

Temporal chiral spiral in strong magnetic fields

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Symmetry breaking in nature

- Key quantity: Order parameter

$$\langle [iQ_a, \phi_i(x)] \rangle = \langle h_{ai}(x) \rangle$$

- Chiral symmetry breaking in QCD
 - Chiral condensate

$$\langle \left[i \int d^3x' \bar{q}_{x'} \gamma^0 \gamma^5 q_{x'}, \frac{i}{2} \bar{q}_x \gamma^5 q_x \right] \rangle = \langle \bar{q}_x q_x \rangle$$

Spatial pattern of order parameters

- Crystalline order parameters
- ➔ Space-translational symmetry is broken

- Chiral (magnetic) spiral in QCD in large N_c (or strong B)

$$\langle \bar{q}_x q_x \rangle = \sigma \cos \mu_q z$$

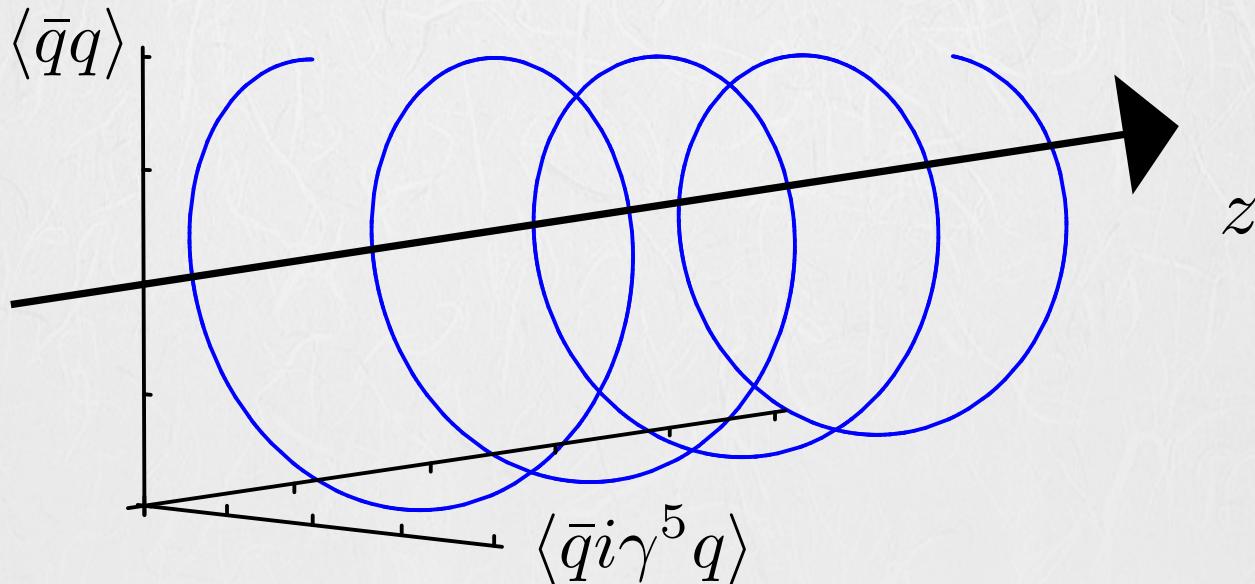
$$\langle \bar{q}_x i\gamma^5 q_x \rangle = \sigma \sin \mu_q z$$

