in SM: CKM phase and theta angle



from J. de vries

ELECTRIC DIPOLE MOMENT OF ELECTRON

[e cm]

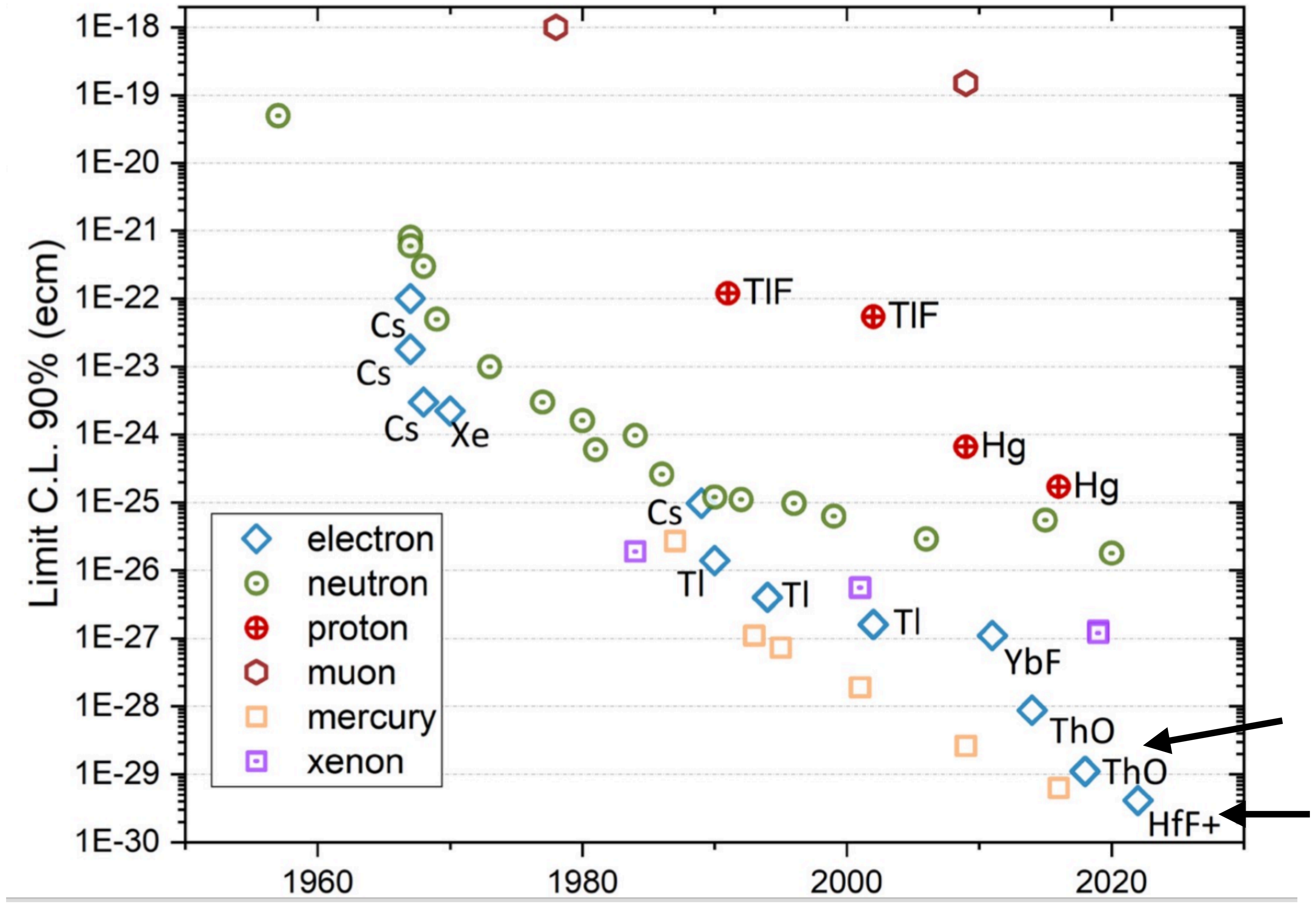


ACME

Boulder

Adelmann et al 2102.08838

ELECTRIC DIPOLE MOMENT OF ELECTRON

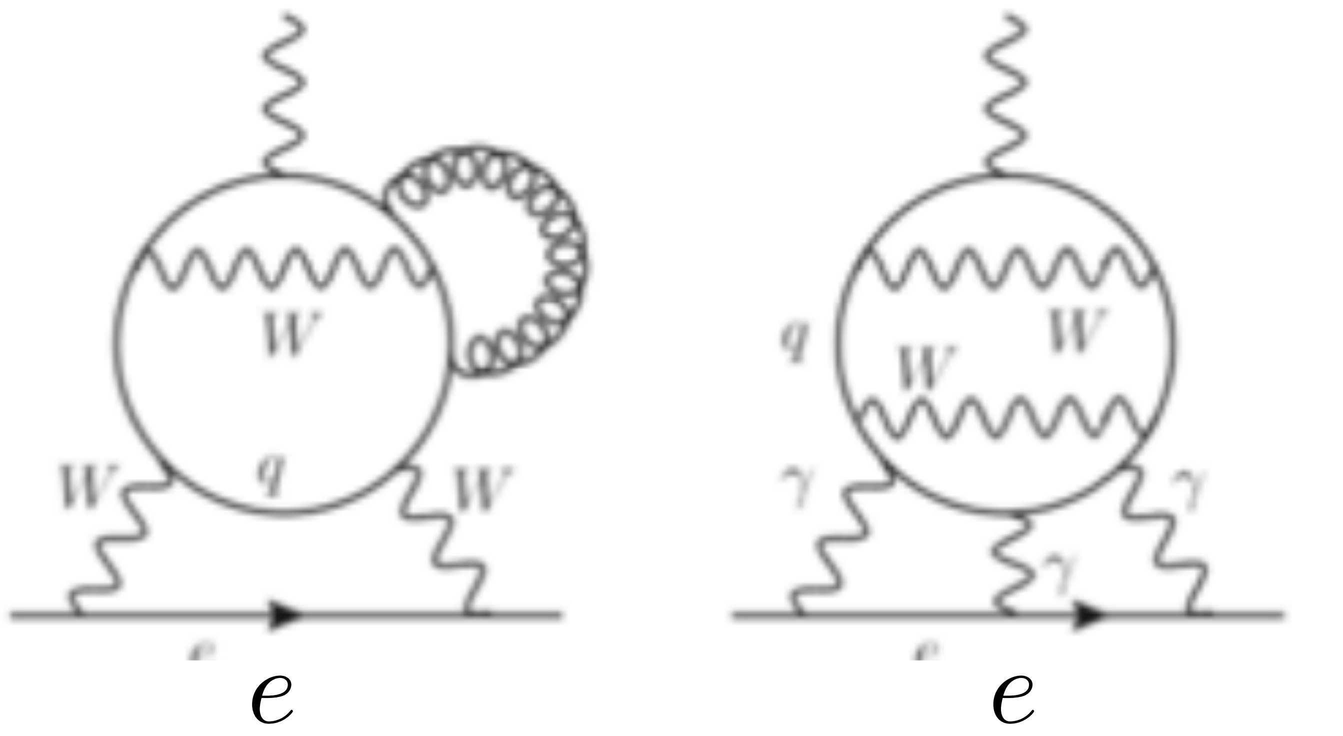


ACME

Boulder

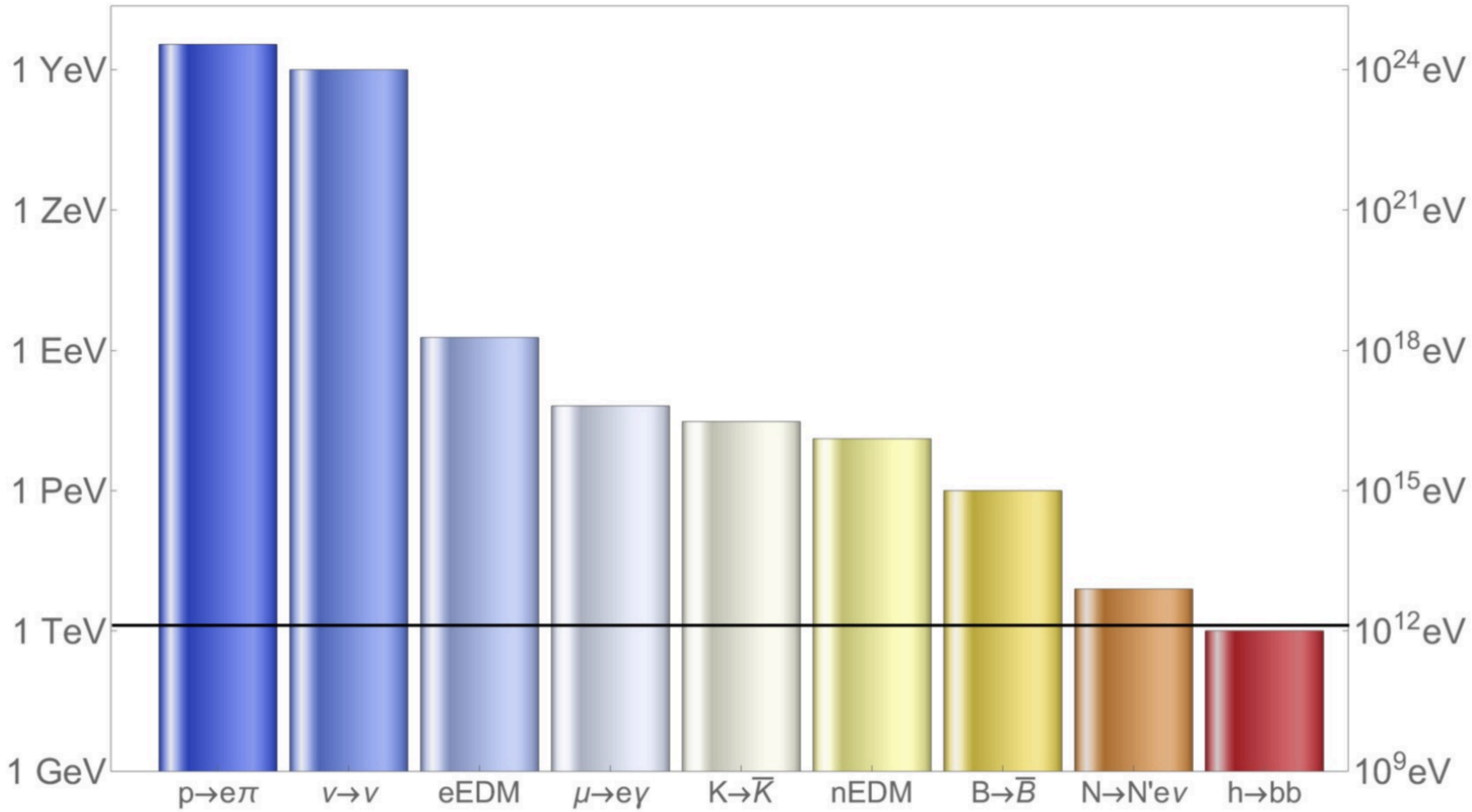
Adelmann et al 2102.08838

eEDM in SM: CKM phase



$$|d_e| \sim 10^{-44}\, e\,\mathrm{cm}$$

PHYSICS REACH OF ELECTRON EDM



$$\mathcal{L}_{\mathrm{eEDM}} = \frac{C_d}{\Lambda^2}\bar{e}_L\sigma^{\mu\nu}\gamma^5 e_R F_{\mu\nu}\varphi$$

from A. Falkowski

TYPICAL SIZE OF ELECTRON EDM

