Instituto de Física
Universidade Federal Fluminense

Phenomenological constraints on the bulk viscosity of QCD

Gabriel S. Denicol (UFF)

J.-F. Paquet, C. Gale, S. Jeon, C. Shen

Quark Matter 2017

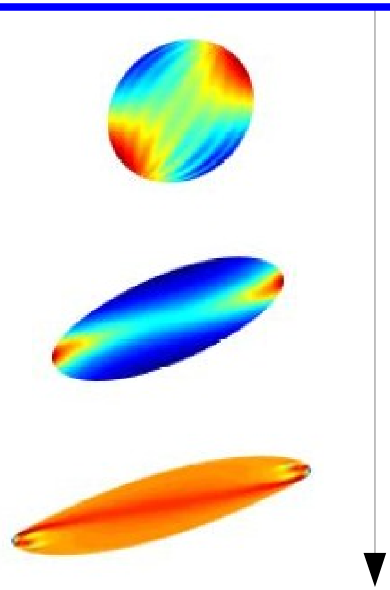
Motivation

Understand transport properties of QCD matter

Shear viscosity

Resistance to deformation

$$\pi^{\mu\nu} = 2\eta\nabla^{\langle\mu}u^{\nu\rangle}$$



Mean-free path (dilute gas)

Bulk viscosity

Resistance to expansion

$$\Pi = -\zeta\nabla_\mu u^\mu$$

Internal dof (dilute gas)

Charge diffusion

$$q^\mu = \kappa\nabla^\mu\frac{\mu_B}{T}$$

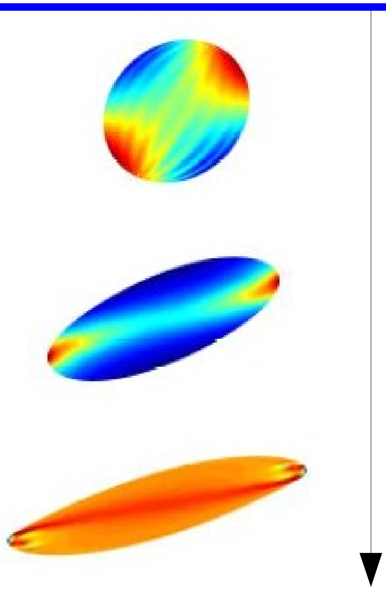
Motivation

Understand transport properties of QCD matter

Shear viscosity

Resistance to deformation

$$\pi^{\mu\nu} = 2\eta\nabla^{\langle\mu}u^{\nu\rangle}$$



Bulk viscosity

Resistance to expansion

$$\Pi = -\zeta\nabla_{\mu}u^{\mu}$$

Charge diffusion

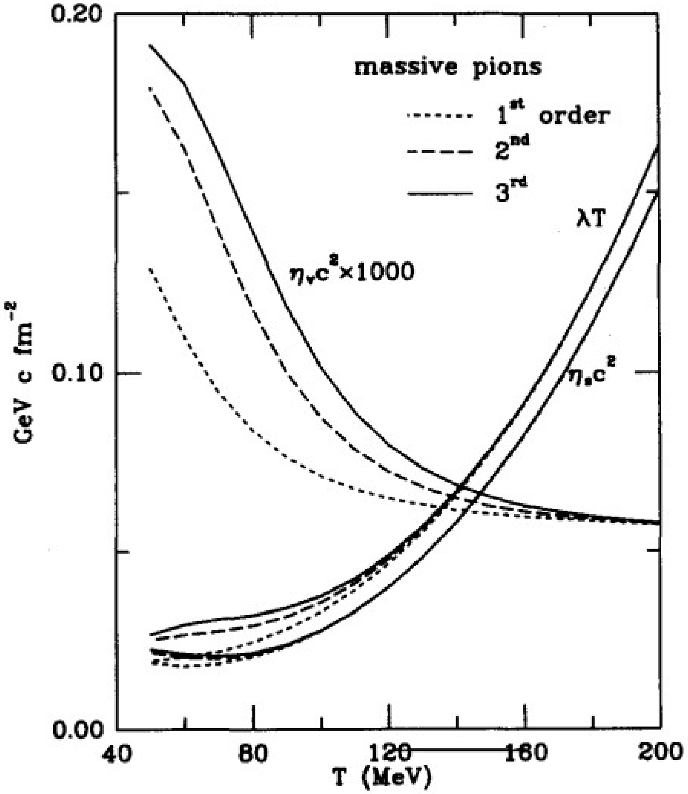
$$q^{\mu} = \kappa\nabla^{\mu}\frac{\mu_B}{T}$$

HIC is the best option to understand these properties

Some known limits

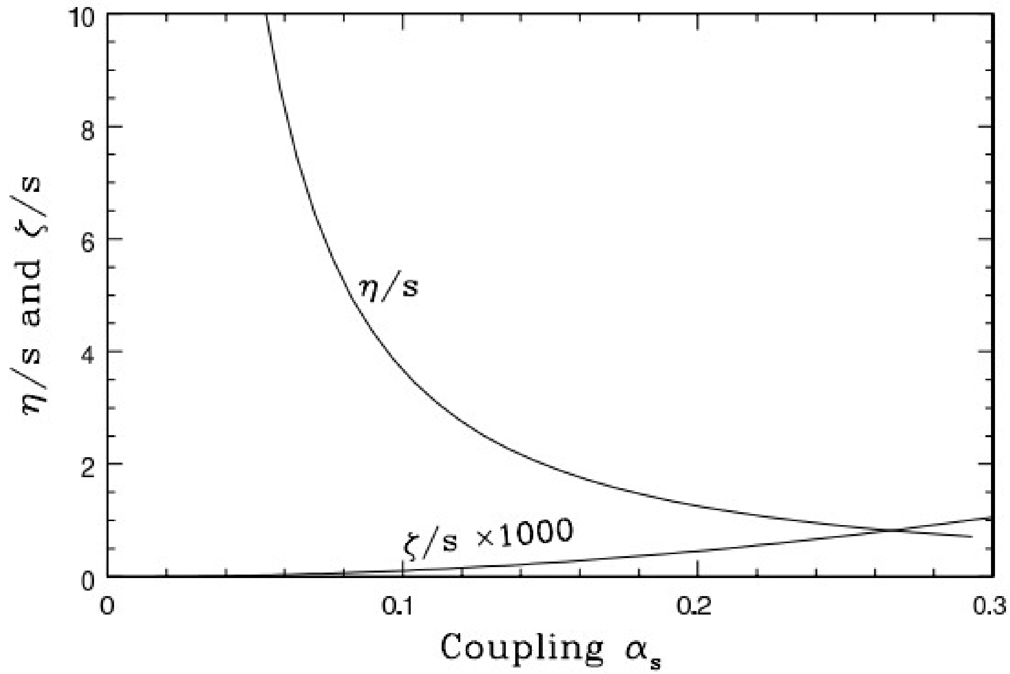
Bulk viscosity ~1000 times smaller than shear

