The QCD phase transition in dynamical models at high baryon density

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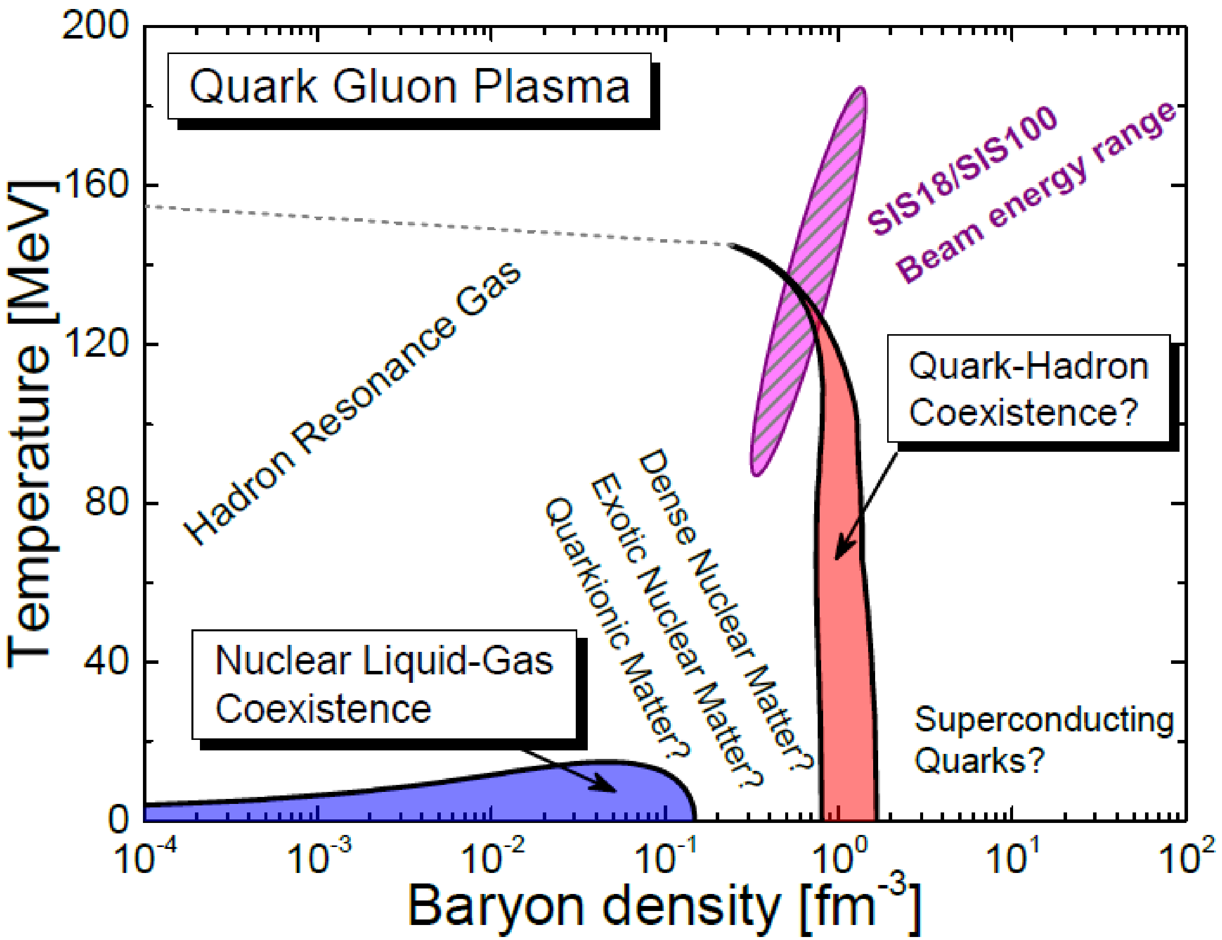
ErUM-Data IDT

SAMSON

- What is high density/chemical potential matter?
- Why do we want dynamical models?
- What should these models be able to describe
- What can our „standard models“ do?
- What is there to improve?
- Consequences for Dileptons
- Can charm be useful here too?

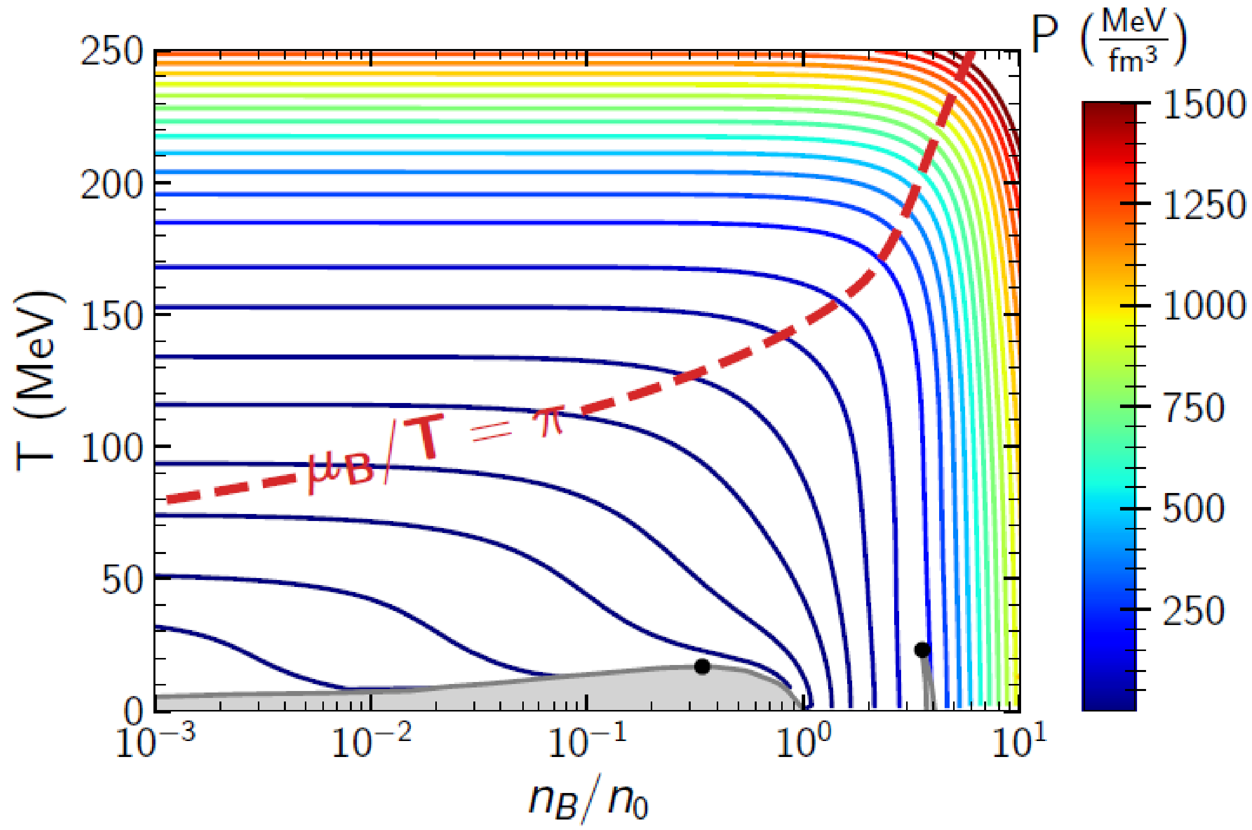
- Special interest: The high density chiral/deconfinement transition (if it exists)



What is „high density"?

A. Motornenko, JS and H. Stoecker, ``From Cosmic Matter to the Laboratory,' Astron. Nachr., 1 (2021)

One possible definition: Fermion dominated matter?



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).
- First principle calculations seem to fail for fermionic matter.

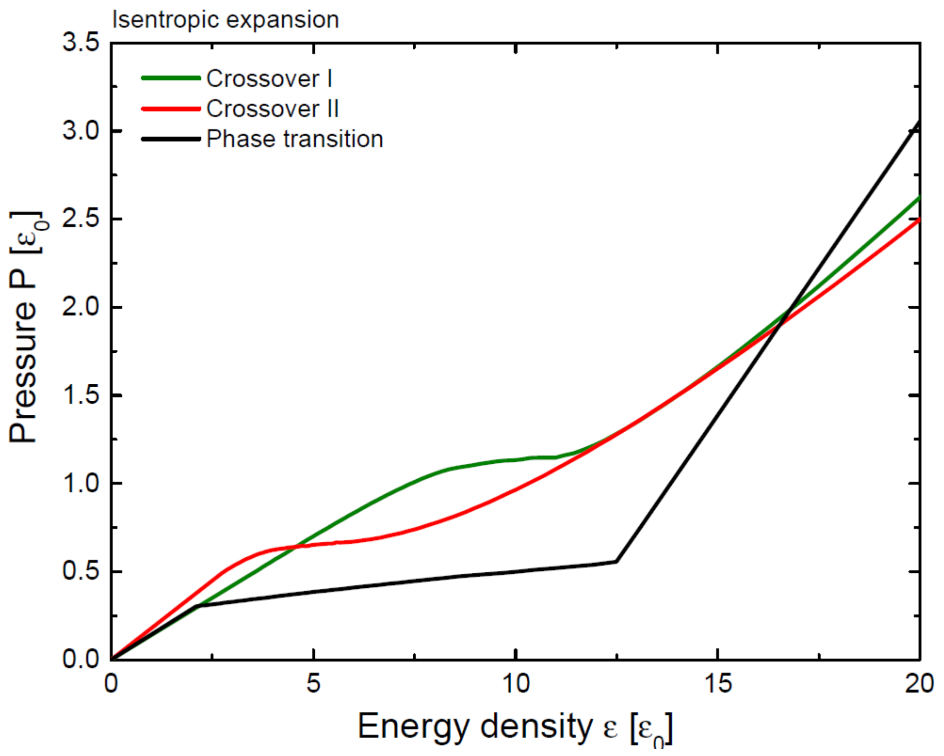
A. Motornenko, **JS**, V. Vovchenko, S. Schramm and H. Stöcker, (Quark Matter 2019), Wuhan, China, November 3-9 2019

- Some observables focus on final state
  - E.g. the thermal fits to multiplicities
  - Don't really carry much information on the phase structure
- How to probe the high T and density? (ideally)
  - Find a way to describe the space time evolution of the collision
  - Fold that with some effect that should be sensitive
  - Get the observable
- Examples:
  - Flow: sensitivity to EoS and transport properties
  - Electromagnetic probes: sensitivity to Temperature and density evolution
  - Rare sub-threshold production: sensitive to re-scattering probability

Two features: softening and clustering

There are usually two types of effects discussed for a PT in HIC

1. The softening
   - A result of equal pressure in coexisting phases.
   - Work is done to increase volume not accelerate.
   - Different scenarios of softening are possible
   - Can be easily included via a Maxwell construction



General rule: There are no easy solutions and many aspects to be considered

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   - A result of equal pressure in coexisting phases.
   - Work is done to increase volume not accelerate.
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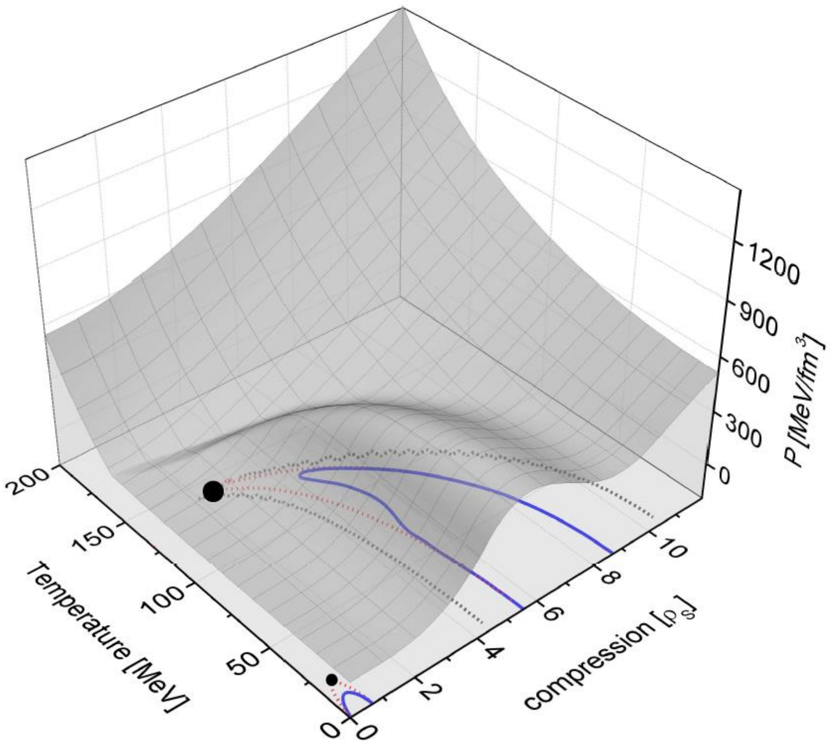
2. Clustering and Fluctuations
   - Can be caused by instabilities at the PT.
   - Critical phenomena, interesting but difficult to describe

