Is the Chiral Magnetic Effect fast enough ?

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2105.05855 [hep-ph], Phys. Rev. D. nnnnn

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

Holotube, 13 July, 2021

Outline

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

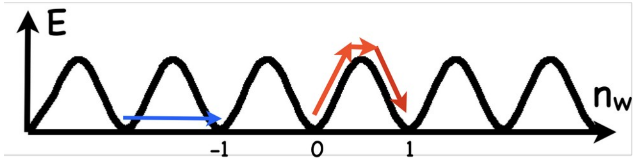
CME @ HIC

(Brookhaven Lab Youtube channel)

Video link: Hot Quark Soup at RHIC

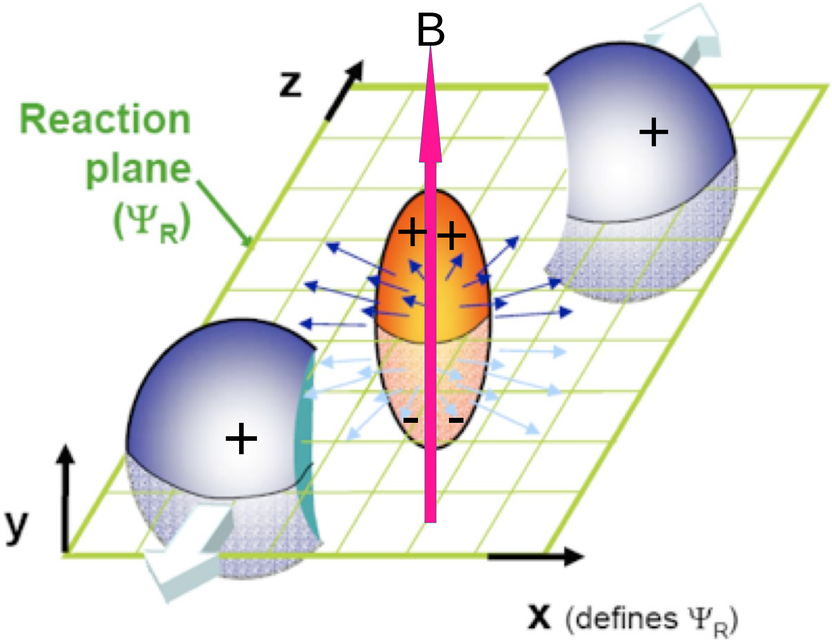
CME @ HIC

Quark Gluon Plasma:



$$\partial_\mu J^\mu_A = \frac{N_f}{32\pi^2}\epsilon^{\mu\nu\rho\lambda}G^a_{\mu\nu}G^a_{\rho\lambda}$$

QCD out of equilibrium topological gluon field configurations



QCD axial anomaly induces Q_5

Spectators induce strong magnetic field

CME leads to charge separation

Strong non-equilibrium physics

[Kharzeev, McLarren, Warringa]

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]

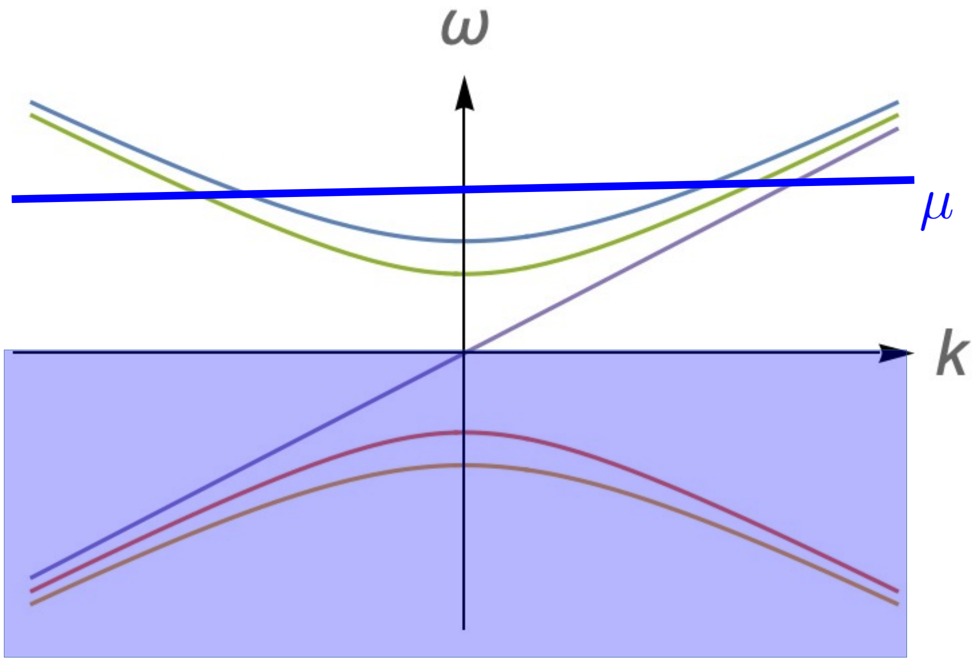
[Vilenkin] 1980,
[Alekseev,Chaianov, Fröhlich]
[Giovaninni, Shaposhnikov],...

Equilibrium quantity, not the chiral charge !

Lifetime!

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:

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

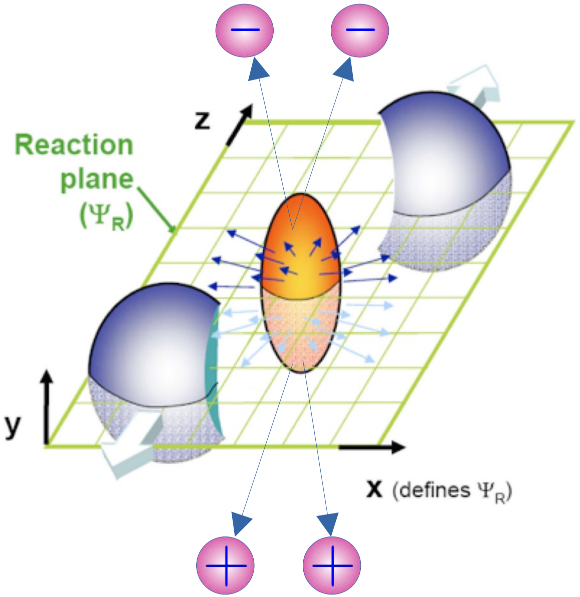
CME current stems from LLL only

CME @ HIC

How to measure CME?

