Is the Chiral Magnetic Effect fast enough ?

Instituto de Física Teórica UAM-CSIC

EXCELENCIA SEVERO OCHOA

Campus Internacional excelencia UAM CSIC+

Karl Landsteiner

Phys. Rev. D. 104 (2021) 046009
2105.05855 [hep-ph]

With: J. Ghosh, S. Grieninger, S. Morales-Tejera

6th International Conference on Chirality, Vorticity and Magnetic fields in HICs, Stony Brook 2021

Outline

- CME and equilibrium
- Out-of-equilibrium CME in Holography
  - Generic model properties
  - Matching to QCD
- Conclusions & Outlook

CME @ HIC

Axial anomaly (QED): $$\partial_\mu J_5^\mu = c\,\epsilon^{\mu\nu\rho\lambda} F_{\mu\nu} F_{\rho\lambda}$$

CME: $$\vec{J} = 8c\,\mu_5 \vec{B}$$

[Fukushima, Kharzeev,Warringa]

[Vilenkin] 1980
[Alekseev,Chaianov, Fröhlich]
[Giovaninni, Shaposhnikov],...

Equilibrium quantity, not the chiral charge !

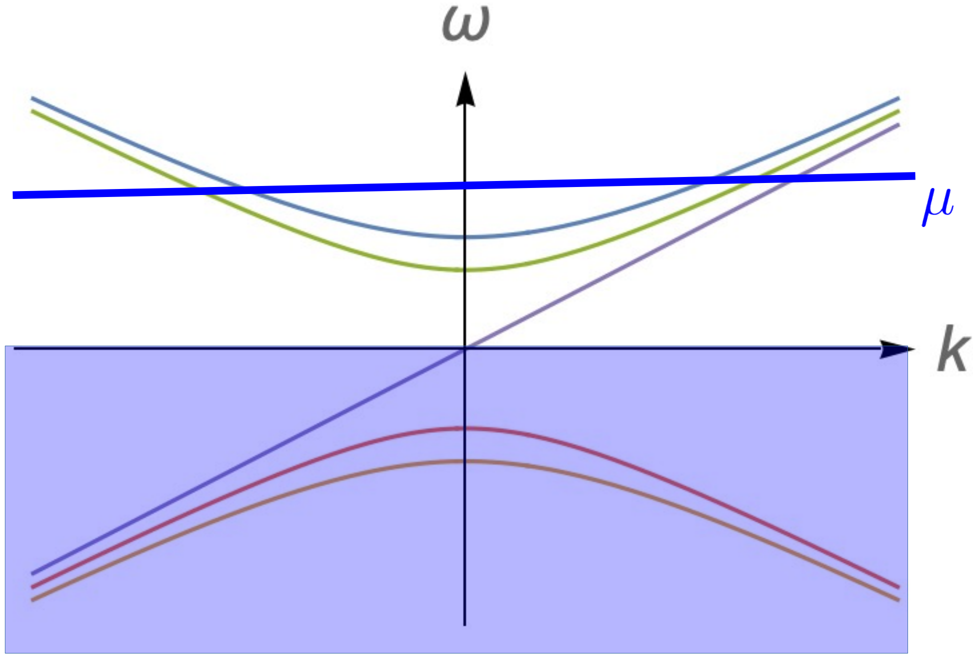
Lifetime!

Theory subtelties (covariant vs. consistent anomalies)
[Gynther, K.L., Pena-Benitez, Rebhan], 1005.2587 [K.L. 1610.04413]

$$\vec{J} = 8c(\mu_5 - A_5^0)\vec{B}$$

CME @ HIC

Chiral fermion in (very strong) magnetic field:



Lowest Landau Level:

$$J = \frac{eB}{2\pi}\int_0^{\infty}\frac{dk}{2\pi}\left[n_F(\mu,T) - n_F(-\mu,T)\right] = \frac{\mu}{4\pi^2}eB$$

Higher Landau Levels:

$$J = \frac{eB}{2\pi}\int_{-\infty}^{+\infty}\frac{dk}{2\pi}\frac{\partial\epsilon}{\partial k}\left(n_F(\mu,T,k^2)\right) = 0$$

CME current stems from LLL only

CME @ HIC

arXiv.org > nucl-th > arXiv:1608.00982

Nuclear Theory

[Submitted on 2 Aug 2016 (v1), last revised 12 Aug 2016 (this version, v2)]

Chiral Magnetic Effect Task Force Report

Vladimir Skokov, Paul Sorensen, Volker Koch, Soeren Schlichting, Jim Thomas, Sergei Voloshin, Gang Wang, Ho-Ung Yee

Theory Uncertainties:

A) the initial distribution of axial charges,

B) the evolution of the magnetic field,

C) the dynamics of the CME during the pre-equilibrium stage,

D) the uncertainties in the hadronic phase and the freeze-out.

CME @ HIC

How long does it take to build up the CME current if one starts out with J=0 ?

- Quark Gluon Plasma: strongly coupled fluid
- One of the success stories of holography
- Especially successful for CME, CVE

Shear viscosity: $\frac{\eta}{s} = \frac{1}{4\pi}$ [Policastro, Son, Starinets]

Equilibration, isotropisation times: $\tau \approx 0.5 fm/c$ [Chesler, Yaffe]

[Newman], [Yee], [Erdmenger, Kaminski, Haack, Yarom], [Banerjee, Bhattacharya, Bhattacharyya, Dutta, Loganayagam, Surowka]
[Rebhan, Schmitt, Stricker], [Gynther, K.L., Pena-Benitez, Rebhan], [K.L., Megias, Melgar, Pena-Benitez],
[Ammon, Grieninger, Hernandez, Kaminski, Koirala, Leiber ,Wu], ...

