# Theory Challenges for CBM

Jan Steinheimer

09/23/2014

HIC for FAIR Helmholtz International Center

FIAS Frankfurt Institute for Advanced Studies

# Goals of CBM

## 'It's a major goal of the CBM experiment to investigate:'

- The transformation from hadrons to quarks and gluons at large (baryon) densities (aka deconfinement).
- Is there a true phase transition in QCD?
- And an associated critical point?
- What is the nature of chiral symmetry restoration and how is it related to deconfinement?

## It's Methods

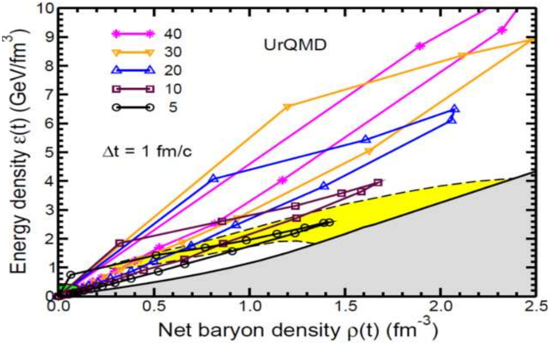
- Use the accelerator build at the FAIR facility (SIS 100/300) to collide heavy nuclei at fixed target beam energies ranging from $2-40$ A GeV.
- Measure the properties of produced light hadrons, heavy flavor hadrons and electromagnetic probes.

The CBM physics Book, Lecture Notes in Physics 814

# CBM

## Experimental parameters

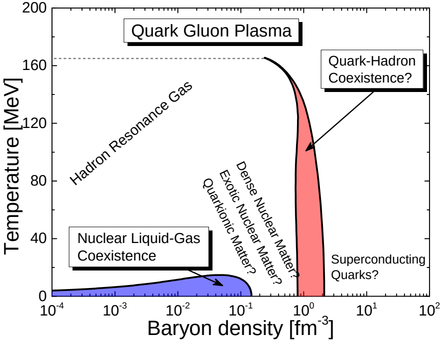
- The maximum net baryon densities expected range from $0.5$ to $2.5$ $fm^{-3}$.
- The maximum energy densities expected range from $2$ to $10$ $GeV/fm^3$.




I. C. Arsene, L. V. Bravina, W. Cassing, Y. B. Ivanov, A. Larionov, J. Randrup, V. N. Russkikh and V. D. Toneev et al., Phys. Rev. C **75**, 034902 (2007)

# Phase diagrams

Since the relevant quantities in heavy ion collisions are the densities, maybe we should consider also the phase diagram in density.




Data from: M. Hempel, V. Dexheimer, S. Schramm and I. Iosilevskiy, Phys. Rev. C 88, no. 1, 014906 (2013)

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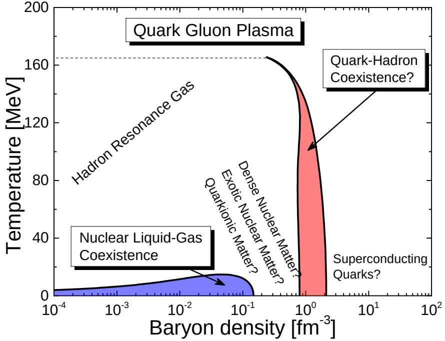


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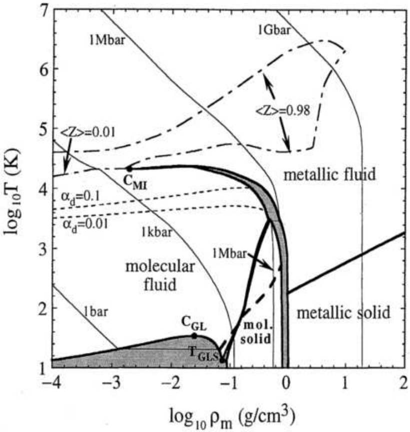


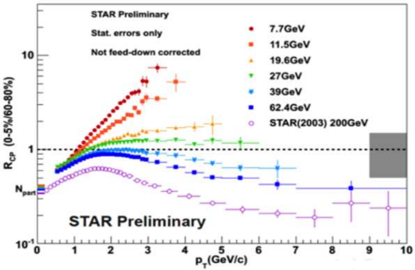

Kitamura H., Ichimaru S., J. Phys. Soc. Japan 67, 950 (1998).

# Previous Signals

## Signals for the QGP at RHIC and LHC

- The quenching of high $p_T$ particles in central, compared to peripheral, or p+p, collisions.

## Signals for Chiral symmetry restoration




$R_{CP}$ is the ratio of central to peripheral $dN/dp_T$ spectra, scaled with the appropriate number of binary scatterings.

