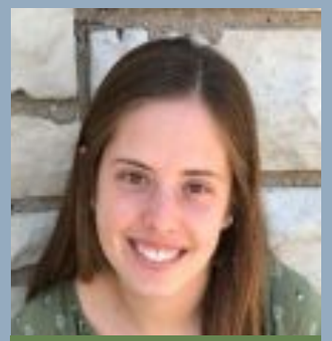
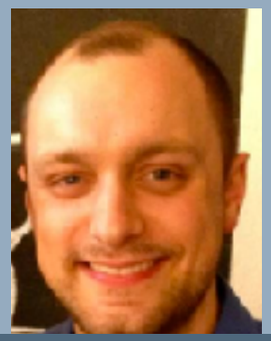
Illinois Center for Advanced Studies of the Universe

Hydrodynamics with Baryon, Strangeness, and Electric Charge conservation

Jacquelyn Noronha-Hostler
University of Illinois Urbana-Champaign



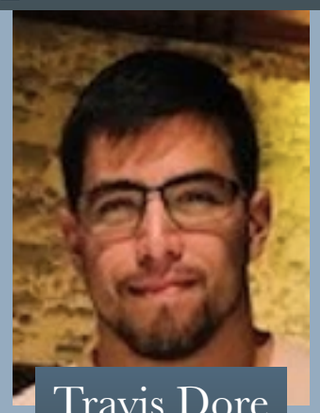
Lydia Spychalla
REU UIUC



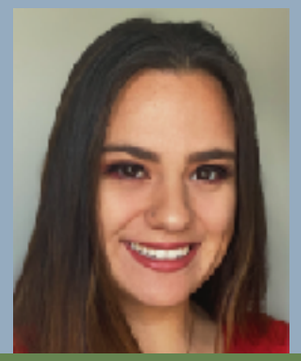
Christopher Plumberg
UIUC postdoc

Hydro Specialists

Dekra Almaalol
UIUC postdoc

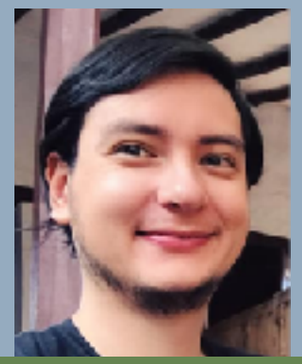


Travis Dore
PhD student



Debora Mroczek
UIUC PhD Student

Equation of State Specialists



Nikolas Cruz Camacho
PhD UIUC

Quark Matter 2022

BSQ Israel Stewart Equations of Motion

Almaalol, Dore, Mroczek, Sievert, JNH to appear soon

$$\tau_\pi \dot{\pi}^{\mu\nu} + \pi^{\mu\nu} = 2\eta\sigma^{\mu\nu} + \frac{\tau_\pi \pi^{\mu\nu}}{2}\theta - \frac{\tau_\pi}{2\beta_\pi}\dot{\beta}_\pi \pi^{\mu\nu} - \frac{2\eta}{\beta}\left(\gamma_1^q \nabla^{\langle\mu} n_q^{\nu\rangle} + \frac{1}{2} n_q^{\langle\mu} \nabla^{\nu\rangle} \gamma_1^q\right)$$

$$\tau_\Pi \dot{\Pi} + \Pi = -(\zeta + \frac{\tau_\Pi}{2}\Pi)\theta - \frac{\tau_\Pi}{2\beta_\Pi}\dot{\beta}_\Pi \Pi - \frac{\zeta}{\beta}\left(\gamma_0^q D_\mu n_q^\mu + \frac{1}{2} n_q^\mu \nabla_\mu \gamma_0^q\right)$$

$$\tau_{qq'} \dot{n}^\mu_{q'} + n_q^\mu = -\kappa_{qq'}\nabla^\mu \alpha_{q'} + \frac{\tau_{qq'} n^\mu_{q'}}{2}\theta - \frac{\tau_{qq'}}{2\beta_{qq'}}\dot{\beta}_{qq'} n^\mu_{qq'} - \frac{\kappa_{qq'}}{\beta}\left(\gamma_0^{qq'}\nabla^\mu \Pi - \frac{\Pi}{2}\nabla^\mu \gamma_0^{qq'}\right) - \frac{\kappa_{qq'}}{\beta}\left(\gamma_1^{qq'}\nabla_\nu \pi^{\mu\nu} + \frac{\pi^{\mu\nu}}{2}\nabla_\nu \gamma_1^{qq'}\right)$$

