Magnetogenesis from rotating scalar: a la scalar chiral magnetic effect

Chang Sub Shin (IBS-CTPU)

based on 1905.06966

Kohei Kamada, Chang Sub Shin

at IBS BUSAN workshop on BSM

Dec 5, 2019

Outlines

Cosmic Magnetic Fields

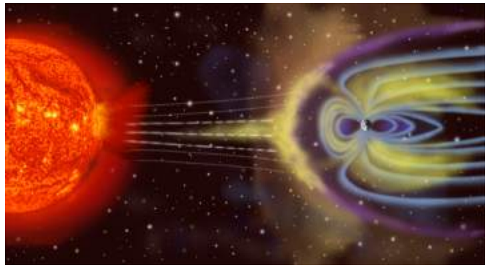
Generation of Cosmic Magnetic Fields

A Concrete Example of Scalar CME

Cosmic Magnetic Fields

Magnetic fields in the Universe

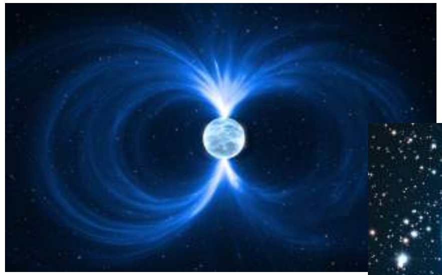
Cosmological magnetic fields are discovered (constrained) for different magnitudes with different scales



B_{earth}
$0.25 - 25\ G$

Magnetic fields in the Universe

Cosmological magnetic fields are discovered (constrained) for different magnitudes with different scales



$B_{\text{neutron}\, star}$

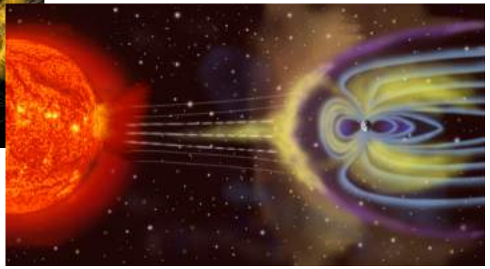
$10^{12} - 10^{15} G$

$B_{\text{white}\, dwarf}$

$10^{3} - 10^{9} G$

$B_{\text{sunsp}ot}$

$1.5 \times 10^{3} G$



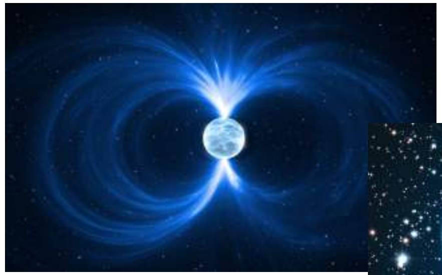
B_{earth}

$0.25 - 25\ G$

Magnetic fields in the Universe

Cosmological magnetic fields are discovered (constrained) for different magnitudes with different scales

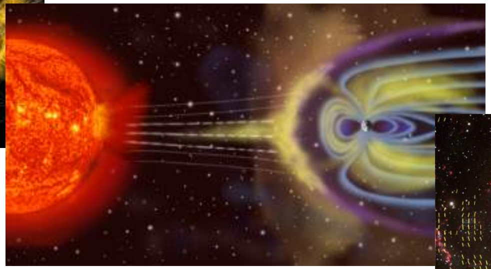
km



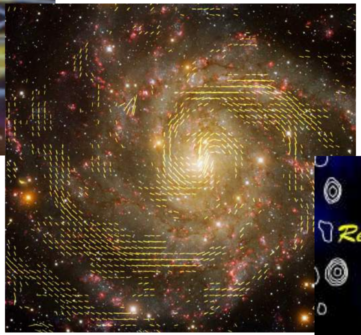
$B_{\text{neutron } star}$
$10^{12} - 10^{15} G$

$B_{\text{white } dwarf}$
$10^{3} - 10^{9} G$

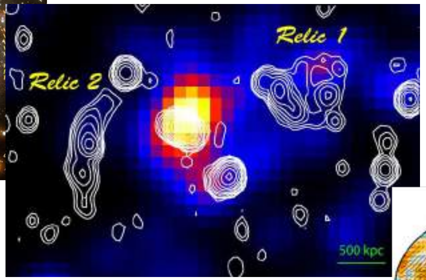
B_{sunspot}
$1.5 \times 10^{3} G$



B_{earth}
$0.25 - 25\ G$

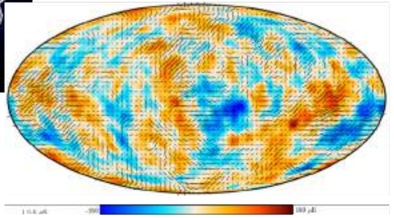


B_{galaxy}
$10^{-6} - 10^{-3} G$



$B_{\text{galaxy cluster}}$
$10^{-9} - 10^{-6} G$

Mpc



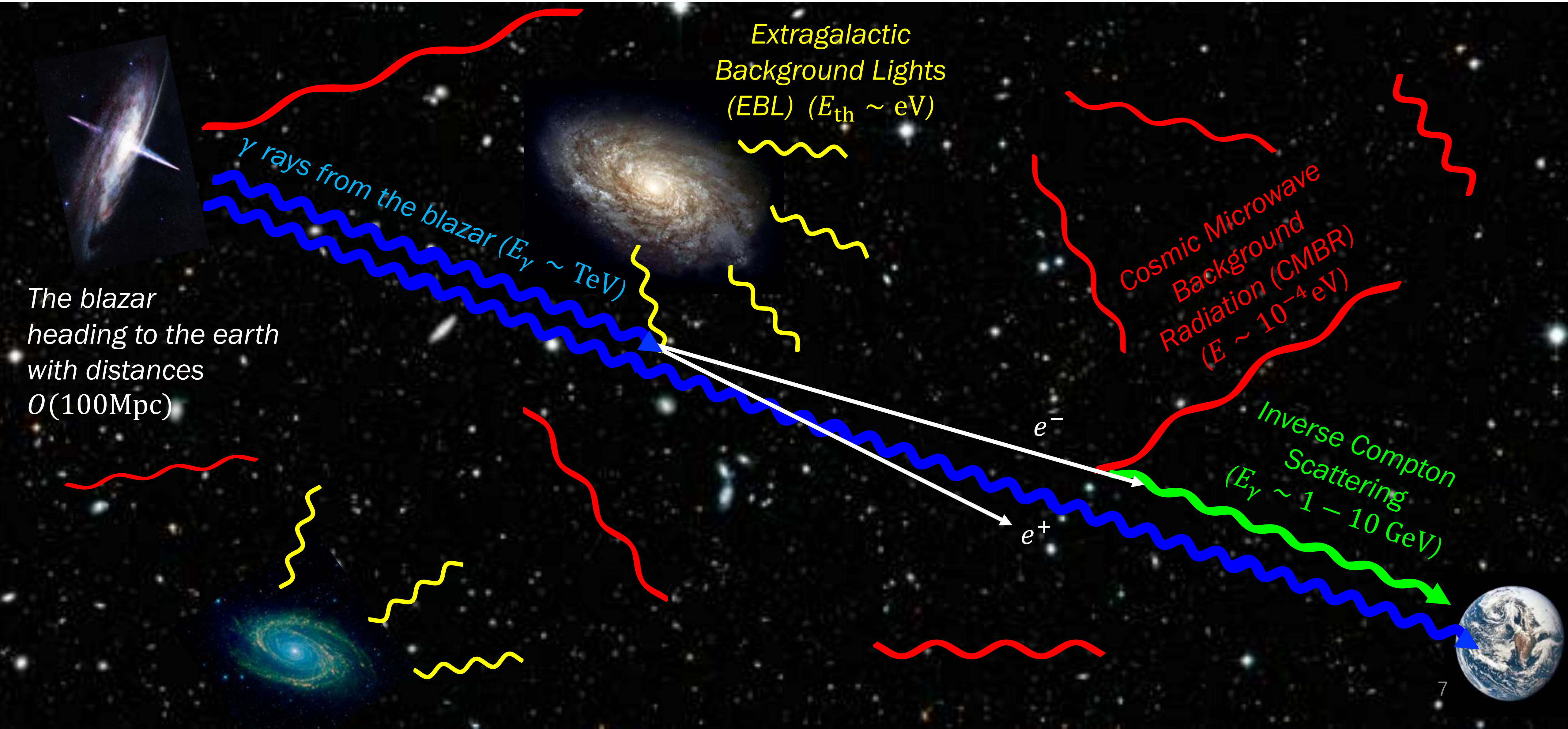
$B_{\lambda > 1\text{Mpc}}$
$< O(10^{-9}) G$

From Synchrotron emission
Faraday rotation
Polarization of dust emission
Zeeman splitting
CMB B mode polarization ...

