The QCD phase transition(s) from model to observable

Jan Steinheimer

09/20/2016

The new/current pig in town

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Let's focus on the current pig(s) in town

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- At the Critical point: enhancement of thermal fluctuations
- At the phase transition: cluster formation due to mechanical instabilities.

Both are rather "difficult" regarding modeling.
Fluctuations amplify the signal, but also uncertainties.

I shouldn't have to emphasize this

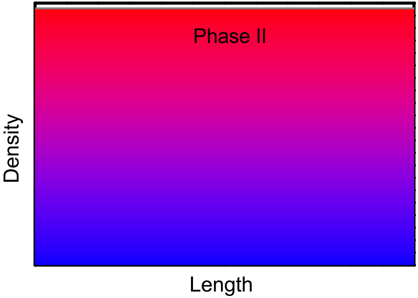
Why dynamical models?

- Finite number of particles and volume
- Conservation laws
- Finite Lifetime
- Can separate out different physics effects
- ...

Non-Equilibrium Phase Transition

Equilibrium Phase Transition (Maxwell construction)

As the system dilutes, the phases are always well separated



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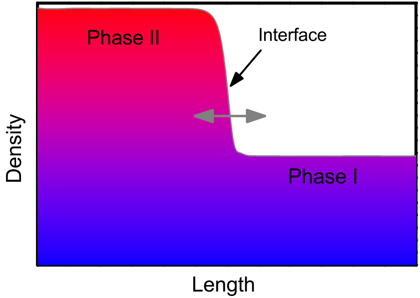

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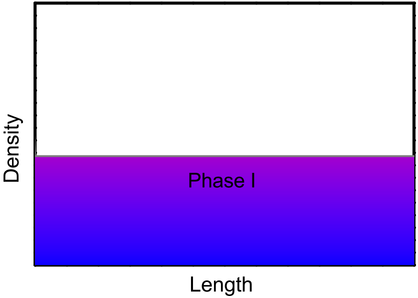

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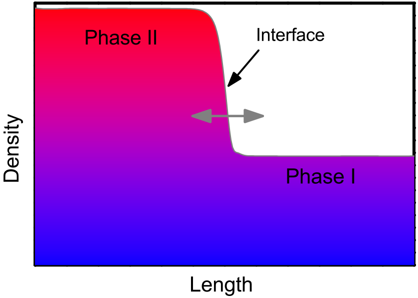

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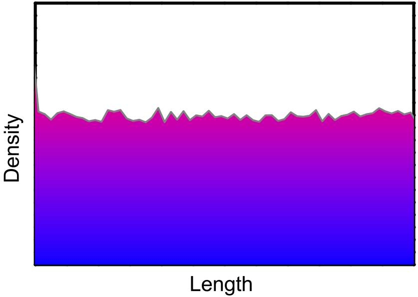

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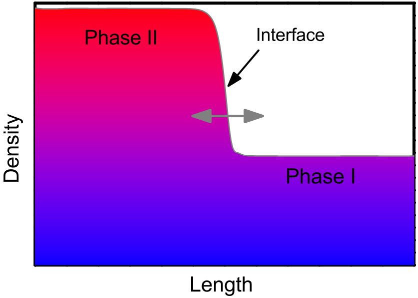

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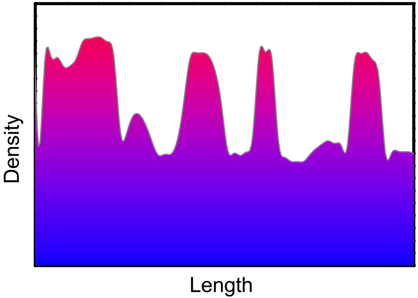

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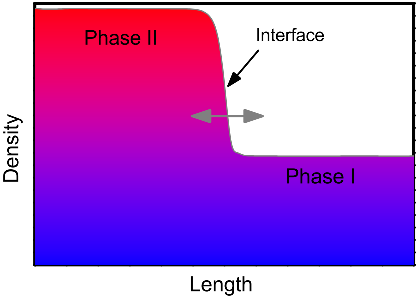

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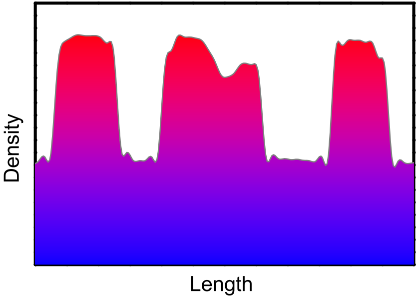

