Investigating the Quark Gluon Plasma with Multi-system Bayesian Analysis in the JETSCAPE framework

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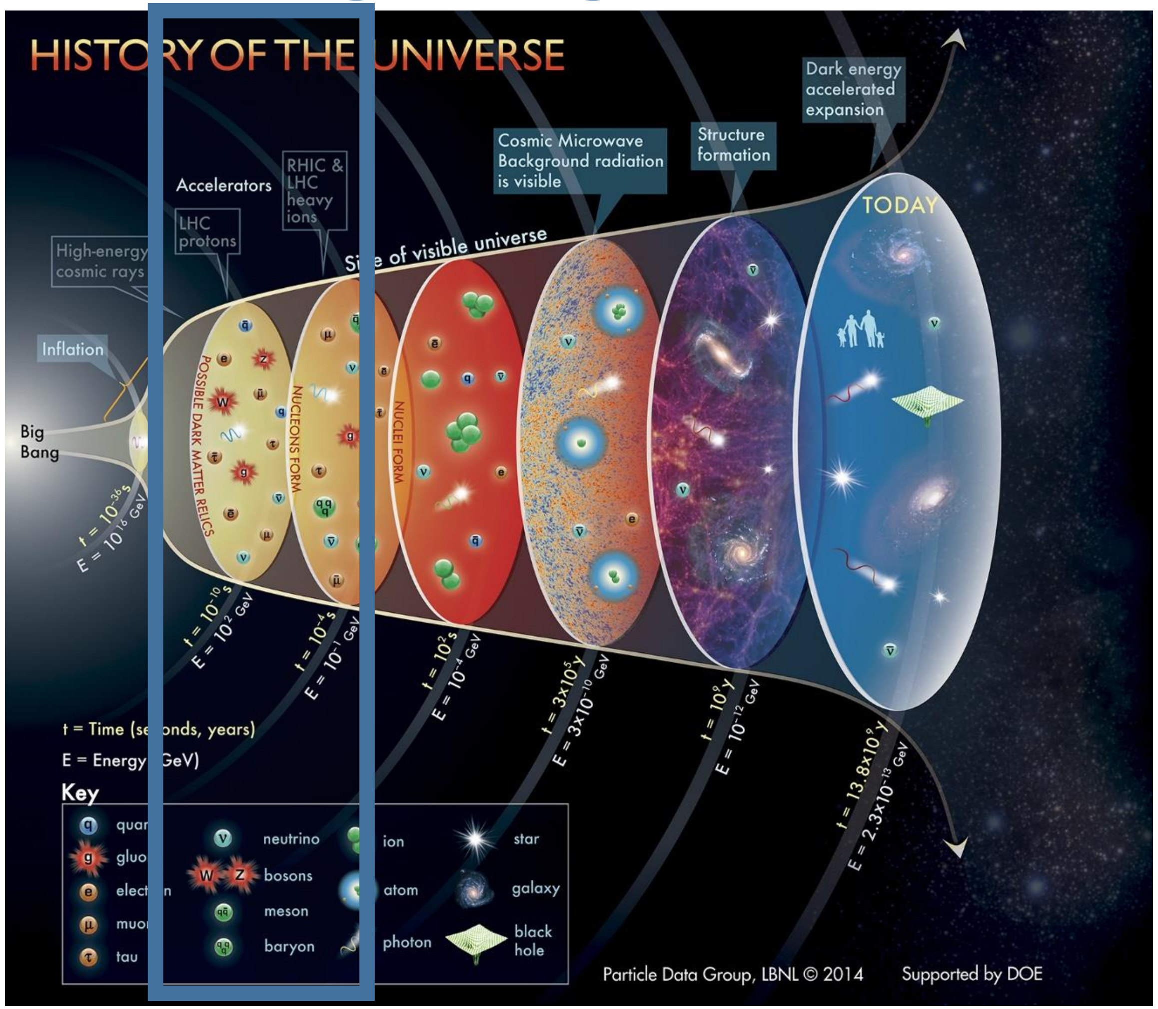
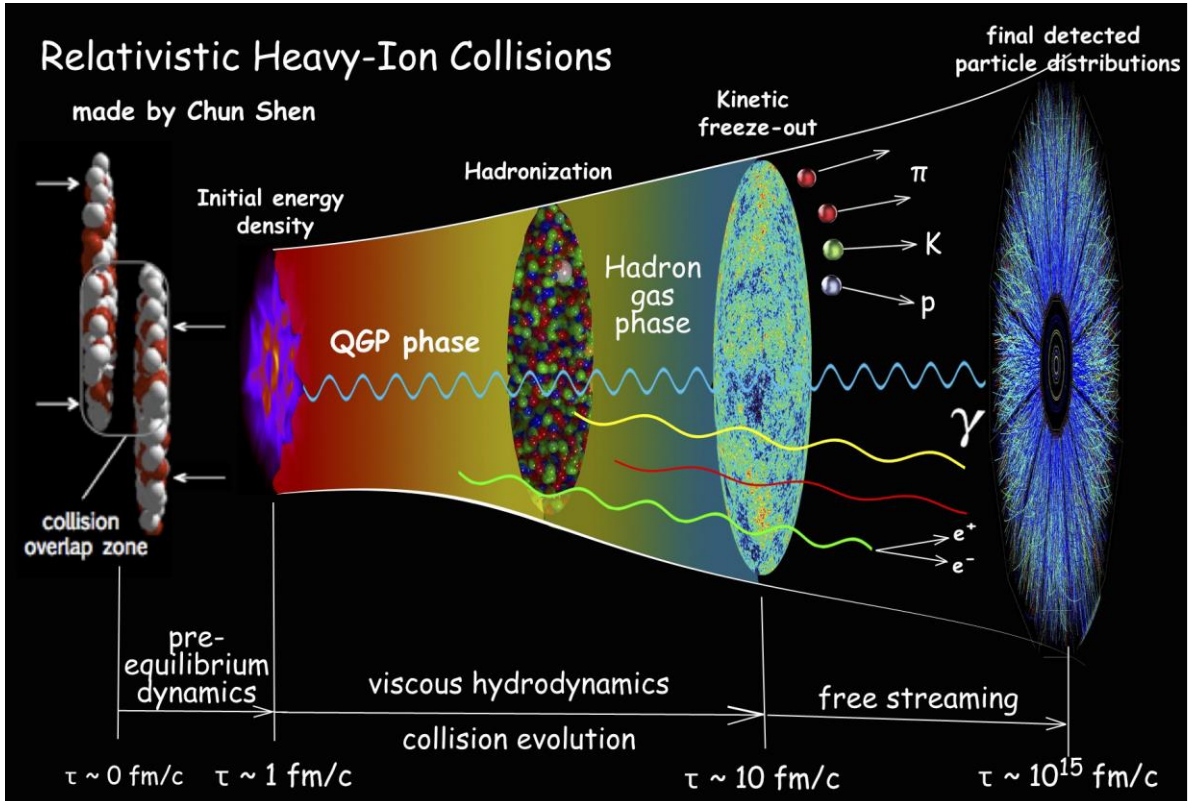
On behalf of JETSCAPE
Wayne State University

CIPANP, 09.03, 2022

From Big Bang to "Little Bang"

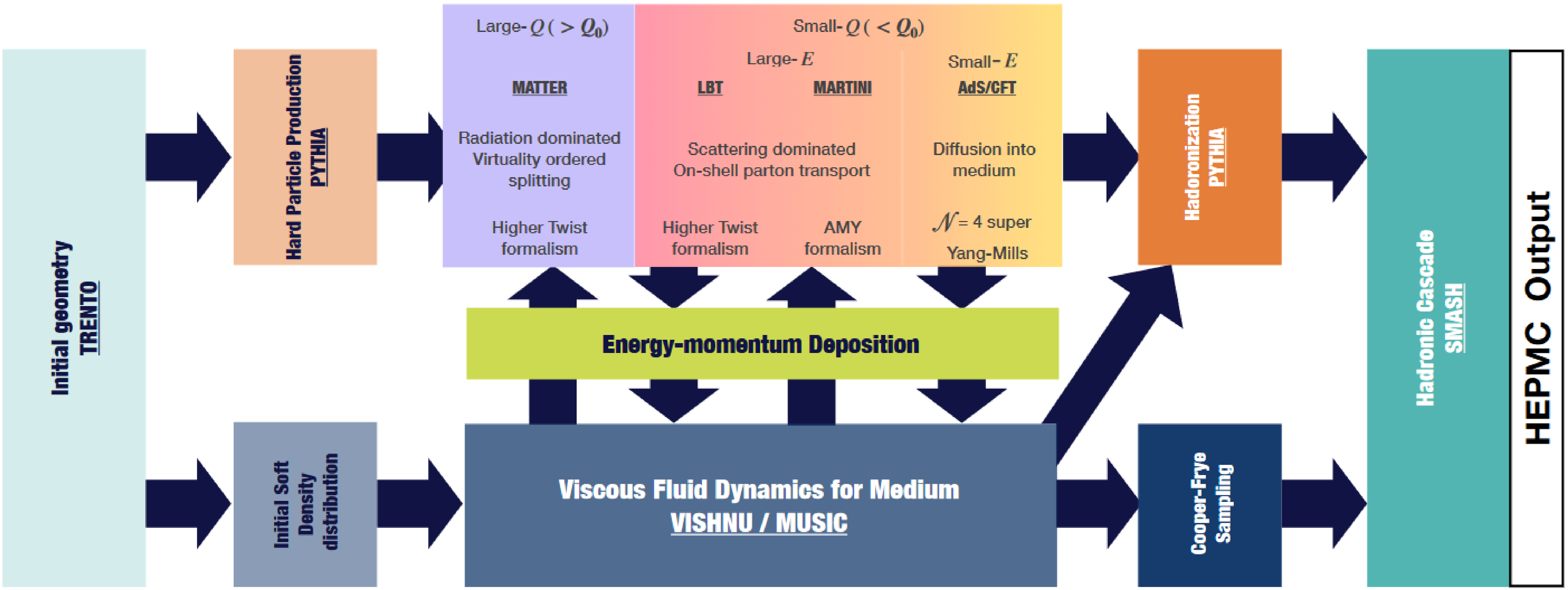




credit: Chun Shen

Figure taken from:
https://mappingignorance.org/2014/10/08/search-cosmic-inflation/