Primordial magnetic fields $B_{\lambda \gtrsim 0.1\text{kpc}} \gtrsim 10^{-30}\ G$
can be a seed of B-fields of galaxy, galaxy cluster by dynamo amplification mechanism:
Motivation to study the magnetic field in cosmic void (Inter-galactic magnetic fields)

Intergalactic magnetic fields

Observation of TeV blazars: indirect way to probe the magnetic fields for given coherence lengths in the cosmic void



Intergalactic magnetic fields

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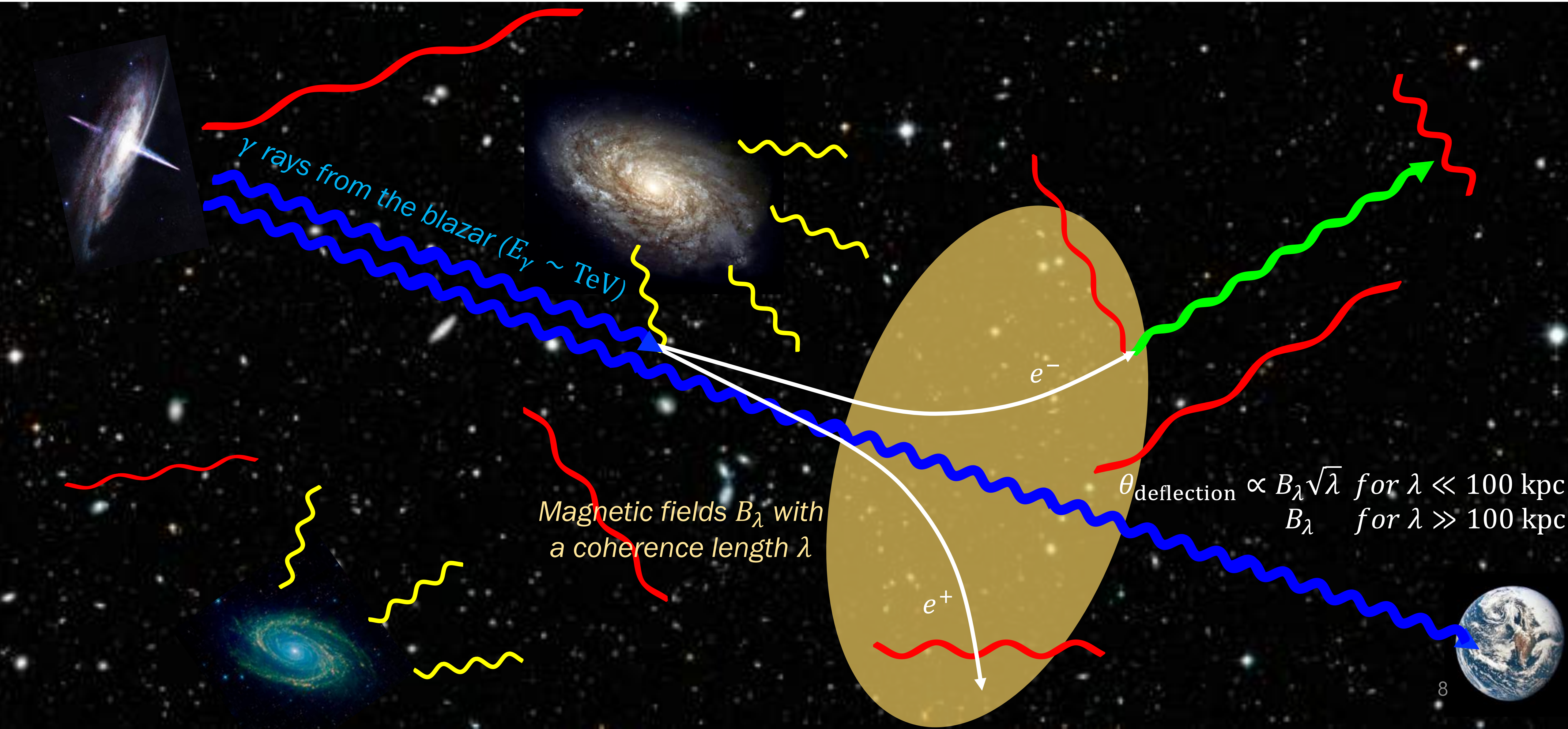
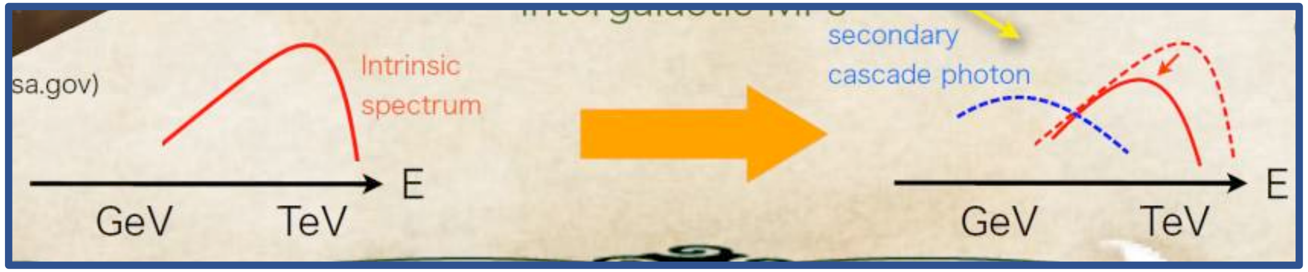


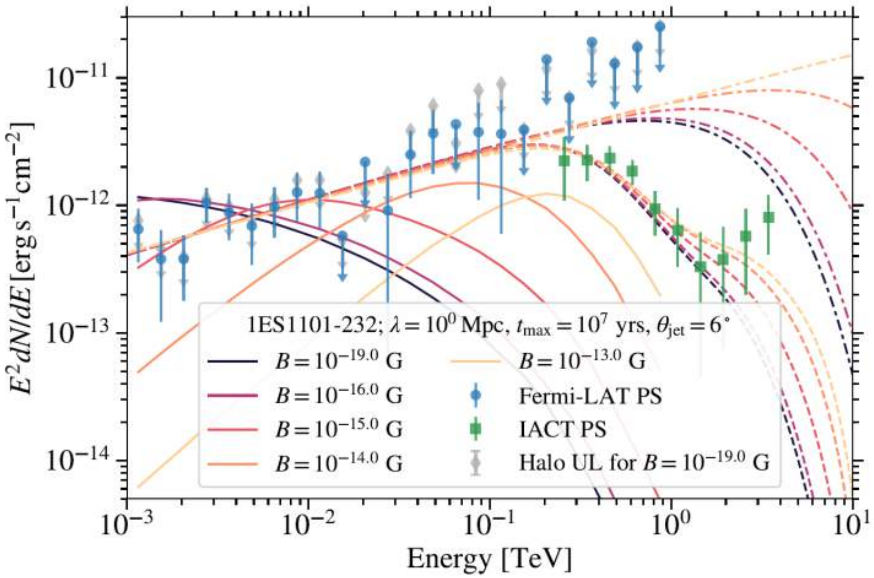
Evidence or constraints for intergalactic magnetic fields

