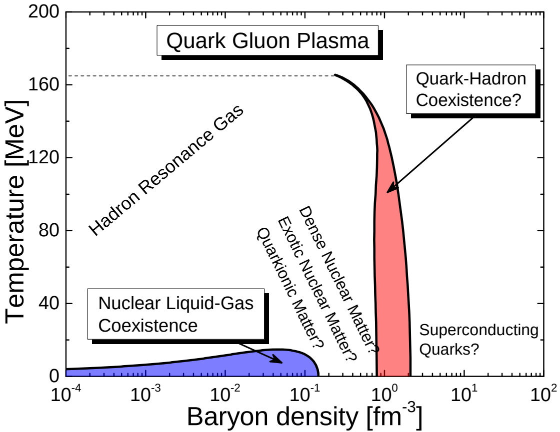
The high density QCD EoS from astrophysical and heavy ion observables

Jan Steinheimer-Froschauer

Frankfurt Institute for Advanced Studies

16.06.2022

The interesting part of the phase diagram



- This is just a sketch.
- QCD based methods break down for $\mu_B/T \gtrsim 3-4$.
- $T_{cep} \lesssim 120$ MeV.
- Results at low density: See other talks.
- High density: room for speculations.

The Strategy

- Calculate/construct an EoS that can be used for finite temperature and density QCD matter.
- We want to understand QCD matter, not neutron star matter or heavy ion collision matter. The latter are mere inputs for simulations.

The Strategy

- Calculate/construct an EoS that can be used for finite temperature and density QCD matter.
- We want to understand QCD matter, not neutron star matter or heavy ion collision matter. The latter are mere inputs for simulations.
- Check consistency with known properties at small μ_B/T and nuclear matter.

The Strategy

- Calculate/construct an EoS that can be used for finite temperature and density QCD matter.
- We want to understand QCD matter, not neutron star matter or heavy ion collision matter. The latter are mere inputs for simulations.
- Check consistency with known properties at small μ_B/T and nuclear matter.
- Use this one EoS to calculate astro and heavy ion observables.

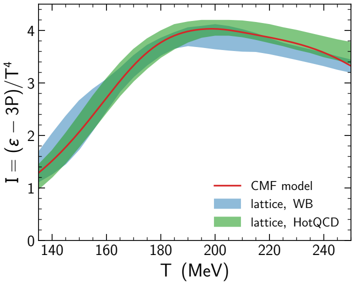
The Strategy

- Calculate/construct an EoS that can be used for finite temperature and density QCD matter.
- We want to understand QCD matter, not neutron star matter or heavy ion collision matter. The latter are mere inputs for simulations.
- Check consistency with known properties at small μ_B/T and nuclear matter.
- Use this one EoS to calculate astro and heavy ion observables.
- Reject unlikely EoS.

The Chiral mean field model (CMF)

- The CMF model is an effective description for QCD matter at finite T and n_B.
- It is based on a chiral mean field Lagrangian and includes hadronic and quark degrees of freedom.
- In the hadronic world chiral symmetry is realized through a parity doublet model including baryons in the lowest octet and decuplet.
- Deconfinement is introduced via a PNJL approach.

- To avoid simultaneous existence of confinded and deconfined quarks an excluded volume mechanism is used.
- Model describes lattice QCD results at the same time as nuclear matter properties.

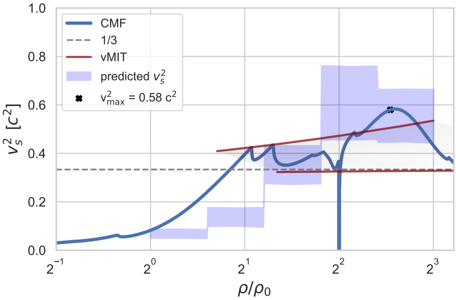


A. Motornenko, JS, V. Vovchenko, S. Schramm and H. Stoecker, Phys. Rev. C **101** (2020) no.3, 034904

The Chiral mean field model (CMF)

- The CMF model is an effective description for QCD matter at finite T and n_B.
- It is based on a chiral mean field Lagrangian and includes hadronic and quark degrees of freedom.
- In the hadronic world chiral symmetry is realized through a parity doublet model including baryons in the lowest octet and decuplet.
- Deconfinement is introduced via a PNJL approach.

