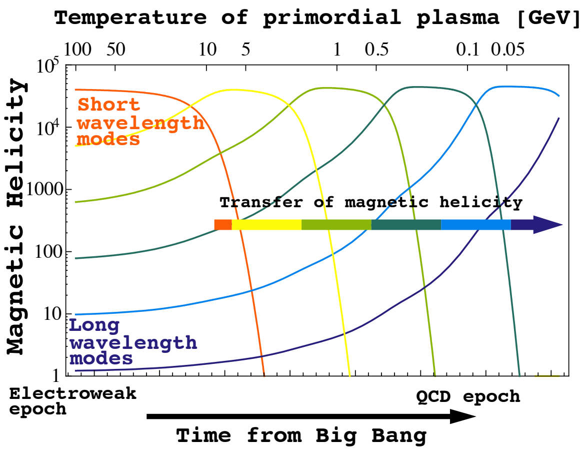
# Chiral Magnetic Effect and Cosmic Magnetic Fields

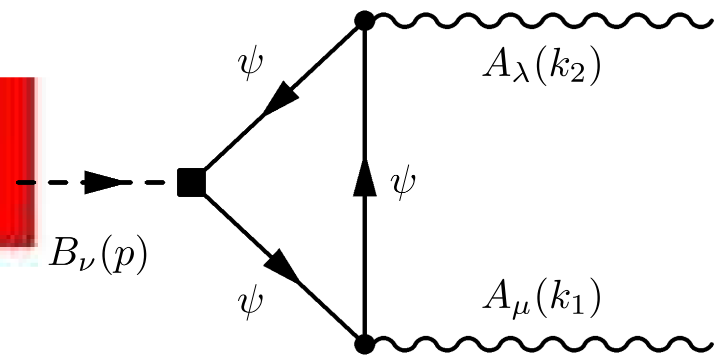




**Oleg RUCHAYSKIY**

LAPTH


December 5, 2013




Based on the old and recent works with
I.Antoniadis, A.Boyarsky, J.Fröhlich, J.Harvey, M.Shaposhnikov, J.Wells


- Phys. Rev. Lett. **108** (2012) 031301 [arXiv:1109.3350]
- Phys. Rev. Lett. **109** (2012) 111602 [arXiv:1204.3604]
- Nucl. Phys. B **824** (2010) 296 [arXiv:0901.0639]
- Nucl. Phys. B **793** (2008) 246 [arXiv:0708.3001]
- Phys. Rev. D **72** (2005) 085011 [arXiv:hep-th/0507098]
- Annals Phys. **301** (2002) 1 [arXiv:hep-th/0203154]

# Outline

- In this talk I argue that the conventional description of relativistic magnetized plasma is incomplete.

- There exists a **subtle quantum effect** that has macroscopic manifestation in the low-energy **classical** hydrodynamic equations

- This effect may be important in "real life" whenever you have **relativistic magnetized plasma** with high densities

  – Early Universe
  – Neutron stars
  – Astrophysical jets
  – Quark-gluon plasma

- I will describe early Universe application and its connection with BSM problems

# Axial symmetry

- Massless fermions can be left and right-chiral (left and right moving):

$$(i\gamma^\mu\partial_\mu - \cancel{m})\psi = \begin{pmatrix} \cancelto{0}{-m} & i(\partial_t + \vec{\sigma}\cdot\vec{\nabla}) \\ i(\partial_t - \vec{\sigma}\cdot\vec{\nabla}) & \cancelto{0}{-m} \end{pmatrix}\begin{pmatrix}\psi_L \\ \psi_R\end{pmatrix} = 0$$

  where $\gamma_5\psi_{R,L} = \pm\psi_{R,L}$ and $\gamma_5 = i\gamma_0\gamma_1\gamma_2\gamma_3$. In the above basis (Peskin & Schroeder conventions)':

$$\gamma_5 = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}$$

- Number of left $N_L = \int d^3x\, \psi_L^\dagger\psi_L$ and right $N_R = \int d^3x\, \psi_R^\dagger\psi_R$ particles is conserved **independently**

  $N_L + N_R$ and $N_L - N_R$ are conserved independently in the free theory

# Axial anomaly

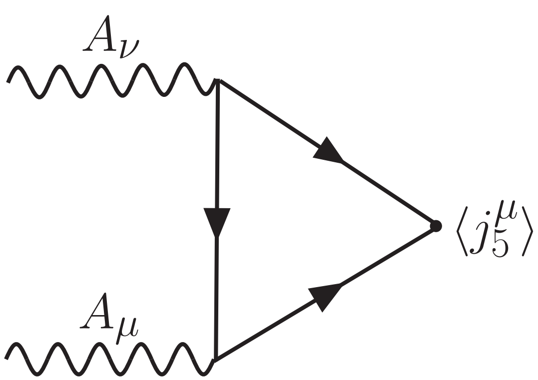
- Gauge interactions respects chirality ($D_\mu = \partial_\mu + eA_\mu$)...

$$\begin{pmatrix} \cancelto{0}{-m} & i(D_t + \vec{\sigma}\cdot\vec{D}) \\ i(D_t - \vec{\sigma}\cdot\vec{D}) & \cancelto{0}{-m} \end{pmatrix} \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix} = 0$$

- ...but the difference of left and right-movers is **not conserved**...

$$\frac{d(N_L - N_R)}{dt} = \int d^3\vec{x}\left(\partial_\mu j^5_\mu\right) = \frac{e^2}{4\pi^2}\int d^3\,\vec{x}\vec{E}\cdot\vec{B}$$

- ...once the quantum corrections are taken into account:




$$\boxed{\frac{d(N_L - N_R)}{dt} \propto \frac{d}{dt}\int \boldsymbol{d^3x\,\vec{A}\cdot\vec{B}}}$$

Magnetic helicity or Chern-Simons number

# Magnetic helicity

- Introduce **magnetic helicity**:

$$\mathcal{H} \equiv \int_V d^3x \vec{A} \cdot \vec{B}$$

- In terms of $B_k^{\pm}$ (left and right circular polarized modes of $B_k$)

$$\mathcal{H}_k = \frac{k}{2\pi^2}(|B_k^+|^2 - |B_k^-|^2) \text{ and } \rho_k = \frac{k^2}{(2\pi)^2}(|B_k^+|^2 + |B_k^-|^2)$$

so that

$$\mathcal{H} = \int dk\, \mathcal{H}_k \qquad \rho = \int dk\, \rho_k$$

- From its definition

$$\frac{d\mathcal{H}}{dt} = -\frac{2}{V}\int_V d^3x\, \vec{E} \cdot \vec{B}$$

# Chiral anomaly explained

**Landau levels:** $E^2 = p_z^2 + e|B|(2n+1) + 2e\vec{B}\cdot\vec{s}$

G.E. Volovik, cond-mat/9802091

- Only particles with $(\vec{B}\cdot\vec{s} < 0)$ have **massless** branches:

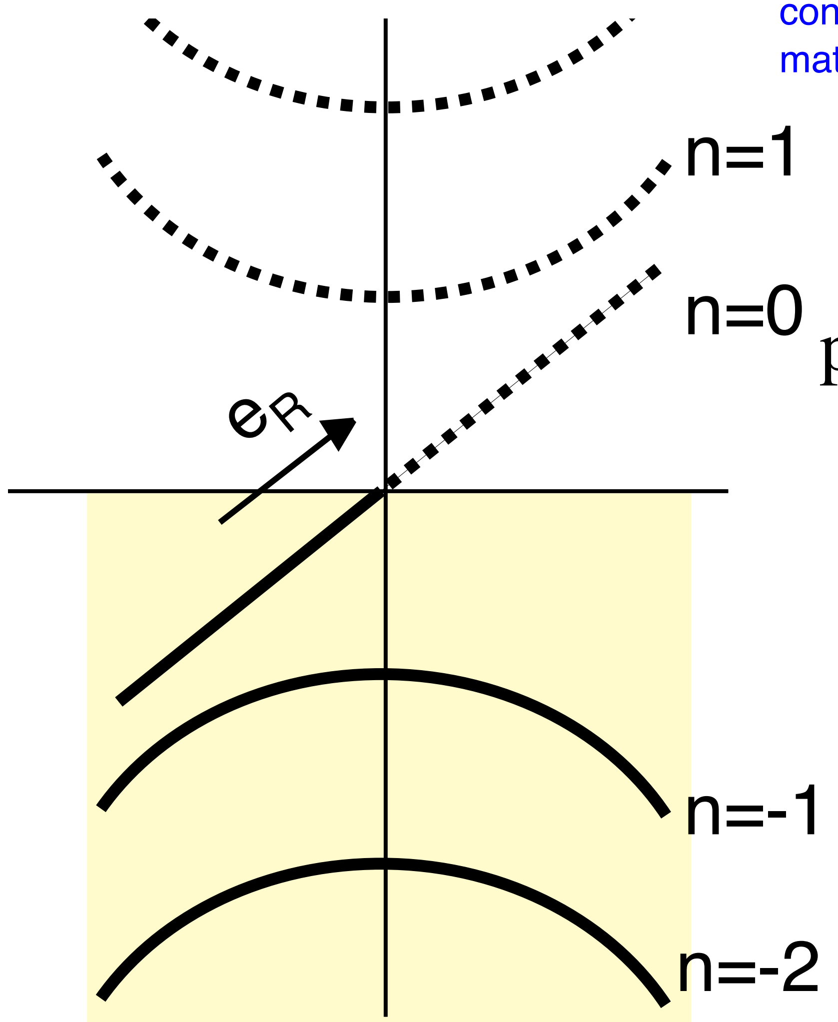
$$E = \begin{cases} -p_z & \text{left branch} \quad (\vec{p}\cdot\vec{s}) > 0 \\ p_z & \text{right branch} \quad (\vec{p}\cdot\vec{s}) < 0 \end{cases}$$

- Electric field $\vec{E} = E\hat{z}$ **creates** right particle (because $p_z(t) = p_z(0) + eEt$)

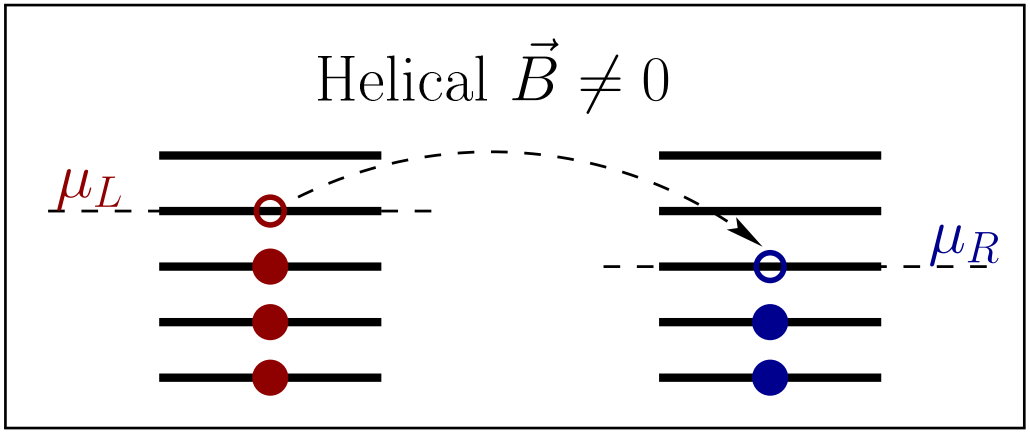
- Electric field destroys left particles

- **Total number** does not change

- **Difference** of left minus right appears – **chiral anomaly!**



# Chiral anomaly at finite fermion densities




- $\mu_L$ – Fermi level for left fermions
- $\mu_R$ – Fermi level for right fermions

- Chiral anomaly for degenerate Fermi gas

$$\Delta N_{L,R} = \int_{t_i}^{t_f} dt\, \dot{N}_{L,R}(t) = \mp \int dt \frac{\alpha}{\pi} \int d^3x\, E \cdot B$$

- The energy change: $\delta\mathcal{E} = \delta N_L \mu_L + \delta N_R \mu_R = \dfrac{\alpha}{2\pi}\mu_5 \displaystyle\int d^3x\, A \cdot B$

- Free energy density: $\delta\mathcal{F} = \displaystyle\int d^3x\, \frac{\alpha}{2\pi}\mu_5 A \cdot B$

Nielsen & Ninomiya (1983);

Rubakov (1986)

# Free energy of magnetic field

- The free energy for static magnetic fields $\mathcal{F}[\vec{A}]$ has the form

$$\mathcal{F}[A] = \frac{1}{2}\int d^3k\, A_i(\vec{k})\Pi_{ij}(k)A_j(-\vec{k}) + \mathcal{O}(A^3)$$

(magnetic field $\vec{B} = \nabla \times \vec{A}$)

- Polarization operator **in plasma** $\Pi_{ij}$ should be rotation invariant and gauge invariant (i.e. transversal: $k_i\Pi_{ij} = 0$). The most general form:

$$\Pi_{ij}(\vec{p}) = (k^2\delta_{ij} - k_ik_j)\Pi_1(k^2) \quad + \quad i\epsilon_{ijn}k^n\Pi_2(k^2)$$

parity-even part    parity-odd part

here and below we will speak only about $\Pi_2(0)$ that we denote simply by $\Pi_2$

- In vacuum $\Pi_{\mu\nu}(k) = (\eta_{\mu\nu}k^2 - k_\mu k_\nu)\Pi(k^2)$

# Free energy and axial anomaly

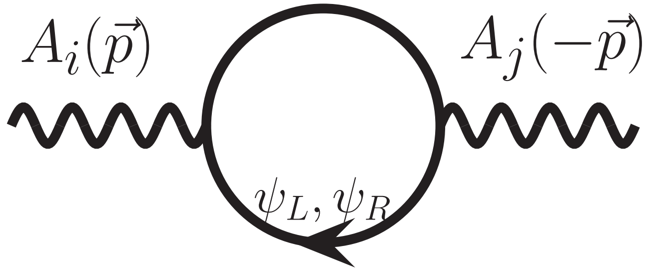
Vilenkin (1978)

Redlich & Wijewardhana (1985);

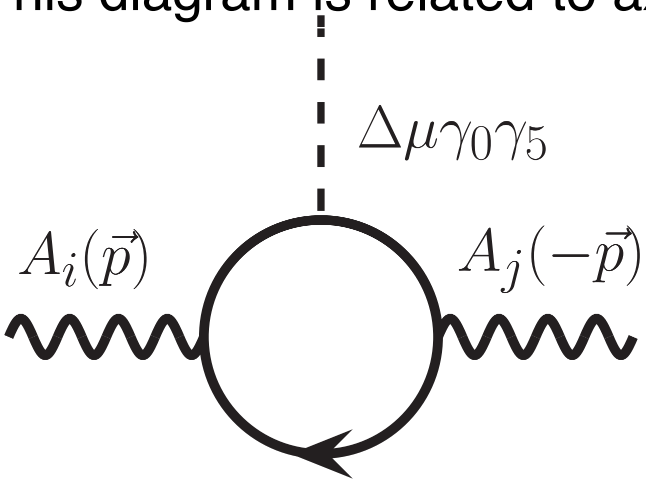
Fröhlich et al. (1998–2001)