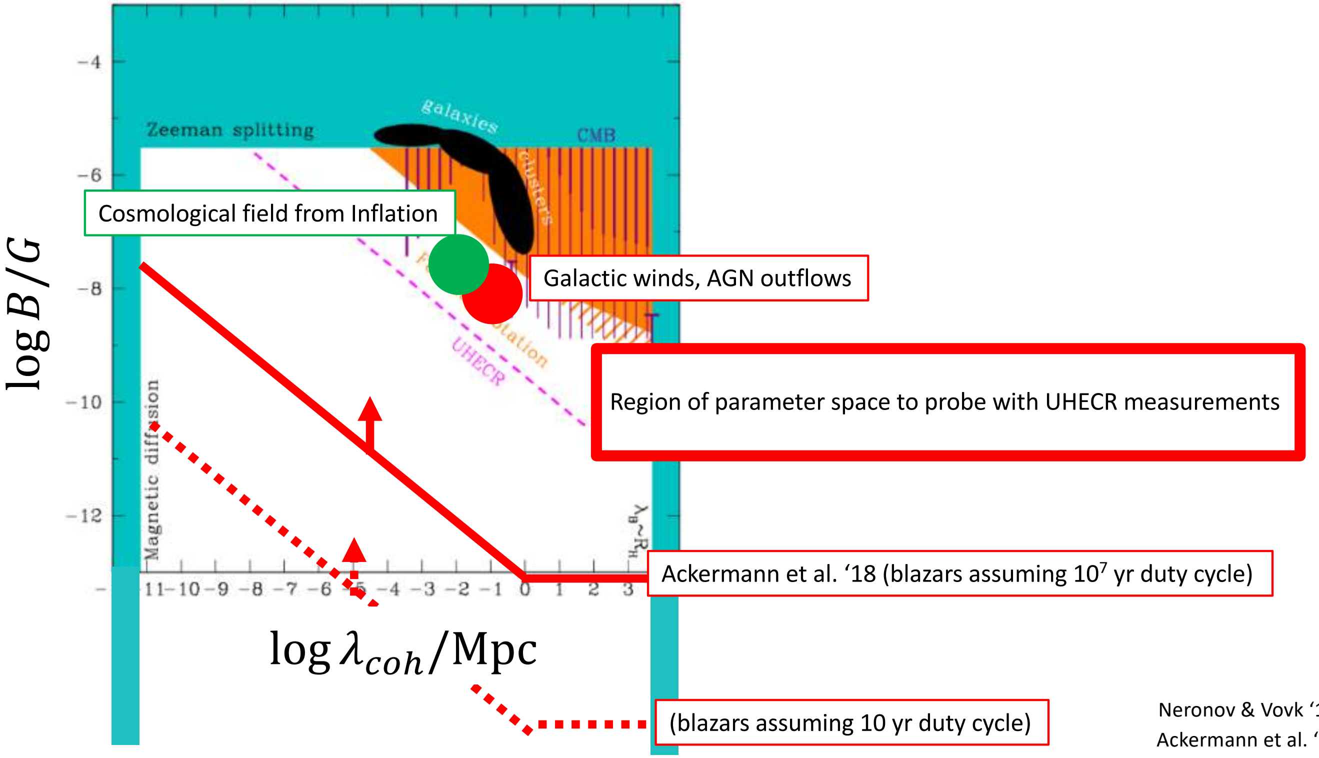
No observation of secondary GeV photons → evidence of intergalactic magnetic fields



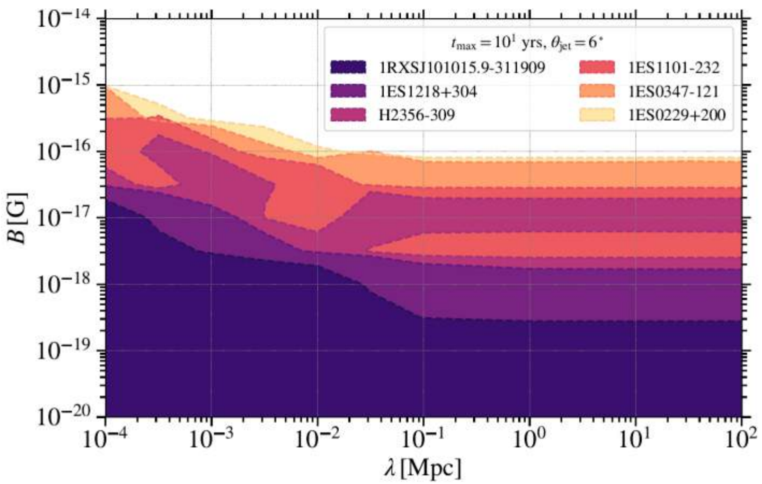
Slides from Kohei Kamada

Neronov, Vovk 1006.3504





Neronov & Vovk '10
Ackermann et al. '18



Slides from Neronov UHECR 2018

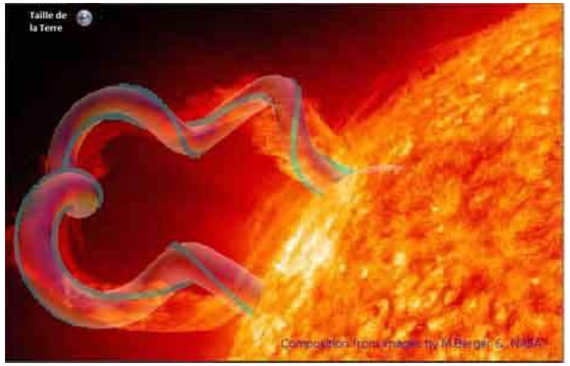
Fermi-LAT 1804.08035

Magnetic helicity

Magnetic helicity is the topological quantity which quantifies e.g. twist, kink, linkage, handedness of magnetic field lines

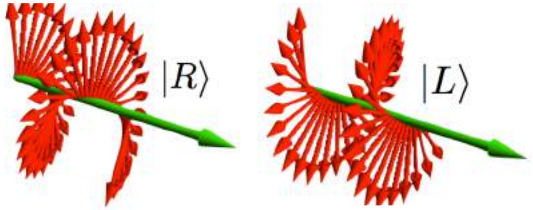
$$H_m \equiv \int_V d^3x\, \vec{A}\cdot\vec{B} \quad (\vec{B} = \nabla\times\vec{A})$$

$H_m = 0$ $\quad$ $H_m = n\Phi^2$ $\quad$ $H_m = \pm 2\Phi_1\Phi_2$



It can be written as the difference between the RH and LH circular polarization modes

$$\frac{dH_m}{dV} \equiv h_m = \int \frac{d^3k}{(2\pi)^3}\, k\left(\left|A_k^R\right| - \left|A_k^L\right|^2\right)$$



Time dependence of the helicity:

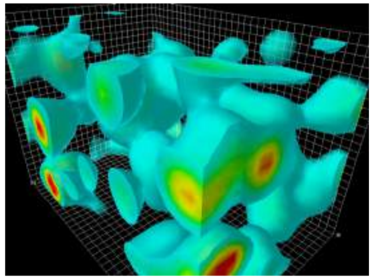
$$\frac{\partial h_m}{\partial t} = -2\,\vec{E}\cdot\vec{B} = \frac{1}{2}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

(hyper) helicity of the magnetic fields can be important for the cosmological evolution in the Early Universe.

$$\partial_\mu J_B = \partial_\mu J_L = \frac{3g^2}{16\pi^2}\mathrm{Tr}\left[W_{\mu\nu}\widetilde{W}^{\mu\nu}\right] - \frac{3g'^2}{32\pi^2}B_{\mu\nu}\tilde{B}^{\mu\nu}$$

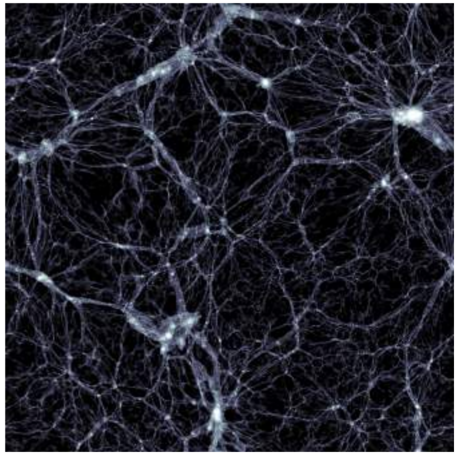
Generation of Cosmic Magnetic fields

New physics beyond the Standard Model can provide the explanation of amplification mechanism from the quantum fluctuations to the primordial magnetic fields for given coherence scales



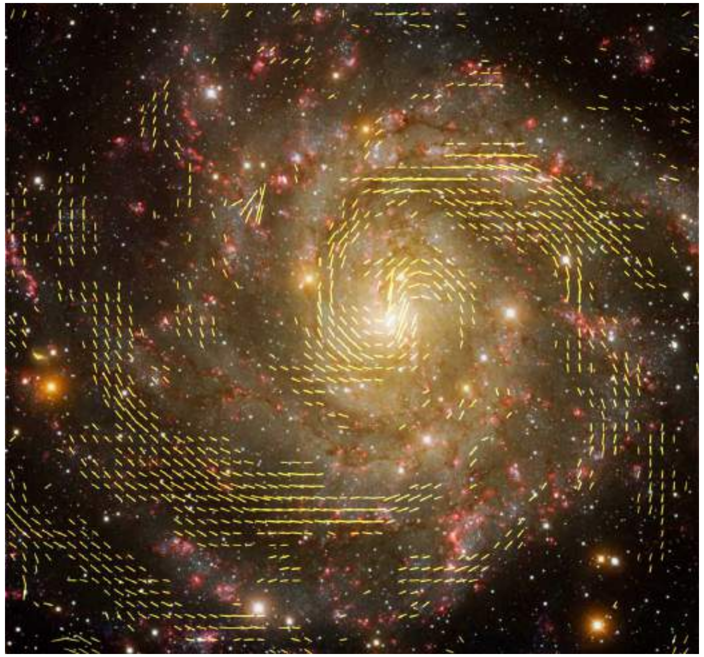
B_{quantum}

Amplify by
New Physics



$B_{\text{primordial}}$

Amplify by
Standard Physics

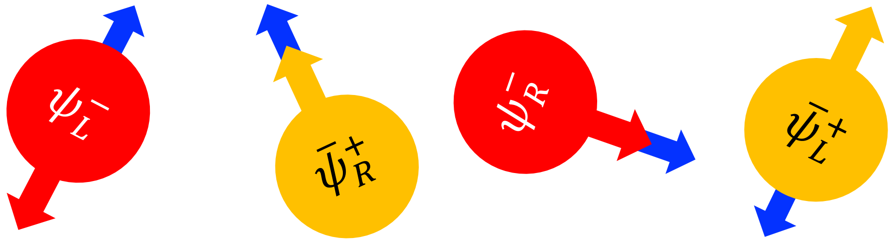


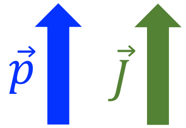
B_{galaxy}

Generation of Cosmic Magnetic Fields

Chiral Magnetic Effect

Step1) Chirality imbalance of (relativistic) fermions ($n_R \neq n_L$) + Magnetic fields → Electric current