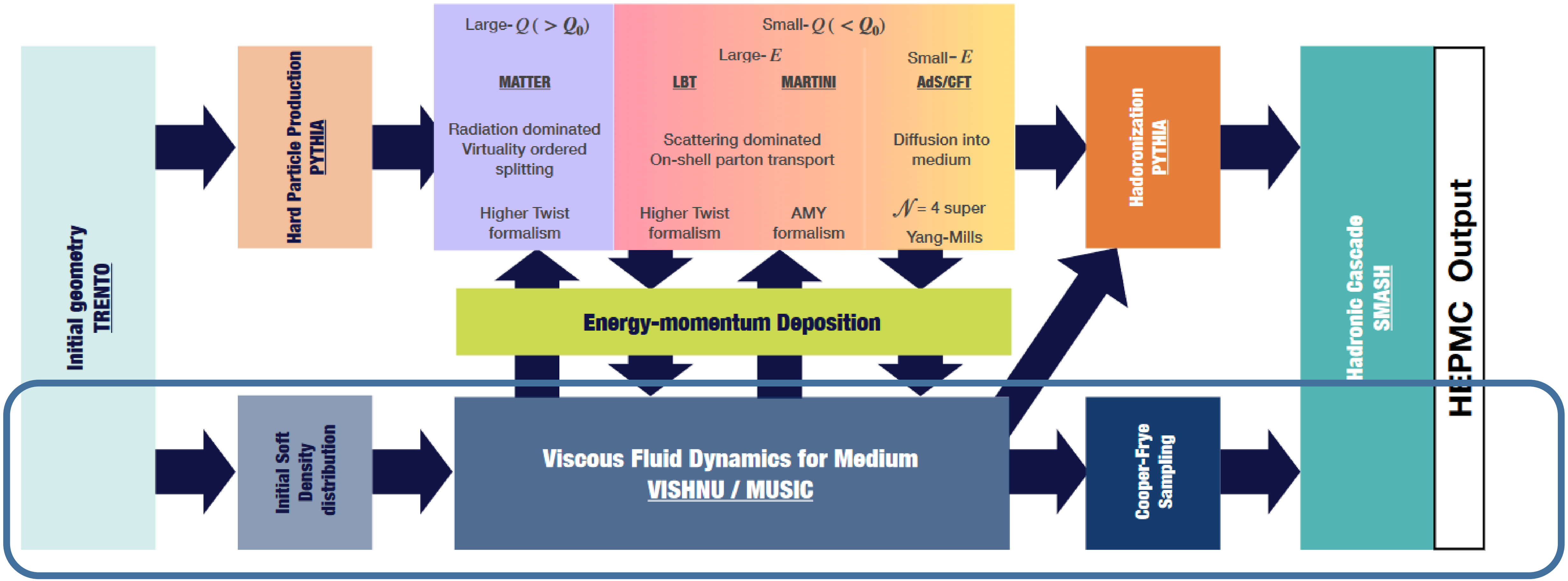
JETSCAPE Framework



Taken from Ron Soltz's slide,
Credit: JETSCAPE Group members

- JETSCAPE framework includes the soft and hard sections.
- You can download the code and add or change your code in the JETSCAPE framework.
- Code link: https://github.com/JETSCAPE/JETSCAPE

JETSCAPE Framework



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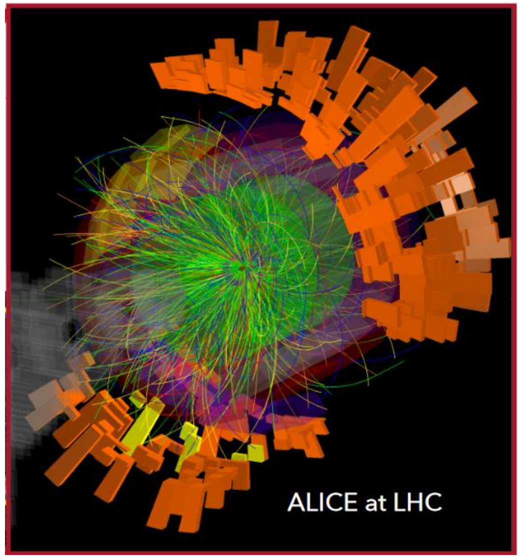
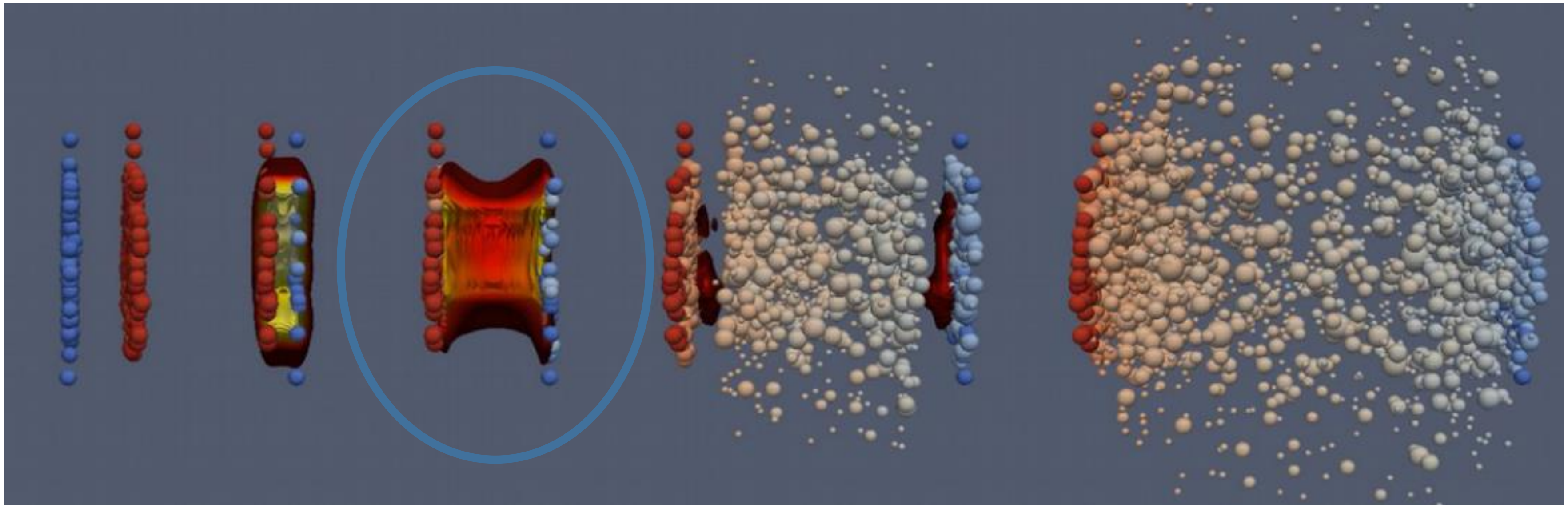
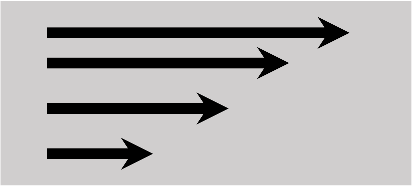
Multi-Stage Description of Heavy-Ion Collisions



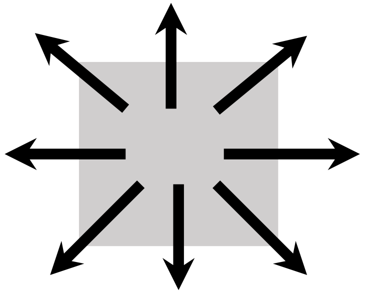


Credit: MADAI collaboration; Hannah Elfner and Jonah Bernhard

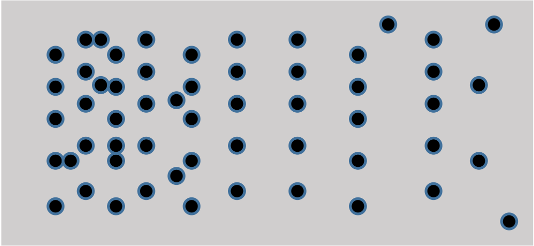
- Quark Gluon Plasma behaviors like fluid.



Shear viscosity acts against the buildup of flow gradients.



Bulk viscosity acts against the buildup of radial flow and longitudinal expansion



Diffusion current acts again the buildup of charge density inhomogeneity (smooth out such gradients)

Ref: Lipei Du JETSPCAE Summary School 2022

Quantifying the QGP

equation of state
shear viscosity
bulk viscosity
charge conductivity
heavy quark diffusion
p_T broadening
energy loss rate
phase boundary
...

anisotropic collective flows
radial collective flows
electromagnetic emission
jet quenching and heavy quarks
rapidity-dependent distributions
identified particle spectra
charge correlation
femtoscope
…

Bayes Theorem

Thomas Bayes

Probabilistic constraints on parameters

Mean value of measurements

Experimental and theoretical **uncertainties**

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

External constraints on parameters:
positivity or range of allowed values, “probabilistic theoretical constraints”, …

Prediction of model for given set of parameters (η/s, ζ/s, initial conditions, …)

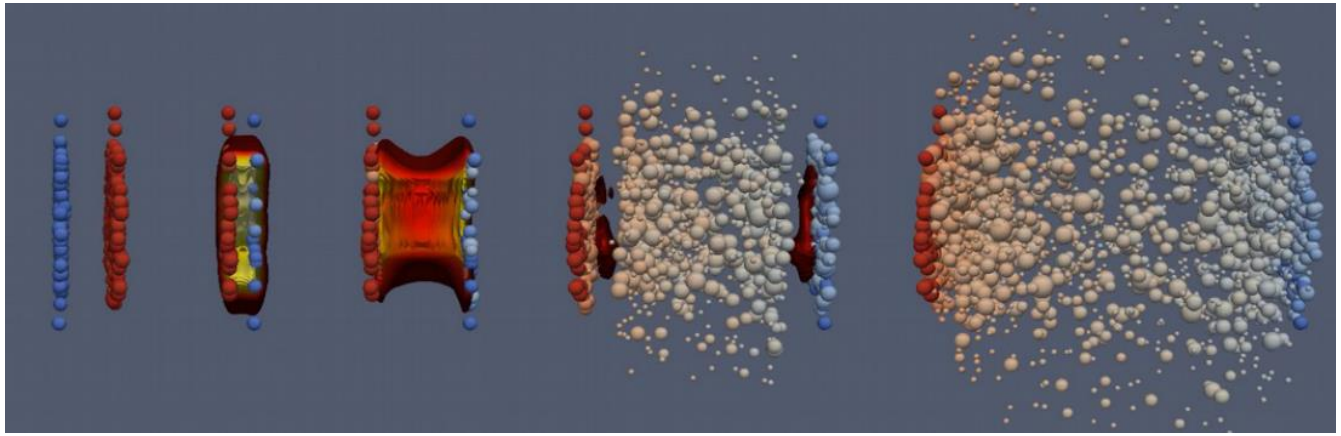
Ref: Jean-Francois, APS, 2021

- Constrain the model parameters by the Bayesian analysis.

