# Flow and transport properties: Assessment and outlook

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September 23, 2022


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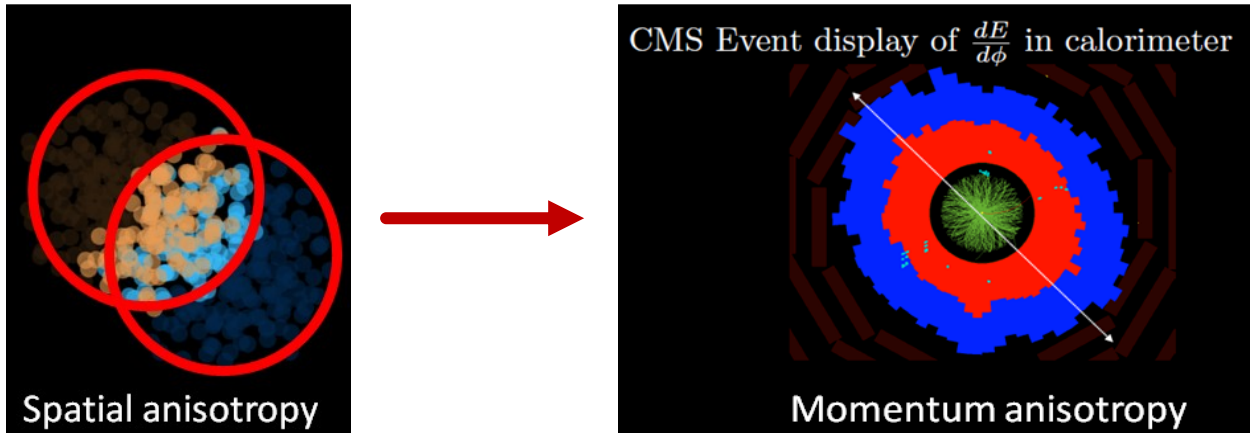
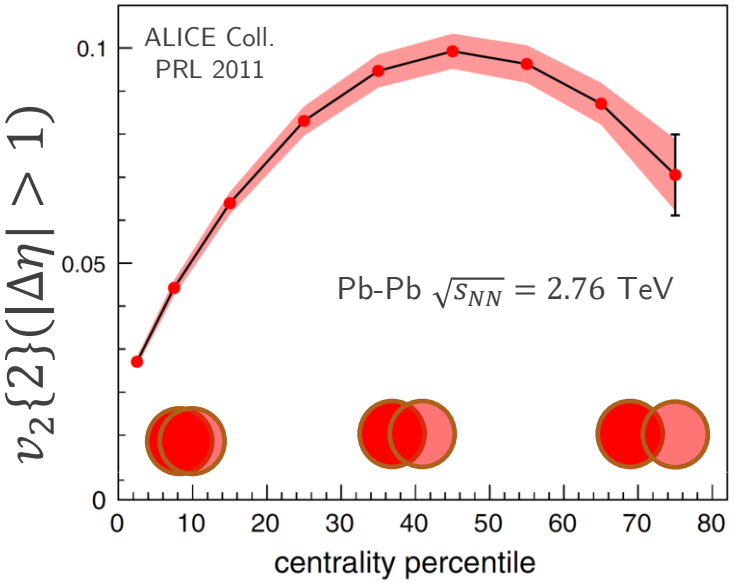
# From impact geometry to momentum anisotropy



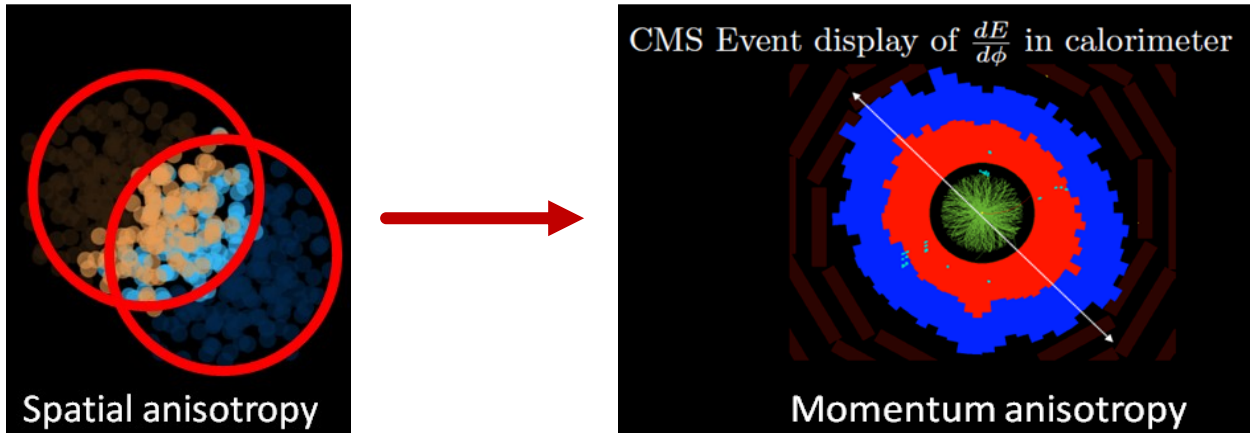

Based on figures by Derek Teaney, CMS Coll., MADAI, H. Elfner and J. Bernhard

"Elliptic flow"




- Spatial anisotropy from partial overlap of nuclei & fluctuation
- Interactions transfer spatial anisotropy into momentum one
- Rapid development of momentum anisotropies consistent with strongly-coupled system

# From impact geometry to momentum anisotropy

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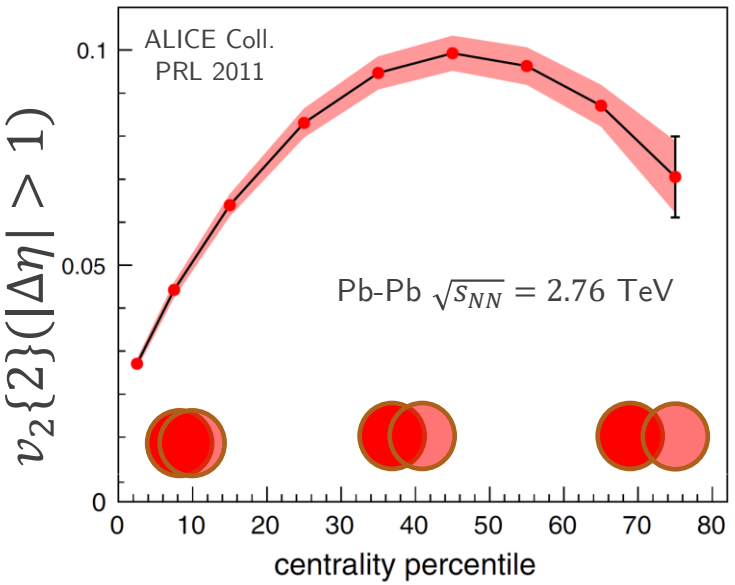
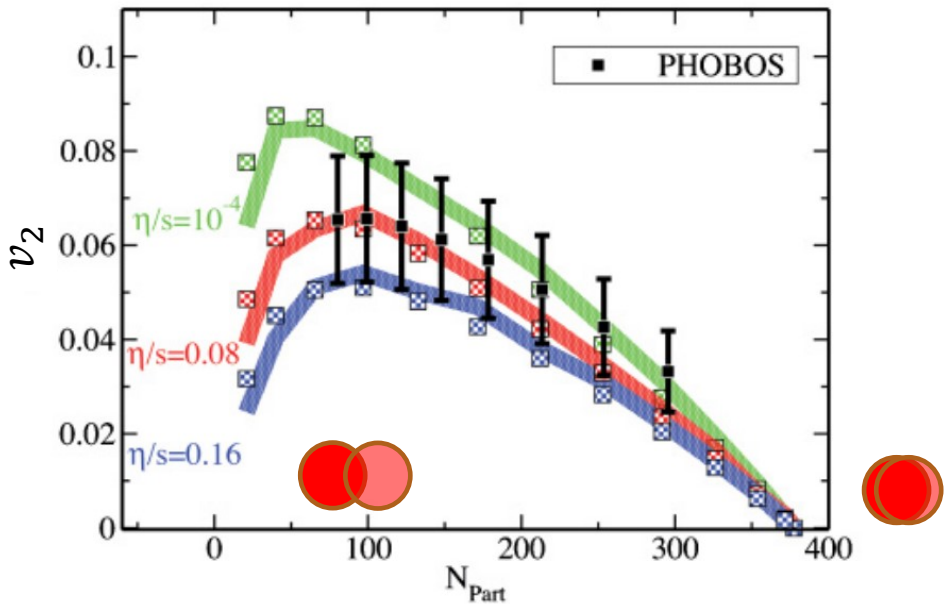


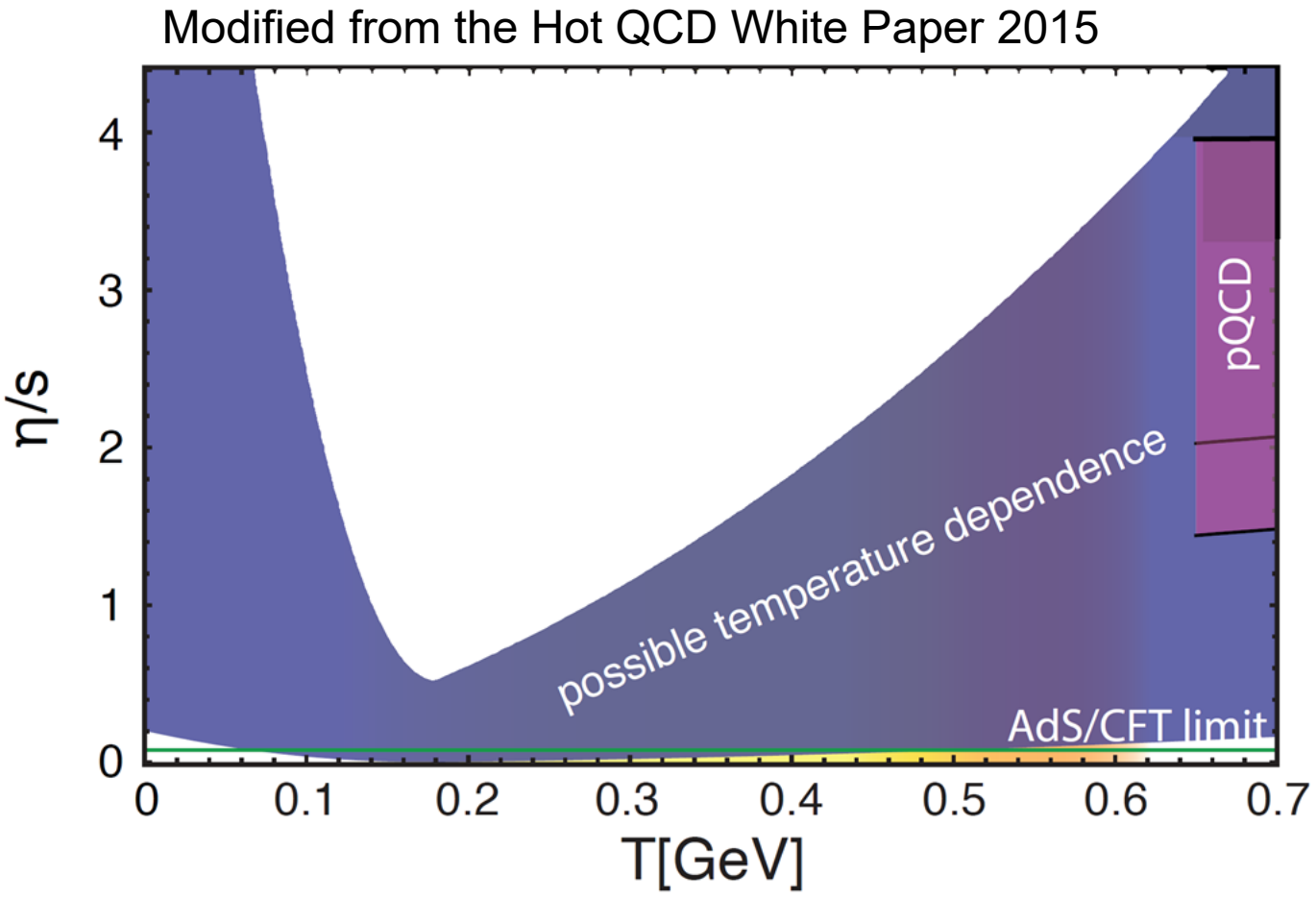

Luzum and Romatschke (2009) PRC




Effect of shear viscosity on $v_2$

(Shear viscosity inversely related to strength of interaction)

