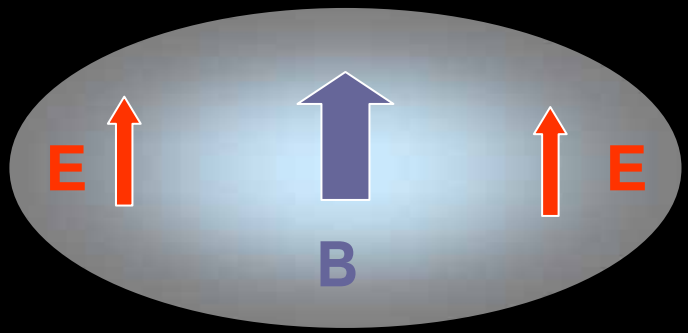
Strong CP Violation & Magnetic Fields

- Prepared for QCD@work2007 -



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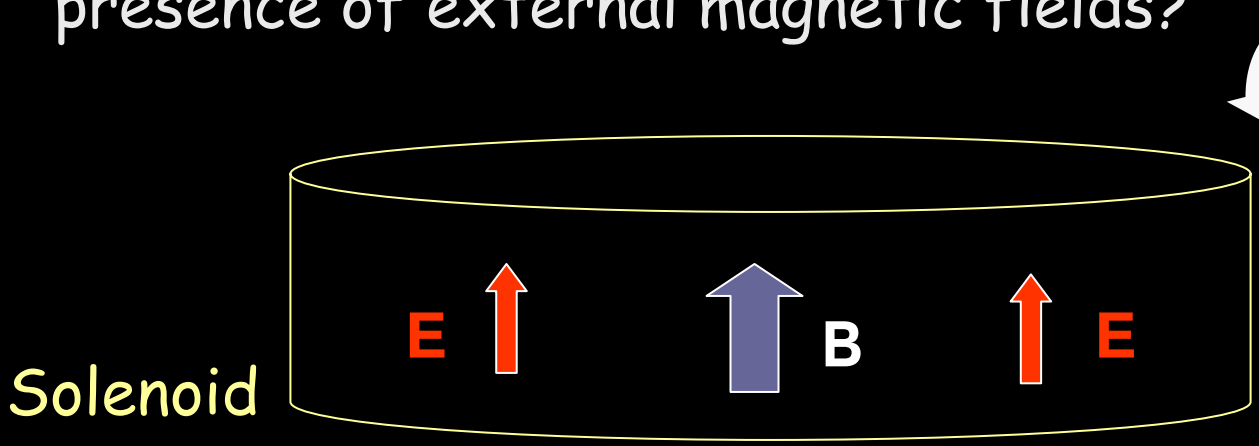
& Raffaele Millo

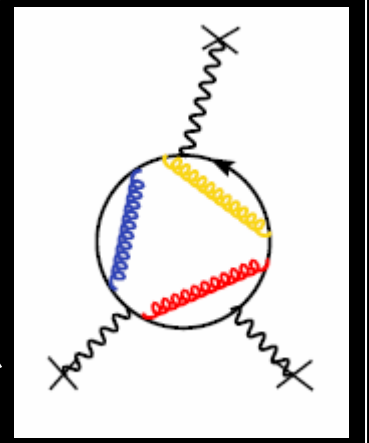
(Trento)

Reference: R. Millo and P. Faccioli ArXiv: 0706.0805 (hep)

The main point of this talk:

Question: what happens to the QCD theta-vacuum in the presence of external magnetic fields?





CP-odd effect

$$S_\theta = \frac{\theta}{32\pi^2}\int d^4x G_{\mu\nu}\tilde{G}^{\mu\nu}$$

Why bother?
Primordial magnetic fields

Universe is permeated by large-scale magnetic fields:

* Strenght: ~ μG
* Correlation length: ~30 kpc

What is the origin of such fields? Two main hypothesis

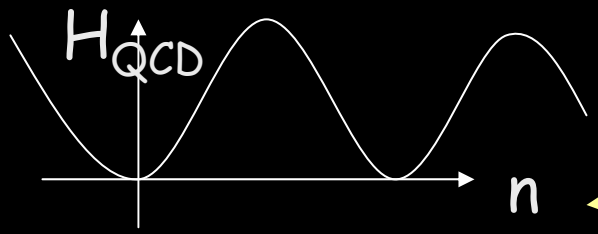
* Primordial
* Astrophysical (i.e. after galaxy formation)

