Describing the strongly-interacting medium with JETSCAPE

GOJKO VUJANOVIC

CO-CONVENER OF JETSCAPE SIMS WORKING GROUP

WAYNE STATE
College of Liberal Arts and Sciences

JETSCAPE WINTER SCHOOL AND WORKSHOP 2019

COLLEGE STATION, TEXAS

JANUARY 12, 2019

Outline

Part I: Simulations (SIMS) and distributed computing

- Who we are and our role is inside the JETSCAPE collaboration

Part II: Modeling of the medium

- TRENTO initial conditions
- Free-streaming
- Hydrodynamical Simulations
- SMASH

Part III: Bayesian Analysis

- JETSCAPE improvements over previous analysis
- Current status and outlook

About SIMS-WG

- SIMS-WG was created ~10 months ago (March 10, 2018) with members:

  Derek Everett, Lipei Du, Mike McNelis, Ulrich Heinz (OSU)

  Weiyao Ke, Jean-François Paquet, Steffen Bass (Duke)

  Chun Shen, Abhijit Majumder (Wayne State)

  Matthew Luzum (University of Sao Paulo)

- SIMS is designed to bridge the gap between the various JETSCAPE groups, i.e. assist other working groups with large-scale simulations.
  - Optimizing the workflow of the JETSCAPE framework to run well in High Performance Computing (HPC) environments.
  - Soft physics most HPC demanding

Current focus of the SIMS WG

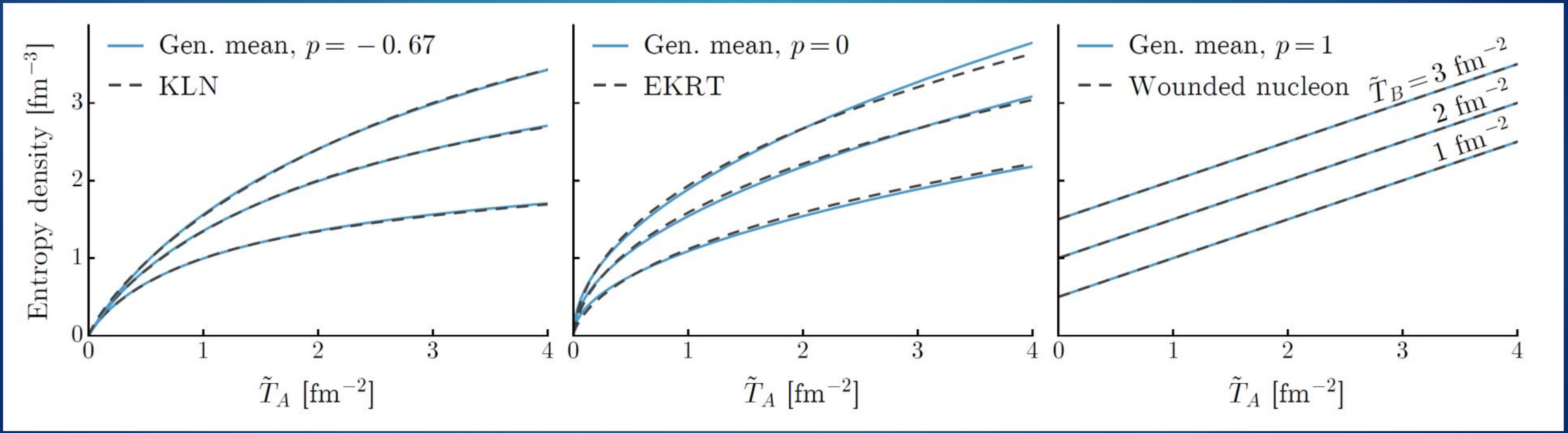
- Jets are sensitive probes of the medium, thus jet energy loss calculations need the best soft physics available.
  - Produce tuned 2+1D & 3+1D media to be used for jet energy loss
  - The tuned media are obtained from a Bayesian analysis
- Currently the JETSCAPE description of the medium relies on a combination of the following models:
  - TRENTO: initial energy (or entropy) density is well described by the
  - Free-streaming evolution of the initial energy profile
  - Hydrodynamical (MUSIC) evolution incl. bulk and shear viscous pressures
  - SMASH hadronic cascade evolving the hadronic distribution until kinetic freeze-out
- Using the best-fit parameters from the Bayesian Analysis performed at Duke (see arXiv:1804.06469), and their framework, SIMS produced 2+1D boost-invariant simulations on the Open Science Grid, and stored the results on OSIRIS.