A. Schmah [STAR Collaboration], J. Phys. Conf. Ser. 426, 012007 (2013).

# Previous Signals

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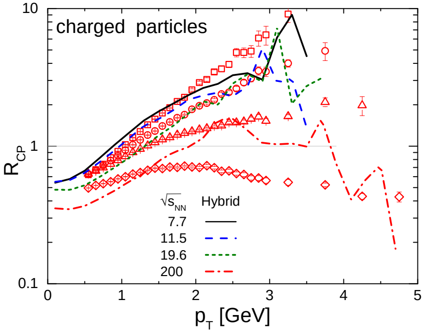
## Signals for Chiral symmetry restoration

Similar behavior in hydrodynamic model without jets. Effect of radial flow.



# Previous Signals

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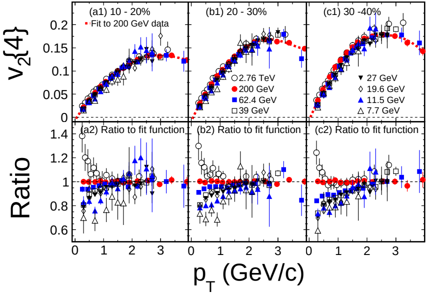
- The quenching of high $p_T$ particles in central, compared to peripheral, or p+p, collisions.
- The formation of elliptic flow, which is nicely described by a low viscosity fluid.




$v_2$ quantifies the transverse azimuthal momentum assymetry $v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$.

L. Adamczyk et al. [STAR Collaboration], Phys. Rev. C 86, 054908 (2012)

## Signals for Chiral symmetry restoration

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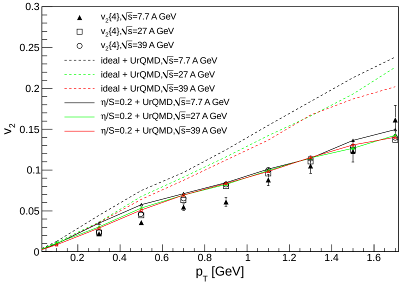
## Signals for Chiral symmetry restoration

Behavior is well reproduced by hydrodynamics with a small viscosity.




I. A. Karpenko, M. Bleicher, P. Huovinen and H. Petersen, J. Phys. Conf. Ser. 503, 012040 (2014)

Apparently collective behavior observed down to lowest beam energies!

# Previous Signals

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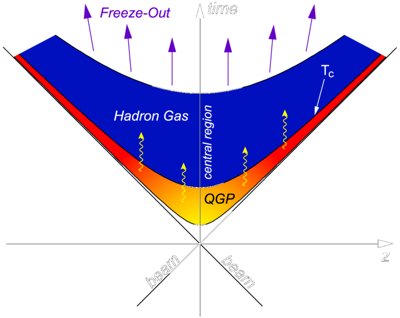
- The formation of elliptic flow, which is nicely described by a low viscosity fluid.
- The transport properties of heavy quarks

## Signals for Chiral symmetry restoration

## Charm is transported not produced

Do charm quarks adopt the collective properties of the expanding QGP?



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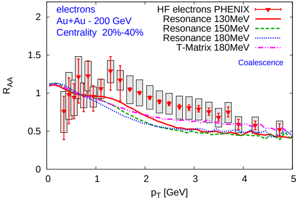
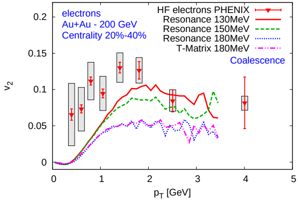
- The formation of elliptic flow, which is nicely described by a low viscosity fluid.
- The transport properties of heavy quarks
  - Low decoupling Temperature: Role of Hadronic Phase?!

## Signals for Chiral symmetry restoration

Simultaneous description of D $R_{AA}$ and $v_2$ is hard to achieve.




T. Lang, H. van Hees, J.S. and M. Bleicher, arXiv:1211.6912 [hep-ph].

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- The formation of elliptic flow, which is nicely described by a low viscosity fluid.
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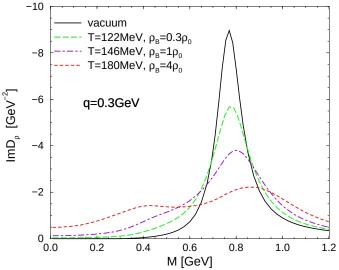
## Signals for Chiral symmetry restoration

- The properties of di-leptons from vector mesons.