$$\frac{dN}{Nd\phi} = 1 + 2v_1 \cos(\phi - \psi_{RP}) + 2v_2 \cos(2(\phi - \psi_{RP})) + 2a_{\pm} \sin(\phi - \psi_{RP}) + \dots$$

P-odd CME $a_+ = -a_-$



CME signal averages out to zero over many collisions: $\langle a_{\pm} \rangle = 0$

Way out: “γ-correlator” $\gamma_{\alpha\beta} = \langle a_\alpha a_\beta \rangle$ – some background P-even

$$\gamma_{\alpha\beta} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle$$

CME @ HIC

“same sign” vs. “opposite sign”   CME signal

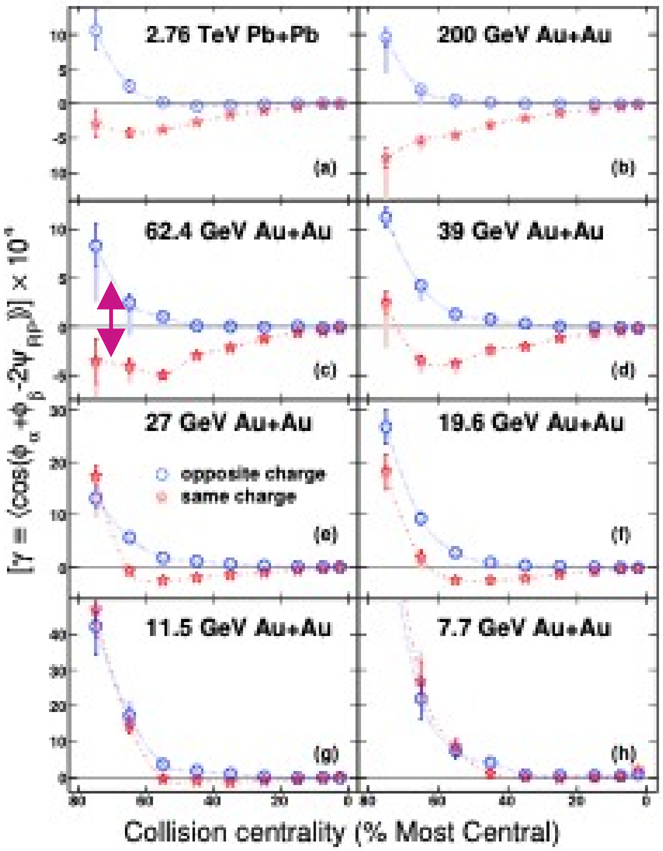
γ_{SS} γ_{OS}

But to soon to declare victory: signal is contaminated by significant backgrounds:

- “Local charge conservation”
- “Transverse momentum conservation”
- “Cluster decay”
- Signal present in p-A collisions

[Star Collaboration] Phys.Rev.Lett. 113 (2014) 052302

[Kharzeev, Liao, Voloshin, Wang] Prog.Part.Nucl.Phys. 88 (2016)

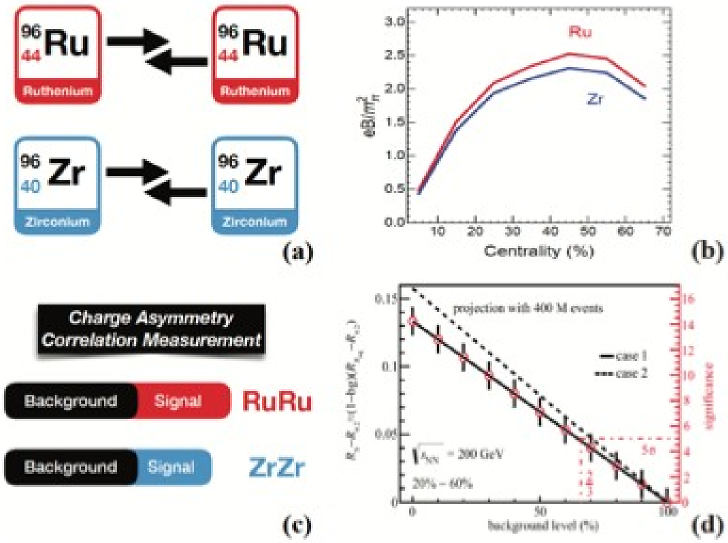


CME @ HIC

Huge effort to get experimental grip on CME: new methods (“event shape engeneering”), new improved correlators, ...

Most important: Isobar run @ RHIC in 2018

Expect ~20% higher CME signal in Ru



Isobar Collisions at RHIC to Test Local Parity Violation in Strong Interactions

D. E. Kharzeev & J. Liao

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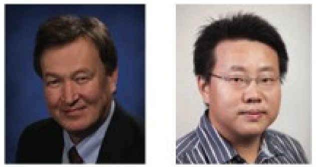
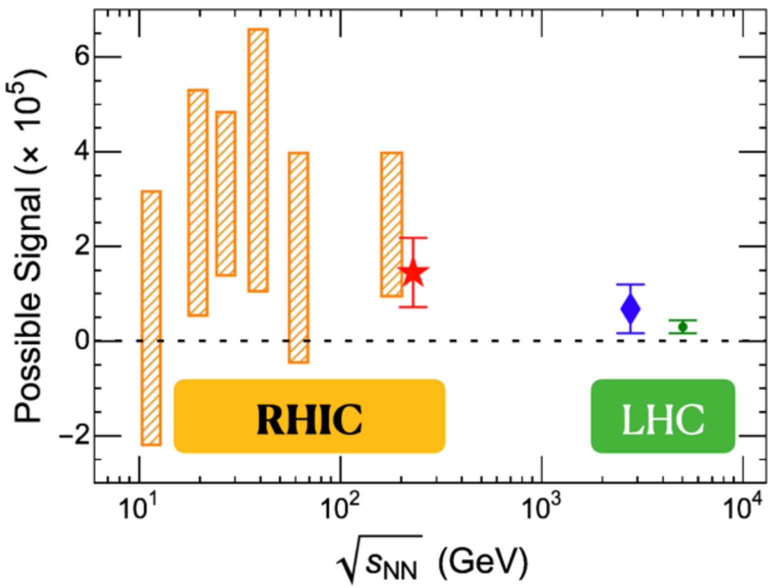


D. E. KHARZEEV J. LIAO

Results expected to be (finally) out this year!