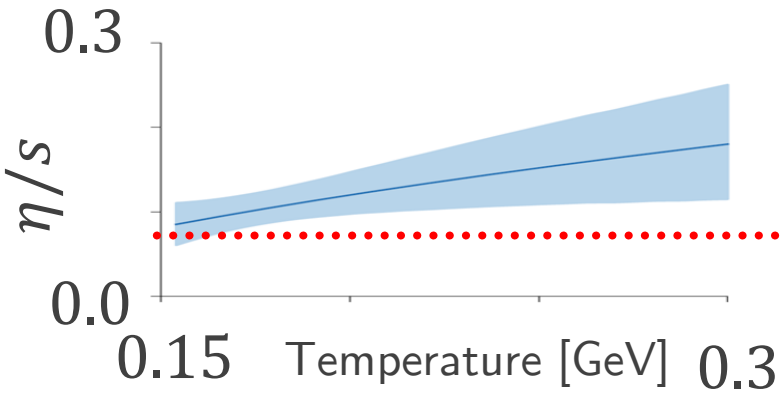
# Shear and bulk viscosity of strongly-coupled quark-gluon plasma

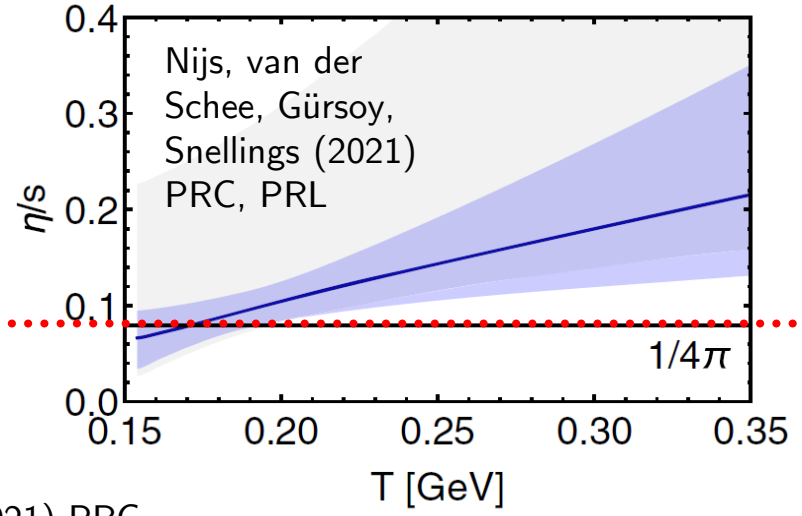



- Constrain temperature dependence of shear viscosity?
  - Minimum value?
  - Where is the minimum?
  - Increase at low and high temp.?
- Study bulk viscosity and constrain its temperature dependence?
  - Peak?

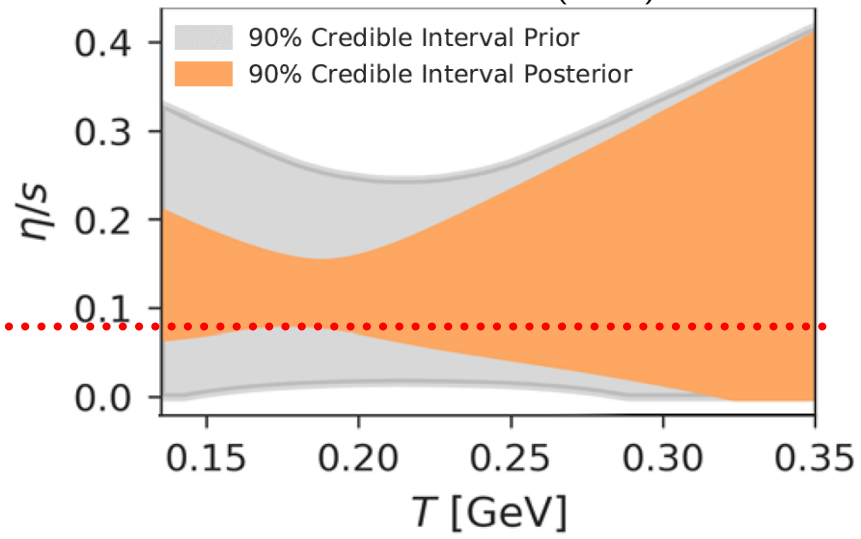
# Shear viscosity calibrations

Bernhard, Moreland, Bass (2019) Nat.Phys.



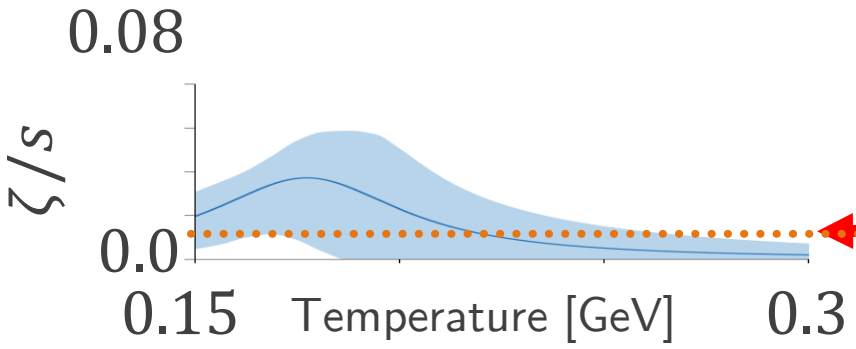

JETSCAPE Collaboration, (2021) PRC, PRL




Similar results from Parkkila, Onnerstad, Kim (2021) PRC

# Bulk viscosity calibrations

Bernhard, Moreland, Bass (2019) Nat.Phys.

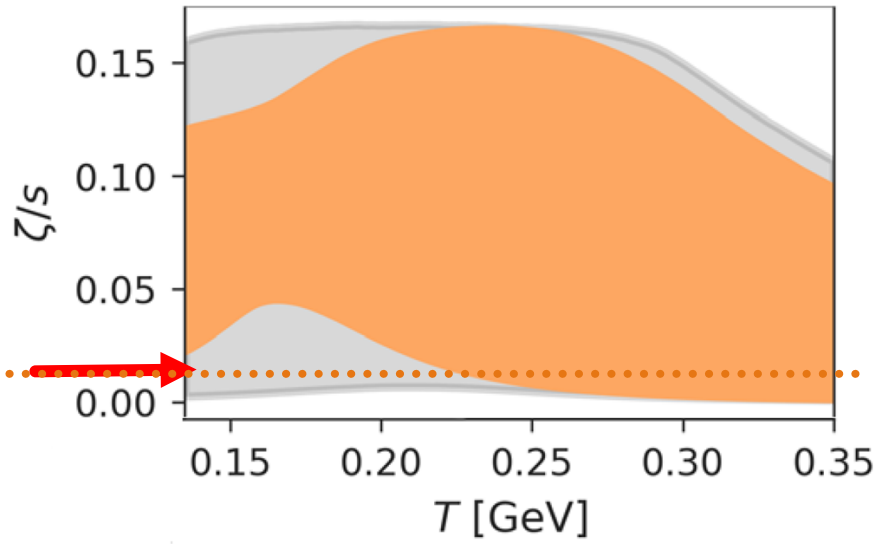



Nijs, van der Schee, Gürsoy, Snellings (2021) PRC, PRL

$\zeta/s < 0.01$

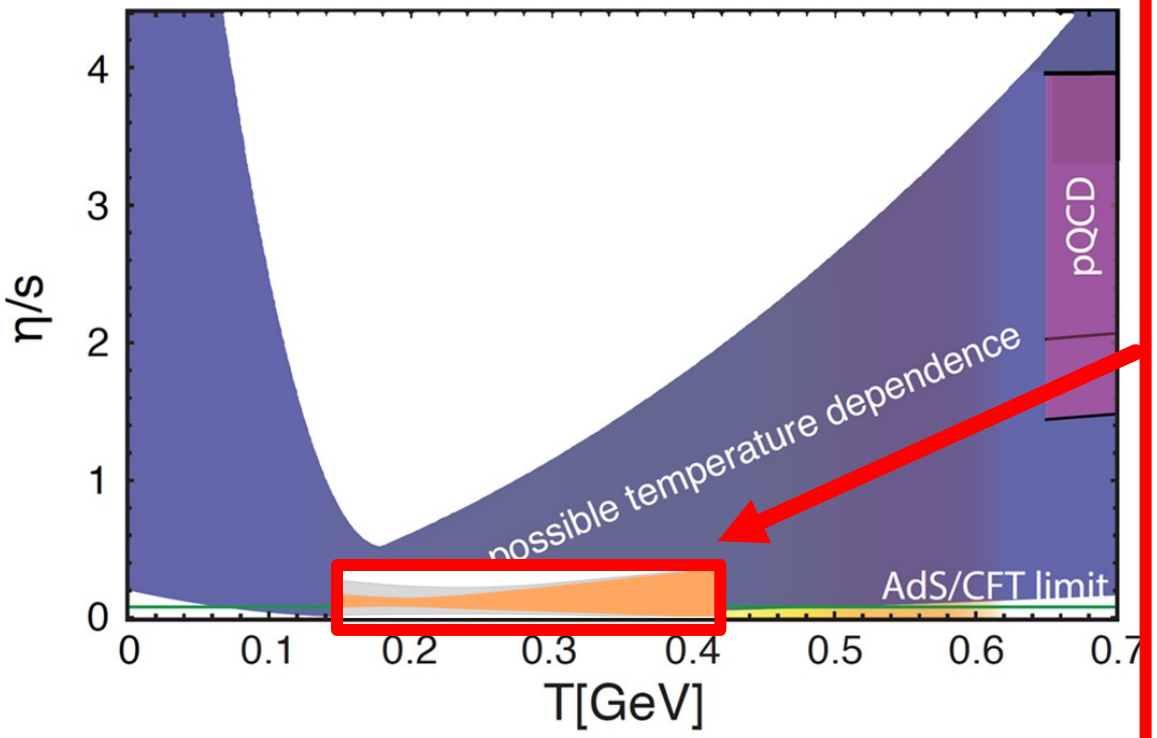
Parkkila, Onnerstad, Kim (2021) PRC: $\zeta/s < 0.03$