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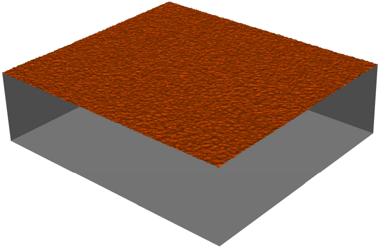
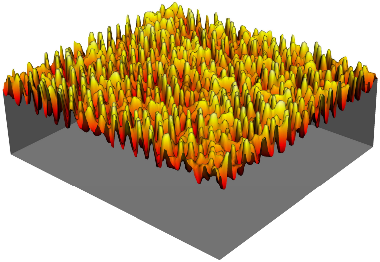




Requires: Fluid dynamics + an EoS with mechanically unstable phase + the surface energy

Can be done, has been done

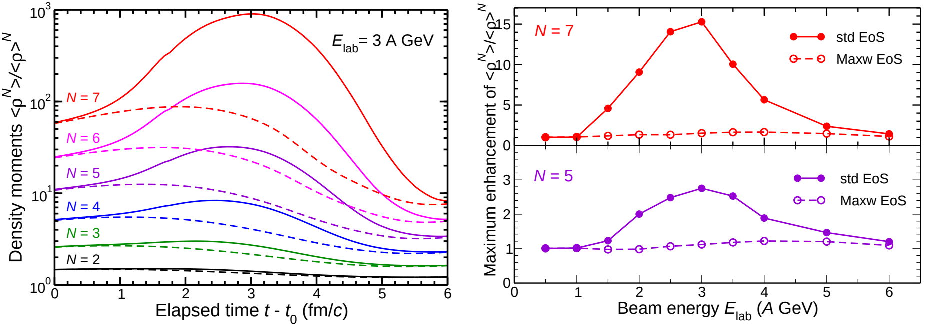
Initialize Random noise in the unstable region and let the phases separate.

Ideal fluid dynamics + an EoS with mechanically unstable phase + the surface energy

Moments of the Baryon Density

Extract moments of the net baryon density distribution:

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



As a function of time

As a function of beam energy

Translate to observables

Usually one measures moments of Number-distributions

- Variance $\sigma^2 = \left\langle \delta N^2 \right\rangle$
- Skewness $S = \left\langle \delta N^3 \right\rangle / (\sigma^2)^{3/2}$
- Kurtosis $\kappa = (\left\langle \delta N^4 \right\rangle / \sigma^4) - 3$

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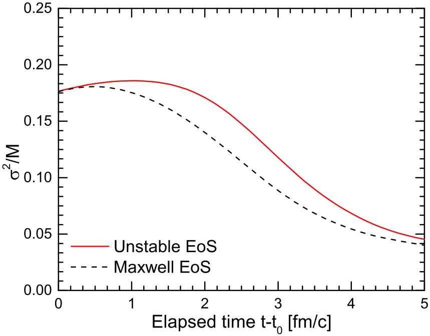

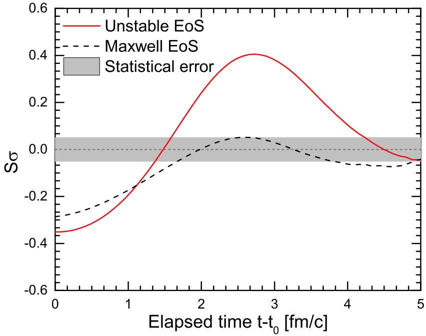

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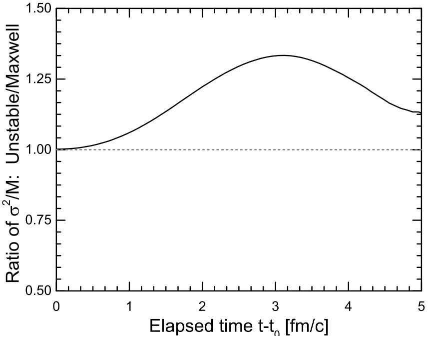
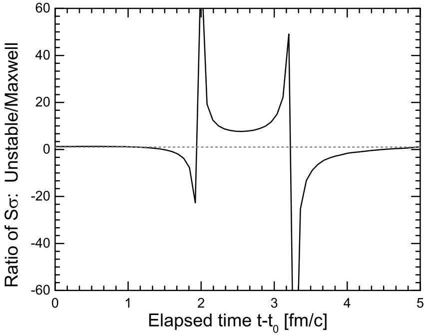
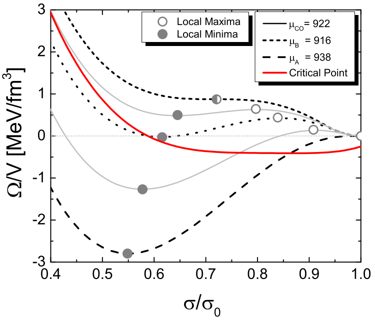




