The high density QCD EoS from heavy ion observables

Jan Steinheimer-Froschauer
many thanks to
A. Motornenko, M. Omana Kuttan, O. Savchuk, E. Most, M Bleicher, H. Stöcker
and many more.

Frankfurt Institute for Advanced Studies

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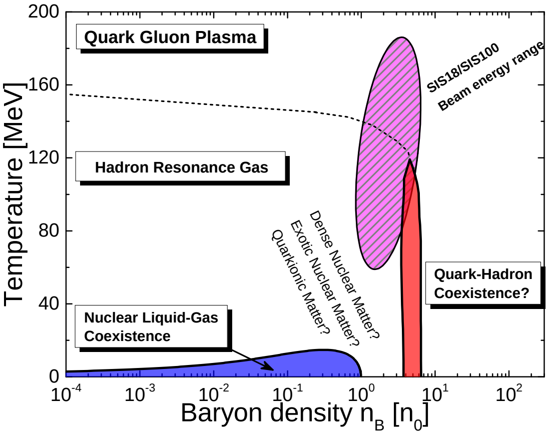
The interesting part of the phase diagram



- This is just a sketch.
- QCD based methods break down for $\mu_B/T \gtrapprox 3-4$.
- $T_{cep} \lessapprox 120$ MeV.
- Results at low density: Crossover is now confirmed.
- High density: room for speculations.

The Strategy

Relying on experimental observations?

We want to understand QCD matter, not neutron star matter or heavy ion collision matter. The latter are mere inputs for simulations.

1. Calculate/construct an EoS that can be used for finite temperature and density QCD matter. Check consistency with known properties at small μ_B/T and nuclear matter.

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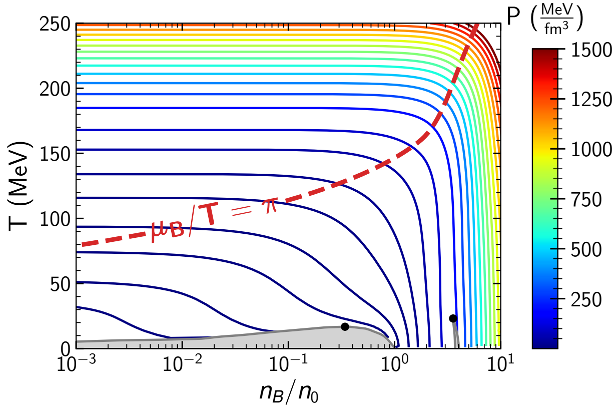
4. Cross check with astrophysical observations.
5. Reject unlikely EoS.

1. The baryonic problem



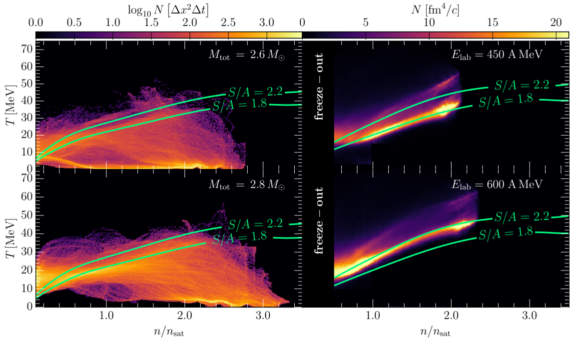
Why do the methods break down?

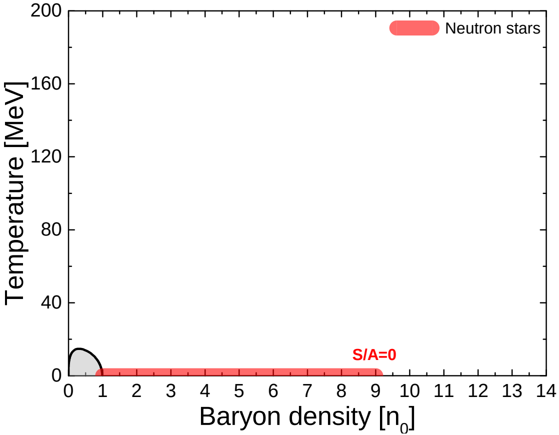
- Sudden change of isobaric lines at this point.
- From Boson (mesons/gluons) dominated matter to fermionic matter (nucleons/quarks).
- Calculations seem to fail for matter where (multi-) baryonic interactions become important.
- Positive: for the region of interest a density dependent EoS may be enough.

