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GUVERNUL ROMÂNIEI

Planul Național de Redresare și Reziliență

Dynamical Axial Charge and Chiral Magnetic Current in a Holographic Plasma

Zimányi School.
Winter Workshop on Heavy Ion Physics

West University of Timișoara

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Overview

- We want to study the dynamics of the Chiral Magnetic Effect in the strongly coupled quark-gluon plasma.
- Holography stands out as it maps the real-time strongly coupled QFT problem into a (still real-time) weakly coupled general relativity problem.
- We will follow a bottom-up approach.

→ Drawbacks: QFT dual not known (but key properties understood).

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

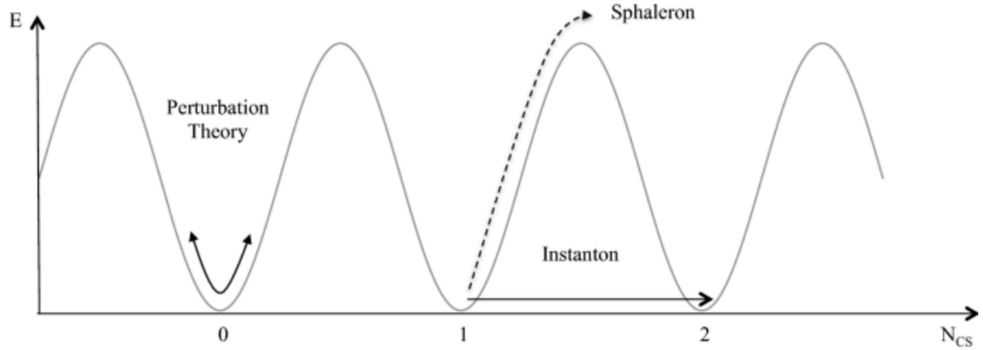
• Financial support by The European Union NextGenerationEU trough the grant No. 760079/23.05.2023, funded by the Romanian ministry of research, innovation and digitalization through Romania's National Recovery and Resilience Plan, call no. PNRR-III-C9-2022-I8, is gratefully acknowledged.

Quark-gluon plasma: Chirogenesis

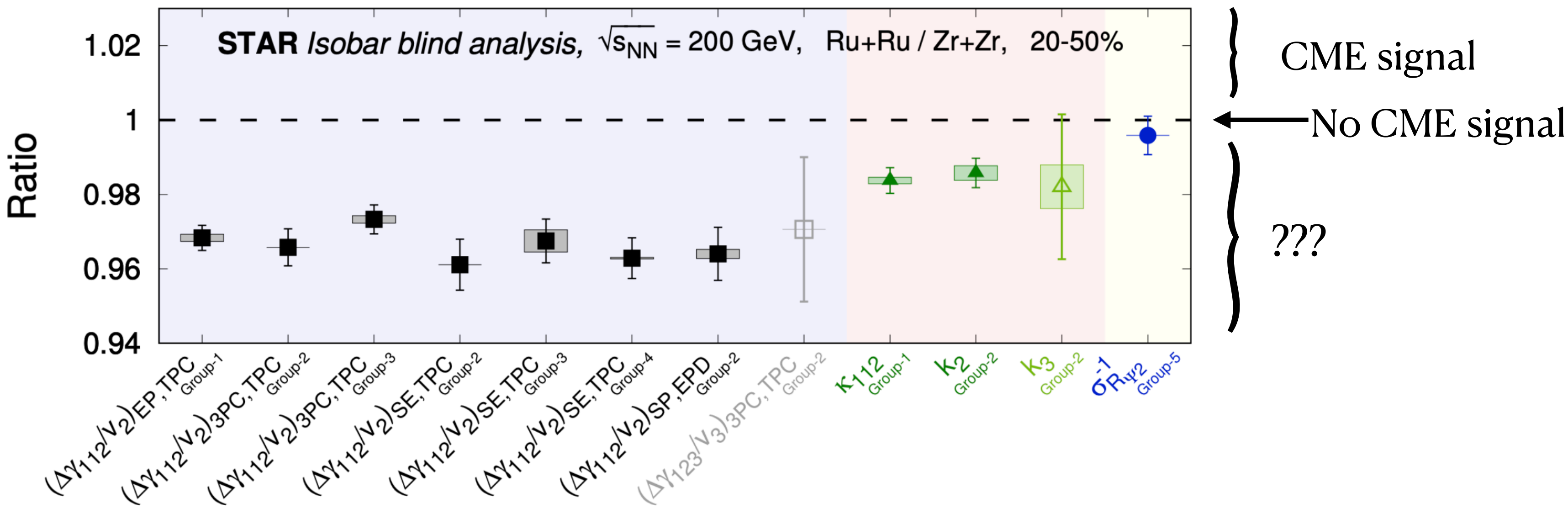
- Initially there is no chiral imbalance and we are in the topologically trivial sector.
- Small probability for tunnelling, but sphalerons are enhanced at high energies ⇒ Generation of non-zero winding number.
- Topologically non-trivial configurations of gauge field generate axial charge through the chiral anomaly.

$$\partial_\mu J_5^\mu \propto -\frac{g^2}{32\pi^2}\epsilon^{\mu\nu\rho\sigma}Tr\{G_{\mu\nu}G_{\rho\sigma}\}$$

- Measurement of CME, CVE can serve to probe topology of gauge fields.



STAR collaboration resutlts



- No CME signal according to the predefined criteria.
- Correcting for different multiplicities [Kharzeev, Liao, Shi (2022)] suggests 6.8 ± 2.6 % signal

Basics of Holography

- It establishes an equivalence between QFTs in d dimensions and quantum gravity in $d+1$dimensions.

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Energy momentum tensor $T^{\mu\nu}$	Metric $g_{\mu\nu}$
Conserved current J^{μ}	Gauge field A_{μ}
Scalar operator $\mathcal{O}$	Scalar field ϕ

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Anomalies in currents in QFT due to coupling to non-dynamical gauge field. ($F\tilde{F}$ term in QCD axial anomaly) ⇛ Chern-Simons term in the bulk

Anomalies in currents in QFT due to dynamical gauge field. ($G\tilde{G}$ term in QCD axial anomaly) ⇛ Mass term for the gauge field in the bulk

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QFT	AdS
Energy momentum tensor $T^{\mu\nu}$	Metric $g_{\mu\nu}$
Conserved current J^{μ}	Gauge field A_{μ}
Scalar operator $\mathcal{O}$	Scalar field ϕ
Temperature T	Black hole
Chemical potential μ	$\int F_{\mu\nu}\eta^{\mu}dx^{\nu}$

Chiral Magnetic Effect in Holography: Stüeckelberg model

$$S = \frac{1}{2\kappa^2}\int_{\mathcal{M}} d^5x\sqrt{-g}\left[R + \frac{12}{L^2} - \frac{1}{4}F^2 - \frac{1}{4}F_{(5)}^2 - \frac{m^2}{2}(A_\mu - \partial_\mu\theta)(A^\mu - \partial^\mu\theta)\right.$$
$$\left. + \frac{\alpha}{3}\epsilon^{\mu\nu\rho\sigma\tau}(A_\mu - \partial_\mu\theta)\left(3F_{\nu\rho}F_{\sigma\tau} + F^{(5)}_{\nu\rho}F^{(5)}_{\sigma\tau}\right)\right] + S_{GHY} + S_{ct}\,,$$

- The model [Jiménez-Alba, Landsteiner, Melgar (2014)] contains:

1. Two gauge fields dual to the $U(1)_A$, $U(1)_V$ currents.
2. Gravity, dual to energy-momentum tensor.
3. Chern-Simons terms: AAA, AVV.
   They account for the abelian contribution to the anomaly in the dual theory.
4. Stueckelberg field and mass term for A_μ which accounts for non-abelian contribution to the anomaly in the dual theory. Think of θ as dual to $Tr\{G\tilde{G}\}$ operator.