CME @ HIC



[Kharzeev, Liao]
Nature Reviews 3, pp.55–63 (2021)

“The data in panel b was compiled by the authors based on the experimental results published in Refs. [65,66,71,78,79], comprising different centrality ranges and with various background assumptions. “

“Caution must be taken as these extractions are often subject to model assumptions and/or poorly controlled systematic uncertainties. Nevertheless, these experimental results, although far from being conclusive, are strongly suggestive of a detectable CME signal, especially in the RHIC energy region”

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

II. 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

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

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

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

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

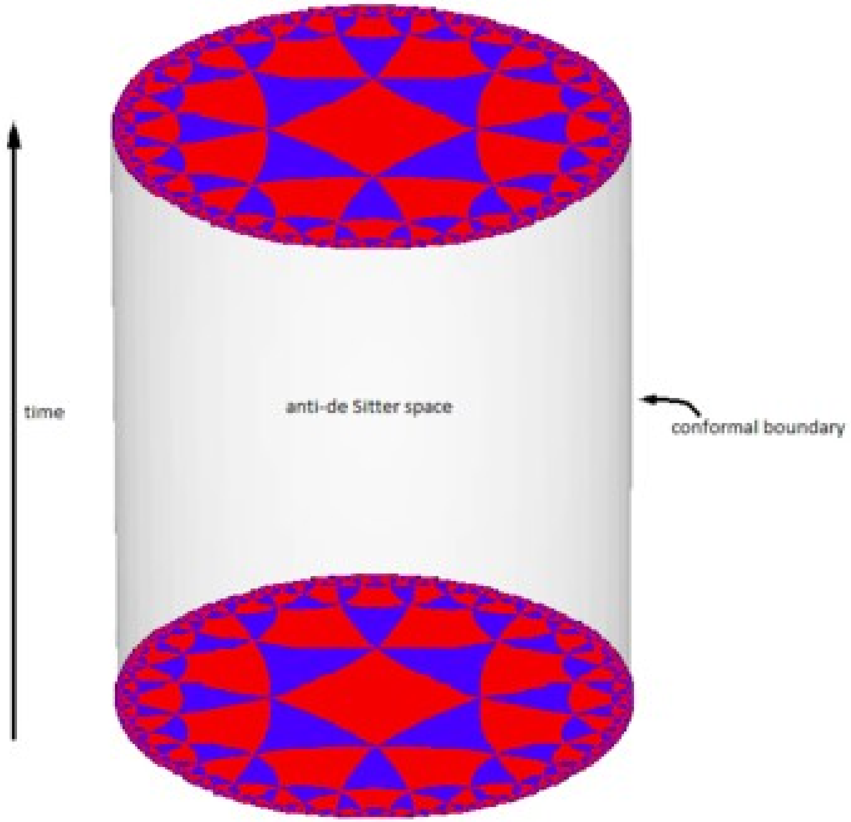
Equilibration, isotropisation times: $\tau \approx 0.5 fm/c$ [Chesler, Yaffe]

[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]

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

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

Ansatz:

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

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

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:

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

Holography

Initial state:

- Static, non-expanding, infinite plasma
- Chiral charge density uniform and constant in time
- Magnetic field is uniform and constant in time
- Energy density 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

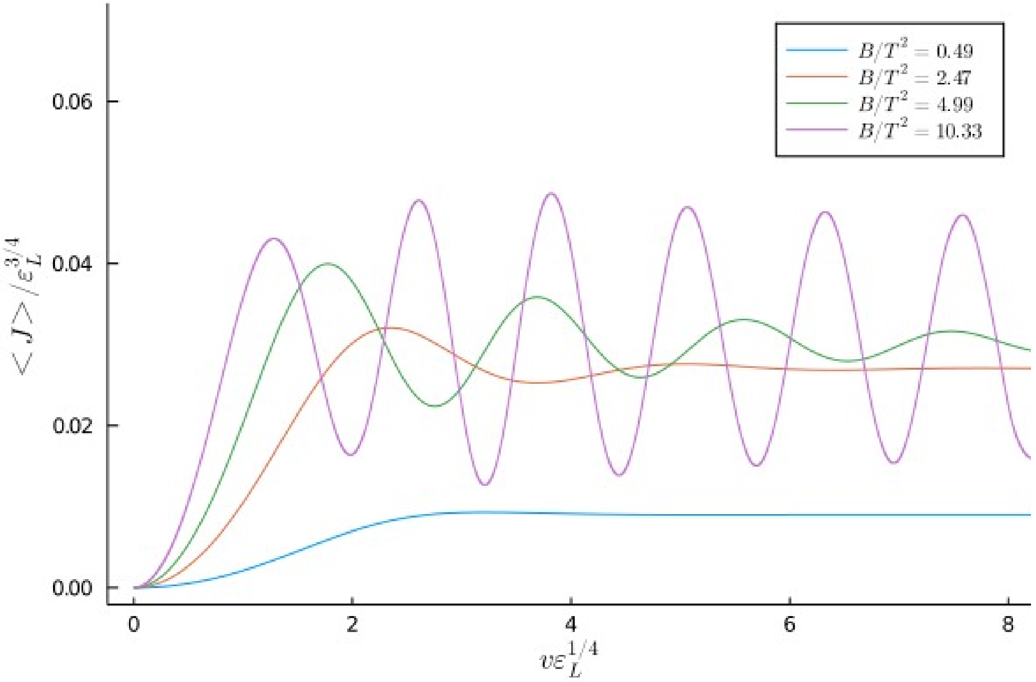
Renormalization scale:

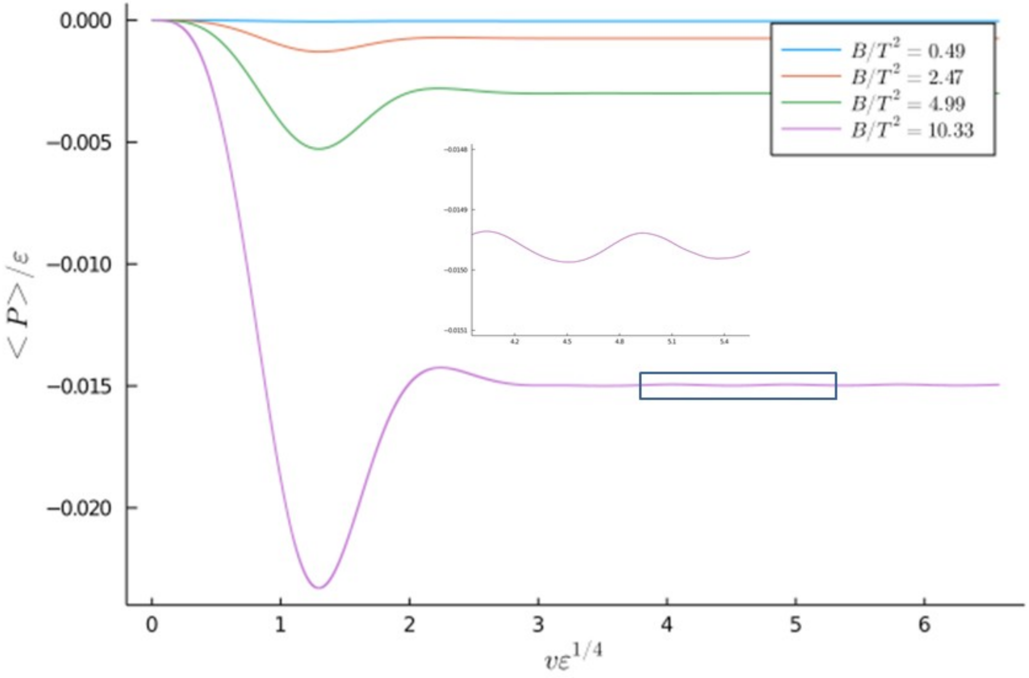
- Numerics $\mu = 1/L$
- Physics $\mu = \sqrt{B}$