A. Motornenko, JS, V. Vovchenko, S. Schramm and H. Stoecker, Nucl. Phys. A 1005 (2021), 121836

Regions of access to the PD - BNSM

- Using BNSM we can also turn on the heat.
- During the post-merger $T < 40$ MeV is reached
- Observables?





E. R. Most, A. Motornenko, JS, V. Dexheimer, M. Hanauske, L. Rezzolla and H. Stoecker, [arXiv:2201.13150 [nucl-th]].

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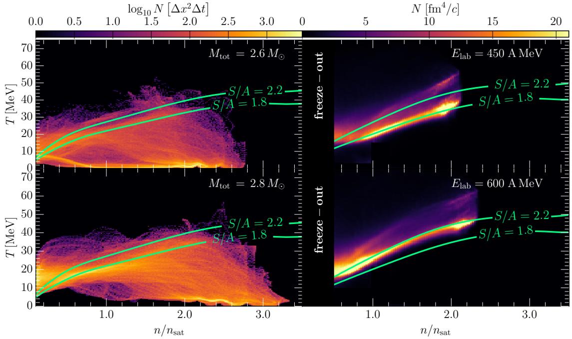

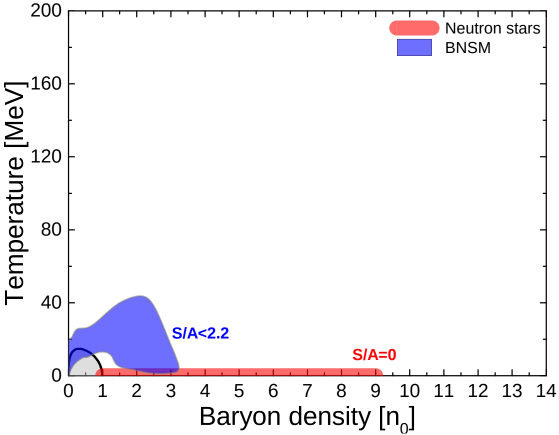

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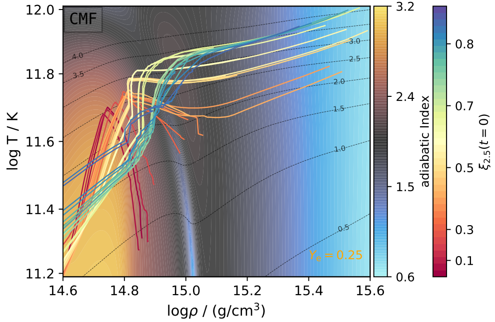
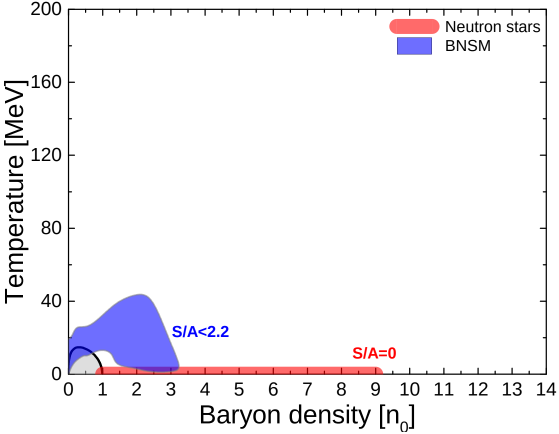
Regions of access to the PD - CCSN

- Core Collapse Supernovae (CCSN) can reach even higher S/A
- GR Hydro simulation with same EoS (CMF model):