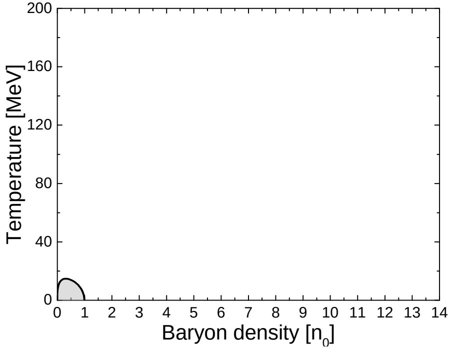
- To avoid simultaneous existence of confinded and deconfined quarks an excluded volume mechanism is used.
- Model describes lattice QCD results at the same time as nuclear matter properties.
- Compressibility of the CMF EoS is $\kappa_0 = 267$ MeV and the symmetry energy is $S_0 = 31.9$ MeV.
- Speed of sound for neutron star matter.



P. Jakobus, A. Motornenko, R. O. Gomes, JS and H. Stoecker, Eur. Phys. J. C **81** (2021) no.1, 41.

Regions of access to the PD - NS

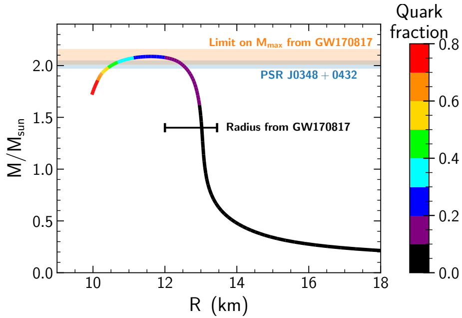
- Starting from the phase diagram in Temperature and density.

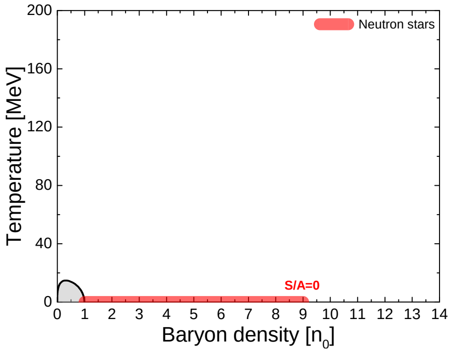


Disclaimer: For now we will ignore any isospin dependence, or assume it can be constraint by measurement.

Regions of access to the PD - NS

- Starting from the phase diagram in Temperature and density.
- For $T = 0$ we can use the mass-radius relation of observed stars.

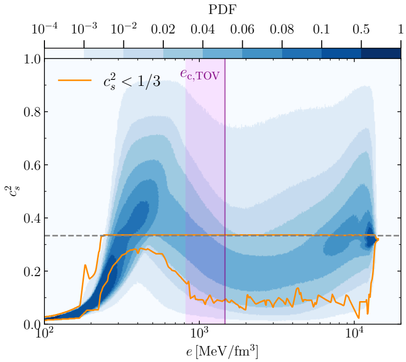


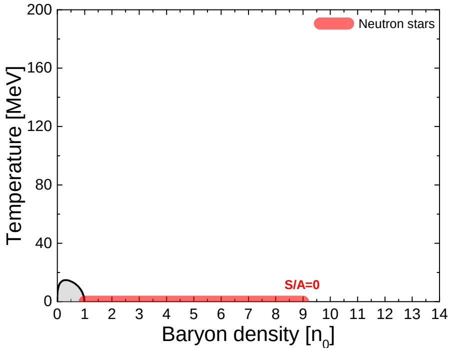


A. Motornenko, JS, V. Vovchenko, S. Schramm and H. Stoecker, Phys. Rev. C **101** (2020) no.3, 034904

Regions of access to the PD - NS

- Starting from the phase diagram in Temperature and density.
- For $T = 0$ we can use the mass-radius relation of observed stars.
- Constraints from neutron star mergers (pre-merger).

