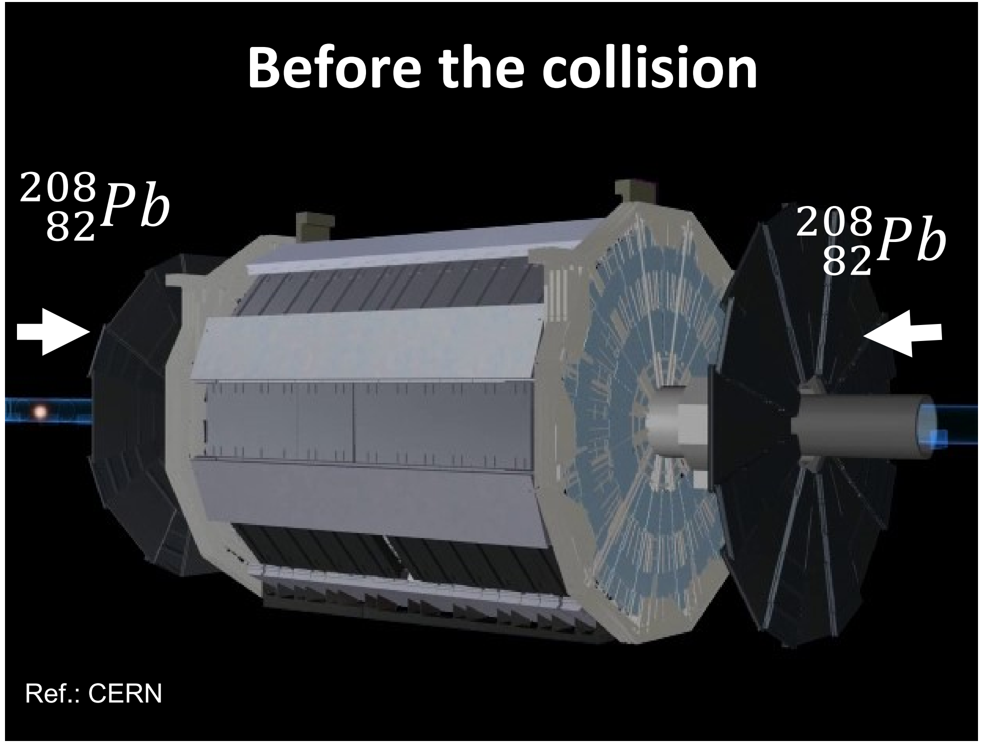
# Bayesian constraints on the viscosities of the quark-gluon plasma

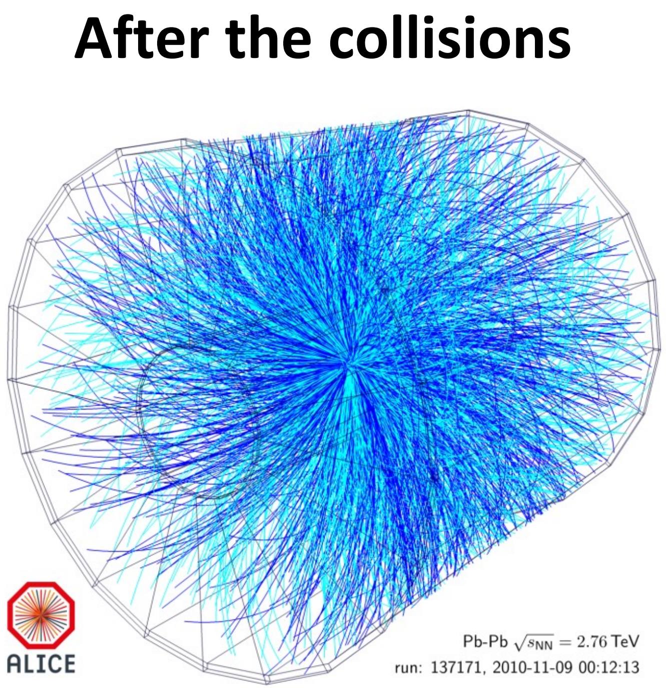
Jean-François Paquet (Duke University)

April 14, 2021

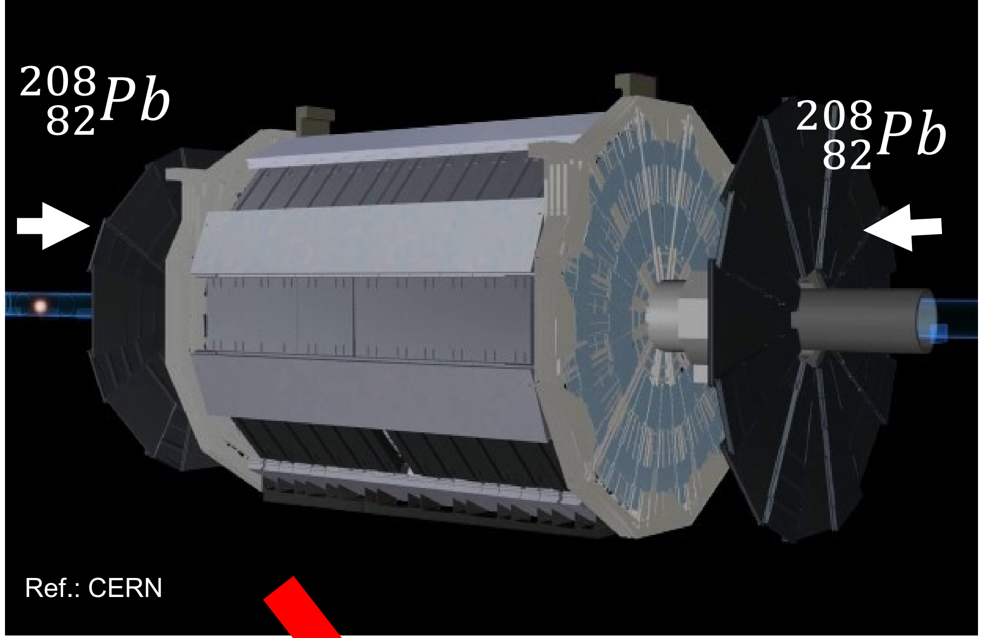
9th Workshop of the APS Topical Group on Hadronic Physics

Live from Durham, NC

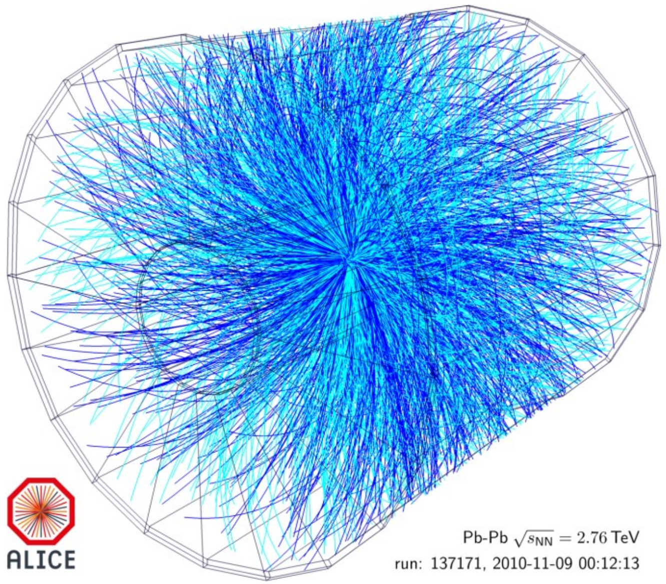

Before the collision
$^{208}_{82}Pb$
$^{208}_{82}Pb$
Ref.: CERN

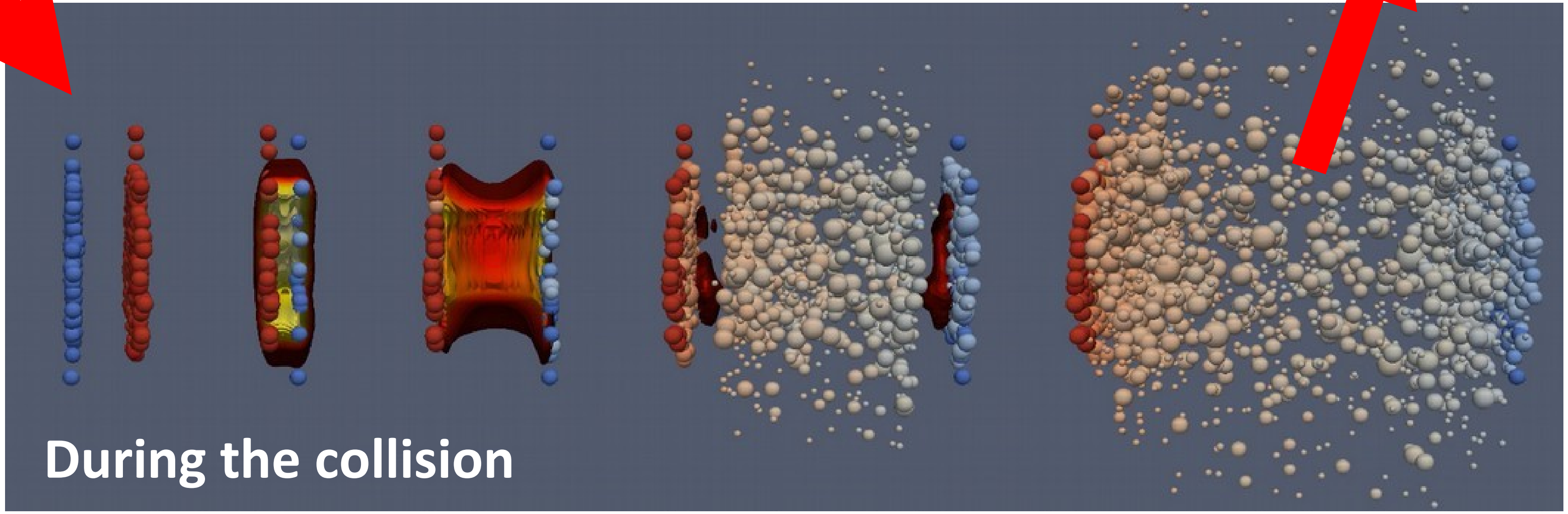

After the collisions
ALICE
Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV
run: 137171, 2010-11-09 00:12:13