P. Jakobus, B. Mueller, A. Heger, A. Motornenko, JS and H. Stoecker, [arXiv:2204.10397 [astro-ph.HE]].

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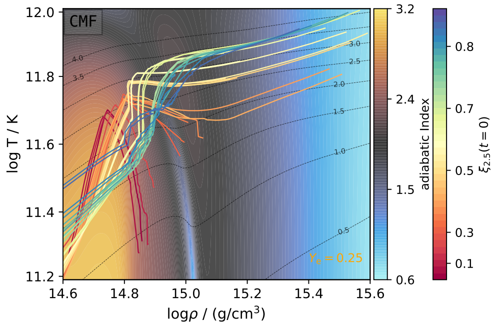
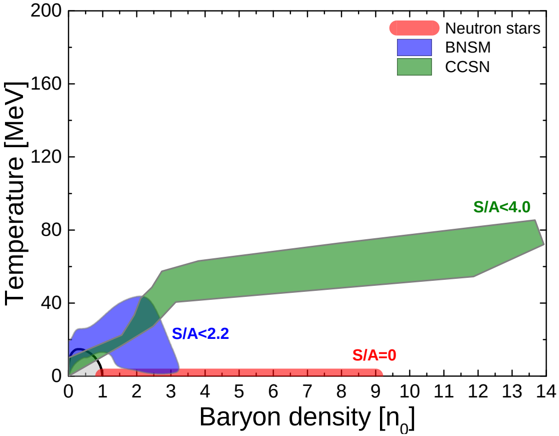
- GR Hydro simulation with same EoS (CMF model):
- Observables: Neutrinos, GW?





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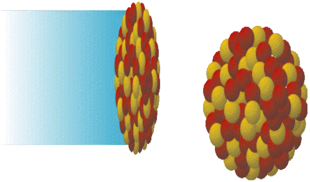
How to study the equation of state using heavy ion collisions

Much of we today think about heavy ion dynamics is motivated by the fluid dynamic picture of HIC:

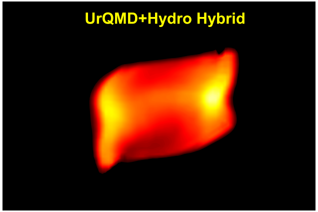
Pre-equilibrium phase

Equilibrated? phase

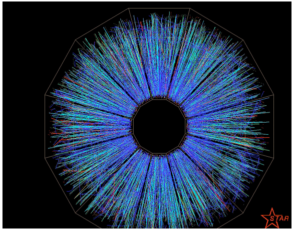
Final stage and particle freeze-out



Non-equilibrium initial state



Fluid dynamic evolution



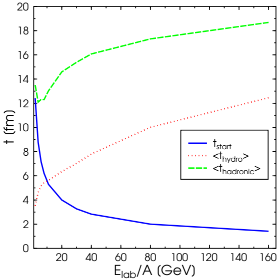
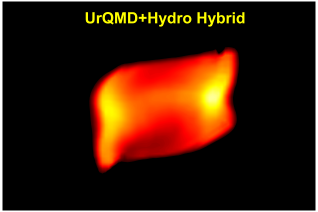
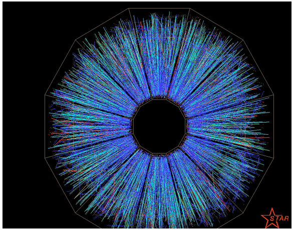
Freeze-out: chemical and thermal

H. Petersen, **JS**, G. Burau, M. Bleicher and H. Stöcker, Phys. Rev. C **78** (2008) 044901

How to study the equation of state using heavy ion collisions

Much of we today think about heavy ion dynamics is motivated by the fluid dynamic picture of HIC:

At low beam energies the initial compression is most relevant.

Pre-equilibrium phase	Equilibrated? phase	Final stage and particle freeze-out
		
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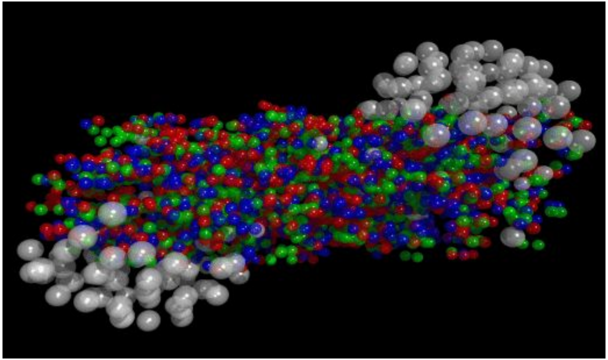
UrQMD for the description

UrQMD is a microscopic transport model

- In cascade mode: Particles follow a straight line until they scatter.
- EoS resembles a hadron resonance gas.



