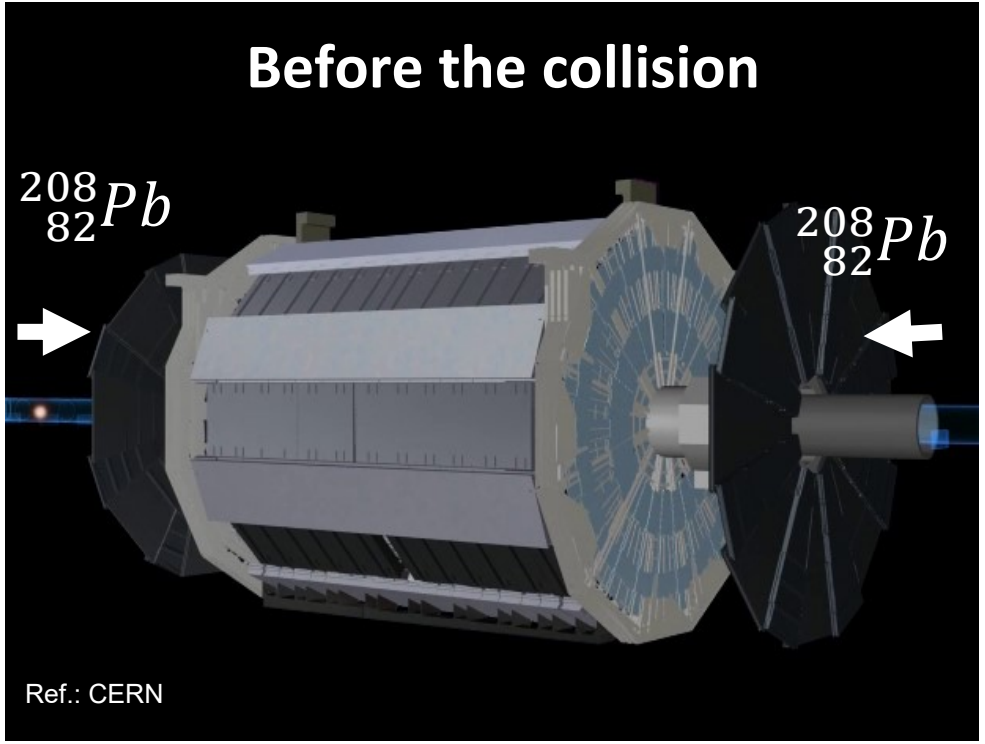
Bayesian inference in heavy ion collisions

Jean-François Paquet (Duke University)

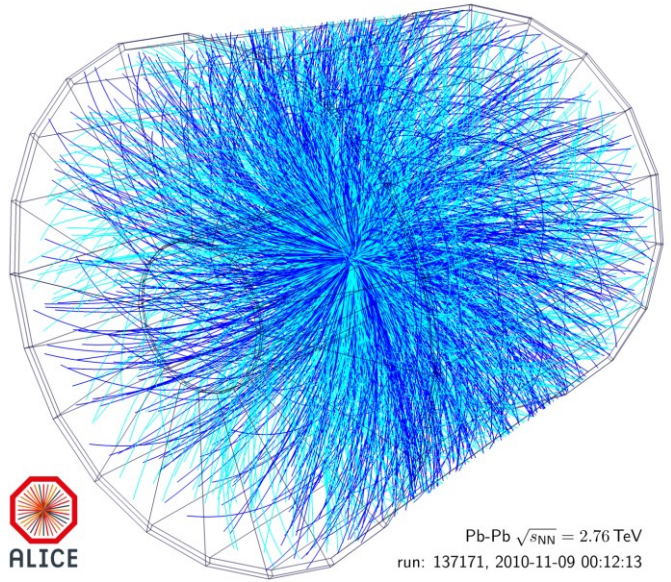
May 17, 2022

Live from Durham,
North Carolina

Before the collision



After the collisions



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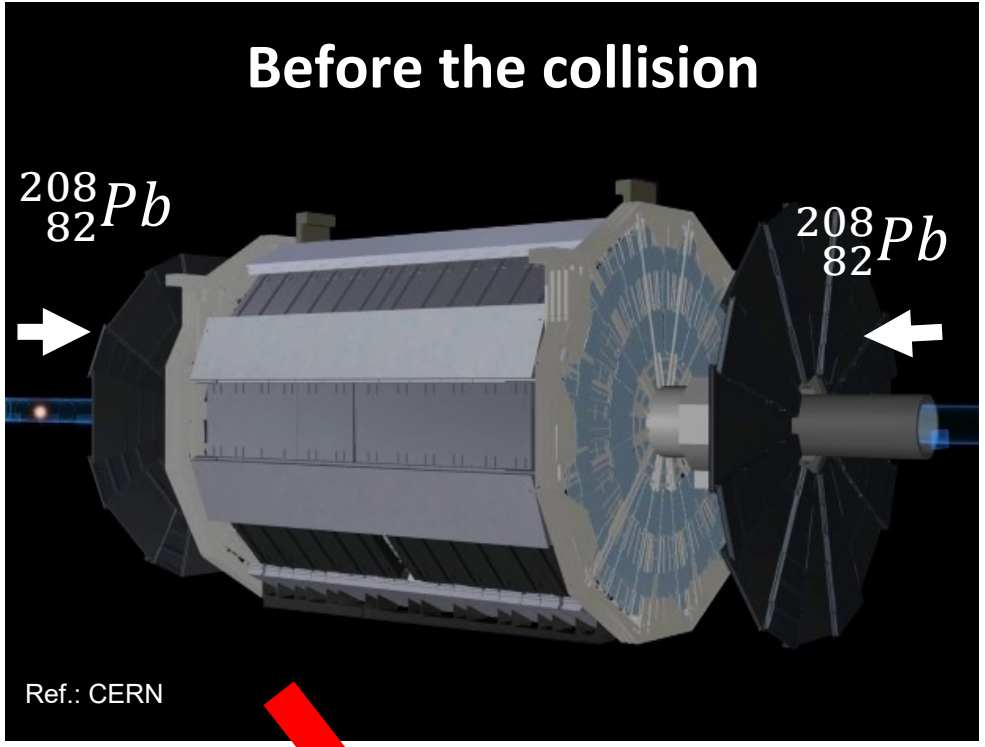
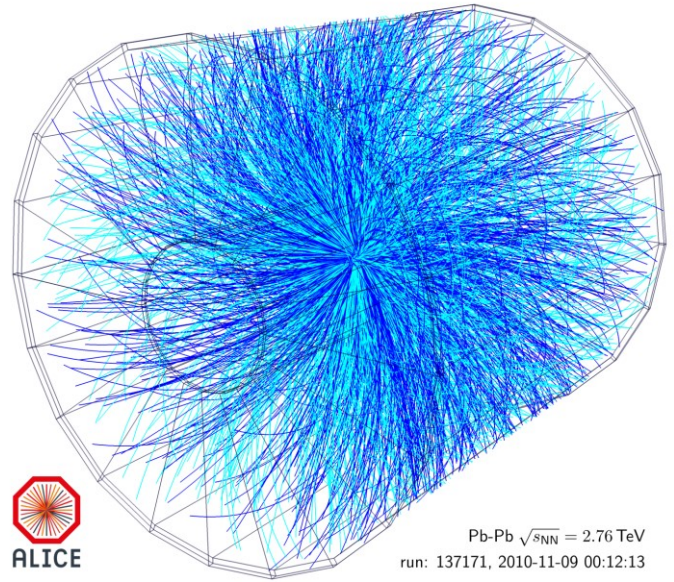
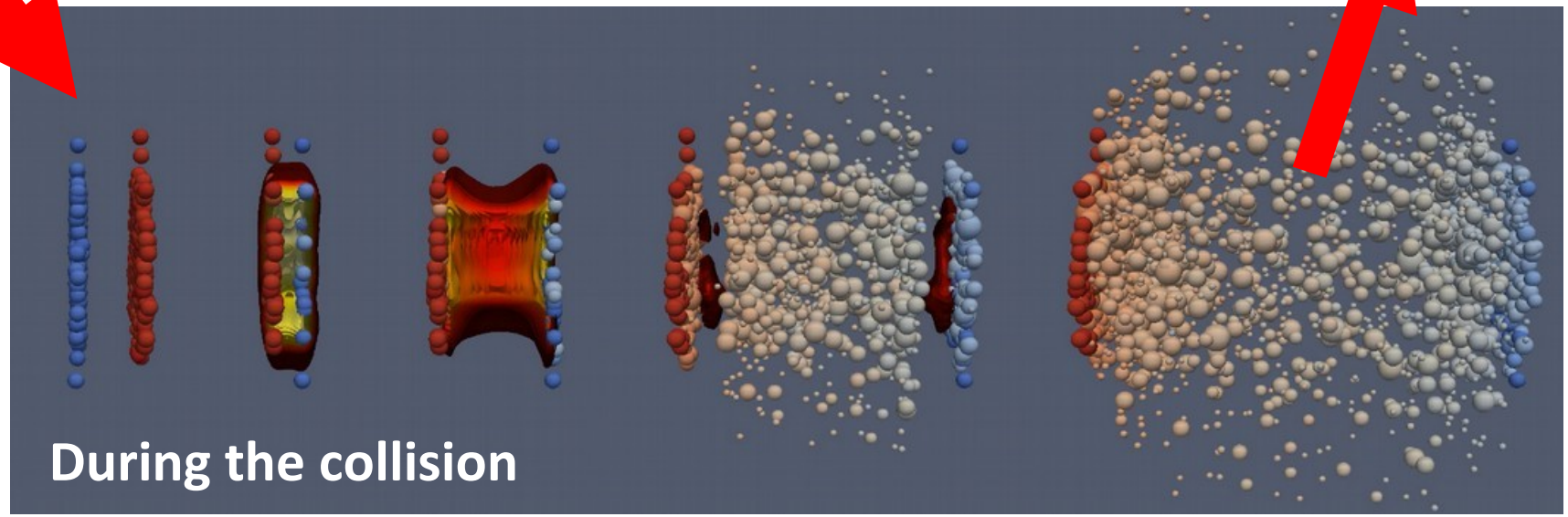