## Before the collision




## After the collisions

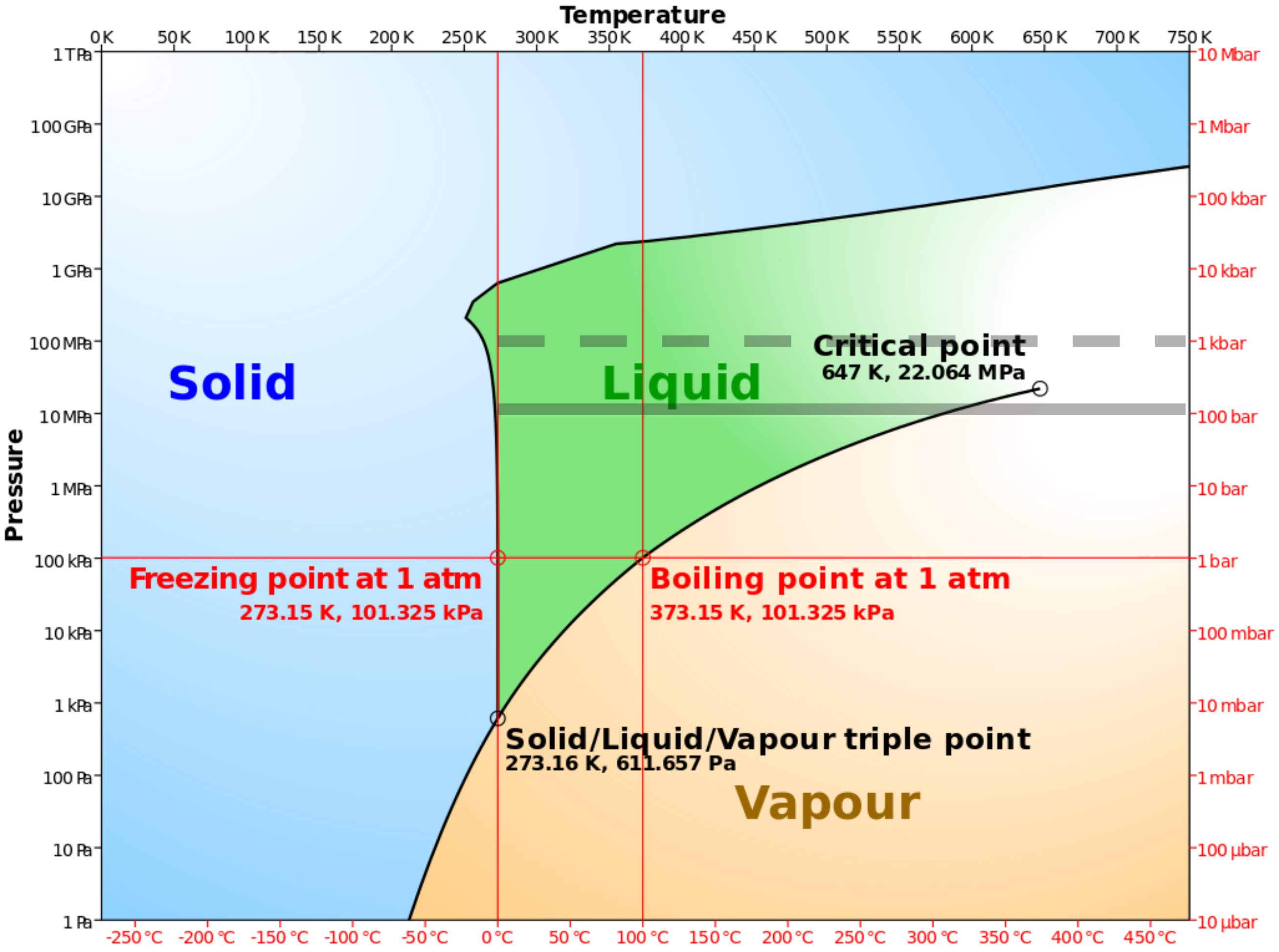



Ref: MADAI collaboration, Hannah Elfner and Jonah Bernhard

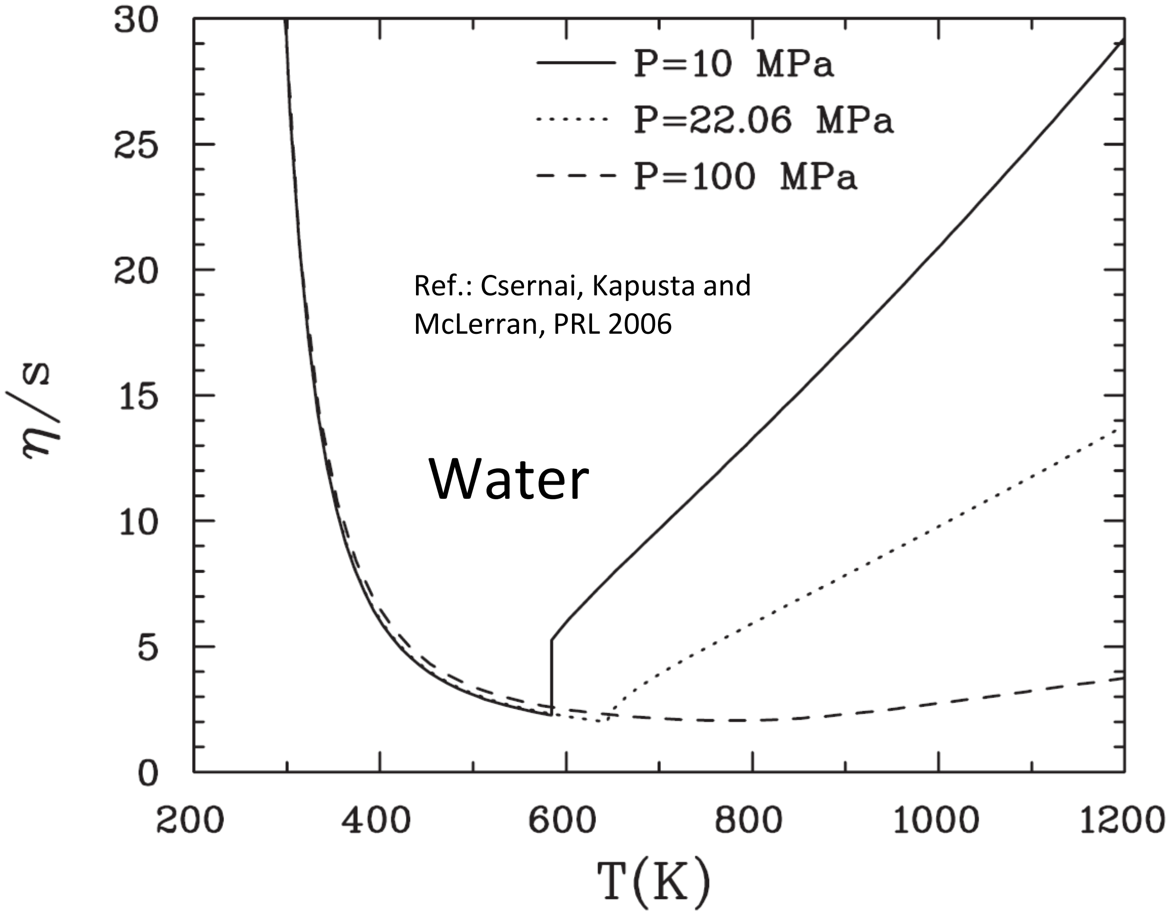
# Viscosities as macroscopic properties of fluids: water

Phase diagram



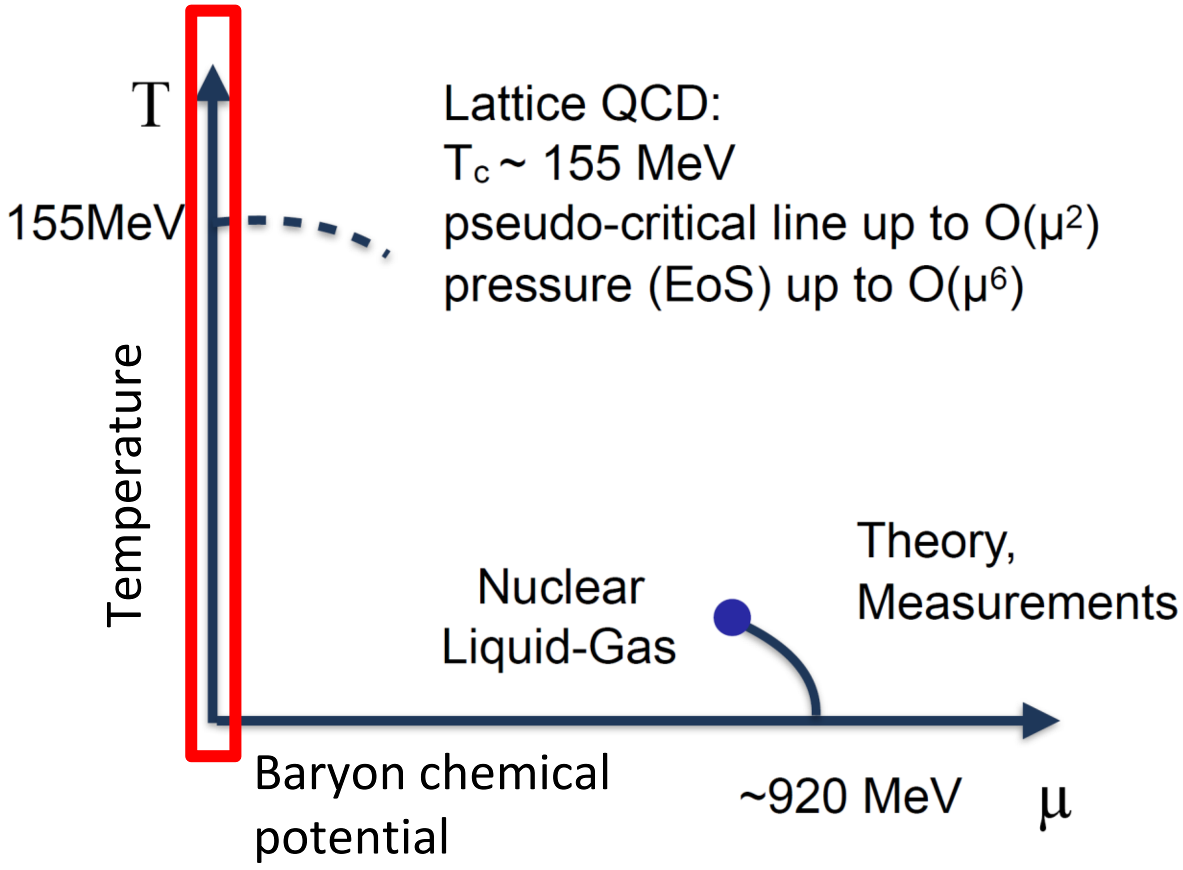

Ref.: https://en.wikipedia.org/wiki/Phase_diagram#/media/File:Phase_diagram_of_water_simplified.svg