Dynamics in UrQMD

UrQMD is a microscopic transport model

- Only $2 \leftrightarrow 2$, $2 \leftrightarrow 1$, $2 \rightarrow N$ and $1 \rightarrow N$ interactions allowed.
- Resonance decays according to PDG values + guesstimates.
- Detailed balance. (Violated in string excitations, annihilations and some dacays)

The Skyrme EoS in UrQMD

To implement any density dependent EoS in UrQMD:
In UrQMD the real part of the interaction is implemented by a density dependent potential energy $V(n_B)$.
Once the potential energy is known, the change of momentum of each baryon is calculated as:

$$\dot{\mathbf{p}}_i = -\frac{\partial H}{\partial \mathbf{r}_i} = -\left(\frac{\partial V_i}{\partial n_i} \cdot \frac{\partial n_i}{\partial \mathbf{r}_i}\right) - \left(\sum_{j \neq i} \frac{\partial V_j}{\partial n_j} \cdot \frac{\partial n_j}{\partial \mathbf{r}_i}\right) , \tag{1}$$

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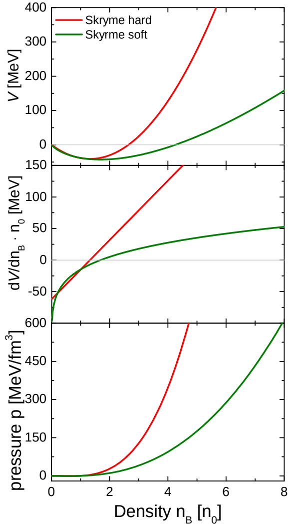
For the potential energy V often a Skyrme model was used that is based on a 2-term expansion in density:

$$U(n_B) = \alpha \cdot n_B + \beta \cdot n_B^\gamma \quad \text{with} \quad U(n_B) = \frac{\partial(n_B \cdot V(n_B))}{\partial n_B} \quad (2)$$

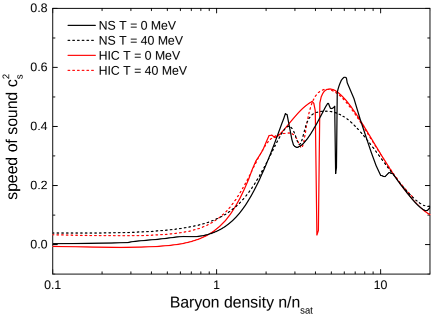
Problem: Once saturation density and binding energy is fixed, only 1 d.o.f. left and EoS likely becomes unphysical. No phase transition possible.

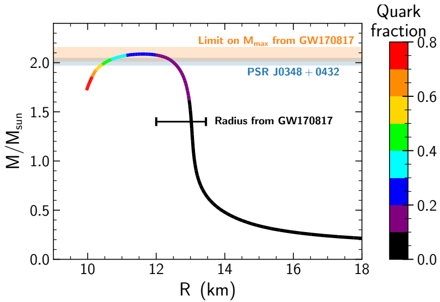


A different effective model: the CMF

Application for cold compact stars

- Compressibility of the CMF EoS is $\kappa_0 = 267$ MeV and the symmetry energy is $S_0 = 31.9$ MeV.
- Speed of sound for neutron star matter.
- Mass radius diagram consistent with astrophysical constraints.





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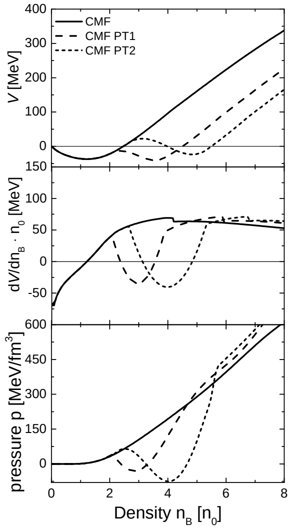
In CMF we can simply use the effective field energy per baryon E_{field}/A calculated from the CMF model:

$$V_{CMF} = E_{\text{field}}/A = E_{\text{CMF}}/A - E_{\text{FFG}}/A\,, \quad (4)$$

A phase transition can be simply included by adding another minimum in the potential energy: leading to (meta-)stable solutions at high density.



