Cosmology with a chiral flavor

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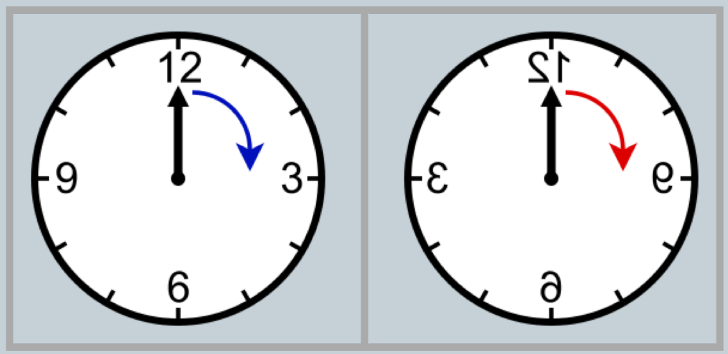
M.A., E. Sabancilar, arXiv 1507.00744
M.A., E. Sabancilar, arXiv 1607.03916
M.A., arXiv 1801.07349

Introduction

- Weak force breaks the parity symmetry, Lee and Yang, Wu et al 1957 in the β-decay processes.
- P-symmetry is violated maximally.



$$10^{-18}\ \text{m} \qquad \not{P}$$

weak interactions are chiral

Introduction

- What about the large scale violation of parity?

  $\sim$ pc-Mpc

- Not yet confirmed observations!
- Astrophysical processes might not account for it.
- If the Universe breaks parity on the large scale, then most probably it originated from inflation.

Introduction

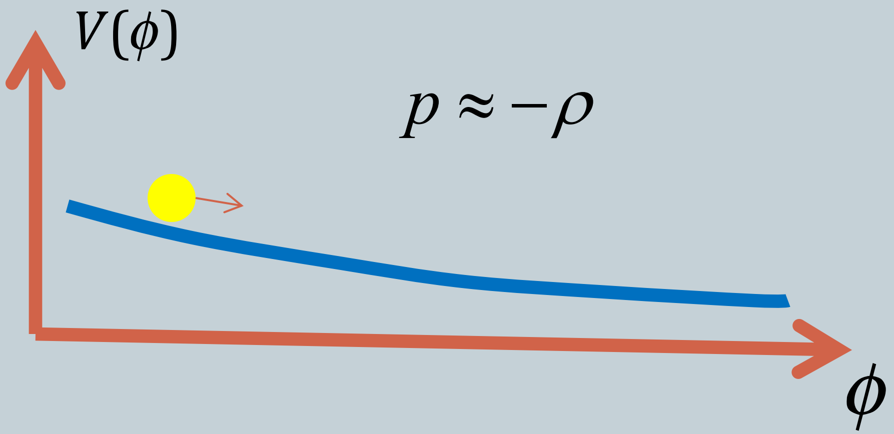
- Why we care?

1. Curiosity.
2. It can tell us more about physics at high energy scales.
3. It can explain the origin of the baryon asymmetry of the Universe.

Outline

- Inflation; natural models
- Generation of chiral (helical) fields from inflation
- Baryon asymmetry of the Universe; baryogenesis via chirality