$$d_e \sim \left(\frac{\alpha}{4\pi}\right)^n \frac{m_e}{\Lambda^2} e \sin\phi \sim \left(\frac{\alpha}{4\pi}\right)^n 4 \times 10^{-24} \left(\frac{\text{TeV}}{\Lambda}\right)^2 e\,\text{cm}$$

↑

suppressed by λ_e

$$\Rightarrow \quad \Lambda \gtrsim 25\,(1)\,\text{TeV} \quad \text{for} \quad n = 1\,(2)$$

TYPICAL SIZE OF ELECTRON EDM

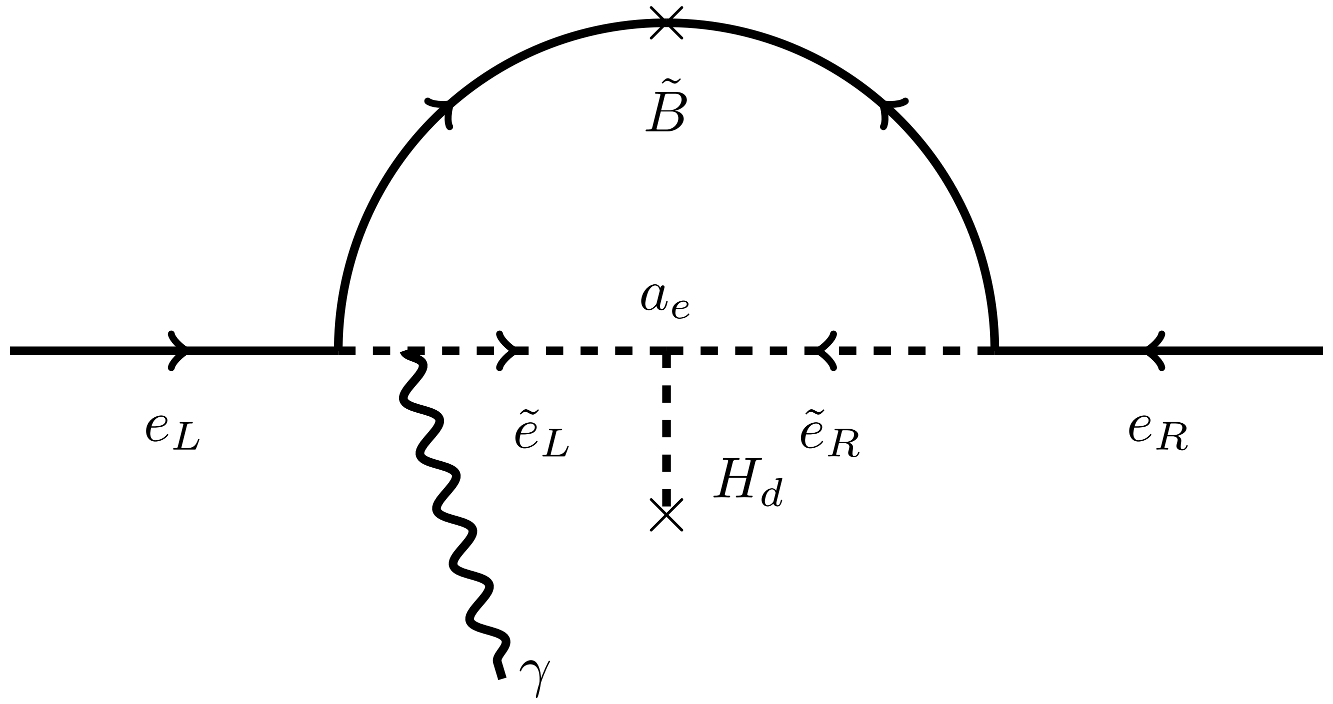
$$d_e \sim \left(\frac{\alpha}{4\pi}\right)^n \frac{m_e}{\Lambda^2} e \sin\phi \sim \left(\frac{\alpha}{4\pi}\right)^n 4 \times 10^{-24} \left(\frac{\mathrm{TeV}}{\Lambda}\right)^2 e\,\mathrm{cm}$$

