Happy Birthday Takeshi!

Low viscosity, rotation, vorticity, turbulence and their experimental signatures

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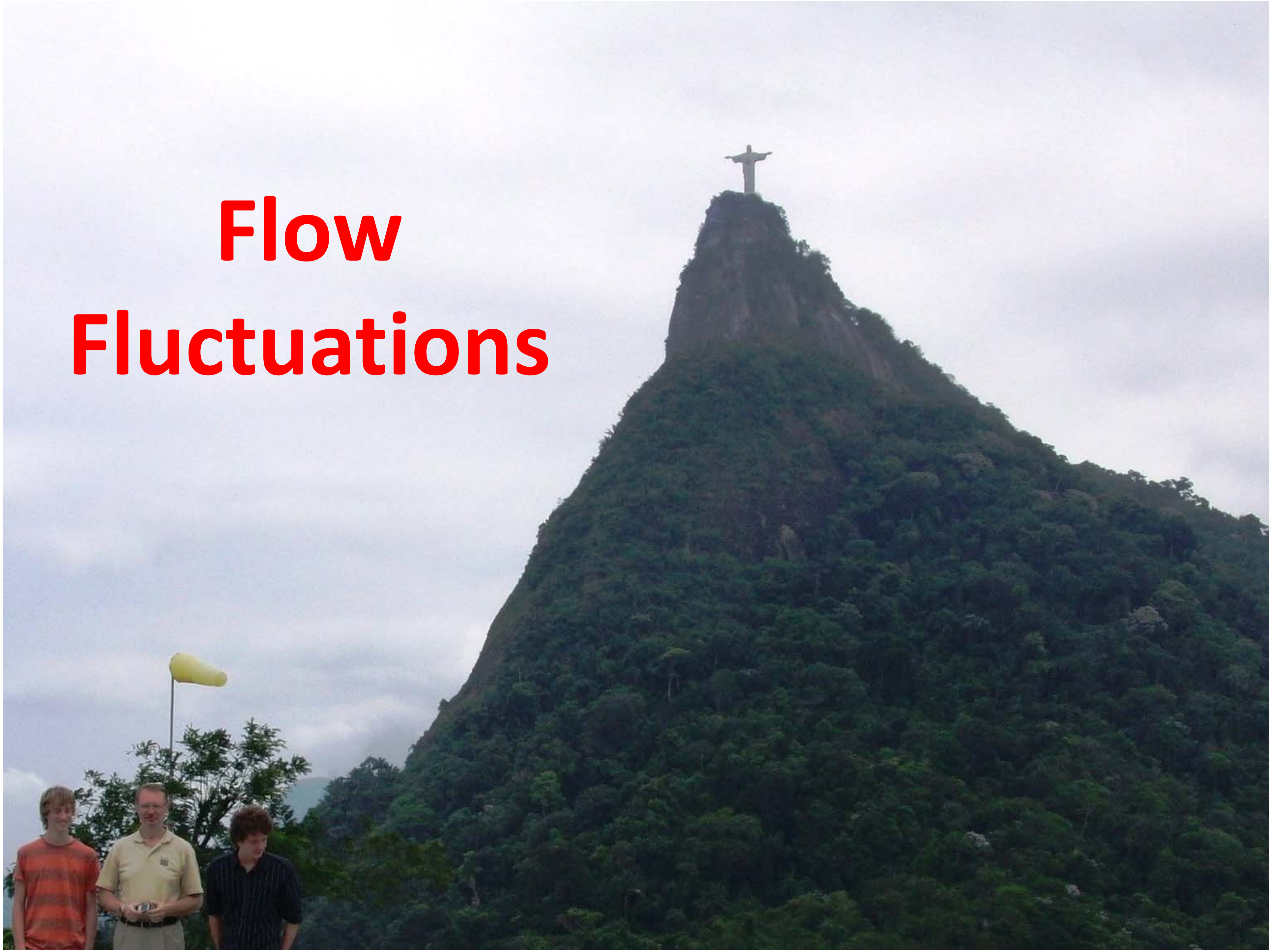
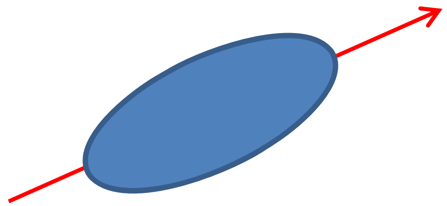
University of Bergen, Norway

9th RELATIVISTIC ASPECTS OF NUCLEAR PHYSICS,
September 23 to 27, 2013, Rio de Janeiro,
Centro Brasileiro de Pesquisas Físicas, Brazil.


Flow
Fluctuations

Central Collisions (A+A)

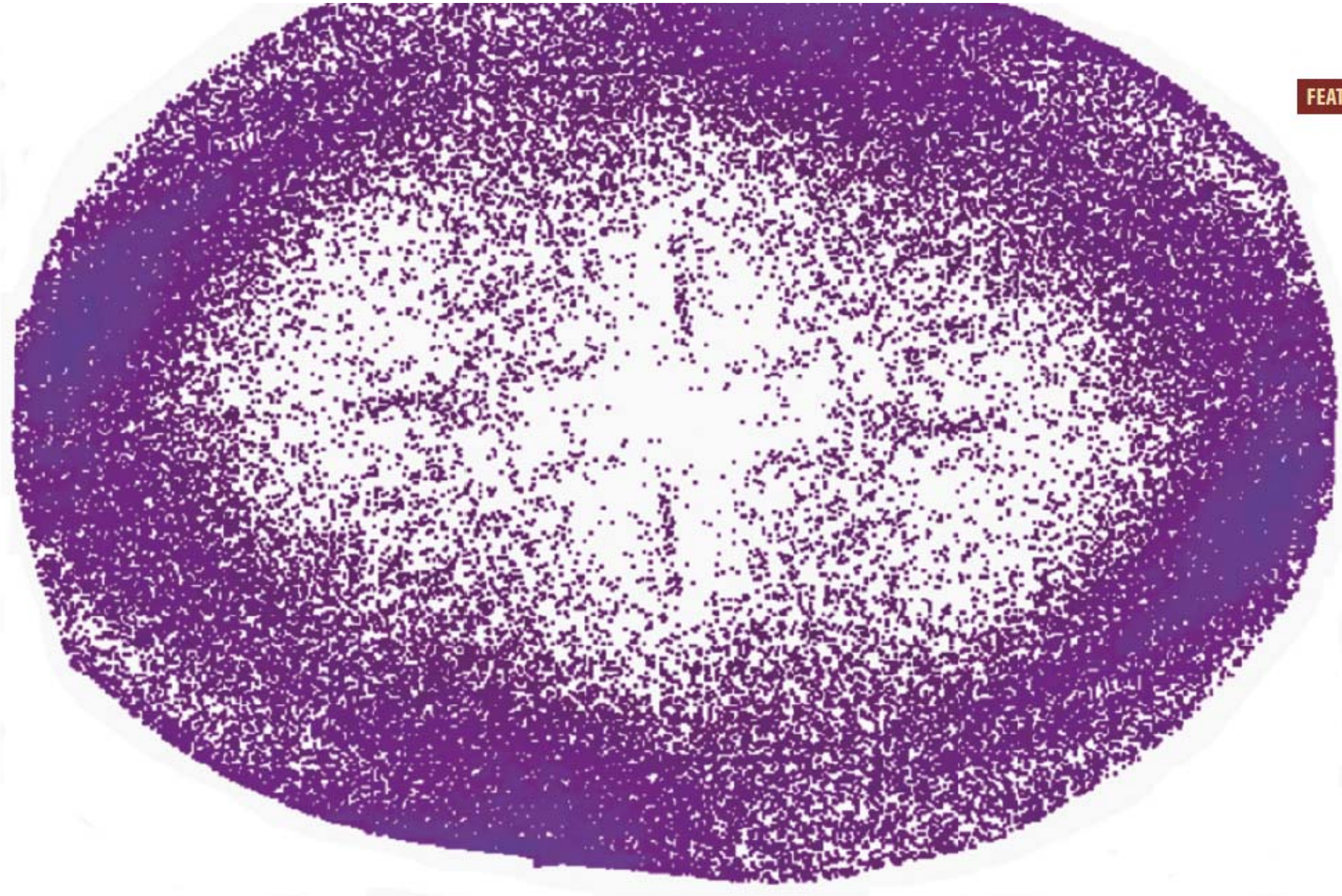


- Global Symmetries
- One symmetry axis: z-axis – given by the beam direction
  - Azimuthal symmetry
  - Longitudinal, +/- z symmetry ➔ rapidity – even
  - Spherical or ellipsoidal flow, expansion
  - Global v_1, v_2, v_3, … v_n = 0 !!

- Fluctuations
- Perfect conditions for fluctuation studies
  - Azimuthal fluctuations - no interference - **perfect, odd & even harmonics**
  - Longitudinal fluctuations - global rapidity-even flow interference
    ➔ (slight) dominance for rapidity-even fluctuations
  - Best for critical fluctuation studies :

$$\frac{d^3N}{dy\,dp_t\,d\phi} = \frac{1}{2\pi}\frac{d^2N}{dy\,dp_t}\left[1 + 2v_1(y,p_t)\cos(\phi - \Psi_1^{EP}) + 2v_2(y,p_t)\cos(2(\phi - \Psi_2^{EP})) + \cdots\right]$$

FEATURES

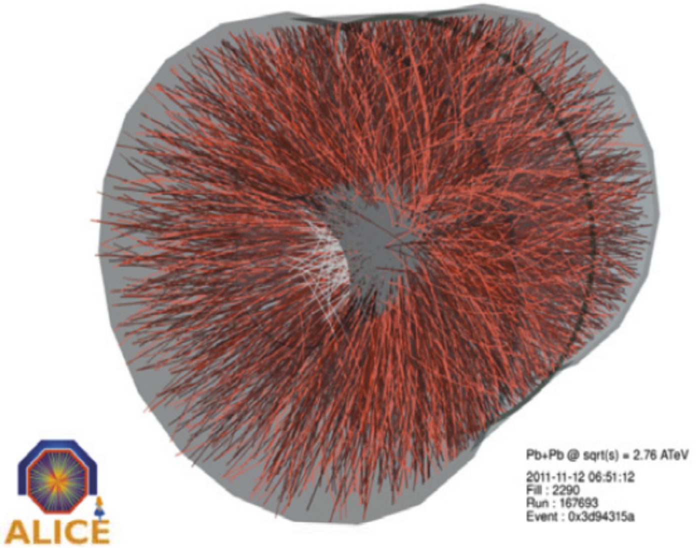


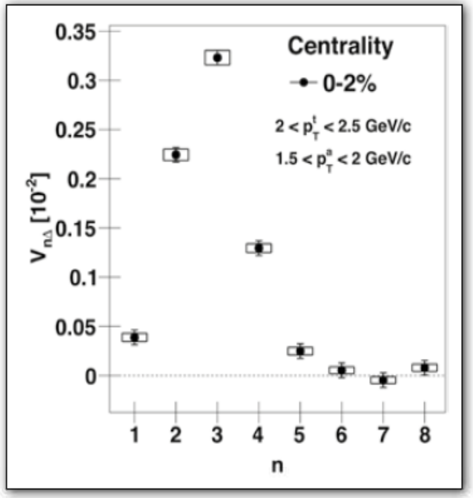
The Quark-Gluon Plasma, a nearly perfect fluid

L. Cifarelli [1], L.P. Csernai [2] and H. Stöcker [3] - DOI: 10.1051/epn/2012206

europhysicsnews
THE MAGAZINE OF THE EUROPEAN PHYSICAL SOCIETY

This is a direct proof of low viscosity !





◂ **FIG 4:** Multipole moments of the azimuthal distribution of emitted particles in central lead on lead collisions detected by the Time Projection Chamber of the ALICE detector. From ref. [2b].

▴ **FIG 3:** The final particles created in a lead on lead collision as reconstructed by the Time Projection Chamber of the ALICE detector. The chamber is filled in by the charged particle tracks rather evenly and densely in a near central collision. As flow fluctuation studies indicate the multipole moments up to 5 can be significantly identified. At higher energy and so higher charged particle multiplicity one can expect to see even higher multipole moments.

and according to present expectations it is around the low RHIC and the SPS energies. The present CERN studies could be well complemented by studying a system where the QGP is just created and critical fluctuations in dense hadronic of baryonic matter can be studied. Apart from the drop of collective directed flow due to the rapid softening of the matter at the critical point, there are many other observables, which open new ways of studies. The revolutionary fluctuation studies have an effect on the studies at the critical point also, with many new results coming from

References

[1] K. Aamodt *et al.*, (ALICE Collaboration), *Phys. Rev. Lett.* 105, 252302 (2010)

[2] K. Aamodt *et al.*, (ALICE Collaboration) arXiv:1105.3865v1 [nucl-ex], and CERN Courier, October 2011, p. 6

[3] P.K. Kovtun, D.T. Son and A.O. Starinets, *Phys. Rev. Lett.* 94, 111601 (2005)

[4] L.P. Csernai, J.I. Kapusta, L.D. McLerran, *Phys. Rev. Lett.* 97, 152303 (2006)

▾ **FIG 5:** Yields of anti-particle clusters in the mid rapidity region (|y|<0.5) of most central collisions of Pb+Pb/Au+Au as a function of the center-of-mass beam energy.

L.P. Csernai: Inroduction to Relativistic Heavy IonCollisions (Wiley, 1994).

PRL 97, 152303 (2006) PHYSICAL REVIEW LETTERS week ending 13 OCTOBER 2006

Strongly Interacting Low-Viscosity Matter Created in Relativistic Nuclear Collisions

Laszlo P. Csernai,[1,2] Joseph I. Kapusta,[3] and Larry D. McLerran[4]

Due to low viscosity at the phase transition, several new phenomena occur in high energy Heavy Ion collisions:

- high multipolarity azimuthal fluctuations, up to v8,

- rotation (v1), shear, vorticity,

- Turbulence in the transverse and, reaction planes,

- Kelvin Helmholz Instability (KHI).

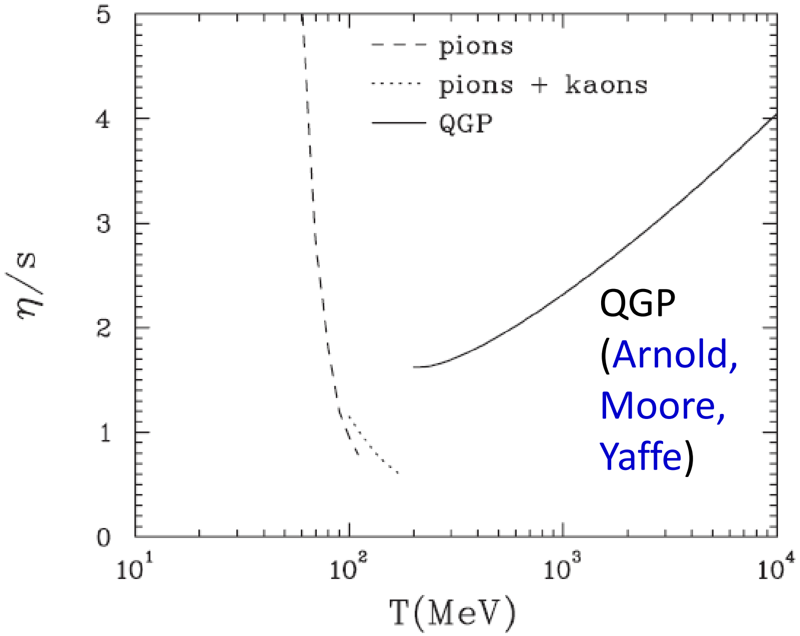
These may lead to observable consequences:

- change of v1 flow

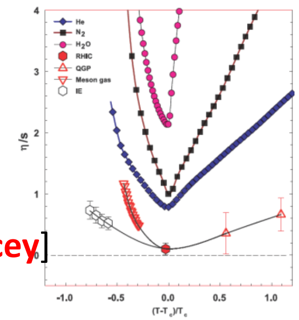
- Differential HBT

- Observable POLARIZATION of Λ and $\bar{\Lambda}$ in the reaction plane (x), pointing into the -y direction.

[Kovtun, Son, Starinets (2005)]



[Roy Lacey]

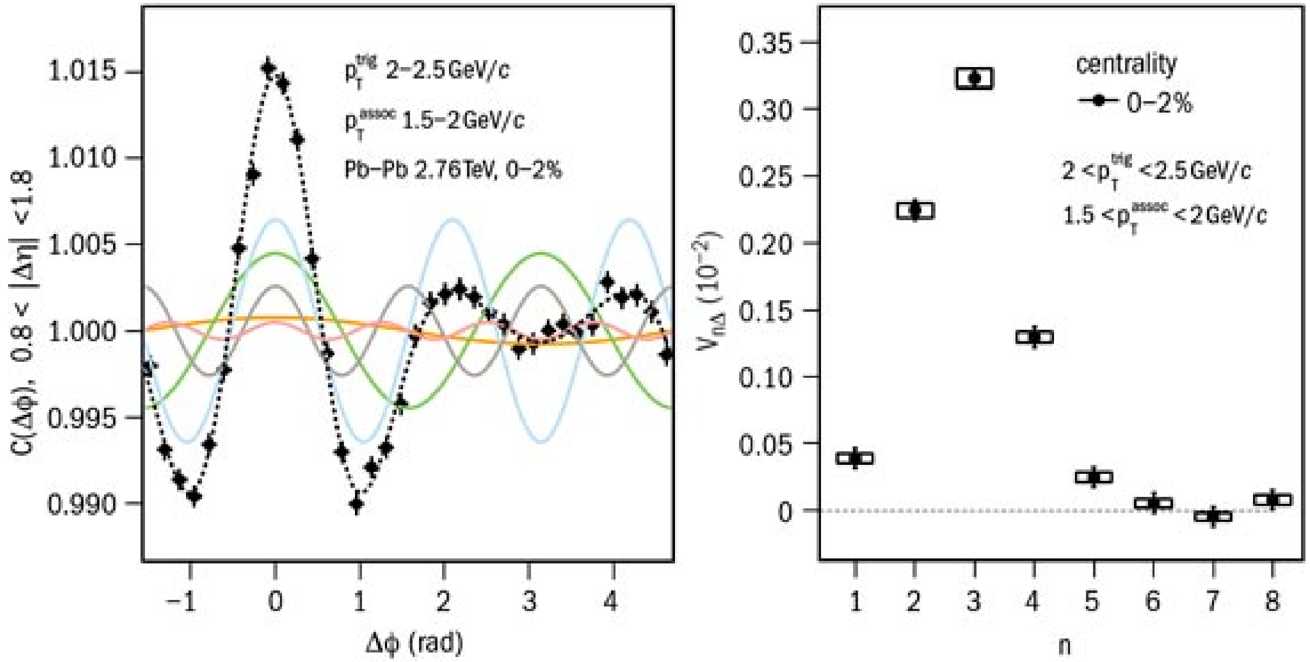


CERN COURIER

Sep 23, 2011

Oct. 2011, p. 6

ALICE measures the shape of head-on lead-lead collisions

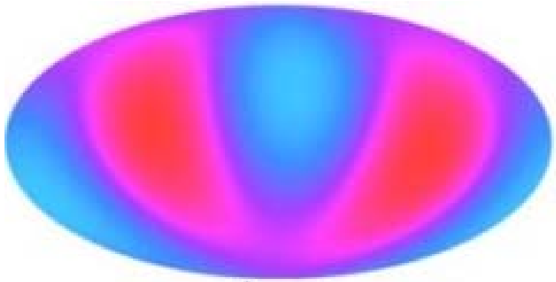


Flow originating from initial state fluctuations is significant and dominant in central and semi-central collisions (where from global symmetry no azimuthal asymmetry could occur) !

