New effects in quark-gluon plasma: gravity and quantum anomalies

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“Particle physics at medium and high energies”,
Russia, Protvino,
June 2-5, 2026

based on works:

[GP, O. Teryaev, V. Zakharov, PRL, (2022)]
[GP, O. Teryaev, V. Zakharov, Phys. Lett. B, 840, (2023)]
[D. Lapygin, GP, O. Teryaev, V. Zakharov, PRD 112 (2025)]
[GP, 2601.02083 (2026)]
[GP, O. Teryaev, 2604.04222 (2026)]

Contents

- **Introduction:**

  Anomalous effects – theory and experiment, polarization.

- **Kinematical Vortical Effect:**

  "Cheshire cat's grin" of gravitational chiral anomaly in vortical and accelerated fluid.

- **Entanglement viscosity:**

  Viscosity in accelerated fluid and Kovtun-Son-Starinets bound.

- Conclusion

Part 1

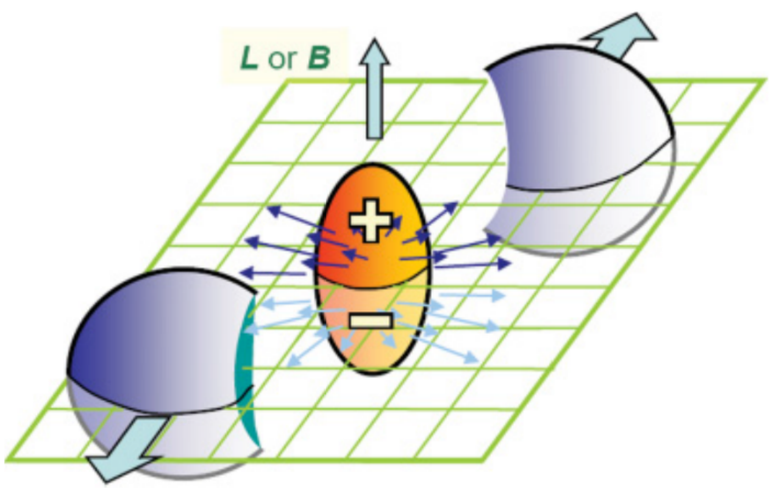
Introduction

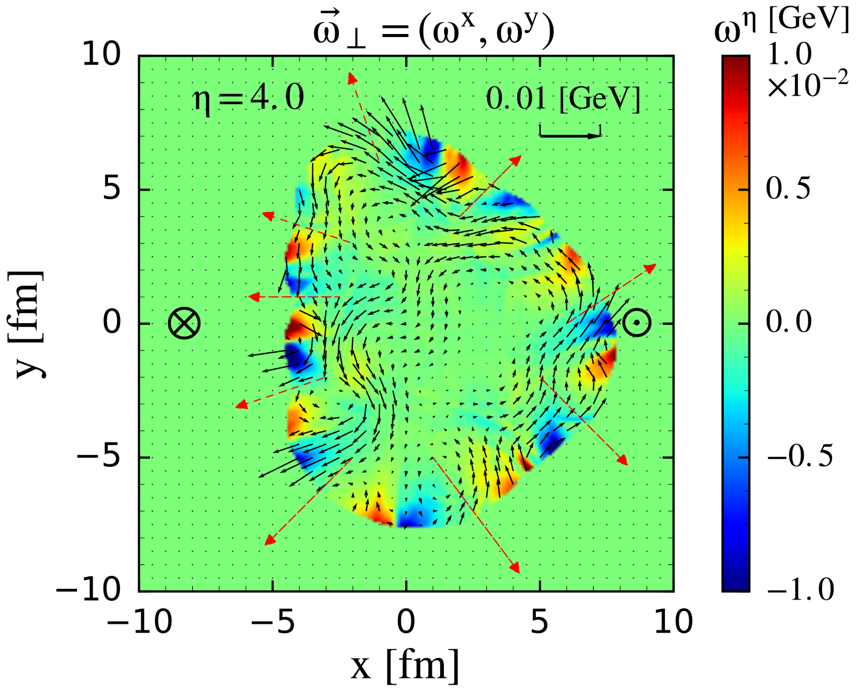
Vorticity and magnetic field in heavy ion collisions

In non-central collisions of heavy ions, huge magnetic fields and huge angular momentum arise. Differential rotation - different at different points: **vorticity** and **vortices**.

– Rotation 25 orders of magnitude faster, than the rotation of the earth:

– The vorticity has order 10^{22} sec^{-1}





[Phys. Rev. Lett. 117, 192301 (2016)]

Chiral effects: CME and CVE

Novel quantum-field effects in relativistic **fluid:**

[V. I. Zakharov, Lect. Notes Phys.871,295(2013), 1210.2186]

- Chiral Magnetic Effect **(CME)**:

[K. Fukushima, D. E. Kharzeev, H. J. Warringa, PRD 78, 074033 (2008), 0808.3382]

$$\langle \hat{j}^{\mu} \rangle = C e^2 \mu_A B^{\mu}$$

- Chiral Vortical Effect **(CVE)**:

[D. T. Son, P. Surowka, PRL 103, 191601 (2009), 0906.5044]

$$\langle \hat{j}^{\mu}_A \rangle = C(\mu^2 + \mu_A^2)\omega^{\mu}$$

Associated with **axial anomaly** in the electromagnetic field:

$$\langle \partial_\mu \hat{j}^{\mu}_A \rangle = -\frac{Ce^2}{8} \varepsilon^{\mu\nu\alpha\beta} F_{\mu\nu} F_{\alpha\beta}$$

Huge magnetic field and **vorticity** in heavy-ion collisions

⇓

Chiral effects can be potentially **observed** in collider experiments

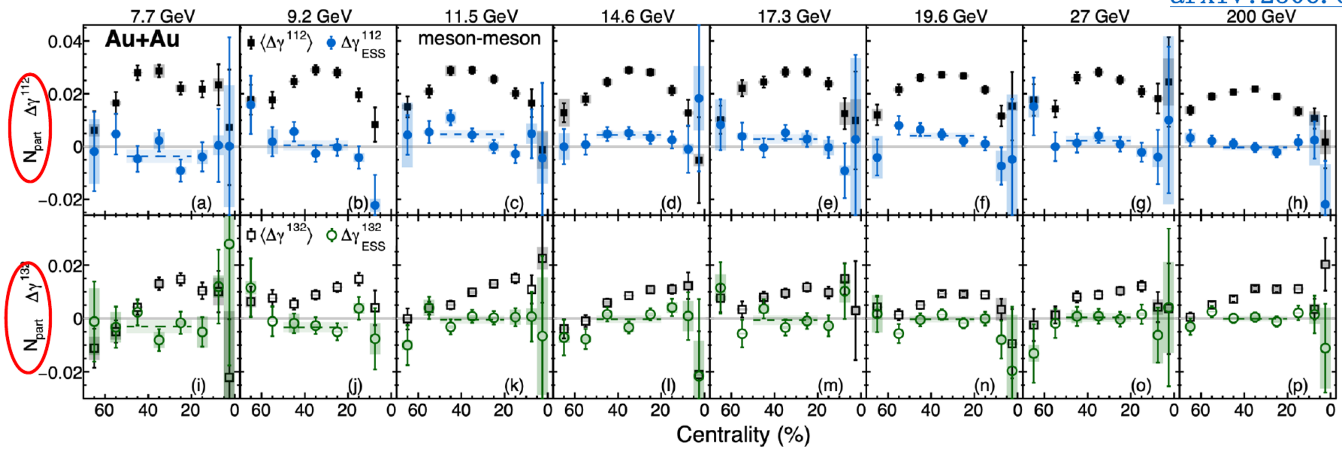
CME search: recent results from CHIRALITY (Brasil, July 2025)