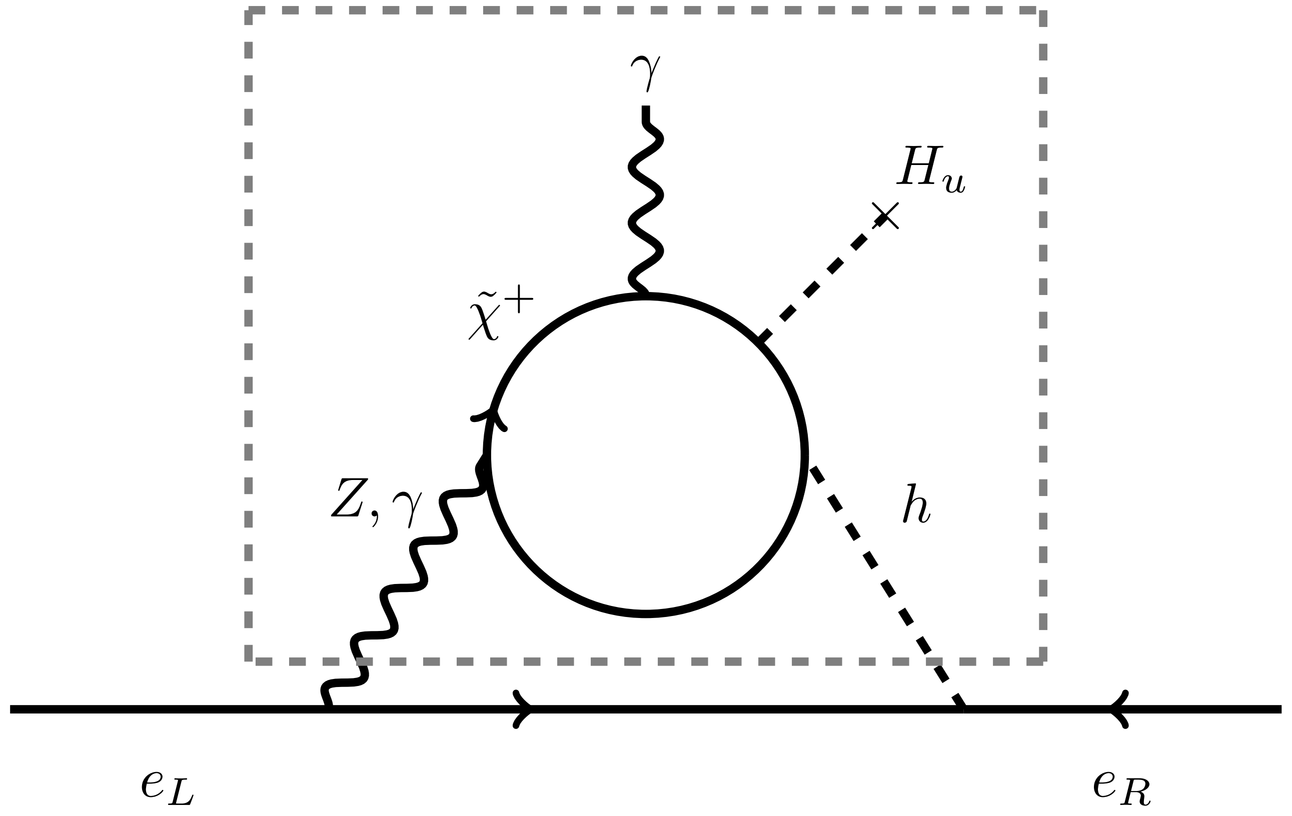
↑

suppressed by λ_e

$$\Rightarrow \quad \Lambda \gtrsim 25\,(1)\,\mathrm{TeV} \quad \text{for} \quad n = 1\,(2)$$

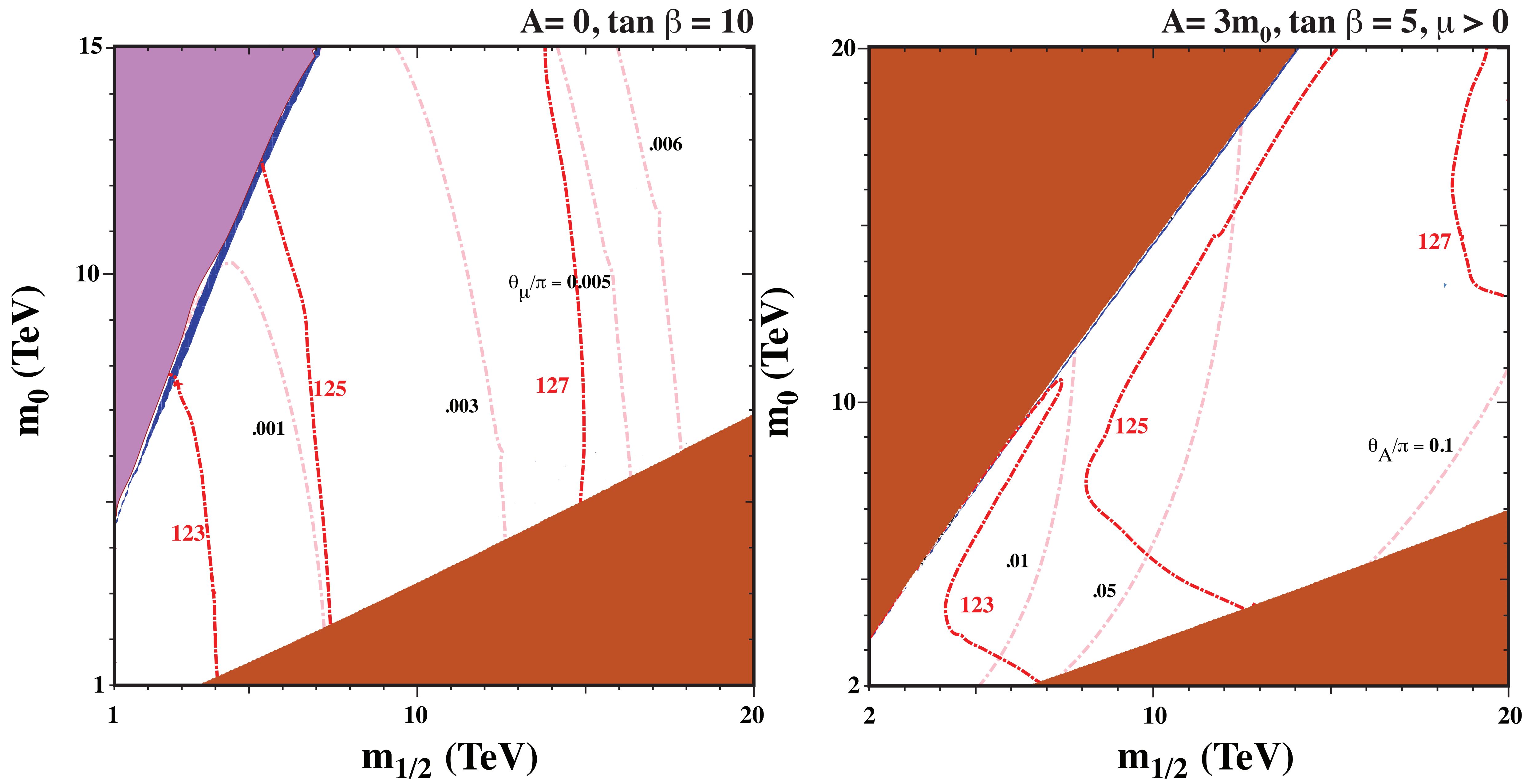
e.g. SUSY





TYPICAL SIZE OF ELECTRON EDM

$$d_e \sim \left(\frac{\alpha}{4\pi}\right)^n \frac{m_e}{\Lambda^2}\, e \sin\phi \sim \left(\frac{\alpha}{4\pi}\right)^n 4\times 10^{-24}\left(\frac{\text{TeV}}{\Lambda}\right)^2 e\,\text{cm}$$



$$\Rightarrow \quad \Lambda \gtrsim 25\,(1)\,\text{TeV} \quad \text{for} \quad n = 1\,(2)$$

Kaneta et al 2303.02822

CMSSM: $|d_e| \sim 10^{-26} e \cdot \text{cm} \times \alpha_{\text{em}} \left(\frac{10\,\text{Tev}}{\tilde{m}}\right)^2 |\tan\beta \sin\phi_\mu - \sin\phi_a|$

