# Suppression of baryon diffusion and transport in a baryon rich strongly coupled QGP

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Romulo Rougemont,Jorge Noronha PRL115(2015)no.20,202301
Future work + Renato Critelli, Stefano Finazzo, Israel Portillo, and Claudia Ratti

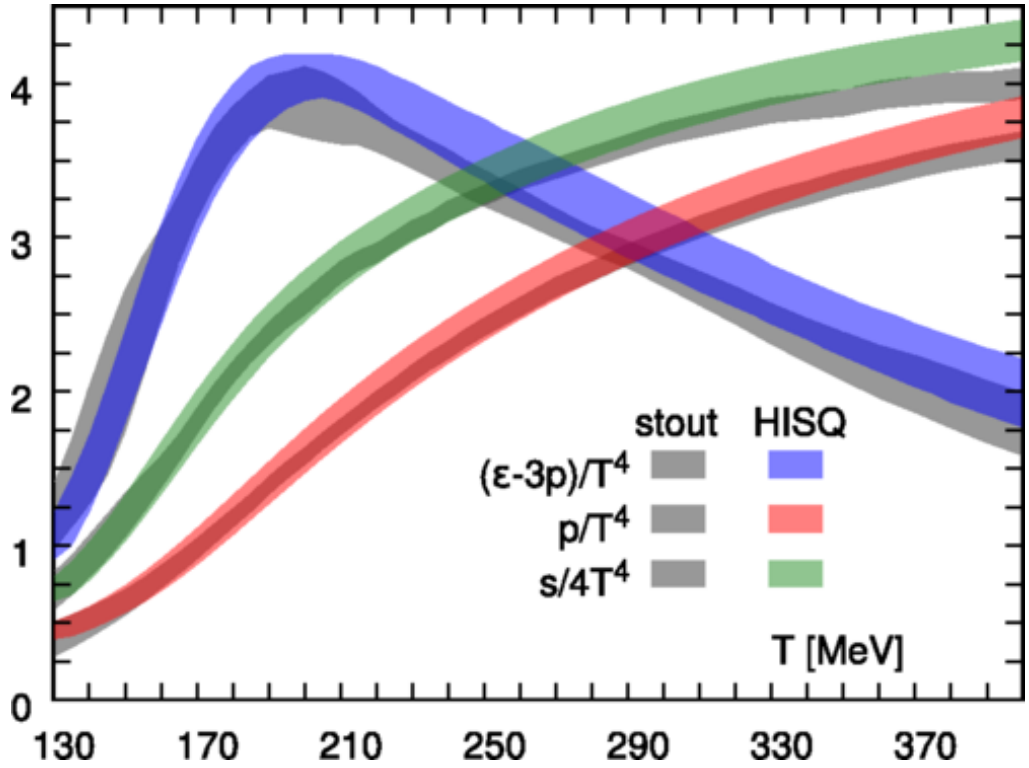
RHIC & AGS User's Meeting
June $7^{th}$ 2016

# Outline


1. Lattice QCD
2. Black Hole Engineering
3. Critical Point
4. Transport Coefficients
5. Freeze-out Line
6. Conclusion and Outlook

# The Success of Lattice QCD

Equation of State agrees for stout (WB) and HISQ (HotQCD) actions

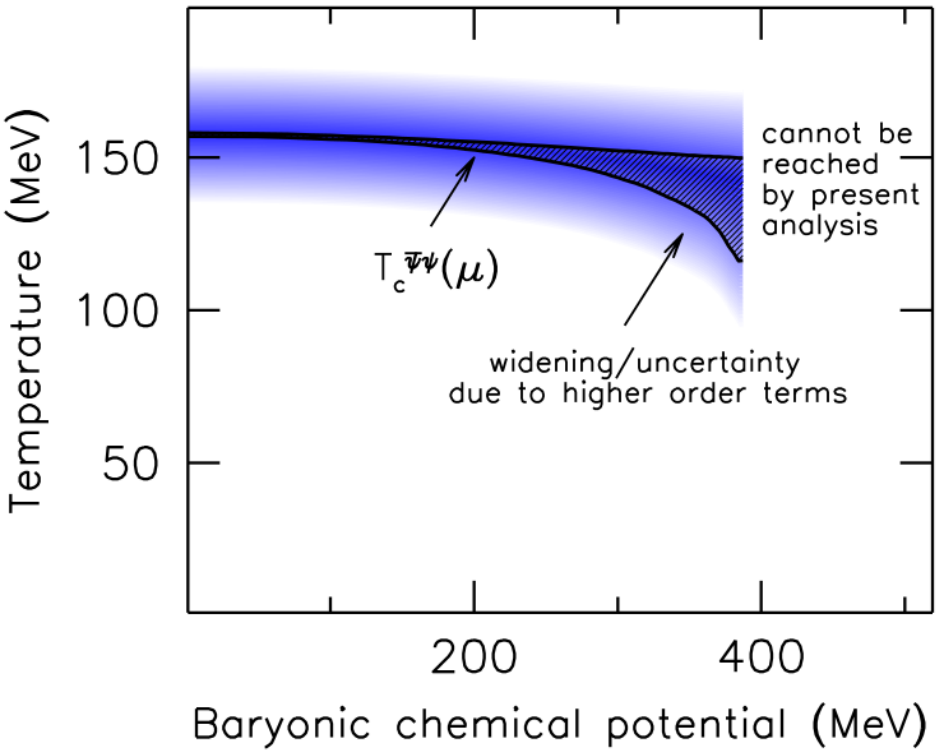



WB Phys.Lett. B730 (2014) 99-104
HotQCD Phys.Rev. D90 (2014) 094503

# Limitations at Large $\mu_B$ (Sign problem)

Taylor expand pressure in term of $\mu_B$, limits results for large $\mu_B$

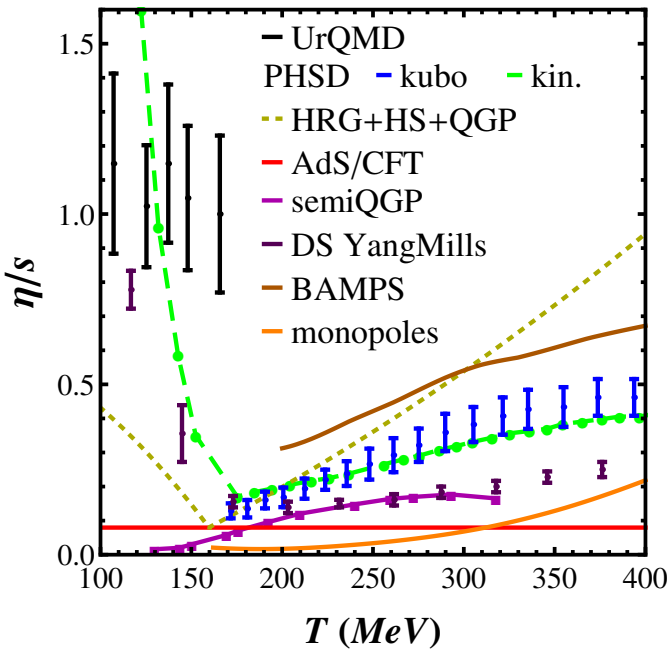
$$\frac{P(\mu_B)}{T^4} = c_0 + c_2\left(\frac{\mu_B}{T}\right)^2 + c_4\left(\frac{\mu_B}{T}\right)^4 + c_6\left(\frac{\mu_B}{T}\right)^6 + \mathcal{O}(\mu_B^8)$$

