Transition from ideal to viscous Mach Cones in a partonic transport model

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in collaboration with A. El, O. Fochler, H. Niemi, Z. Xu and C. Greiner

I. Bouras et al., Phys. Rev. Lett. 103:032301 (2009)

I. Bouras et al., PRC 82, 024910 (2010)

I. Bouras et al., Phys.Lett. B710 (2012)

HGS-HIRe for FAIR
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GOETHE UNIVERSITÄT FRANKFURT AM MAIN

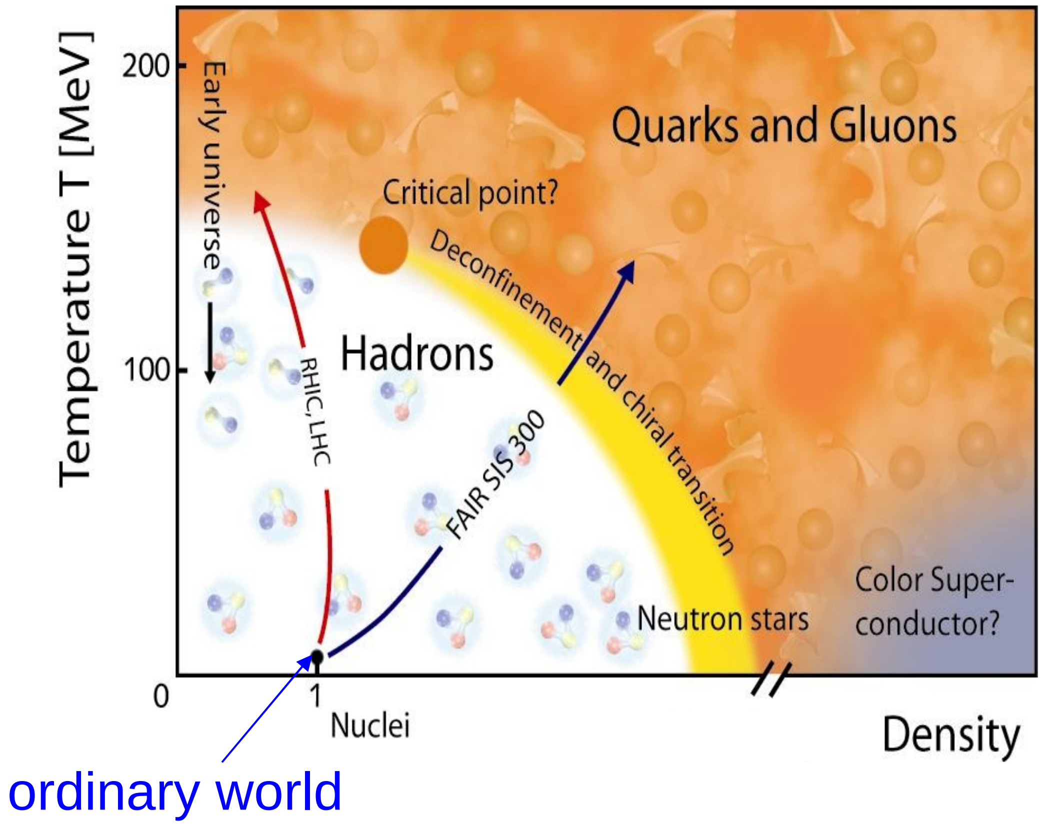
HIC for FAIR
Helmholtz International Center