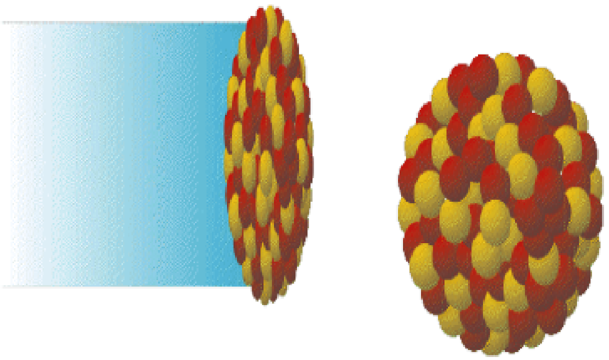


General rule: There are no easy solutions and many aspects to be considered

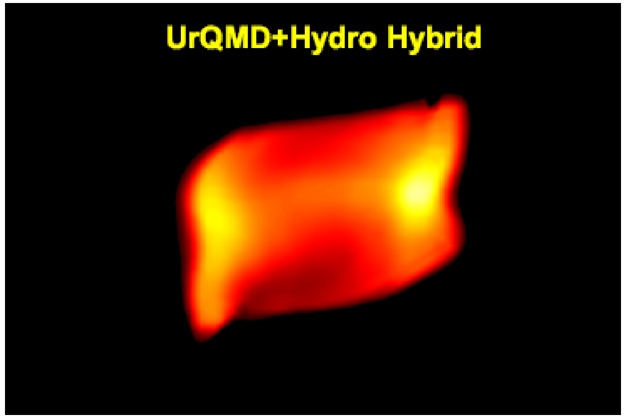
The ‘standard’ model of HIC

Much of we today think about hadronic observables is motivated by the fluid dynamic picture of HIC:

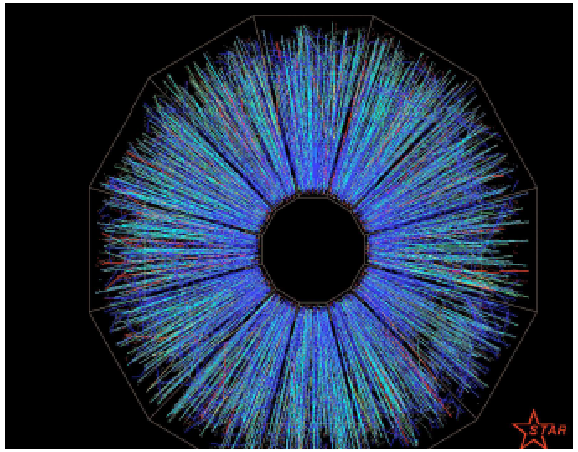
Pre-equilibrium phase | Equilibrated? phase | Final stage and particle freeze-out



Non-equilibrium initial state



Fluid dynamic evolution



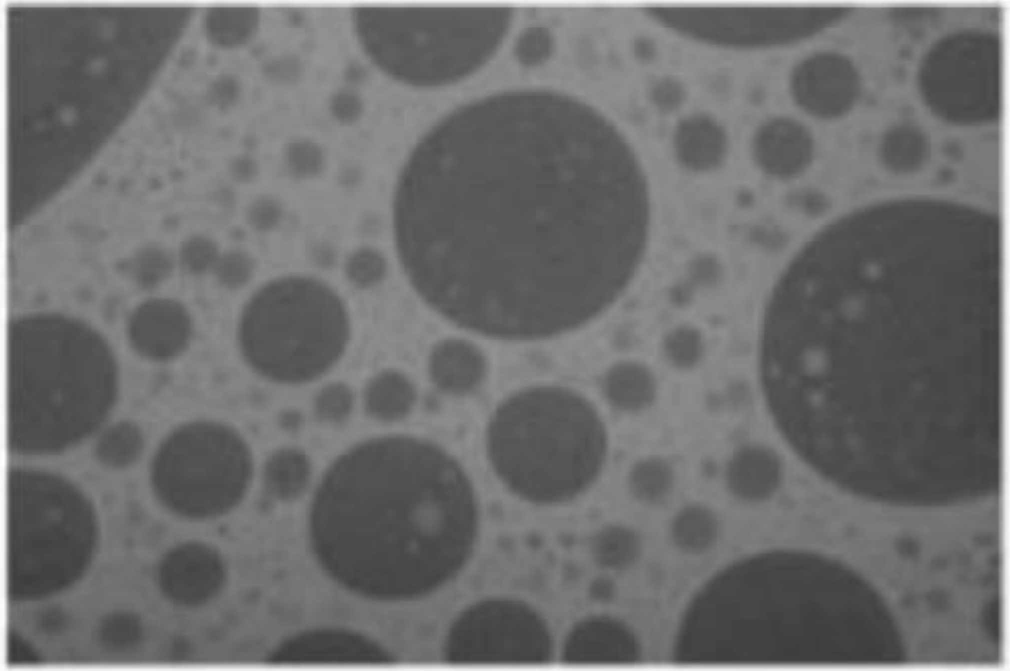
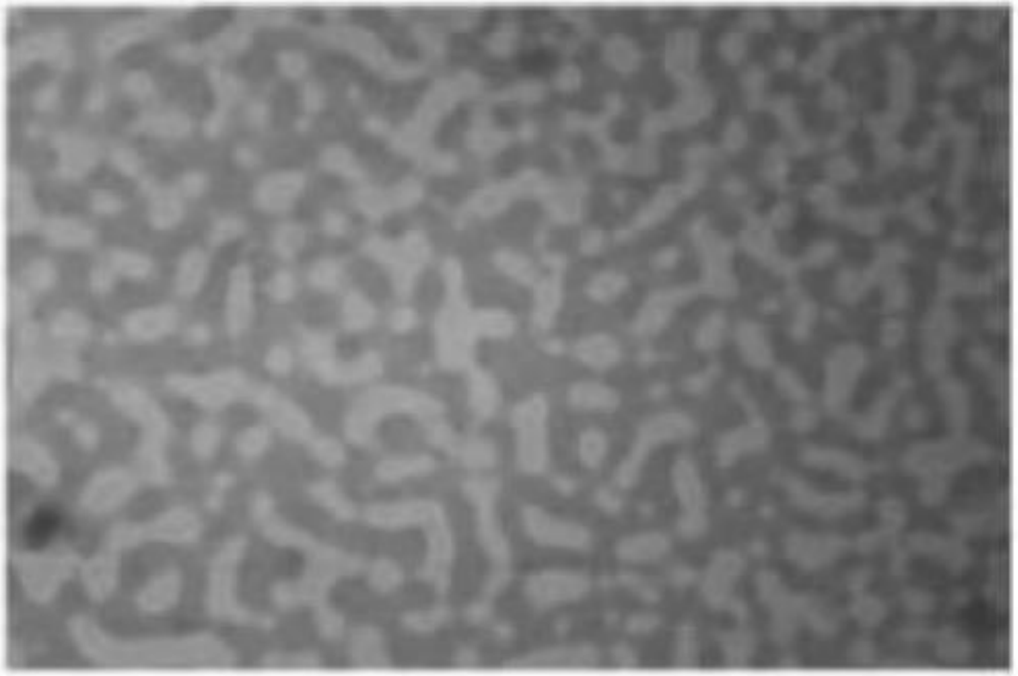
Freeze-out: chemical and thermal

Could be replaced by hydro initial state for low energies

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

Nucleation vs. spinodal decomposition

- Nucleation: Thermal fluctuations serve as seeds for bubble formation. (e.g. ice in water). SLOW!
- Spinodal decomposition: System is quenched below separation temperature. Instabilities occur (e.g. hot oil + water). FAST!

How to do a phase transition in fluid dynamics

- To dynamically describe the process of phase separation, fluid dynamics needs to be augmented
  - Most important: a gradient term
  - Modifies the dispersion relation.

Calculation in a box with periodic boundaries

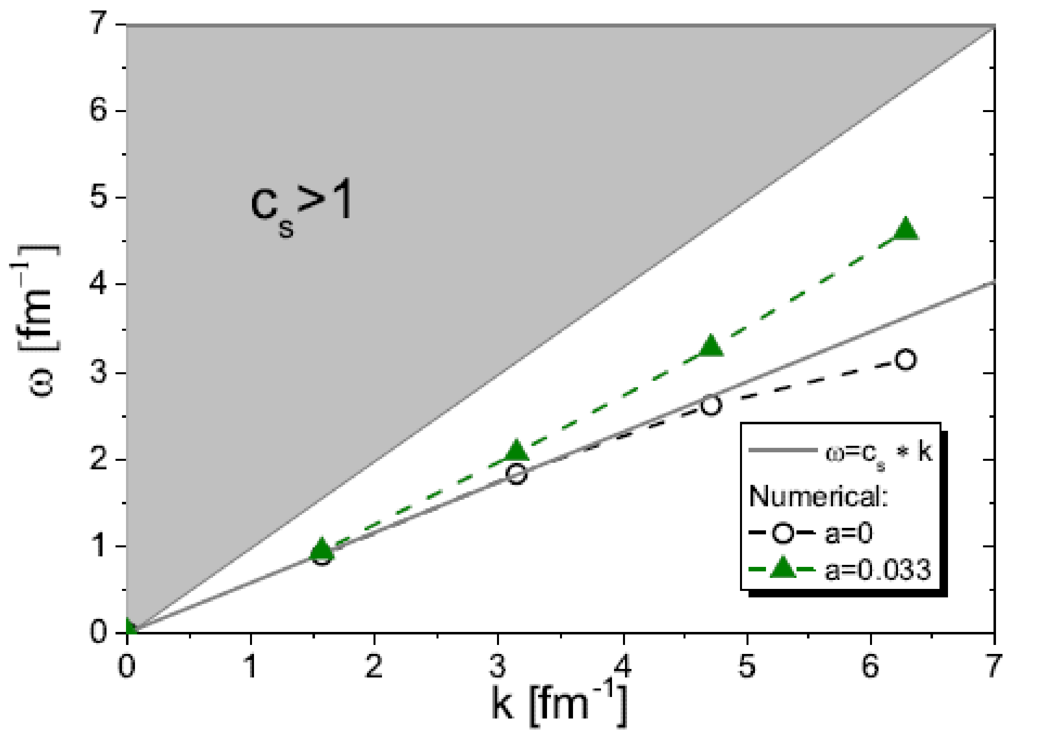
Ideal fluid dynamics: $\omega^2 = c_s^2 k^2$

\+ Gradient term: $\omega^2 = c_s^2 k^2 + a^2 \frac{(\varepsilon_s/h)}{(\rho/\rho_s)^2} k^4$

\+ Shear and bulk viscosity: $\omega^2 = c_s^2 k^2 + a^2 \frac{(\varepsilon_s/h)}{(\rho/\rho_s)^2} k^4 - \mathrm{i}\zeta \frac{\omega}{h_0} k^2$

See e.g.:
V. V. Skokov and D. N. Voskresensky, Nucl. Phys. A 828 (2009), 401-438
and
J. Randrup, Phys. Rev. C 79 (2009), 054911