- In plasma with the different number of left and right particles

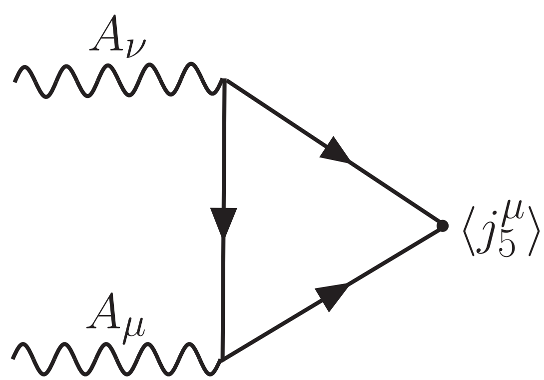
$$\boxed{\Pi_2 = \frac{\alpha}{\pi}\mu_5}$$




- This diagram is related to axial anomaly




$\Leftrightarrow$



# Chiral Magnetic effect

- **Chiral Magnetic Effect** is an electric current in the presence of the chiral chemical potential $\mu_5$:

$$\vec{j} = \frac{\delta \mathcal{F}}{\delta \vec{A}} = \frac{2\alpha}{\pi}\mu_5 \vec{B}$$

- Let us compare this with the Ohmic current $\vec{j}_{\text{Ohm}} = \sigma \vec{E}$

- Indeed, let us compare this w consider transformation w.r.t. **time-reversal symmetry** $\mathcal{T}$:

$$\left.\begin{array}{c} \vec{j} \stackrel{\mathcal{T}}{\to} -\vec{j} \\ \vec{B} \stackrel{\mathcal{T}}{\to} -\vec{B} \\ \vec{E} \stackrel{\mathcal{T}}{\to} +\vec{E} \end{array}\right\} \Longrightarrow \begin{cases} \sigma \stackrel{\mathcal{T}}{\to} -\sigma & \text{– dissipative current} \\ \mu_5 \stackrel{\mathcal{T}}{\to} \mu_5 & \text{– \textbf{non}-dissipative current} \end{cases}$$

Vilenkin'78;

Redlich & Wijewardhana (1985);

Rubakov'86;

Cheianov, Fröhlich, Alexeev'98;

Fröhlich & Pedrini'00,'02;

Fukushima, Kharzeev, Warringa'08

Son & Surowka'09

# Chern-Simons term

- In coordinate space $\Pi_2 \neq 0$ leads to a **Chern-Simons term**:

$$\mathcal{F}[A] = \frac{1}{2}\int d^3x \left(\vec{B}^2 + \Pi_2 \vec{A}\cdot\vec{B}\right)$$

- The Chern-Simons term
  - contains less derivatives than $(\nabla \times A)^2$
  - can be both positive and negative

- The matrix $\Pi_{ij}$ has a negative eigenvalue for

$$k < \Pi_2 \Longrightarrow \textbf{Instability!}$$

# Maximally helical configuration

- The unstable mode will have a form

$$\vec{A}(\vec{x}) = A_0\Big(\cos(kz), \sin(kz), 0\Big)$$

- For this configuration the magnetic field

$$\vec{B}(\vec{x}) = -k\vec{A}(\vec{x})$$

(*maximally helical* configuration)

- On this configuration $\vec{B}^2 = k\vec{A}\cdot\vec{B}$ and are homogeneous
- The effective action:

$$\mathcal{F}[A] = \frac{1}{2}\int d^3x \left(k^2 - k\Pi_2\right) A_0^2 < 0$$

for $k < \Pi_2 \Longrightarrow$ **increasing $A_0$ we decrease the free energy**

# Maxwell equations

- The presence of difference of chemical potential of left and right fermions leads to additional terms in the effective Lagrangian for electromagnetic fields – **Chern-Simons term**

- As a result Maxwell equations contain current, **proportional to** $\mu_5$ — MHD turns into **chiral MHD**:

Kharzeev'11

Vilenkin (1978)

Redlich & Wijewardhana (1985);

Fröhlich et al. (1998–2001)

Joyce & Shaposhnikov (1997)

$$\begin{aligned}\mathrm{curl}\,\vec{E} &= -\frac{\partial \vec{B}}{\partial t}\\ \mathrm{curl}\,\vec{B} &= \sigma\vec{E} + \frac{2\alpha}{\pi}\mu_5\vec{B}\end{aligned}$$

Chiral magnetic effect

- **In addition**, $\mu_5$ should be allowed to **become dynamical**:

$$\frac{d(N_L - N_R)}{dt} \propto \frac{d\mu_5}{dt} \propto \frac{\alpha}{\pi}\int d^3x\,\vec{E}\cdot\vec{B}$$

# New degree of freedom

Boyarsky, Fröhlich, **O.R.**, PRL (2012)

$$\mathrm{curl}\,\vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

Chiral magnetic effect

$$\mathrm{curl}\,\vec{B} = \sigma \vec{E} + \frac{2\alpha}{\pi}\mu_5 \vec{B}$$

$$\frac{\partial \mu_5}{\partial t} \propto \frac{2\alpha}{\pi}\int d^3x\,\vec{E}\cdot\vec{B} - \Gamma_{\text{flip}}\mu_5$$

Chiral anomaly

Finite mass breaks chiral symmetry

- Without $B$ chirality flipping reactions drive $\mu_5 \to 0$ ($\mu_5 = \mu_0 e^{-\Gamma_{\text{flip}} t}$)
- Without $\mu_5$ finite conductivity drives $B \to 0$ ($B_k = B_0 e^{-\frac{k^2 t}{\sigma}}$)

# Instability

- Maxwell equations with $\mu_5$ are **unstable**:

$$\frac{\partial B}{\partial t} = \frac{1}{\sigma}\nabla^2 B + \frac{\alpha\mu_5}{\pi}\,\mathrm{curl}\,B$$

magnetic diffusion

- Exponential growth for $k < \dfrac{\alpha}{\pi}\mu_5$ (for one of the circular polarizations depending on the sign of $\mu_5$) — **generation of helical magnetic fields**

$$B_\pm = B_0 \exp\left(-\frac{k^2}{\sigma}t \pm \frac{\alpha}{\pi}\frac{k\mu_5}{\sigma}t\right)$$

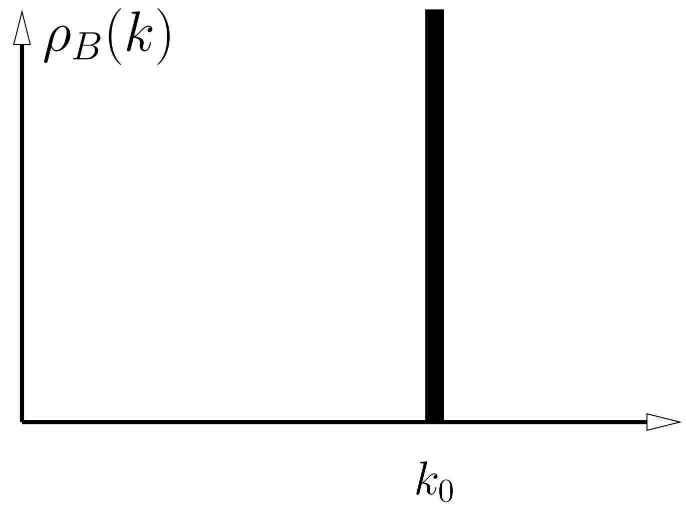
# Attractor solution

- Consider **sharply peaked at $k_0$ maximally helical field**

$$\frac{d\mu_5}{dt} = -\rho_B\Big(\mu_5 - \bar{\mu}_5\Big) - \cancel{\Gamma_{\text{flip}}\mu_5}$$

$$\frac{d\rho_B}{dt} = \frac{\rho_B}{t_\sigma}\left(\frac{\mu_5}{(\bar{\mu}_5)} - 1\right)$$

where $t_\sigma = \frac{2\sigma}{k_0^2}$ and $\rho_B \gg \Gamma_{\text{flip}}$



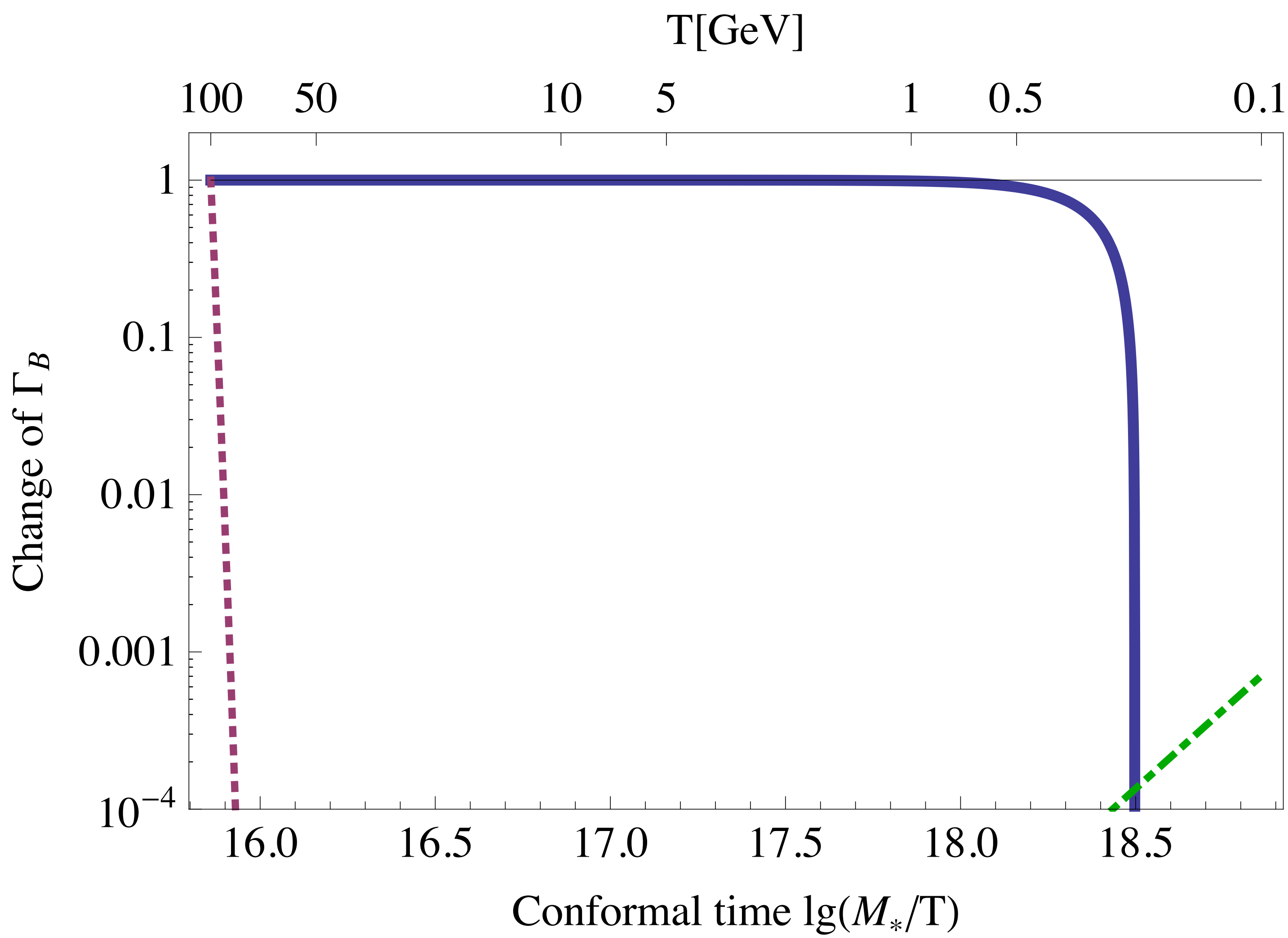

- Large $\rho_B$ drives $\mu_5$ to an **attractor solution** $\boxed{\bar{\mu}_5 = \frac{2\pi k_0}{\alpha}}$

- Electric conductivity of the plasma is **finite** but **magnetic diffusion is compensated by the presence of $\mu_5$**

**O.R.** with A. Boyarsky, J. Fröhlich PRL 2012 **[1109.3350]**

# Evolution of magnetic energy of one mode

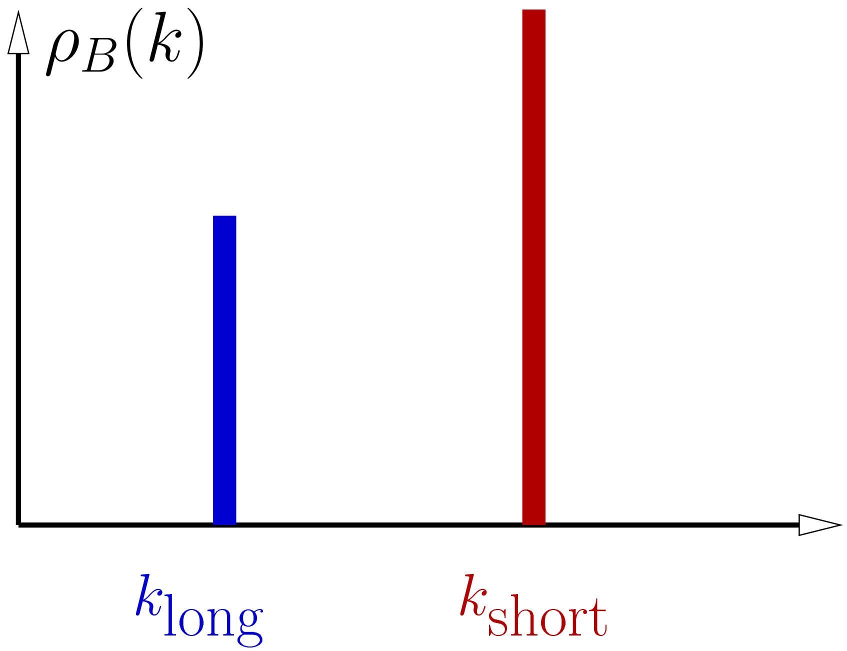
PRL (2012) [1109.3350]

