Novel Chiral Structure Realized by Rotation

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QCD with Environmental Effects

*Temperature

*Density (Chemical Pot.)

*θ angle

*Magnetic Field

*Gravity

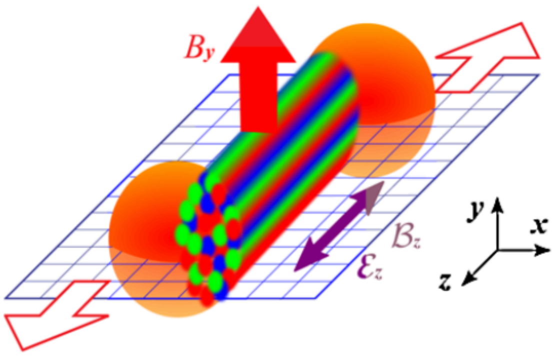
Rotation

QCD Thermodynamics

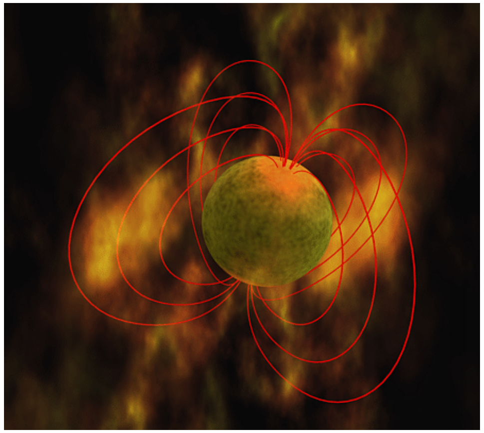
External Source

Relativistic Systems with eB

Heavy-ion collisions	$eB \sim 10^{18}\,\mathrm{G}$	Skokov, Illarionov, Toneev (2009)
Magnetar(surface)	$eB \sim 10^{15}\,\mathrm{G}$	Duncan, Thompson (1992)
Magnetar(interior)	$eB \sim 10^{18-20}\,\mathrm{G}$	Lai, Shapiro (1991) Ferrer et al. (2010)

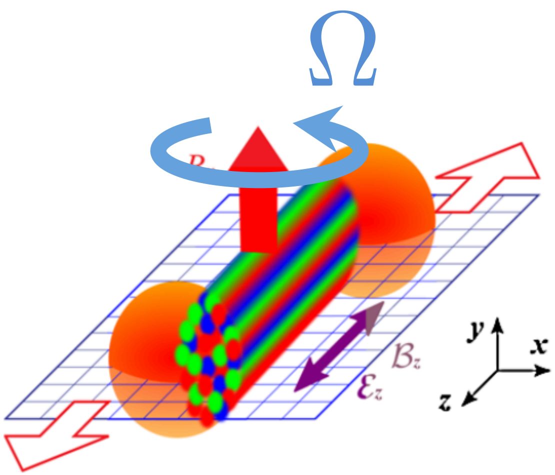


10.1103/PhysRevLett.104.212001



Relativistic Systems with Ω

Heavy-ion collisions	$\Omega \sim \Lambda_{\rm QCD}$?	Csernai et al. (2011)
Magnetar	$R\Omega \sim 10^{-1}$	Marshall et al. (2004)



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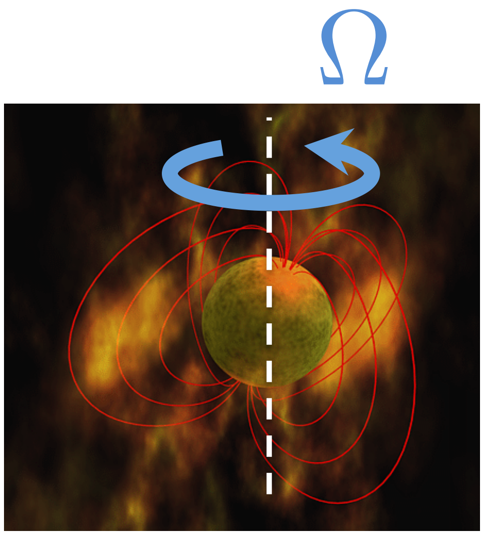
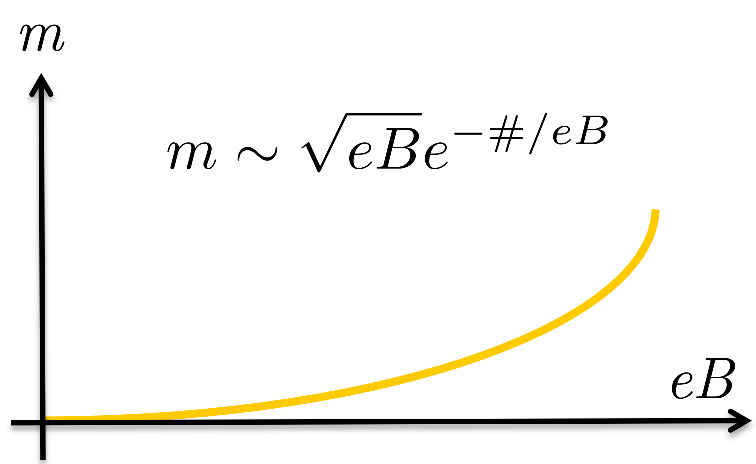