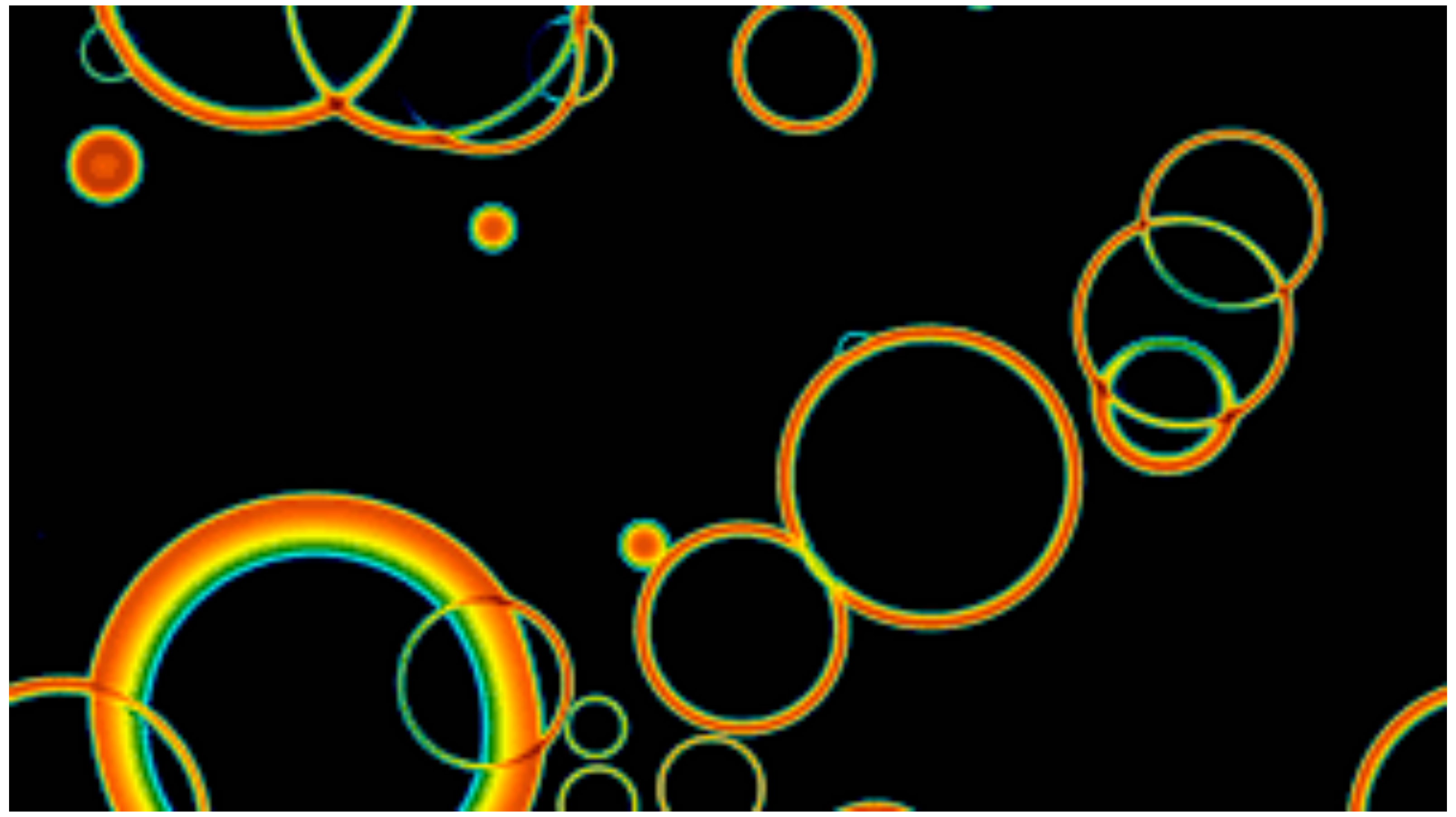
PLAN

1. Electric dipole moments : very sensitive probe of CPV new physics
2. Implications for electroweak baryogenesis

Why is everything made out of matter?

$$Y_b = \frac{n_b - n_{\bar{b}}}{s} \sim 10^{-10}$$

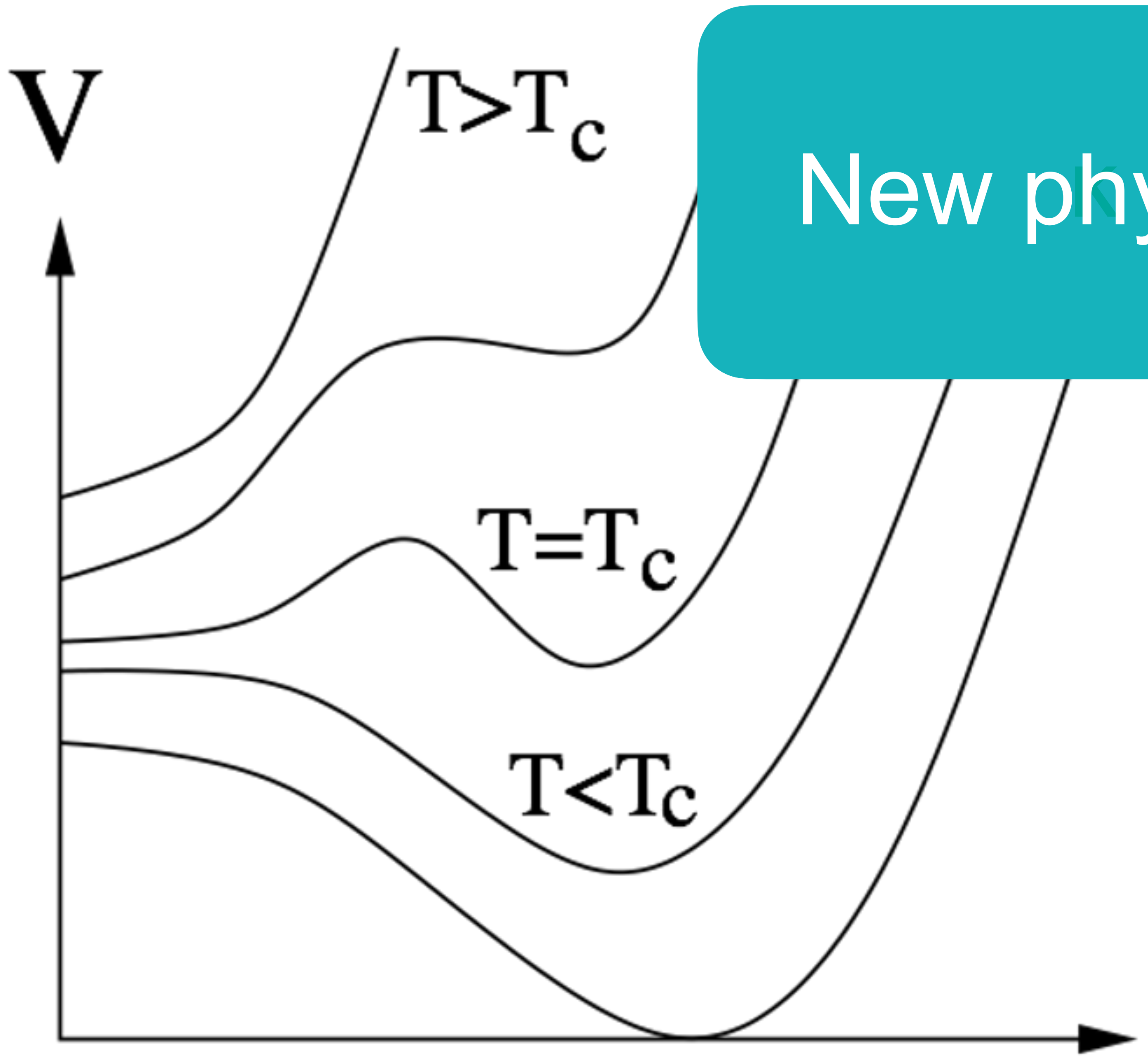
ELECTROWEAK BARYOGENESIS



Sakharov conditions:

1. Baryon number violation: sphalerons
2. C- and CP-violation: new CP violation at EW scale
3. Out of equilibrium: 1st order EW phase transition

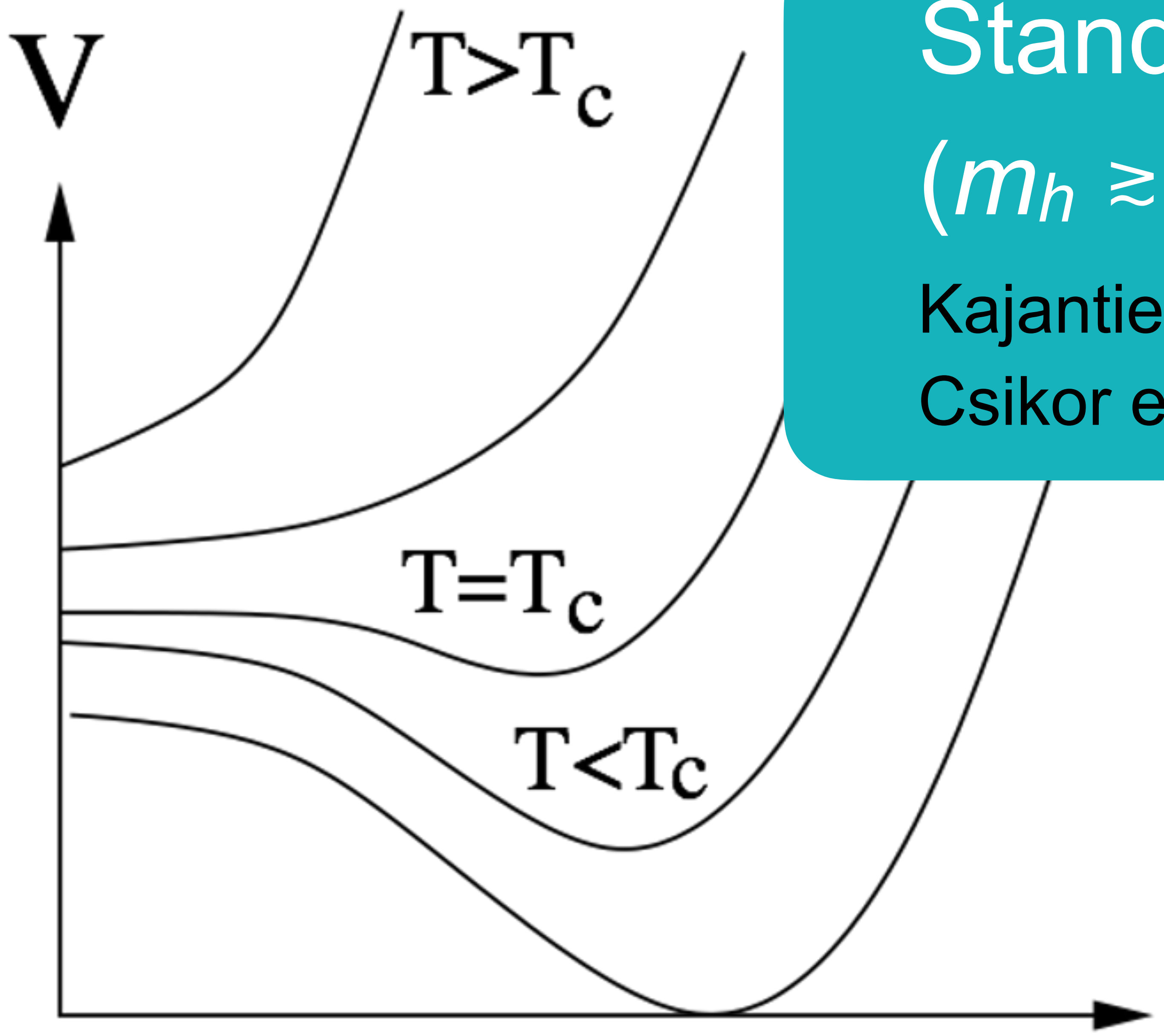
EW PHASE TRANSITION



New physics

from Cline ’06

1st order



Standard Model ($m_h \gtrsim 65$ GeV)