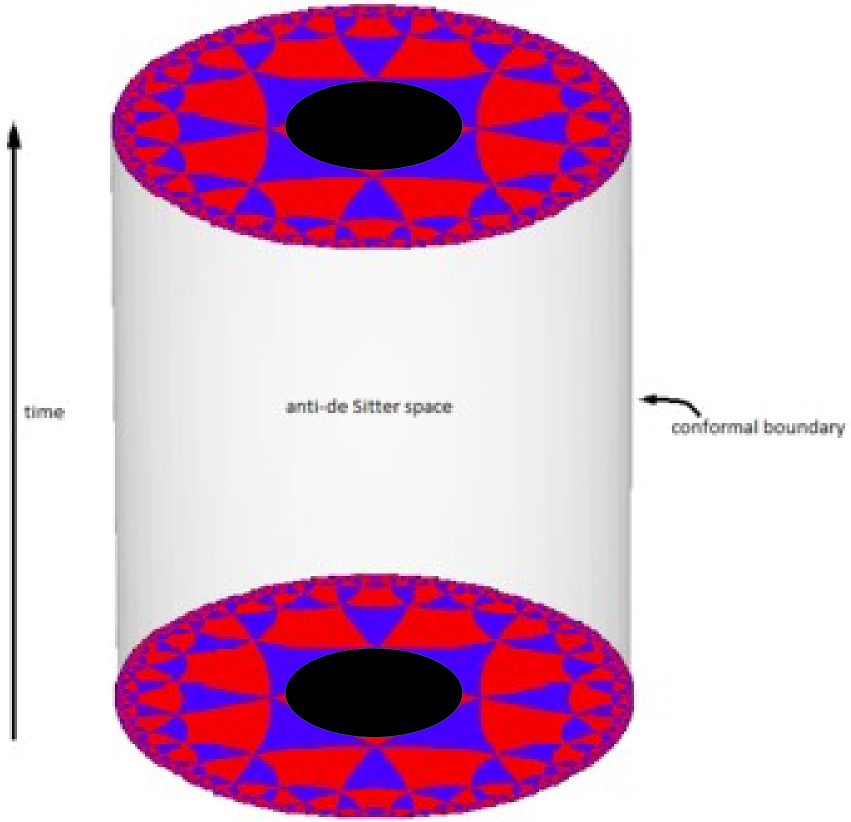
Investigate this question in a holographic setup

[Lin, Yee], [Ammon, Grieninger, Jimenez-Alba, Malcedo, Melgar],[K.L., Lopez, Milans del Bosch],
[Fernandez-Pendas, K.L.], [Morales-Tejera, K.L.], [Cartwright]

Quantum simulation approach 2D model: [Kharzeev, Kikuchi]

TALKS at this conference: *M.Kaminski* and *C.Cartwright*

Holography



Gravity in asymptotically AdS = QFT

Holographic Dictionary	
Metric	Energy Momentum Tensor
Gauge field	Conserved current = symmetry
Scalar field	Scalar operator
Boundary value	**Coupling**
Black Hole	**Temperature**

Holography

Holographic bottom-up approach: chose symmetries, simplest Lagrangian

$$S = \frac{1}{2\kappa^2}\int d^5x\sqrt{-g}\left[R + \frac{12}{L^2} - \frac{1}{4}F_V^2 - \frac{1}{4}F_A^2 + \frac{\alpha}{3}\epsilon^{\mu\nu\rho\lambda\sigma}A_\mu\left(3F^V_{\nu\rho}F^V_{\lambda\sigma} + F^A_{\nu\rho}F^A_{\lambda\sigma}\right)\right]$$

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

$$V_\mu = (0,0,-y\,B/2, x\,B/2, V_z(v,u)) \quad , \quad A_\mu = (-Q_5(v,u),0,0,0,0)$$

Asympotic expansion:

$$Q_5(v,u) = \frac{u^2}{2}q_5 + \mathcal{O}(u^3)\,,$$
$$V_z(v,u) = u^2\,V_2(v) + \mathcal{O}(u^3)\,,$$
$$\Sigma(v,u) = \frac{1}{u} + \lambda(v) + \mathcal{O}(u^5)\,,$$
$$\xi(v,u) = u^4\left(\xi_4(v) - \frac{B^2}{12}\log(u)\right) + \mathcal{O}(u^5)\,,$$
$$f(v,u) = \left(\frac{1}{u} + \lambda(v)\right)^2 + u^2\left(f_2 + \frac{B^2}{6}\log(u)\right) - 2\dot\lambda(v) + \mathcal{O}(u^3)\,.$$

Operators:

$$J_z = \frac{1}{\kappa^2}V_2(v)$$
$$J_5^0 = \frac{1}{2\kappa^2}q_5$$
$$T^v{}_v = \frac{1}{4\kappa^2}\left[6f_2 - B^2\log(\mu L)\right]$$
$$T^x{}_x = T^y{}_y = -\frac{1}{8\kappa^2}\left[B^2 + 4f_2 - 16\xi_4(v) - 2B^2\log(\mu L)\right]$$
$$T^z{}_z = -\frac{1}{4\kappa^2}\left[2f_2 + 16\xi_4(v) + B^2\log(\mu L)\right]$$