J. Steinheimer, A. Motornenko, A. Sorensen, Y. Nara, V. Koch and M. Bleicher, [arXiv:2208.12091 [nucl-th]].

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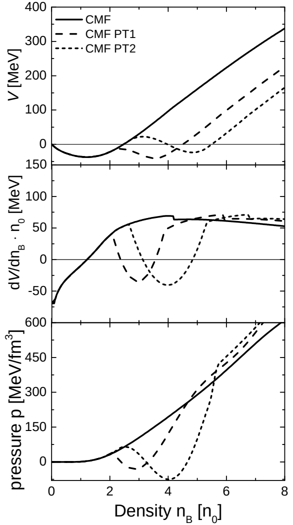
Disadvantage: Only density dependence + no change in d.o.f.
Advantage: Consistent description throughout, i.e. no change of model or d.o.f. required.
⟶ Focus on the effects of the equation of state and dynamic phase separation.



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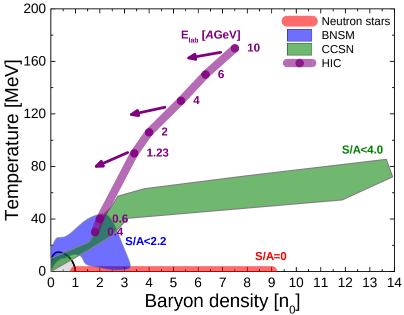
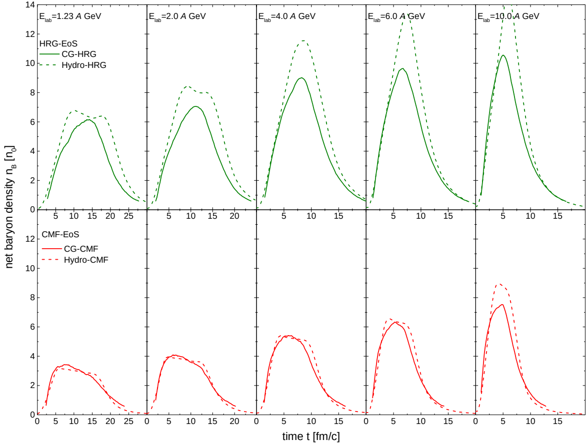
1. HIC UrQMD vs. hydro, regions of access

- Including the CMF EoS in UrQMD vs. a hadron resonance gas baseline.
- Bulk evolution consistent with 3+1D hydro + CMF
- Initial compression from CMF model in UrQMD



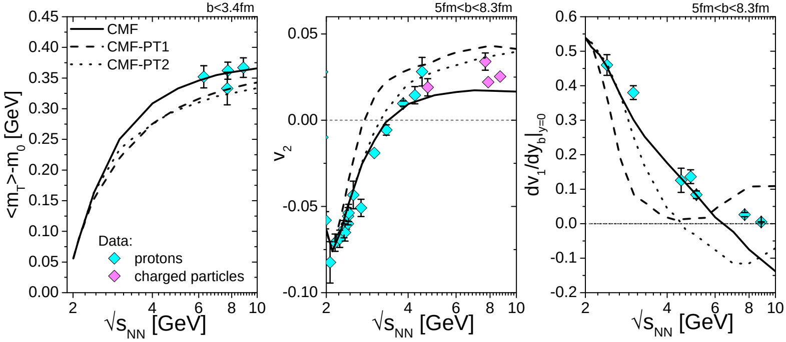


M. Omana Kuttan, A. Motornenko, JS, H. Stoecker, Y. Nara and M. Bleicher, Eur. Phys. J. C 82 (2022) no.5, 427

2. Results on flow

- The CMF EoS gives good results on all flow coefficients.
- Significant effects of a phase transition on all flow observables.
- Minimum in the slope of the directed flow confirmed.
- Sensitivity only up to $\approx 4n_0$.

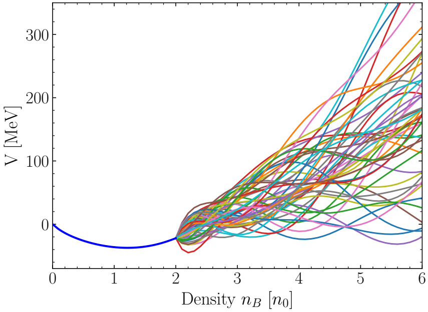
- $m_T = p_T^2 + m^2$
- $v_1 = p_x/p_T$
- $v_2 = (p_x^2 - p_y^2)/p_T^2$



JS, A. Motornenko, A. Sorensen, Y. Nara, V. Koch and M. Bleicher, [arXiv:2208.12091 [nucl-th]].