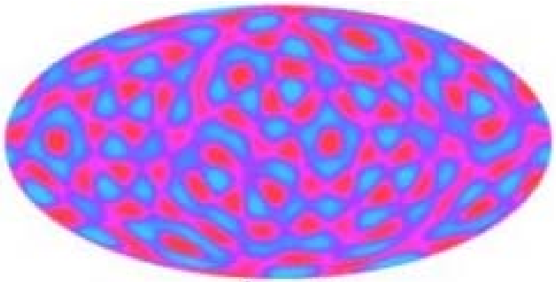
Low viscosity → Fluctuations

oil

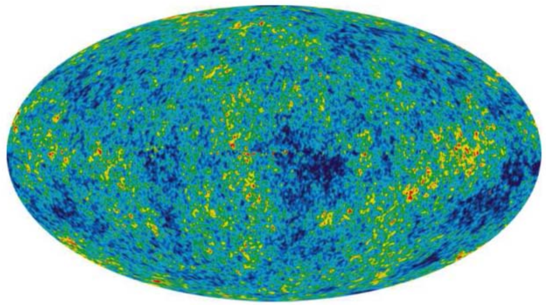
water

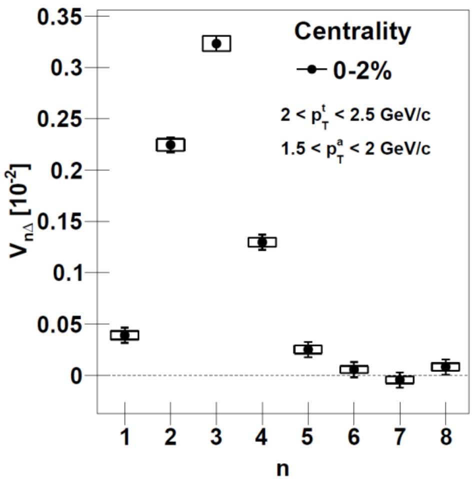


$\ell = 2$

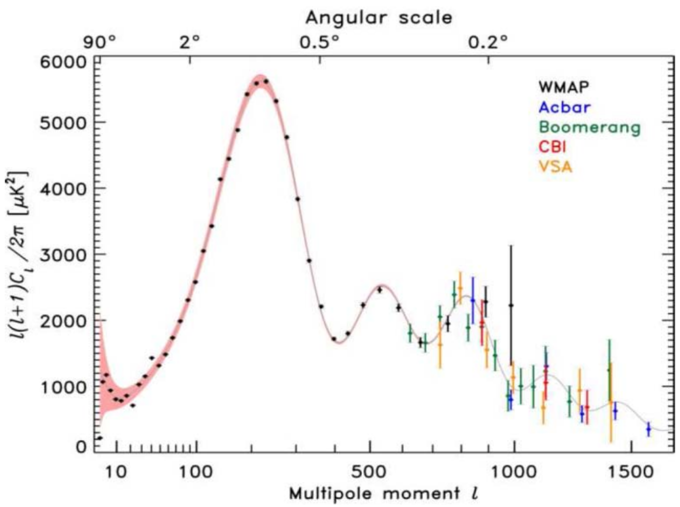


$\ell = 16$





Measurable azimuthal fluctuations up to n=8 are evidence for low viscosity



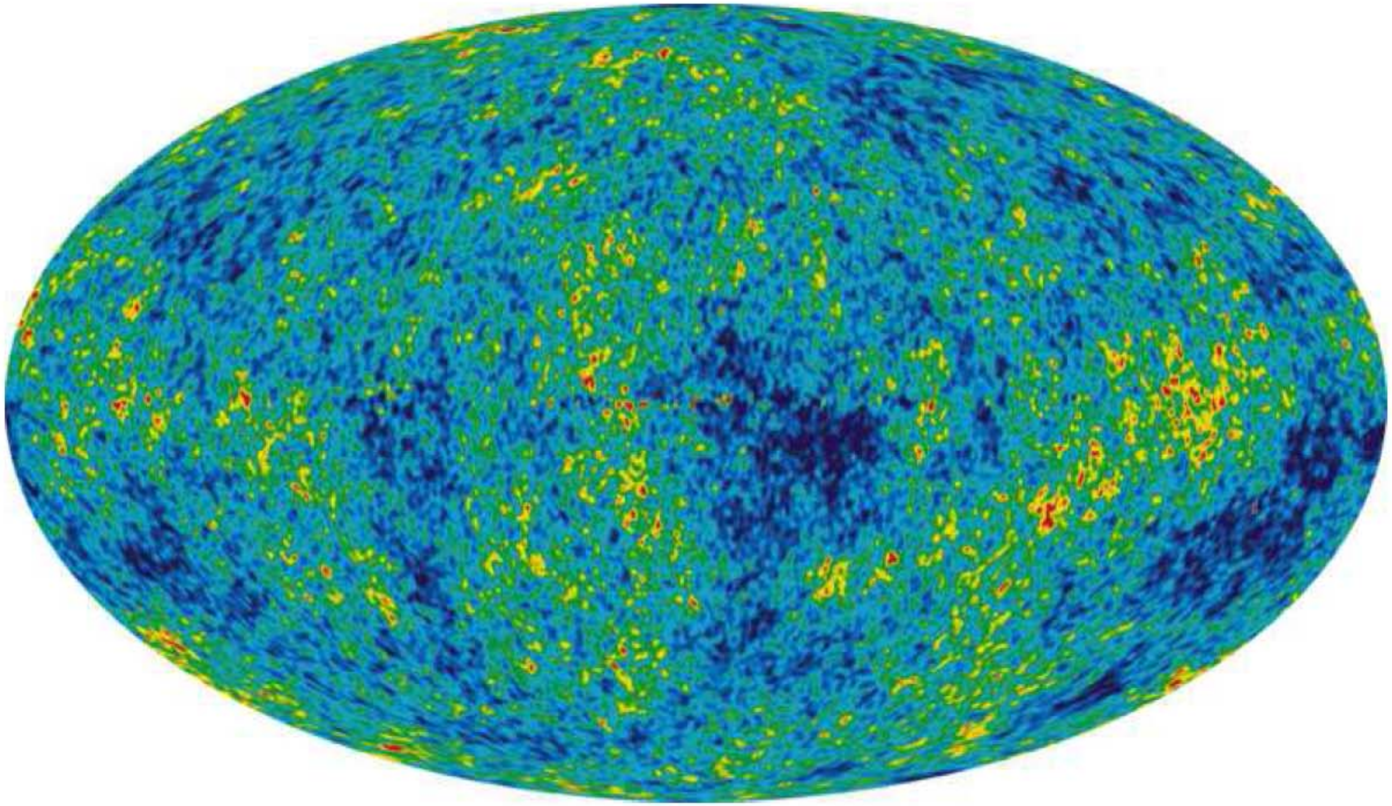


Figure 32: The CMB radiation temperature fluctuations from the 5-year WMAP data seen over the full sky. The average temperature is 2.725K, and the colors represents small temperature fluctuations. Red regions are warmer, and blue colder by about 0.0002 K.

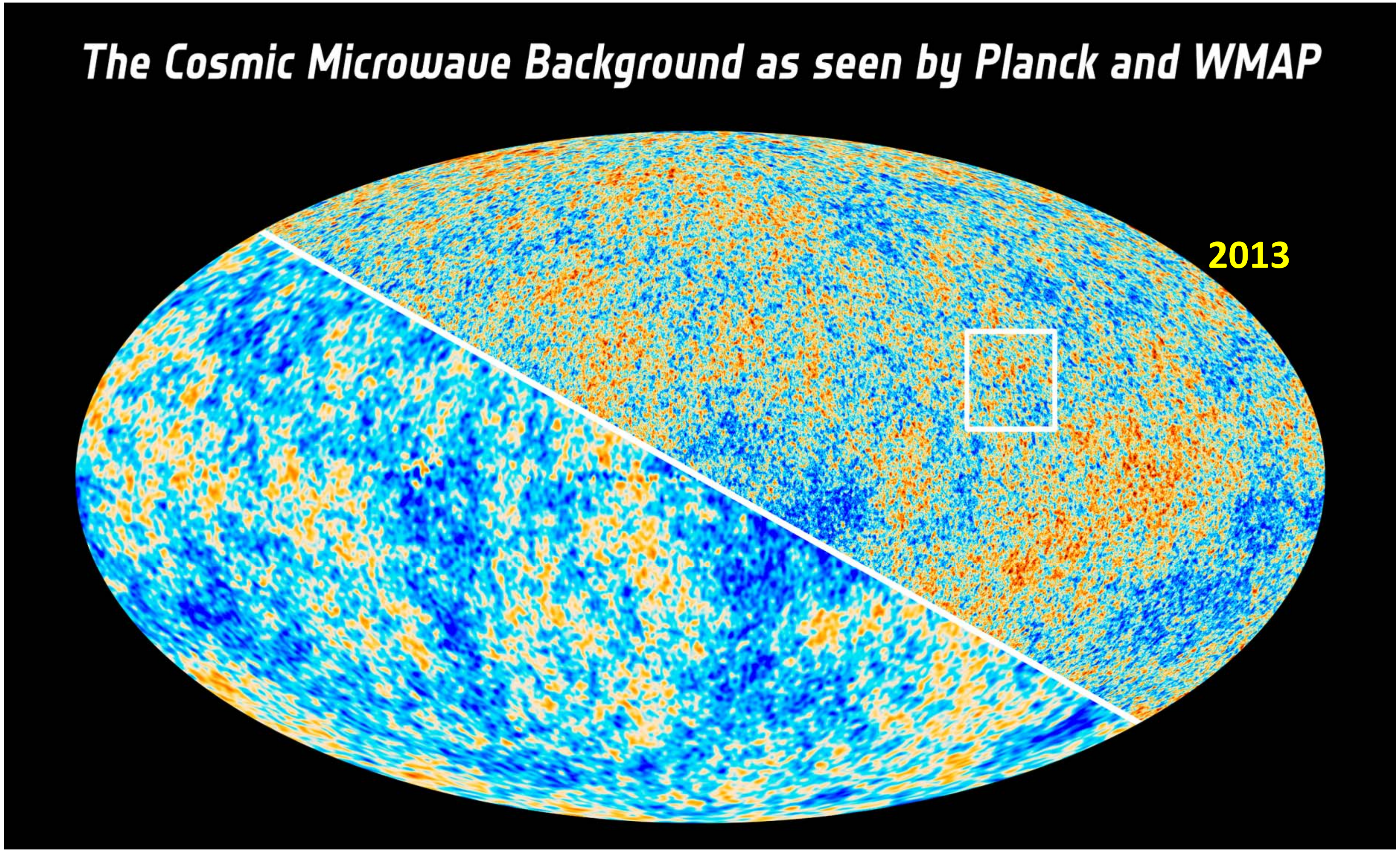
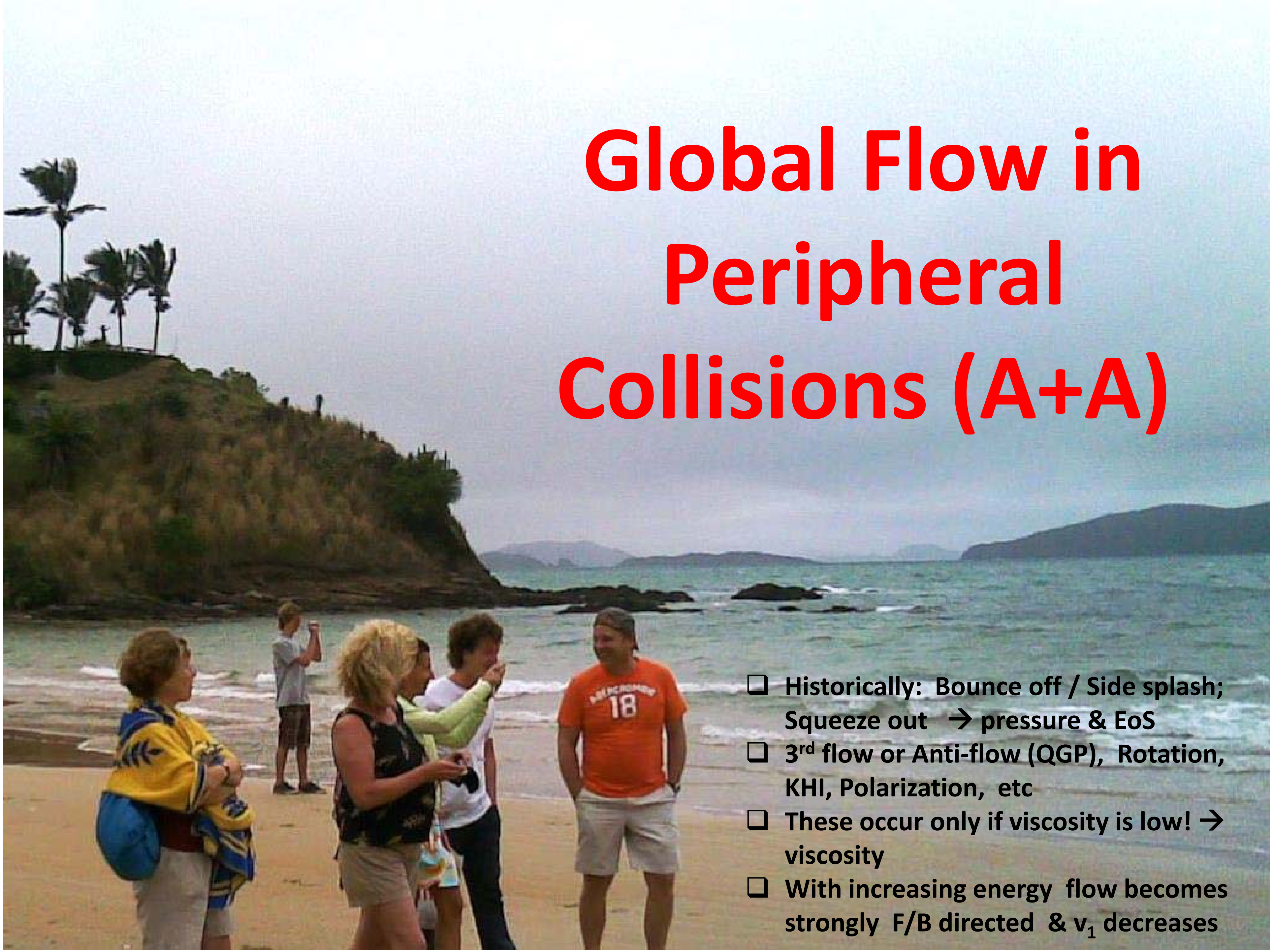


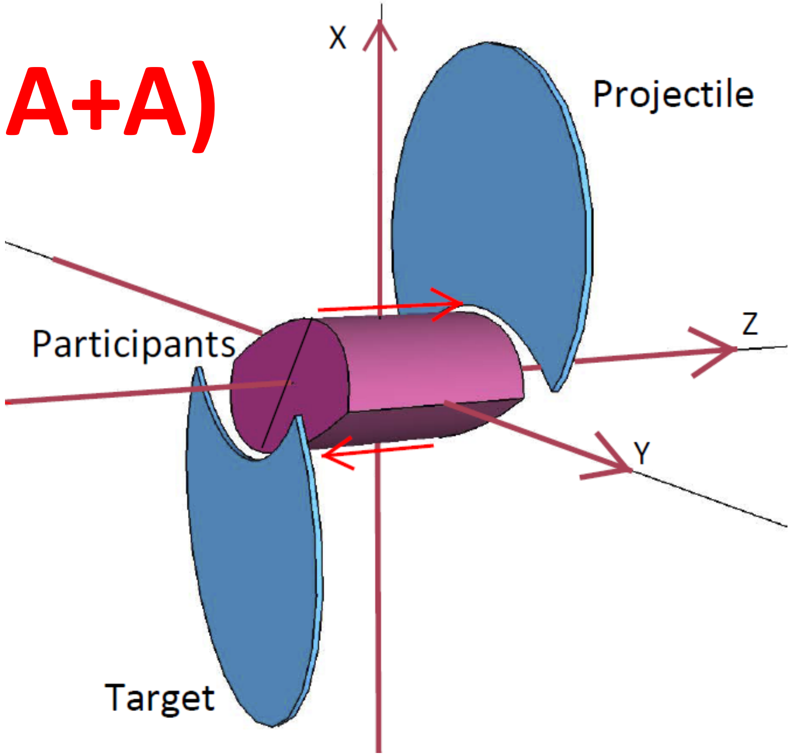
Figure 32: The CMB radiation temperature fluctuations from the 5-year WMAP data seen over the full sky. The average temperature is 2.725K, and the colors represents small temperature fluctuations. Red regions are warmer, and blue colder by about 0.0002 K.



Global Flow in Peripheral Collisions (A+A)

- Historically: Bounce off / Side splash; Squeeze out → pressure & EoS
- 3rd flow or Anti-flow (QGP), Rotation, KHI, Polarization, etc
- These occur only if viscosity is low! → viscosity
- With increasing energy flow becomes strongly F/B directed & v_1 decreases

Peripheral Collisions (A+A)



- Global Symmetries
- Symmetry axes in the global CM-frame:
  - (y ←→ -y)
  - (x,z ←→ -x,-z)
  - Azimuthal symmetry: ϕ-even (cos nϕ)
  - Longitudinal z-odd, (rap.-odd) for $v_{\_odd}$
  - Spherical or ellipsoidal flow, expansion

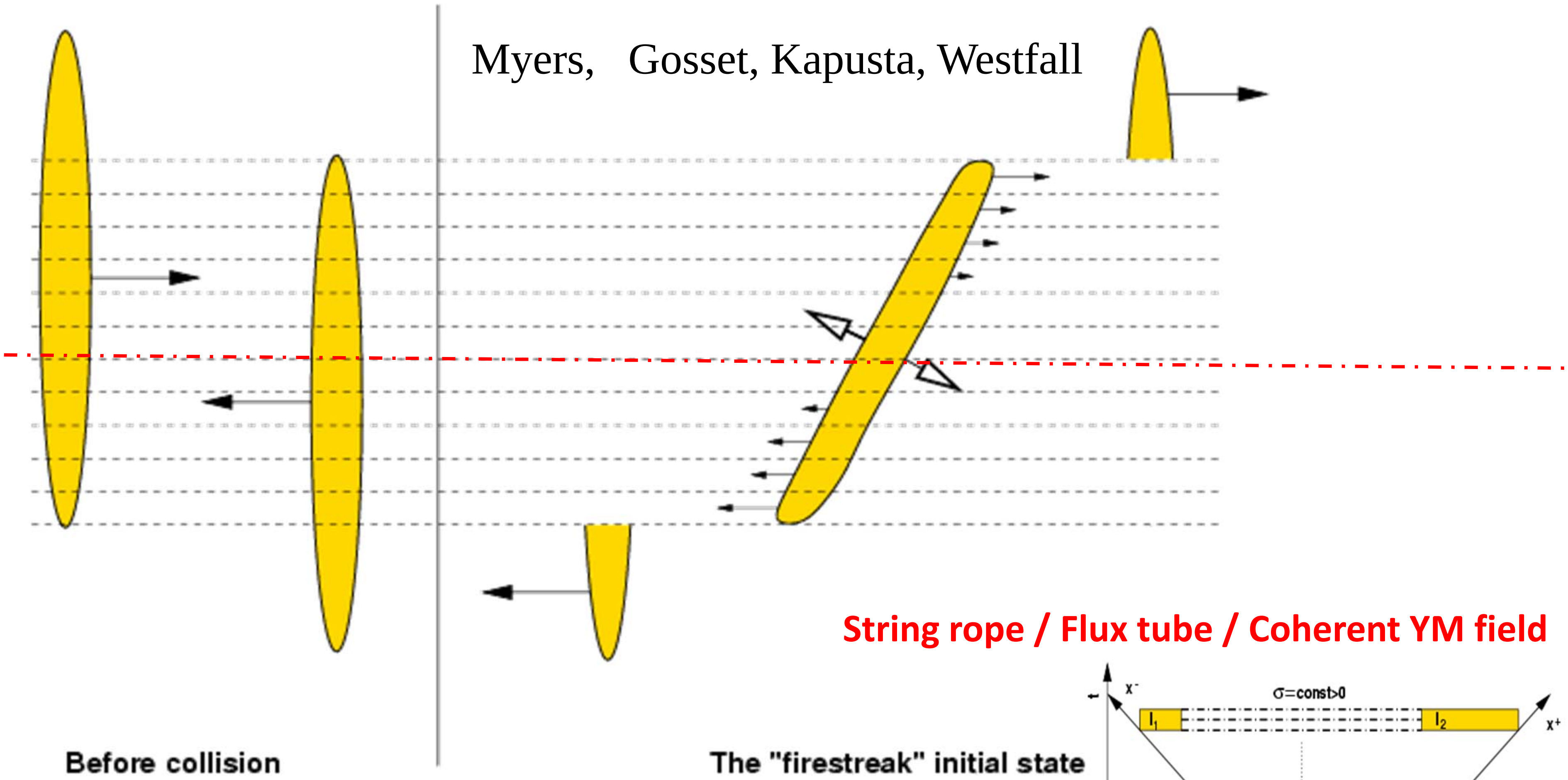
$$\frac{d^3N}{dy\,dp_t\,d\phi} = \frac{1}{2\pi}\frac{d^2N}{dy\,dp_t}\left[1 + 2v_1(y,p_t)\cos(\phi) + 2v_2(y,p_t)\cos(2\phi) + \cdots\right]$$

$$\frac{d^3N}{dy\,dp_t\,d\phi} = \frac{1}{2\pi}\frac{d^2N}{dy\,dp_t}\left[1 + 2v_1(y-y_{CM},p_t)\cos(\phi-\Psi_{RP}) + 2v_2(y-y_{CM},p_t)\cos(2(\phi-\Psi_{RP})) + \cdots\right]$$

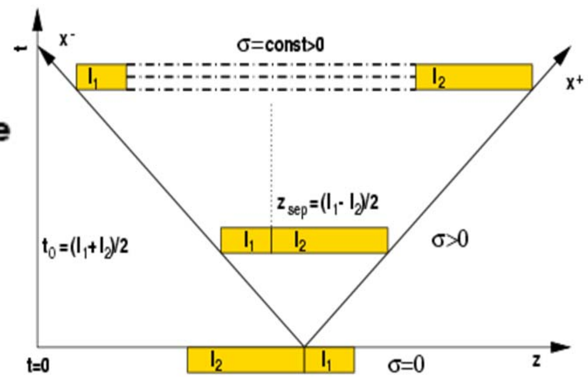
- Fluctuations
- Global flow and Fluctuations are simultaneously present → ∃ interference
  - Azimuth - Global: even harmonics - Fluctuations : odd & even harmonics
  - Longitudinal – Global: v1, v3 y-odd - Fluctuations : odd & even harmonics
  - The separation of Global & Fluctuating flow is a must !! (not done yet)

„Fire streak” picture – 3 dim.