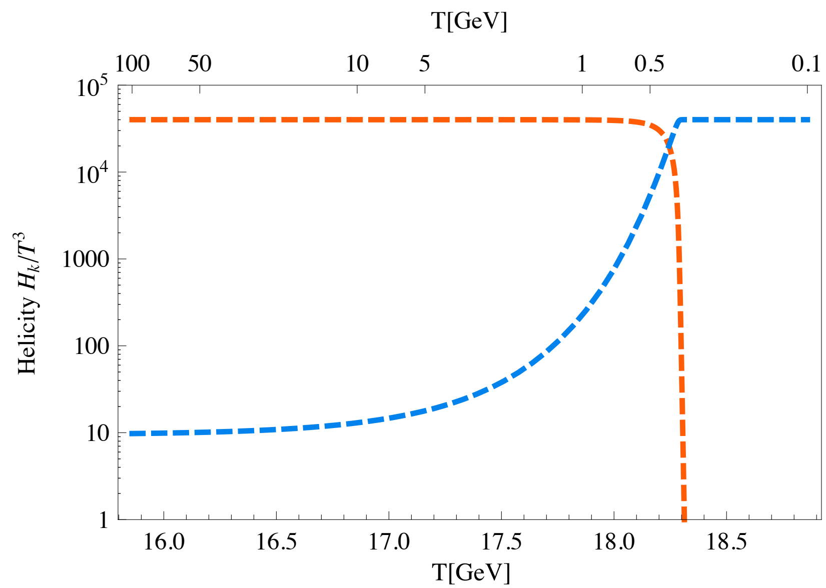


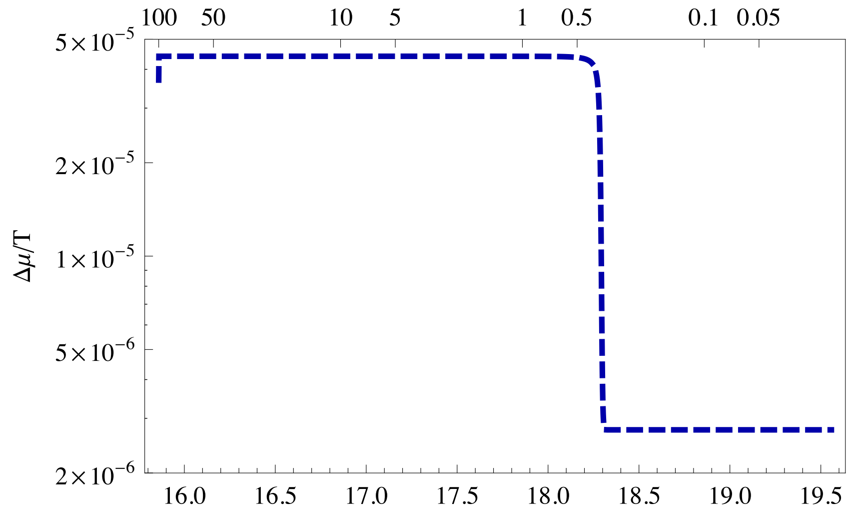

See also Tashiro et al. [1206.5549]

Relative change of magnetic energy of a single mode in the chiral MHD

# Two modes

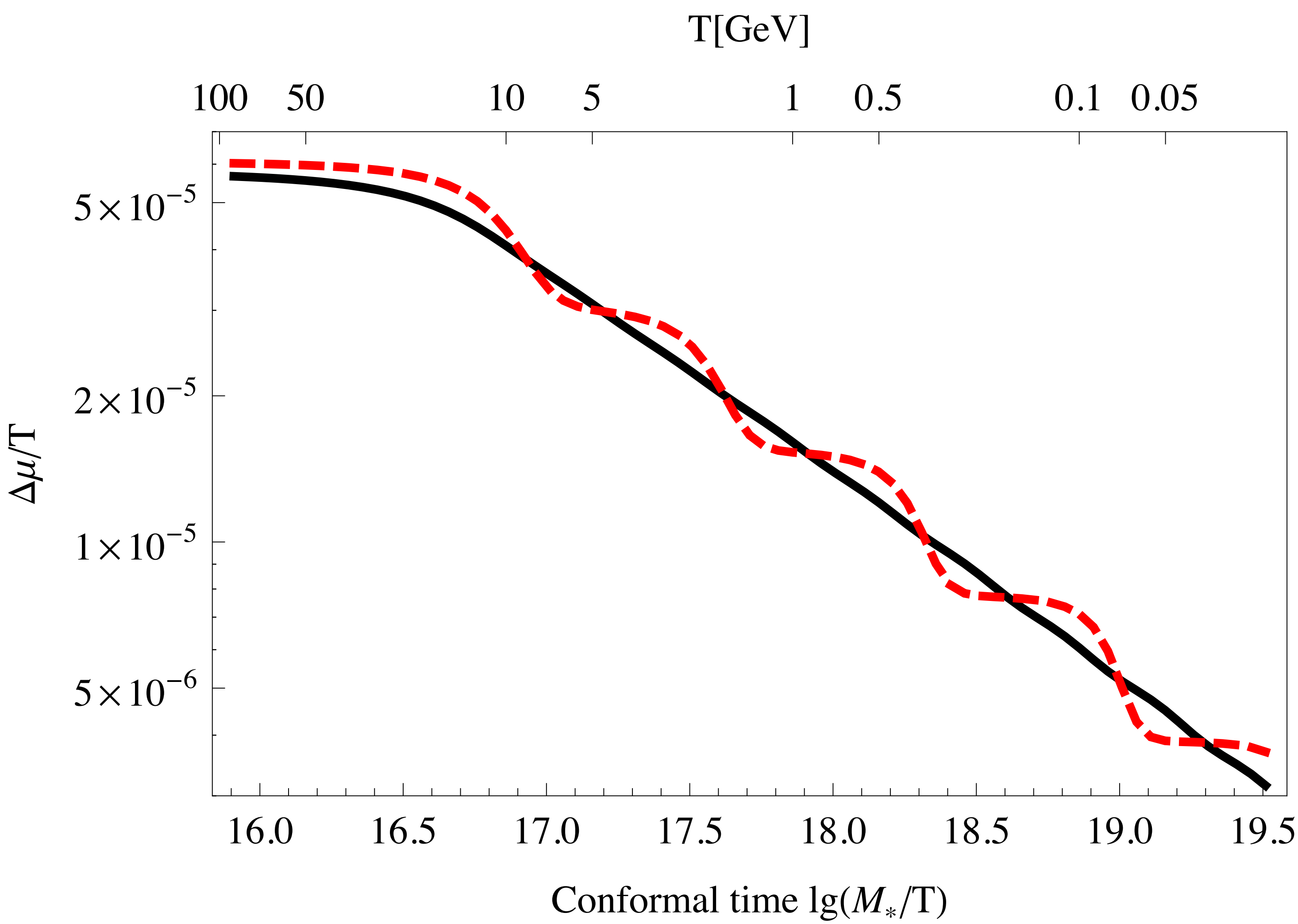


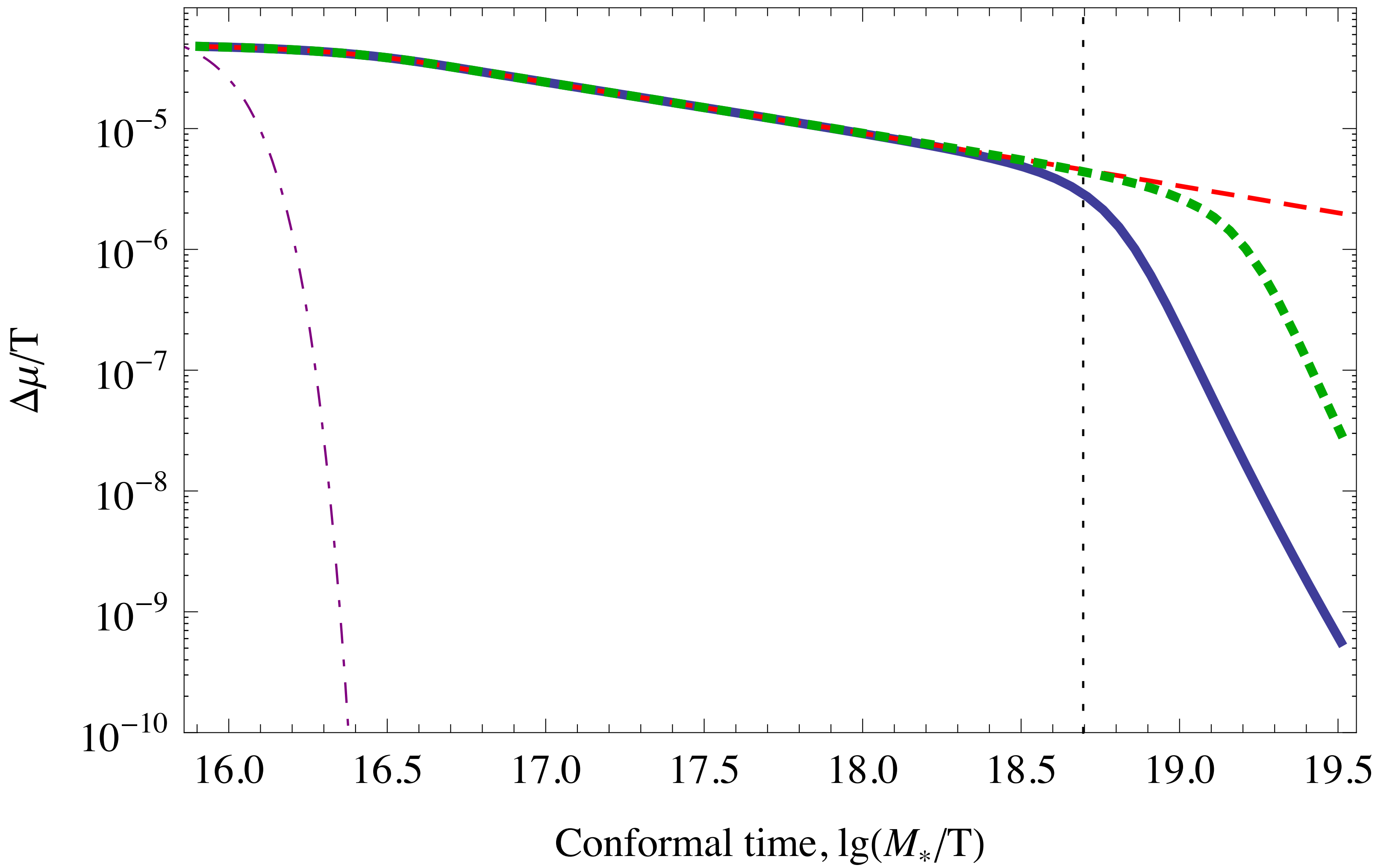

- In case of two modes the helicity gets transferred from the shorter one to the longer one
- Chemical potential follows the wave-number of the mode with higher helicity $\mu = \frac{2\pi k}{\alpha}$