pions gas



Prakash *et al*, Phys. Rept. 227, 321 (1993)

pQCD

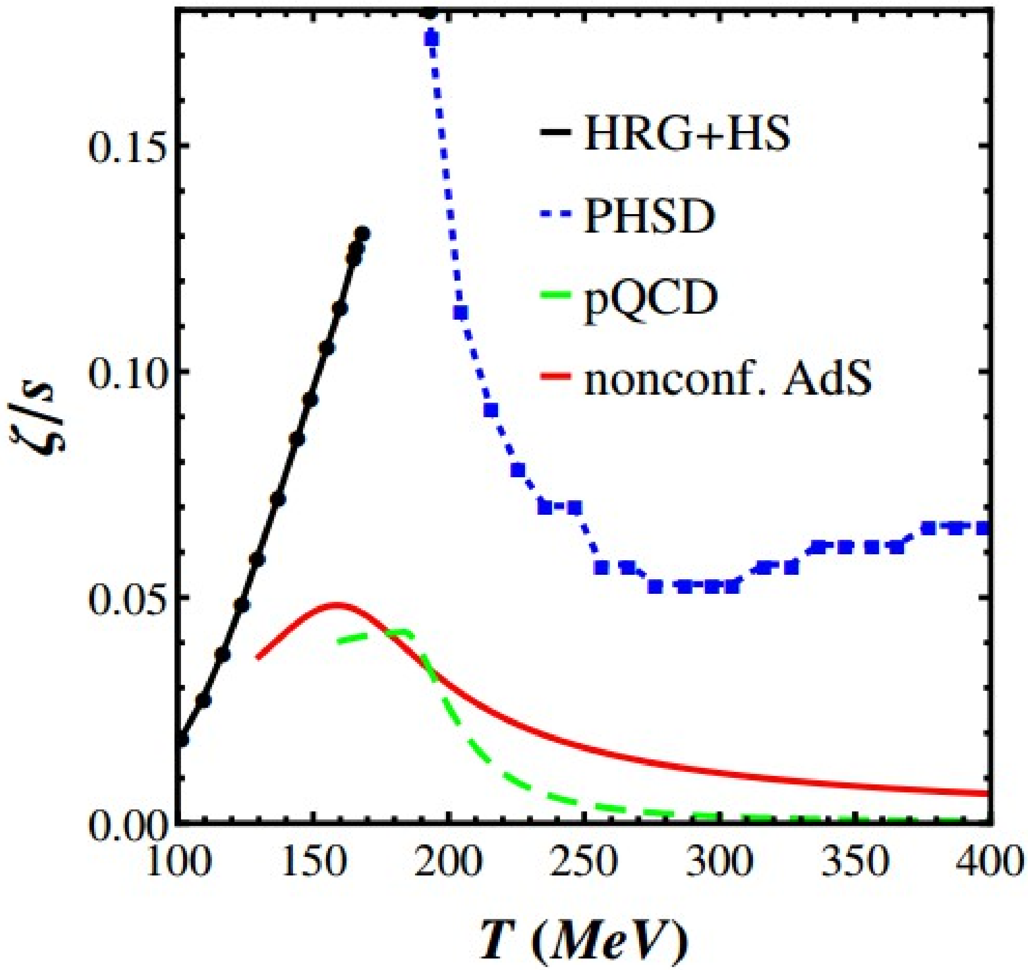


Arnold *et al*, PRD 74, 085021 (2006)

Near phase transition it is not known

Extrapolations and models

Finazzo *et al,* JHEP 1502, 051 (2015)

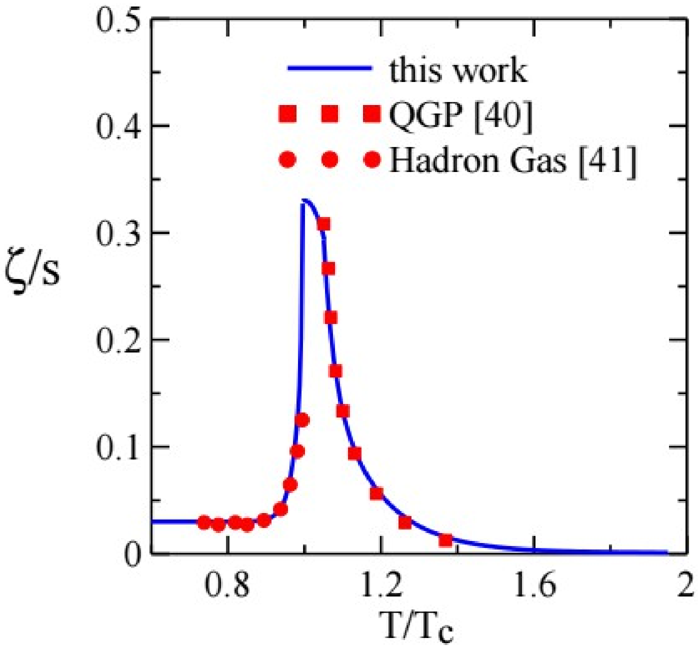


We need guidance from experiment

IP-Glasma + MUSIC + UrQMD

Ryu *et al*, PRL 115, no. 13, 132301 (2015)