Excited QCD
Peniche, Portugal

May, 2012

Motivation

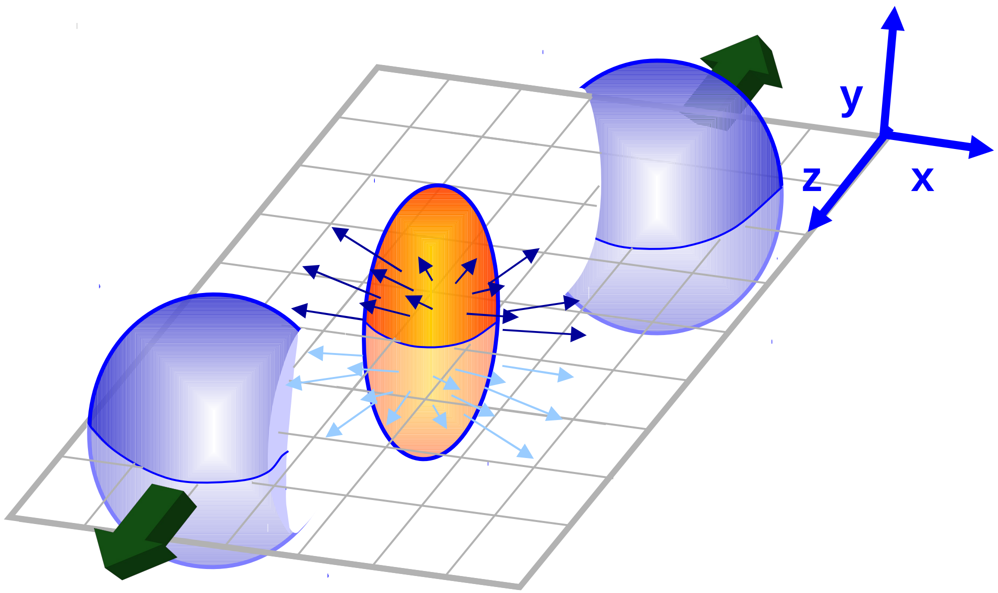
QCD Phase diagram

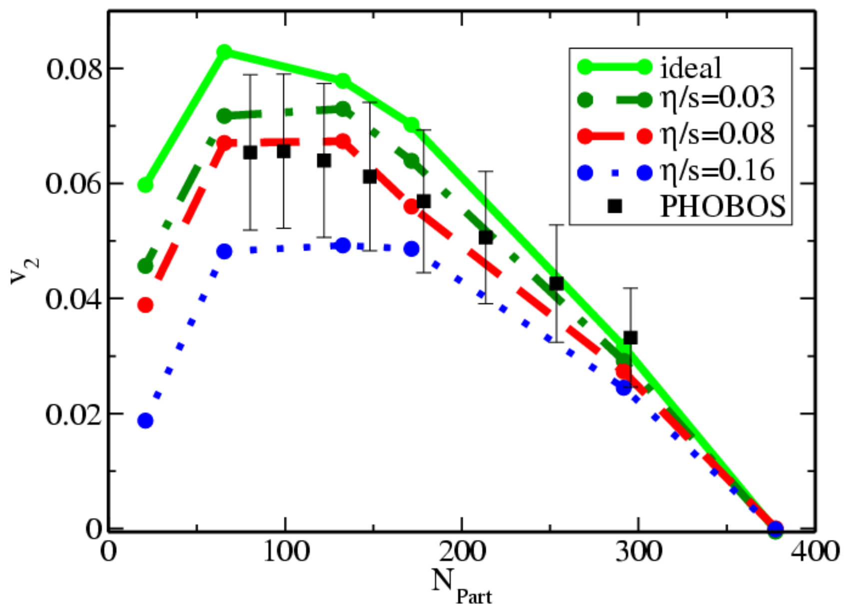


QCD is most probably the theory we have to describe

Motivation

Elliptic Flow

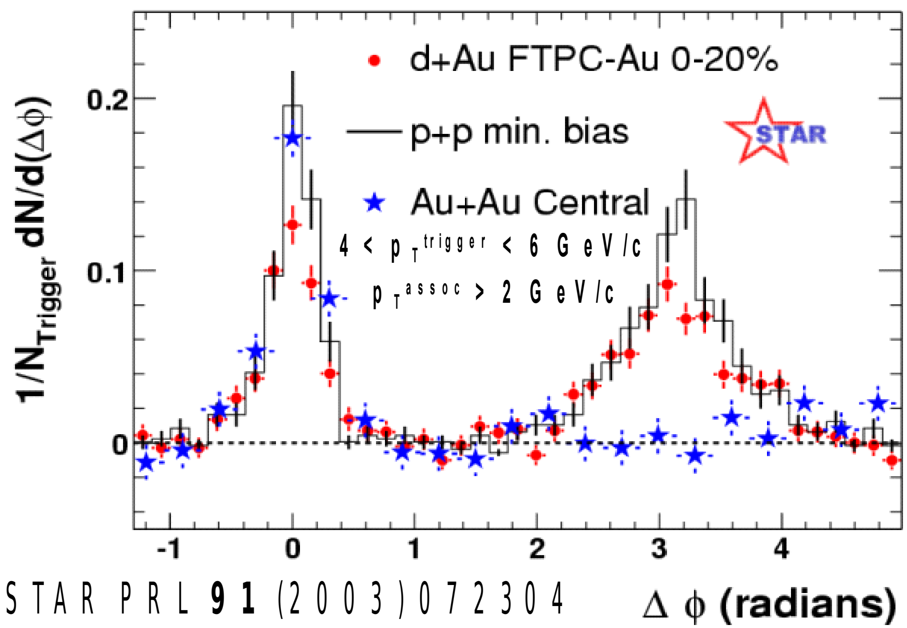




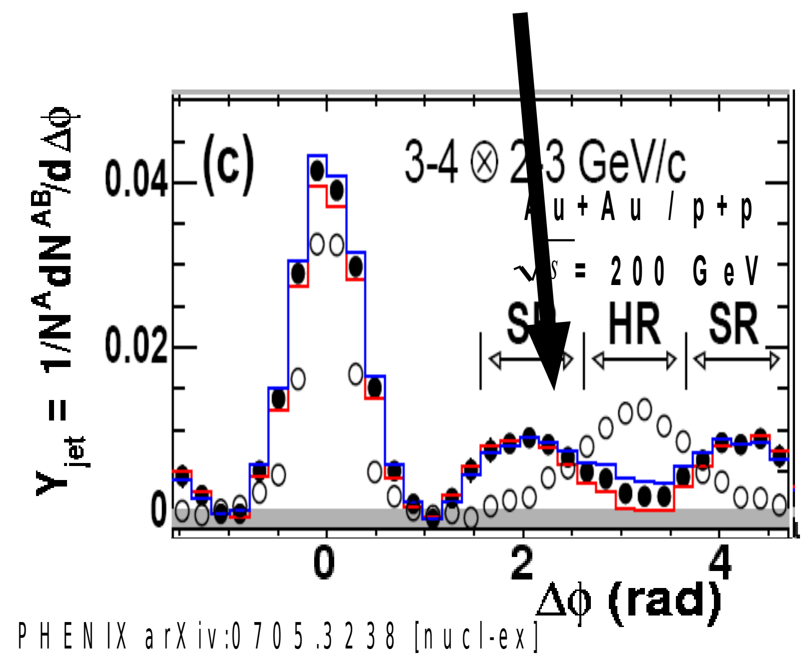
- Matter behaves like a nearly perfect fluid
- Early thermalization

Motivation

Jet-Quenching and Two-particle correlations



Mach Cones???



- Jet-physics is another good observable ot understand the Porperties of the matter

Do Mach Cones have something to do with double peaks?
→ Then answer is given in the end of the talk

Motivation

- We need in general the full QCD to describe the evolution of HIC
- Since we can not solve QCD in a satisfied way, we need models which approximate this evolution

- Matter has a collective behaviour → hydrodynamics

- Jet-Quenching gives us a good observable to study microscopic porperties

- → need a model combining both phenomena in one framework
- Needed to investigate Mach Cones and their related two-particle correlations

The Parton Cascade BAMPS

- Transport algorithm solving the **Boltzmann equation** using Monte Carlo techniques

$$p^{\mu}\partial_{\mu} f(x,p)=C_{22}+C_{23}+\ldots$$

Boltzmann
Approach for
Multi-
Parton
Scatterings

- Stochastic interpretation of collision rates

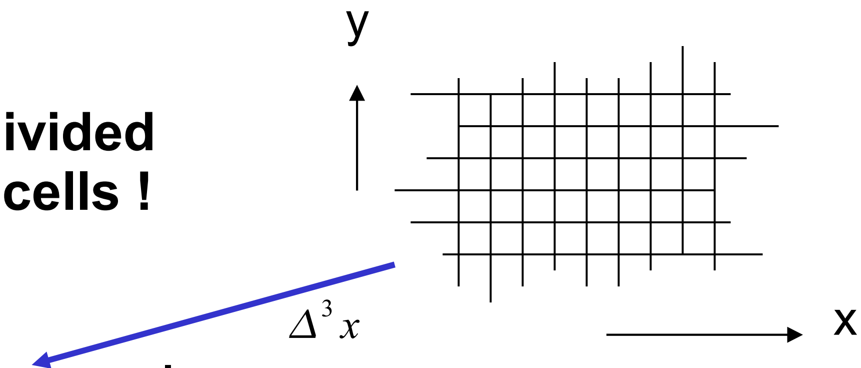
$$P_{2i}=v_{rel}\frac{\sigma_{2i}}{N_{test}}\frac{\Delta t}{\Delta^3 x}$$

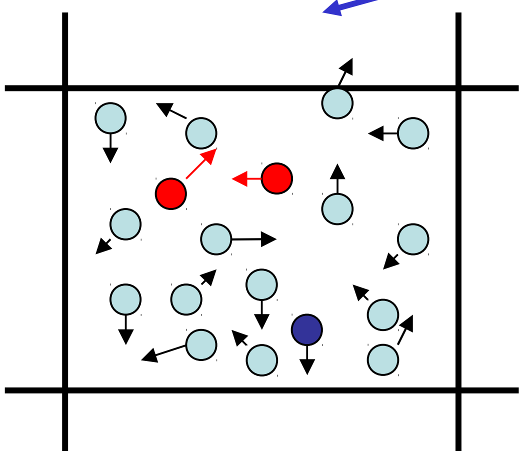
Z. Xu & C. Greiner,
Phys. Rev. C 71 (2005) 064901

- In general:
  pQCD interactions, 2 ↔ 3 processes,
  quarks and gluons

The Parton Cascade BAMPS

Space is divided into small cells !





Boltzmann
Approach for
Multi-
Parton
Scatterings

$$\text{for } 2\rightarrow 2 \quad P_{22} = v_{rel} \frac{\sigma_{22}}{N_{test}} \frac{\Delta t}{\Delta^3 x}$$

$$\text{for } 2\rightarrow 3 \quad P_{23} = v_{rel} \frac{\sigma_{23}}{N_{test}} \frac{\Delta t}{\Delta^3 x}$$

$$\text{for } 3\rightarrow 2 \quad P_{32} = \frac{1}{8 E_1 E_2 E_3} \frac{I_{32}}{N_{test}^2} \frac{\Delta t}{(\Delta^3 x)^2}$$