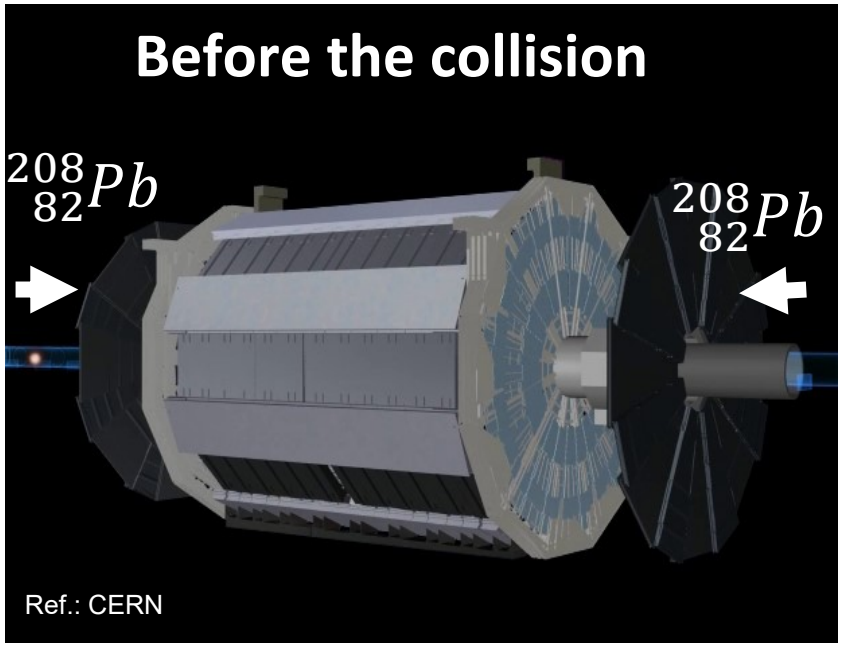
After the collisions





Ref: MADAI collaboration, Hannah Elfner and Jonah Bernhard

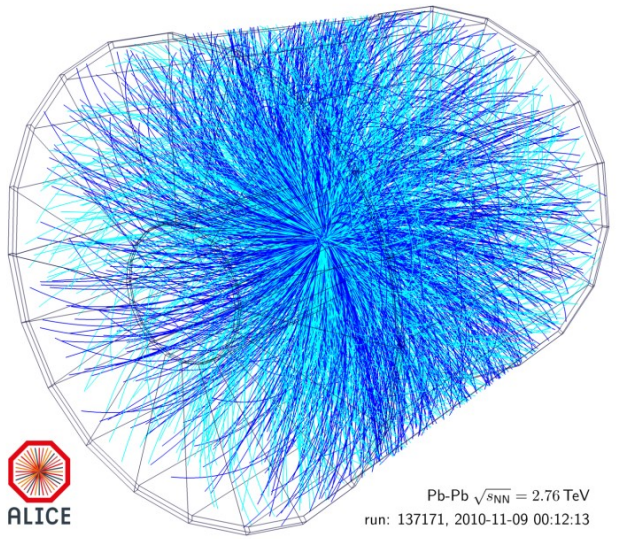
Many-body properties of nuclear matter



Simulation of the collisions

(Sensitive to many-body properties of nuclear matter)

After the collisions



What properties of hot nuclear matter are consistent with the measurements?

- Properties of the quark-gluon plasma (equation of state, viscosity, …)
- Properties of energetic partons interacting with the quark-gluon plasma (“$\hat{q}$”, …)

Near-equilibrium properties of the quark-gluon plasma

- Equilibrium properties of fluid:
  thermodynamics, equation of state

Ref: Wikipedia

- Near-equilibrium properties?

Wave propagating at the speed of sound c_s

$$\text{Perturbation} \propto \exp\left[i\, c_s\, k\, t - i\, \vec{k}\cdot\vec{x} - \left(\frac{4}{3}\frac{\eta}{s} + \frac{\zeta}{s}\right)\frac{k}{2T}\, k\, t\right]$$

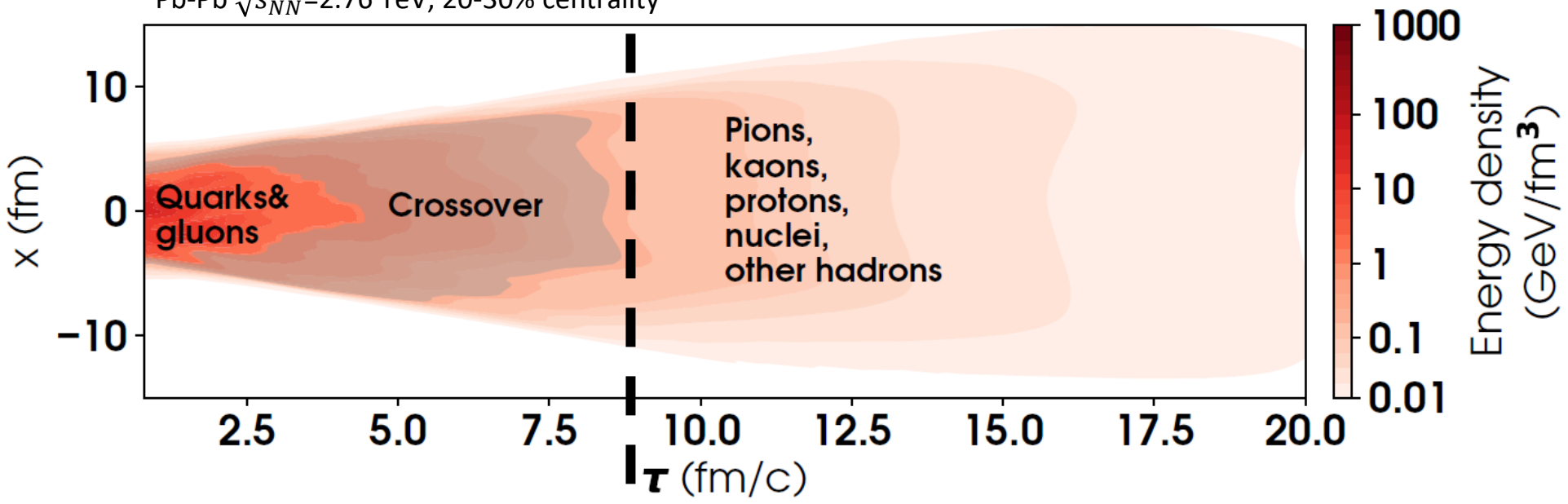
Decay rate of perturbation

- Specific shear viscosity η/s and bulk viscosity ζ/s are **"transport coefficients"**
  ("s" is the entropy density)