# Evolution of chemical potential



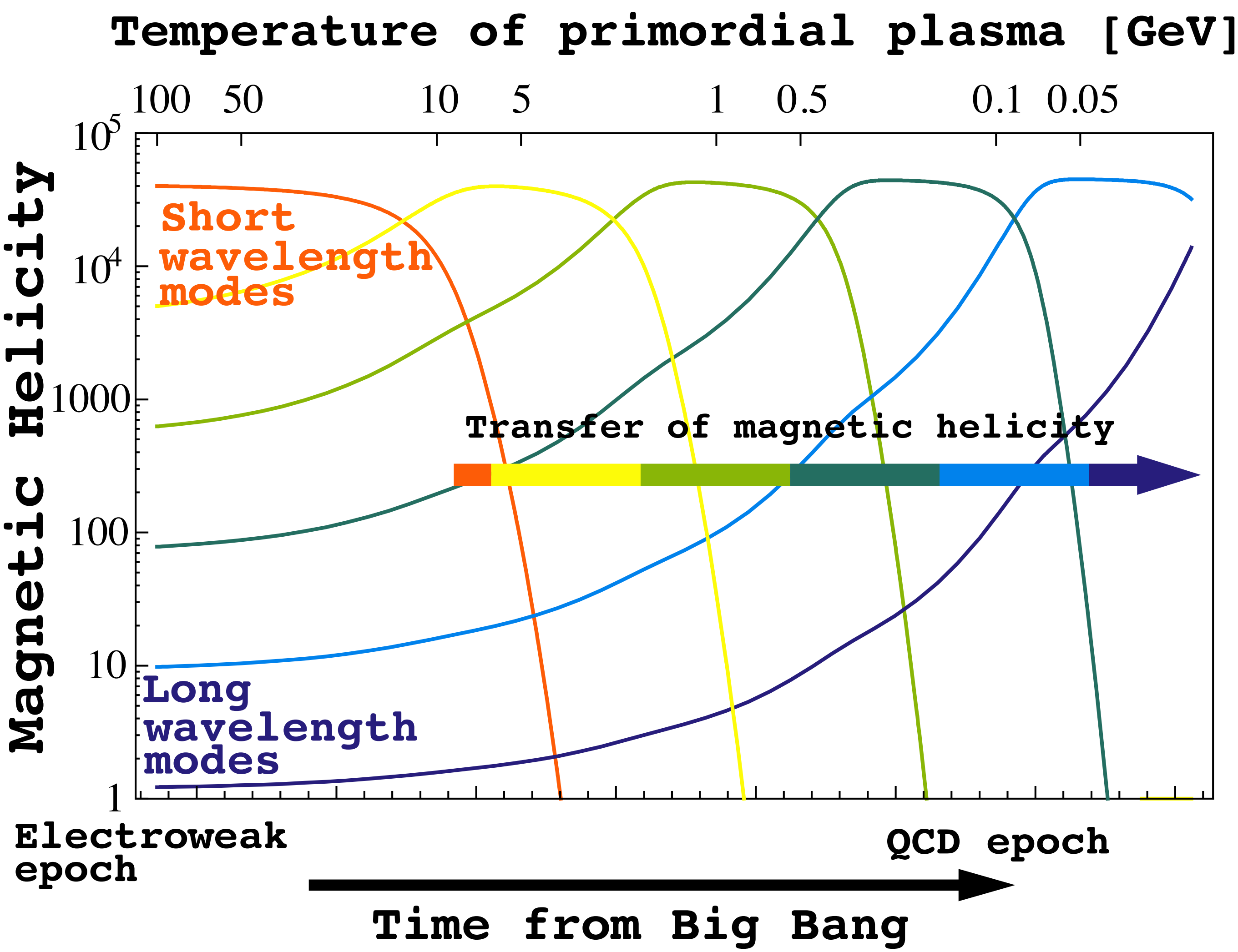

Process continues while $\rho_B \gg \Gamma_{\text{flip}}$

# Evolution of chemical potential



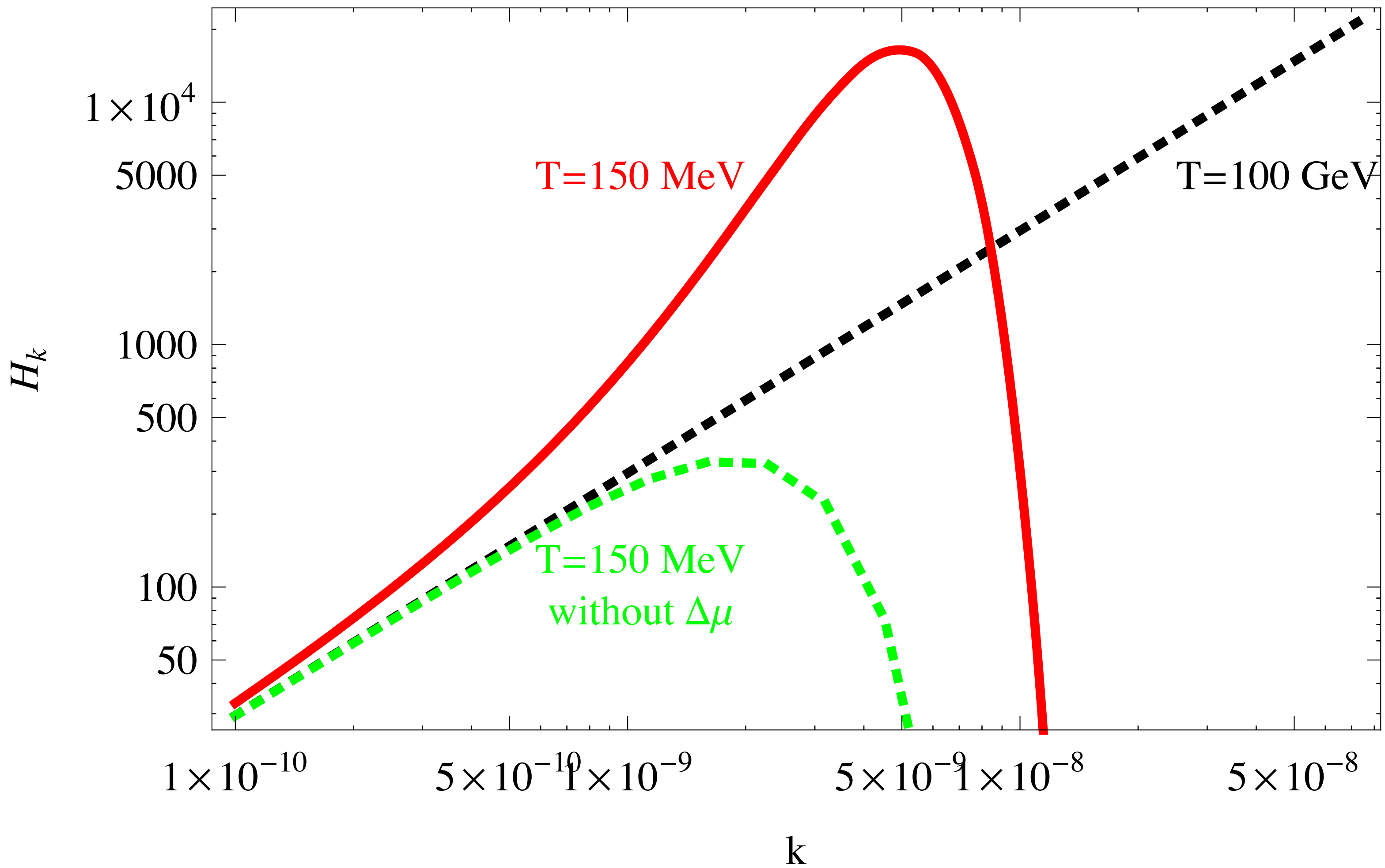

Continuous initial spectrum with $\mathcal{H}_k \propto k$ and fraction of magnetic energy density $5 \times 10^{-5}$ (blue) or $5 \times 10^{-4}$ (green). Red – evolution without flip

# Evolution of helicity spectrum




Process continues while $\Gamma_B \gg \Gamma_{\text{flip}}$ (recall that $\Gamma_B \propto \rho_B$)

# Evolution of helicity spectrum




Inverse cascade without turbulence!

# In short

**Change in magnetic helicity** is coupled to the chiral chemical potential $\mu_5(t)$

$$\boxed{\text{Change of magnetic helicity}} \quad \Longrightarrow \quad \boxed{\text{Change of } \mu_L - \mu_R}$$

1. **Change in magnetic helicity** excites $\mu_5$ and then evolution of **already existing** magnetic fields occurs differently

2. Presence of $\mu_5$ **excites helical magnetic fields**

$$\boxed{\text{Change of } \mu_L - \mu_R} \quad \Longrightarrow \quad \boxed{\text{Change of magnetic helicity}}$$

*Consequences for the “real world” physics?*

# Phenomenological consequences

Can be important in "real life" whenever you have **relativistic magnetized plasma**

- Early Universe (Cosmological magnetic fields)
  - Many mechanisms to generate helical magnetic fields at electroweak epoch in the early Universe. Usually they survival against dissipation is problematic.
  - New mechanism of generation of cosmological magnetic fields?
- Neutron stars
- Astrophysical jets
- Quark-gluon plasma

## Consequences:
## Magnetic Field in the Early Universe

# Magnetic fields in the Universe

- Our Universe today is magnetized: (earth, stars, galaxies, clusters of galaxies)
- Magnetic fields in the spiral (i.e. rotating) galaxies can be generated by turbulent effect from tiny primordial seeds ("dynamo mechanism")
- Magnetic fields in **elliptical galaxies**?
- Magnetic fields in **clusters of galaxies** $\neq$ sum of magnetic fields of galactic magnetic fields
- Even **intergalactic medium** seems to be filled with magnetic fields
- Are we observing the evidence of process **in the very early Universe**?

Neronov & Vovk'10; Dolag et al.'10 Tavecchio et al.'11

## Magnetic fields in the early Universe

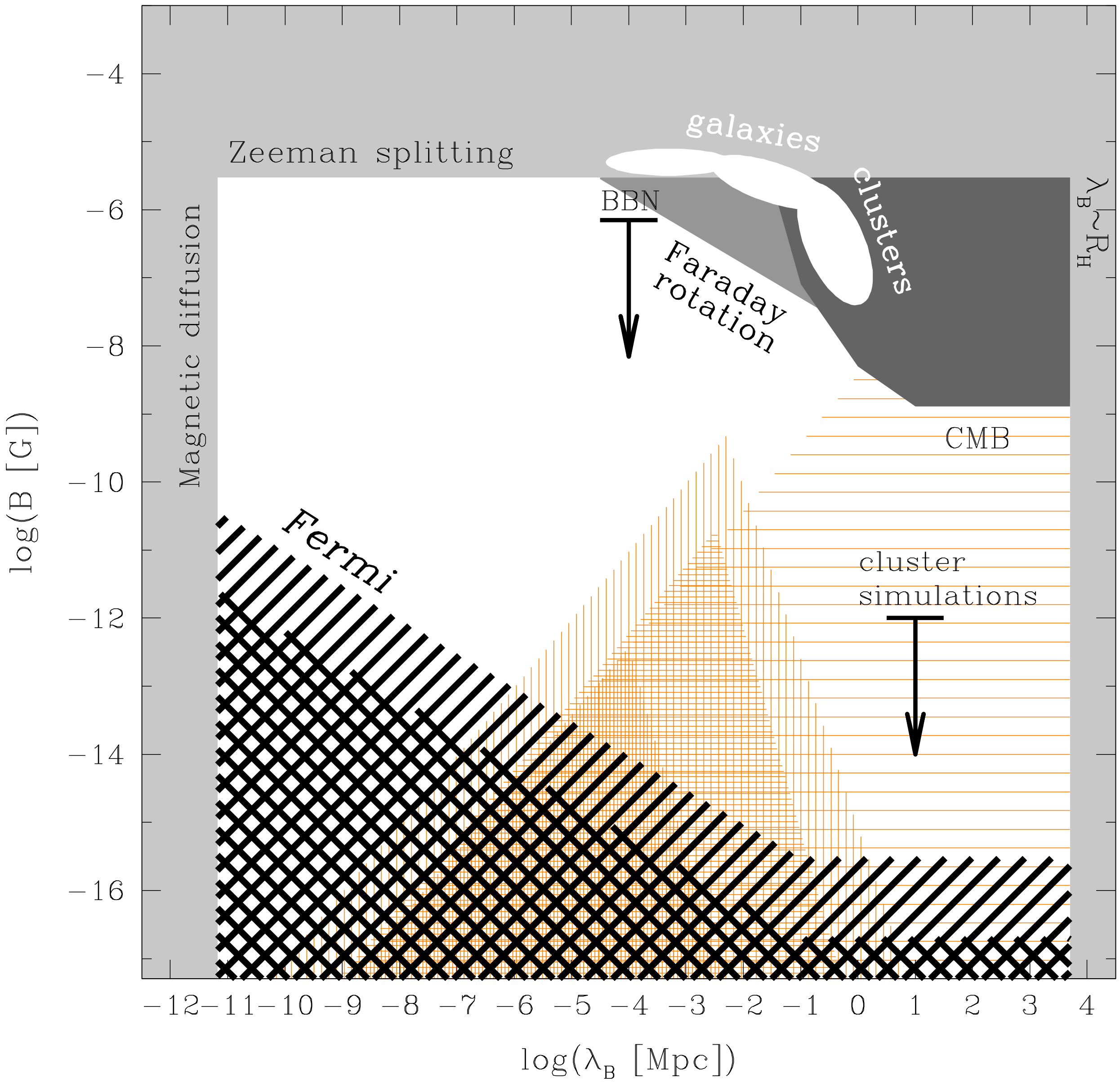
- Magnetic fields affect every important process in the early Universe:
  - Change the nature of electroweak phase transition
  - Affect baryogenesis
  - Leave its imprints in production of gravity waves
  - Affect BBN
  - Leave its imprints in CMB
  - Affect structure formation
  - Could have played a role of seeds of galactic magnetic fields

Many, many works. . . Recent reviews: Widrow et al.'11; Kandus et al.'11; Yamazaki et al.'12

- Many mechanisms of generation of primordial magnetic fields exist, usually associated with violent events (at inflation, electroweak transition, QCD transition, etc.)

- It is commonly believed that **noticeable magnetic fields** are **not generated in the Universe filled with Standard Model particles**

# Evidence for magnetic fields in voids?

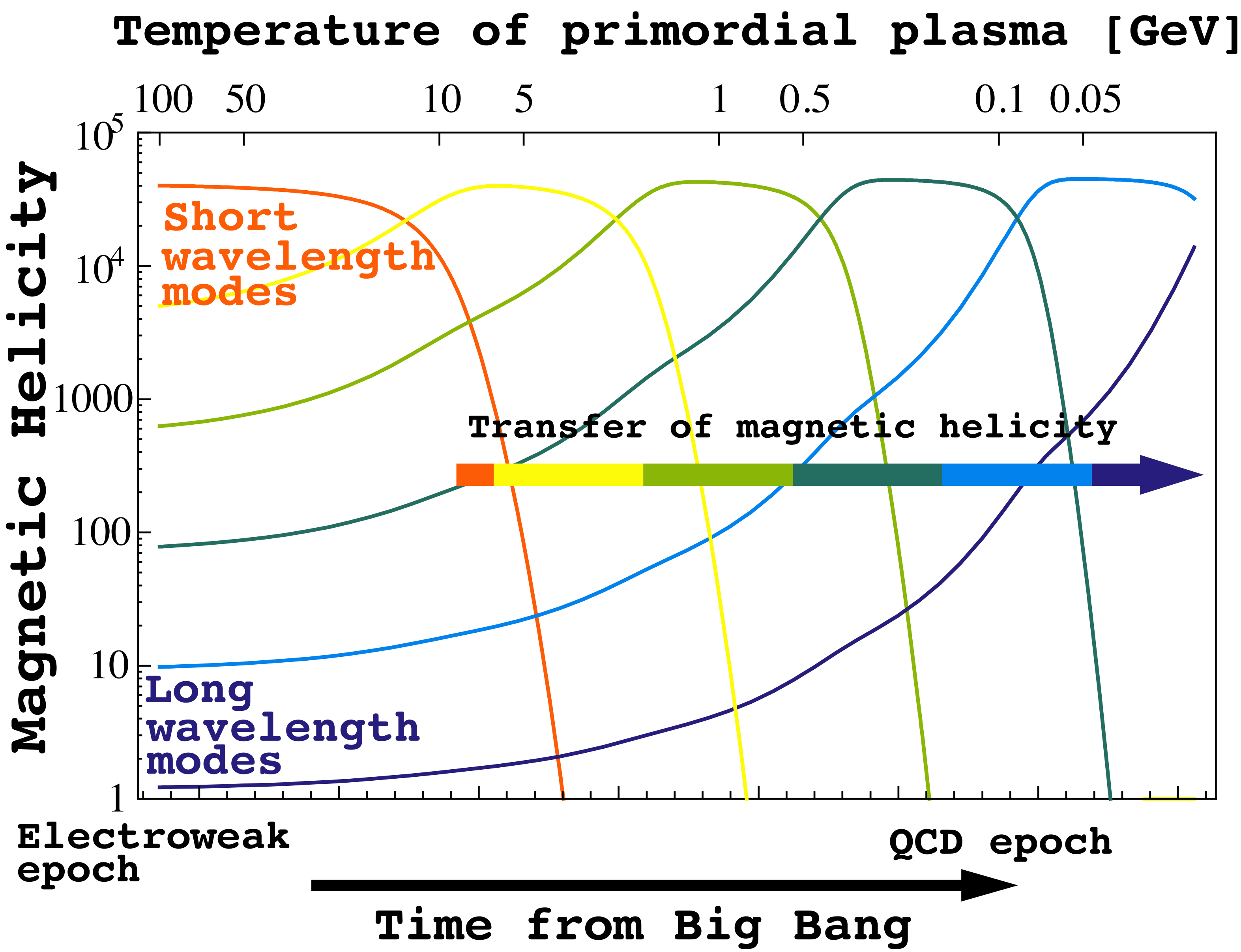



Neronov & Vovk, Science (2010);

Dolag et al. (2010);

Tavecchio et al. (2011)