The axial current gets an anomalous dimension:
$[J_5] = 3 + \Delta$, with
$\Delta = -1 + \sqrt{1 + m^2}$

$F = dV \quad F_5 = dA$

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- System and initial state:

1. Static, non-expanding, infinite plasma.
2. $B\,,\epsilon$ uniform and constant in time.
3. Vanishing CME initially.
4. Two initial states:
   A. $n_5(0) \neq 0\,, \dot{n}_5(0) = 0$
   B. $n_5(0) = 0\,, \dot{n}_5(0) \neq 0$

Parameter space:

$(\alpha\ , B\,, \epsilon\,, \Delta)$

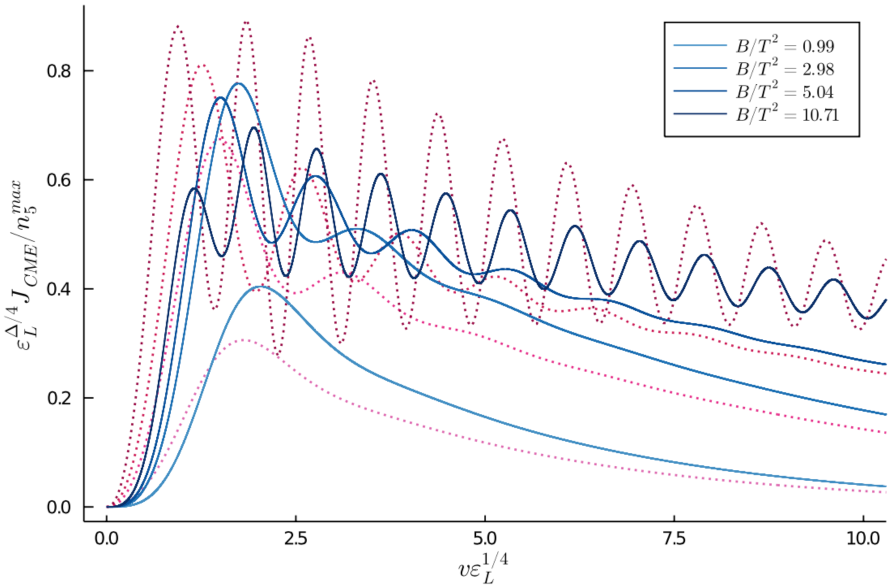
Provide one dimensionless ratio for a given α and Δ.

B/T^2

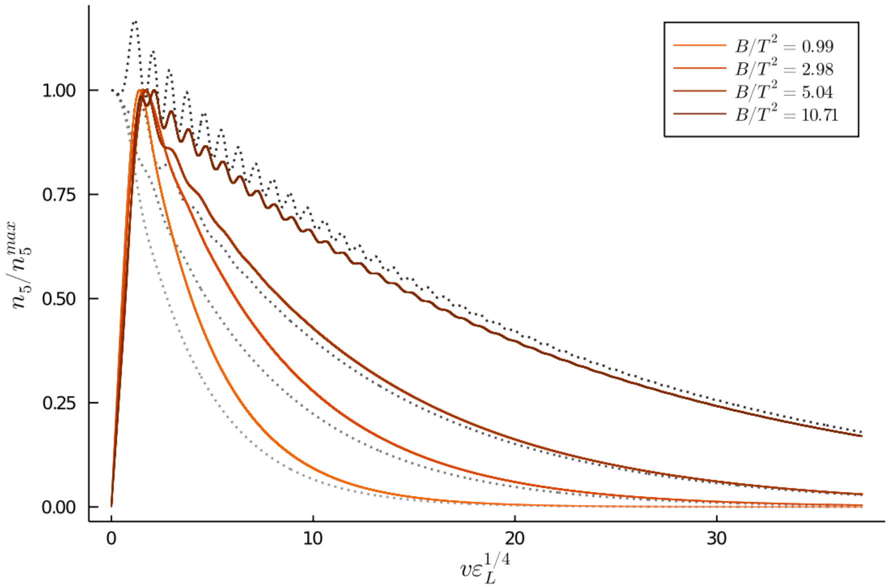
[S. Grieninger, SMT (2023)]

Chiral Magnetic Effect in Holography: Results

Chiral magnetic current



Axial charge



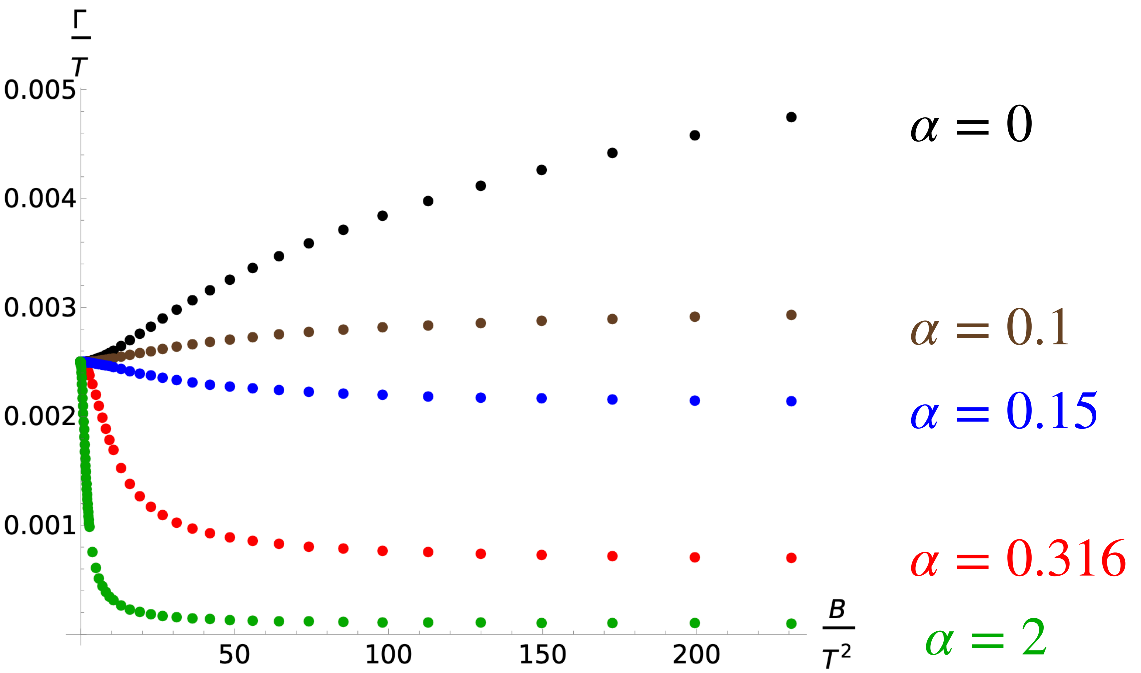
Same conclusions as for $\Delta = 0$, i.e. oscillations and time response. Axial charge is longer lived as we increase the magnetic field. This conclusion is reversed for $\alpha < 0.15$ in agreement with the QNMs computed in [Grieninger, Kharzeev (2023)]

$\alpha_{CS} = 1.5$
$\Delta \simeq 0.29$

[S. Grieninger, D. Kharzeev (2023)]

Chiral Magnetic Effect in Holography: Results

Interplay between abelian and non-abelian contributions to the anomaly



Axial charge relaxation rate as function of B/T^2 for five different values of the abelian anomaly ($\alpha = \{0, 0.1, 0.15, 0.32, 2\}$ corresponding to (black, brown, blue red and green)). We fixed $m_s L = 0.04$. For small magnetic fields the dependence on B/T^2 is quadratic.

Chiral Magnetic Effect in Holography: LHC and RHIC

RHIC

Centrality bin	10 – 20%	20 – 30%	30 – 40%	40 – 50%
$(n_5/s)_0$	0.065	0.078	0.095	0.119
T_0 (GeV)	0.341	0.329	0.312	0.294
$eB_{max}(m_\pi^2)$	2.34	3.1	3.62	4.01
T_{sim} (GeV)	0.429	0.414	0.393	0.370
$eB_{sim}(m_\pi^2)$	1.87	2.48	2.90	3.20

LHC

Centrality bin	10 – 20%	20 – 30%	30 – 40%	40 – 50%
$(n_5/s)_0$	0.039	0.045	0.059	0.075
T_0 (GeV)	0.48	0.47	0.43	0.40
$eB_{max}(m_\pi^2)$	59.2	78.5	91.7	101.6
T_{sim} (GeV)	0.87	0.85	0.78	0.73
$eB_{sim}(m_\pi^2)$	2.28	3.02	3.53	3.91

$$B(\tau) = \frac{B_{max}}{1 + \tau^2/\tau_B^2}$$

$$T(\tau) = T_0 \left(\frac{\tau_0}{\tau}\right)^{1/3}$$

$\tau_0 \simeq 0.6\, fm/c \simeq \tau_B^{RHIC}$

$\tau_B^{LHC} \simeq 0.02\, fm/c$

$\alpha_{qgp} = 0.316$

[Shi, Jiang, Lilleeskov,Liao (2018)]

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Choose simulation time in between the plasma formation ($\tau \sim 0.1 fm/c$) and equilibration ($\tau \sim 0.6 fm/c$) times