Possible scenarios of a broadening or mass shifted $\rho$

R. Rapp and J. Wambach, Adv. Nucl. Phys. 25, 1 (2000)

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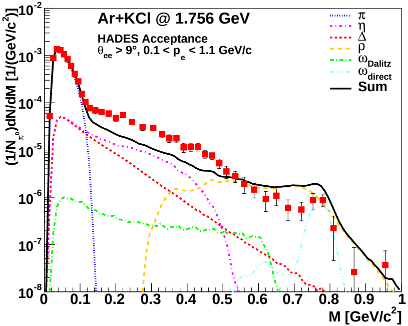
## Signals for Chiral symmetry restoration

- The properties of di-leptons from vector mesons.

Model calculation needs to take into account all the other hadronic contributions to di-lepton rates.



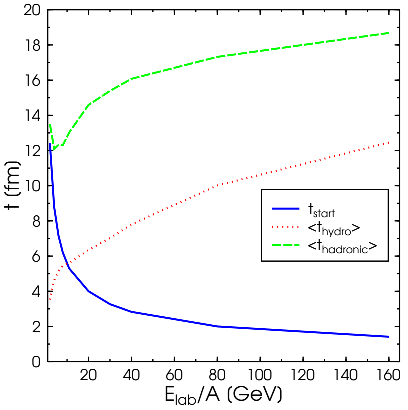

S. Endres, H. van Hees, J. Weil and M. Bleicher, J. Phys. Conf. Ser. 503, 012039 (2014)

What is the connection to chiral symmetry restoration?

# Crucial Ingredient

### Lessons learned so far

- Fluid Dynamics works even down to FAIR energies.
- Important to take into account hadronic phase!

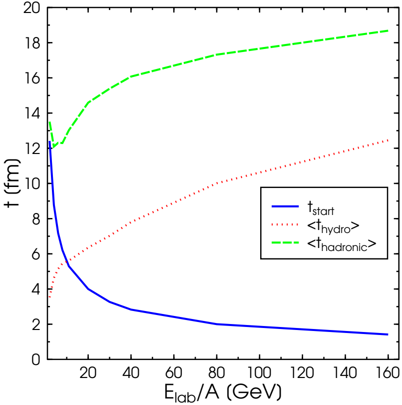



H. Petersen, J.S., G. Burau, M. Bleicher and H. Stöcker, Phys. Rev. C 78, 044901 (2008)

# Crucial Ingredient

## Lessons learned so far

- Fluid Dynamics works even down to FAIR energies.
- Important to take into account hadronic phase!
- If at all, observables only sensitive to aspects of deconfinement.
- No smoking gun signal for the phase transition defined yet.

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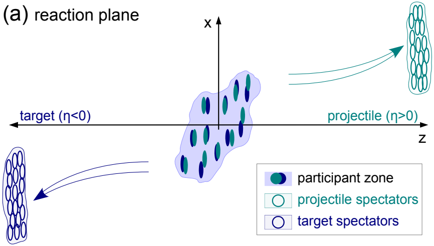
# The $v_1$ story

## Maybe:

- Early studies proposed the directed flow as a signal of the phase transition
- They where done using only 1 or 2 fluid dynamics.

## What is directed flow?

Deflection of matter in the reaction plane: $v_1 = \langle p_x / p_T \rangle \, (y)$




B. Abelev et al. [ALICE Collaboration], Phys. Rev. Lett. 111, no. 23, 232302 (2013)

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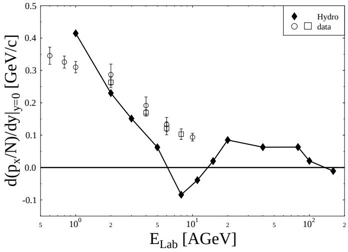
## What is directed flow?

One is interested in the slope of $v_1 = \langle p_x/p_T \rangle (y)$ w.r.t the rapidity.




K. Paech, M. Reiter, A. Dumitru, H. Stoecker and W. Greiner, Nucl. Phys. A 681, 41 (2001)

# The $v_1$ story

## Maybe:

- Early studies proposed the directed flow as a signal of the phase transition
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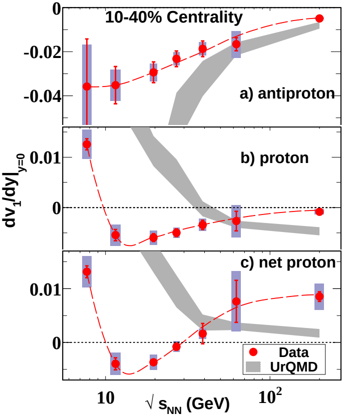
- Resent STAR measurements show a negative slope of net proton $v_1$.
- Is it the phase transition?

## STAR data

Data on the net proton $v_1$ slope show the predicted behavior.