Optimistic results:

(talk of Huan Zhong Huang, University of California Los Angeles)

Beam Energy Scan II - Event Shape Selection

arXiv:2506.00275



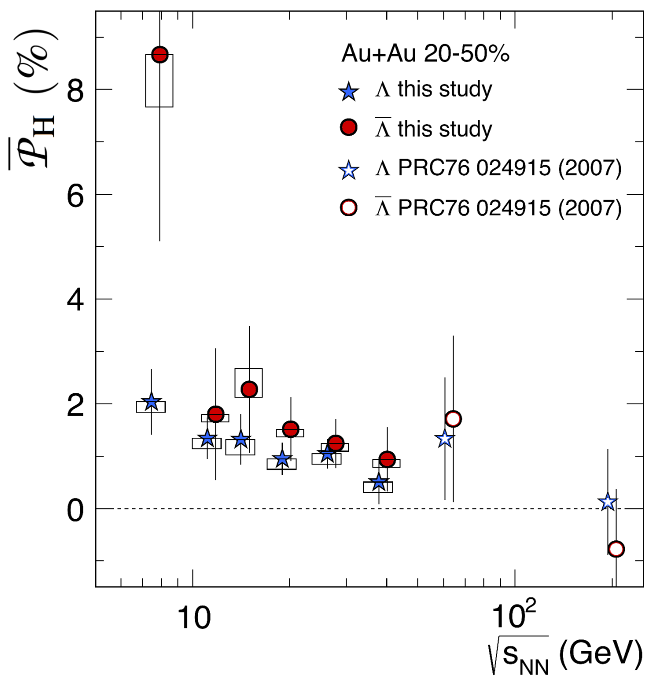
- Charge separation signal after applying ESS:
  - At 200 GeV, using ZDC-SMD planes, no signal is observed.
  - At 19.6, 14.6 and 11.5 GeV, a finite charge separation (around 3σ) in the 20-50% centrality.
  - At 9.2 and 7.7 GeV, data favor the zero-CME scenario.
- Background indicator after ESS is consistent with zero at all energies.

Chirality 13 Huan Huang, UCLA

web: https://www.ictp-saifr.org/wp-content/uploads/2025/07/02-Huan-Zhong-Huang.pdf

Vorticity and polarization

Rotation transforms into **polarization** - an analogue of the Barnett effect.



[Nature 548 (2017) 62-65 arXiv:1701.06657 [nucl-ex]]

STAR Collaboration

- Generation of **hyperon polarization**.
- Can be explained via relationship with vorticity within various approaches.
- Based on **Chiral Vortical Effect (CVE)** – Dubna group

[Rogachevsky, Sorin, Teryaev, Phys.Rev.C82 (2010) 054910]

CVE: $$\langle j^5_\mu \rangle = \left(\frac{T^2}{6} + \frac{\mu^2}{2\pi^2} \right) \omega_\mu$$

similar to proton spin:

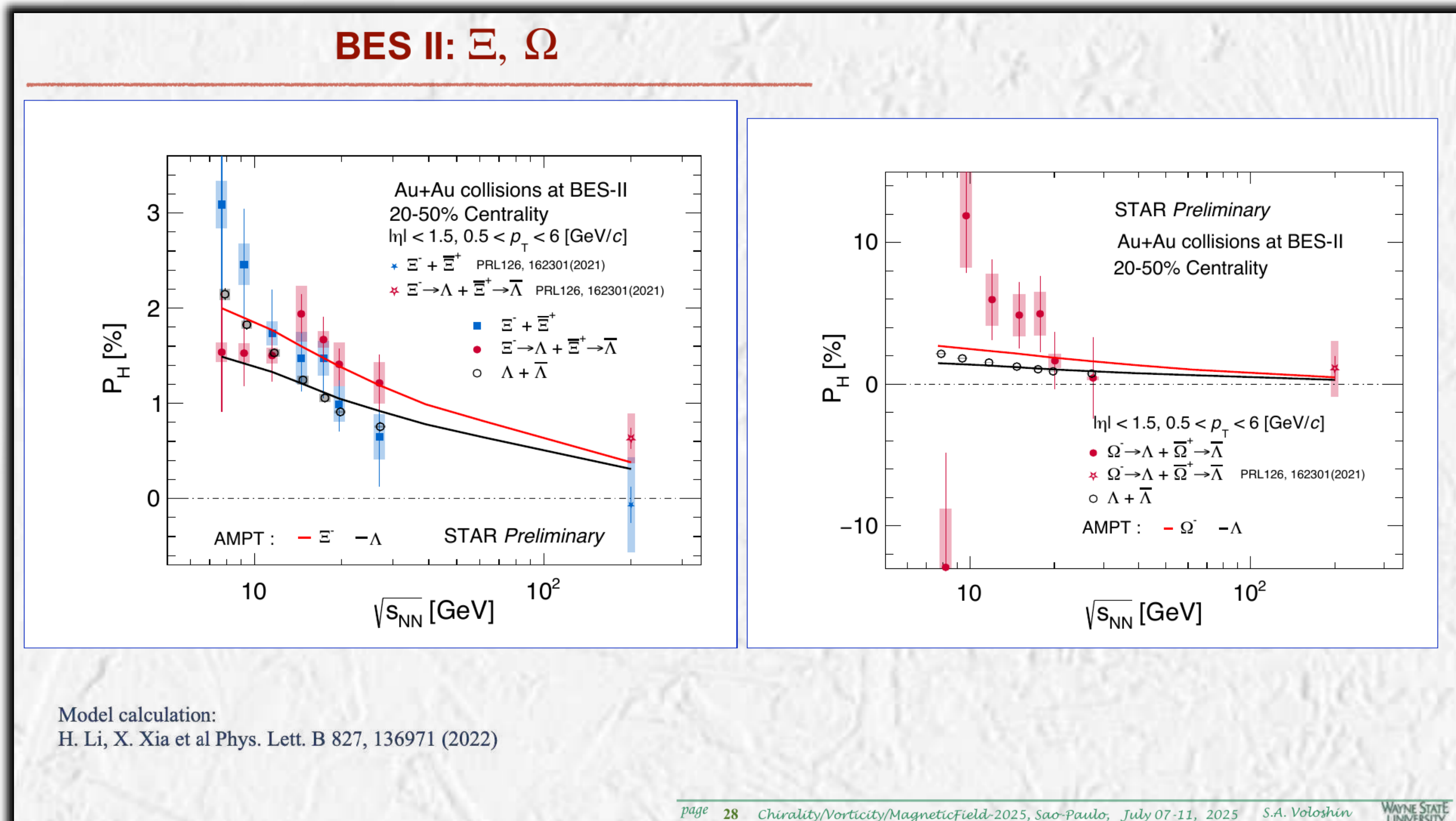
[Efremov, Soffer, Teryaev, Nucl.Phys.B 346 (1990) 97-114]

proton spin → hyperon polarization,
gluon field → chemical potential*4-velocity

Vorticity and polarization: recent results from CHIRALITY (Brasil, July 2025)

