Global Properties of the Quark Gluon Plasma

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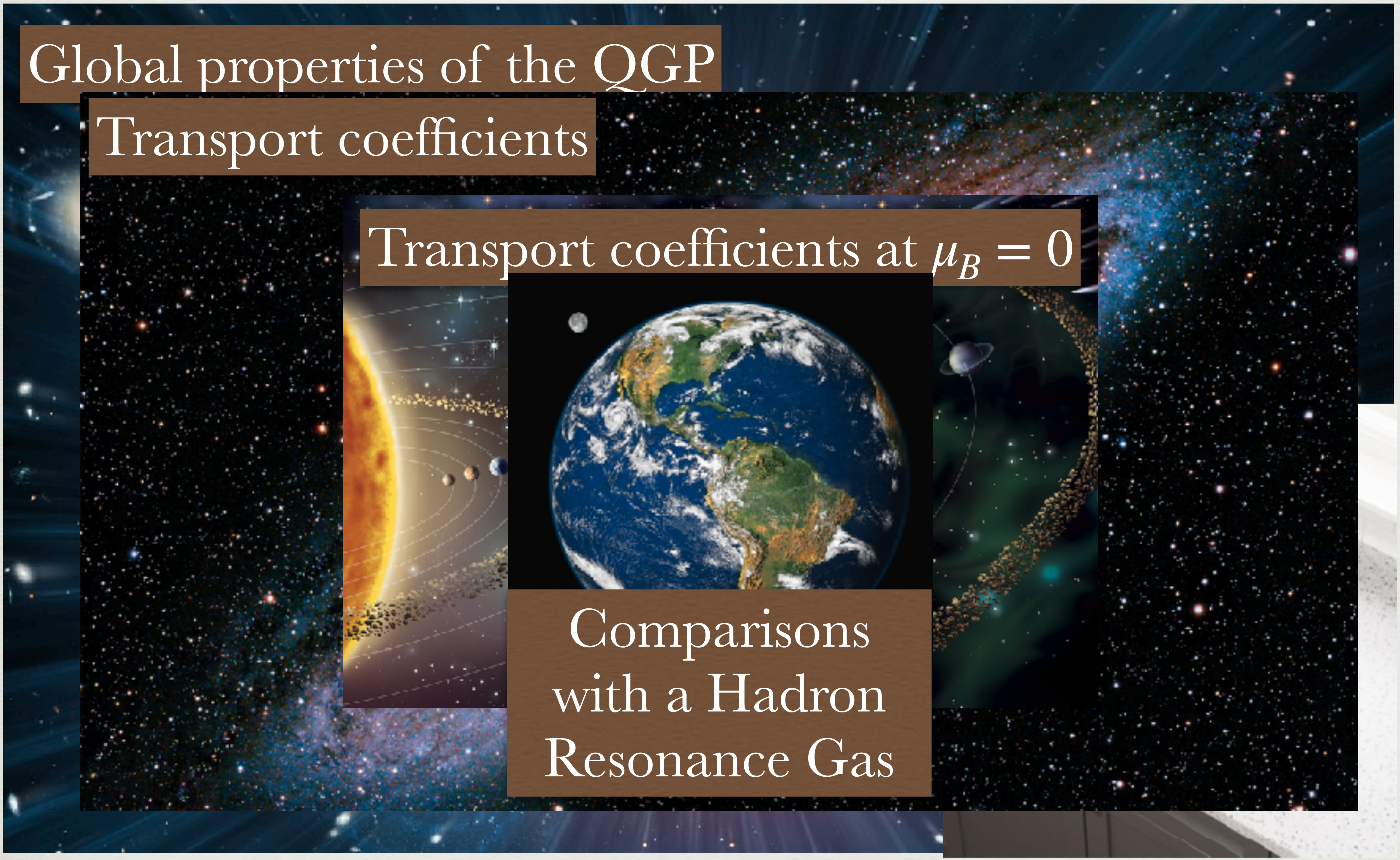
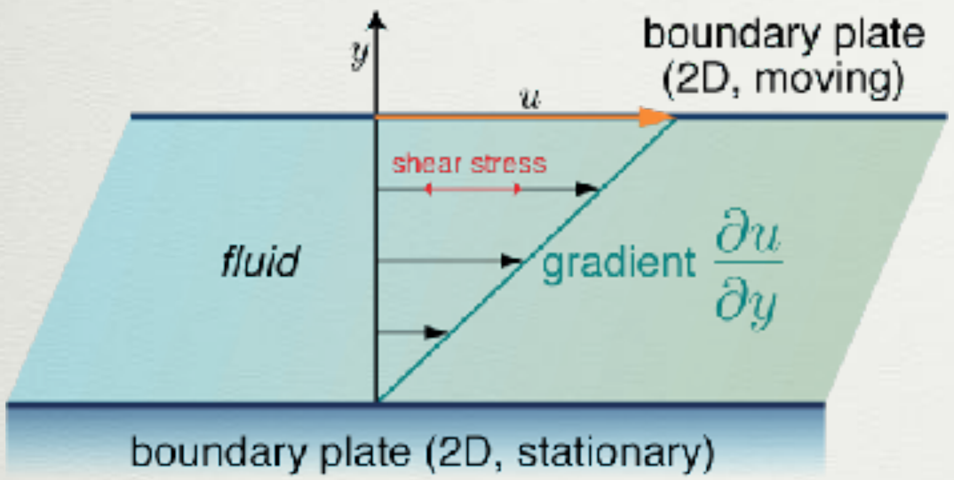
Narrowing my focus



Transport Coefficient of the QGP

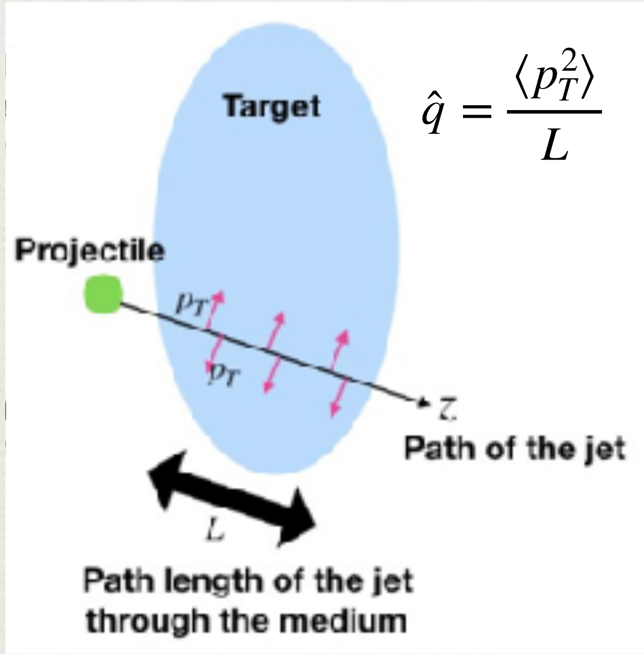
Shear Viscosity $\eta/s(T,\mu_B,\mu_S,\mu_Q)$



Bulk Viscosity $\zeta/s(T,\mu_B,\mu_S,\mu_Q)$

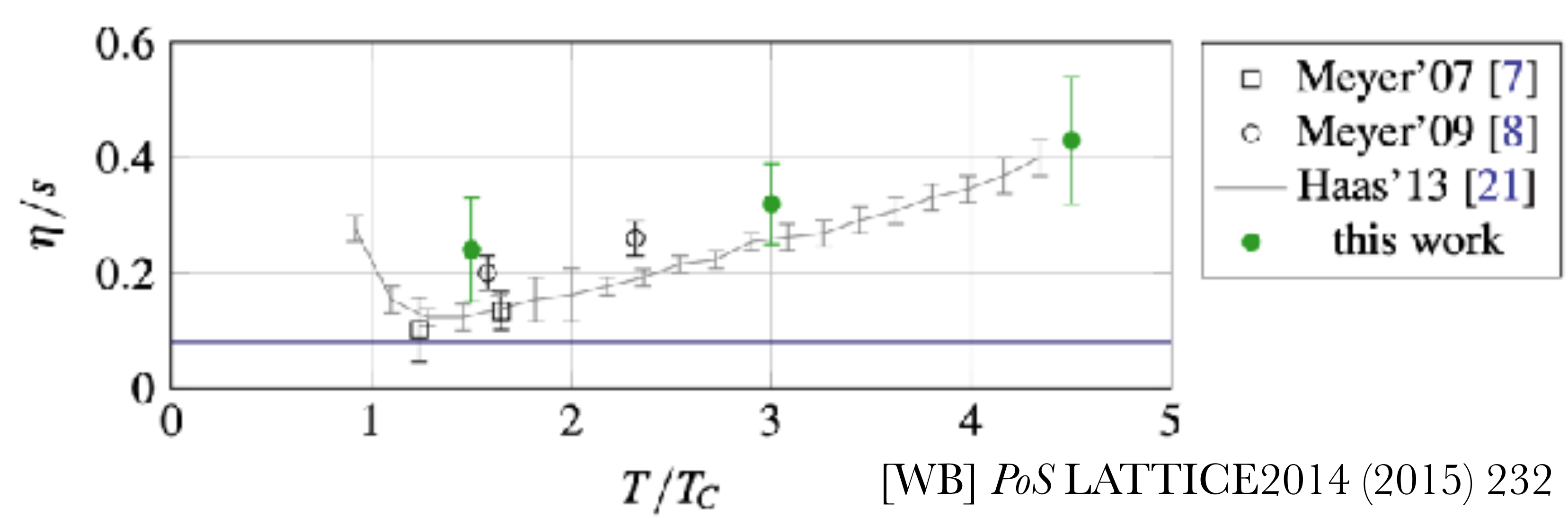
BSQ+C Diffusion
$\kappa_{ij}(T,\mu_B,\mu_S,\mu_Q)$