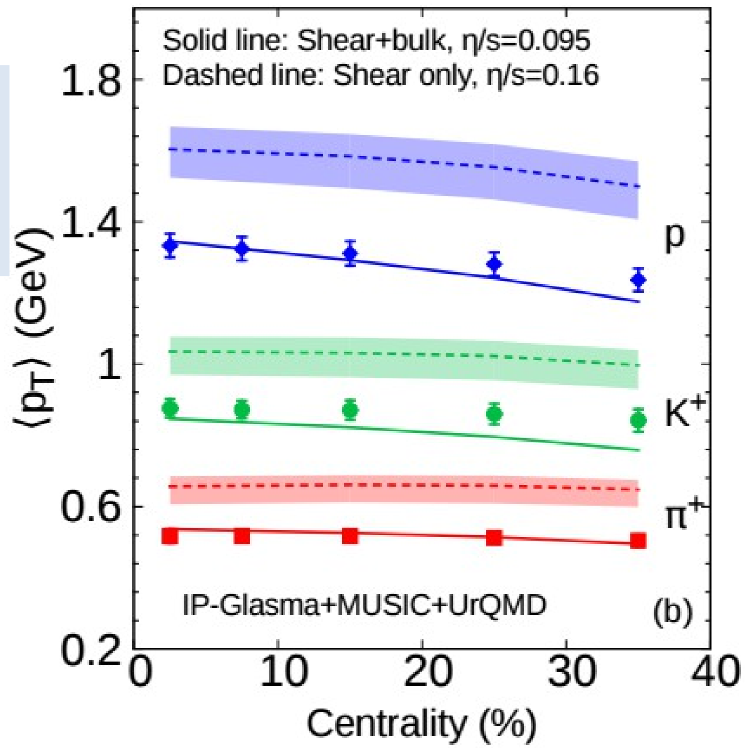
T_{switch} = 145 MeV



IP-Glasma initial conditions lead to high mean pT

→

Bulk viscosity reduces mean pT



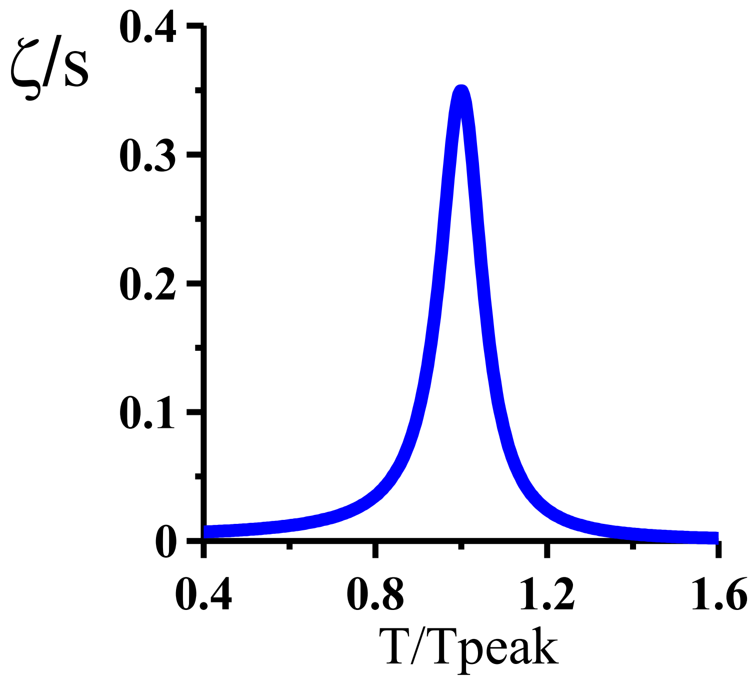
bulk viscosity increases multiplicity, reduces $<p_T>$, and reduces Vn

Similar results from Duke+Ohio and Schenke&Monnai.

What you will see in this talk

We investigate some properties of the bulk viscosity of QCD matter

simple parametrization (normalization, width, and Tc):



$$\frac{\zeta}{s}(T) = B_{\mathrm{norm}} \frac{B_{\mathrm{width}}^2}{\left(\frac{T^2}{T_{\mathrm{peak}}^2} - 1\right)^2 + B_{\mathrm{width}}^2}$$

Make use of Bayesian statistical analysis

See S. Pratt lecture, S. Bass plenary talk

Model

Ryu *et al*, PRL 115, no. 13, 132301 (2015)

IP-Glasma + MUSIC + Cooper-Frye

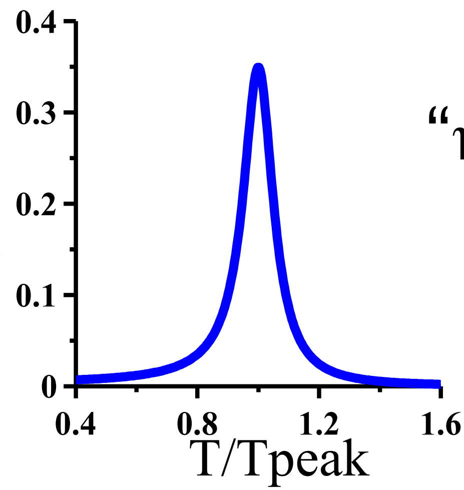
$\tau_0 = 0.4$ fm

T_{fo}=145 MeV

free parameters

$\zeta/s(T)$ parametrized as

$$\frac{\zeta}{s}(T) = B_{\rm norm}\frac{B_{\rm width}^2}{\left(\frac{T^2}{T_{\rm peak}^2}-1\right)^2+B_{\rm width}^2}$$



"η/s" = constant

$\varepsilon_{\rm hydro} = C\,\varepsilon_{\rm IP\text{-}Glasma}$

Parameter	$\epsilon_{\rm normalisation}$	$\langle\eta/s\rangle_{\rm eff}$	$B_{\rm norm}$	$B_{\rm width}$	$T_{\rm peak}$
Minimum	0.7	0.01	0.03	0.005	0.145
Maximum	1.5	0.25	0.6	0.2	0.22

Model

Ryu *et al*, PRL 115, no. 13, 132301 (2015)

IP-Glasma + MUSIC + Cooper-Frye

$\tau_0 = 0.4$ fm

T_{fo}=145 MeV

Emulator from MADAI

See S. Pratt lecture, S. Bass plenary talk
Novak et al, PRC89, 034917 (2014), 1303.5769.

500 random parameter samples (100 events per parameter sample)

Observables considered (20-30%)

RHIC

Observable	N^{π^+}	$\langle p_T^{\pi^+} \rangle$	$v_2\{2\}$	$v_3\{2\}$
p_T cut (GeV)	$p_T > 0$	$p_T > 0$	$p_T > 0.15$	$p_T > 0.15$
Value	135	0.411 GeV	0.0642	0.0183
Uncertainty	10	0.021 GeV	0.000075	0.0001

LHC

N^{π^+}	$\langle p_T^{\pi^+} \rangle$	$v_2\{2\}$	$v_3\{2\}$
$p_T > 0$	$p_T > 0$	$p_T > 0.2$	$p_T > 0.2$
307	0.512 GeV	0.0831	0.0293
20	0.017 GeV	0.0034	0.0015