Normal matter



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- In the unstable region between the phase boundaries the speed of sound will be imaginary.
- Any undulations will grow exponentially with a wave number dependent growth rate

$$\gamma_k^2 = |v_s|^2 k^2 - a^2(\varepsilon_s/h)(\rho/\rho_s)^2 k^4$$

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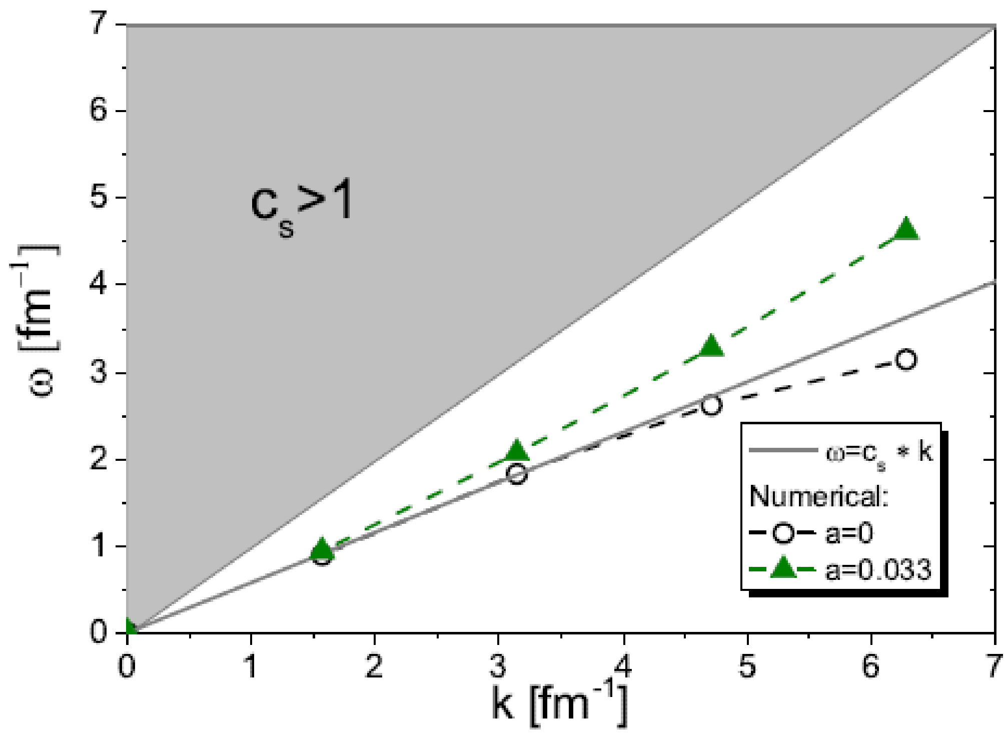
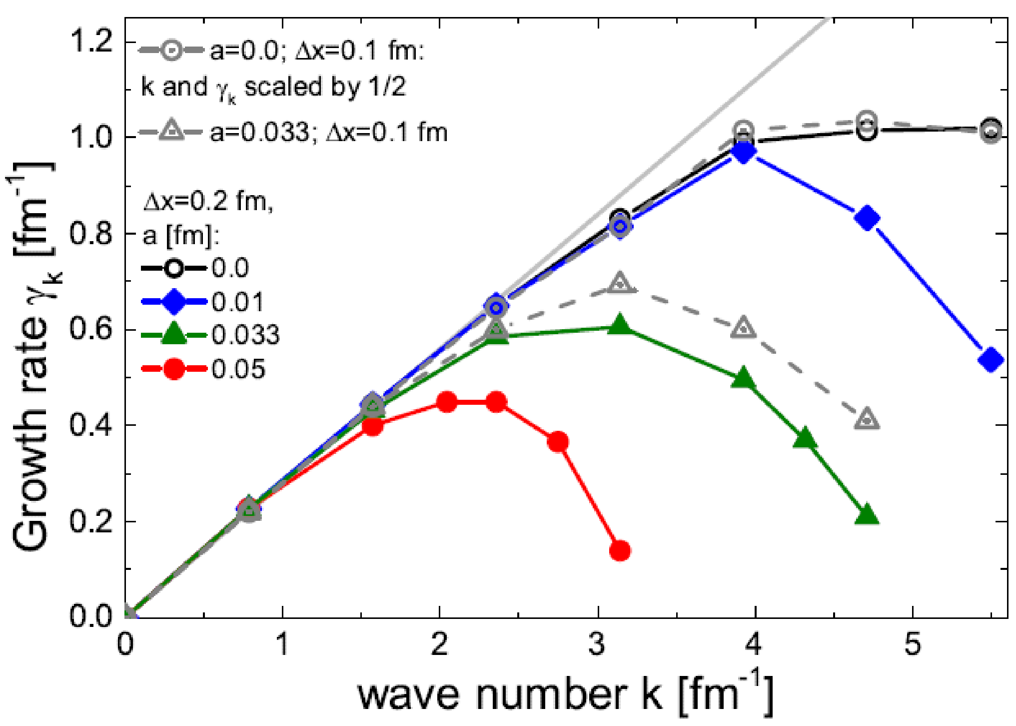


mechanically unstable matter



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Viscosity: the growth rate γ_+ is reduced by $\approx \frac{1}{2}\xi k^2/\bar{h}$

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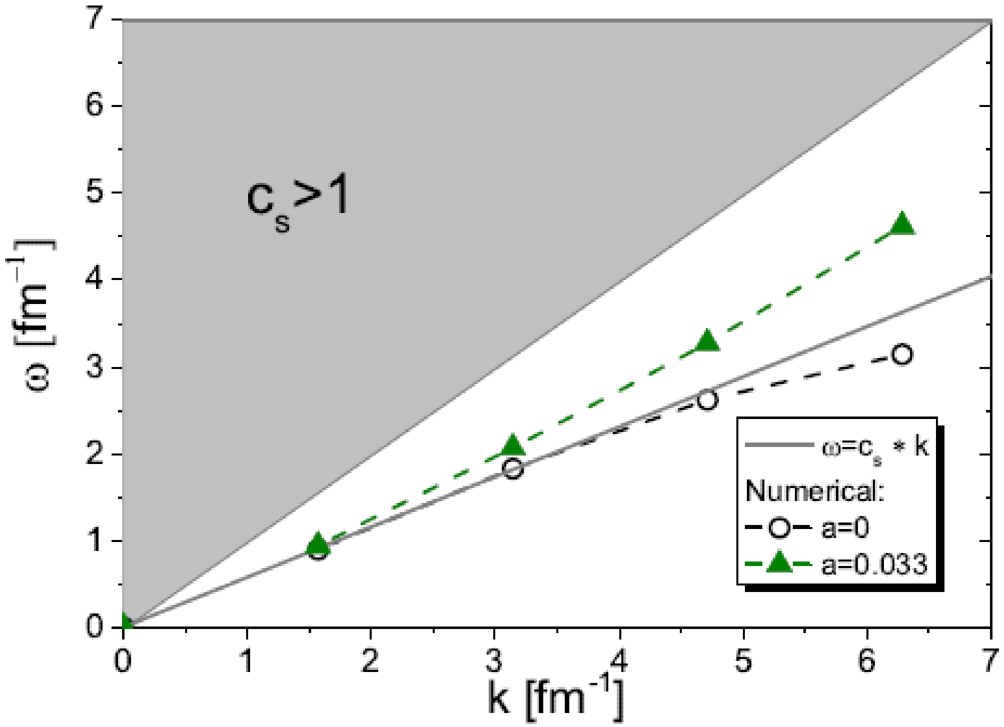

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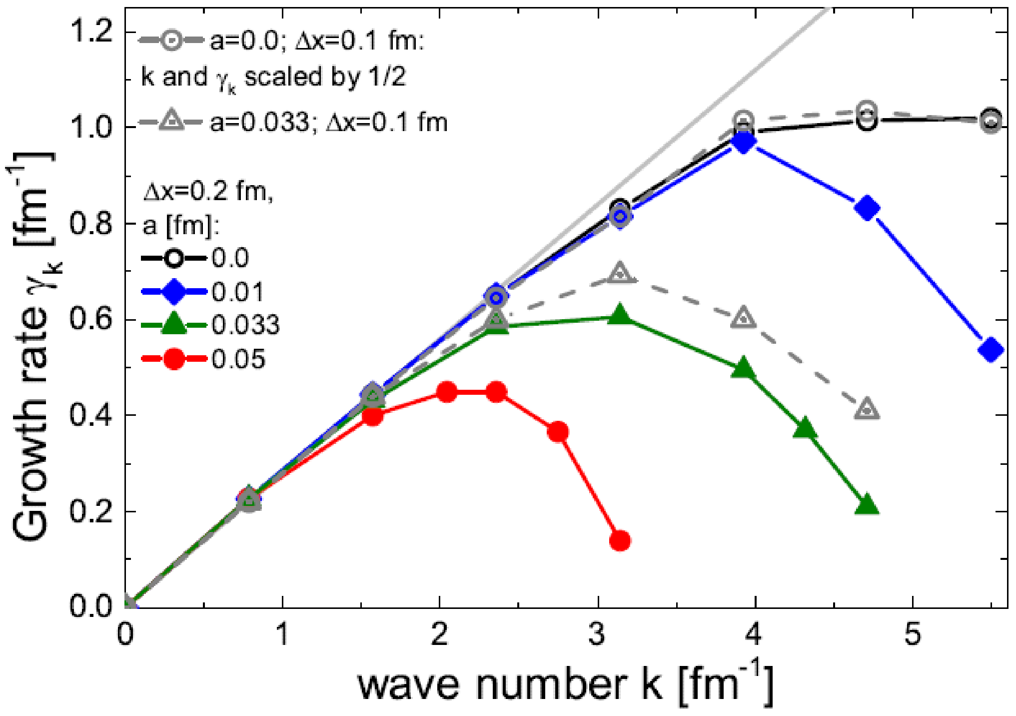
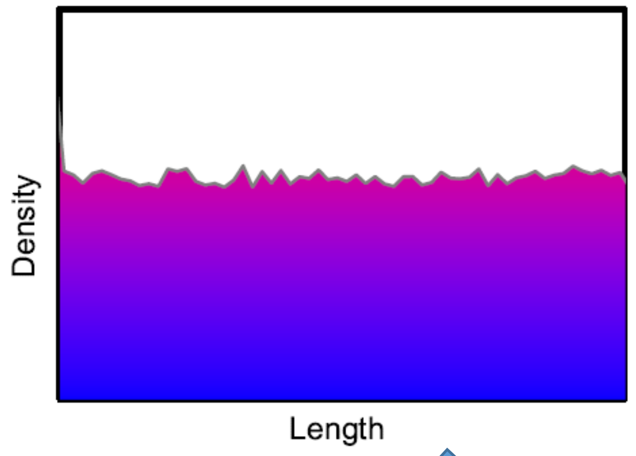


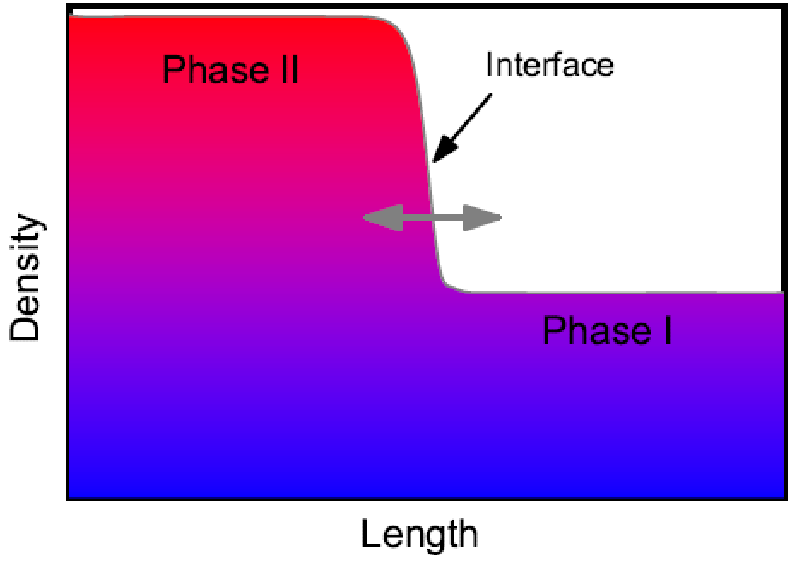
The two scenarios of phase separation

1. Equilibrium construction (Maxwell)
2. Non-equilibrium separation through instabilities



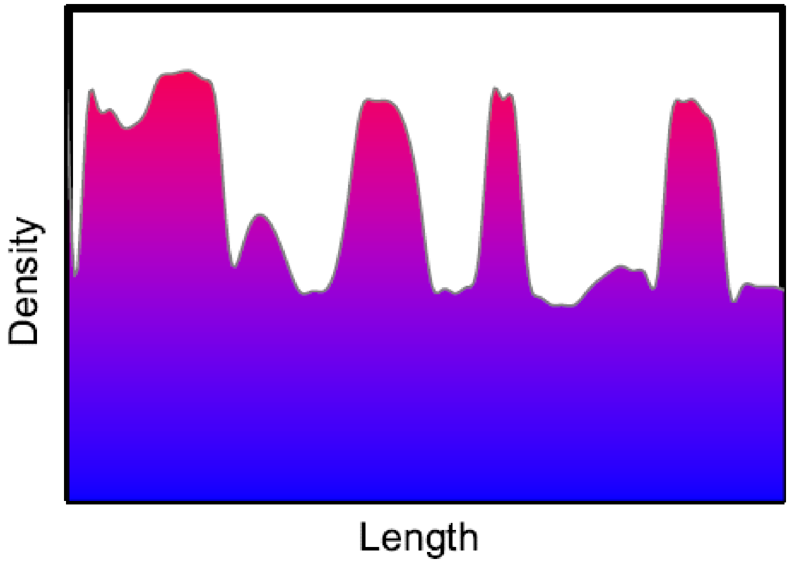
Equilibrium Phase Transition (Maxwell construction)