JETSCAPE : arXiv: 2011.01430, 2010.03928

Hybrid Model Simulations

- Large parameter space are explored.
- A parameterized initial condition (**TRENTo**)
- The viscous hydrodynamic evolution (**MUSIC**)
- The hadron cascade afterburner (SMASH)



TRENTo+ Free-Streaming → MUSIC → iSS → SMASH

JETSCAPE : arXiv: 2011.01430, 2010.03928

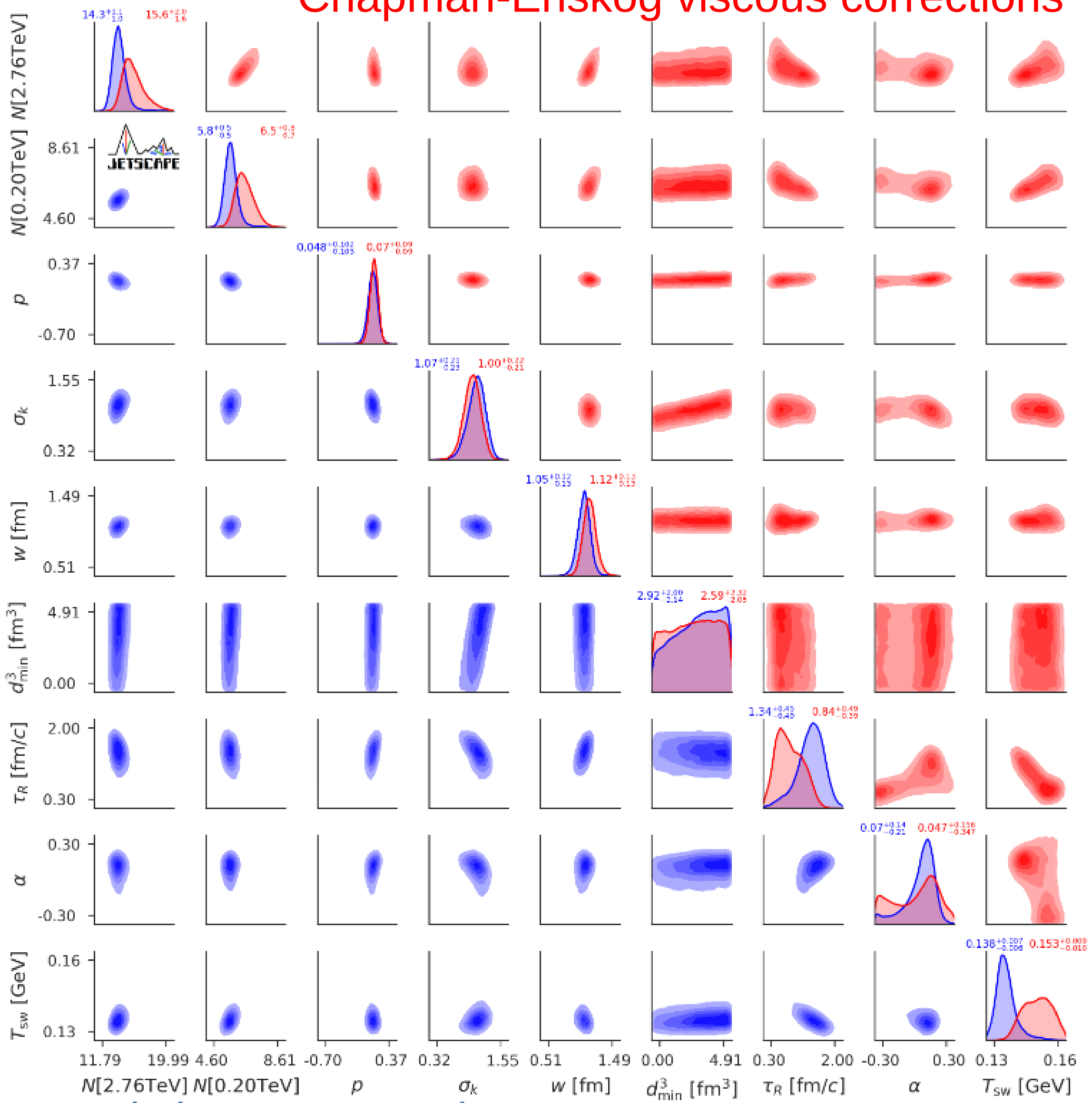
Parameter	Symbol	Prior	Parameter	Symbol	Prior
Norm. Pb-Pb 2.76 TeV	N[2.76 TeV]	[10, 20]	temperature of (η/s) kink	T_η	[0.13, 0.3] GeV
Norm. Au-Au 200 GeV	N[0.2 TeV]	[3, 10]	(η/s) at kink	$(\eta/s)_{\mathrm{kink}}$	[0.01, 0.2]
generalized mean	p	[–0.7, 0.7]	low temp. slope of (η/s)	a_{low}	[–2, 1] GeV^{-1}
nucleon width	w	[0.5, 1.5] fm	high temp. slope of (η/s)	a_{high}	[–1, 2] GeV^{-1}
min. dist. btw. nucleons	d^3_{min}	[0, 1.7^3] fm^3	shear relaxation time factor	b_π	[2, 8]
multiplicity fluctuation	σ_k	[0.3, 2.0]	maximum of (ζ/s)	$(\zeta/s)_{\max}$	[0.01, 0.25]
free-streaming time scale	τ_R	[0.3, 2.0] fm/c	temperature of (ζ/s) peak	T_ζ	[0.12, 0.3] GeV
free-streaming energy dep.	α	[–0.3, 0.3]	width of (ζ/s) peak	w_ζ	[0.025, 0.15] GeV
particlization temperature	T_{sw}	[0.135, 0.165] GeV	asymmetry of (ζ/s) peak	λ_ζ	[–0.8, 0.8]

Posterior Distributions

At particlization, different models of viscous corrections to the equilibrium distribution are used.

- **Grad's** method (14-moments method in the relativistic context).
- The first-order Chapman-Enskog (**CE**) expansion in the Relaxation Time Approximation.
- The Pratt-Torrieri-Bernhard (**PTB**), the modified equilibrium distribution to remains positive-definited.

Chapman-Enskog viscous corrections



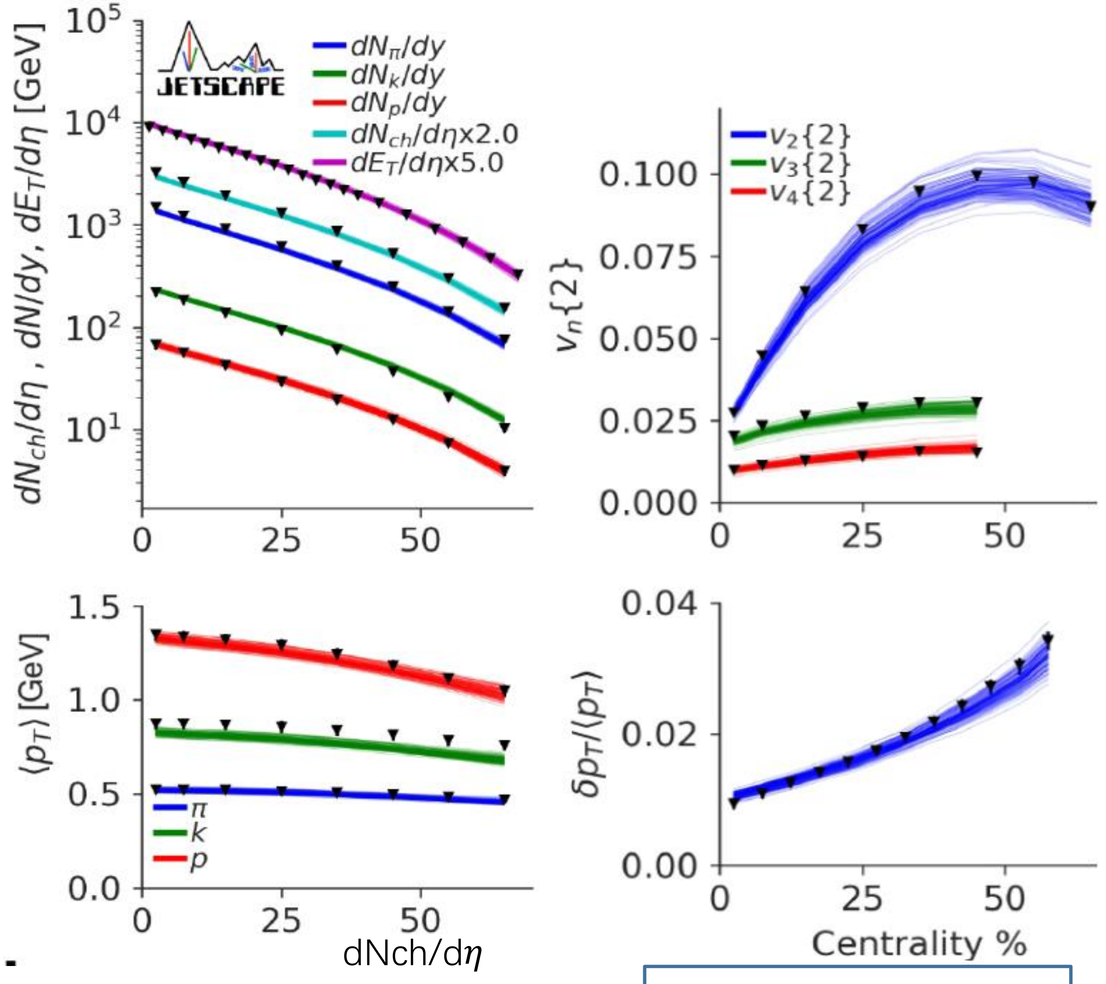
Grad viscous corrections

See:
McNelis, Everett, Golden & Heinz, arXiv: 1912.08271;
McNelis, APS DNP2019, and references therein