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

Holography

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



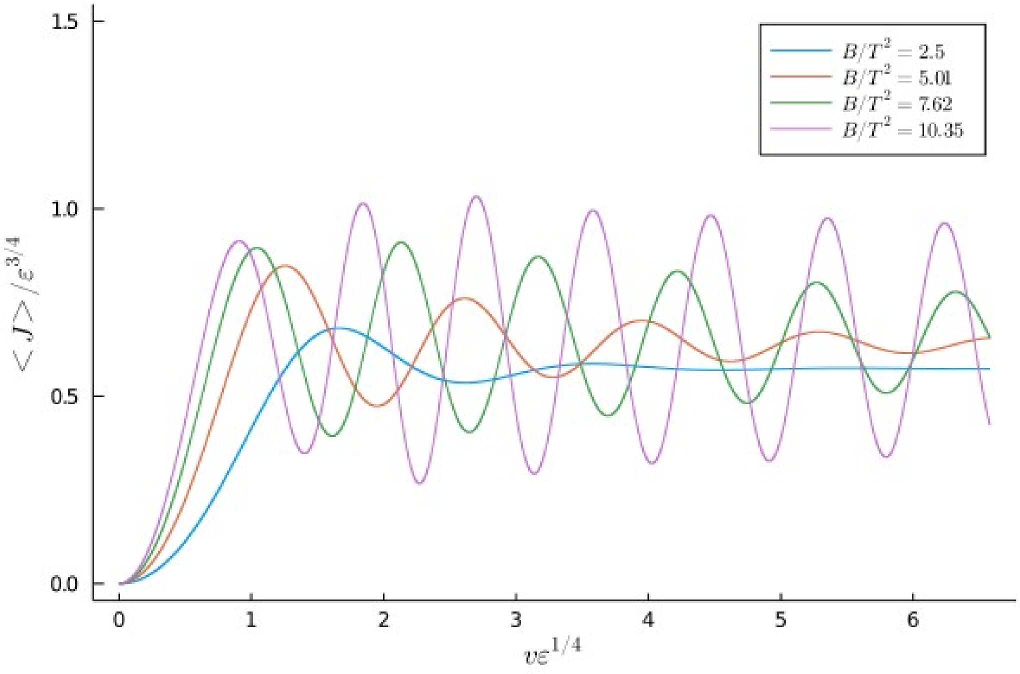


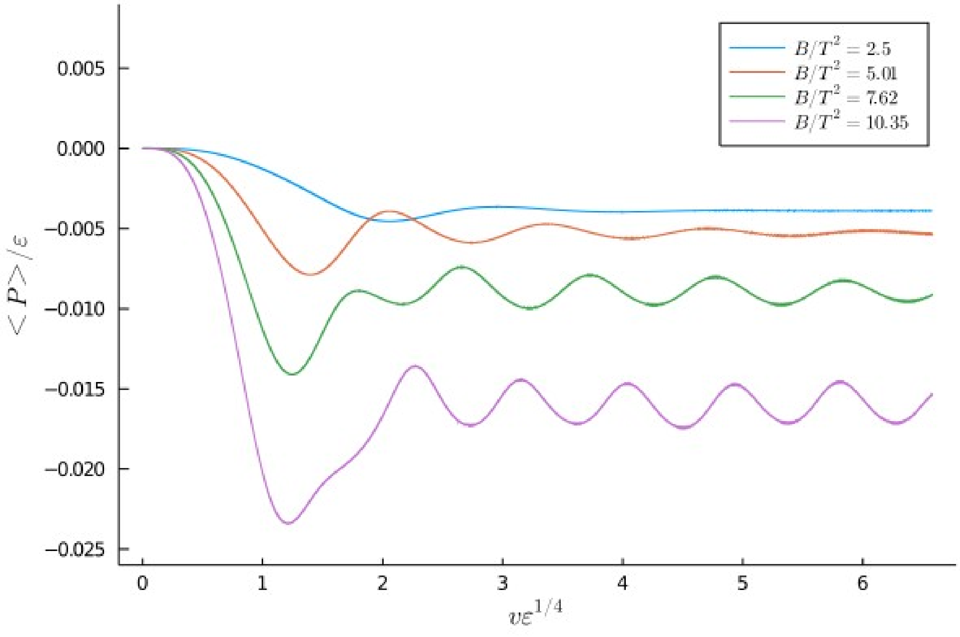
Current

Pressure anisotropy

Holography

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





Current

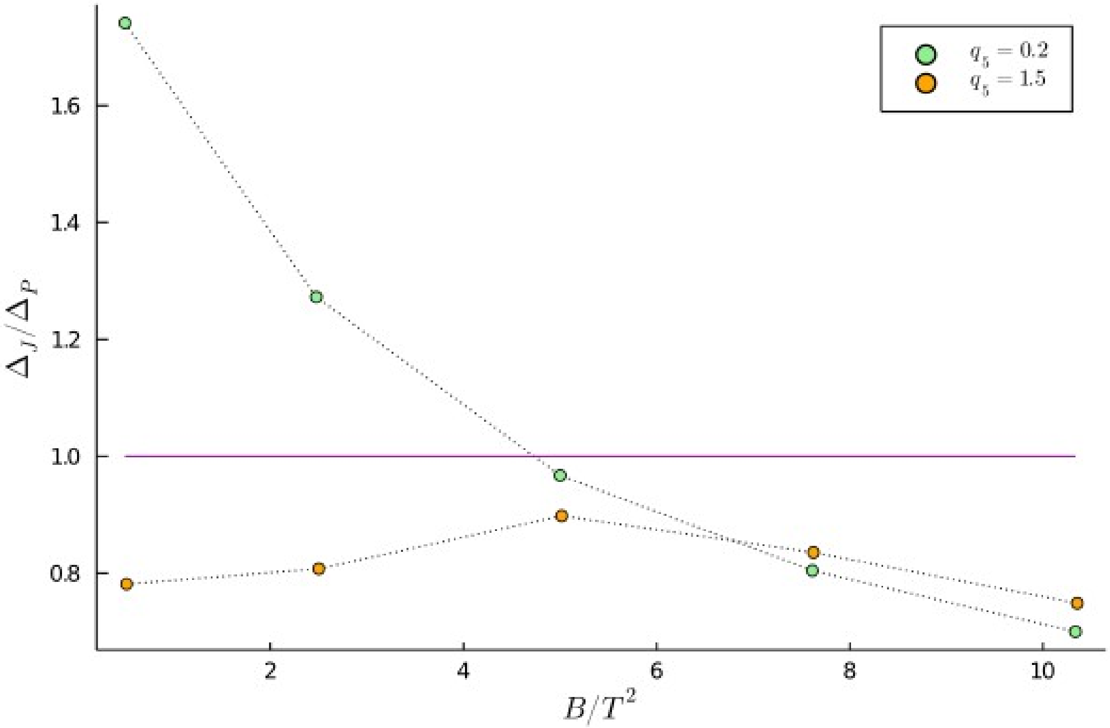
Pressure anisotropy

Holography

- Almost undamped oscillations
- QNMs near the real axis [Ammon, Grieninger, Jimenez-Alba, Malcedo, Melgar]
- Equilibration much delayed
- Define build up time to first maximum
- Observation: fast for large magnetic field
- Large magnetic field: lowest Landau Level
- 2D physics ! $J_5^\mu = \epsilon^{\mu\nu} J_\nu$
- Operator relation
- 4D “delay” becomes shorter as B field grows

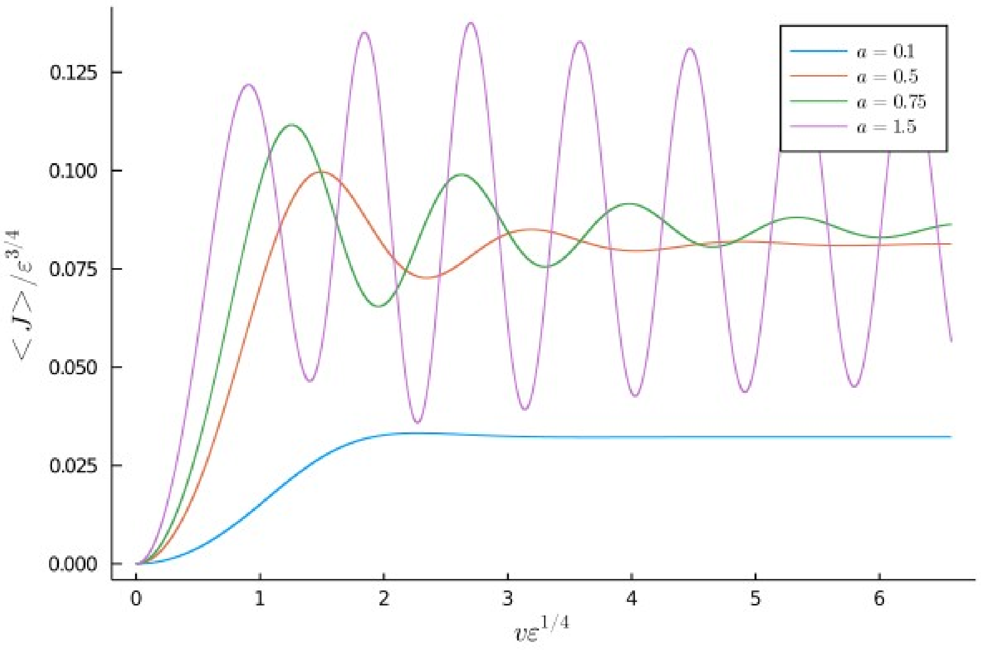
Holography

Who is faster: Pressure or CME?