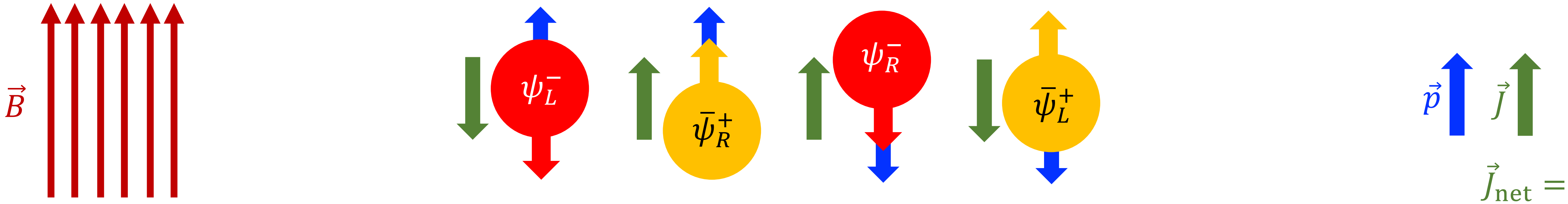




$$h_{R/L} = \frac{\vec{s} \cdot \vec{p}}{|p|} = \pm\frac{1}{2} \qquad \mu_m \propto \pm e\, h_{R/L}$$

Chiral Magnetic Effect

Step1) Chirality imbalance of (relativistic) fermions ($n_R \neq n_L$) *+ Magnetic fields → Electric current*



$\vec{J}_{\mathrm{net}} = 0$

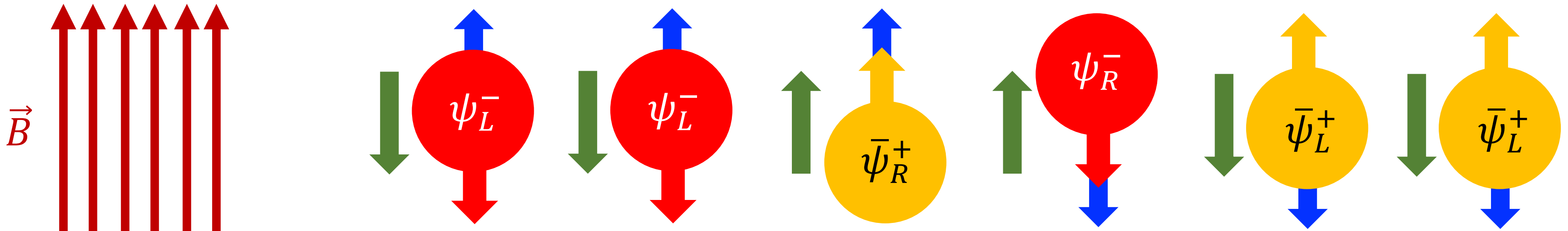
$$h_{R/L} = \frac{\vec{s}\cdot\vec{p}}{|p|} = \pm\frac{1}{2}$$

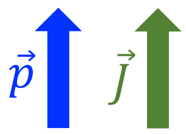
$$\mu_m \propto \pm e\, h_{R/L}$$

$$n_R = n_L$$

Chiral Magnetic Effect

Step1) Chirality imbalance of (relativistic) fermions ($n_R \neq n_L$) + Magnetic fields → Electric current

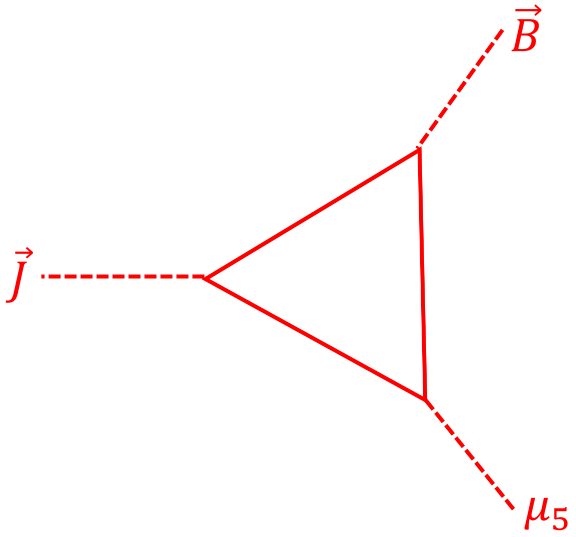




$\vec{J}_{\rm net} \neq 0$

$n_R \neq n_L$

$$h_{R/L} = \frac{\vec{s}\cdot\vec{p}}{|p|} = \pm\frac{1}{2} \qquad \mu_m \propto \pm e\, h_{R/L}$$



$$\partial_\mu J^\mu = \frac{e^2}{16\pi^2}\left(F_{L\mu\nu}\tilde{F}_L^{\mu\nu} - F_{R\mu\nu}\tilde{F}_R^{\mu\nu}\right)$$

$$\left(A_{R\mu} = A_\mu + A_\mu^5, \quad A_{L\mu} = A_\mu - A_\mu^5\right)$$

$$(A_0^5 = \mu_5)$$

$$\vec{J}_{\rm CME} = \frac{e^2}{2\pi^2}\mu_5\vec{B}$$

Alekseev, Cheianov, Froehlich 9803346
Charbonneau, Zhitnitsky 0701308
Fukushima, Kharzeev, Warringa 0808.3382

Magnetogenesis via Chiral Magnetic Effect

Joyce, Shaposhnikov 9703005
Tashiro, Vachaspati, Vilenkin 1206.5549

Step2) From Maxwell equations (ignoring fluid vorticity)

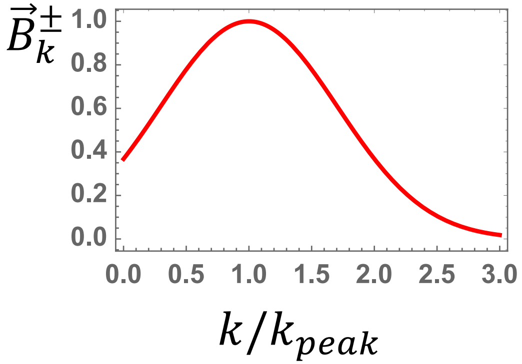
$$\nabla\times\vec{B} = \frac{\partial\vec{E}}{\partial t} + \vec{J}, \qquad \nabla\times\vec{E} = -\frac{\partial\vec{B}}{\partial t} \qquad \left(J \simeq J_{\rm Ohm} + J_{\rm CME} = \sigma(\vec{E} + \vec{v}\times\vec{B}) + \frac{e^2}{2\pi^2}\mu_5\vec{B}\right)$$

for the length scale of interest $\lambda \sim \nabla^{-1} \gg \frac{1}{\sigma v}, \frac{1}{e^2 T}$, $(\sigma \sim T/e^2)$

$$\partial_t\vec{B} \approx \frac{1}{\sigma}\left(\nabla^2\vec{B} + \frac{e^2\mu_5}{2\pi^2}\nabla\times\vec{B}\right) \rightarrow \frac{d}{d\tau}\vec{B}_k^{\pm} + \frac{1}{\sigma}k\left(k \mp \frac{e^2\mu_5}{2\pi^2}\right)\vec{B}_k^{\pm} = 0 \qquad \left(d\tau = \frac{dt}{a(t)}\right)$$

could yield the instability of one polarization mode for the coherence length $\lambda \sim 1/k_{peak}$

$$\left|\vec{B}_k^{\pm}\right| \sim |B_0^{\pm}| \exp\left(\frac{\tau}{\sigma}k_{peak}^2\right) e^{-\frac{\tau}{\sigma}(k \mp k_{peak})^2} \qquad \left(k_{peak} = \frac{e^2\mu_5}{2\pi^2}\right)$$



Helicity density is given by

$$h_m \sim \frac{T^3|B_0^+|^2}{\sqrt{2\pi^2\tau/\sigma}} k_{peak} \exp\left(2\frac{\tau}{\sigma}k_{peak}^2\right)$$