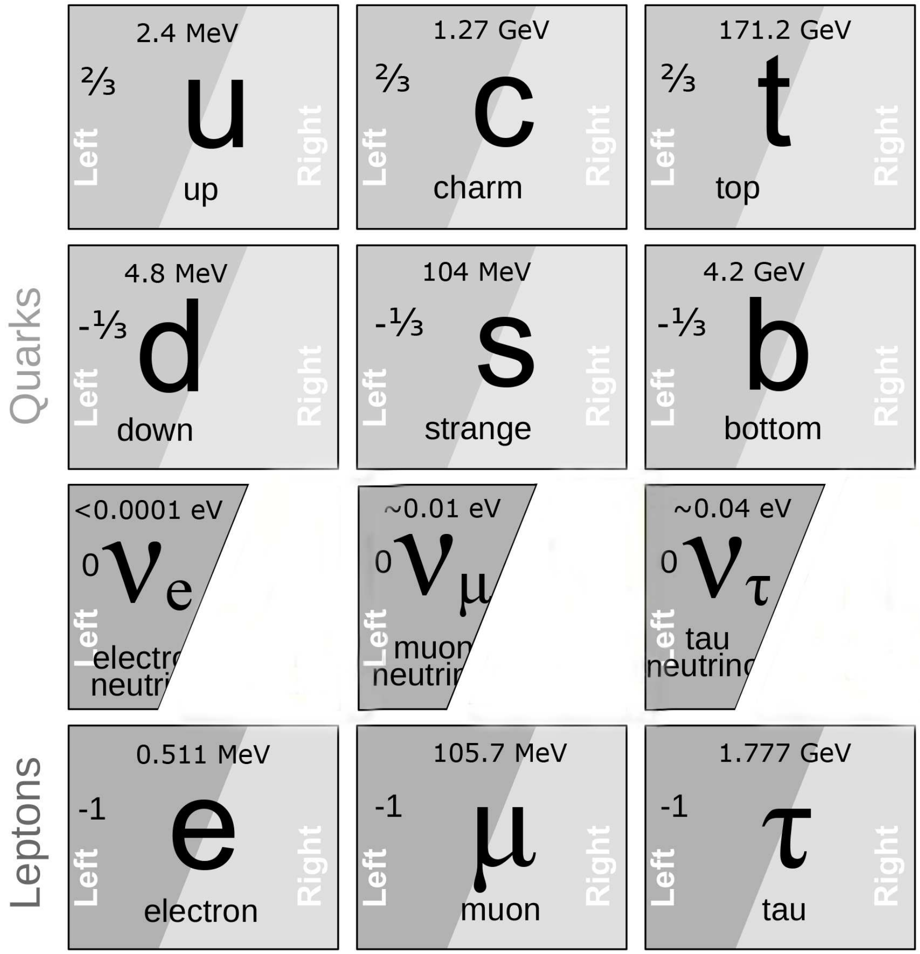
# Survival of helical fields

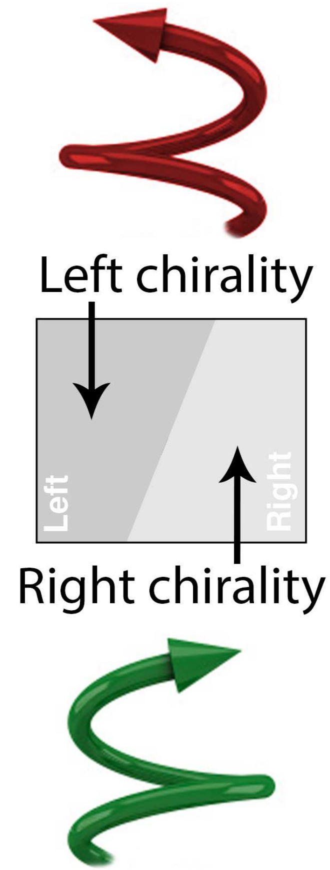


# *Generation of cosmic magnetic field*

For magneto-genesis — baryo-genesis connection see e.g. many works by Vachaspati, Joyce & Shaposhnikov, Cornwall, Tashiro et al.

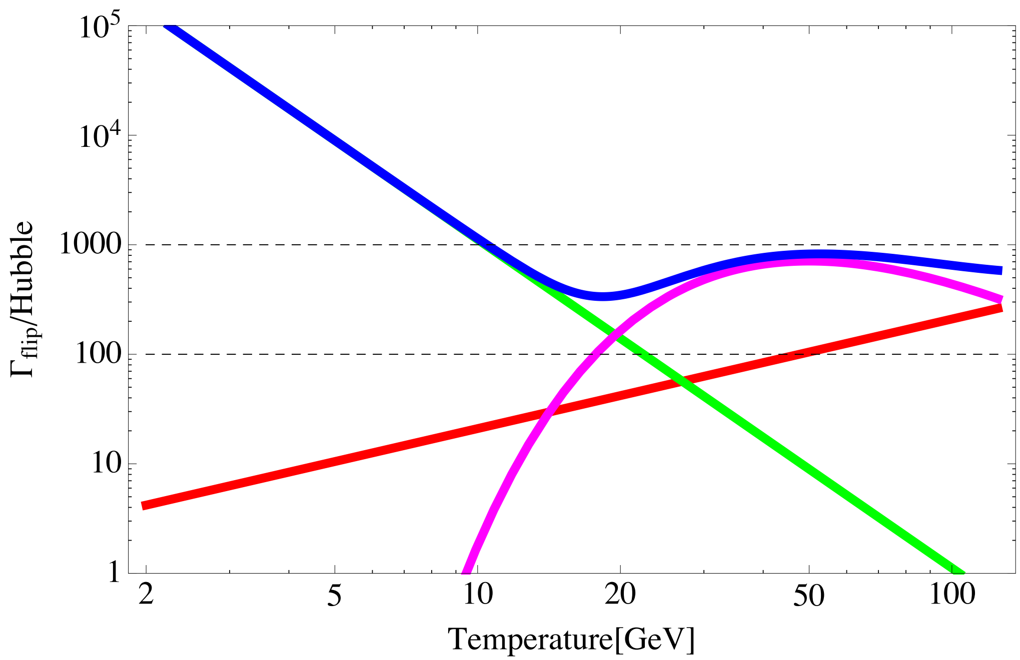
# Parity-odd structure of the Standard Model



# What can create $\mu_5$ in the early Universe?

- Although $\left(\frac{m_e}{80\ \text{TeV}}\right)^2 \sim 10^{-17}$ chirality flipping reactions are in thermal equilibrium for $T < 80$ TeV and drive $\mu_L - \mu_R$ to zero **exponentially fast** (suppression of at least $e^{-1000}$ over one Hubble time)




Symmetric phase:

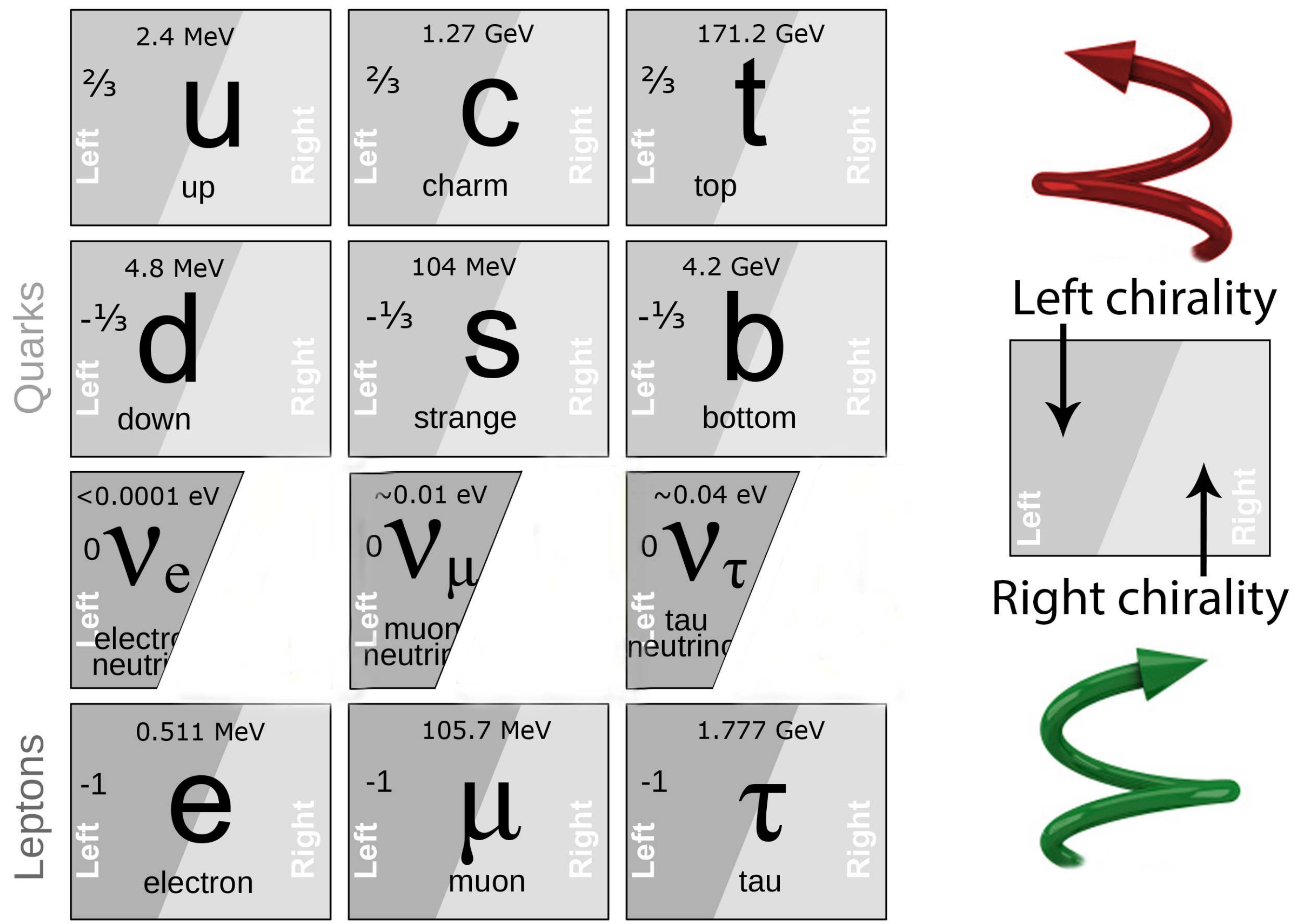
- $\Gamma_{\textbf{high-temp}} \sim \frac{80\ \text{TeV}}{M_*} T$

Broken phase:

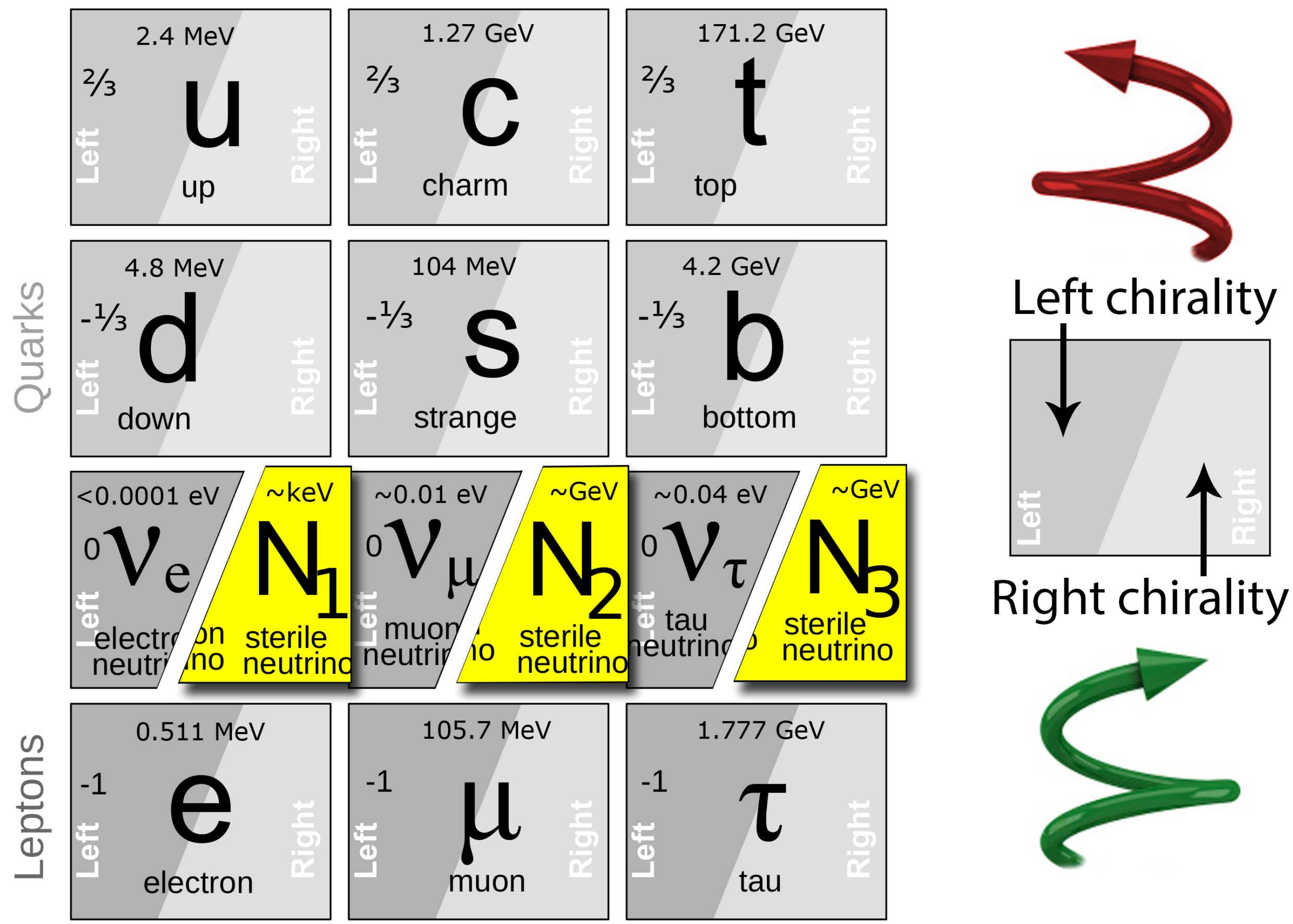
- $\Gamma_{\text{EM}} \propto \alpha^2 T \left(\frac{m_e}{3T}\right)^2$

- $\Gamma_{\text{W}} \propto G_F^2 T^5 \left(\frac{m_e}{3T}\right)^2$

# Parity-odd structure of the Standard Model



# Oscillations $\Rightarrow$ new particles!




**Right components of neutrinos?!**

# Right-handed neutrinos?

**Recall** gauge charges of neutrinos and Higgs:

– $\nu_{e,\mu,\tau}$: upper component of the SU(2) doublet, U(1)$_Y$ charge = $-1$
– Higgs boson: SU(2) doublet, U(1)$_Y$ charge = $1$

- **Dirac mass term:** $$(m_{\text{Dirac}})_{\alpha I} = \langle H \rangle F_{\alpha I}\, \bar{\nu}_\alpha\, N_I$$
  – $N_I$ – new particles, *right-handed* fermions, $I = 1, 2, \ldots, \mathcal{N}$
  – $F_{\alpha I}$ – Yukawa matrix, size $3 \times \mathcal{N}$ (Neutrino Yukawa matrix needs not be square. One can have any number of sterile neutrinos $\mathcal{N} = 1, 2, 3, 4, 5, \ldots$)