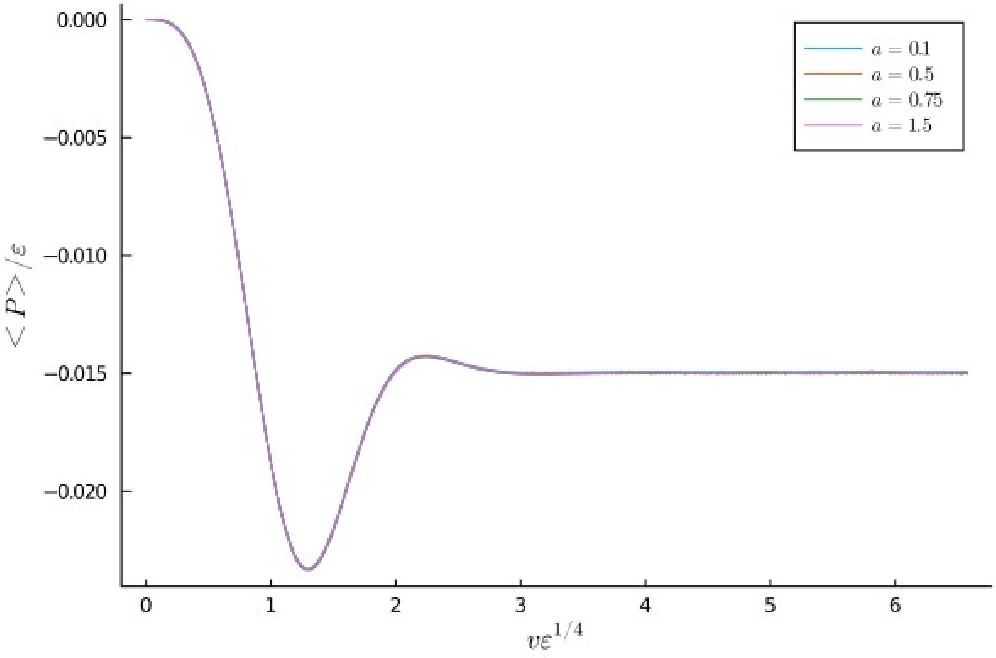


Holography

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



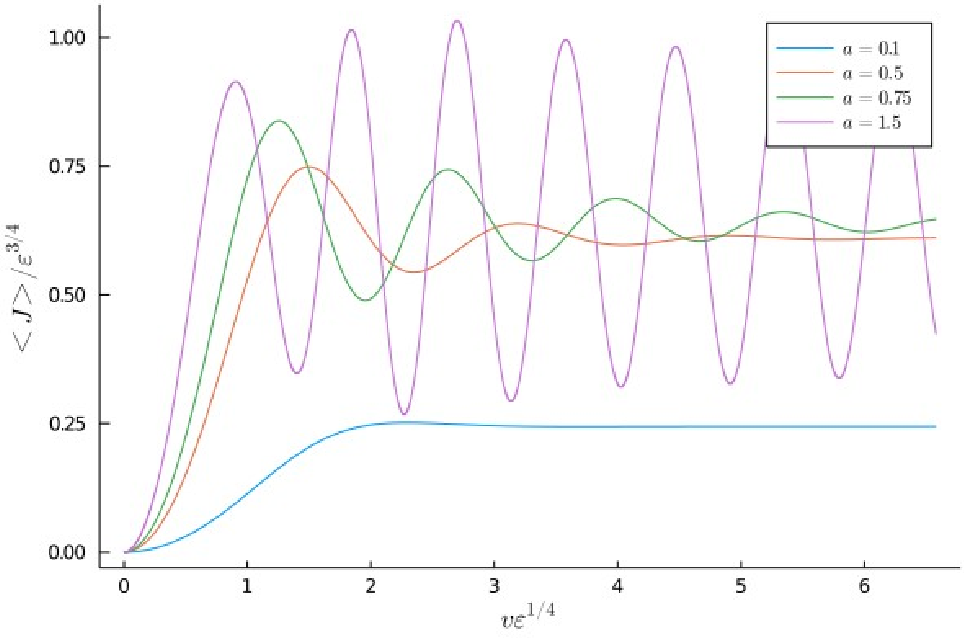
Current

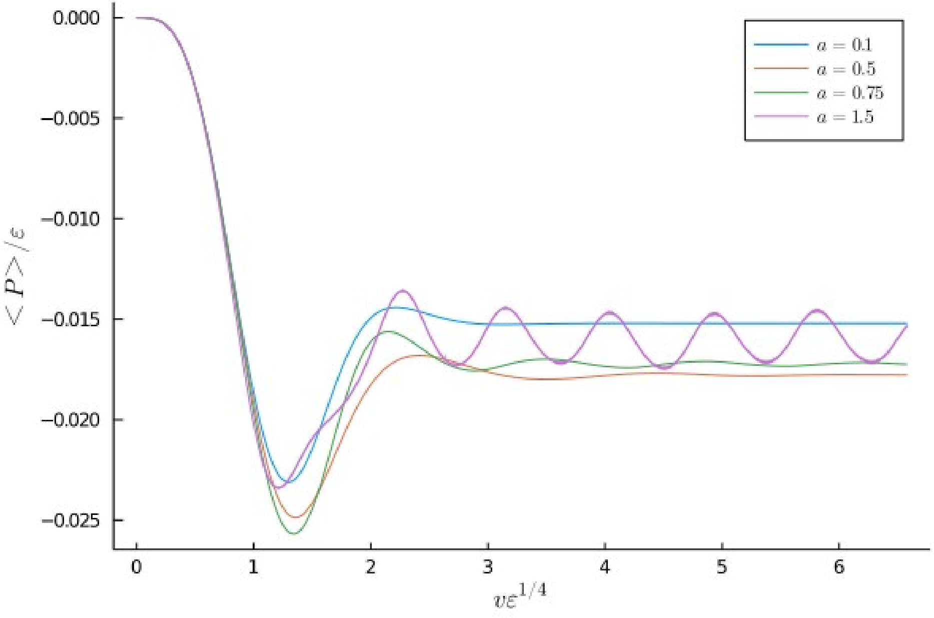


Pressure anisotropy

Holography

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



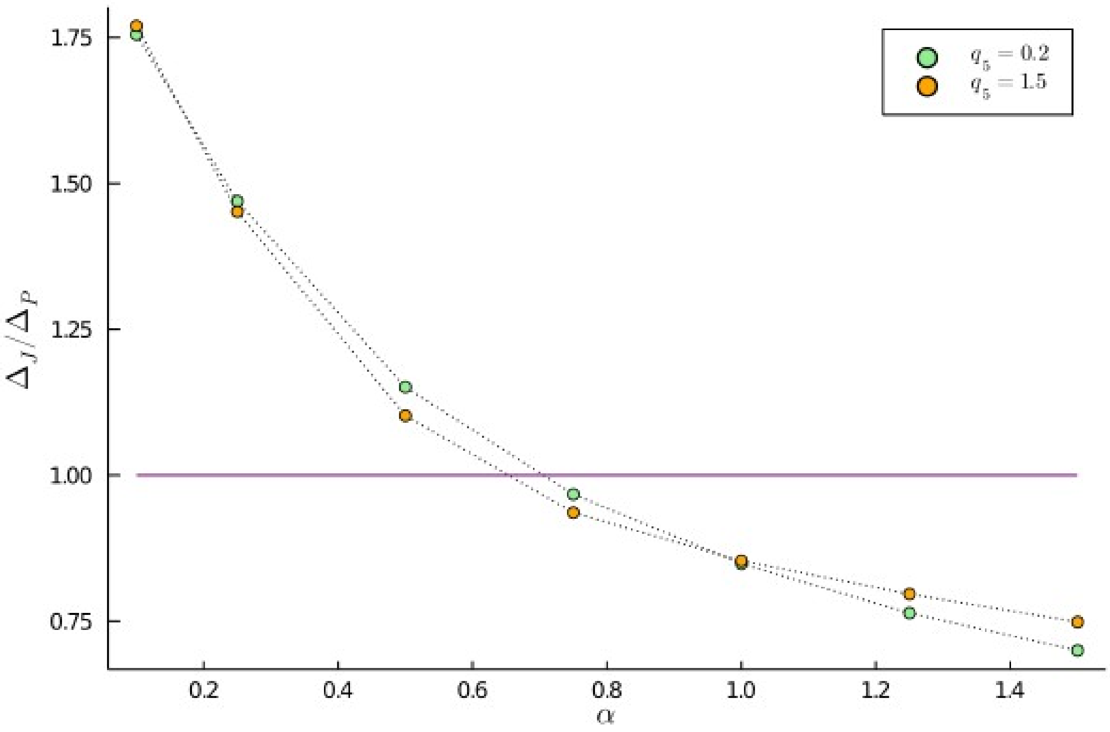


Current

Pressure anisotropy

Holography

Who is faster: Pressure or CME?



Holography

Trying to connect to the real world (aka wading knee-deep in the swampland...)