Kajantie et al. ’96
Csikor et al. ‘98

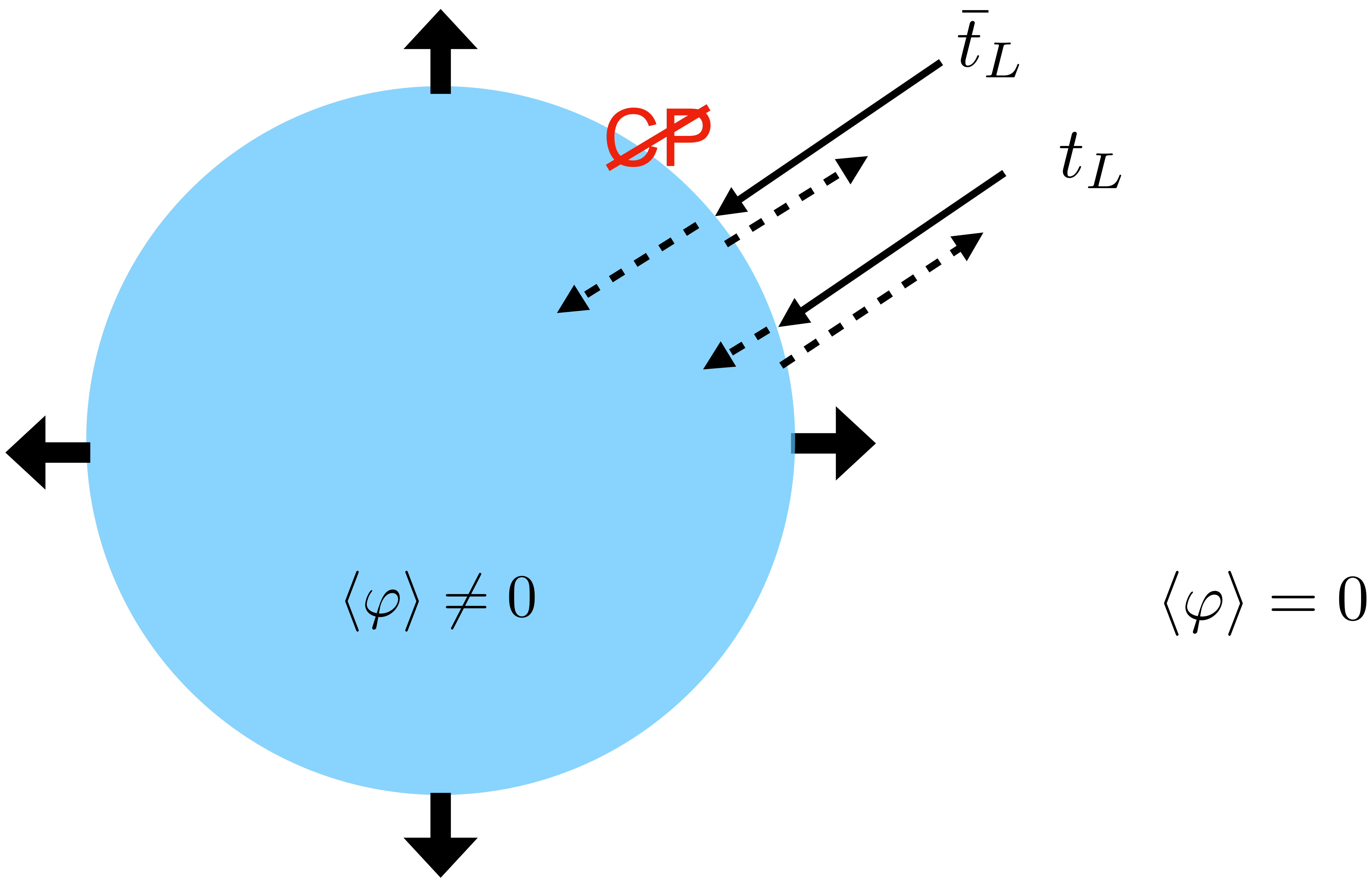
2nd order/cross over

ELECTROWEAK BARYOGENESIS IN A NUTSHELL

Cohen, Kaplan and Nelson 1991

$$\mathcal{L} \supset \frac{y_t}{\sqrt{2}}\varphi\left(1 + c\frac{\varphi^2}{\Lambda^2}\right)\bar{t}_L t_R + \text{h.c.}$$

