Non-equilibrium Dynamics (NeD-2019)

Harmonic flow coefficients and Hydrodynamic Events

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Collaboration with
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FÍSICA NUCLEAR E APLICAÇÕES

Harmonic flow coefficients and Hydrodynamic Events

1. Coase Grainings and Hydrodynamics
2. Event by Event Hydrodynamics and Granuality
3. Degenerate Nature of Harmonic Coefficients
4. Quantum effects?

Hydrodynamic Variables

$$(T^{\mu\nu}) = \begin{pmatrix} (\varepsilon + P)\,\gamma^2 - P & (\varepsilon + P)\,\gamma^2 \boldsymbol{\beta} \\ (\varepsilon + P)\,\gamma^2 \boldsymbol{\beta} & (\varepsilon + P)\,\gamma^2 \boldsymbol{\beta}\boldsymbol{\beta}^T + P\hat{\mathbf{I}} \end{pmatrix}$$

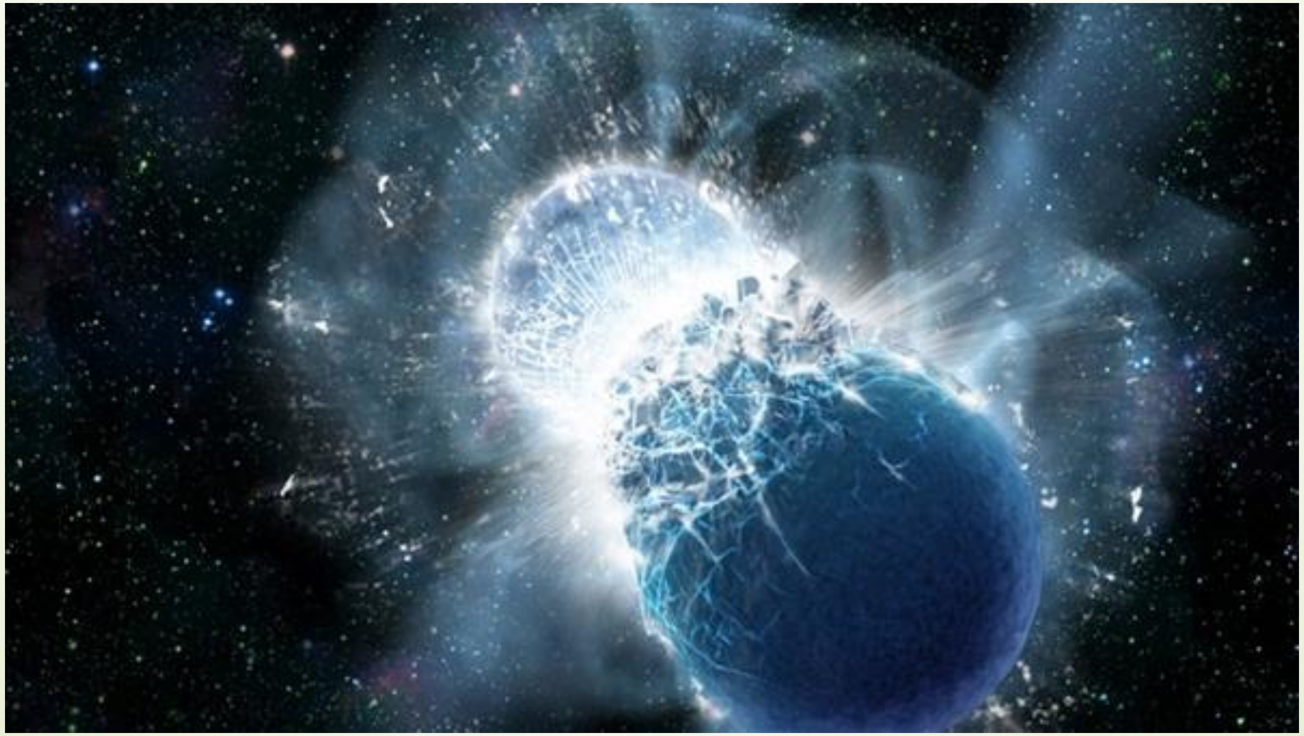
$$T_{\mu\nu} = T_{\mu\nu}(x)$$

(ideal case)

$$\partial^{\mu} T_{\mu\nu} = 0$$ + Eauation of States

Hydrodynanics = Dynamics of Continuum media

For macroscopic objects, we do not much about the validity....



Several Types of Coarse Graining

- Space-like coarse graining
- Time-like coarse graining
- Nature of observables (event average)

Pre-harmonic flow analysis

Starting brom Landau, a huge list of hydrodynamic approach on particle Productions in high energy pp or nuclear collisions

Several Types of Coarse Graining

- Space-like coarse graining
- Time-like coarse graining
- Nature of observables

Several Types of Coarse Graining

- <u>Space-like coarse graining</u>

- <u>Time-like coarse graining</u>

- Nature of observables (**event average**)

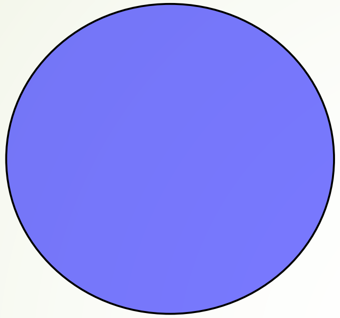
Phys. Rev. C 55, 1455 (1997), S. Paiva, Y. Hama, and T. Kodama,
JPhys.G: Nuclear and Particle Physics 27, 75, 2001, T Osada, CE Aguiar, Y Hama, T Kodama

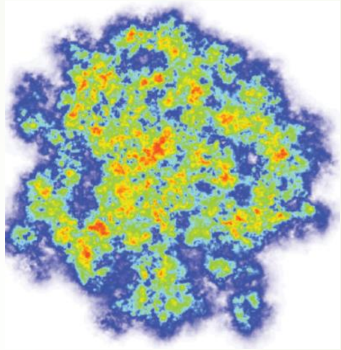
- **Thanks to Klaus Werner for the suggestion of use of event generator, NEXUS !!**