μ_q : Quark number chemical potential

Spatial pattern of order parameters

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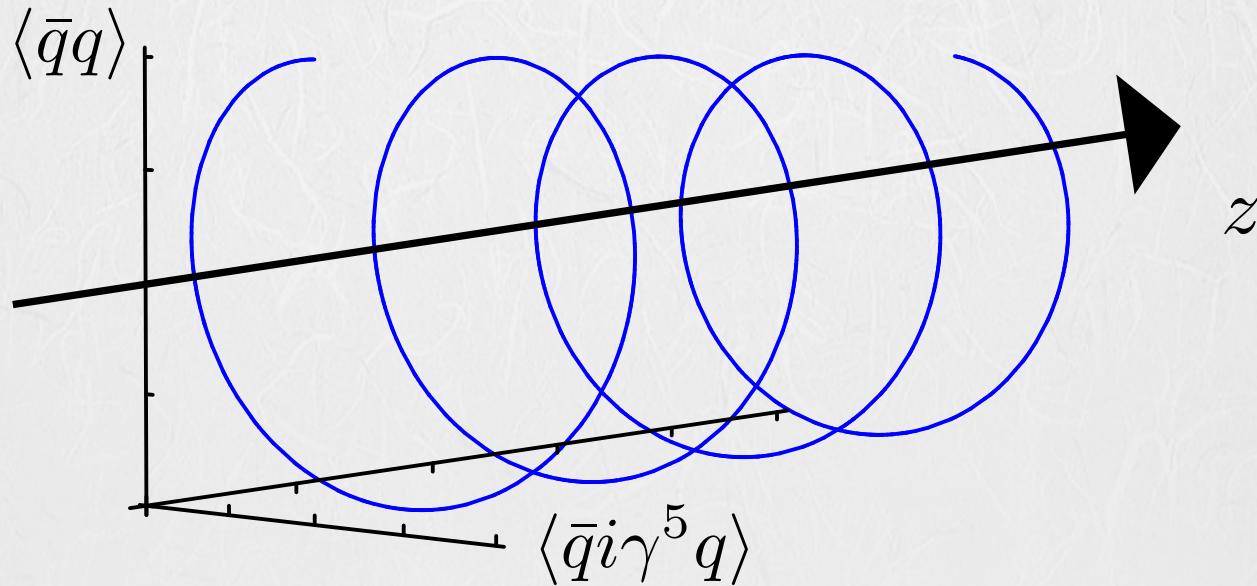


Temporal pattern of order parameters?

- Quantum time crystal [Wilczek, PRL (2012)]

In QCD?

- Temporal analogue to the chiral magnetic spiral

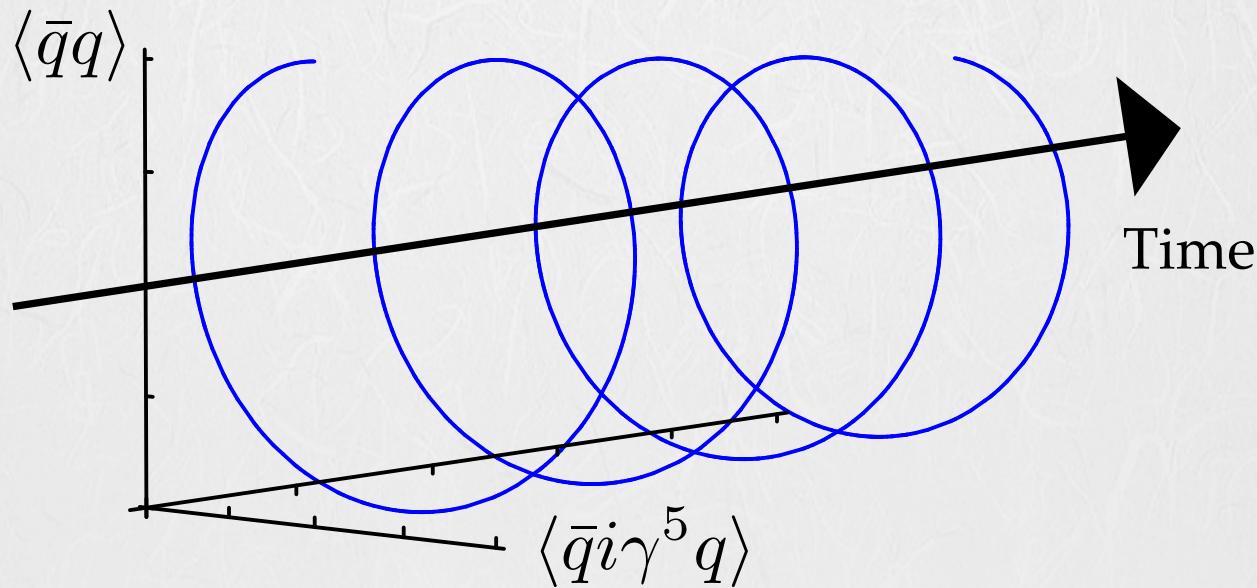


Temporal pattern of order parameters?