Big polarization for **higher spins:**

(talk of Sergei A. Voloshin, Wayne State University)



web: https://www.ictp-saifr.org/wp-content/uploads/2025/07/02-Sergei-Voloshin.pdf

Part 2

Kinematical Vortical Effect

[GP, O. Teryaev, V. Zakharov, PRL, 129(15):151601, (2022)]

[GP, Teryaev, O. V., & Zakharov, V. I. (2023). Phys. Lett. B, 840]

[Khakimov R. V., GP, Teryaev O. V., Zakharov V. I. (2024), Phys. Rev. D, 109(10)]

Beyond CME/CVE: what about gravitational anomaly?

What about the **gravitational chiral anomaly**?

- The gravitational chiral anomaly grows **rapidly** with **spin**:

$$\langle \nabla_\mu \hat{j}^\mu_A \rangle_S = \frac{(S - 2S^3)}{96\pi^2 \sqrt{-g}} \varepsilon^{\mu\nu\rho\sigma} R_{\mu\nu\kappa\lambda} R_{\rho\sigma}{}^{\kappa\lambda}$$

[M. J. Duff, in First School on Supergravity (1982) arXiv:1201.0386]

Relationship with **temperature term** in CVE current:

[K. Landsteiner, E. Megias, and F. Pena-Benitez, Phys. Rev. Lett., 107:021601, (2011)]

Quantum anomaly: modification of hydrodynamics

- The gravitational chiral anomaly has the **4th order** in gradients – it is to be related to the **3rd order** terms in gradient expansion of the axial current.
- Hydrodynamic expansion of the axial current up to the **3rd order** in gradients:

Survive in flat spacetime

$$j_\mu^{A(3)} = \xi_1(T)w^2 w_\mu + \xi_2(T)\alpha^2 w_\mu + \xi_3(T)(\alpha w)w_\mu + \xi_4(T)A_{\mu\nu}w^\nu + \xi_5(T)B_{\mu\nu}\alpha^\nu$$

arbitrary coefficients

"gravitational" currents

Key moment: [D.T. Son, P. Surowka, PRL, 103 (2009) 191601]

Apply **quantum anomaly** as **modification** of **hydrodynamic** equation for current:

$$\nabla_\mu j_A^\mu = \mathcal{N}\,\epsilon^{\mu\nu\alpha\beta} R_{\mu\nu\lambda\rho} R_{\alpha\beta}{}^{\lambda\rho}$$

Novel effect: the Kinematical Vortical Effect (KVE)

- **Conservative** (anomalous) relation fixes **relationship** between **anomaly** and **transport** coefficients.

- Let's move on to the limit of **flat space-time**. Despite the absence of a gravitational field, there **remains a contribution** to the axial current induced by the **gravitational** chiral **anomaly**:

$$j^A_\mu = \lambda_1(\omega_\nu\omega^\nu)\omega_\mu + \lambda_2(a_\nu a^\nu)w_\mu \quad \Leftarrow \quad R_{\mu\nu\alpha\beta} = 0$$

Main result:

$$\boxed{\frac{\lambda_1 - \lambda_2}{32} = \mathcal{N}} \quad \Leftarrow \quad \nabla_\mu j^\mu_A = \mathcal{N}\epsilon^{\mu\nu\alpha\beta}R_{\mu\nu\lambda\rho}R_{\alpha\beta}{}^{\lambda\rho}$$

- A new type of anomalous transport – the **Kinematical Vortical Effect (KVE)**.

- Does not explicitly depend on temperature and density → determined only by the **kinematics** of the flow.

Direct check for spins 1/2 and 3/2

Spin 1/2

- **Axial current:** KVE

$$j^A_\mu = \left(\frac{T^2}{6} + \frac{\mu^2}{2\pi^2} - \frac{\omega^2}{24\pi^2} - \frac{a^2}{8\pi^2}\right)\omega_\mu$$

[GP, O.V. Teryaev, V.I. Zakharov, JHEP, 02:146, 2019],
[A. Vilenkin, PRD20:1807–1812, 1979]

- **Anomaly:**

[L. Alvarez-Gaume, E. Witten, Nucl. Phys., B234:269, 1984]

$$\nabla_\mu j^\mu_A = \frac{1}{384\pi^2\sqrt{-g}}\varepsilon^{\mu\nu\alpha\beta}R_{\mu\nu\lambda\rho}R_{\alpha\beta}{}^{\lambda\rho}$$

- **Hydro/gravity** relationship is fulfilled!

$$\frac{\lambda_1 - \lambda_2}{32} = \mathcal{N}$$

$$\left(-\frac{1}{24\pi^2} + \frac{1}{8\pi^2}\right)\Big/ 32 = \frac{1}{384\pi^2}$$

Spin 3/2 (coupled to spin 1/2)

[Stephen L. Adler. Phys. Rev. D, 97(4):045014, 2018]

- **Axial current:** KVE

$$j^\mu_{A,RSA} = \left(\frac{5}{6}T^2 + \frac{5}{2\pi^2}\mu^2 - \frac{53}{24\pi^2}\omega^2 - \frac{5}{8\pi^2}a^2\right)\omega^\mu$$

[GP, Teryaev, O. V., & Zakharov, V. I. (2023). Phys. Lett. B, 840]

- **Anomaly:**

[GP, Teryaev, O. V., & Zakharov, V. I. (2022). Phys. Rev. D, 106(2)]

$$\nabla_\mu j^\mu_A = \frac{-19}{384\pi^2\sqrt{-g}}\varepsilon^{\mu\nu\alpha\beta}R_{\mu\nu\lambda\rho}R_{\alpha\beta}{}^{\lambda\rho}$$

- **Hydro/gravity** relationship is fulfilled!

$$\left(-\frac{53}{24\pi^2} + \frac{5}{8\pi^2}\right)\Big/ 32 = -\frac{19}{384\pi^2}$$

"Cheshire cat's grin", experimental prospects

- Effect is associated with **gravitational** anomaly, but survives in **flat space-time** (the "**Cheshire cat grin**").