Energy Loss
$\hat{q}(T,\mu_B,\mu_S,\mu_Q)$



+ Vorticity,
2nd-order,
heat conductivity

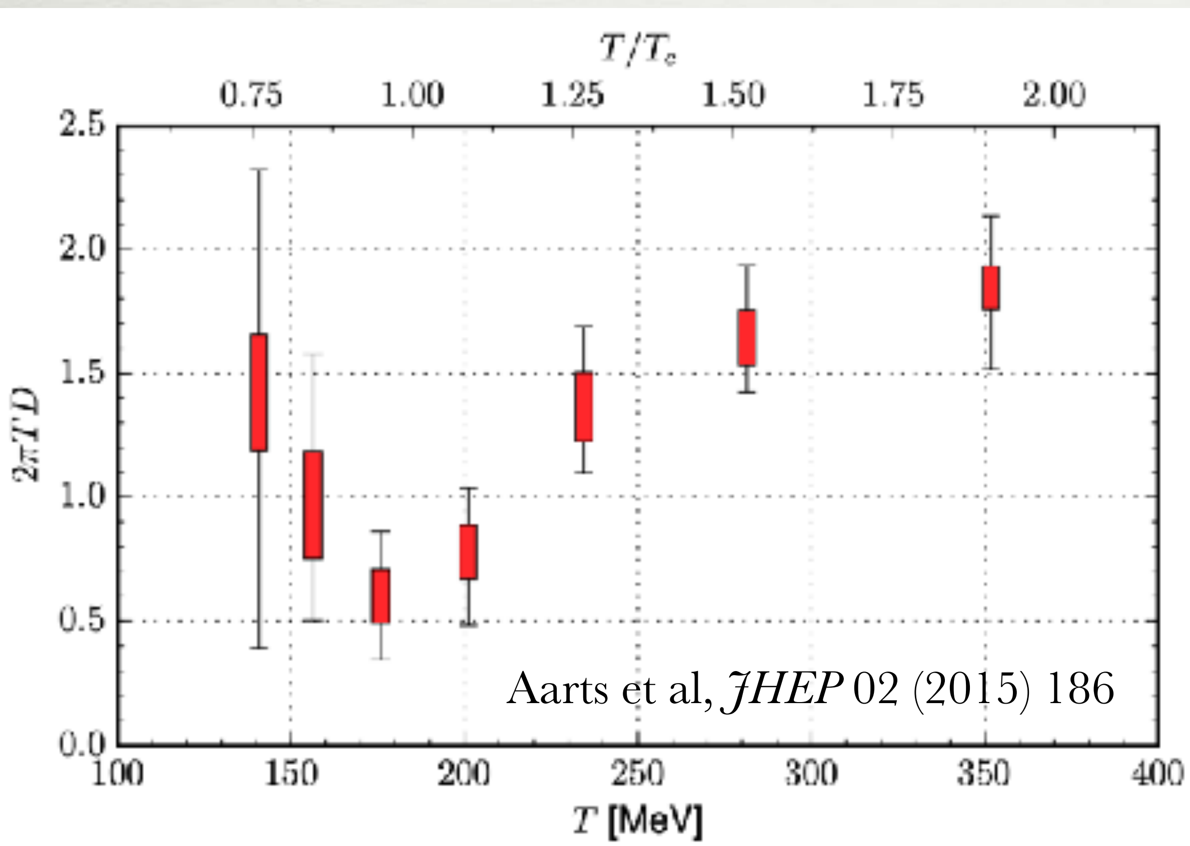
Attempts from QCD



[WB] *PoS* LATTICE2014 (2015) 232

Recent algorithms made for Quantum Computers

[NuQS] *arXiv:2104.02024 [hep-lat]*



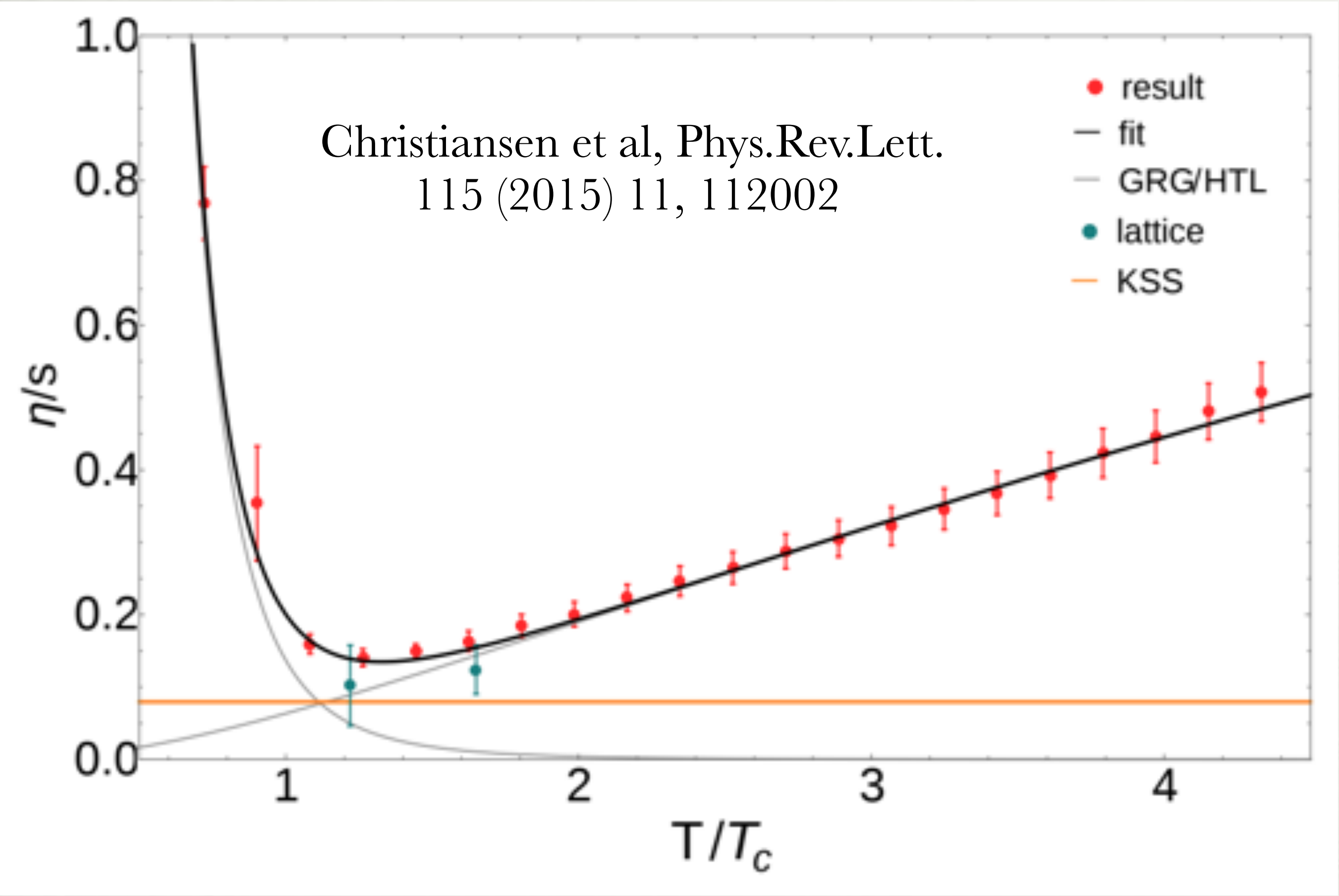
Aarts et al, *JHEP* 02 (2015) 186

Inversion Problem: correlation functions from Lattice QCD in Euclidean time, must convert to Minkowski time.