Holography

Initial state:

- Energy and axial charge corresponding to (T,μ_5) in final state
- Magnetic field is uniform and constant in time
- Dynamical pressure anisotropy vanishes $\xi = 0$
- CME current is absent $V_z = 0$

Final state:

- Dynamical pressure anisotropy determined by magnetic field
- CME current has approached equilibrium expression

Compare to:

[Chesler, Yaffe] 2010 "Isotropization", no magnetic field

[Fuini, Yaffe] 2016 Magnetic field, no chiral charge, no CME

Holography

Numerical Methods:

- Pseudo-spectral methods
- Chebyshev Polynomials
- Chebyshev-Lobatto grid $x_n = \cos(n\pi/N)$
- Keep apparent horizon fixed $\lambda(v)$
- Subtract logs for better convergence
- Time evolution 4th order Runge-Kutta

[Chesler, Yaffe] JHEP 07 (2014) 086

Implementation:

- Mathematica (original code, somewhat slow)
- julia

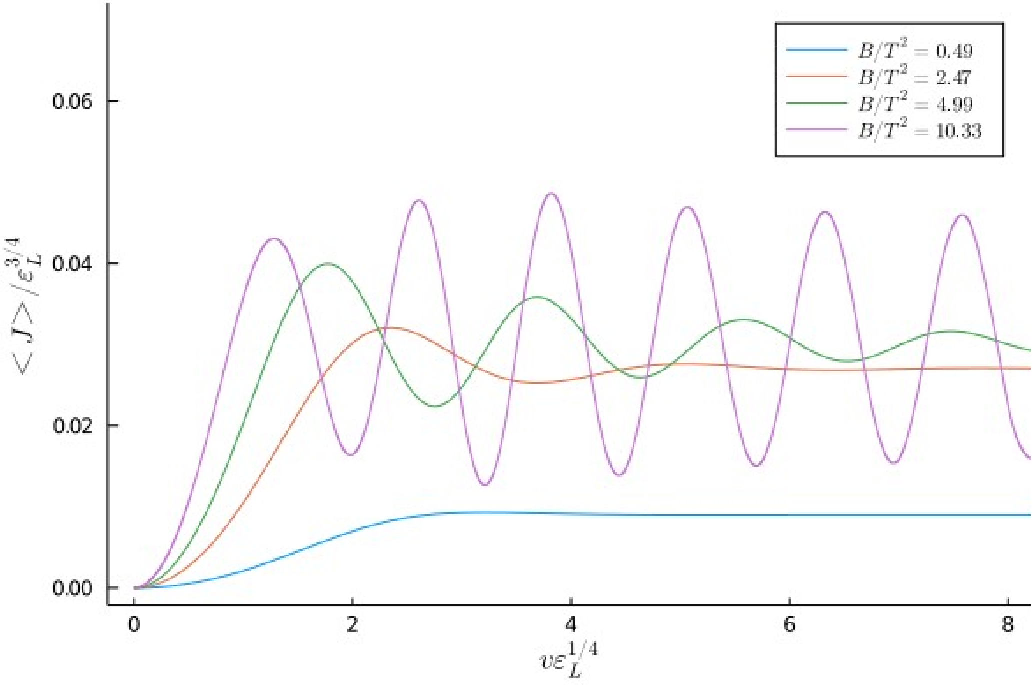
Renormalization scale:

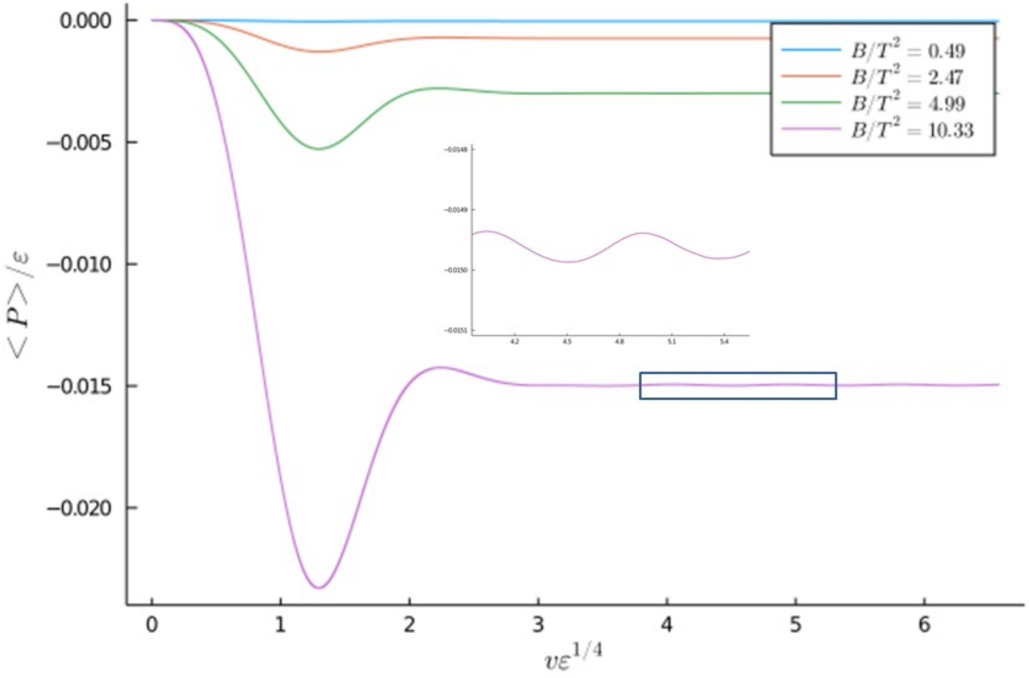
- Numerics $\mu = 1/L$
- Physics $\mu = \sqrt{B}$