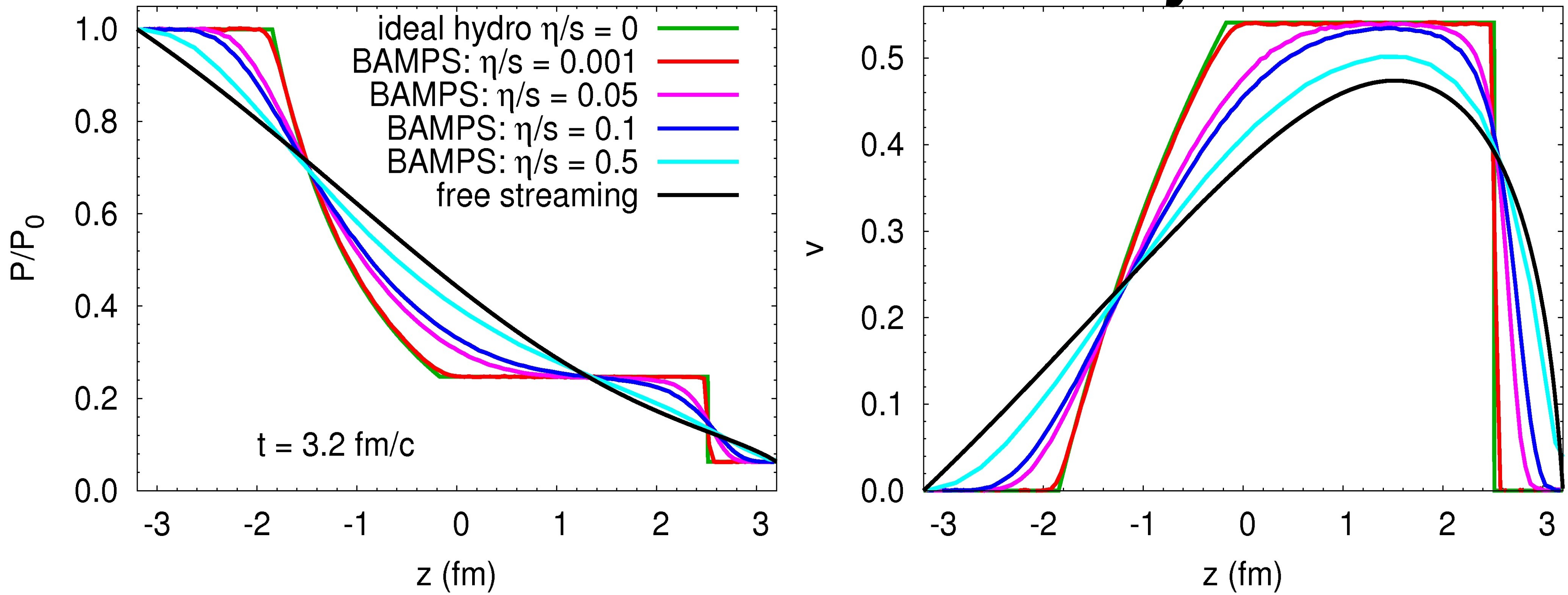
Z. Xu & C. Greiner,
Phys. Rev. C 71 (2005) 064901

$$I_{32} = \frac{1}{2} \int \frac{d^3 p'_1}{(2\pi)^3 2 E'_1} \frac{d^3 p'_2}{(2\pi)^3 2 E'_2} |M_{123\rightarrow 1'2'}|^2 (2\pi)^4 \delta^{(4)}(p_1 + p_2 + p_3 - p'_1 - p'_2)$$

The Relativistic Riemann Problem

Investigation of Shock Waves in one dimension

Boltzmann solution of the relativistic Riemann problem ->what effects have viscosity?



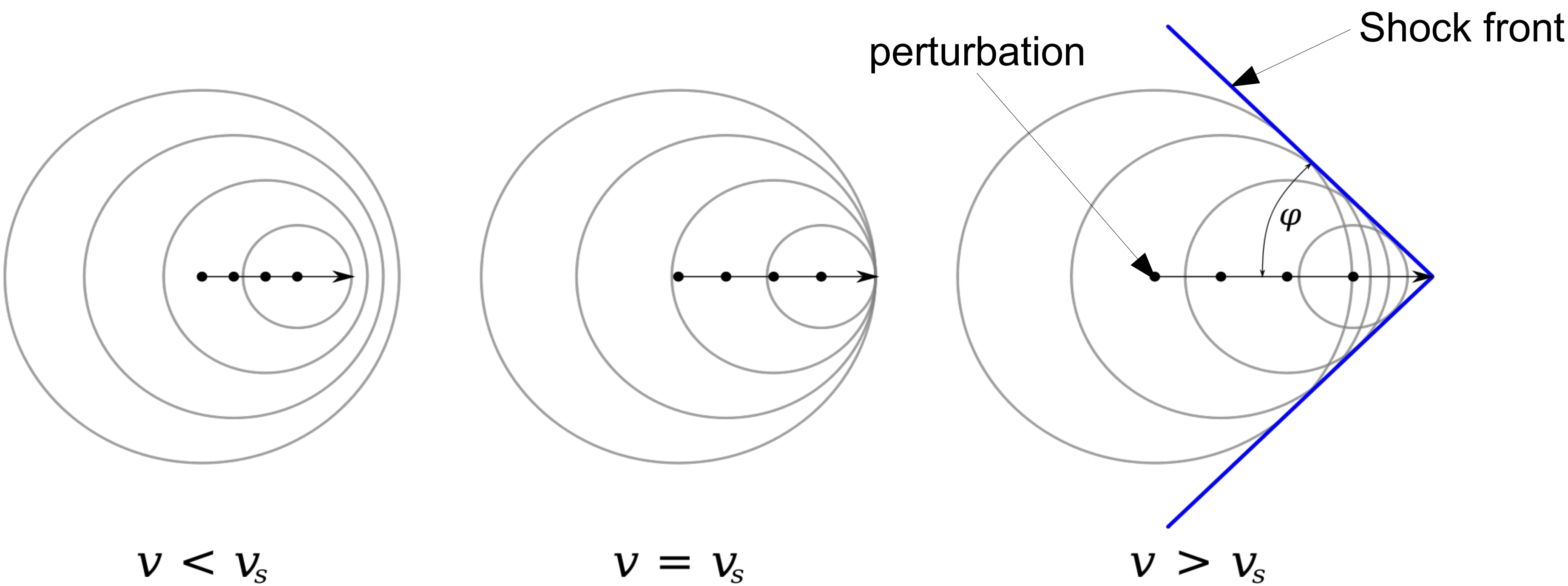
Transition from ideal hydro to free streaming

I. Bouras et al., Phys. Rev. Lett. 103:032301 (2009)

I. Bouras et al., PRC 82, 024910 (2010)

Mach Cones

- If source (perturbation) is propagating faster than the speed of sound, then a Mach Cone structure is observed



idea:

Measured angle → $c_s = \sqrt{\frac{dp}{de}}$ → Equation of state

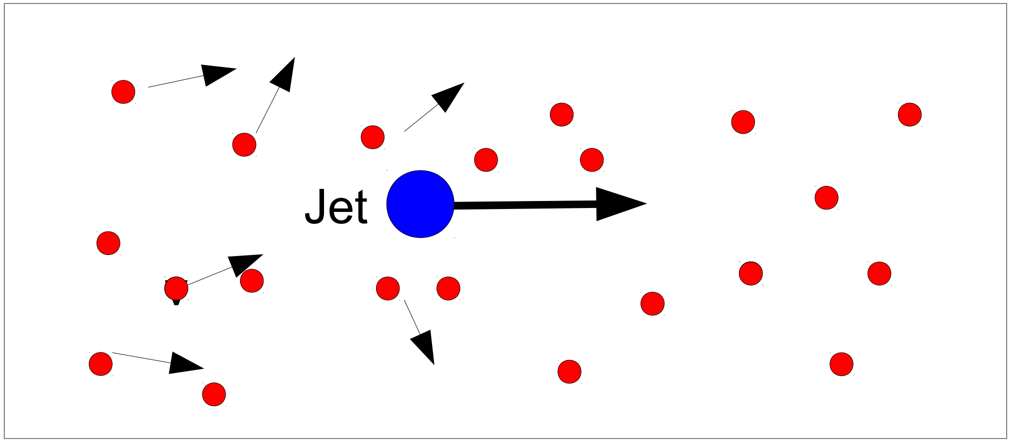
”Source” Terms in BAMPS

1) Punch Through Scenario

2) Pure energy deposition scenario

Punch Through Scenario

A scenario usefull to investigate the shape and development of ideal Mach Cones

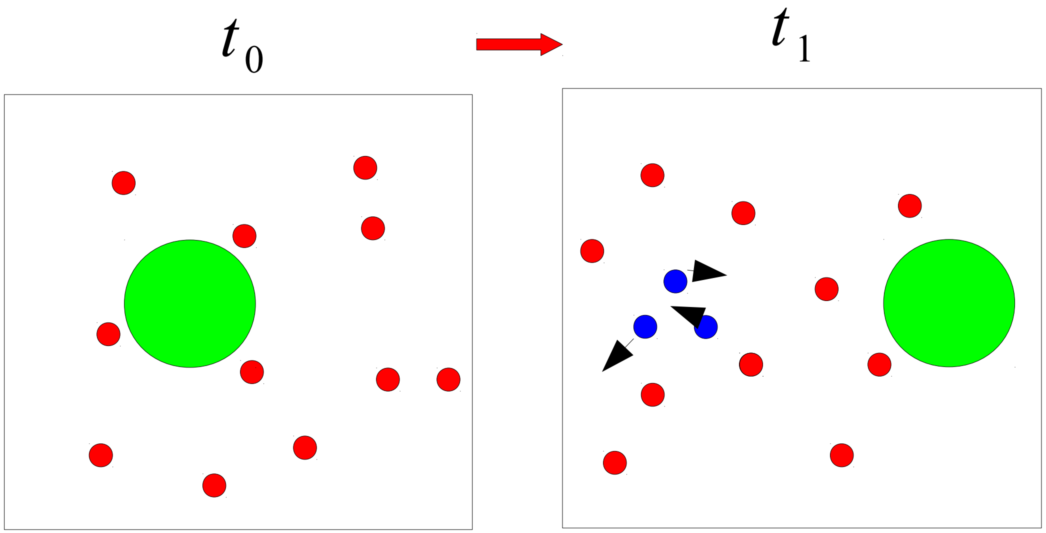


- Jet has finite initial energy and momentum $E = p_z$ and is massless; no transverse momentum $\rightarrow$ $p_x = p_y = 0$
- The Jet deposits energy to the medium due to binary collisions with particles
- After every collision with a thermal particle of the medium the energy of the jet gets recharged to its inital value

Movie:
Evolution of Mach Cones
in BAMPS
For the *Punch Through Scenario*

Pure energy deposition Scenario

Energy deposition via the creation of thermal distributed particles

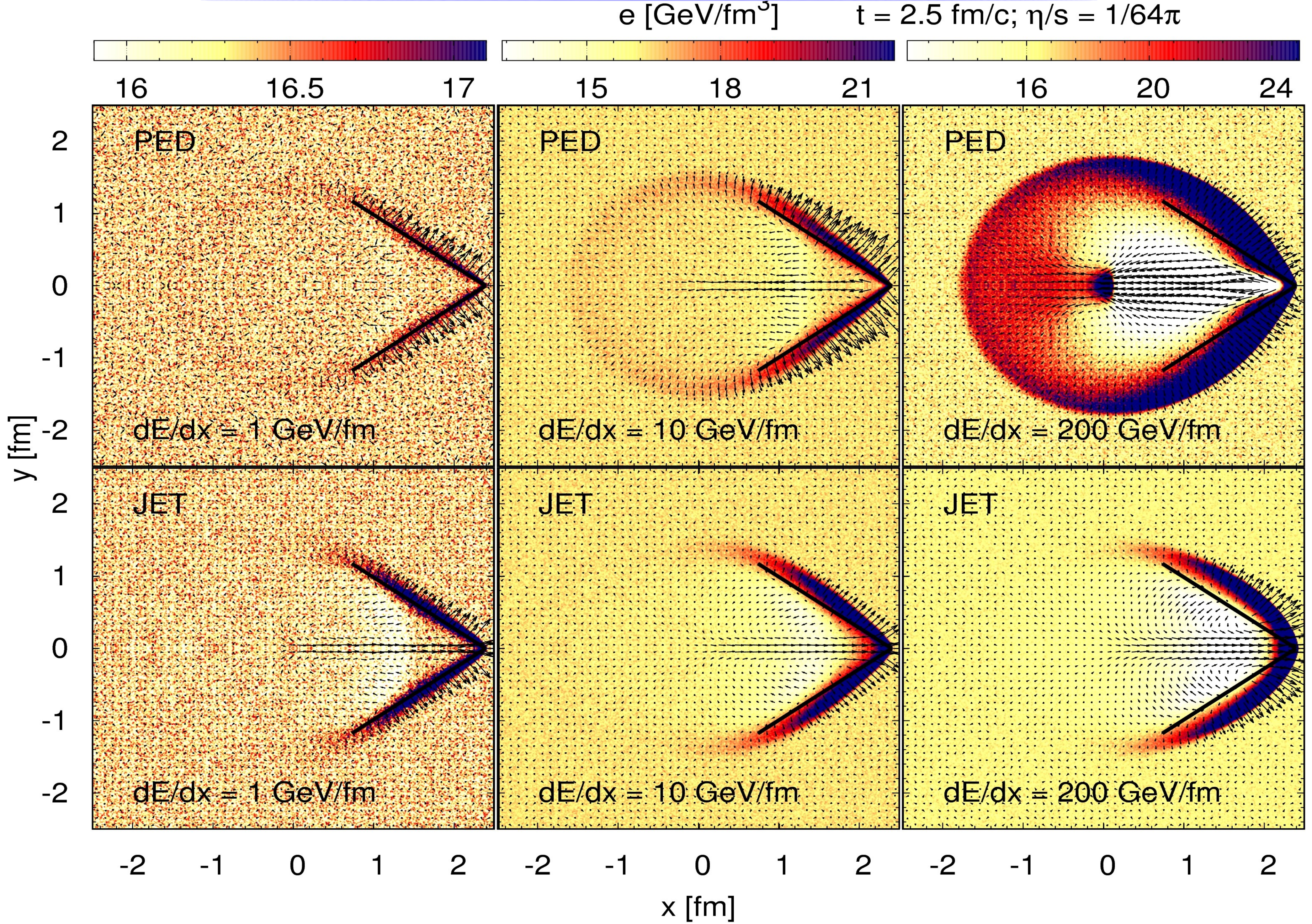


- The source (green) propagates with the speed of light and generates new particles (blue) at different timesteps
- The advantage of that method: a constant energy deposition but no momentum deposition, because new particles are thermal distributed

$$\longrightarrow \quad f_{ped}(x, p) = e^{-E/T}$$

Movie:
Evolution of Mach Cones
in BAMPS
For the *Pure energy deposition scenario*