As the system dilutes, the phases are always well separated

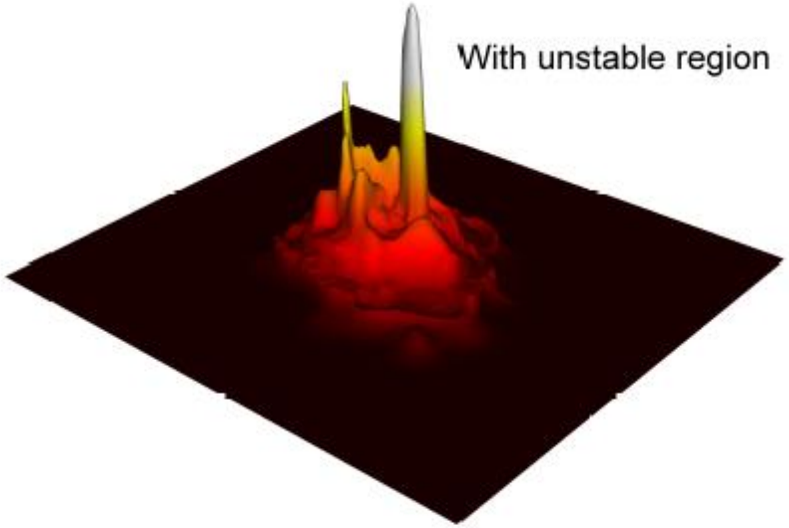


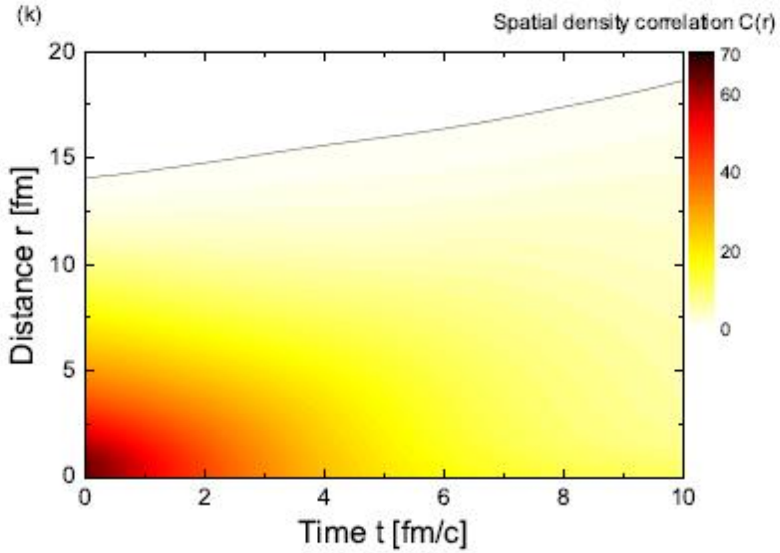
Non-Equilibrium Phase Transition

Phase separation is a dynamical process.

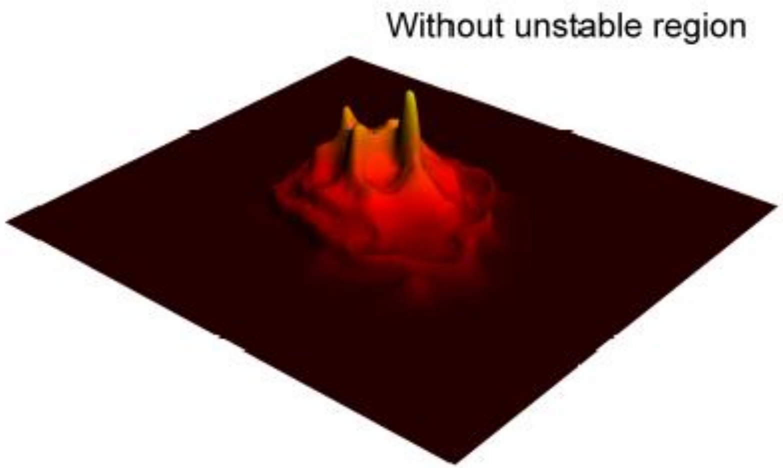


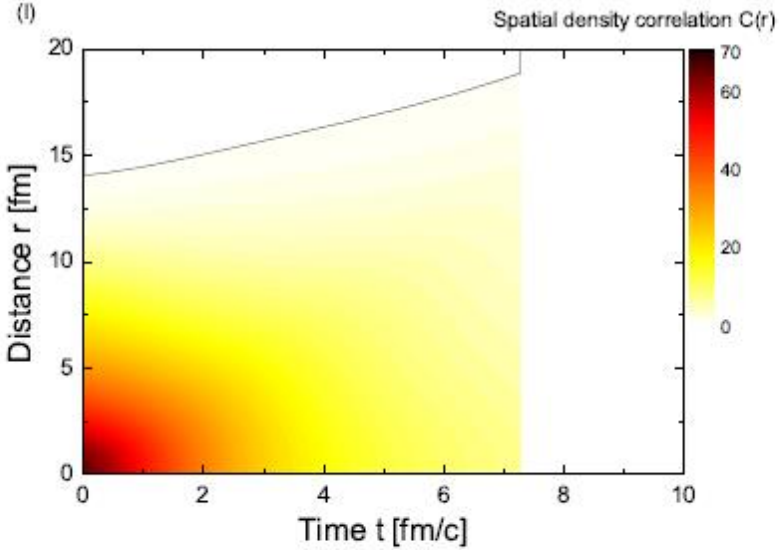
EoS with unstable phase:





EoS with Maxwell construction:

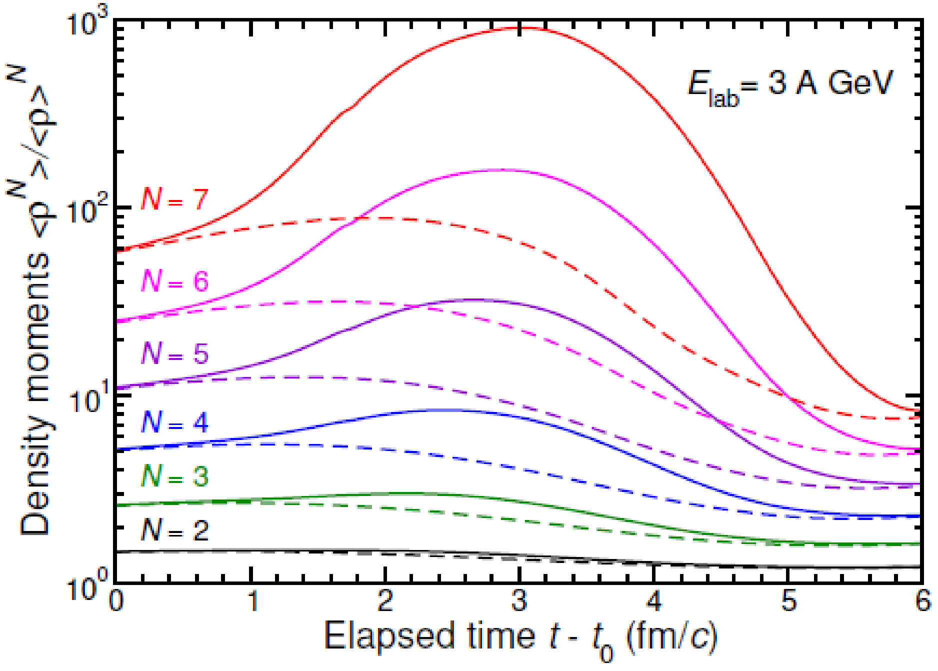




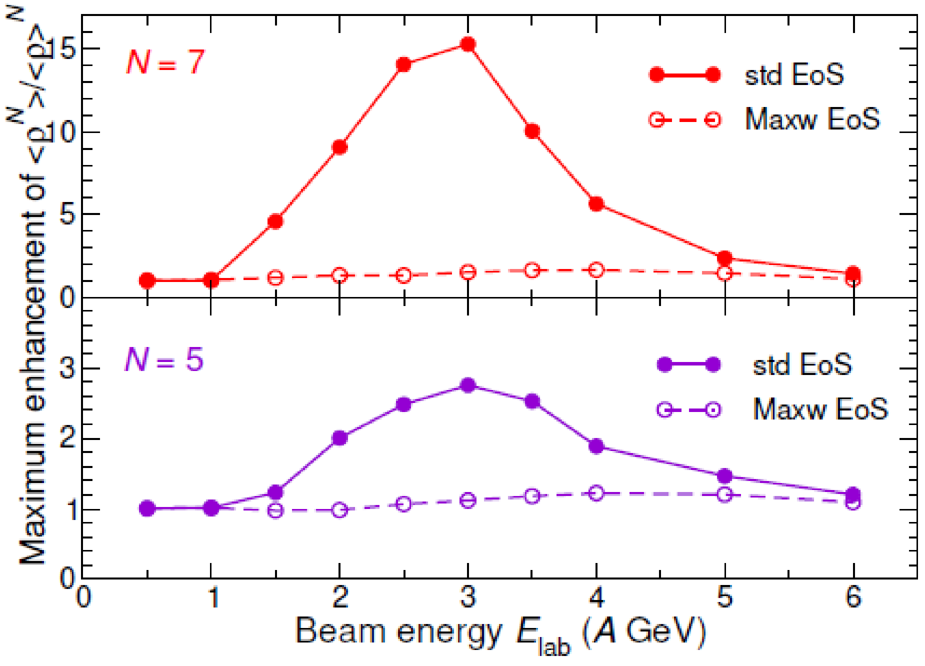
Let's be more quantitative

Define Moments of the net baryon density distribution:

$$\langle \rho^N \rangle \equiv \frac{1}{A} \int \rho(\boldsymbol{r})^N \rho(\boldsymbol{r})\, d^3\boldsymbol{r}$$



As a function of time

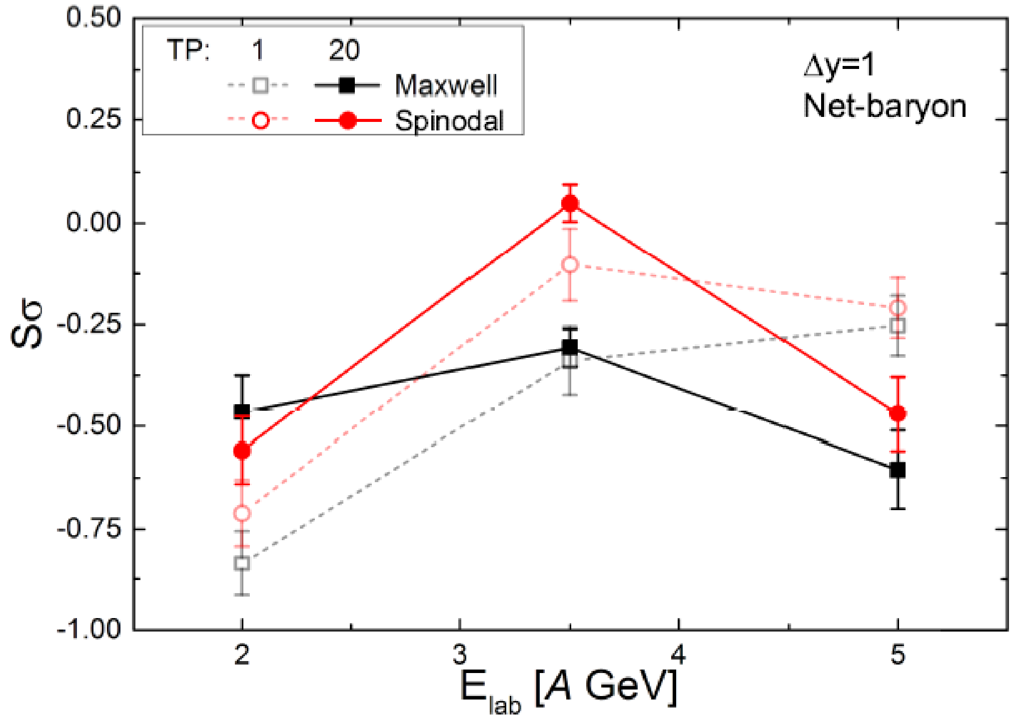


As a function of beam energy

- Remember: These are coordinate space correlations!