[Shi, Jiang, Lilleeskov,Liao (2018)]

$\tau_0 \simeq 0.6\, fm/c \simeq \tau_B^{RHIC}$

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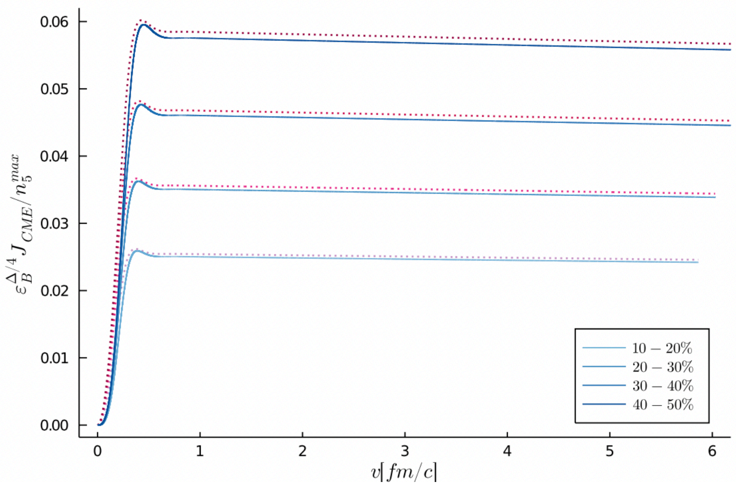
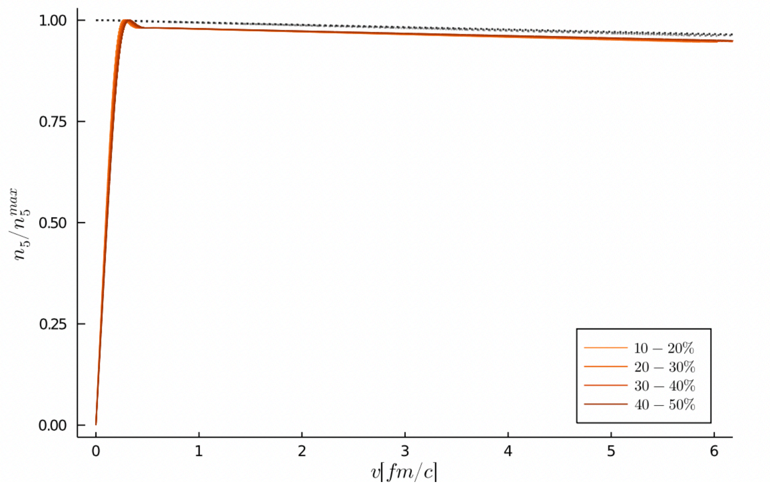
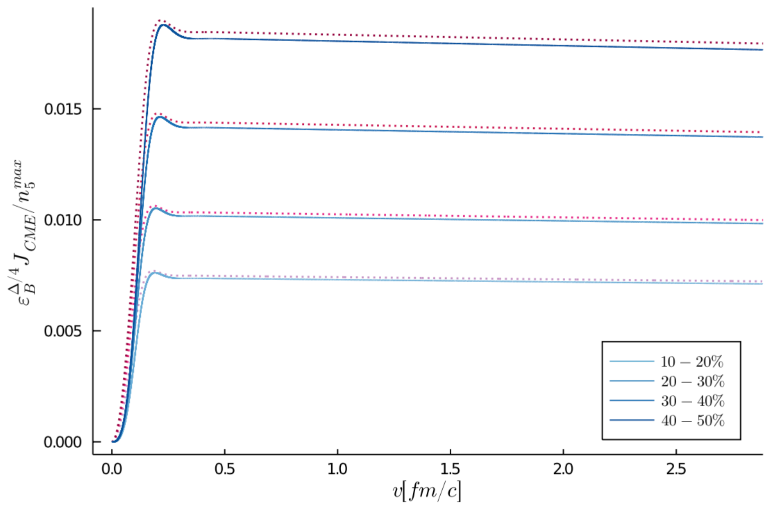
[S. Grieninger, SMT (2023)]

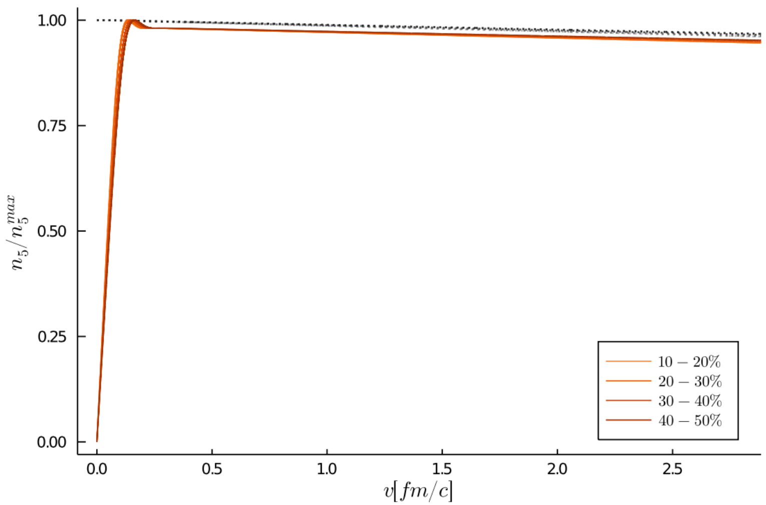
Chiral Magnetic Effect in Holography: (more) Results





RHIC



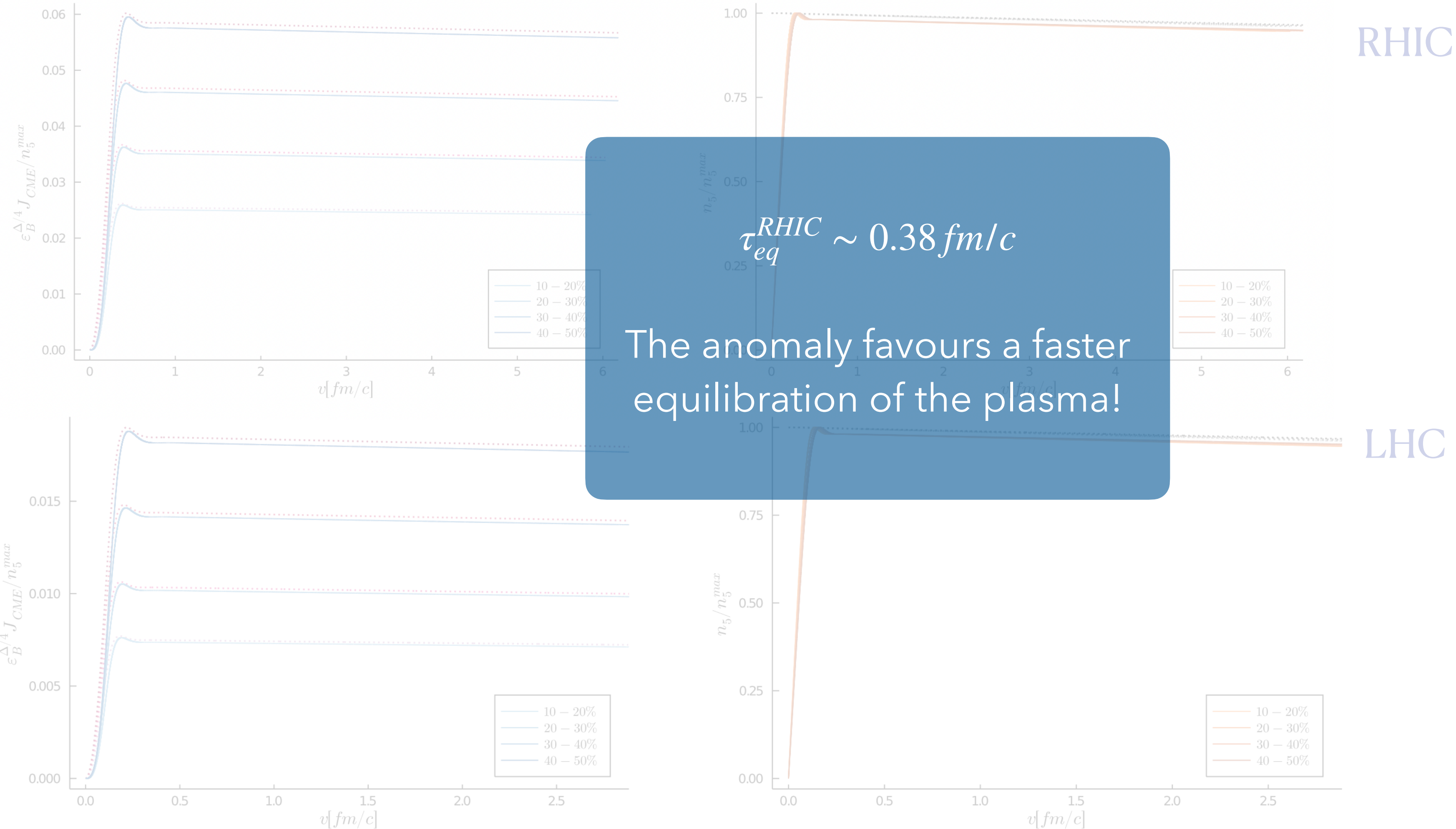


LHC

$\Delta \simeq 0.001$

[J.K. Ghosh, S. Grieninger, K. Landsteiner, SMT (2021)]