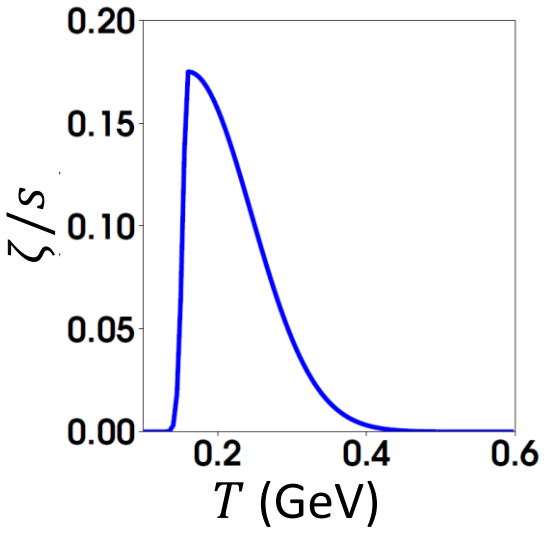
Viscosities affect the evolution of the plasma

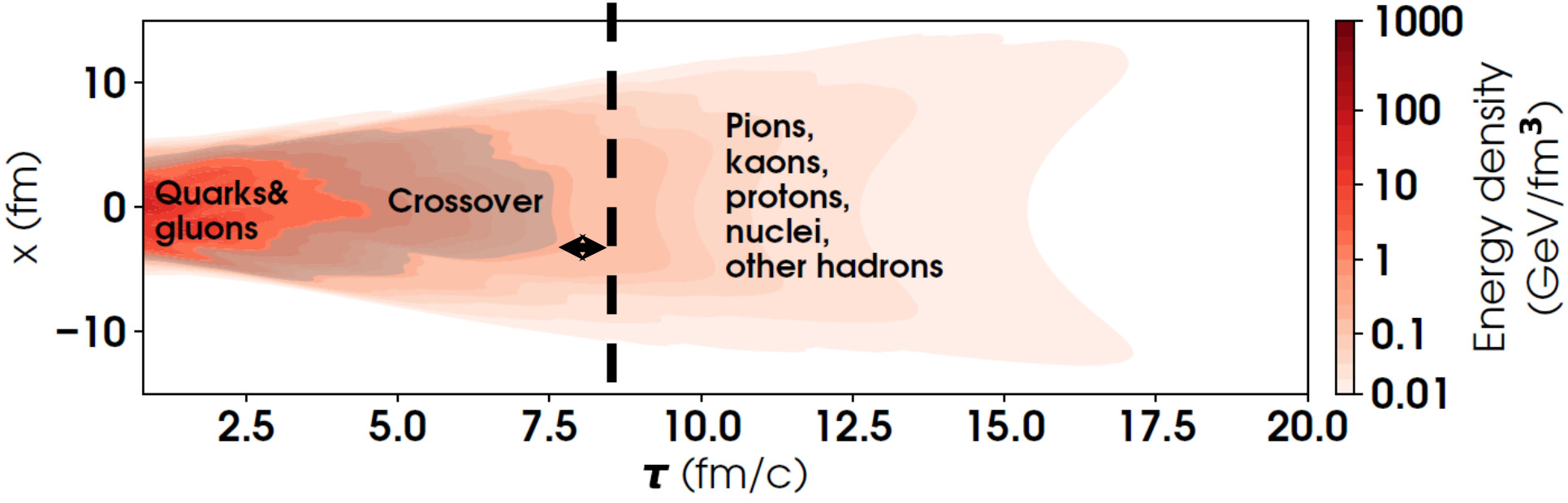
Ref.: Gale, JFP, Schenke and Shen, PRC 2021

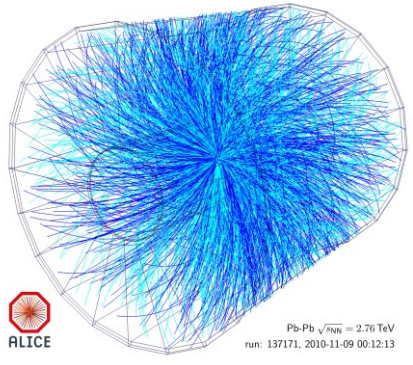
Pb-Pb $\sqrt{s_{NN}}$=2.76 TeV; 20-30% centrality



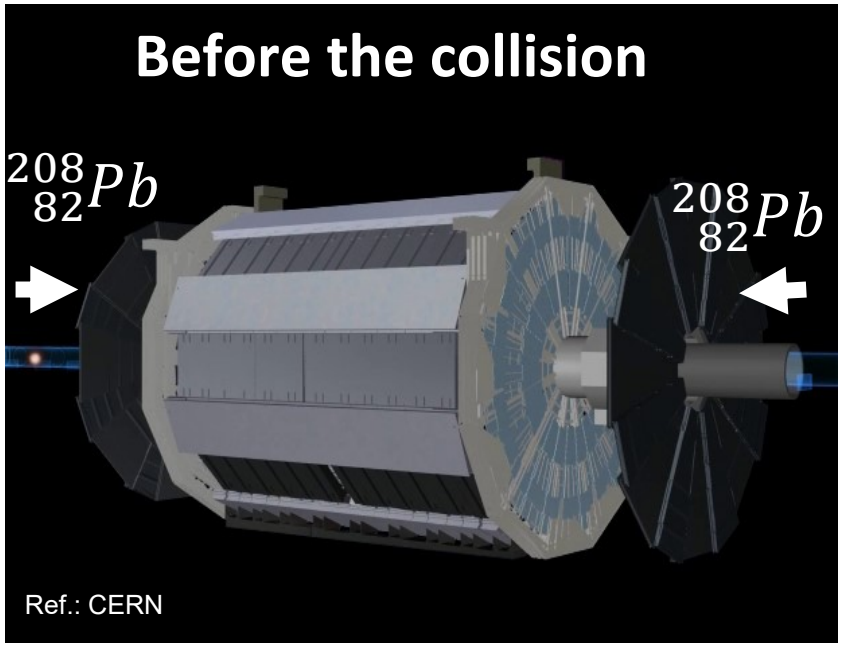
Bulk viscosity







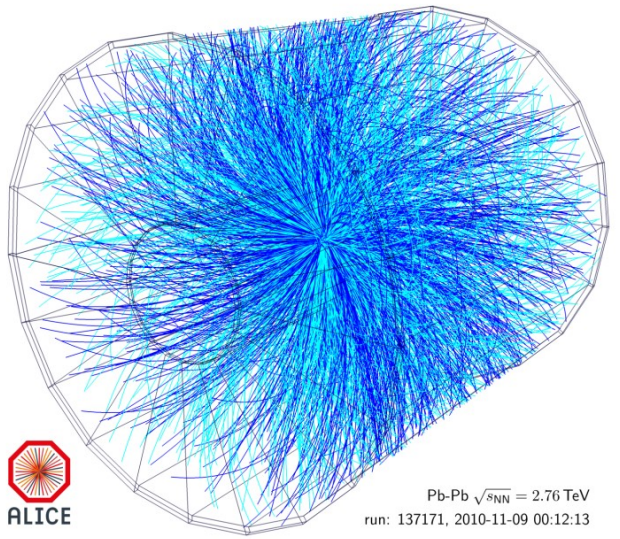
Bayesian inference & inverse problem in heavy ion collisions