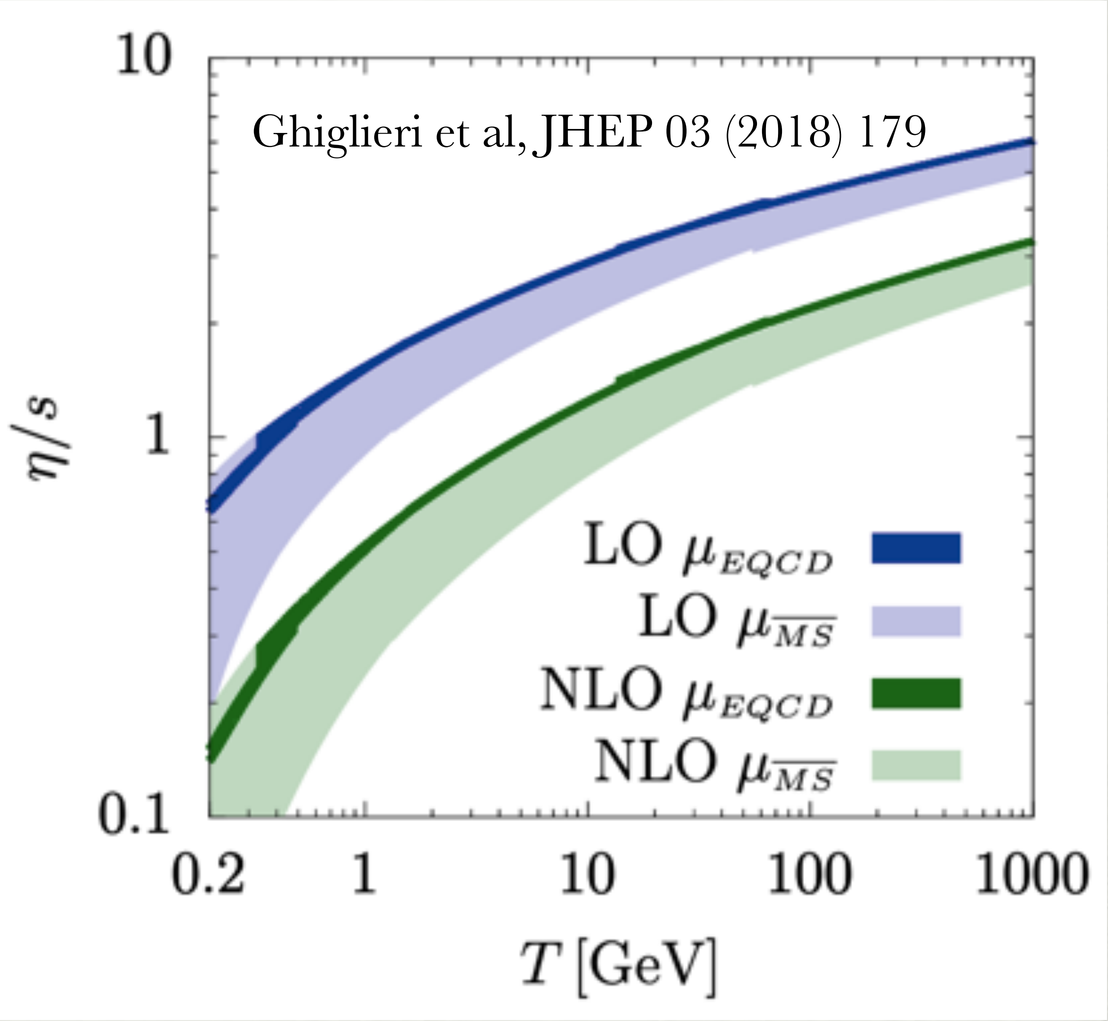
For overview, see Moore 2010.15704

Calculations in certain limits

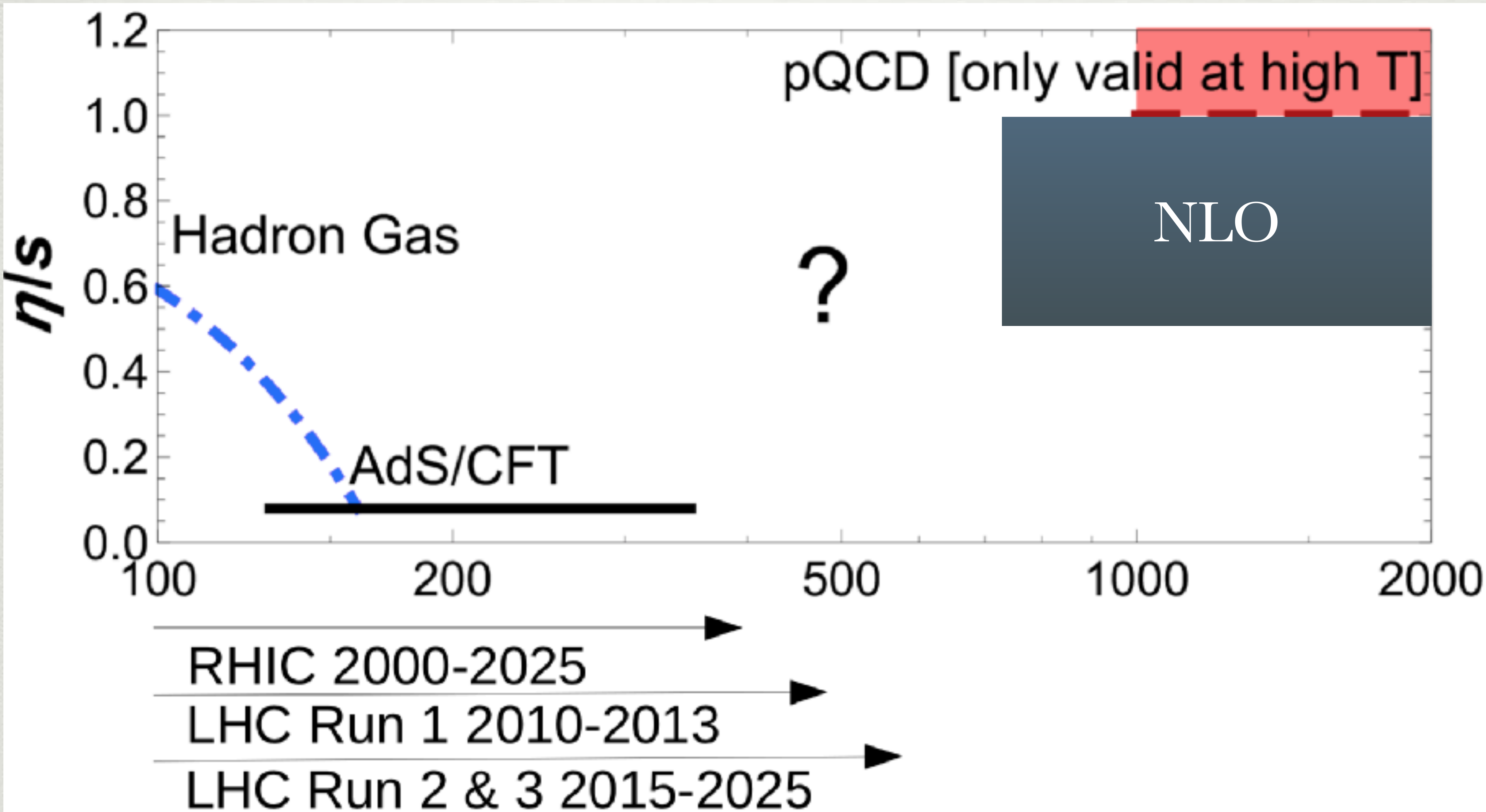
Pure Yang Mills Theory



Perturbative QCD



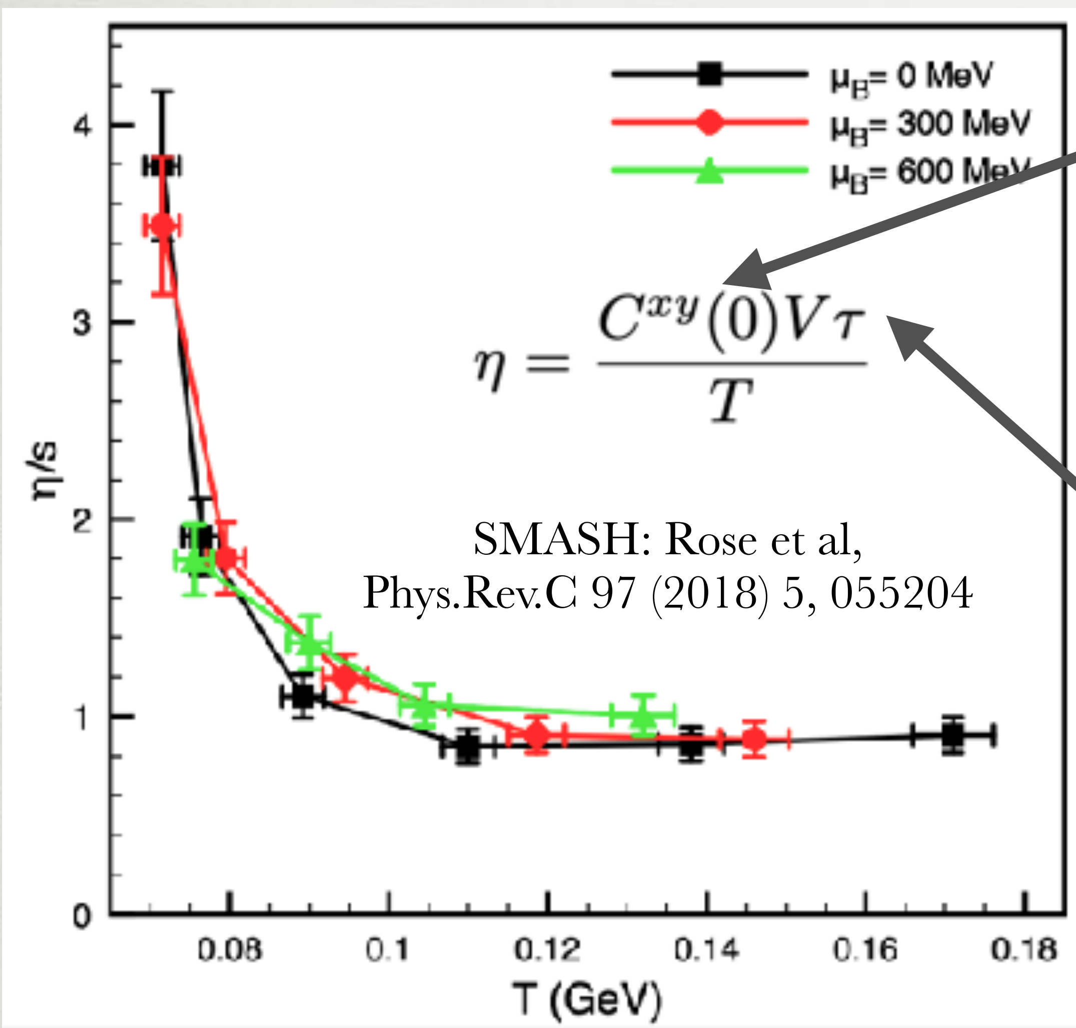
Experimental probes of $\eta/s(T)$



***Hadron Gas**: JNH et al, PRL103(2009)172302; PRC86(2012)024913*
***AdS/CFT:** Kovtun, Son, Starinets PRL94(2005)111601*
***pQCD**: Arnold, Moore, Yaffe JHEP 0011(2000)001 ; JHEP0305(2003)051; NLO Ghiglieri et al, JHEP 03 (2018) 179*