Myers, Gosset, Kapusta, Westfall

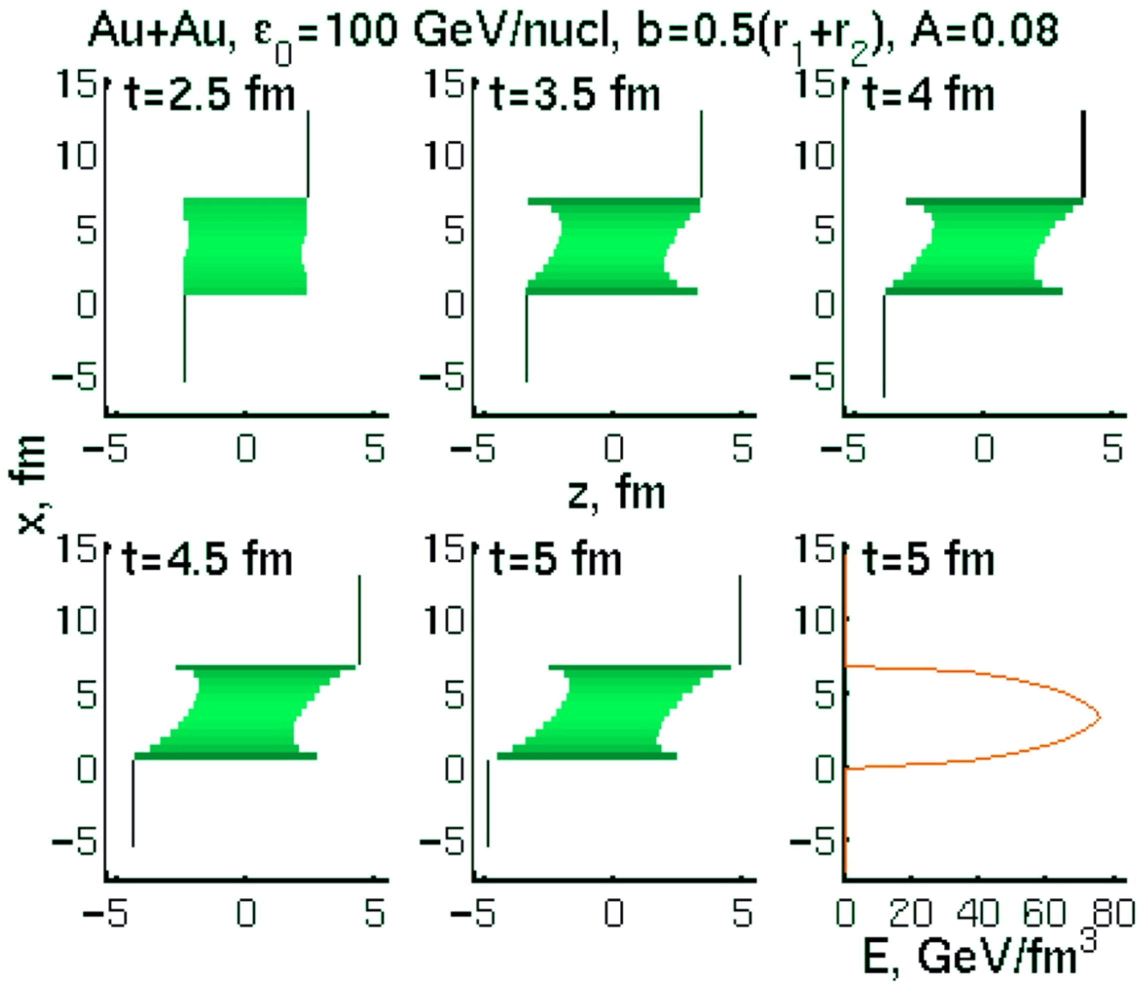


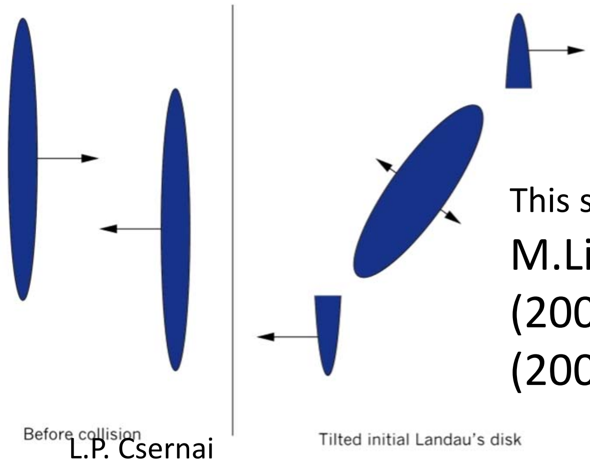
String rope / Flux tube / Coherent YM field



Symmetry axis = z-axis. Transverse plane divided into streaks.

Initial State

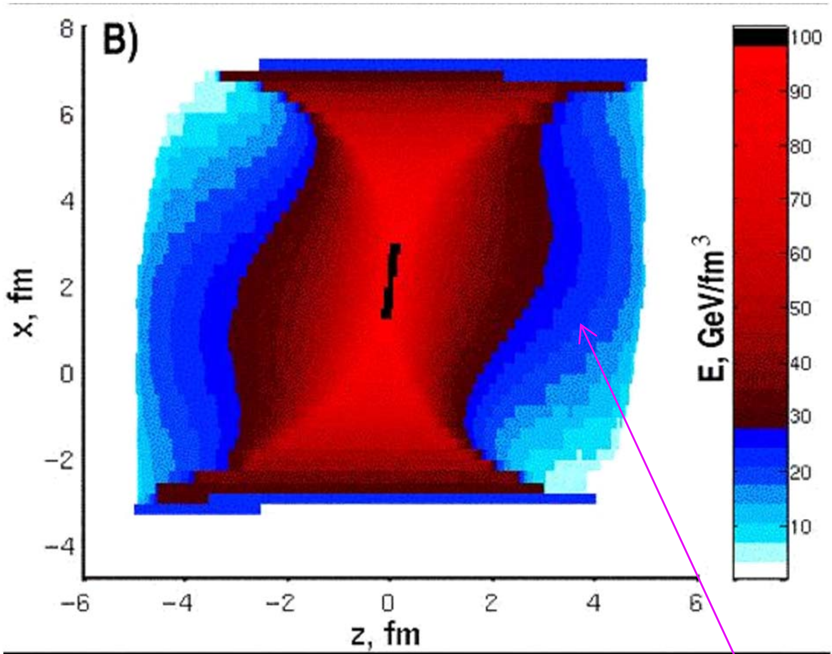




This shape is confirmed by M.Lisa &al. HBT: PLB496 (2000) 1; & PLB 489 (2000) 287.

3rd flow component

Initial state – reaching equilibrium



Initial state by V. Magas, L.P. Csernai and D. Strottman

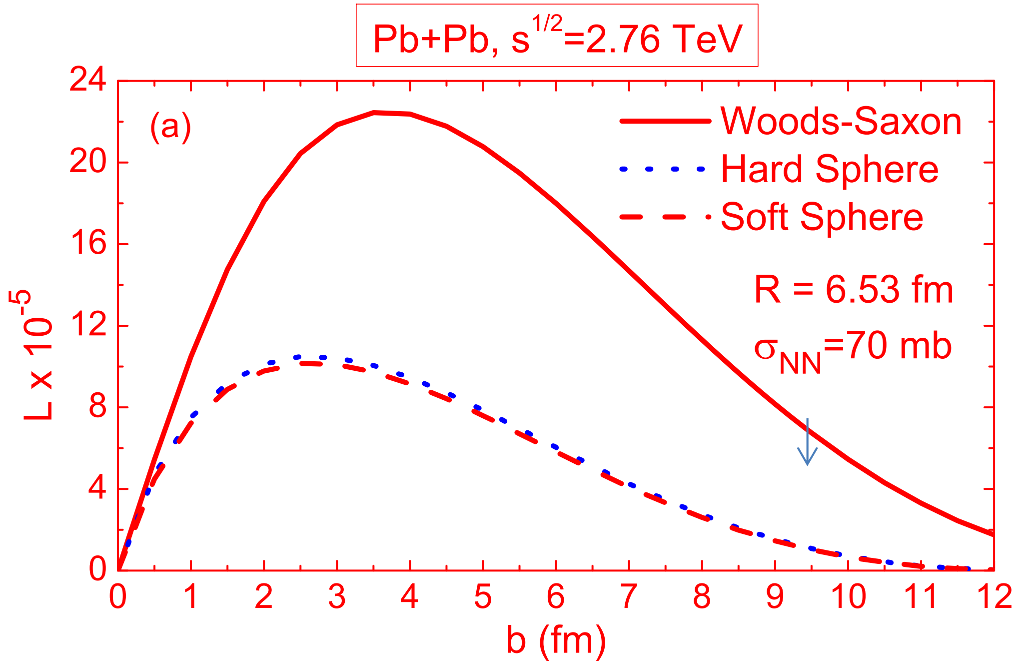
Phys. Rev. C64 (01) 014901;

Nucl. Phy. A 712 (02) 167.

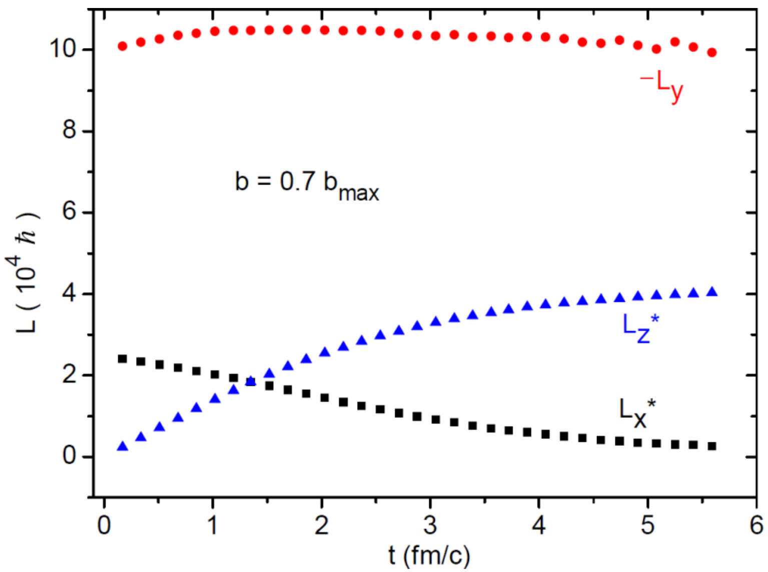
Relativistic, 1D Riemann expansion is added to each stopped streak

Rotation in Peripheral Collisions

Detecting initial rotation



V. Vovchenko,[1] D. Anchishkin,[2] and L. P. Csernai[3]
PHYSICAL REVIEW C **88**, 014901 (2013)

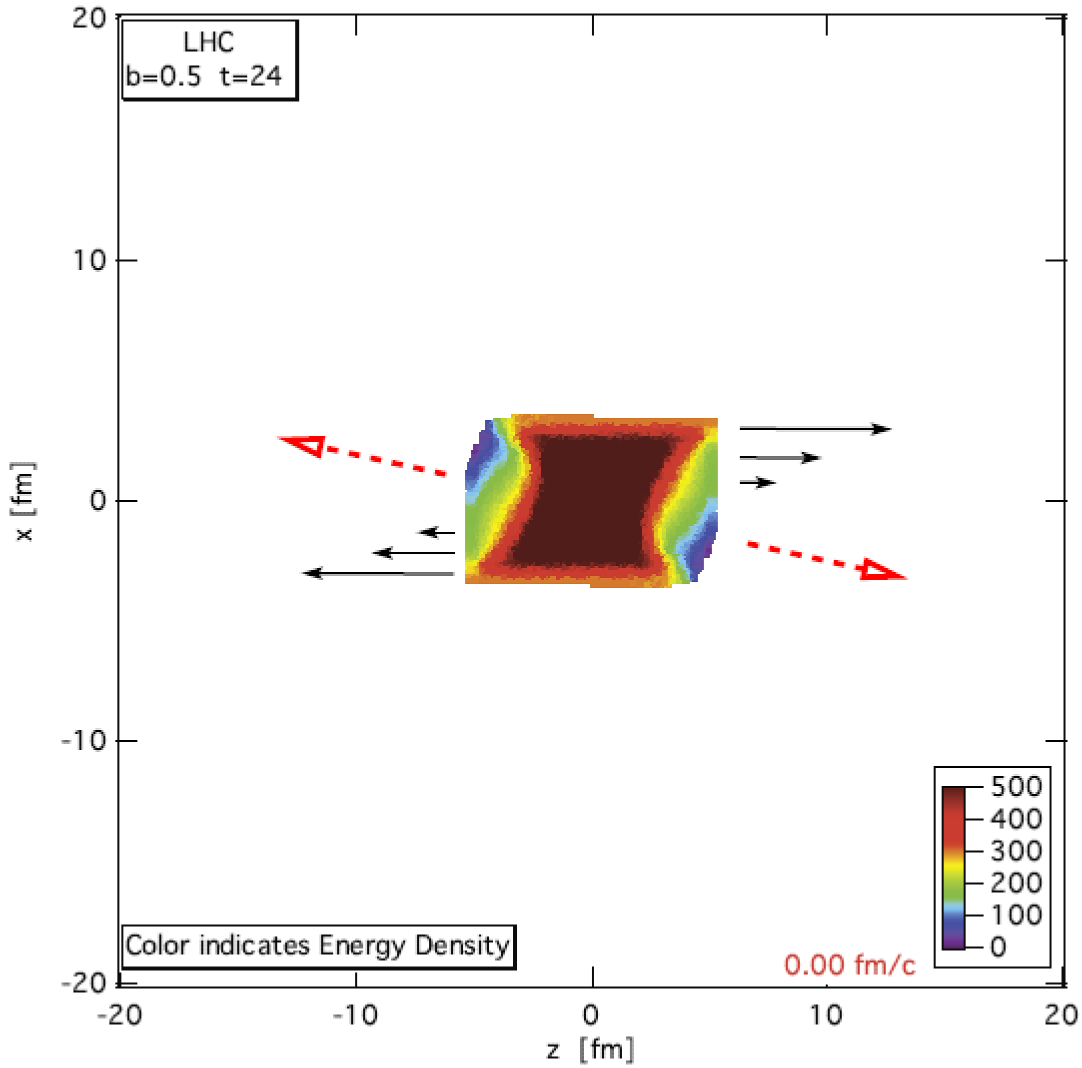


L. P. Csernai,[3] and D. J. Wang[3,4]

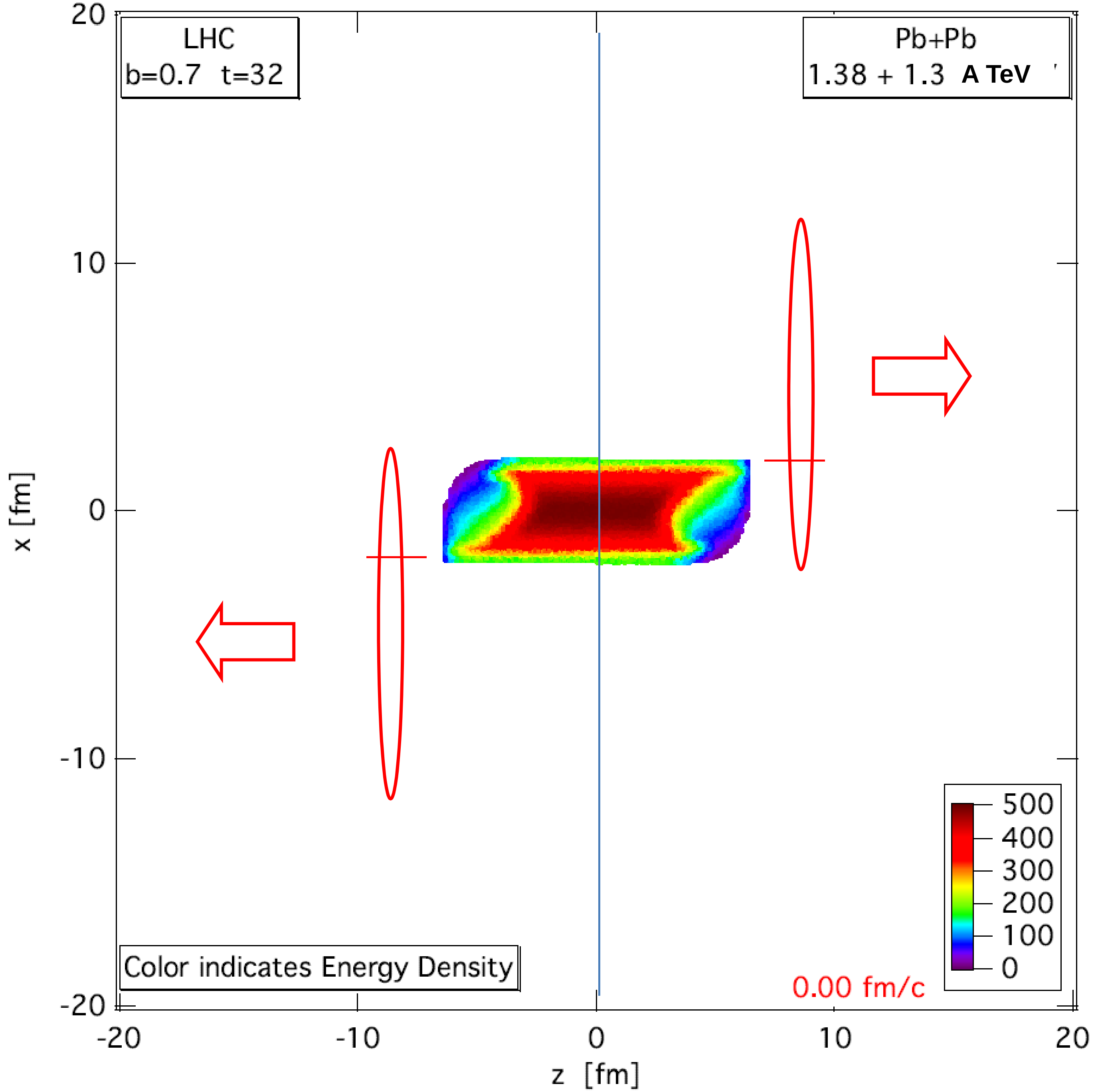
L. P. Csernai,[1,2,3] V. K. Magas,[4] H. Stöcker,[3] and D. D. Strottman[1,3]

PHYSICAL REVIEW C **84**, 024914 (2011)

Anti-flow (v1) at LHC



Initial energy density [GeV/fm3] distribution in the reaction plane, [x,y] for a Pb+Pb reaction at 1.38 + 1.38 ATeV collision energy and impact parameter b = 0.5_bmax at time 4 fm/c after the first touch of the colliding nuclei, this is when the hydro stage begins. The calculations are performed according to the effective string rope model. This tilted initial state has a flow velocity distribution, qualitatively shown by the arrows. The dashed arrows indicate the direction of the largest pressure gradient at this given moment.