L. Adamczyk et al. [STAR Collaboration], Phys. Rev. Lett. 112, 162301 (2014)

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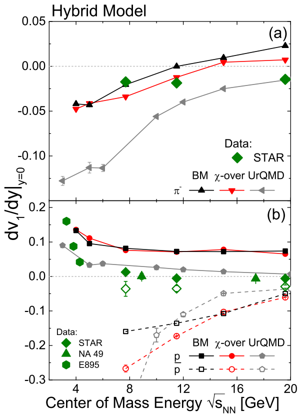
- Standard hybrid-hydro says no

## Hybrid Model

However, when checked with state of the art hydro, no signal is found.




J.S., J. Auvinen, H. Petersen, M. Bleicher and H. Stöcker, Phys. Rev. C 89, 054913 (2014)

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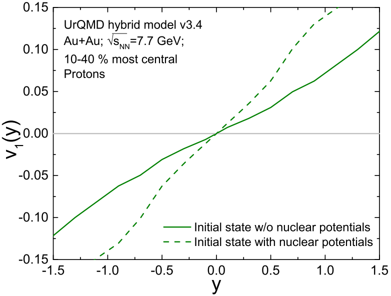
- Standard hybrid-hydro says no
- But changing the initial EoS changes the slope.

## Hybrid Model

However, when the stiffness of the initial state is changed one observes a sensitivity!



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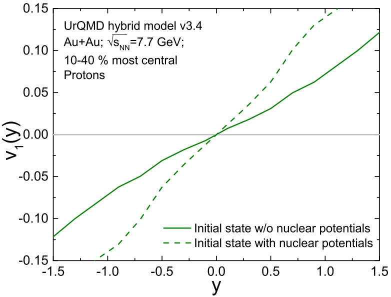
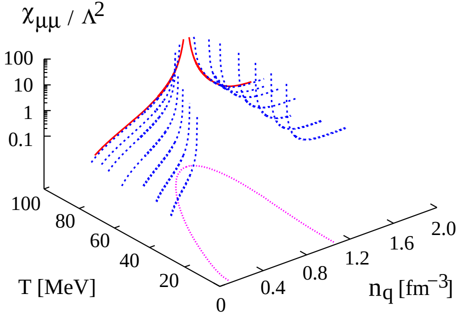



So $v_1$ might be sensitive to the 'softness' of the initial state... but is that the phase transition?

# A Phase Transition in Fluid Dynamics

- In a dynamical scenario, locally the system may not be in phase eq.
- Phase separation occurs.
- What about the surface tension; Can be as important as viscosity.




C.Sasaki, B.Friman and K.Redlich, Phys. Rev. Lett. 99, 232301 (2007)

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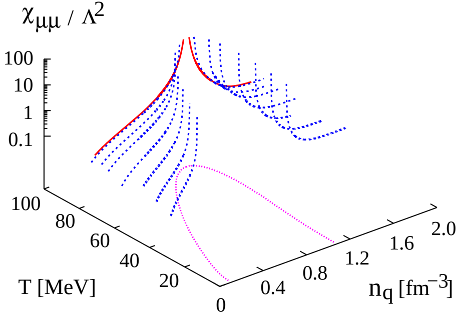


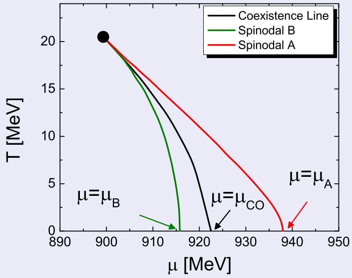

C.Sasaki, B.Friman and K.Redlich, Phys. Rev. Lett. 99, 232301 (2007)

- Susceptibilities diverge due to mechanically unstable phase.
- Separation of the two phases: Spinodal Instabilities.
- It's not the amplitude of the density fluctuation which diverges!

# A possible application from nuclear Physics

How can we describe a first order phase transition in QCD and find observables related to it?

## The nuclear Liquid-Gas phase-transition:

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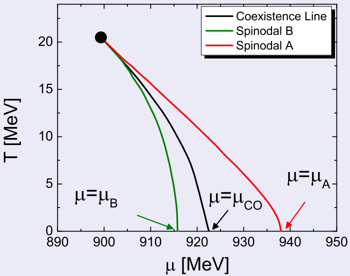
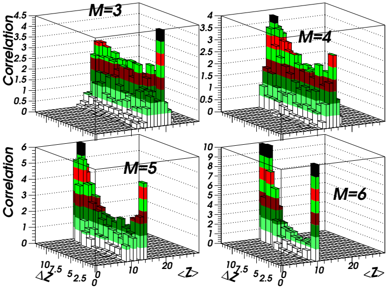