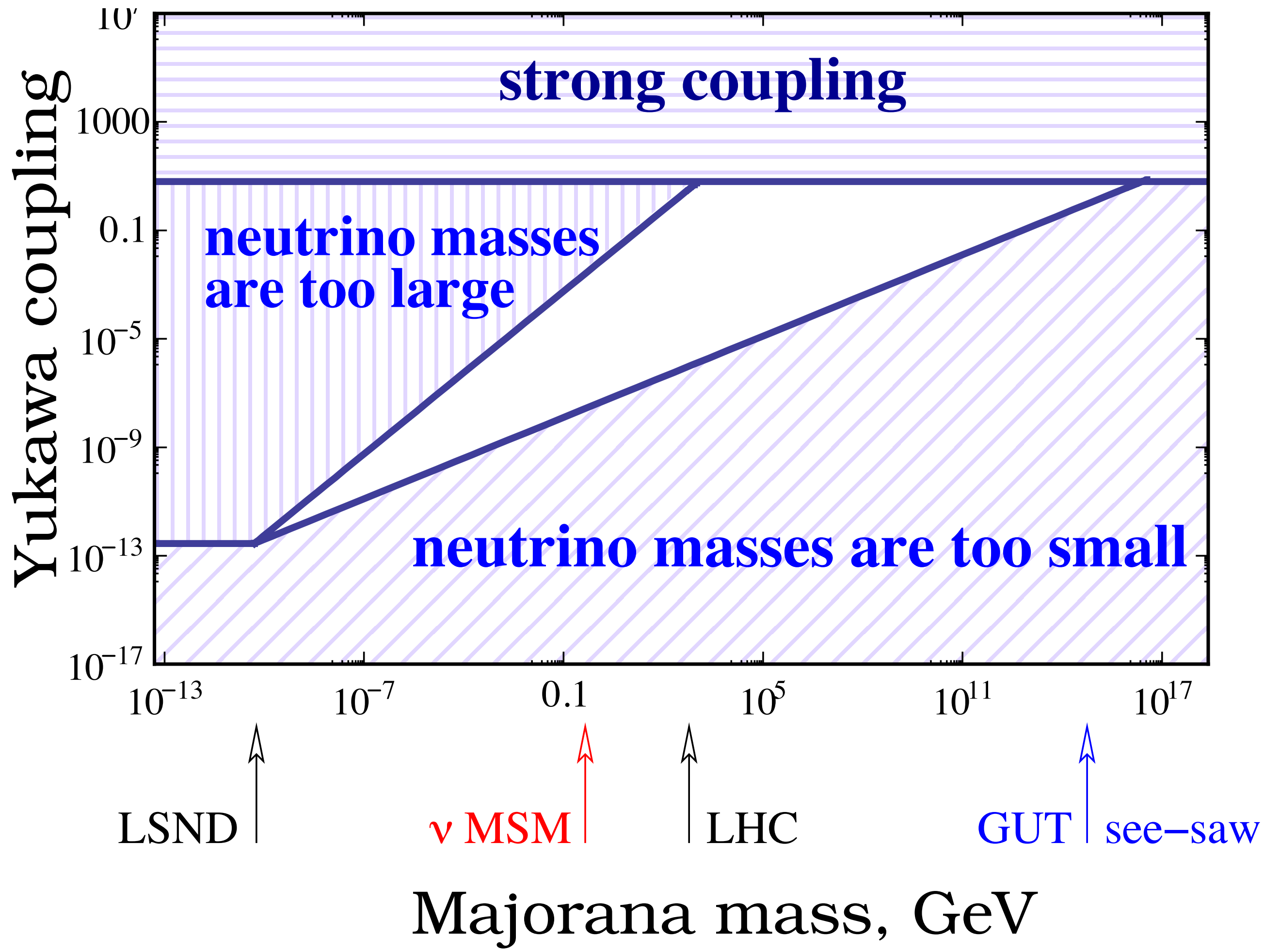
- Right-chiral neutrinos $N_I$ **carry no charge** under the SM interactions (**“sterile neutrinos”**)

- Neutral leptons can have **Majorana mass term**:

$$\boxed{(M_M) = M_{IJ} \bar{N}_I^c N_J \quad I, J = 1, 2 \ldots \mathcal{N}}$$

# Scale of sterile neutrino masses?

1204.5379




See-saw formula

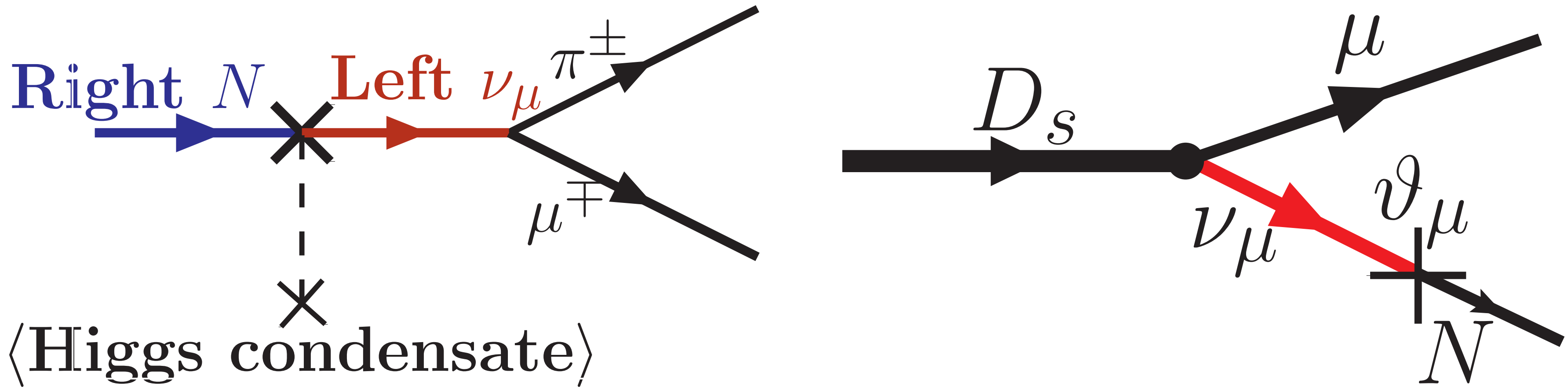
Neutrino Yukawa interaction

$$M_{\text{active}} \sim \frac{v^2|F|^2}{M_{\text{N}}}$$

Neutrino Majorana mass

**Mass of sterile neutrinos is not determined by neutrino oscillations!**

# Properties of sterile neutrino




Sterile neutrinos behave as **superweakly interacting** heavy neutrinos with a smaller Fermi constant $\boxed{\vartheta \times G_F}$

- This **mixing strength** or **mixing angle** is

$$\vartheta^2_{e,\mu,\tau} \equiv \frac{|M_{\text{Dirac}}|^2}{M^2_{\text{Majorana}}} = \frac{\mathcal{M}_{\text{active}}}{M_{\text{sterile}}} \approx 5 \times 10^{-11} \left(\frac{1\ \text{GeV}}{M_{\text{sterile}}}\right)$$

## Properties of sterile neutrino

For example, 1 GeV sterile neutrino has Yukawa coupling $\mathcal{O}(10^{-8})$ and mixing angle $\vartheta^2 \sim 5 \times 10^{-11}$

- This number means that for each $2 \times 10^{10}$ decays of, say, $D$-meson that produces $\nu_\mu$ there will be **1** right-chiral neutrino with the mass $1$ GeV produced!
- Can be searches
  - "Rare event" experiments
  - Early Universe where densities of particles were very high
- Previous "rare event" searches have never reached the sensitivity dictated by the see-saw mechanism

# Neutrino Minimal Standard Model ($\nu$MSM)

– Two neutrino mass splitting $\Rightarrow$ need (at least) two sterile neutrinos

– Leptogenesis? Possible, but they need to be heavy ($10^{12}$ GeV) **or** quasi-degenerate in mass (and then as light as MeV)

– Are they Dark matter? $\Rightarrow$ No way! Very short lifetime

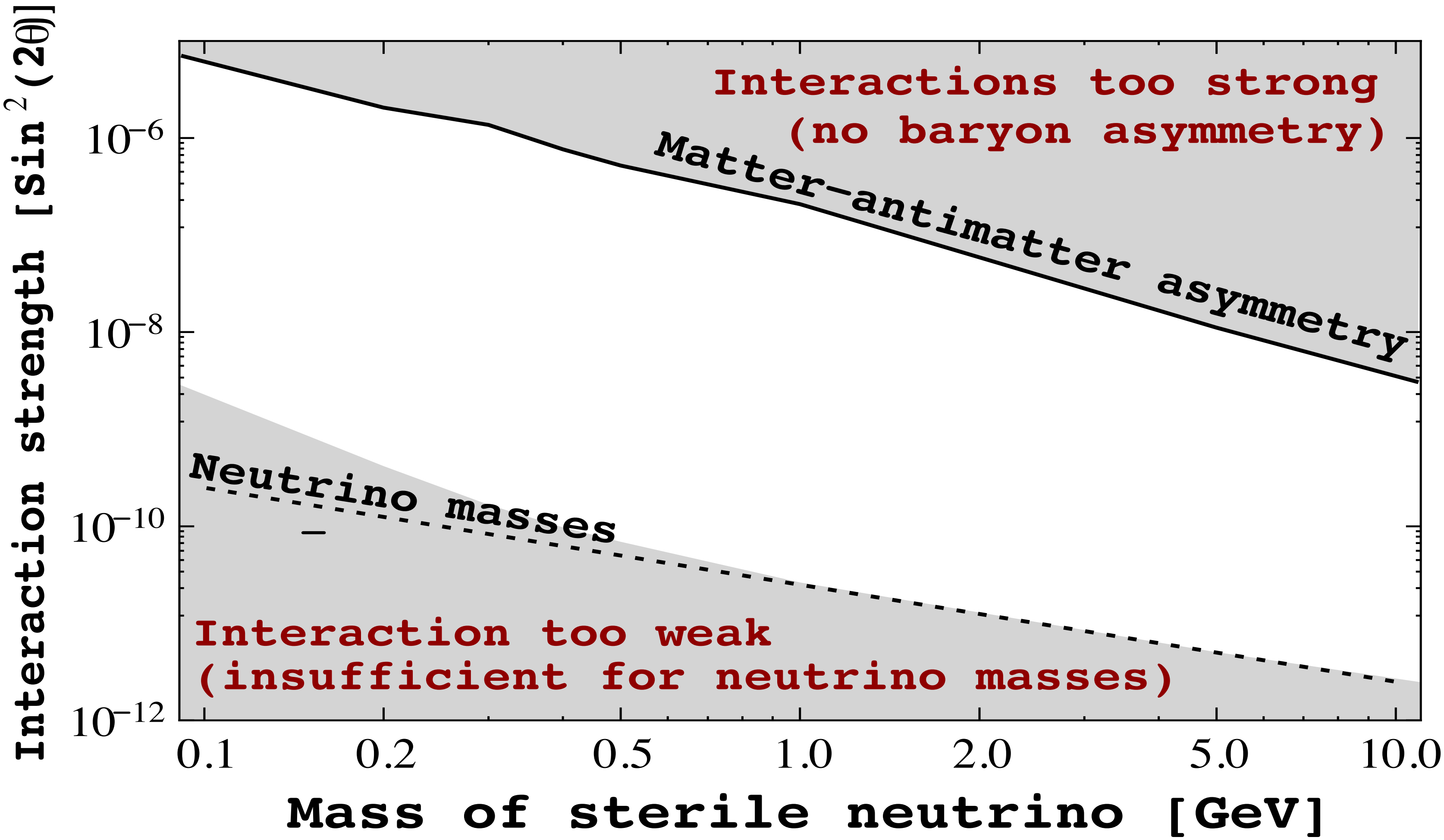
– Third sterile neutrino? $\Rightarrow$ Yes! Great DM (but two other should prepare for it correct initial conditions)

| | N mass | $\nu$ masses | eV $\nu$ anoma–lies | BAU | DM | $M_H$ stability | direct search | experi–ment |
|---|---|---|---|---|---|---|---|---|
| GUT see–saw | $10^{10-16}$ GeV | YES | NO | YES | NO | NO | NO | – |
| EWSB | $10^{2-3}$ GeV | YES | NO | YES | NO | YES | YES | LHC |
| $\nu$ MSM | keV – GeV | YES | NO | YES | YES | YES | YES | a'la CHARM |
| $\nu$ scale | eV | YES | YES | NO | NO | YES | YES | a'la LSND |

**Review: Boyarsky, O.R., Shaposhnikov Ann. Rev. Nucl. Part. Sci. (2009), [0901.0011]**

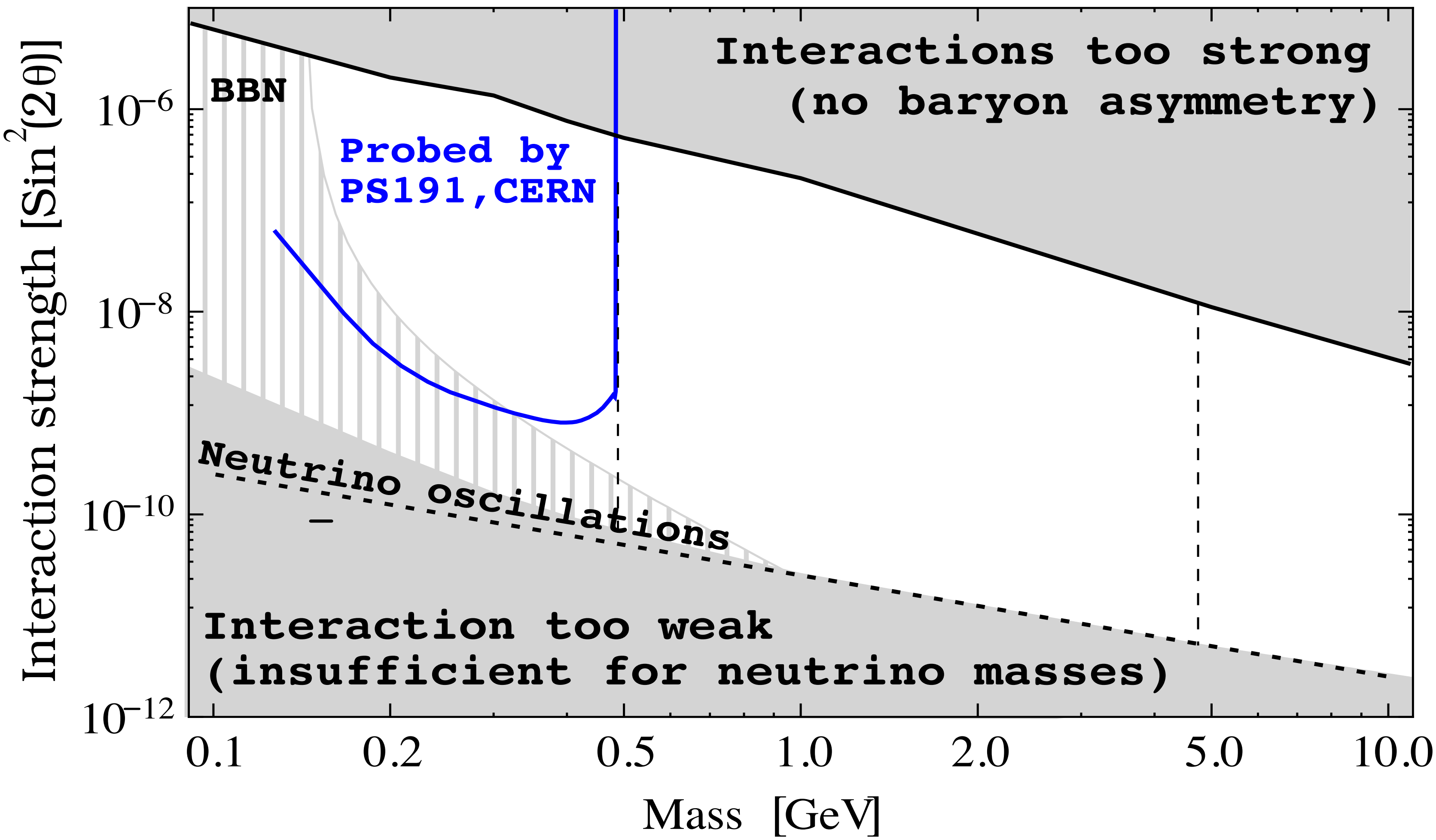
# Parameter space of heavy sterile neutrinos