JETSCAPE : arXiv: 2011.01430, 2010.03928

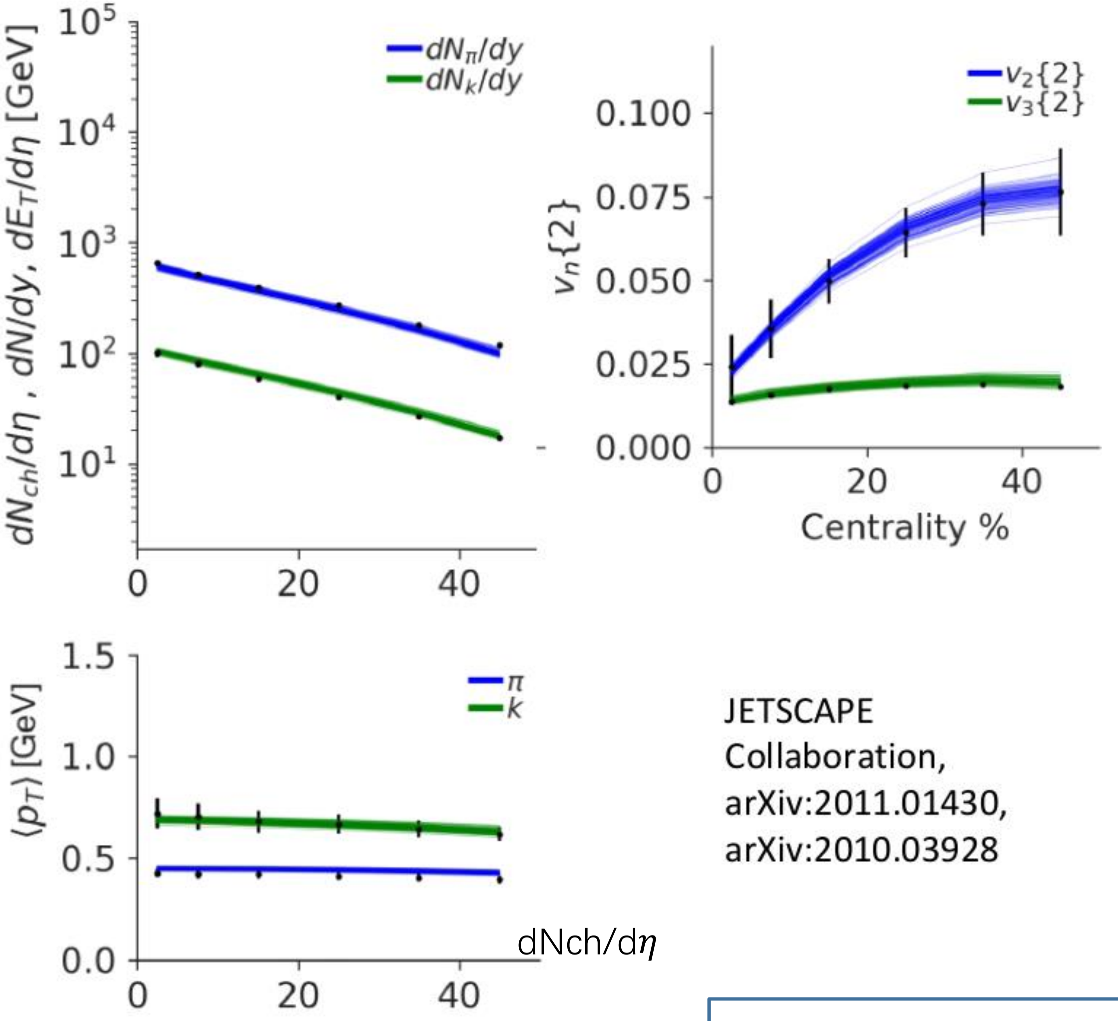
Agreement with Data

Play up the Widget, it's fun!: http://jetscape.org/sims-widget/



JETSCAPE : arXiv: 2011.01430, 2010.03928

Pb+Pb at 2.76 TeV

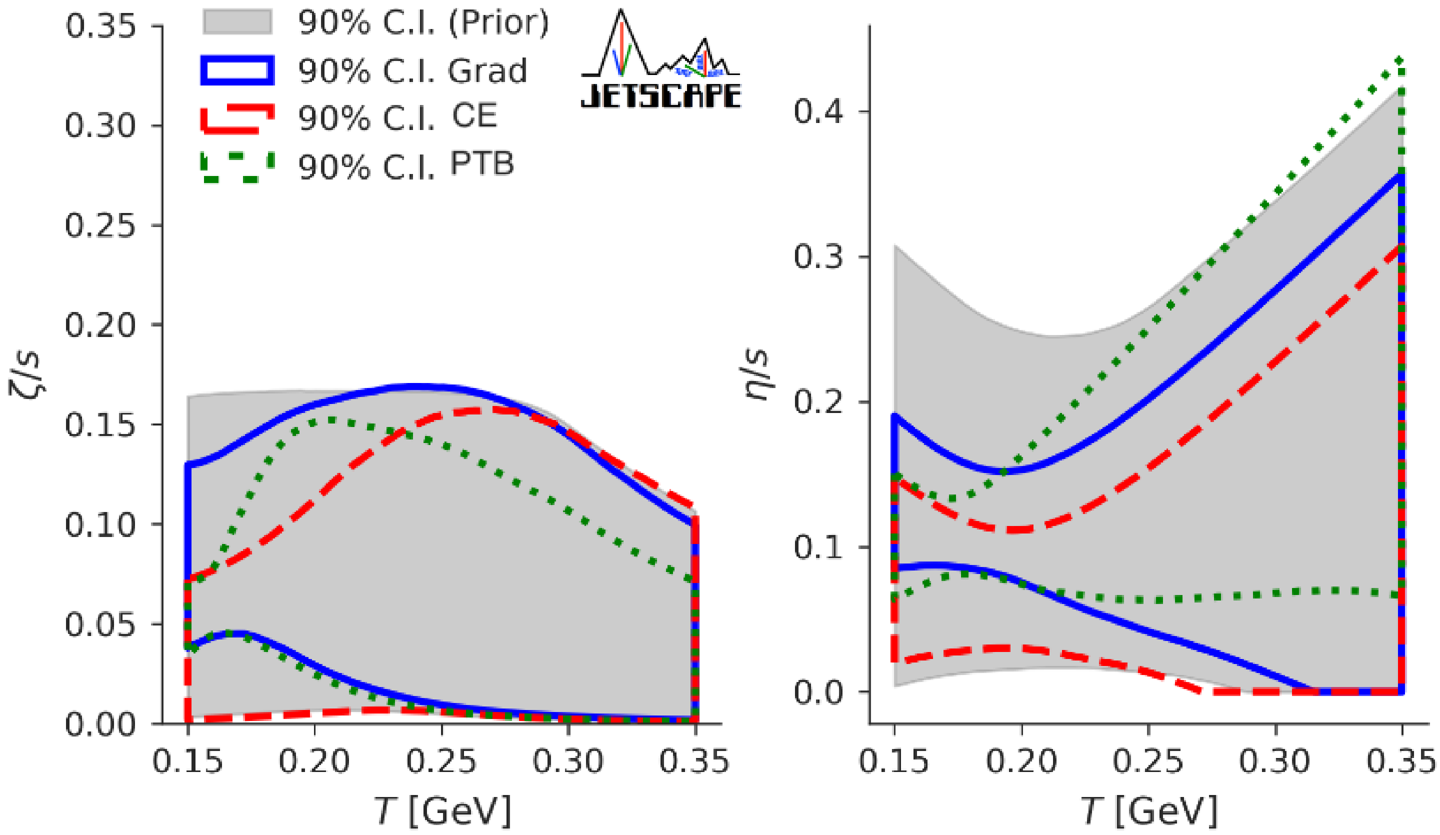


JETSCAPE Collaboration, arXiv:2011.01430, arXiv:2010.03928

Au+Au at 200 GeV

- The observables predicted by the Grad viscous correction, drawn from posterior resulting by fitting the ALICE data and STAR data.