2. Statistical analysis of available flow data

- Using Bayesian inference methods we can try to constrain the EoS from flow data
- Use UrQMD as described but parameterize $V(n_B)$ with a seventh order polynomial.



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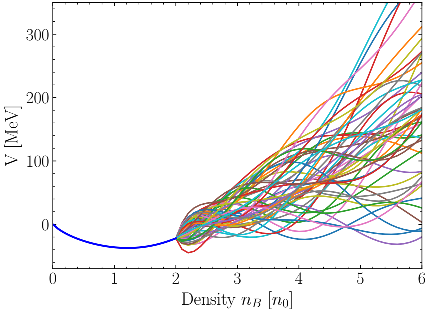
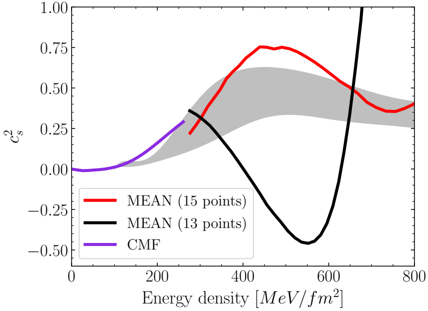


M. Omana Kuttan, JS. K. Zhou and H. Stoecker, in preparation

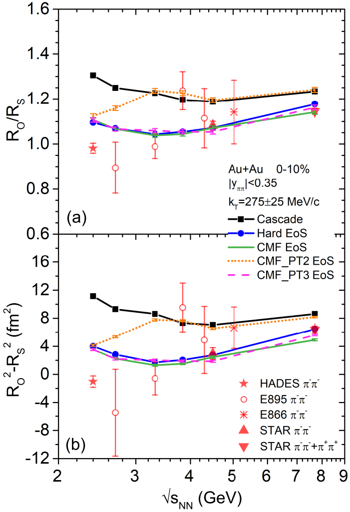
- Results depend strongly on the data used.
- If all data on the mean m_T and v_2 are used, constraints are similar to those from astrophysics (NS and BNSM).



3. HBT

- Hanbury-Brown-Twiss (HBT) correlations for charged pions are a tool to measure the freezeout volume and time.
- Pions that are emitted close in coordinate space are correlated in momentum space.
- Simulation with a PT show a clear maximum.
- 'Old' data seem inconclusive, newest STAR data have much smaller error and favor the no-PT scenario.
- Sensitivity only up to $\approx 4n_0$.

P. Li, T. Reichert, A. Kittiratpattana, JS, M. Bleicher, Q. Li



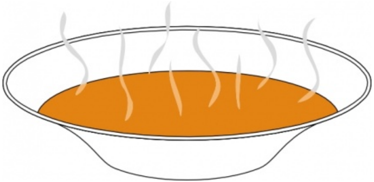
4. Dileptons

Electromagnetic probes offer a chance to probe the whole time evolution of the fireball.

In particular di-lepton pairs created by the decay of hadrons or quark annihilation.

- $\rho \to e^+ + e^-$
- $q + \overline{q} \to e^+ + e^-$

Process sensitive to the medium in which it takes place (T and ρ_B).



F. Seck, T. Galatyuk, A. Mukherjee, R. Rapp, **JS** and J. Stroth, [arXiv:2010.04614 [nucl-th]].

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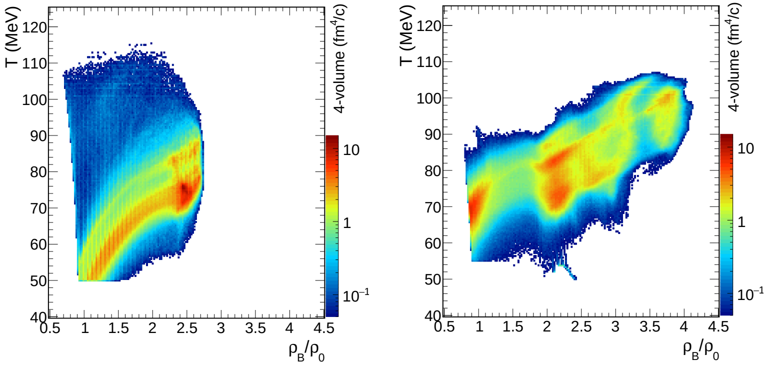
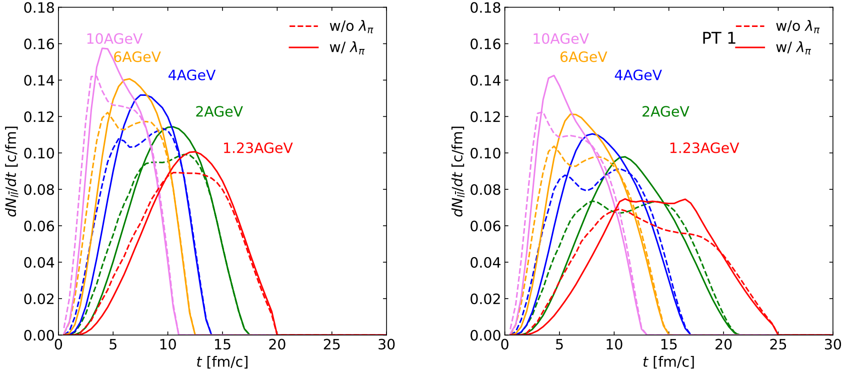