Simulation of the collisions

(Sensitive to many-body properties of nuclear matter)

After the collisions



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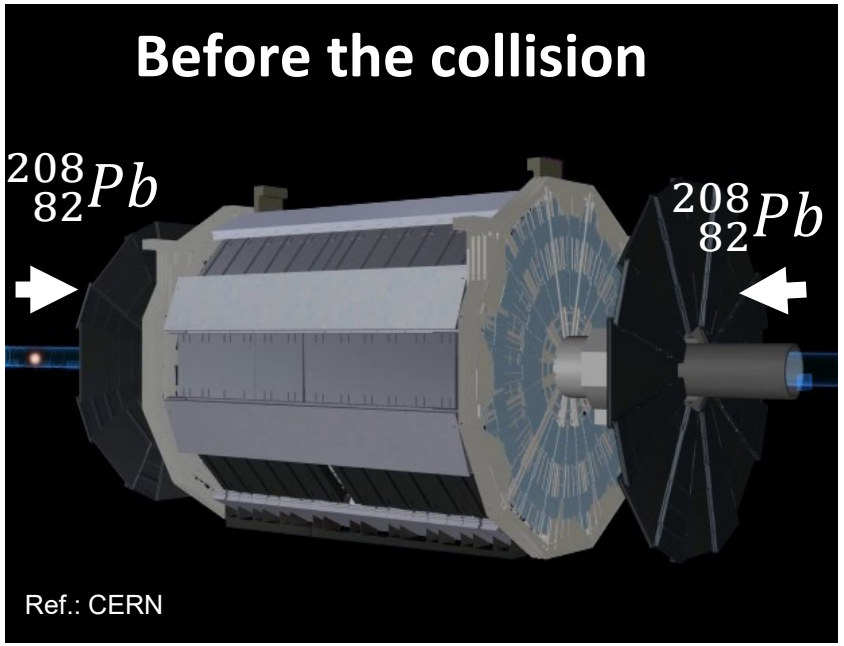

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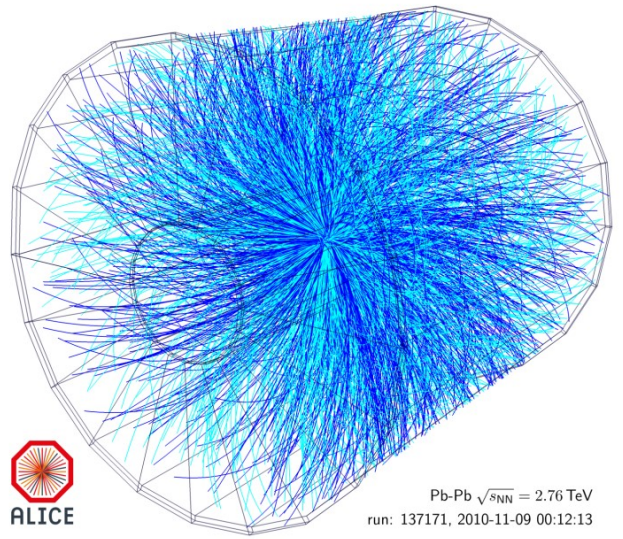


Bayes' theorem

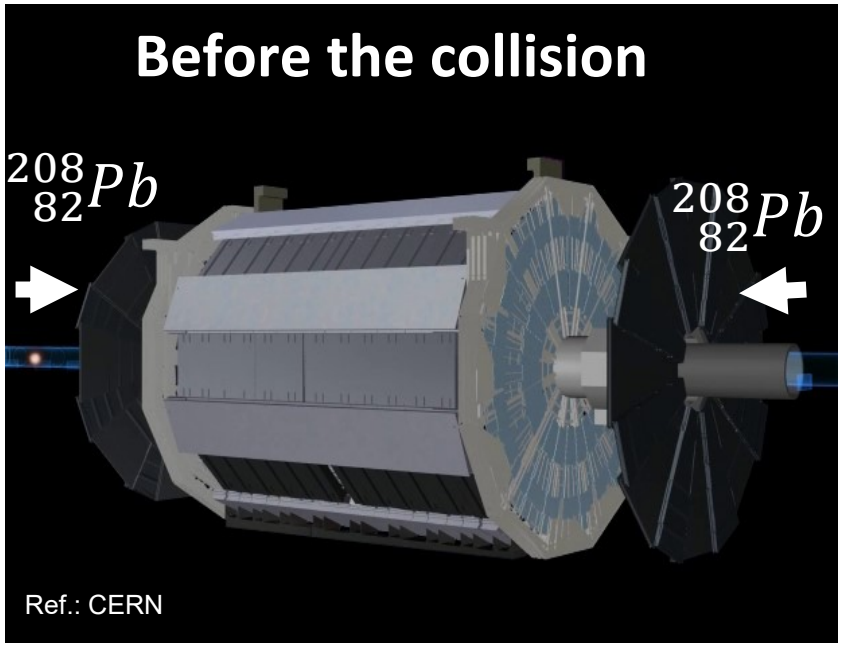
$$\mathbf{prob(obs)} \times \mathbf{prob(param|obs)} = \mathbf{prob(p, obs)} = \mathbf{prob(param)} \times \mathbf{prob(obs|param)}$$

Evidence × **Posterior** = **Joint** = **Prior** × **Likelihood**

Outputs **Inputs**

Adapted from: John Skilling - "Foundations and algorithms" in Bayesian Methods in Cosmology, Cambridge University Press, 2009.

Bayesian inference & inverse problem in heavy ion collisions



Simulation of the collisions

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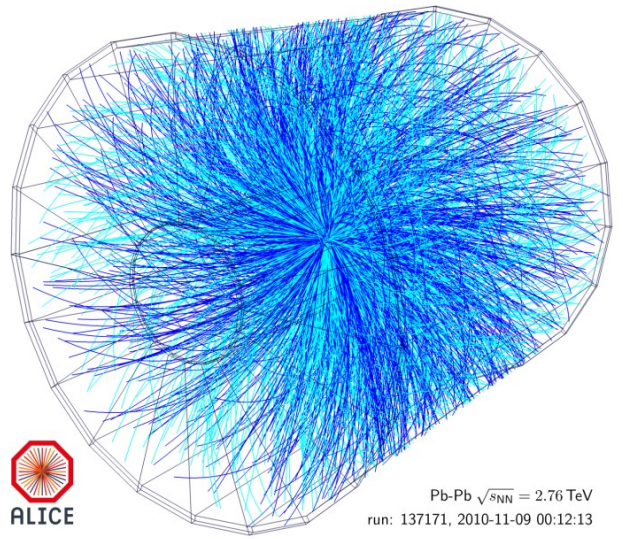

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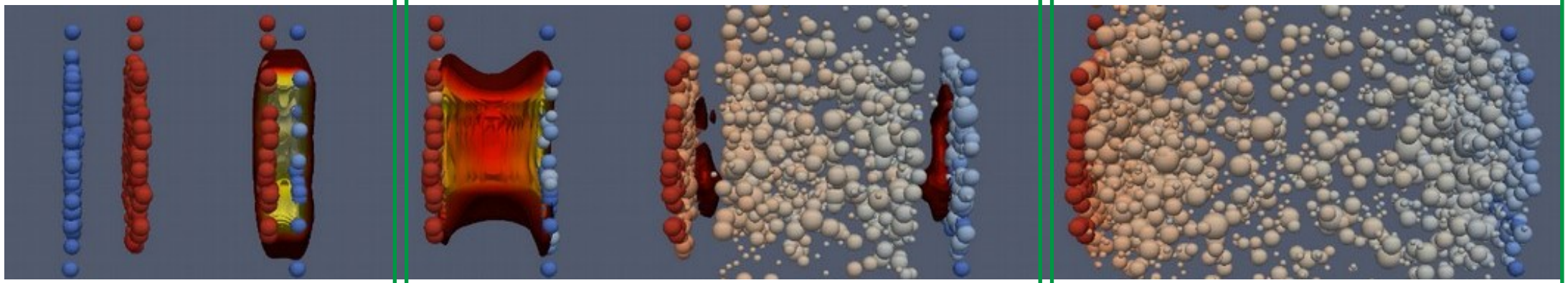
Evidence × **Posterior** = **Joint** = **Prior** × **Likelihood**

$$\propto exp\left[-\frac{\big(obs - model(param)\big)^{T}(covariance\ matrix)^{-1}\big(obs - model(param)\big)}{2}\right]$$