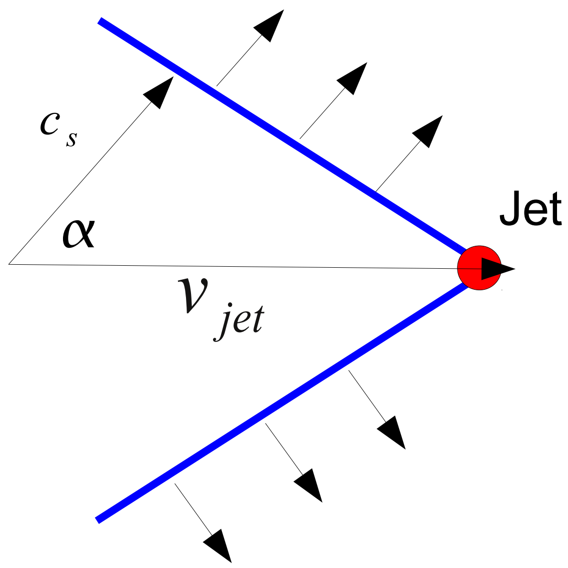
Ideal Solutions of Mach Cones



Mach Cones

Mach angle dependence

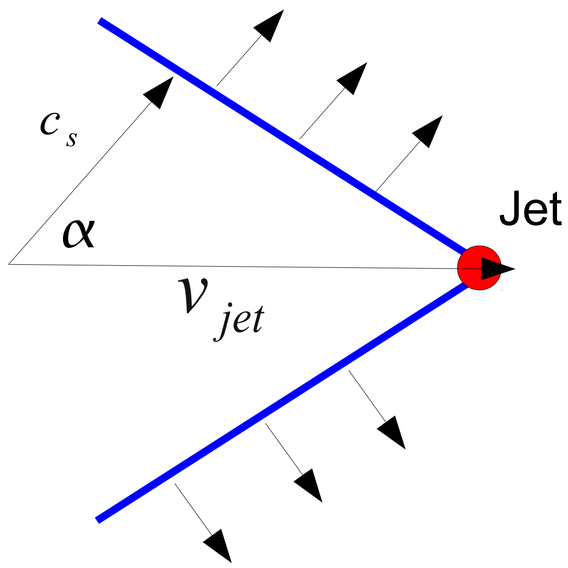
Scenario for a very weak perturbation



Mach Cones

Mach angle dependence

Scenario for a very weak perturbation



- In the case of a perfect fluid, i.e. $\eta=0$, the Mach angle is

$$\alpha=\arccos\frac{c_s}{v_{jet}}\approx 54.7^o$$

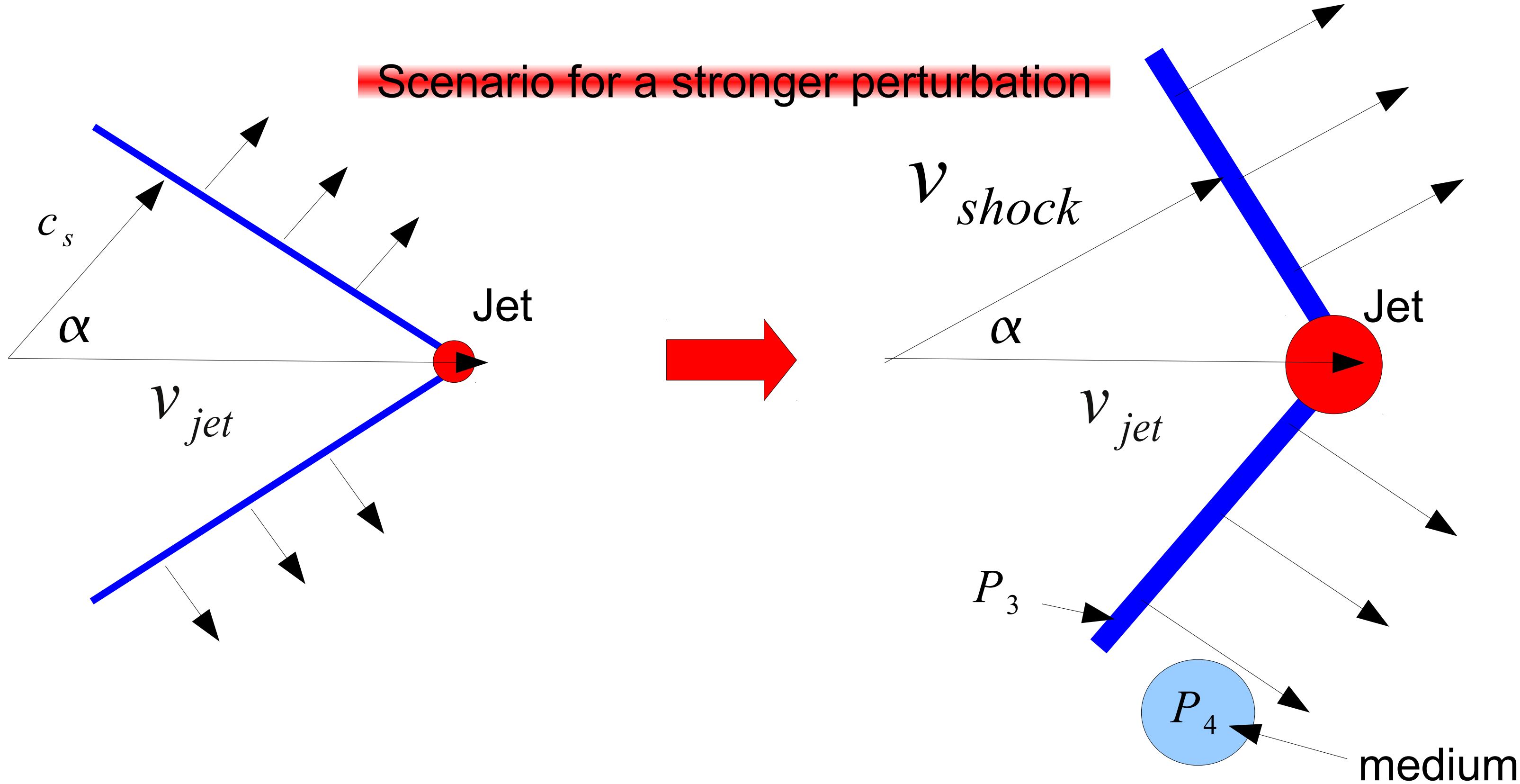
for a massless Boltzmann gas, i.e. $e=3P$, with $c_s=1/\sqrt{3}$ and $v_{jet}=1$

- This is only valid for small perturbation, i.e. energy of the jet is infinite small