Hadron resonance gas

Transport



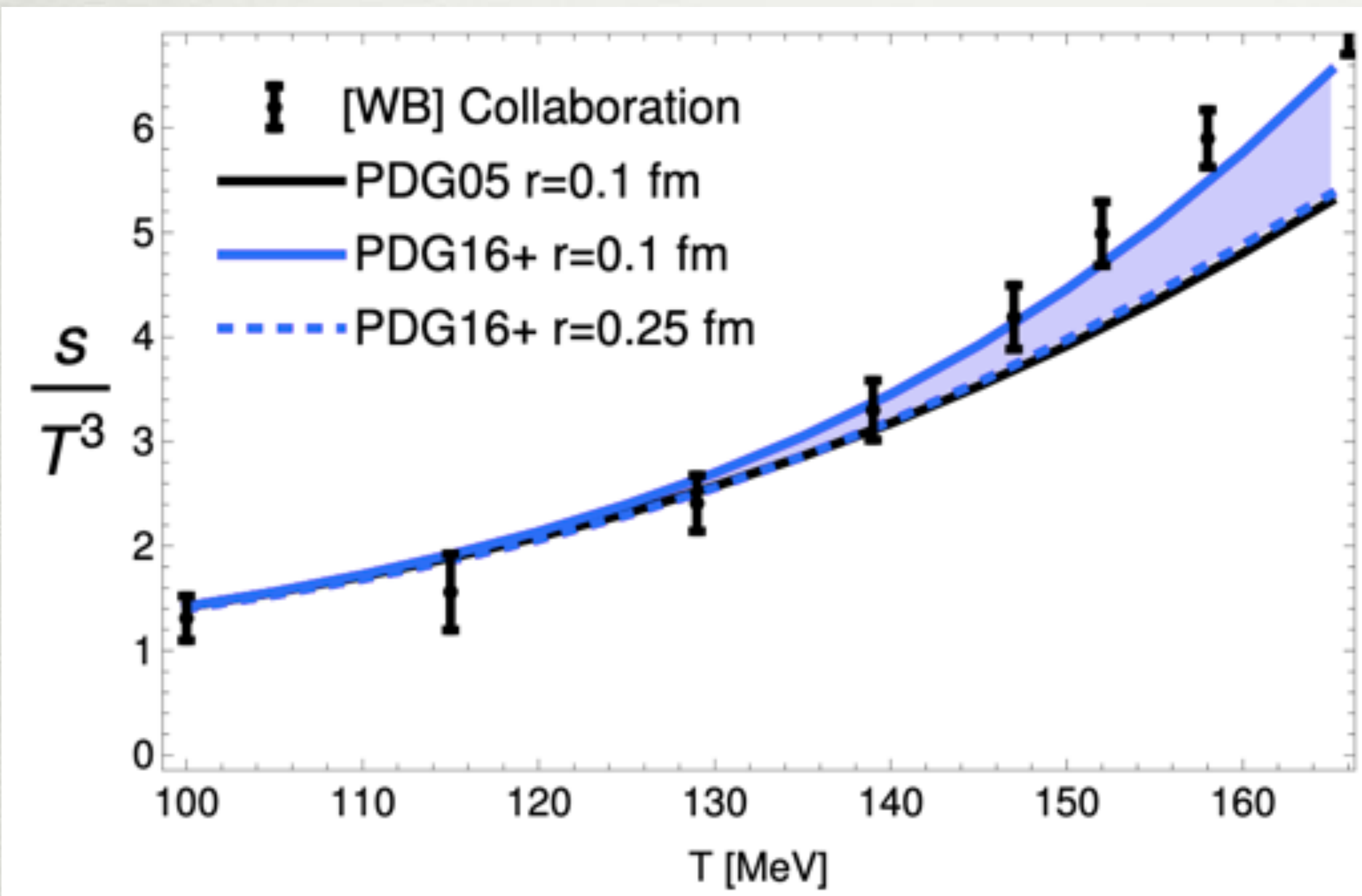
Depends on # of particles, μ's

Contains microscopic i.e. σ's

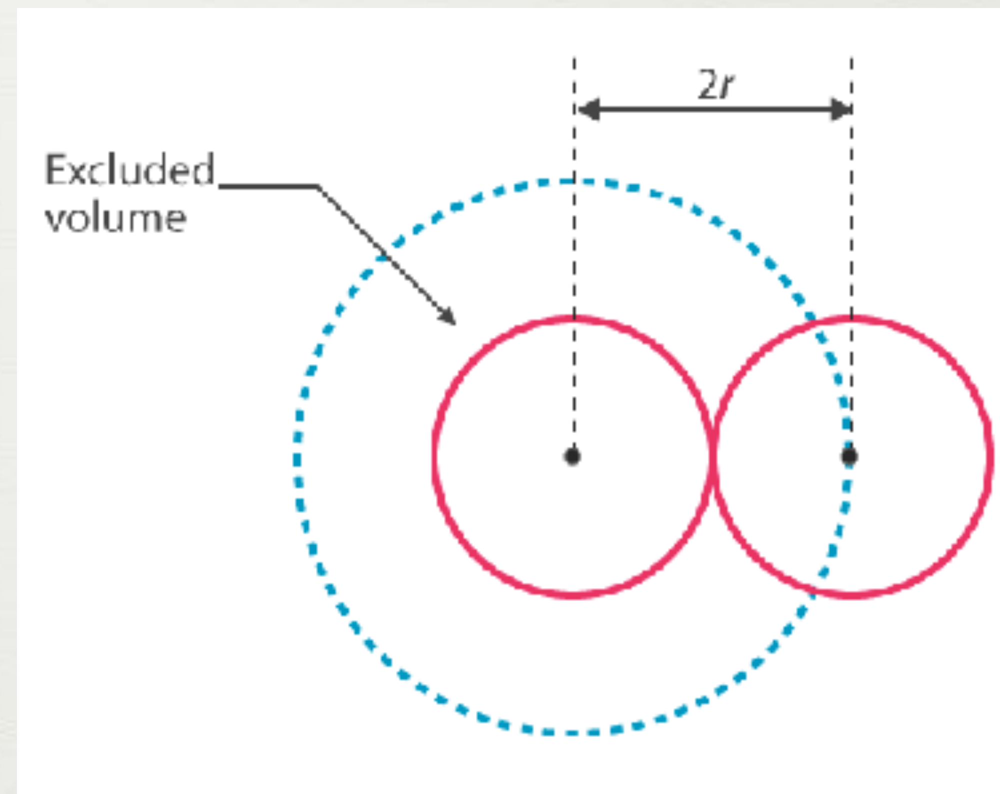
Minimum $\eta/s \sim 1$

Hadron resonance gas

1. Determine radius from Lattice QCD



Excluded Volume



Assume all hadrons have the same volume

To relax this assumption, see Albright et al, *Phys.Rev.C* 90 (2014) 2, 024915

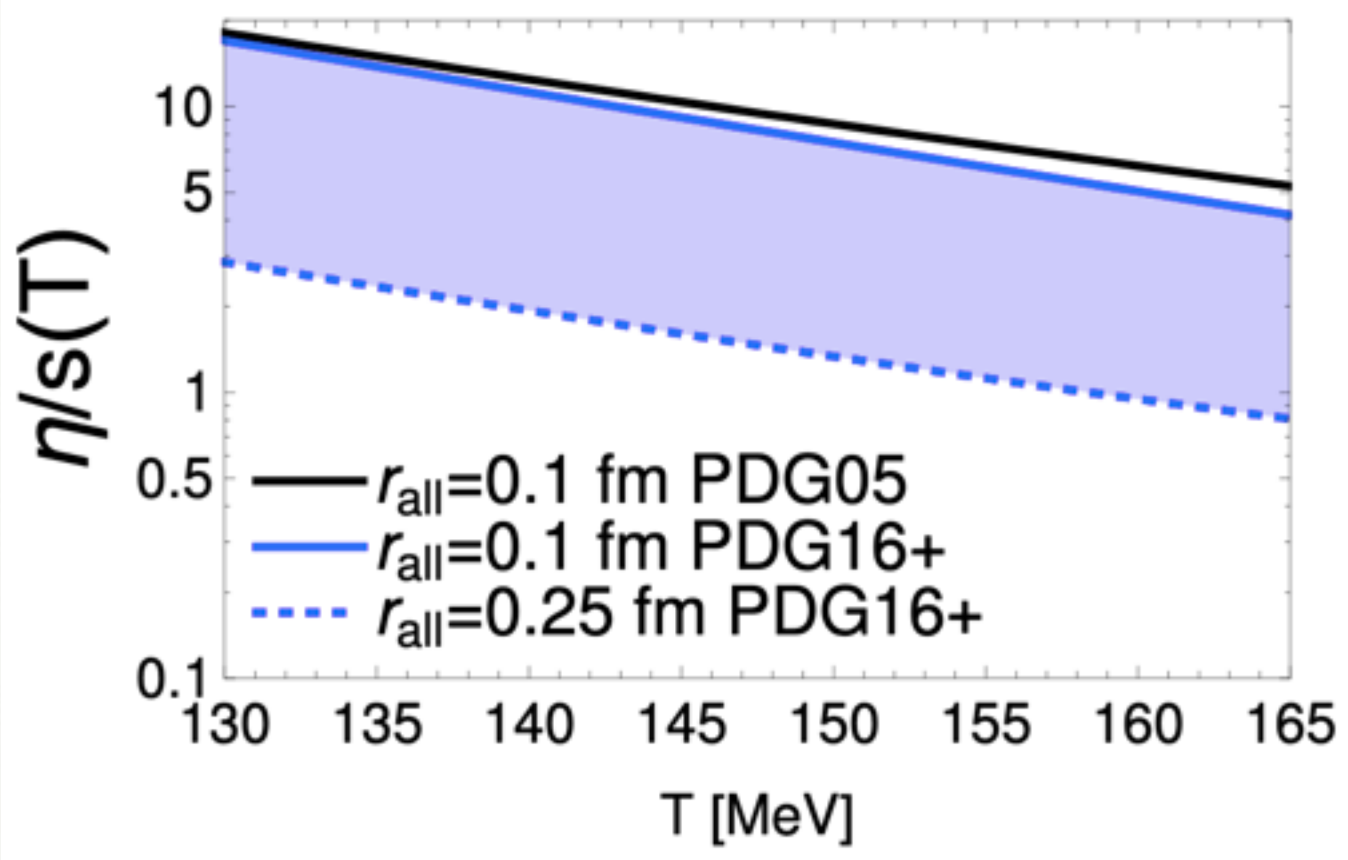
Hadron resonance gas

2. Calculate shear viscosity

$$\eta^{HRG} = \frac{5}{64\sqrt{8}}\frac{1}{r^2}\frac{1}{n}\sum_i n_i \frac{\int_0^\infty p^3 e^{-\sqrt{p^2+m_i^2}/T+\tilde{\mu}_i}dp}{\int_0^\infty p^2 e^{-\sqrt{p^2+m_i^2}/T+\tilde{\mu}_i}dp}$$