Inflation



Inflation

- One needs to keep the slow-roll parameters small

$$\varepsilon = \frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2 << 1$$

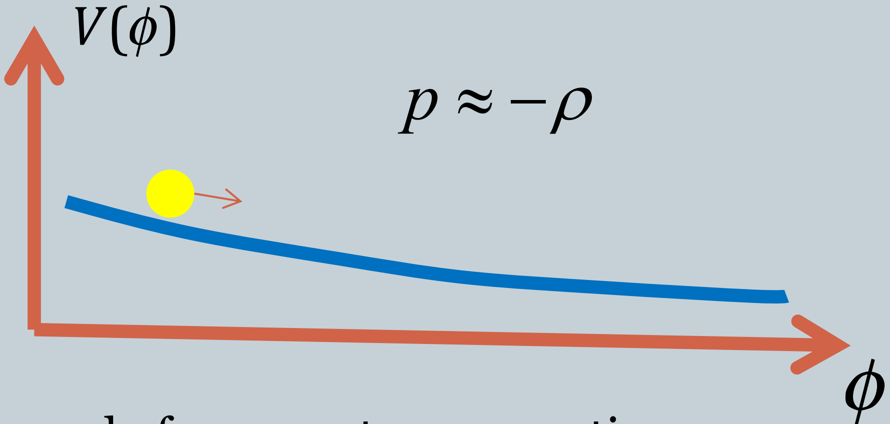
$$\eta = M_p^2 \frac{V''}{V} << 1$$

- Constraints from Planck's on CMB power spectrum

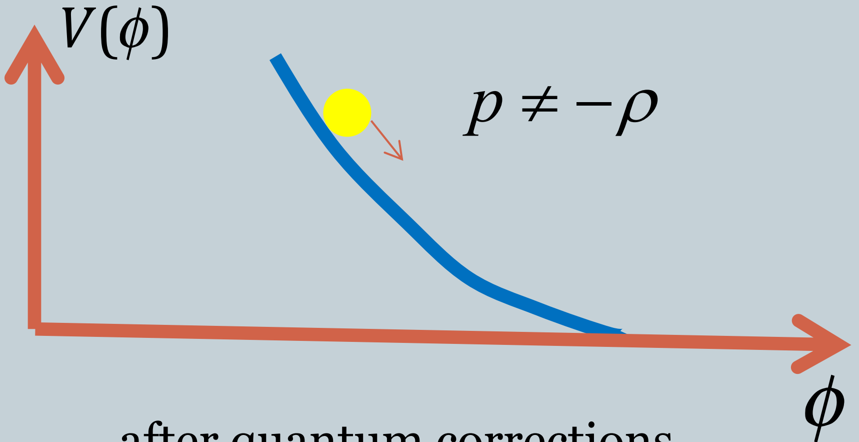
$$n_s - 1 = 2\eta - 6\varepsilon << 1$$

Inflation

- Generally speaking quantum corrections of the inflaton will spoil the small slow-roll parameters
- $V = m^2\phi^2$ $\qquad \eta \approx \frac{m^2}{H^2}$ $\xrightarrow{\text{Quantum corrections}}$ $\eta \approx \frac{\Lambda^2}{H^2} > 1$



before quantum corrections



after quantum corrections

Inflation

- To solve it we invoke a symmetry: shift symmetry

$$\phi \to \phi + c$$

- Then, we suitably break the shift symmetry

- ϕ is an axion (essence behind natural models of inflation)

Freese, Frieman, and Olinto 1990

Inflation

- Example

$$\ell \supset i\overline{\Psi} D_\mu \gamma^\mu \Psi + \left(\overline{\Psi}_L \Phi \Psi_R + c.c.\right)$$

$$+\frac{1}{2}\left(\partial_\mu \Phi\right)^2 + \underbrace{\lambda\left(\Phi^* \Phi - f^2\right)^2}_{f \le M_P} + \underbrace{\left(G_{\mu\nu}\right)^2}_{SU(N)} + \underbrace{\left(F_{\mu\nu}\right)^2}_{U_y(1)}$$