PIC-hydro

Pb+Pb 1.38+1.38 A TeV, b= 70 % of b_max

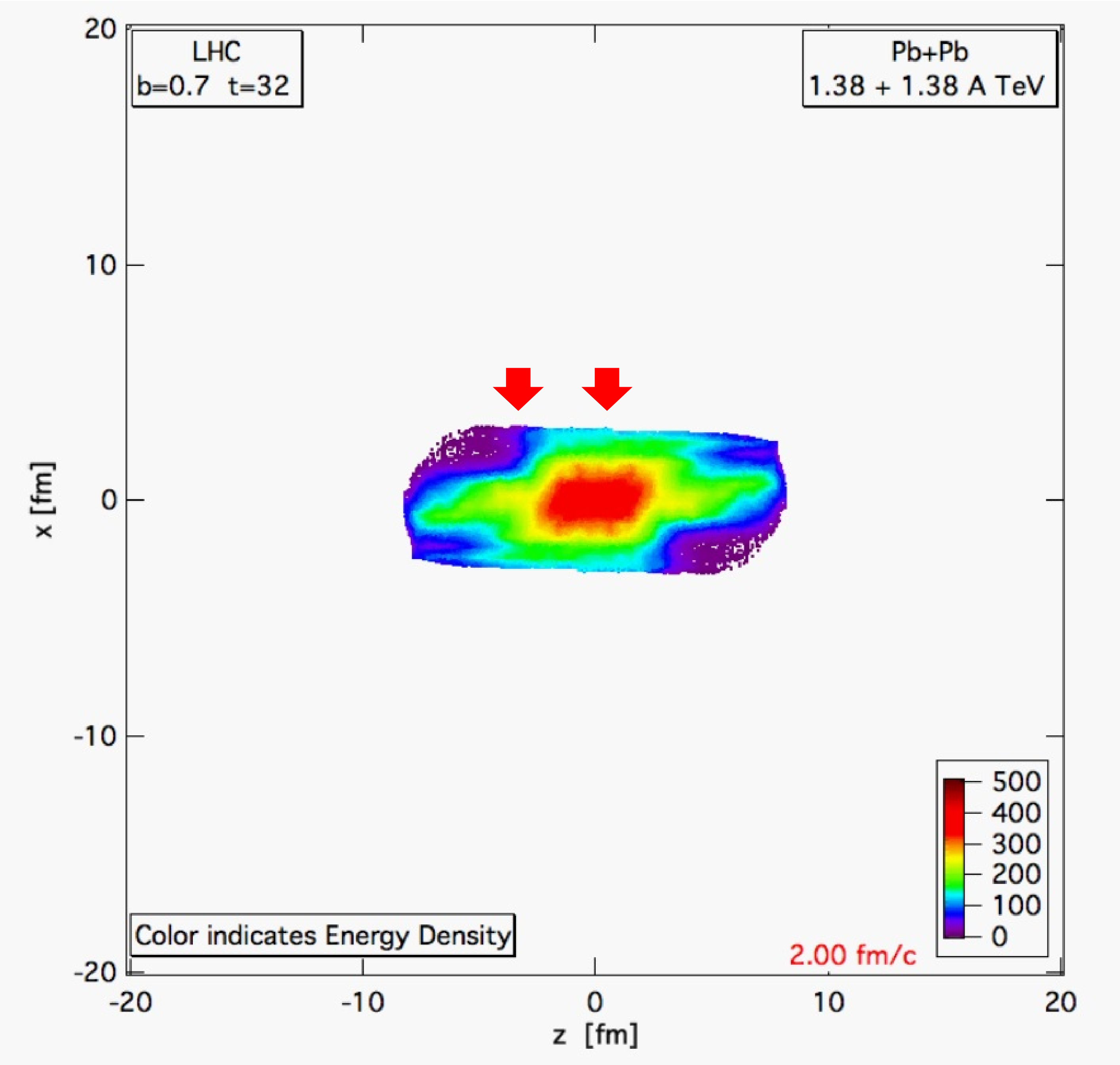
Lagrangian fluid cells, moving, ~ 5 mill.

MIT Bag m. EoS

FO at T ~ 200 MeV, but calculated much longer, until pressure is zero for 90% of the cells.

Structure and asymmetries of init. state are maintained in nearly perfect expansion.

..\zz-Movies\LHC-Ec-1h-b7-A.mov


LHC
b=0.7 t=32
Pb+Pb
1.38 + 1.38 A TeV
20
10
0
-10
-20
x [fm]
-20
-10
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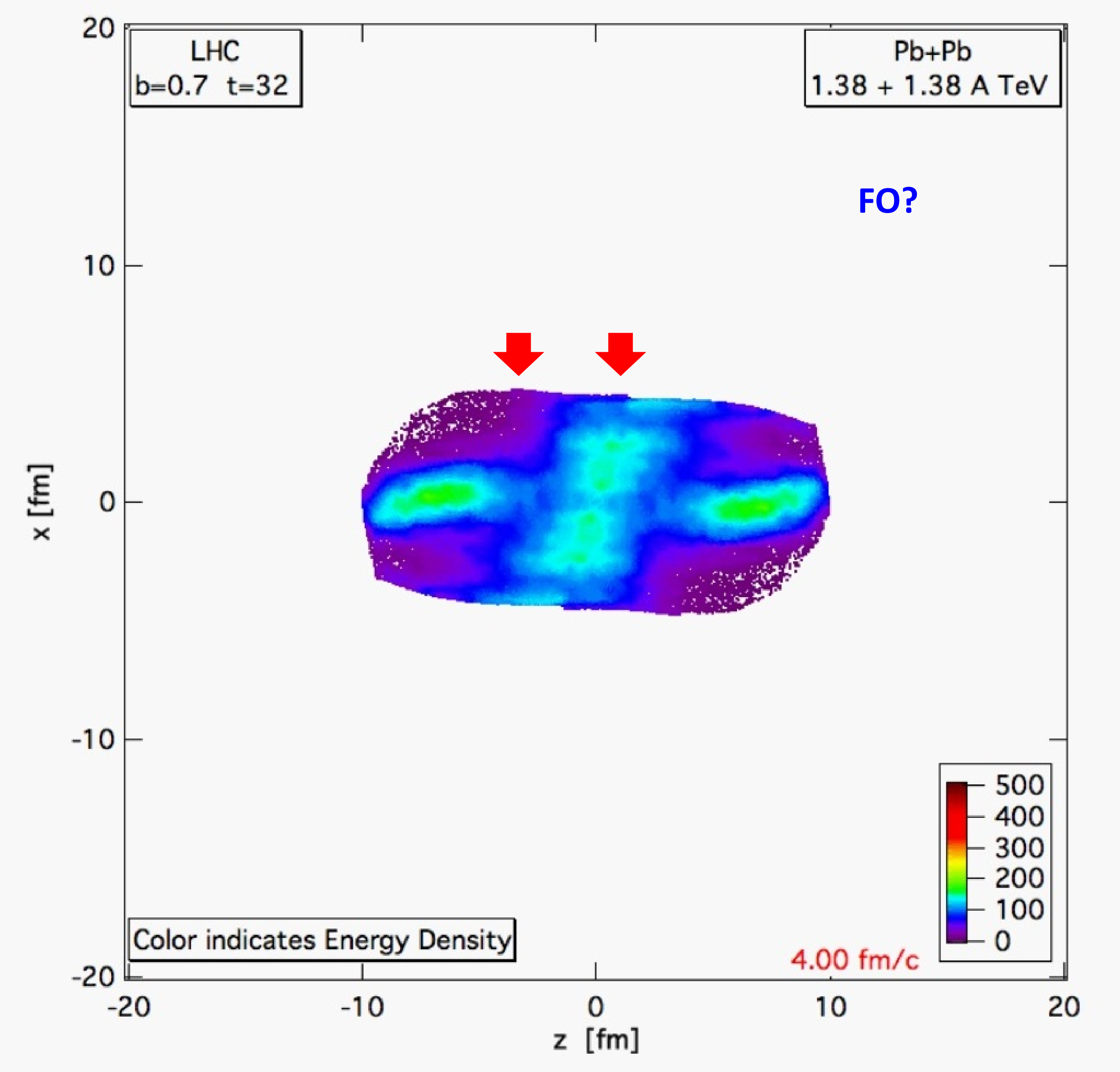
10
20
z [fm]
500
400
300
200
100
0
Color indicates Energy Density
2.00 fm/c


LHC
b=0.7 t=32
Pb+Pb
1.38 + 1.38 A TeV
FO?
20
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x [fm]
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Color indicates Energy Density
4.00 fm/c
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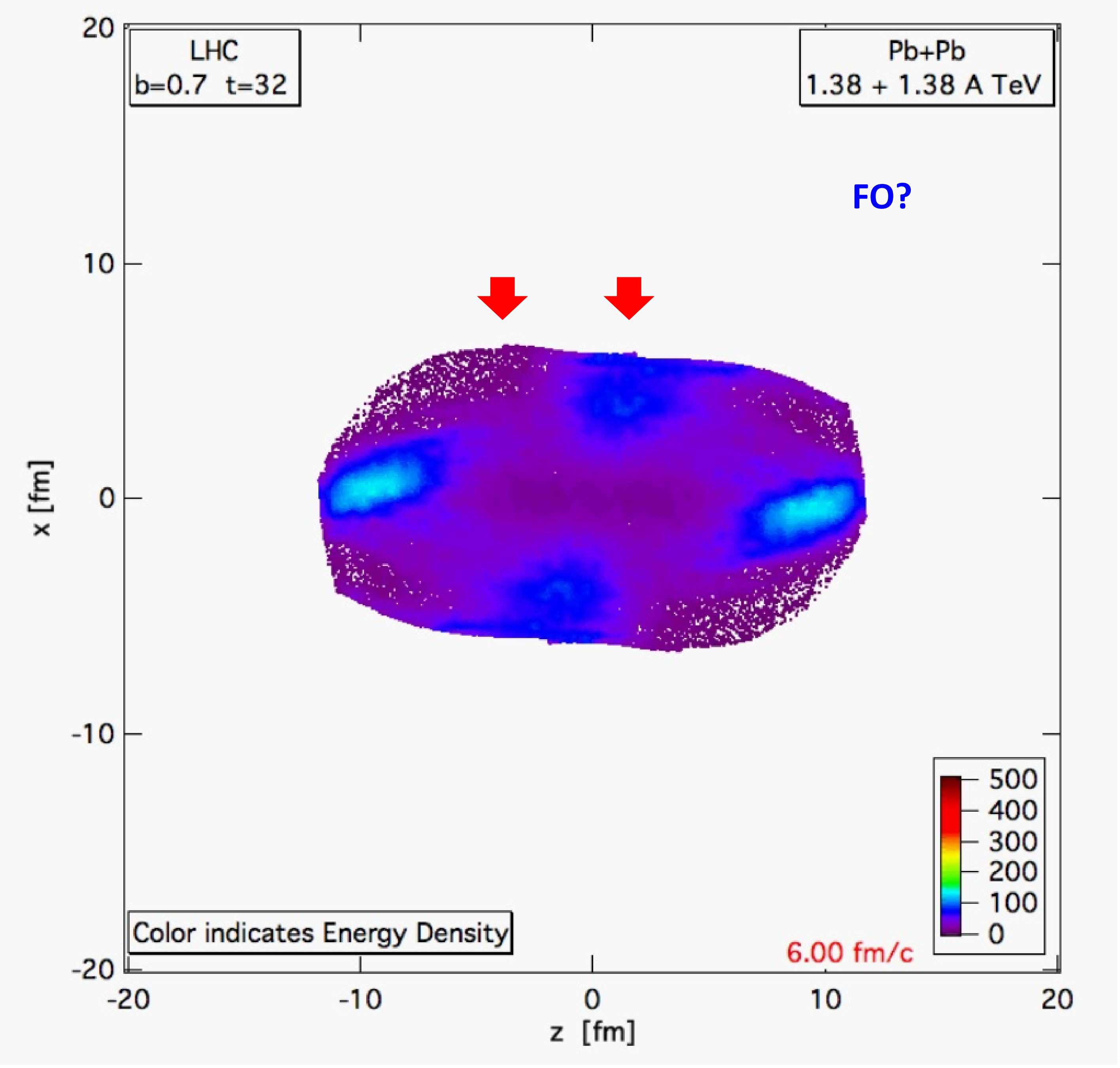
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Pb+Pb
1.38 + 1.38 A TeV
FO?
Color indicates Energy Density
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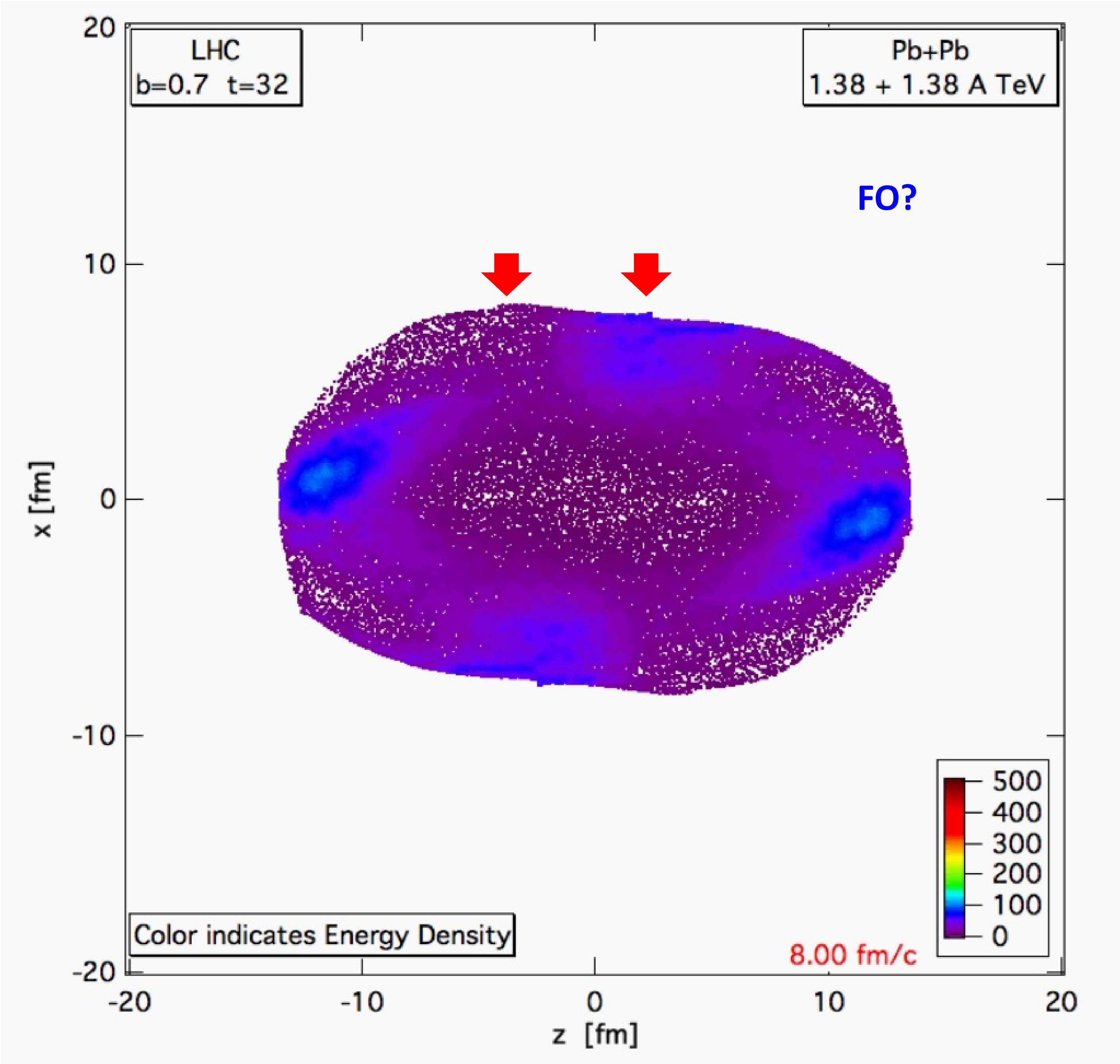
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Pb+Pb
1.38 + 1.38 A TeV
FO?
x [fm]
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Color indicates Energy Density
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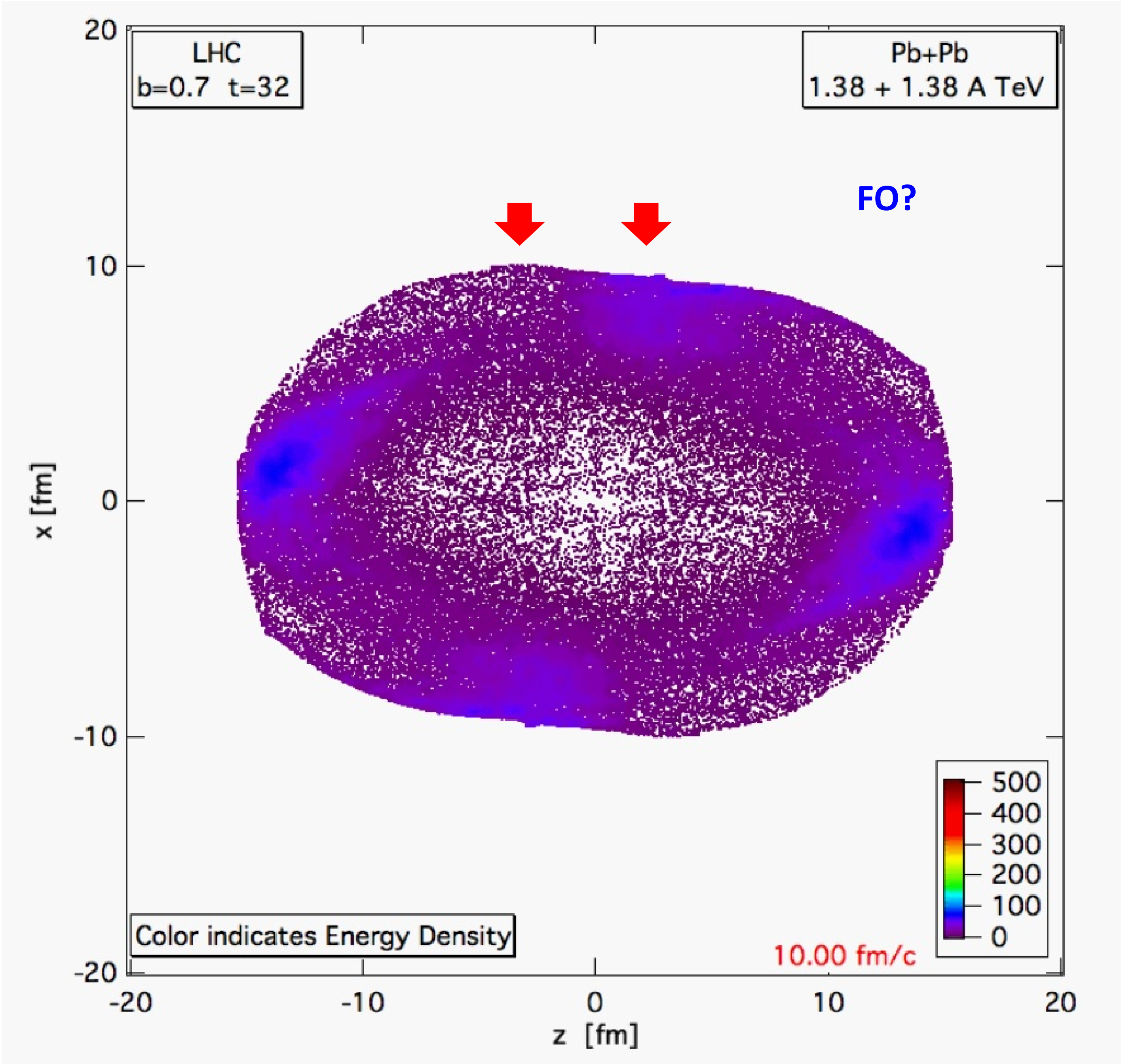