The Critical Point



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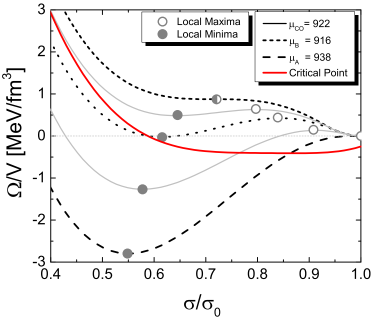

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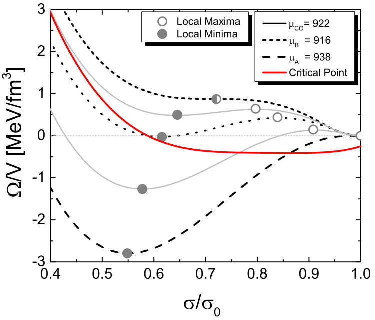

Can be done:

- Fluid dynamics
- + The correct EoS
- + thermal fluctuations / explicit propagation of chiral field
- = chiral fluid dynamics

M.Nahrgang, S.Leupold, C.Herold and M.Bleicher, Phys. Rev. C **84, 024912 (2011)**

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- Effects of the final/hadronic phase.
- Measuring deuterons?

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In this non-equilibrium system the notion of a volume is ill-defined.

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- The system under investigation is small and rapidly expanding.
- Emission of particles does not occur at a fixed time.
- Even more so for kinetic freeze-out
- Usually (an average) N_{part} is taken as proxy for the volume. Or better the energy content of the system.

How to constrain volume fluctuations

We will use the introduced fluid dynamics model with a mechanically unstable phase

- We can select events with any given N_{part}
- Use Cooper-Frye for particle production
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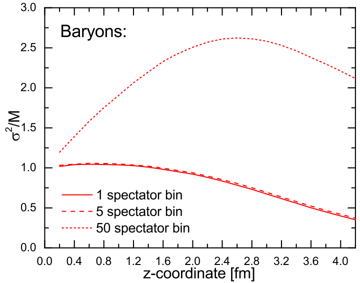

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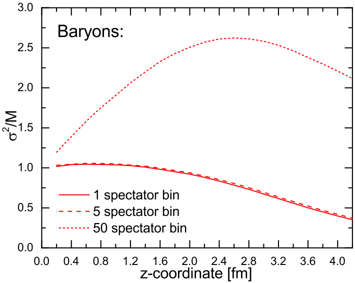

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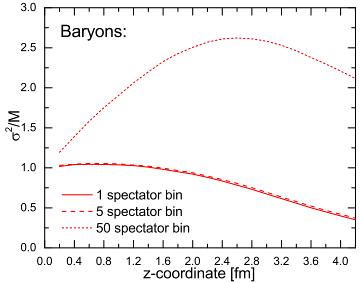

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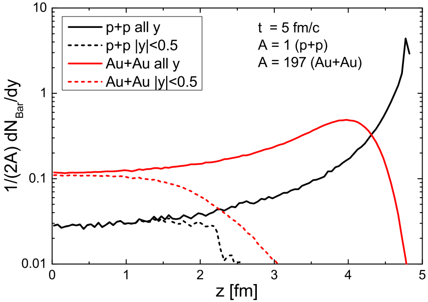
- Interesting z-dependence.
- Problem: N_{part} definition in models $\neq$ definition in experiment.

The stopping mechanism

Stopping in transport

- For beam energies $> \sqrt{s_{\mathrm{NN}}} \approx 7$ GeV $\rightarrow$ string excitation.
- For simplicity string models employed have instant energy loss.



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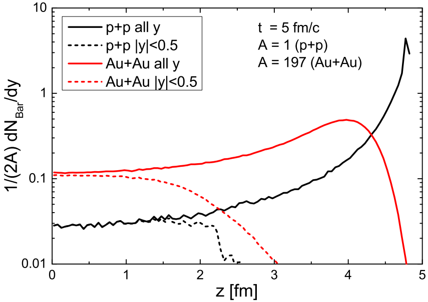

- Strong correlation between rapidity and z-coordinate.
- Stopping in A+A due to secondary interactions.