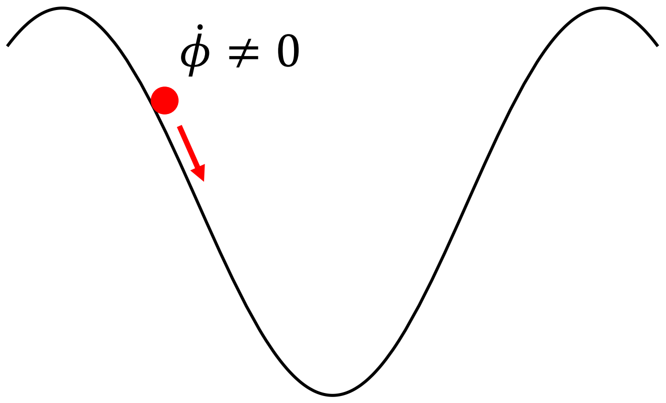
And μ_5 *will rapidly decrease as the helicity increases exponentially : saturated around* $h_{msat} \sim (4\pi/e^2)\mu_{5in}T^2$

$$\frac{d\mu_5}{dt} \simeq -\frac{e^2}{4\pi T^2}\frac{dh_m}{dt} \rightarrow \mu_5(\tau) \simeq \mu_{5in} - \frac{e^2}{4\pi}\frac{T\,|B_0^+|^2}{\sqrt{2\pi^2\tau/\sigma}} k_{peak} \exp\left(2\frac{\tau}{\sigma}k_{peak}^2\right)$$

Axion-Like Particle with Anomalous Coupling

In the case with CME, the origin of $\mu_5 \neq 0$ is unclear. *Axion-like particle can give the alternative source of μ_5*

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 + \Lambda^4 \cos\frac{\phi}{f} + \frac{g_{\phi\gamma}}{32\pi^2 f}\phi\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$



Anber Sorbo 0606534
and many others

The Maxwell equations:

$$\nabla\times\vec{B} = \frac{\partial\vec{E}}{\partial t} + \frac{g_{\phi\gamma}\dot{\phi}}{8\pi^2 f}\vec{B} \;\rightarrow\; \vec{J}_{eff} = \frac{g_{\phi\gamma}\dot{\phi}}{8\pi^2 f}\vec{B}$$

Instability arises around the mode $k \sim \xi(\tau)/\tau$

$$\frac{d^2}{d\tau^2}\vec{A}_k^{\pm} + k^2\left(1 \pm \frac{\xi(\tau)}{k\tau}\right)\vec{A}_k^{\pm} = 0$$

$$\left(\xi = \frac{g_{\phi\gamma}\,\dot{\phi}}{16\pi^2 H f}\right)$$

e.g. During inflation for the light axion ($m_\phi \lesssim H$), $3H\dot{\phi} \simeq -\partial_\phi V \sim -m_\phi^2\phi \sim m_\phi^2 f$, *Tachyonic instability happens if $\xi\pi \gg 1$*

$$|\vec{B}| \sim \frac{10^{-2}\exp(\pi\xi)}{\xi^{\frac{5}{2}}}H_{inf}^2, \qquad \lambda \sim \frac{\pi\xi}{H_{inf}}, \qquad \frac{dh}{dt} \sim \xi|\vec{B}|^2$$

$$\left(\text{However ... } \xi\pi = \frac{g_{\phi\gamma}\,\dot{\phi}}{16\pi\, Hf} \sim \frac{g_{\phi\gamma}\, m_\phi^2}{16\pi\, H^2} \gg 1 \rightarrow g_{\phi\gamma} \gtrsim O(100)\right)$$

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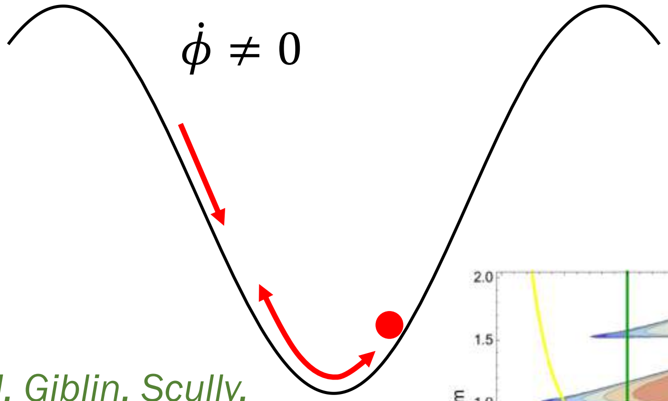

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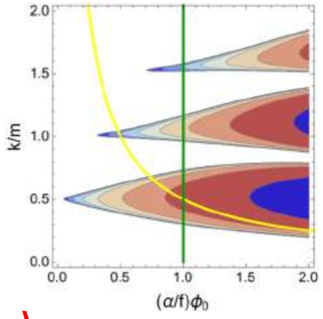
Adshead, Giblin, Scully, Sfakianakis 1502.06506 and many others



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$$\left(\xi = \frac{g_{\phi\gamma}\,\dot{\phi}}{16\pi^2 H f}\right)$$

After reheating: parametric resonance can occur since $\dot{\phi} \sim \cos m_\phi t$ (both RH, LH modes are produced)

In any case $g_{\phi\gamma} \gtrsim O(100)$ is necessary.

Another problem: If there are the light charged fermions ψ, $\phi\, F\tilde{F}$ coupling can be shifted to $\partial_\mu \phi\, \bar{\psi}\gamma^\mu\psi$ by chiral rotation.

gauge field production → fermion production: *Schwinger effects etc. prevent the exponential growing of B-fields*

During inflation case : $|\vec{B}| \lesssim 3\pi^2\xi^2 H_{inf}^2$ *Domcke, Mukaida 1806.08769*

Rotating scalar field

Considering the complex scalar field with a kinetic energy along θ direction for $V(\phi) = m^2|\phi|^2$

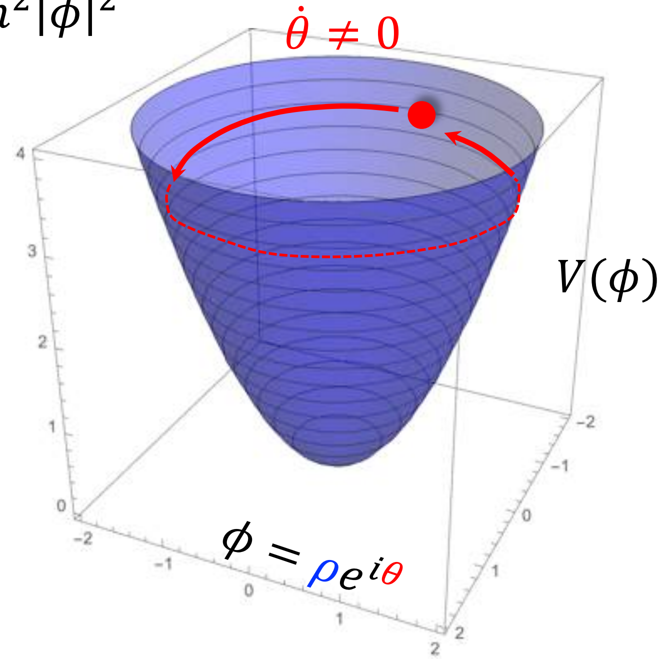
If the charged fermion has the mass by ϕ as

$$\mathcal{L}_{fermion} = \bar{\psi} i\gamma^\mu(\partial_\mu - iq\, A_\mu)\psi - (y\phi\, \psi_L\psi_R + h.c.),$$

during rotation along θ direction, the fermion becomes heavy with the mass $m_\psi = y\rho$.