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



# Viscosities as macroscopic properties of nuclear plasmas

Phase diagram



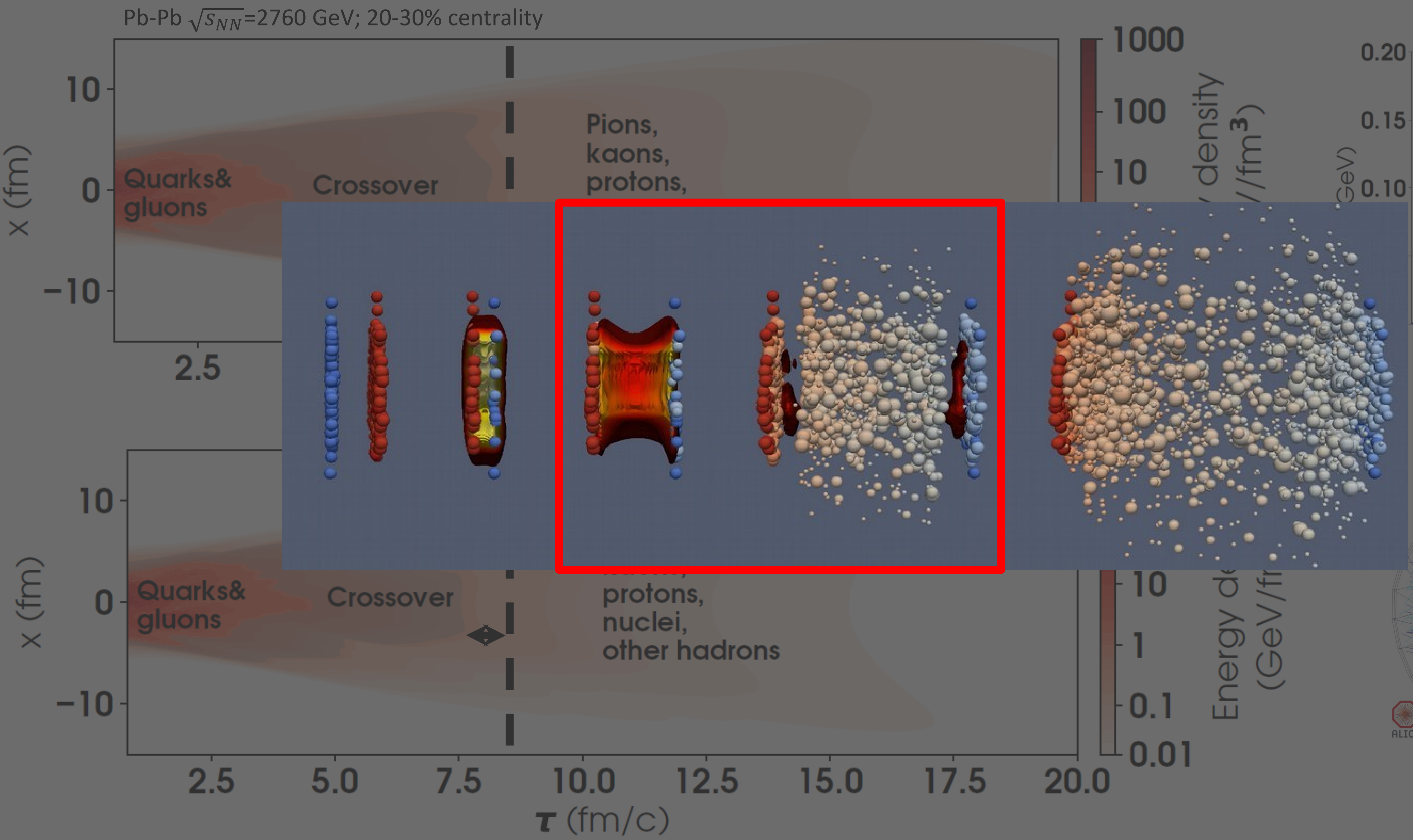

Ref.: Volker Koch - Search for the Critical End Point
[Student day - Quark Matter 2019]

Shear and bulk viscosity to entropy density ratio

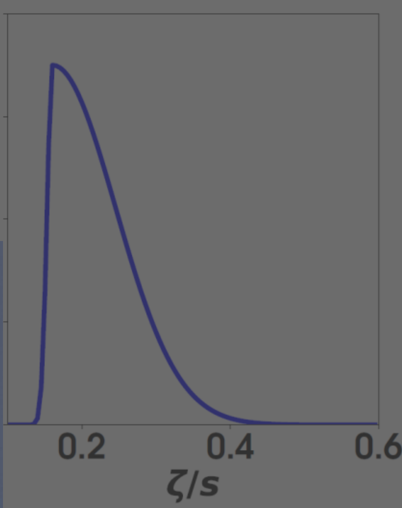
$$\eta/s(T,\mu_B=0) = ?$$

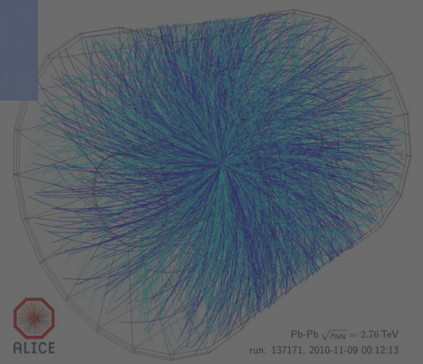
$$\zeta/s(T,\mu_B=0) = ?$$

# Viscosities affect the evolution of the plasma



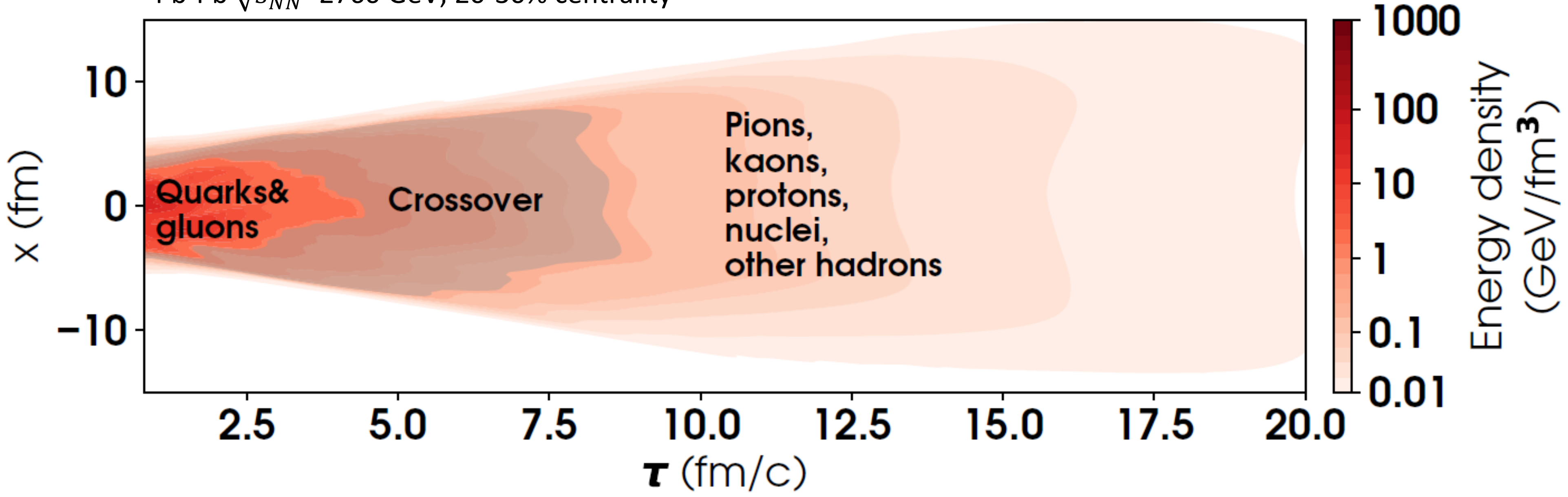

Bulk viscosity



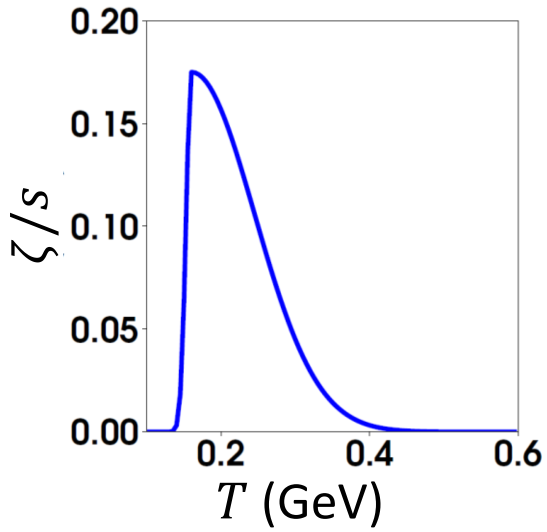



# Hydrodynamic evolution of the plasma

Pb-Pb $\sqrt{s_{NN}}$=2760 GeV; 20-30% centrality




Bulk viscosity

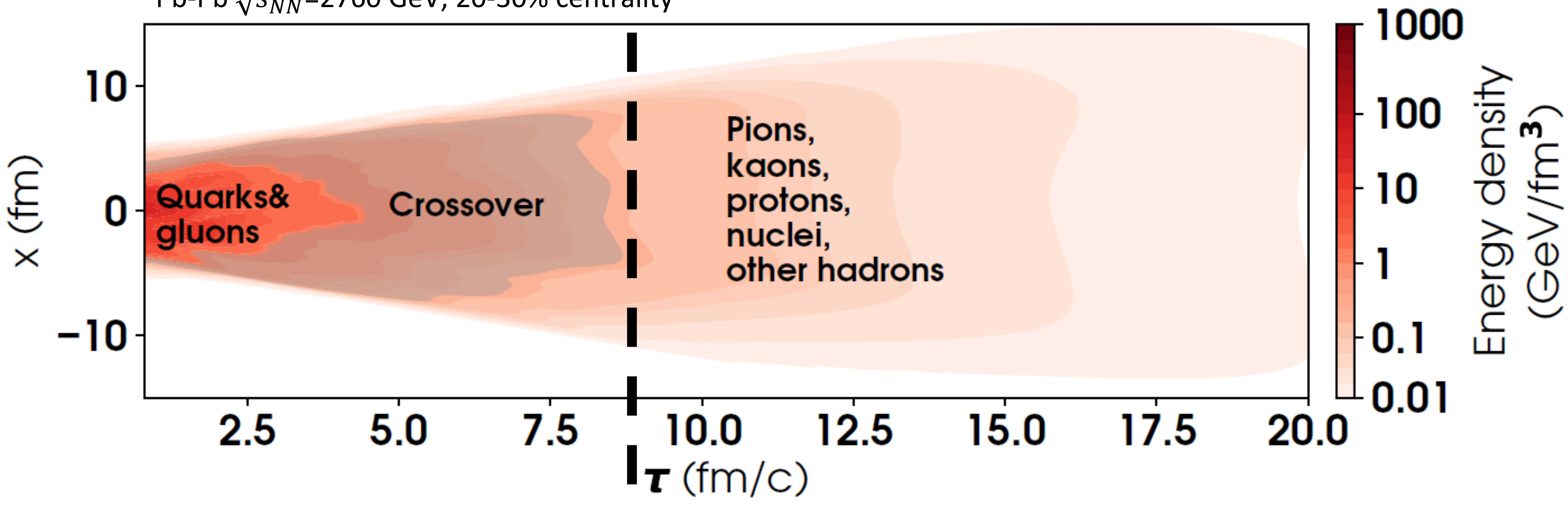



Ref.: Gale, JFP, Schenke and Shen (2021) NPA; [+in preparation]

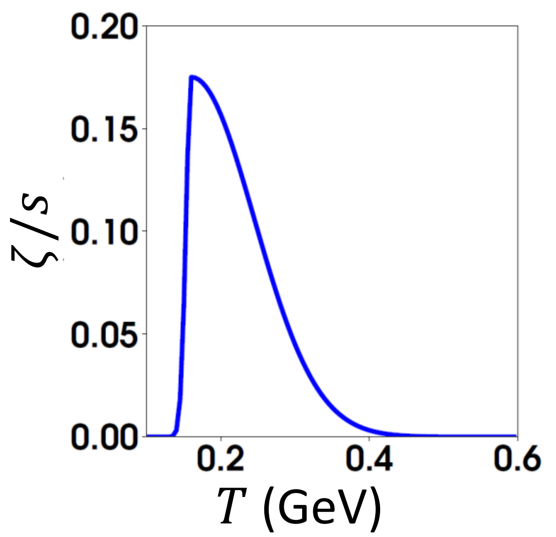
# Viscosities affect the evolution of the plasma