The stopping mechanism

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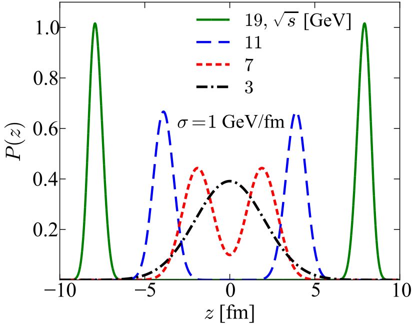
- Question 1: How well are the secondaries understood?
- Question 2: What if there is no instant energy loss?

Constant deceleration:



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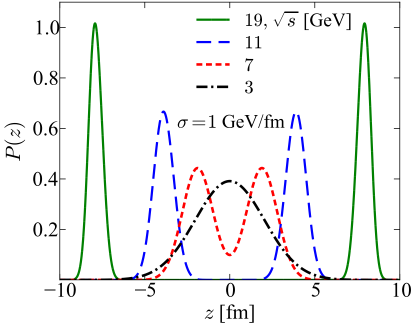

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Energy loss is more complicated.

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May be relevant for v_1 too!?

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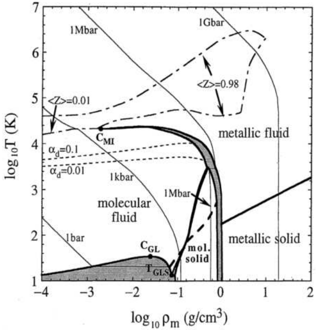

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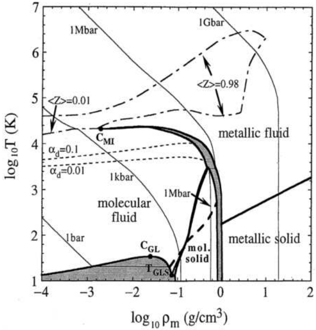

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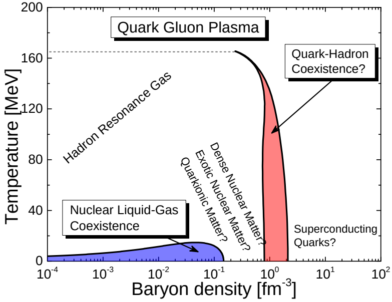

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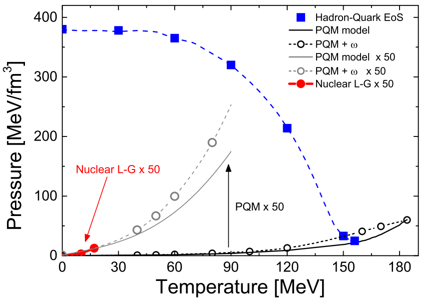

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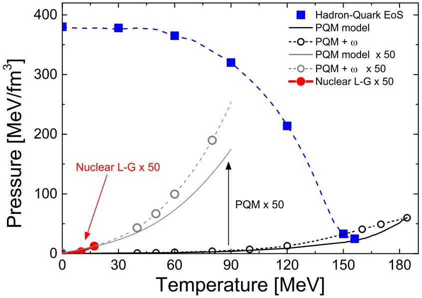

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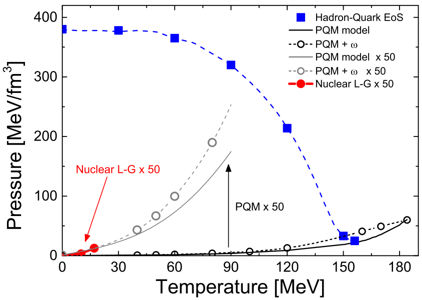

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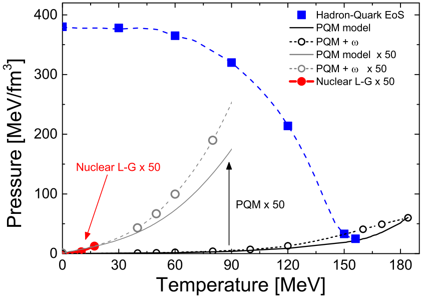

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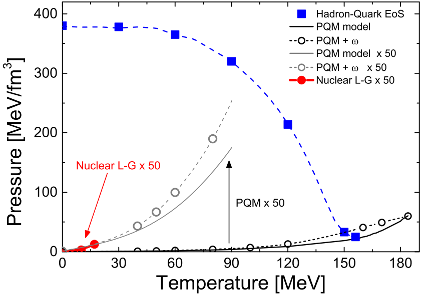

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- One cannot separate small μ_B and large μ_B regions.
- Standard quark based models usually fail this test.