Integrating out the fermion yields

$$\mathcal{L}_{eff} = c_A \frac{e^2}{16\pi^2}\theta(x)\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$



Nonzero $\dot{\theta}$ implies the nonzero PQ charge $(U(1)_{PQ}$: $\phi \to \phi e^{i\alpha}$, $\psi_L\psi_R \to e^{-i\alpha}\psi_L\psi_R)$,

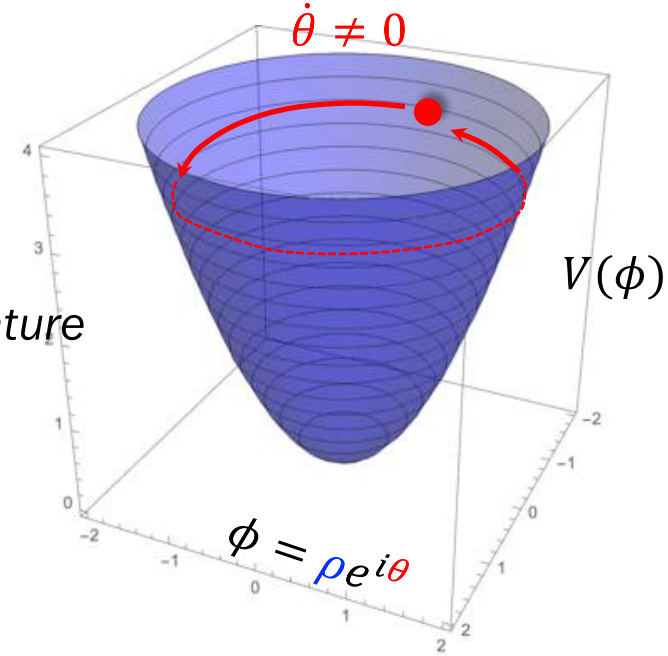
$$J^0_{PQ} = 2\rho^2\dot{\theta}$$

which is conserved until the breaking effect by the exponentially increasing B(E)-fields becomes important

$$\partial_\mu J^\mu_{PQ} \simeq 2\rho^2\ddot{\theta} = -c\frac{e^2}{16\pi^2}F\tilde{F} = -c_A\frac{e^2}{8\pi^2}\frac{dh_m}{dt} \quad \to h_{msat} = \frac{16\pi^2}{c_A e^2}\rho^2\,\dot{\theta}_{in}$$

Rotating scalar field

Tachyonic instability happens if $\theta(t)$ *cycles many times within a Hubble time*



No charged light fermions during magnetogenesis,

Maximally helical,

Long time evolution by approximate $U(1)_{PQ}$ *like a chiral symmetry at high temperature*

But how can we give such initial conditions (the large value of ρ*, and initial kick along* θ*-direction)?*

A Concrete Example of Scalar CME

Kamada CSS, 1905.06966

Dynamical origin of the rotating scalar

Affleck-Dine mechanism

Scalar potential = PQ symmetric term + small PQ breaking term + Hubble induced negative mass squares

e.g.

$$V(\phi) = (m^2 + c\,H^2)|\phi|^2 - (\epsilon\phi^4 + h.c.) + \frac{|\phi|^6}{\Lambda^2} \qquad \left(m^2 > 0, c < 0, \epsilon \sim \frac{m}{\Lambda}\ \text{(SUSY case)},\ H^2 = \frac{\rho_{tot}}{3M_P^2} \propto \frac{1}{a^3}\right)$$

The Hubble induced negative mass squared is dominant at the early Universe : $H^2 \gg m^2 \rightarrow \langle\phi\rangle = \rho \sim \sqrt{H\Lambda} \gg m$

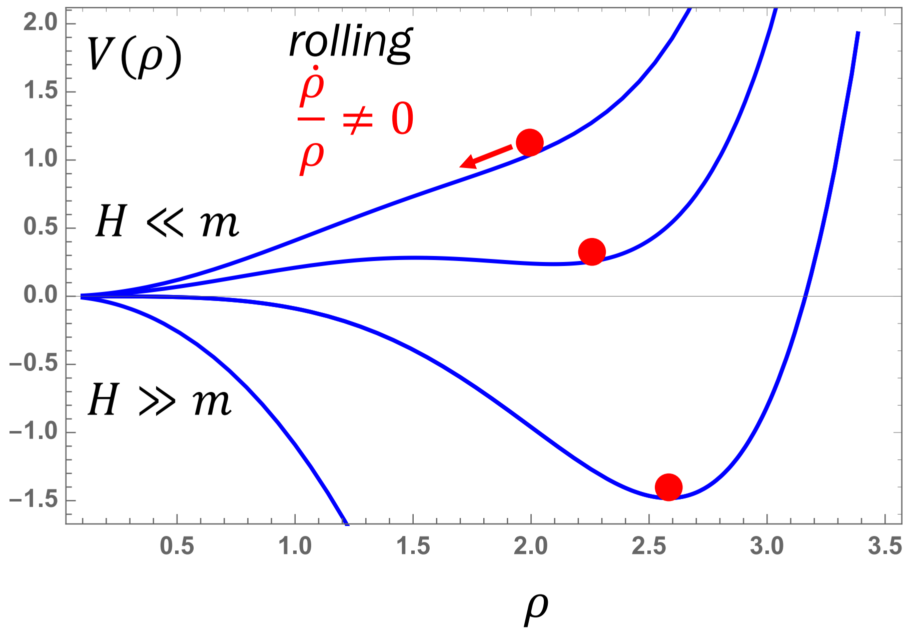
$$V(\rho,\theta) = (m^2 + cH^2)\rho^2 - 2\epsilon\rho^4 + \frac{\rho^6}{\Lambda^2} - 2\epsilon\rho^4\,(\cos 4\theta - 1)$$

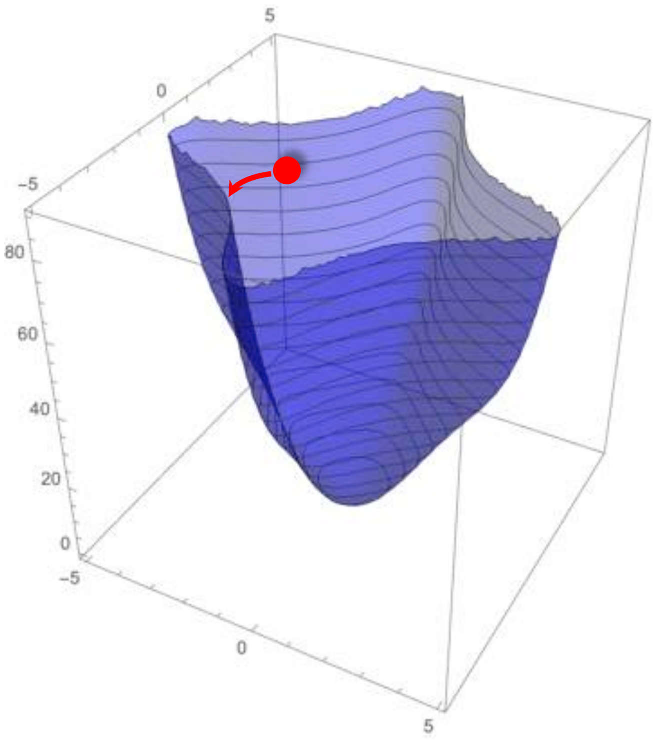
During $H^2 \gg m^2$*, along the* θ *direction, the field is frozen since* $m_\theta^2 \sim \epsilon\rho^2 \sim m\,H \ll H^2$

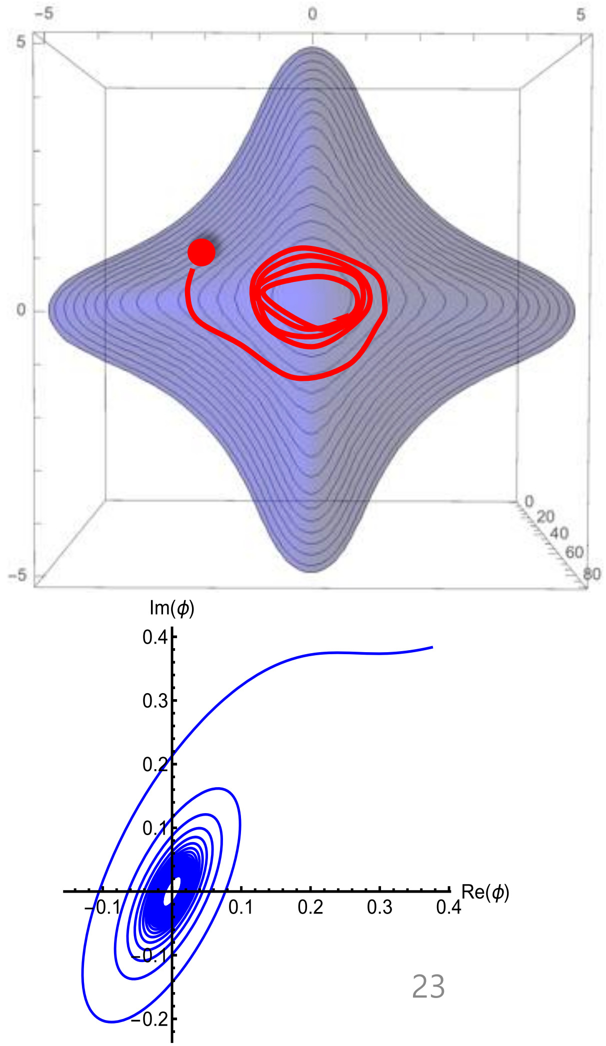
Small PQ breaking terms plays the important when $H \sim m$ *to induce "rolling" and "kicking"*

Dynamical origin of the rotating scalar

$$V(\phi) = (m^2 + c\,H(t)^2)|\phi|^2 - (\epsilon\phi^4 + h.c.) + \frac{|\phi|^6}{\Lambda^2}$$