The Importance of Model Uncertainties



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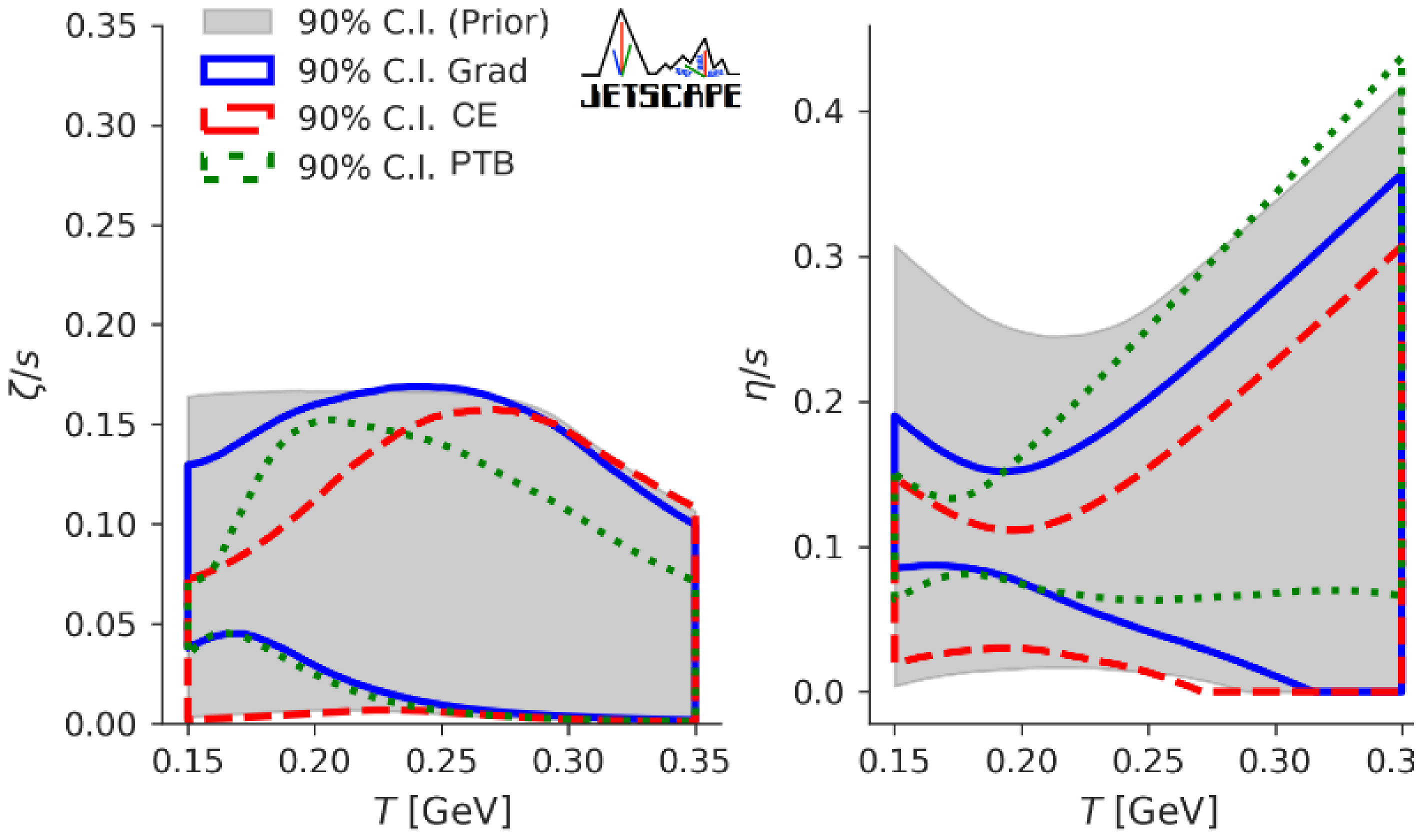
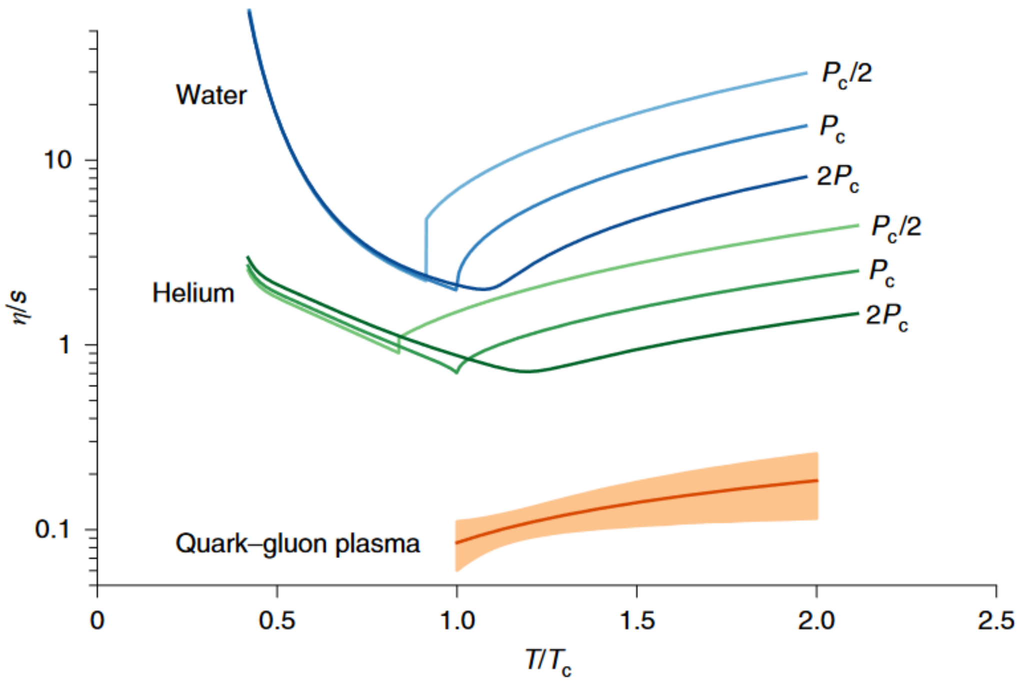
- The reliable phenomenological constraints to date on the QGP viscosities.

The Importance of Model Uncertainties





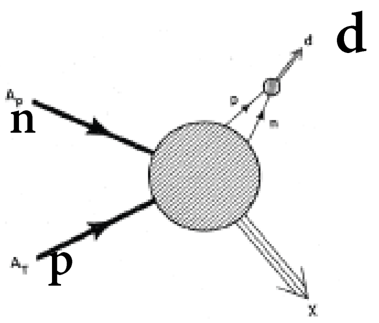
JETSCAPE : arXiv: 2011.01430, 2010.03928

J. E. Bernhard, etc, al. Nature Phys. 15, 1113 (2019).

- The reliable phenomenological constraints to date on the QGP viscosities.

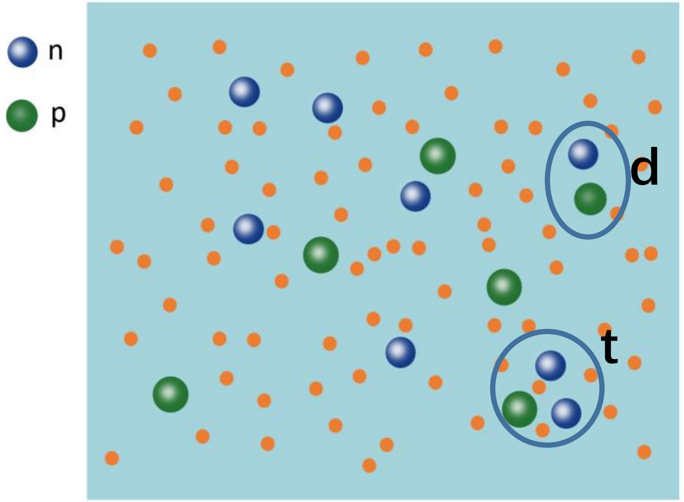
Light Nuclei Analysis

- **Question**: Only light hadrons observables included before, how about light nuclei, e.g. deuteron ?
- Light nuclei are more sensitive to each of the mentioned theoretical uncertainties, with a particular sensitivity to bulk viscosity.
- Investigate the production mechanisms of light cluster in heavy-ion collisions.



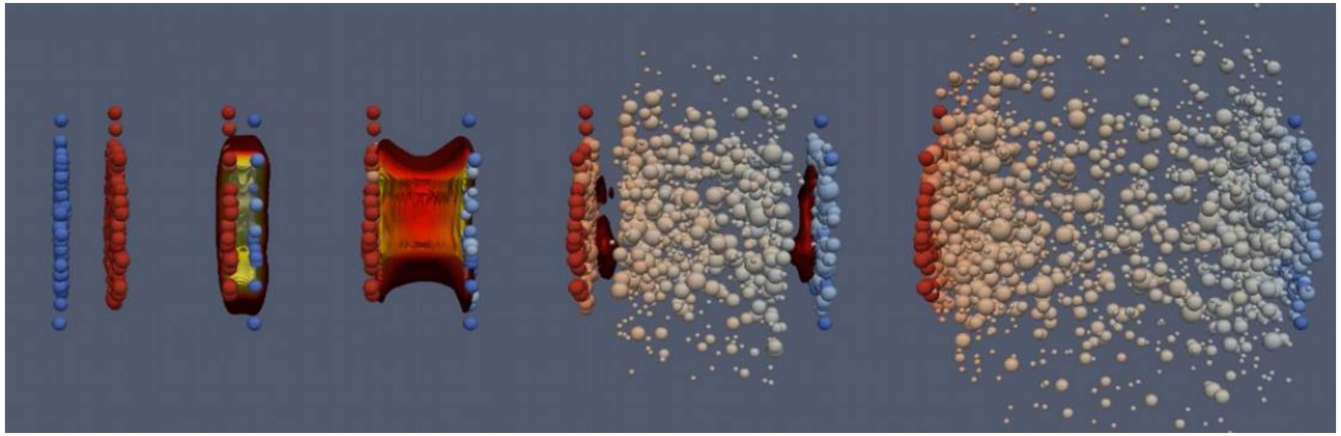
$$\pi NN \leftrightarrow \pi d, NNN \leftrightarrow Nd, NN \leftrightarrow \pi d,$$

Transport model: break up and re-form during hadronic evolution.



Coalescence model: combine nucleons closed in phase-space into light nuclei at kinetic freeze-out.