Model

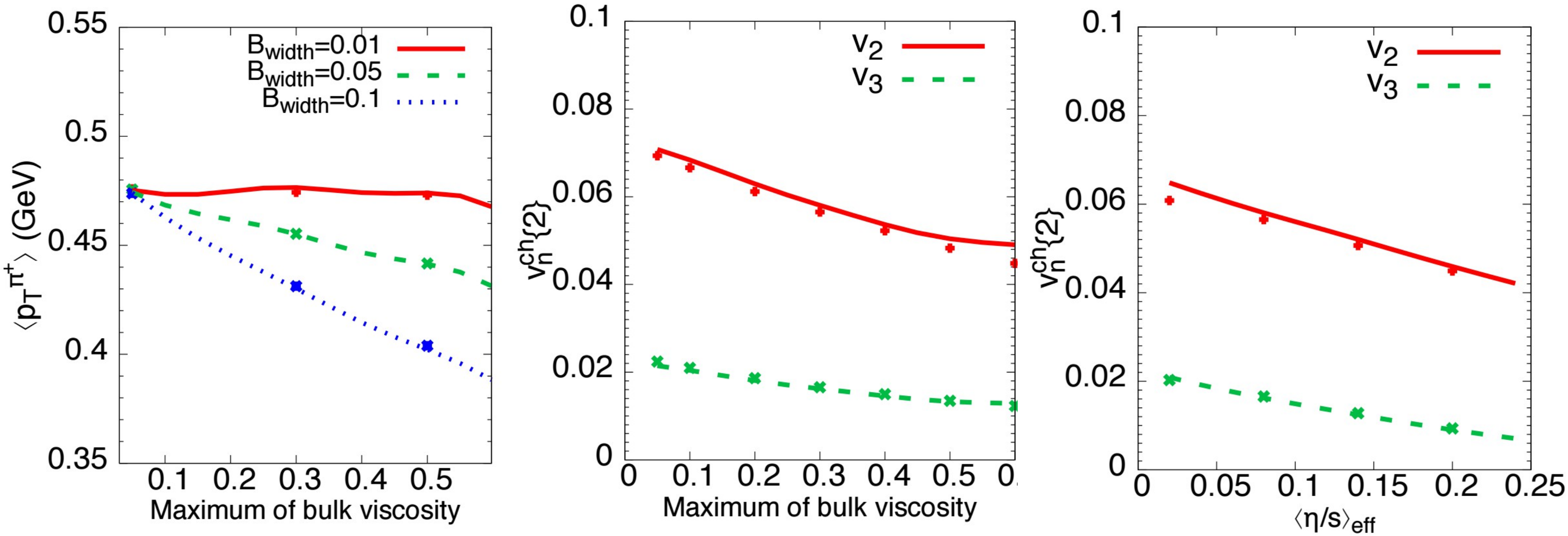
Ryu *et al*, PRL 115, no. 13, 132301 (2015)

IP-Glasma + MUSIC + Cooper-Frye

$\tau_0 = 0.4$ fm T=145 MeV

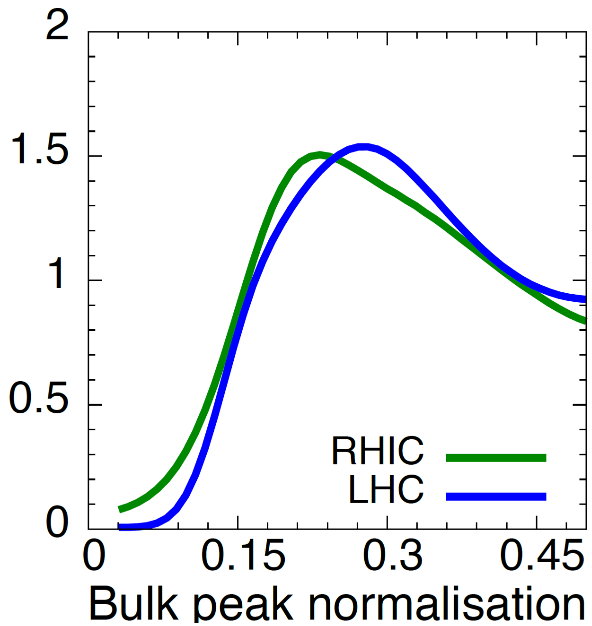
Emulator from MADAI Novak et al, PRC89, 034917 (2014), 1303.5769.

500 random parameter samples (100 events per parameter sample)



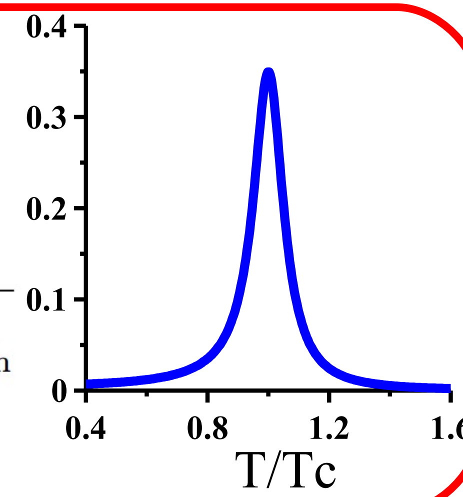
Works well (Points = hydro calculations, lines = emulator)