- Is it possible to observe **KVE** in **experiment**?

- Should contribute **vortical polarization**, like CVE.
- Observe a **gravitational chiral anomaly** in QGP from polarization?

The **good** news: for spin 3/2 it is enhanced by cubic growth with spin

The **bad** news: should be suppressed by mass $e^{-m/T}$ (omega baryon is heavy).

So far, the accuracy of the experiment is only sufficient to measure **1st-order** (not **3rd-order**) effects in gradients.

Part 3

Entanglement viscosity

[GP, 2601.02083 (2026)]

[D. Lapygin, GP, O. Teryaev, V. Zakharov, PRD 112 (2025) 6]

[GP, O. Teryaev, 2604.04222 (2026)]

From chiral to conformal gravitational anomaly

There is another famous **anomaly**:

- **Conformal** gravitational **anomaly** in 4d:

quadratic in the **Riemann tensor**

$$\langle \hat{T}^{\mu}_{\mu} \rangle = a(-H + \frac{2}{3}\Box R) - bE_4 + c\Box R$$

- **Conformal anomalies** transport effects are **not so well studied**.

[M. N. Chernodub, Phys. Rev. Lett. 117, 141601 (2016), arXiv:1603.07993 [hep-th]]
[C.-S. Chu and R.-X. Miao, Phys. Rev. Lett. 121, 251602 (2018), arXiv:1803.03068 [hep-th]]
[Yang, Gao, Liang, Prokhorov, Shi Pu, Teryaev, Zakharov, arXiv: 2604.23849]

Unruh effect in accelerated fluids

Formulation

The **Minkowski vacuum** is perceived by an **accelerated** observer as a medium with a finite (**Unruh**) **temperature:**

$$T_U = \frac{a}{2\pi}$$

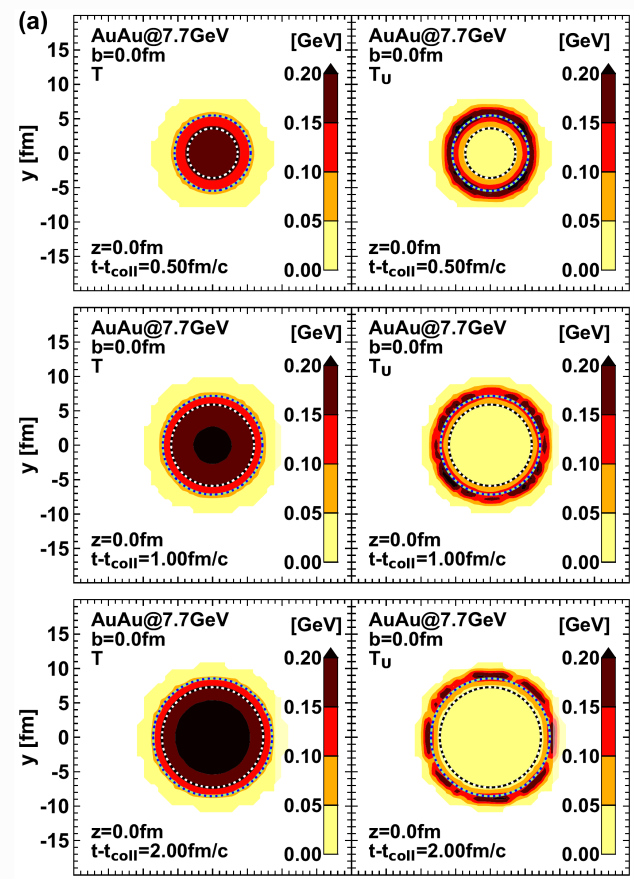
- **Entanglement** plays central role

[Blasone, (2018), e-Print: 1911.06002]

in **HICs**

- Extreme acceleration at the **initial moments** after collision from modeling:

$$a \sim 1\,GeV \sim 10^{32}\,m/sec^2$$



[Prokhorov, G. Yu., Shohonov, D. A., Teryaev, O. V., Tsegelnik, N. S., & Zakharov, V. I. (2025). Phys. Rev. C, 112(6), 064907]

Minimal viscosity bound, spectral functions

Bound inspired by string theory:

- **There are no completely ideal fluids!**
- It is believed that QGP near this limit

$$\frac{\eta}{s} \geqslant \frac{1}{4\pi}$$

KSS-bound

[Kovtun, Son, Starinets, PRL (2005)]

- Another well-known bound for **bulk viscosity** also from holography:

  [Buchel, PLB (2008), arXiv:0708.3459]

$$\frac{\zeta}{\eta} \geqslant 2\left(\frac{1}{p} - c_s^2\right)$$

- We will use **universal spectral representation** valid for **"any"** theory:

  [A. Cappelli, D. Friedan, and J. I. Latorre. Nucl. Phys. B, 352:616–670, 1991]

$$\langle 0|\hat{T}_{\alpha\beta}(x)\hat{T}_{\rho\sigma}(x')|0\rangle_M = \frac{A_d}{(d-1)^2}\int_0^\infty d\mu\, c^{(0)}(\mu)\Pi^{(0)}_{\alpha\beta,\rho\sigma}(\partial')G_d(x-x',\mu) + \frac{A_d}{(d-1)^2}\int_0^\infty d\mu\, c^{(2)}(\mu)\Pi^{(2)}_{\alpha\beta,\rho\sigma}(\partial')G_d(x-x',\mu)$$

spectral function

scalar propagator

Entanglement viscosity and c-theorem

Main result:

$$\eta(\rho) = k_d \rho \int_0^\infty d\mu\, c^{(2)}(\mu)\mu^2 K_0(\mu\rho)$$

$$\zeta(\rho) = \frac{2k_d\rho}{(d-1)^2} \int_0^\infty d\mu\, c^{(0)}(\mu)\mu^2 K_0(\mu\rho)$$

$\rho = 1/\alpha$

- **Unitarity:**

$c^{(0)}(\mu) \geq 0$ $\quad$ $c^{(2)}(\mu) \geq 0$

$$\eta, \zeta \geq 0$$

$$\Downarrow$$

$$\partial_\mu s^\mu \geq 0$$

- **Unitarity** underlies **thermal irreversibility**
- **Analogy** with the **irreversibility** of **renormalization group flows**

[Andrea Cappelli, Daniel Friedan, and Jose I. Latorre. Nucl. Phys. B, 352:616–670, 1991]

- **Novel anomalous effect** in systems with **extreme acceleration** α:

$$\langle \hat{T}^\mu_\mu \rangle = a(-H + \frac{2}{3}\Box R) - bE_4 + c\Box R$$

⇐ conformal anomaly

$$\eta = 8a\alpha^3$$

Isotropy sum rule: Pascal's law for Unruh radiation

- Introduce criterion of **isotropy** of **Unruh radiation**:

$$\frac{\partial p_{||}}{\partial T} = \frac{\partial p_{\perp}}{\partial T}$$

- **Novel sum rule**, relating $c^{(0)}(\mu)$ and $c^{(2)}(\mu)$ spectral functions:

$$\int_0^\infty d\mu \left\{ c^{(0)}(\mu)\mathcal{A}^{(0)}(\mu,\rho) + c^{(2)}(\mu)\mathcal{A}^{(2)}(\mu,\rho) \right\} = 0$$