JS and J. Randrup, Phys. Rev. Lett. 109, 212301 (2012)

An example for the full evolution using the HQ-EoS



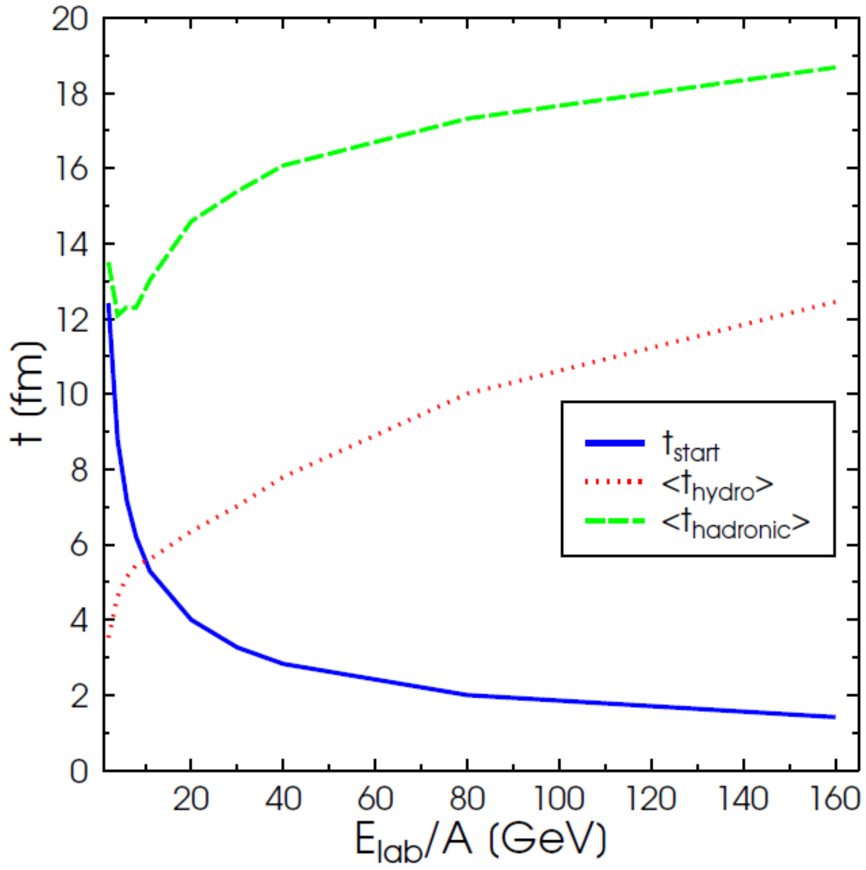
- Full model simulations for fluctuations are scarce
- Separation of the two phases: Spinodal Instabilities.

- Small enhancement of Skewness observed (relevant is the TP=1 line)
- Fluid dynamics is computationally expansive: no Kurtosis yet

JS, L. Pang, K. Zhou, V. Koch, J. Randrup and H. Stoecker, JHEP 12, 122 (2019)

Why the standard model may actually fail

- The time until hydro starts rises drastically for low beam energies
- Cannot simply separate the initial state and expansion stages anymore.
- Both may depend on the EoS
- Has consequences on:
  - Observables which develop early, like v1, v2
  - The maximally achievable compression



H. Petersen, J.S., G. Burau, M. Bleicher and H. Stöcker,' Phys. Rev. C 78, 044901 (2008)

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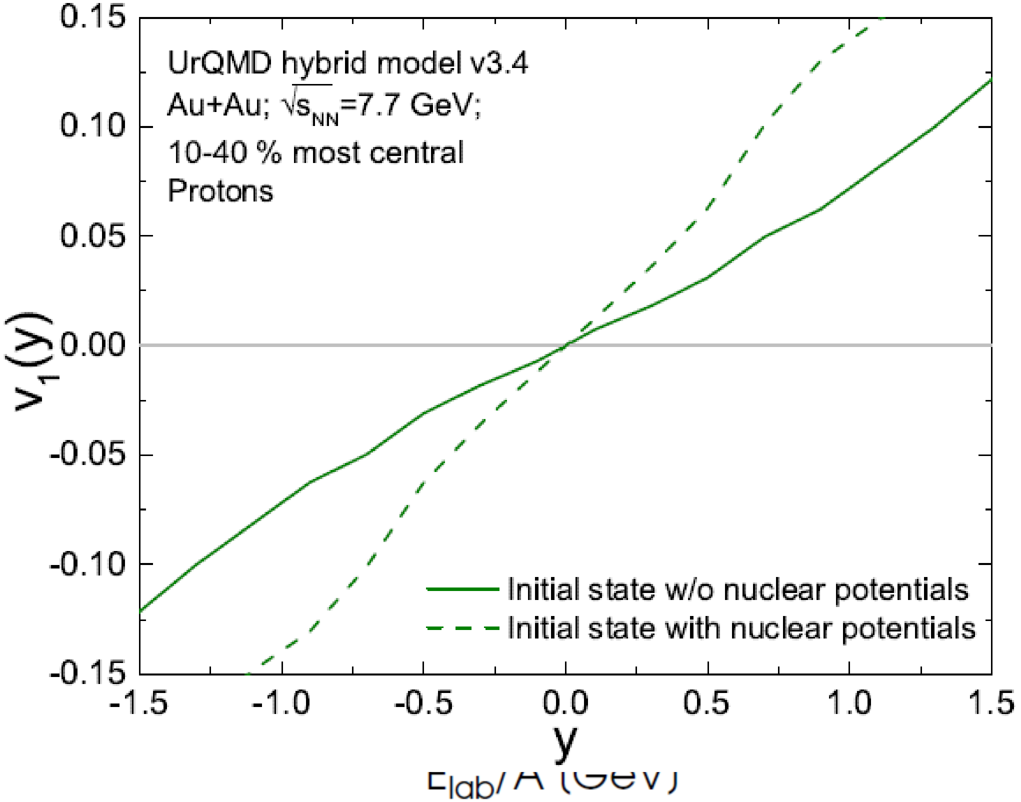


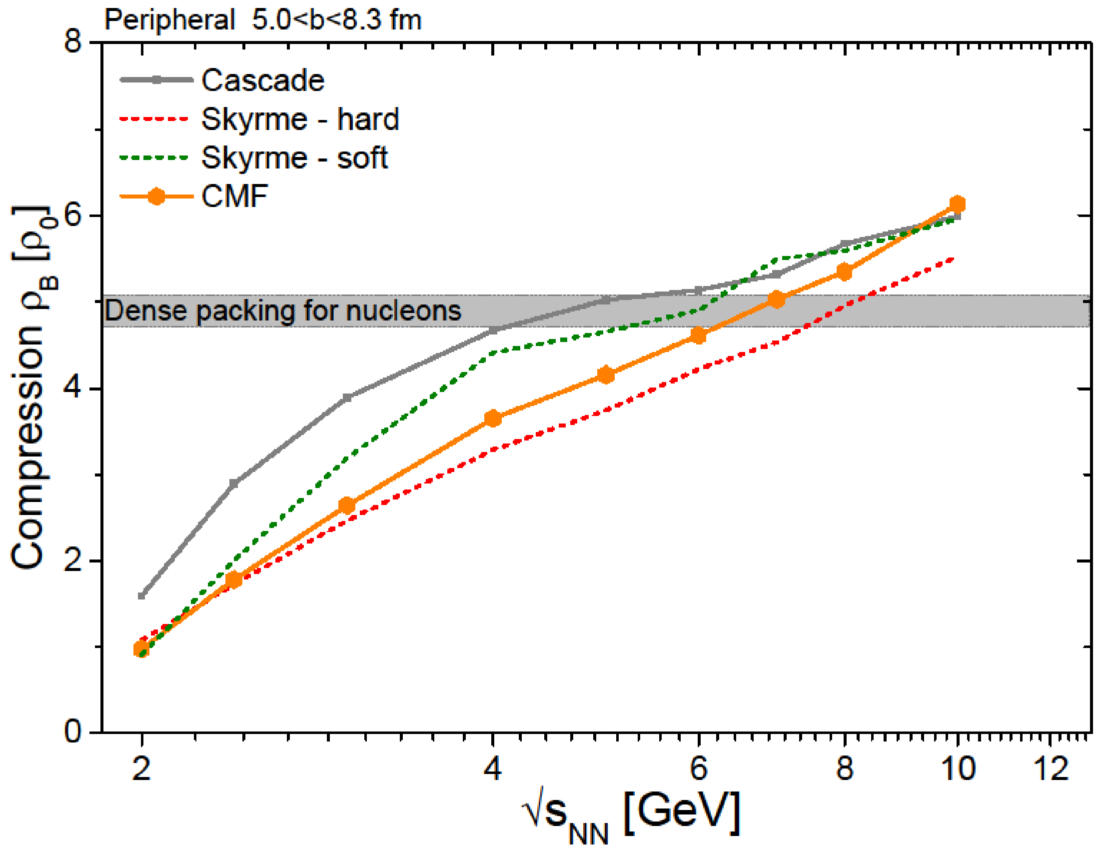
H. Petersen, J.S., G. Burau, M. Bleicher and H. Stöcker,' Phys. Rev. C 78, 044901 (2008)

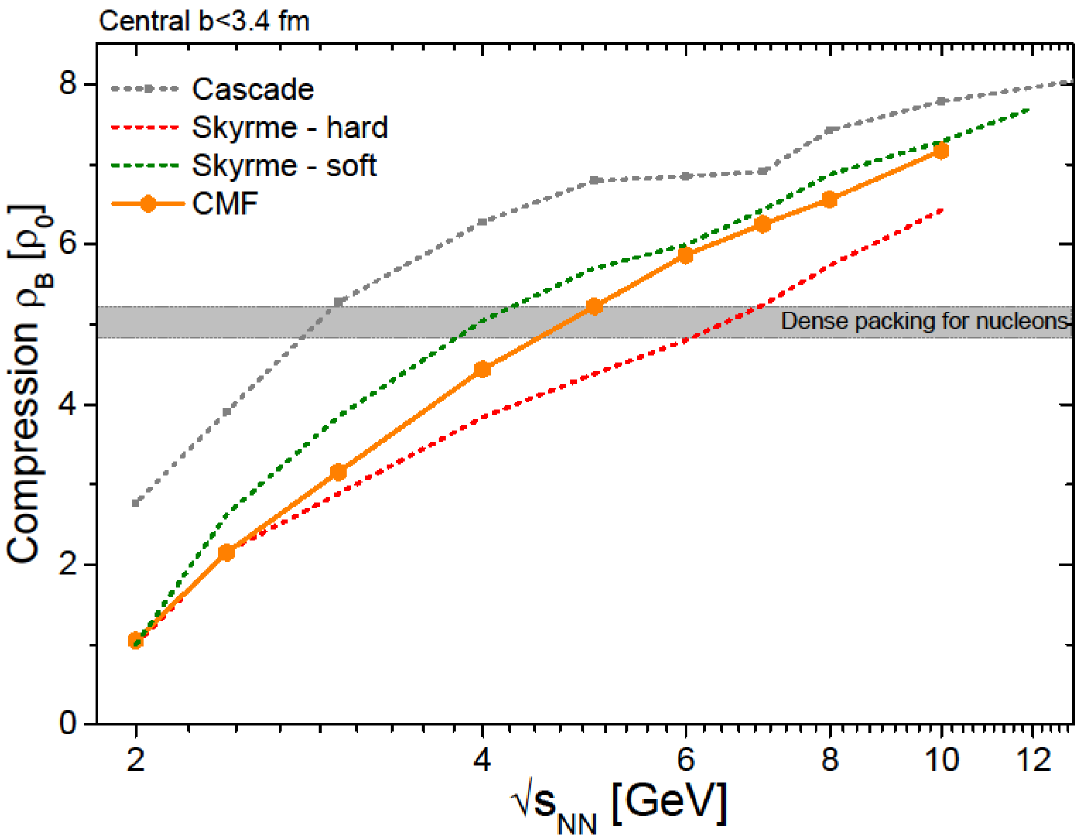
How to solve that problem

1. Either use fluid dynamics from the very beginning
   1. Includes the EoS throughout
   2. Difficult to include initial state fluctuations
   3. Assumes instant equilibration (maybe close to reality at low beam energies)
2. Introduce the same EoS as in the hydro in the model that is used to calculate the EoS
3. Replace everything by full microscopic transport with EoS