$$\frac{\epsilon_B}{B^2} = \frac{\epsilon_L}{B^2} + \frac{1}{4}\log(BL^2)$$

Holography

B-field dependence: $q_5 = 0.2 \quad , \quad \alpha = 1.5$



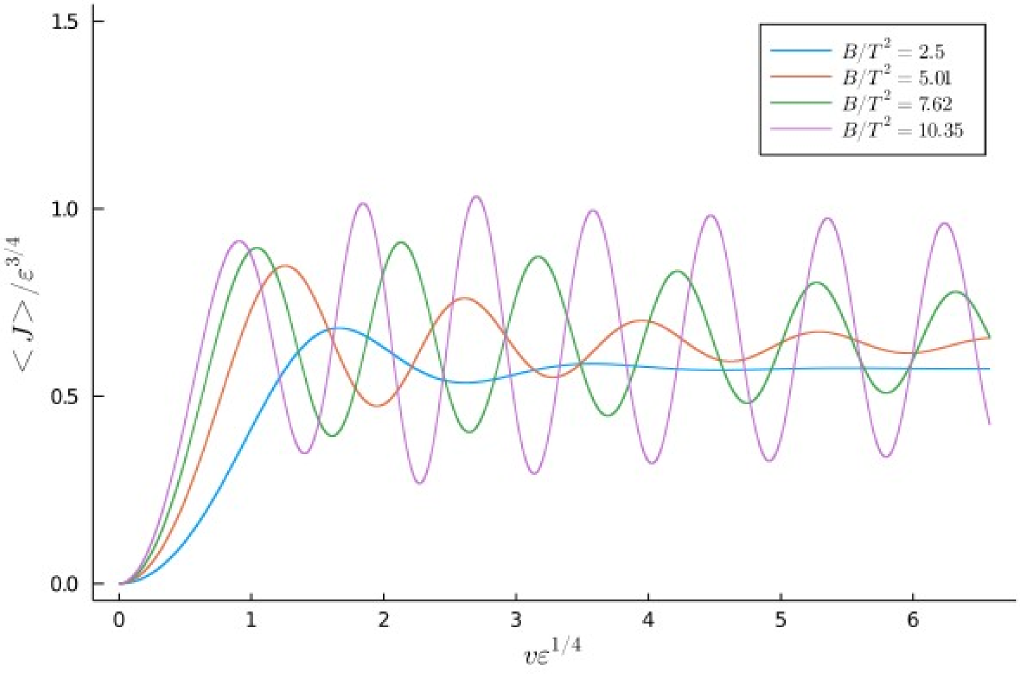


Current

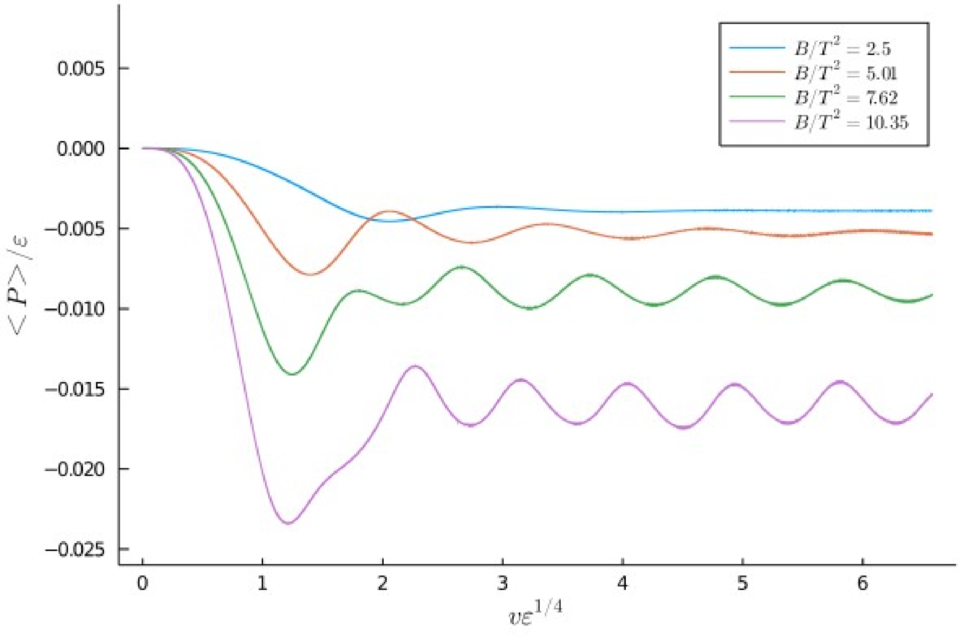
Pressure anisotropy

Holography

B-field dependence: $q_5 = 1.5 \ , \ \alpha = 1.5$



Current



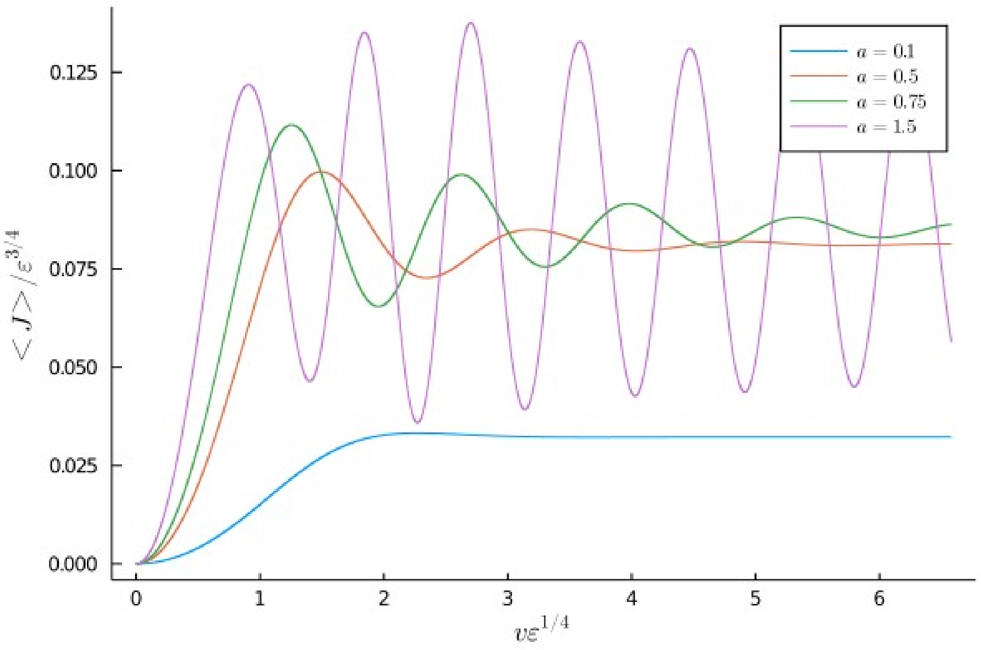