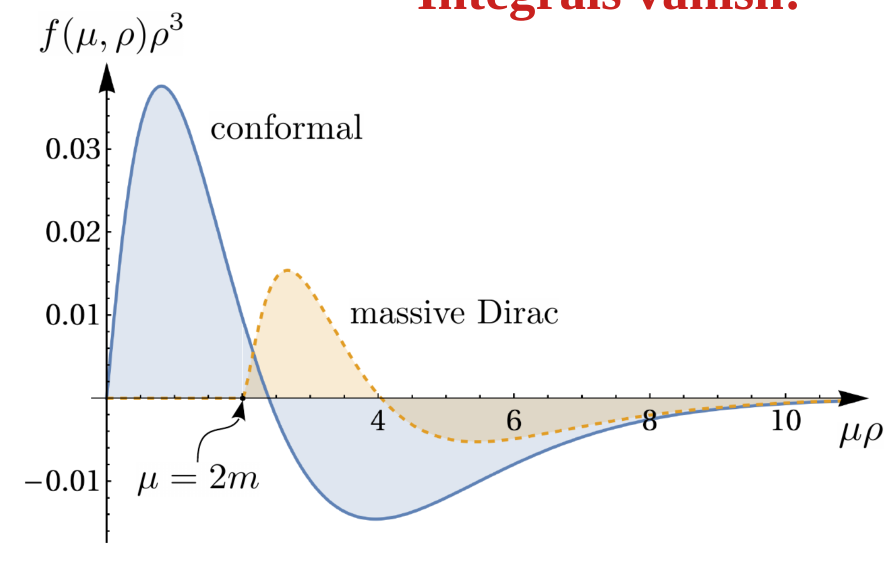
(combinations of Bessel functions)

- Postulation of **Pascal law**
- It is a criterion of **fluidity**
- Can be compared with the **Burkhardt-Cottingham sum rule**

[Hugh Burkhardt and W. N. Cottingham. Annals Phys., 56:453–463, 1970]

- **Verification:**

Integrals vanish!



Spectral functions of **massive fermions**:

$$c^{(2)}(\mu,m) = \frac{2^{\lfloor d/2 \rfloor}(d-1)\Gamma\left(\frac{d}{2}\right)^2}{8\pi^d}\mu^{d-3}\left(1-\frac{4m^2}{\mu^2}\right)^{\frac{d-1}{2}} \cdot \left(1+\frac{8}{d-1}\cdot\frac{m^2}{\mu^2}\right)\theta(\mu-2m)\,.$$

$$c^{(0)}(\mu,m) = \frac{2^{\lfloor d/2 \rfloor}(d^2-1)\Gamma\left(\frac{d}{2}\right)^2}{2\pi^d}m^2\mu^{d-5}\left(1-\frac{4m^2}{\mu^2}\right)^{\frac{d-1}{2}} \cdot \theta(\mu-2m)\,,$$

Entanglement viscosity and bounds for η/s and ξ/η

- Use obtained **"spectral"** formulas for viscosities and the results of **modular Hamiltonian** approach:

[M. Smolkin and S. N. Solodukhin, Phys. Rev. D 91, no.4, 044008 (2015)]

- Apply **isotropy sum rule** - the medium is a fluid → Everything is simplified!

Shear entanglement viscosity

We finally obtain:

$$\frac{\eta}{c_V} = \frac{1}{4\pi} \Rightarrow \frac{\eta}{s} = \frac{1}{4\pi c_s^2}$$

Relationship between **KSS bound** and **causality**:

Causality: $c_s^2 < 1 \Rightarrow \frac{\eta}{s} > \frac{1}{4\pi}$

- Obtained **without holography**

Bulk entanglement viscosity

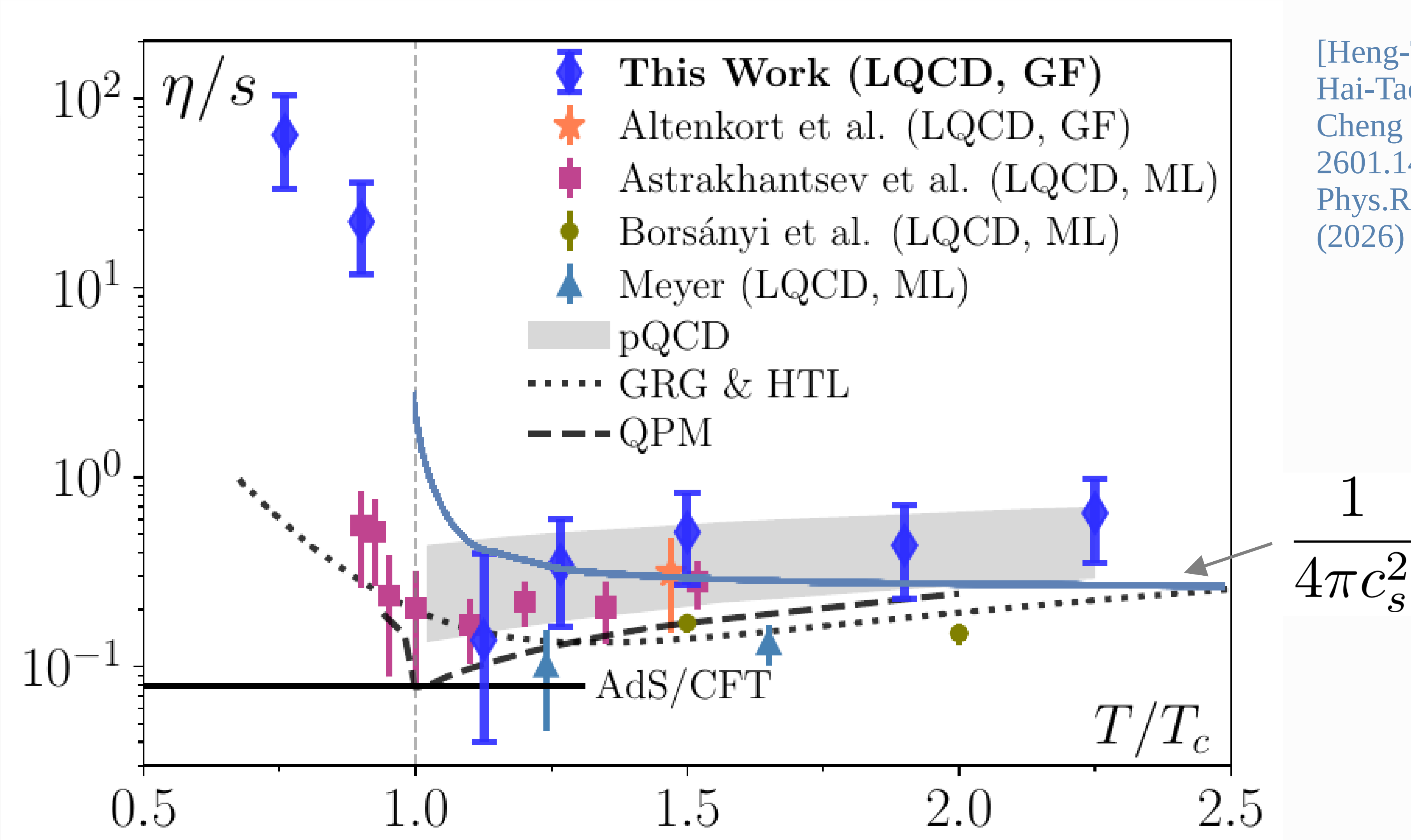
Bulk viscosity saturates **known bound**:

$$\frac{\zeta}{\eta} = 2\left(\frac{1}{d-1} - c_s^2\right)$$

[Buchel, PLB (2008), arXiv:0708.3459]

- Obtained **without holography**

Preliminary results: comparison with lattice



[Heng-Tong Ding, Hai-Tao Shu, Cheng Zhang, 2601.14967, Phys.Rev.D 113 (2026) 7, 074503]

- Naive comparison: explains the **excess** at **high temperatures**
- **Violated** near T_c - **non-hydrodynamic** behavior of the QGP near the transition?

Conclusion

Summary & Conclusion

- The **relationship** between the axial current in **vortical** and **accelerated** fluid $j_5^\mu \sim \omega^2 \omega^\mu$ and $a^2 \omega^\mu$, the **Kinematical Vortical Effect** (**KVE**), and the **gravitational** chiral **anomaly** $\nabla j_5 \sim R\tilde{R}$ has been established:

  -- **"Cheshire cat's grin"** of gravity

- Thermal quantum radiation in a space with a horizon has an **entanglement viscosity**:

  -- Anology with irreversibility of **renormalization group flows**

- **Novel isotropy sum rule** for fundemental spectral functions $c^{(0)}(\mu)$ and $c^{(2)}(\mu)$ is obtained from **Pascal law** for Unruh radiation.

- It is shown (**without using holography**) that the entanglement viscosities **saturate both known bounds** for **η/s** and **ξ/η**:

  -- **Novel** formula for **local ratio** with speed of sound:

$$\frac{\eta}{s} = \frac{1}{4\pi c_s^2}$$

Thank you for your attention!