[1]

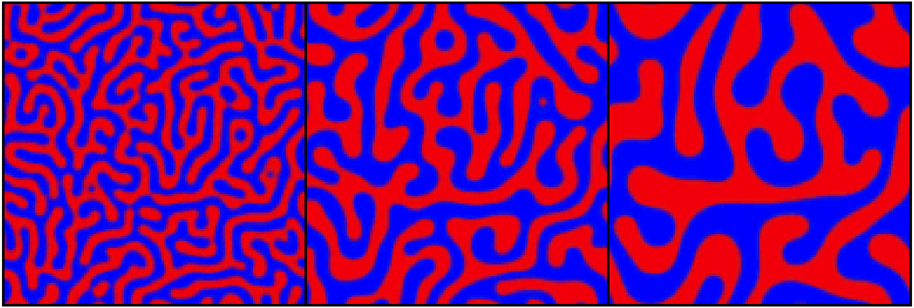



- Study higher-order charge correlations for fragments.
- Observe an enhancement of events with nearly equal-sized fragments.
- Spinodal decomposition in the nuclear Liquid-Gas phase-transition!

[1] B. Borderie *et al.* [INDRA Collaboration], Phys. Rev. Lett. **86**, 3252 (2001)

# Non-Equilibrium Phase Transition

"Spinodal decomposition is essentially a mechanism for the rapid unmixing of a mixture of liquids or solids from one thermodynamic phase, to form two coexisting phases."

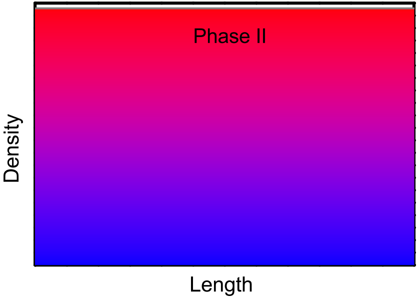


I takes place for example when one quenches a mixture of two substances rapidly below the demixing temperature. Then, the two substances separate locally, giving rise to the complicated structures which can be seen on the leftmost picture.

# Non-Equilibrium Phase Transition

### Equilibrium Phase Transition (Maxwell construction)

As the system dilutes, the phases are always well separated



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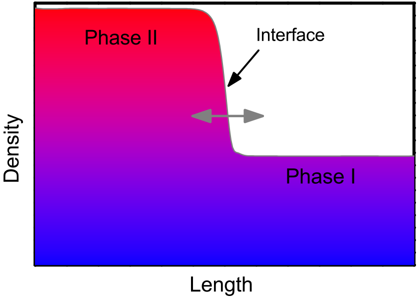

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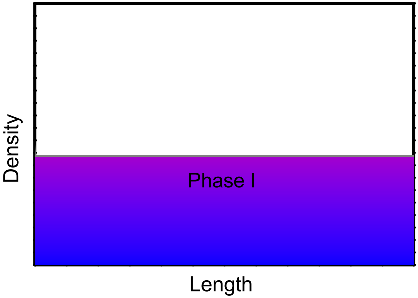

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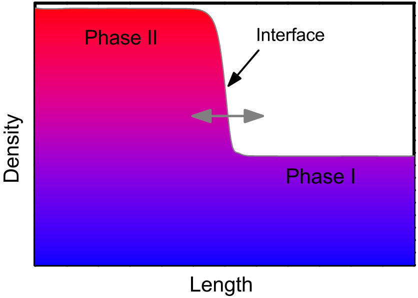
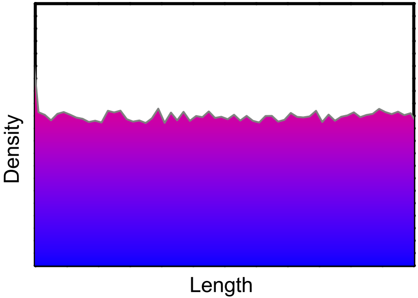
### Non-Equilibrium Phase Transition

Phase separation is a dynamical process.



