Bayesian constraints on the viscosities of the quarkgluon plasma



Jean-François Paquet (Duke University)



April 14, 2021

Live from Durham, NC

9th Workshop of the APS Topical Group on Hadronic Physics







After the collisions





Viscosities as macroscopic properties of fluids: water

Phase diagram

Shear viscosity to entropy density ratio (at different point in the phase diagram)



Ref.: https://en.wikipedia.org/wiki/Phase_diagram#/media/File:Phase_diagram_of_water_simplified.svg

Jean-François Paquet (Duke)

Viscosities as macroscopic properties of nuclear plasmas



Ref.: Volker Koch - Search for the Critical End Point [Student day - Quark Matter 2019]

Viscosities affect the evolution of the plasma



Hydrodynamic evolution of the plasma



Ref.: Gale, JFP, Schenke and Shen (2021) NPA; [+in preparation]

Viscosities affect the evolution of the plasma

Ref.: Gale, JFP, Schenke and Shen (2021) NPA; [+in preparation]



Viscosities and other model parameters









Ref: MADAI collaboration, Hannah

Elfner and Jonah Bernhard

$au = "0^+$ ": Nuclei collide

- Trento ansatz used to parametrize the energy deposition
- 5 parameters: (i-iii) nucleon width, fluctuation & minimum distance, (iv) transparency parameter, (v) normalization

$\tau \sim 0.1$ fm: "Pre-equilibrium phase"

- Free-streaming
- Free-streaming time is parameterized

$\underline{\tau} \sim 1$ fm: Beginning of "hydrodynamic phase"

- 2+1D relativistic viscous hydrodynamics [MUSIC]
- Equation of state: hadron resonance gas + lattice QCD [HotQCD]
- Shear and bulk viscosity: $\frac{\eta}{s}(T)$ and $\frac{\zeta}{s}(T)$ parametrized
- Shear relaxation time normalization

$\underline{\tau}\sim 10$ fm: End of "hydrodynamic phase"

- Fluid converted to hadrons [iS3D]: Cooper-Frye at temperature T_{sw}
- Viscous corrections in Cooper-Frye: 4 different models
- Hadronic interactions with SMASH hadronic transport





Calibrating on measurements



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JETSCAPE Collaboration, arXiv:2011.01430, arXiv:2010.03928

Mean value of measurements

posterior(p|D)
$$\propto$$
 prior(p) $\times exp\left(-\frac{1}{2}\left(D - Model(p)\right)^{T} Cov^{-1}\left(D - Model(p)\right)\right)$

Prediction of model for given set of parameters $(\eta/s, \zeta/s, initial$ conditions, ...)

JETSCAPE Collaboration, arXiv:2011.01430, arXiv:2010.03928

$$\begin{array}{c} \begin{array}{c} \mbox{Mean value of}\\ \mbox{measurements} \end{array} & \begin{array}{c} \mbox{Experimental}\\ \mbox{and theoretical}\\ \mbox{uncertainties} \end{array} \\ \mbox{posterior}(p|D) \propto prior(p) \times exp \left(-\frac{1}{2} \left(D - Model(p) \right)^T Cov^{-1} \left(D - Model(p) \right) \right) \end{array}$$

Prediction of model for given set of parameters $(\eta/s, \zeta/s, initial$ conditions, ...)

$$\begin{array}{c} \mbox{Mean value of measurements} \\ \mbox{measurements} \\ \$$

Probabilistic constraints
on parameters

$$posterior(p|D) \propto prior(p) \times exp \begin{pmatrix} Mean value of measurements and theoretical uncertainties \\ -1 (D - Model(p))^T Cov^{-1} (D - Model(p)) \end{pmatrix}$$

External constraints on parameters:
positivity or range of allowed values, "probabilistic theoretical constraints", ...
Mean value of measurements $(\eta/s, \zeta/s, initial conditions, ...)$