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In QCD?

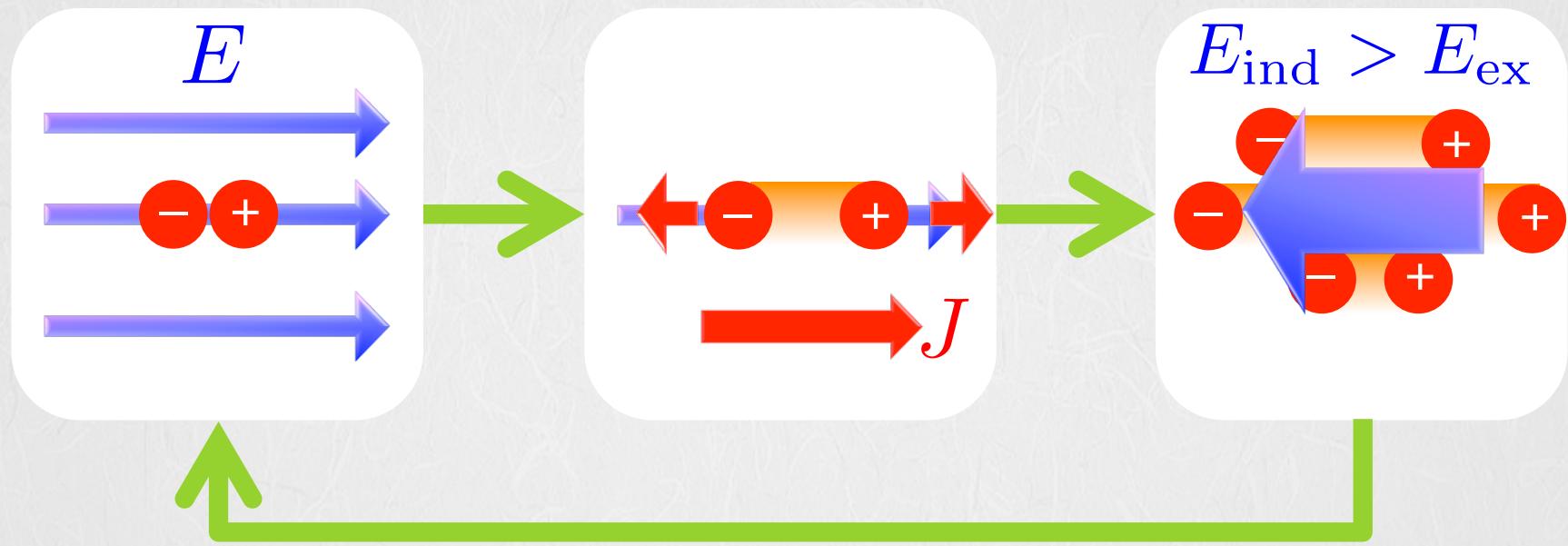
- Temporal chiral spiral



- QCD vacuum at strong B and finite E

Schwinger mechanism

- With quark back reaction

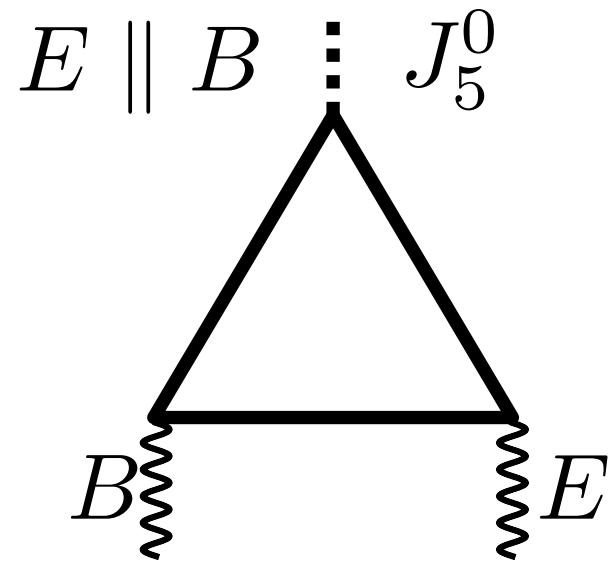


- (Damping) oscillation of electric field

Axial anomaly

- Electric field can induce axial charge

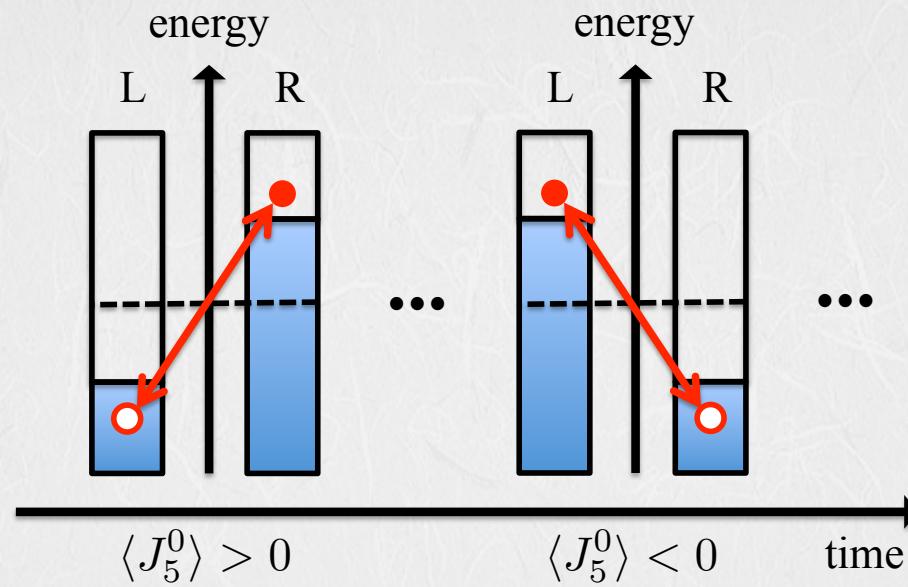
$$\partial_\mu j_5^\mu = N_c \frac{eB}{2\pi} \frac{eE}{\pi}$$



- Oscillation of axial charge

Temporal chiral spiral

○ Oscillation of axial charge



- Pairing between different chiralities
- ➔ Becomes time-dependent

Lowest Landau Level (LLL) approximation

- Axial anomaly keeping only with LLL contribution

$$\frac{d}{dt} \int dz \ j_5^0 = \frac{eN_L N_c}{\pi} \int dz \ E$$

- Maxwell equation in “1+1”d

$$N_L = eBV_{\perp}/(2\pi)$$