An example of effective model

A hadronic part

The parity doublet model: nucleons (hyperons) and their parity partners belong to the same multiplet and so are true chiral partners.

$$+$$

A quark+gluon part

Use a simple version of the PNJL model

$$+$$

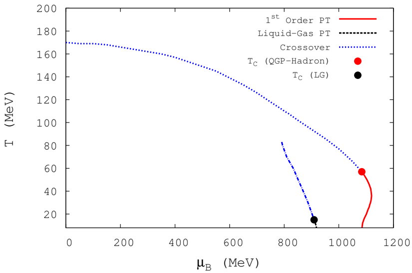
A way to suppress hadrons in the QGP

Use excluded volume

$$=$$

An effective Q-H model

Work in progress: A. Mukherjee, JS and S. Schramm



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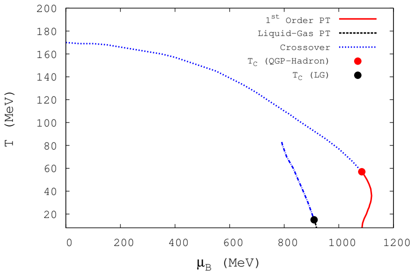

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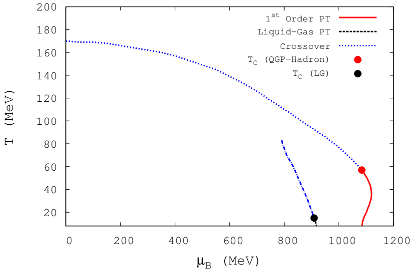

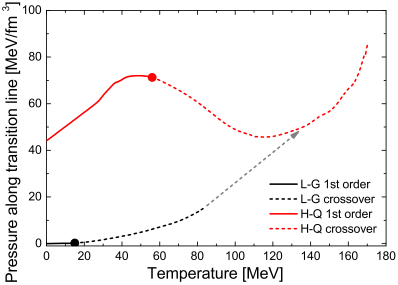

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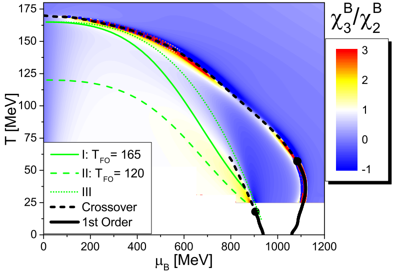
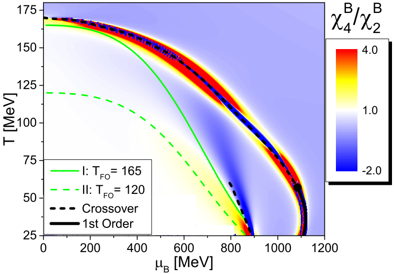
- Pressure vs. Temperature along transition lines.
- High density: Intermingling between both transitions.

Intermingling between both transitions

Normalized cumulants as function of T and μ_B.





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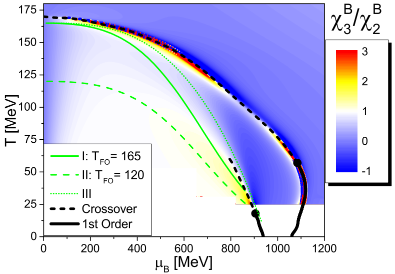

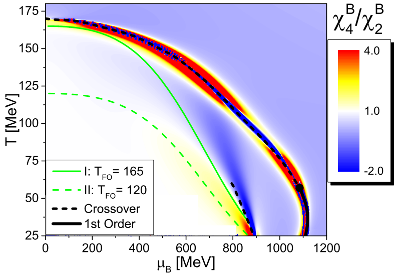

- The nuclear L-G effects are relevant also at larger temperatures!