Distinct differences CMF with or without a phase transition

F. Seck, T. Galatyuk, A. Mukherjee, R. Rapp, **JS** and J. Stroth, [arXiv:2010.04614 [nucl-th]].

4. Dileptons

- Dilepton emission is sensitive to the time-integrated bulk evolution properties.
- Results from the UrQMD+CMF(+PT) transport model.
- Effect due to extended lifetime.



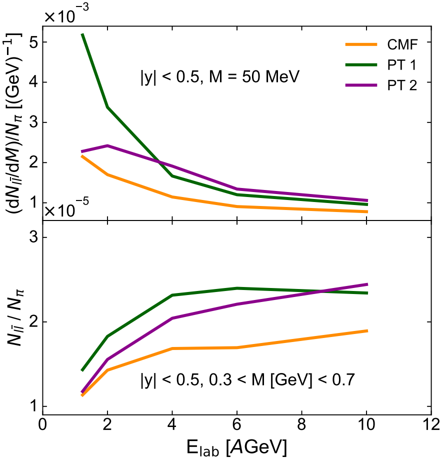
O. Savchuk, A Motornenko, JS, V. Vovchenko, M. Bleicher, M. Gorenstein, T. Galatyuk, [arXiv:2209.05267 [nucl-th]].

4. Dileptons

- Hydro simulations have suggested a strong increase (of factor 2) of the dilepton yield for a phase transition:
F. Seck, T. Galatyuk, A. Mukherjee, R. Rapp, JS and J. Stroth, [arXiv:2010.04614 [nucl-th]].

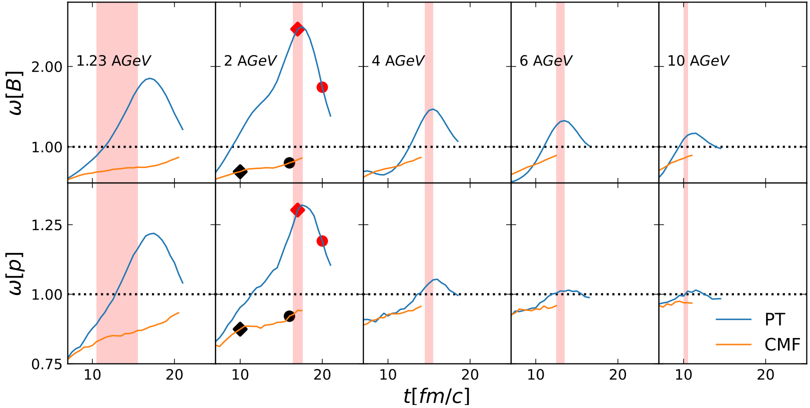
- A significant increase of the low mass dilepton yield is observed when a phase transition is included in the UrQMD-CMF model.

O. Savchuk, A Motornenko, JS, V. Vovchenko, M. Bleicher, M. Gorenstein, T. Galatyuk, [arXiv:2209.05267 [nucl-th]].



5. Fluctuations

- As we employ a QMD approach local clumping in the unstable phase can occur.
- This leads to enhanced fluctuations of the baryon number in coordinate space, already observed in the scaled variance.