- Based on v-USPhydro (at $\mu_B = 0$ 10 eqs for η/s & ζ/s)
  Noronha-Hostler et al, *Phys.Rev.C* 88 (2013) 4, 044916; *Phys.Rev.C* 90 (2014) 3, 034907
- BSQ (coupled matrix!) → +6 new coupled differential eqs and 6 new 1st-order diffusion transport coefficients
- 4D EOS(lattice QCD),10 new thermodynamic derivatives
  JNH, Paolo Parotto, Claudia Ratti, Jamie Stafford Phys.Rev.C 100 (2019) 6, 064910

See also Monnai *Nucl.Phys.A* 847 (2010) 283-314;
Fotakis et al, 2203.11549 [nucl-th]

Testing 2+1 BSQ hydro simulations

Almaalol, Carzon, Cruz Camacho, Dore, Mroczek, Plumberg, Spychalla, Sievert, JNH to appear soon

- Stability analysis for BSQ Israel Stewart: Lyapunov functional (Eckart Frame)Gavassino *Class.Quant.Grav.* 38 (2021) 21, 21LT02

Thermo: $\frac{1}{\varepsilon+p}\frac{1}{c_s^2} > 0\,;\, \frac{1}{\varepsilon+p}\frac{\partial\varepsilon}{\partial s}\bigg|_p \frac{\partial p}{\partial s}\bigg|_{\mu_B/T} > 0$

Transport Coefficients: $\beta_\Pi > 0; \beta_\pi > 0$

Thermo+Transport:

$$\frac{\kappa_n^{BB}}{2\lambda^2} - \frac{(\gamma_{n\Pi}^B)^2}{\beta_\Pi} - \frac{(\gamma_{n\pi}^B)^2}{\beta_\pi} > (\varepsilon+p)\left(T^2\frac{\partial s}{\partial\varepsilon}\bigg|_p \frac{\partial s}{\partial p}\bigg|_{\mu_B/T}\left(\frac{\partial(\mu_B/T)}{\partial s}\bigg|_p\right)^2 - \frac{1}{4}c_s^2\left(\frac{\partial(\mu_B/T)}{\partial p}\bigg|_s\right)^2\right)$$

+ many more

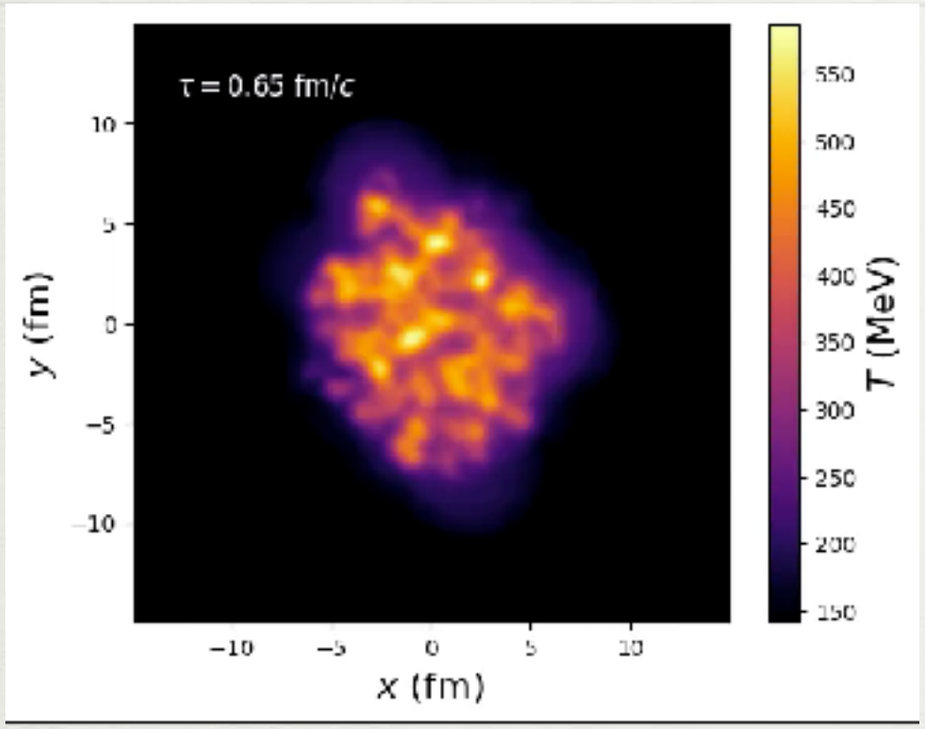
- Passes Gubser Check for ideal BSQ currents