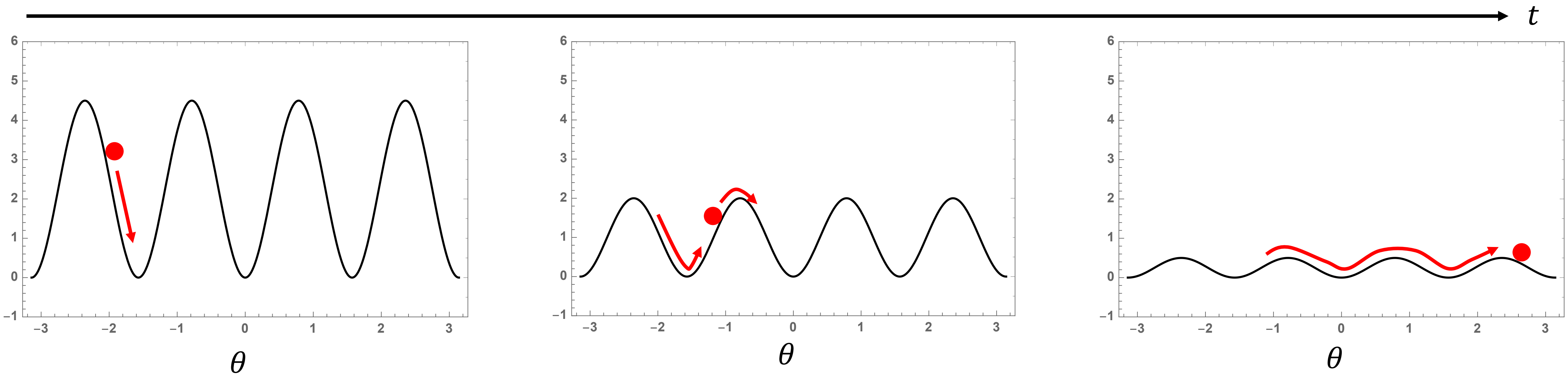


A large number of rotations around $\epsilon\rho(t_{osc})^2 \ll m^2$ because of PQ breaking effect becomes suppressed

Dynamical origin of the rotating scalar

Along the θ direction, as $\rho(t)$ decreases, the potential barrier becomes lower. The axion has the enough kinetic energy to go over the wall, and rotates for a long time

$$V_{eff}(\theta) = 2\epsilon\rho(t)^4\,(1 - \cos 4\theta)$$

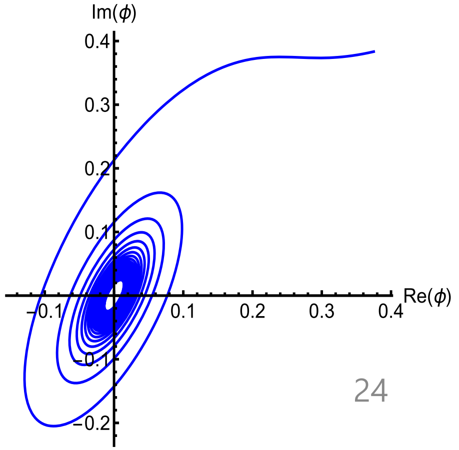


$$\dot{\theta} \sim m$$

During oscillation, H becomes smaller than m, so that

$$\xi = \frac{c_A e^2}{8\pi^2}\frac{\dot{\theta}}{H} \sim \frac{c_A e^2}{8\pi^2}\frac{m}{H} = O(1-10)$$

Is obtainable



Generation of B-field and helicity

B-fields, helicity are exponentially growing and saturated during the rotation of theta-field.

When they are generated

$$\left(h_{sat} \simeq \frac{8\pi^2}{c_A e^2}\, a(\tau_{osc})^3 \rho_{osc}^2\, \dot{\theta},\ \ k_{peak} = \frac{c_A e^2}{4\pi^2}\dot{\theta}\right)$$

$$B_{sat} \simeq \left(\frac{k_{peak}}{a(\tau_{osc})}\frac{h_{sat}}{a(\tau_{osc})^3}\right)^{\frac{1}{2}} \simeq 10^{12} GeV \left(\frac{\rho_{osc}}{10^{12} GeV}\right)\left(\frac{\dot{\theta}}{10^3 GeV}\right)$$

$$\lambda_{coh} \simeq 2\pi \left(\frac{k_{peak}}{a(\tau_{osc})}\right)^{-1} \simeq \left(\frac{3}{c_A\ GeV}\right)\left(\frac{\dot{\theta}}{10^3 GeV}\right)^{-1}$$

At the present Universe, adiabatic evolution and conserved comoving helicity ($\lambda B^2 \propto 1/a^3$) followed by magnetohydrodynamics to rearrange the fields as ($\lambda(t_0) \sim 1pc \left(\frac{B(t_0)}{10^{-14}G}\right)$)

$$B(t_0) \simeq 10^{-16} G \left(\frac{T_{RH}}{10^8 GeV}\right)^{1/3} \left(\frac{H_{osc}}{GeV}\right)^{-\frac{2}{3}} \left(\frac{\rho_{osc}}{10^{12} GeV}\right)^{\frac{2}{3}} \left(\frac{\dot{\theta}}{10^3 GeV}\right)^{1/3}$$

$$\lambda_{coh}(t_0) \simeq 10^{-2} pc \left(\frac{T_{RH}}{10^8 GeV}\right)^{1/3} \left(\frac{H_{osc}}{GeV}\right)^{-\frac{2}{3}} \left(\frac{\rho_{osc}}{10^{12} GeV}\right)^{\frac{2}{3}} \left(\frac{\dot{\theta}}{10^3 GeV}\right)^{1/3}$$

Two Higgs Doublet Model

In the minimal extension of the Standard Model, the Higgs is a good candidate for the AD field. To impose the PQ symmetry, two Higgs doublet model can be naturally taken.

$$-\mathcal{L} = \cdots + Y_u\, Q H_u u^c + Y_d\, Q\, H_d d^c + Y_e\, L\, H_d e^c + h.c. + V(H_u, H_d)$$

with $U(1)_{PQ}$: $H_u \to e^{i\alpha} H_u,\ H_d \to e^{i\alpha} H_d,\ Qu^c \to e^{-i\alpha} Qu^c,\ Qd^c \to e^{-i\alpha} Qd^c,\ Le^c \to e^{-i\alpha}\, Le^c$

Motivated by SUSY,

$$V(H_u, H_d) = m_u^2 |H_u|^2 + m_d^2 |H_d|^2 - \left(\frac{A}{\Lambda} (H_u H_d)^4 + h.c. \right) + g^2 (|H_u|^2 - |H_d|^2)^2 + \frac{(|H_u|^2 + |H_d|^2)|H_u H_d|^2}{\Lambda^2}$$

$$+\underline{(b(S) H_u H_d + h.c.)}$$

can be generated after magnetogenesis

Along the direction, $|H_u| = |H_d| = \rho(x),\ H_u H_d \to \rho(x)^2 e^{i\theta(x)}$*, and all charged fermions become massive with* $m_\psi = Y_\psi \rho$.

Also $SU(2)_L \times U(1)_Y \to U(1)_{EM}$ *gauge bosons massive* $m_{W/Z} \sim g\rho$

Massless degrees: photon, and neutrino, gluon. Light scalars: ρ *and* θ*. Integrating out all charged fermions*

$$\mathcal{L}_{eff} = (\partial_\mu \rho)^2 + \rho^2 (\partial_\mu \theta)^2 - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - V(\rho, \theta) + \frac{e^2}{2\pi^2}\, \theta\, F_{\mu\nu} \tilde{F}^{\mu\nu} + L(G_\mu, \nu)$$

Implication for baryogenesis

Kamada, Long 1610.03074
Kamada CSS, 1905.06966

As $\rho(t) \to 0$, $m_W, m_\psi \to 0$, and $SU(2)_L \times U(1)_Y$ is recovered:

$$F_{\mu\nu} \to W^3_{\mu\nu} + B_{\mu\nu}$$

After the reheating, the non-abelian magnetic field ($W^3_{\mu\nu}$) will quickly decay though its screening mass of $O(m_W \sim g^2 T)$, while there is no such a screening for the hyper-magnetic field ($B_{\mu\nu}$) with a helicity H_m from magnetogenesis.