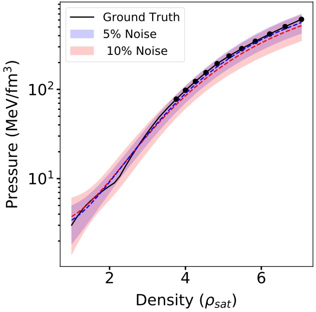


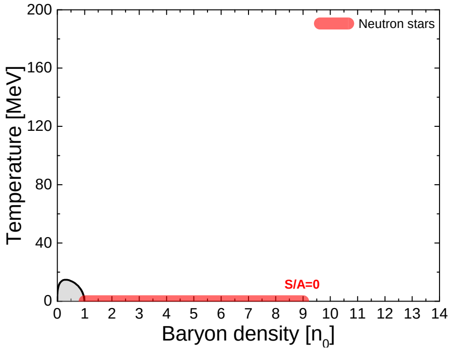


S. Altiparmak, C. Ecker and L. Rezzolla, [arXiv:2203.14974 [astro-ph.HE]].

Regions of access to the PD - NS

- Starting from the phase diagram in Temperature and density.
- For $T = 0$ we can use the mass-radius relation of observed stars.
- Constraints from neutron star mergers (pre-merger).
- New ML methods: See talk by Shriya Soma (Wed 9:00)

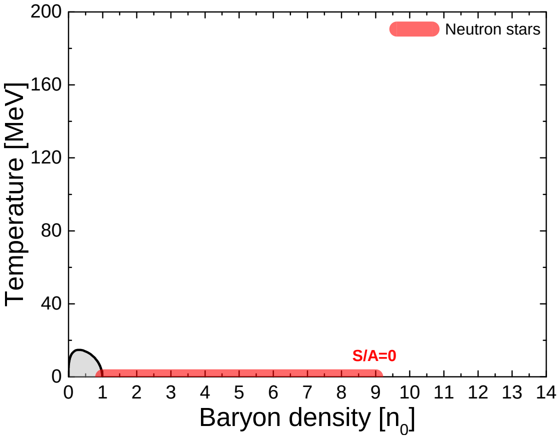




S. Soma, L. Wang, S. Shi, H. Stöcker and K. Zhou, [arXiv:2201.01756 [hep-ph]].

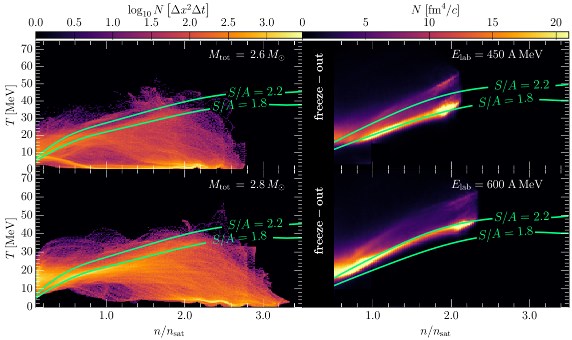
Regions of access to the PD - BNSM - See talk by A. Motornenko (Wed.)

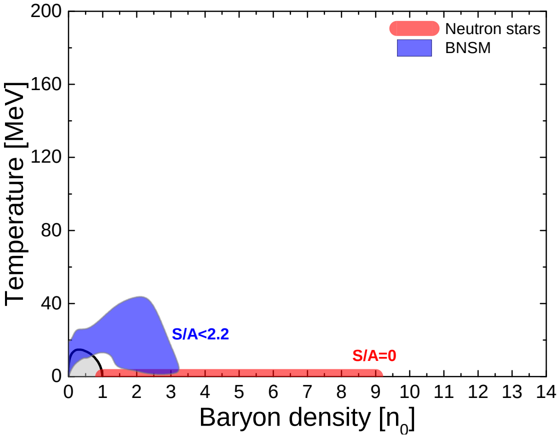
- Using BNSM we can also tun on the heat.



Regions of access to the PD - BNSM - See talk by A. Motornenko (Wed.)

- Using BNSM we can also tun on the heat.
- During the post-merger $T < 40$ MeV is reached
- Again, the same CMF EoS is used. Observables?

