# Event-by-event hydrodynamics

F.Grassi[1]

[1]Instituto de Física, Universidade de São Paulo, Brazil

# Outline

# I. Introduction

## What is event-by-event hydrodynamics?

Provide initial conditions $\rightarrow$ Solve hydrodynamics equations $\rightarrow$ Compute observables

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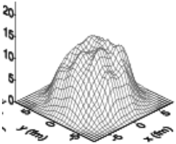
|---|---|---|---|---|

Traditional approach ($<$ 2010):

smooth initial conditions: $\epsilon_0(x, y)$




$\rightarrow$ run once

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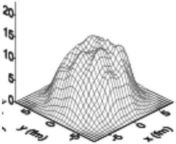
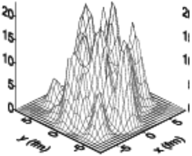


$\rightarrow$ run once

Event-by-event approach:

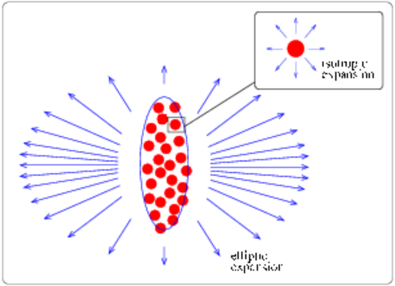
fluctuating initial conditions: $\epsilon_0(x, y)$



$\rightarrow$ run many times should mimick experiment better

- ▷ 3+1
  - SPheRIO group:
    NeXus initial conditions+ **ideal** hydro since 2001
  - H.Petersen et al.:
    UrQMD initial conditions+ **ideal** hydro since 2007
  - K.Werner et al.:
    EPOS initial conditions+ **ideal** hydro since 2010
  - B.Schenke et al.:
    MC Glauber & half gaussians w/plateau + **viscous** hydro since 2010
- ▷ 2+1
  - Holopainen et al.: MC Glauber since 2010
  - Qiu & Heinz’: MC Glauber or fKLN since 2010
  - Staig & Shuryak: $\sim$ analytical since 2010

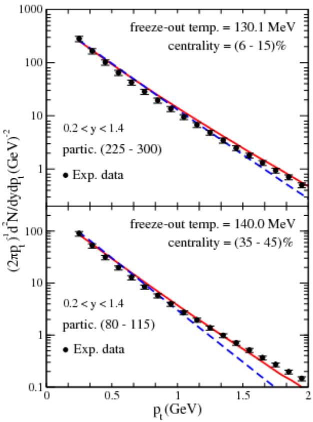
# WHAT DO WE EXPECT?



Hot spots expand
more violently and $\sim$ isotropically

# II. $p_\perp$ spectra

## Hardening due to stronger radial flow/hot spots

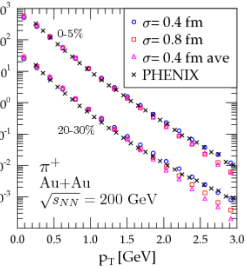


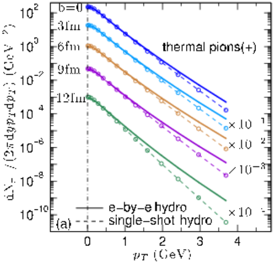

R.Andrade, FG, Y.Hama, T.Kodama, W.L.Qian PRL101(2008)112301

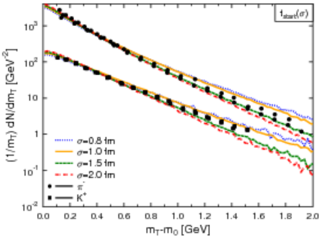
Effect increases for more peripheral collisions (diluted matter)

Confirmed in more detail by later studies

Note: effect is stronger for smaller granularity (but $t_{start}(\sigma) \searrow$)

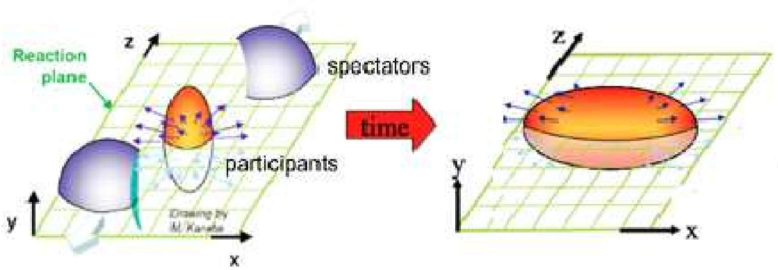


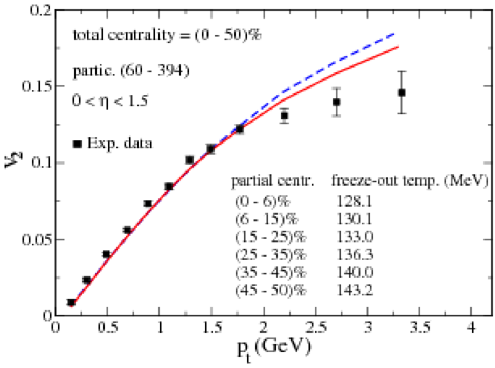

H.Holopainen et al. PRC83(2011)034901, Z.Qiu & U.Heinz PRC84(2011)024911, H.Petersen et al. JPG38(2011)045102.