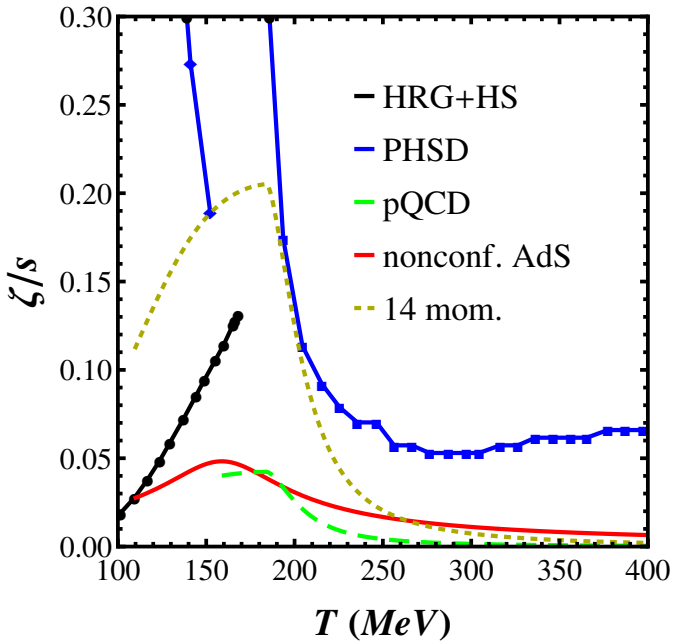



Phys.Lett. B751 (2015) 559-564

# Limitations for transport properties

- Lattice has technical difficulties to compute transport properties
- We're left with a number of models that don't converge...




JNH arXiv:1512.06315 (see for references)

# Filling in the gaps with Black Hole Engineering

What we need...

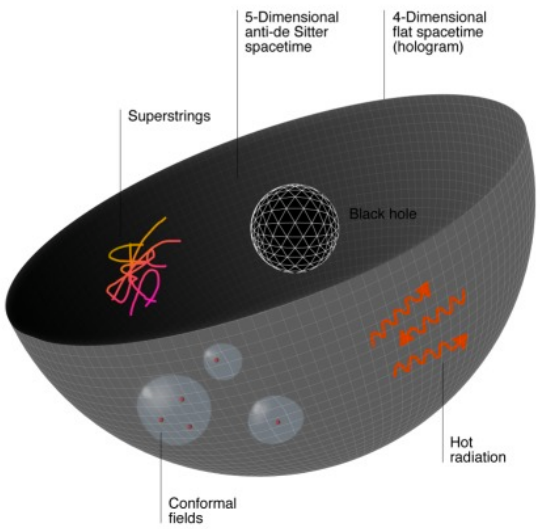
- Strongly coupled system
- Non-conformal equation of state
  - Equation of State at large baryon chemical potentials
  - Critical Point
- Perfect fluidity
  - Ability to compute transport coefficients near crossover and at large $\mu_B$

**A solution**

Gauge/gravity duality - Black Hole Engineering

# Gauge/gravity duality

Maldacena, Gubser, Polyakov, Witten, 1998




Strong coupling limit of QFT in 4 dimensions (with many d.o.f.)

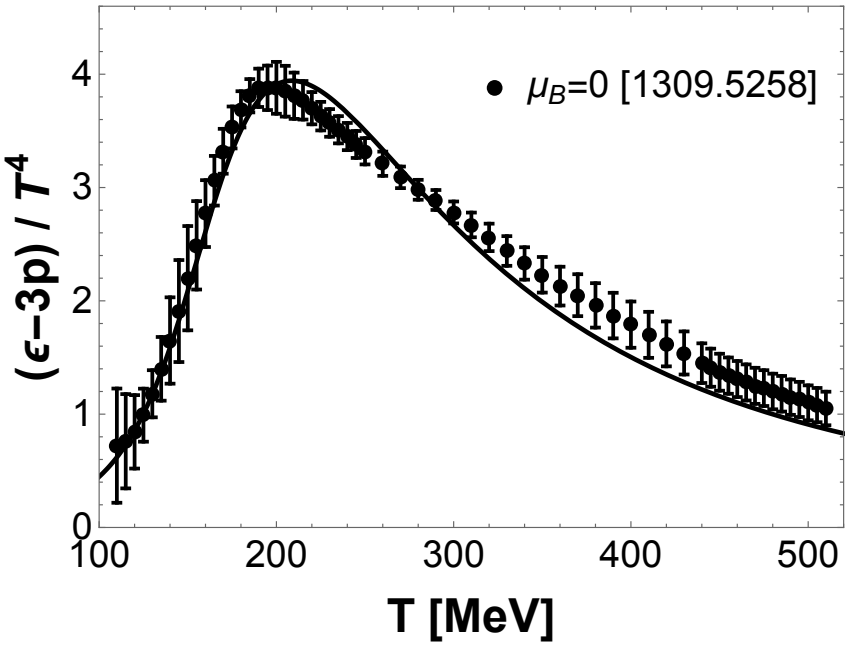
$\Updownarrow$

String Theory/Classical gravity in d>4 dimensions

curved spacetime $= (t, x, y, z, r)$ where $r$ is the holographic coordinate

# non-conformal Equation of State

$$S = \frac{1}{2\kappa^2}\int_{\mathcal{M}_5} d^5x\sqrt{-g}\left[\mathcal{R} - \frac{1}{2}(\partial_\mu\phi)^2 - \underbrace{V(\phi)}_{\substack{\phi\neq const\\ (nonconformal)}} - \underbrace{\frac{f(\phi)}{4}F^2_{\mu\nu}}_{\mu_B\neq 0}\right]$$