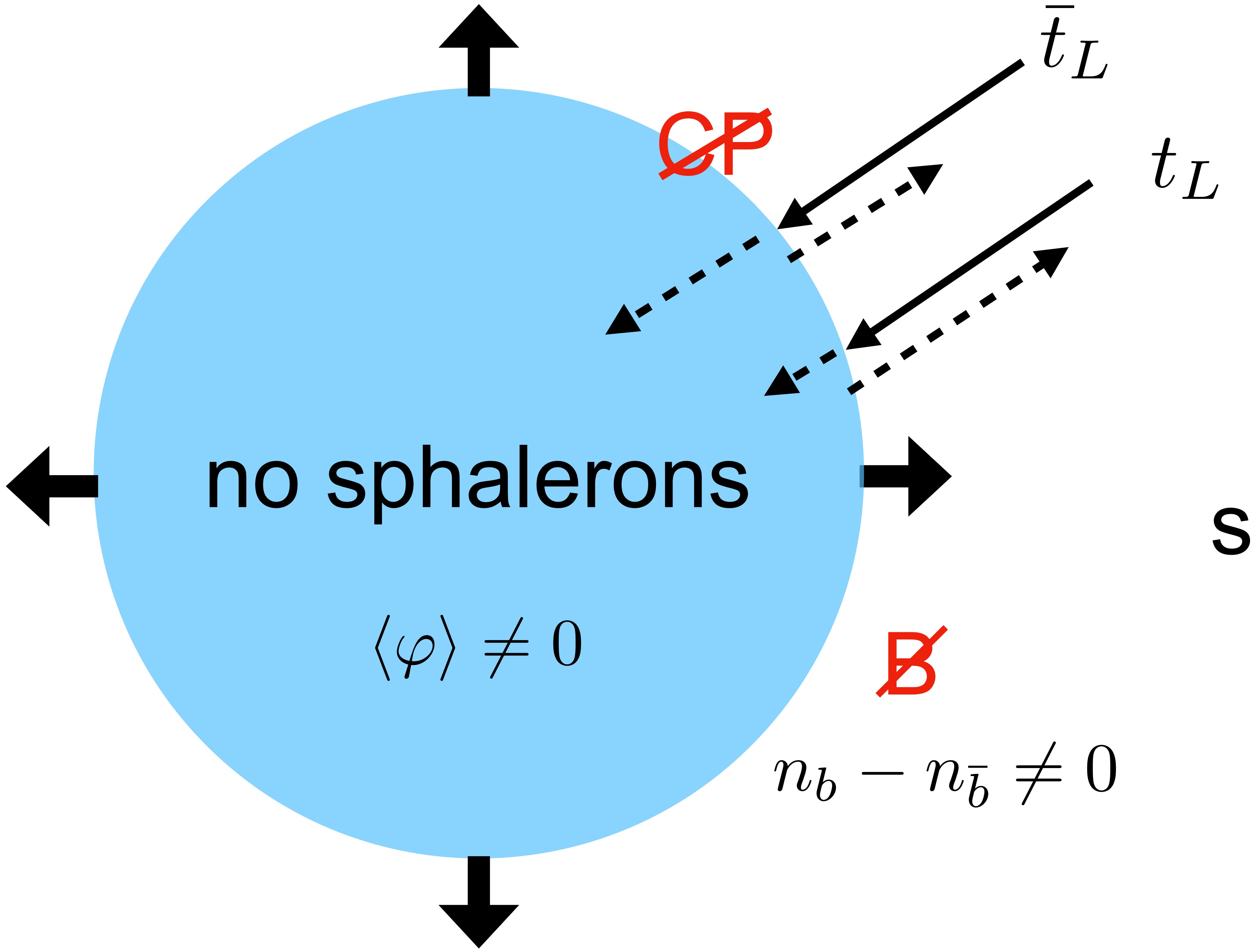
CP violation



ELECTROWEAK BARYOGENESIS IN A NUTSHELL

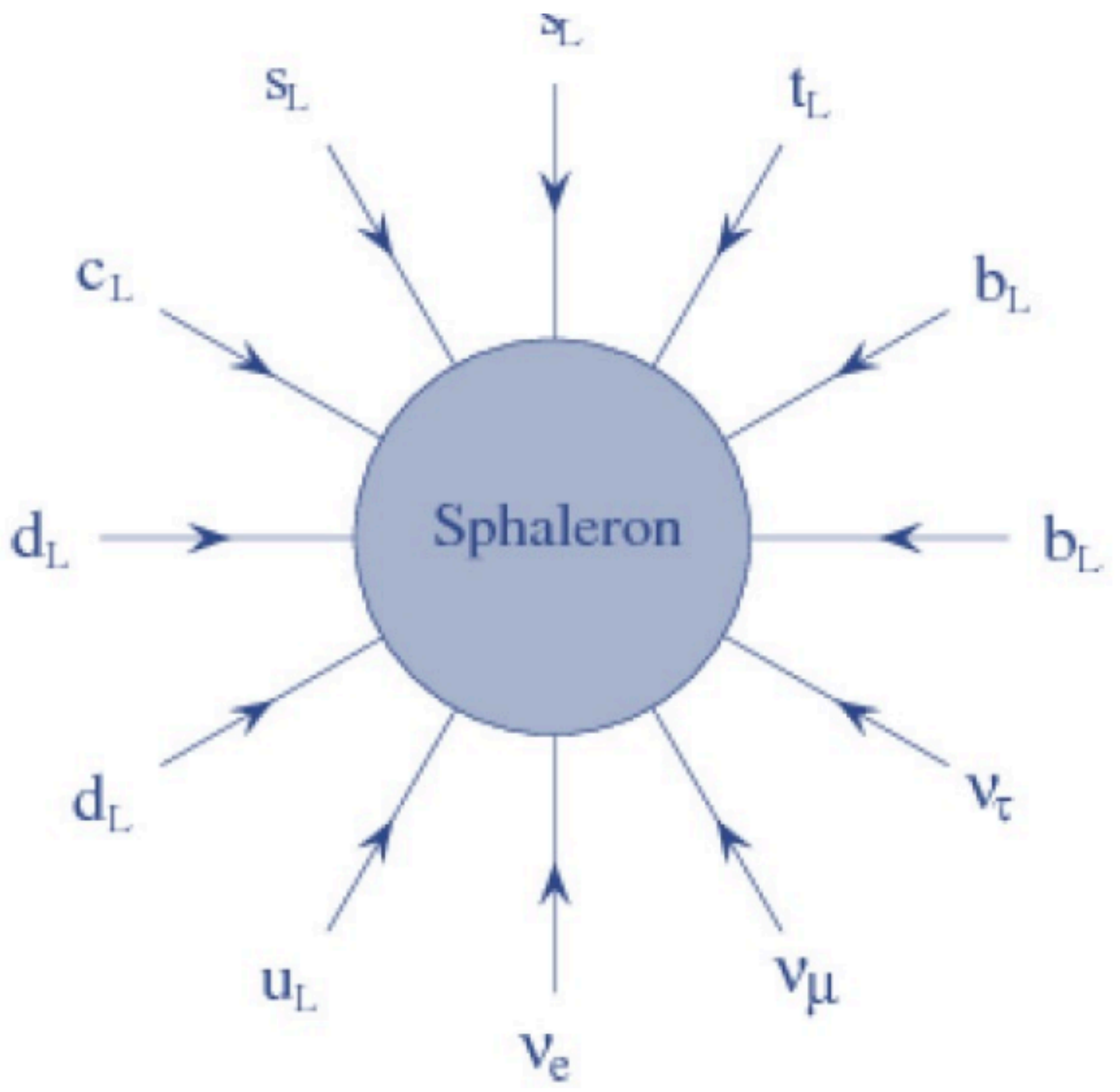
$$\mathcal{L} \supset \frac{y_t}{\sqrt{2}}\varphi\left(1 + c\frac{\varphi^2}{\Lambda^2}\right)\bar{t}_L t_R + \text{h.c.}$$

CP violation



sphalerons

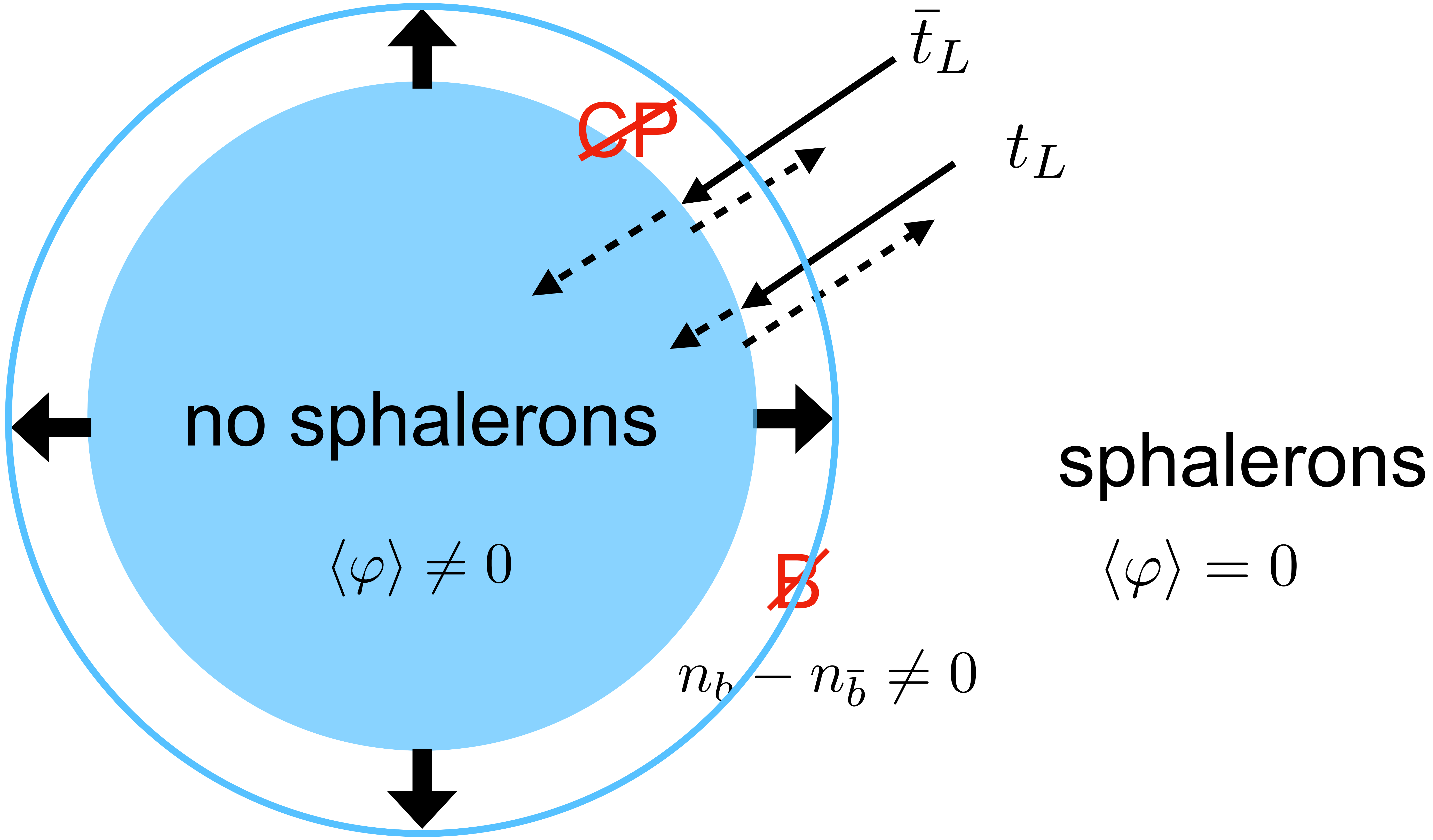
$\langle\varphi\rangle = 0$



ELECTROWEAK BARYOGENESIS IN A NUTSHELL

$$\mathcal{L} \supset \frac{y_t}{\sqrt{2}}\varphi\left(1 + c\frac{\varphi^2}{\Lambda^2}\right)\bar{t}_L t_R + \text{h.c.}$$