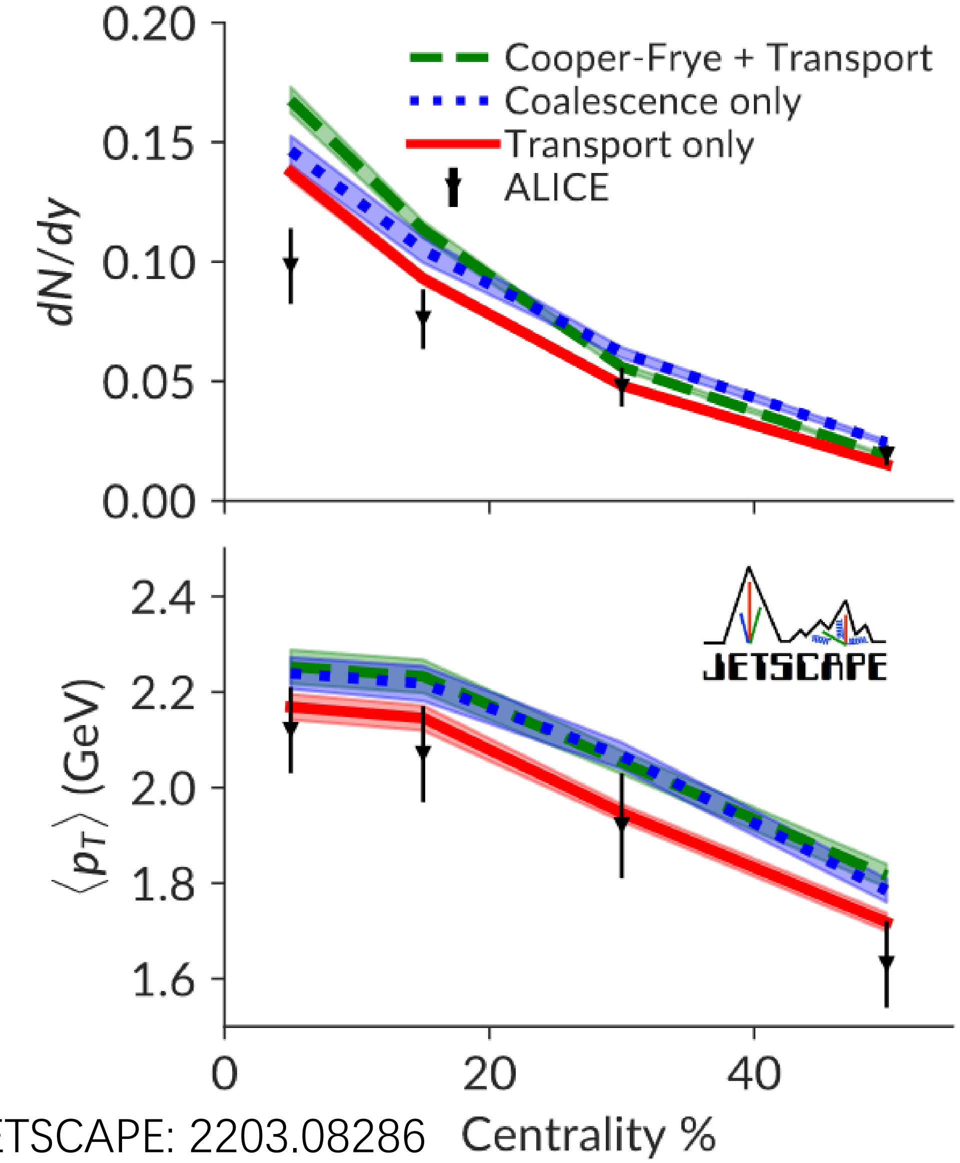
Different Deuteron Production Mechanisms



- **Transport only**: deuterons not present at particlization, followed by hadronic transport with deuteron Reactions.
- **Cooper-Frye + Transport**: deuterons present at particlization and allowed to react in the hadronic transport;

$$\pi NN \leftrightarrow \pi d, NNN \leftrightarrow Nd, NN \leftrightarrow \pi d,$$

- **Coalescence only**: deuterons not present at particlization, hadronic transport without deuteron reactions, followed by coalescence at kinetic freeze-out.
- Differences are non-negligible but small.



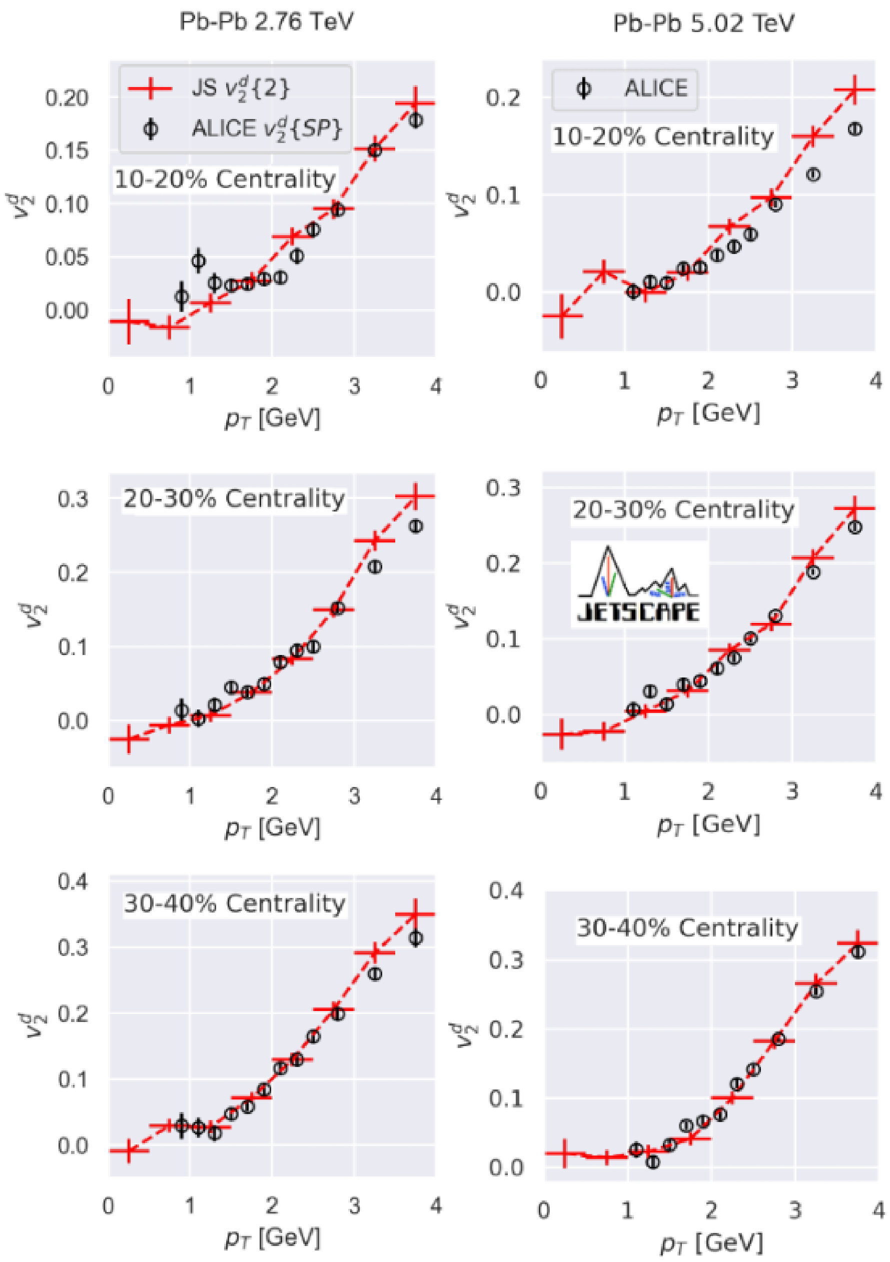
JETSCAPE: 2203.08286

Collective Flow of Deuteron

- With parameters extracted from previous Bayesian analysis, we predict collective flow for Deuteron (Here, use the Transport only mechanism).
- It’s a parameter free prediction.

parameter	value	parameter	value	parameter	value
N(2.76 TeV)[GeV]	14.2	τ_R[fm/c]	1.48	$(\zeta/s)_{\max}$	0.13
N(5.02 TeV)[GeV]	18.8	α	0.047	$T_{\zeta,c}$[GeV]	0.12
$T_{\eta,\mathrm{kink}}$[GeV]	0.22	p	0.06	w_ζ[GeV]	0.089
$a_{\eta,\mathrm{low}}[\mathrm{GeV}^{-1}]$	-0.76	σ_k	0.98	λ_ζ	-0.19
$a_{\eta,\mathrm{high}}[\mathrm{GeV}^{-1}]$	0.22	w[fm]	1.12	b_π	4.5
$(\eta/s)_{\mathrm{kink}}$	0.096	$d^3_{\min}[\mathrm{fm}^3]$	2.97	T_{sw}[GeV]	0.136

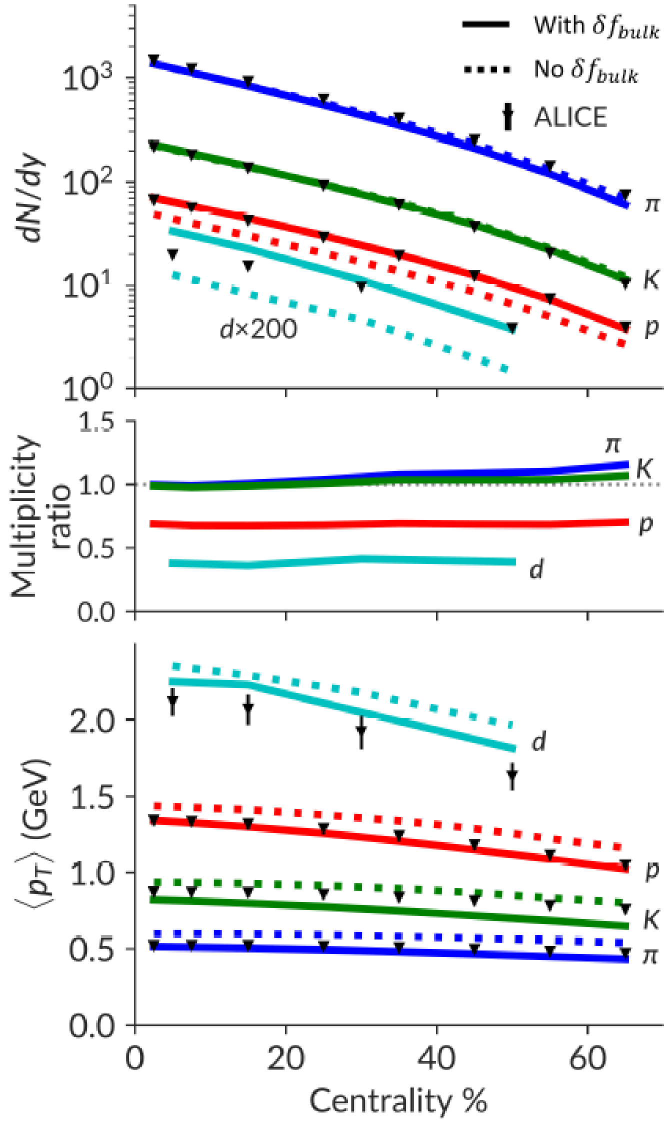
JETSCAPE: 2203.08286



Deuteron's Sensitivity to Medium Properties

- Deuteron is more sensitive to bulk viscous correction than light hadrons (pion, kaon and proton).
- Mean p_T gets reduced by the bulk viscous correction.
- The changes in the distributions of protons and pions feed down to the deuterons.