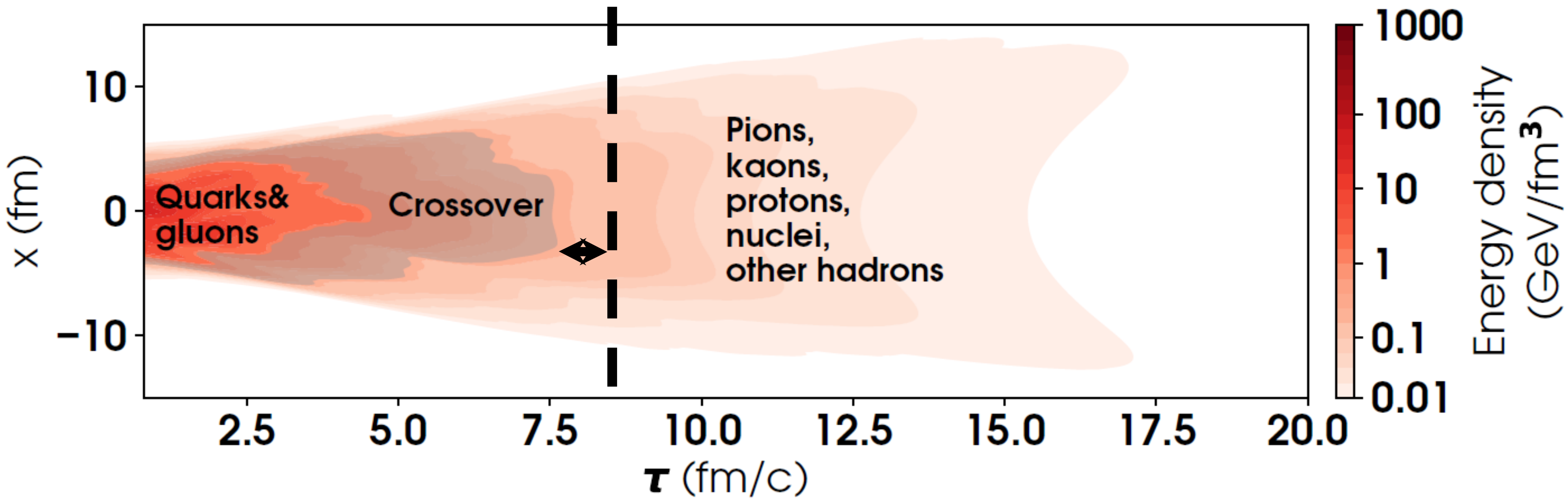
Ref.: Gale, JFP, Schenke and Shen (2021) NPA; [+in preparation]

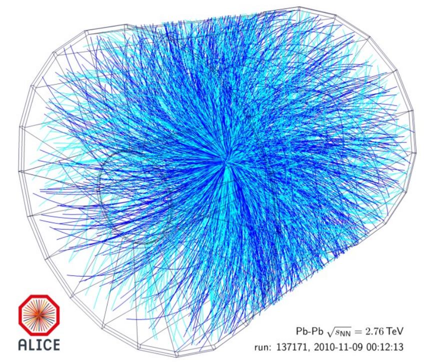
Pb-Pb $\sqrt{s_{NN}}$=2760 GeV; 20-30% centrality




Bulk viscosity

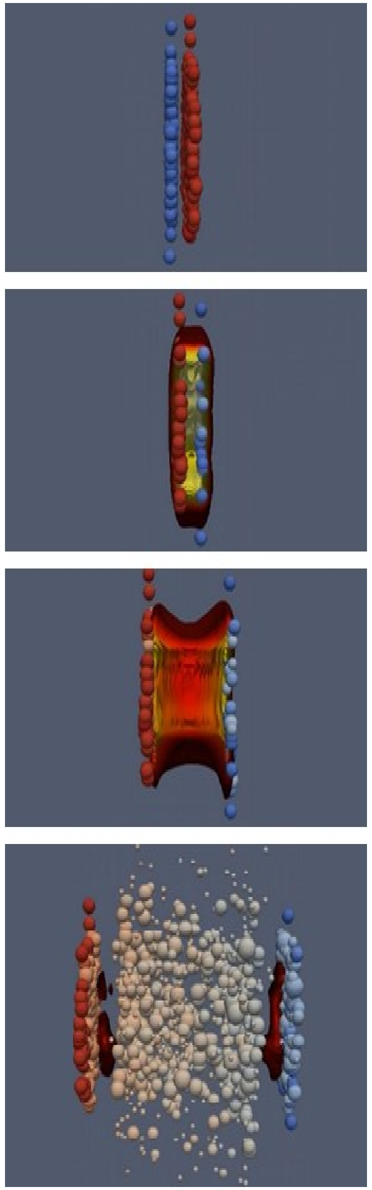


# Viscosities and other model parameters

JETSCAPE Collaboration, arXiv:2011.01430, arXiv:2010.03928



Ref: MADAI collaboration, Hannah Elfner and Jonah Bernhard

**$\tau =$ "$0^+$": 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"**

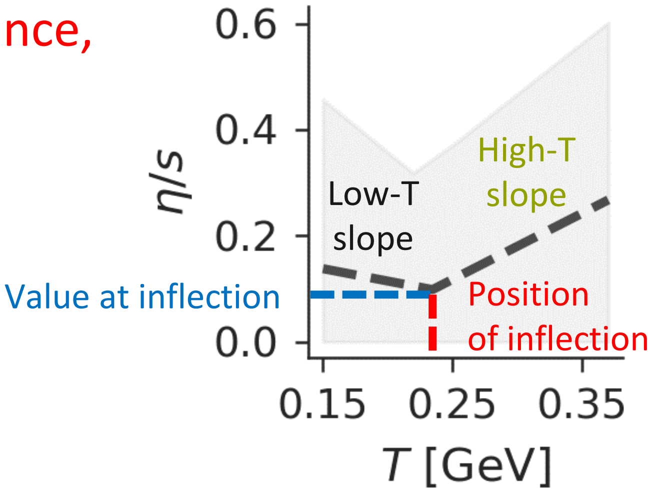
- Free-streaming
- Free-streaming time is parameterized

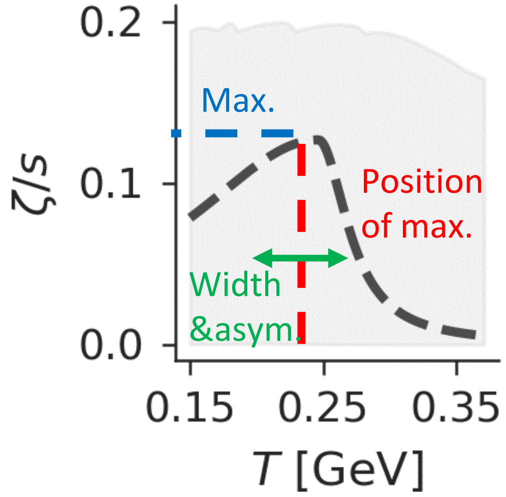
**$\tau \sim 1$ fm: Beginning of "hydrodynamic phase"**

- 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

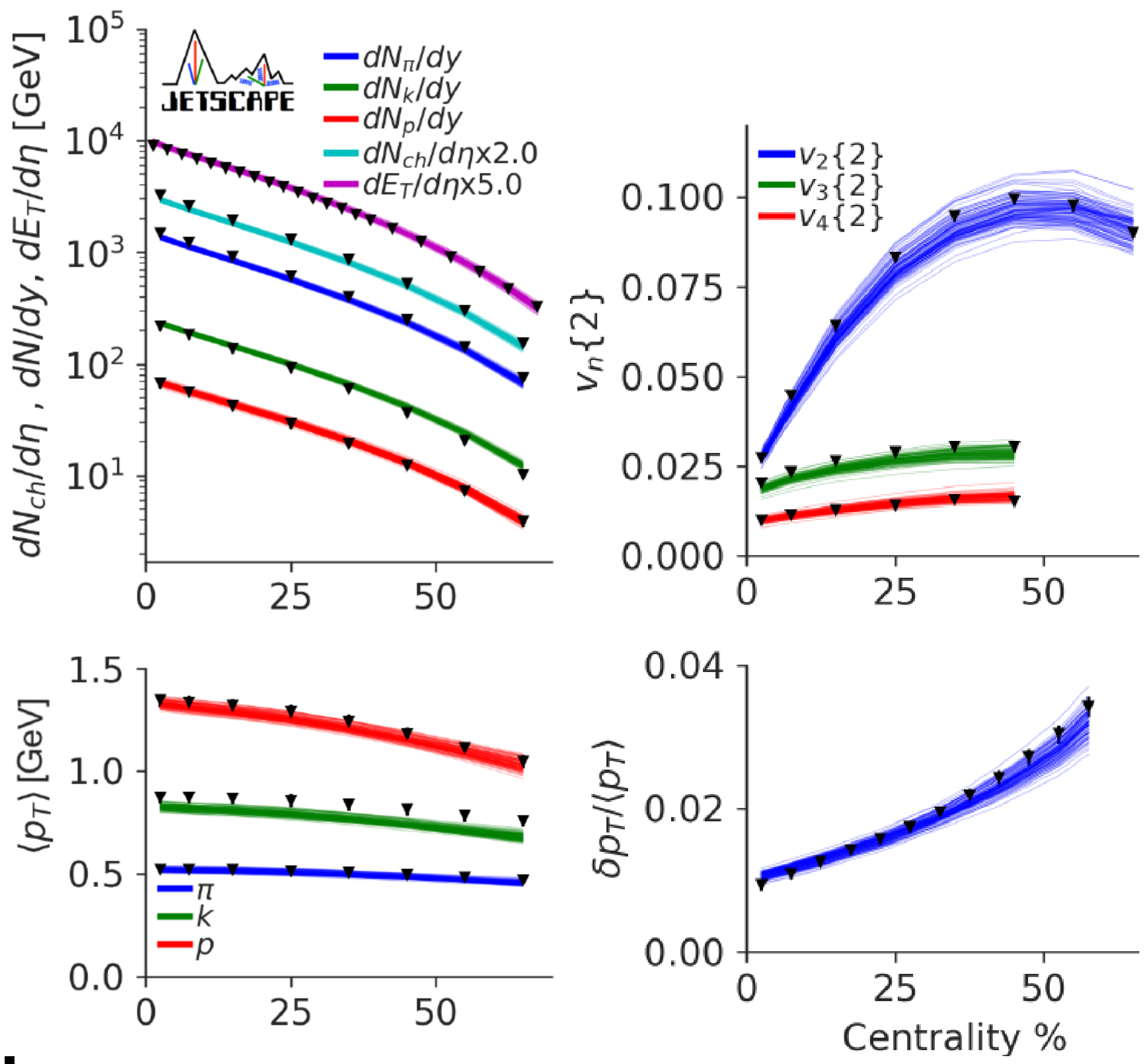
**$\tau \sim 10$ fm: End of "hydrodynamic phase"**