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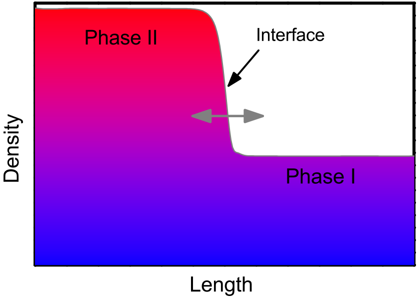


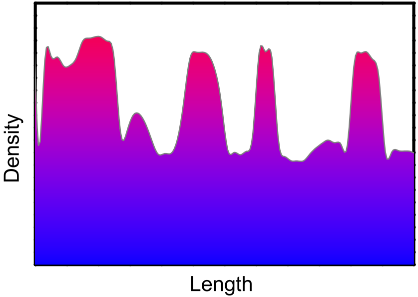

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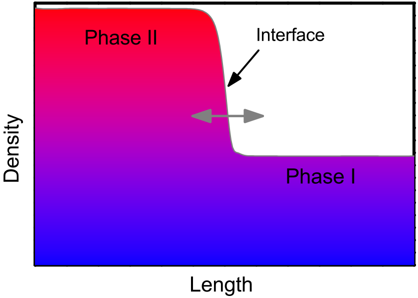


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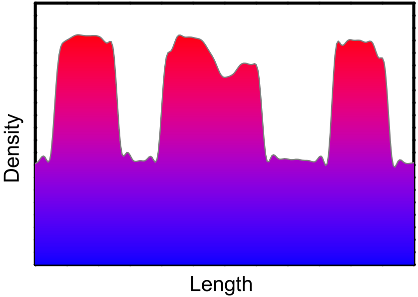
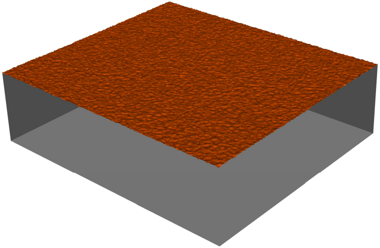
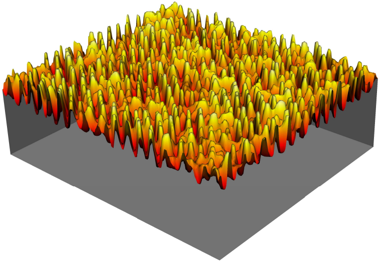


# Show Animation I

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

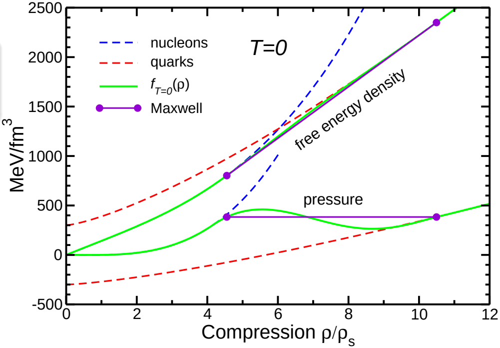




How to include this in fluid dynamics?

Obtain the free energy density $f_T(\rho) = \epsilon_T(\rho) - Ts_T(\rho)$ by a spline between a Gas of int. nucleons+pions and a QGP.

$\partial_\rho^2 f_T(\rho) > 0$: (Meta-)Stable
$\partial_\rho^2 f_T(\rho) < 0$: Unstable




Alternatively: Do a Maxwell construction.

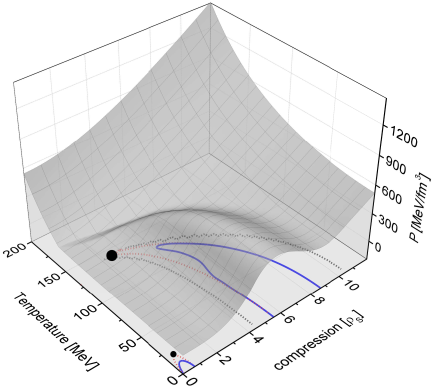
# Constructing an Effective EoS

Obtain the free energy density $f_T(\rho) = \epsilon_T(\rho) - T s_T(\rho)$ by a spline between a Gas of int. nucleons+pions and a QGP.

$\partial^2_\rho f_T(\rho) > 0$: (Meta-)Stable
$\partial^2_\rho f_T(\rho) < 0$: Unstable

Fluid evolution: $T \neq$ const. but $S/A =$ const.

$c_s^2\big|_T < 0$: Isothermal spinodal
$c_s^2\big|_{S/A} < 0$: Isentropic spinodal



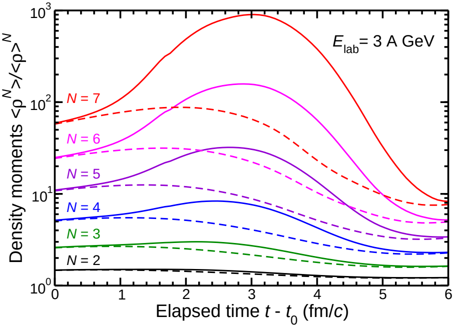

Alternatively: Do a Maxwell construction.