Pressure anisotropy

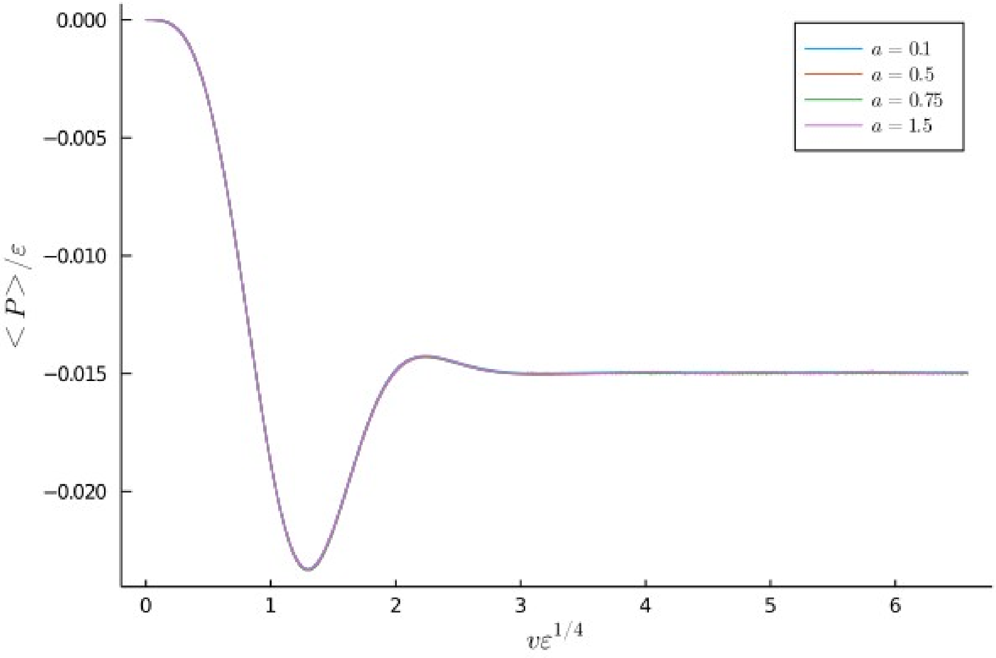
Holography

- Almost undamped oscillations: QNMs near the real axis
  [Ammon, Grieninger, Jimenez-Alba, Malcedo, Melgar]
- Define build up time to first maximum
- Observation: faster for larger magnetic field
- Lowest Landau Level: 2D physics! Operator relation $J_5^\mu = \epsilon^{\mu\nu} J_\nu$