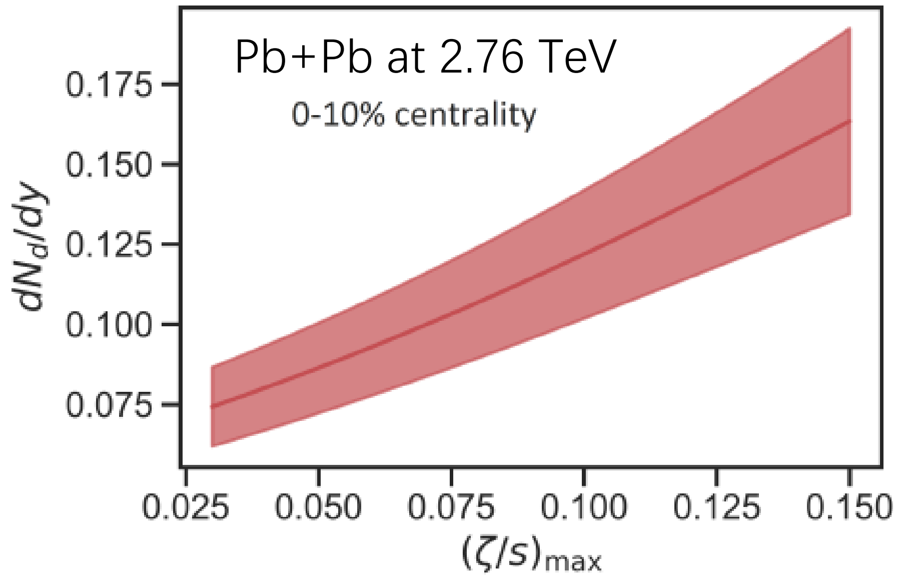
JETSCAPE: 2203.08286



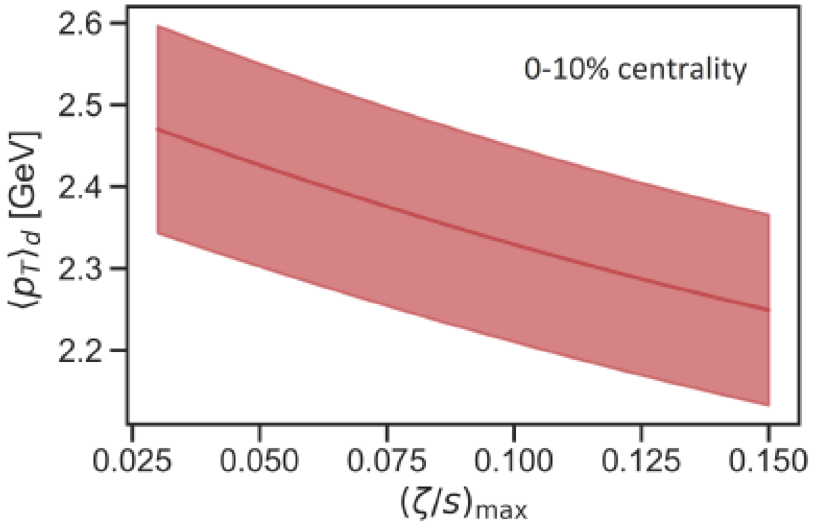
"Cooper-Frye+Transport" scenario

Bayesian Deuteron Analysis

parameter	min.	max
$(\zeta/s)_{\max}$	0.03	0.15
k	0.3	2
w [fm]	0.5	1.5



Three main parameters control the homogeneity of the energy density.
$(\zeta/s)_{\max}$: The bulk viscosity.
k: controls the magnitude of the fluctuations of the deposited energy in each nucleon-nucleon collision.
w: "nucleon width", controls the transverse radius of the nucleon



- Deuteron is particularly sensitive to bulk viscosity.

JETSCAPE: 2203.08286

Bayesian Deuteron Analysis

Main parameters control the homogeneity of energy density.

$(\zeta/s)_{max}$: The bulk viscosity.
k: controls the magnitude of the fluctuations of the deposited energy nucleon-nucleon collision.
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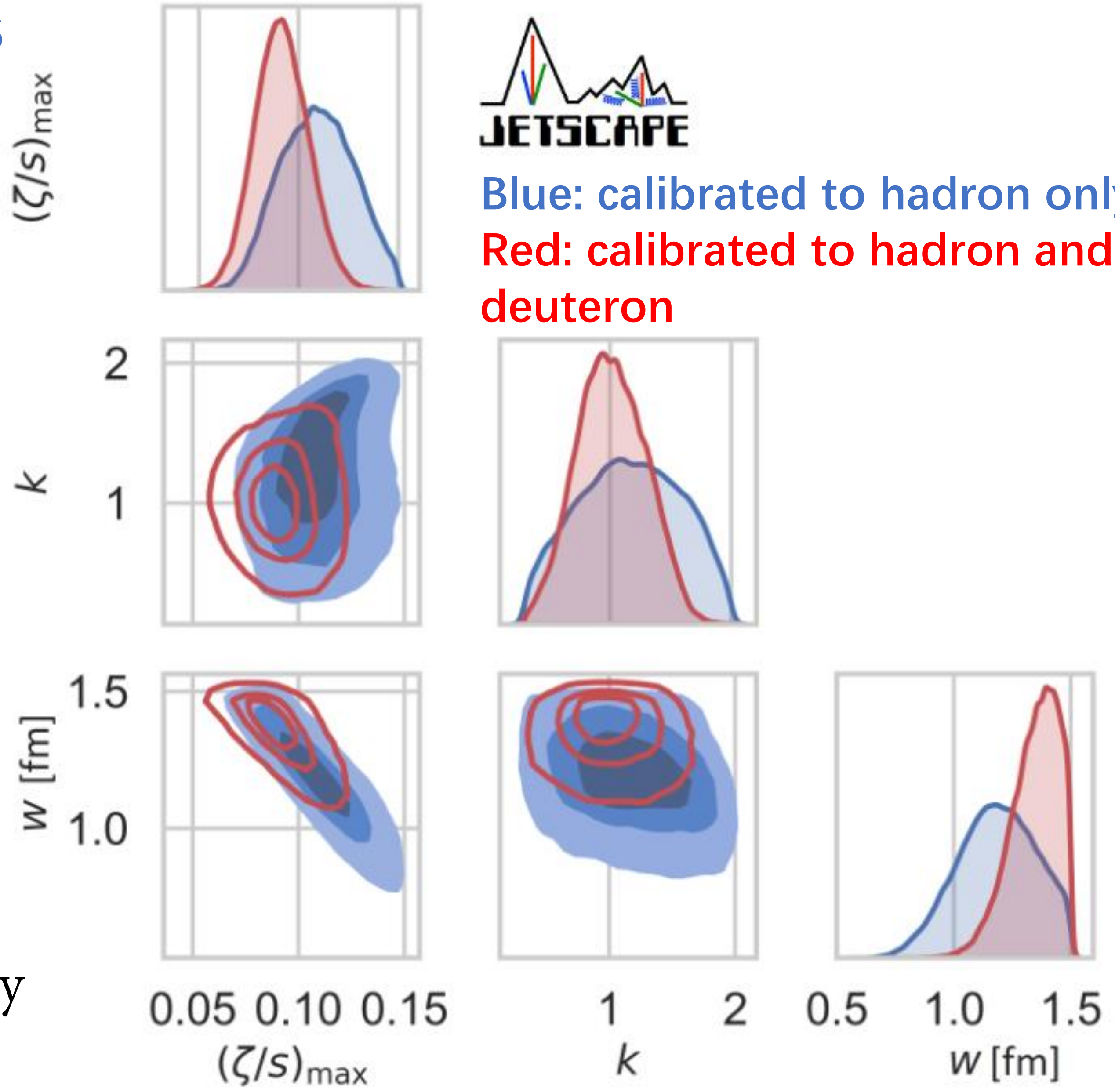
- Adding deuteron observables provide a more robust constraint of the bulk viscosity in heavy ion collision