O. Savchuk, et.al., in preparation

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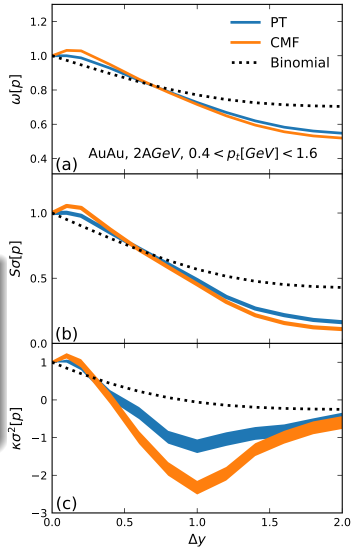
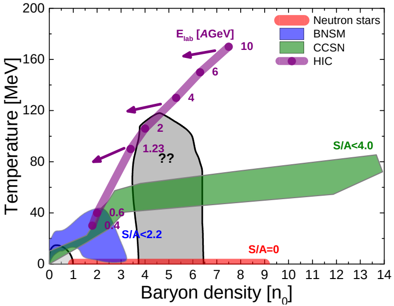
- While in coordinate space the fluctuations/correlations are enhanced due to the phase transition.
- In momentum space no enhancement is observed.
- The crossover scenario even shows an increased scaled variance. This is due to the larger radial flow pushing into the spectators leading to larger volume fluctuations.

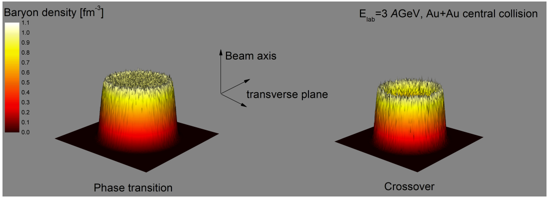


O. Savchuk, et.al., in preparation

Summary and conclusions

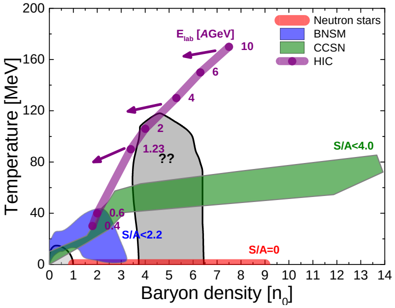
- Can use HIC and BNSM to scan the high density QCD PD.
- Especially for HIC in the FAIR-regime new ideas/methods for old and new models are necessary.
- This work: Phase transitions in transport shown to influence observables.
- Best results obtained for model w/o phase transition, consistent with astrophysical observations (sensitivity only up to $\approx 4n_0$).
- Only consistent models can be used for statistical analyses of large datasets available now and in the future.
- Still room for development of critical phenomena, relativistic treatment of transport models...

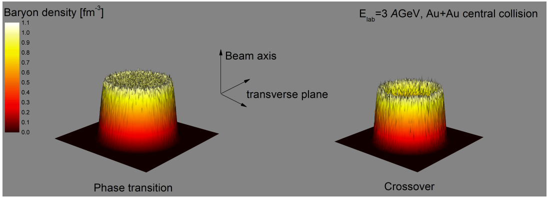




Summary and conclusions

- Can use HIC and BNSM to scan the high density QCD PD.
- Especially for HIC in the FAIR-regime new ideas/methods for old and new models are necessary.
- This work: Phase transitions in transport shown to influence observables.
- Best results obtained for model w/o phase transition, consistent with astrophysical observations (sensitivity only up to $\approx 4n_0$).
- Only consistent models can be used for statistical analyses of large datasets available now and in the future.
- Still room for development of critical phenomena, relativistic treatment of transport models...





- The minimum of v_1 coincides with the maximum of the dilepton emission.
- The effect on HBT and maximum of the fluctuation enhancement seems to occur at even lower beam energies.
- Effects don't occur at the same beam energy: **Need consistent modeling!!**

4. Light nuclei production

- The double ratio $t \cdot p/(d^2)$ is thought to be sensitive to spatial baryon fluctuations at freeze-out.
  K. J. Sun, L. W. Chen, C. M. Ko, J. Pu and Z. Xu, Phys. Lett. B **781** (2018), 499-504
- Can be studies by coalescence in UrQMD.
  P. Hillmann, K. Käfer, JS, V. Vovchenko and M. Bleicher,' J. Phys. G **49**, no.5, 055107 (2022)
- We see a very small enhancement in the scenario with a phase transition.
- Important to use realistic EoS with proper hadronic/nuclear matter.