LHC
b=0.7 t=32
Pb+Pb
1.38 + 1.38 A TeV
FO?
x [fm]
z [fm]
Color indicates Energy Density
10.00 fm/c
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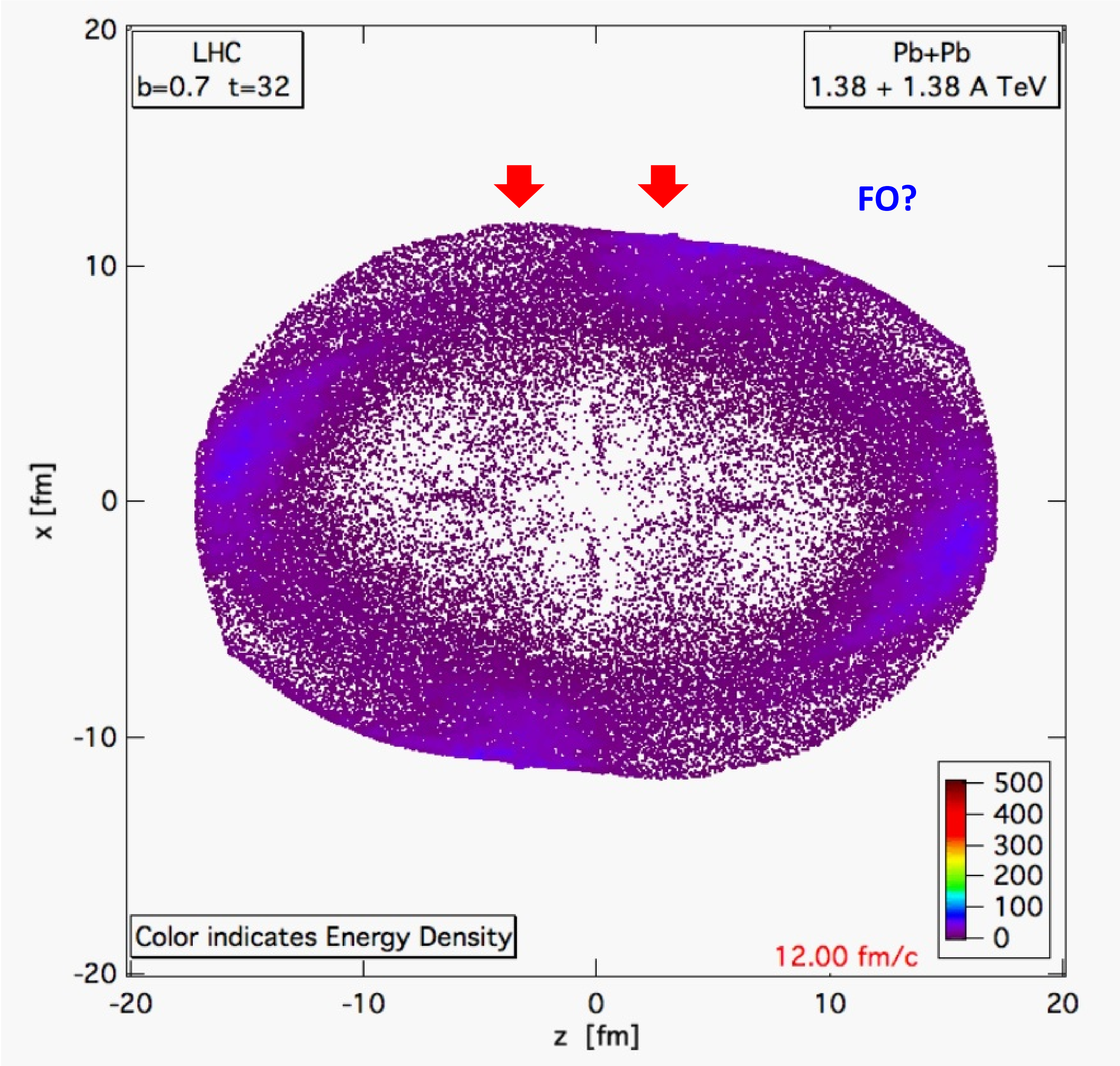

LHC
b=0.7 t=32
Pb+Pb
1.38 + 1.38 A TeV
FO?
x [fm]
z [fm]
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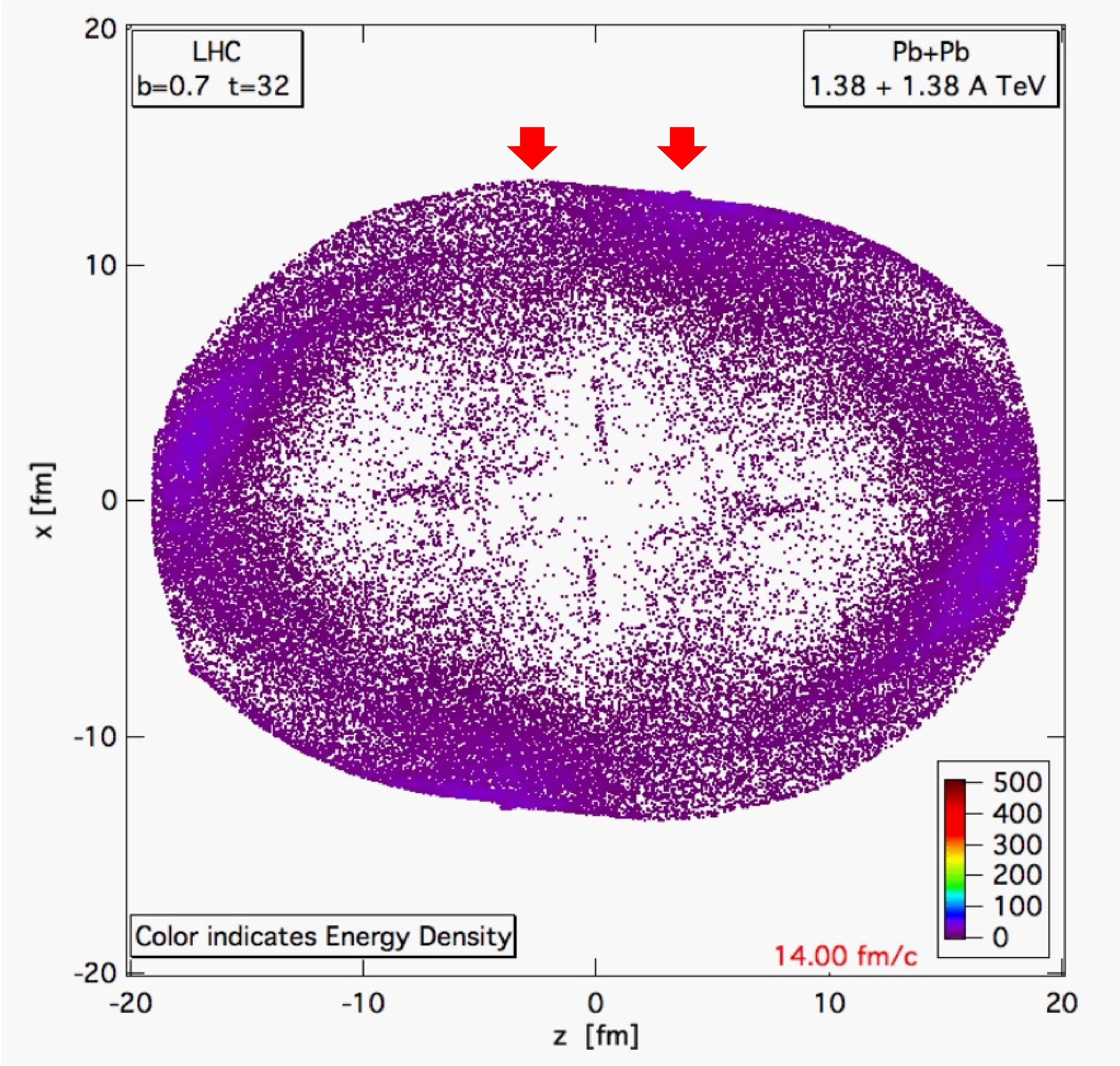
Color indicates Energy Density
12.00 fm/c


LHC
b=0.7 t=32
Pb+Pb
1.38 + 1.38 A TeV
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x [fm]
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z [fm]
Color indicates Energy Density
14.00 fm/c
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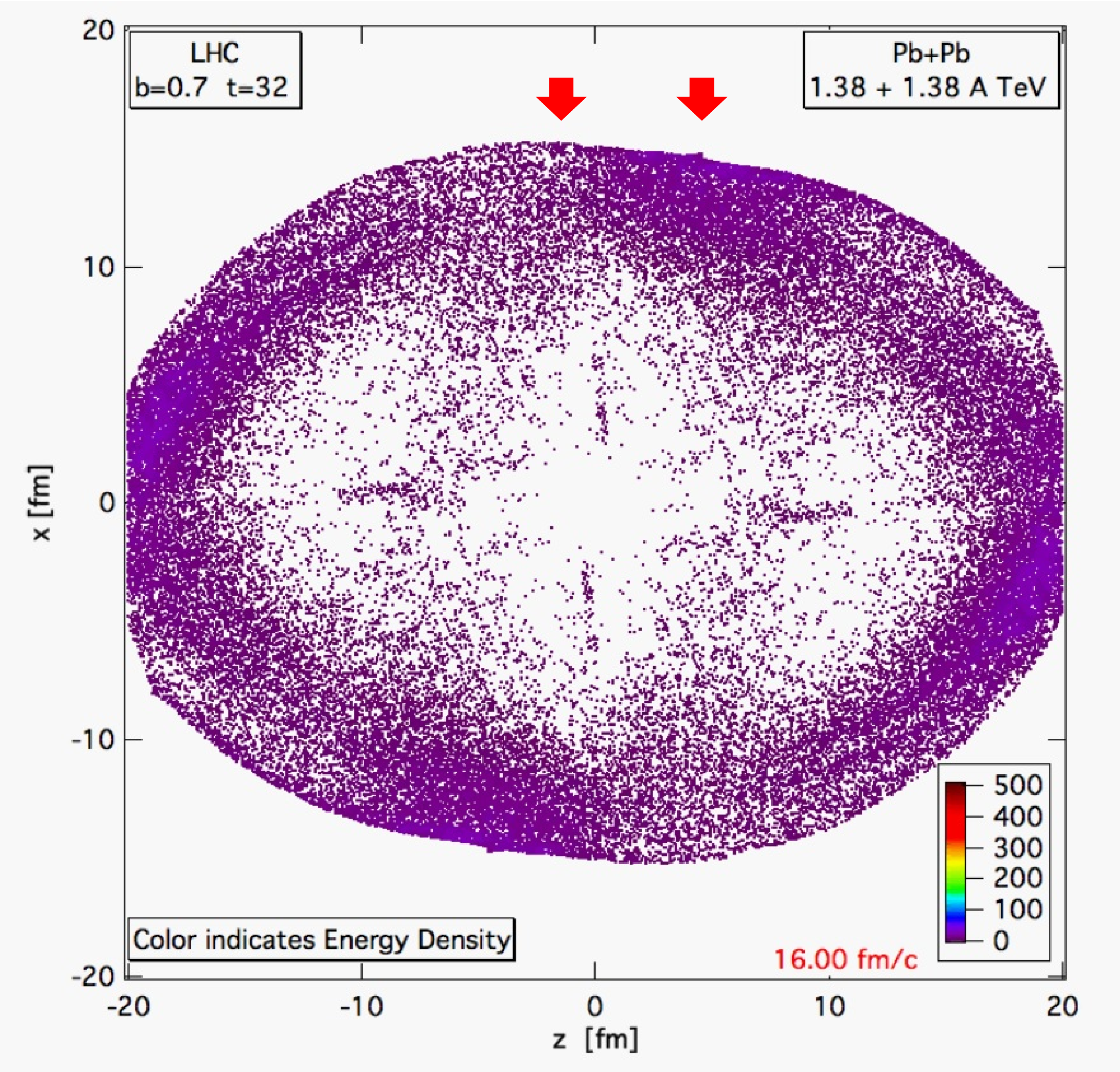

LHC
b=0.7 t=32
Pb+Pb
1.38 + 1.38 A TeV
x [fm]
z [fm]
Color indicates Energy Density
16.00 fm/c
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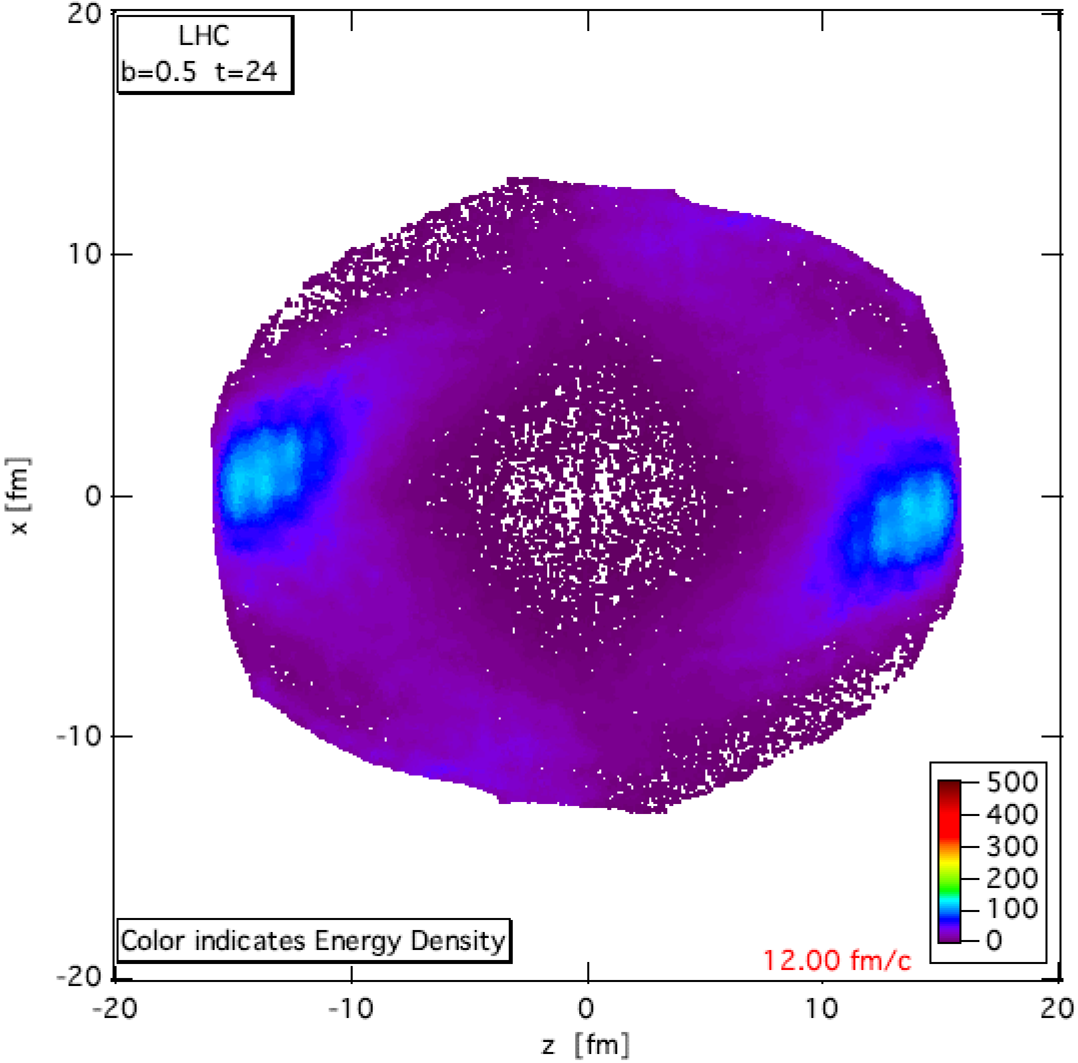
Anti-flow (v1)



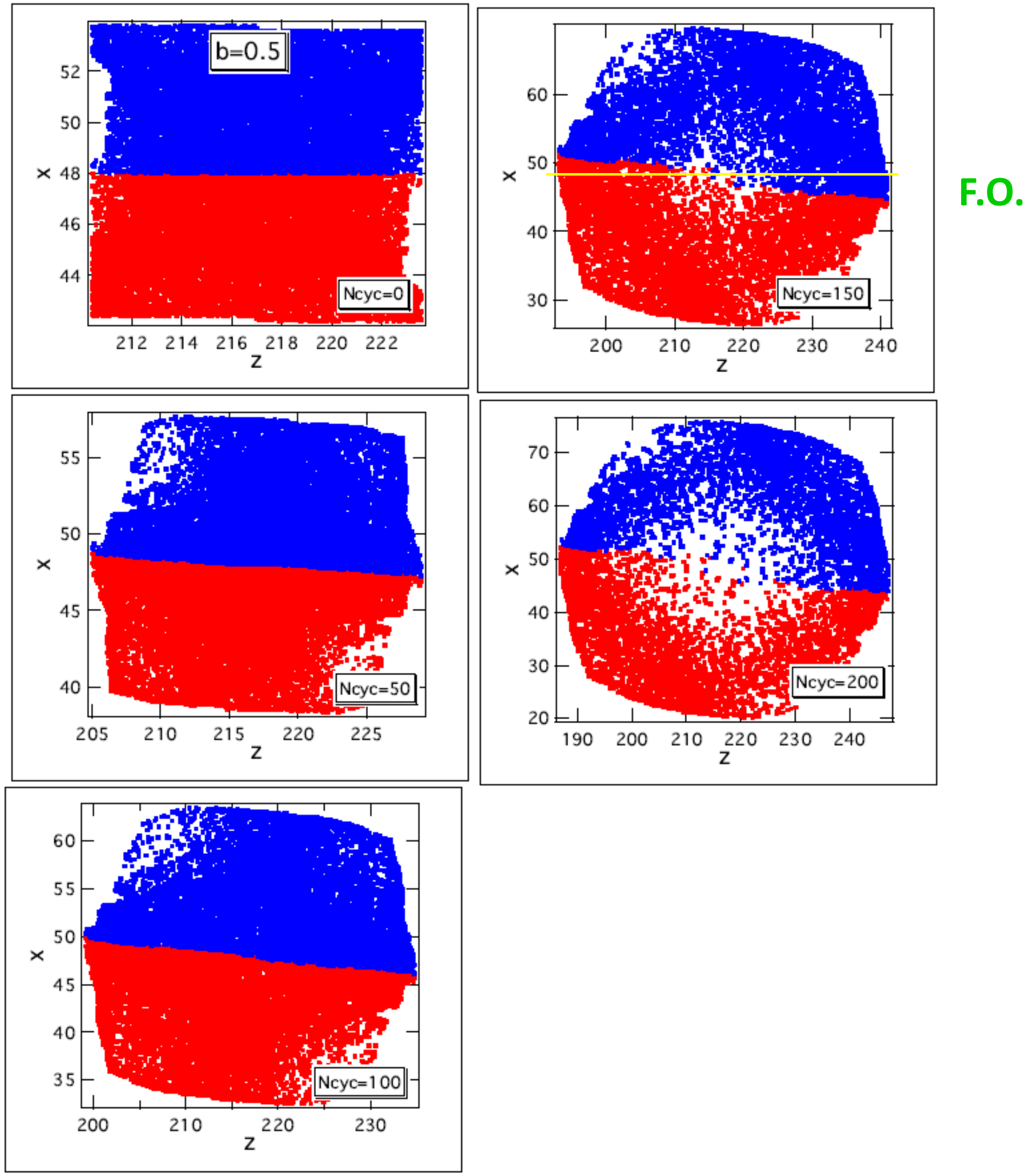
The energy density [GeV/fm3] distribution in the reaction plane, [x,z] for a Pb+Pb reaction at 1.38 + 1.38 A.TeV collision energy and impact parameter b = 0.5b_max at time 12 fm/c after the formation of the hydro initial state. The expected physical FO point is earlier but this post FO configuration illustrates the flow pattern.