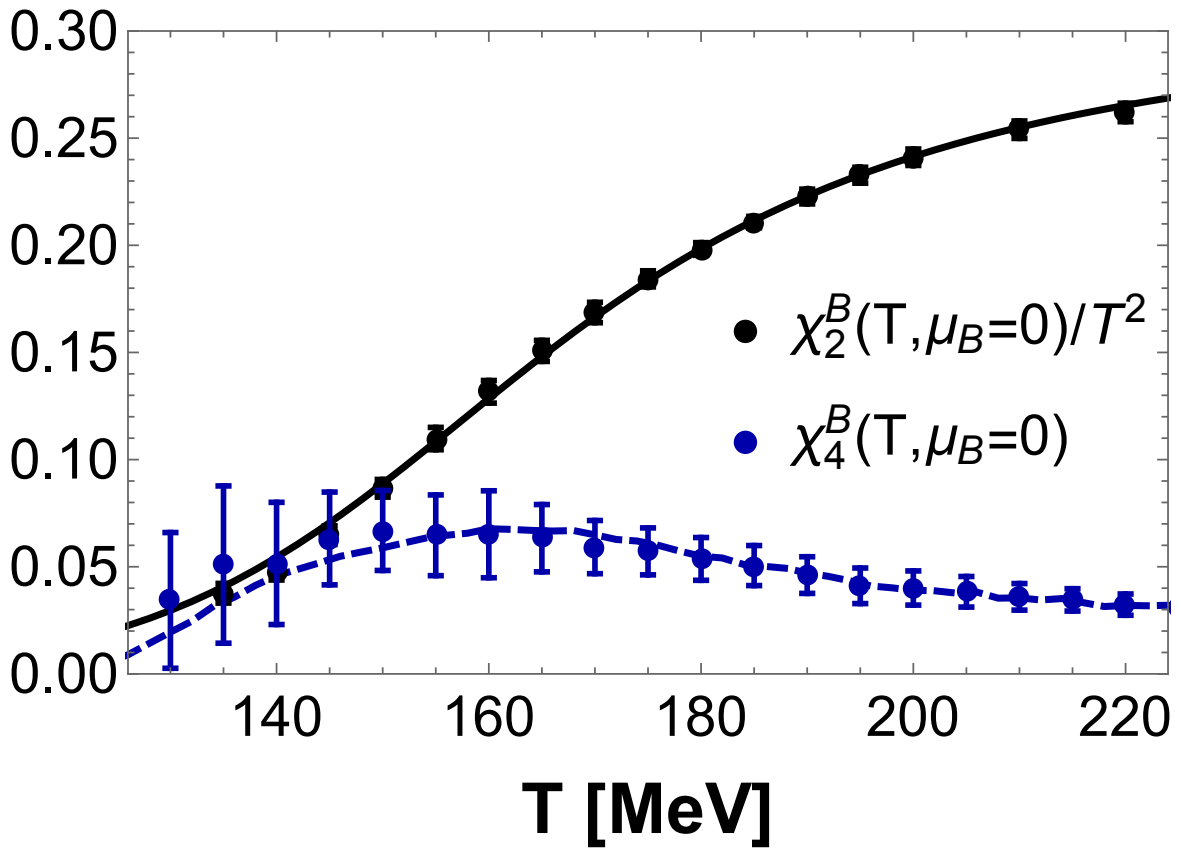



$\kappa^2$ gravitational constant
$V(\phi)$ dilaton potential
$f(\phi)$ Maxwell-Dilaton coupling
all fixed to lattice data at $\mu_B = 0$

$\rightarrow$ non-conformality!
Allows for $\zeta/s > 0$!

# Baryon susceptibilities

Derivatives of the pressure $\chi_n^B = \partial^n p/\partial\mu_B^n = \partial^{n-1}\rho/\partial\mu_B^{n-1}$




R. Rougemont,J. Noronha, JNH, PRL115(2015)no.20,202301

# Perfect Fluidity

Shear viscosity to entropy density*

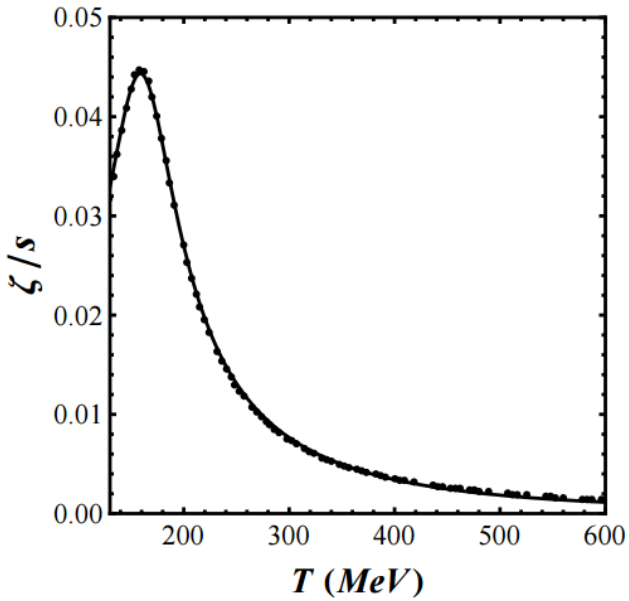
$$\frac{\eta}{s} = \frac{1}{4\pi}$$

Kovtun,Son,Starinets, 2005

*Possible to get $\eta/s(T)$ with

- Magnetic field PRD90(2014)no.6,066006
- higher-order derivatives of the action PRD77(2008)126006