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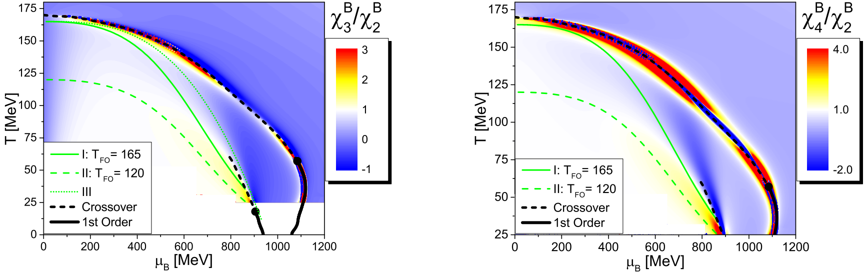
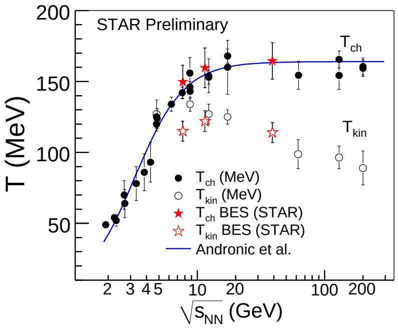


- The nuclear L-G effects are relevant also at larger temperatures!
- A study of the cumulants should never neglect the role of both transitions

Intermingling between both transitions

- When do the fluctuations freeze out?



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- When do the fluctuations freeze out?
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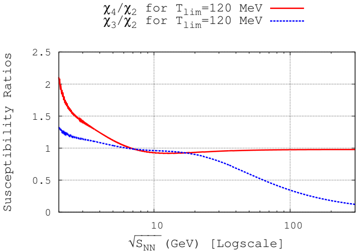

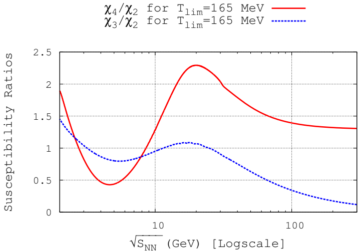

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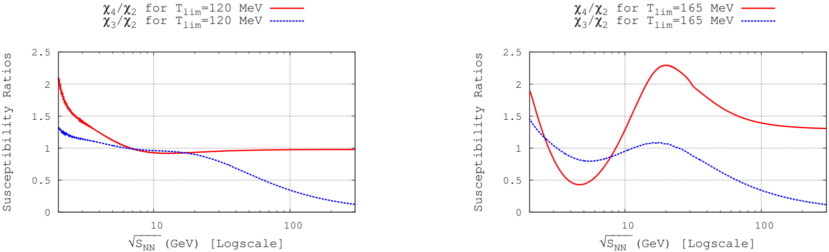
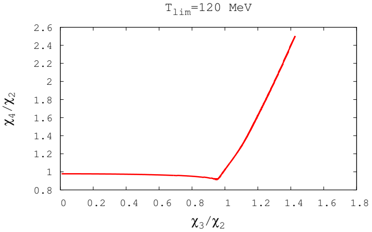
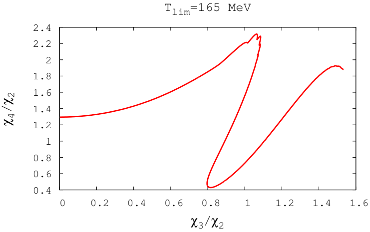


Of course another freeze out scenario is also possible.

Whats with the banana shape?

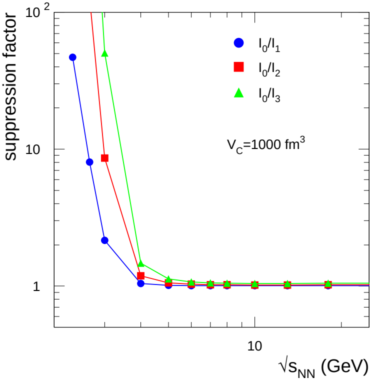
- An idea was put forward that the normalized cumulants as function of each other give a characteristic shape.
- In the presence of two transitions the picture becomes more complicated.





The (Non-)Strange EoS

- At the beam energies of SIS100/FAIR/BESII strangeness is severely suppressed/ out-of-equilibrium.



A. Andronic et al., Nucl. Phys. A 772, 167 (2006)

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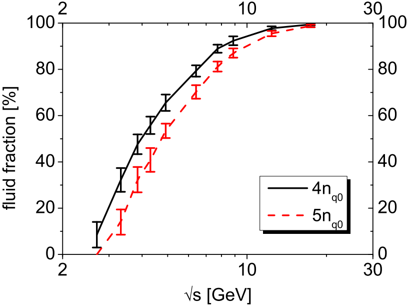

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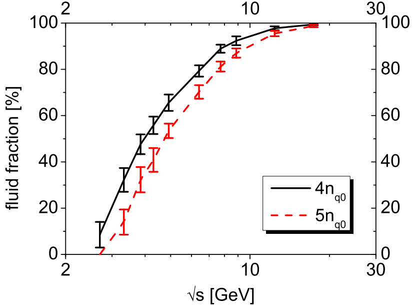
- Think about strangeness distillation and iso.spin distillation.