- 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

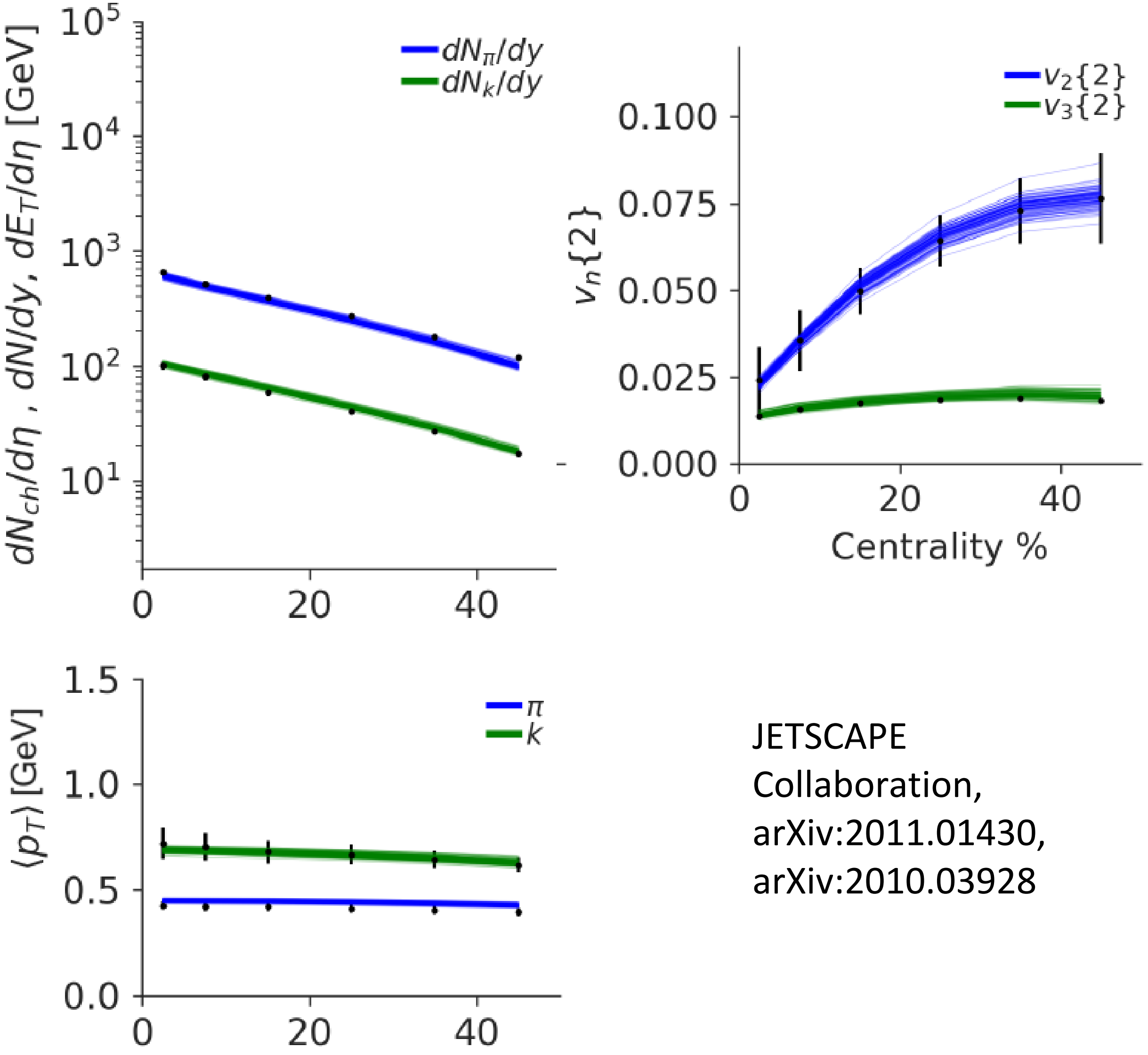


# Calibrating on measurements




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




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

JETSCAPE Collaboration, arXiv:2011.01430, arXiv:2010.03928

# Bayes constraints on model parameters

JETSCAPE Collaboration, arXiv:2011.01430, arXiv:2010.03928

**Mean** value of **measurements**

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

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

# Bayes constraints on model parameters

JETSCAPE Collaboration, arXiv:2011.01430, arXiv:2010.03928

**Mean** value of **measurements**

Experimental and theoretical **uncertainties**

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

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

# Bayes constraints on model parameters

JETSCAPE Collaboration, arXiv:2011.01430, arXiv:2010.03928

**Mean** value of **measurements**

Experimental and theoretical **uncertainties**

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

**External constraints on parameters**:
positivity or range of allowed values, "probabilistic theoretical constraints", …

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

# Bayes constraints on model parameters

JETSCAPE Collaboration, arXiv:2011.01430, arXiv:2010.03928

**Mean** value of **measurements**

Experimental and theoretical **uncertainties**

**Probabilistic constraints on parameters**

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

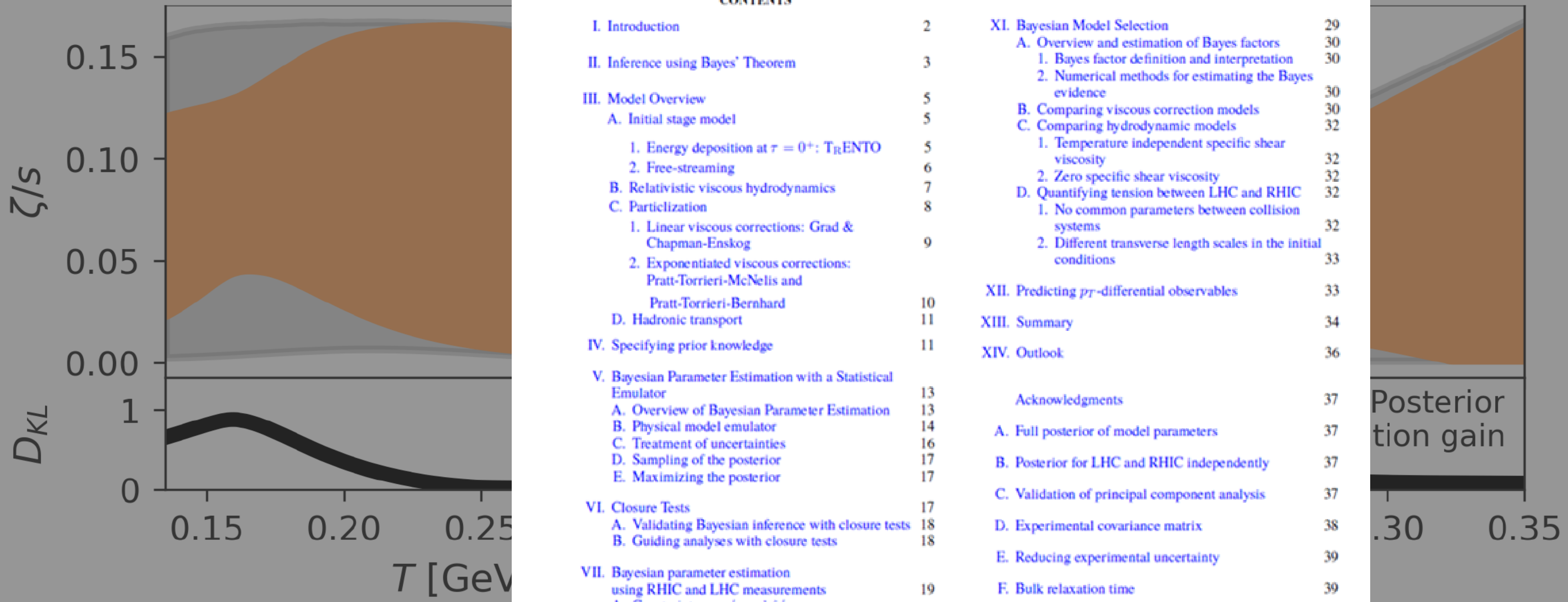
**External constraints on parameters**:
positivity or range of allowed values, "probabilistic theoretical constraints", …

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

# Latest constraints ... -gluo

JETSCAPE Collaboration, arXiv:2011.01430, arXiv:2010.03928

Bulk visc ... y




## 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,[10,11] 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. Wolpert[12]


CONTENTS



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


JETSCAPE Collaboration, arXiv:2011.01430, arXiv:2010.03928

# Latest constraints ... -gluon

Bulk visc ... y

JETSCAPE Collaboration, arXiv:2011.01430, arXiv:2010.03928

## 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,[10,11] 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. Wolpert[12]

CONTENTS



Model description

Priors

Closure tests

Bayesian parameter estimation

Observables sensitivity study

Bayesian model selection

Validation against additional data

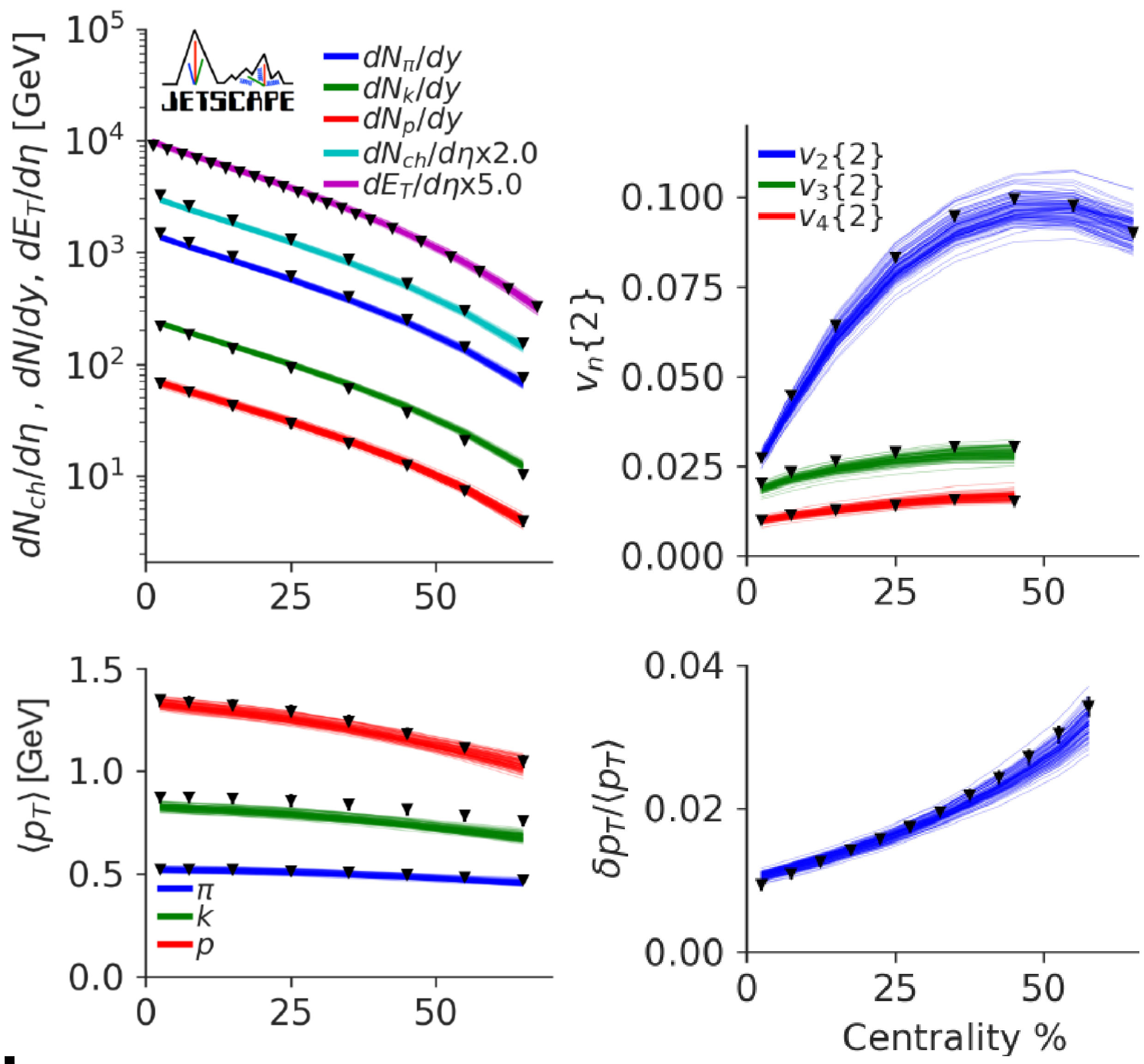
Validation of hydrodynamics against external solutions