Blue: calibrated to hadron only
Red: calibrated to hadron and deuteron



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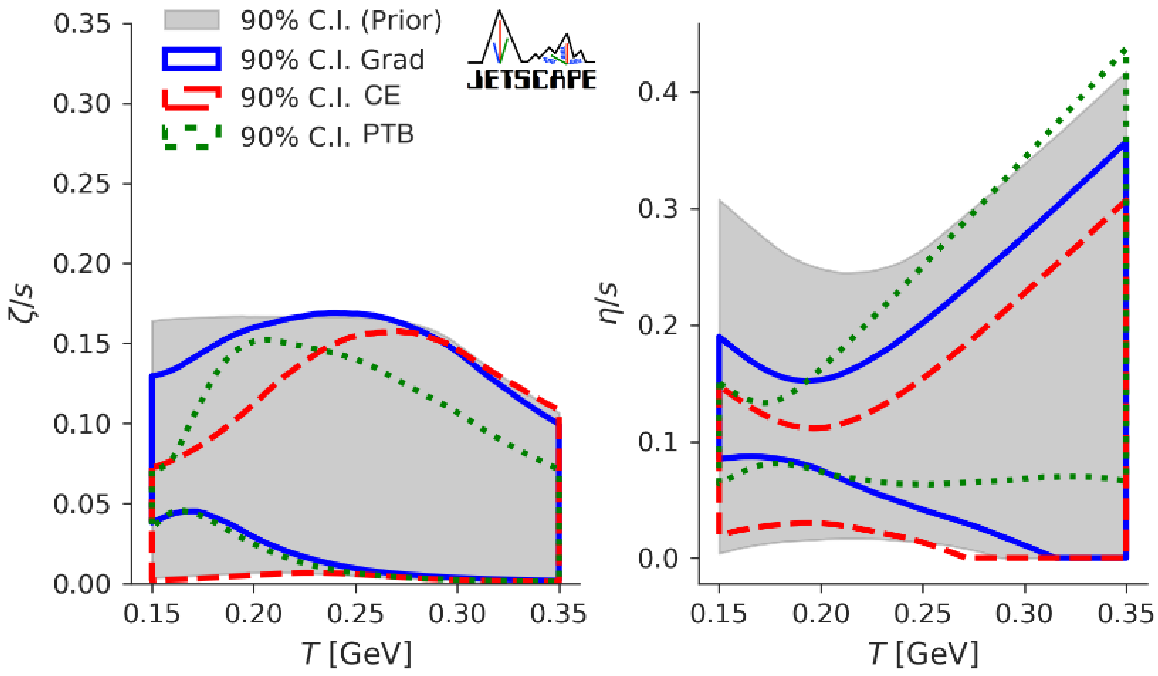
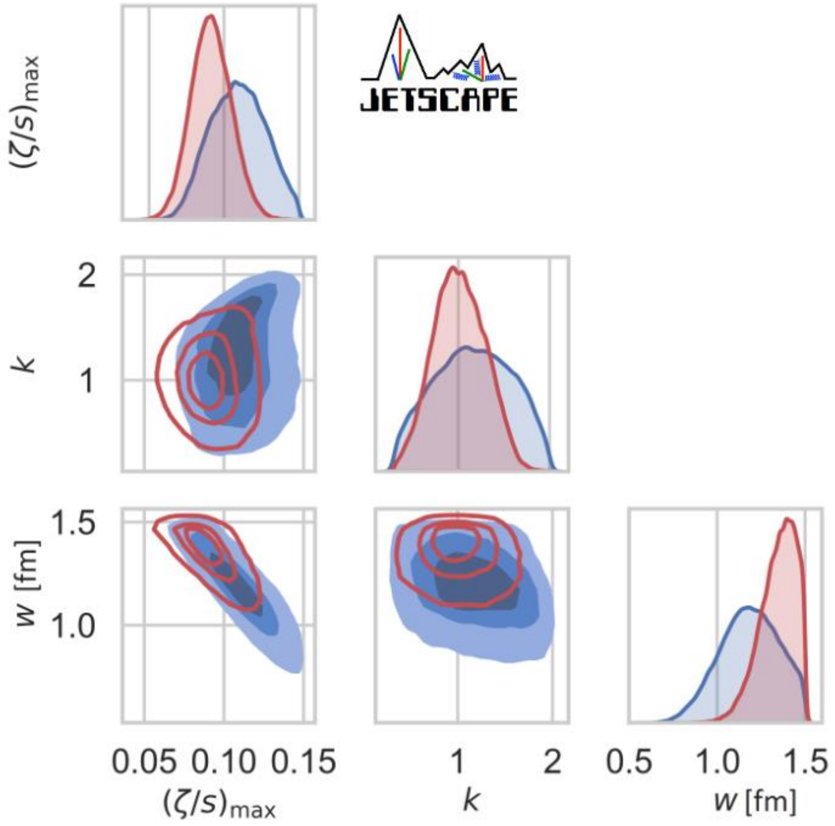
Summary

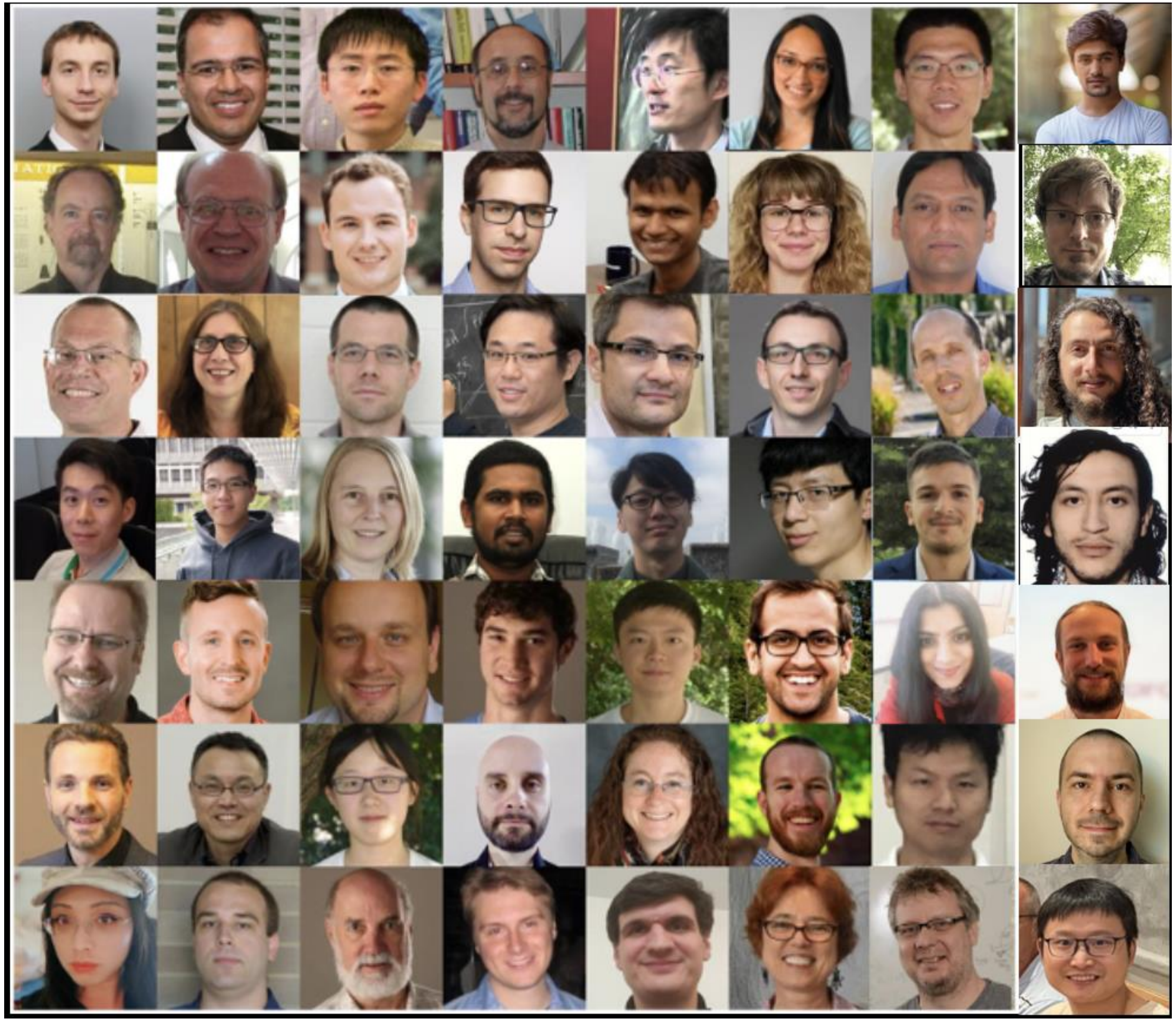
- "State-of-the-art" constraints on the QGP viscosities from recent JETSCAPE analysis.
- Including model uncertainties.
- Adding light nuclei provide a new way to better constraint the bulk viscosity in heavy ion collisions.





Acknowledgements

JETSCAPE Collaboration



https://jetscape.org/
https://github.com/JETSCAPE

Questions?

Back Up

From fluid to particles: Viscous corrections

- Hydrodynamics is a coarse-grained description
- Momentum distribution of hadrons corresponding to fluid's energy-momentum tensor?

Fluid description	Hadronic momentum distribution
Ideal hydrodynamics & local thermal equilibrium	Equilibrium: Fermi-Dirac (baryons), Bose-Einstein (mesons)
Viscous hydrodynamics & deviation from equilibrium	?

<u>Different ansätze to map energy-momentum tensor to hadron momentum distributions:</u>

- 14 Moments (Grad):

$$f_n = f_{n,thermal} + \delta f_n;\ \delta f_n = f_{n,\mathrm{eq}}\bar{f}_{n,\mathrm{eq}}\left(c_T\, m_n^2 + c_E(u\cdot p)^2 + c_\pi^{<\mu\nu>} p_{\langle\mu}p_{\nu\rangle}\right)$$

- Chapman-Enskog - Relaxation Time Approximation (R.T.A.):

$$f_n = f_{n,thermal} + \delta f_n; \quad \delta f_n = f_{n,\mathrm{eq}}\bar{f}_{n,\mathrm{eq}}\left[\frac{\Pi}{\beta_\Pi}\left(\frac{(u\cdot p)\mathcal{F}}{T^2} + \frac{(-p\cdot\Delta\cdot p)}{3(u\cdot p)T}\right) + \frac{\pi_{\mu\nu}p^{\langle\mu}p^{\nu\rangle}}{2\beta_\pi(u\cdot p)T}\right],$$

- Pratt-Bernhard:

$$f_n = \frac{z_\Pi}{\det\Lambda} g_n \left[\exp\left(\frac{\sqrt{p_i' p_i' + m_n^2}}{T}\right) + \Theta_n\right]^{-1} \qquad p_i = \Lambda_{ij}p_j'$$

$$\Lambda_{ij} = (1+\lambda_\Pi)\delta_{ij} + \frac{\pi_{ij}}{2\beta_\pi}$$

See:
McNelis, Everett, Golden & Heinz, in preparation;
McNelis, APS DNP2019,
and references therein

Ref: Jean-Francois, APS, 2021