Coarse Graining for event by event fluctuations

Nucleus shape fluctuates in every collision

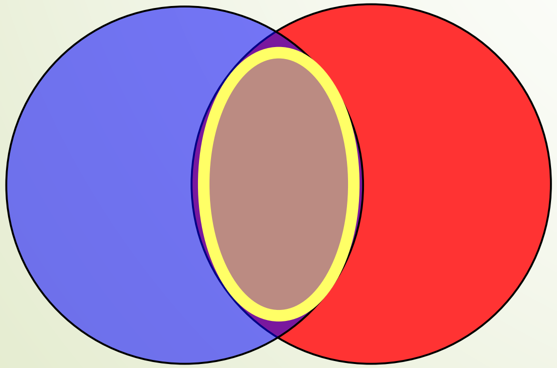
Pb

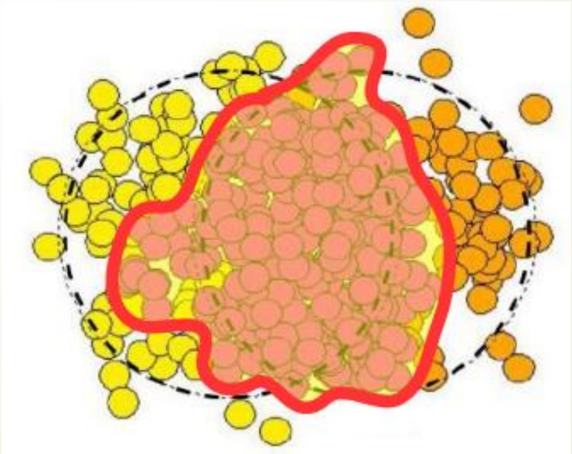


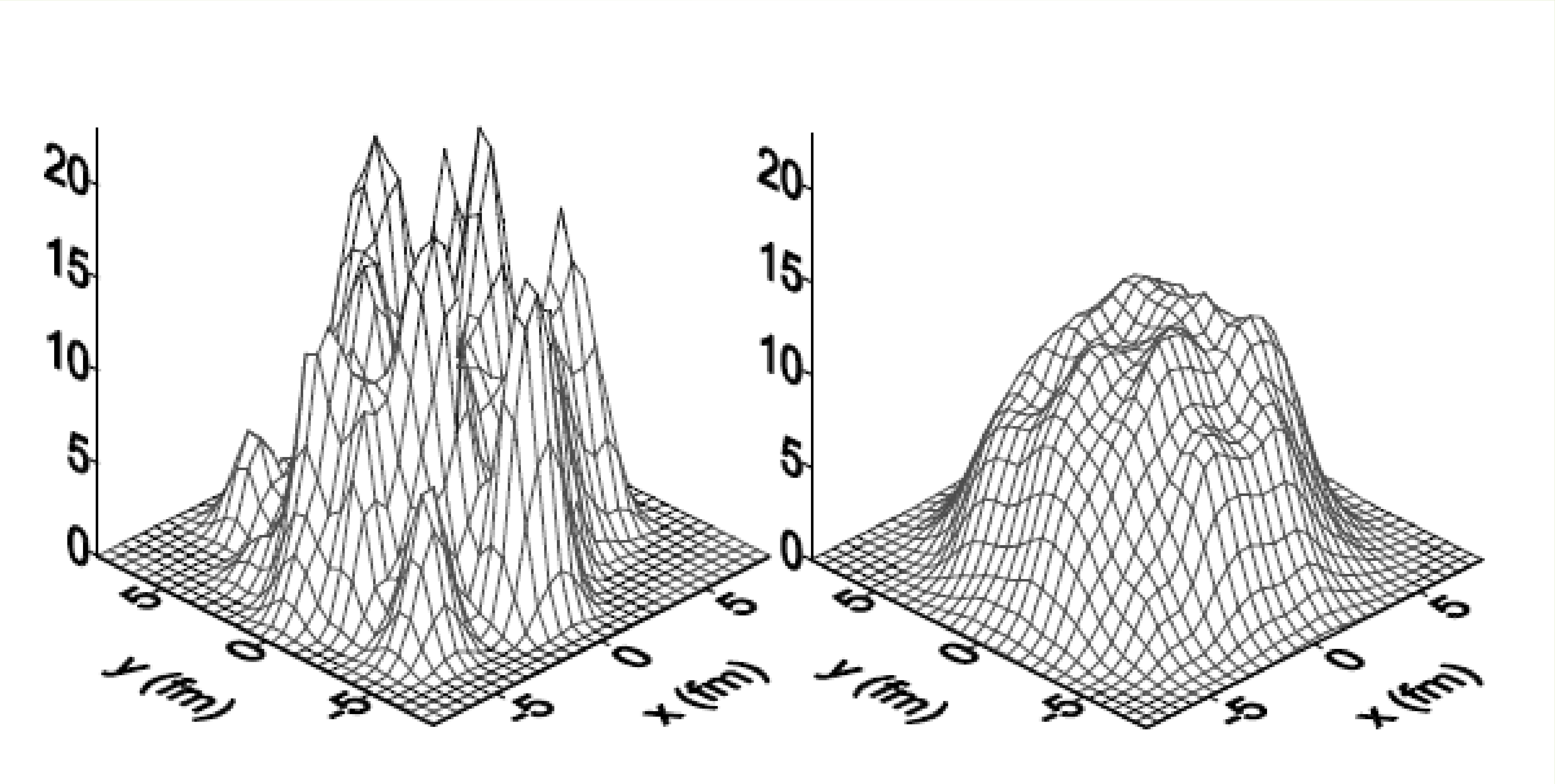


Collision Geometry is dramatically affected

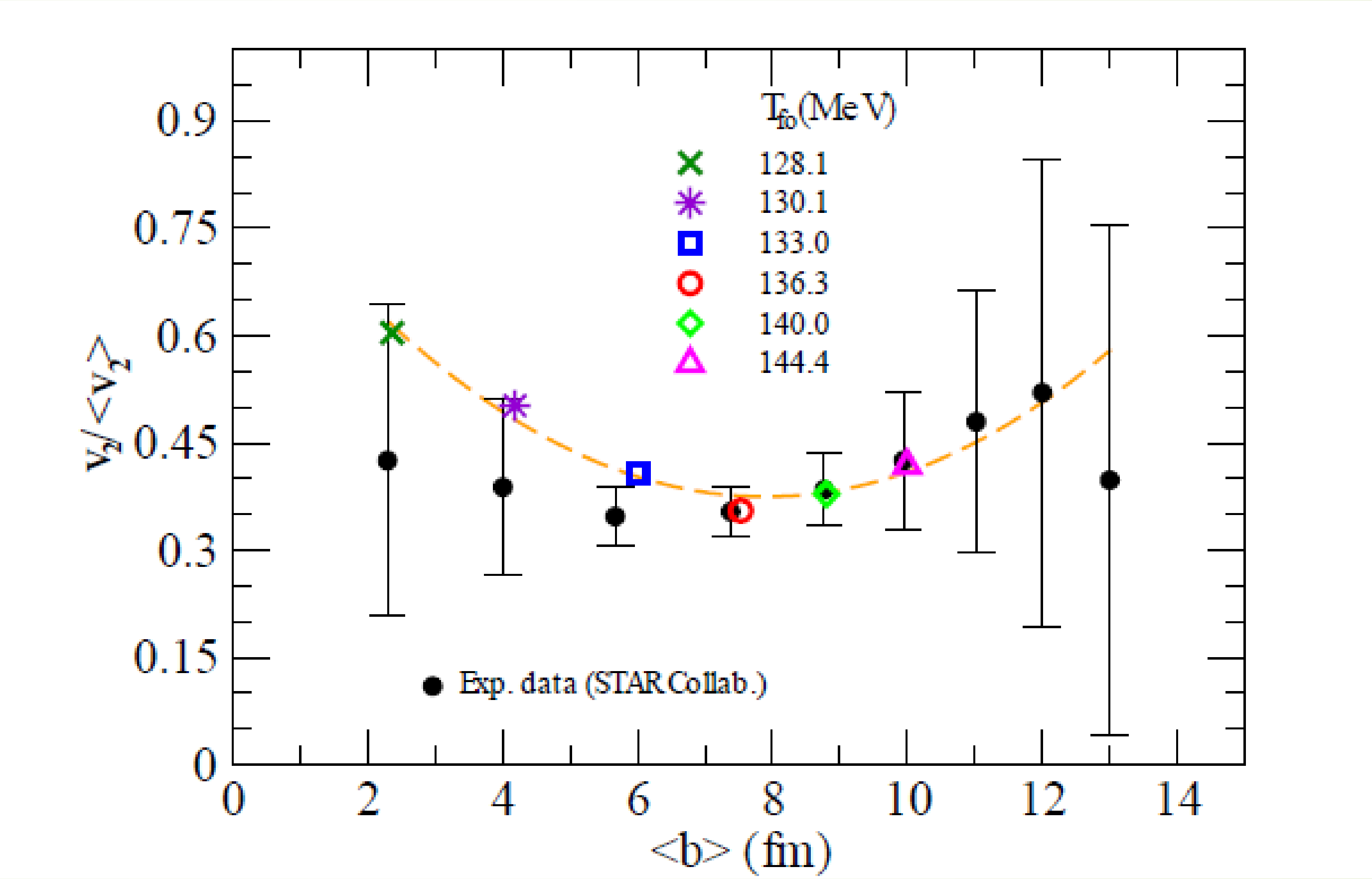
For v_2 scale, we look at the scale of



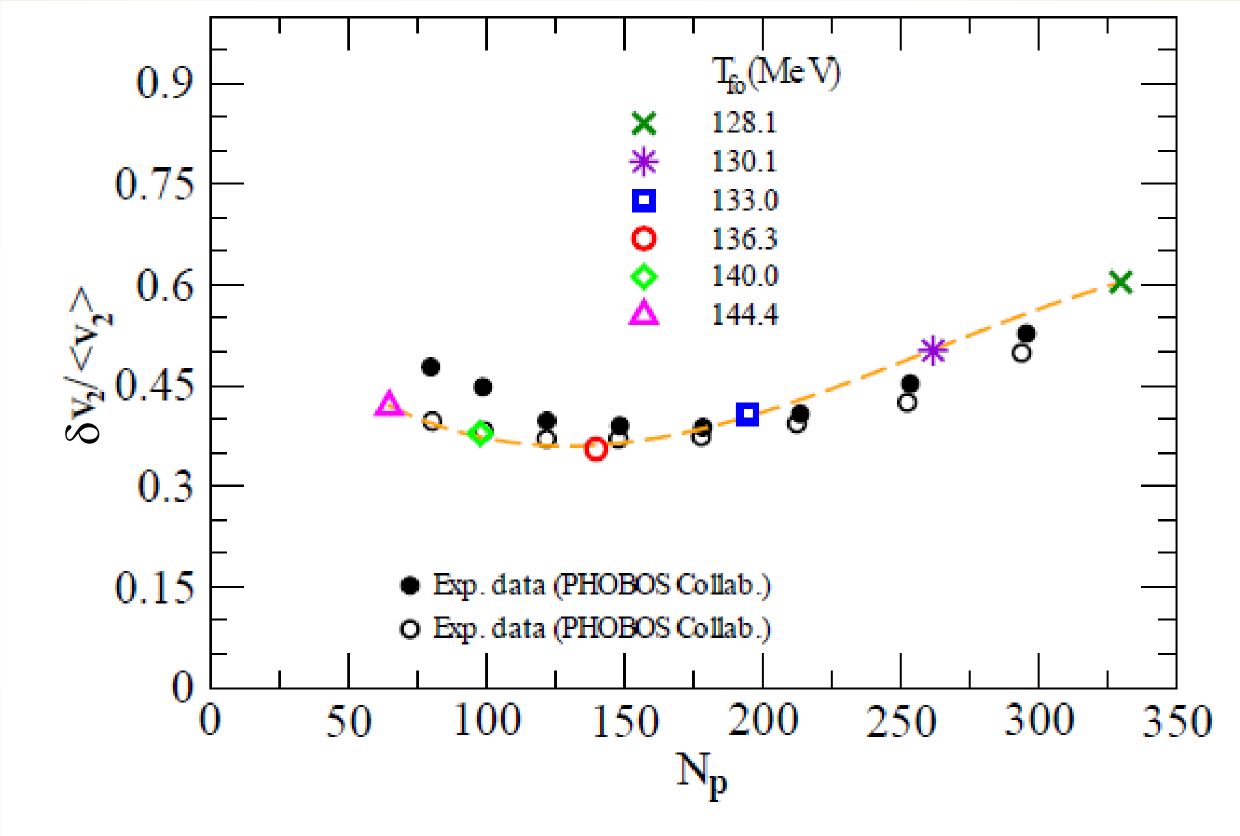




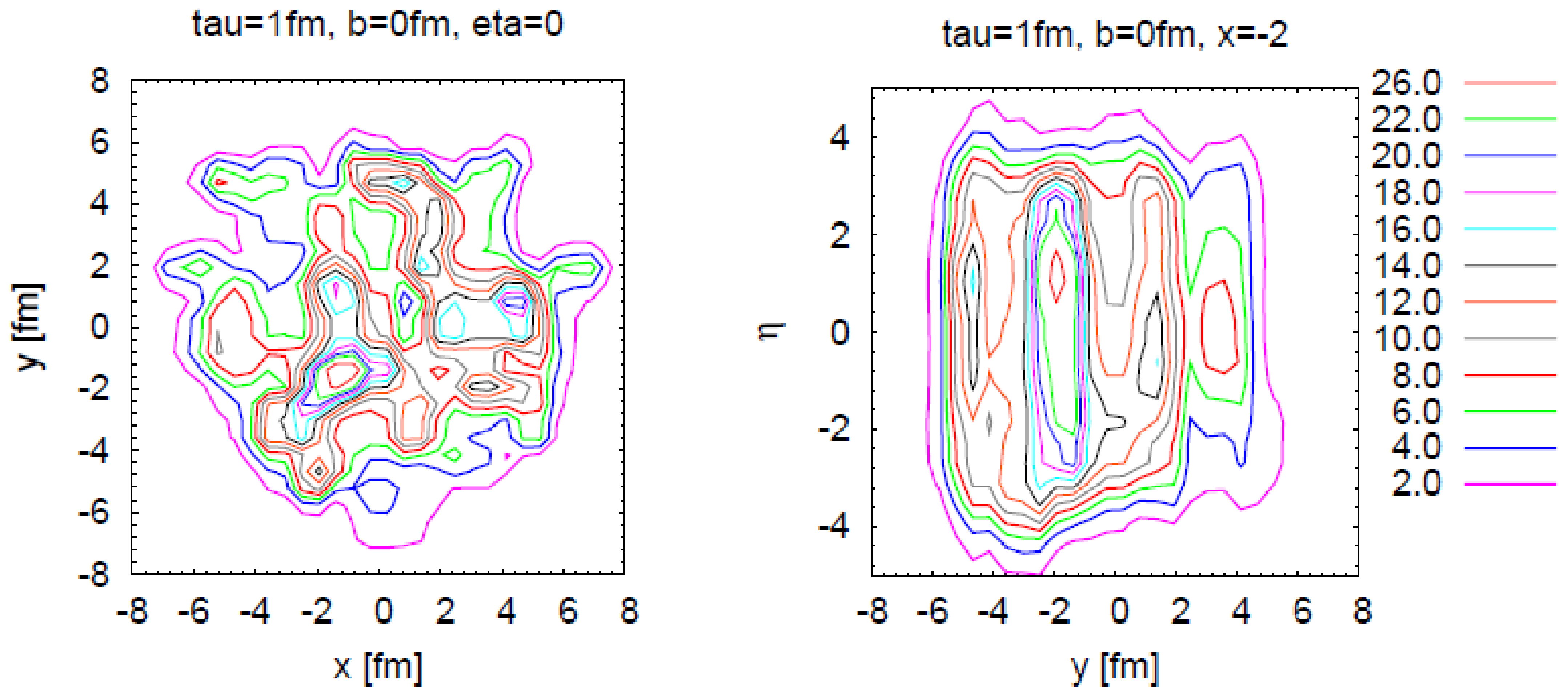
20
15
10
5
0
5
0
-5
y (fm)
x (fm)
20
15
10
5
0
5
0
-5
y (fm)
x (fm)

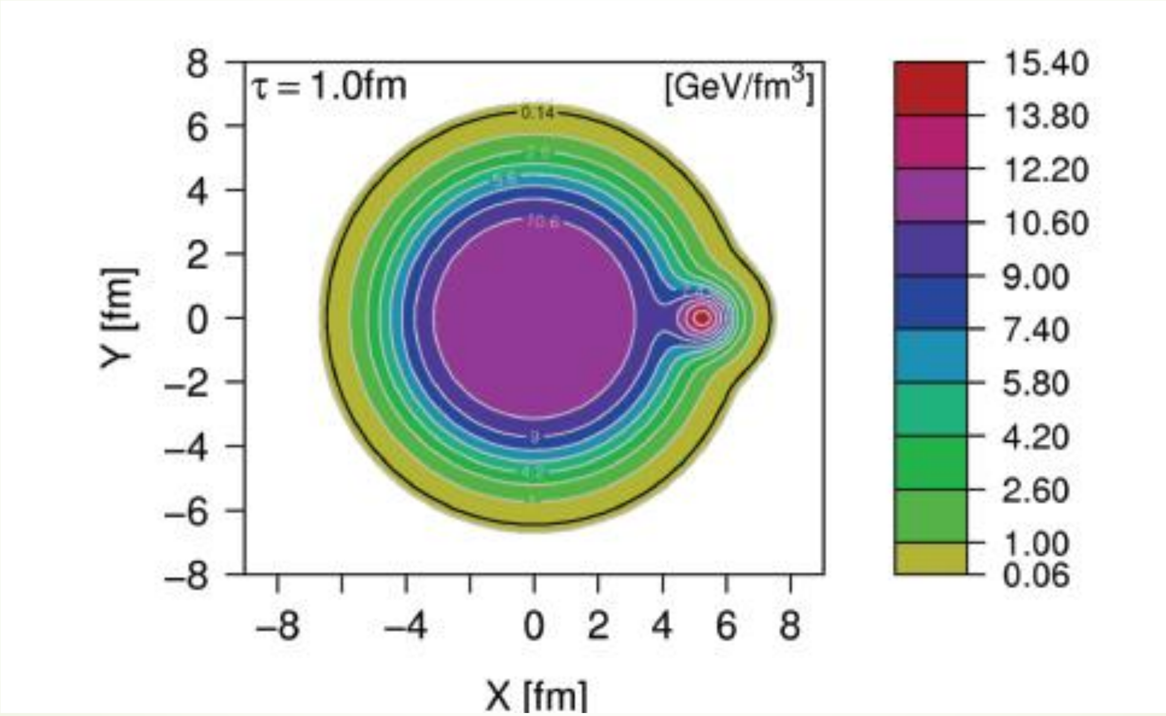


T_{fo}(MeV)
128.1
130.1
133.0
136.3
140.0
144.4
Exp. data (STAR Collab.)
$v_2/<v_2>$
<b> (fm)
0
0.15
0.3
0.45
0.6
0.75
0.9
0
2
4
6
8
10
12
14

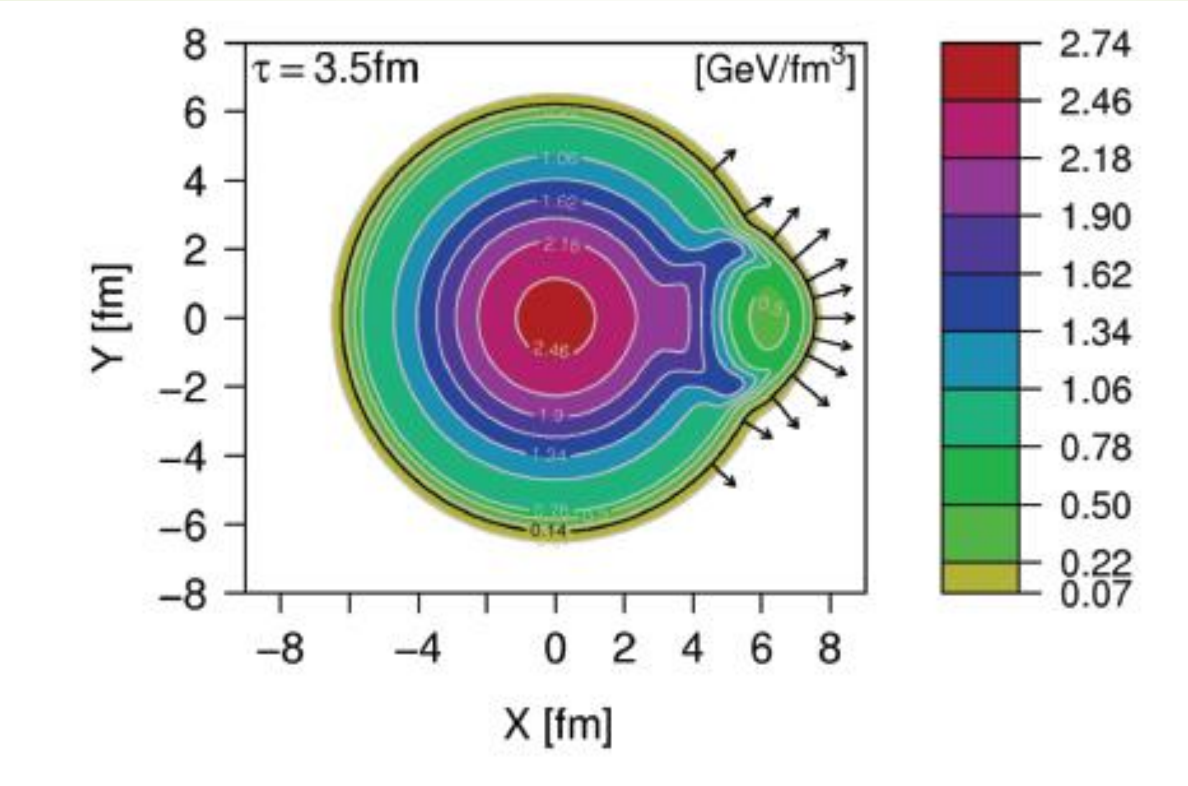


T_{fo}(MeV)
128.1
130.1
133.0
136.3
140.0
144.4
Exp. data (PHOBOS Collab.)
Exp. data (PHOBOS Collab.)
$\delta v_2/\langle v_2\rangle$
N_p
0
0.15
0.3
0.45
0.6
0.75
0.9
0
50
100
150
200
250
300
350

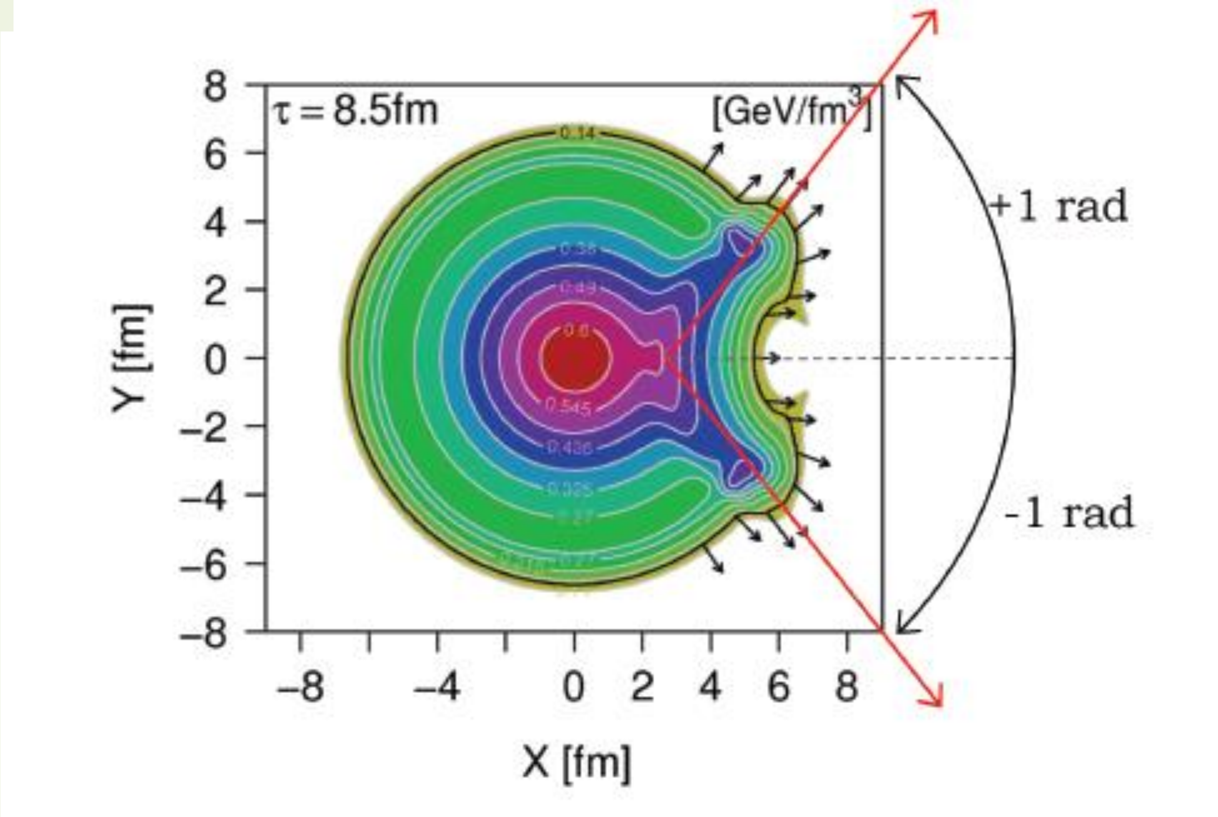

tau=1fm, b=0fm, eta=0
y [fm]
x [fm]
tau=1fm, b=0fm, x=-2
η
y [fm]
26.0
22.0
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0