https://indico.ihep.su/event/922/attachments/1194/1909/PPIHE2026-poster.pdf

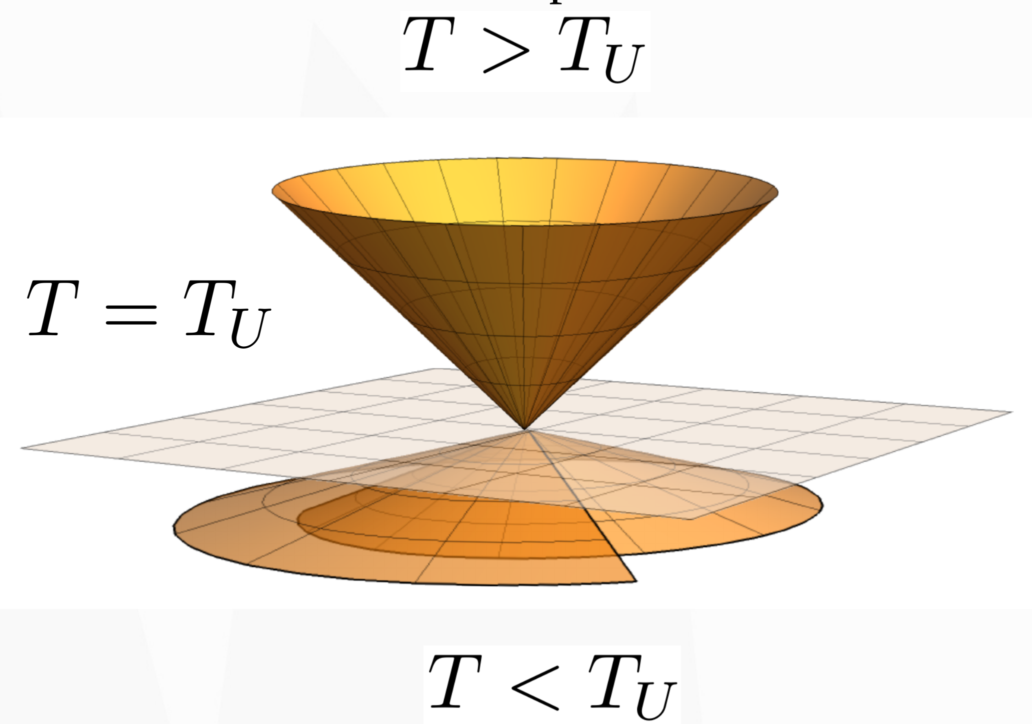
Additional slides

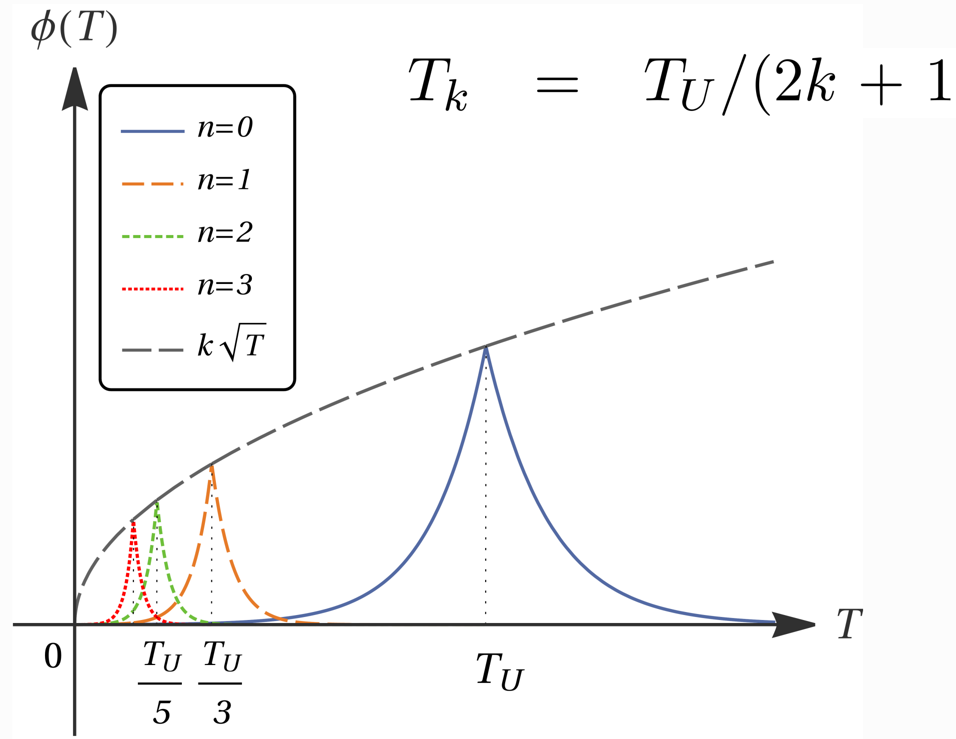
Part 4

Novel quantum phase transition in accelerated media

Phase transition: singularity at the horizon

Euclidean Rindler space





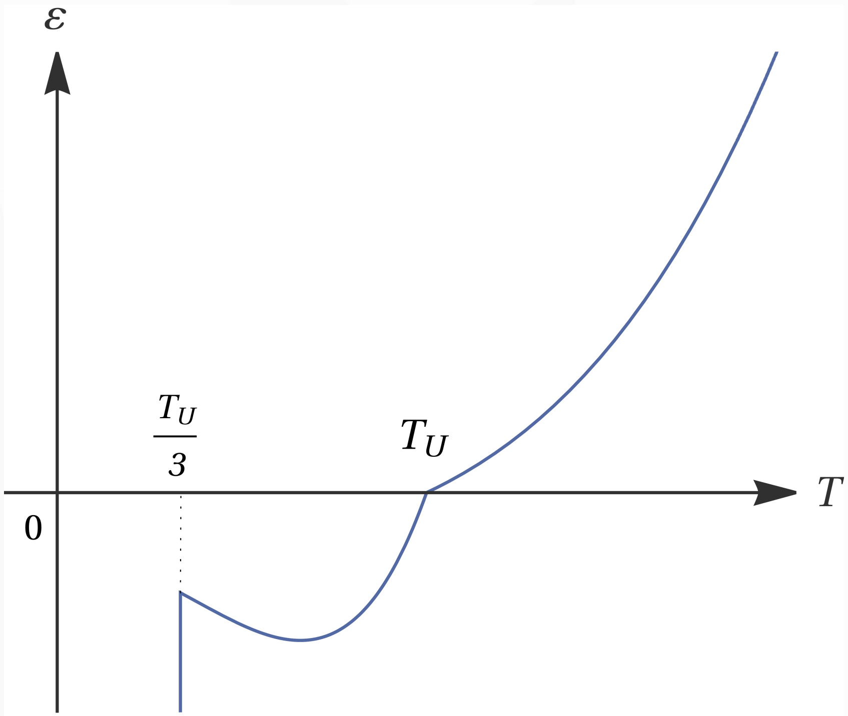
- When geometry changes from cone to plane, **lowest Matsubara modes** become **singular on the horizon** and change solution. This leads to **peaks** in the behavior of the modes.
- The situation repeats for other pairs of higher Matsubara modes at the points

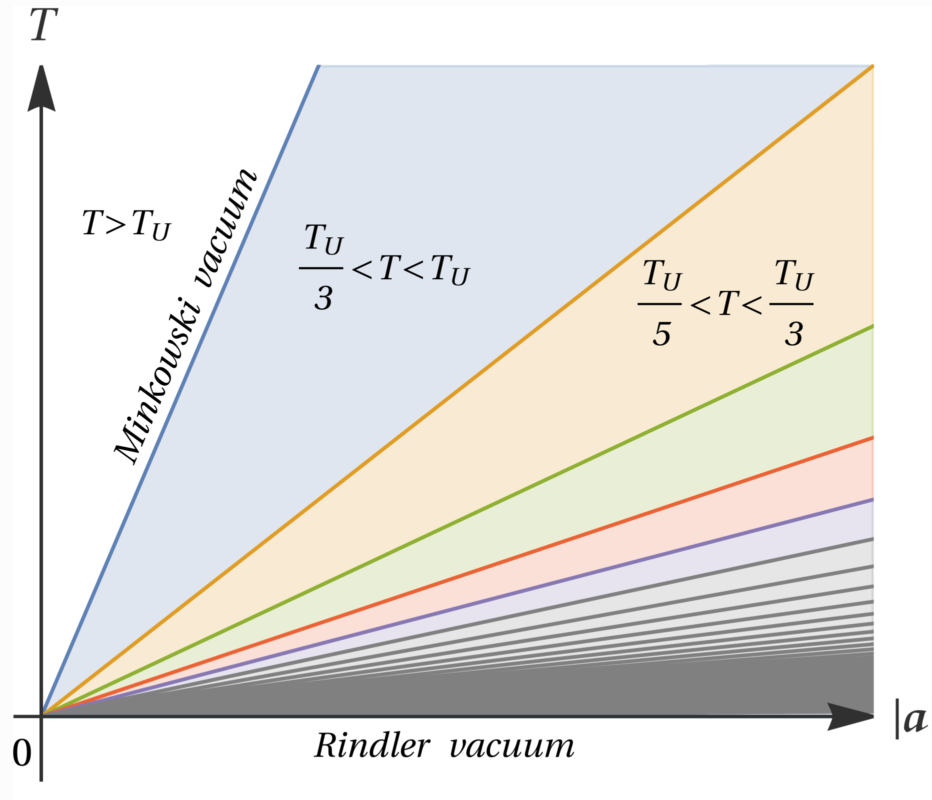
"Casimir-like" accleleration terms in EMT:

$$\langle \hat{T}^{\mu\nu} \rangle^0_{\text{fermi}} = \left(\frac{7\pi^2 T^4}{60} + \frac{T^2|a|^2}{24} - \frac{17|a|^4}{960\pi^2}\right) u^\mu u^\nu - \left(\frac{7\pi^2 T^4}{180} + \frac{T^2|a|^2}{72} - \frac{17|a|^4}{2880\pi^2}\right) \Delta^{\mu\nu} + \mathcal{O}(a^6)$$