Asaka, Canetti, Gorbunov, Shaposhnikov, 2005–2011




If we detect sterile neutrinos with masses in GeV range, we can check directly if they can explain **both** for neutrino flavour oscillations and **baryon asymmetry of the Universe**

# Parameter space of heavy sterile neutrinos




Dolgov et al. (2000–2001)

Canetti, Gorbunov, Shaposhnikov (2009–2012)

Ruchayskiy & & Ivashko [1202.2841] – BBN bounds

White paper on sterile neutrinos [1204.5379]

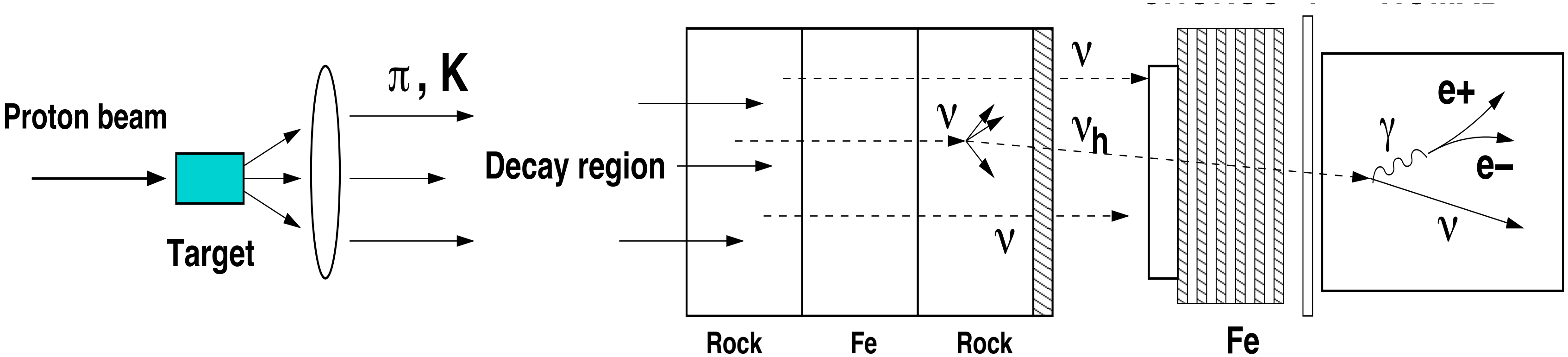
# A dedicated experiment

W. Bonivento, A. Boyarsky, H. Dijkstra, U. Egede, M. Ferro-Luzzi, B. Goddard, A. Golutvin, D. Gorbunov, R. Jacobsson, J. Panman, M. Patel, **O. Ruchayskiy**, T. Ruf, N. Serra, M. Shaposhnikov, D. Treille

## Proposal to Search for Heavy Neutral Leptons[1]at the SPS

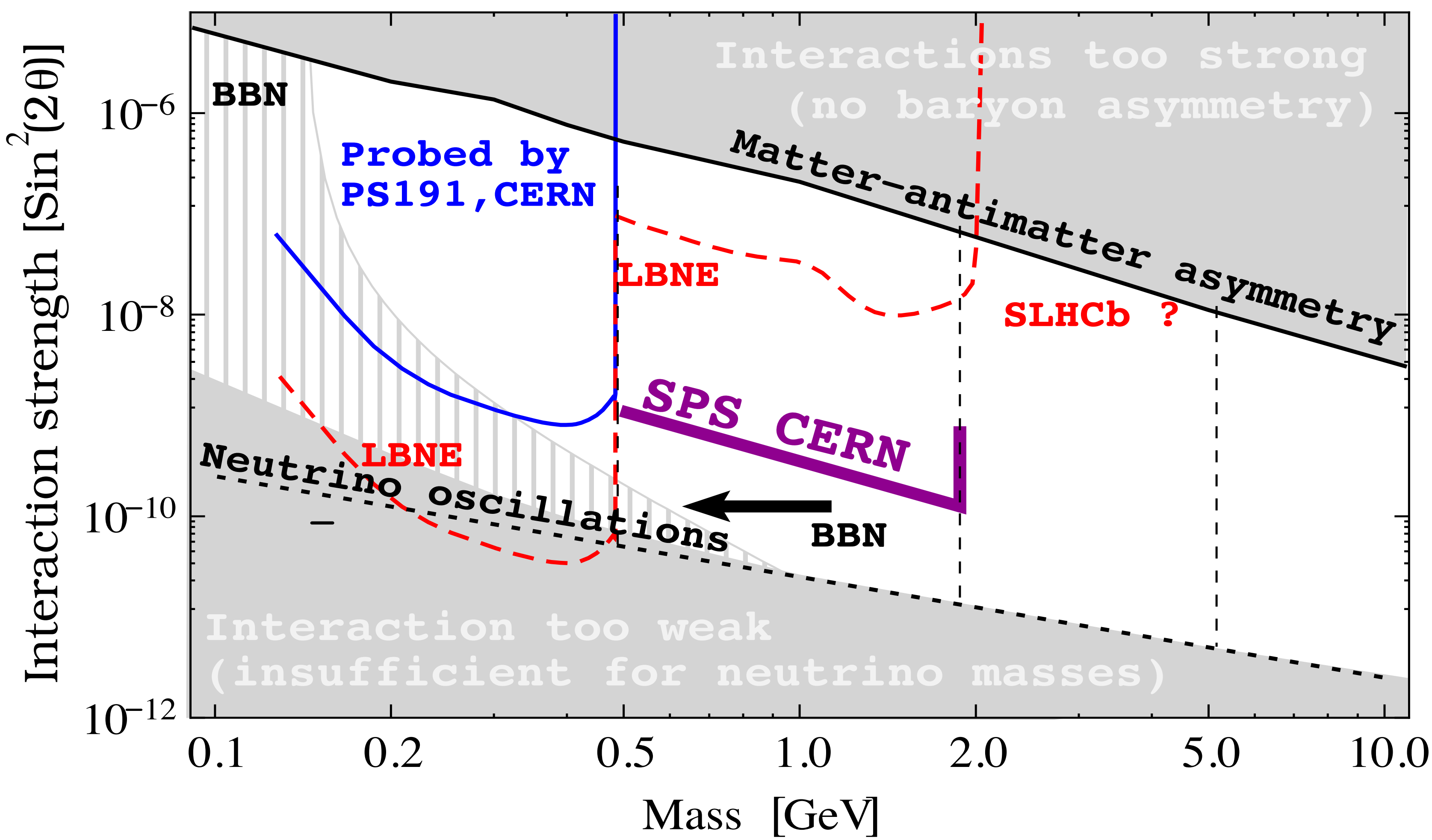
Expression of Interest. Submitted to the CERN SPS council on October 7, 2013

**[arXiv:1310.176]**




[1]"Heavy neutral leptons" == "sterile neutrino"

# Parameter space of heavy neutral leptons



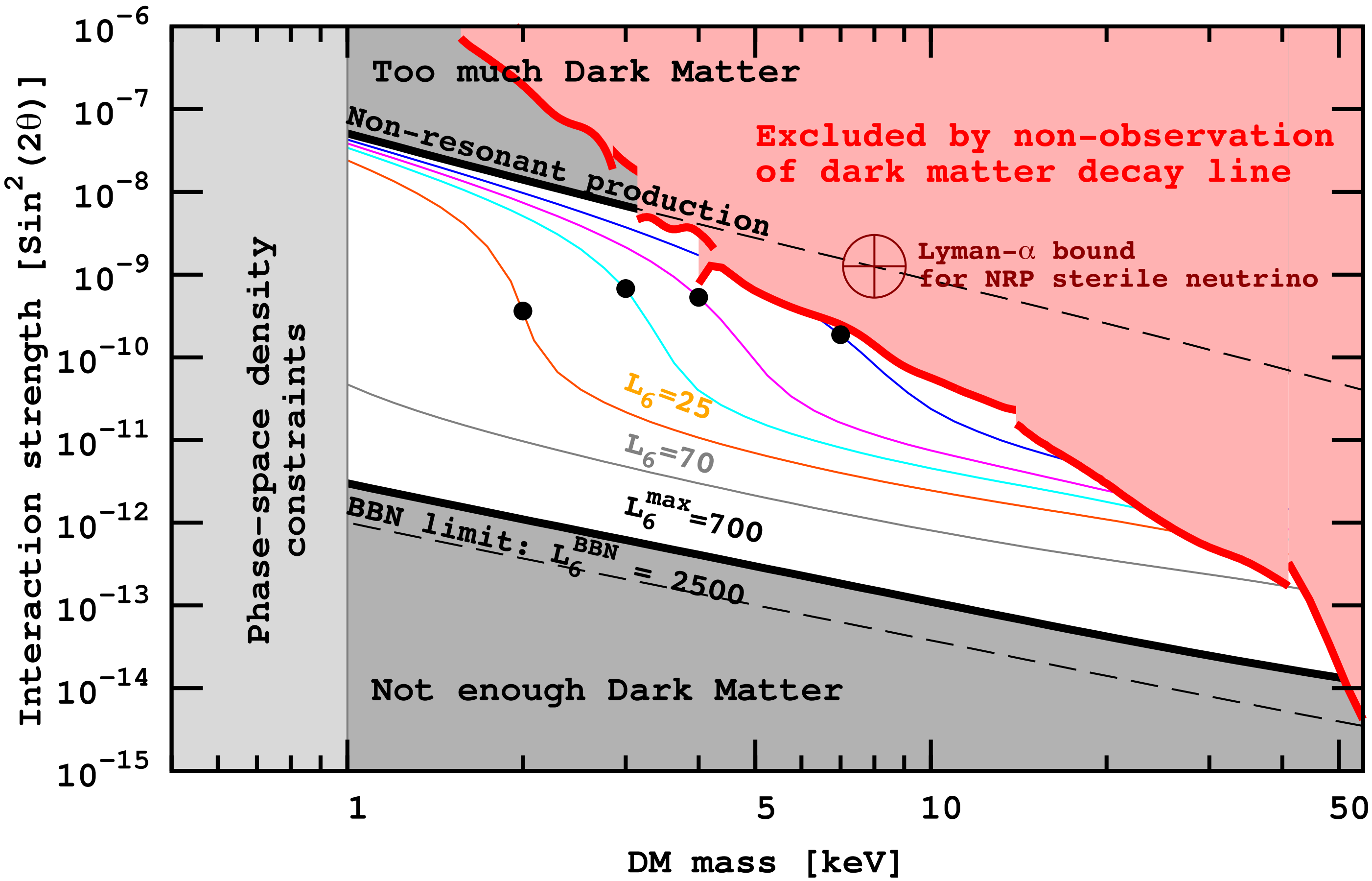

Asaka, Canetti, Gorbunov, Shaposhnikov, 2005–2011;

**O.R** & Ivashko [1112.3319] – revised accelerator bounds

LBNE white paper [1110.6249]

Magenta – dedicated experiments, see the Expression of Interest [arXiv:1310.176].
Also in Proposal to European Strategy Preparatory Group[arXiv:1301.5516]

# Sterile neutrino DM status



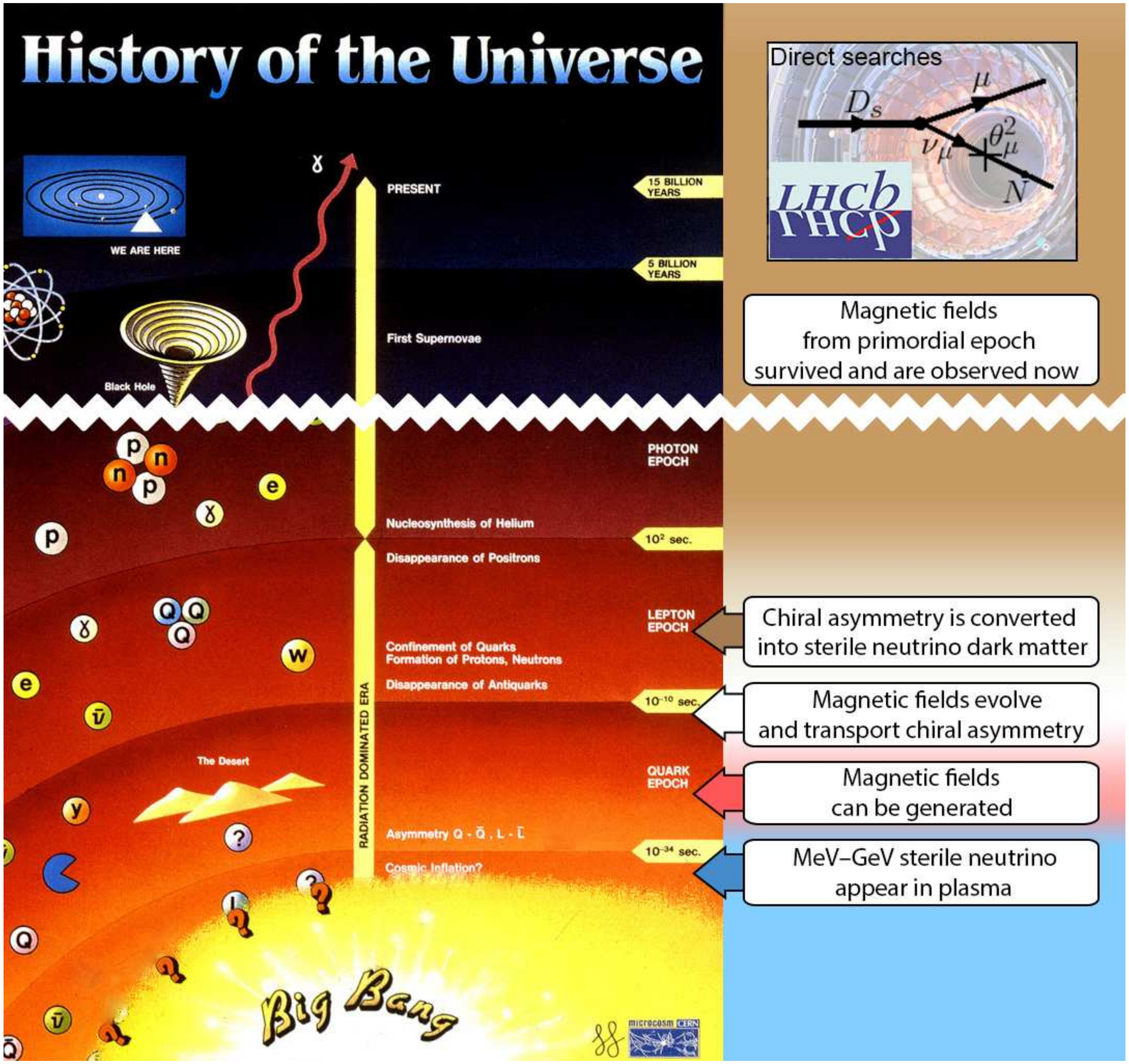

**O.R.** with Lesgourgues, Viel PRL 2009

Review: [0901.0011]