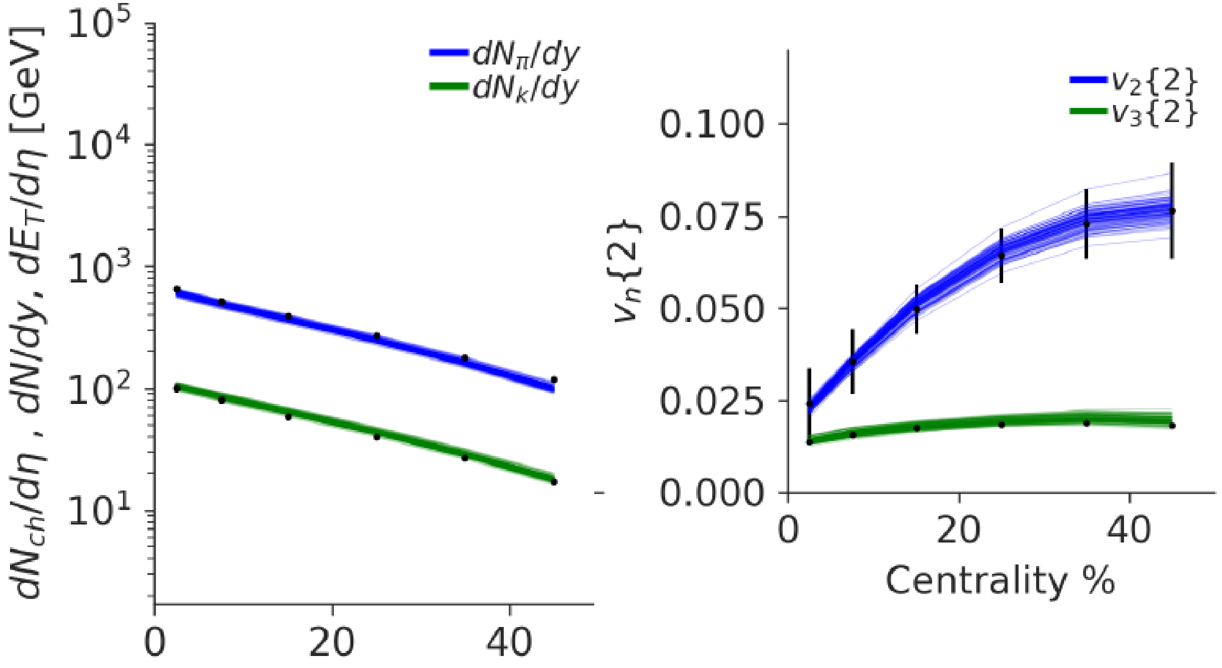
Hadronic transport validation

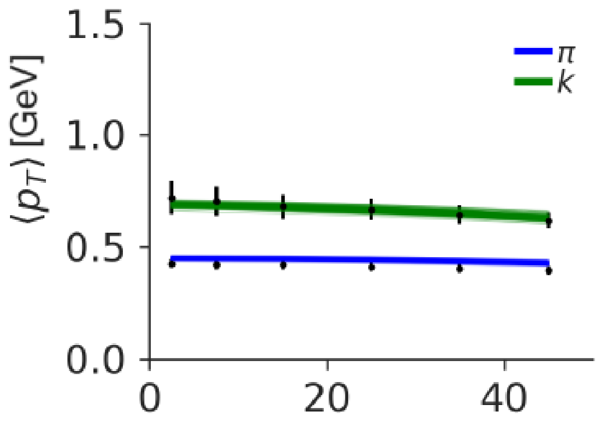
▪ F ... infe

▪ State of the art multi-s ... h

# Agreement with measurements



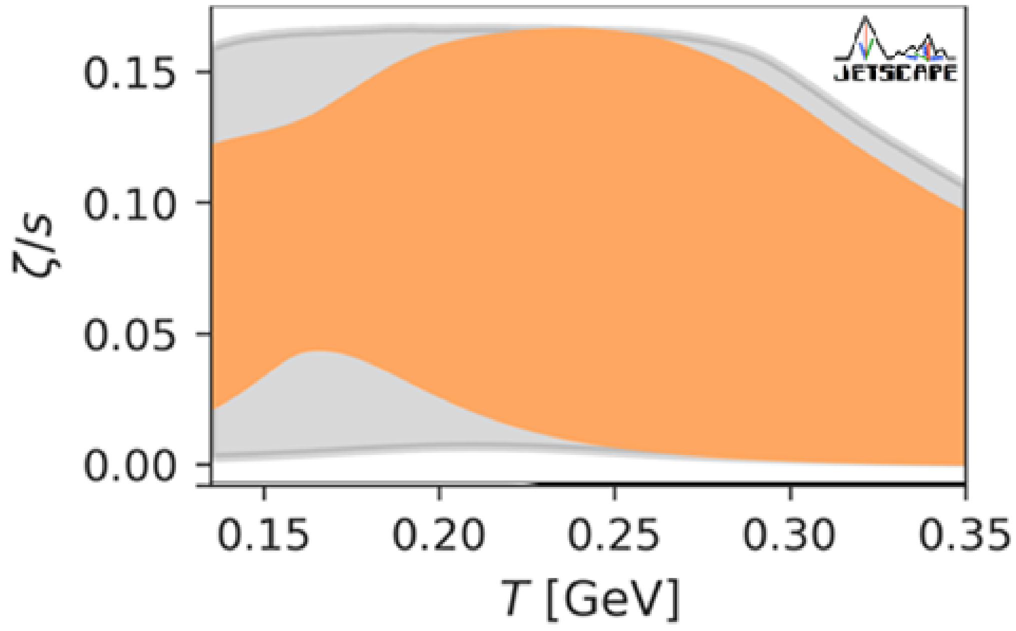

JETSCAPE Collaboration, arXiv:2011.01430, arXiv:2010.03928

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

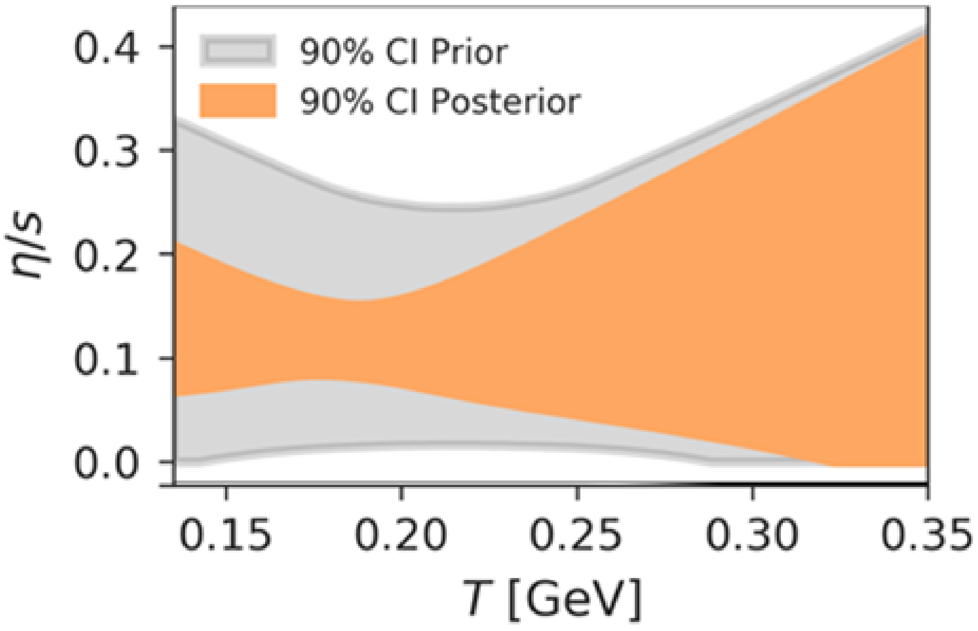
AuAu $\sqrt{s_{NN}}$=200 GeV, STAR Collaboration (RHIC)