non-conformal EOS needed for bulk viscosity

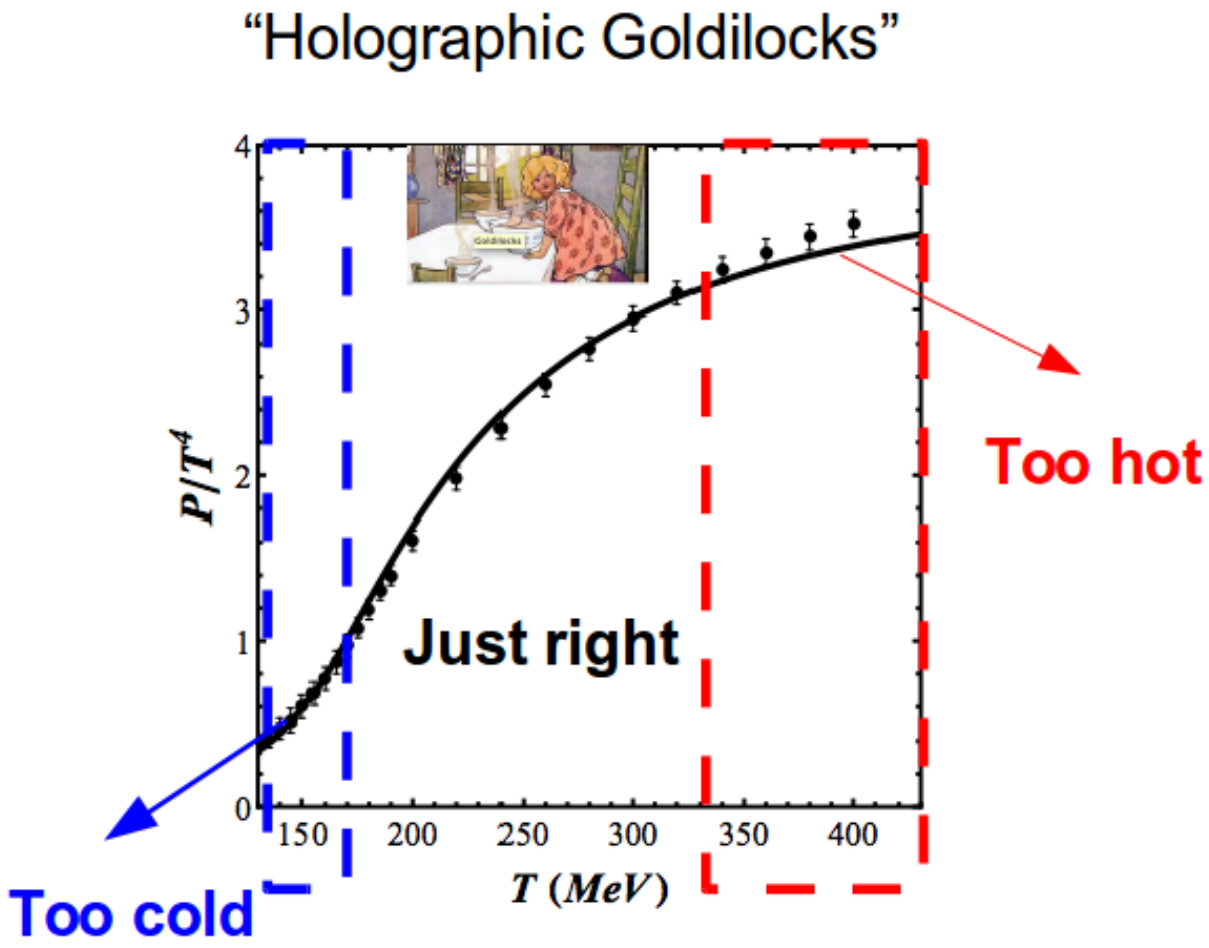



+16 more second order transport coefficients

S. Finazzo, R. Rougemont, H. Marrochio, J. Noronha, JHEP 1502 (2015) 051

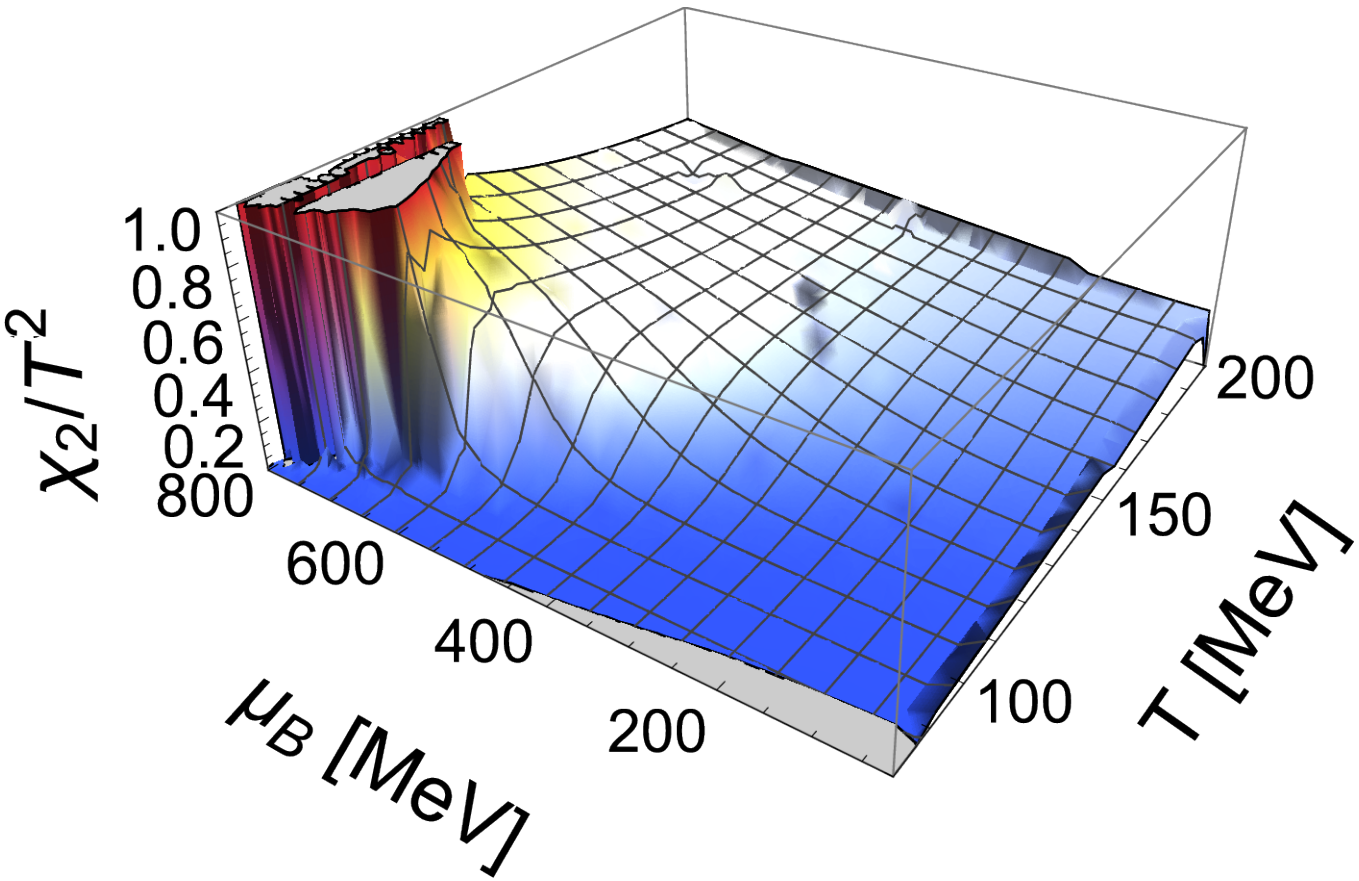
# Transition Region-Goldilocks Zone

Only concerned with the transition region



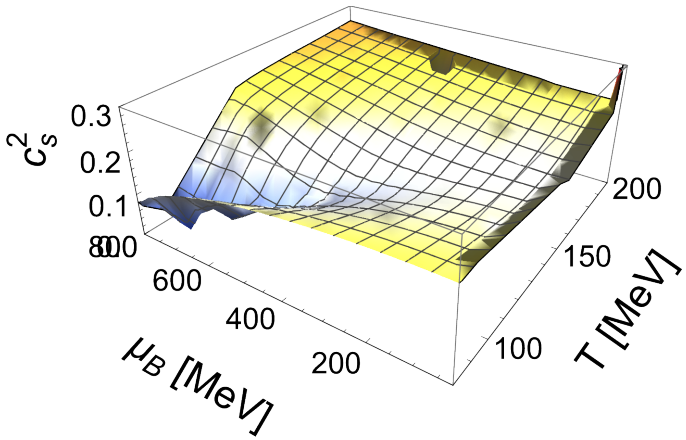
# Critical Point

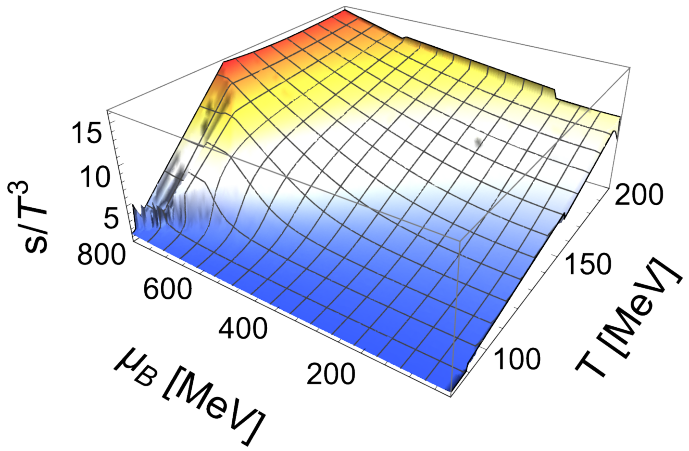
Critical Point ($T = 725$ MeV and $\mu_B = 90$ MeV) emerges naturally from the theory