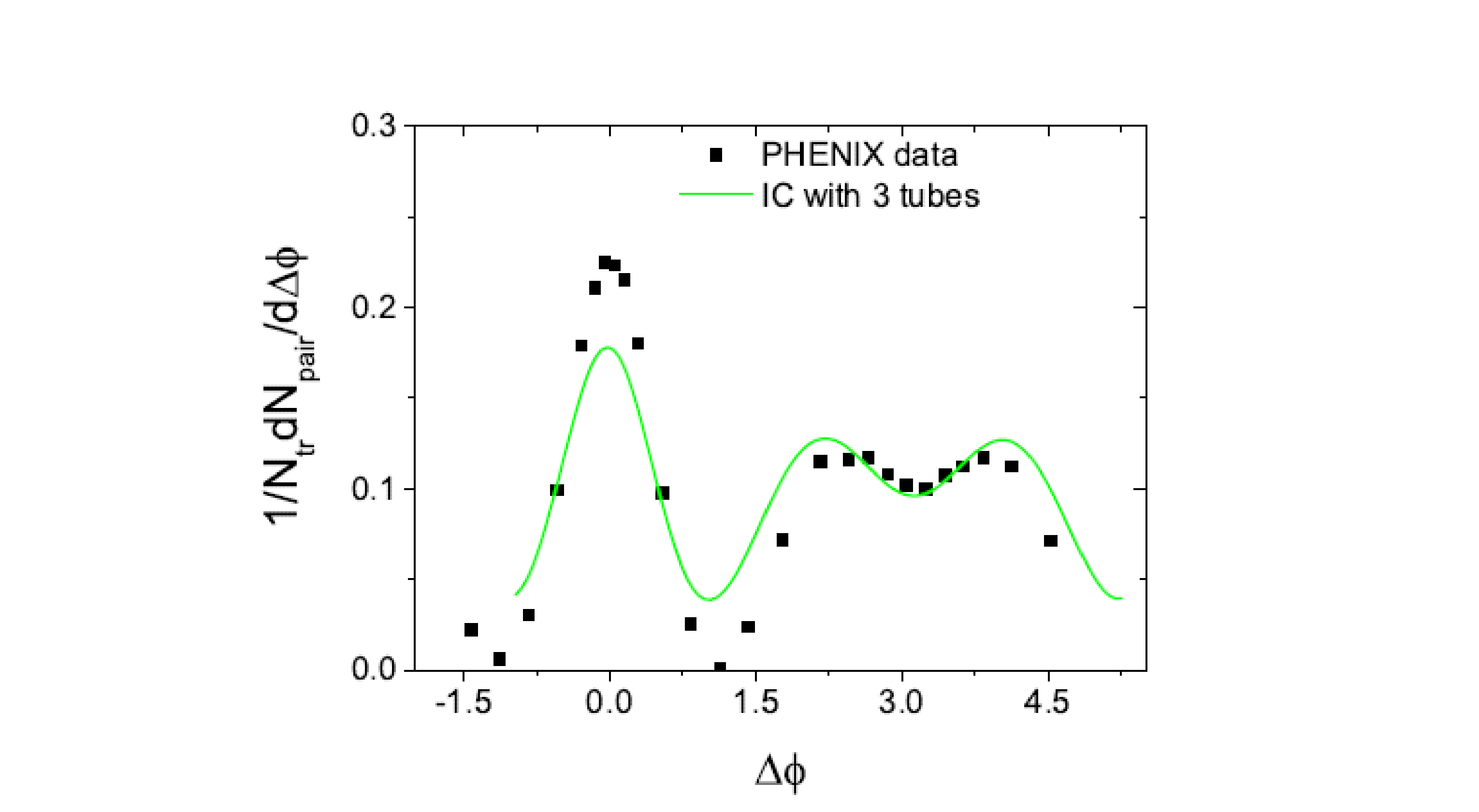
$\tau = 1.0$fm
[GeV/fm^3]
Y [fm]
X [fm]
15.40
13.80
12.20
10.60
9.00
7.40
5.80
4.20
2.60
1.00
0.06



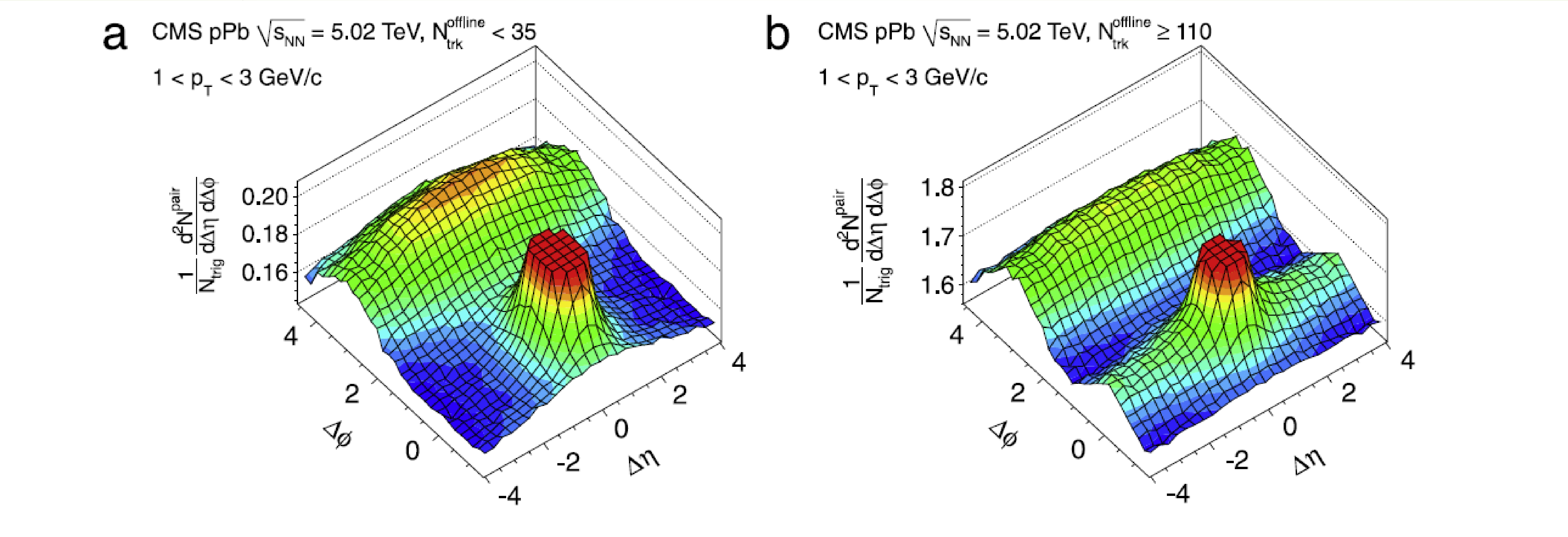
τ = 3.5fm
[GeV/fm^3]
Y [fm]
X [fm]
8
6
4
2
0
−2
−4
−6
−8
−8
−4
0
2
4
6
8
2.74
2.46
2.18
1.90
1.62
1.34
1.06
0.78
0.50
0.22
0.07



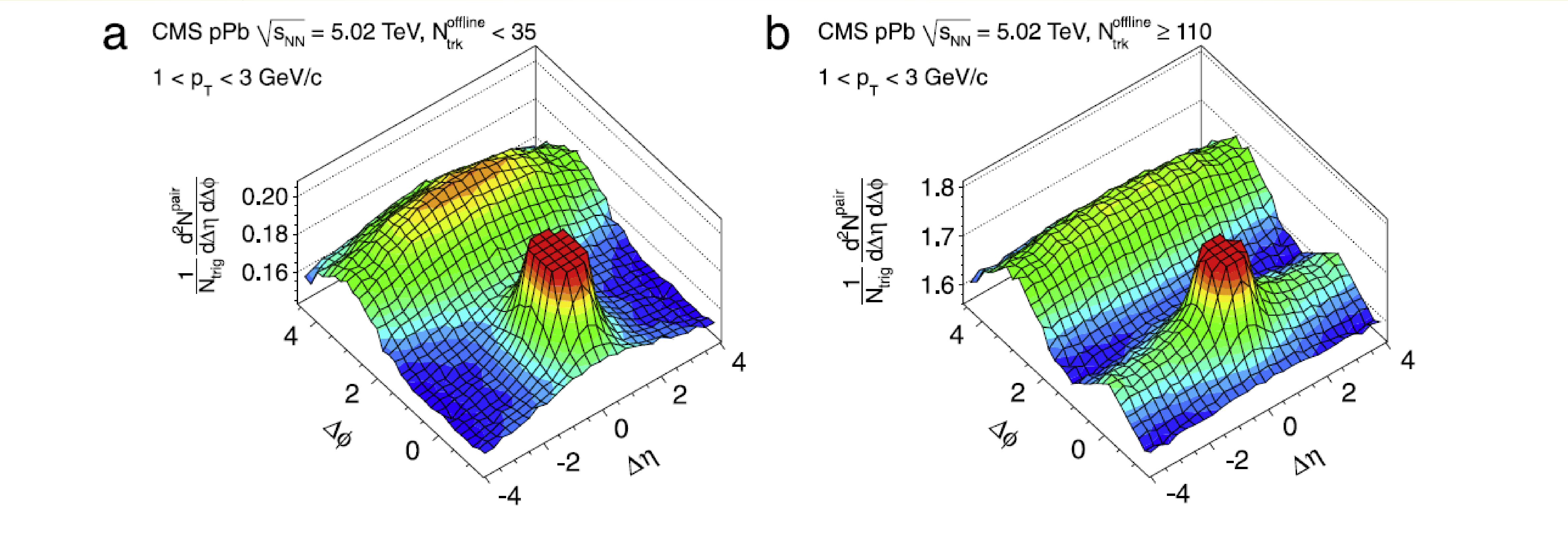
τ = 8.5fm
[GeV/fm3]
+1 rad
-1 rad
Y [fm]
X [fm]


PHENIX data
IC with 3 tubes
0.3
0.2
0.1
0.0
-1.5
0.0
1.5
3.0
4.5
$1/N_{tr}dN_{pair}/d\Delta\phi$
$\Delta\phi$

Also for Ridge



Also for Ridge



Thus we thought the presence of granualities in EbE initial conditions are fundamental... but

Harmonic Flow Analysis
(now the basis of Hydrodynaic Model)

$$\frac{\mathrm{d}N}{\mathrm{d}y\mathrm{d}\phi} = \frac{\mathrm{d}N}{\mathrm{d}y}\left[1 + 2v_1\cos\left(\phi - \psi_1\right) + 2v_2\cos\left[2\left(\phi - \psi_2\right)\right] + \ldots\right],$$

$$v_n = \frac{\int \mathrm{d}\phi \cos\left[n\left(\phi - \psi_n\right)\right]\frac{\mathrm{d}N}{\mathrm{d}y\mathrm{d}\phi}}{\int \mathrm{d}\phi \frac{\mathrm{d}N}{\mathrm{d}y\mathrm{d}\phi}} = \left\langle \cos\left[n\left(\phi - \psi_n\right)\right]\right\rangle,$$

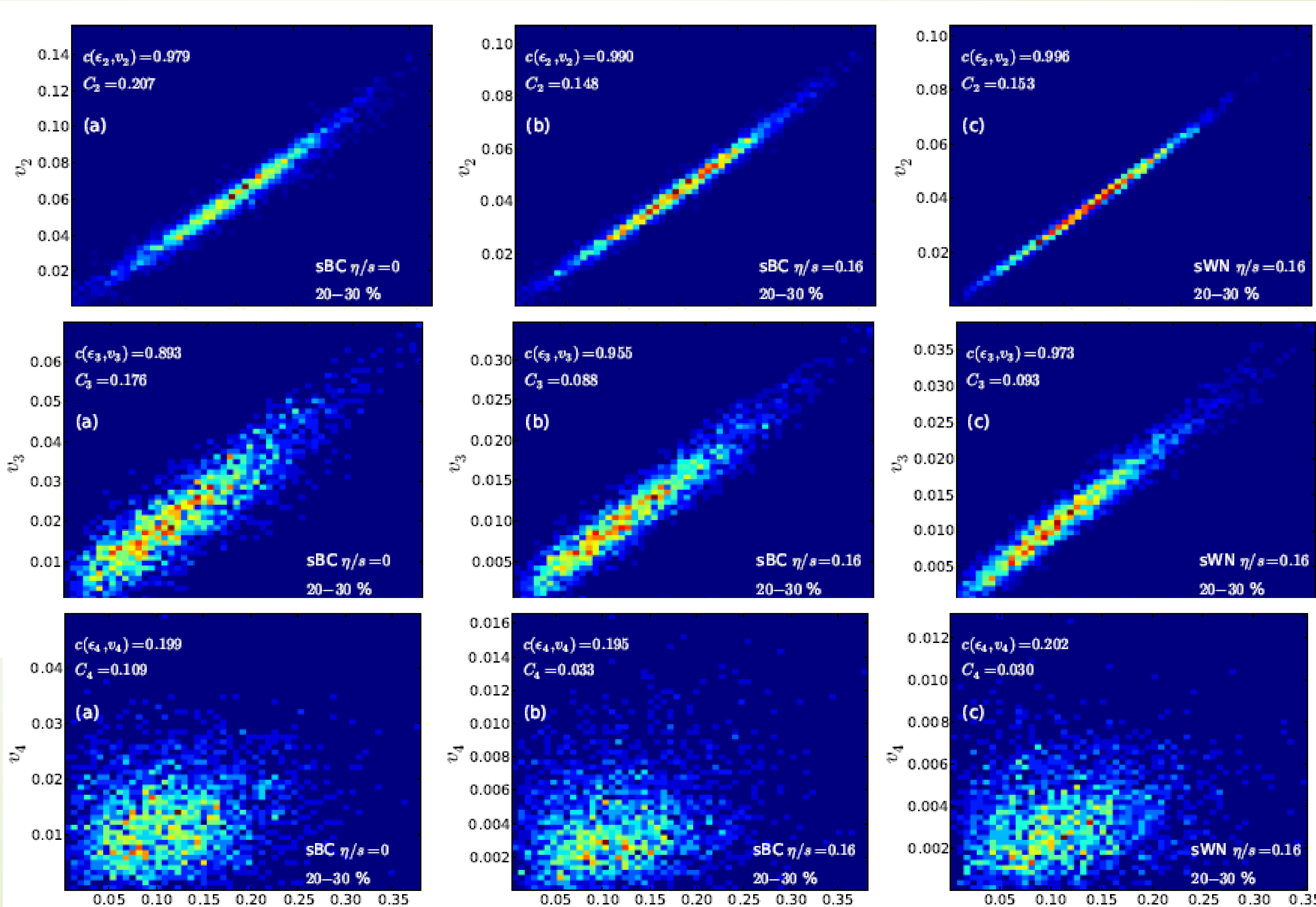
$$v_n = v_n(p_T; b)$$

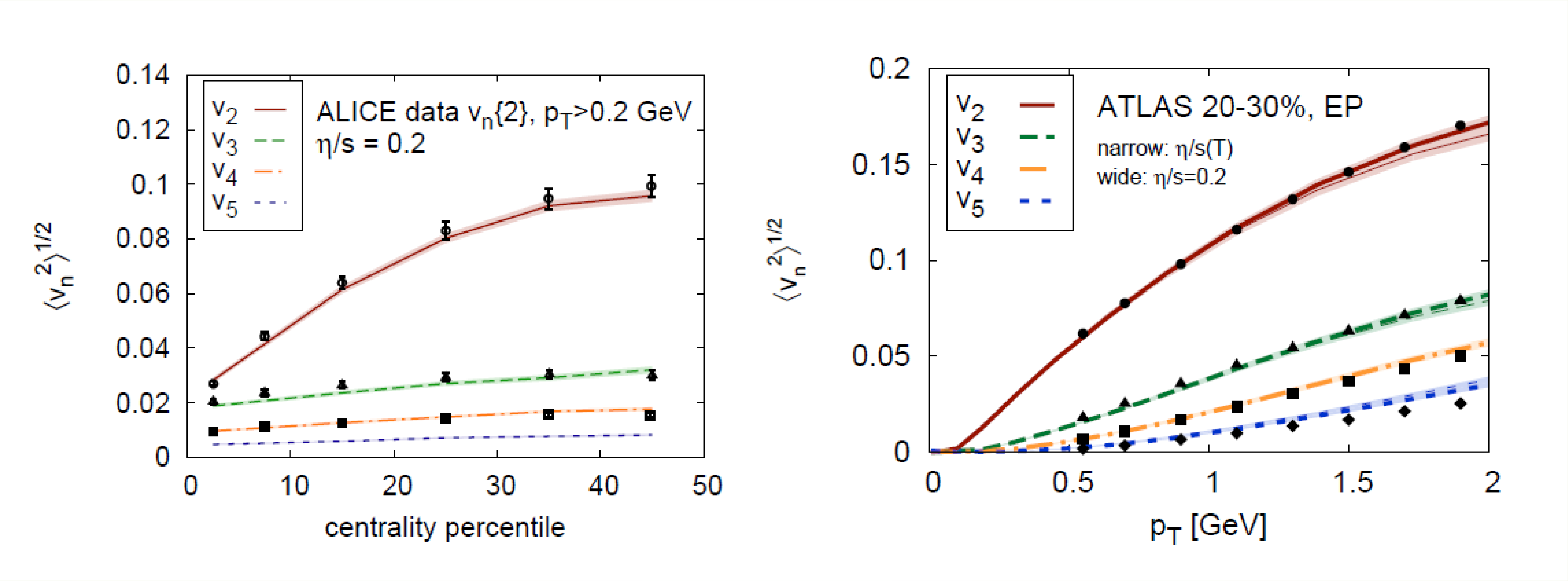
B.Alver, G.Roland (2010)

Great Success and can be used to determine the EoS and transport coefficients !