JETSCAPE Collaboration, (2021) PRC, PRL

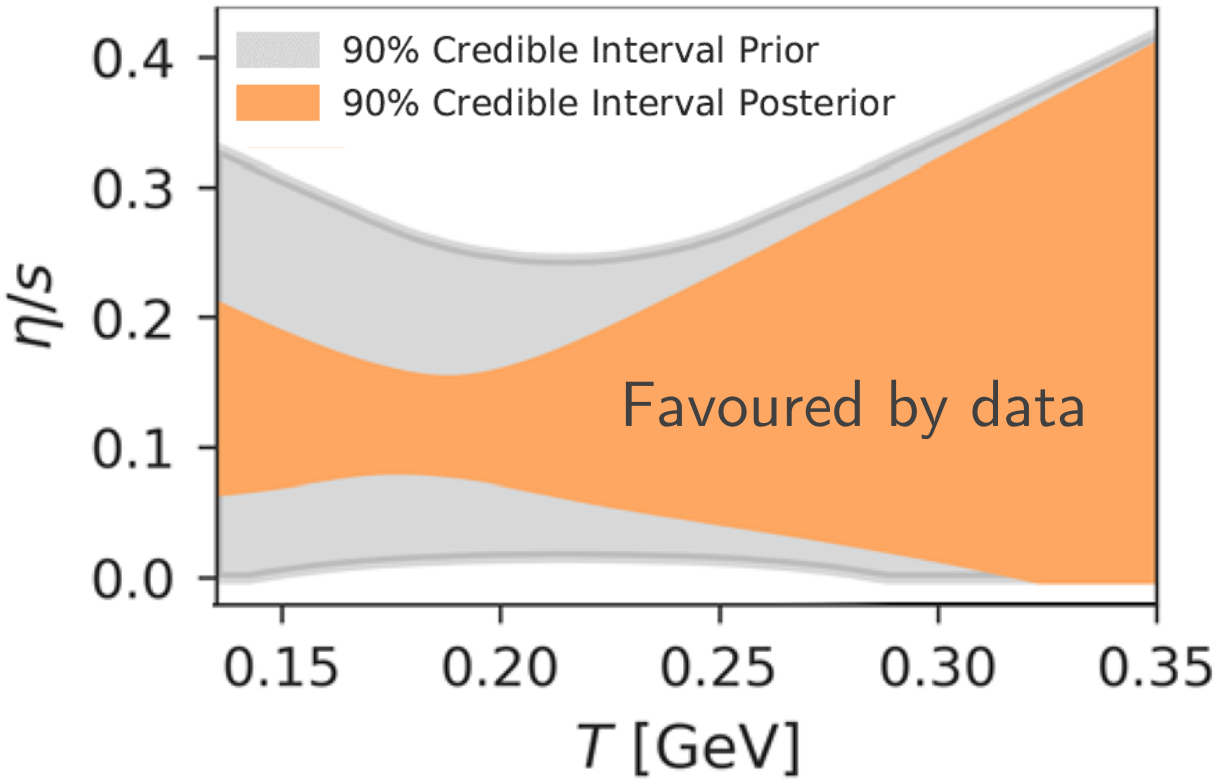


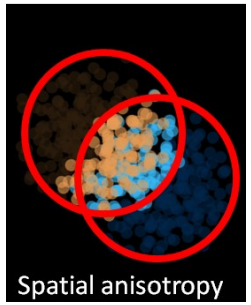
# Shear viscosity of strongly-coupled quark-gluon plasma

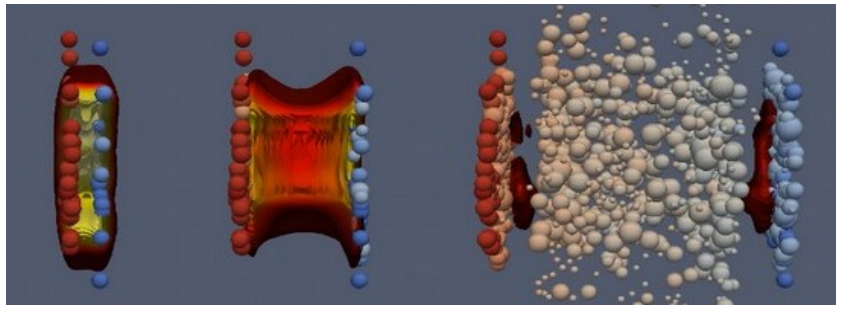
Modified from the Hot QCD White Paper 2015

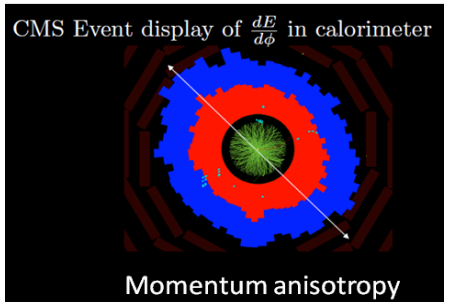



JETSCAPE Collaboration, (2021) PRC, PRL





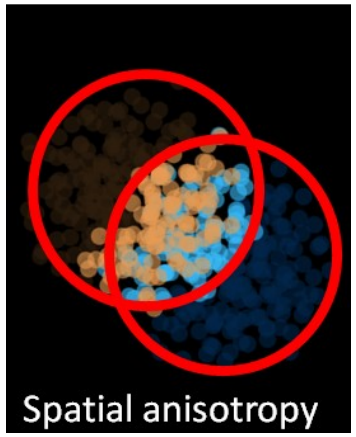


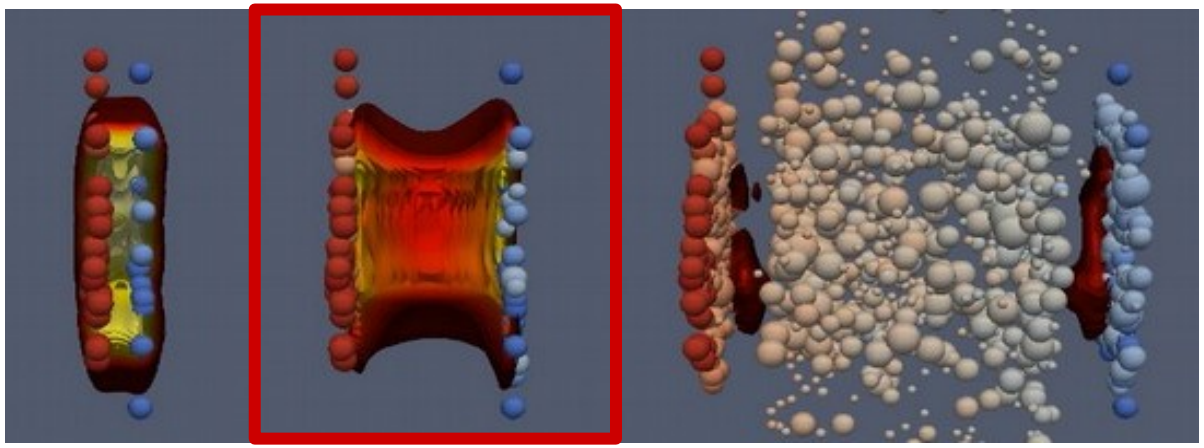

# OUTLOOK ON CONSTRAINING THE VISCOSITIES:

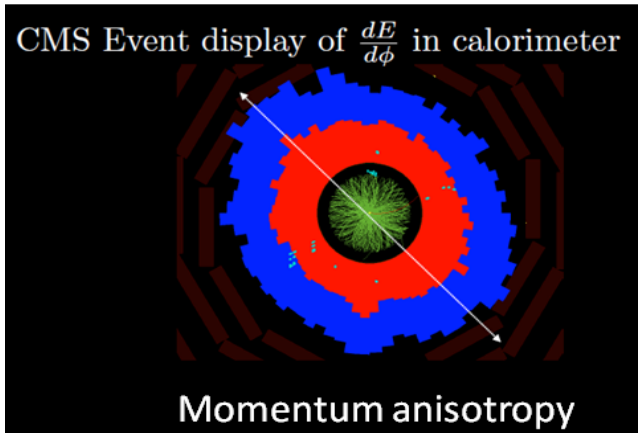
## BEYOND THE CURRENT "STANDARD MODEL" OF COLLISIONS

# Multistage simulations of heavy ion collisions

Based on figures by Derek Teaney, CMS Coll., MADAI, H. Elfner and J. Bernhard





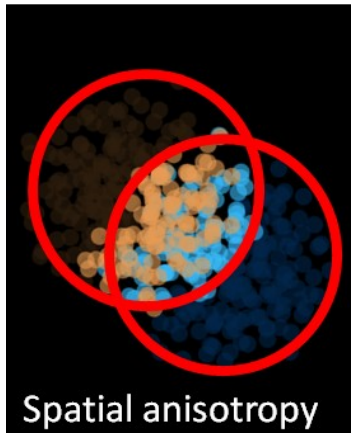

**Energy deposition** → **Early dynamics** → **Hydrodynamics** → **Hadronic transport**

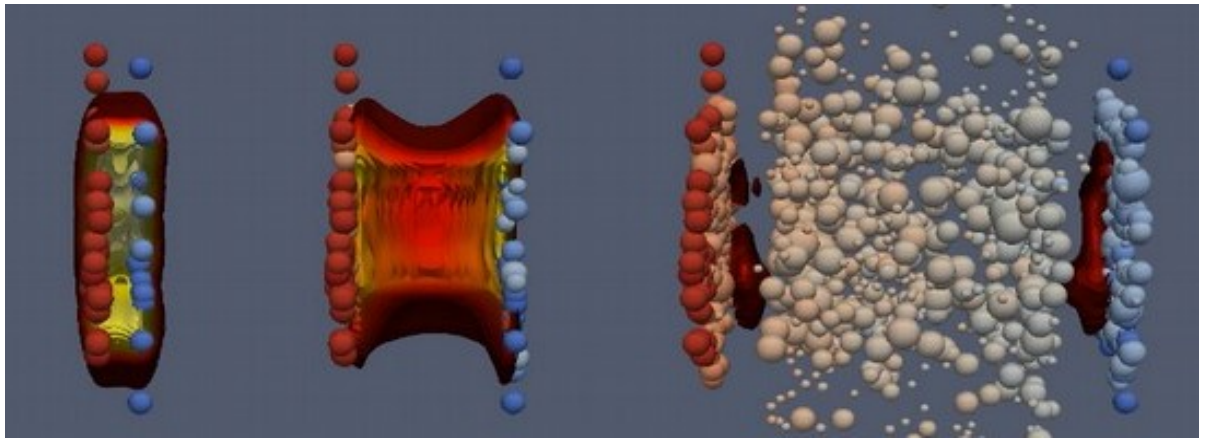
- Energy-momentum tensor of plasma: $T^{\mu\nu} = \epsilon u^\mu u^\nu - (P(\epsilon) + \Pi)(g^{\mu\nu} - u^\mu u^\nu) + \pi^{\mu\nu}$
- Conservation of energy and momentum: $\partial_\nu T^{\mu\nu} = 0$
- Mueller-Israel-Stewart-type relativistic viscous hydrodynamics

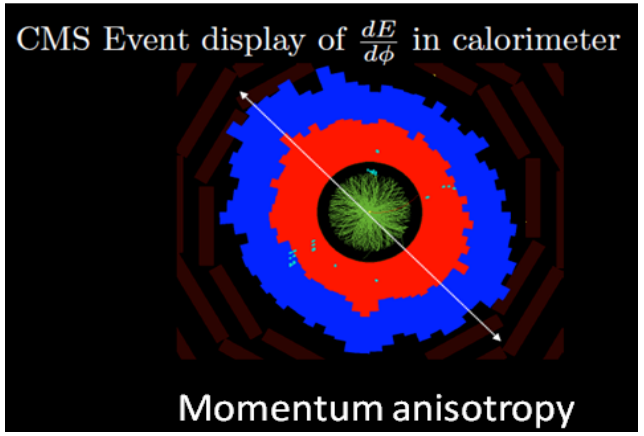
$$\tau_\pi \Delta^{\mu\nu}_{\alpha\beta} \dot{\pi}^{\alpha\beta} + \boxed{\pi^{\mu\nu} = 2\,\eta(T)(\partial^\mu u^\nu + \cdots)} + (2^{\text{nd}}\text{ order}); \quad \tau_\Pi \dot{\Pi} + \boxed{\Pi = -\zeta(T)\,\partial_\mu} u^\mu + (2^{\text{nd}}\text{ order});$$