Magnetic Catalysis

* **Attractive interaction**
* **Large magnetic field**

Klimenko (1992)
Gyusynin, Miransky, Shovkovy (1994)



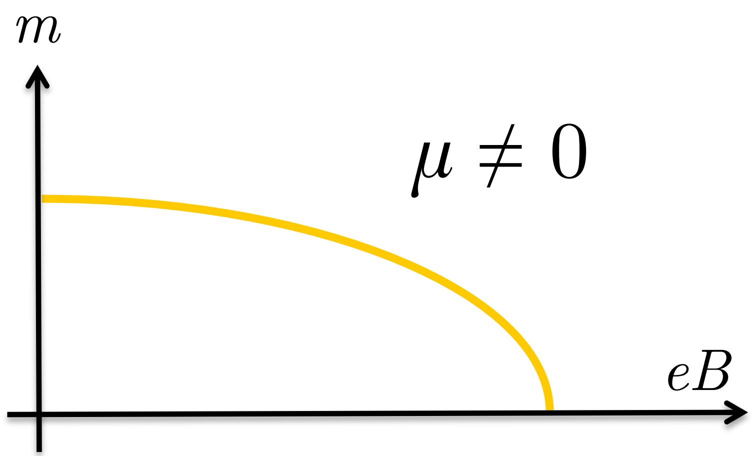
Increasing eB ⟶ Increasing m

Magnetic Catalysis

Magnetic Inhibition

* **Attractive interaction**
* **Large magnetic field**
* **Density**

Ebert, Klimenko (1999)
Preis, Rebhan, Schmitt (2012)



Increasing eB ⟶ ***Decreasing*** m

Magnetic Inhibition / Inverse Magnetic Catalysis

“Rotational Magnetic Inhibition”

* **Attractive interaction**

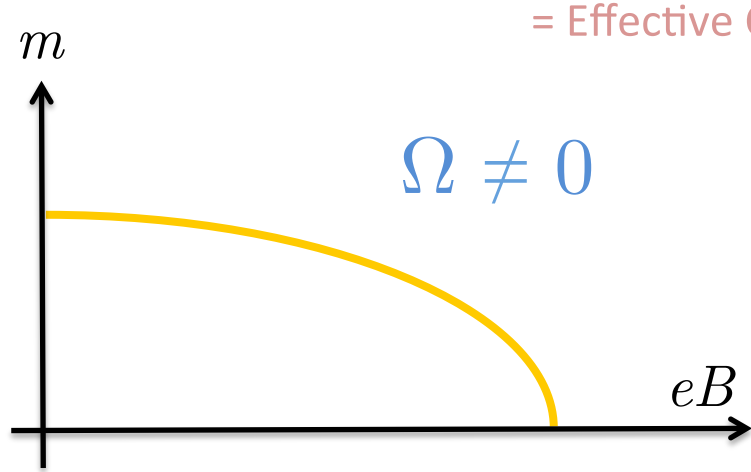
* **Large magnetic field**

* **Rotation**

$$E \to E + (L_z + S_z)\Omega$$

Rest   Rot.

Rotational Energy
= Effective Chemical Potential



Increasing eB ⟶ ***Decreasing*** m

“Rotational Magnetic Inhibition”

Fermions with eB and Ω

Rotation $V^\mu = e^\mu_i V^i$

Dirac eq. $$\Big[i\gamma^\mu(D_\mu + \Gamma_\mu) - m\Big]\psi = 0$$

Magnetic field

$$A_i = (0, By/2, -Bx/2, 0)$$

Rotation

$$g_{\mu\nu} = \begin{pmatrix} 1 - r^2\Omega^2 & y\Omega & -x\Omega & 0 \\ y\Omega & -1 & 0 & 0 \\ -x\Omega & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

$$(E + \underline{\Omega\ell + \Omega s_z})^2 = eB(2n + 1 - 2s_z) + p_z^2 + m$$

Rotational Energy

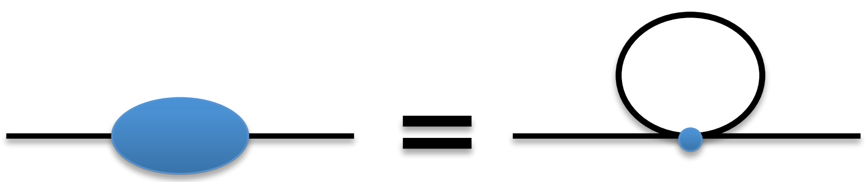
NJL Model with eB and Ω

$$S = \int d^4x \sqrt{-\det(g_{\mu\nu})}\,\mathcal{L}(\bar{\psi}, \psi)$$

$$\mathcal{L} = \bar{\psi}\big[i\gamma^\mu(D_\mu + \Gamma_\mu)\big]\psi + \frac{G}{2}\big[(\bar{\psi}\psi)^2 + (\bar{\psi}\gamma_5\psi)^2\big]$$