Mach Cones

Mach angle dependence

Scenario for a stronger perturbation

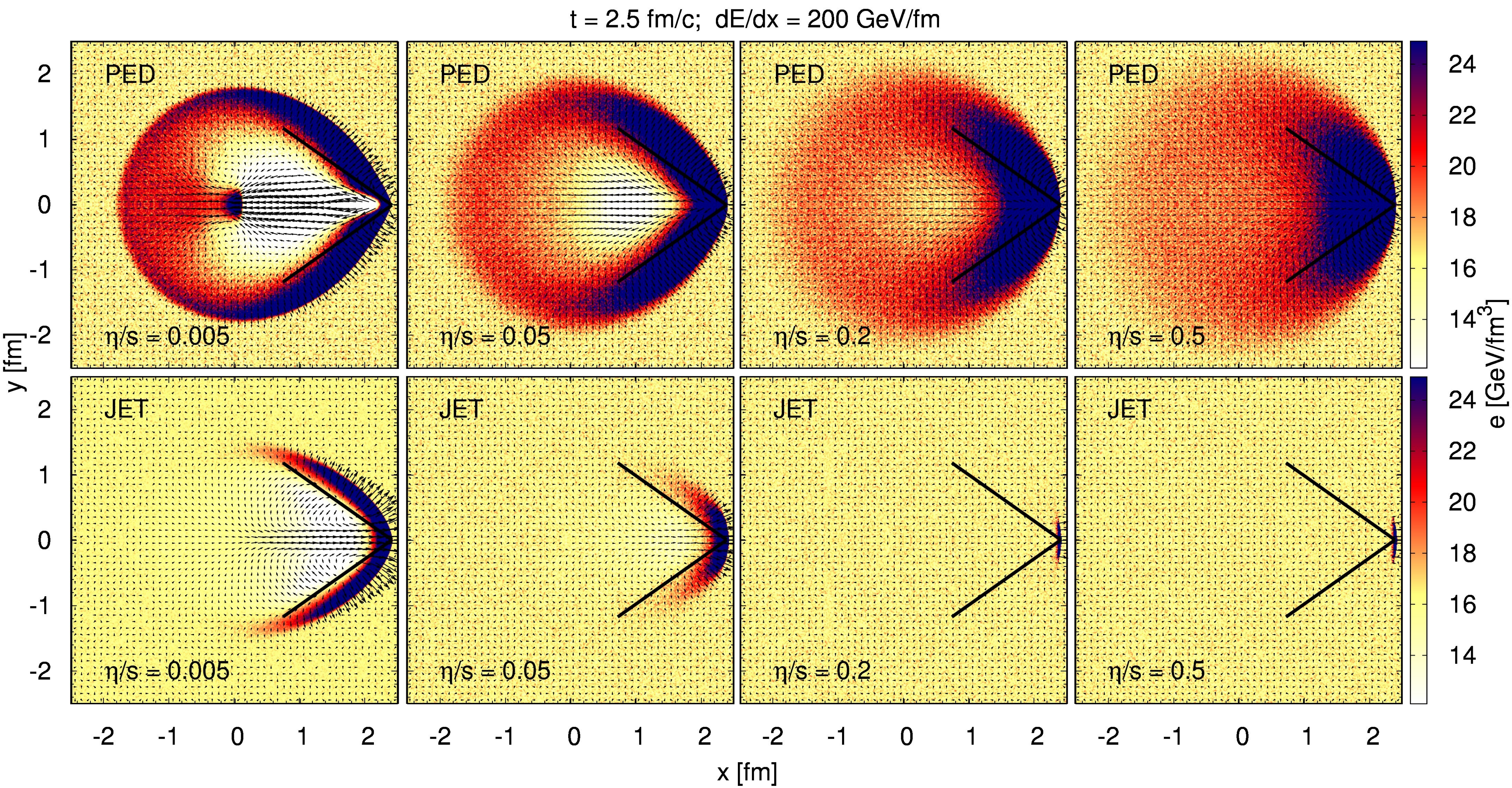


- In the case of a stronger perturbation the energy deposition is larger and therefore shock waves develop which exceed the speed of sound. Therefore the angle is approximately given by

$$\alpha = \arccos \frac{v_{shock}}{v_{jet}} \qquad v_{shock} = \left[\frac{(P_4 - P_3)(e_3 + P_4)}{(e_4 - e_3)(e_4 + P_3)} \right]^{\frac{1}{2}}$$

- The emission angle α changes to smaller values than in the weak perturbation case

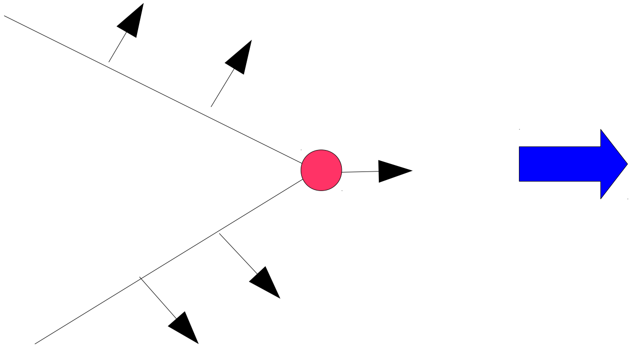
Viscous Solutions of Mach Cones

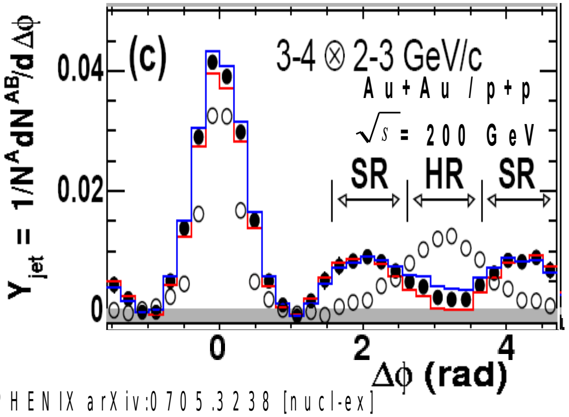


Mach Cones in BAMPS

Two Particle Correlations

- First, we (have) expect(ed) that the double peak observed in experimental data is a hint for a conical structure...because of the naive picture





PHENIX arXiv:0705.3238 [nucl-ex]

Mach Cones in BAMPS

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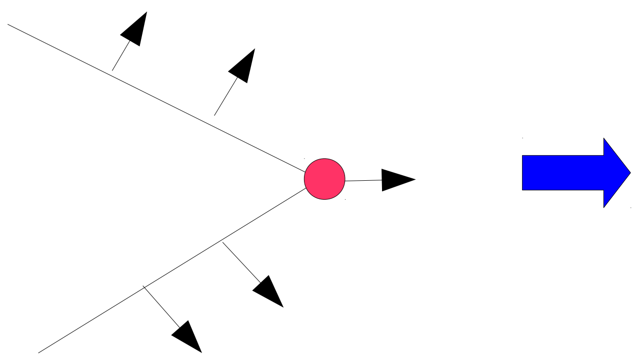
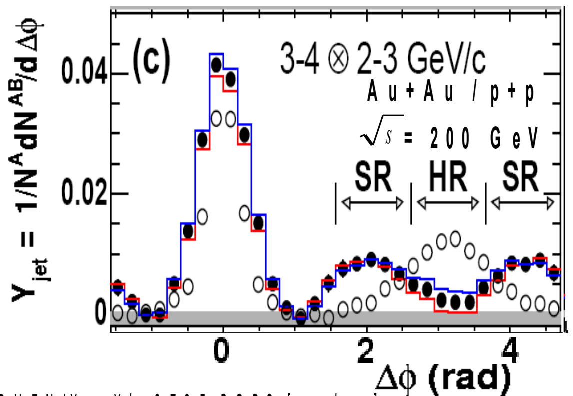




PHENIX arXiv:0705.3238 [nucl-ex]

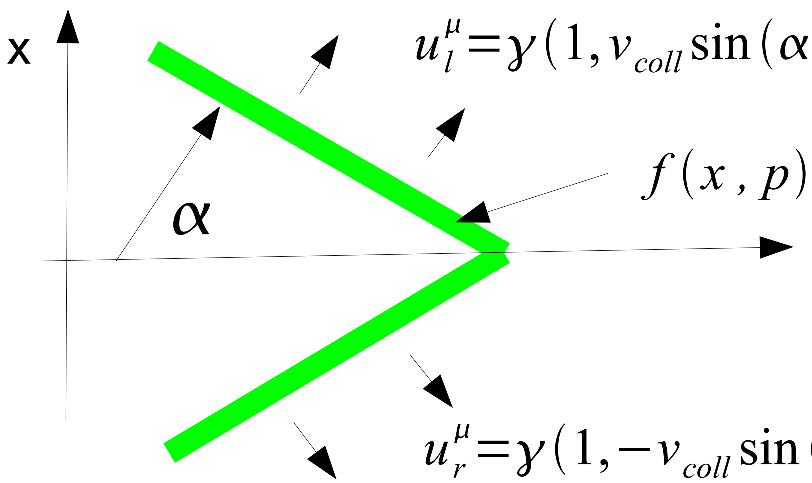
- But....
  1) viscosity is not zero in heavy-ion collisions (HIC)...and as we have already seen, viscosity in order expected in HIC destroys the conical structure to a very weak signal
  2) The jet in reality has not infinite energy....and the formation-time is finite
  3) The angle changes of the Mach Cone changes depending on the energy deposition
  4) The diffusion wake and head shock will have a big contribution...as we will see..

- However, one can can find an analytical expression for the two-particle correlations of Mach Cones....