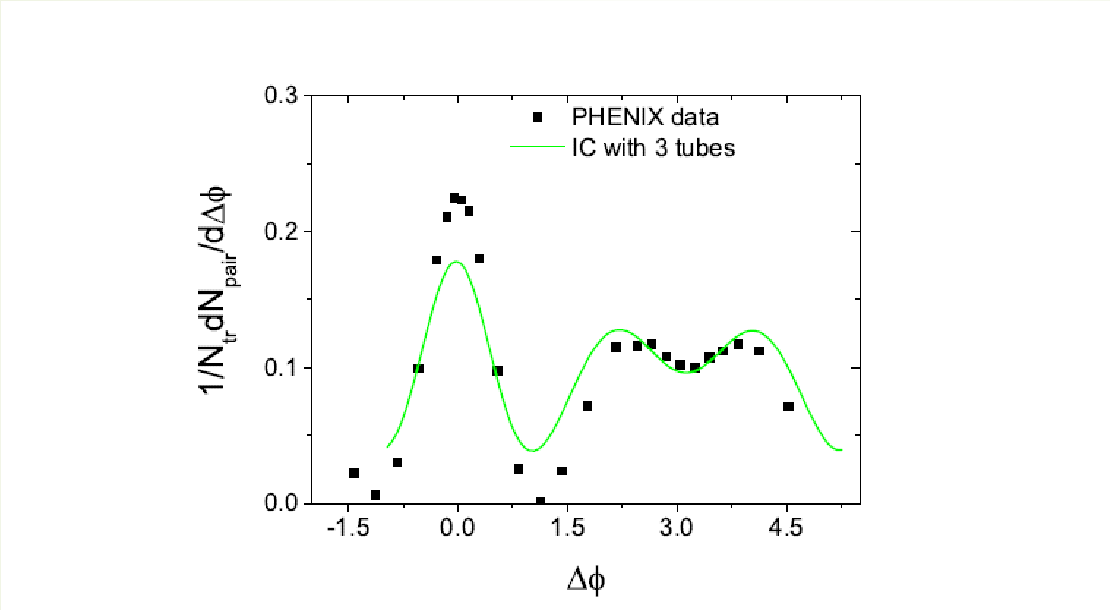
EbE Correlation (e_n - v_n)

H. Niemi, G. S. Denicol, H. Holopain, P. Huovinen (2012)





ALICE data $v_n\{2\}$, p_T>0.2 GeV
η/s = 0.2
v_2
v_3
v_4
v_5
$\langle v_n^2\rangle^{1/2}$
centrality percentile
ATLAS 20-30%, EP
narrow: η/s(T)
wide: η/s=0.2
p_T [GeV]



Two hadron correlation -> Just a triangular flow V_3

Success of Hydrodynamic Approach

↓

Determine EoS and Transport coefficients

- Search for the critical point
- EoS for Baryon Rich Matter

Success of Hydrodynamic Approach

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Determine EoS and Transport coefficients

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EbE Fluctuation vs Use of EoS

Success of Hydrodynamic Approach

Determine EoS and Transport coefficients

- Search for the critical point
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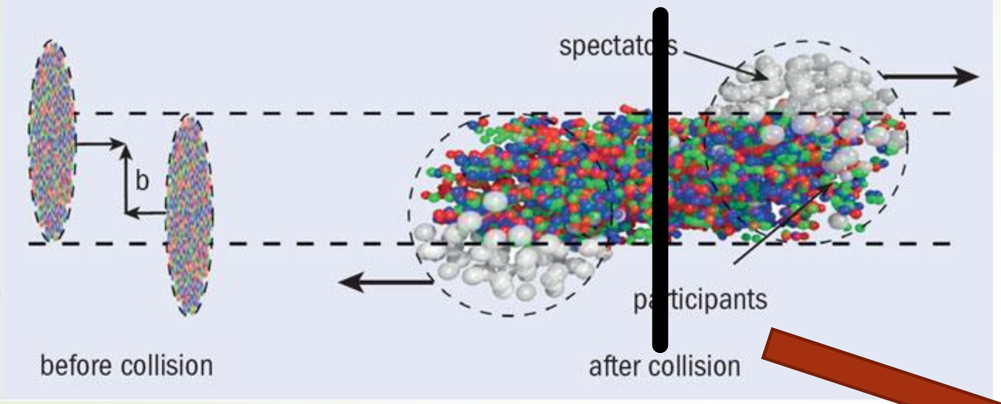
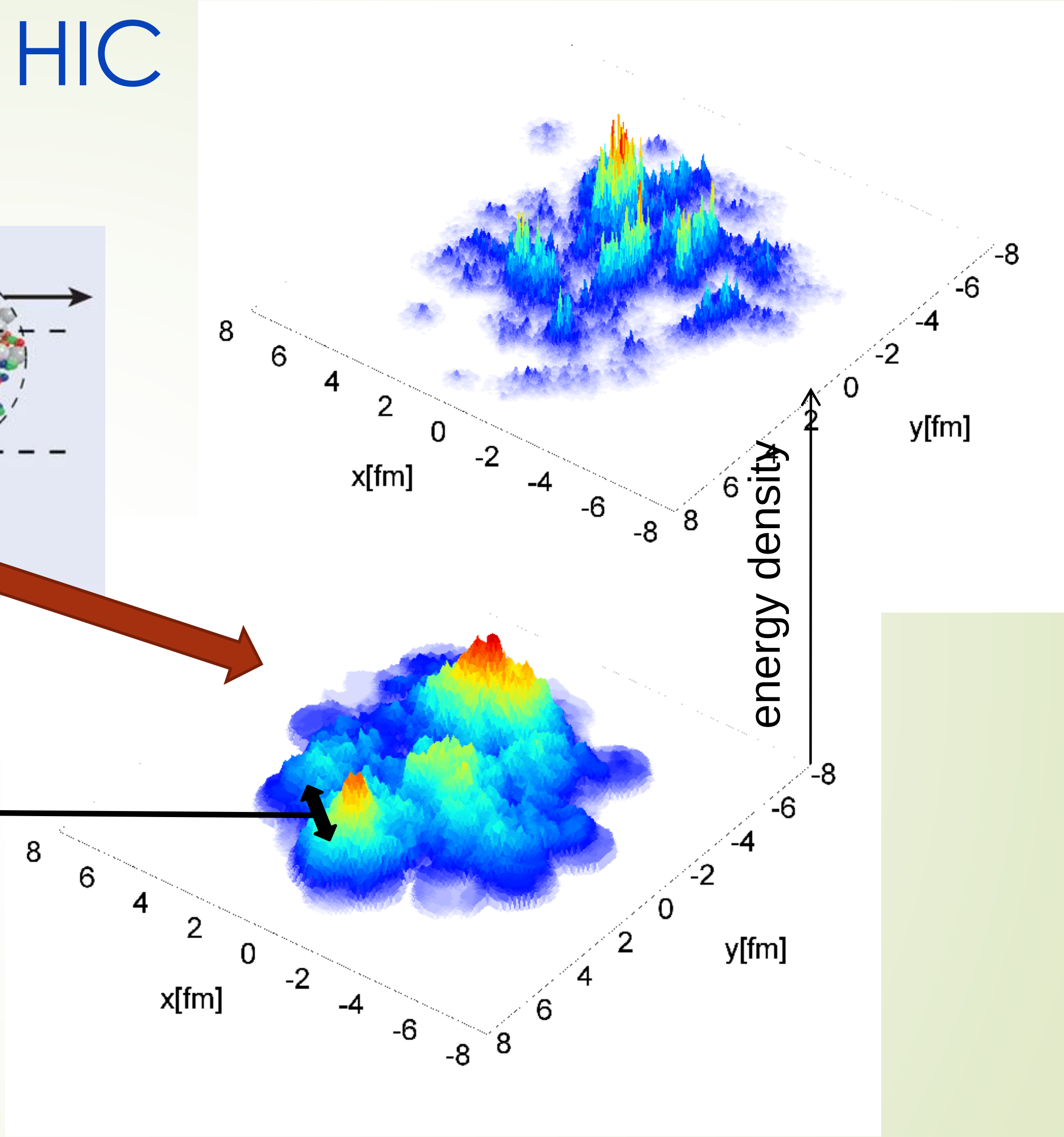
EbE Fluctuation vs Use of EoS 

How quantitatively precise?

Initial condition in HIC





The width of one peak

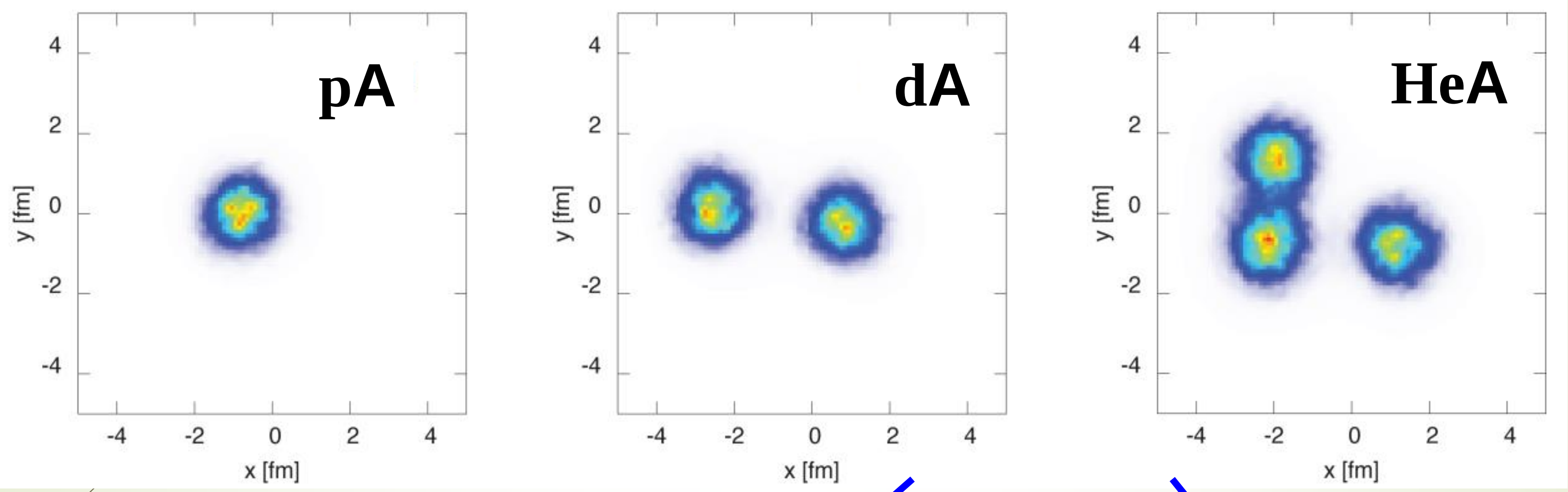
~ 1 fm (= 10^{-15} m)

The grid size for hydro simulation

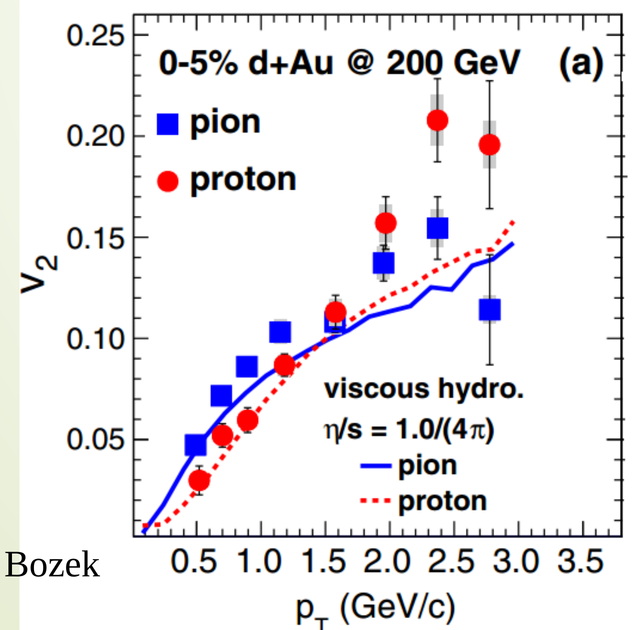
≤ 0.1 fm

Schenke et al., PRL108, 252301 (`12)

Hydrodynamic description of small systems?

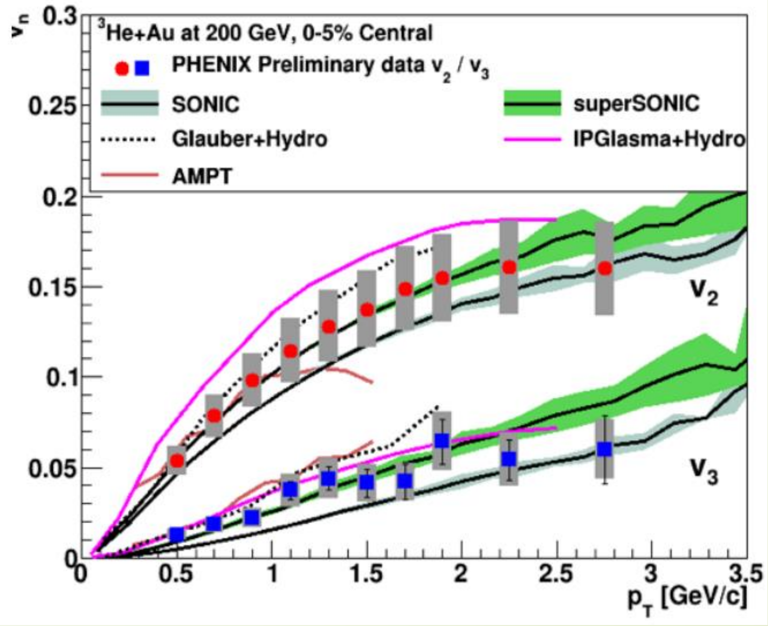


Good agreement with calculations

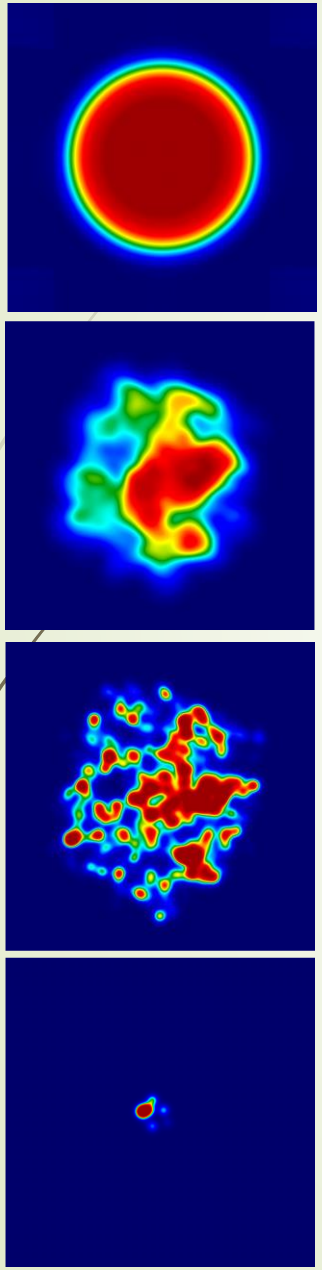


Calculation by Bozek

Calculation by Romatschke



Fluid-dynamics is being applied to describe small distance/time scales



Smooth Initial conditions — $\lambda \sim 5$ fm

Fluctuations in nucleon positions — $\lambda \sim 1$ fm

Local entropy fluctuations (NBD)
sub-fermionic fluctuations — $\lambda \sim 0.3$ fm

proton-nucleus collisions — $\lambda \sim 0.3$ fm or smaller

Hydrodynamic Evolution

$$T_{\mu\nu} = T_{\mu\nu}(x)$$

$$\partial^{\mu} T_{\mu\nu} = 0$$ + Eauation of States

Hydrodynamic Evolution

$$T_{\mu\nu} = T_{\mu\nu}(x)$$

$$\partial^{\mu} T_{\mu\nu} = 0$$

+ Eauation of States (Local equilibrium)
+ Dissipative Correction
+ Freezeout Process

Hydrodynamic Evolution

$$T_{\mu\nu} = T_{\mu\nu}(x)$$

$$\partial^{\mu} T_{\mu\nu} = 0$$

+ Eauation of States (Local equilibrium)
+ Dissipative Correction
+ Freezeout Process

We enforce to close the system in terms of energy-momentum tensor...