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Cooper-Frye, the big Poissonizer

How is Cooper-Frye used

$$E\frac{dN}{d^3p} = \int_\sigma f(x,p)p^\mu d\sigma_\mu$$

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- Does C.-F. reproduce the moments in coordinate space?

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- We will use the results of the fluid dynamical simulations with an unstable phase.
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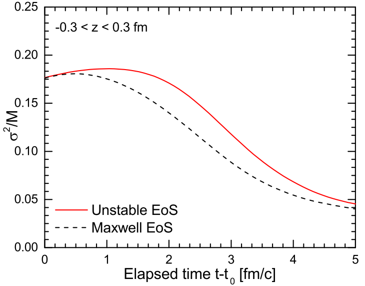

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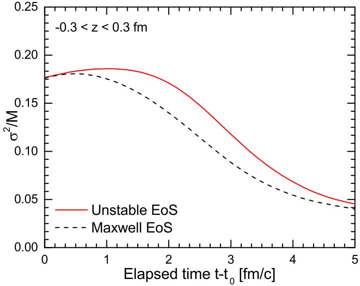

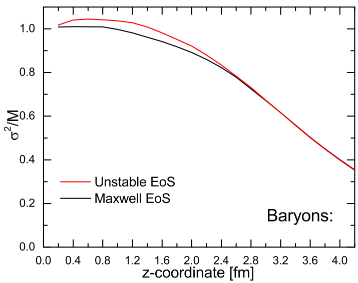

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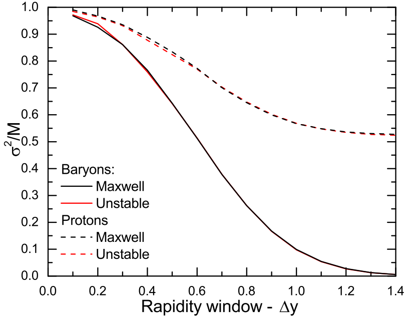

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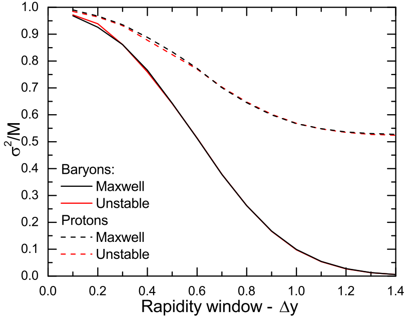

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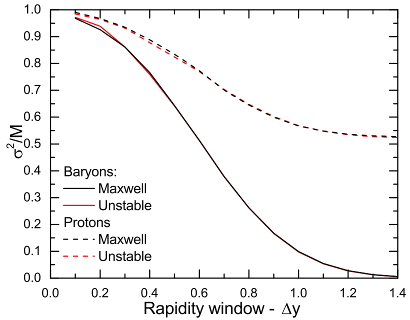

- Instead of cutting in coordinate space, cutting in momentum space
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- Raises the question whether one should use C-F for particle production in studies related to fluctuations.
- Can we come up with a better scheme?
- An event generator that reproduced the desired moments.

Whats happens after the Cooper-Frye?

The hadronic rescattering J. Steinheimer, V. Vovchenko, J. Aichelin, M. Bleicher and H. Stöcker. arXiv:1608.03737 [nucl-th].

- The density just after hadronization is still large enough for sufficient rescatterings to take place.
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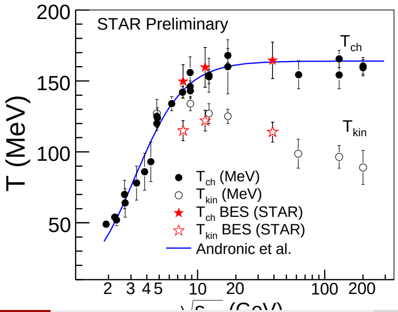

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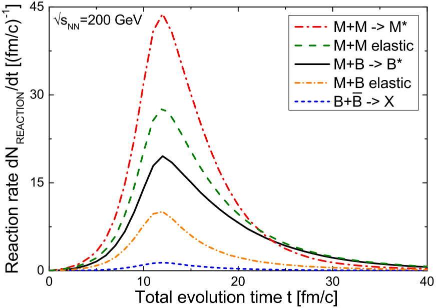