Some examples on initial compression depending on the EoS

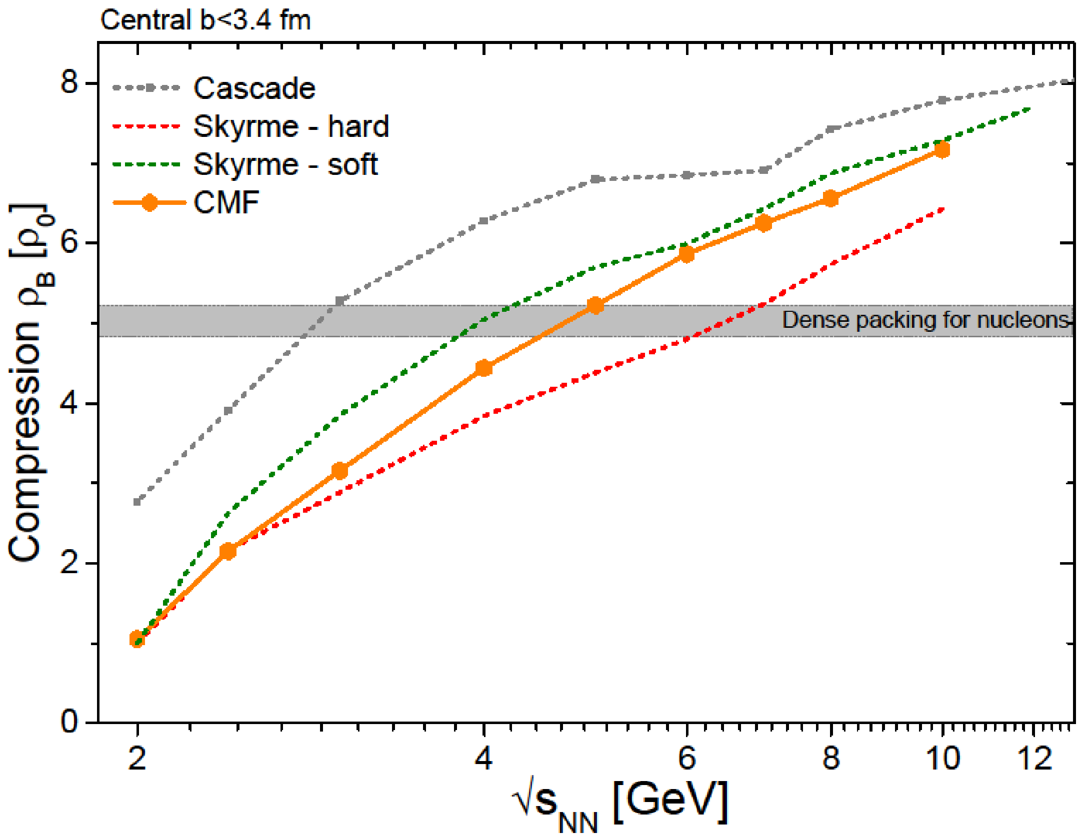
- Comparison of initial compression in different versions of the UrQMD model:
  - Cascade: Standard implementation
  - Skyrme: hard or soft density dependent Skyrme potential
  - CMF: Density dependent QMD potential from chiral mean field theory with crossover

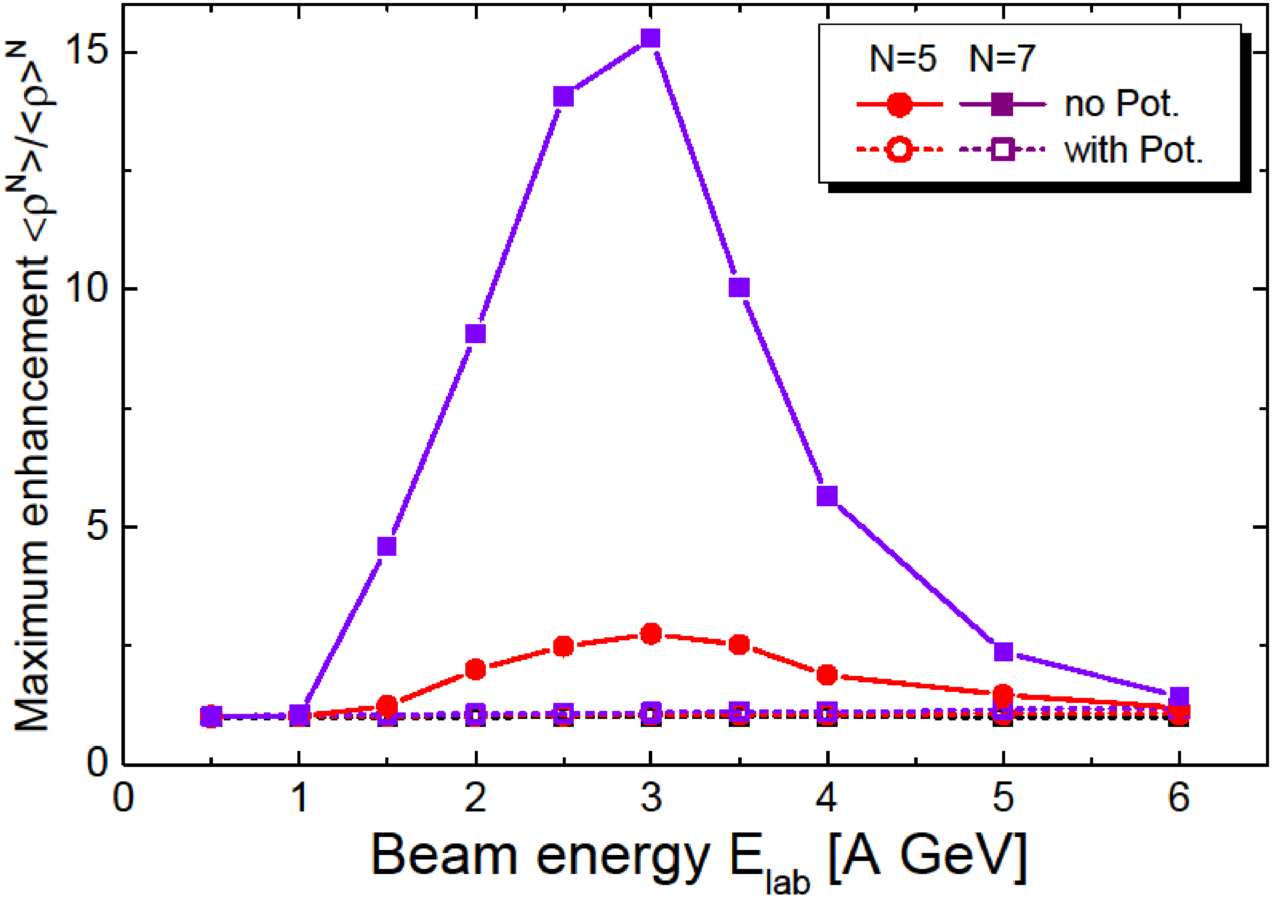




Consequences for the phase transition

- If the initial state is calculated using the Skyrme EoS, the phase transition suddenly is missed





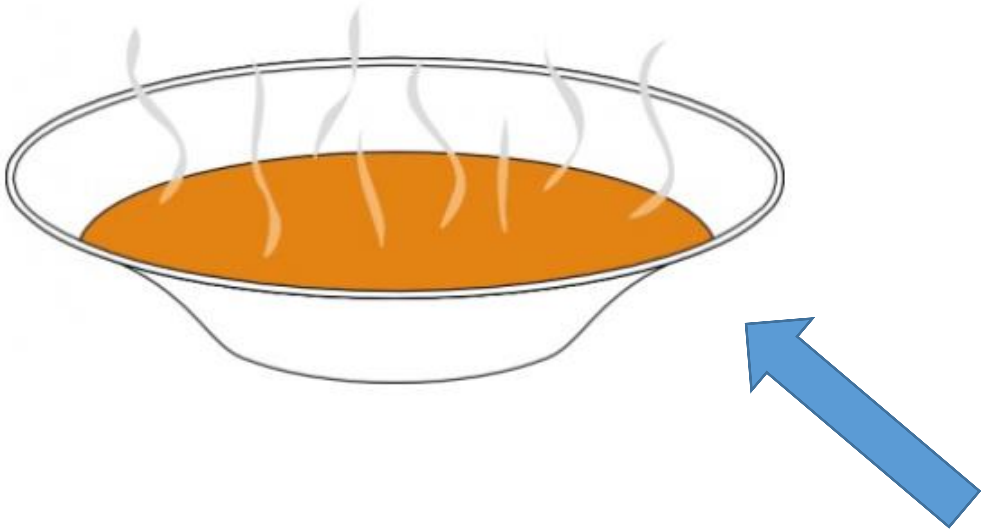
Consequences for dileptons

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.

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

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

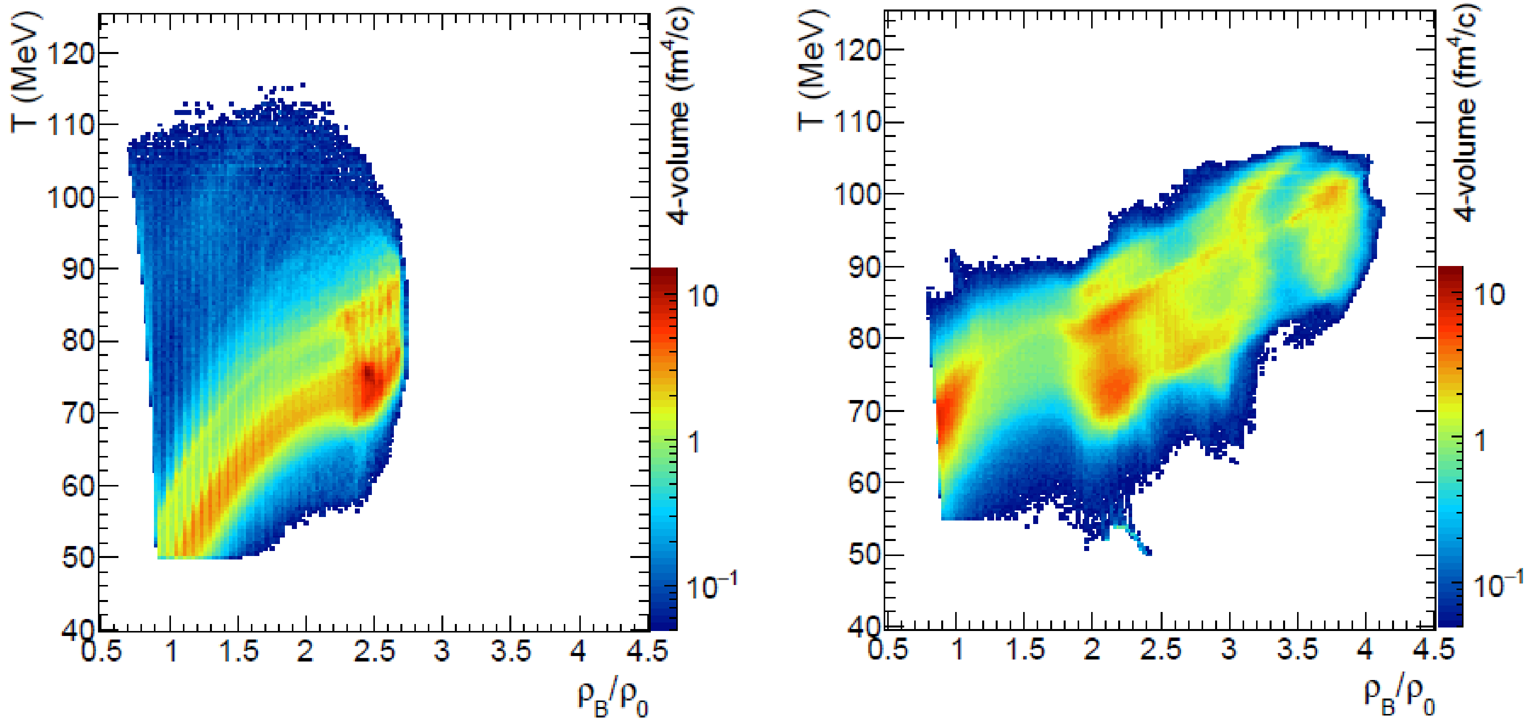


Highly sophisticated picture of HIC

Distinct differences with or without a phase transition

An even more sophisticated picture:
3+1 D fluid dynamics from the beginning to include effect from compression

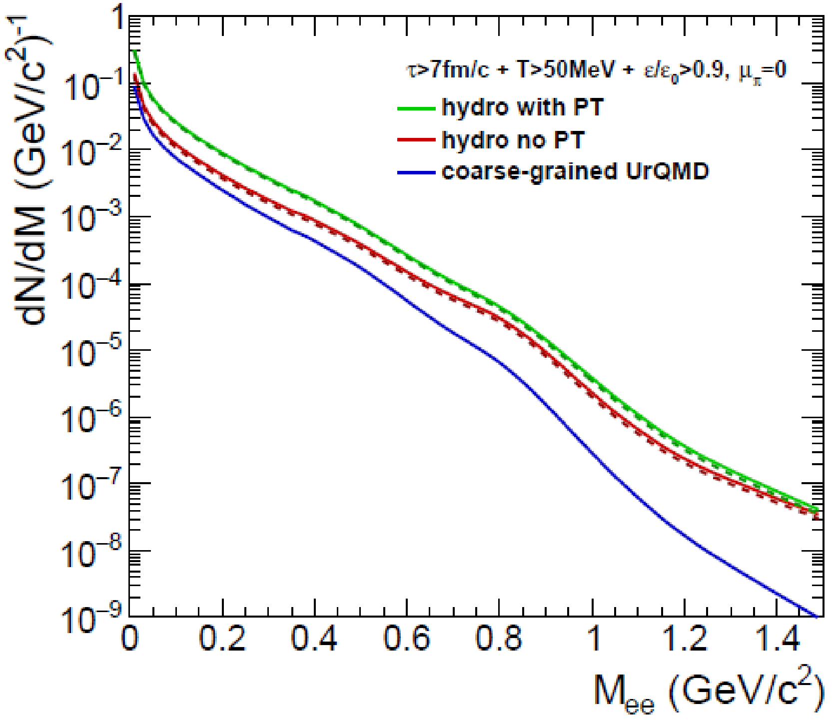
- Using the space-time evolution of the system we can calculate the emission rates.
- Already by eye we see significant differences in the evolution.