Chiral Magnetic Effect in Holography: (more) Results



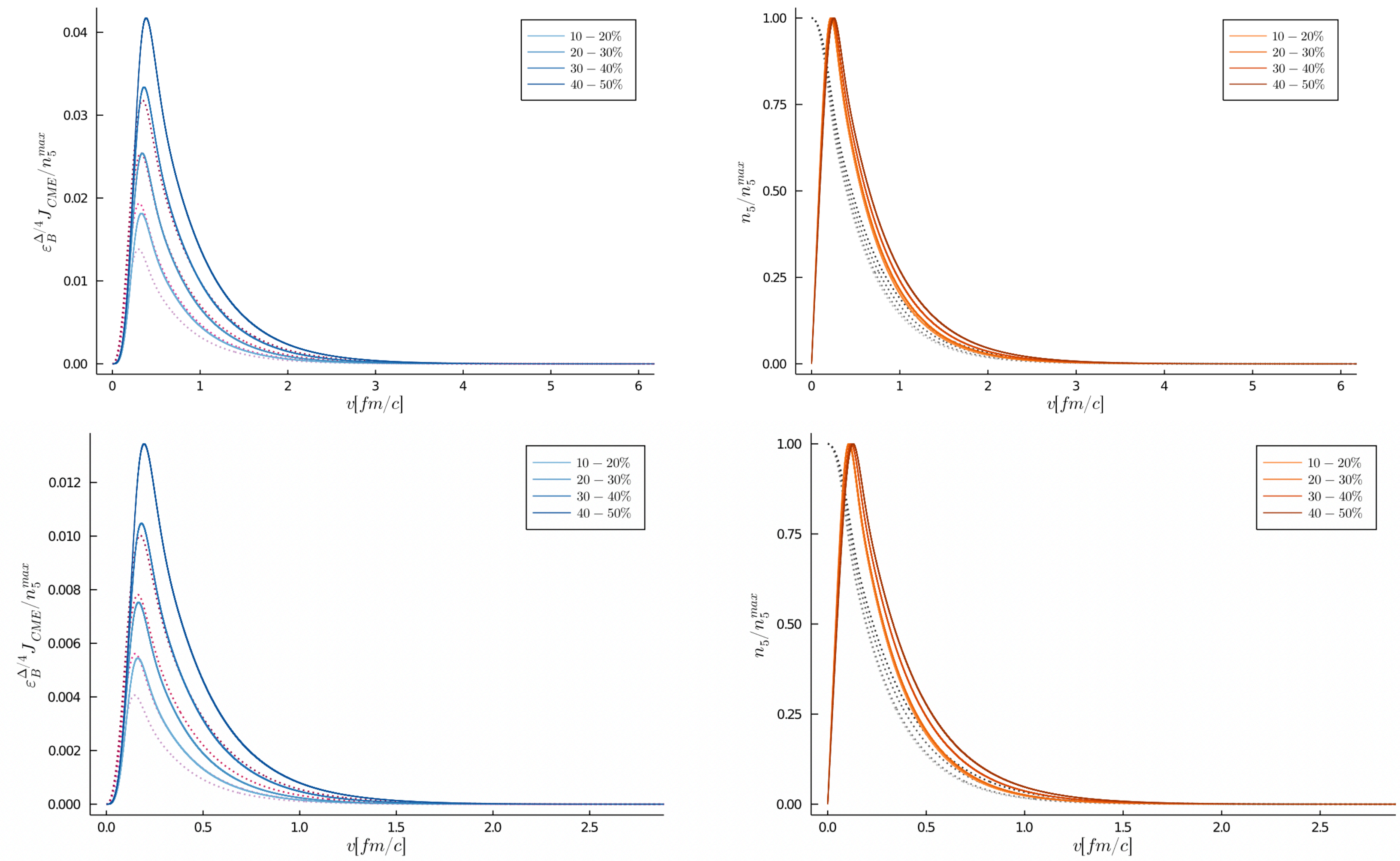
$$\tau_{eq}^{RHIC} \sim 0.38\, fm/c$$

The anomaly favours a faster equilibration of the plasma!

$\Delta \simeq 0.001$

[S. Grieninger, SMT (2023)]

Chiral Magnetic Effect in Holography: (more) Results



RHIC

LHC

$\Delta \simeq 0.29$

[S. Grieninger, SMT (2023)]

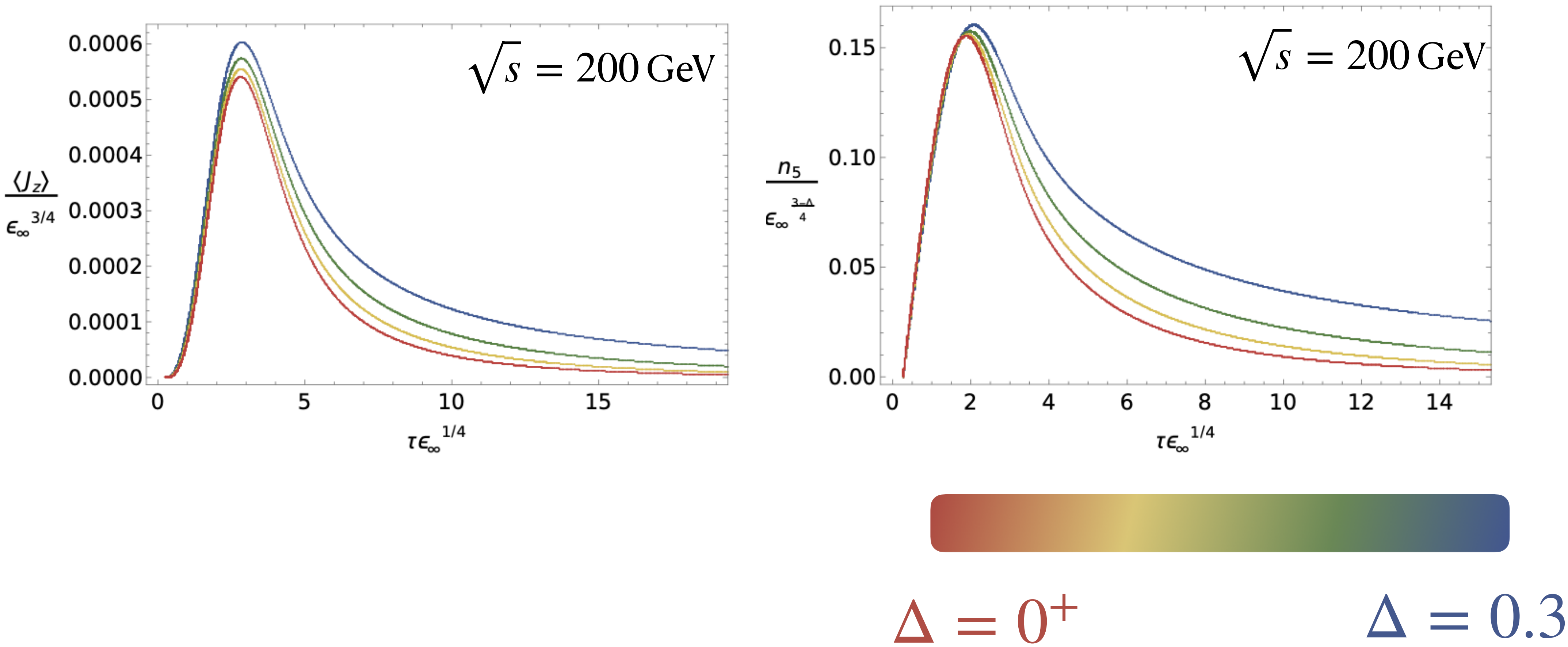
Chiral Magnetic Effect in Holography: Expanding Plasma

- We study a boost invariant expanding plasma. The expansion takes place in a direction transverse to the magnetic field.