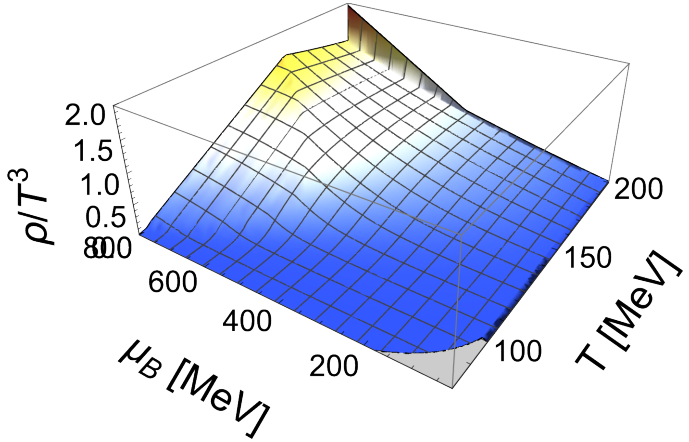
# Equation of State at finite $\mu_B$

Everything at $\mu_B > 0$ is a prediction



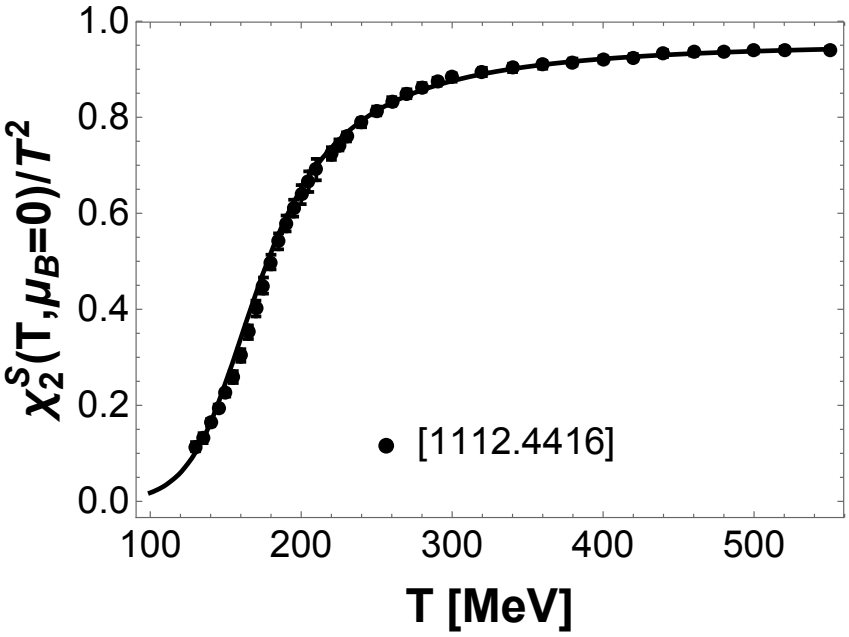



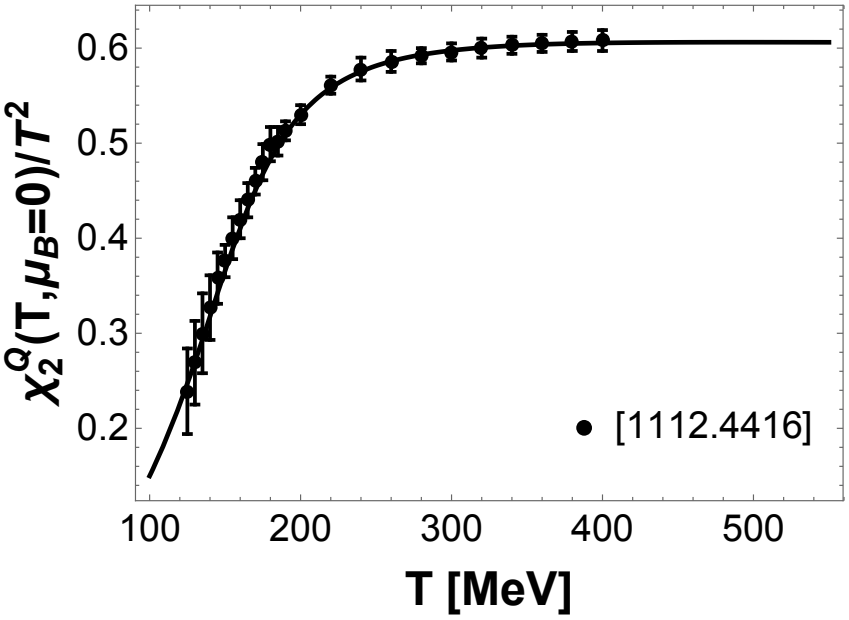

Critical behavior very sensitive to $\mu_B = 0$ Lattice QCD input



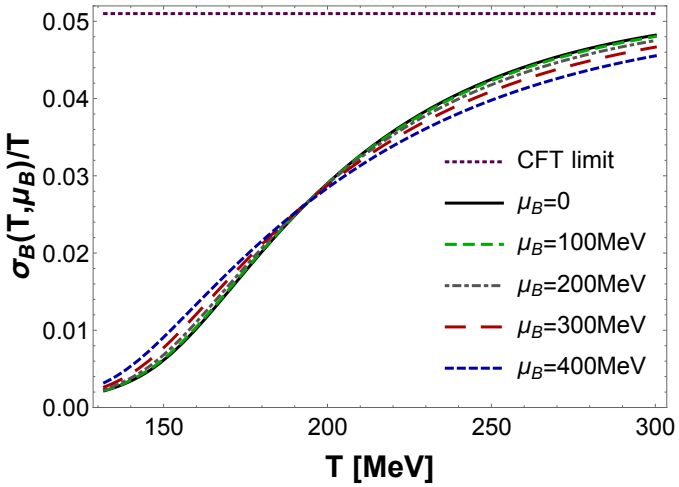
# Strangeness and Electric Charge

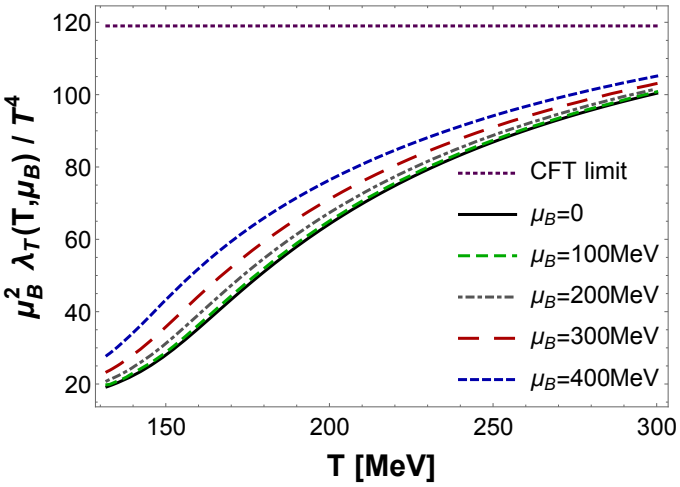