Holography

Anomaly dependence: $q_5 = 0.2 \quad , \quad B = 2$



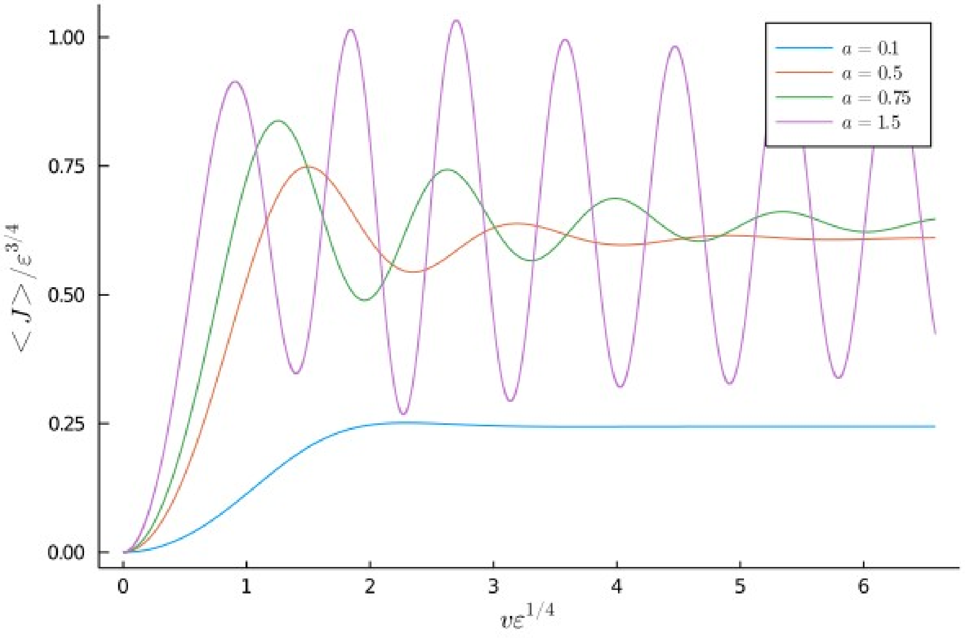


Current

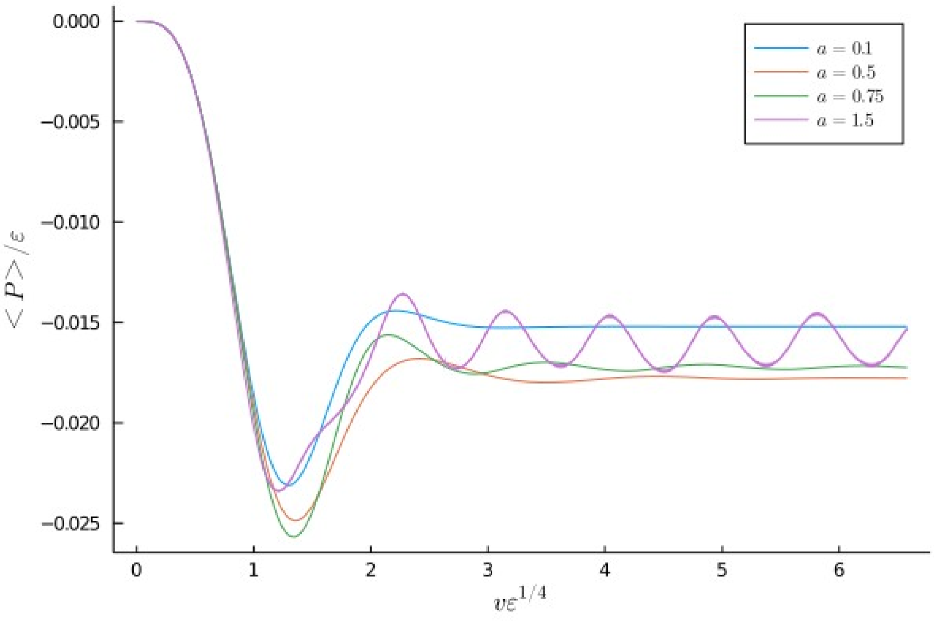
Pressure anisotropy

Holography

Anomaly dependence: $q_5 = 1.5 \quad , \quad B = 2$



Current



Pressure anisotropy

Holography

Matching couplings to QCD:

➔ Gravitational coupling: match to entropy

$$s_{BH} = \frac{4\pi^2 T^3}{2\kappa^2} \qquad s_{SB} = 4\left(\nu_b + \frac{7}{4}\nu_f\right)\frac{\pi^2 T^3}{90}$$

$$s_{BH} = \frac{3}{4} s_{SB} \qquad \Longrightarrow \quad \kappa^2 \approx 12.5$$

➔ Chern Simons coupling: match to anomaly

$$\frac{\alpha}{2\kappa^2} = \mathcal{A}_{QCD} = \frac{1}{8\pi^2} \qquad \Longrightarrow \alpha \approx 0.316$$

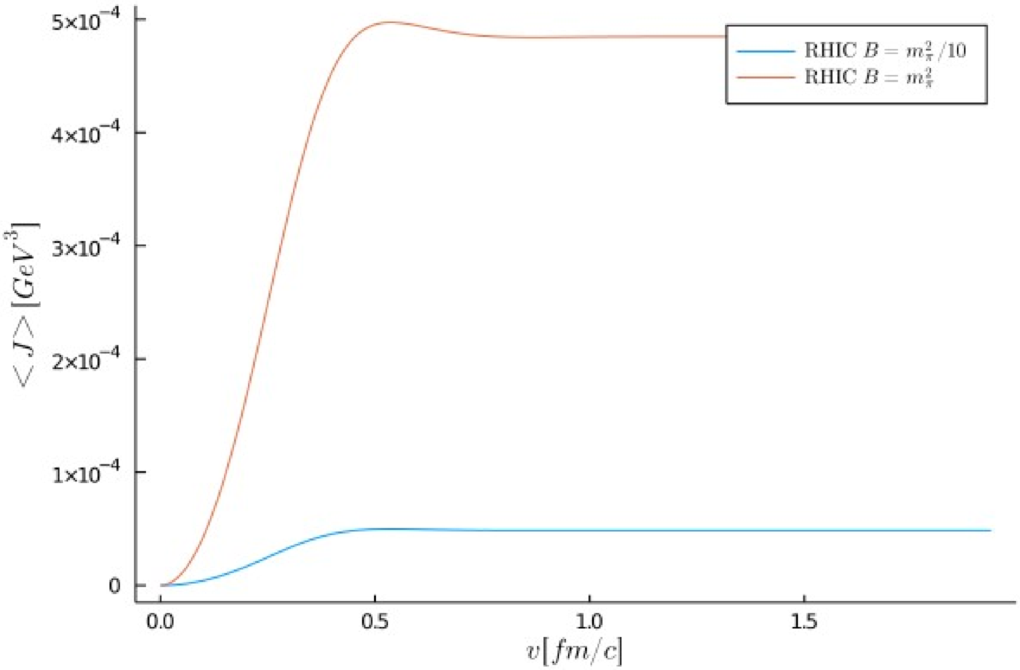
Holography

Physical parameters:

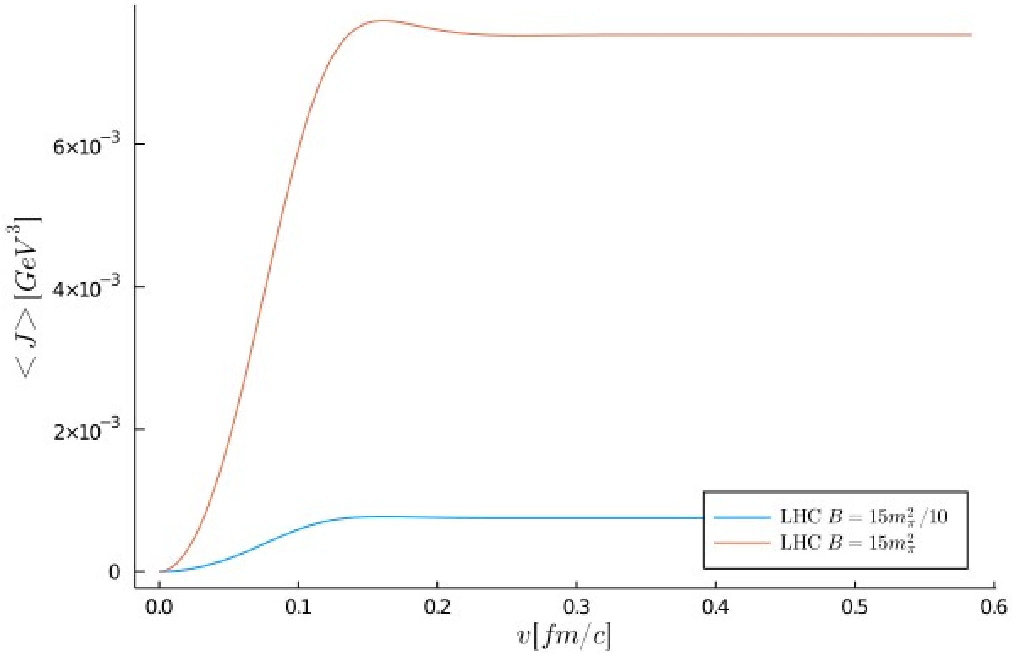
	"RHIC"	"LHC"
T	300MeV	1000MeV
μ_5	10 (100) MeV	10 (100) MeV
B	1 (0.1) m_π^2	15 (1.5) m_π^2