Gap eq.
(mean field approx.)

$$m = G\,\mathrm{tr}[S(x,x)]$$

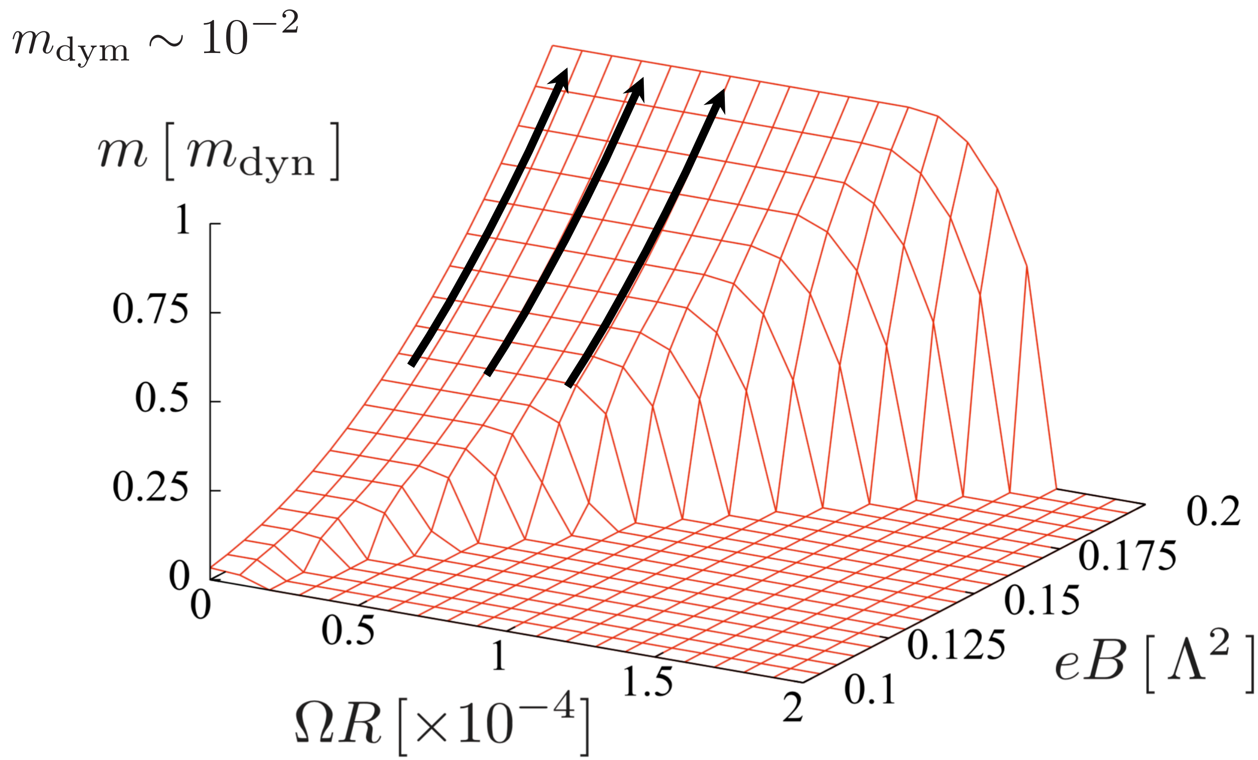


NJL in finite density
Ebert, Klimenko (1999)