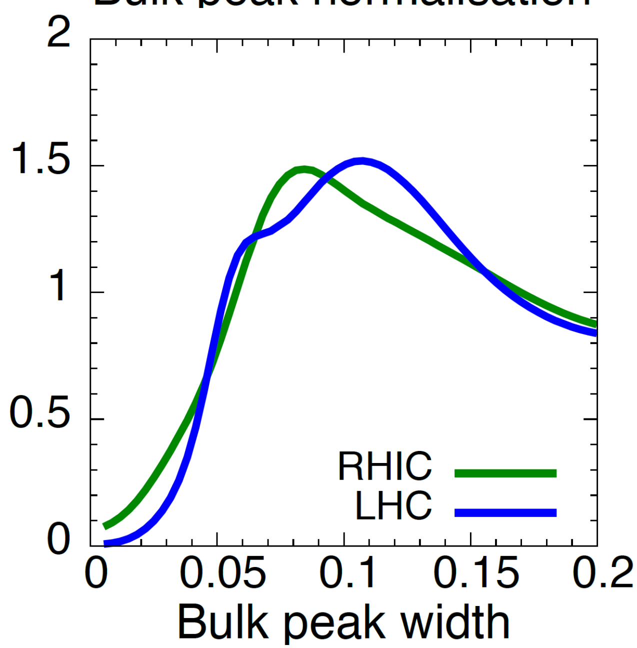
Results – probability distributions

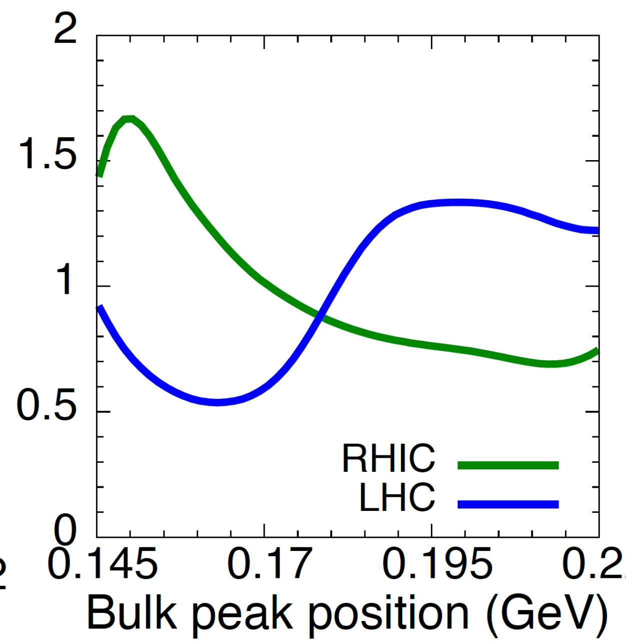


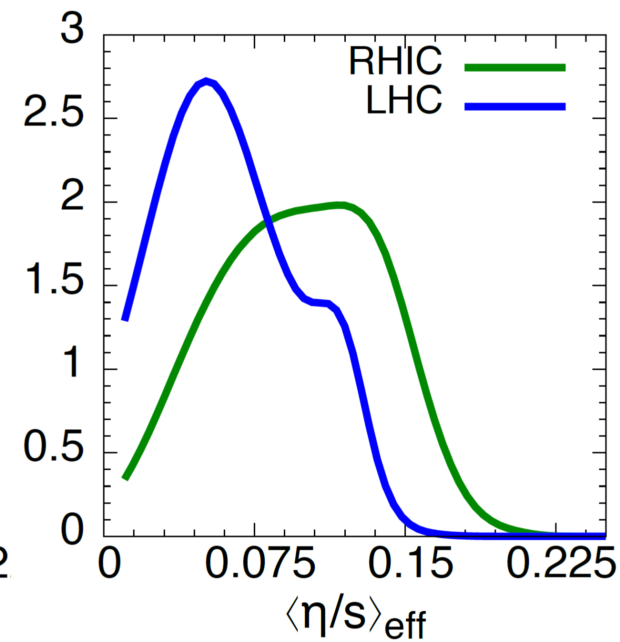
$\zeta/s(T)$ parametrized as

$$\frac{\zeta}{s}(T) = B_{\mathrm{norm}} \frac{B_{\mathrm{width}}^2}{\left(\frac{T^2}{T_{\mathrm{peak}}^2} - 1\right)^2 + B_{\mathrm{width}}^2}$$