Mach Cones in BAMPS

Two Particle Correlations
Analytical solution

Assume two wings in thermal equilibrium



$$u_l^\mu = \gamma\left(1, v_{coll}\sin(\alpha), 0, v_{coll}\cos(\alpha)\right)$$

$$f(x,p) = e^{-u_\mu p^\mu / T}$$

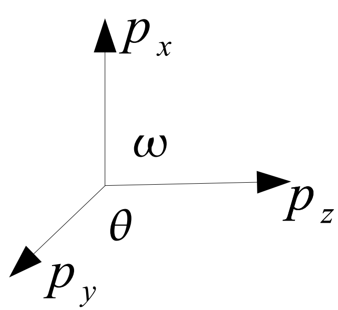
$$u_r^\mu = \gamma\left(1, -v_{coll}\sin(\alpha), 0, v_{coll}\cos(\alpha)\right)$$

alpha is a const and corresponds to the Mach angle, where v_coll is the collective velocity of matter velocity in the wings

Mach Cones in BAMPS

Two Particle Correlations
Analytical solution

- We are looking for the angle ω, which is the angle in the p_x and p_z plane

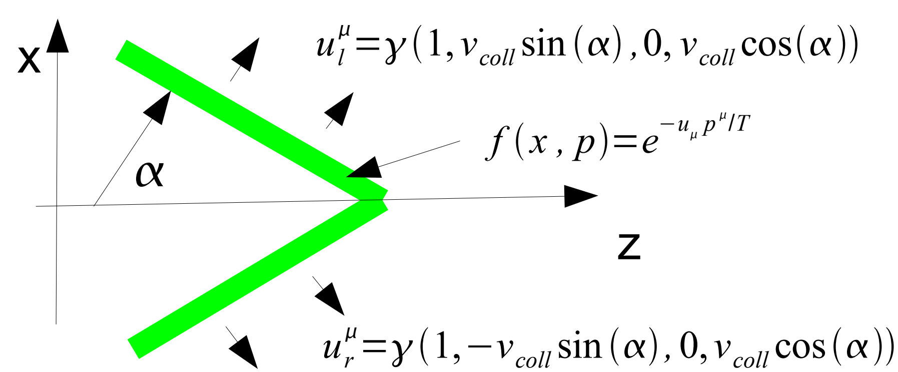


$$p_z = p\cos(\omega)\sin(\theta)$$
$$p_x = p\sin(\omega)\sin(\theta)$$
$$p_y = p\cos(\theta)$$

One calculate for each wing the particle distribution

$$\Rightarrow \quad \frac{dN}{d\omega} = \frac{V}{(2\pi)^3} \iint p^2 \sin(\theta) e^{-u_\mu p^\mu / T} dp\, d\theta$$

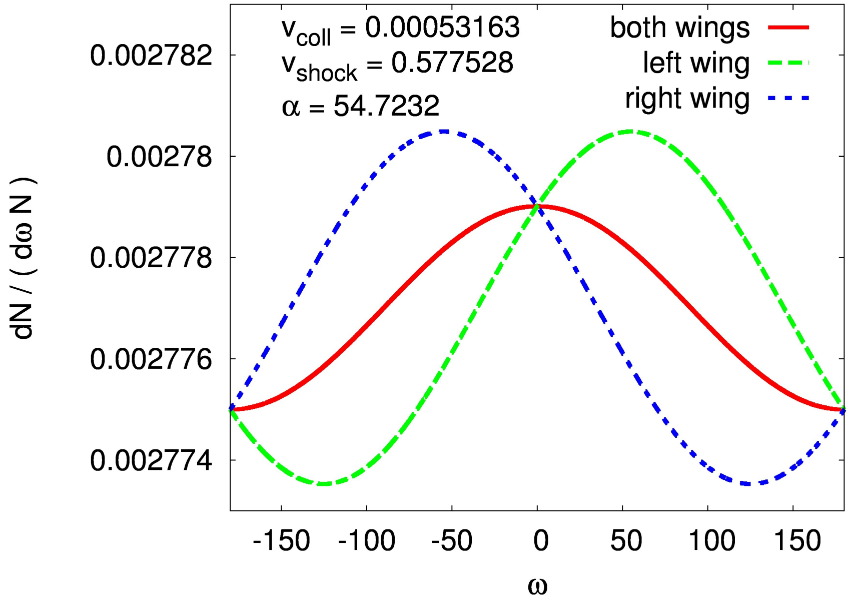
In the end one has to add both contributions!



Mach Cones in BAMPS

Two Particle Correlations
Analytical solution - Results

Taking the very weak perturbation case in account, we do not observe a double peak structure as we expected.



alpha and v_coll depends on the ratio of density in the wing and medium in rest

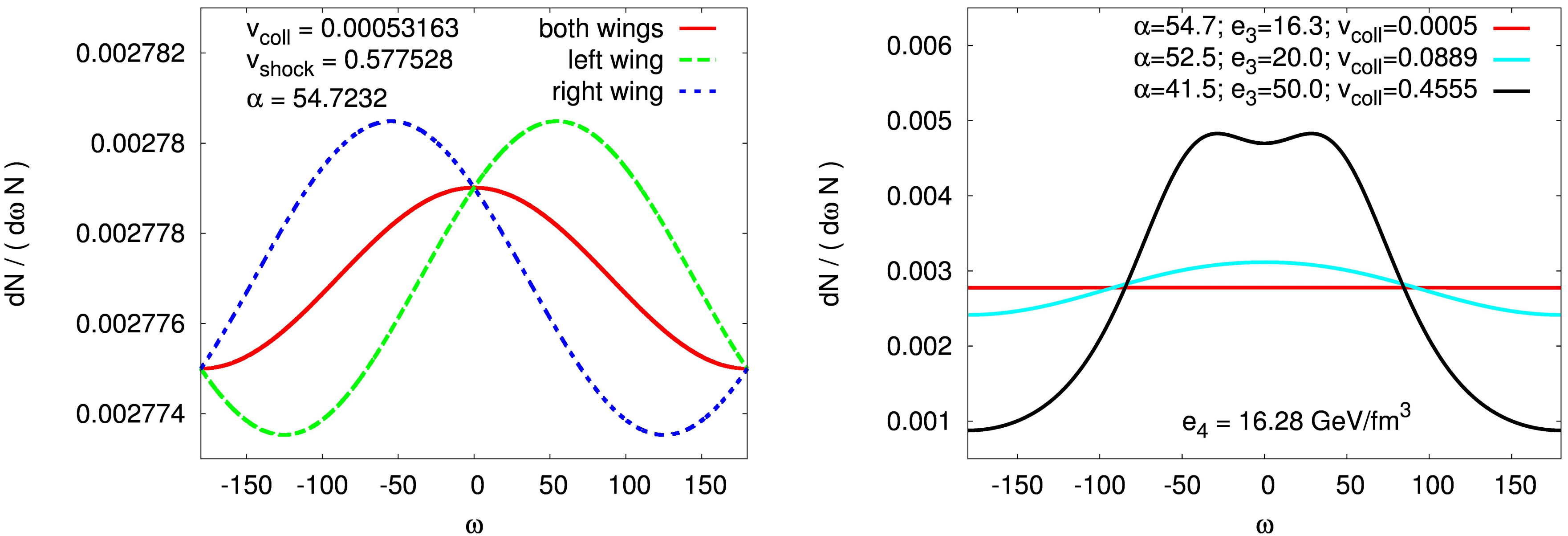
Mach Cones in BAMPS

Two Particle Correlations
Analytical solution - Results

Taking the very weak perturbation case in account, we do not observe a double peak structure as we expected.