$B = \frac{m_\pi^2}{\tau}$ $\quad T_0 = 300\,\text{MeV}$ $\quad \tau_0 = 0.6\,fm/c$ $\quad \alpha_{qgp} = 0.316$

[S. Grieninger, SMT (2023)]

Chiral Magnetic Effect in Holography: Expanding Plasma



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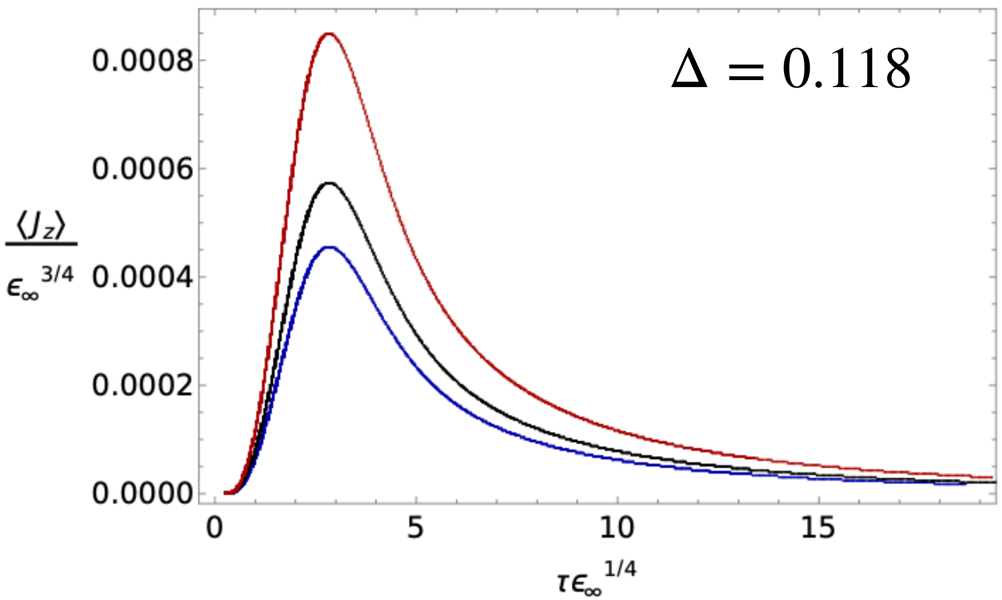
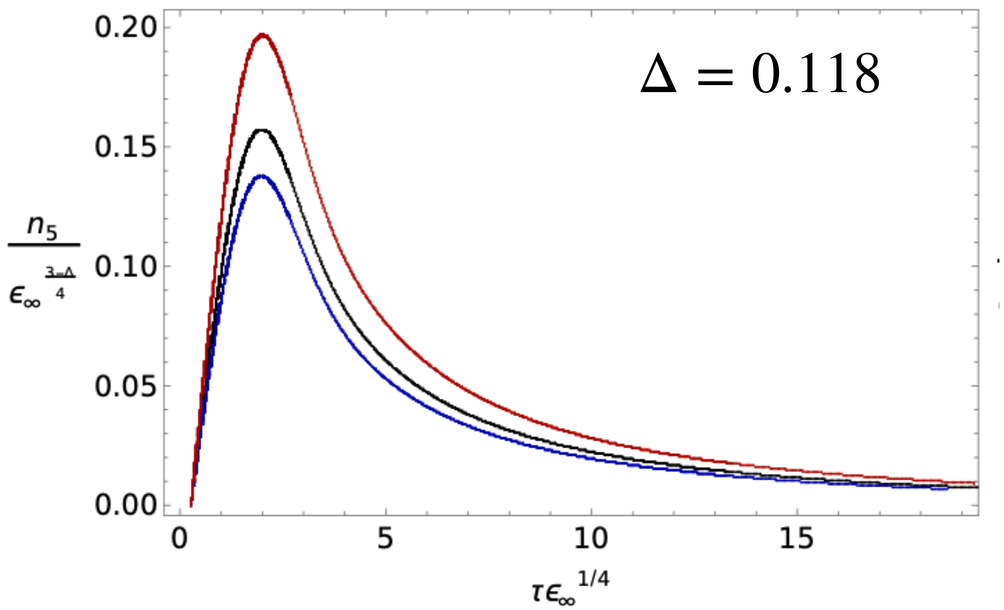




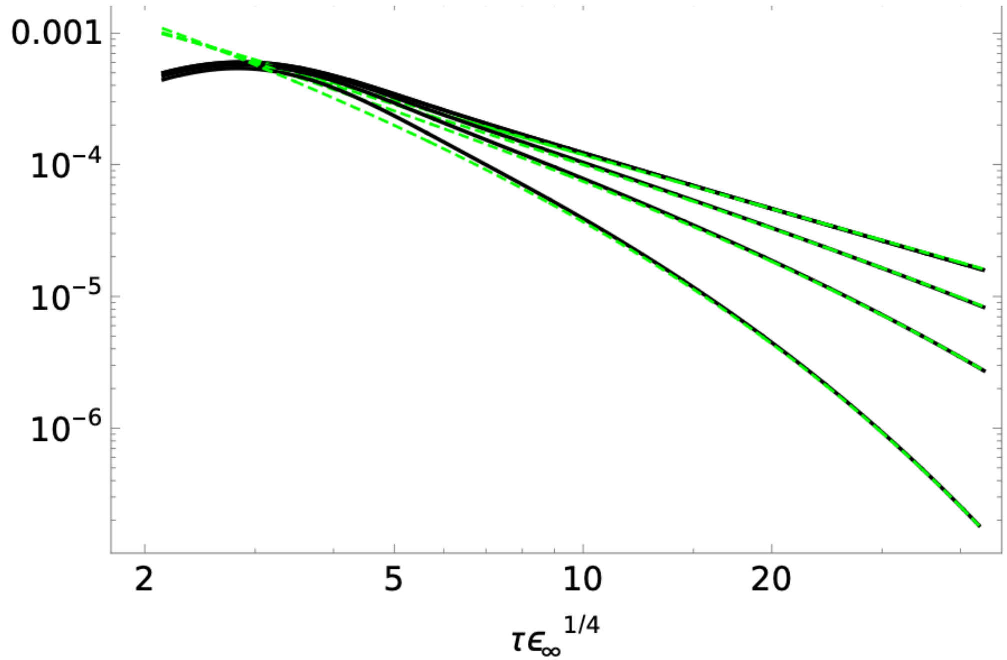
$\sqrt{s} = 250\,\mathrm{GeV}$ $200\,\mathrm{GeV}$ $150\,\mathrm{GeV}$

[S. Grieninger, SMT (2023)]

Chiral Magnetic Effect in Holography: Expanding Plasma

- One is able to provide a near-equilibrium formula for the chiral magnetic effect with a non-conserved axial charge.

$$\langle J_{\mathrm{CME}} \rangle = \frac{24\pi^2}{19\,\kappa_5^2}\frac{\alpha}{3(1-\Delta)} A_v(\tau,1)\,B(\tau)$$



Discussion & Outlook

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- We have studied the onset of the CME and its dependence w.r.t. the magnetic field in a simple holographic model akin to the sQGP. First with conserved axial charge and later including its dynamics.

    1. The abelian contribution to the anomaly favour the faster equilibration of the plasma.
    2. Axial charge lifetime is increased as we increase the magnetic field.
    3. As the plasma expands, axial charge dissipates faster due to the non-trivial dependence of the dissipation rate with the magnetic field $\Gamma(B)$.
    4. For the non-expanding case, the CME seems to be favoured at lower energies. For the expanding case the conclusion is reversed. The result is very sensitive to the treatment of the magnetic field and a realistic time-dependent one needs to be included (ongoing).
    5. A near-equilibrium formula is given for the CME when axial charge is not conserved.

- Improve holographic models to include confinement, a field dual to $Tr\{GG\}$... Asymmetric shock-wave collisions.

Thank you!