# Beyond the current "standard model" of collisions

Based on figures by Derek Teaney, CMS Coll., MADAI, H. Elfner and J. Bernhard






**Energy deposition** → **Early dynamics** → **Hydrodynamics** → **Hadronic transport**

- Theoretical uncertainties limit accuracy of constraints on viscosity

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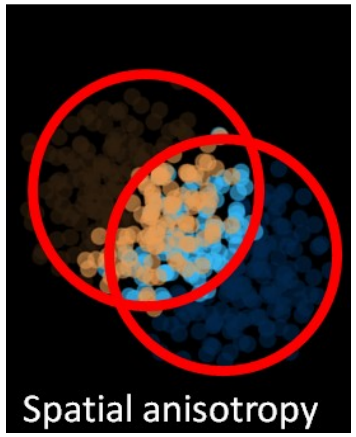
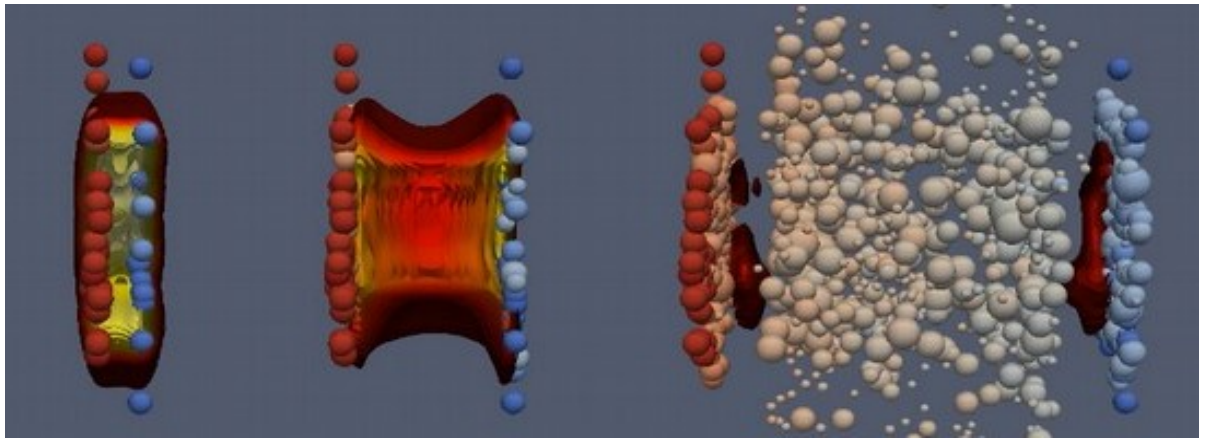
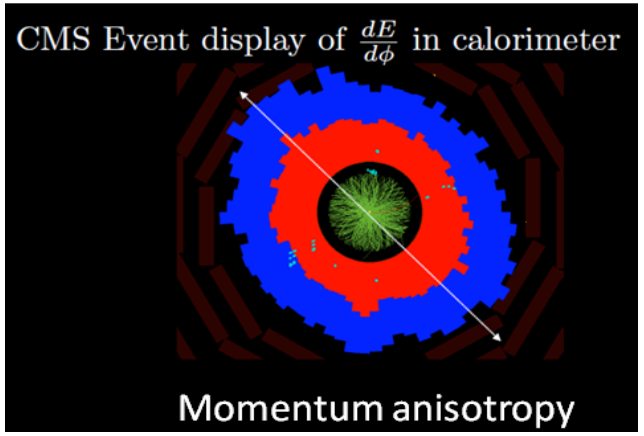
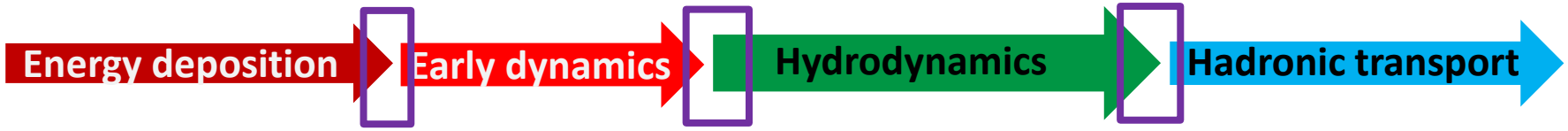


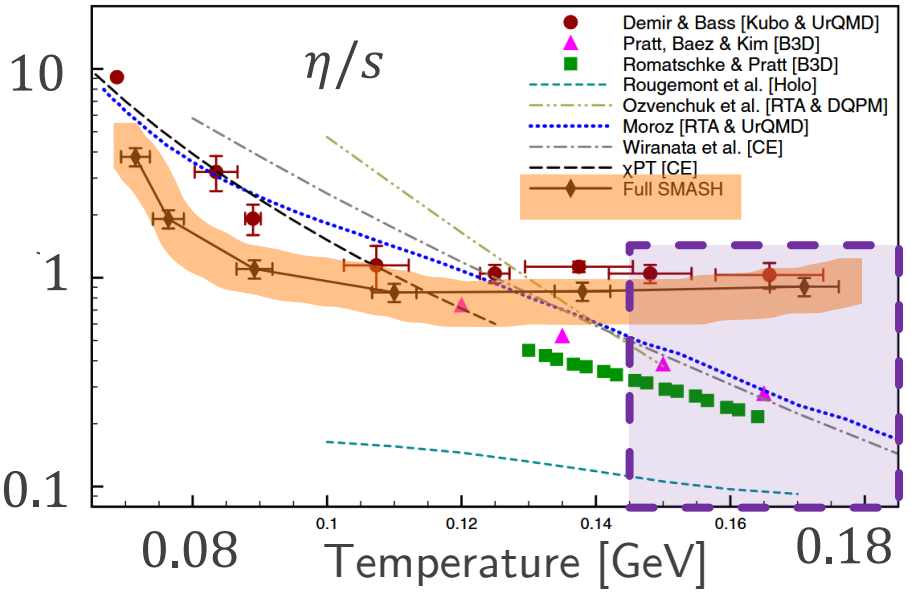


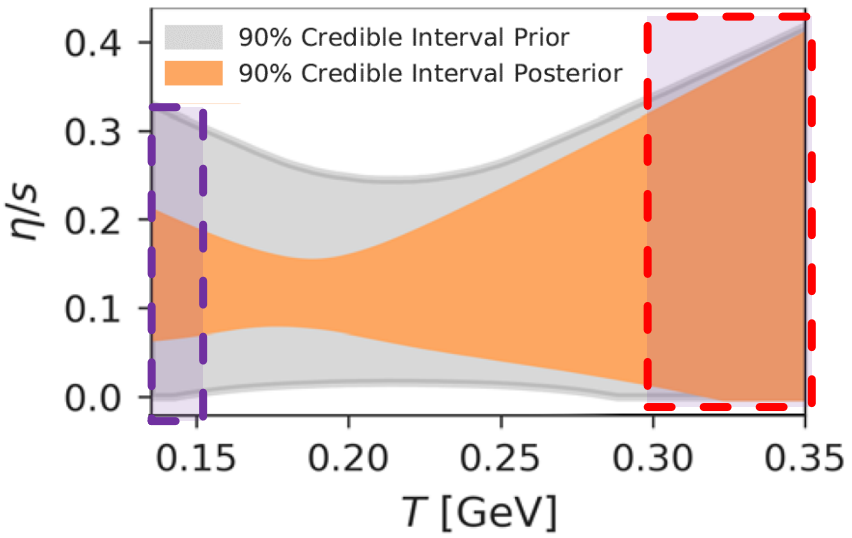




- Theoretical uncertainties limit accuracy of constraints on viscosity
  - Need smooth transition between stages of collision

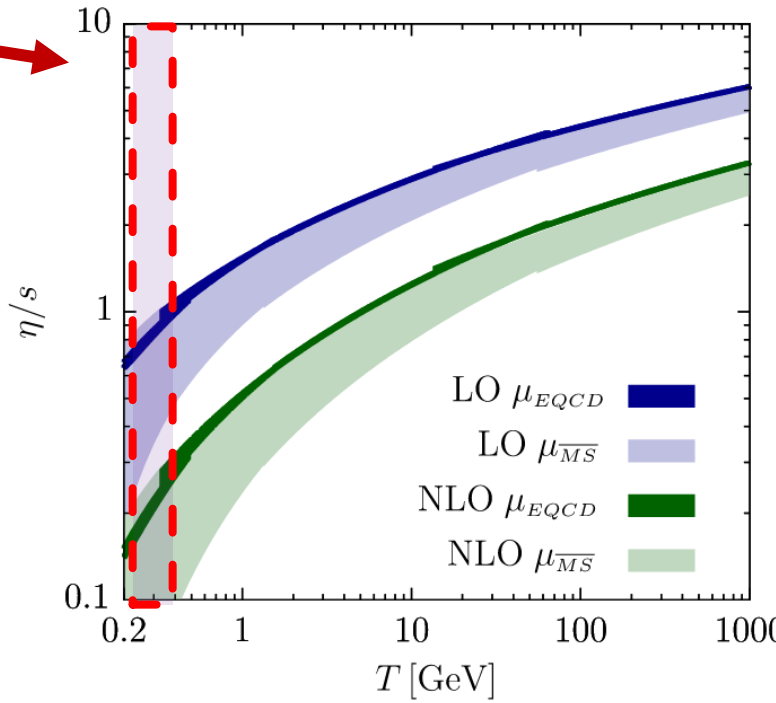
# Smooth transition between models and their viscosities