changes below critical temperature

Phase diagram and jump in heat capacity





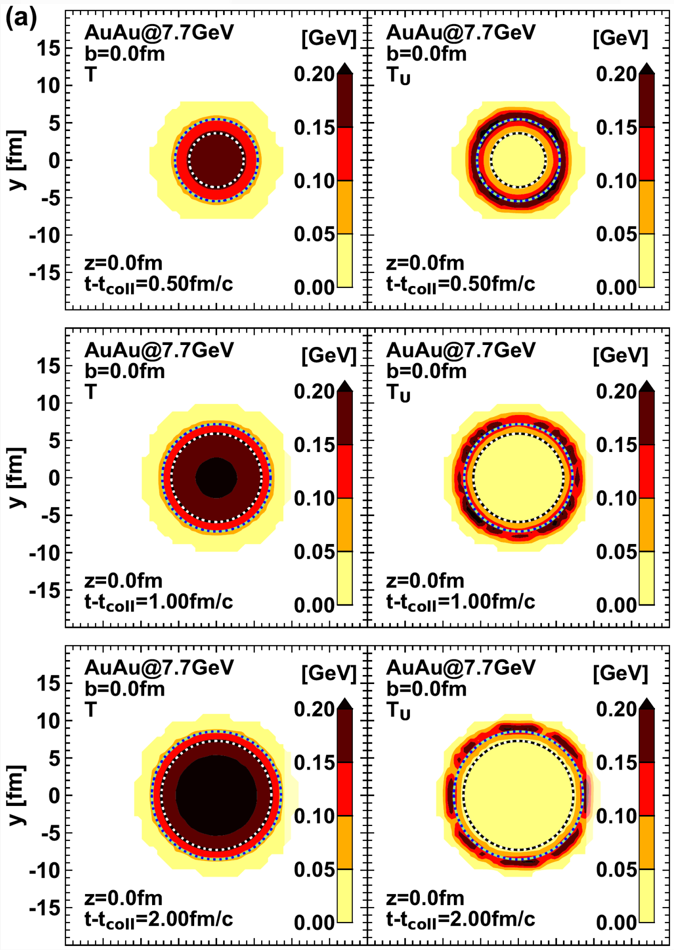
We confirm instabilties at the points:

phase diagram

$$T_k = T_U/(2k+1)$$

Comparison with PHSD modeling

- The collision of two gold nuclei Au-Au are considered.
- The parton-hadron-string dynamics (PHSD) model is used: **[Cassing, Bratkovskaya, Nucl.Phys.A (2009)]**
- The space distributions of acceleration and temperature and their time evolution were obtained.



- The acceleration is maximum at the **initial time moments** and has the order of:

$$a \sim 1\,GeV \sim 10^{32}\,m/sec^2$$

-- acceleration is **extremely large in nature**

[Вергелес,Николаев, Обухов, Силенко, Теряев, УФН 2023, e-Print: 2204.00427]

- Indeed, **states with** $T < T_U$ **are formed.**
- The region $T < T_U$ corresponds predominantly to the hadron phase, and region $T > T_U$ to the quark-gluon phase.
- The prediction about the connection between **hadronization** and **phase transition at Unruh temperature** is qualitatively confirmed

Universal spectral representation

- **Universal spectral representation:**

[A. Cappelli, D. Friedan, and J. I. Latorre. Nucl. Phys. B, 352:616–670, 1991]
[M. Smolkin and S. N. Solodukhin, Phys. Rev. D 91, no.4, 044008 (2015)]
[S. N. Solodukhin. The a-theorem and entanglement entropy. 4 2013.]

$$\langle 0|\hat{T}_{\alpha\beta}(x)\hat{T}_{\rho\sigma}(x')|0\rangle_M = \frac{A_d}{(d-1)^2}\int_0^\infty d\mu\, c^{(0)}(\mu)\Pi^{(0)}_{\alpha\beta,\rho\sigma}(\partial')G_d(x-x',\mu) + \frac{A_d}{(d-1)^2}\int_0^\infty d\mu\, c^{(2)}(\mu)\Pi^{(2)}_{\alpha\beta,\rho\sigma}(\partial')G_d(x-x',\mu)$$

spectral function — scalar propagator

- Valid for “any” theory: different spins, conformal, nonconformal, interacting...
- For unitary theory: $c^{(0)}(\mu) \geq 0$ $c^{(2)}(\mu) \geq 0$
- Only $c^{(0)}(\mu)$ for 2d theory: positivity $c^{(0)}(\mu) \geq 0$ ⇒ irrevesibilty of renormalisation group flows

Unitarity provides irrevesibilty of renormalisation group flows

[A. B. Zamolodchikov. JETP Lett., 43:730–732, 1986]

Direct verifiaction

- Can be **verified** in **conformal** case in **any dimensions**.
- Can be **verified** in **nonconformal** case: free massive Dirac field in any dimensions.

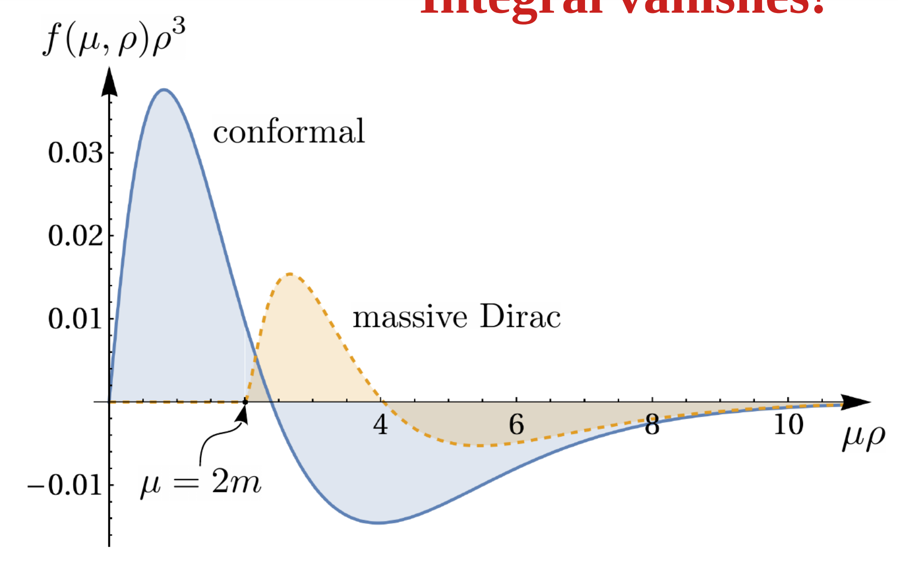
Spectral functions of **massive fermions**:

$$c^{(2)}(\mu,m) = \frac{2^{\lfloor d/2\rfloor}(d-1)\Gamma\left(\frac{d}{2}\right)^2}{8\pi^d}\mu^{d-3}\left(1-\frac{4m^2}{\mu^2}\right)^{\frac{d-1}{2}} \cdot\left(1+\frac{8}{d-1}\cdot\frac{m^2}{\mu^2}\right)\theta(\mu-2m)\,.$$

$$c^{(0)}(\mu,m) = \frac{2^{\lfloor d/2\rfloor}(d^2-1)\Gamma\left(\frac{d}{2}\right)^2}{2\pi^d}m^2\mu^{d-5}\left(1-\frac{4m^2}{\mu^2}\right)^{\frac{d-1}{2}} \cdot\theta(\mu-2m)\,,$$

[Andrea Cappelli, Daniel Friedan, and Jose I. Latorre. Nucl. Phys. B, 352:616–670, 1991]

Integral vanishes!



Scalar field:

- Satisfied for conformal scalar field
- Violated for massless nonconformal scalar field
- Open question - improved massive scalar field

- Anysotropic contribution $T_{\mu\nu} \sim a_\mu a_\nu$
  [Frolov, V., & Serebryanyi, E. (1987), Phys. Rev. D, 35, 3779–3782]
- Surface terms in the modular Hamiltonian can be important
  [Herzog, C., & Nishioka, T. (2016). JHEP, 12, 138.]