- Since $\mu_S < \mu_B$ and $\mu_Q << \mu_B$, assume $\mu_S \sim \mu_B \sim 0$
- Caveat: only valid when $\mu_S/\mu_B$ and $\mu_Q/\mu_B$ are small

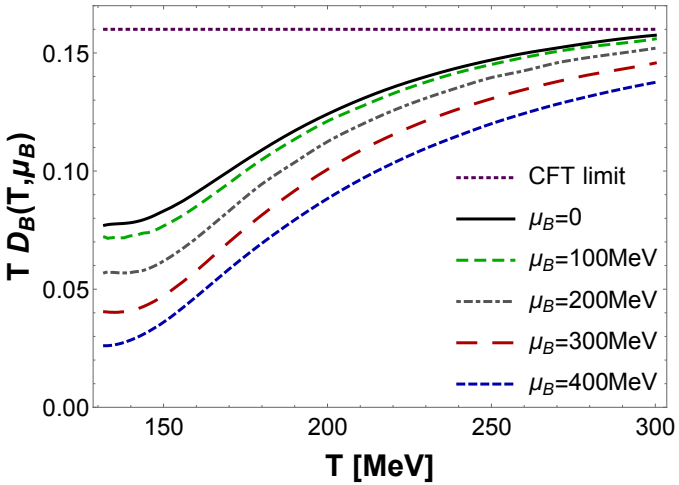


# Baryon Transport Coefficients




DC Conductivity

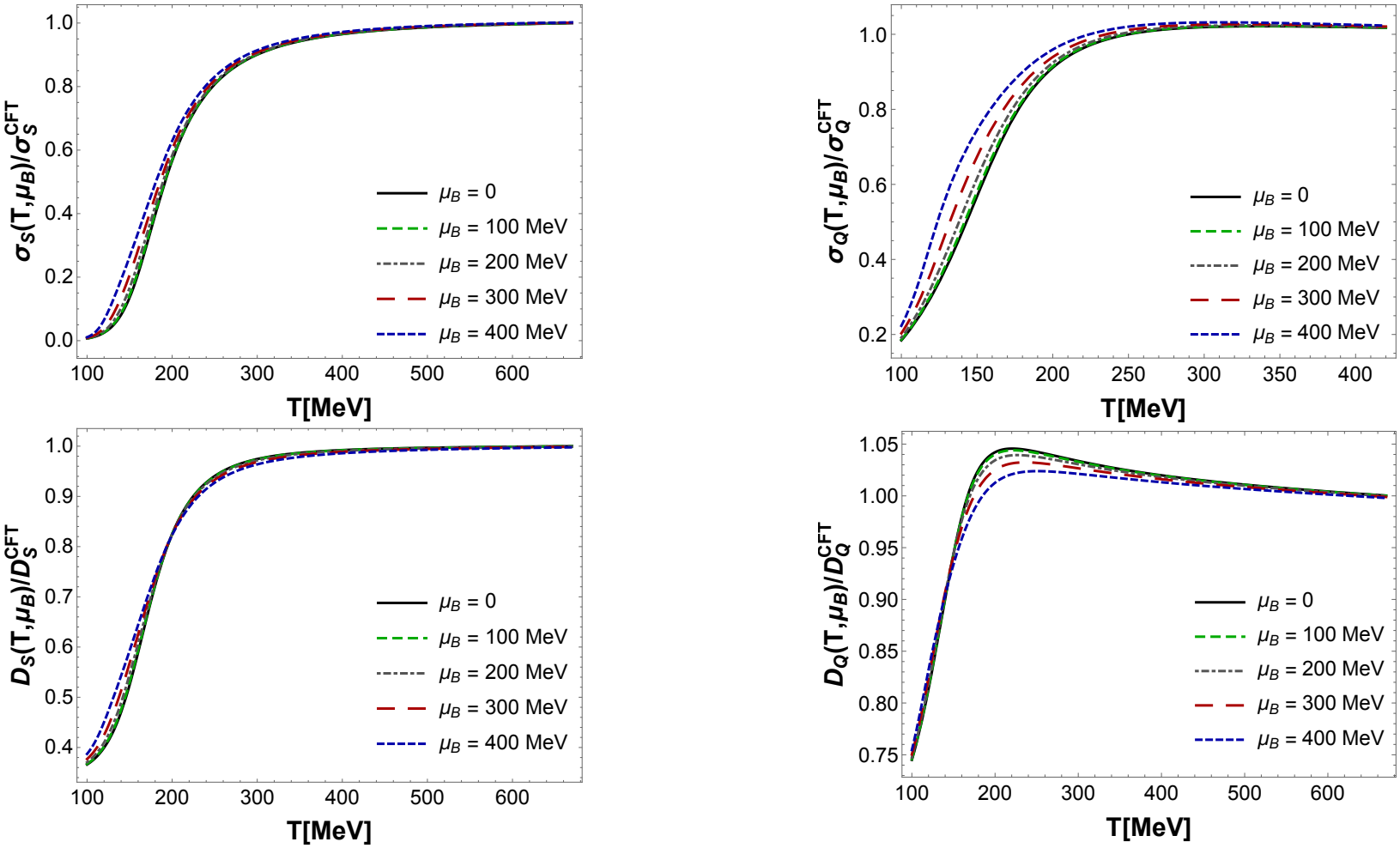
$$\sigma_B = -\frac{\Lambda}{2\kappa^2\phi_A^{1/\nu}}\lim_{\omega\to 0}\frac{h(r)f(\phi)e^{2A(r)}\mathrm{Im}\left[a^*(r,\omega)a'(r,\omega)\right]}{\omega}$$