Rose, Torres-Rincon, Schäfer, Oliinychenko, Petersen (2018) PRC



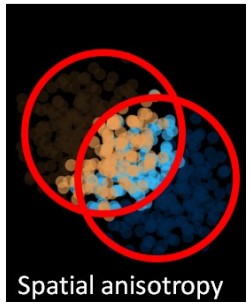



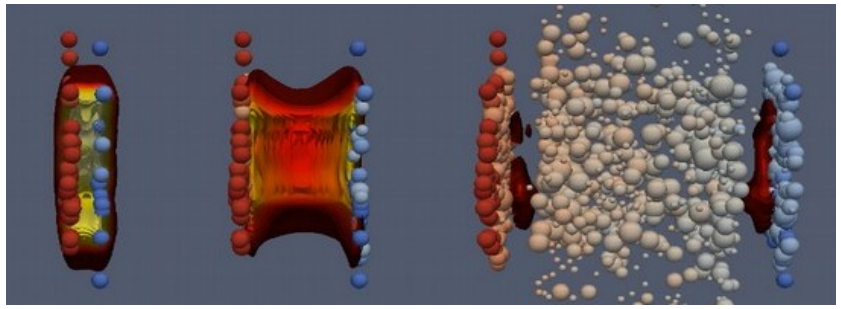

Ghiglieri, Moore, Teaney (2018) JHEP

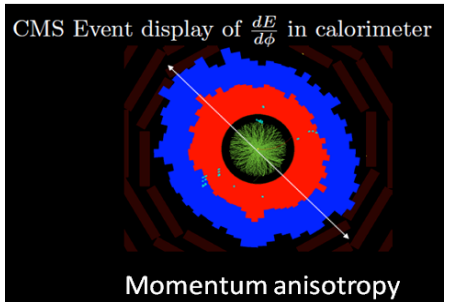



Interacting hadronic gas for $T < \sim 150$ MeV

Weakly-coupled quark-gluon plasma at high temperature



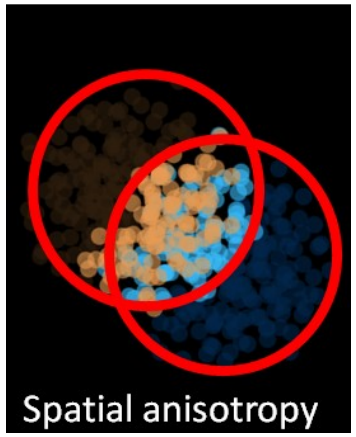



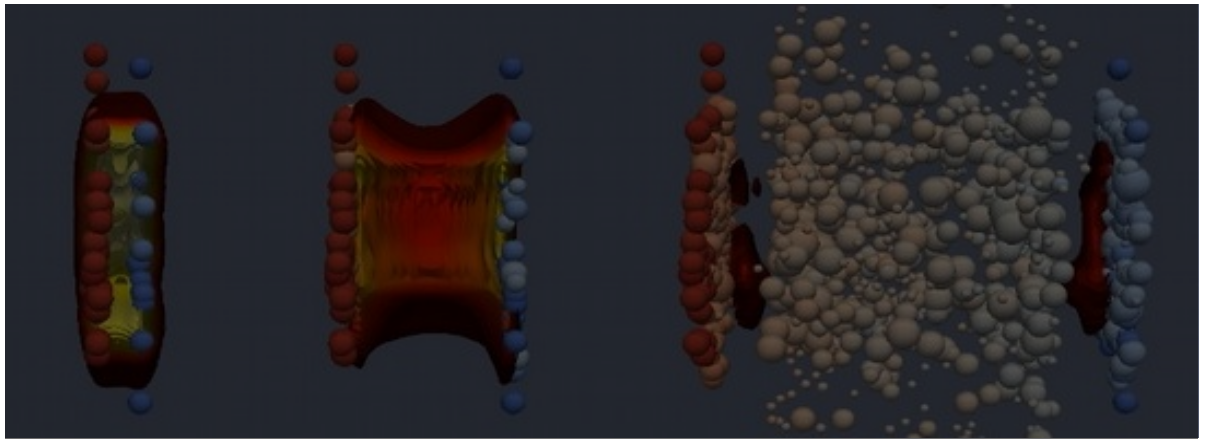


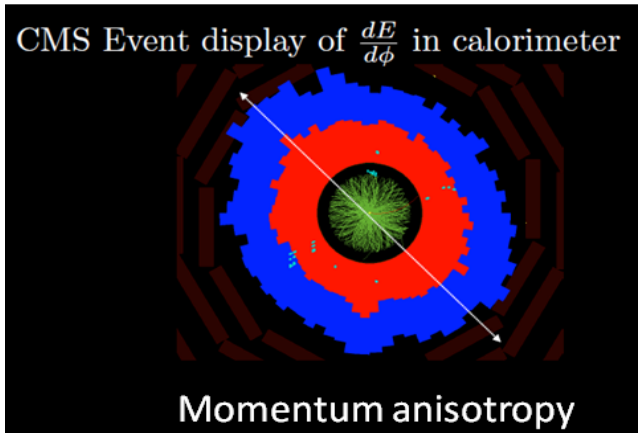

# OUTLOOK ON CONSTRAINING THE VISCOSITIES:

## EXPERIMENTAL AND THEORETICAL COLLABORATIONS

# Leverage observables that target specific stages

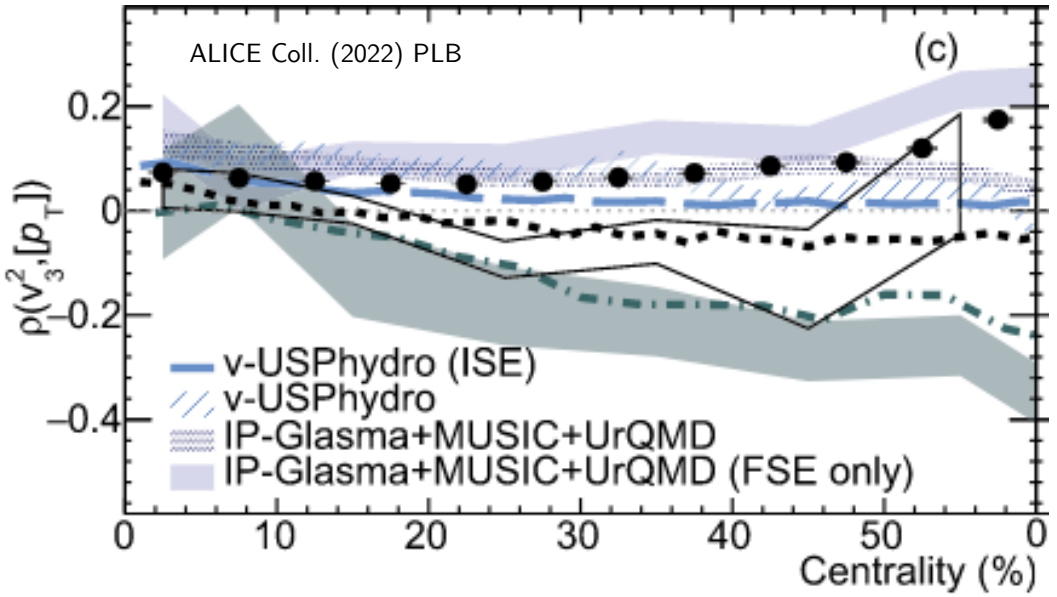





**Energy deposition**

Constraining energy deposition: See J. Jia's talk on Sat.

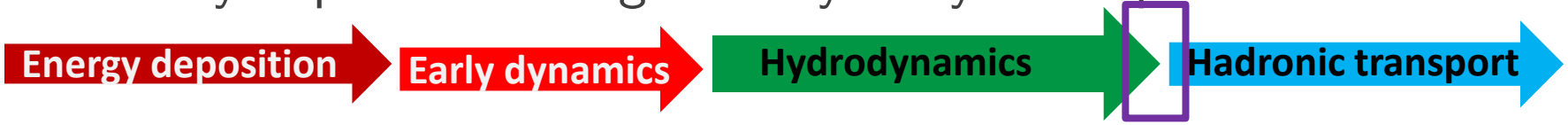



$$\rho_n = \frac{\left\langle \frac{E_i}{S}\varepsilon_n^2 \right\rangle - \left\langle \frac{E_i}{S} \right\rangle \left\langle \varepsilon_n^2 \right\rangle}{\sigma_{E_i/S}\sigma_{\varepsilon_n^2}} \frac{f'(\langle E_i/S \rangle)}{|f'(\langle E_i/S \rangle)|}$$

Giacalone, Gardim, Noronha-Hostler, Ollitrault (2020) PRC

# Considering theoretical uncertainties of observables

- Viscosity is probed through the hydrodynamic phase

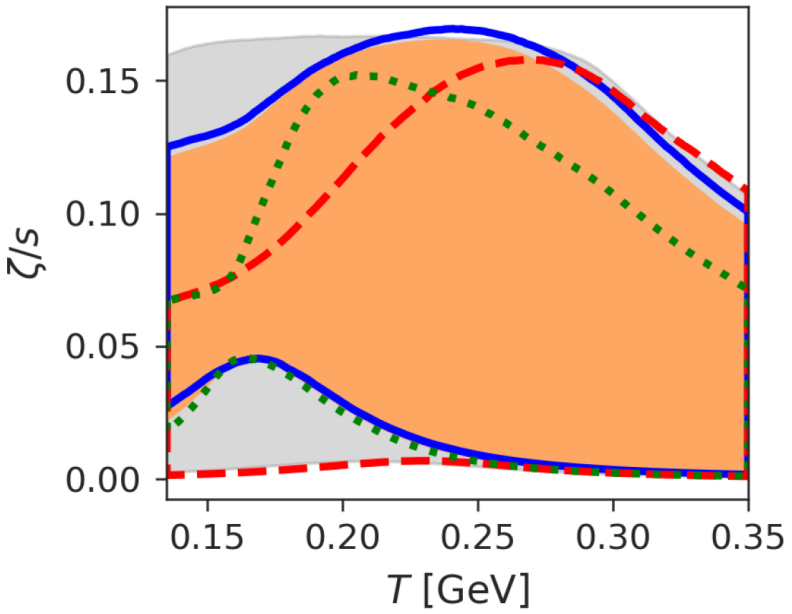


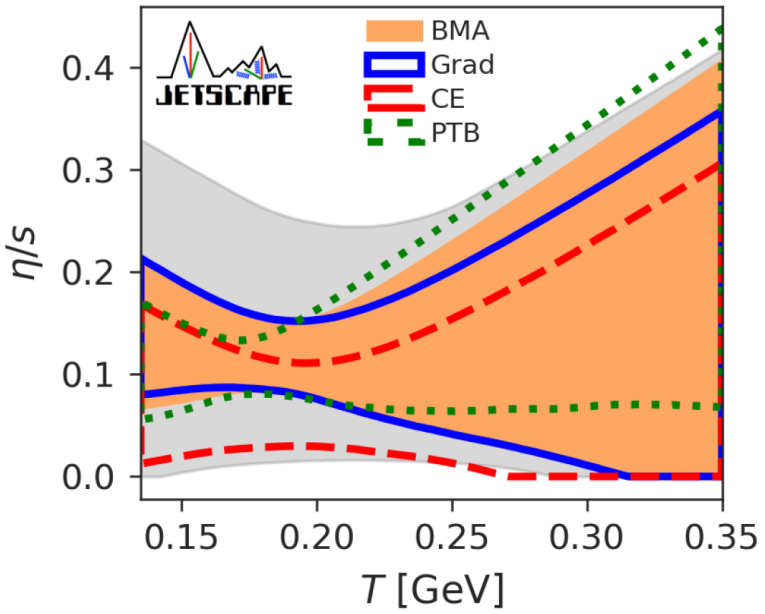

$$\partial_\nu T^{\mu\nu} = 0; \qquad T^{\mu\nu} = \epsilon u^\mu u^\nu - (P(\epsilon) + \Pi)(g^{\mu\nu} - u^\mu u^\nu) + \pi^{\mu\nu}$$

$$T^{\mu\nu} = \sum_n g_n \int \frac{d^3P}{(2\pi)^3 P^0} P^\mu P^\nu f_n(P)$$

Hadron momentum distributions; deviate from Fermi-Dirac/Bose-Einstein distribution

JETSCAPE Collaboration, (2021) PRC, PRL



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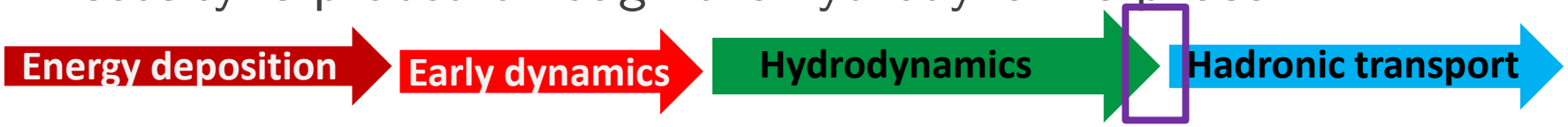
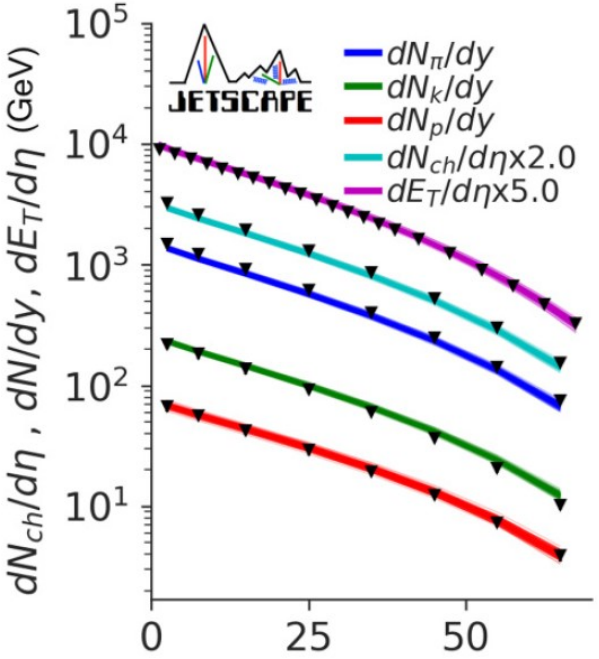


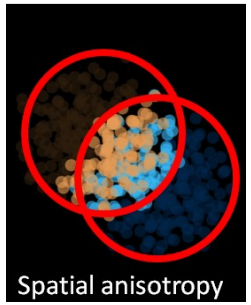

$$\partial_\nu T^{\mu\nu} = 0; \qquad T^{\mu\nu} = \epsilon u^\mu u^\nu - (P(\epsilon) + \Pi)(g^{\mu\nu} - u^\mu u^\nu) + \pi^{\mu\nu}$$

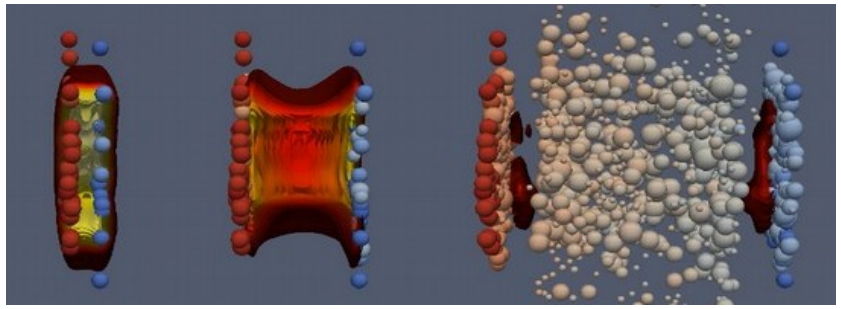
Reduced modelling uncertainties for energy/momentum-based observables (e.g. transverse energy)