Black points – allowed by Ly-$\alpha$ forest data

Only resonantly produced sterile neutrinos are consistent with all data $\Rightarrow$ to precise the properties of sterile neutrino Dark Matter **one should predict the value of lepton asymmetry** $L_6$

# Early Universe with Sterile Neutrinos



# CMF instability in the $\nu$MSM

- At $T$ just below 100 GeV lepton asymmetry in the left neutrino sector is generated very fast. Weak reactions transform left-electron sector appears **and** right electrons follow via chirality flip $\Rightarrow \mu_5$ **between left and right electrons appears**

- Evolution of the **difference** of chemical potential:

$$\frac{\partial \mu_5}{\partial t} = -\Gamma_{\text{flip}}\,\mu_5 + \mathcal{S}(t) + \cancel{\frac{e^2}{16\pi^2}\vec{E}\cdot\vec{H}}$$

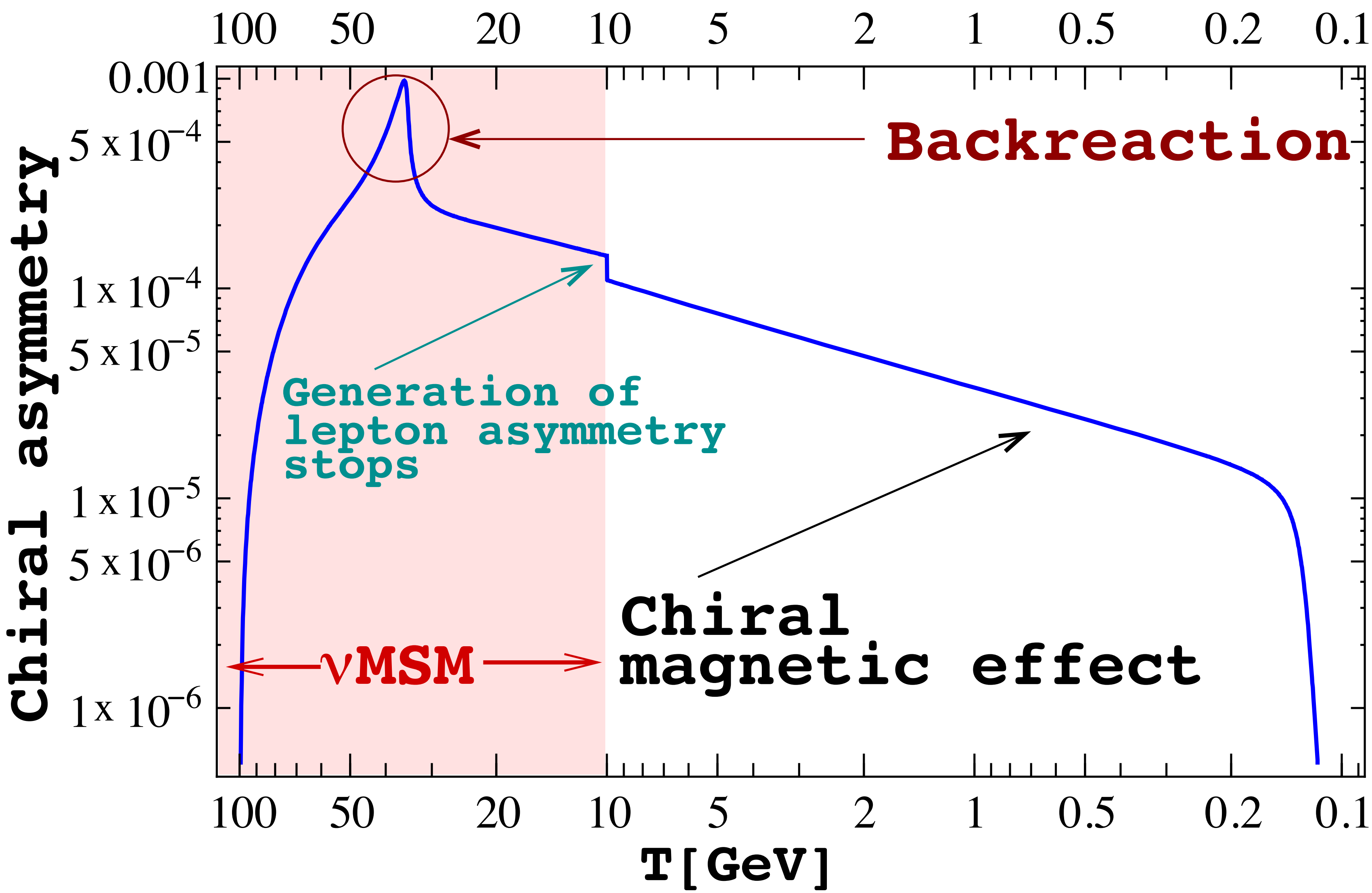
Chirality flipping rate

Source of left-right asymmetry

- …and instability quickly develops: $B \propto e^{\lambda_k(t)}$ with

$$\lambda_k(T) \sim \frac{k(\alpha\mu_5 - k)}{\sigma}\frac{M_{Pl}}{T^2}$$

# Evolution of chiral asymmetry in $\nu$MSM

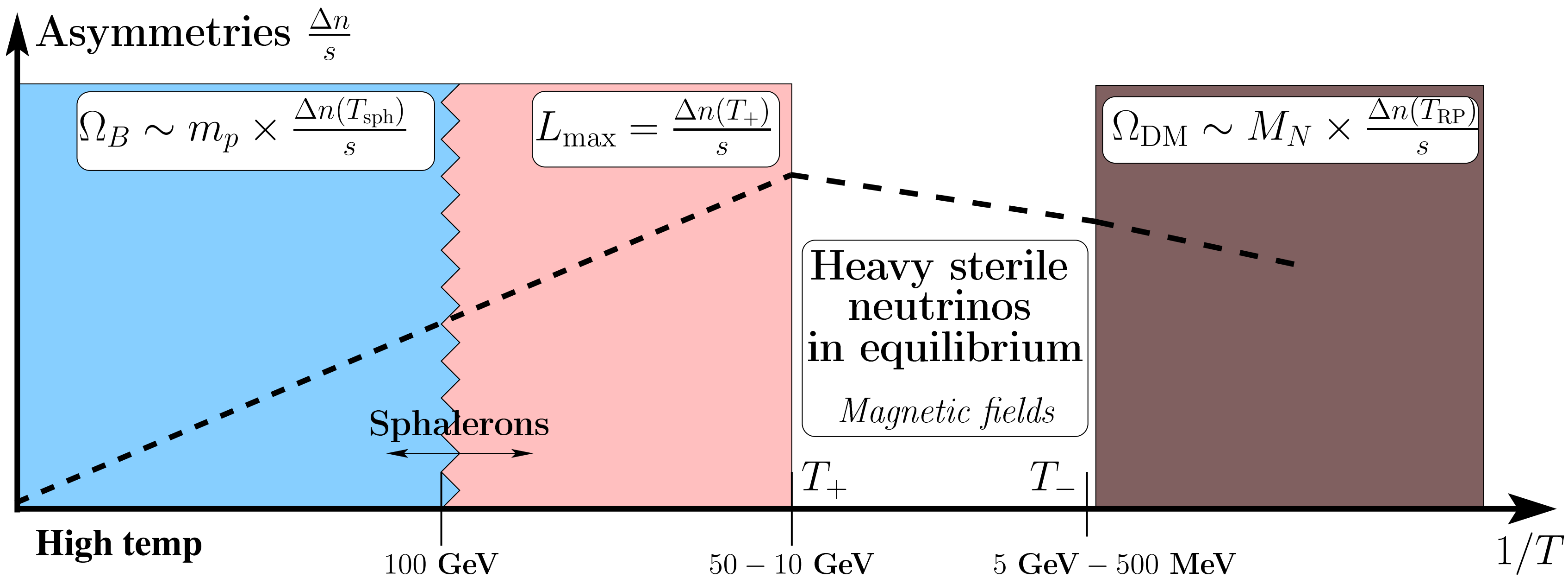



**O.R.** with J. Fröhlich & A. Boyarsky Phys. Rev. Lett. (2012)

work in progress

# Lepton asymmetry in the $\nu$MSM

- Sterile neutrinos with mass $\sim$ GeV have small Yukawas ($\sim 10^{-8}$)
- They are out-of-equilibrium in the early Universe and can generate significant lepton number

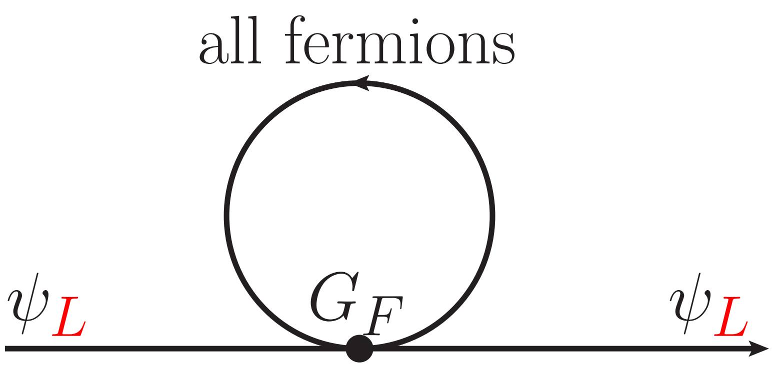



See Tashiro et al. (2012) & (2013) for other connections between leptogenesis and magneto-genesis

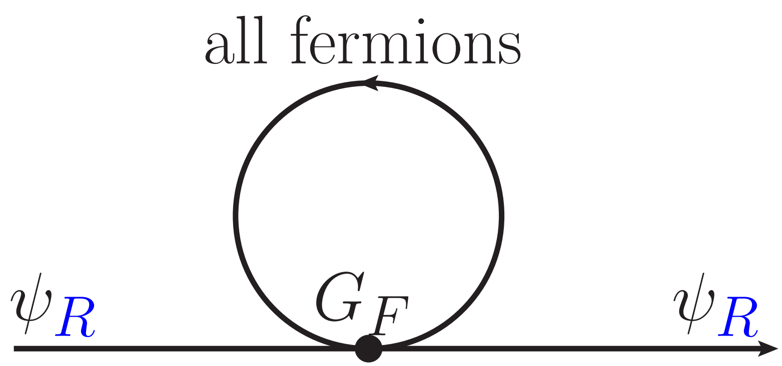
Boyarsky, Shaposhnikov, **O.R.** [1204.3604]

Gorbar et al. [1111.3401]

- Weak corrections lead to the **change of dispersion relations** of left/right particles




$\neq$

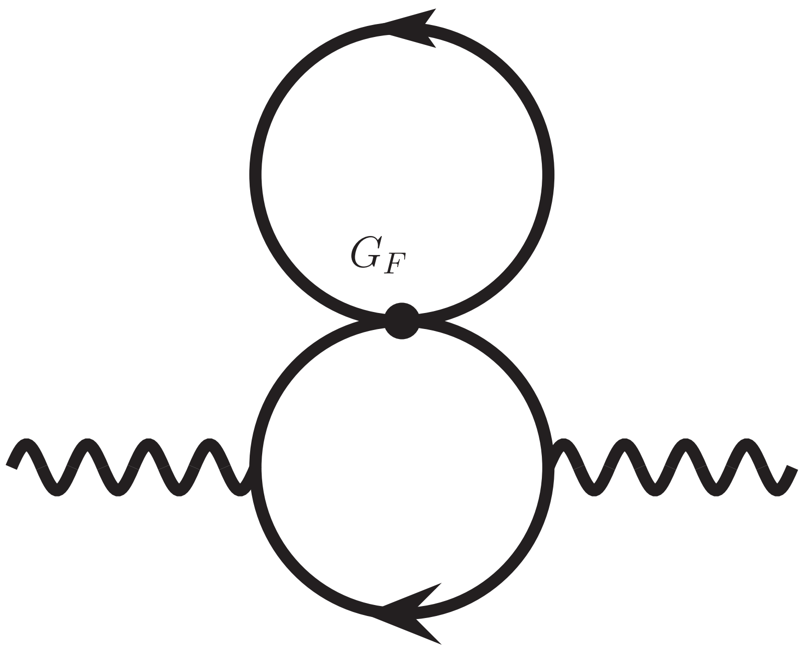



- Dispersion relations get modified:

$$E^2 = (|\vec{p}|^2 \pm \mu_5)^2 + m^2$$

- The resulting $\mu_5$ is proportional to the **asymmetry** of all fermions, running in the loops: $\boxed{\mu_5 \propto G_F(n - \bar{n})}$

# Chern-Simons term




Boyarsky,
Shaponshnikov,
**O.R.**
[1204.3604]

$$\Pi_2 = \frac{\alpha}{2\pi} G_F \times (c_1 \text{ baryon number} + c_2 \text{ lepton numbers}) \neq 0$$

## Summary: axions and chiral anomaly at finite temperature

- Chern-Simons term should be added to the Standard Model Lagrangian and finite densities of lepton and/or baryon number

- System with chiral anomaly when put at non-zero temperature **necessarily** contains an effective axion degree of freedom in its spectrum!

- This additional **IR degree of freedom** is the difference of chemical potentials of left and right particles should me made dynamical and significantly affects evolution.

- Evolution of such systems **is not described** by the standard MHD equations (as was previously believed) but rather by chiral MHD

Thank you for your attention!