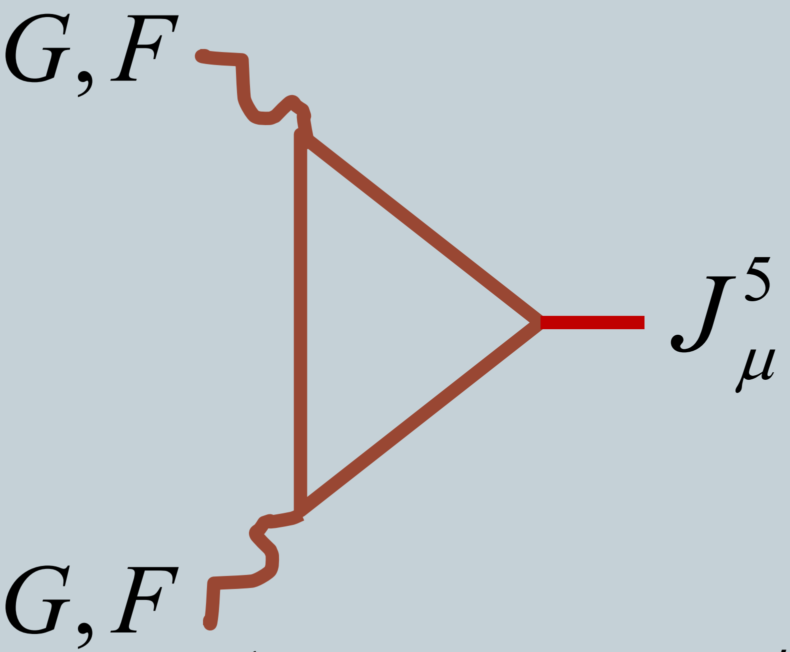
$$D_\mu = \partial_\mu - \underbrace{igB_\mu}_{SU(N)} - \underbrace{ieA_\mu}_{U_y(1)}$$

$$U_{PQ}(1): \quad \Psi_L \to e^{i\alpha}\Psi_L \qquad \Psi_R \to e^{-i\alpha}\Psi_R \qquad \Phi \to e^{2i\alpha}\Phi$$

$$\Phi = f e^{i\phi/f}$$

Inflation

- However, $U_{PQ}(1)$ is anomalous



$\phi \rightarrow \phi + 2\alpha$

axion

$$\underbrace{\ell_{eff}}_{E<<f} = \frac{1}{2}\left(\partial_{\mu}\phi\right)^{2} + g^{2}\frac{\phi}{32\pi^{2} f} G_{\mu\nu}\tilde{G}_{\mu\nu} + e^{2}\frac{\phi}{32\pi^{2} f} F_{\mu\nu}\tilde{F}_{\mu\nu}$$

Inflation

- At strong scale Λ will confine and the instantons will break the shift to a discrete shift symmetry:

$$\ell_{eff\ \mathrm{total}} = \ell_{eff} + \Lambda^4 \cos\left(\frac{\phi}{f}\right):$$

$$\phi \rightarrow \phi + 2\pi f$$

- The parameter $m^2 \equiv \dfrac{\Lambda^4}{f^2}$ is naturally small

Inflation

- Axion inflation has other problem: one needs to have $f > 10 M_P$ to achieve slow-roll.

- The axions couple to the fermions: $\ell \supset i \dfrac{\partial_\mu \phi}{f} \bar{\psi} \gamma^\mu \gamma^5 \psi$

- Both terms $i \dfrac{\partial_\mu \phi}{f} \bar{\psi} \gamma^\mu \gamma^5 \psi$ $\quad e^2 \dfrac{\phi}{32\pi^2 f} F_{\mu\nu} \tilde{F}_{\mu\nu}$

Lead to CP violating effects (even on the large scale!)

Generation of chiral fields from inflation

Chiral-field production

- Let us consider the hyper $U_y(1)$ field

$$\ell \supset \frac{1}{2}\left(\partial_\mu \phi\right)^2 - \frac{1}{4}\left(F_{\mu\nu}\right)^2 + \alpha \frac{\phi}{4f} F_{\mu\nu} \tilde{F}_{\mu\nu}$$

axion=inflaton

- In FRW background: $\left(\frac{\partial^2}{\partial \tau^2} - \nabla^2 - \alpha \frac{\phi'}{f} \nabla \times \right)\vec{A} = 0$

Field and Carroll 1998, M.A., Sorbo 2006

Chiral-field production

- In helicity bases:

$$\vec{A} = A_+ \overrightarrow{\varepsilon_+} + A_- \overrightarrow{\varepsilon_-}$$

$$\left[\frac{d^2}{d\tau^2} + \underbrace{k^2 \pm \frac{2k\xi}{|\tau|}}_{M_\pm^2(\tau)} \right] A_\pm = 0$$