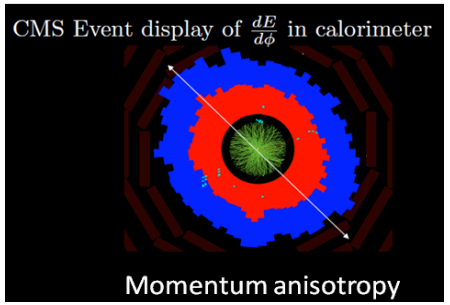
[ Analogy: inclusive and exclusive observables in p-p collisions ]




- Also, consider the objective of the measurement
  - E.g. smaller systems (p+A) to push our understanding
  - Larger central collisions to constrain viscosity



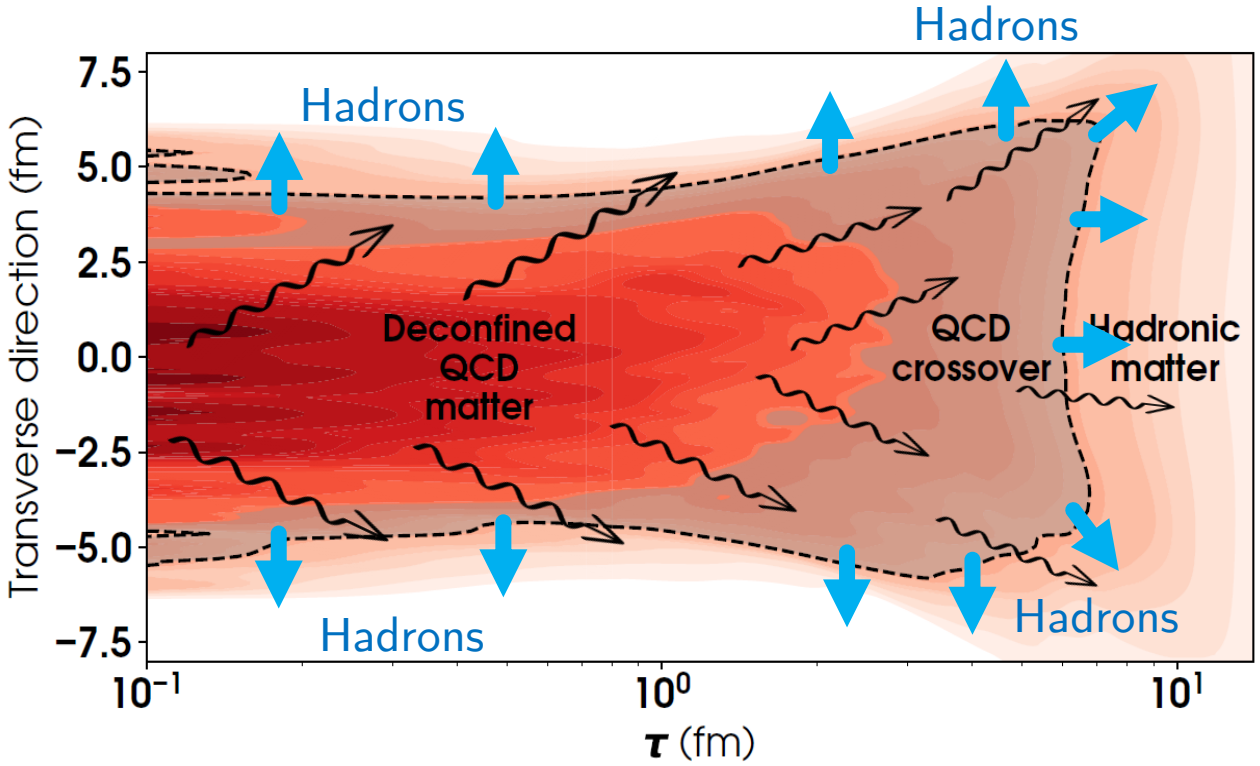



# OUTLOOK ON CONSTRAINING THE VISCOSITIES:

## MULTIMESSENGER

# Beyond soft hadrons: electromagnetic probes

- Photons ($\gamma$) and dileptons ($l^+l^-$) are "holistic" probes: produced at all stages, reflects the local properties of the plasma




Considerable progress over past decade:

- Emission rates studied at NLO and on lattice
- Pre-equilibrium photons & dileptons
- $\gamma$ & $l^+l^-$ from hadronic transport

**Considerable opportunities with more&better data**

# Beyond soft hadrons: electromagnetic probes from early time

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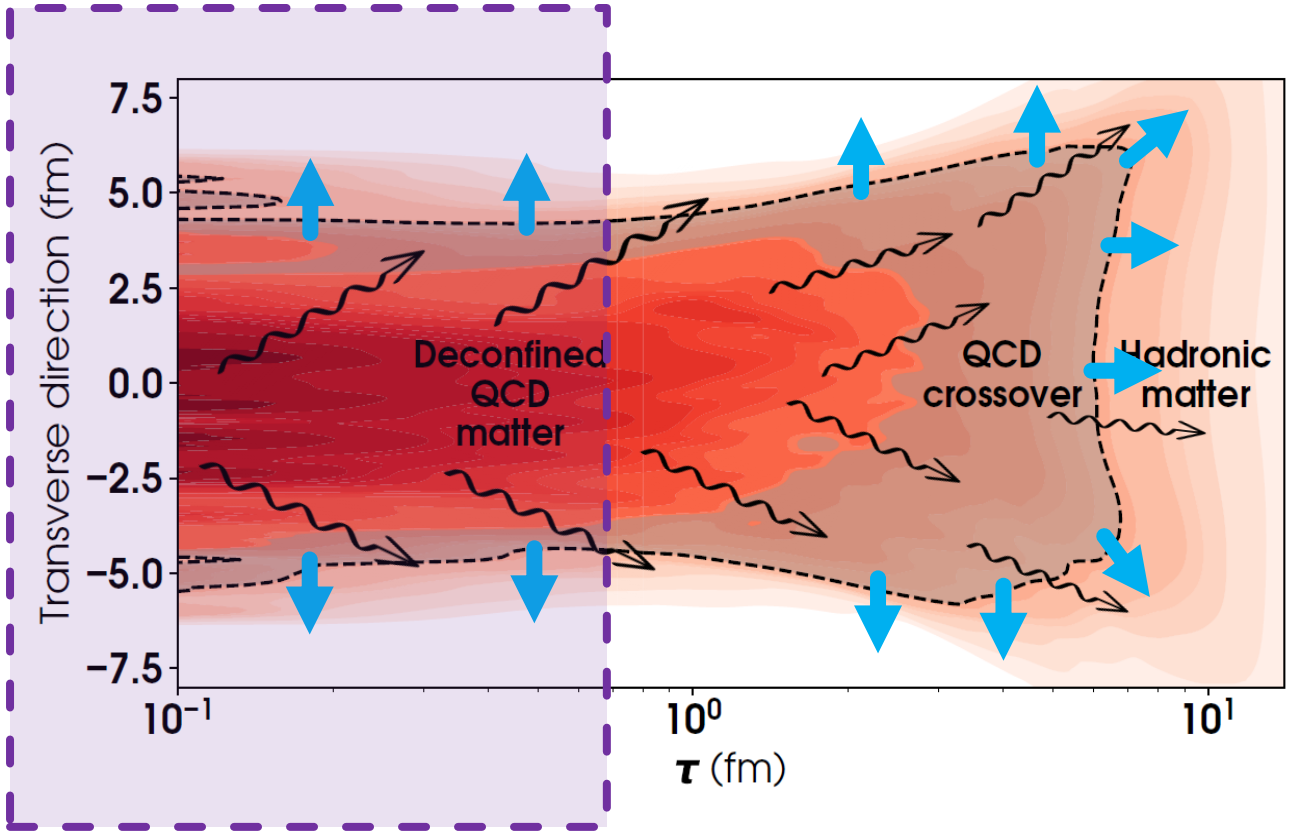
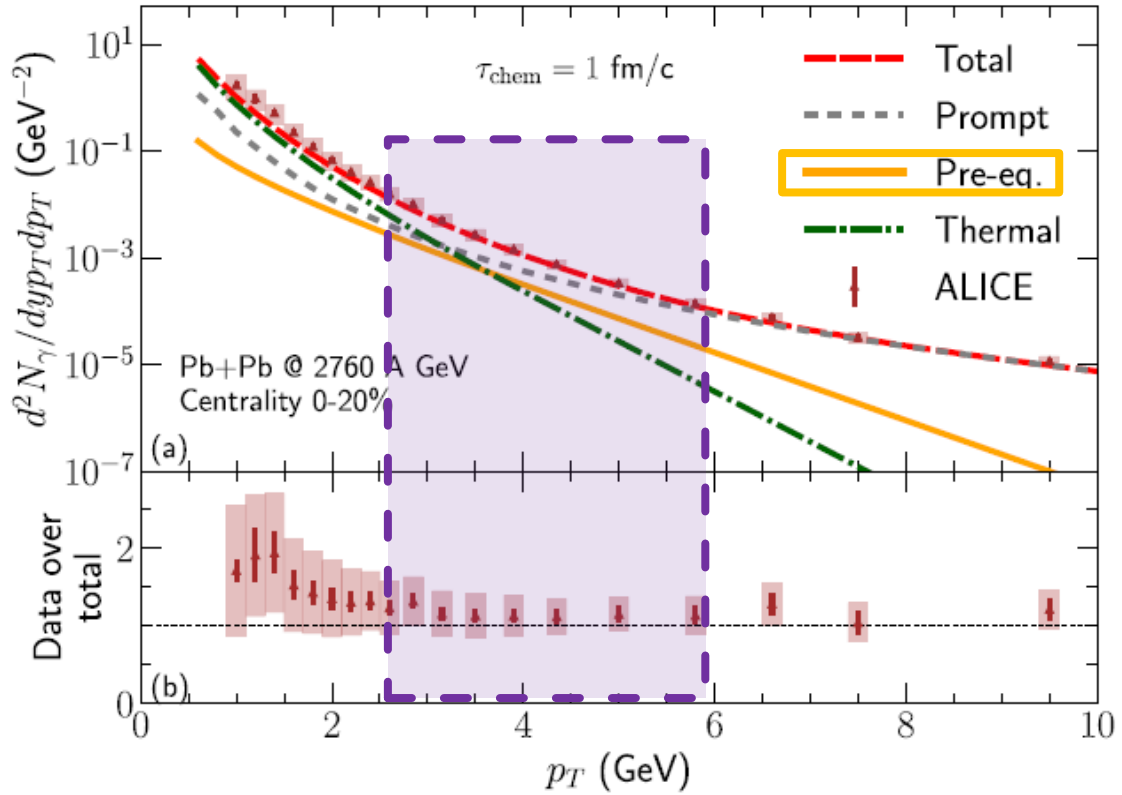
  produced at all stages, reflects the local properties of the plasma