Baryon diffusion $D_B = \sigma_B/\chi_2^B$

Thermal conductivity

$$\lambda_T = (\sigma_B/T)\left[(\epsilon+p)/\rho\right]^2$$

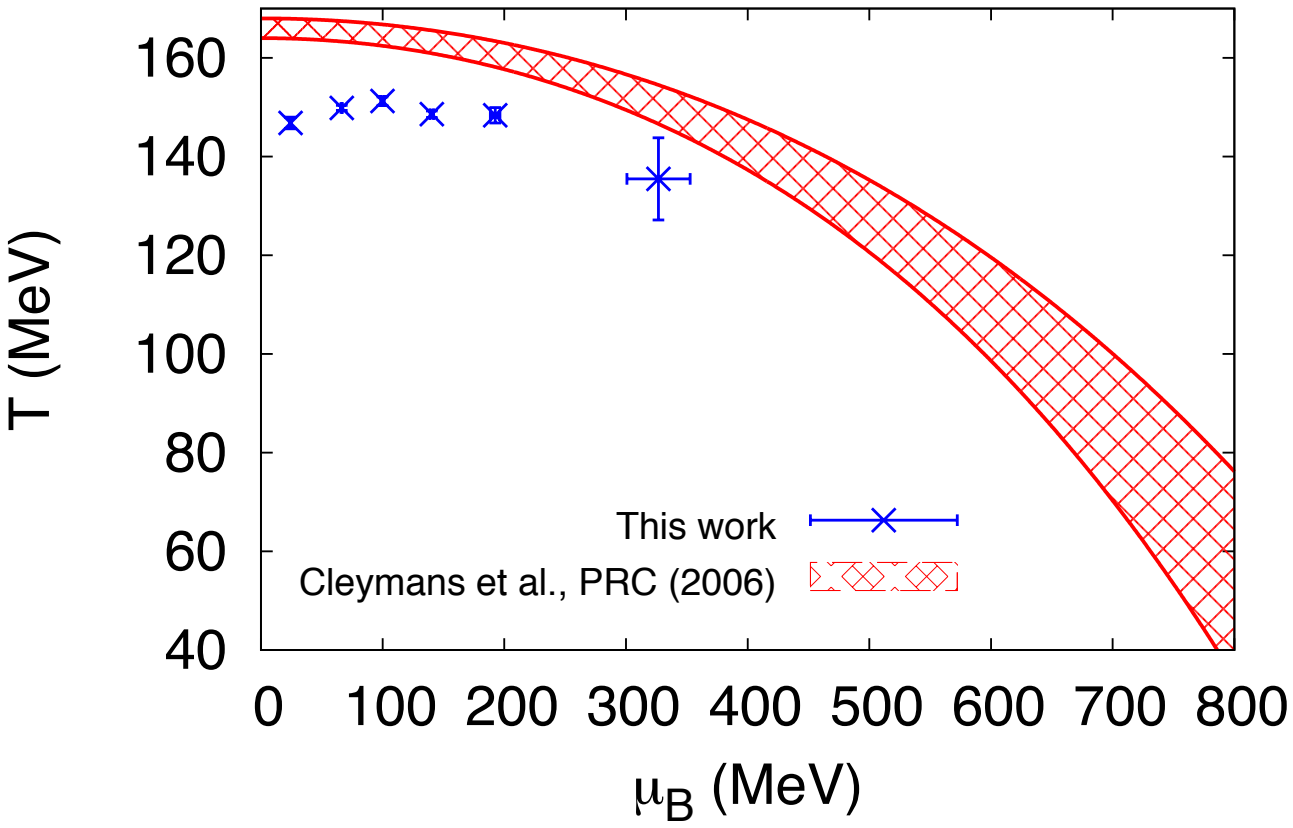
# Strange and Electric Charge Transport Coefficients



# What defines the transition region?

- Compare derivatives of the pressure e.g. $\chi_2^B/\chi_1^B$ to experimental data
  - Need ratios that are not strongly affected by decays, acceptance cuts etc.
  - Work in progress...
- Determine the inflection point of the $\chi_n^{BSQ}$'s across $\mu_B$
- Determine the inflection point of the transport coefficients across $\mu_B$
  - Should the inflection point of transport coefficients match the chemical freeze-out line?