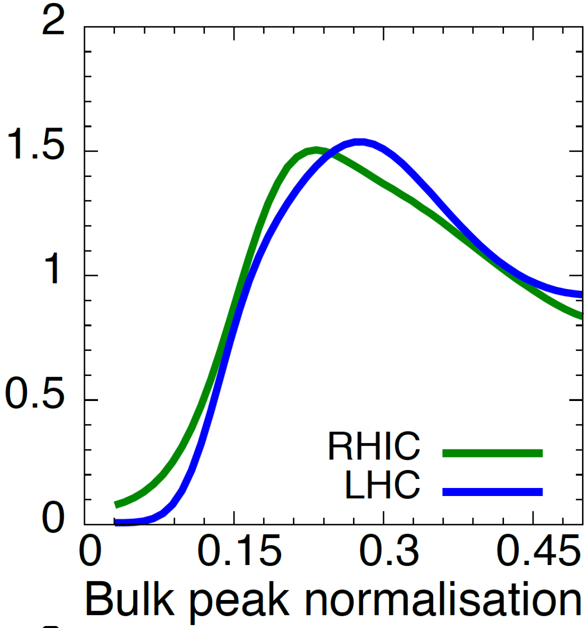




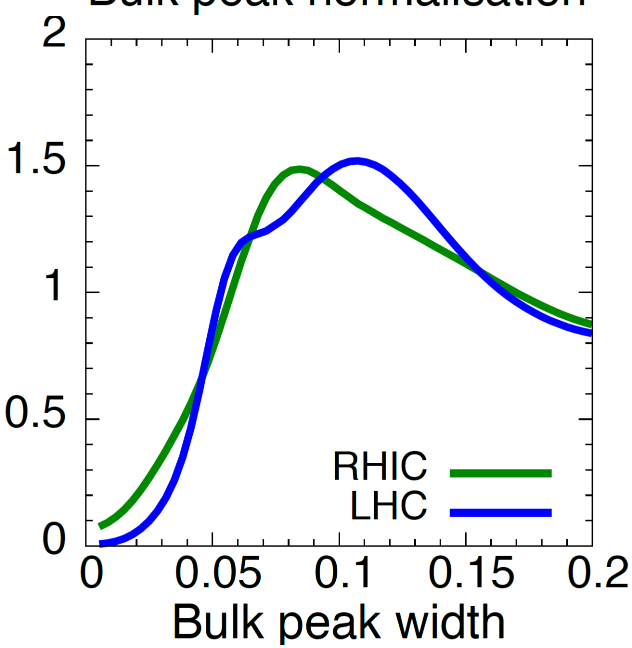


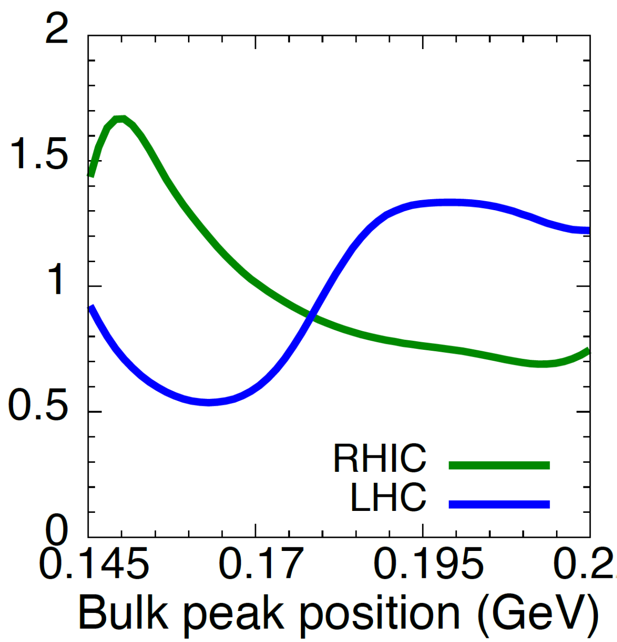


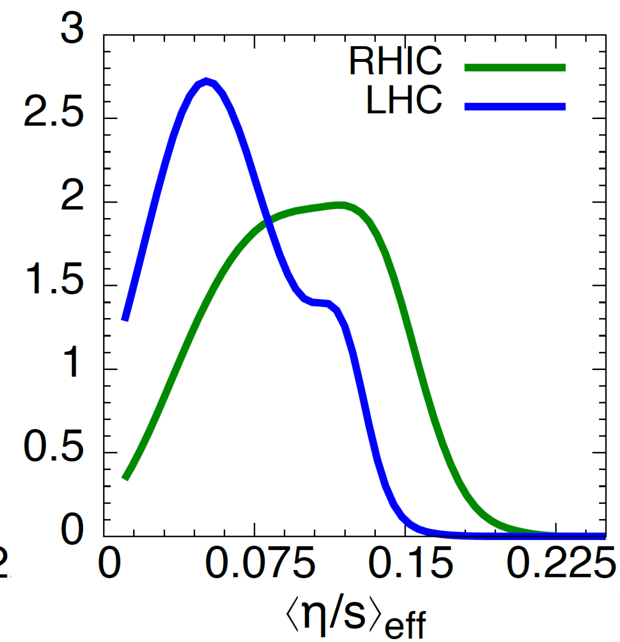
Results – probability distributions



- Data from RHIC and LHC lead to consistent values of $\zeta/s(T_c)$ and bulk width ☺
- Value extracted for T_c varies significantly with collision energy ☹

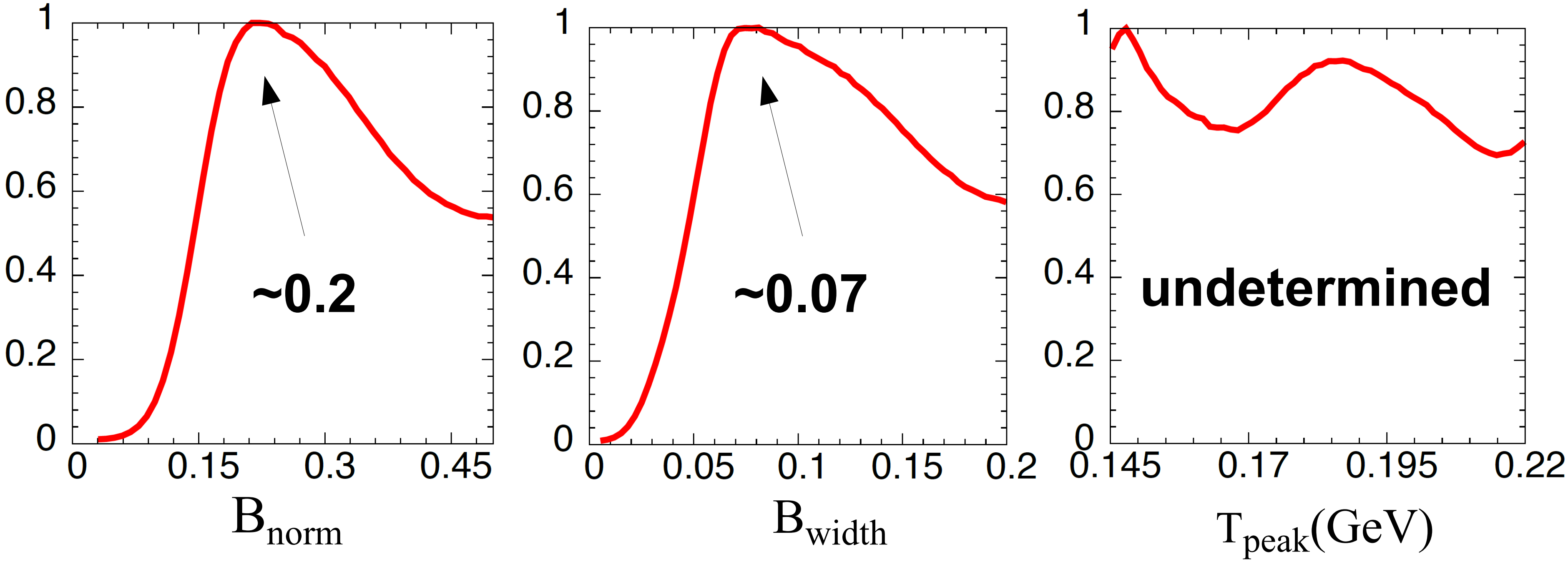






Results – RHIC+LHC combined probability distributions

$$\frac{\zeta}{s}(T) = B_{\rm norm}\frac{B_{\rm width}^2}{\left(\frac{T^2}{T_{\rm peak}^2}-1\right)^2 + B_{\rm width}^2}$$