CP violation

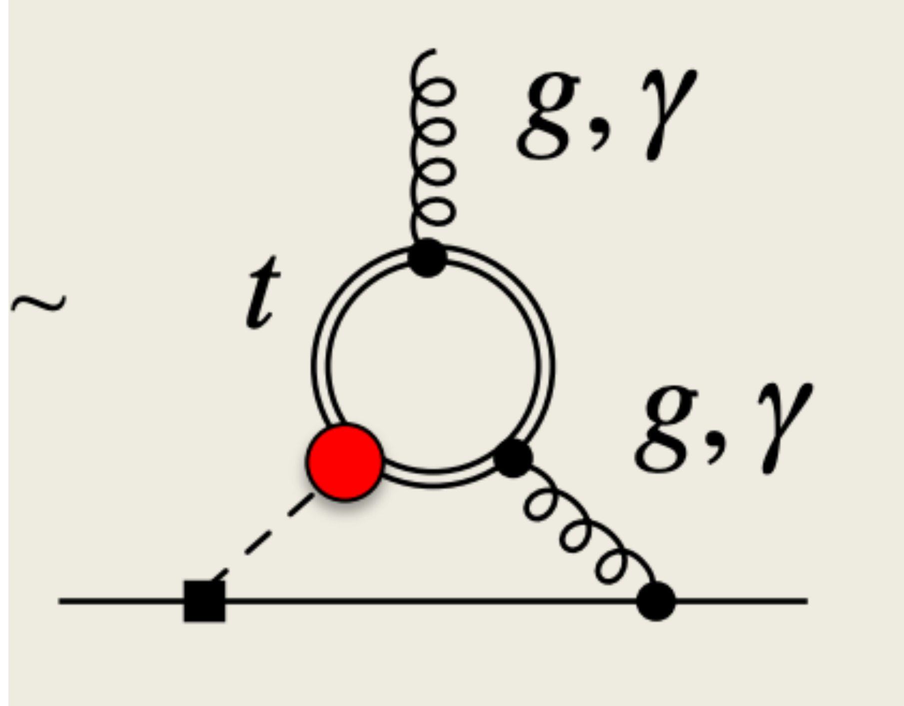


ELECTRIC DIPOLE MOMENT OF ELECTRON

top quark

$$\mathcal{L} \supset \frac{y_t}{\sqrt{2}}\phi\left(1 + c\frac{\phi^2}{\Lambda^2}\right)\bar{t}_L t_R + \text{h.c.}$$

$d_e \sim$



$$\Lambda \gtrsim 10\,\text{TeV}$$

b, c, τ

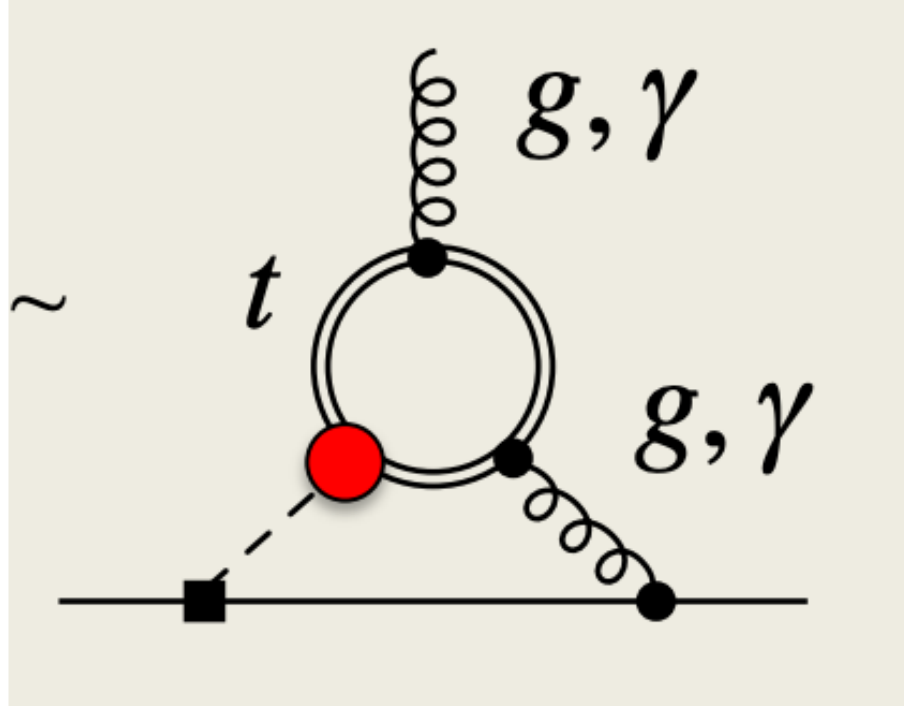
$$\Lambda \gtrsim 0.7,\ 0.6,\ 0.2\,\text{TeV}$$

ELECTRIC DIPOLE MOMENT OF ELECTRON

top quark

$$\mathcal{L} \supset \frac{y_t}{\sqrt{2}}\phi\left(1 + c\frac{\phi^2}{\Lambda^2}\right)\bar{t}_L t_R + \text{h.c.}$$

$d_e \sim$



$$\Lambda \gtrsim 10\,\text{TeV}$$

b, c, τ

$$\Lambda \gtrsim 0.7,\ 0.6,\ 0.2\,\text{TeV}$$

is CPV enough to obtain observed baryon asymmetry?

BOLTZMANN EQUATIONS

$$\frac{\mathrm{d}f}{\mathrm{d}t} = \frac{\partial f}{\partial t} + \frac{\mathrm{d}\vec{x}}{\mathrm{d}t} \cdot \nabla_{\vec{x}} f + \underset{\uparrow}{\frac{\mathrm{d}\vec{p}}{\mathrm{d}t}} \cdot \nabla_{\vec{p}} f = \underset{\uparrow}{C[f]}$$

$$n(\vec{x}, t) = g_s \int \frac{\mathrm{d}^3\vec{p}}{(2\pi)^3} f(\vec{x}, \vec{p}, t)$$

force

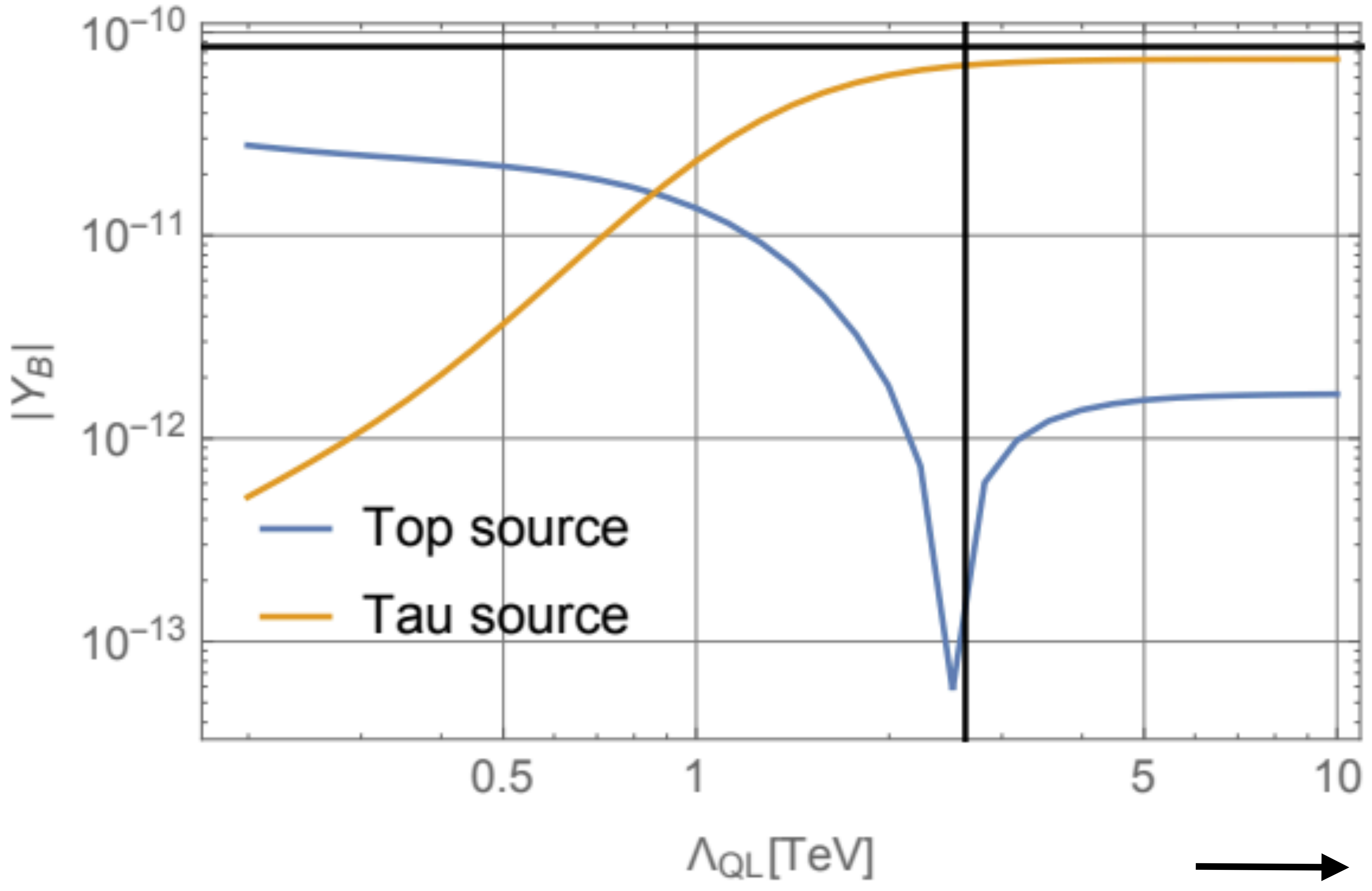
collision term

- WKB/semiclassical source
- vev insertion approximation (VIA)