# Moments of the Baryon Density

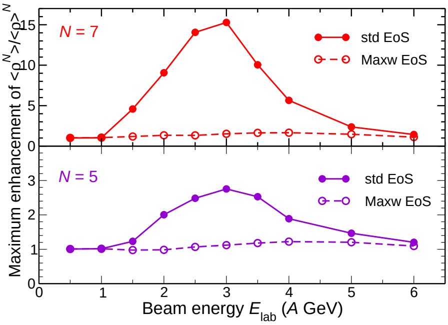
## Let's be more quantitative

Define Moments of the net baryon density distribution:

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




As a function of time




As a function of beam energy

# Dynamics models for the phase transition

## What else can be done

- Thermal fluctuations as seeds to be amplified.

# Dynamics models for the phase transition

## What else can be done

- Thermal fluctuations as seeds to be amplified.
- Dynamical evolution of the chiral fields: Critical slowing down.
- Can be included when the dynamics of the chiral field(s) are separated from the heat bath.
- Separately solve the equations of motion for the heat bath (quarks) and the chiral field

# Dynamics models for the phase transition

## What else can be done

- Thermal fluctuations as seeds to be amplified.
- Dynamical evolution of the chiral fields: Critical slowing down.
- Can be included when the dynamics of the chiral field(s) are separated from the heat bath.
- Separately solve the equations of motion for the heat bath (quarks) and the chiral field

## Chiral fluid dynamics

Use a quark based chiral model Lagrangian:

$$\mathcal{L} = \mathcal{L}_{kin} - U(\sigma) - \mathcal{U}(\ell, \bar{\ell}) \text{ with } \mathrm{V_{eff}} = \mathrm{U} + \mathcal{U} + \Omega_{\mathrm{q\bar{q}}} \quad (1)$$

Derive the Langevin equation of motion incl. friction and noise

$$\partial_\mu \partial^\mu \sigma + \eta_\sigma(T) \partial_t \sigma + \frac{\partial V_{\mathrm{eff}}}{\partial \sigma} = \xi_\sigma \quad (2)$$

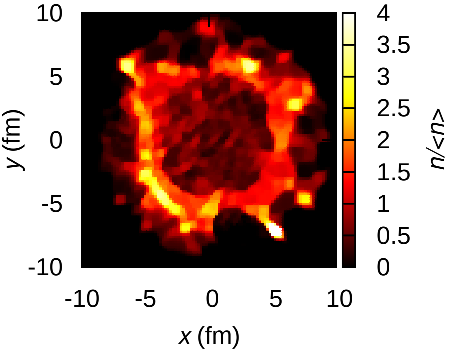
And propagate the heat bath with ideal fluid dynamics using a source term

$$\partial_\mu T_q^{\mu\nu} = S^\nu \ . \quad (3)$$

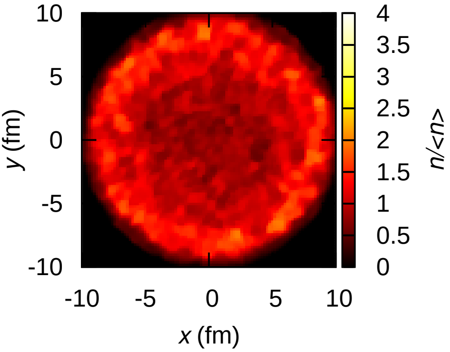
M. Nahrgang, S. Leupold, C. Herold and M. Bleicher, Phys. Rev. C 84, 024912 (2011)

# Dynamics models for the phase transition

System with a first order transition




System with a critical point

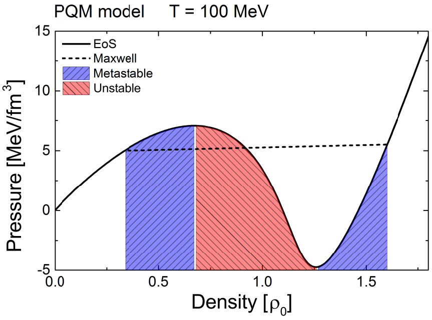



Strong 'clumping' of the baryon number observed, even at late times

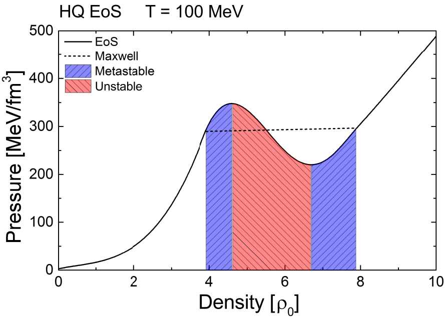
# How Important is the specific EoS?

How sensitive is this result on the EoS? The specific model used?

Use the PQM model, a constituent quark $\sigma$ model with Polyakov Loop potential.




Use an EoS constructed from a hadronic nucleon-pion model plus a bag model.