Example: shear and bulk viscosity of the quark-gluon plasma

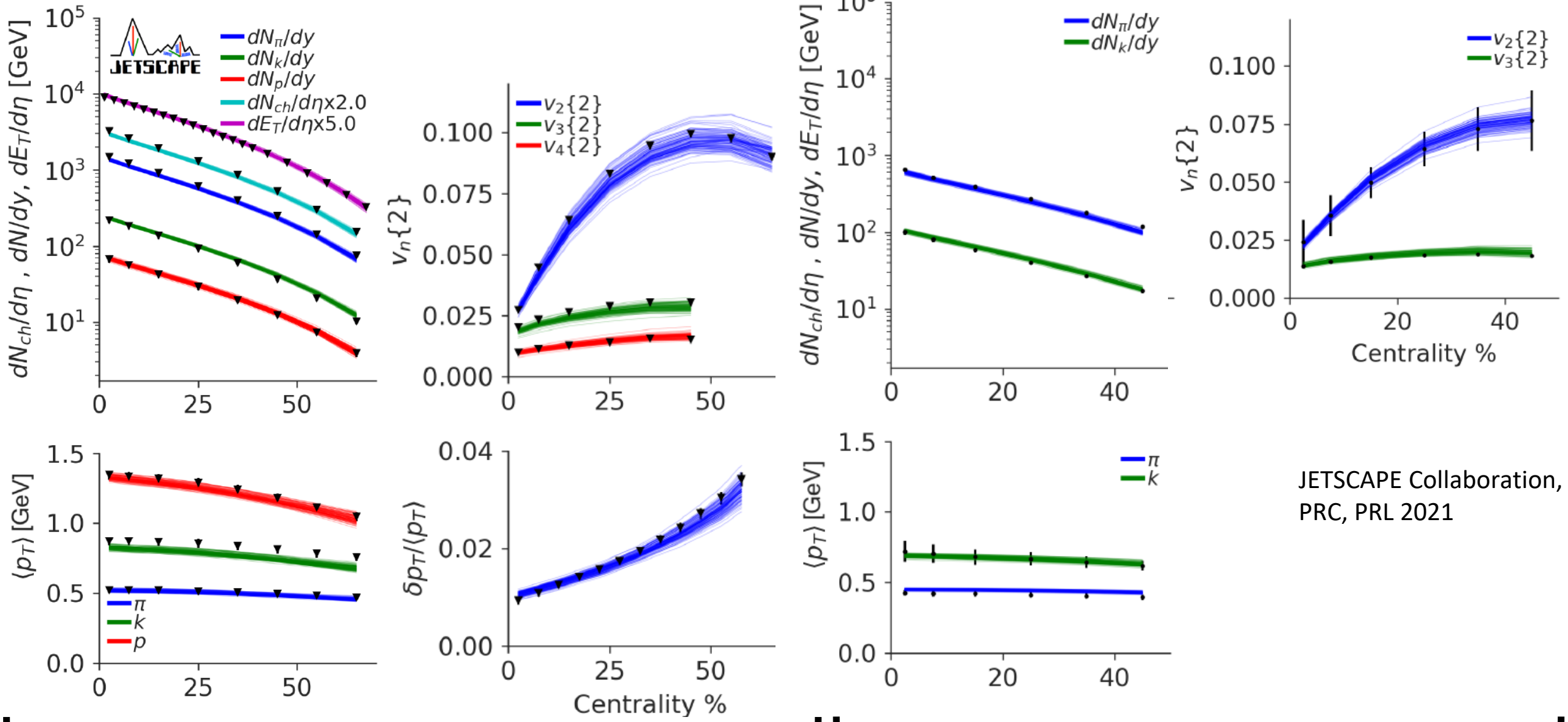
Model:

Initial stage (Trento+freestream.)	Relativistic viscous fluid dynamics	Relativistic hadronic transport
		
7 parameters	9 parameters	1 parameter

Data: all at midrapidity, from STAR Au-Au $\sqrt{s_{NN}}$=200 GeV and ALICE Pb-Pb $\sqrt{s_{NN}}$=2760 GeV

- Pion, kaon & proton multiplicity at midrapidity
- Pion, kaon & proton mean transverse momentum at midrapidity
- Charged hadron anisotropic flow ($v_{2/3/4}\{2\}$)
- Mean transverse momentum fluctuations; transverse energy

Example: shear and bulk viscosity of the quark-gluon plasma



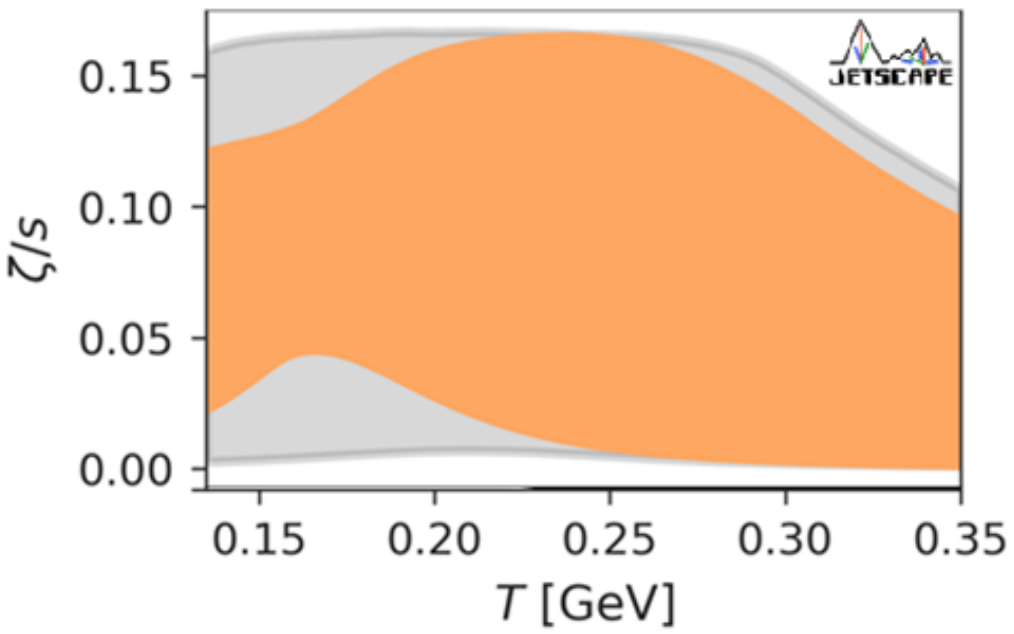
JETSCAPE Collaboration, PRC, PRL 2021

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

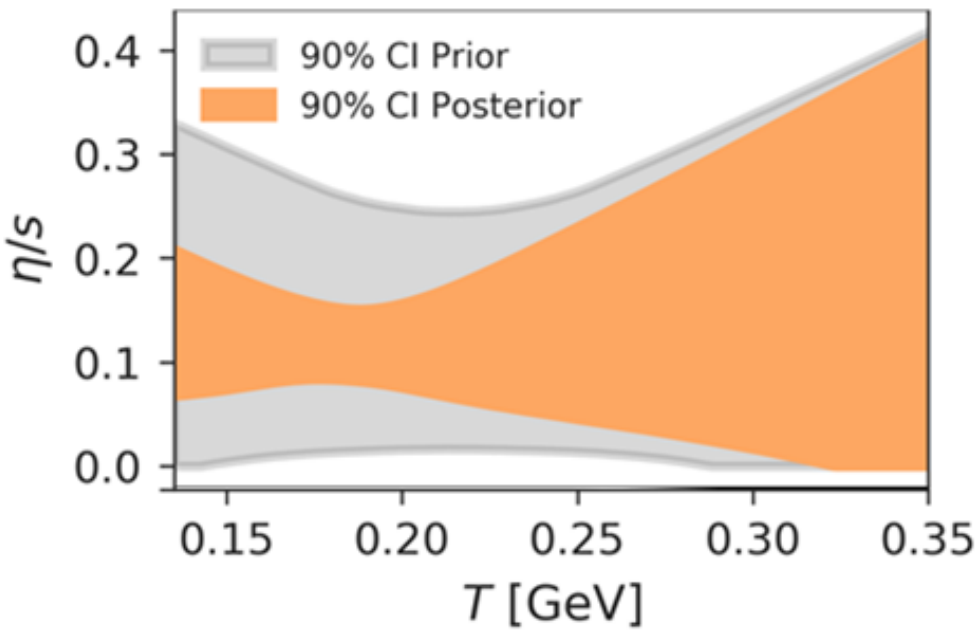
AuAu $\sqrt{s_{NN}}$=200 GeV, STAR Collaboration (RHIC)