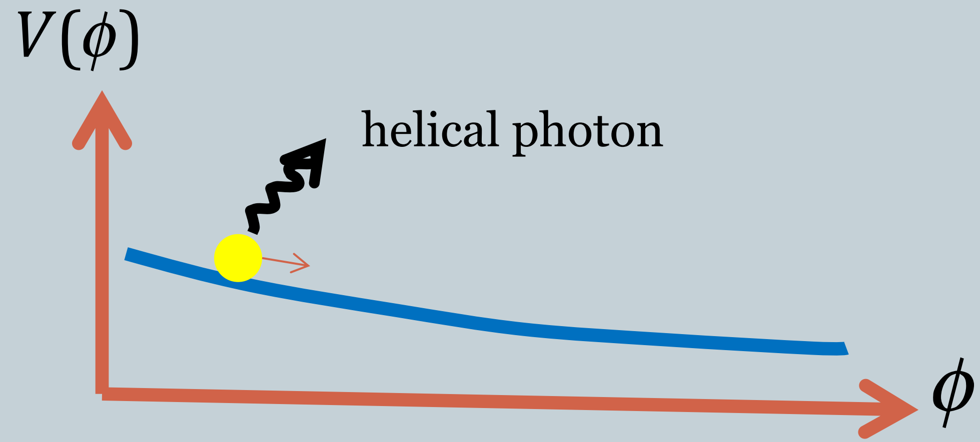
- We take $\xi > 0$

$M_+^2 > 0 \Rightarrow$ no particle production

$M_-^2 \approx 0 \Rightarrow$ particle production $\quad \underbrace{A_- \propto e^{\pi\xi}}_{\text{parity violating effect}} \quad \xi \sim O(10)$

Chiral-field production

Generation of helical field while the inflaton is rolling down



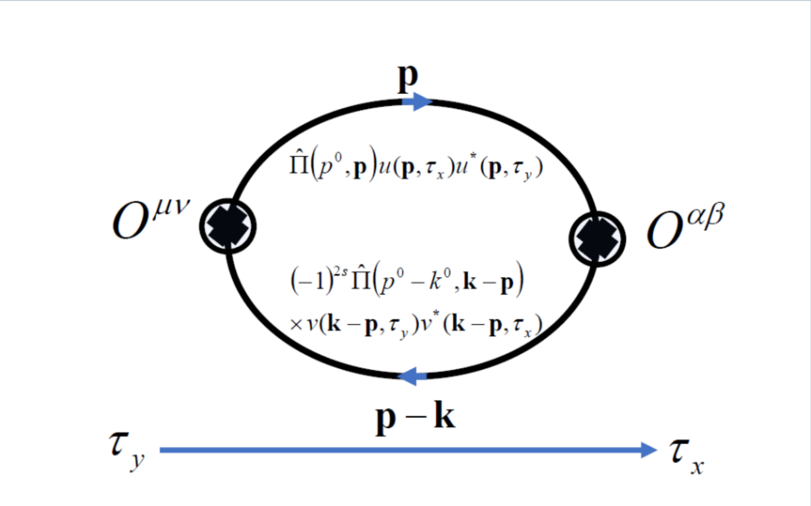
The generation of helical fermions follow the same line. The production is limited by Pauli blocking.

Adshead and Sfakianakis 2015

Chiral-field production

- There will also be gravitational waves accompanying the generation of helical fields.

Sorbo 2011, M.A. and Sabancilar 2016, M.A. 2018



$$\varepsilon^{++}(k)\varepsilon^{++}(k')\langle T_{\mu\nu}(k)T_{\alpha\beta}(k')\rangle \neq$$

$$\varepsilon^{--}(k)\varepsilon^{--}(k')\langle T_{\mu\nu}(k)T_{\alpha\beta}(k')\rangle$$