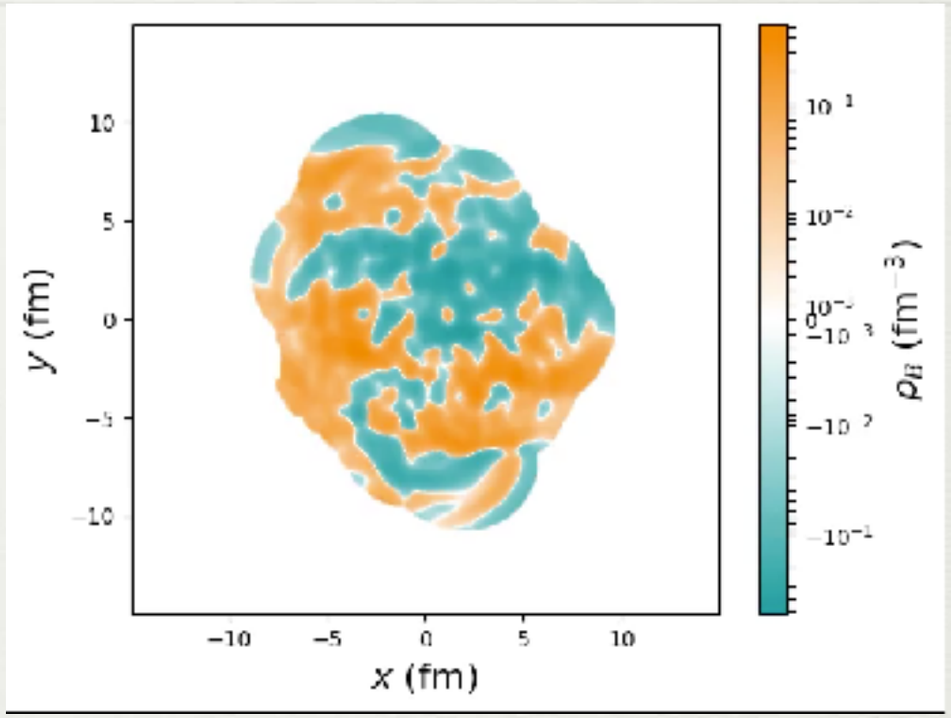
Denicol et al, *Phys.Rev.C* 98 (2018) 3, 034916