TRENTO

- An *effective* model of the distribution of the entropy density

$$\frac{dS}{dy} = N\left(\frac{T_A^p + T_B^p}{2}\right)^{\frac{1}{p}} = \begin{cases} \max(T_A, T_B) & p \to \infty \\ (T_A + T_B)/2 & p = 1 \\ \sqrt{T_A T_B} & p = 0 \\ 2T_A T_B/(T_A + T_B) & p = -1 \\ \min(T_A, T_B) & p \to -\infty \end{cases}$$

- Explained in detail by Prithwish Tribedy during school
- $T_{A,B}$ is a participant nucleon density



Figures from Jonah Bernhard's PhD thesis on arxiv:1804.06469

Free-Streaming

- Our free-streaming model exactly solves the collisionless Boltzmann equation

$$p^\mu \partial_\mu f = 0$$

- Assumptions:
  - Ultrarelativistic massless particles
  - Isotropic in p_x and p_y : $f\left(p_x, p_y\right) \to f(p_T)$
  - Assumes a Gaussian profile in the longitudinal momentum direction

$$f(\tau_0, x, y, \eta; p_T, \xi) = \exp\left[\frac{(\eta-\xi)^2}{2\sigma^2}\right] \hat{f}(\tau_0, x, y, \eta; p_T)$$

- Use solution to construct $T^{\mu\nu} = \int d\xi d\phi_p p_T dp_T \, p^\mu p^\nu f$ to match to hydro, using Landau prescription $T^{\mu\nu} u_\nu = \epsilon u^\mu$

Viscous hydrodynamics

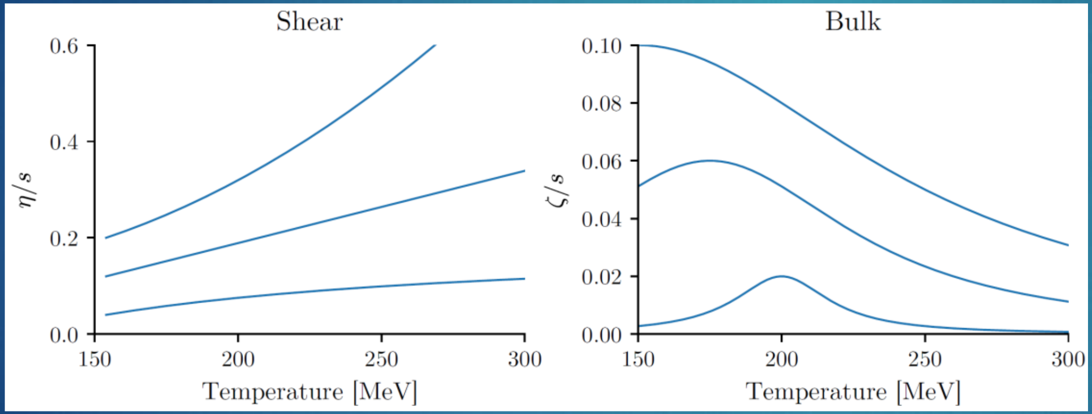
- Dissipative hydrodynamic equations :