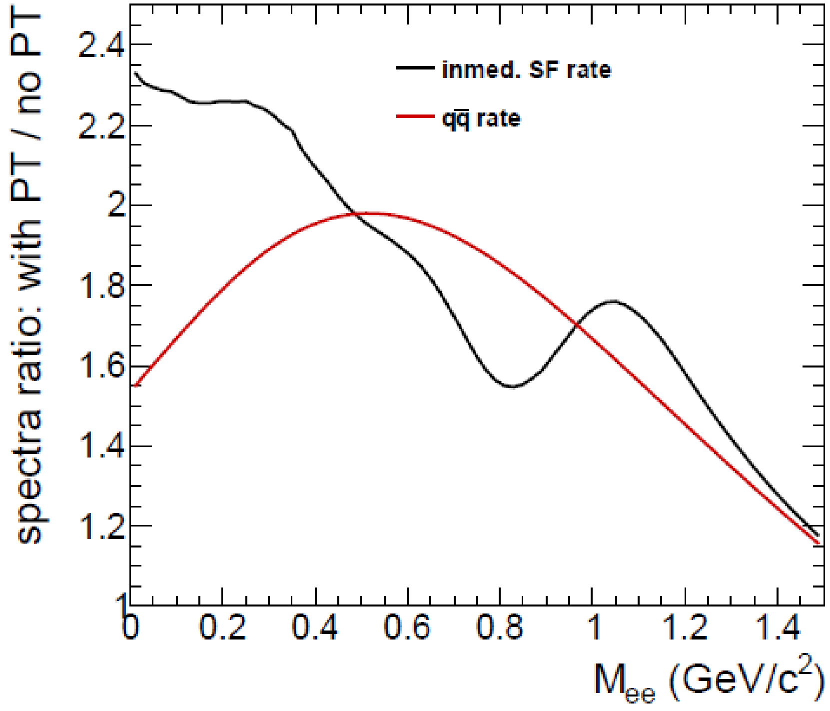


F. Seck, T. Galatyuk, A. Mukherjee, R. Rapp, JS and J. Stroth, [arXiv:2010.04614 [nucl-th]].

Indeed di-lepton emission shows a significant effect

- A simulation for Au+Au at the current SIS18 beam energy.
- A factor 2 enhancement of di-lepton emission due to extended 'cooking'.





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

Consequences for charm production at CBM

VOLUME 55, NUMBER 24 PHYSICAL REVIEW LETTERS 9 DECEMBER 1985

Subthreshold Kaon Production as a Probe of the Nuclear Equation of State

J. Aichelin and Che Ming Ko[(a)]

Joint Institute for Heavy Ion Research, Holifield Heavy Ion Research Facility, Oak Ridge, Tennessee 37831

(Received 11 June 1985; revised manuscript received 23 September 1985)

The production of kaons at subthreshold energies from heavy-ion collisions is sensitive to the nuclear equation of state. In the Boltzmann-Uehling-Uhlenbeck model, the number of produced kaons from central collisions between heavy nuclei at incident energies around 700 MeV/nucleon can vary by a factor of ~ 3, depending on the equation of state.

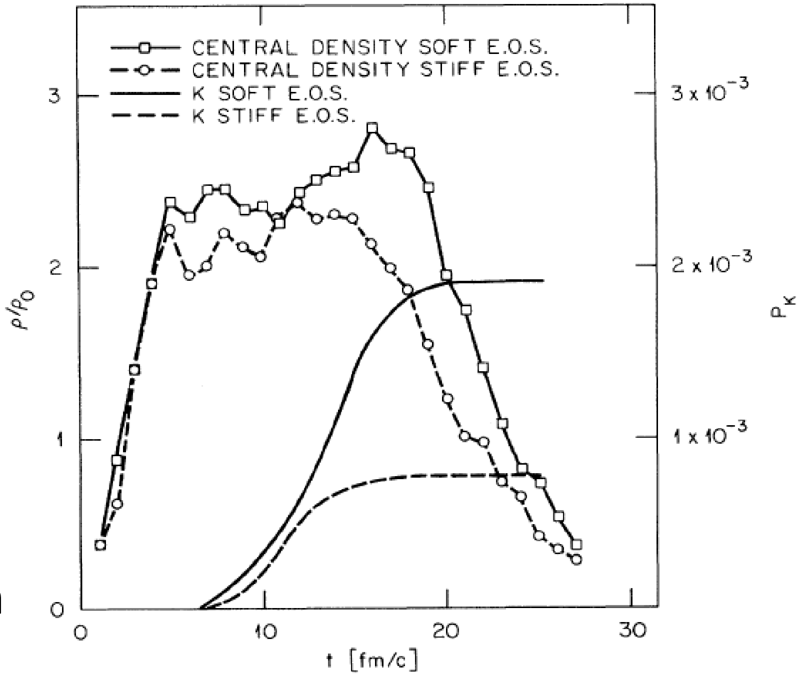
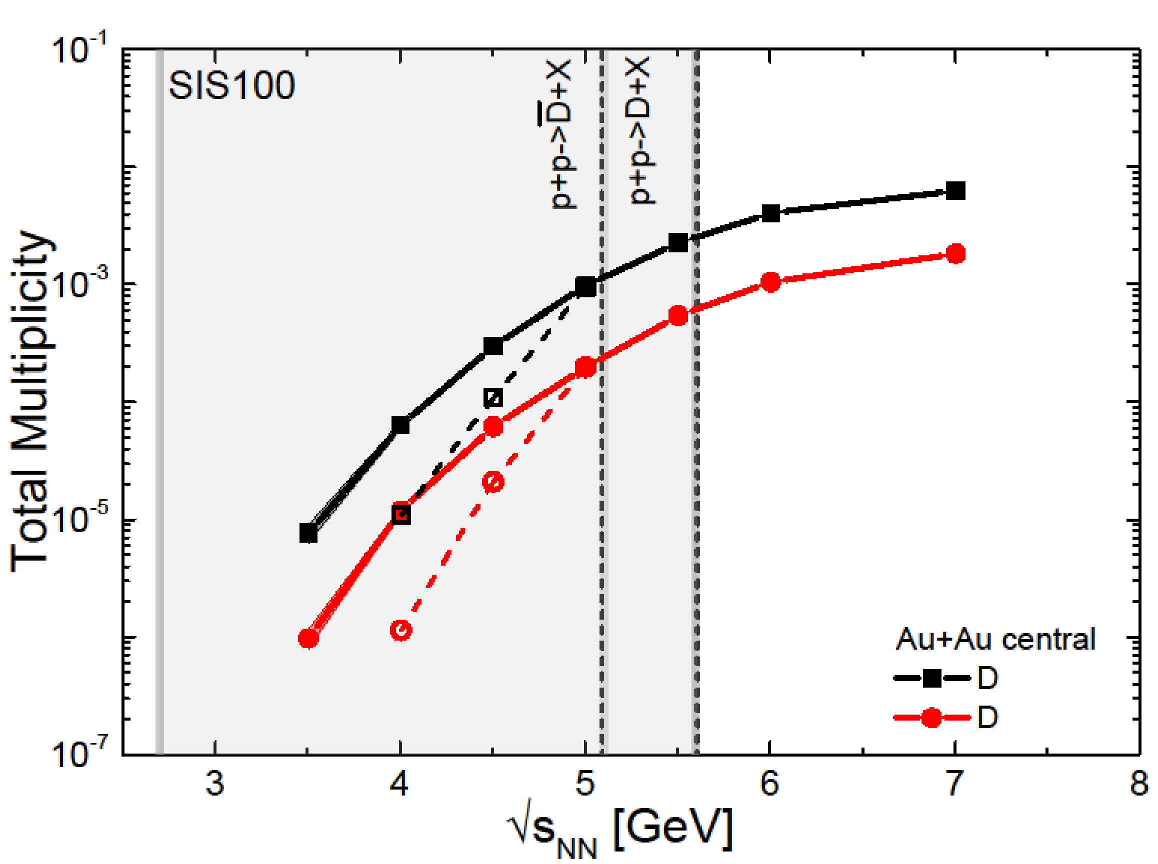


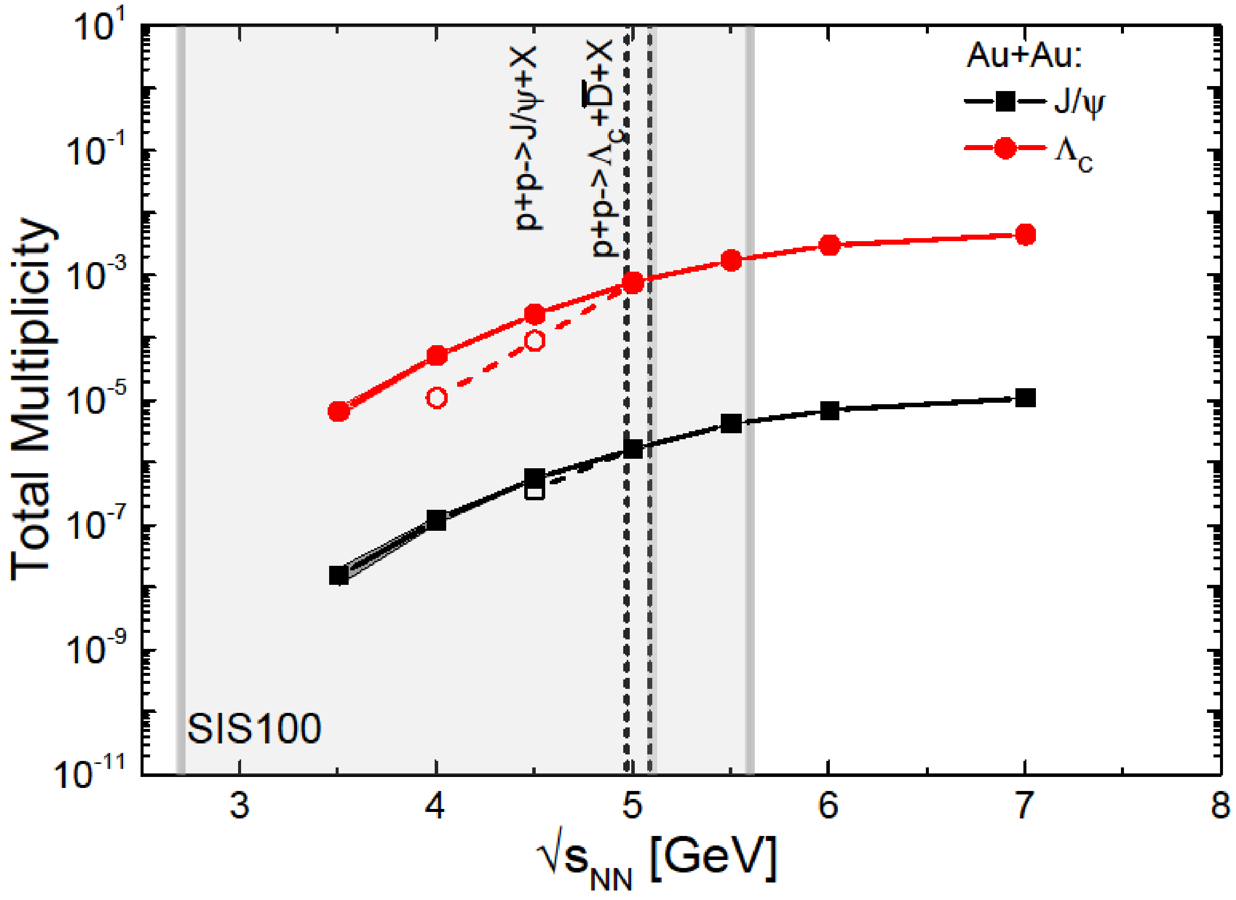
FIG. 1. Central density ρ/ρ_0 and total kaon-production probability P_K as functions of the collision time for reactions between Nb nuclei at an incident energy 700A MeV and at an impact parameter $b = 0.5$ fm.