Latest constraints

Bulk visce



- Result of Bayesian infe
- State-of-the art multi-s hydrodynamics

Multi-system Bayesian constraints on the transport coefficients of QCD matter

D. Everett,¹ W. Ke,^{2,3} J.-F. Paquet,⁴ G. Vujanovic,⁵ S. A. Bass,⁴ L. Du,¹ C. Gale,⁶ M. Heffernan,⁶ U. Heinz,¹ D. Liyanage,¹ M. Luzum,⁷ A. Majumder,⁵ M. McNelis,¹ C. Shen,^{5,8} Y. Xu,⁴ A. Angerami,⁹ S. Cao,⁵ Y. Chen,^{10,1} J. Coleman,¹² L. Cunqueiro,^{13,14} T. Dai,⁴ R. Ehlers,^{13,14} H. Elfner,^{15,16,17} W. Fan,⁴ R. J. Fries,^{18,19} F. Garza,^{18,19} Y. He,²⁰ B. V. Jacak,^{2,3} P. M. Jacobs,^{2,3} S. Jeon,⁶ B. Kim,^{18,19} M. Kordell II,^{18,19} A. Kumar,⁵ S. Mak,¹² J. Mulligan,^{2,3} C. Nattrass,¹³ D. Oliinychenko,³ C. Park,⁶ J. H. Putschke,⁵ G. Roland,^{10,11} B. Schenke,²¹ L. Schwiebert,²² A. Silva,¹³ C. Sirimanna,⁵ R. A. Soltz,^{5,9} Y. Tachibana,⁵ X.-N. Wang,^{20,2,3} and R. L. Wolpert¹²

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JETSCAPE Collaboration, -gluo arXiv:2011.01430, arXiv:2010.03928

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Latest constraints

Bulk visc

0.15 Model description Priors 0.00 **Closure tests** Bayesian Ge parameter estimation ata of the art multi-s **Observables**

sensitivity study

Multi-system Bayesian constraints on the transport coefficients of QCD matter

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XI. Bayesian Model Selection

evidence

viscosity

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Acknowledgments

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1. Physics models

2. Prior distributions

3. Experimental data

2. SMASH

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4. The σ meson

resonance gases

H. Multistage model validation

external solution

1. Validation of second-order viscous

hydrodynamics implementation

5. Sampling particles on mass-shell

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B. Comparing viscous correction models

C. Comparing hydrodynamic models 1. Temperature independent specific shear

2. Zero specific shear viscosity

D. Quantifying tension between LHC and RHIC

1. No common parameters between collision

2. Different transverse length scales in the initial

1. Bayes factor definition and interpretation

2. Numerical methods for estimating the Bayes

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D. Hadronic transport

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C. Treatment of uncertainties

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E. Maximizing the posterior

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B. Constraints on η/s and ζ/s

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momentum distributions

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B. Guiding analyses with closure tests

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VI. Closure Tests

uncertainties

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Chapman-Enskog

C. Particlization



JETSCAPE Collaboration, arXiv:2011.01430, arXiv:2010.03928

Bayesian model selection

JETSCAPE Collaboration.

Validation against additional data

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Validation of hydrodynamics against external solutions

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Agreement with measurements



PbPb $\sqrt{s_{NN}}$ =2760 GeV, ALICE Collaboration (LHC)

AuAu $\sqrt{s_{NN}}$ =200 GeV, STAR Collaboration (RHIC)

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Latest constraints on the viscosities of quark-gluon plasma



Bulk viscosity

Shear viscosity

How to understand Bayesian constraints



Bulk viscosity

Shear viscosity

- Compare with priors
- Kullback–Leibler divergence D_{KL} can quantify prior-posterior differences

JETSCAPE

Collaboration,

arXiv:2011.01430,

arXiv:2010.03928

The importance of including theoretical uncertainties



Bulk viscosity

Shear viscosity

JETSCAPE Collaboration, arXiv:2011.01430, arXiv:2010.03928

 Different line colours are different "particlization model" (particlization = transition from hydrodynamics to hadronic transport)

The importance of including theoretical uncertainties



Bulk viscosity

Shear viscosity

- Different line colours are different "particlization model" (particlization = transition from hydrodynamics to hadronic transport)
- Shaded average is "Bayesian model average": average weighted by degree of agreement with data ("Bayes factor")