# III. Elliptic flow $v_2$



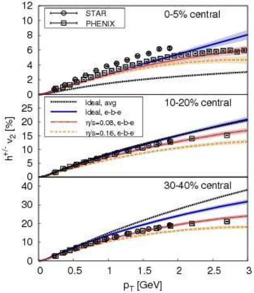

$b \neq 0$: $v_2$ dominated by geometry (standard picture),
decreases if there are hot spots
(cf. isotropic expansion)

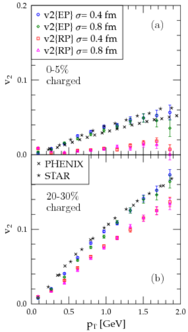
$b = 0$: $v_2$ is zero for smooth initial conditions
and $\neq 0$ if there are hot spots.

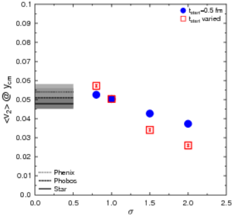



R.Andrade, FG, Y.Hama, T.Kodama, W.L.Qian PRL101(2008)112301

# Confirmed in more detail by later studies
# Note: effect is stronger for larger granularity



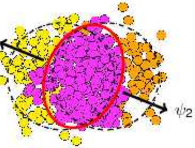

B. Schenke et al. PRL106(2011)042301, H.Holopainen et al. PRC83(2011)034901, H.Petersen et al. JPG38(2011)045102.

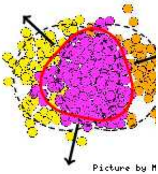
# IV. Higher flow harmonics $v_n$'s

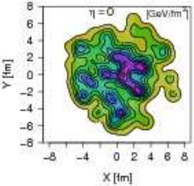
Angular particle distribution

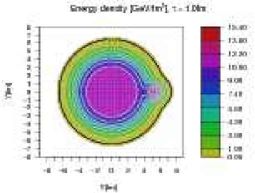
$$\frac{dN}{d\phi} = \frac{N}{2\pi}[1 + \sum_{n=1}^{\infty} 2\, v_n \cos(\phi - \psi_n)]$$

▷ For smooth initial conditions (of idential nuclei): $v_{n\,odd} = 0$
▷ For fluctuating initial conditions: all $v_n \neq 0$,
due to the overall geometry of the interacing region or to the presence of tubes.

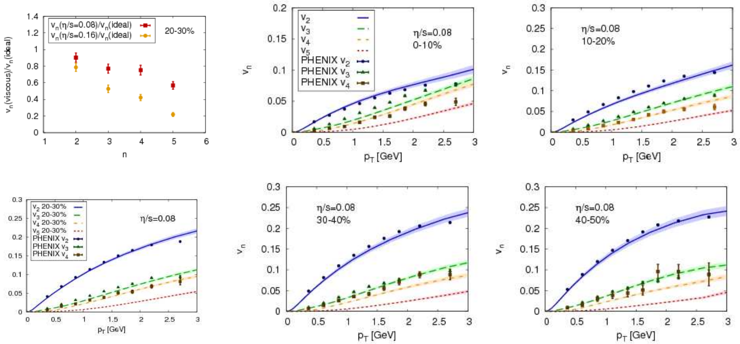


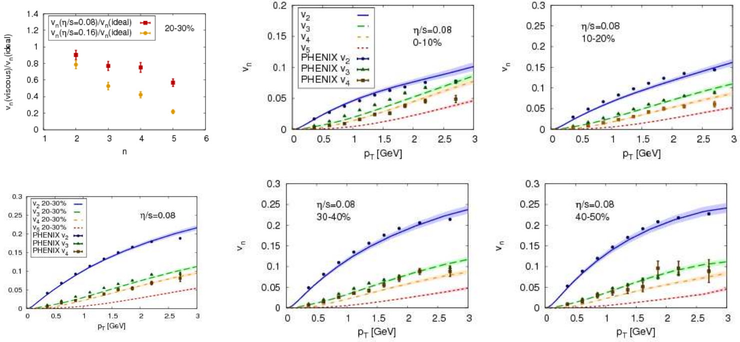
## $v_n$'s sensitive to $\eta/s$ (particularly for large $n$)