# Latest constraints on the viscosities of quark-gluon plasma

Bulk viscosity

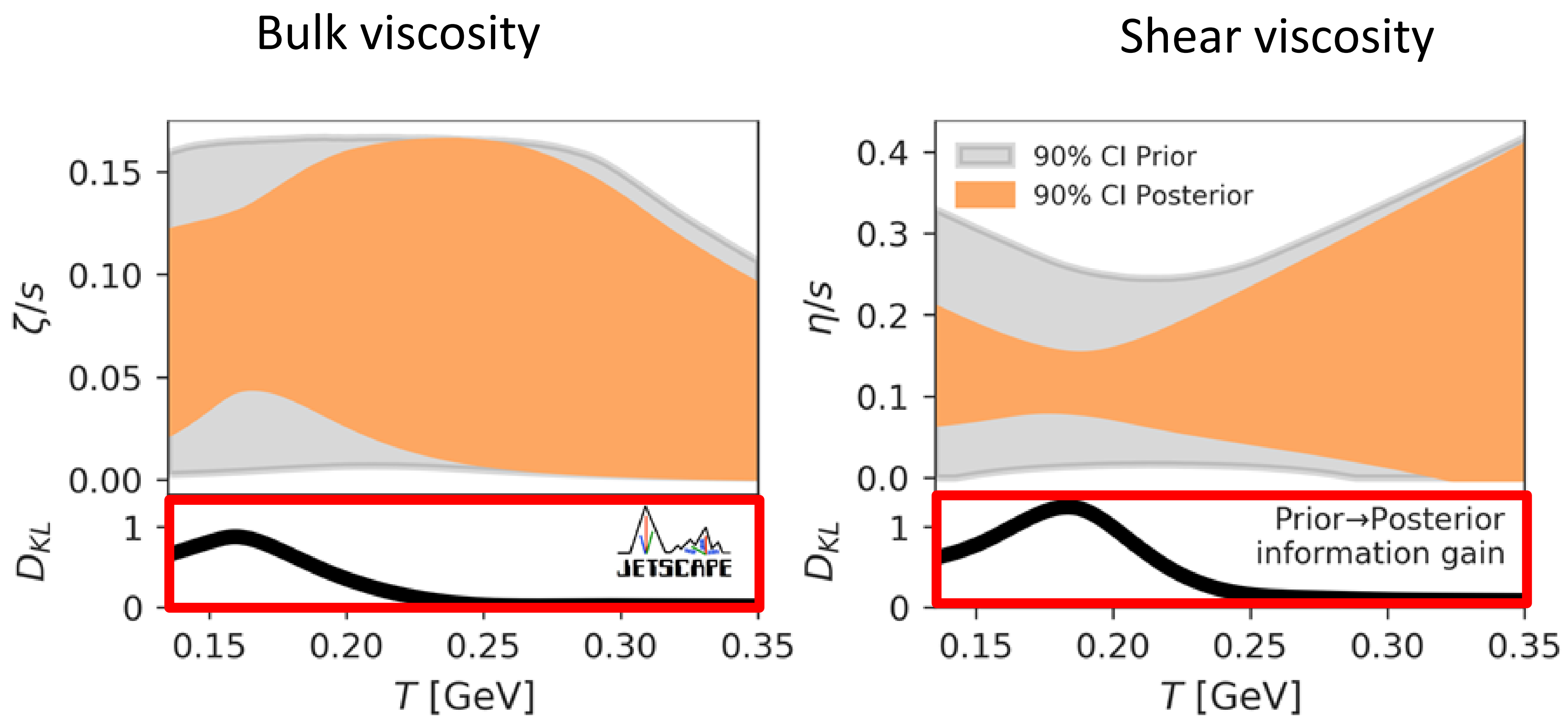



Shear viscosity




JETSCAPE Collaboration, arXiv:2011.01430, arXiv:2010.03928

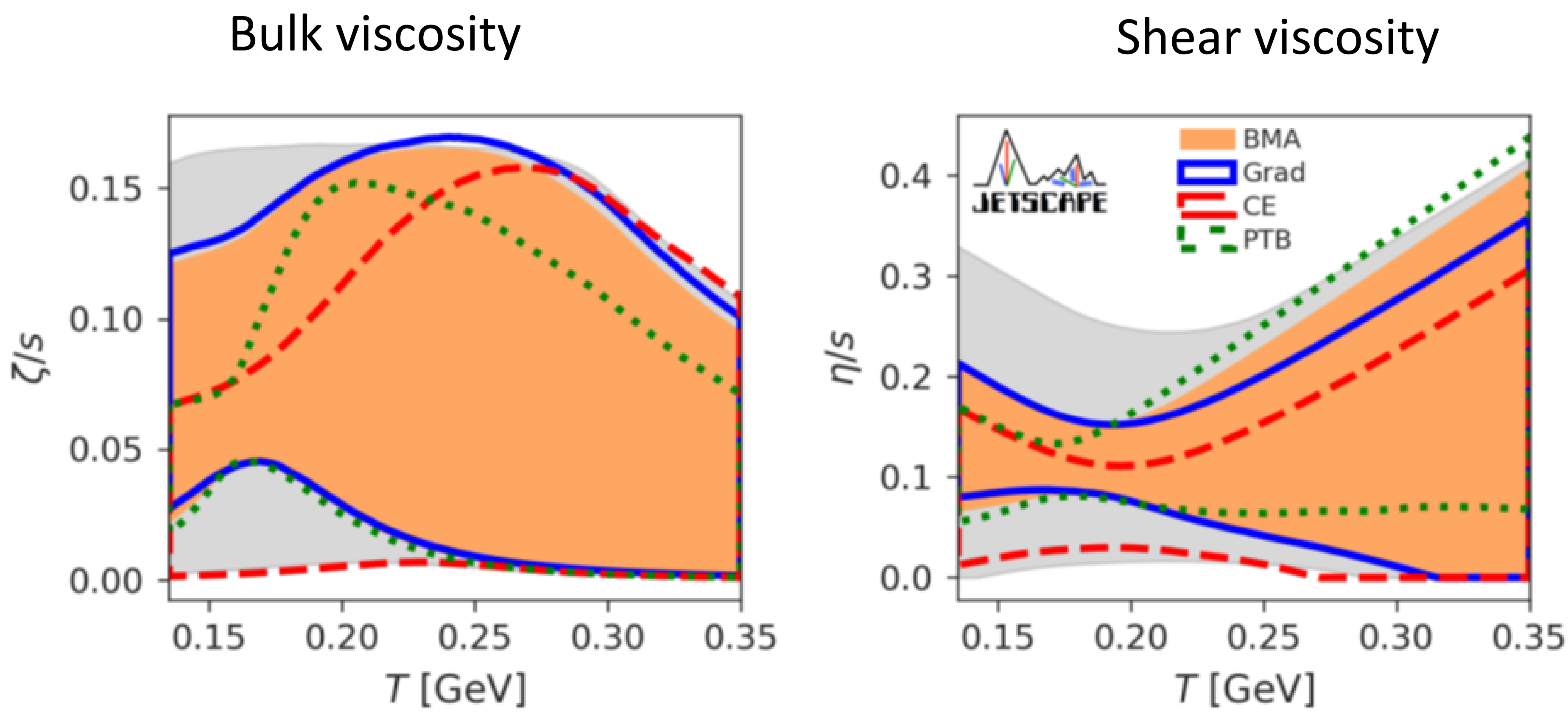
# How to understand Bayesian constraints




JETSCAPE Collaboration, arXiv:2011.01430, arXiv:2010.03928

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

# The importance of including theoretical uncertainties

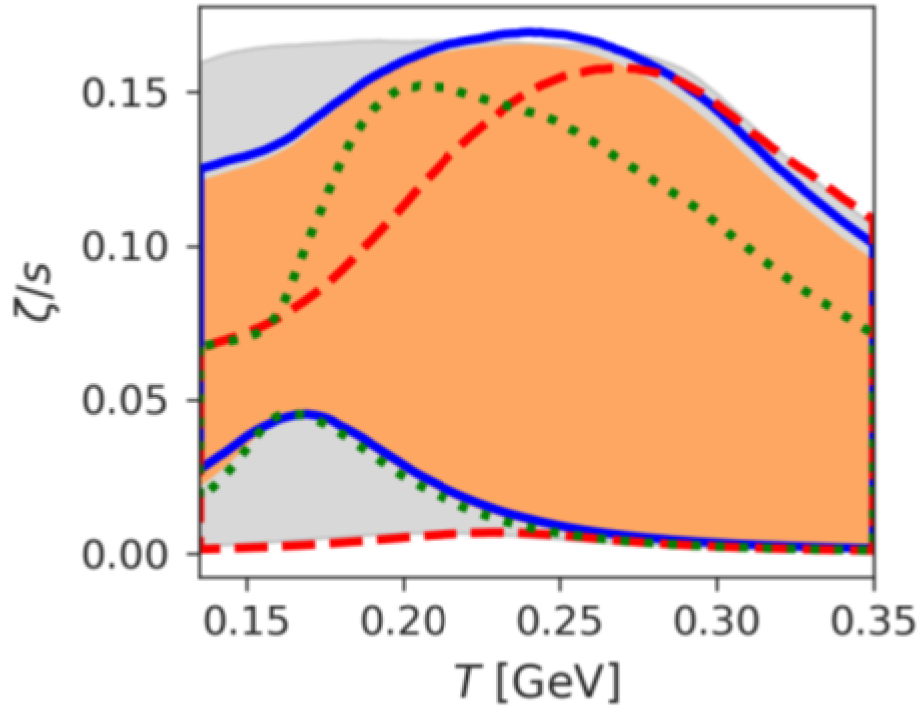



JETSCAPE Collaboration, arXiv:2011.01430, arXiv:2010.03928

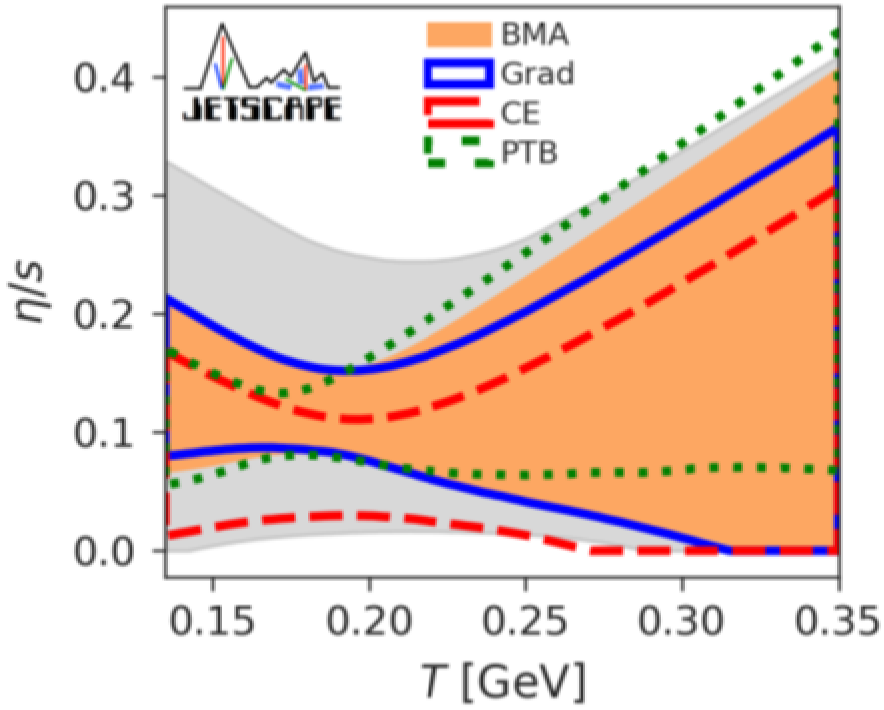
- Different line colours are different “particlization model” (particlization = transition from hydrodynamics to hadronic transport)