Induced Vacuum Electric Dipole Moment

Starting point: induced polarization in the QCD vacuum:

$$p_z = \frac{1}{V}\int d^3r\, r_z\, \rho(r)$$

$$\rho(r) = \langle \theta \,|\, J_0(r) \,|\, \theta \rangle_{A_\mu^{ext}} \qquad |\,\theta\rangle = \sum_n e^{in\theta}\,|n\rangle$$



Calculation of the VEDM

$$\langle \theta | J_0(x) | \theta \rangle_{A_\mu^{ext}} = \left(\frac{\delta}{\delta i a_\mu(x)} Z_{QCD}[\theta, a_\mu] \right)_{a_\mu = A_\mu^{ext}}$$

$$Z_{QCD}[\theta, a_\mu] \approx Z_{\chi pt}[\theta, a_\mu] = \int DU e^{i \int dt \, L_{\chi pt}[a_\mu, \theta]}$$

$$L_{\chi pt} = L^{(2)}{}_{\chi pt}[a_\mu] + L^{(4)}{}_{\chi pt}[a_\mu] + L_{anom.}[\theta]$$

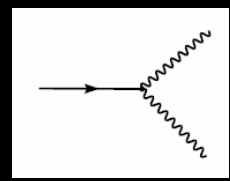
The role of the anomaly (1)

Chiral and axial anomalies are crucial for this effect.

* The axial anomaly enters, to leading $1/N_c$ through

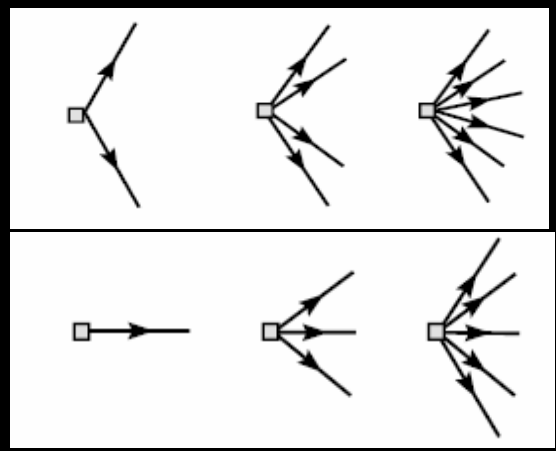
$$\mathbf{L}_{anom}[\theta] = -\frac{f_\pi^2 a}{4N_c}\left(\frac{i}{2}\log\left[\frac{\det U}{\det U^+}\right] - \theta\right)$$

* The chiral anom. enter through the Wess-Zumino coupling in $\mathbf{L}^{(4)}_{\chi pt}$ (which accounts for $\pi \rightarrow \gamma\,\gamma$):



The role of the anomaly (2)

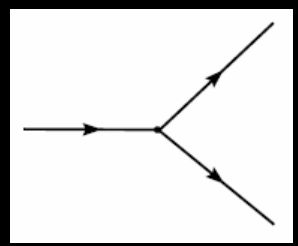
$$J_\mu^{e/m}(x) = \frac{\delta \mathbf{L}[a_\mu, \theta]}{\delta i a_\mu(x)} =$$



non-anom.

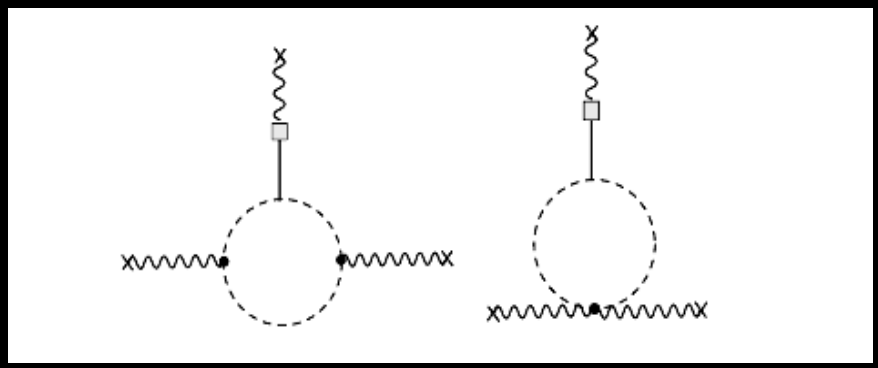
anom. (WZ)