$$\partial_\mu T^{\mu\nu} = 0 \qquad T^{\mu\nu} = T_0^{\mu\nu} + \pi^{\mu\nu} - \Delta^{\mu\nu}\,\Pi \qquad T_0^{\mu\nu} = \varepsilon u^\mu u^\nu - P\Delta^{\mu\nu}$$

$$\tau_\pi \dot{\pi}^{\langle\mu\nu\rangle} + \pi^{\mu\nu} = 2\eta\sigma^{\mu\nu} - \delta_{\pi\pi}\pi^{\mu\nu}\theta + \phi_7 \pi_\alpha^{\langle\mu}\pi^{\nu\rangle\alpha} - \tau_{\pi\pi}\pi_\alpha^{\langle\mu}\sigma^{\nu\rangle\alpha} + \lambda_{\pi\Pi}\Pi\sigma^{\mu\nu}$$

$$\tau_\Pi \dot{\Pi} + \Pi = -\zeta\theta - \delta_{\Pi\Pi}\Pi\theta + \lambda_{\Pi\pi}\pi^{\mu\nu}\sigma_{\mu\nu}$$

- Example of temperature parametrizations for η and ζ



$$\frac{\eta}{s}(T) = a + b(T - T_c)^c$$

$$\frac{\zeta}{s}(T) = \frac{A}{\left(\frac{T - T_c}{\sigma_T}\right)^B + C}$$

- Other than ζ and η, all transport coefficients are in PRC **90** 024912 (2014).
- $P(\varepsilon)$: Lattice QCD EoS from Hot QCD collaboration [PRD 90, 094503 (2014)]

Hydro & SMASH

- Hydro d.o.f → hadrons used in SMASH: Cooper-Frye prescription

  $E\frac{d^3N}{d^3p} = \int d^3\Sigma_\mu p^\mu f$ w/ $d^3\Sigma_\mu$ freeze-out surface element

- For a viscous medium, f is typically computed via the following ansatz $f = gZ\left[\exp\left(y_p\right) \mp 1\right]^{-1}$
  - g is the degeneracy factor (e.g. spin degeneracy)
  - Z is an overall normalization
  - y_p includes both inviscid and viscous pieces.
- SMASH solves a system of Boltzmann equations for i^{th} hadron

$$p_i^\mu \partial_\mu f_i = C\{f_i\}$$

More about f

- y_p in the local rest frame is typically expressed in two categories
  - Moment expansion:

$$y_p = y_{0,p} + \delta y_p + O\left(\left(\delta y_p\right)^2\right) \Rightarrow f_p = f_{0,p} + \delta f_p$$

$$f_{0,p} = g\left[\exp\left(\frac{\sqrt{m^2 + \boldsymbol{p}^2}}{T}\right) \mp 1\right]^{-1} \; ; \; \delta f_p = f_{0,p}(1 \pm f_{0,p})\delta y_p$$