Chiral-field production

- The imbalance in the correlator translates into a chirality of the gravitational waves (GW) power spectrum (you need to measure the polarization)

$$\Delta\chi = \frac{P^- - P^+}{P^- + P^+}$$

$$P^+ \propto \varepsilon^{++} \langle TT \rangle$$

$$P^- \propto \varepsilon^{--} \langle TT \rangle$$

$$\Delta\chi = C \frac{H^2}{M_p^{\ 2}}$$

$C \sim O(1)$ fermions

M.A., Sabancilar 2016

$C \sim e^{4\pi\xi}$ photons

Sorbo 2011

Chiral-field production

- Breaking the microscopic parity →

1-Macroscopic helical coherent fields +macroscopic chiral GW for bosonic fields

2-Macroscopic chiral GW for fermions

Baryon Asymmetry of the Universe (BAU)

BAU

- The generated hyper $U_Y(1)$ field stores helicity

$$h = \int d^3x \left\langle \vec{A} \bullet \vec{B} \right\rangle \propto N_{CS}$$

Topology of the magnetic field

$$\frac{dh}{dt} = -2\int d^3x \left\langle \vec{E} \bullet \vec{B} \right\rangle \propto \int d^3k k^2 \left[|A_-|^2 - |A_+|^2 \right]$$

- When $|A_-| = |A_+|$ no helicity is stored

- The baryon and lepton currents of the Standard Model are anomalous

$$\partial_\mu J^\mu_f = \underbrace{C^f_y \frac{\alpha_y}{16\pi} F_{\mu\nu}\tilde{F}^{\mu\nu}}_{\text{Hyper U(1) field}} + \underbrace{C^f_w \frac{\alpha_w}{16\pi} w_{\mu\nu}\tilde{w}^{\mu\nu}}_{\text{Weak}} + \underbrace{C^f_s \frac{\alpha_s}{16\pi} G_{\mu\nu}\tilde{G}^{\mu\nu}}_{\text{strong}}$$

	C_y	C_w	C_s
Q	$N_c N_w y_Q^2$	N_c	N_w
L	$N_w y_L^2$	1	0
u_R	$-N_c y_{u_R}^2$	0	-1
d_R	$-N_c y_{d_R}^2$	0	-1
e_R	$-y_{e_R}^2$	0	0

$$Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad L = \begin{pmatrix} \nu_e \\ e \end{pmatrix}, \quad \mathrm{u}_R, d_R, e_R$$

BAU

- Integrate the anomaly equation

$$\frac{dN_f}{dt} = -C_y^f \frac{\alpha_y}{4\pi} \int d^3x \vec{E} \cdot \vec{B} = C_y^f \frac{\alpha_y}{8\pi} \frac{dh}{dt}$$

- The helicity stored in the hyper field is transferred into baryon number when $T >> 100$ Gev.

M.A., Sabancilar 2015

BAU

- What about the diffusion of the fields?

$$\partial_t \vec{B} = \underbrace{\nabla \times \left(\vec{v} \times \vec{B} \right)}_{\text{advection}} + \underbrace{\frac{1}{\sigma} \nabla^2 \vec{B}}_{\text{dissipation}}$$