Several Types of Coarse Graining

- Space-like coarse graining
- Time-like coarse graining
- Event average (obsrvables)

Hydrodynamic Evolution

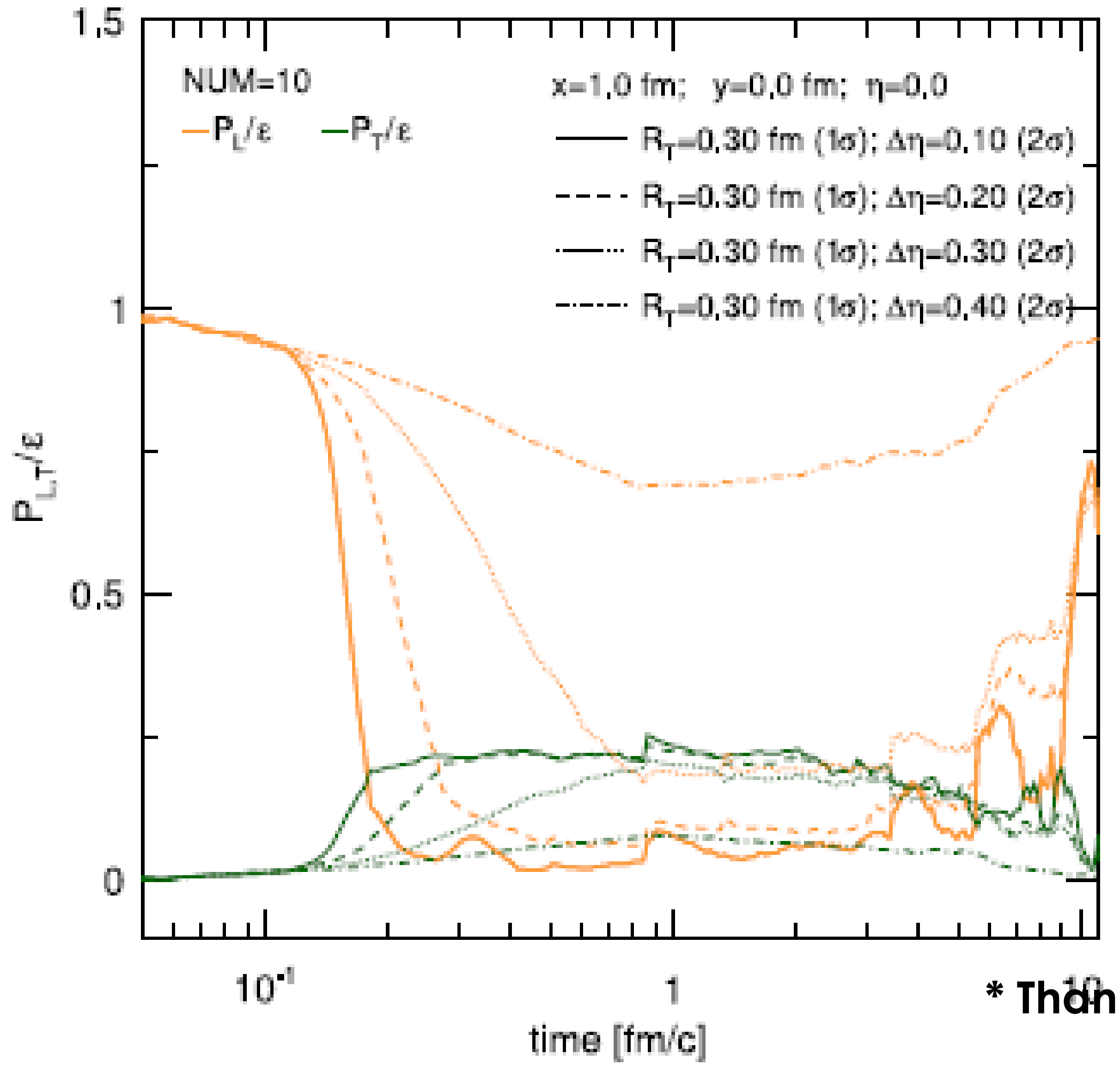
What happens with the "Event Average?

$$T_{\mu\nu} = T_{\mu\nu}(x)$$

$$\partial^{\mu} T_{\mu\nu} = 0$$

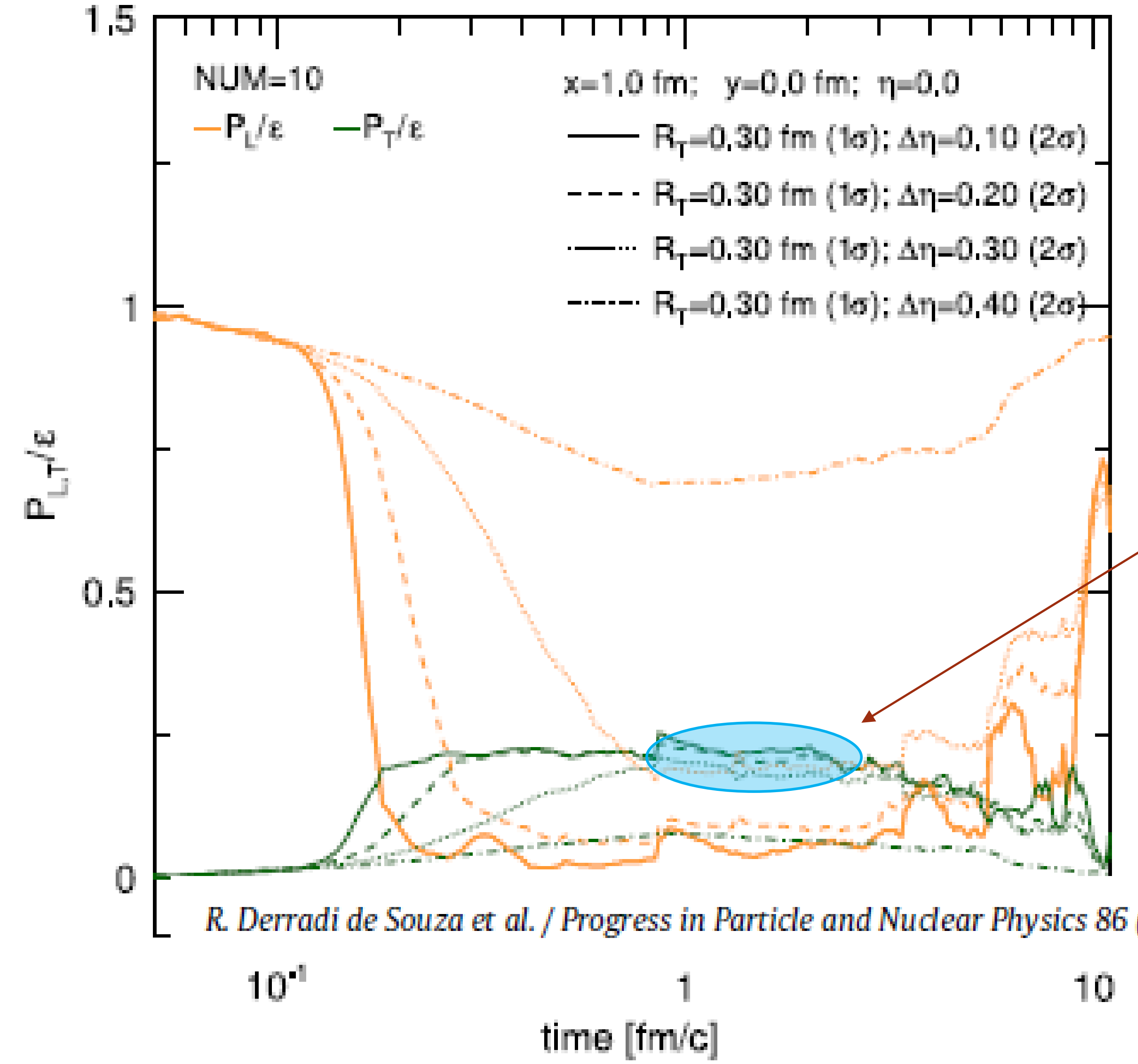
+ Eauation of States (Local equilibrium)
+ Dissipative Correction
+ Freezeout Process

PHSD Representation of Energy&Momentum Tensor



* Thanks to Elena and collaborators

R. Derradi de Souza et al. / Progress in Particle and Nuclear Physics 86 (2016) 35–85



R. Derradi de Souza et al. / Progress in Particle and Nuclear Physics 86 (2016) 35–85

Thermal equilibrium:

Only very small fraction of space-tame domain

Basic Question:
In Hydrodynamic description,

The harmonic coefficients really carry sufficient Information for the quantitative analysis??

Basic Question:
In Hydrodynamic description,

The harmonic coefficients really carry sufficient Information for a <u>quantitative analysis</u>??

↓

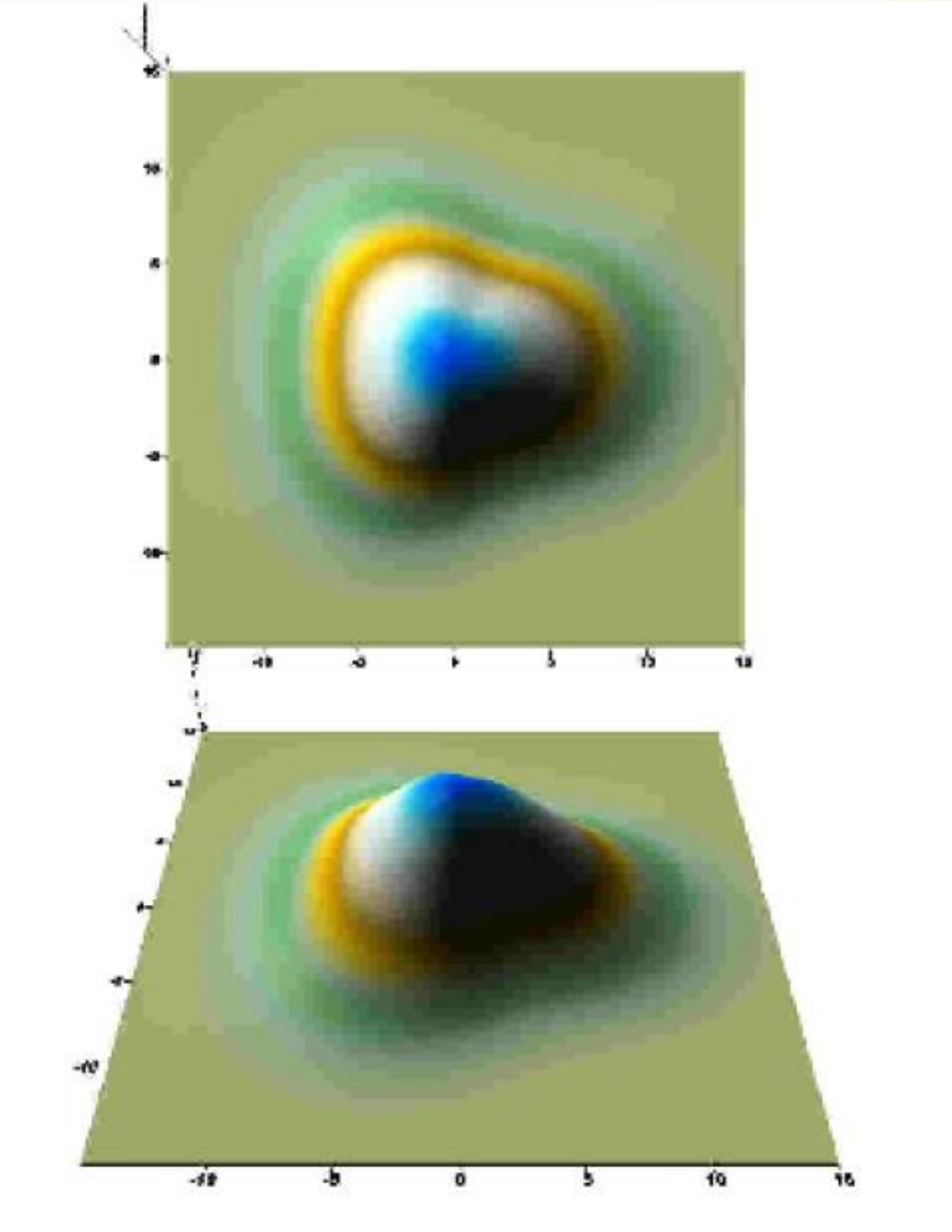
Are there other initial states which give rise to the same behavior of the harmonic coefficients?

An example: ***Smooth***

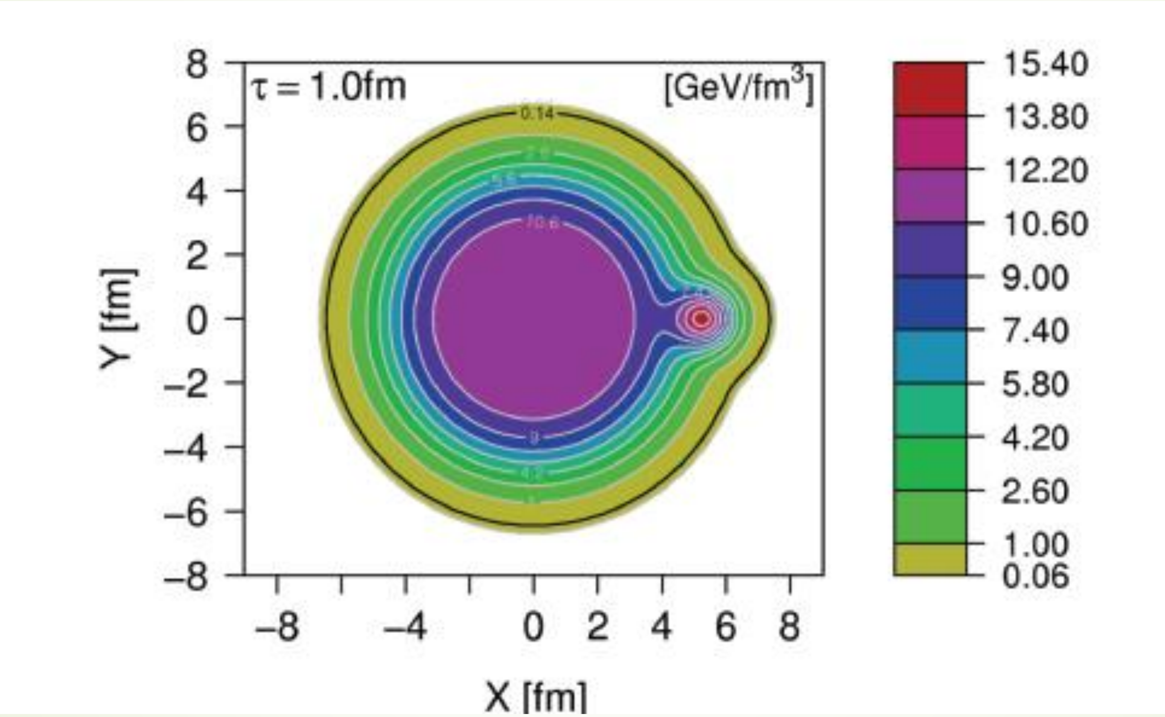
$$\varepsilon\left(r,\theta\right)=Z\ \exp\left\{-\frac{r^{2}}{R^{2}\left(\theta\right)}\right\}$$

$$R(\theta)=R_{0}\left(1+\sum_{n=2}C_{n}\cos n\left(\theta-\theta_{n}\right)\right)^{1/2}$$