[LP. Csernai, V.K. Magas, H. Stöcker, D. Strottman, Phys. Rev. **C84** (2011) 02914]

Turbulence – Kelvin Helmholtz Instability

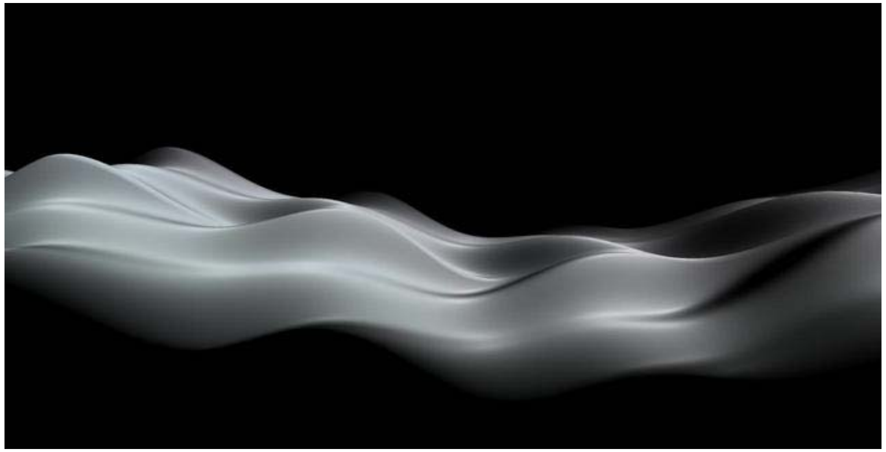
Rotation

The rotation is illustrated by dividing the upper / lower part (blue/red) of the initial state, and following the trajectories of the marker particles.



Turbulence ?

Low viscosity → Non-linearity & Turbulence



oil

water

Viscous liquid shows smooth sinusoidal waves, while a non-viscous fluid has sharp, non-sinusoidal waves, leading to turbulence.

A typical turbulent phenomenon is the Kelvin-Helmholtz instability

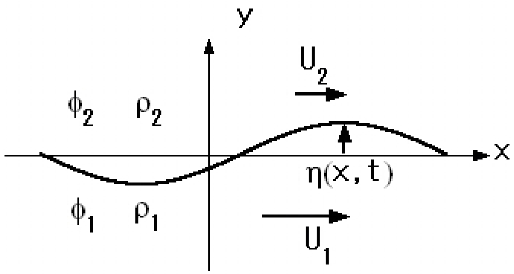
Kelvin-Helmholtz Instability (KHI)

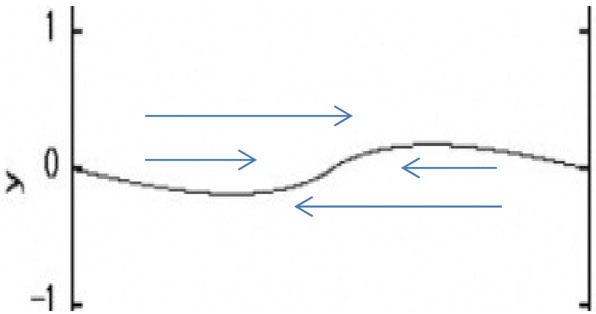
- Turbulent fluctuations are common in **air*** and **water***
- Usually ∃ source*
- Usually damped, but weakly
- ∃ quasi-stationary and developing instabilities
- For KHI the source is shear-flow

KHI in air from above

The Kelvin – Helmholtz instability

- Initial, almost sinusoidal waves





- Well developed, non-linear wave

The interface is a layer with a finite thickness, where viscosity and surface tension affects the interface. Due to these effects singularity formation is prevented in reality. The roll-up of a sheet is observed

[Chihiro Matsuoka, Yong Guo Shi, Scholarpedia]

Kelvin-Helmholtz instability in high-energy heavy-ion collisions

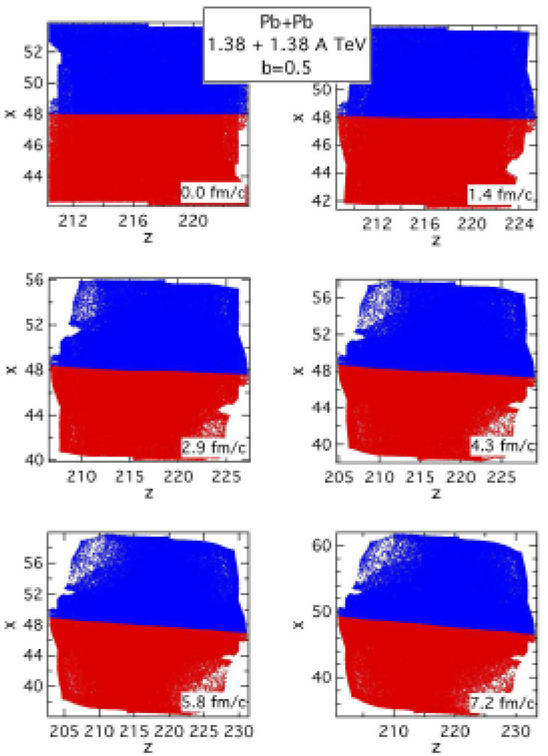
L.P. Csernai[1,2,3], D.D. Strottman[2,3], and Cs. Anderlik[4]

PHYSICAL REVIEW C **85**, 054901 (2012)

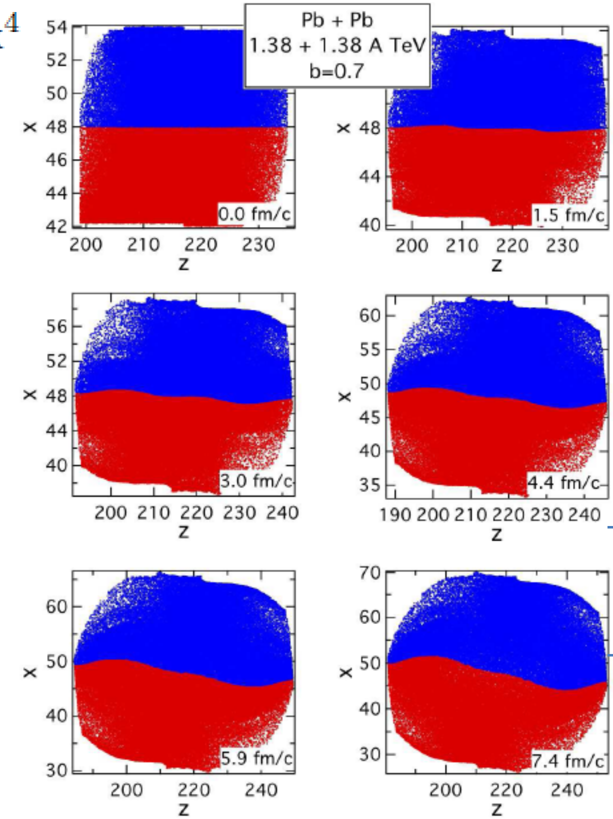
arXiv:1112.4287v3 [nucl-th]

KHI →

ROTATION

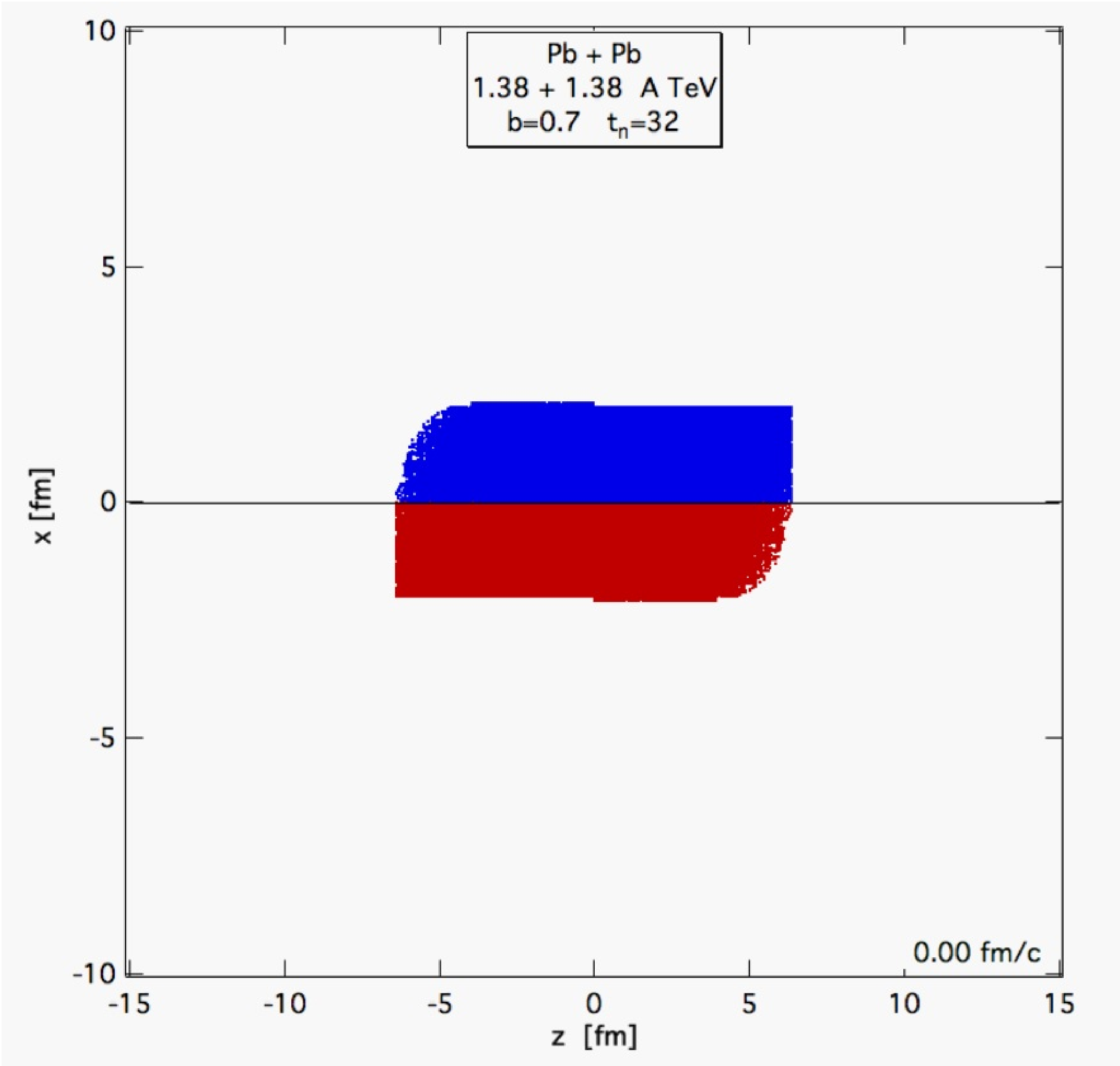


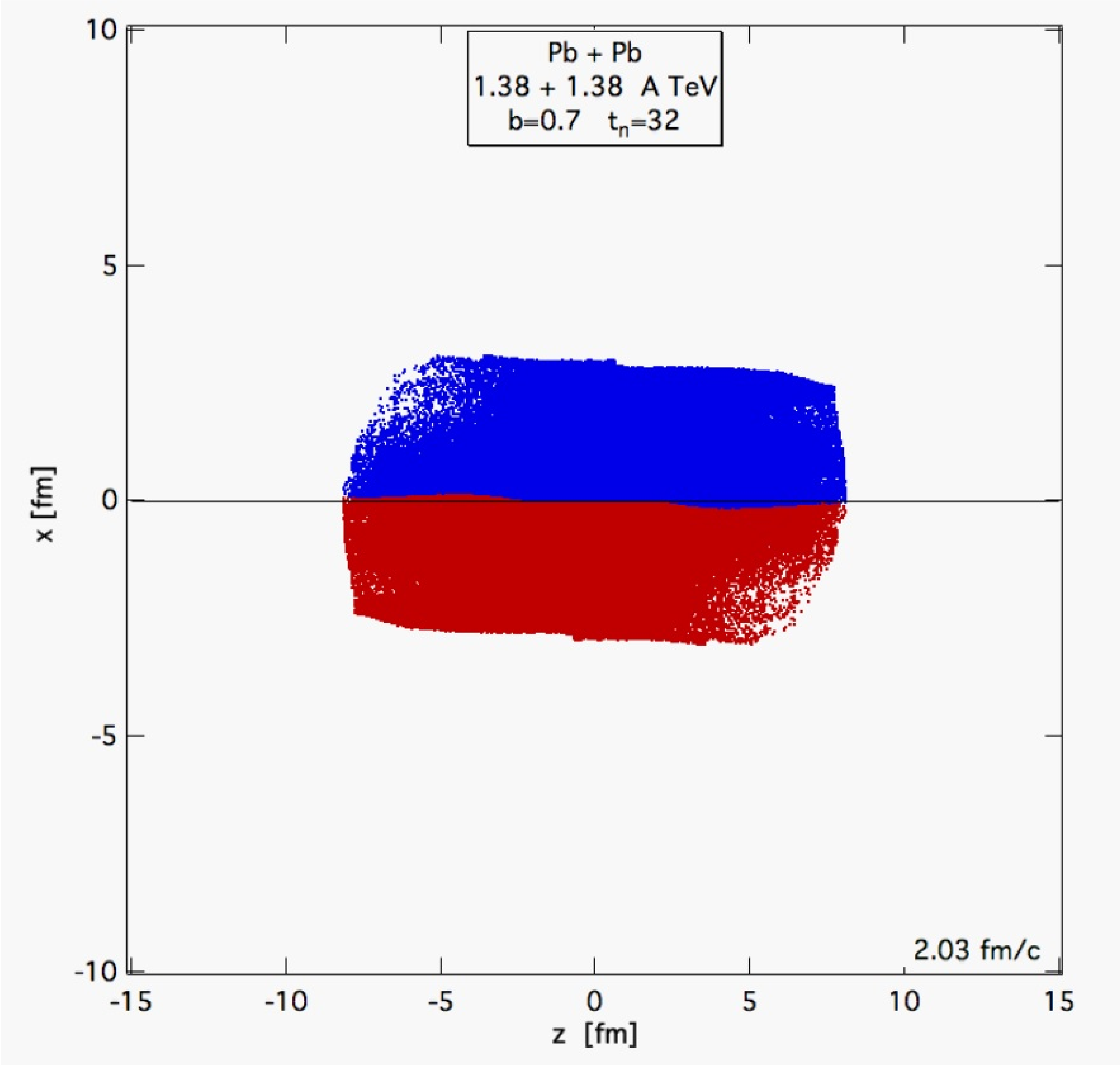
KHI

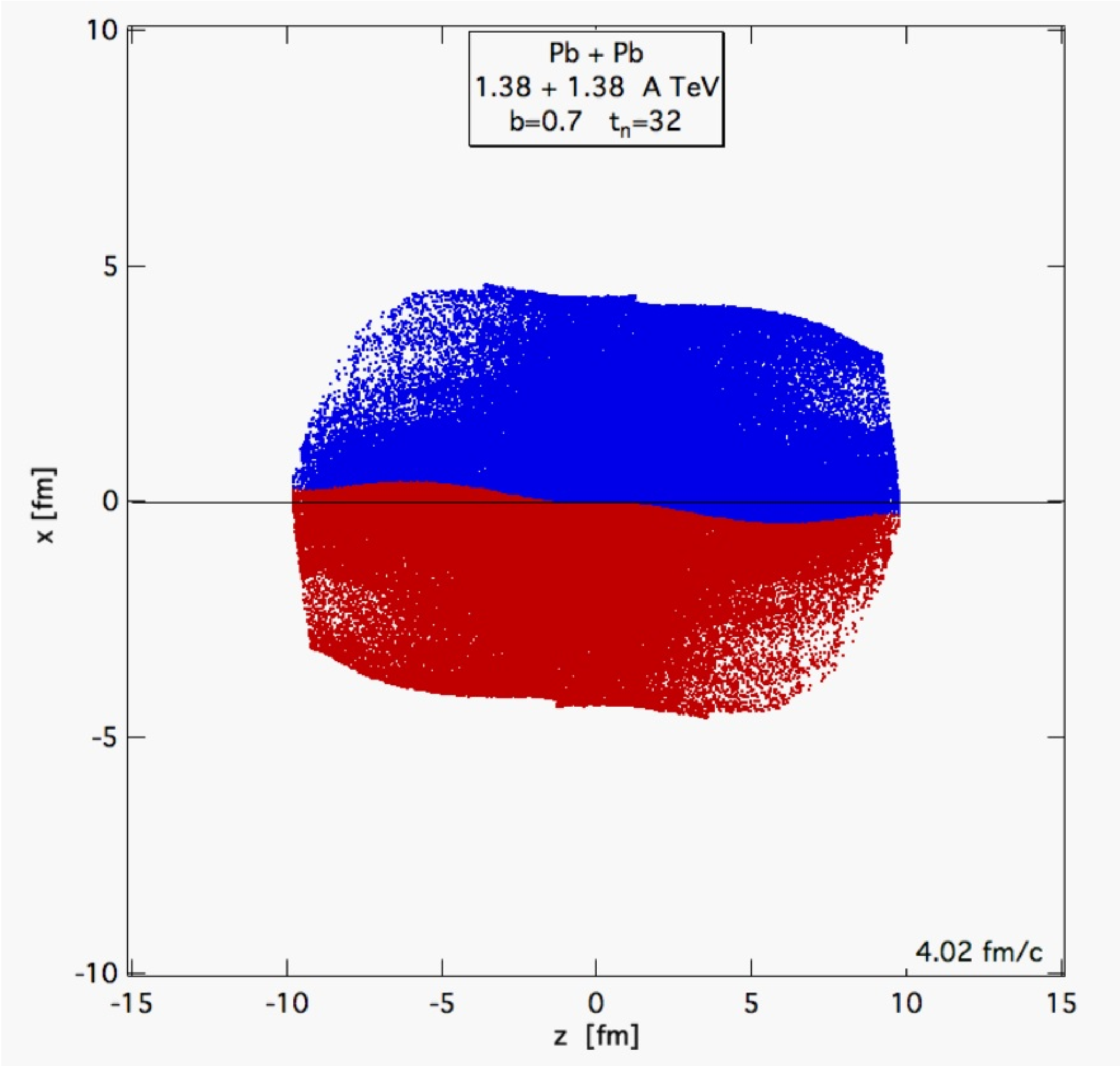


2.4 fm

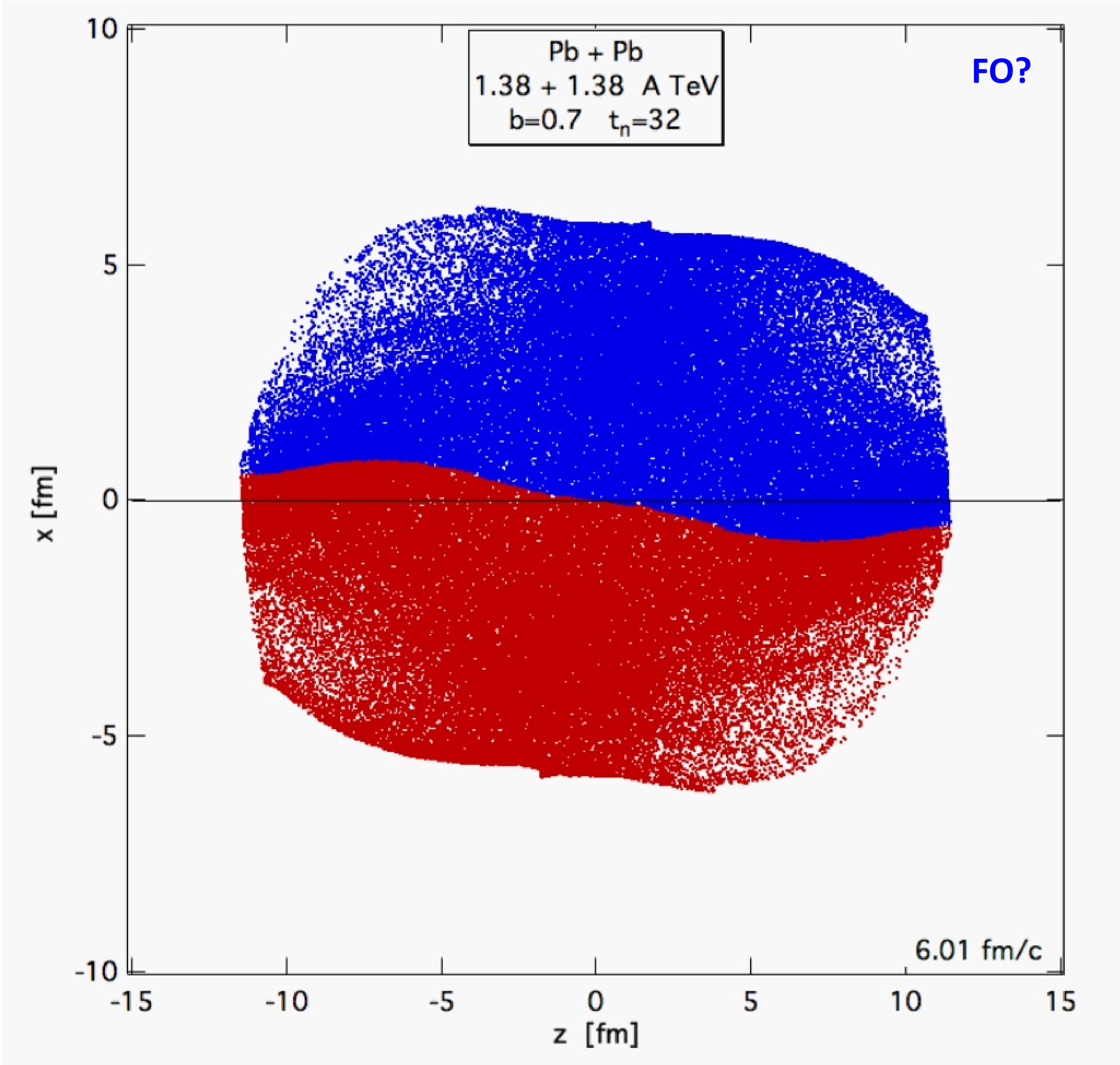
FIG. 1: (color online) Growth of the initial stage of Kelvin-Helmholtz instability in a 1.38A + 1.38A TeV peripheral, $b = 0.7b_{\max}$, Pb+Pb collision in a relativistic CFD simulation using the PIC-method. We see the positions of the marker particles (Lagrangian markers with fixed baryon number content) in the reaction plane. The calculation cells are $dx = dy = dz = 0.4375$fm and the time-step is 0.04233 fm/c The number of randomly placed marker particles in each fluid cell is 8^3. The axis-labels indicate the cell numbers in the x and z (beam) direction. The initial development of a KH type instability is visible from $t = 1.5$ up to $t = 7.41$ fm/c corresponding from 35 to 175 calculation time steps).