Example: shear and bulk viscosity of the quark-gluon plasma

Bulk viscosity



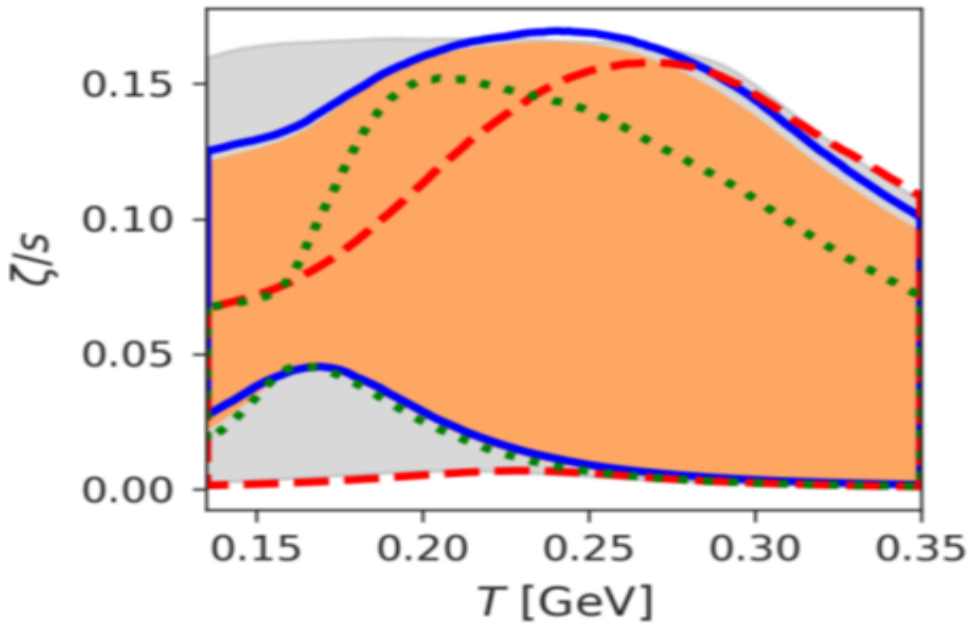
Shear viscosity



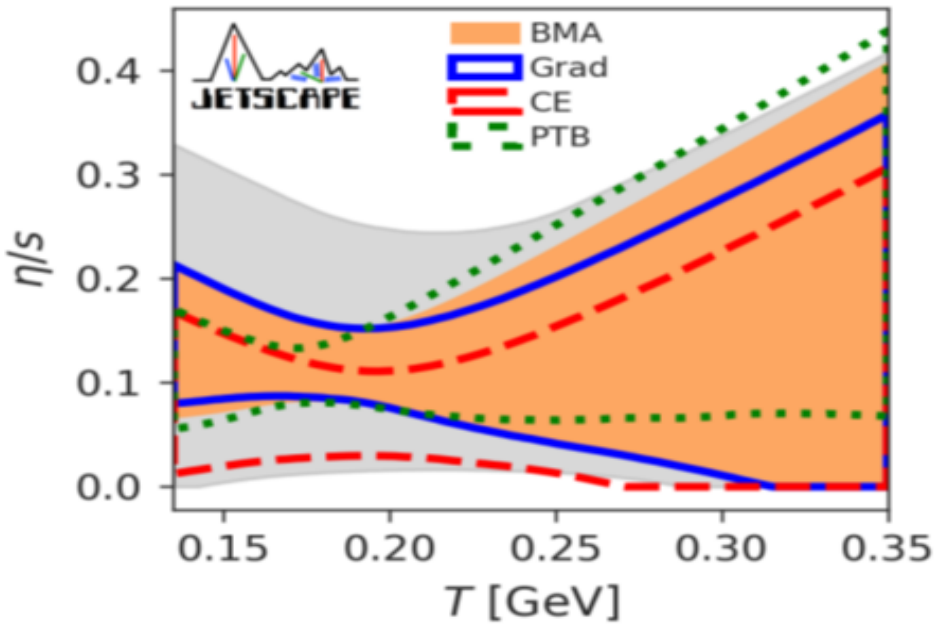
JETSCAPE Collaboration, PRC,PRL 2021

Example: shear and bulk viscosity of the quark-gluon plasma

Bulk viscosity



Shear viscosity



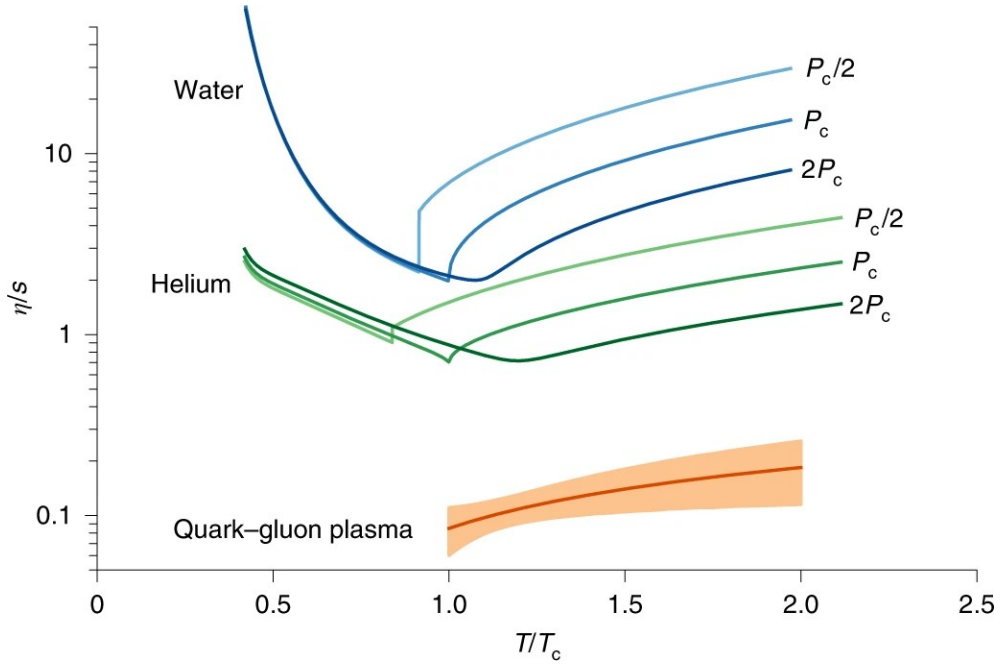
JETSCAPE Collaboration, PRC,PRL 2021

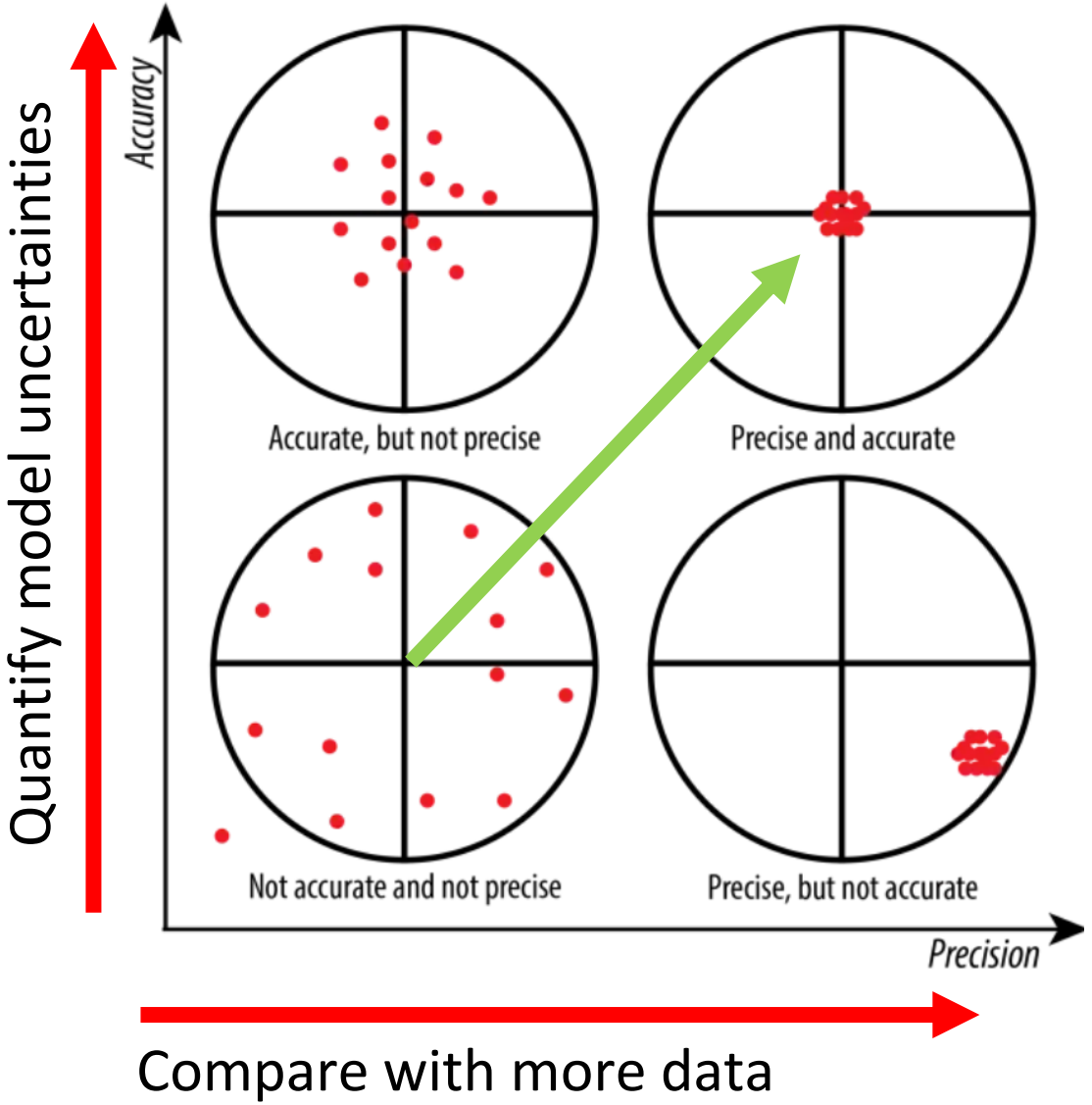
- Different lines = different transition models from hydrodynamics to hadronic transport
- Shaded average is “Bayesian model average”:
  average weighted by degree of agreement with data (“Bayes factor”/evidence)