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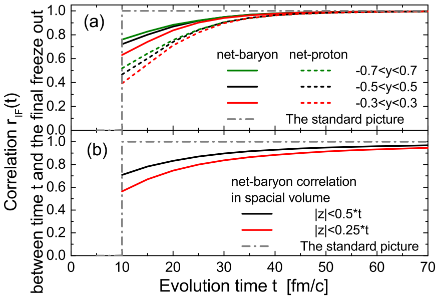

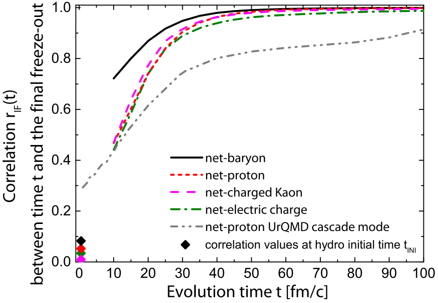

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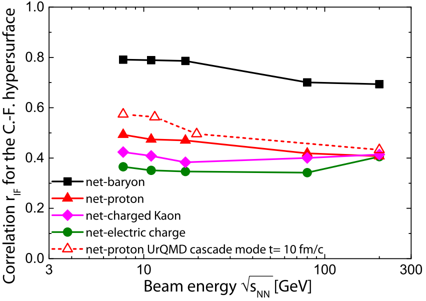

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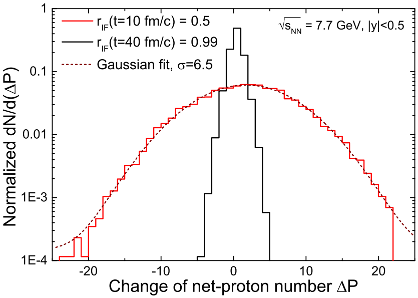

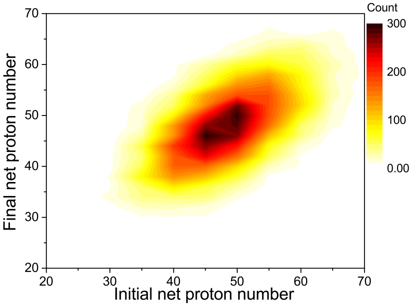

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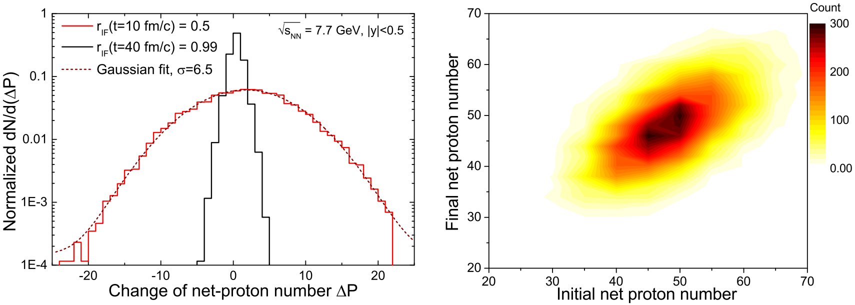

- Survival time of different orders of cumulants?
- Need for non-Poisson event generator.

Deuteron effects

Corrections from nuclei

- Besides efficiency effects and the no-neutron problem

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The deuteron yield n_d in an event with initial proton multiplicity n_i then fluctuates according to a Poisson distribution

$$P_d(n_d|n_i) = \lambda_d^{n_d} \frac{e^{-\lambda_d}}{n_d!} = \left(B n_i^2\right)^{n_d} \frac{e^{-B n_i^2}}{n_d!}$$

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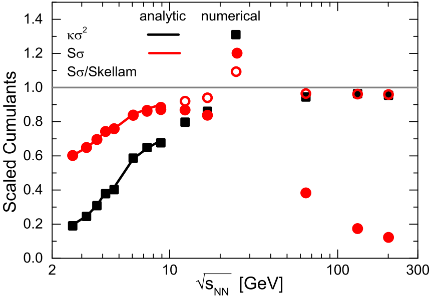

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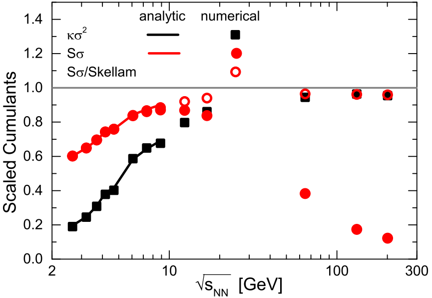
- Results depends on how much proton and neutron number is correlated.



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Is it worth the effort?