Pb + Pb
1.38 + 1.38 A TeV
b=0.7 t_n=32
0.00 fm/c
x [fm]
z [fm]
10
5
0
-5
-10
-15
-10
-5
0
5
10
15


Pb + Pb
1.38 + 1.38 A TeV
b=0.7 t_n=32
2.03 fm/c
x [fm]
z [fm]
10
5
0
-5
-10
-15
-10
-5
0
5
10
15



Pb + Pb
1.38 + 1.38 A TeV
b=0.7 t_n=32
4.02 fm/c
x [fm]
z [fm]
10
5
0
-5
-10
-15
-10
-5
0
5
10
15


Pb + Pb
1.38 + 1.38 A TeV
b=0.7 t_n=32
FO?
6.01 fm/c
x [fm]
z [fm]
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5
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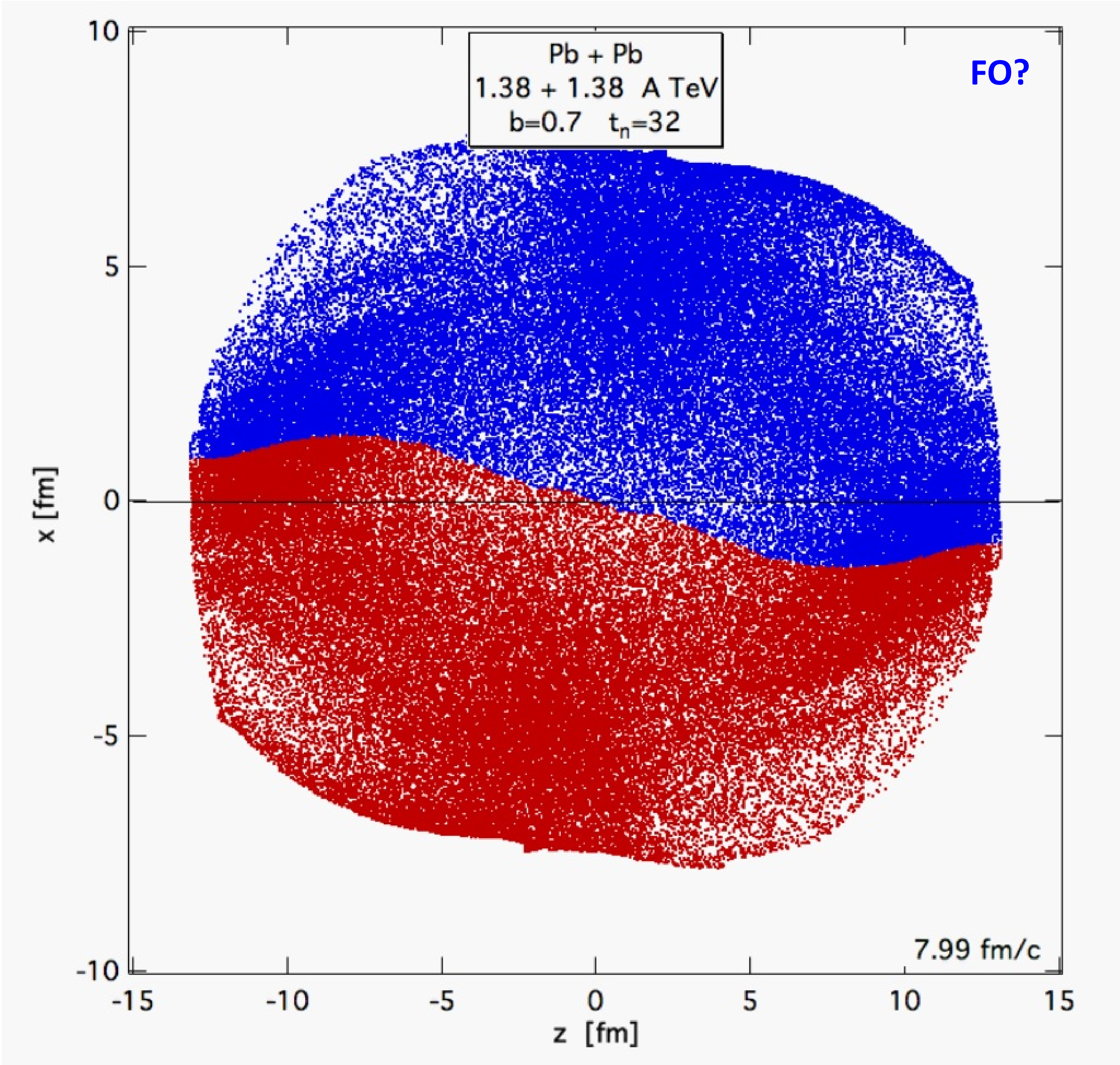
-5
0
5
10
15


Pb + Pb
1.38 + 1.38 A TeV
b=0.7 t_n=32
FO?
7.99 fm/c
x [fm]
z [fm]
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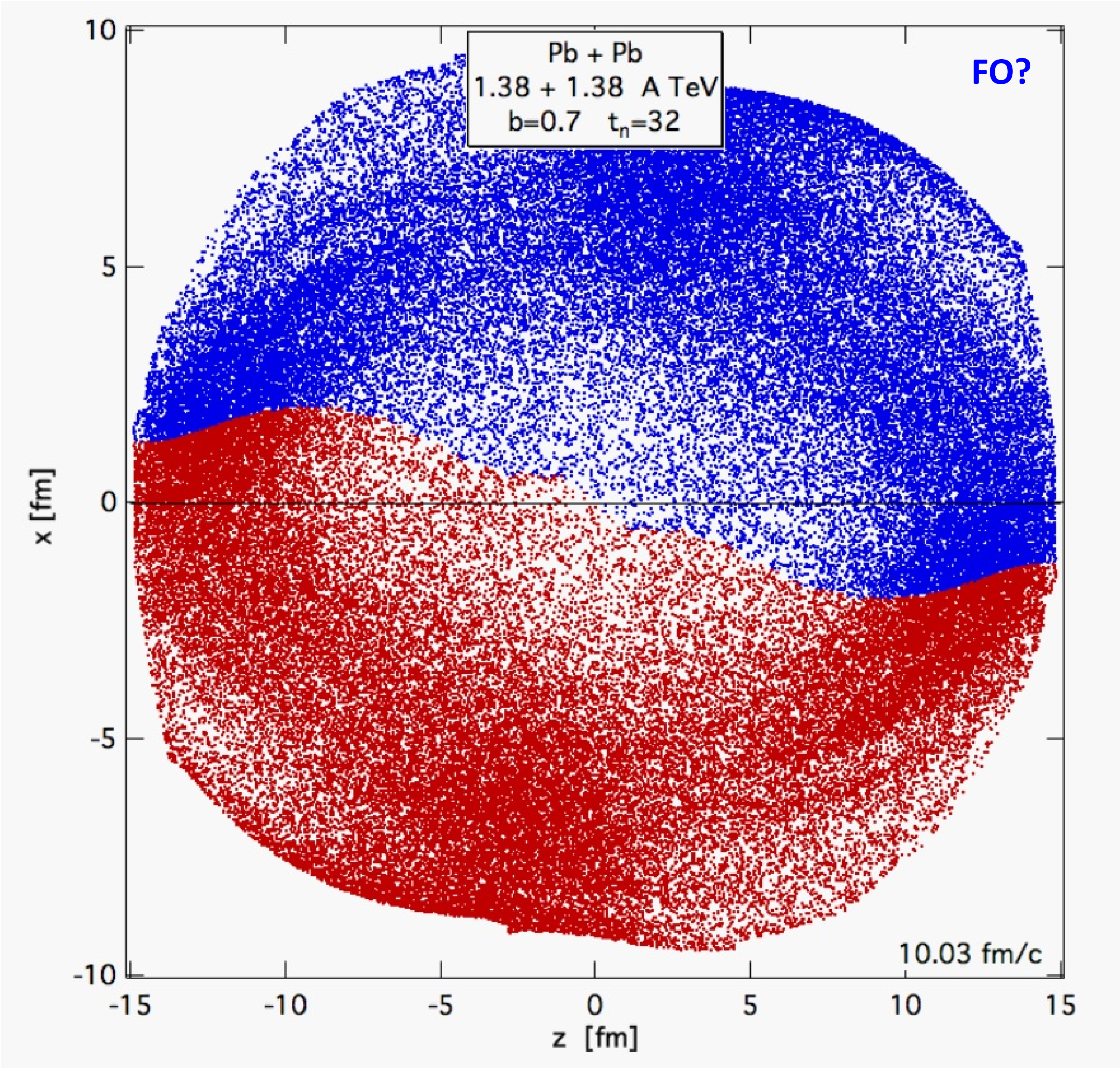
-5
0
5
10
15



Pb + Pb
1.38 + 1.38 A TeV
b=0.7 t_n=32
FO?
10.03 fm/c
x [fm]
z [fm]
10
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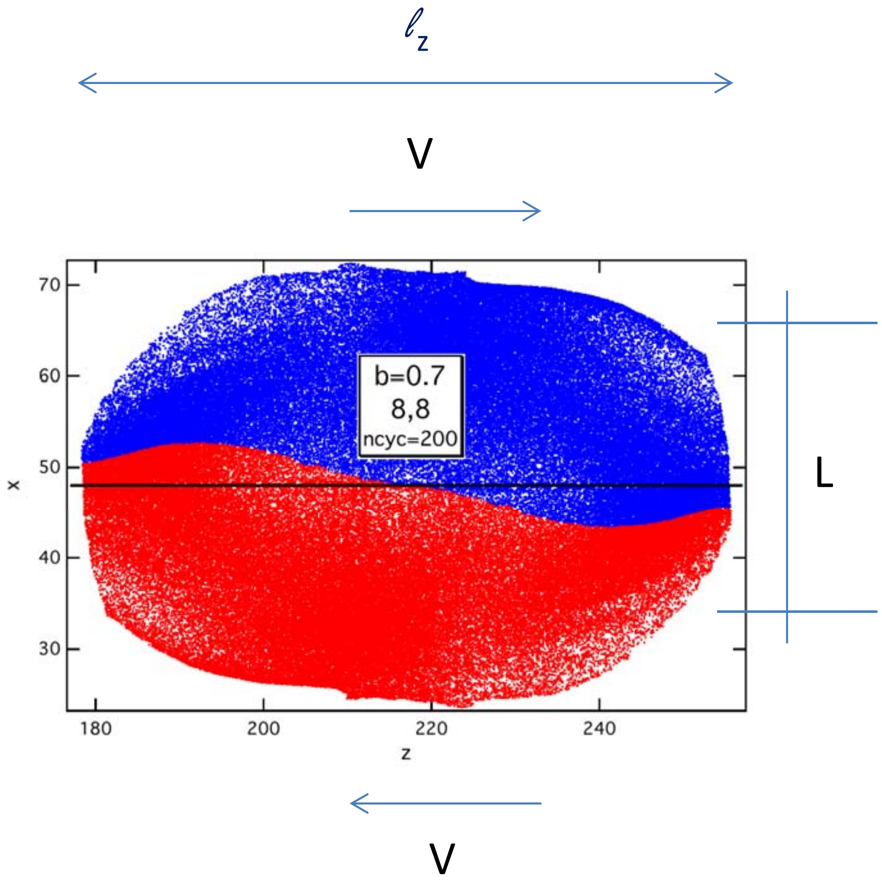
-15
-10
-5
0
5
10
15

The Kelvin – Helmholtz instability (KHI)



Our resolution is $(0.35 fm)^3$ and 8^3 markers/fluid-cell →
~ 10k cells & 10Mill m.p.-s

- Shear Flow:
- L=(2R-b) ~ 4 – 7 fm, init. profile height
- ℓ_z=10–13 fm, init. length (b=.5-.7b_{max})
- V ~ ±0.4 c upper/lower speed →
- Minimal wave number is
  k = .6 - .48 fm^{-1}
- KHI grows as $\propto \exp(st)$, where
  $s = kV$ →
- Largest k or shortest wave-length will grow the fastest.
- The amplitude will double in
  2.9 or 3.6 fm/c for (b=.5-.7b_{max})
  without expansion, and with favorable viscosity/Reynolds no. Re=LV/ν .
- → this favors large L and large V

The Kelvin – Helmholtz instability (KHI)

- **Formation of critical length KHI (Kolmogorov length scale)**
- ∃ critical minimal wavelength beyond which the KHI is able to grow. Smaller wavelength perturbations tend to decay. (similar to critical bubble size in homogeneous nucleation).
- **Kolmogorov**: $\lambda_{Kol} = [\nu^3/\epsilon]^{1/4}.$
- Here $\epsilon = \dot{e}/\rho \quad \propto \quad T\dot{\sigma}/\rho \quad \propto \quad \nu,$ is the specific dissipated flow energy.
- We estimated: $\lambda_{Kol} = \begin{cases} 2.1 \ \div \ 5.4 \text{ fm for } b = 0.5 b_{max} \\ 1.4 \ \div \ 3.6 \text{ fm for } b = 0.7 b_{max} \end{cases}$
- It is required that $l_z > \lambda_{Kol}$. → we need $b > 0.5\ b_{max}$
- Furthermore
  Re = 0.3 – 1 for "$\eta/s = 1$" and
  Re = 3 – 10 for "$\eta/s = 0.1$"

PHYSICAL REVIEW C **87**, 034906 (2013)

$$\Omega(z,x) \equiv w(z,x)\omega(z,x)$$

Flow vorticity in peripheral high-energy heavy-ion collisions

L. P. Csernai,[1] V. K. Magas,[2] and D. J. Wang[1]

$$\Theta \equiv \nabla_\mu u^\mu = \partial_\mu u^\mu,$$

$$w_{ik} \equiv (N_{cell}/E_{tot}) \quad E_{ik}.$$

$$\omega^\mu_\nu \equiv \frac{1}{2}(\nabla_\nu u^\mu - \nabla^\mu u_\nu),$$

$$\omega_y \equiv \omega_{xz} \equiv \frac{1}{2}(\partial_z v_x - \partial_x v_z)$$

If $\partial_\tau u^\mu \equiv \dot{u}^\mu = u^\alpha \partial_\alpha u^\mu$ is negligible

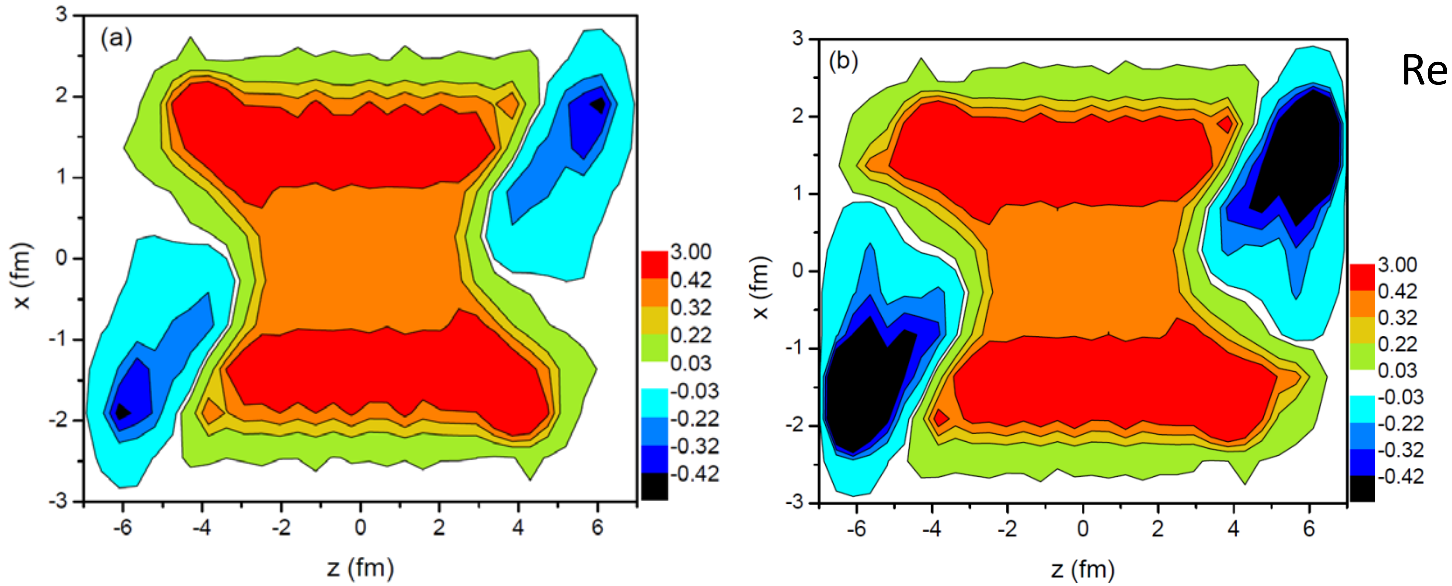
$$\omega^x_{\ z} = -\omega^z_{\ x} = \frac{1}{2}(\partial_z \gamma v_x - \partial_x \gamma v_z) = \frac{1}{2}\gamma(\partial_z v_x - \partial_x v_z) + \frac{1}{2}(v_x \partial_z \gamma - v_z \partial_x \gamma)$$

$\Omega(z,x)$

Classical

Relativistic

Reaction plane only



Max = 3. c/fm

FIG. 1: The classical (left) and relativistic (right) weighted vorticity, Ω_{zx}, calculated in the reaction, [x-z] plane at t=0.17 fm/c. The collision energy is $\sqrt{s_{NN}}$ = 2.76 TeV and $b = 0.7 b_{max}$, the cell size is $dx = dy = dz = 0.4375 fm$. The average vorticity in the reaction plane is 0.1434 / 0.1185 for the classical / relativistic weighted vorticity respectively.