→ Only if the shock gets stronger a double peak is observed

→ If the shock gets stronger, also v_coll gets larger and therefore the double peak is clearer

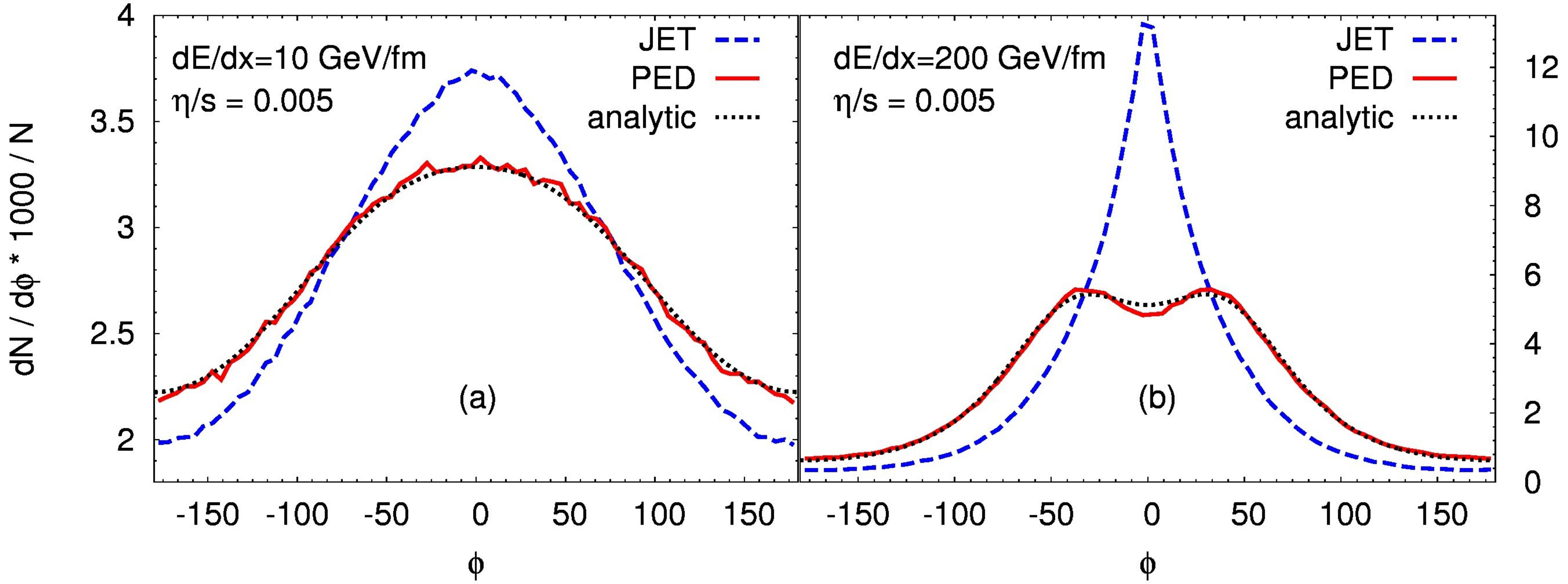


alpha and v_coll depends on the ratio of density in the wing and medium in rest

Mach Cones in BAMPS

Two Particle Correlations for ideal solution
Numerical Results

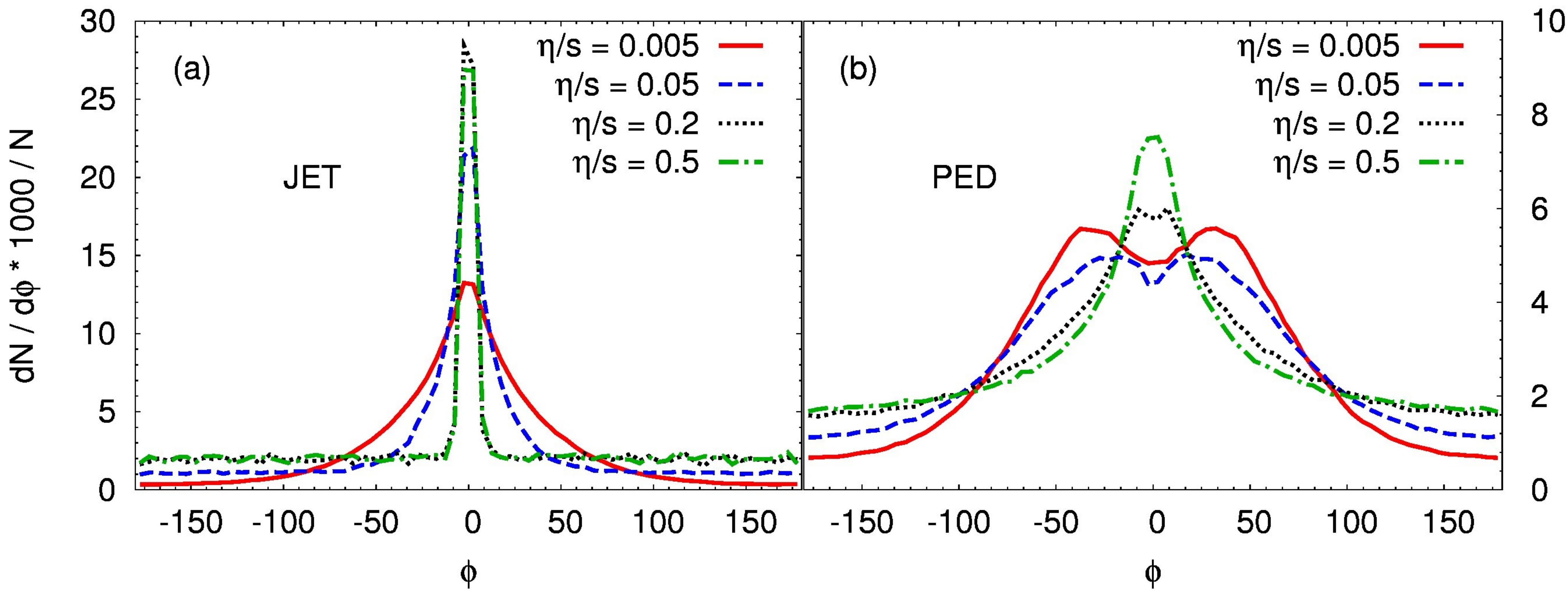
10 GeV/fm　　200 GeV/fm



The source term plays a big role for observation a double peak structure

Mach Cones in BAMPS

Two Particle Correlations for viscous solution
Numerical Results



Viscosity does not help for the development fo the double peak structure

Conclusion

- BAMPS is an excellent benchmark to investigate phenomena like shock waves and Mach Cones in the ideal and viscous region

- Extraction of the EOS is not easy because $\rightarrow$ angle not constant and finite viscosity

- Mach Cones might exist in heavy-ion collisions...

  ...but have **NOT** to be the origin of the famous ”double peak structure”....

Thank you

The Parton Cascade BAMPS

<u>For this setup :</u>

- Boltzmann gas, isotropic cross sections, elastic processes only
- Implementing a constant η/s, we locally get the cross section σ_{22}:

$$\eta = \frac{4}{15}\frac{\epsilon}{R^{tr}}$$

Transport collision rate R^{tr}

For isotropic elastic collisions:

$$R_{22}^{tr} = n\frac{2}{3}\sigma_{22}$$

$$\epsilon = 3\mathrm{nT}$$

$$s = 4\mathrm{n} - n\ \ln(\lambda_{fug})$$

$$\lambda_{fug} = \frac{n}{n_{eq}} \qquad n_{eq} = \frac{g}{\pi^2}T^3$$

g = 16 for gluons

Z. Xu & C. Greiner,
Phys.Rev.Lett.100:172301,2008

$$\Rightarrow \quad \sigma_{22} = \frac{6}{5}\frac{T}{s}\left(\frac{\eta}{s}\right)^{-1}$$