Smooth

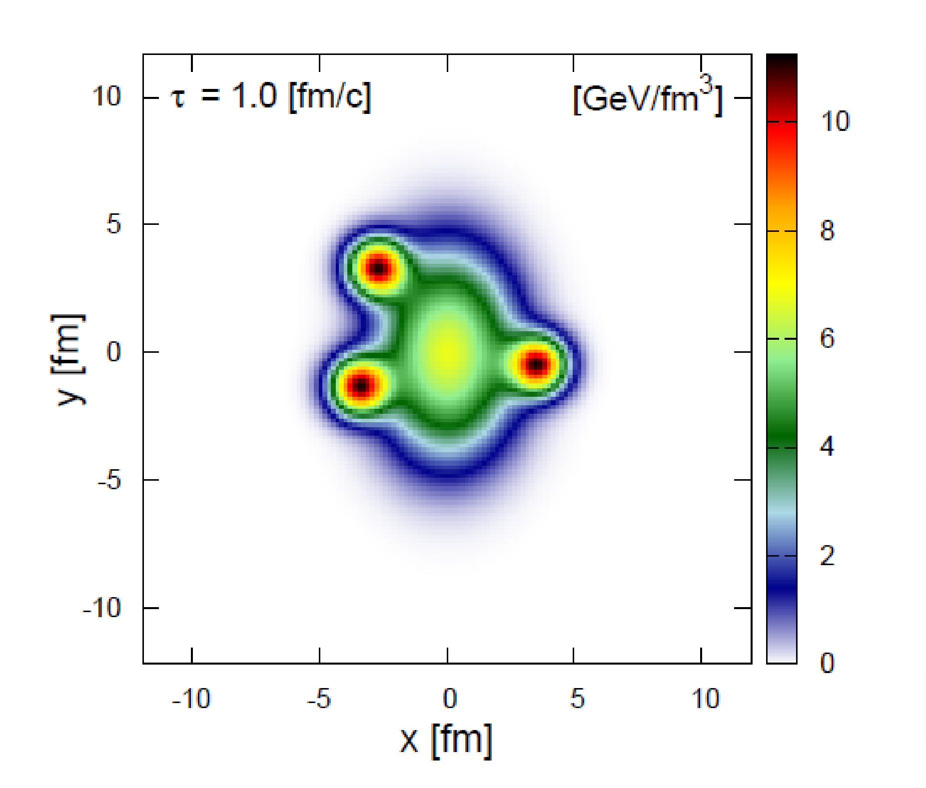


Comare with *Granular*



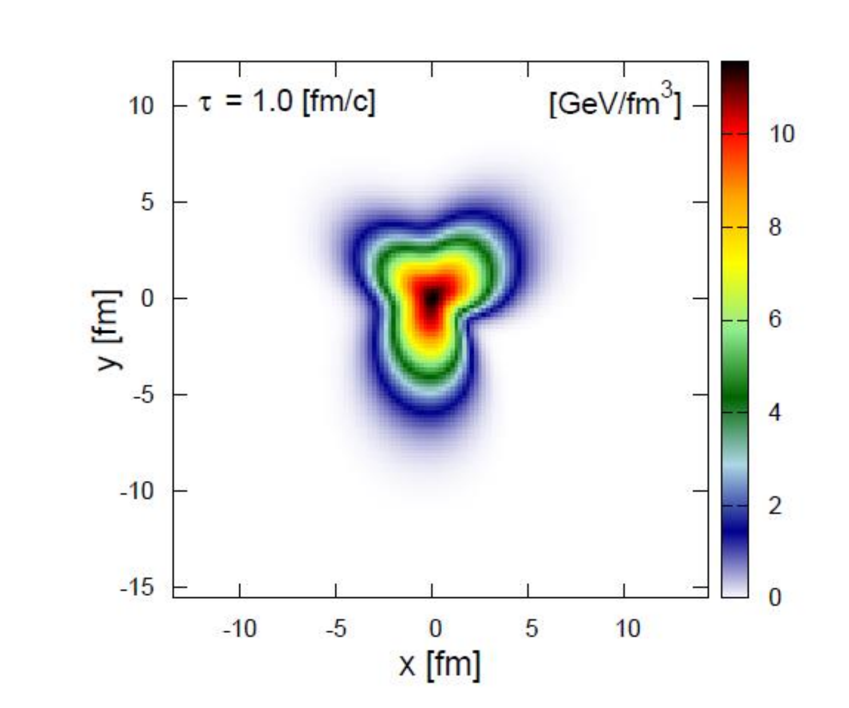
Granular

or

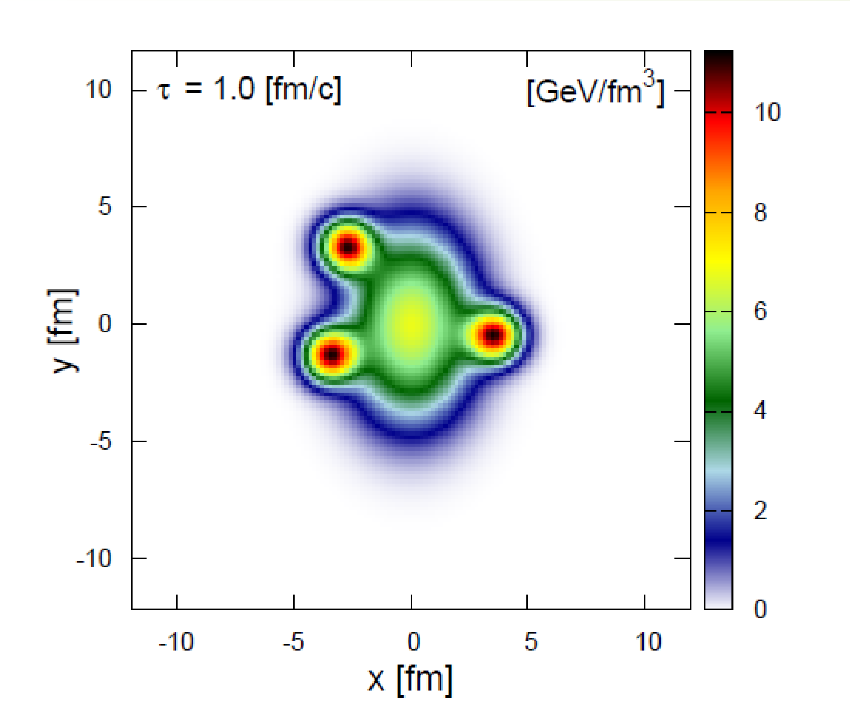


etc....

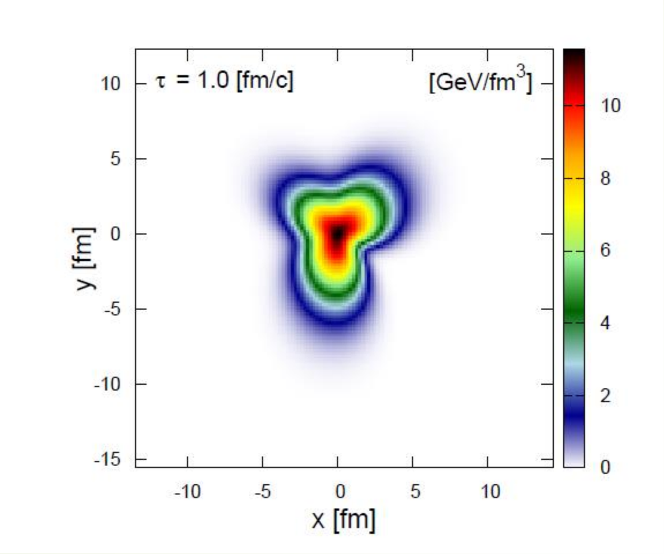
Compare two different initial conditions, having in average the same anisotropic distribution coefficients, $\{\varepsilon_n\}$, one ***smooth***, other with ***granularities***.

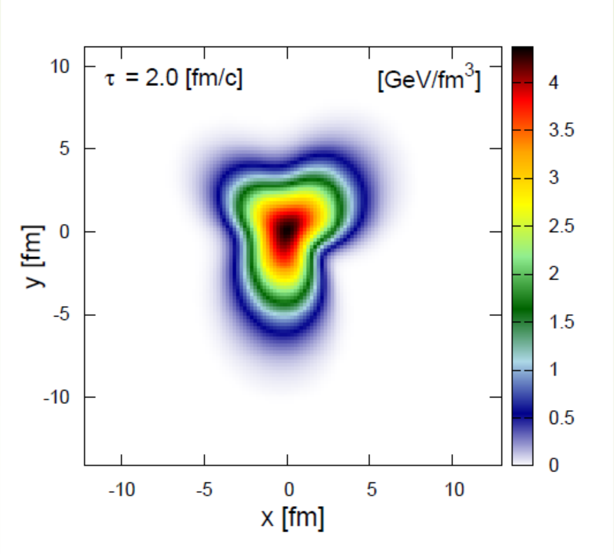


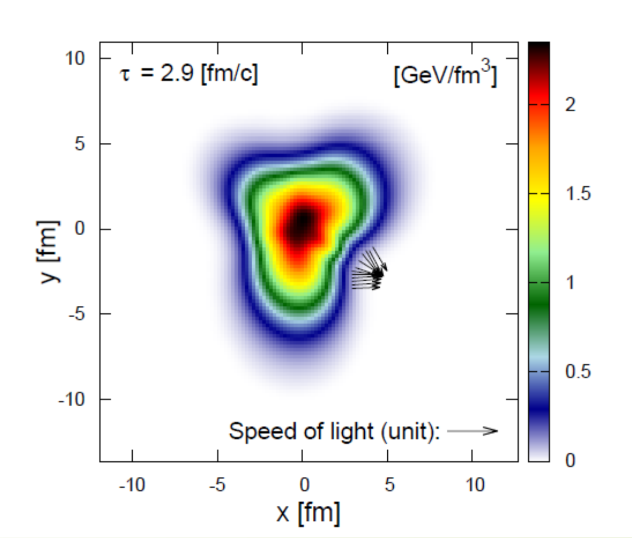
VS

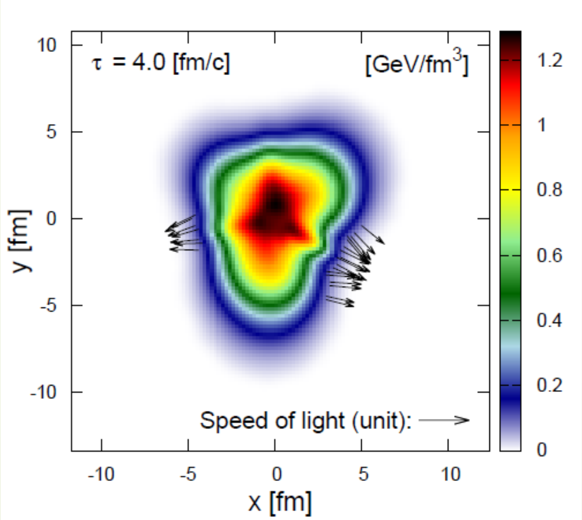


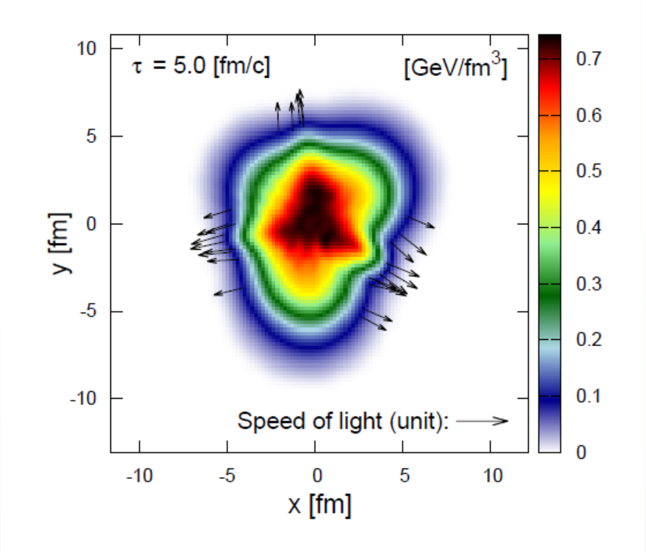
Smooth

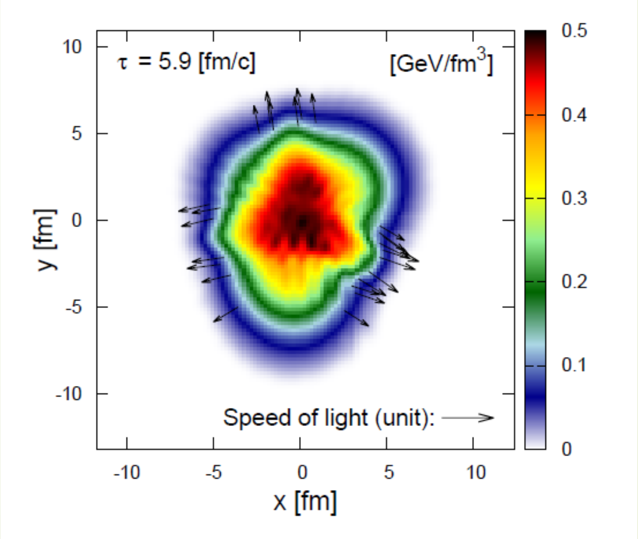

τ = 1.0 [fm/c]
[GeV/fm3]
y [fm]
x [fm]


τ = 2.0 [fm/c]
[GeV/fm3]
y [fm]
x [fm]

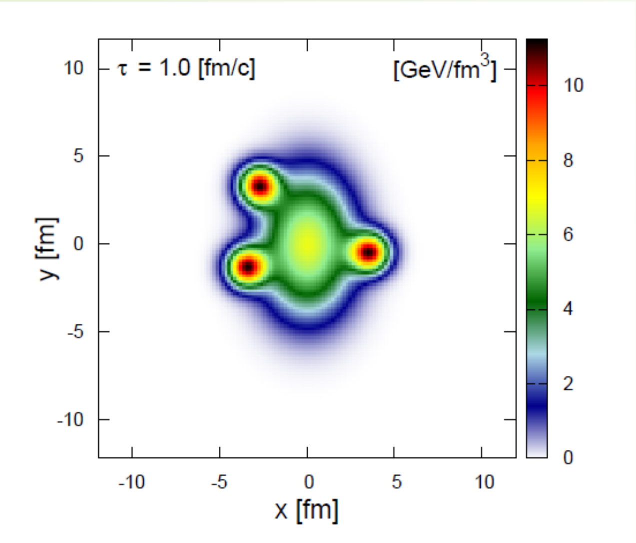

τ = 2.9 [fm/c]
[GeV/fm3]
Speed of light (unit):
y [fm]
x [fm]

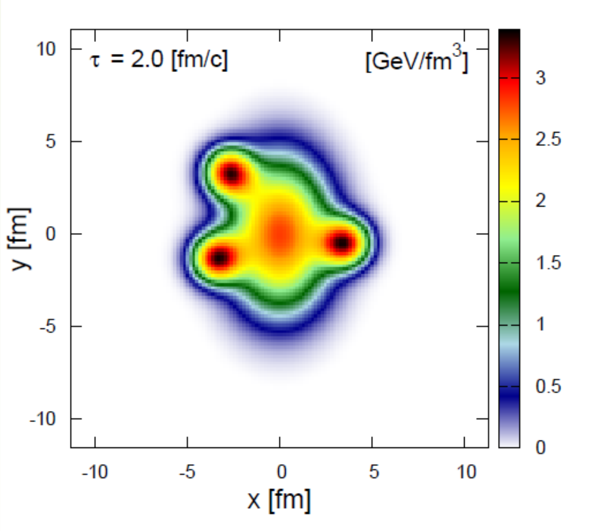

τ = 4.0 [fm/c]
[GeV/fm3]
Speed of light (unit):
y [fm]
x [fm]

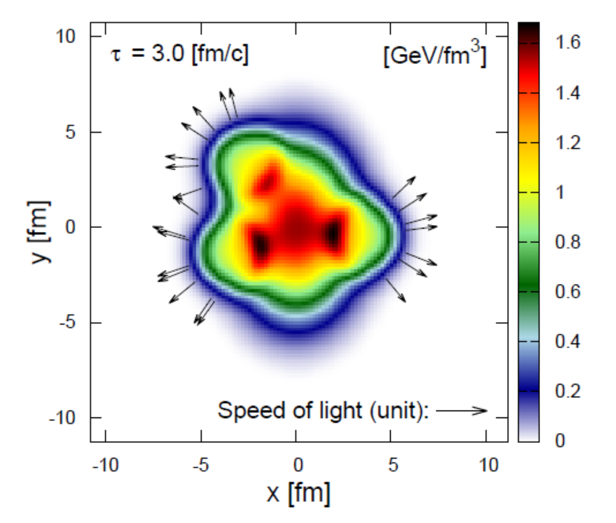

τ = 5.0 [fm/c]
[GeV/fm3]
Speed of light (unit):
y [fm]
x [fm]