[J.K. Ghosh, S. Grieninger, K. Landsteiner, SMT (2021)]

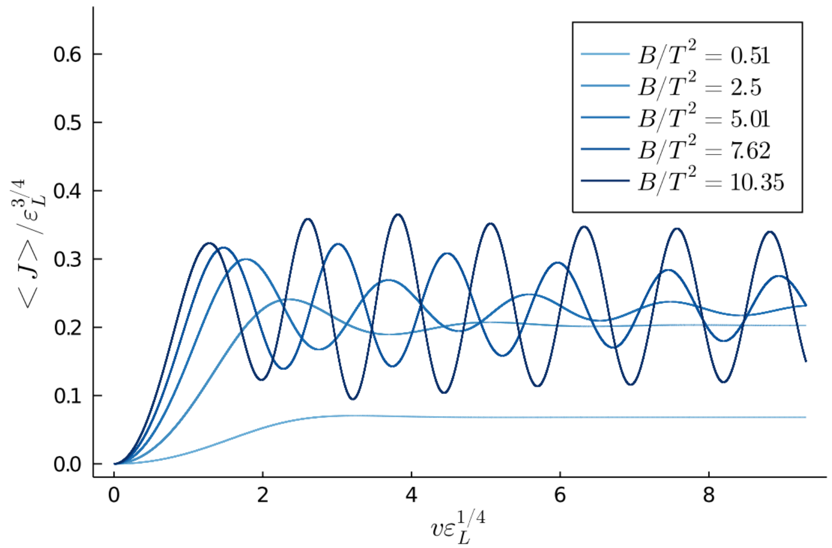
Previous Results…

$$\Delta = 0$$

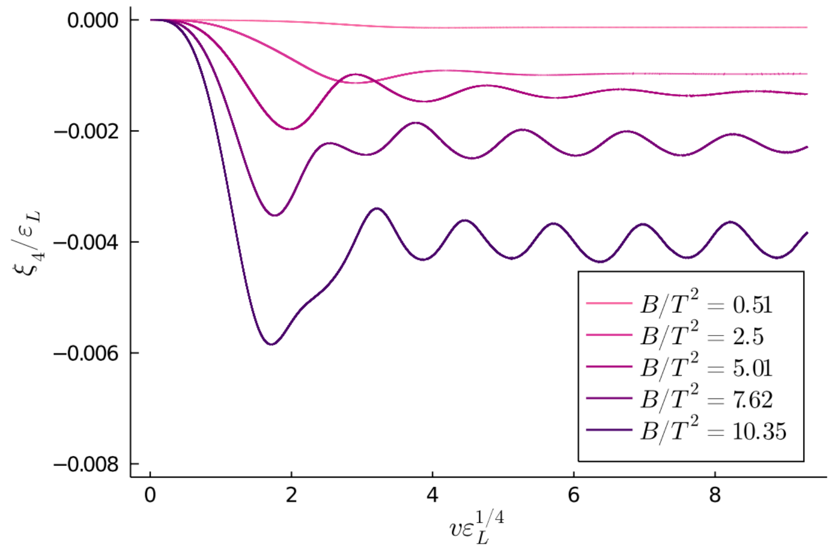
[J.K. Ghosh, S. Grieninger, K. Landsteiner, SMT (2021)]

Chiral Magnetic Effect in Holography: Results

Chiral magnetic current



Dynamical pressure anisotropy



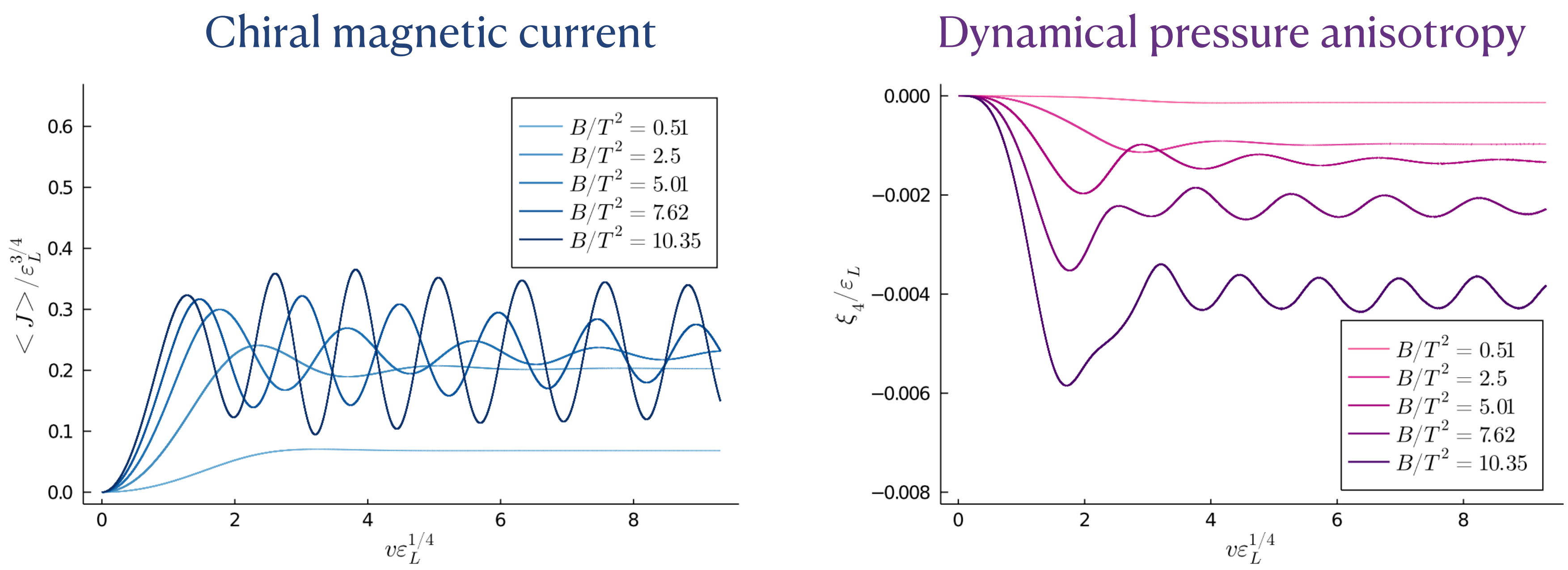
$\alpha_{CS} = 1.5$

$\mu_5/T \in (0.02, 0.11)$

$\epsilon_L = 12$

[J.K. Ghosh, S. Grieninger, K. Landsteiner, SMT (2021)]

Chiral Magnetic Effect in Holography: Results



As we increase the magnetic field, the chiral magnetic current builds up faster and faster. Both CME current and pressure anisotropy display oscillatory behaviour for high magnetic fields.

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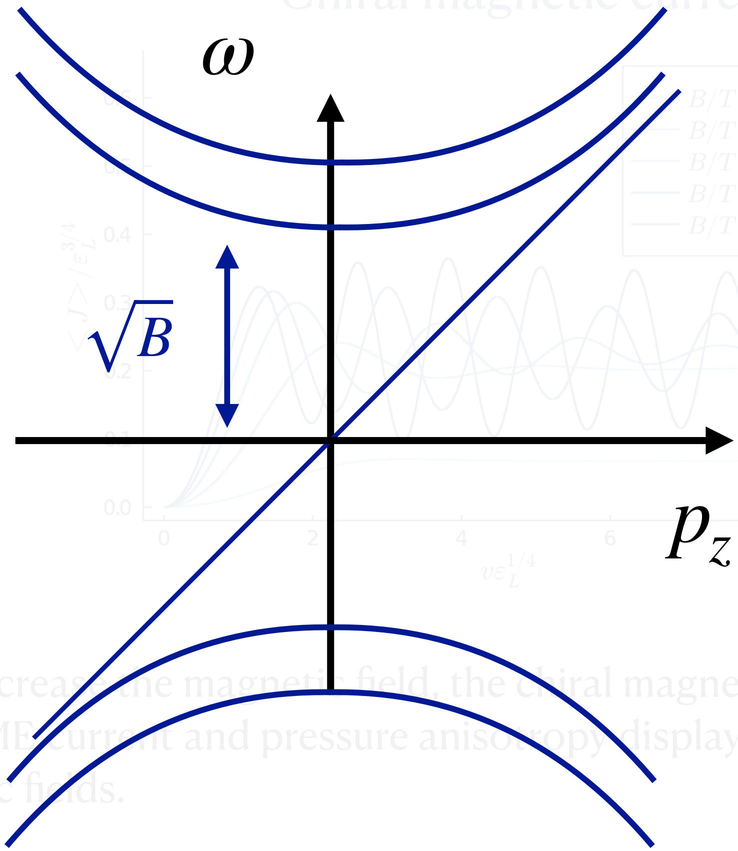
Weak-coupling intuition

Landau Levels



$$\omega_{p_z,n} = \pm\sqrt{p_z^2 + 2Bn}$$

- As we increase B, fermions are in the LLL.
- Physics is 1+1 dimensional.
- The CME_{1+1} is an operator relation, and there cannot be axial charge without CME current.