B. Schenke et al.. arXiv:1109.6289

This permits to pinpoint $\eta/s$

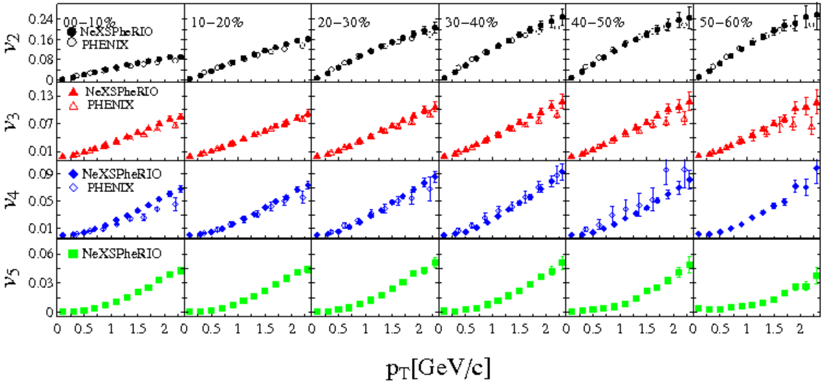
# $v_n$'s sensitive to $\eta/s$ (particularly for large $n$)




B. Schenke et al.. arXiv:1109.6289

This permits to pinpoint $\eta/s$?

## $v_n$'s expected to be sensitive on granularity (cf.isotropic expansion)

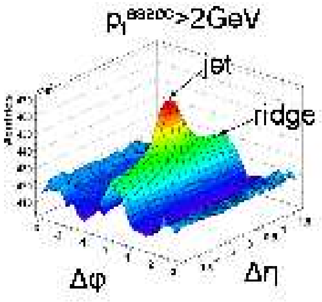



F.Gardim, FG, M.Luzum, J.-Y.Ollitrault *in progress*

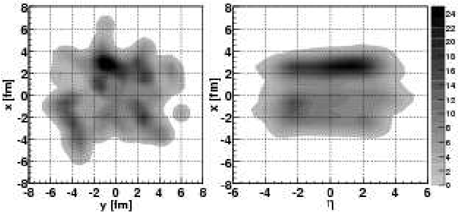
▷ Ideal hydro with NeXus initial conditions gives also a good description of the $v_n(p_\perp)$'s.
▷ Both viscosity *and* granularity must be taken into account for the $v_n(p_\perp)$'s.

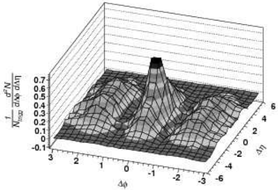
# V. Two-particle correlations in $\Delta\eta - \Delta\phi$

Observation of structures elongated along the collision axis (at RHIC and LHC)



# Reproduced by hydro with tubular initial conditions



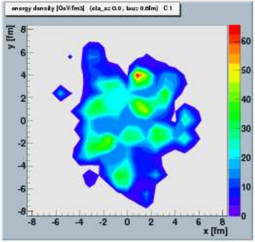

$\Delta\phi$ correlation
if particles
from same tube

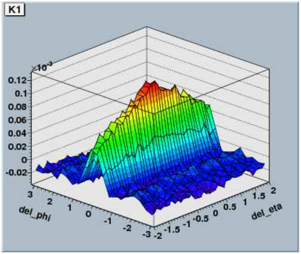
$\Delta\eta$ correlation
if particles
from same tube

WHY NOT JUST
NEAR-SIDE
RIDGE?

J.Takahashi, B.Tavares, W.-L.Qian, F.Grassi, Y.Hama, T.Kodama, N.Xu
PRL103(2009)242301

# Similar results from EPOS

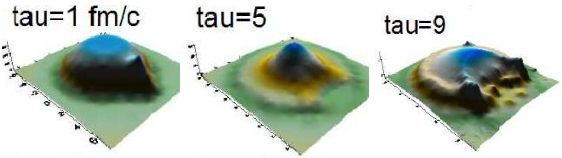



K.Werner Iu. Karpenko, T. Pierog, M. Bleicher, K. Mikhailov PRC82(2010)044904

# HOW TO OBTAIN BOTH NEAR AND AWAY-SIDE RIDGES?

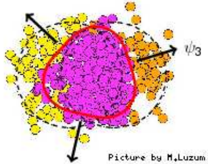
## 1)Tube-based




$\Rightarrow$ $dN/d\phi$ has two peaks (+hole),
$\Rightarrow dN/d\Delta\phi$ has three peaks .

R.Andrade, F.Grassi, Y.Hama, W.-L.Qian NPA854(2011)81

## 2)Geometry-based




$\Rightarrow dN/d\phi$ has three peaks,
$\Rightarrow dN/d\Delta\phi$ has three peaks.

B.Alver & G.Roland PRC81(2010)054905

# VI. Conclusion

- Traditional approach: hydro with smooth initial conditions.
- New approach: event-by-event hydrodynamics.

It is necessary

- to compare with certain data:

  $v_2(b=0)$,

  odd $v_n$,

  two particle correlations in $\Delta\eta - \Delta\phi$,

  as well as (not presented):

  $v_2$ fluctuations,

  $v_2(\eta)$,

  $v_1^{even}$,

  interferometry,

- to make precise statements on

  $\eta/s$ using $v_n(p_\perp)$

  relation initial conditions-flow (ex. $\epsilon_n$ and $v_n$'s).

- To be used in an efficient way, it will require close cooperation with experimentalists.