$$\mathbf{L}_{anom}[\theta] =$$



CP-odd diagrams must include the chiral anomaly through the Wess-Zumino e/m coupling to photons

Magnetically-induced VEDM



For an external magnetic field:

$$\bar{B} = (0, 0, B_0 \cos \bar{\omega} t)$$

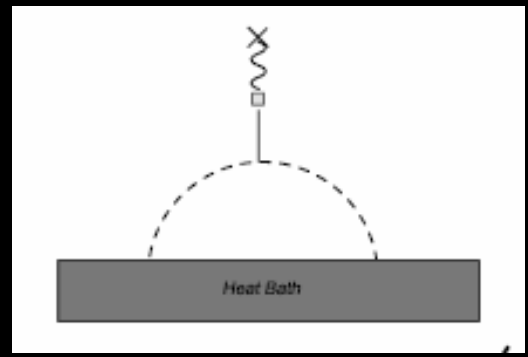
$$p_z(t) \approx -\theta \alpha^2 \frac{5\pi}{36} \frac{B_0^{\,3}}{f_\pi^{\,2} m_\eta^{\,4}} \bar{\omega}^2 (\cos \bar{\omega} t - \cos 3\bar{\omega} t)$$

Note:
* Two characteristic response modes
* Polariz. vanishes for ω->0 (energy cons.)
* Result is param. free (leading order & 1/Nc)

Vacuum polarization by primordial magnetic fields

Repeat calculation at T> 0:

$(0 < T << 4\pi f_\pi)$



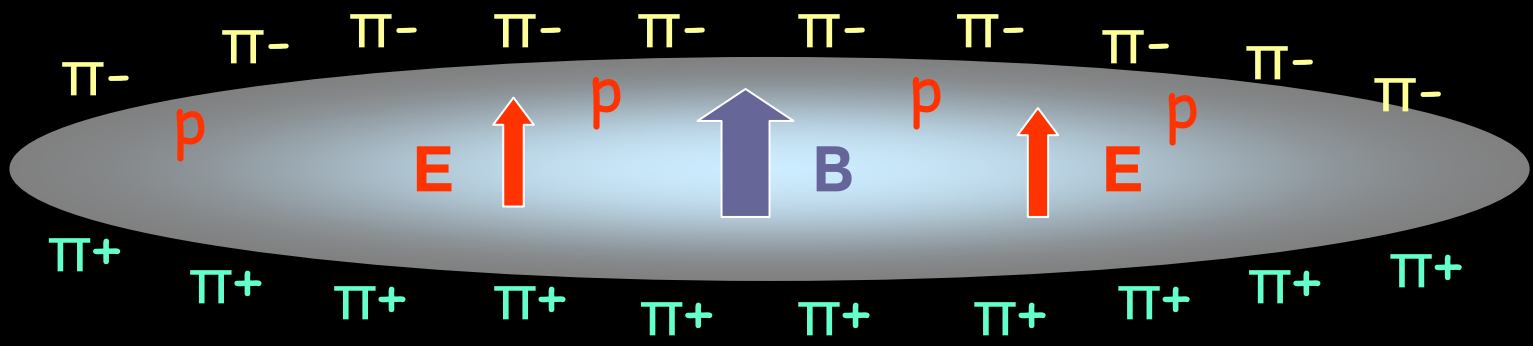
$$p_z \approx \theta\alpha \frac{25B_0}{24\pi} \frac{m_\pi^2}{f_\pi^2 m_\eta^2} \int \frac{d^3p}{(2\pi)^3 2\omega} \frac{1}{e^{\frac{\omega}{T}} - 1}$$