$$R_m = \frac{v\sigma}{k_p}$$

k_p → wave vector at end of inflation

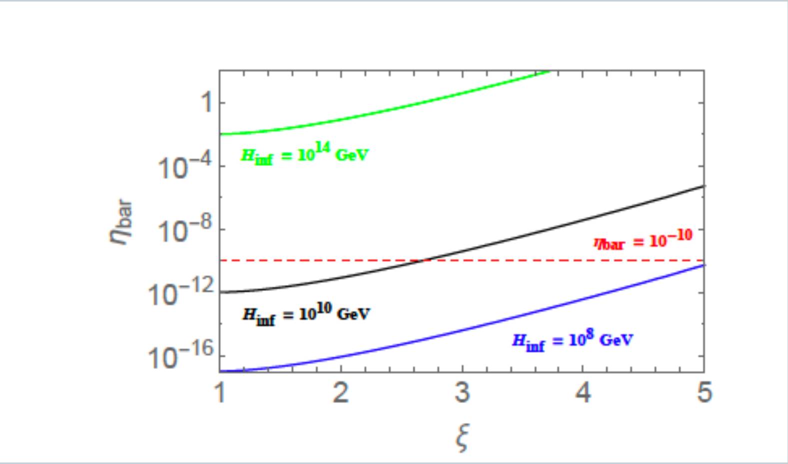
$R_m >> 1$ turbulence

↓

inverse cascade

- The anomaly equation

$$\frac{\partial \eta_f}{\partial t} = \underbrace{C_y^f \frac{\alpha_y}{4\pi s} h^{\bullet}}_{\text{helicity source}} - \underbrace{C_w^f \Gamma_w (\eta_Q + \eta_L)}_{\text{weak sphaleron}} - \underbrace{C_s^f \left(\eta_Q - \eta_{u_R} - \eta_{d_R} \right)}_{\text{strong sphaleron}}$$



$$Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad L = \begin{pmatrix} \nu_e \\ e \end{pmatrix}, \quad u_R, d_R, e_R$$

M.A. and Sabancilar 2015

BAU

- After the onset of the EW phase (transition) crossover:

$$\mathrm{U}_y(1) \rightarrow \mathrm{U}_{em}(1)$$

- Then baryogenesis shuts off.

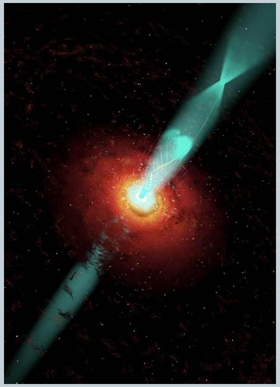
- There should be a relic of helical magnetic field

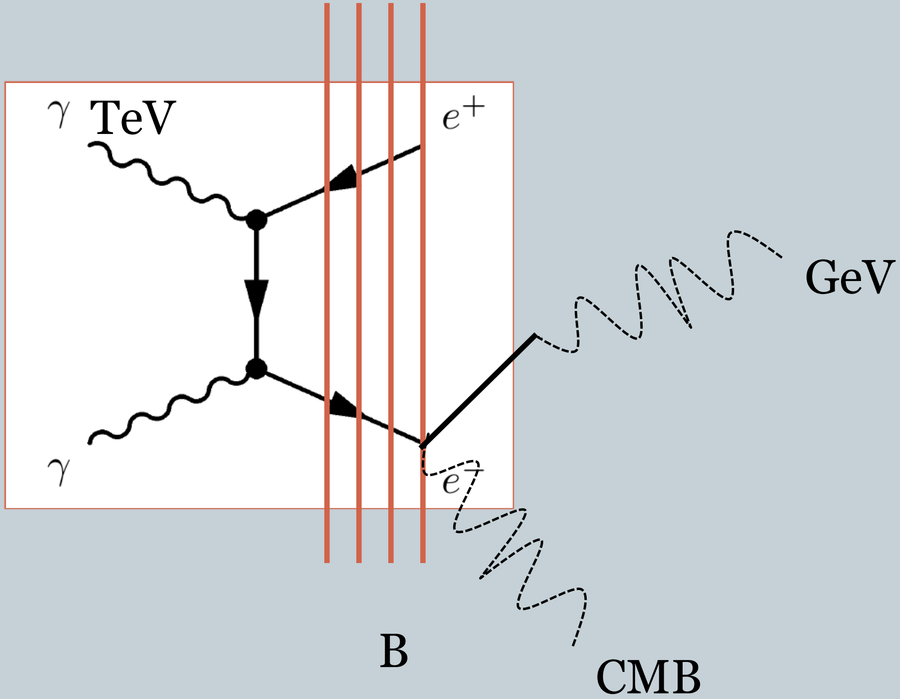
$$B \approx 10^{-17}\mathrm{G} \qquad 10^{-5}\mathrm{pc}$$

Kamada, Long 2016

BAU

- We need evidence!
- TeV Blazars





Tashiro, Chen, Ferrer , Vachaspati 2014

Conclusion

- Parity could be broken on the large scale
- This happens if there is helical field on a very large scale
- Natural inflation provides a mechanism to generate helical (chiral) fields
- It also provides a solution to the baryon asymmetry of the Universe
- More observational data is needed to confirm/rule out helical fields