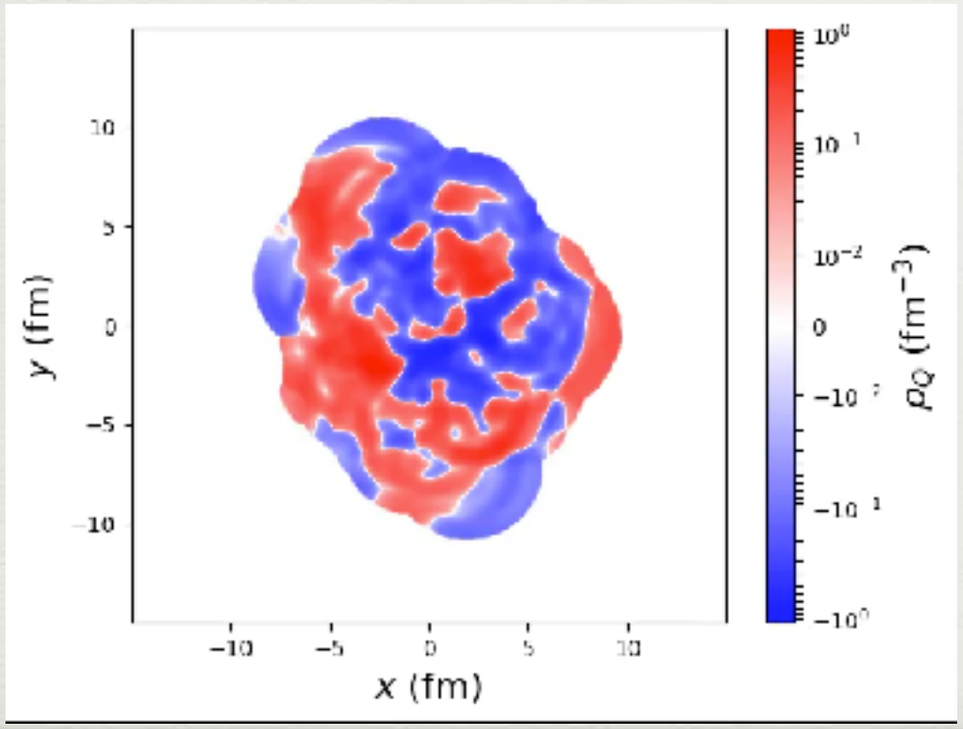
ICCING (Poster 827) Carzon et al, *Phys.Rev.C* 105 (2022) 3, 034908

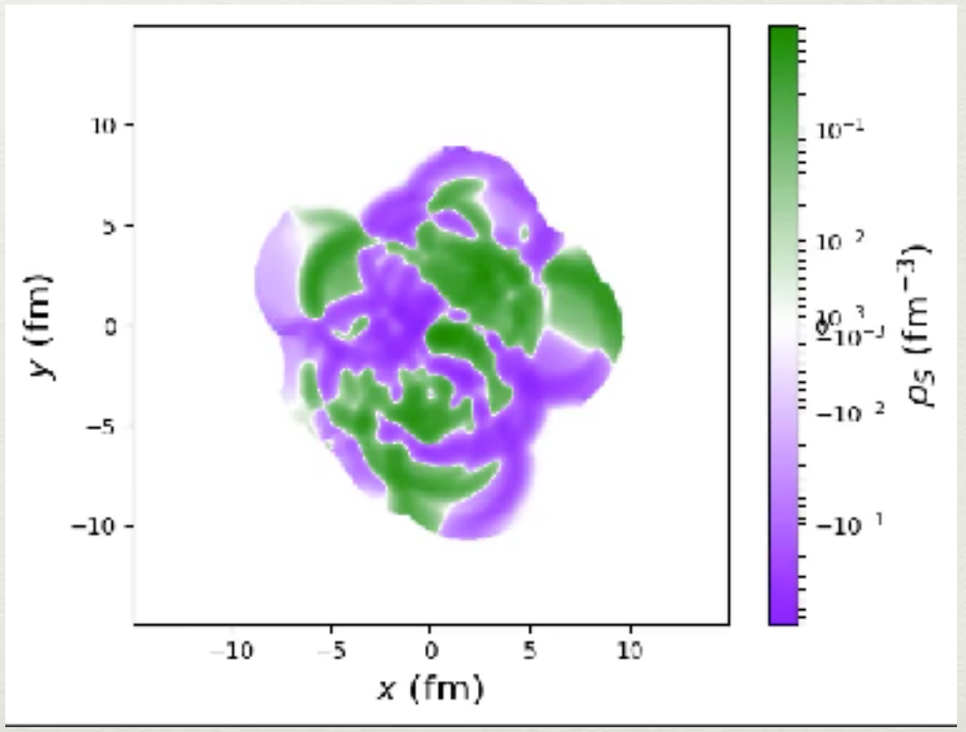
ICCING+v-USPhydro with BSQ

Almaalol, Carzon, Cruz Camacho, Dore, Mroczek, Plumberg, Spychalla, Sievert, JNH to appear soon