Then from quantum anomaly for baryon number

$$\partial_\mu J_B = \partial_\mu J_L = \frac{3g^2}{16\pi^2} \mathrm{Tr}\left[W_{\mu\nu}\widetilde{W}^{\mu\nu}\right] - \frac{3g'^2}{32\pi^2} B_{\mu\nu}\tilde{B}^{\mu\nu}$$

The change of hyper magnetic helicity can be the source of baryogenesis

$$\Delta B = \Delta L = 3\,\Delta N_{CS} - \frac{3g'^2}{16\pi^2}\Delta H_{mY}$$

Electroweak phase transition is smooth (crossover). Massless $U_X(1)$ gauge boson is adiabatically decomposed as

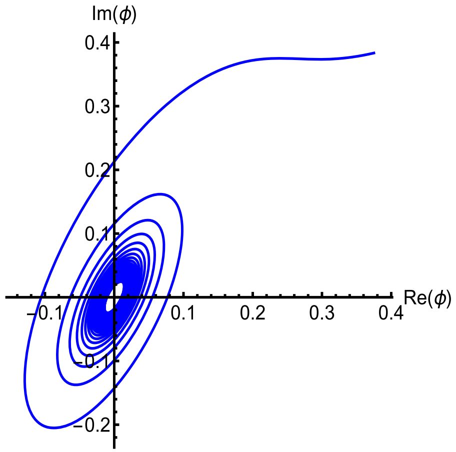
$$X_\mu(T) = B_\mu \cos\theta_W(T) + W^3_{\mu\nu} \sin\theta_W(T) \quad \left(X_\mu(T \gg m_W) \to B_\mu,\ X_\mu(T \ll m_W) \to A_\mu\right)$$

conserving the helicity as $H_m\big(X_\mu(T \gg m_W)\big) = H_m\big(X_\mu(T \ll m_W)\big)$ which gives $\Delta H_{mY} \sim \Delta\theta_W H_m$, $\Delta N_{CS} \sim \Delta\theta_W H_m \to \Delta B \propto \Delta\theta_W H_m$

$$\frac{n_B}{s} = \left(\frac{a_{osc}}{a_{RH}}\right)^3 \left(\frac{\dot{\theta}\rho^2_{osc}}{s(T_{RH})}\right) \sim 10^{-10}$$

Comparing with AD baryogenesis, Spontaneous baryogenesis

Affleck-Dine baryogenesis



$U(1)_B$: $\phi \to e^{i\alpha}\phi$

ϕ is the scalar baryon

$J^0_B = 2\rho^2\,\dot{\theta}$

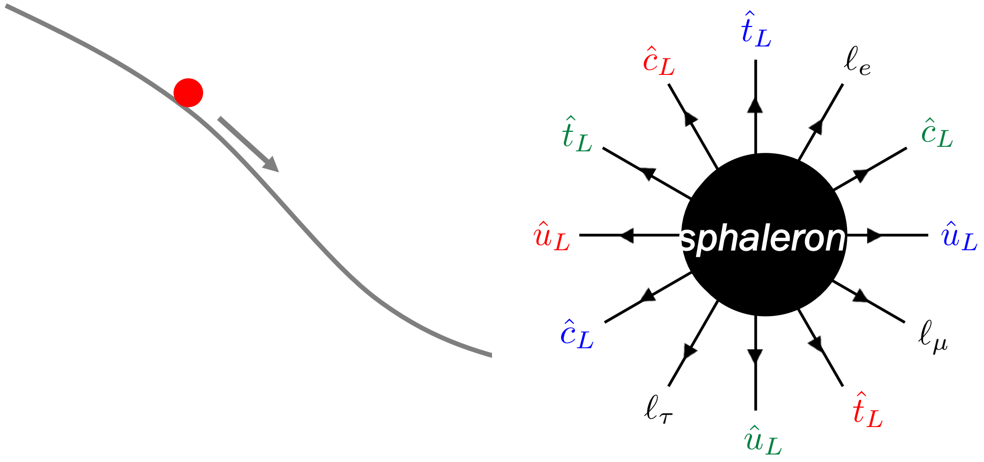
Baryon number is generated

$\phi \to q\ell$

Decay to light quarks (baryons)

Affleck Dine 1985 Nucl. Phys. B 249 361

Axionic Spontanoueous baryogenesis



$$\frac{g^2}{16\pi^2}\frac{\phi}{f}\,\mathrm{Tr}\big[W_{\mu\nu}\widetilde{W}^{\mu\nu}\big]$$

ϕ is neutral under $U(1)_B$

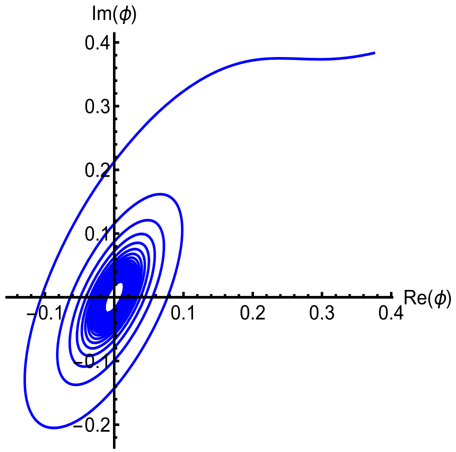
$$\dot{n}_B = \frac{3}{2}\frac{\Gamma_{sph}}{T}\left(\frac{\dot{\phi}}{f} - \frac{13}{2}\frac{n_B}{T^2}\right)$$

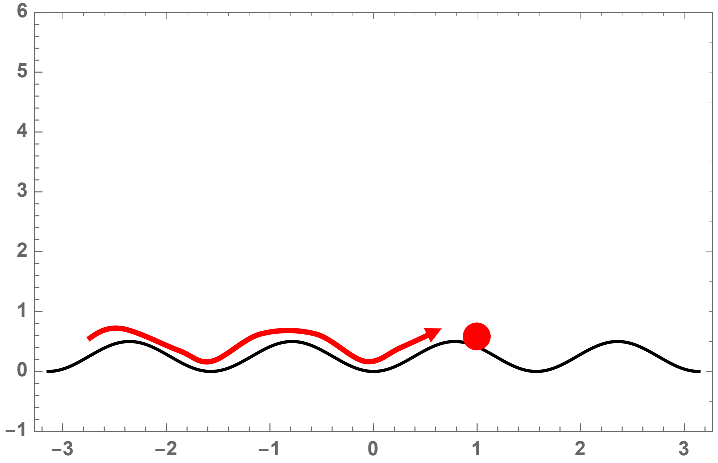
Baryon number is generated via rolling of ϕ, sphaleron process

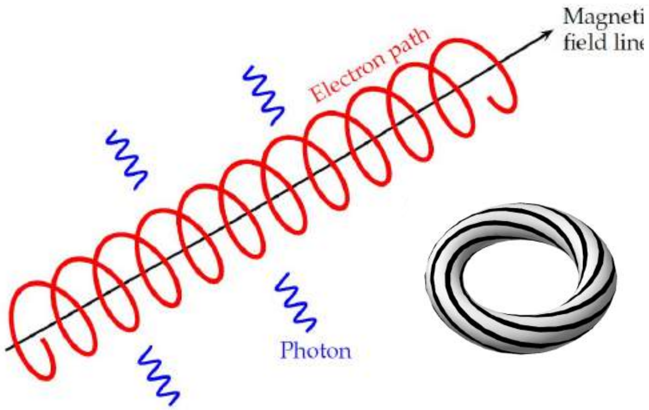
Jeong, Jung, CSS 1811.03294, etc.

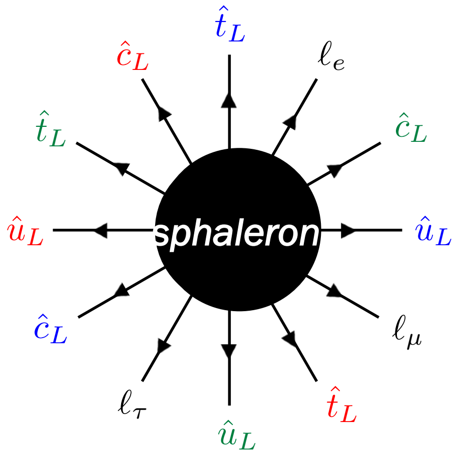
Comparing with AD baryogenesis, Spontaneous baryogenesis

Our magneto-baryogenesis









$$U(1)_{PQ}:\ \phi \to e^{i\alpha}\phi$$

$$J^0_{PQ} = 2\rho^2\,\dot{\theta}$$

PQ number is generated

$$\frac{e^2}{16\pi^2}\dot{\theta}\,(B_{\mu\nu}\tilde{B}^{\mu\nu} + W^3_{\mu\nu}W^{3\mu\nu} + \text{mixing})$$

Helical B-field is generated before reheating

$$\dot{n}_B = -\frac{3g'^2}{16\pi^2}\frac{dh_Y}{dt} + \cdots$$

Baryon number is generated
during EWPT

Summary

The intergalactic magnetic field is the interesting subject to understand the origin of cosmic magnetic fields, and the TeV gamma-ray spectrum

There are several ideas to generate primordial magnetic fields. For each case, there is some limitation from the UV point of view.

The Affleck-Dine type rotating scalar fields driven by small PQ breaking terms generate maximally helical magnetic fields like the case from Chiral Magnetic Effect. This idea can overcome several problems raised in magnetogenesis.

Thanks to the helicity, baryon asymmetry also can be generated with a reasonable value.