TOP VS LEPTON SOURCE IN VIA

status last year

de Vries, MP, v/d Vis 2018



observed asymmetry

cutoff: $\Lambda_t = 7.1\,\text{TeV}$

$\Lambda_\tau = 1\,\text{TeV}$

→

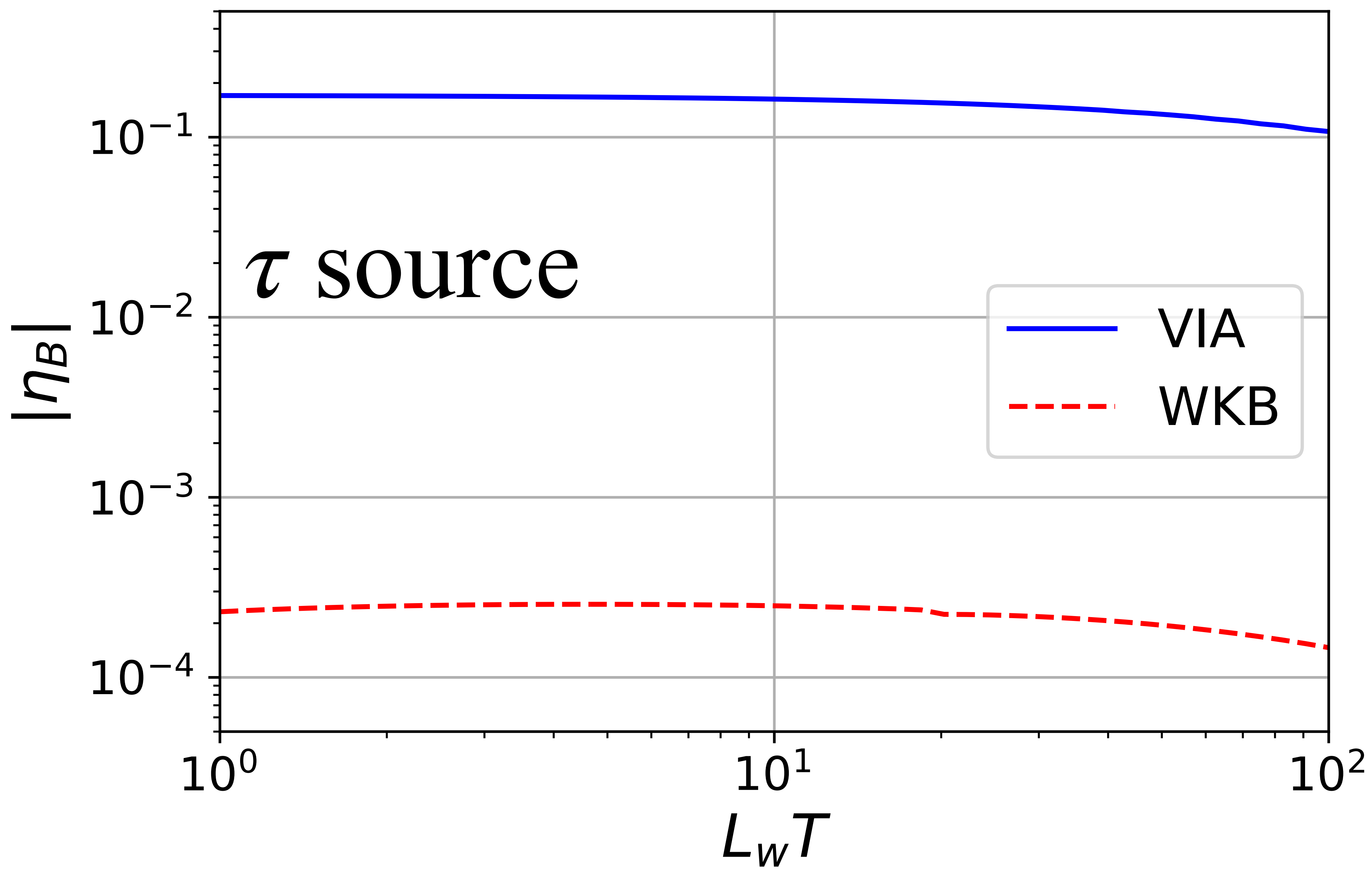
top-tau interaction

$$\mathcal{L} \supset \frac{1}{\Lambda_{\text{QL}}^2} \bar{\tau}_L \tau_R \bar{t}_R t_L + \text{h.c.}$$

LEPTON SOURCE IN WKB AND VIA

status last year

Cline and Laurent 2021



very different predictions!

LEPTON SOURCE IN WKB AND VIA

VIA source term has two contributions which exactly cancel (at leading order in the derivative expansion)

White, MP, v/d Vis 2022

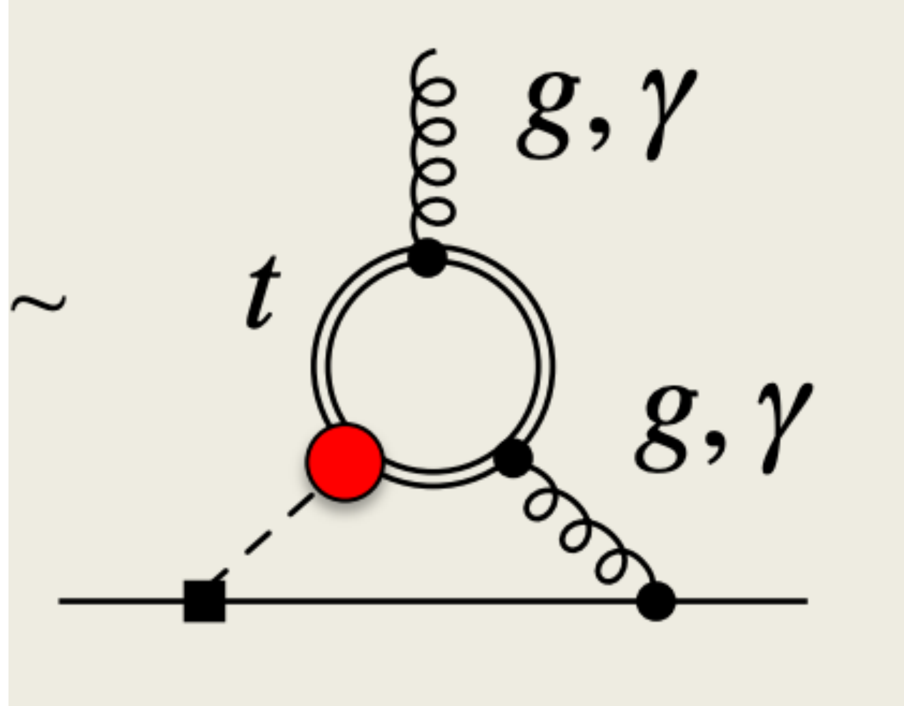
status this year!!

ELECTRIC DIPOLE MOMENT OF ELECTRON

top quark

$$\mathcal{L} \supset \frac{y_t}{\sqrt{2}}\phi\left(1 + c\frac{\phi^2}{\Lambda^2}\right)\bar{t}_L t_R + \mathrm{h.c.}$$

$d_e \sim$



$$\Lambda \gtrsim 10\,\mathrm{TeV}$$

b, c, τ

$$\Lambda \gtrsim 0.7,\ 0.6,\ 0.2\,\mathrm{TeV}$$

eEDM rules out simplest scenarios

PLAN

1. Electric dipole moments: very sensitive probe of CPV new physics

2. Implications for electroweak baryogenesis: eEDM rules out vanilla EWBG

to save EWBG: hide CPV e.g. in two-step phase transition
resonant (flavor) effects
explore different dynamics