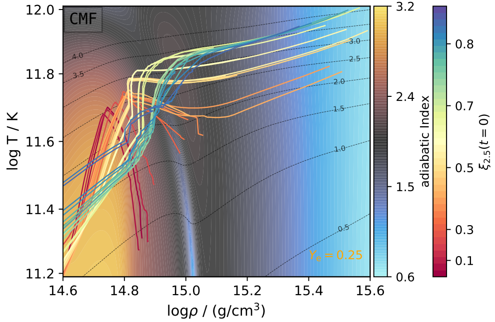


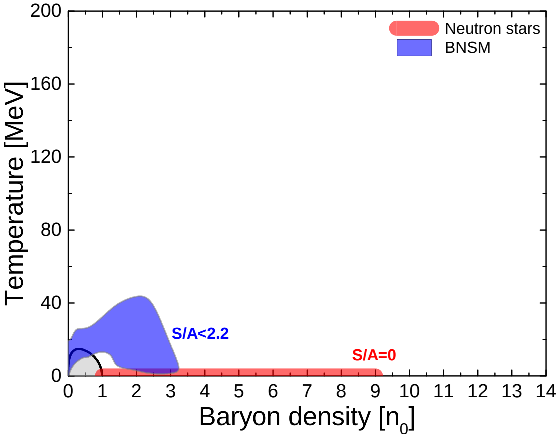


E. R. Most, A. Motornenko, JS, V. Dexheimer, M. Hanauske, L. Rezzolla and H. Stoecker, [arXiv:2201.13150 [nucl-th]].

Regions of access to the PD - CCSN

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

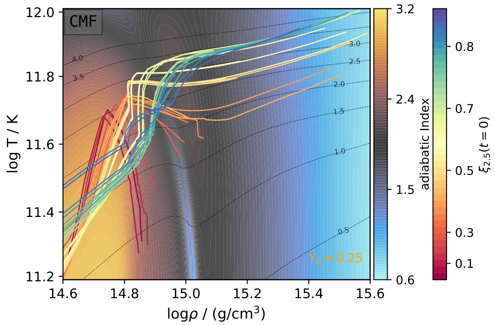


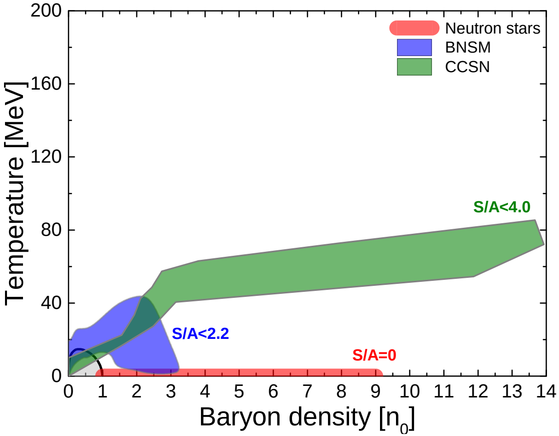


P. Jakobus, B. Mueller, A. Heger, A. Motornenko, JS and H. Stoecker, [arXiv:2204.10397 [astro-ph.HE]].

Regions of access to the PD - CCSN

- Core Collapse Supernovae (CCSN) can reach even higher S/A
- GR Hydro simulation with CMF model:
- Observables: Neutrinos, GW?



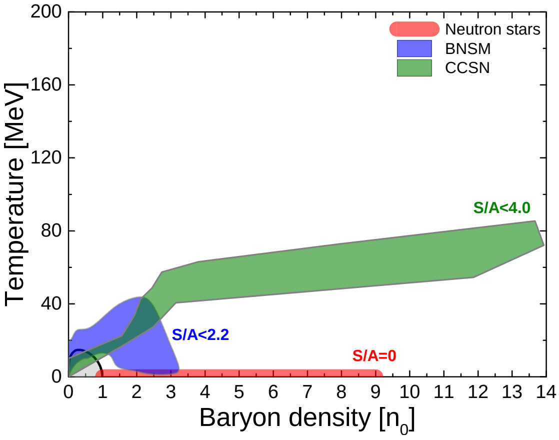


P. Jakobus, B. Mueller, A. Heger, A. Motornenko, JS and H. Stoecker, [arXiv:2204.10397 [astro-ph.HE]].

Regions of access to the PD - HIC

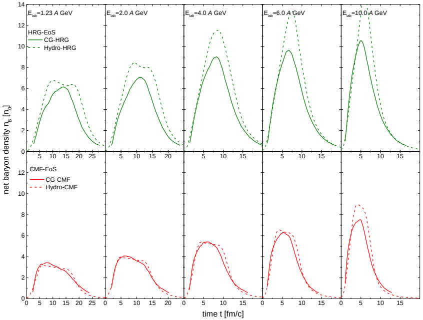
- A method was devised to implement any density dependent EoS in UrQMD.
- Bulk evolution consistent with 3+1D hydro + CMF

