Connections between heavy-ion collisions and neutron star mergers

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QCD Phase Diagram in Equilibrium
Lattice QCD and holography

New resummation scheme to reach larger $\mu_B$

Predicts CP at $\{T_c = 89, \mu_B = 724\}$ MeV

For $T \sim 150$ MeV reaches $\mu_B \sim 525$ MeV

Fitting to just Lattice QCD at $\mu_B = 0$ captures $\mu_B > 0$ EOS

Grefa, JNH et al, arXiv:2102.12042
Critical Point:
Peak in $\kappa_4/\kappa_2$ only clear signature

3D Ising (leading order terms only) Stephanov. PRL 107 (2011)


Mroczek Tues.
QCD phase diagram
HADES best for EOS at finite T

- Extracted average temp $T = 71 \pm 2.1$ MeV
- Density estimates highly model dependent but $\rho \sim 2\rho_0$
- Min. Measurable T from thermal fits: $\{T_{\text{chem}}, \mu_B^{\text{chem}}\} = \{47 \pm 5, 799 \pm 22\}$

Nucleus-Nucleus collisions = mini-neutron star mergers?
Neutron star mergers combine the fundamental forces:

<table>
<thead>
<tr>
<th>Electromagnetism</th>
<th>Gravity</th>
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<tbody>
<tr>
<td>Large B field, visual signals</td>
<td>Gravitational Waves</td>
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- **Strong Force**: Nuclei, nucleons, quarks
- **Weak Force**: Neutrinos, Strange decays
Caveats: Strangeness and Electric Charge

- Strangeness neutrality: $\langle \rho_S \rangle = 0$

- Short lifetime, strangeness conserved

- Charge: p vs. n in ions
  $0.4 \langle \rho_Q \rangle \sim \langle \rho_B \rangle$

- Long lifetime, weak decay: $s \rightarrow u + W^-$

- Strangeness most likely *not* in equilibrium

- Electrically neutral for stability $\langle \rho_Q \rangle = 0$
Heavy-ions: phase transition at larger $\mu_B$

Degrees of freedom by density

Layers of a neutron star

- $n_d \sim 1.5 \cdot 10^{-3} n_{sat}$
- $n_p \sim 0.2 n_{sat}$
- $n_l \sim 0.5 n_{sat}$
- $n_q \sim 2 n_{sat}$

Baryon densities

- Outer crust (nuclei)
- Neutron Drip
- Pasta
- Liquid nuclear matter
- Deconfined QCD Matter?

Parameters

- $n_i \sim 5 \cdot 10^{-7} n_{sat}$
- $E_{sym}$
- $p(n)$

Hyperons?
Constraints at low T and large $\rho_B$

LIGO/VIRGO: Inspiral from Gravitational Waves

NICER: Observations of isolated Neutron Star

Late-stage Inspiral, Merger, Post-merger, ...
Mass Twins: 1st-order PT in Neutron Stars

Current constrain not yet precise enough to confirm/deny

See also Alford, Han, Prakash

*Phys. Rev. D* 88 (2013) 8, 083013
Can we directly compare heavy-ions to neutron stars?
Previous attempts: Heavy-Ion “Data”

- Fermi-liquid/$\pi$, p, n transport assumed
- Quarks d.o.f not checked
- Extrapolate to $T=0$, neutron matter
- Compare to $v_1$ and $v_2$ only in mid-central collisions

$\sqrt{s_{NN}} = 1.5 - 4.7$ GeV

Danielewicz, Lacey, Lynch Science 298 (2002) 1592-1596

Used extensively in nuclear astrophysics to exclude EOS
20 year old heavy-ion “data” used to exclude $M > 2.5M_\odot$

- Stiff EOS are excluded because of this heavy-ion “data”
- Does a hadronic transport model/fermi-liquid actually work well compared to modern low-energy heavy-ion collisions?

HADES can shed-light on the heavyions to neutron stars?

- $\sqrt{s_{NN}} = 1 - 3$ GeV
- Modern flow measurements
- Studies of kurtosis (looking for 1st order phase transition)
- Multi-particle flow cumulants
- More centralities, $p_T$, $\eta$ dependence
HADES *almost* a mini NS-NS merger

Not clear if HADES can be best described by transport or hydrodynamics + transport. Neither fits all data.


Mohs et al, arXiv 2012.11454
QCD Phase Diagram in Out-of-Equilibrium
QCD Phase Diagram
Out-of-Equilibrium

Most et al, 
Phase transitions in hadronic transport

Such an approach allows for better systematic checks.
Far-from-equilibrium initial conditions in heavy-ion collisions can dramatically affect the extraction of the EOS.
3+1 BSQ hydro needed for low-beam energies


Relativistic viscous hydrodynamics+BSQ conserved charges + critical fluctuations+Cartesian Coordinates

Cooper Frye+charge conservation+ df corrections

Flow Observables of identified particles

Transport coefficients are affected by the dynamic universality class at the critical point. Second order transport coefficients?

Memory effects of the critical point? Fluctuations of conserved charges+ acceptance cuts

Initial Conditions BSQ Distribution +full Tmunu

Equation of State

Dynamics

Transport Coefficient $s$

$T_0 \sim 300 \text{ GeV}$

$\tau_0 \sim 1 \text{ fm}$

Expanding, cooling Quark Gluon Plasma

Hadron Resonance Gas

Comparisons to Data
Initial hydro results

3+1 B hydro

\[
\begin{align*}
    C_B = 0.0 & \quad & C_B = 1.2 & \quad & C_B = 0.4 & \quad & \text{STAR data}
\end{align*}
\]


0-5% Au+Au @ 19.6 GeV

1+1 BS hydro


See also, Du, Heinz Comput. Phys. Commun. 251 (2020) 107090
BSQ equations of motion

\[ \mu_B = 0 \]

- shear+bulk viscosity gives 11 coupled differential equations

- Addition of BSQ (coupled matrix!) leads to +6 new coupled differential equations and 6 new 1st-order diffusion transport coefficients

- BSQ diffusion requires 4D EOS+10 new thermodynamic derivatives

- Criticality + relativistic viscous hydro still open question!

2+1 BSQ relativistic viscous hydrodynamics + ICCING

Coming Soon!

Almaalol, Carzon, Cruz Camacho, Dore, Mroczek, Plumberg, Spychalla, Sievert, JNH

Stephanov, Nahrgang, Basar, Yin, Schaeffer, Yee, An, Martinez, Teaney, Akamatsu, Yan, Rajagopal, Weller, Ridgway, Du, Heinz, Song
Bulk viscosity in neutron star mergers, comparable to heavy-ions!

New approach to understand the microscopic degrees of freedom in neutron stars

Alford, Harris, Most, Noronha, JNH, Pretorius, Plumberg, Witek, Yunes
To appear soon
Summary

• STAR Fixed Target: NEED for low-energy heavy-ion collisions to constrain EOS at finite $T$

• What is important to measure? Spectra, fluctuations, flow, HBT, …

• Equation of State: lots of progress but hydrodynamics needs a wider range of $\mu_B$, $\mu_S$, $\mu_Q$

• BSQ hydrodynamics needed, critical fluctuations.

• Neutron star mergers now incorporating viscosity