Gale, Paquet, Schenke, Shen (2022) PRC



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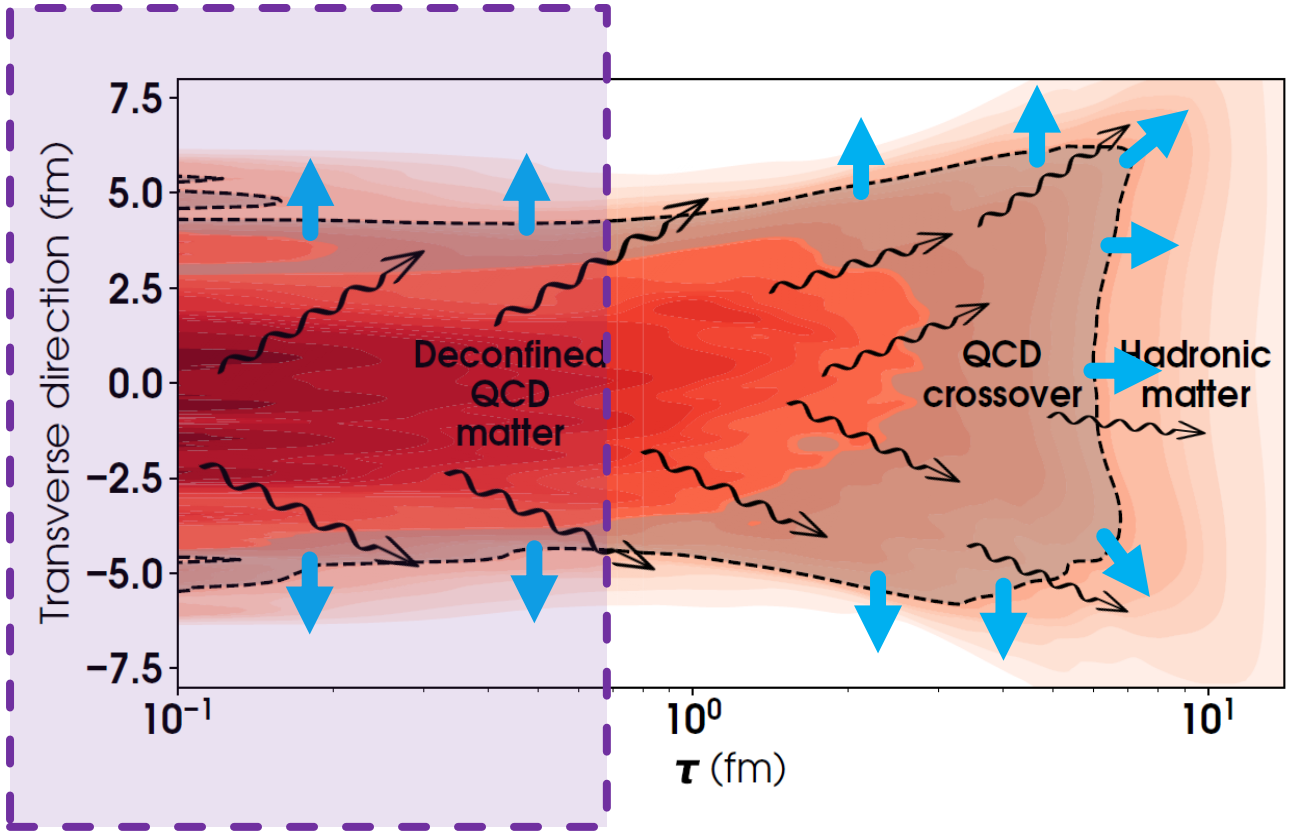


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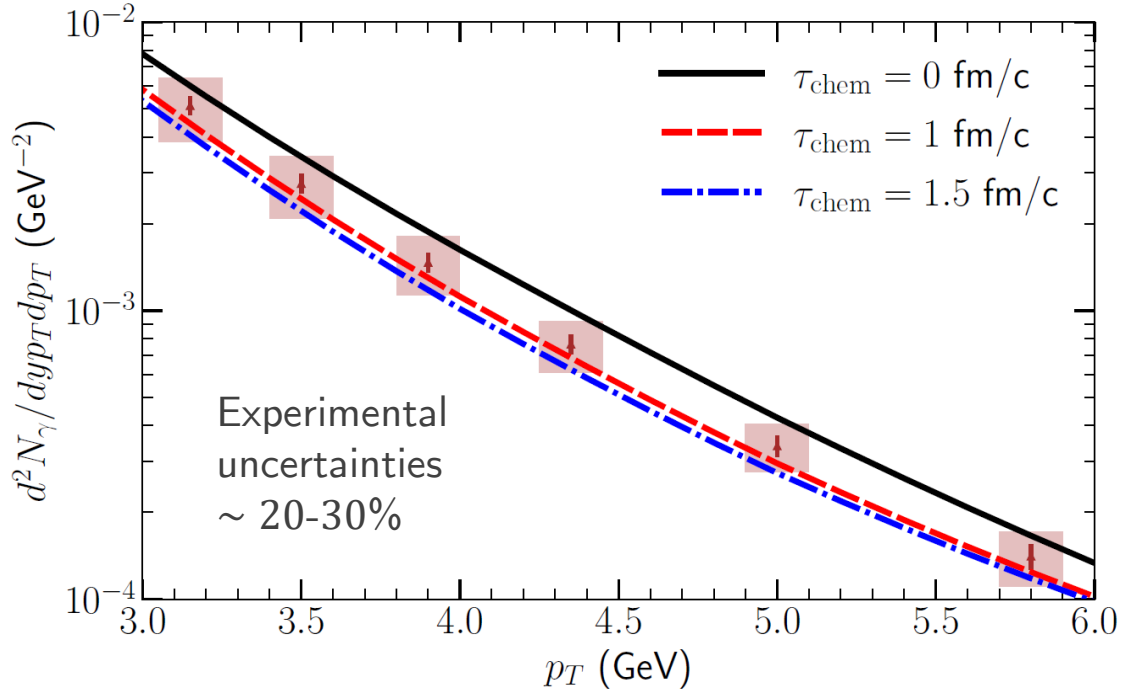
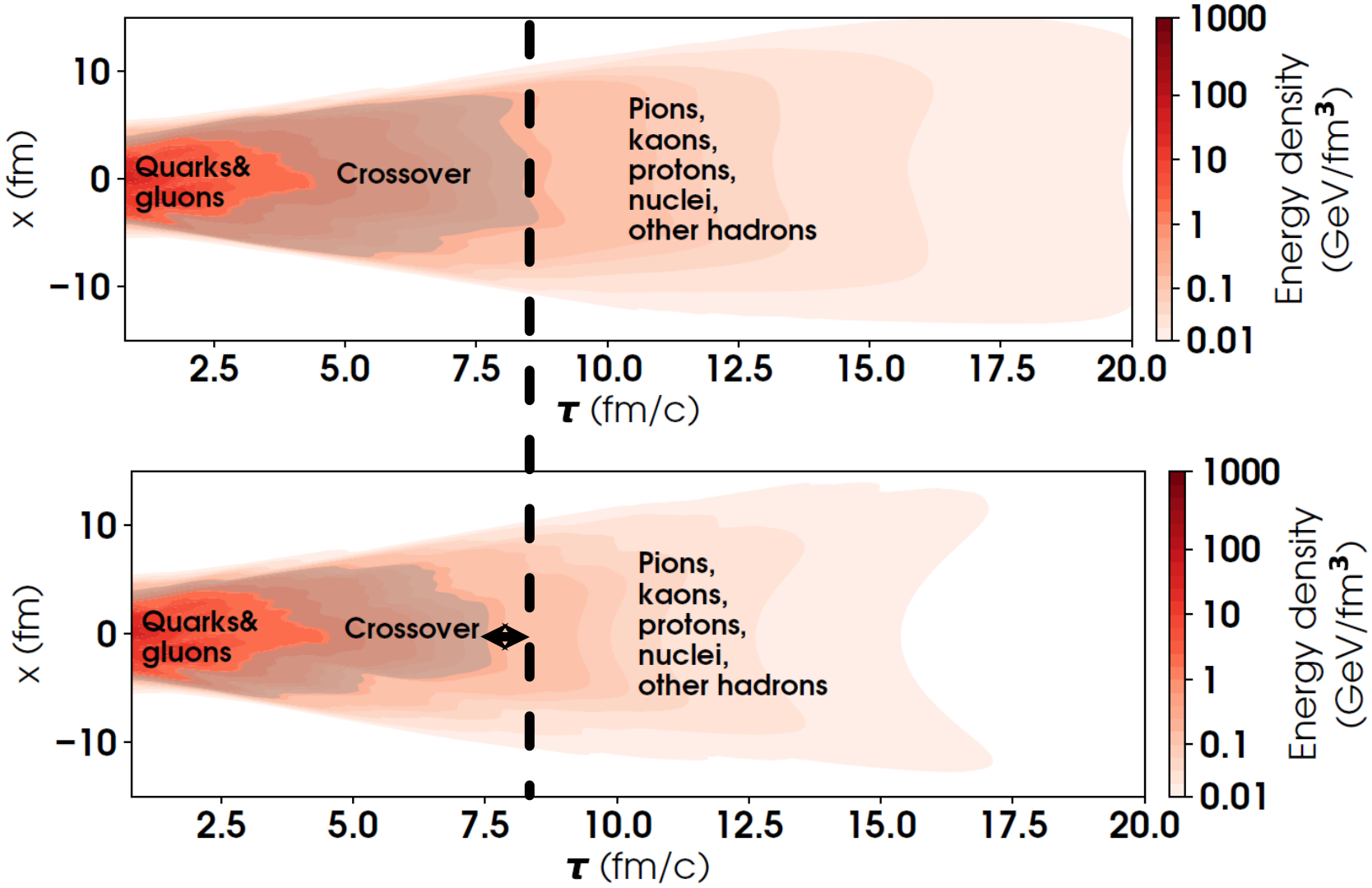
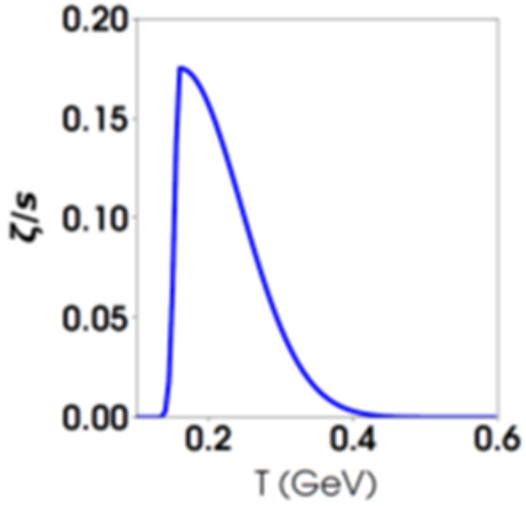
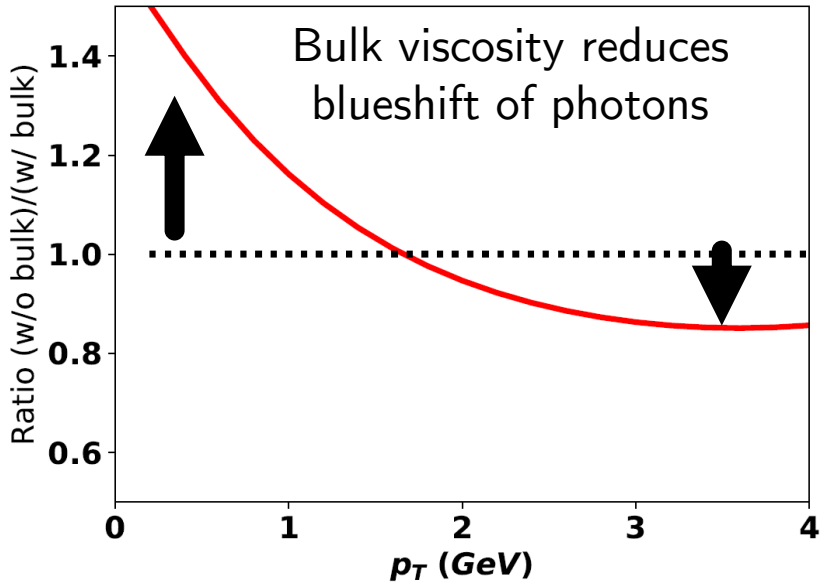
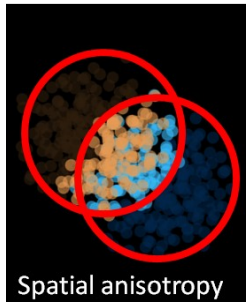