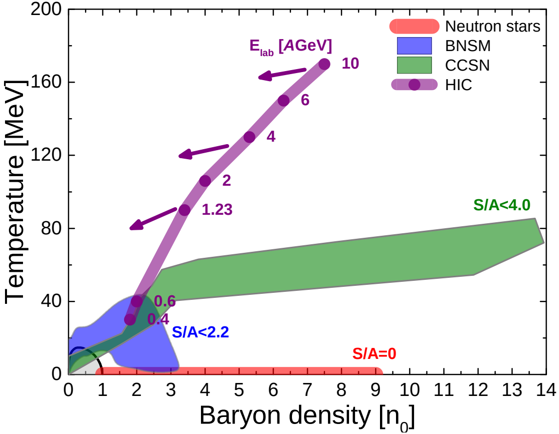
M. Omana Kuttan, A. Motornenko, JS, H. Stoecker, Y. Nara and M. Bleicher, Eur. Phys. J. C **82** (2022) no.5, 427



Regions of access to the PD - HIC

- A method was devised to implement any density dependent EoS in UrQMD.
- Bulk evolution consistent with 3+1D hydro + CMF
- Initial compression from CMF model in UrQMD



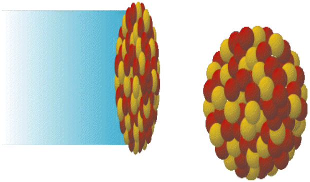


M. Omana Kuttan, A. Motornenko, JS, H. Stoecker, Y. Nara and M. Bleicher, Eur. Phys. J. C **82** (2022) no.5, 427

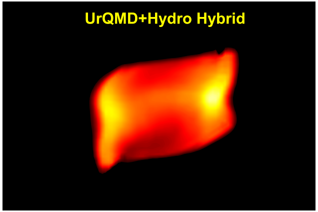
How to study the equation of state using heavy ion collisions

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

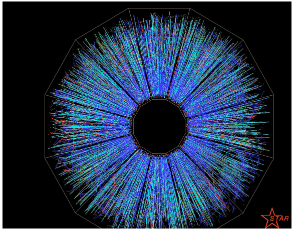
Pre-equilibrium phase | Equilibrated? phase | Final stage and particle freeze-out



Non-equilibrium initial state



Fluid dynamic evolution



Freeze-out: chemical and thermal

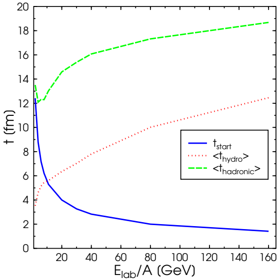
H. Petersen, **JS**, G. Burau, M. Bleicher and H. Stöcker, Phys. Rev. C **78** (2008) 044901

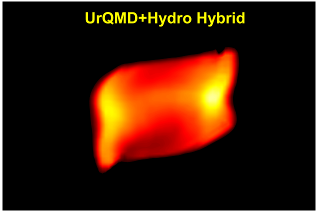
How to study the equation of state using heavy ion collisions

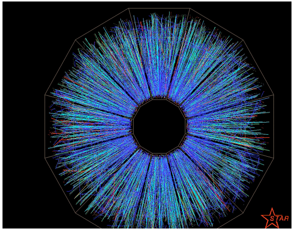
Much of we today think about heavy ion dynamics is motivated by the fluid dynamic picture of HIC:

At low beam energies the initial compression is most relevant.