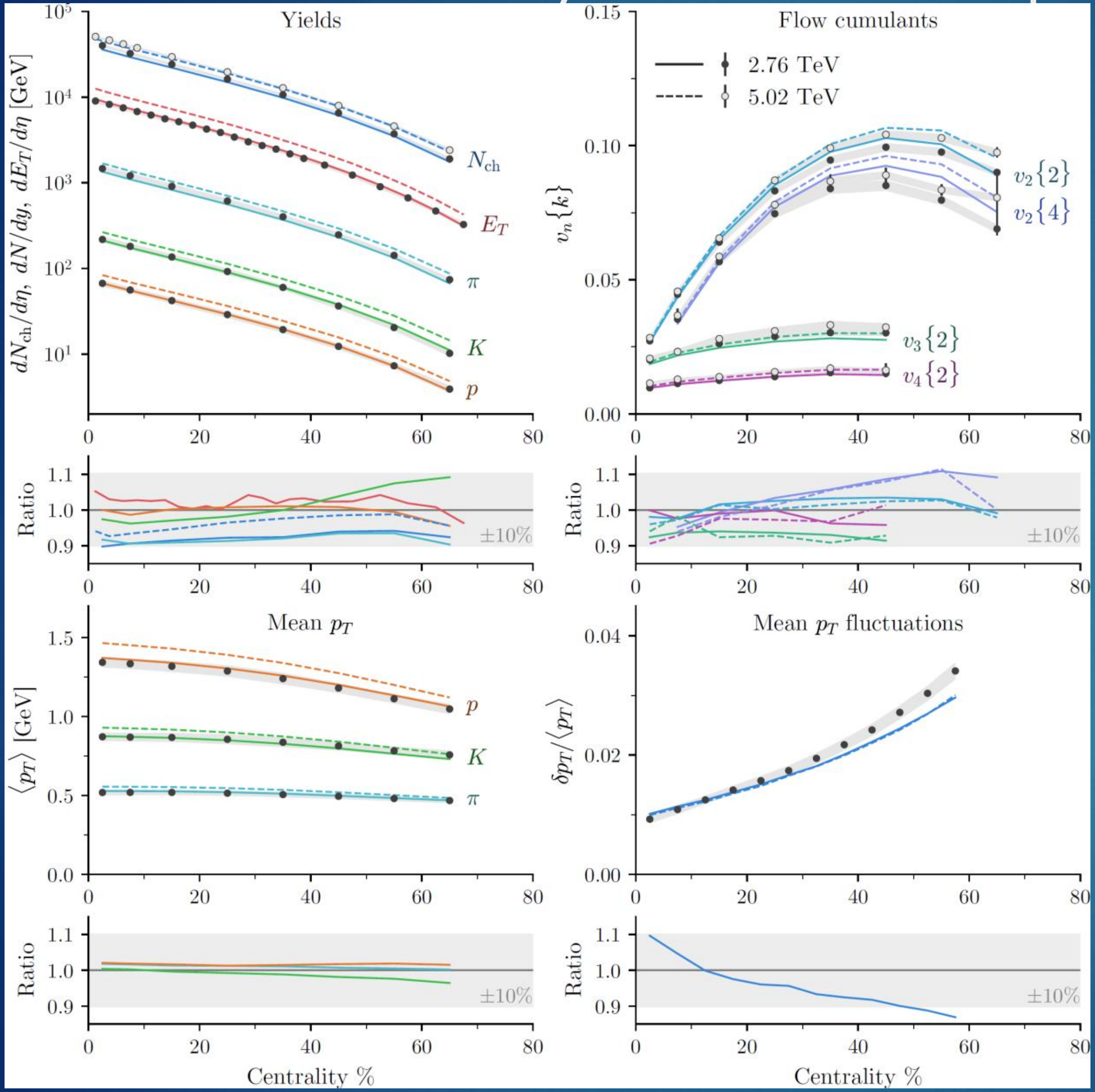
$$\delta y_p = m^2 A_T(T)\Pi + \left(m^2 + \boldsymbol{p}^2\right)A_E(T)\Pi + \frac{p^i p^j \pi_{ij}}{2(\epsilon + P)T^2}$$

  - Deformed distribution ansatz

$$f_{0,p} = gZ\left[\exp\left(\frac{\sqrt{m^2 + \boldsymbol{p}'^2}}{T + \delta T}\right) \mp 1\right]^{-1} \; where \; p_i = M_{ij}(\Pi, \pi_{ij})p'_j$$

- f will discussed by Mike McNelis (see his talk tomorrow)
- Bayesian determination of parameters may depend on f.
- Effect of f of Bayesian parameter determination will be explored for the first time by the SIMS WG in JETSCAPE

Duke theory-data comparison



- A good description of various soft observables using 2+1D TRENTO+FS+hydro + UrQMD
- Jonah Bernhard's of deformed f assumes