weak coupling : Catalysis

strong coupling : Inhibition

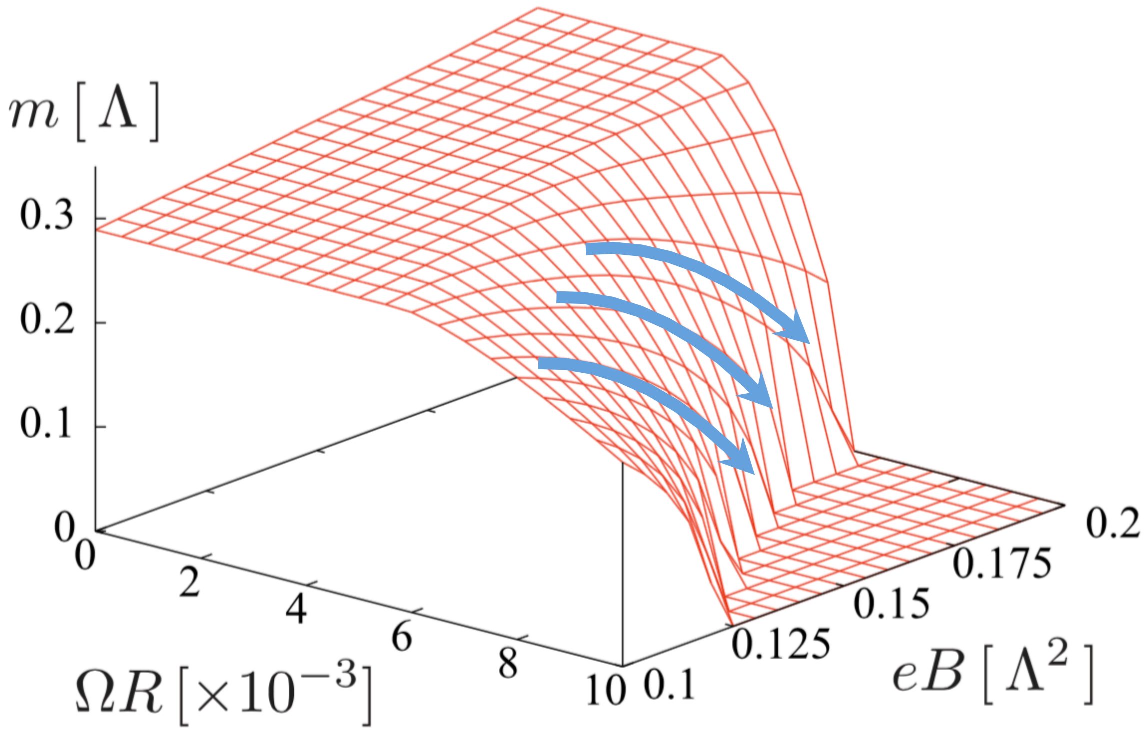
Weak Coupling $(T = 0)$



Increasing eB ⟶ Increasing m

Magnetic Catalysis

Strong Coupling $(T = 0)$



Increasing eB ⟶ ***Decreasing*** m

"Rotational Magnetic Inhibition"

Chen, Huang, Fukushima, KM (2016)

How Rotation Affects Fermions

Fermi dist. $$\frac{1}{1-e^{-\beta\{\varepsilon-|\Omega(\ell+1/2)|\}}} \longrightarrow \theta\Big(\varepsilon-|\Omega(\ell+1/2)|\Big)$$

If there exists a mode that satisfies $\varepsilon-\Omega|\ell+1/2|<0$

rotation affects the fermion dynamics

$1/\sqrt{eB} \ll R$ ⟶ The wave func. is localized

⟶ R can be regarded as infinite

Eigen-mode $$\varepsilon=\sqrt{2neB+p_z^2+m^2}$$

Rotation with a strong magnetic field affects a system

Without Magnetic Field

The wave func. is *no longer* localized ⟶ R should be finite

Eigen-mode $\varepsilon = \sqrt{p_{\ell,\,k}^2 + p_z^2 + m^2}$ $\phi(r) \sim J_\ell(p_{\ell,\,k} r)$

$$J_\ell(p_{\ell,\,k} R) = 0 \longrightarrow p_{\ell,\,k} = \xi_{\ell,\,k}/R$$

IR mode

$$\varepsilon - \Omega(\ell + 1/2) \geq \frac{\xi_{\ell,\,1}}{R} - \Omega(\ell + 1/2)$$

$$= \frac{1}{R}\left[\xi_{\ell,\,1} - \Omega R(\ell + 1/2)\right]$$

$$\geq \frac{1}{R}\left[\xi_{\ell,\,1} - (\ell + 1/2)\right] > 0$$

Causality

$$\Omega R \leq 1$$

e.g.

$$\xi_{0,\,1} = 2.40483 > 1/2$$

Rotation itself leads to NOTHING

Ebihara, Fukushima, KM (2016)

Summary

- Rotation itself never changes dynamics (at zero temperature)

- eB with rotation $\simeq$ eB with density

- A High eB or T allows us to ignore the boundary effect

$$\boldsymbol{j}_\mathrm{A} = \frac{T^2\boldsymbol{\Omega}}{12} + \frac{\Omega^2\boldsymbol{\Omega}}{48\pi^2} + O(\Omega R^{-2}) \quad \text{for} \quad T \gg R^{-1} \geq \Omega$$

Vilenkin (1980)

- For a small eB or T, the boundary effect should be taken into account