Clear preferred values,
Good agreement between RHIC and LHC

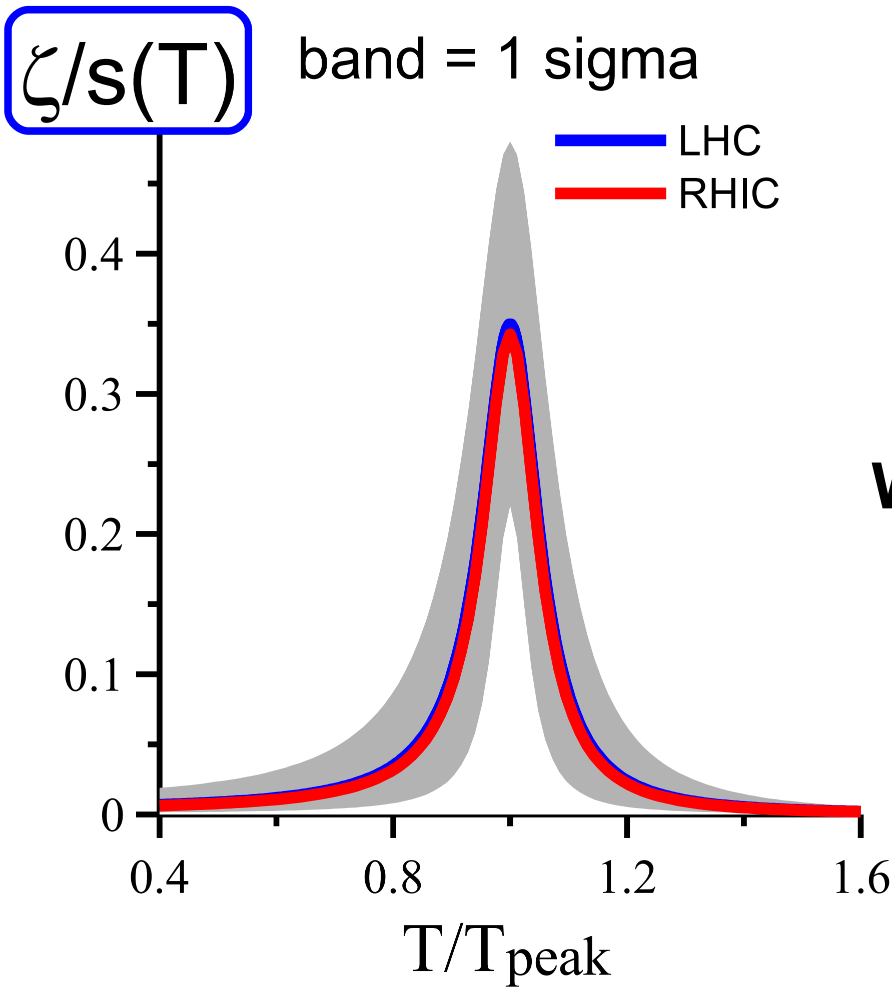
LHC prefers high T_{peak}

RHIC prefers low T_{peak}

need other observables ...

Extraction of ζ/s(T) with MADAI Emulator

Model: IP-Glasma + MUSIC (bulk&shear)



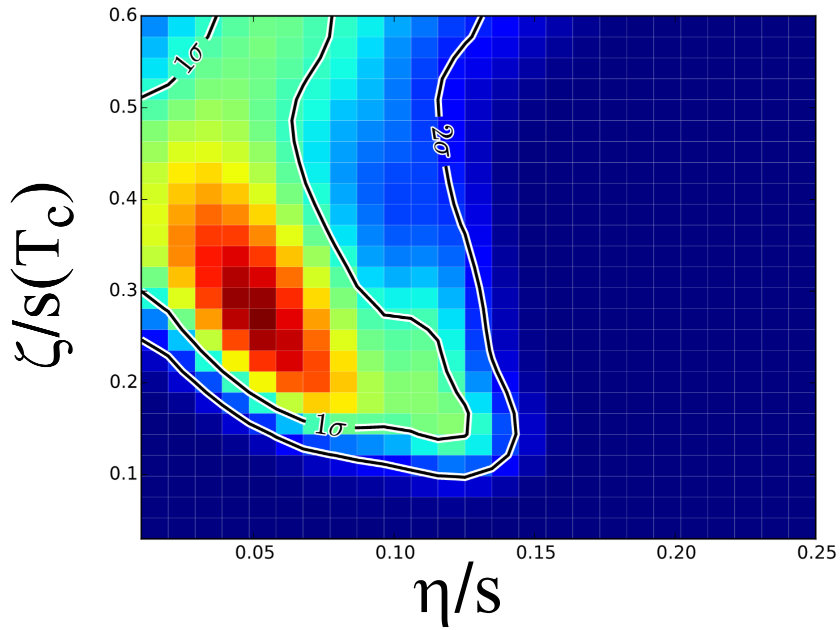
ζ/s(T) parametrized as a Breit-Wigner distribution

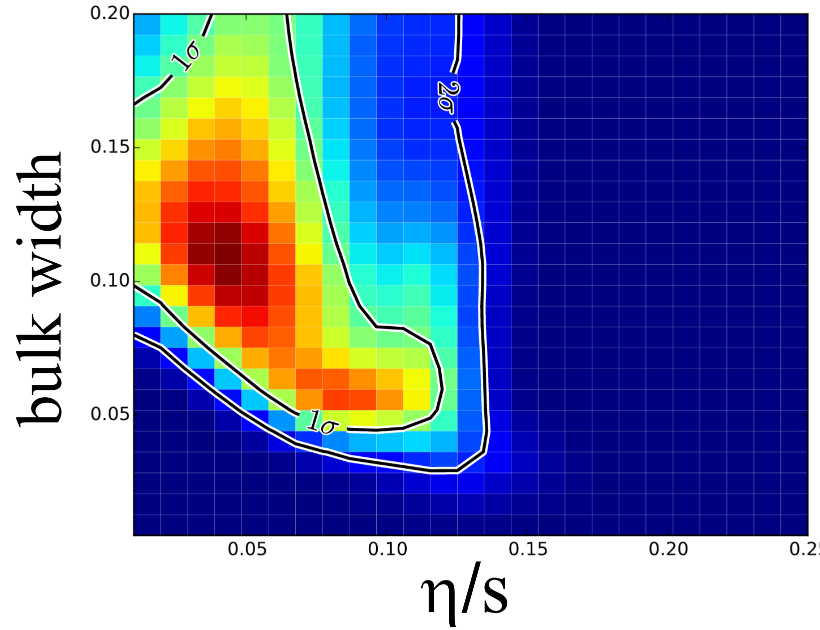
$$\frac{\zeta}{s}(T) = B_{\rm norm} \frac{B_{\rm width}^2}{\left(\frac{T^2}{T_{\rm peak}^2} - 1\right)^2 + B_{\rm width}^2}$$

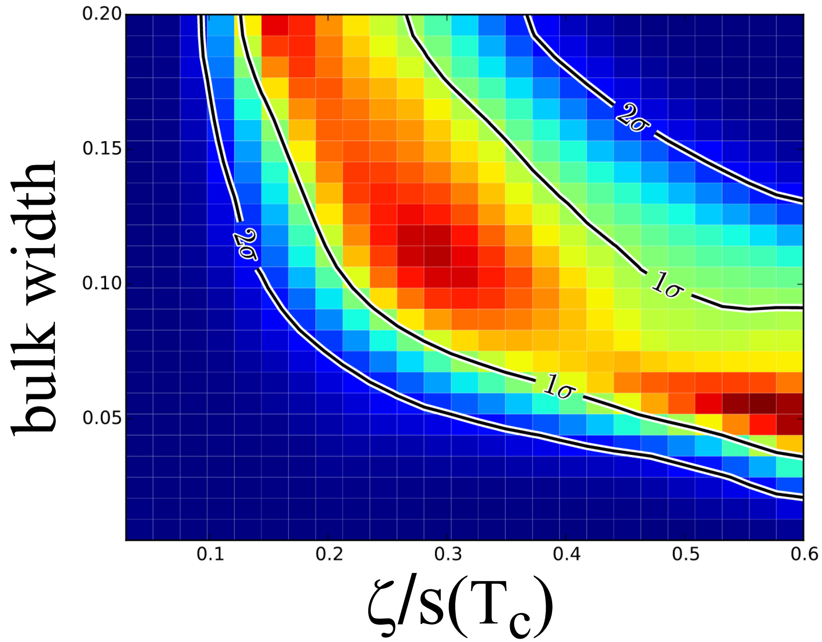
Within this model, shape of bulk viscosity seems to be well determined

But temperature where it peaks is unknown ...