# The importance of including theoretical uncertainties

Bulk viscosity



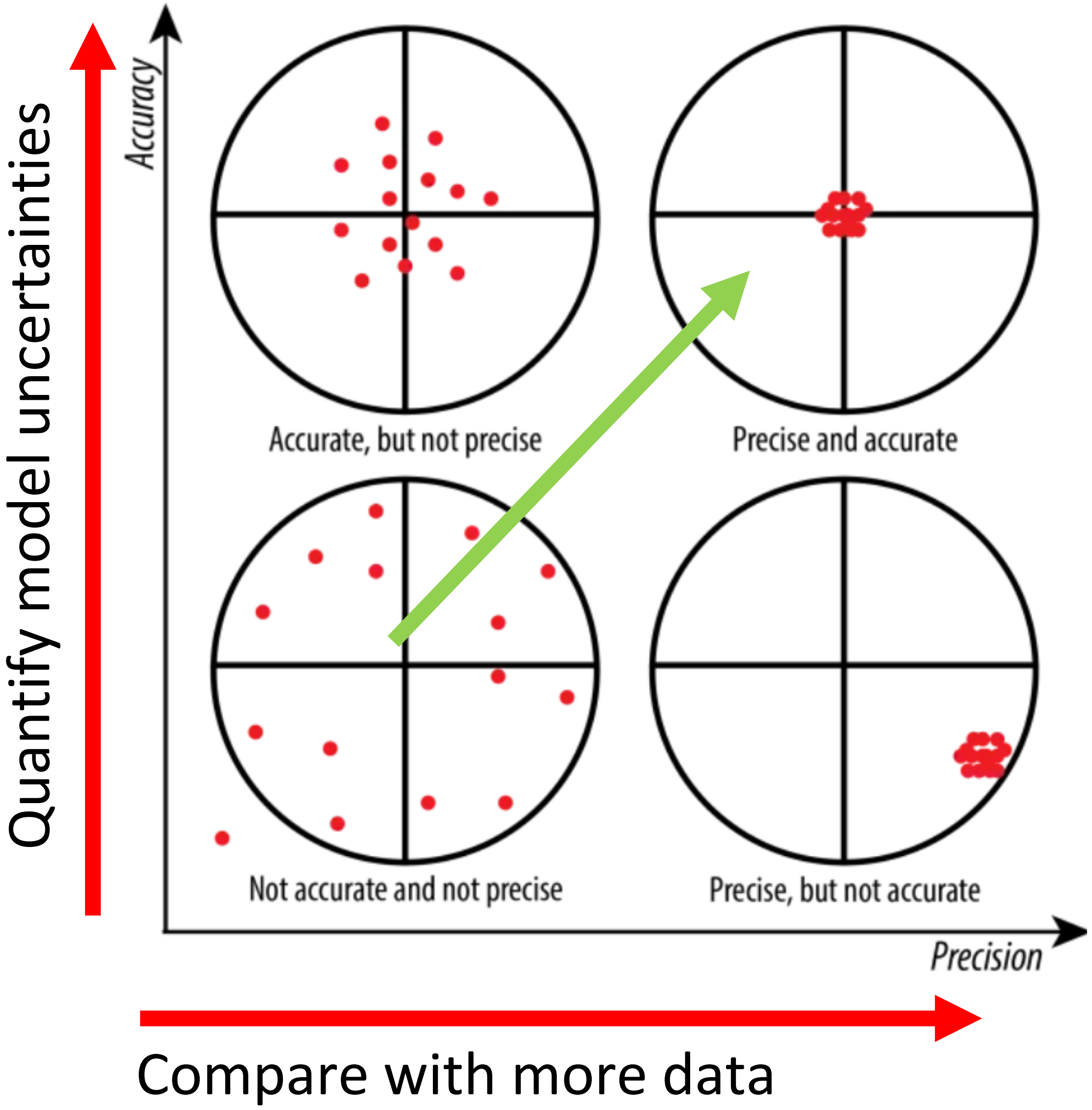

Shear viscosity



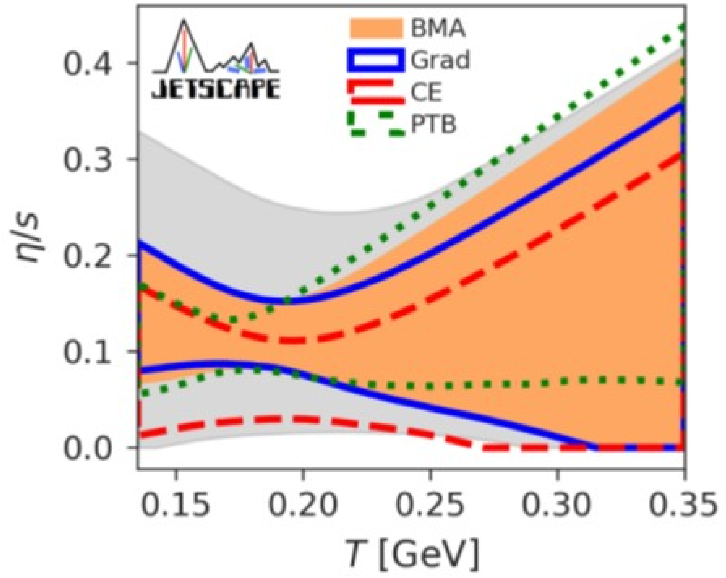

JETSCAPE Collaboration, arXiv:2011.01430, arXiv:2010.03928

- 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



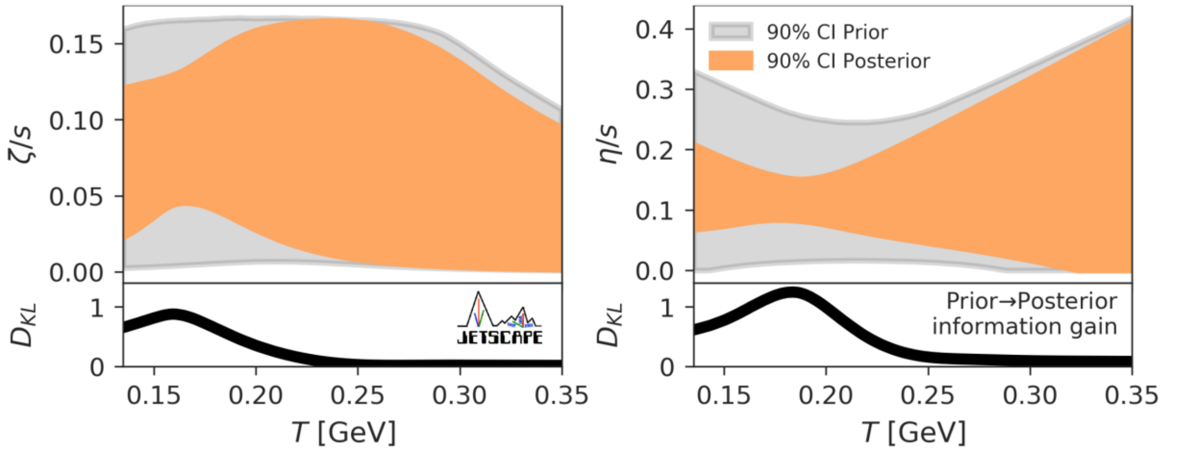

- Important not to confuse narrow constraints with accurate ones
- Relaxing model assumptions generally lead to weaker but more accurate constraints
- More data + inclusion/reduction of model uncertainties = Better constraints on viscosities




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

# 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 $\neq$ 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
  ⇒ **<u>Initial conditions</u>**; 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/1827929)
[https://inspirehep.net/literature/1821941](https://inspirehep.net/literature/1821941)

arXiv | 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 | Cornell University

High Energy Physics - Phenomenology

**arXiv:2010.03928** (hep-ph)

[Submitted on 8 Oct 2020]

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

**This work was supported by:**

NSF

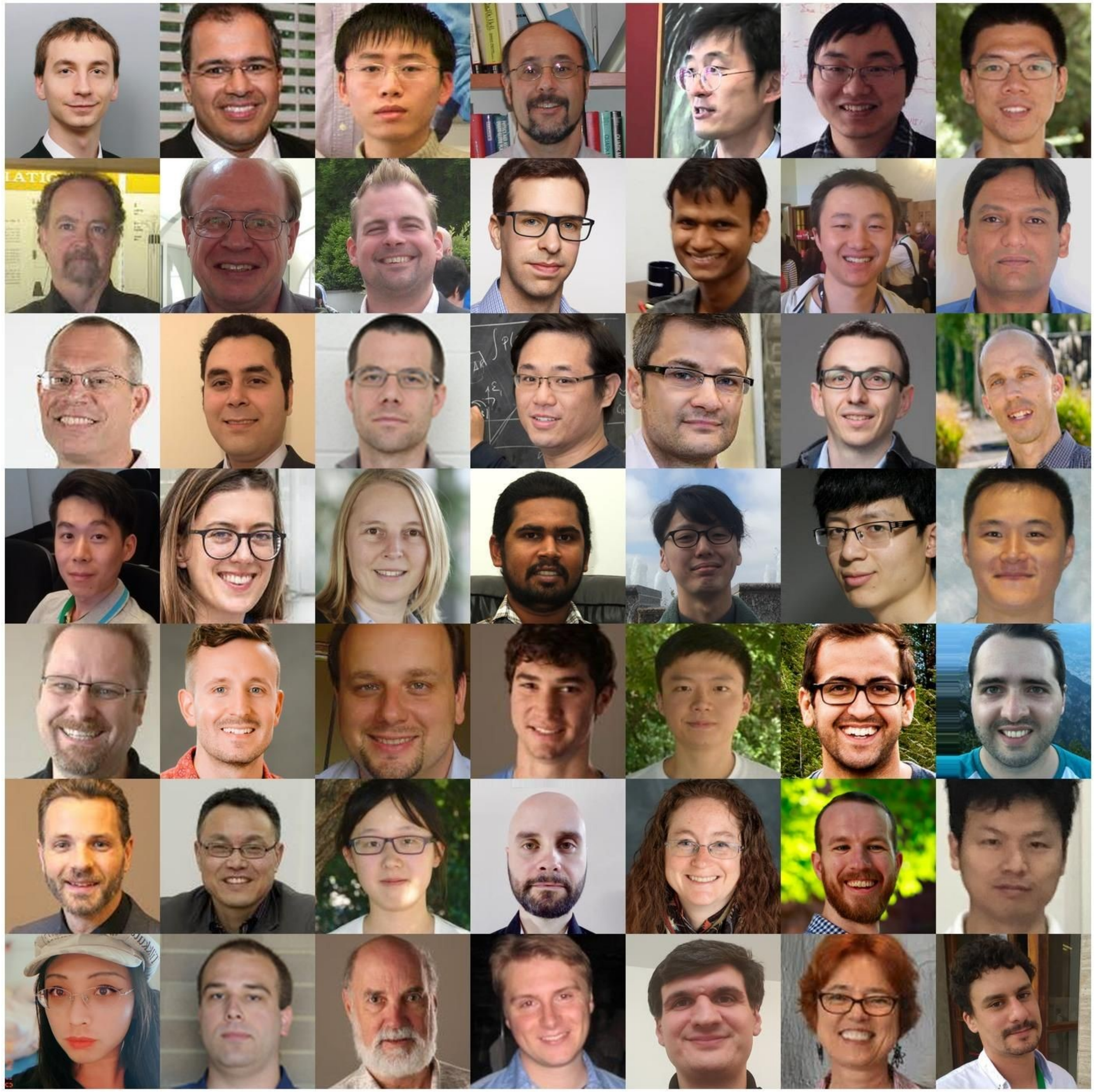
U.S. DEPARTMENT OF ENERGY | Office of Science

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

XSEDE
Extreme Science and Engineering Discovery Environment

**Computational resources from XSEDE & TACC**

# The JETSCAPE Collaboration



D. Everett (Ohio State U.), W. Ke (UC, Berkeley and LBNL, NSD), J.-F. Paquet (Duke U.), G. Vujanovic (Wayne State U.), S.A. Bass (Duke U.), L. Du (Ohio State U.), C. Gale (McGill U.), M. Heffernan (McGill U.), U. Heinz (Ohio State U.), D. Liyanage (Ohio State U.), M. Luzum (Sao Paulo U.), A. Majumder (Wayne State U.), M. McNelis (Ohio State U.), C. Shen (Wayne State U. and RIKEN BNL), Y. Xu (Duke U.), A. Angerami (LLNL, Livermore), S. Cao (Wayne State U.), Y. Chen (MIT, LNS and MIT, Cambridge, Dept. Phys.), J. Coleman (Duke U.), L. Cunqueiro (Tennessee U. and Oak Ridge), T. Dai (Duke U.), R. Ehlers (Tennessee U. and Oak Ridge), H. Elfner (Darmstadt, GSI and Frankfurt U. and Frankfurt U., FIAS), W. Fan (Duke U.), R.J. Fries (Texas A-M, Cyclotron Inst. and Texas A-M), F. Garza (Texas A-M, Cyclotron Inst. and Texas A-M), Y. He (CCNU, Wuhan, Inst. Part. Phys. and Hua-Zhong Normal U., LQLP), B.V. Jacak (UC, Berkeley and LBNL, NSD), P.M. Jacobs (UC, Berkeley and LBNL, NSD), S. Jeon (McGill U.), B. Kim (Texas A-M, Cyclotron Inst. and Texas A-M), M. Kordell, II (Texas A-M, Cyclotron Inst. and Texas A-M), A. Kumar (Wayne State U.), S. Mak (Duke U.), J. Mulligan (UC, Berkeley and LBNL, NSD), C. Nattrass (Tennessee U.), D. Oliinychenko (LBNL, NSD), C. Park (McGill U.), J.H. Putschke (Wayne State U.), G. Roland (MIT, LNS and MIT, Cambridge, Dept. Phys.), B. Schenke (Brookhaven), L. Schwiebert (Wayne State U.), A. Silva (Tennessee U.), C. Sirimanna (Wayne State U.), R.A. Soltz (Wayne State U. and LLNL, Livermore), Y. Tachibana (Wayne State U.), X.-N. Wang (CCNU, Wuhan, Inst. Part. Phys. and Hua-Zhong Normal U., LQLP and UC, Berkeley and LBNL, NSD), R.L. Wolpert (Duke U.)

# Questions?

# References for multistage model

JETSCAPE Collaboration, arXiv:2011.01430, arXiv:2010.03928

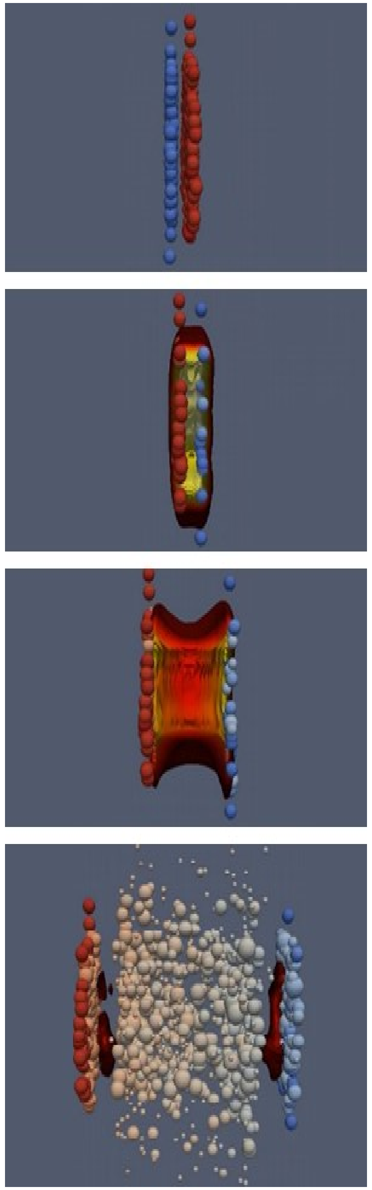


Figure ref.: J. Bernhard, H. Petersen, MADAI Collaboration

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

- Trento ansatz used to parametrize the energy deposition

Ref.: Moreland, Bernhard, Bass (2015) PRC92,011901

## $\tau \sim 0.1$ 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

## $\tau \sim 10$ 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

$$\frac{y_{model} - y_{exp}}{\sigma_{exp}}$$