➔ Gravitational coupling: match to entropy

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

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

➔ Chern Simons coupling: match to anomaly

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

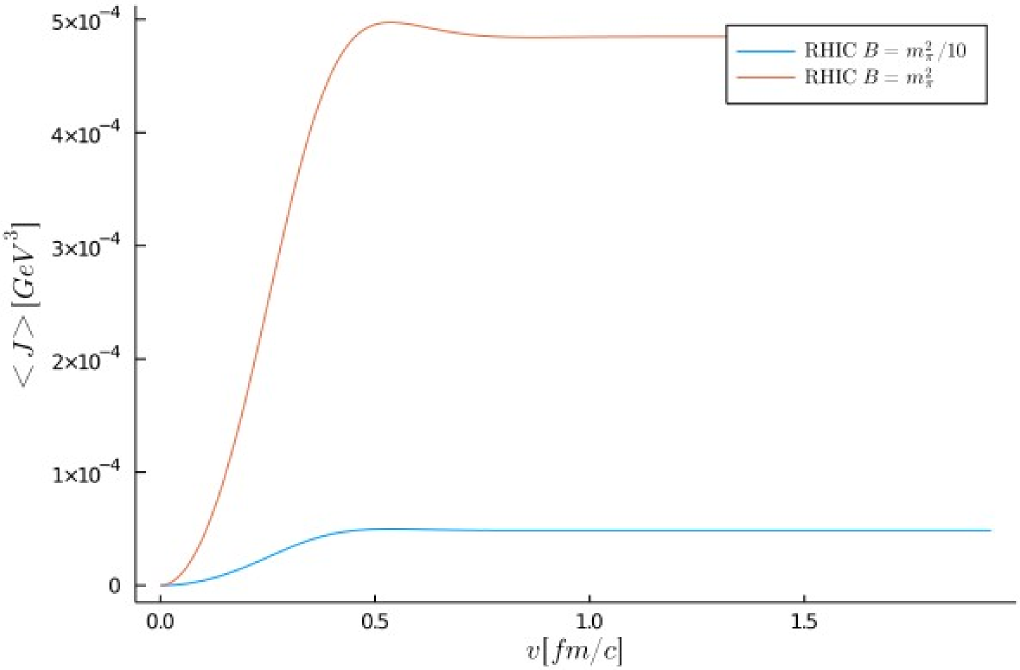
Holography

Physical parameters:

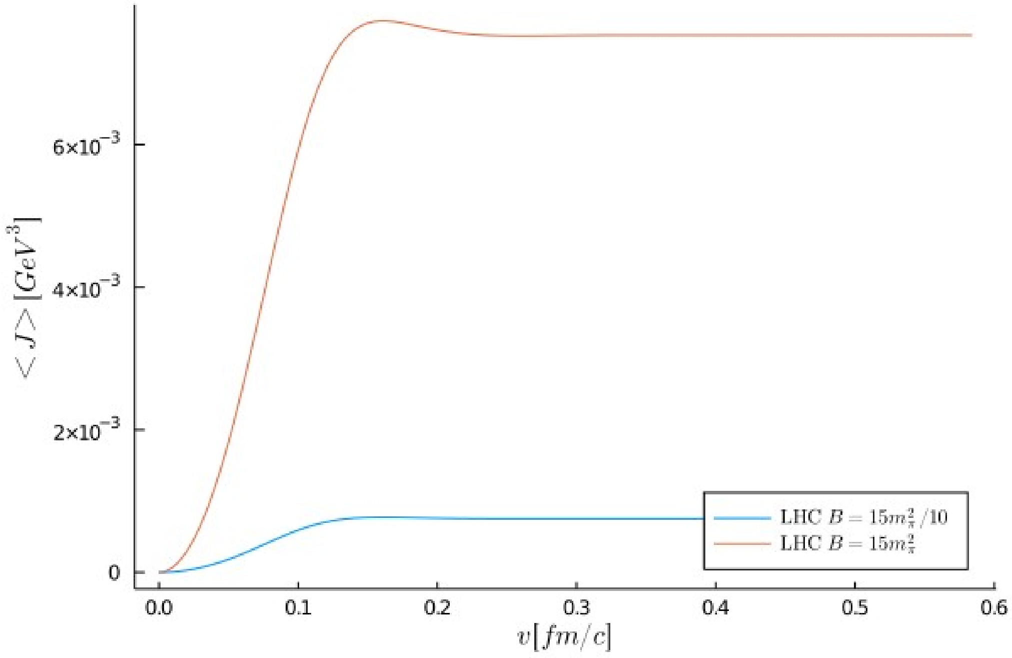
	RHIC	LHC
T	300MeV	1000MeV
μ_5	10 (100) MeV	10 (100) MeV
B	1 (0.1) m_π^2	15 (1.5) m_π^2