Holography

CME current



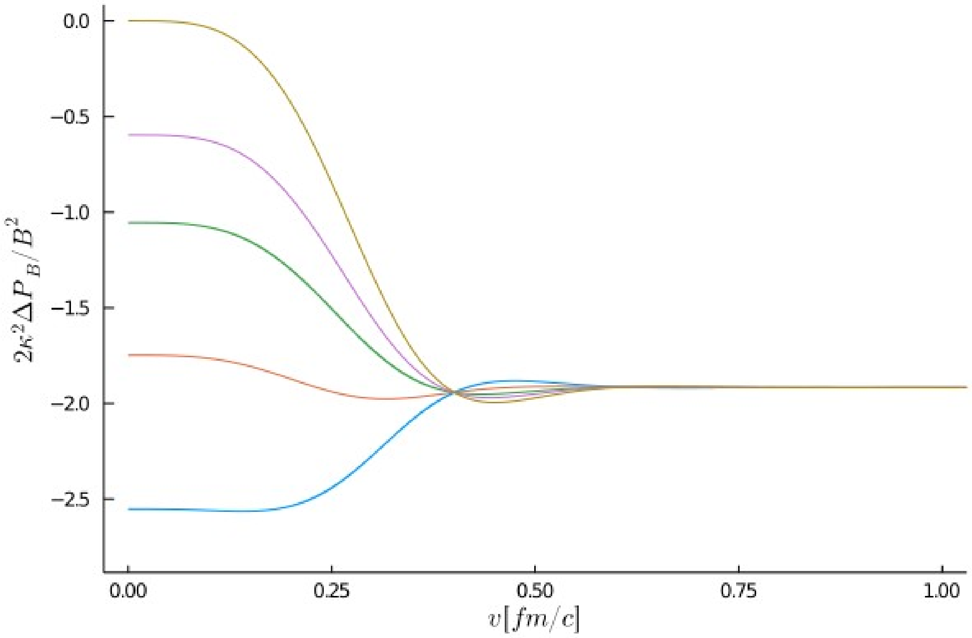
RHIC



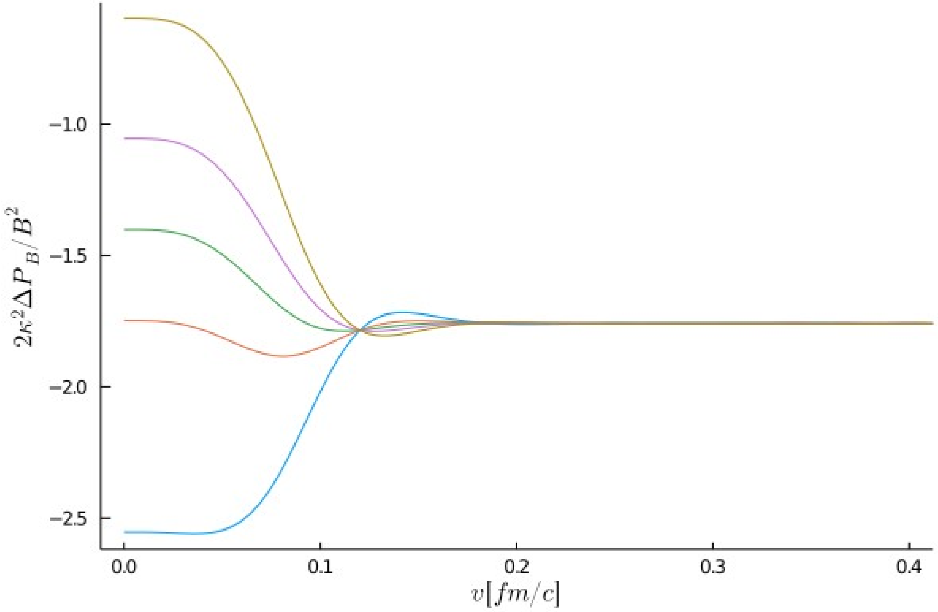
LHC

Holography

Pressure anisotropy (large B)



RHIC



LHC

$$2\kappa^2 \frac{\Delta P_B}{B^2} = 12\,\frac{\xi_4(v)}{B^2} + \frac{1}{2}\,\log(BL^2) - \frac{1}{4}$$

$$4\kappa^2 \frac{\epsilon_B}{B^2} = 6\,\frac{f_2}{B^2} - \frac{1}{2}\log(BL^2)$$

Holography

- No oscillations !
- Equilibration time: within 10% of final value [Chesler, Yaffe]

RHIC $B = m_\pi^2$					
δP_i	-2.55	-1.75	-1.05	-0.60	0.00
$v_{\mathrm{eq}}^{\langle J\rangle}$ in [fm/c]	0.380	0.380	0.380	0.380	0.380
$v_{\mathrm{eq}}^{\langle \Delta P\rangle}$ in [fm/c]	0.383	0.418	0.334	0.344	0.350

RHIC $B = 0.1 m_\pi^2$					
δP_i	-3.70	-2.90	-2.55	-2.21	-1.75
$v_{\mathrm{eq}}^{\langle J\rangle}$ in [fm/c]	0.380	0.380	0.380	0.380	0.380
$v_{\mathrm{eq}}^{\langle \Delta P\rangle}$ in [fm/c]	0.383	0.418	0.310	0.334	0.344

LHC $B = 15\, m_\pi^2$					
δP_i	-2.55	-1.75	-1.40	-1.05	-0.60
$v_{\mathrm{eq}}^{\langle J\rangle}$ in [fm/c]	0.114	0.114	0.114	0.114	0.114
$v_{\mathrm{eq}}^{\langle \Delta P\rangle}$ in [fm/c]	0.114	0.187	0.085	0.098	0.103

LHC $B = 1.5\, m_\pi^2$					
δP_i	-3.70	-2.90	-2.55	-2.21	-1.75
$v_{\mathrm{eq}}^{\langle J\rangle}$ in [fm/c]	0.114	0.114	0.114	0.114	0.114
$v_{\mathrm{eq}}^{\langle \Delta P\rangle}$ in [fm/c]	0.114	0.187	0.085	0.098	0.103

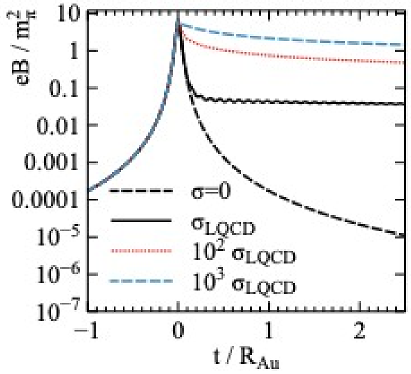
Compare to

- Without anomaly [Chesler, Yaffe]: τ ~0.5 fm/c
- Experimental estimate [U. Heinz]: τ~0.3 fm/c

Holography

Lifetime of magnetic field

- Highly uncertain
- Rapid decay in vacuum
- Medium effects can prolong lifetime considerably
- Many different estimates in literature



[McLerran, Skokov]] Nucl.Phys.A 929 (2014) 184

Latest available estimate: [Guo, Feng, Liao, Shi] Phys.Lett.B 798 (2019) 134929

$$\tau_B = \frac{117}{\sqrt{s}} GeV\, fm/c$$

$\tau_B^{RHIC} \approx 0.6 fm/c$ ✓ $\tau_B^{LHC} \approx 0.02 fm/c$ ✗

Summary and Outlook

- ***Holography allows to address important issues for CME@HIC***
- ***Even simple models give interesting results***
- ***Indicates that***
  - ***CME@LHC is not effective***
  - ***CME@RHIC is save***
- ***Many model improvements are possible***

(Dynamical B-field, expanding plasma, finite axial lifetime, …)

↑

C. Cartwright's talk on Friday

THANKS!