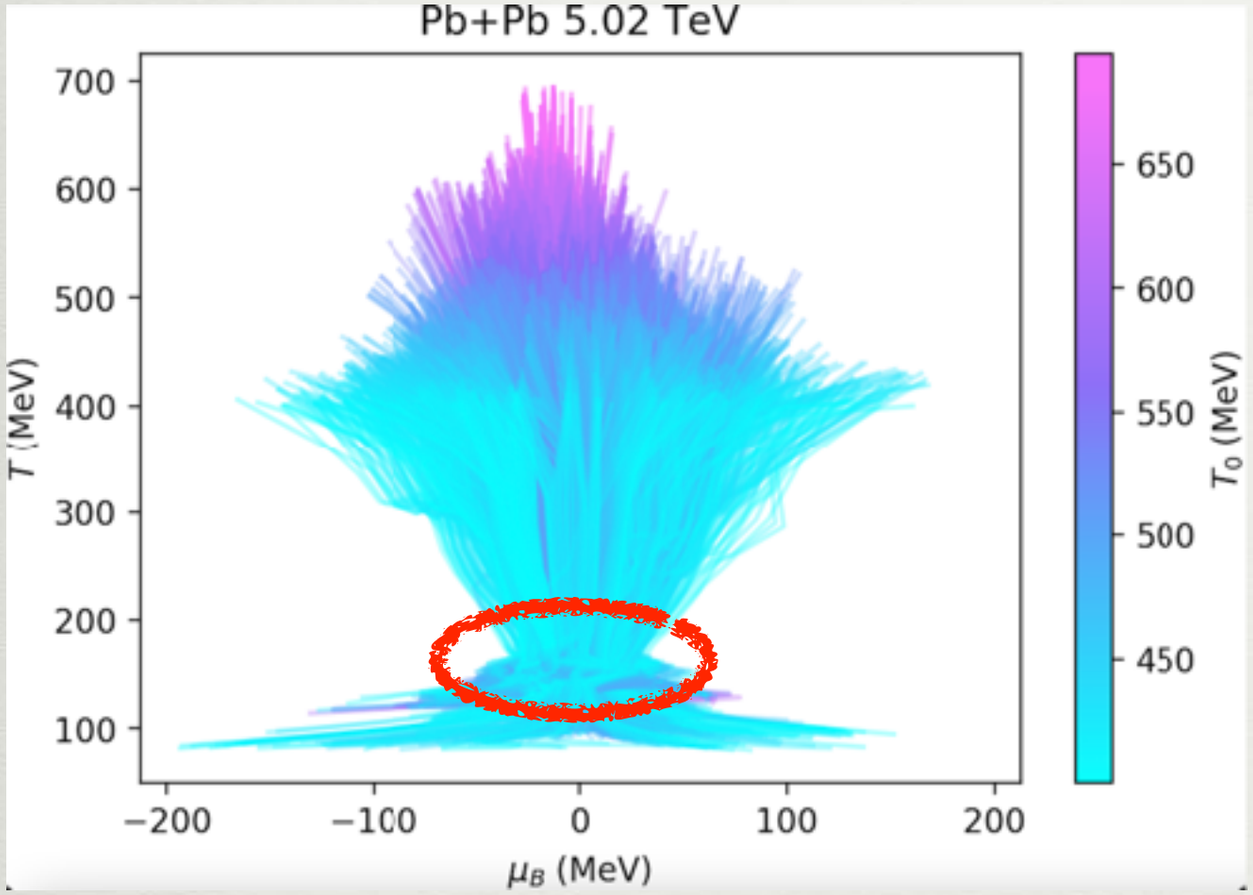






BSQ fluctuations remain at LHC

Fluctuations of BSQ preserved until freeze-out at LHC



net-B=0, local baryon number fluctuations large

Almaalol, Carzon, Cruz Camacho, Dore, Mroczek, Plumberg, Spychalla, Sievert, JNH to appear soon