Pre-equilibrium phase	Equilibrated? phase	Final stage and particle freeze-out







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

Any EoS in UrQMD

A method was devised to implement any density dependent EoS in UrQMD:
In UrQMD the real part of the interaction is implemented by a density dependent potential $U(n_B)$.
Once the mean field potential is known, the change of momentum of each baryon is calculated as:

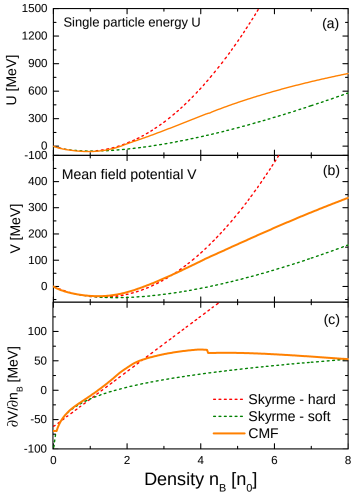
$$\dot{\mathbf{p}}_i = -\frac{\partial H}{\partial \mathbf{r}_i} = -\frac{\partial V(n_B)}{\partial n_B} \cdot \frac{\partial n_B(\mathbf{r}_i)}{\partial \mathbf{r}_i} \,. \qquad (1)$$

In the Skyrme approach the density dependence is given by a simple form:

$$U_{\text{Skyrme}}(n_B) = \alpha(n_B/n_0) + \beta(n_B/n_0)^{\gamma} \,. \qquad (2)$$

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

$$V_{CMF} = E_{\text{field}}/A = E_{\text{CMF}}/A - E_{\text{FFG}}/A \,, \qquad (3)$$



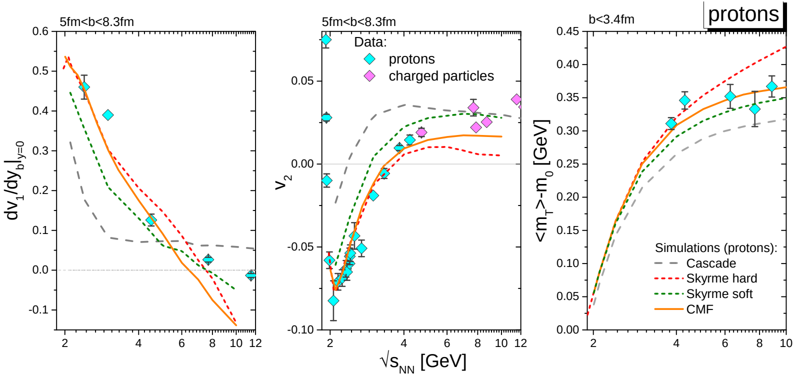
M. Omana Kuttan, A. Motornenko, JS, H. Stoecker, Y. Nara and M. Bleicher, Eur. Phys. J. C **82** (2022) no.5, 427

Results on flow

- As we have seen before, the bulk evolution works properly

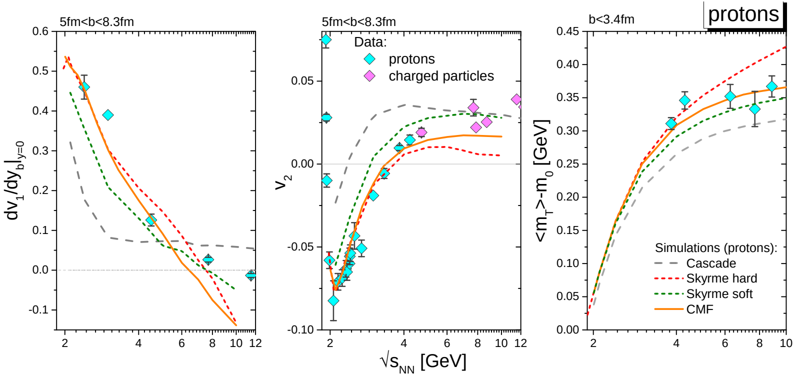
Results on flow

- As we have seen before, the bulk evolution works properly
- Flow is much more sensitive to the details of the equation of state.



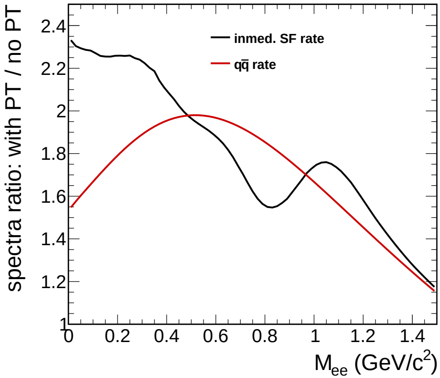
Results on flow

- As we have seen before, the bulk evolution works properly
- Flow is much more sensitive to the details of the equation of state.
- The CMF EoS gives good results on all flow coefficients without having to deal with uncertainties like particlization and initial state or transport coefficients.