$$J_a^5 = \epsilon_{ab} J^b$$

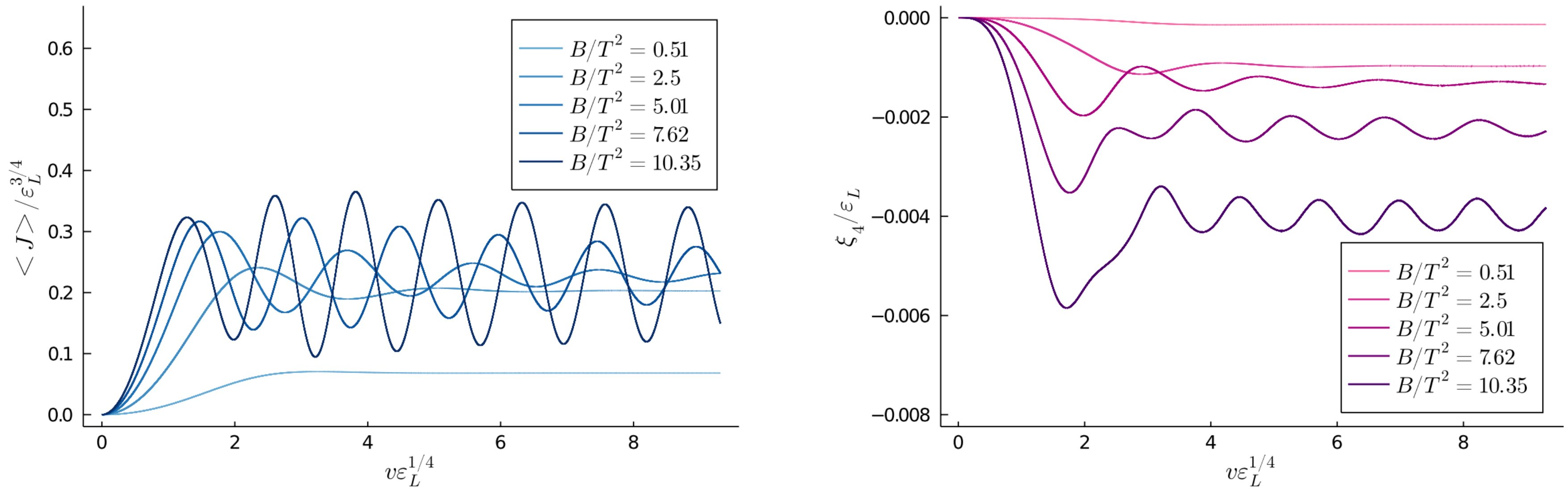
Instantaneous response

[J.K. Ghosh, S. Grieninger, K. Landsteiner, SMT (2021)]

Chiral Magnetic Effect in Holography: Results

Chiral magnetic current

Dynamical pressure anisotropy



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$\mu_5/T \in (\, 0.02\, , 0.11\,)$

$\epsilon_L = 12$

Chiral Magnetic Effect in Holography: LHC and RHIC

- We match the anomaly of our model with the anomaly of 3-flavour QCD, and we match the entropy density of the black hole to 3/4 of Stefan-Boltzmann limit.

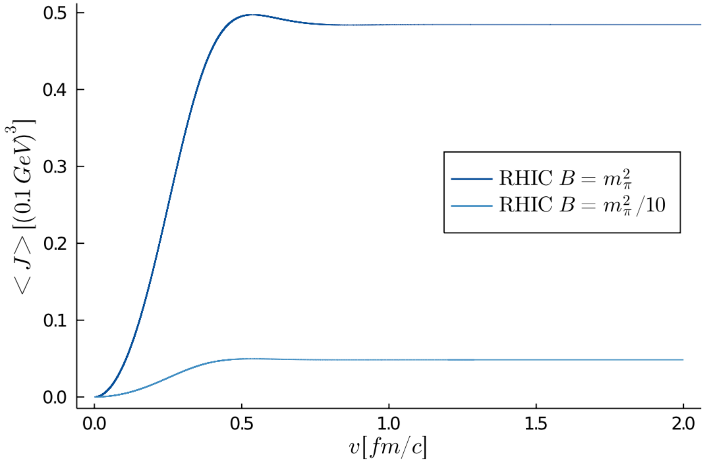
$$\alpha_{qgp} = 0.316$$

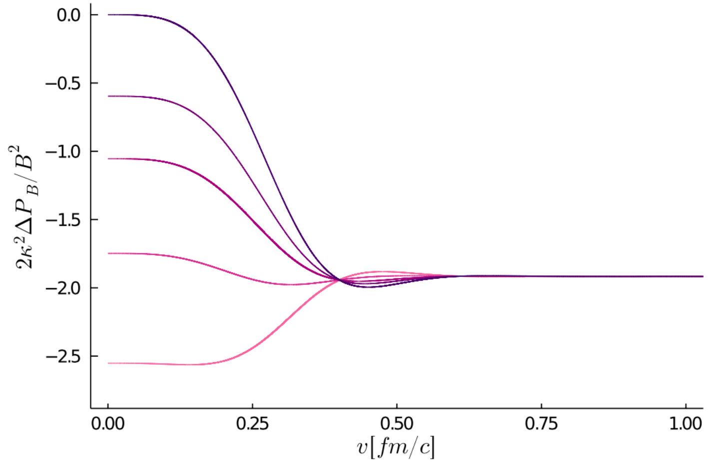
- We simulate for both LHC and RHIC accelerators. We fix the two dimensionless ratios μ_5/T and B/T^2 according to:

	RHIC	LHC
T	300 MeV	1000 MeV
μ_5	10 MeV	10 MeV
B	m_π^2	$15\, m_\pi^2$

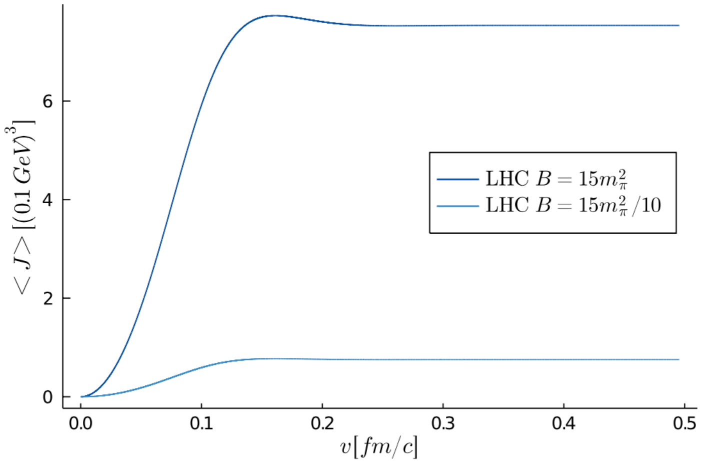
[J.K. Ghosh, S. Grieninger, K. Landsteiner, SMT (2021)]

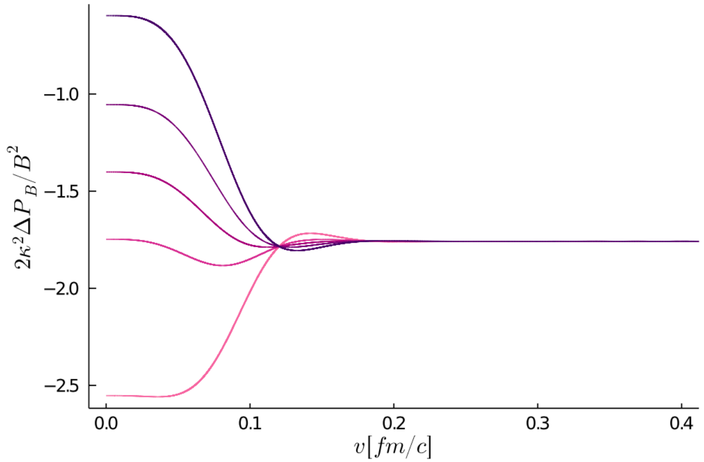
Chiral Magnetic Effect in Holography: LHC and RHIC