Formula adjusted from Gorenstein et al, *Phys.Rev.C* 77 (2008) 024911

Excluded Volume

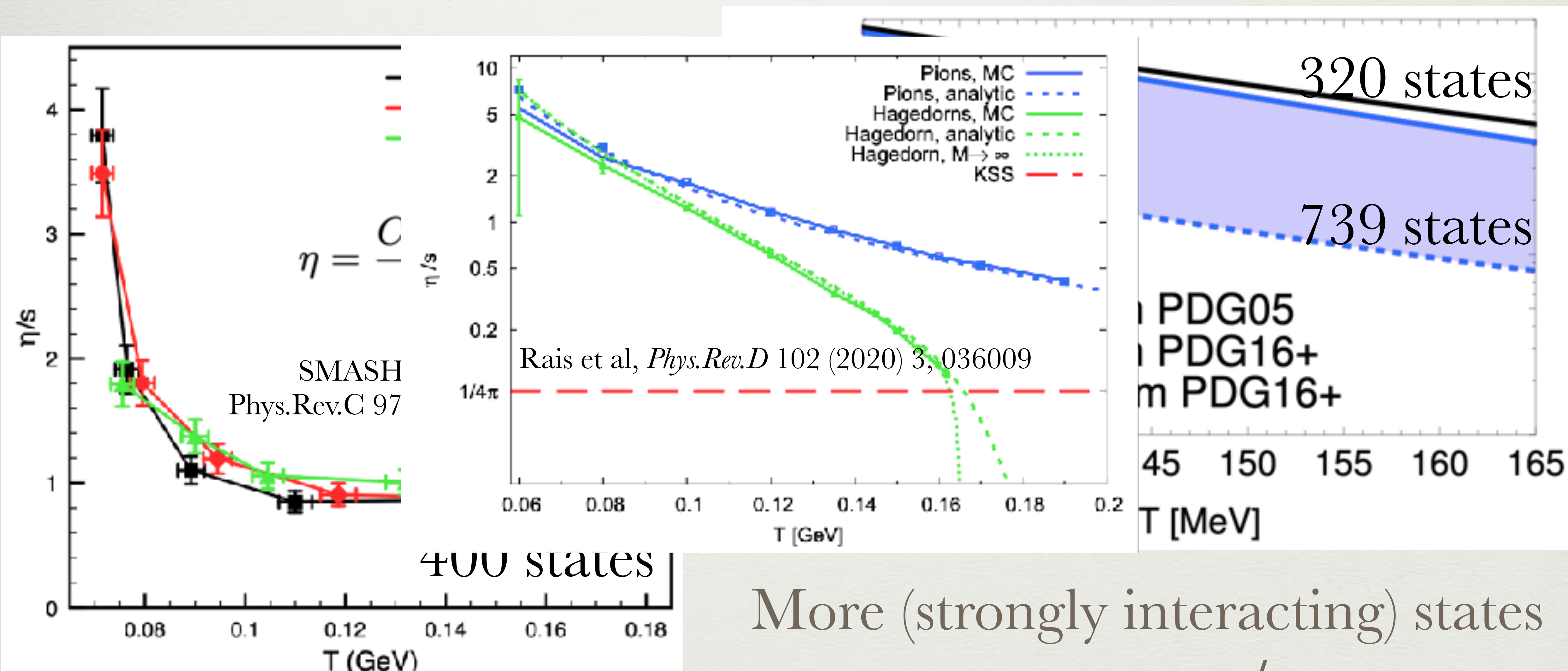


Minimum $\eta/s \sim 0.7$

Hadron resonance gas

Transport

Excluded Volume



More (strongly interacting) states suppress η/s

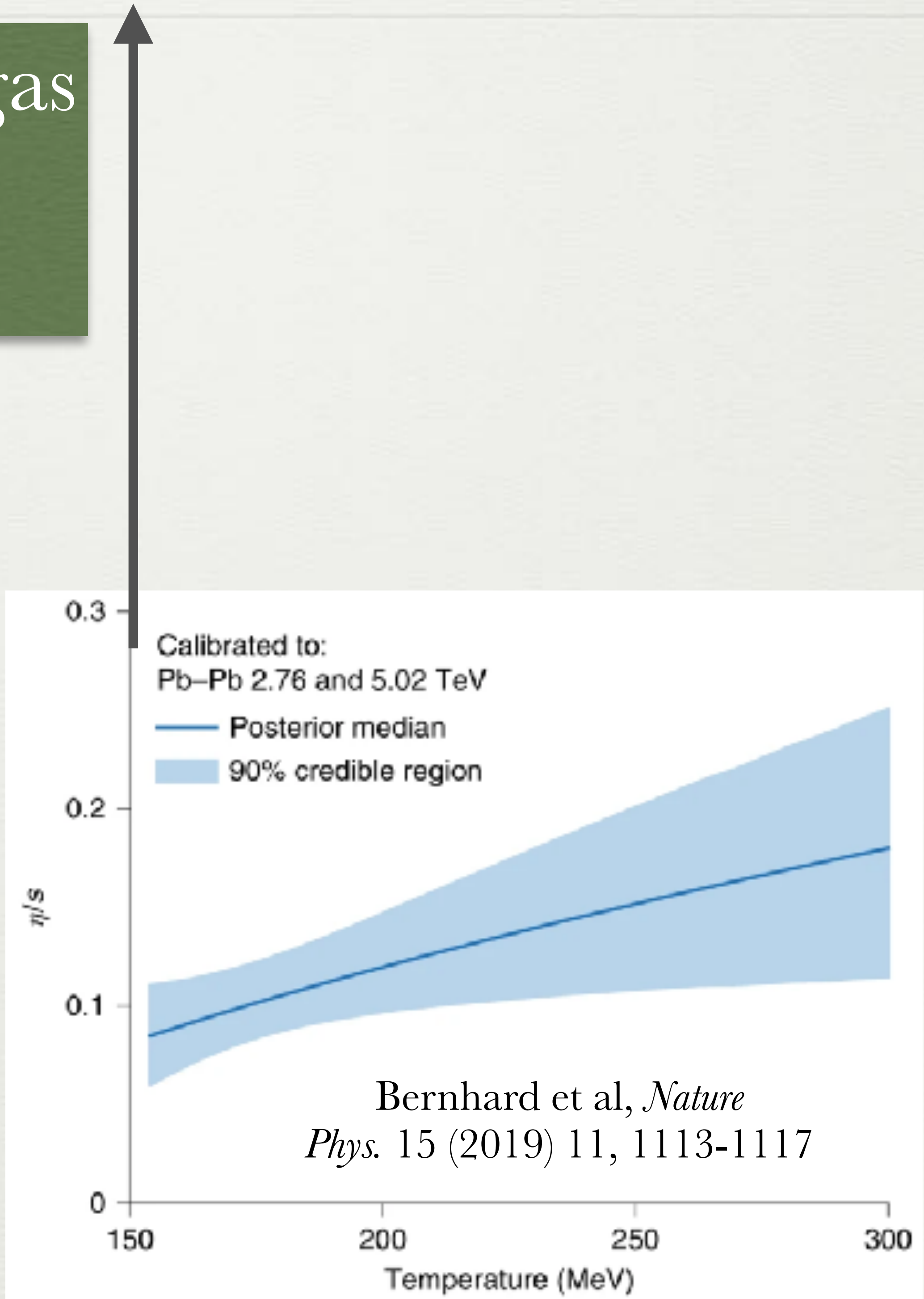
JNH et al, *Phys.Rev.Lett.* 103 (2009) 172302;
Phys.Rev.C 86 (2012) 024913;
Rais et al, *Phys.Rev.D* 102 (2020) 3, 036009