$$\frac{d}{dt} \int dz \ E = -\frac{e}{V_{\perp}} \int dz \ j^3$$

- Quantum harmonic oscillator

$$j_5^\mu = -\epsilon^{\mu\nu} j_\nu$$

$$m_\gamma^2 = e^3 N_c B / (2\pi^2)$$

Chiral magnetic wave (CMW)

○ (Gapless) Collective mode

$$\langle j^\mu \rangle = -\frac{eN_L N_c}{\pi} \frac{\epsilon^{\mu\nu}}{\square + m_\gamma^2} \partial_\nu E$$

$$\langle j_5^\mu \rangle = \frac{eN_L N_c}{\pi} \frac{1}{\square + m_\gamma^2} \partial^\mu E$$

- CMW must be nondissipative

○ How scalar and pseudoscalar condensates behave?

Temporal chiral spiral induced by electric fields

- CMW couples to scalar and pseudoscalar condensates

$$\langle \bar{q}q \rangle = \langle \bar{q}q \rangle_0 \cos \left(\frac{2e}{\square + m_\gamma^2} E \right)$$

$$\langle \bar{q}i\gamma^5 q \rangle = \langle \bar{q}q \rangle_0 \sin \left(\frac{2e}{\square + m_\gamma^2} E \right)$$