Holography

CME current



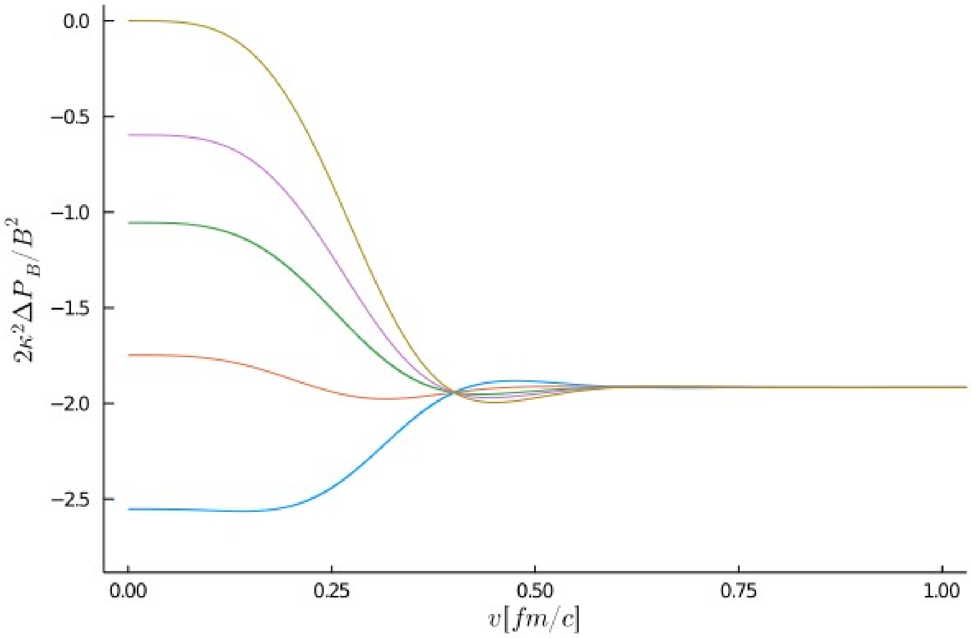
RHIC



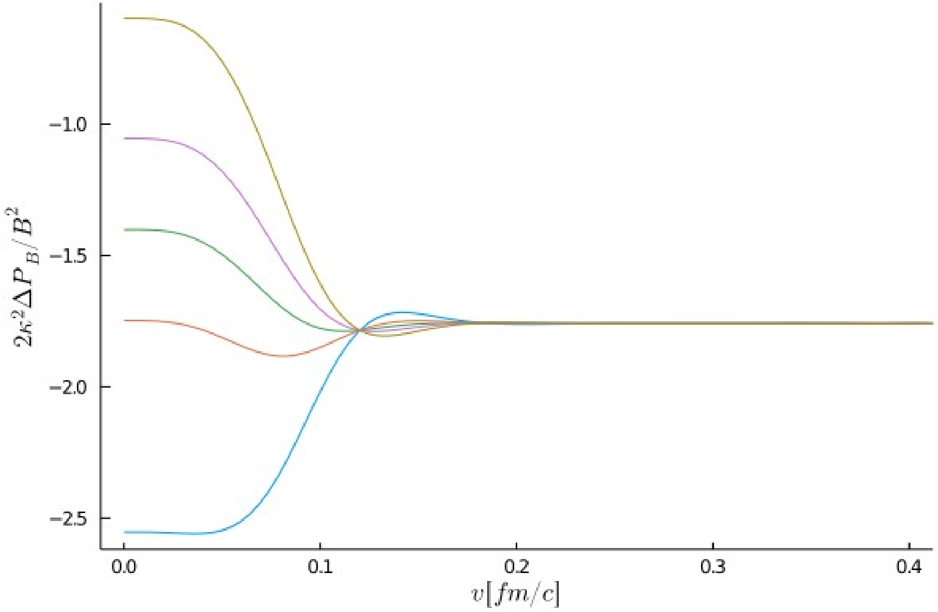
LHC

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
$v_{\rm eq}^{\langle J \rangle}$ in [fm/c]	0.380	0.380	0.380	0.380	0.380
$v_{\rm eq}^{\langle \Delta P \rangle}$ 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
$v_{\rm eq}^{\langle J \rangle}$ in [fm/c]	0.380	0.380	0.380	0.380	0.380
$v_{\rm eq}^{\langle \Delta P \rangle}$ in [fm/c]	0.383	0.418	0.310	0.334	0.344

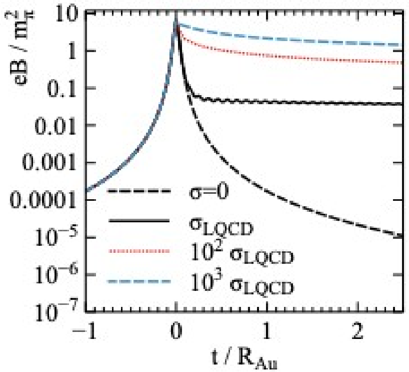
LHC $B = 15\, m_\pi^2$					
δP_i	-2.55	-1.75	-1.40	-1.05	-0.60
$v_{\rm eq}^{\langle J \rangle}$ in [fm/c]	0.114	0.114	0.114	0.114	0.114
$v_{\rm eq}^{\langle \Delta P \rangle}$ in [fm/c]	0.114	0.187	0.085	0.098	0.103
LHC $B = 1.5\, m_\pi^2$					
δP_i	-3.70	-2.90	-2.55	-2.21	-1.75
$v_{\rm eq}^{\langle J \rangle}$ in [fm/c]	0.114	0.114	0.114	0.114	0.114
$v_{\rm eq}^{\langle \Delta P \rangle}$ 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

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

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

Summary and Outlook

- ***Holography allows to address important issues for CME@HIC***
- ***Even simple models give interesting results***
- ***Compatibility with experimental trend***
- ***Many model improvements are possible***
- ***Dynamical B-field, expanding plasma, finite axial lifetime, …***
- ***Despite near future experimental prospect, little activity in community***
- ***Call for concerted effort? Needs more dialogue with Nucl-Phys community?***

THANKS!