Note: * T>0 *static* B can polarize the vacuum

* $o(\theta\alpha)$ rather than $o(\theta\alpha^2)$

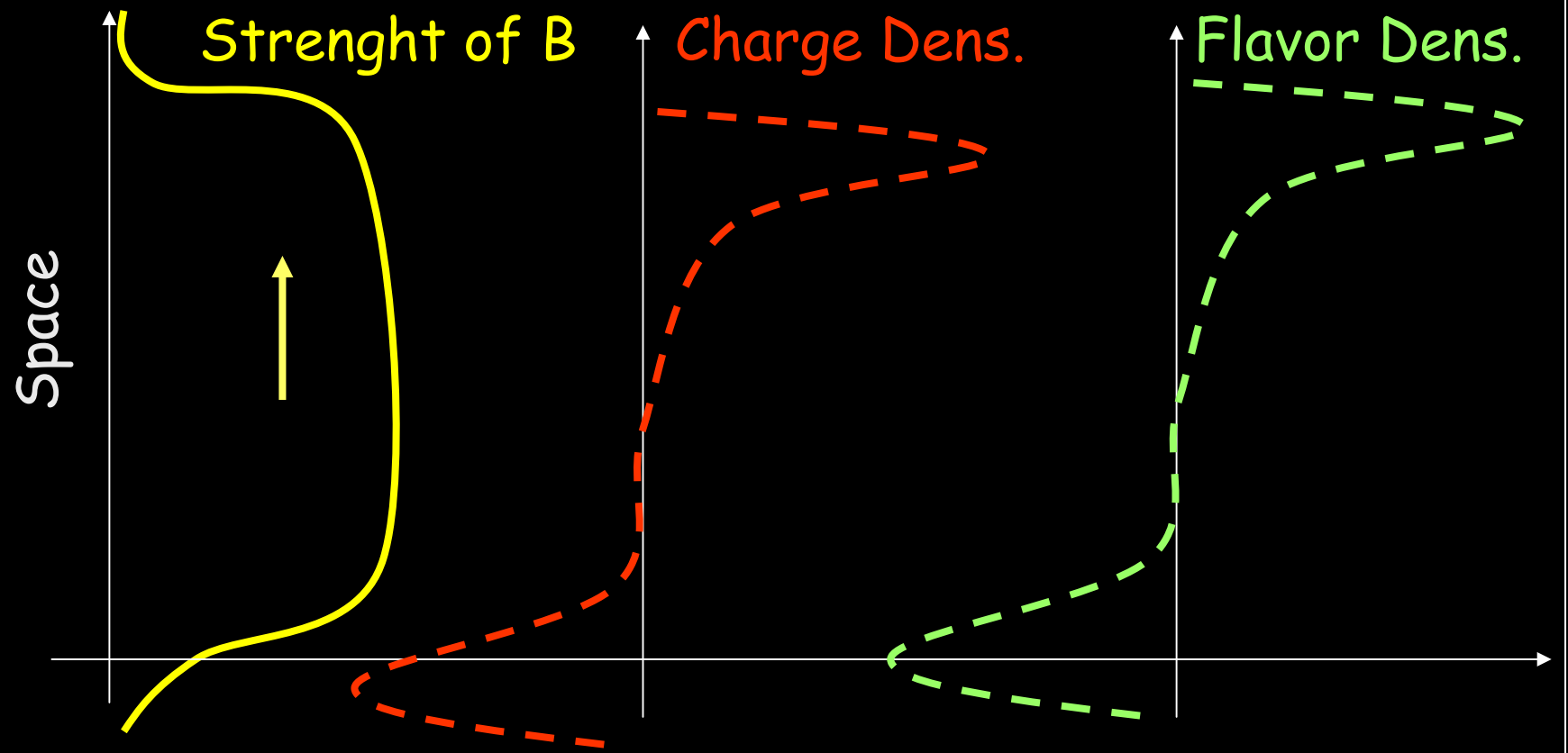
Linking primordial magnetic fields and strong CP violations

Strong interaction were
CP-violating at the end at the hadronic epoch,
then primordial magnetic fields must have induced
a macroscopic (astrophysical) separation of electric
charge and flavor



NB:CP-odd effect!