Bayesian inference in heavy ion collisions

Viscosity of the quark-gluon plasma

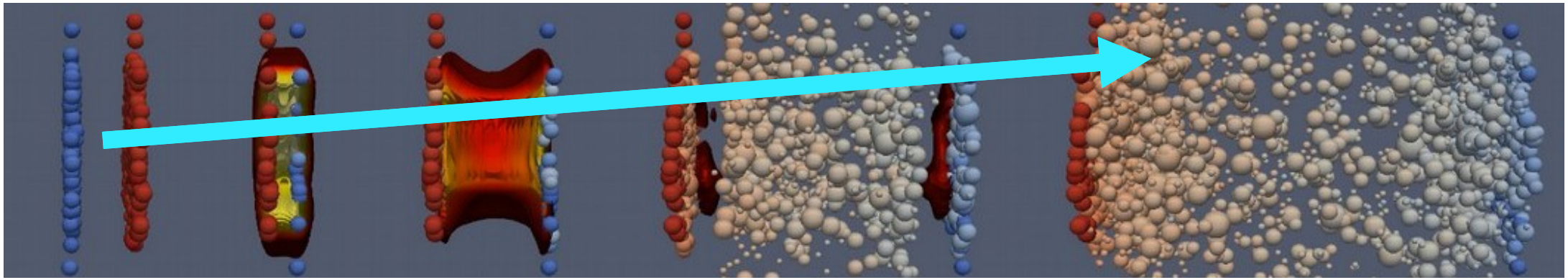
- Nijs, van der Schee, Gürsoy & Snellings, PRC, PRL 2021
- Parkkila, Onnerstad, Taghavi, Mordasini & Bilandzic (arXiv:2111.08145)
- Auvinen, Eskola, Huovinen, Niemi, Paatelainen & Petreczky, PRC 2020
- Bernhard, Moreland & Bass, Nature Physics 2019:



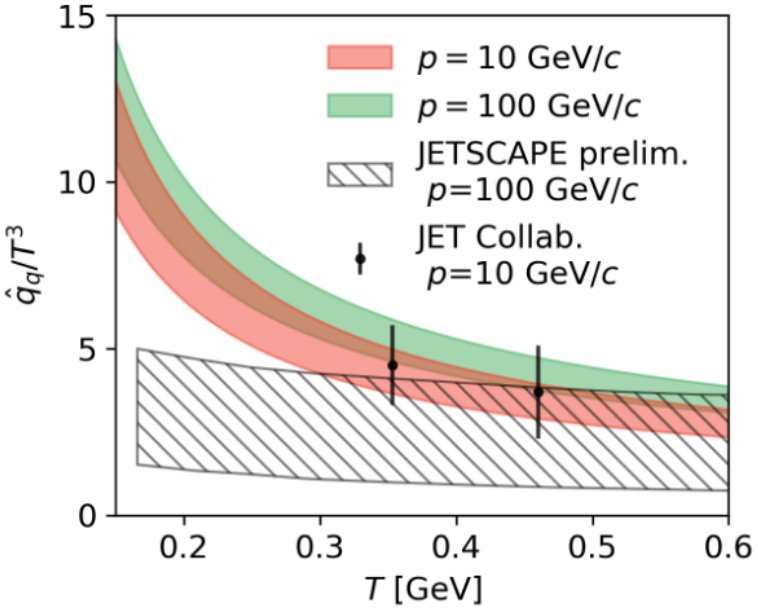


Ref.: https://wp.stolaf.edu/it/gis-precision-accuracy/

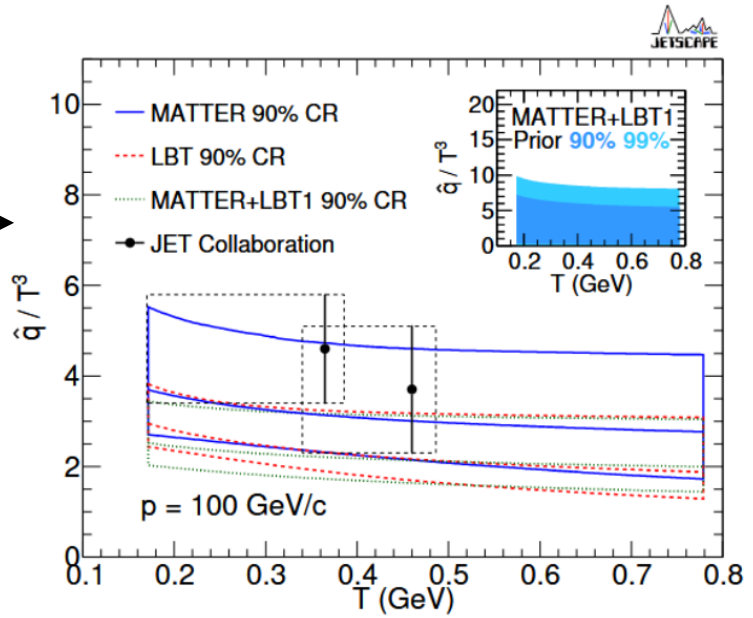
Bayesian inference in heavy ion collisions: parton energy loss



How do (heavy quarks)/(light quarks)/gluons interact with quark-gluon plasma?