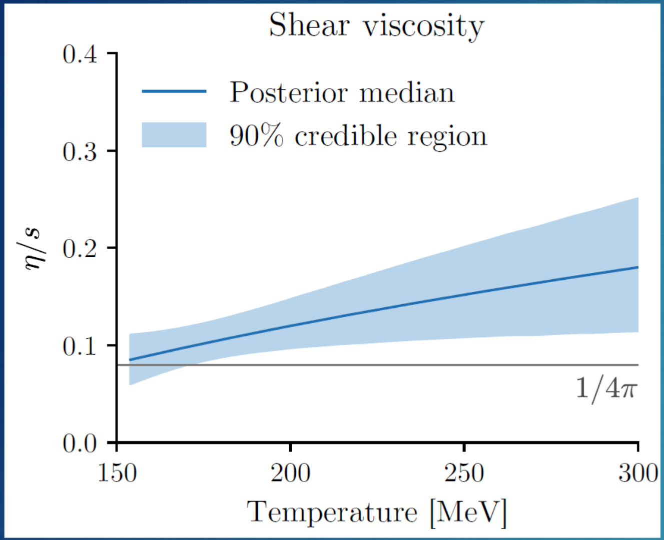
$$\delta T = 0; Z = \frac{z_\Pi}{\det(M)};$$

$$M_{ij} = (1 + \lambda_\Pi)\delta_{ij} + \pi_{ij}\tau_R/2\eta$$

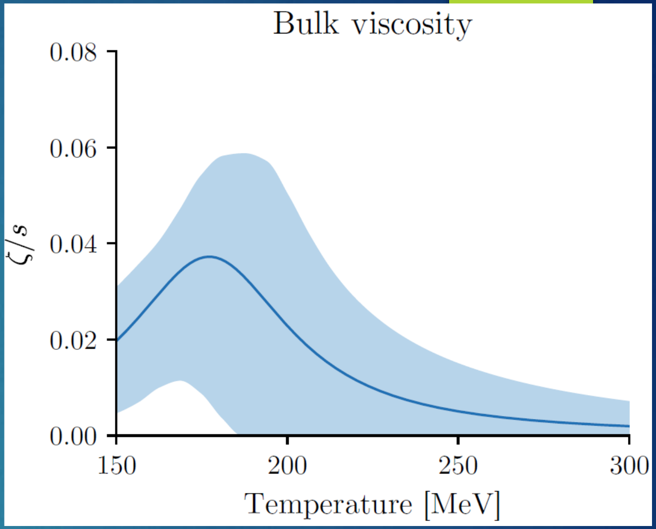
- Discrepancies between theorical calc. & data $\lesssim$10%.

Figures from Jonah Bernhard's PhD thesis, arxiv:1804.06469

Duke Best-Fit



Figures from Jonah Bernhard's PhD thesis on arxiv:1804.06469



$$\frac{\eta}{s}(T) = \left(\frac{\eta}{s}\right)_{min} + \left(\frac{\eta}{s}\right)_{slope} \cdot (T - T_c)\left(\frac{T}{T_c}\right)^{\left(\frac{\eta}{s}\right)_{crv}}$$

$$\frac{\zeta}{s}(T) = \frac{(\zeta/s)_{max}}{1 + \left(\frac{T - (\zeta/s)_{T_0}}{(\zeta/s)_{width}}\right)^2}$$

- The particular best fit parameters in $\eta/s(T)$ and $\zeta/s(T)$ obtained by Duke group (spearheaded by Jonah Bernhard), depend on
  - the choice of f in the Cooper-Frye prescription
  - 3+1D versus 2+1D simulations
- JETSCAPE SIMS will explore these two effects, as well as provide 3+1D media needed for accurate jet energy loss calculations

Current Status

- Gearing up toward full scale 3+1D QGP simulations (code status)
  - 3+1D TRENTO initial conditions (Duke) ✓
  - 3+1D Free-streaming (OSU) ✓
  - 3+1D Hydro (McGill ✓)
  - Particle sampler needed for hydro→SMASH
    - 3+1D particle sampler ✓
    - Different δf parametrizations for shear and bulk viscous effects ✓
  - SMASH hadronic transport ✓