Comparison to Bayesian Analysis

Hadron Resonance gas
PDG16+
$\eta/s \sim 0.7$

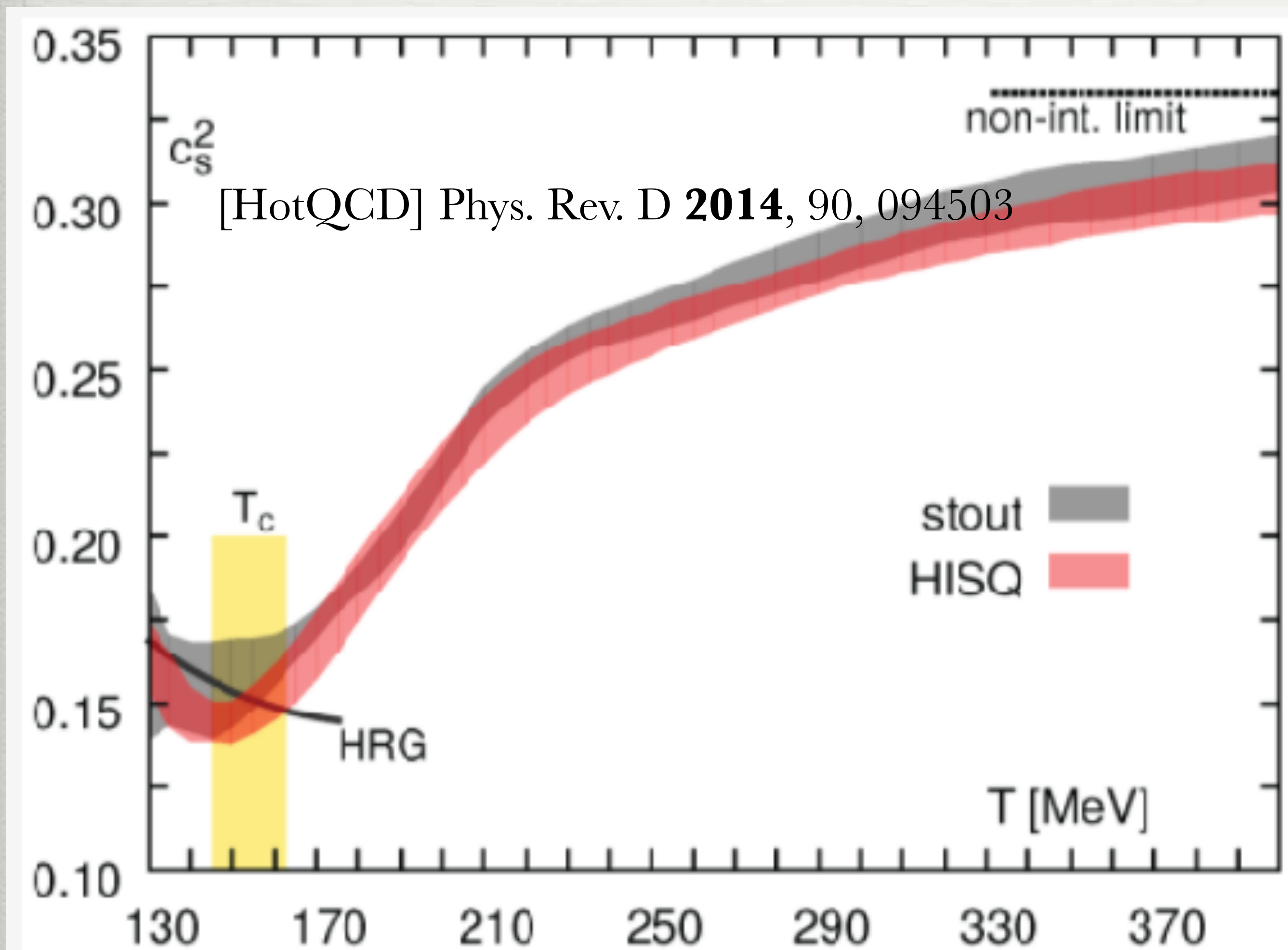
pQCD
$\eta/s \sim 0.5$

More (unmeasured) states and N-body interactions may be needed



Bernhard et al, *Nature Phys.* 15 (2019) 11, 1113-1117

Bulk Viscosity

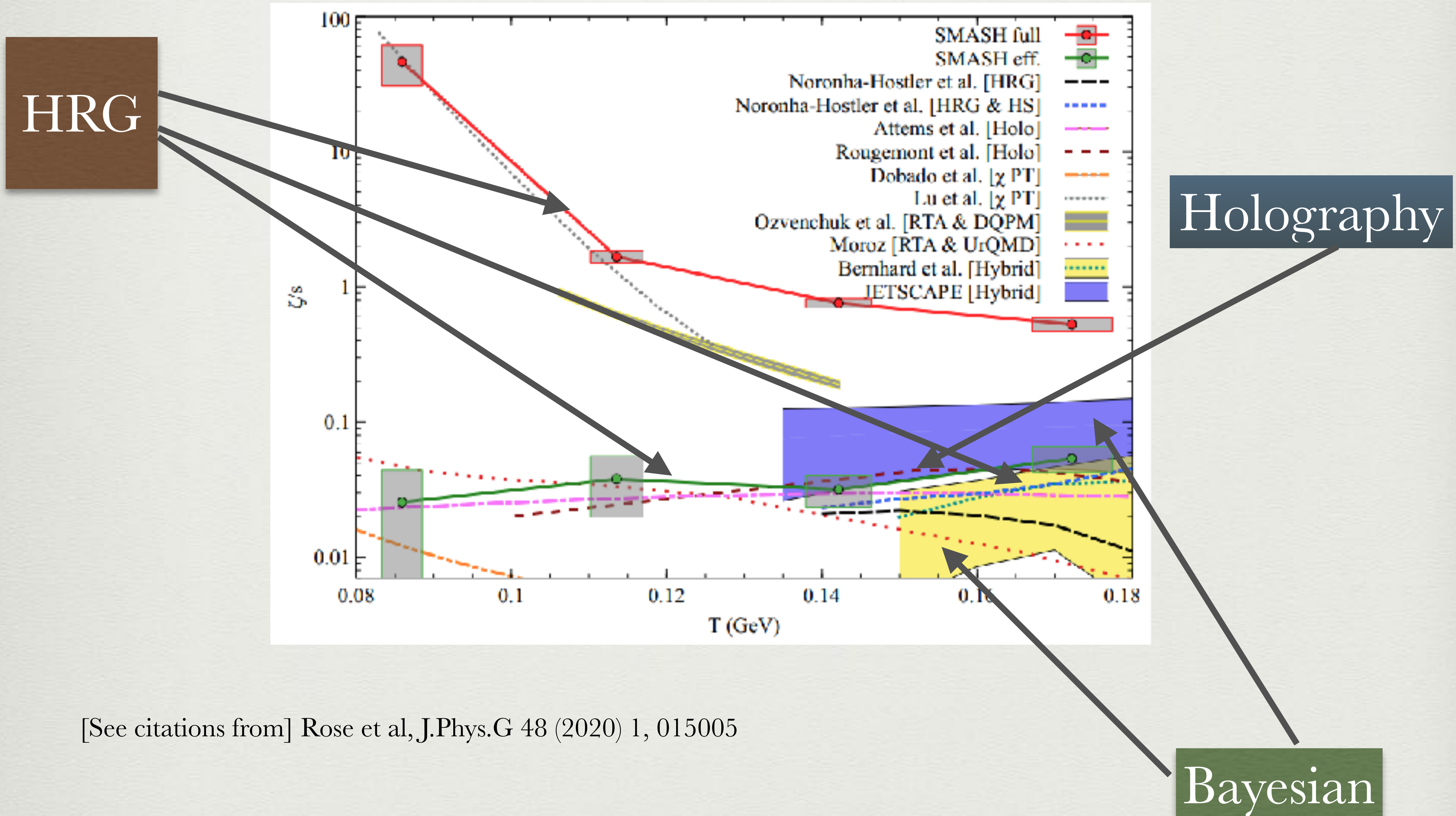


Scales with $\zeta/s(T) \propto \left(\frac{1}{3} - c_s^2\right)^n$

See review for more details
Czajka et al, JHEP 07 (2019) 145

Expect a peak at the cross-over phase transition

Bulk viscosity



[See citations from] Rose et al, J.Phys.G 48 (2020) 1, 015005

Energy Loss $\hat{q}/T^3$ in the HRG

$$\hat{q}_{HRG}(T) = \frac{\hat{q}_N}{\rho_N}\left[\frac{2}{3}\rho_M(T) + \rho_B(T)\right]$$

JET collaboration Phys. Rev. C90, 014909 (2014)

Saturation Density

$$\rho_N \sim (0.15 - 0.17) fm^{-3}$$

Extracted jet transport for a quark at the center of a large nucleus from HERMES

$$\hat{q}_N \sim (0.024 \pm 0.008)\ GeV^2/fm$$

Deng and Wang, Phys. Rev. C81, 024902(2010), [HERMES], Nucl. Phys. B780, 1(2007)

Assume high inflection temperature

Energy Loss $\hat{q}/T^3$

$$\hat{q}_{HRG}(T) = \frac{\hat{q}_N}{\rho_N}\left[\frac{2}{3}\rho_M(T) + \rho_B(T)\right]$$