- Without back reaction

→ Unstable to applying a constant electric field

Temporal chiral spiral induced by electric fields

- Instantaneous electric field: $E(t) = (E_0/m_\gamma)\delta(t)$

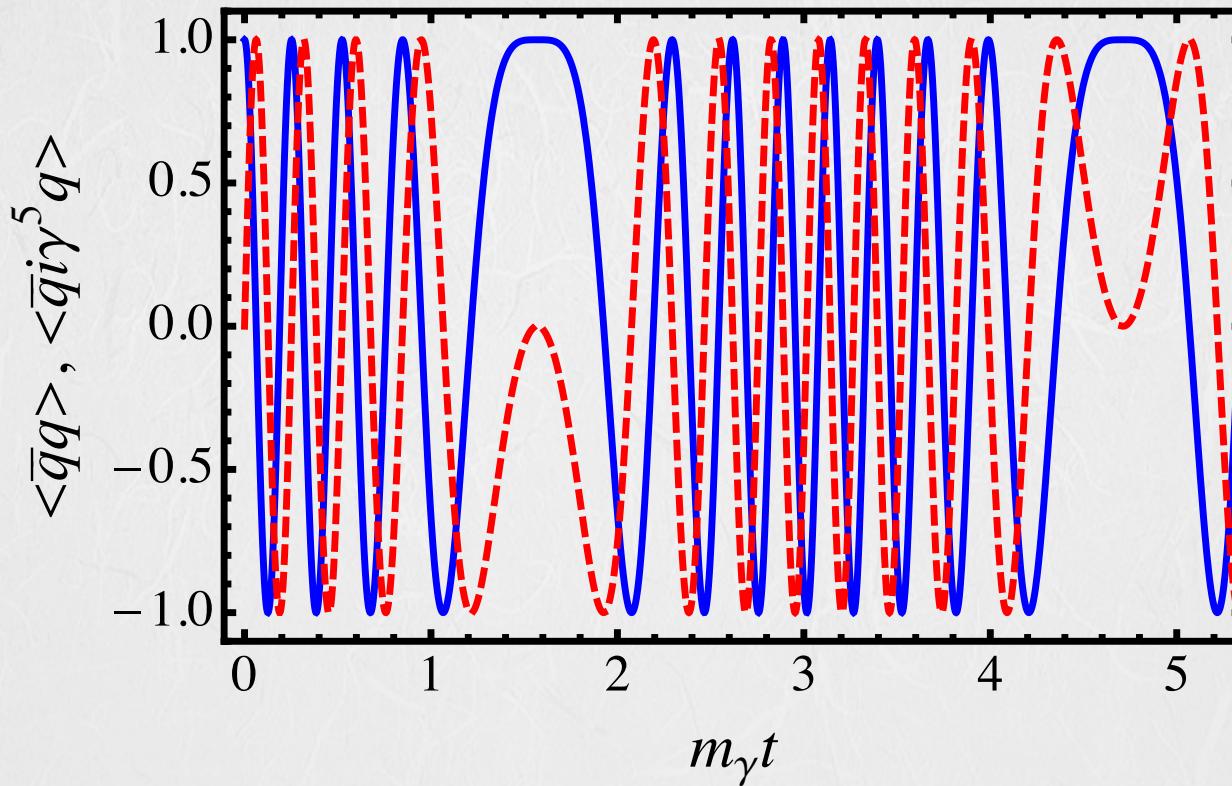
$$\langle \bar{q}q \rangle = \langle \bar{q}q \rangle_0 \cos \left(\frac{2e}{m_\gamma^2} E_0 \sin m_\gamma t \right)$$

$$\langle \bar{q}i\gamma^5 q \rangle = \langle \bar{q}q \rangle_0 \sin \left(\frac{2e}{m_\gamma^2} E_0 \sin m_\gamma t \right)$$

$$|m_\gamma t - k\pi| \ll 1 \quad \omega = 2eE_0/m_\gamma$$

Temporal chiral spiral induced by electric fields

- Instantaneous electric field: $E(t) = (E_0/m_\gamma)\delta(t)$



$$|m_\gamma t - k\pi| \ll 1 \quad \omega = 2eE_0/m_\gamma$$

Summary

- Quantum time crystal in QCD
 - Temporal analogue to chiral magnetic spiral
 - QCD vacuum in strong magnetic and finite electric fields
- Future prospects
 - Generalization to charged meson condensates
 - Effect of finite quark mass
 - Application to HIC experiments/ Magnetars