✓: package ready for large-scale simulations

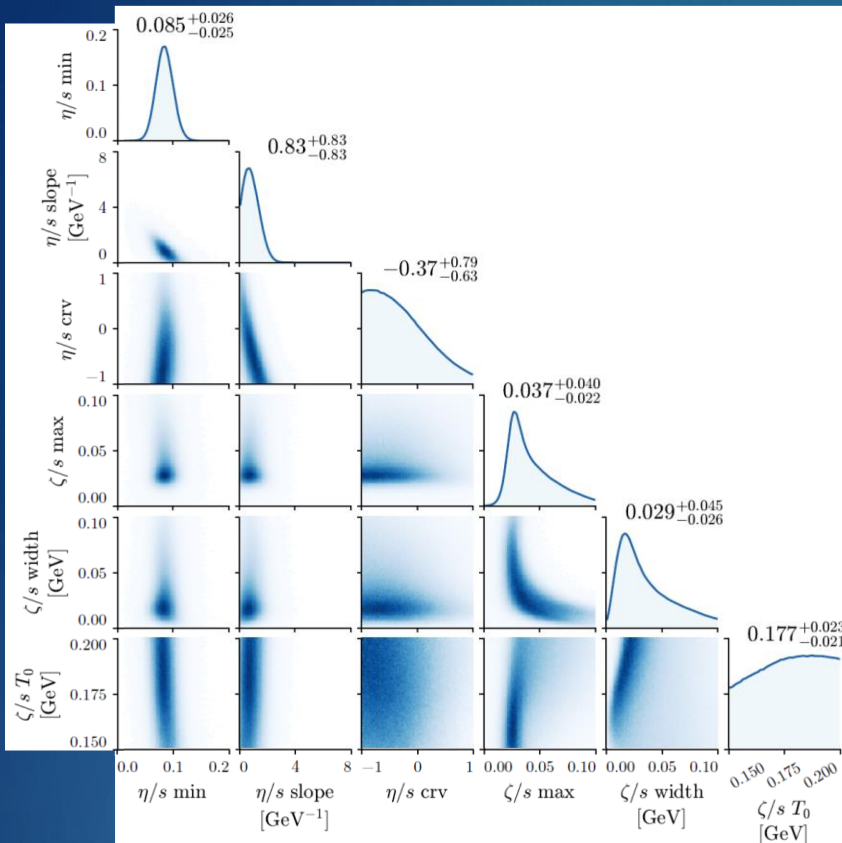
✓: package being validated before being deployed in large-scale simulations

Outlook

- Preparations under way for Bayesian analysis of soft observables using the JETSCAPE framework on TACC
  - 2+1D simulations to establish a region of parameter space where more resources should be spent when 3+1D simulations are explored. Also we can compare our results with Duke results.
  - Determine how much parameters are affected by δf.
  - Constrain new parameters present in 3+1D simulations
  - Are parameters common in 2+1D & 3+1D simulations affected by the dimensionality of the simulation?

Backup Slides

Duke Best-Fit



Figures from Jonah Bernhard's PhD thesis on arxiv:1804.06469

$$\frac{\eta}{s}(T) = \left(\frac{\eta}{s}\right)_{min} + \left(\frac{\eta}{s}\right)_{slope} \cdot (T - T_c)\left(\frac{T}{T_c}\right)^{\left(\frac{\eta}{s}\right)_{crv}}$$

$$\frac{\zeta}{s}(T) = \frac{(\zeta/s)_{max}}{1 + \left(\frac{T - (\zeta/s)_{T_0}}{(\zeta/s)_{width}}\right)^2}$$