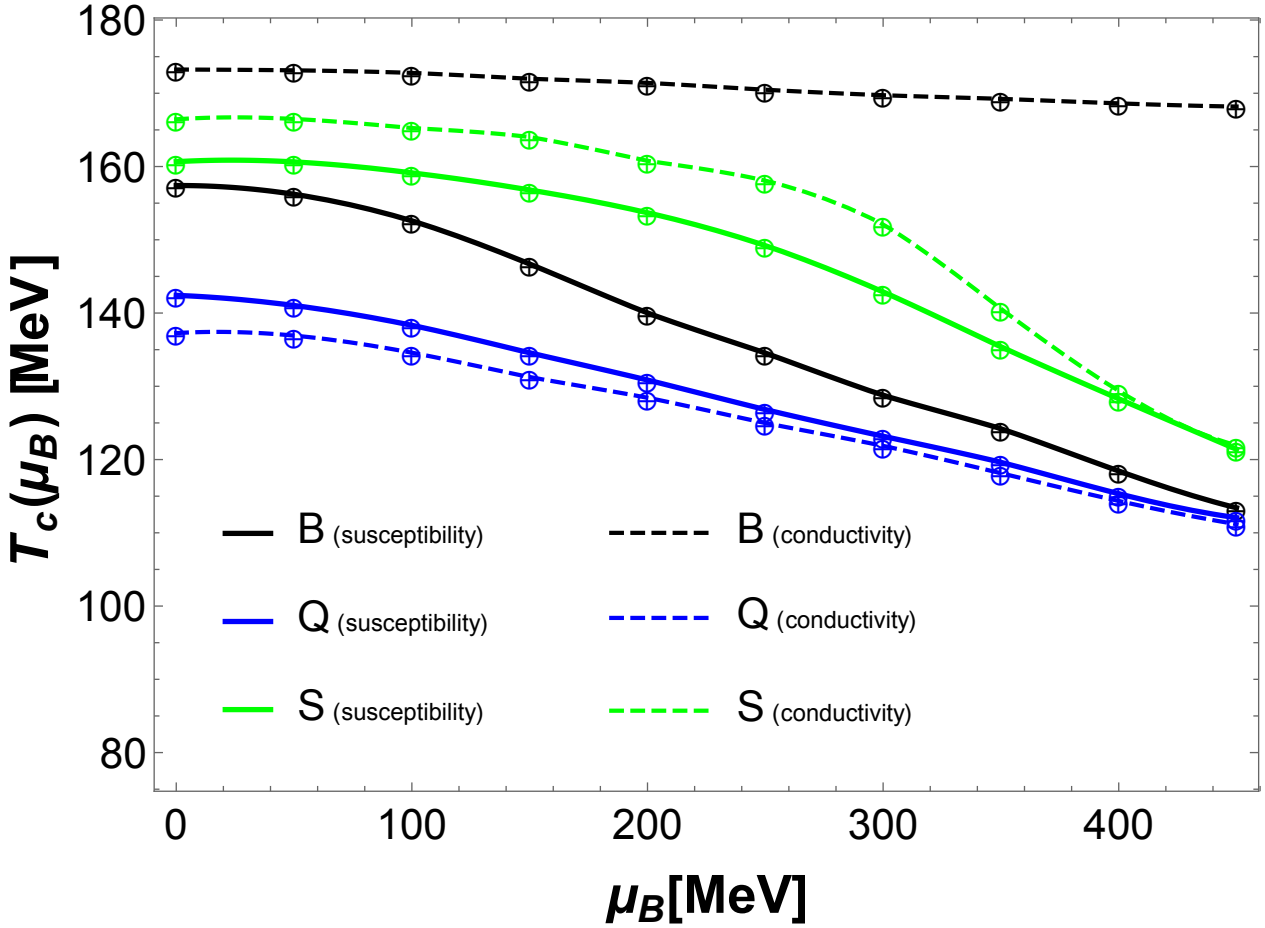
# Extraction of the freeze-out line from susceptibilities




Phys.Lett. B738 (2014) 305-310

# Inflection Points: Equilibrium vs. Dynamics

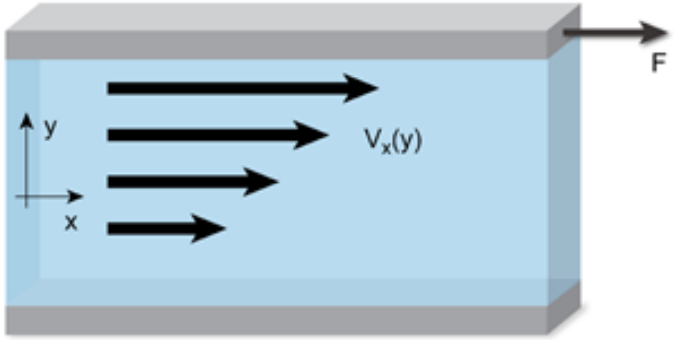
- $T^{eq}_{c,S}(\mu_B) \sim T^{dyn}_{c,S}(\mu_B)$ and $T^{eq}_{c,Q}(\mu_B) \sim T^{dyn}_{c,Q}(\mu_B)$
- $T^{eq}_{c,B}(\mu_B)$ decreases with $\mu_B$ whereas $T^{dyn}_{c,B}(\mu_B) = const$



# Conclusions and Outlook

- Gauge/gravity duality/Black hole engineering provides a strongly interacting theory, non-conformal EoS that matches lattice, and calculable transport coefficients
- Critical Point arises at $T = 725$ MeV and $\mu_B = 90$ MeV sensitive to Lattice data at $\mu_B = 0$!
- Near crossover, $\mu_B \geq 0$, transport coefficients are suppressed compared to conformal field theory
- For the future- freeze-out line compared to experimental data, parametrized EoS for hydro codes etc
- Theory work is needed! Inclusion of multiple nonzero chemical potentials

# Transport Coefficients Calculations




From kinetic theory

$$\frac{\eta}{s} = \frac{1}{3} n \langle p \rangle l_{mfp}$$

where $l_{mfp} = 1/n\sigma$ and $\sigma$ is the cross-section

# Kubo Formula

$$\eta\left(\delta_{ik}\delta_{jl}+\delta_{il}\delta_{jk}-\frac{2}{3}\delta_{ij}\delta_{kl}\right)+\zeta\delta_{ij}\delta_{kl}=-\lim_{\omega\to 0}\frac{1}{\omega}ImG^{R}_{ij,kl}(\omega)$$

$$G^{R}_{ij,kl}(\omega)=-i\int d^3xdte^{i\omega t}\theta(t)\langle\left[T_{ij}(t,\vec{x}),T_{kl}(0,0)\right]\rangle$$

We get the shear viscosity

$$\eta=-\lim_{\omega\to 0}\frac{1}{\omega}ImG^{R}_{xy,xy}(\omega)$$

Tracing over *ij* and *kl* we get the bulk viscosity

$$\zeta=-\frac{1}{18}\lim_{\omega\to 0}\frac{1}{\omega}ImG^{R}_{ii,jj}(\omega)$$

# Coordinate changes

$$T = \frac{\Lambda}{4\pi\phi_A^{1/\nu}\sqrt{h_0^{\rm far}}}, \quad \mu_B = \frac{\Phi_0^{\rm far}\Lambda}{\phi_A^{1/\nu}\sqrt{h_0^{\rm far}}}, \quad s = \frac{2\pi\Lambda^3}{\kappa^2\phi_A^{3/\nu}},$$
$$\rho = -\frac{\Phi_2^{\rm far}\Lambda^3}{\kappa^2\phi_A^{3/\nu}\sqrt{h_0^{\rm far}}}, \tag{1}$$

where $\Lambda \approx 831$ MeV is the energy scale conversion factor

$$\begin{aligned} V(\phi) &= -12\cosh(0.606\phi) + 0.703\phi^2 - 0.1\phi^4 + 0.0034\phi^6, \\ f(\phi) &= \frac{\mathrm{sech}(1.2\,\phi - 0.69)}{3\,\mathrm{sech}(0.69)} + \frac{2e^{-100\,\phi}}{3}. \end{aligned} \tag{2}$$

# Equation of Motion

$$a''(r) + \left(2A'(r) + \frac{h'(r)}{h(r)} + \frac{f'(\phi)}{f(\phi)}\phi'(r)\right) a'(r) + \frac{e^{-2A(r)}}{h(r)}\left(\frac{\omega^2}{h(r)} - f(\phi)\Phi'(r)^2\right) a(r) = 0. \tag{3}$$