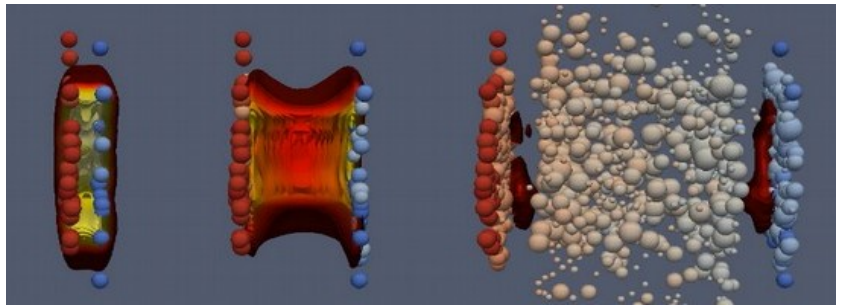
# Beyond soft hadrons: electromagnetic probes

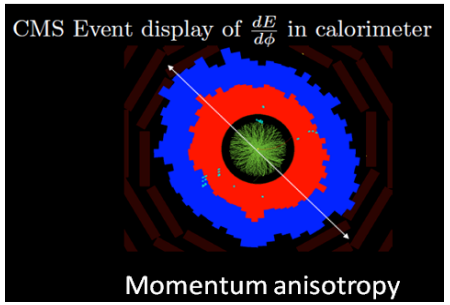






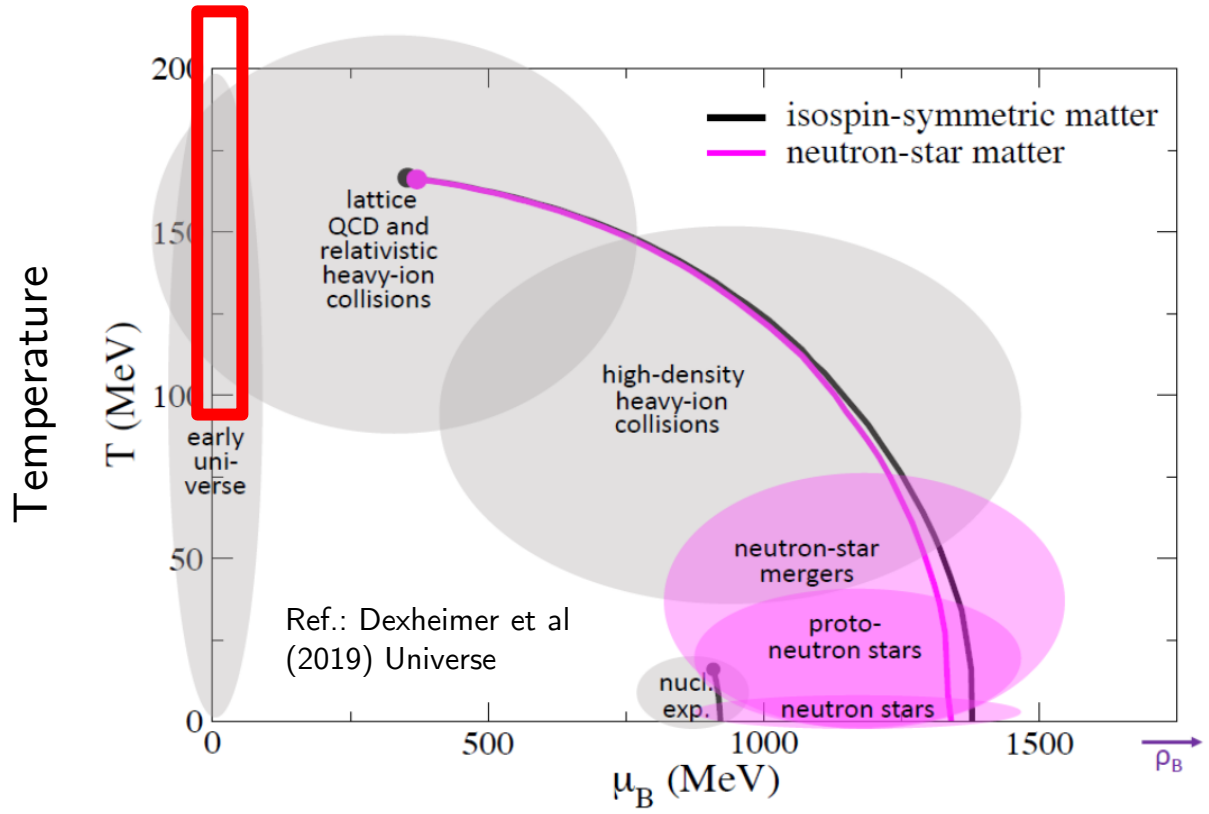

# MORE TRANSPORT COEFFICIENTS

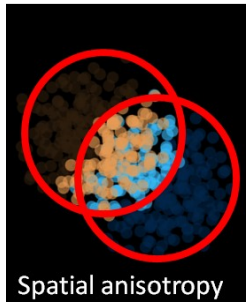
# More transport coefficients

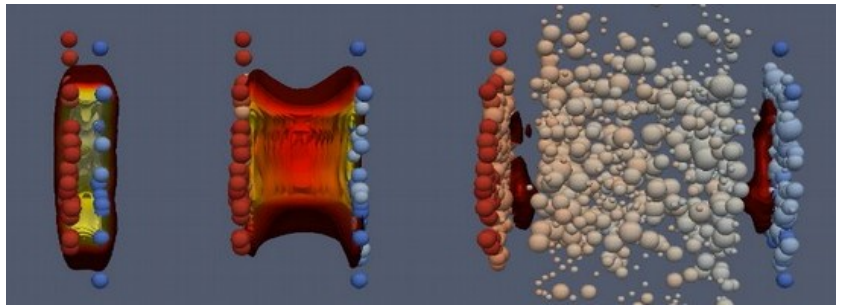
- Other conserved charges:
  e.g. finite baryon density
  - $\eta/s(T,\mu_B)$, $\zeta/s(T,\mu_B)$
  - Charge diffusion

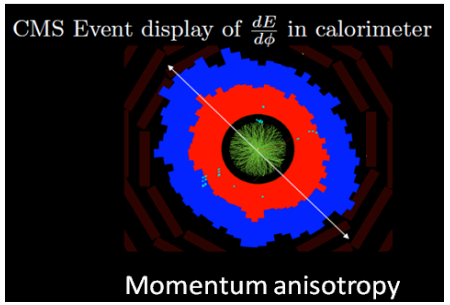
- Second order transport coefficients?
  (need to account for hydrodynamic fluctuations?)

$$\tau_\pi \Delta^{\mu\nu}_{\alpha\beta} \dot{\pi}^{\alpha\beta} + \pi^{\mu\nu} = 2\,\eta(\partial^\mu u^\nu + \cdots) + (2^{\text{nd}}\ \text{order})$$




Spatial anisotropy



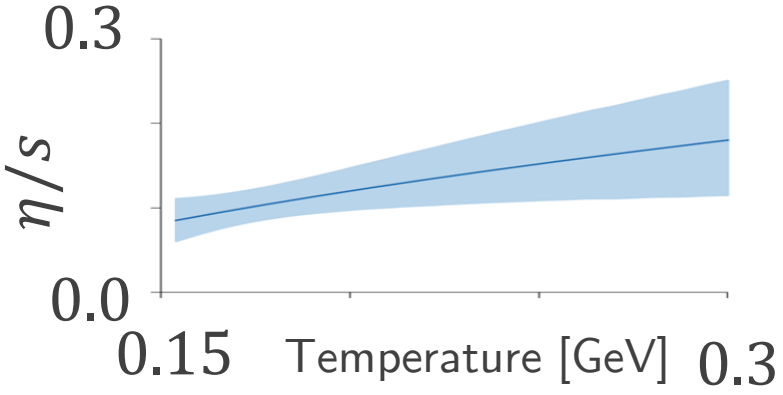

CMS Event display of $\frac{dE}{d\phi}$ in calorimeter
Momentum anisotropy

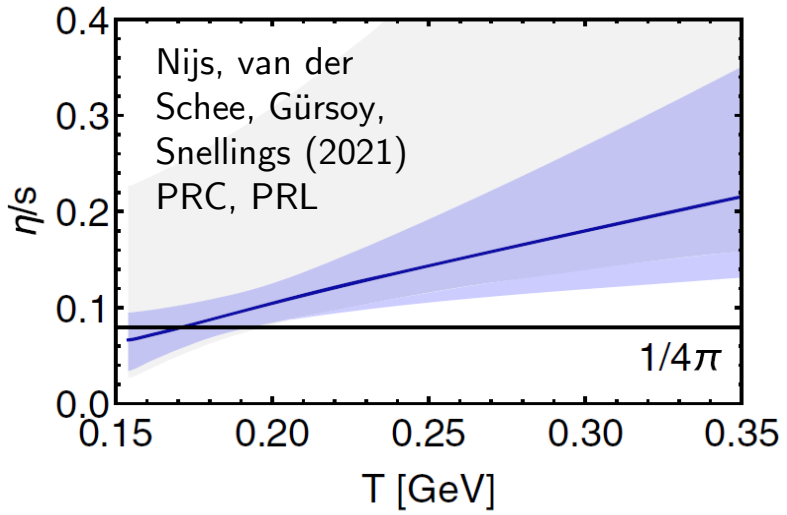
# SUMMARY

# Summary

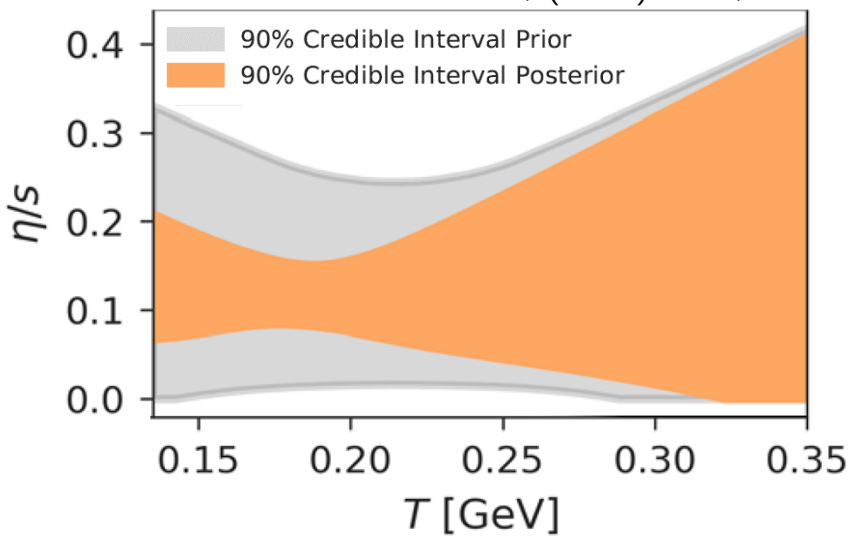
- Considerable progress over past decade, with strong community involvement

Bernhard, Moreland, Bass (2019) Nat.Phys.



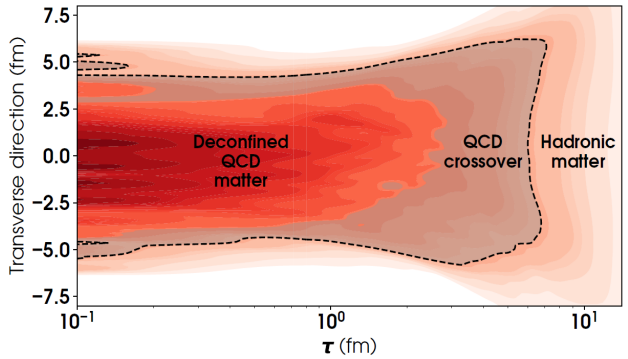

JETSCAPE Collaboration, (2021) PRC, PRL




- Specific shear viscosity $\eta/s$ at T=150-200 MeV remains constrained around 0.1-0.15
- Temperature dependence of specific bulk viscosity $\zeta/s$ still under investigation

# Outlook

- Precision constrains on viscosities with community-wide efforts
  - Consider capabilities of theory to describe measurements
  - Measurements to isolate and study specific collision stages
  - Leverage photons and dileptons, and additional probes




- Necessitates continued strong funding of:
  - Theoretical research groups, including multidisciplinary ones (e.g. statistics)
  - Topical collaborations and other theory/experimental collaboration

Support critical to ensure that the knowledge generated by analyses of RHIC data are fully incorporated into our understanding of emergent QCD.