In a nutshell:

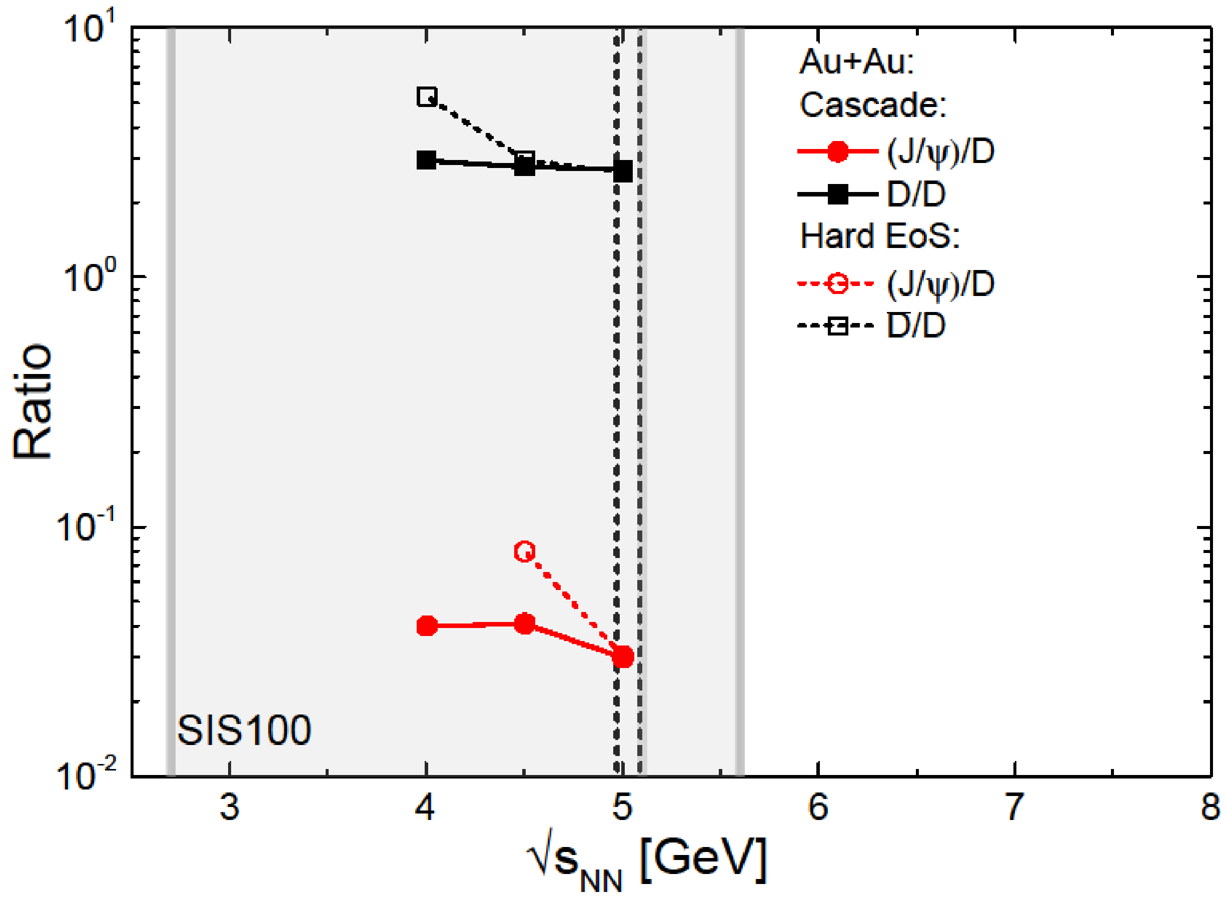
- Softer EoS leads to higher compression leads to more secondary interaction
- Thus the larger probability to produce particles sub-threshold

What happens if we introduce nuclear potentials?





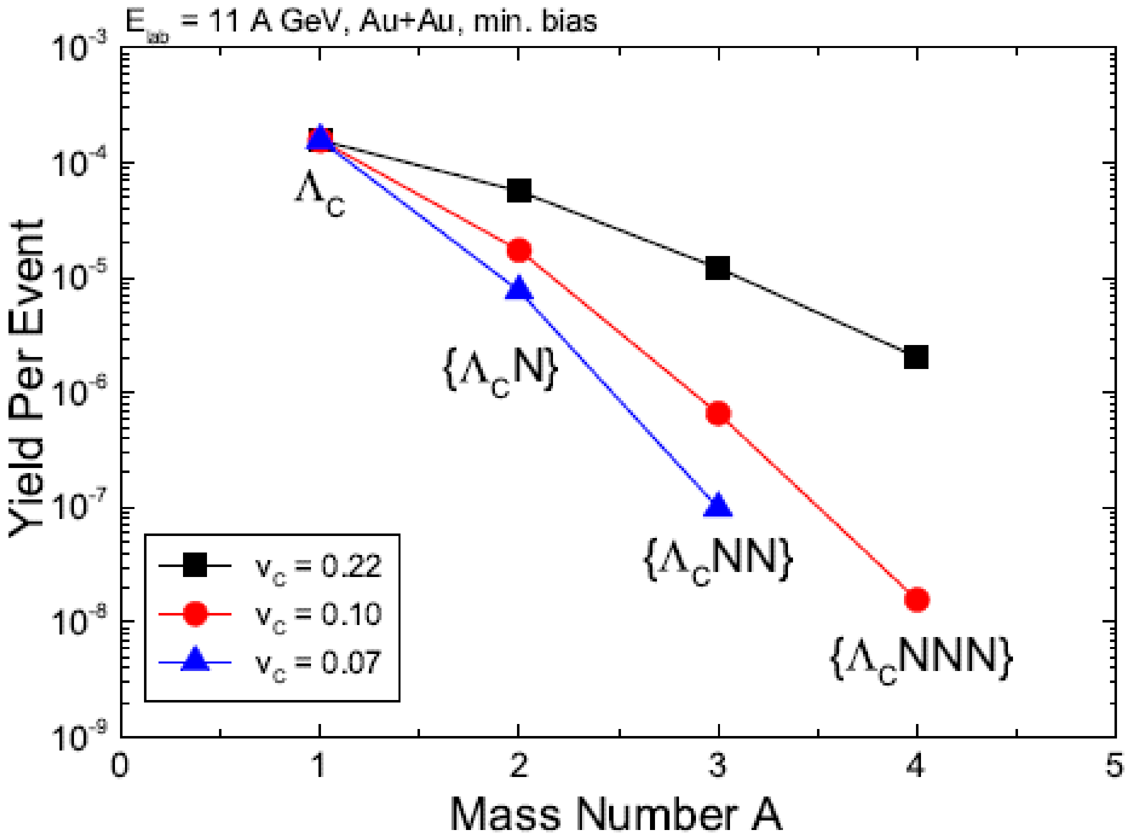
Charmed ratios



Charmed nuclei

- Nuclei with one or more bound Λ_c are called charmed (super-)nuclei.
- Very useful to understand charmed nuclear interactions.
- Studies at J-PARC discussed.

Our prediction from coalescence:

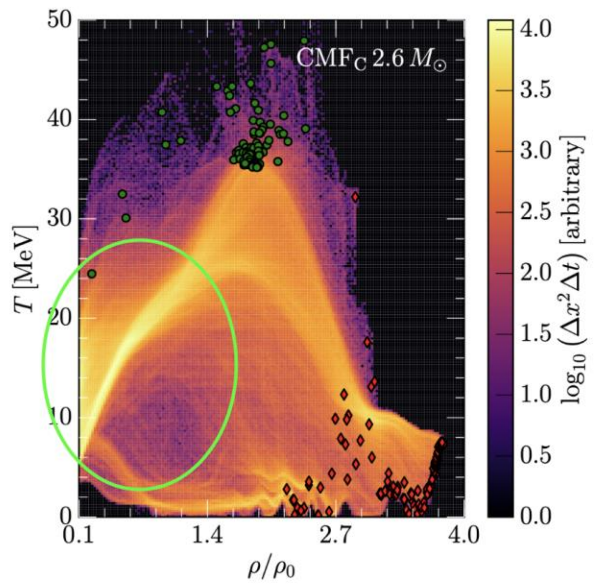


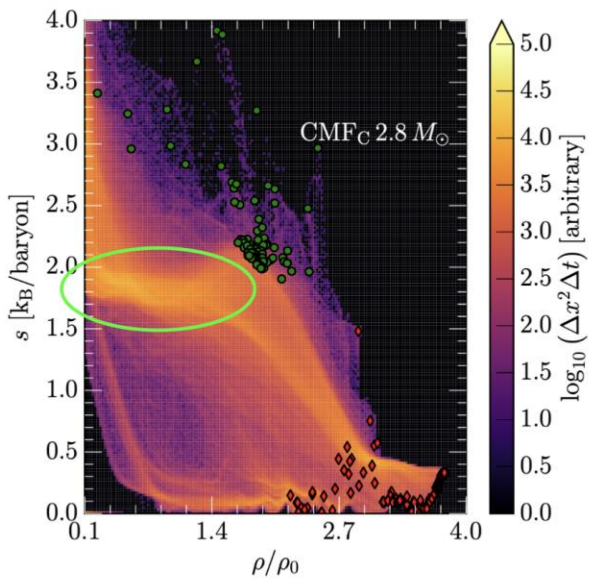
- Is the Λ_c so much more difficult to measure? Hopeless?

Summary and conclusions

- We still don’t know much of QCD matter when fermions dominate.
- At low beam energies the EoS influences the compression stage
- This has drastic consequences on observables
- Clear signal: Dileptons are enhanced due to phase transition
- Charm production at CMB: a baryometer?
- Still open modelling/theory questions:
  - A proper relativistic QMD description
  - Or: fully viscous hydro that can be used for the initial compression
  - How to implement the EoS?

NS merger vs. HIC: range of beam energies

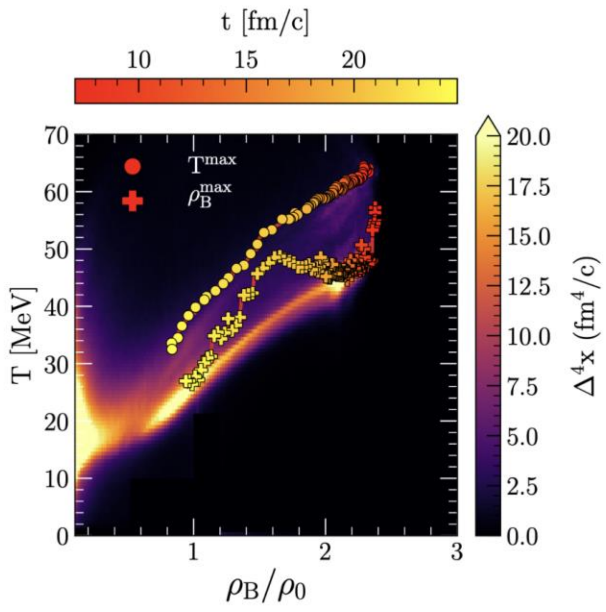


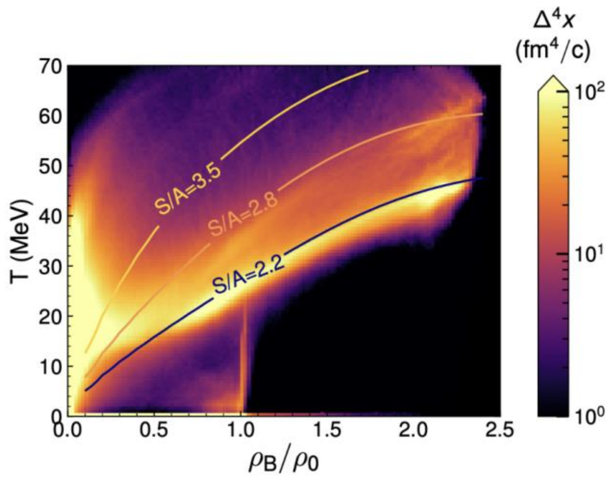


Many thanks for Elias Most.

Magneto-GR-Fluid dynamics for BNSM with 2.8 solar masses.

- One EoS for simultaneous description of HIC and BNSM
- Entropy per baryon in BNSM ~ 2
- Similar to HIC at ~ 500 MeV/nucleon
- Densities differ!
- Approaches are complementary.





Fluid dynamics for Au+Au collision at 600 MeV/nucleon

In preparation: E. Most, A. Motornenko, V. Dexheimer, JS, L. Rezzolla and H.Stoecker

- Instabilities in relativistic fluid dynamics
- Can be readily extended for realistic simulations