Dileptons comparison with hydro

Hydro simulations have suggested a strong increase of the dilepton yield for a phase transition:

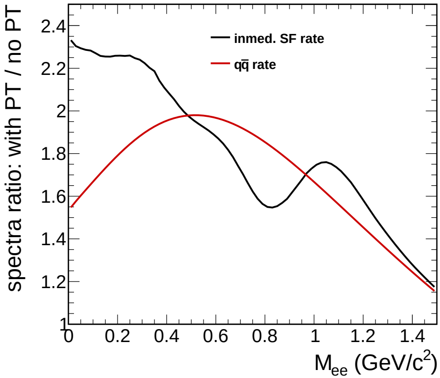


Different dilepton rates give both an increase of factor 2.

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

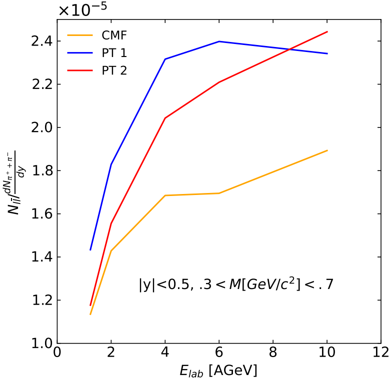
Dileptons comparison with hydro

Hydro simulations have suggested a strong increase of the dilepton yield for a phase transition:



Different dilepton rates give both an increase of factor 2.
F. Seck, T. Galatyuk, A. Mukherjee, R. Rapp, JS and J. Stroth, [arXiv:2010.04614 [nucl-th]].

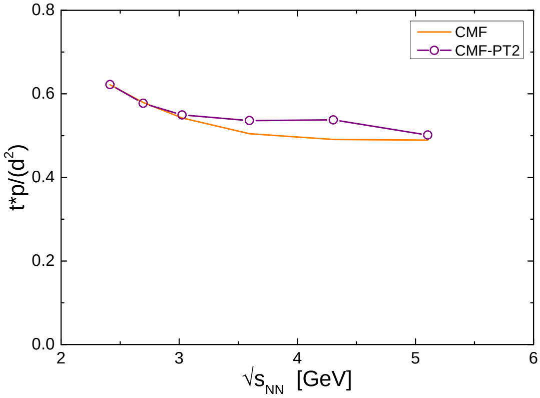
Similar results can be obtained from the UrQMD+CMF(+PT) transport model:



A significant increase of the low mass dilepton yield is observed when a phase transition is included in the UrQMD-CMF model.
Oleh Savchuk, et.al., in preparation

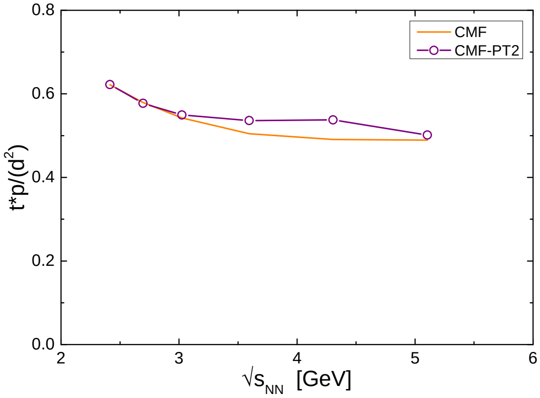
Light nuclei production

- The double ratio $t \cdot p/(d^2)$ is thought to be sensitive to spatial baryon fluctuations. (see talk by Kai Jia Sun on Tuesday)
  K. J. Sun, L. W. Chen, C. M. Ko, J. Pu and Z. Xu, Phys. Lett. B **781** (2018), 499-504



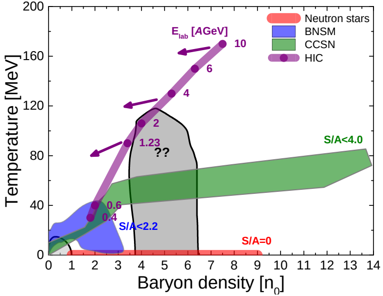
Light nuclei production

- The double ratio $t \cdot p/(d^2)$ is thought to be sensitive to spatial baryon fluctuations. (see talk by Kai Jia Sun on Tuesday)
  K. J. Sun, L. W. Chen, C. M. Ko, J. Pu and Z. Xu, Phys. Lett. B **781** (2018), 499-504
- We see a very small enhancement in the scenario with a phase transition.
- Important to use realistic EoS with proper hadronic/nuclear matter.
- For details on the coalescence method employed see talk by Tom Reichert on Tuesday.