RHIC

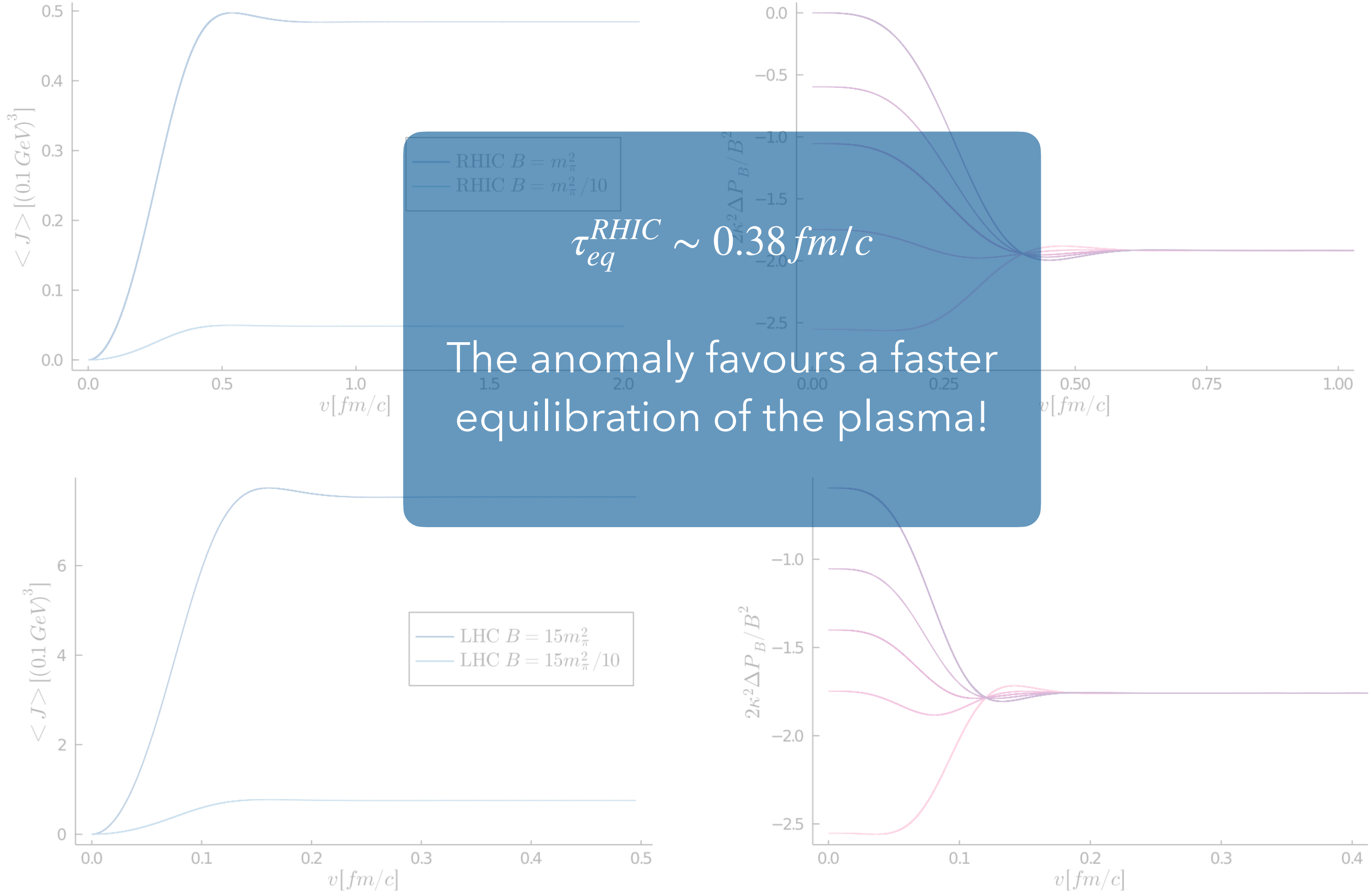




LHC

[J.K. Ghosh, S. Grieninger, K. Landsteiner, SMT (2021)]

Chiral Magnetic Effect in Holography: LHC and RHIC



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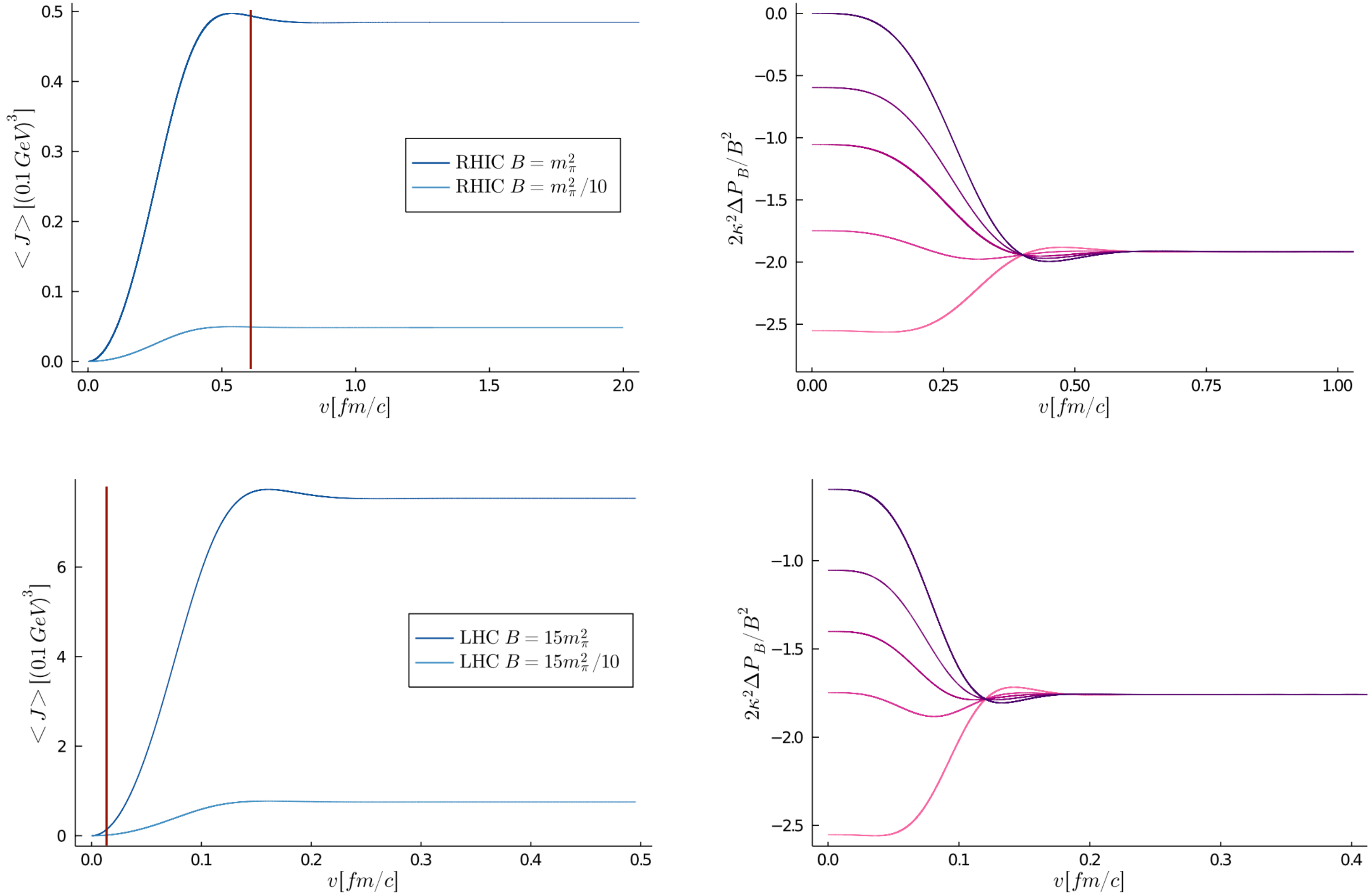

RHIC:
$\tau_B \sim 0.6\ fm/c$

LHC:
$\tau_B \sim 0.02\ fm/c$

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$$\left. + \frac{\alpha}{3}\epsilon^{\mu\nu\rho\sigma\tau}(A_\mu - \partial_\mu\theta)\left(3F_{\nu\rho}F_{\sigma\tau} + F_{\nu\rho}^{(5)}F_{\sigma\tau}^{(5)}\right)\right] + S_{GHY} + S_{ct}\,,$$

- The chiral magnetic effect requires the presence of:

1. Axial charge
2. Magnetic field
3. Stueckelberg field
4. Metric ansatz

$$A = -\epsilon A_t(v,u)dv$$

$$V = \frac{B}{2}(xdy - ydx) + \epsilon V_z(v,u)dz$$

$$\theta = \epsilon\theta(v,u)$$

$$ds^2 = -f(v,u)dv^2 - \frac{2L^2}{u^2}dvdu$$
$$+\Sigma(v,u)^2\left[e^{\xi(v,u)}(dx^2 + dy^2) + e^{-2\xi(v,u)}dz^2\right]$$

$F = dV \quad F_5 = dA$