Precision vs accuracy



Ref.: https://wp.stolaf.edu/it/gis-precision-accuracy/

- Important not to confuse narrow constraints with accurate ones
- Relaxing model assumptions generally lead to weaker but more accurate constraints
- More data + inclusion/reduction of model uncertainties = Better constraints on viscosities



Summary: Bayesian constraints on $\eta/s(T)$ and $\zeta/s(T)$ of QCD

- "State-of-the-art" constraints on the QCD viscosities from recent JETSCAPE analysis
- Systematic constraints
- Importance of prior-posterior comparisons
- Including model uncerts increases accuracy
- Precision ≠ accuracy



<u>Outlook</u>:

- Additional data can constrain viscosity at higher temperature; model dependence? [Nijs, Van Der Schee, Gürsoy, Snellings, 2010.15134,2010.15130]
- Additional source of theoretical uncertainties must be accounted for \Rightarrow **Initial conditions**; Also, equation of state [Auvinen et al (2020) PRC]
- Experimental uncertainties: correlations between uncertainties [2102.11337]

arXiv:2011.01430 is a systematic framework that can include future improvements

Acknowledgements

Bayesian inference results are from the JETSCAPE Collaboration, with **Derek Everett** (OSU) & **Weiyao Ke** (UC Berkeley & LBNL) driving the effort.

See:

https://inspirehep.net/literature/1827929 https://inspirehep.net/literature/1821941



Cornell University

High Energy Physics - Phenomenology

arXiv:2011.01430 (hep-ph)

[Submitted on 3 Nov 2020 (v1), last revised 6 Nov 2020 (this version, v2)]

Multi-system Bayesian constraints on the transport coefficients of QCD matter



arXiv:2010.03928 (hep-ph)

[Submitted on 8 Oct 2020]

Phenomenological constraints on the transport properties of QCD matter with data-driven model averaging



XSEDE

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Computational resources from XSEDE & TACC

This work was supported by:





Office of Science

J.-F.P. was supported by the U.S. Department of Energy (DOE) under award number DE-FG02-05ER41367 and by the National Science Foundation (NSF) under award number ACI-1550300

The JETSCAPE Collaboration



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Questions?

References for multistage model



$\underline{\tau} = "0^+$ ": Nuclei collide

Trento ansatz used to parametrize the energy deposition
 Ref.: Moreland, Bernhard, Bass (2015) PRC92,011901

JETSCAPE Collaboration, arXiv:2011.01430, arXiv:2010.03928



$\tau \sim 0.1$ fm: "Pre-equilibrium phase"

Free-streaming
 Ref.: Everett (2018), https://github.com/derekeverett/freestream-milne

$\tau \sim 1$ fm: Beginning of "hydrodynamic phase"

- 2+1D relativistic viscous hydrodynamics [MUSIC]
- Equation of state: hadron resonance gas + lattice QCD [HotQCD Collaboration (2014) PRD90,094503]
- Shear and bulk viscosity

MUSIC ref.: Schenke, Jeon, Gale (2010) PRC82,014903; (2011) PRL106,042301; Paquet, Shen, Denicol, Luzum, Schenke, Jeon, Gale (2016) PRC93,044906

Hadron resonance gas + lattice combination: https://github.com/j-f-paquet/eos_maker

$\underline{\tau} \sim 10$ fm: End of "hydrodynamic phase"

- Fluid converted to hadrons [iS3D]
- Hadronic interactions with SMASH hadronic transport

iS3D ref.: McNelis, Everett, Golden & Heinz, in preparation; https://github.com/derekeverett/iS3D

SMASH ref.: Weil, Steinberg, Staudenmaier, Pang, Oliinychenko, Mohs, Kretz, Kehrenberg, Goldschmidt, Bäuchle, Auvinen, Attems, Petersen (2016) PRC94, 054905 https://smash-transport.github.io/



Agreement with measurements



 σ_{exp}