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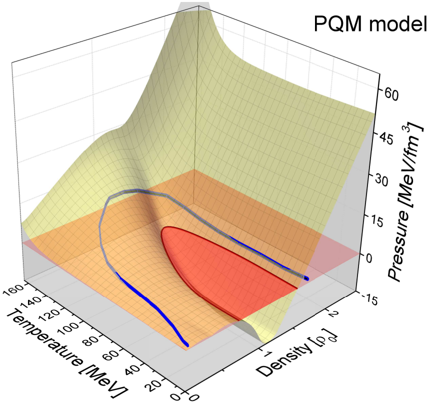


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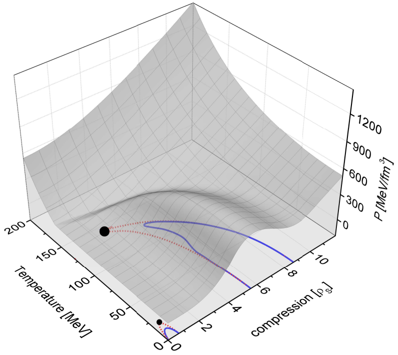
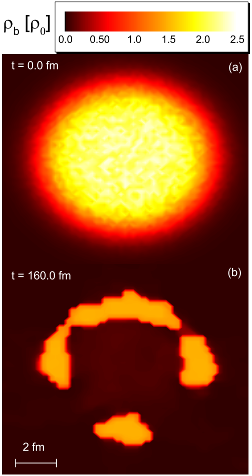
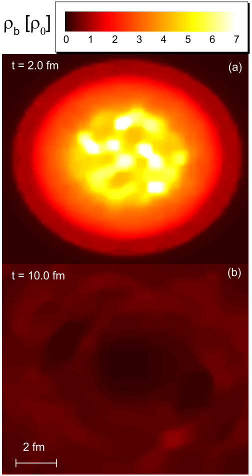


# Droplet Formation

Initialize a symmetric system + fluctuations and let it evolve:

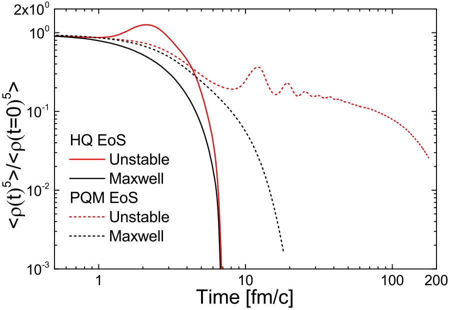



The PQM model produces almost stable droplets of quark matter.

# Fluctuations Compared

Initialize a symmetric system + fluctuations and let it evolve:



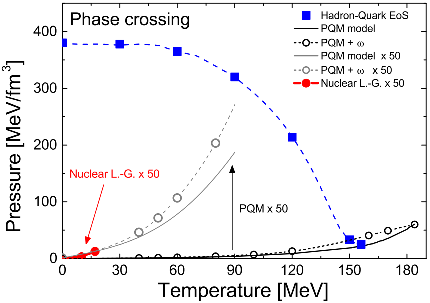

The droplets in the PQM model have a long lifetime, one can even see oscillation. Average 5th power of density is enhanced in both cases.

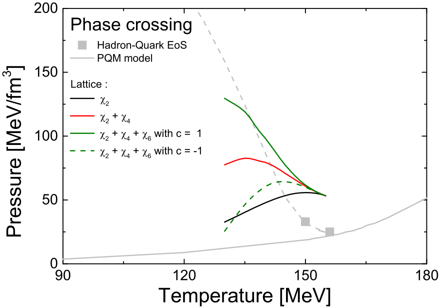
## The Conclusion

The Equation of State matters!

# Differences in the EoS

There are significant differences in the EoS along the transition curve, depending on the nature of the transition:




Is the PQM, at high densities, just a bad model for the Liquid gas transition

# Messages to take Home

- Bulk observables can be described by fluid dynamics even for CBM energies.
- So it seems we have the models to describe a phase transition.
- Including viscosity is work in progress.
- Once the medium evolution is there we have methods to include also heavy quarks and electromagnetic probes.

# What about the EoS

## The Challenges

- We need to better constrain the EoS therefore constraining signals.
- Use lattice at $\mu_B = 0$, thermodynamics + susceptibilities.
- Use neutron stars. CBM is between lattice and neutron stars!
- Big opportunities for collaboration between effective model (field theory/effective QCD) and dynamical model (transport/hydro) guys

Otherwise we cannot make the consistent, quantitative predictions need for CBM!

# What we need

We're not there yet!

## In other Words

A lively discussion on the EoS, and possible observable consequences.
Distinguish between onset of deconfinement and a real phase transition.