- The particular best fit parameters in $\eta/s(T)$ and $\zeta/s(T)$ obtained by Duke group (spearheaded by Jonah Bernhard), depend on
  - the choice of f in the Cooper-Frye prescription
  - 3+1D versus 2+1D simulations
- JETSCAPE SIMS will explore these two effects, as well as provide 3+1D media needed for accurate jet energy loss calculations

Modules used in simulations so far

- Using the best-fit parameters from the Bayesian Analysis performed at Duke (see arXiv:1804.06469), and their framework, SIMS produced 2+1D boost-invariant simulations on the Open Science Grid (OSG) consisting of:
  - TRENTO initial entropy density [PRC 92, 011901, 2015];
  - Free-streaming evolution [PRC 91, 064906, 2015] of the initial profile up to $\tau \sim$1.2 fm/c [arxiv:1804.06469];
  - Hydrodynamical evolution (OSU VISH 2+1D) including bulk and shear viscous pressure, was ran T_{ch} =151 MeV [PRC 91, 064906, 2015];
  - From T_{ch}, particle production is computed via Cooper-Frye. Note: UrQMD hadronic cascade evolution can be generated upon request.
  - Anisotropic flow (v_n), and event-plane angles (Ψ_n) of charged pions computed, needed for e.g. v_n of jets.
  - Hydro simulations are stopped below T_{ch}, at T_{kin}= 140 MeV, to allow for hydro estimate of possible jet energy loss after the hydrodymamical evolution (e.g. UrQMD).

2+1D Simulations produced for JETSCAPE

- On OSG, about 5,000 events were performed in a wide list of centrality classes (see backup slide for details)
- Also provided: 1 event-averaged simulation for testing of jet energy loss codes inside JETSCAPE framework
- Each optimized 2+1D simulation took <1.5 hours to complete on OSG
- Further optimizations were made to reduce disk usage (via e.g. HDF5 file formats)
- Results occupy 2TB of data stored on OSiRIS
- Stored on OSiRIS are:
  - Initial condition profiles, including binary collision density, for each event
  - Entire free-streaming + hydrodynamical evolution for each event
  - Entire freeze-out hypersurface for each event
  - Final (soft) hadron anisotropic flow (v_n), and event-plane angles (Ψ_n) for each event

Events simulated using current (Duke) best fit

- List of centrality classes (at least 200 events per centrality class):
  - Au-Au $\sqrt{s_{NN}}$ = 200 GeV: 0-10%, 0-80%, 10-20%, 10-40%, 20-30%, 30-40%, 40-50%, 40-80%, 50-60%, 60-70%, Min Bias
  - Pb-Pb $\sqrt{s_{NN}}$ = 2760 GeV: 0-5%, 0-10%, 0-20%, 5-10%, 10-20%, 10-30%, 20-30%, 30-40%, 40-50%, 40-60%, 40-80%, 50-70%, 60-70%, Min Bias
  - Pb-Pb $\sqrt{s_{NN}}$ = 5020 GeV: 0-5%, 0-10%, 5-10%, 10-20%, 10-30%, 20-30%, 30-40%, 30-50%, 40-50%, 50-60%, 50-70%, Min Bias

The setup: OSG+OSiRIS

- A single 2+1D simulation is relatively inexpensive computationally, but lots of single-core simulations are needed.
- Open Science Grid (OSG) is ideal for distributed workload
  - 100+ sites in US
  - Universities & National Labs
  - Wide range of core count and core architecture per site
    - − Difficult to predict execution time; not suited for multi-threaded jobs
    - + Can continue running jobs at lower priority, if one runs out of allocation
- Results stored on Open Storage Research Infrastructure (OSiRIS)
  - Dedicated storage facility that all JETSCAPE members can access
  - Attached to other HPC infrastructures via high-speed backbone
  - Supports Globus: a research data management provider aware of the high-speed architecture ⇒ efficient data transfer to any local HPC facility used for jet energy loss calculations