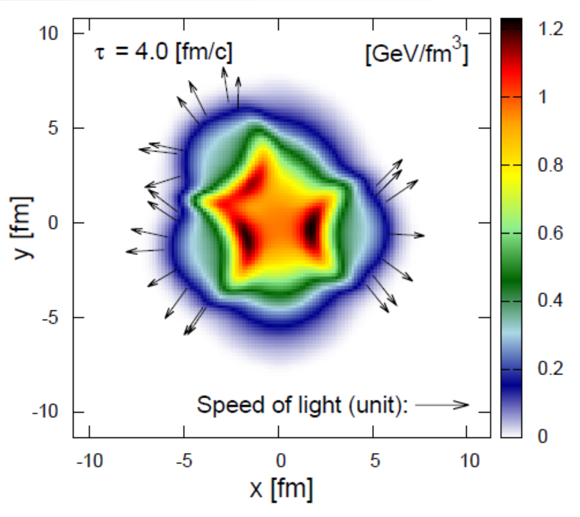

τ = 5.9 [fm/c]
[GeV/fm3]
Speed of light (unit):
y [fm]
x [fm]

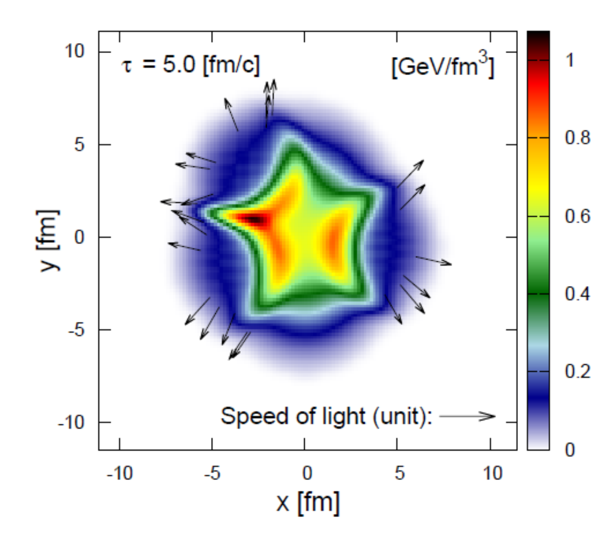
Granular

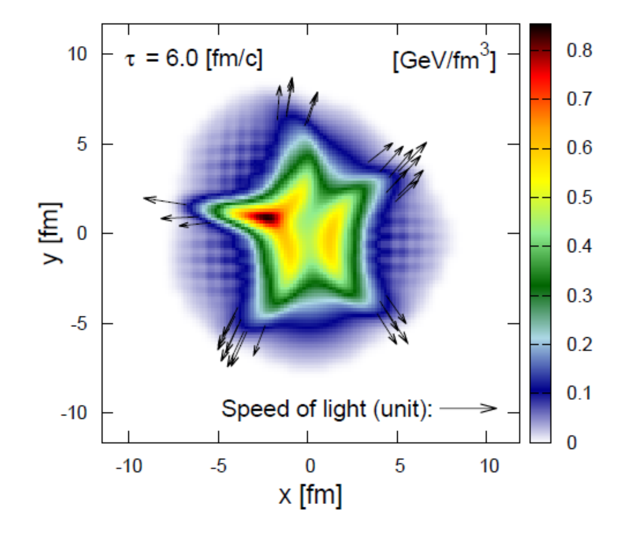

τ = 1.0 [fm/c]
[GeV/fm³]
x [fm]
y [fm]


τ = 2.0 [fm/c]
[GeV/fm³]
x [fm]
y [fm]


τ = 3.0 [fm/c]
[GeV/fm³]
Speed of light (unit):
x [fm]
y [fm]


τ = 4.0 [fm/c]
[GeV/fm³]
Speed of light (unit):
x [fm]
y [fm]


τ = 5.0 [fm/c]
[GeV/fm³]
Speed of light (unit):
x [fm]
y [fm]

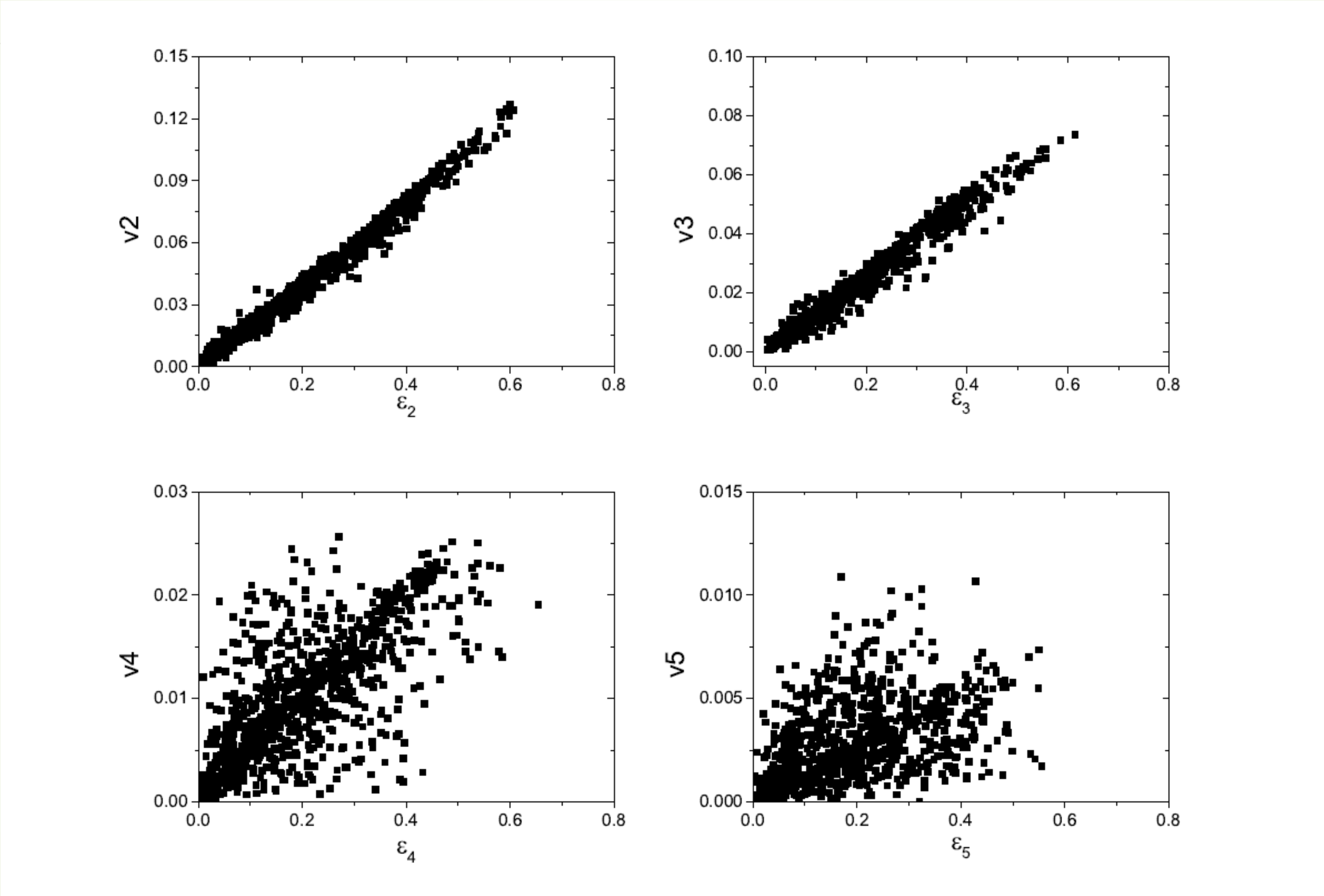

τ = 6.0 [fm/c]
[GeV/fm³]
Speed of light (unit):
x [fm]
y [fm]

Tuning to have the same enegy density anisotropy with smooth and granular initial conditions, their time evolutions are totally different.

But statistically,...

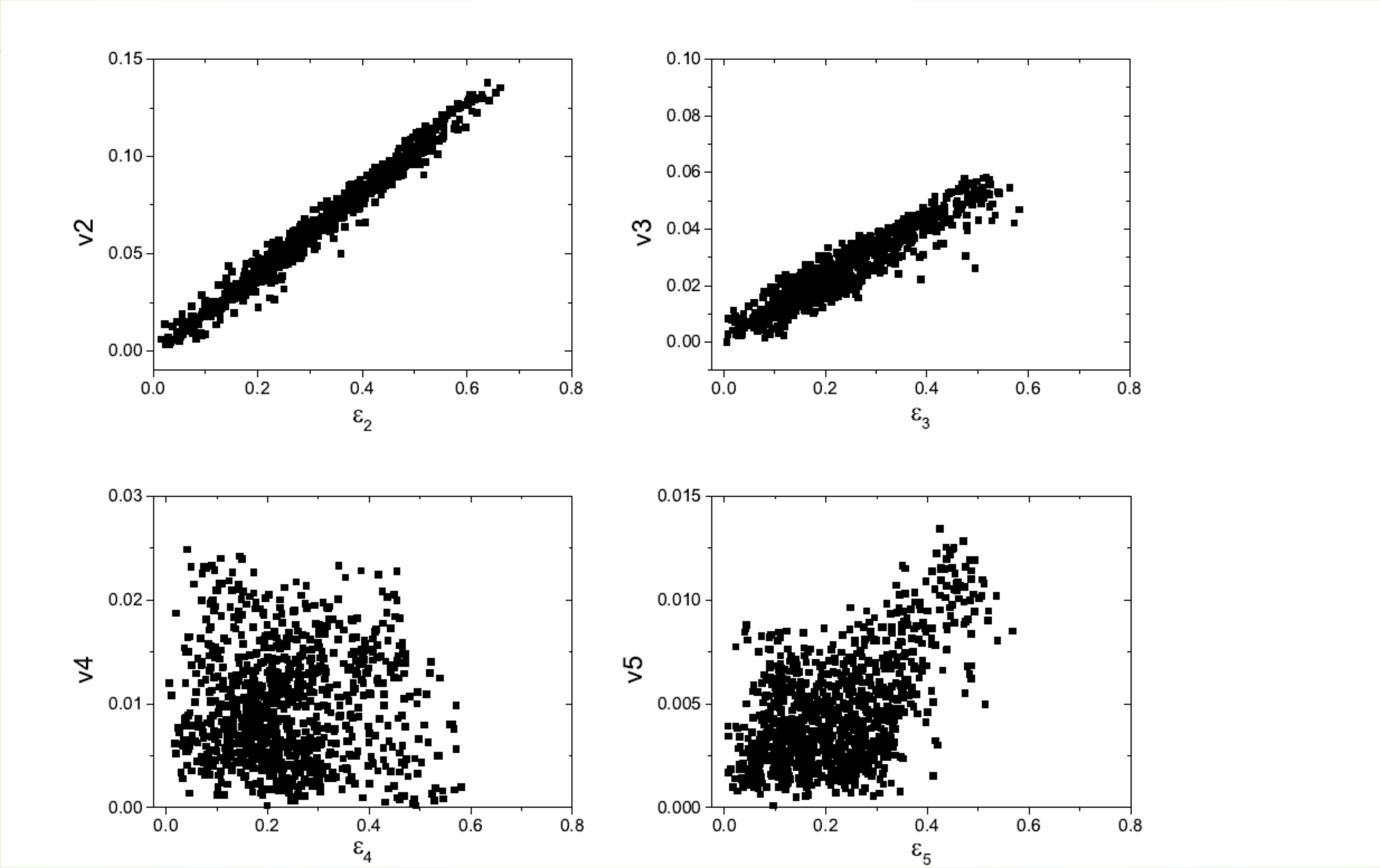
Smooth

Correlation between ε_n x v_n



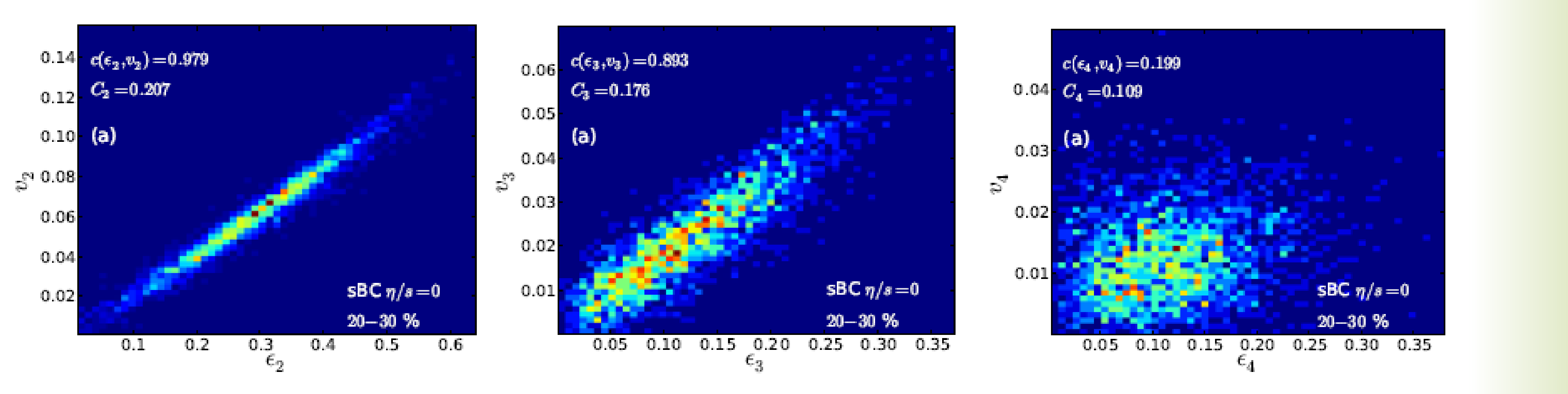
Granular

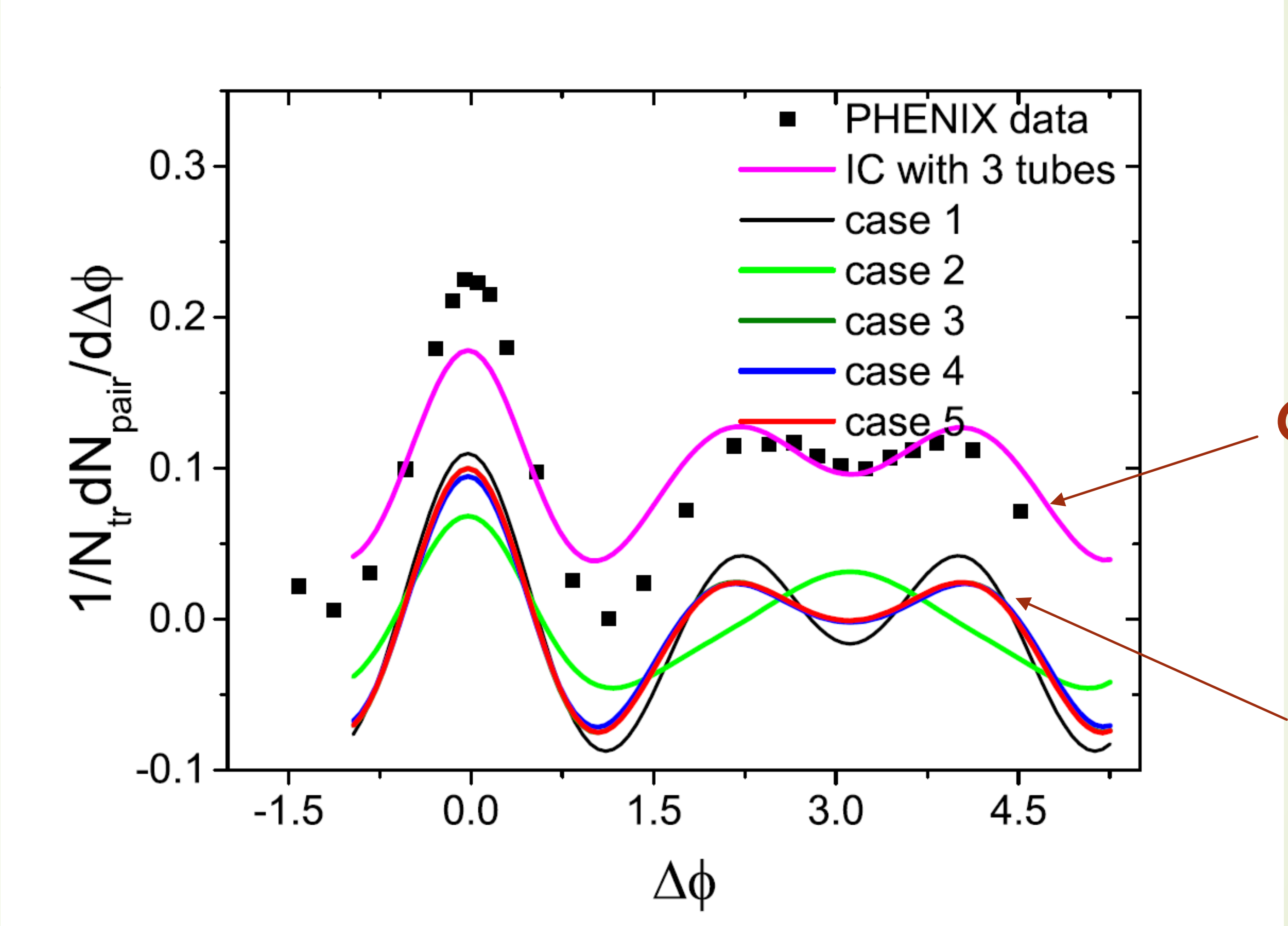
Correlation between ε_n x v_n



EbE Correlation (e_n - v_n)