Charge & flavor profiles in the primordial magnetic domains



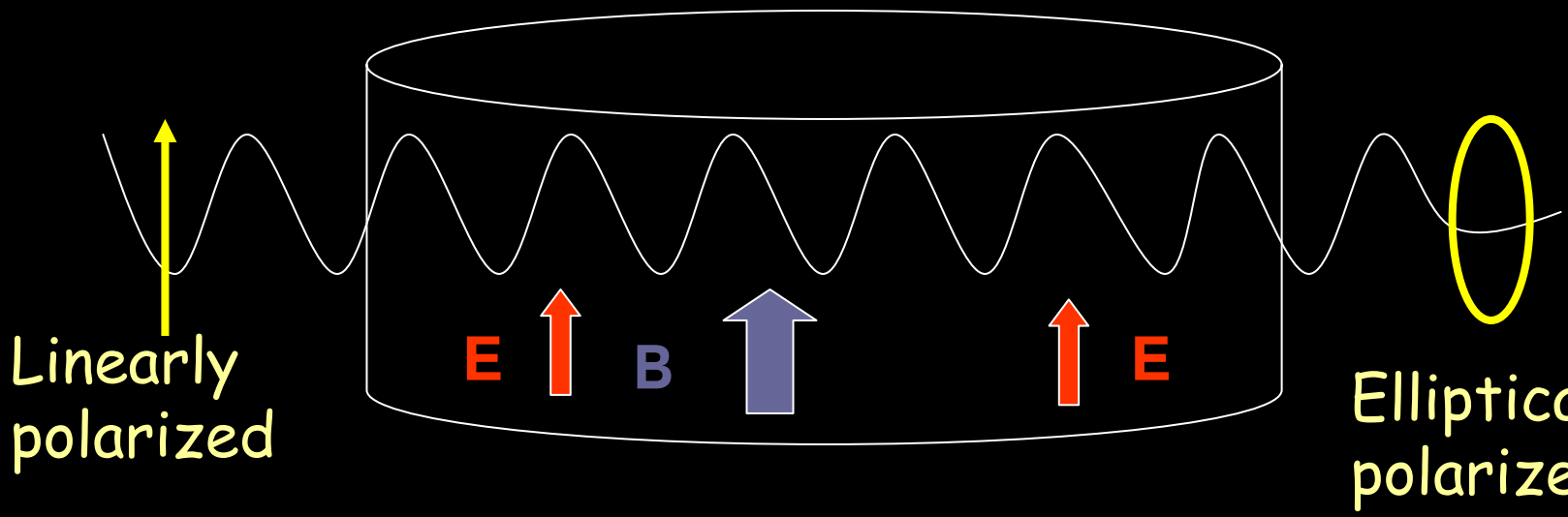
Consequences:

The fate of the charge separation depends on the details of the subsequent stages of the expansion

When T or θ became sufficiently small after the end of the hadronic epoch, we expect large annihilation events.

The resulting low-energy γ-rays would be visible only if the annihilation took place after the decoupling of matter and radiation. What signatures? What consequences?

Future direction: PVLAS experiment



Can we explain the induced ellipticity without having to invoke axions? -Work in progress-

Conclusions

Magnetic fields + CP violation → flavor (charge) asymmetry over macroscopic distance scales

Ch.pt + 1/Nc

$$p_z(t) \approx -\theta\alpha^2 \frac{5\pi}{36} \frac{B_0^{\,3}}{f_\pi^{\,2} m_\eta^{\,4}} \bar{\omega}^2 (\cos\bar{\omega}t - \cos 3\bar{\omega}t) \qquad T=0$$

$$p_z \approx \theta\alpha \frac{25 B_0}{24\pi} \frac{m_\pi^{\,2}}{f_\pi^{\,2} m_\eta^{\,2}} \int \frac{d^3p}{(2\pi)^3 2\omega} \frac{1}{e^{\frac{\omega}{T}} - 1} \qquad T>0$$

* Cosmological Consequences?
* Experimental consequences (PVLAS)?