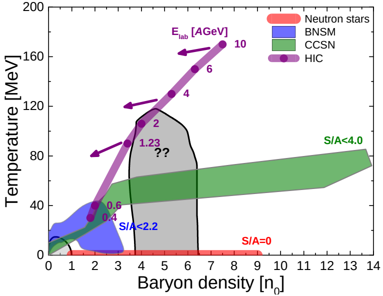
Summary and conclusions

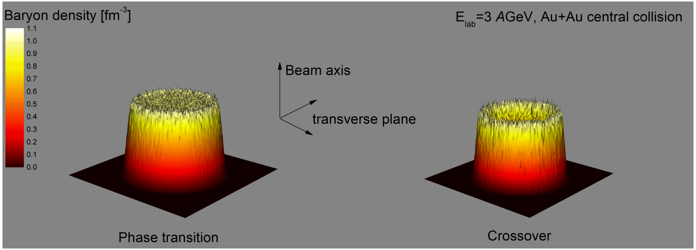
- We can now use NS, BNSM, CCSN and HIC to scan the high dnesity QCD phase diagram.
- Important treasure: The EoS that binds them all!



Summary and conclusions

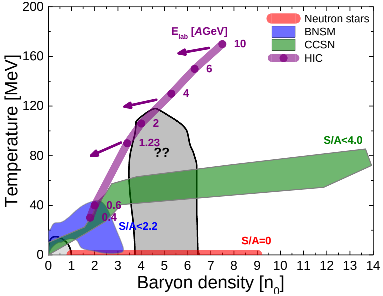
- We can now use NS, BNSM, CCSN and HIC to scan the high dnesity QCD phase diagram.
- Important treasure: The EoS that binds them all!
- Especially for HIC new ideas/methods for old and new models are necessary.
- E.g.: Phase transitions in transport.

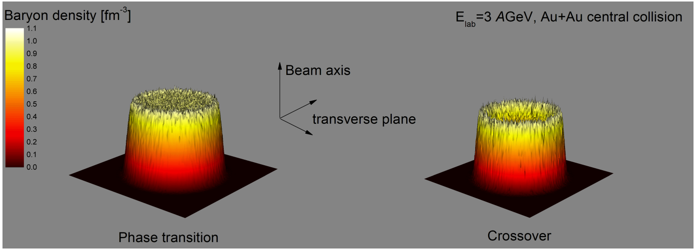




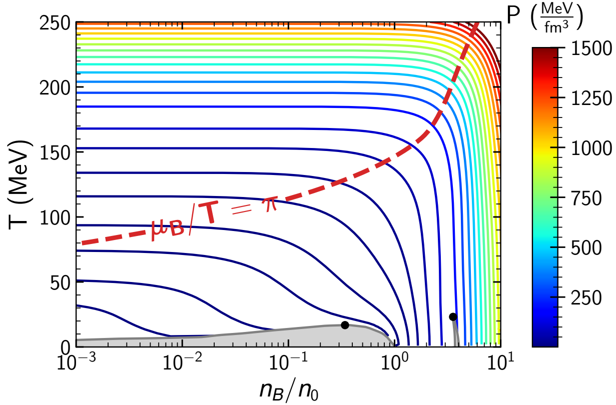
Summary and conclusions

- We can now use NS, BNSM, CCSN and HIC to scan the high dnesity QCD phase diagram.
- Important treasure: The EoS that binds them all!
- Especially for HIC new ideas/methods for old and new models are necessary.
- E.g.: Phase transitions in transport.
- See also poster by Manjunath Omana Kuttan for DL methods to study the EoS in HIC.





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.

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