H. Niemi, G. S. Denicol,
H. Holopain, P. Huovinen
(2012)





Granular

Smooth

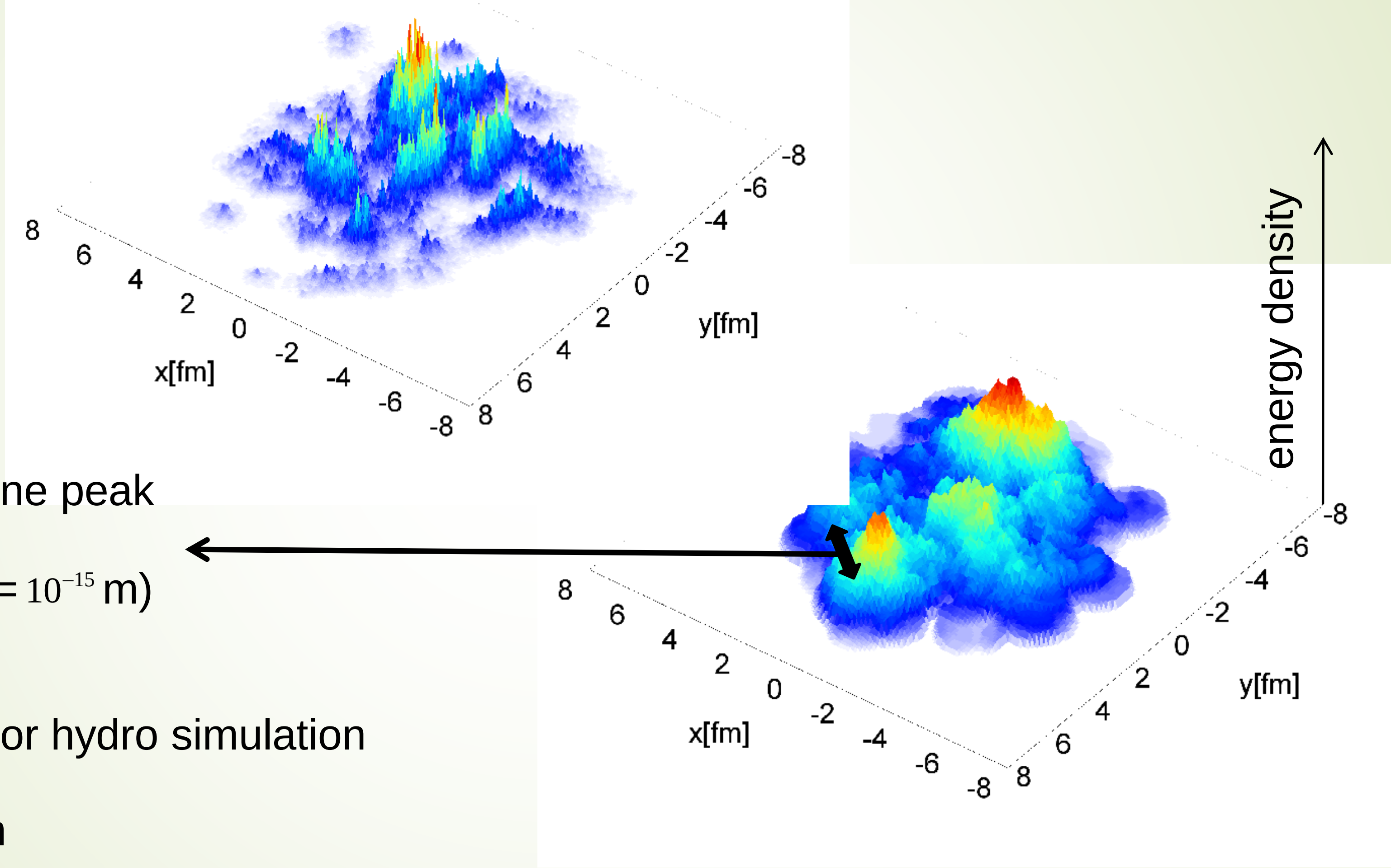
Further detailed studies are in progress on the effects of EoS and Transport coefficients, system size, pT and centrality dependence, etc. But, aparently only fitting Harmonic Flow coefficients is not enough to determine the dynamics on EbE basis.

Necessity for the higher order observables to see the non-linear responses.

L. Yan, S. Pal, J.-Y. Ollitrault, Nuclear Physics A 956, 340 (2016).
L. Yan, J.-Y. Ollitrault, Physics Letters B 744, 82 (2015)
and recent proposals….

Another importante aspect:
Where are the quantum effects?

Another importante aspect: Where are the quantum effects?



The width of one peak

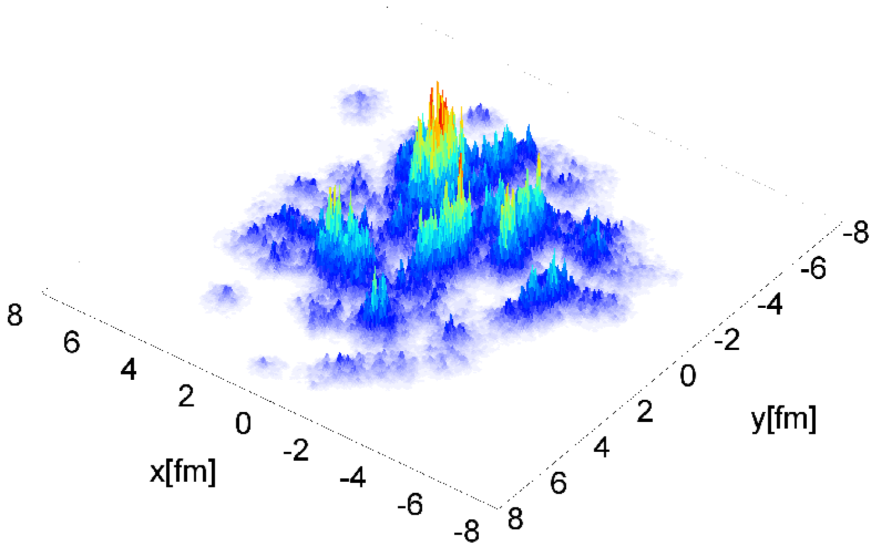
~ 1 fm ($= 10^{-15}$ m)

The grid size for hydro simulation

≤ 0.1 fm

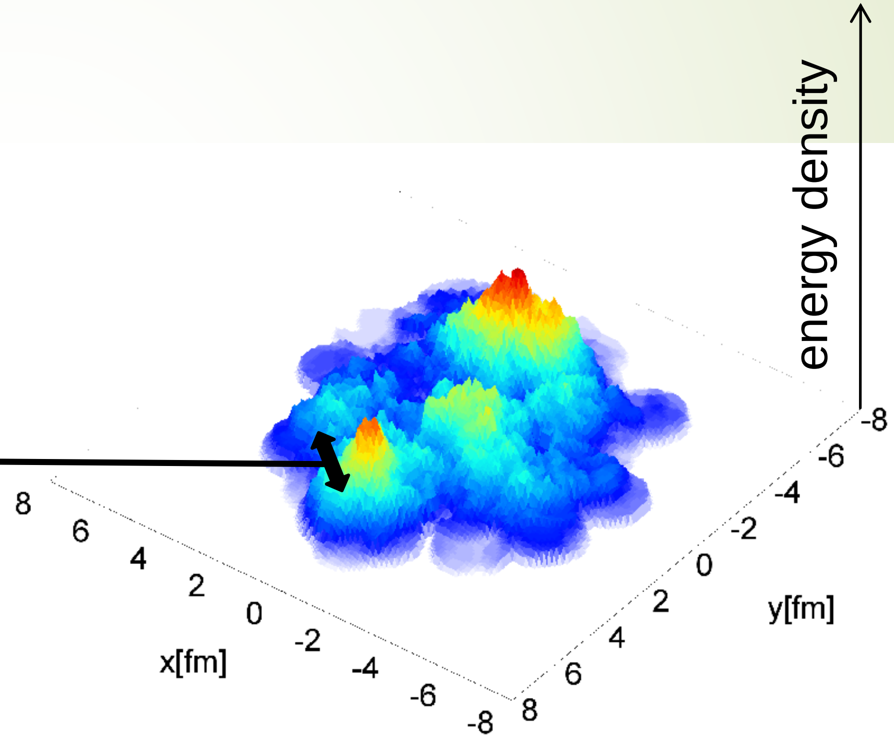
Schenke et al., PRL108, 252301 (`12)

Unceratinty relation affects a lot for small systems and granualities…….



The width of one peak

~ 1 fm

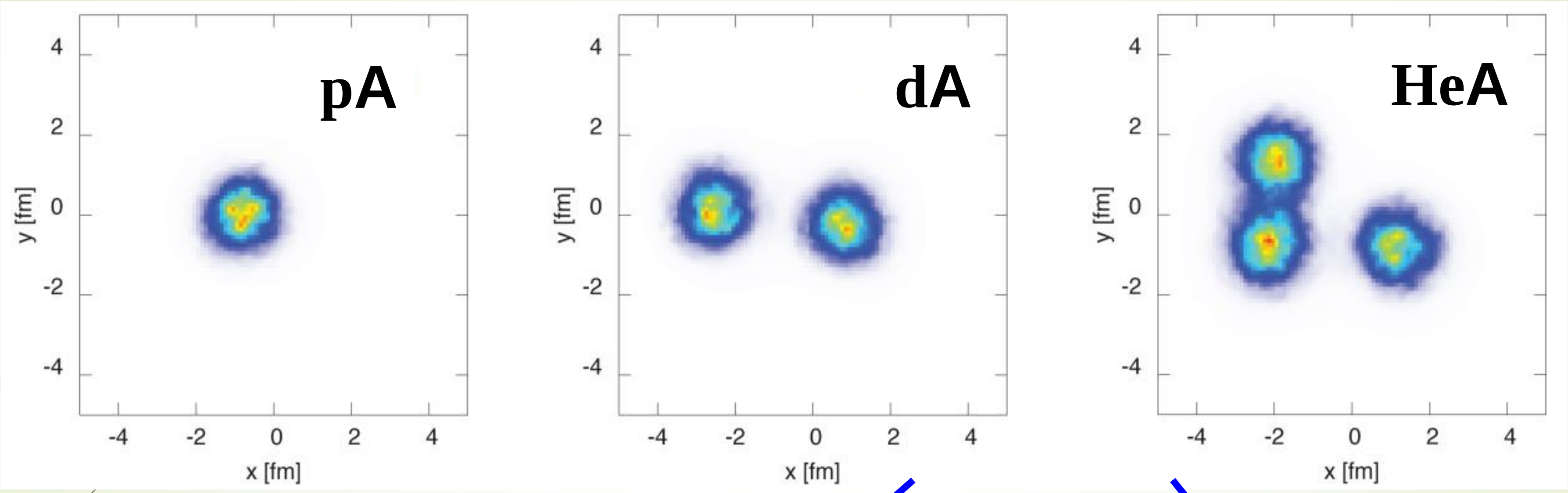


The grid size for hydro simulation

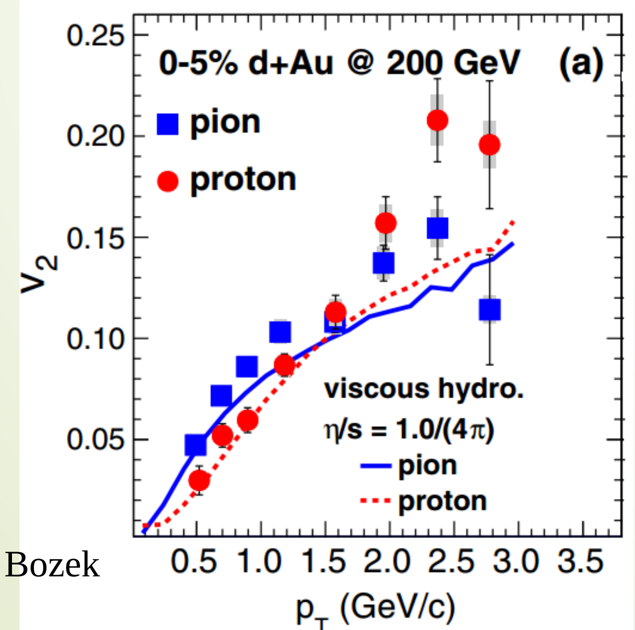
≤ 0.1 fm

$$\Delta p > 1 GeV \ !$$

Hydrodynamic description of small systems?

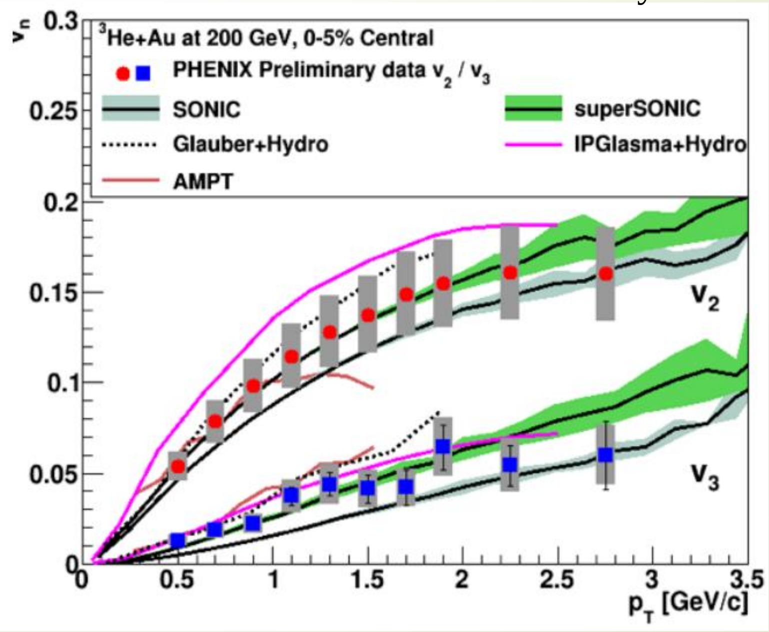


Good agreement with calculations



Calculation by Bozek

Calculation by Romatschke



Quantum Effects in Hydro

↓

Additional Quantum Pressure (the Uncertainty Relation)

T.Koide, T.K. Physics Letters A Volume 382, Issue 22, 5 June 2018, Pages 1472-1480

Well-known the common structure between Hydrodynamics & Schroedinger Equation (even for manybody systems – Gross-Pitaevski)

Quantum Effects in Hydro

↓

Additional Quantum Pressure
(the Uncertainty Relation)

T.Koide, T.K. Physics Letters A Volume 382, Issue 22, 5 June 2018, Pages 1472-1480

$$p_Q = -\frac{1}{2m}\frac{1}{\sqrt{\rho}}\nabla^2\sqrt{\rho}$$

How to formulate the quantum effects covariantly in a hydrodynamic form... ?

Maybe Giorgio ...

Thank you for your attention !