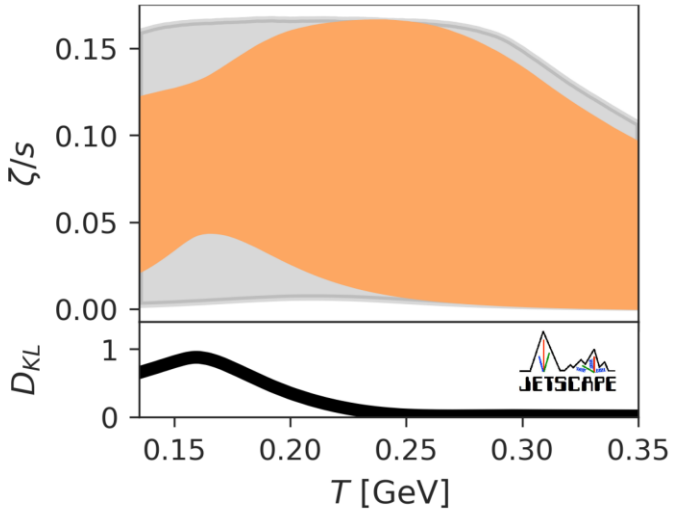


JETSCAPE Collaboration, PRC 2021



Ke, Wang, JHEP 2021

Summary

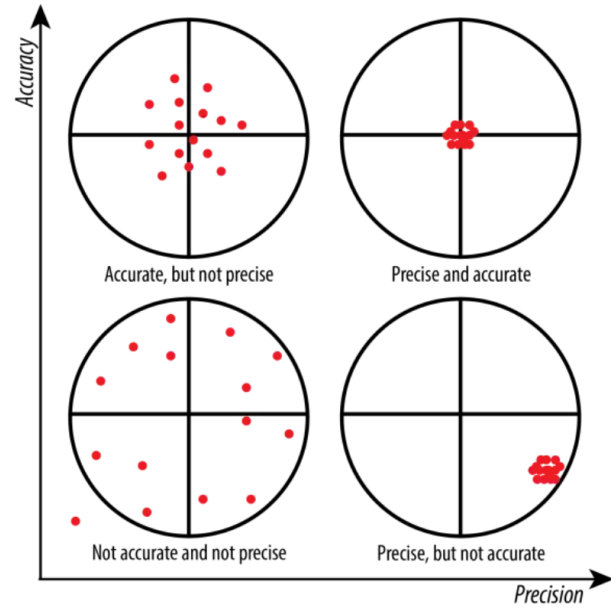


Heavy ion collisions well suited for Bayesian inference:

- Large number of measurements with variable uncertainties
- Mature but complex multistage models with multiple unknowns

Contributions from the JETSCAPE analysis:

- Theoretical uncertainty quantification
- Bayes factors & Bayesian model averaging
- Closure tests, priors, sensitivity analysis, …



Outlook:

- Additional data
- Additional source of theoretical uncertainties must be accounted for
- Experimental uncertainties: correlations between uncertainties [2102.11337]

Acknowledgements

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

PHYSICAL REVIEW C

Multisystem Bayesian constraints on the transport coefficients of QCD matter

D. Everett *et al.* (JETSCAPE Collaboration)
Phys. Rev. C **103**, 054904 – Published 14 May 2021

PHYSICAL REVIEW LETTERS

Editors' Suggestion

Phenomenological Constraints on the Transport Properties of QCD Matter with Data-Driven Model Averaging

D. Everett *et al.* (JETSCAPE Collaboration)
Phys. Rev. Lett. **126**, 242301 – Published 17 June 2021

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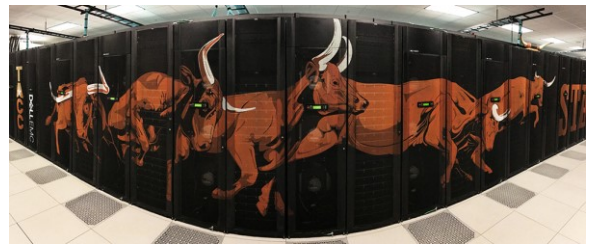
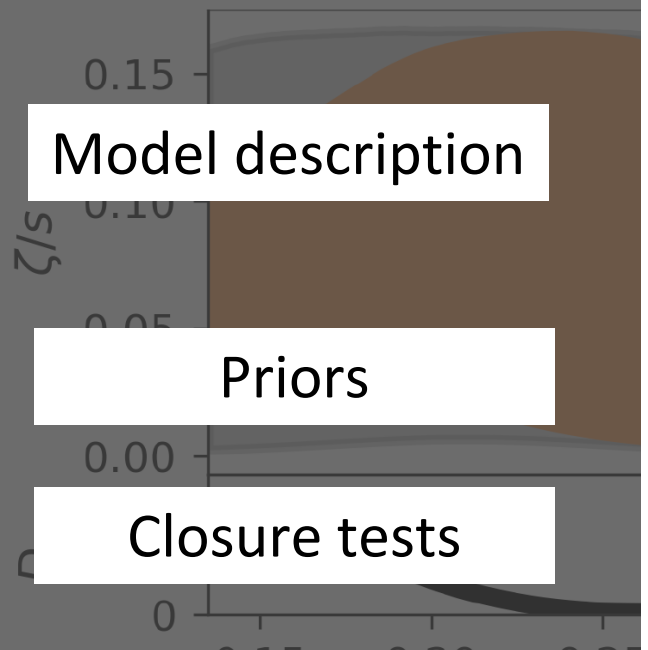
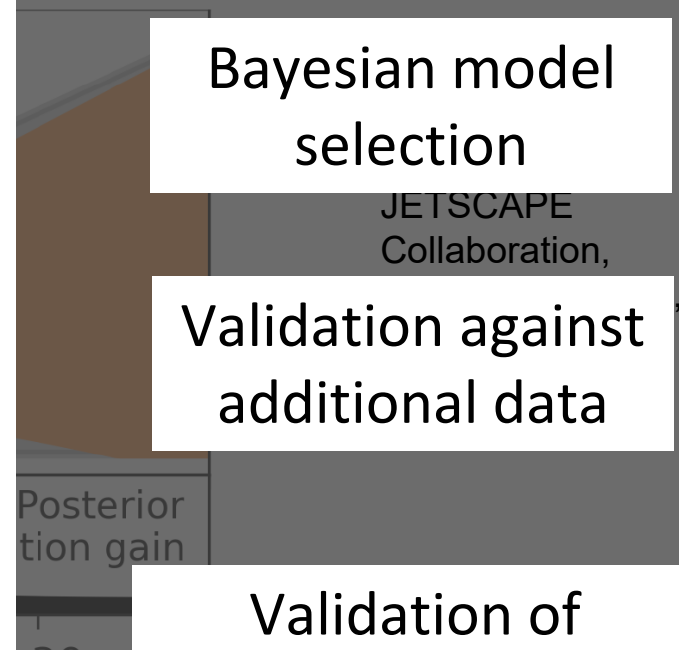


Computational resources from XSEDE & TACC

Latest constraints

Bulk visc





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- State-of-the-art multi-s
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Model description

Priors

Closure tests

Bayesian parameter estimation

Observable sensitivity study

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

JETSCAPE Collaboration, PRC,PRL 2021

Bayesian model selection

JETSCAPE Collaboration,

Validation against additional data

Validation of hydrodynamics against external solutions

Hadronic transport validation

Questions?