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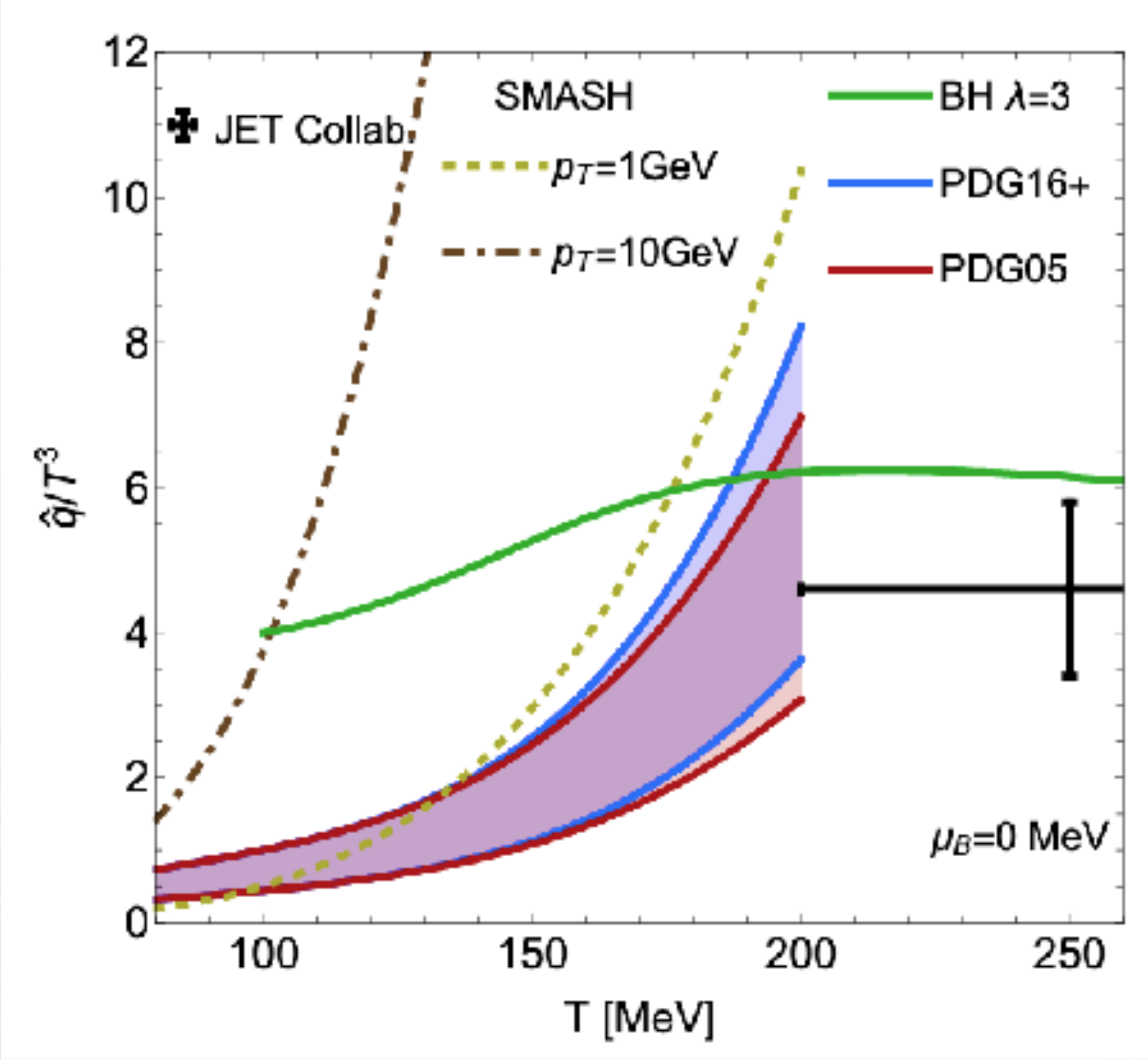
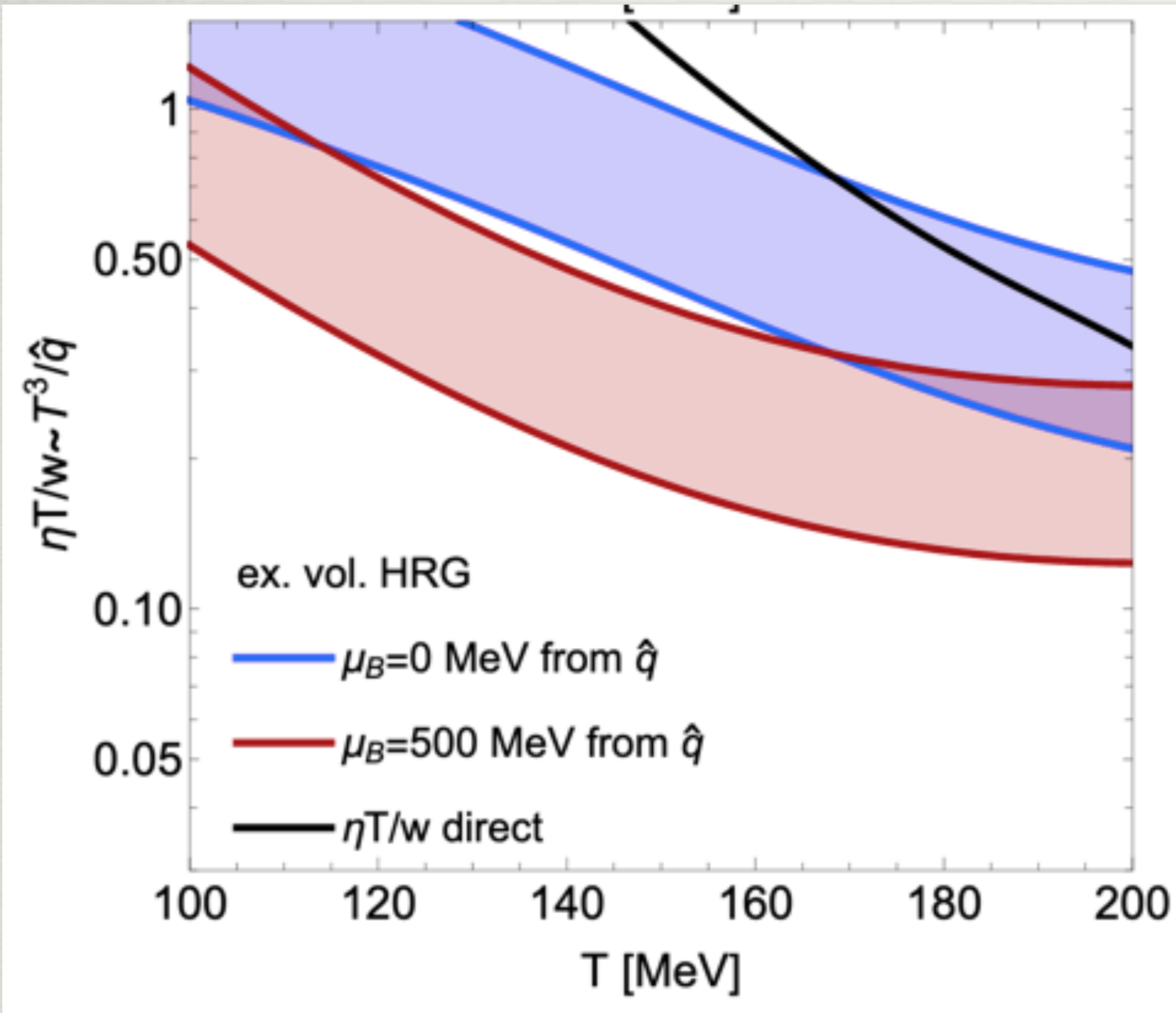
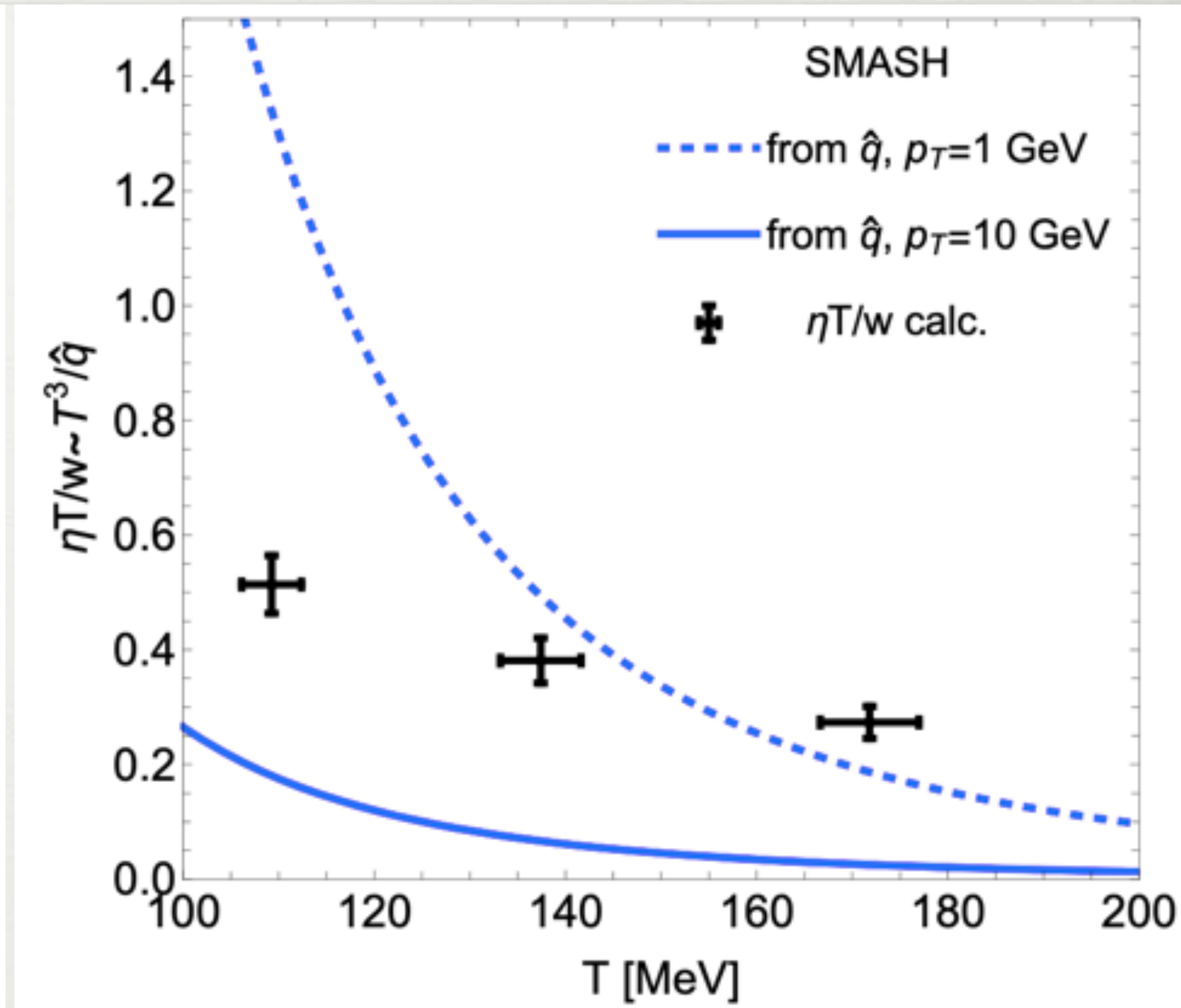


McLaughlin, JNH, et al, arXiv:2103.03329 [nucl-th]
Holography (BH) Rougemont et al, *Phys.Rev.C* 101 (2020) 3, 035208
SMASH: Dorau et al, *Phys.Rev.C* 101 (2020) 3, 035208

Does $\eta T/w \sim \hat{q}/T^3$ hold?

Relation from Majumder, Mueller, Wang, Phys.Rev.Lett. 99 (2007) 192301





McLaughlin, JNH, et al, arXiv:2103.03329 [nucl-th]

Maybe close to the phase transition, but it's not so clear…

Conclusions and Outlook

- While general features of the transport coefficients are understood (minimum of η/s and maximum ζ/s at the transition), the finer details demand more theoretical work
- Theory calculations are more consistent with ζ/s than with η/s
- Possible to smooth connect $\hat{q}/T^3$, consequences?