Correlations (LHC energy)



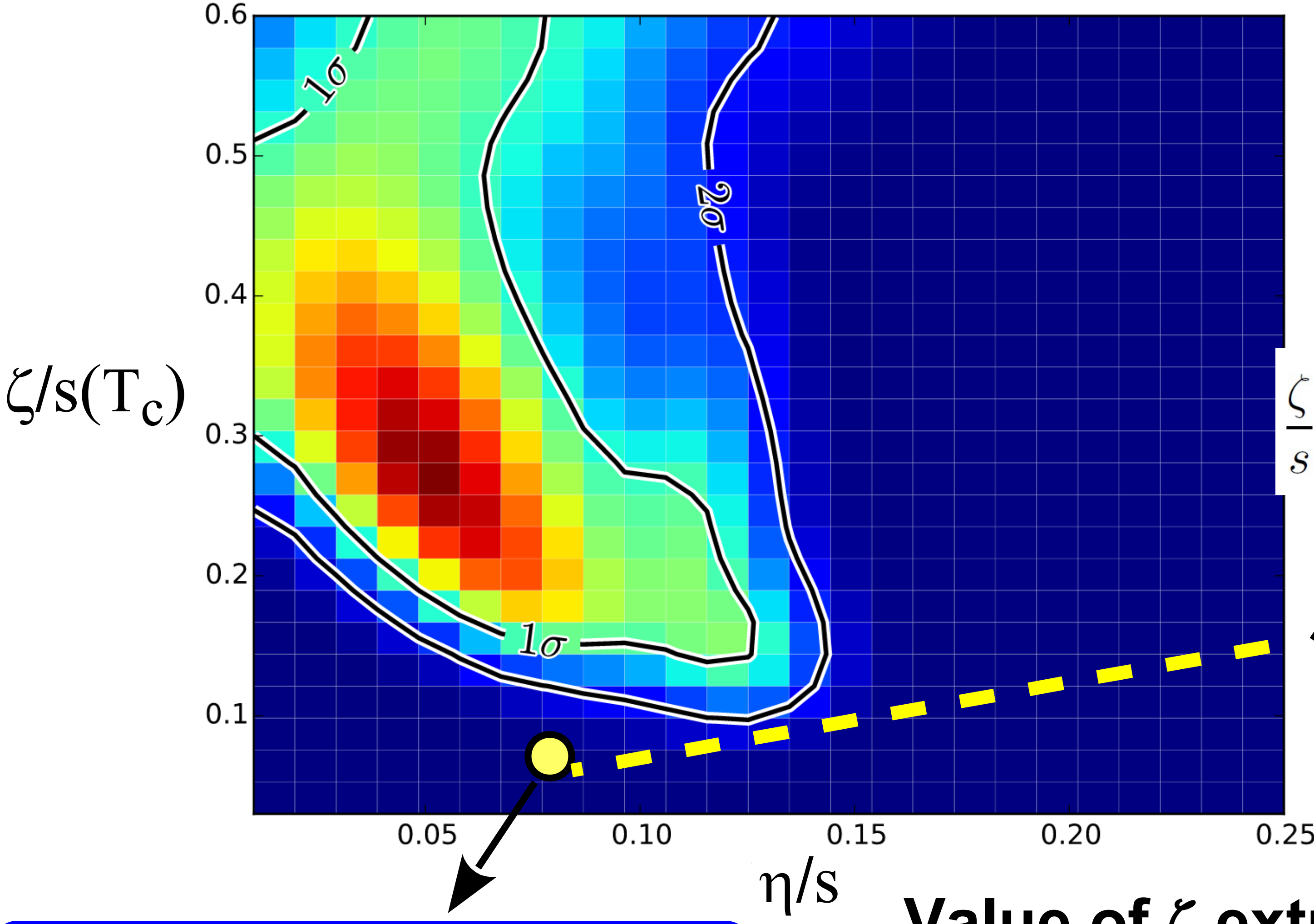




$\zeta/s(T_c)$, η/s, and the width of ζ/s are anti-correlated.

Small values of $\zeta/s(T_c)$ and bulk width are excluded within our model

Correlation between Bulk and Shear



$$\frac{\zeta}{s} = 15\frac{\eta}{s}\left(\frac{1}{3} - c_s^2\right)^2$$

non-conformal holography prediction Finazzo *et al*, arXiv:1412.2968

Value of ζ extracted is much larger than expected

Summary

✔ Some progress in understanding bulk viscosity within our model

(i) Our calculations point to a significant bulk viscosity – not yet understood theoretically

(ii) But we cannot pin down the temperature where it peaks

✔ **Be careful I**: bulk component of nonequilibrium distribution still not very constrained ...

✔ **Be careful II**: model assumptions can affect the results ...

Fluid-dynamical equations

GSD&Niemi&Molnar&Rischke, PRD 85, 114047 (2012)

Inclusion of bulk viscous pressure, shear-stress tensor, and all couplings

$$\dot{\Pi} + \frac{\Pi}{\tau_\Pi} = -\beta_\Pi \theta - \delta_{\Pi\Pi}\Pi\theta + \varphi_1 \Pi^2 + \lambda_{\Pi\pi}\pi^{\mu\nu}\sigma_{\mu\nu} + \varphi_3 \pi^{\mu\nu}\pi_{\mu\nu} ,$$

$$\dot{\pi}^{\langle\mu\nu\rangle} + \frac{\pi^{\mu\nu}}{\tau_\pi} = 2\beta_\pi \sigma^{\mu\nu} + 2\pi_\alpha^{\langle\mu}\omega^{\nu\rangle\alpha} - \delta_{\pi\pi}\pi^{\mu\nu}\theta + \varphi_7 \pi_\alpha^{\langle\mu}\pi^{\nu\rangle\alpha} - \tau_{\pi\pi}\pi_\alpha^{\langle\mu}\sigma^{\nu\rangle\alpha} + \lambda_{\pi\Pi}\Pi\sigma^{\mu\nu} + \varphi_6 \Pi\pi^{\mu\nu}.$$