All y-layers

Classical

Relativistic

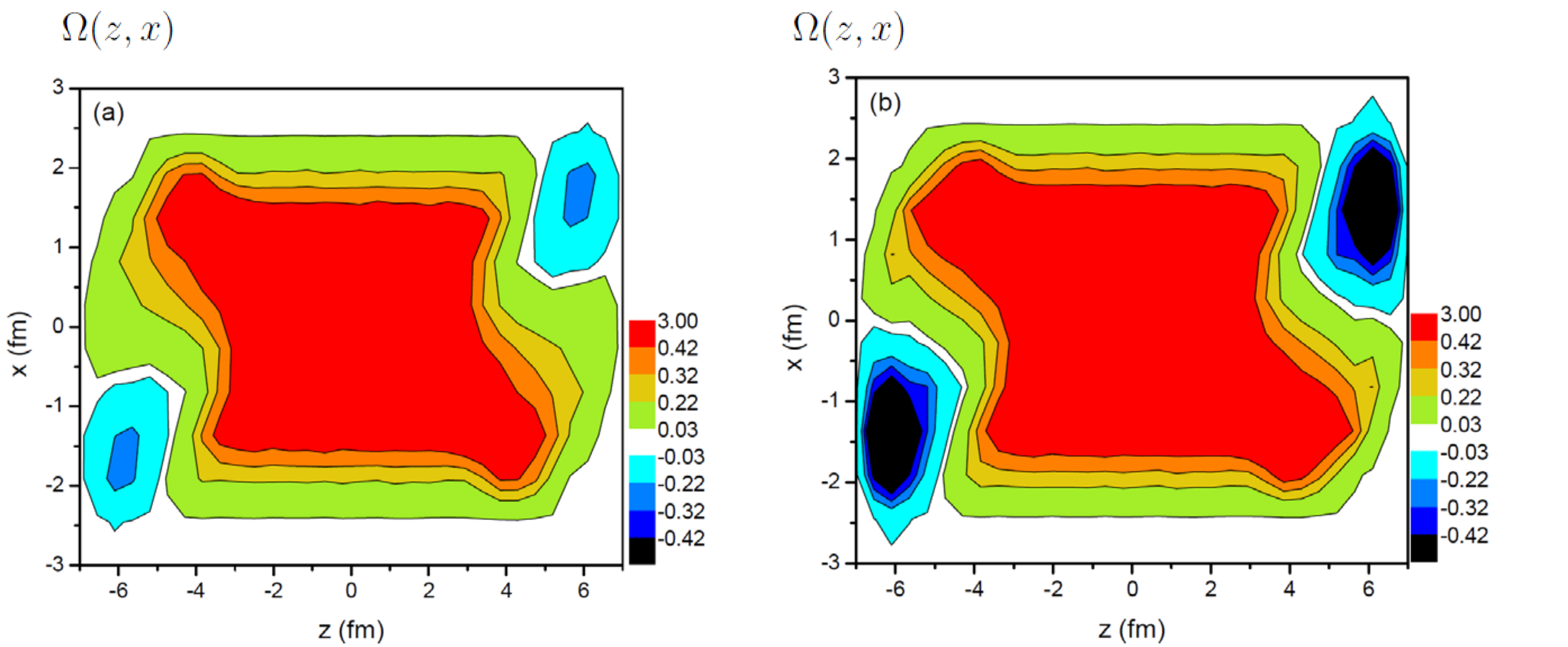


FIG. 4: The classical (left) and relativistic (right) weighted vorticity calculated for all [x-z] layers at t=0.17 fm/c. The collision energy is $\sqrt{s_{NN}} = 2.76$ TeV and $b = 0.7 b_{max}$, the cell size is $dx = dy = dz = 0.4375 fm$.

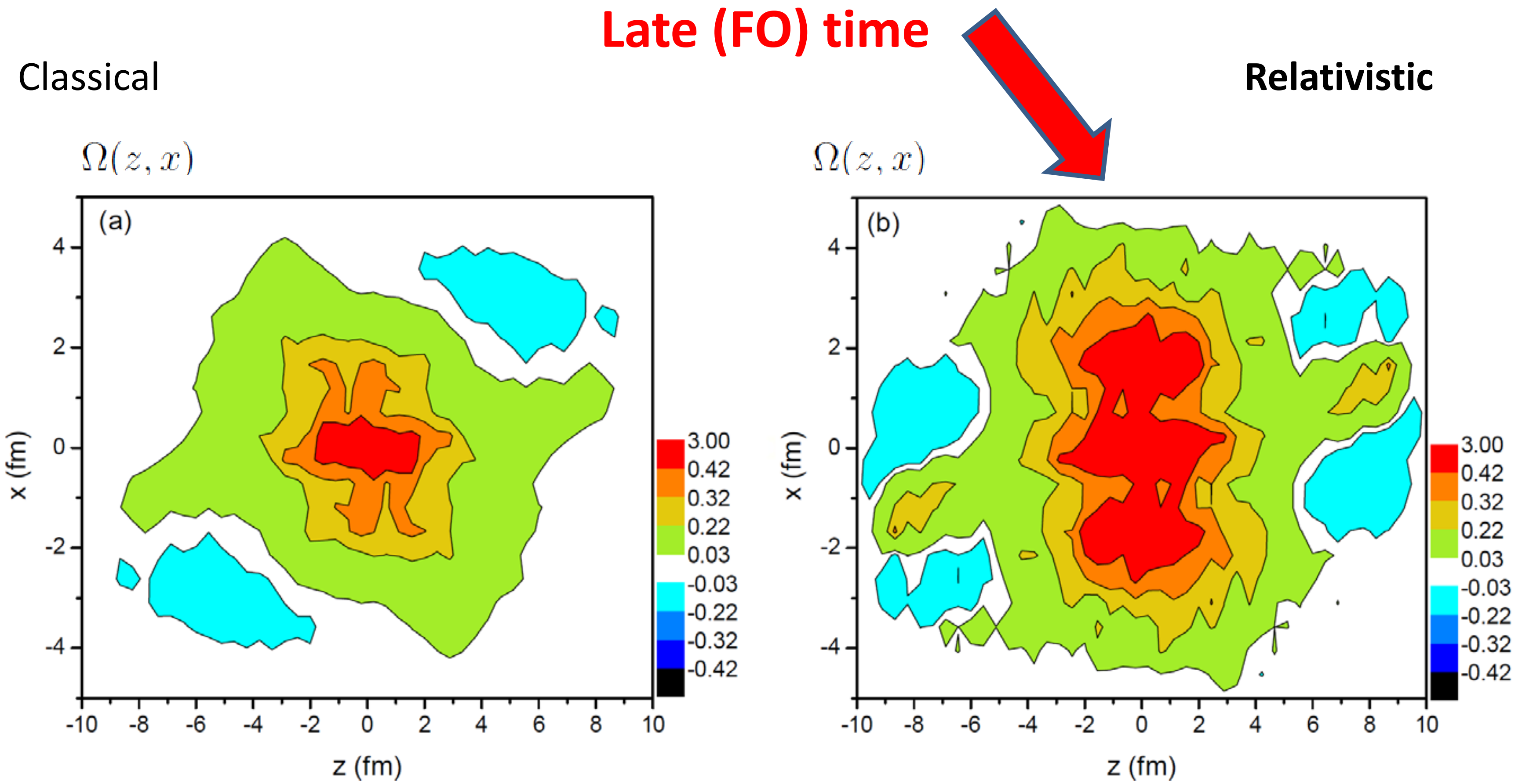


FIG. 5: The classical (left) and relativistic (right) weighted vorticity calculated for all [x-z] layers at t=3.56 fm/c. The collision energy is $\sqrt{s_{NN}}$ = 2.76 TeV and $b = 0.7 b_{max}$, the cell size is $dx = dy = dz = 0.4375 fm$. The average vorticity in the reaction plane is 0.0538 / 0.10685 for the classical / relativistic weighted vorticity respectively.

the surface element $S(t)$. Then we can describe the *circulation* along

$$\Gamma(C(t)) = \oint_{C(t)} \mathbf{v} \cdot d\mathbf{l} = \int\int_{S(t)} \vec{\omega} \cdot \mathbf{n}\, dS$$

where ω is the vorticity

$$\vec{\omega} = \ \mathbf{r}ot\ \mathbf{v}$$

The circulation is conserved for perfect incompressible classical fluids.

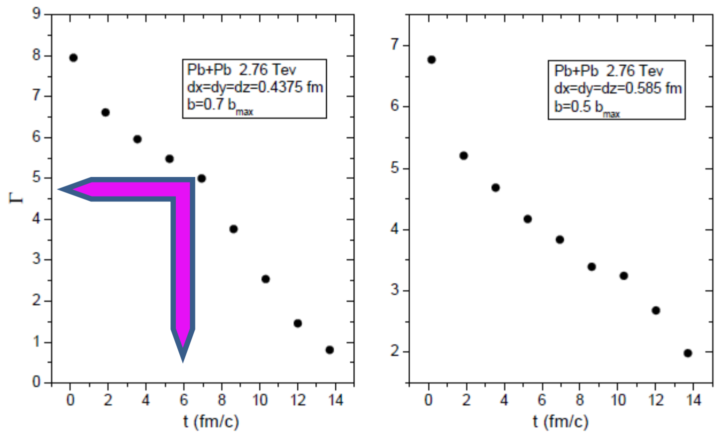
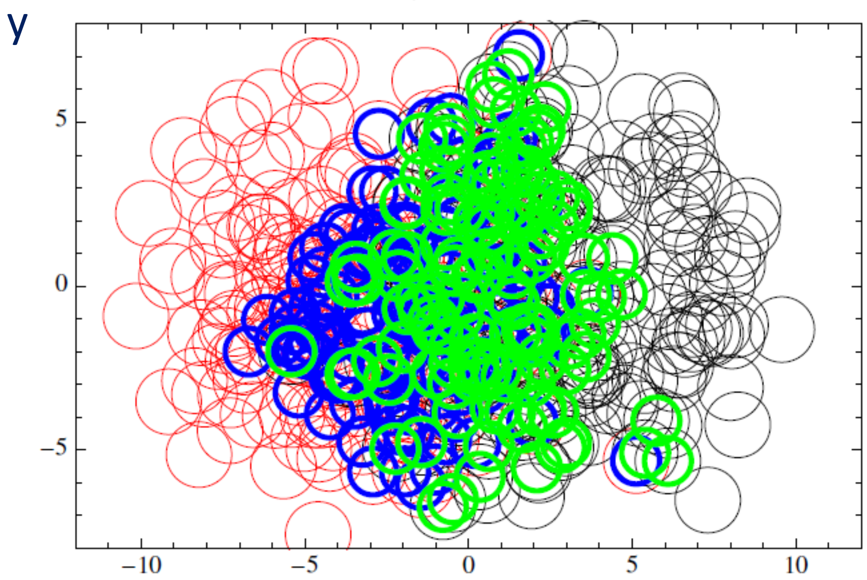
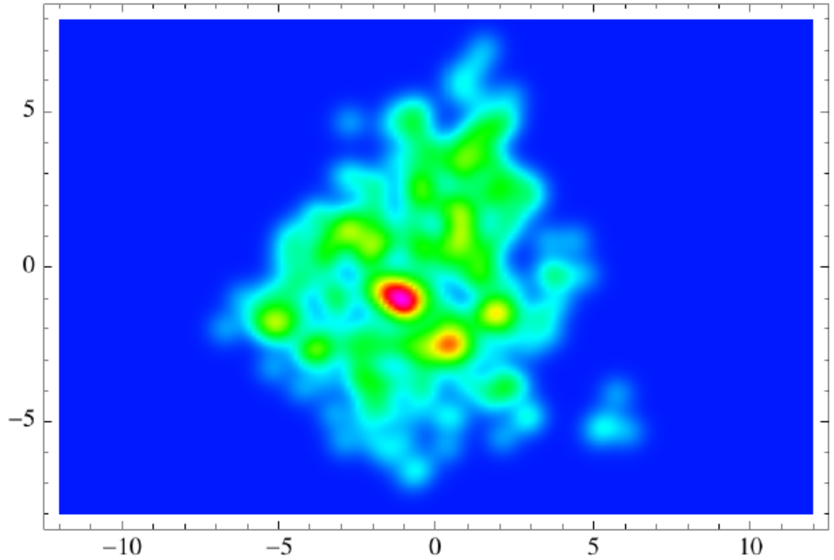


FIG. 7: The time dependence of classical circulation, $\Gamma(t)$, in units of [fm c], calculated for all [x-z] layers and then taking the average of the circulations for all layers. The collision energy is $\sqrt{s_{NN}} = 2.76$ TeV and $b = 0.7 b_{max}$, the cell size is $dx = dy = dz = 0.4375 fm$ (left). For comparison another initial state configuration was also tested for the same collision energy but $b = 0.5 b_{max}$, the cell size is $dx = dy = dz = 0.585 fm$ (right). This configuration shows also the rotation, but due to its less favorable parameters it does not show the KHI. Although at this impact parameter, which is less peripheral the reaction plane has a larger area filled with matter, nevertheless the initial classical circulation is less by about 15%. For the more peripheral case with smaller numerical viscosity the circulation decreases with time faster and the circulation for the two cases becomes equal around $t = 10\,\text{fm/c}$.

Onset of turbulence around the Bjorken flow

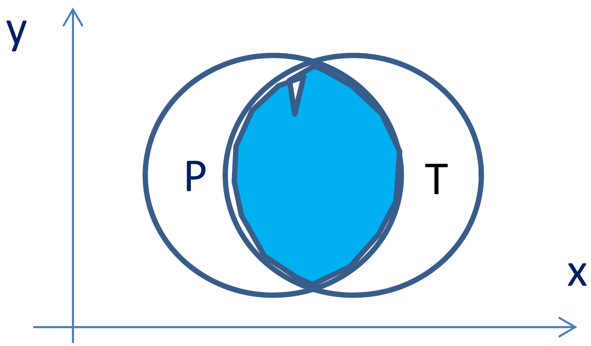
S. Floerchinger & U. A. Wiedemann, JHEP 1111:100, 2011; arXiv: 1108.5535v1





nucleons x [fm] energy density x [fm]

- Transverse plane [x,y] of a Pb+Pb HI collision at $\sqrt{s_{NN}}$=2.76TeV at b=6fm impact parameter
- Longitudinally [z]: **uniform** Bjorken flow, (expansion to infinity), depending on τ only.

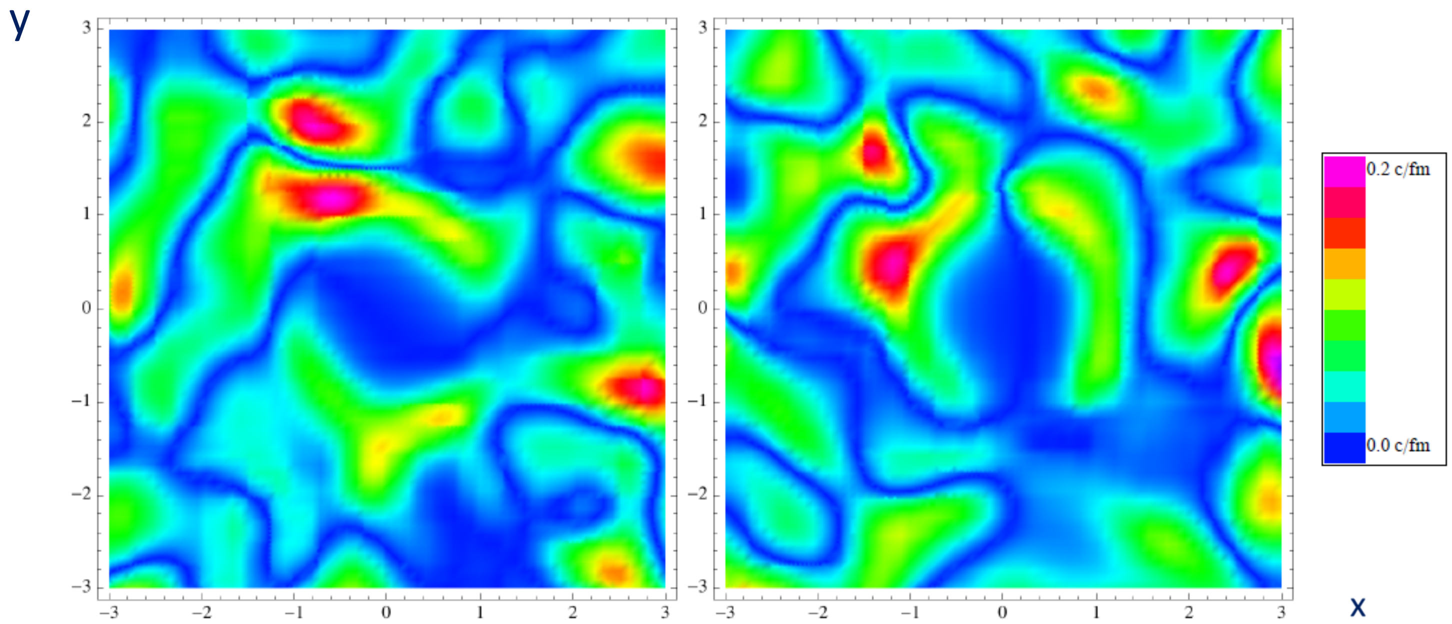


Green and **blue** have the same longitudinal speed (!) in this model. Longitudinal shear flow is omitted.

Onset of turbulence around the Bjorken flow

S. Floerchinger & U. A. Wiedemann, JHEP 1111:100, 2011; arXiv: 1108.5535v1

Max = 0.2 c/fm

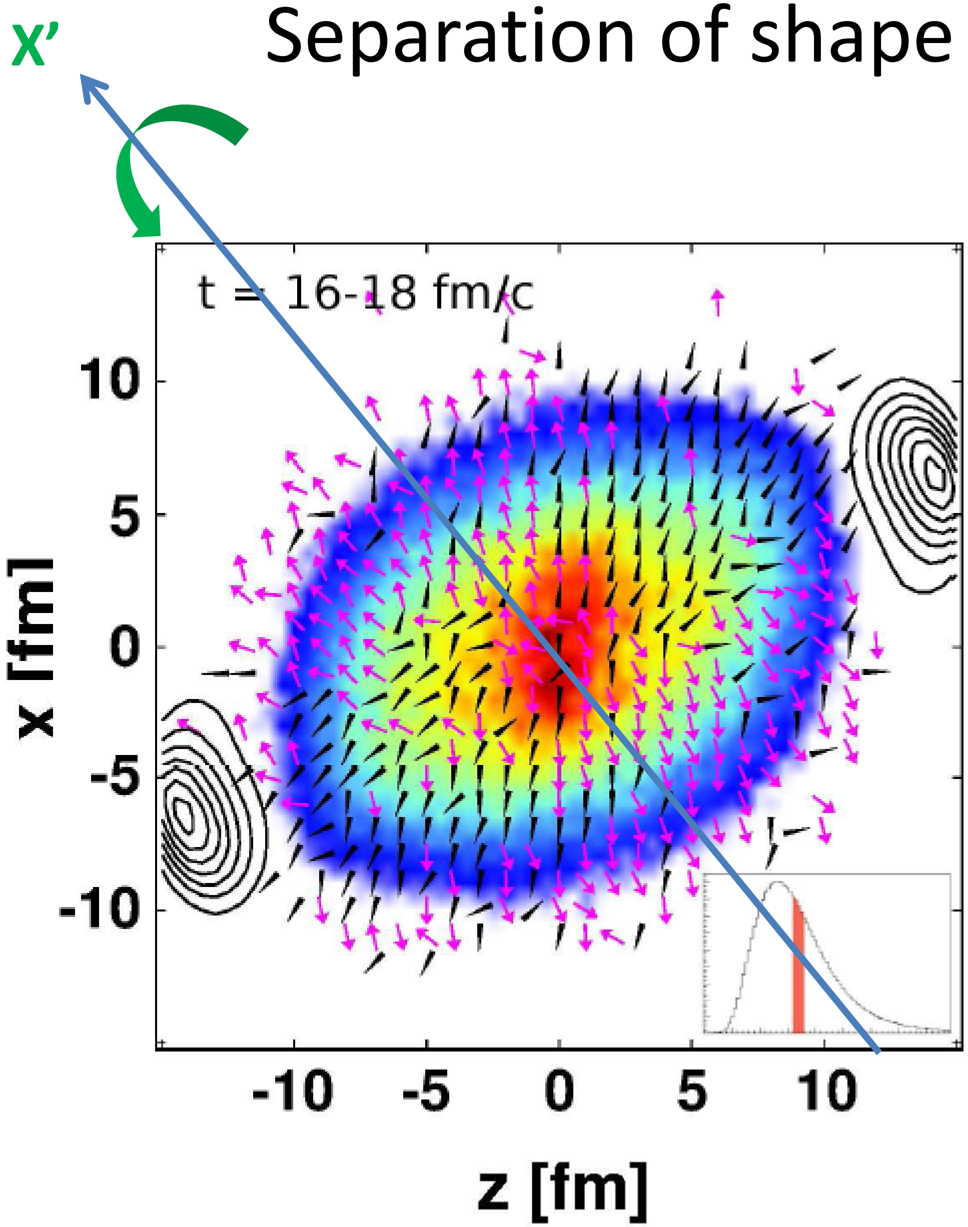


absolute value of vorticity $|\partial_1 u^2 - \partial_2 u^1|$ divergence $|\partial_1 u^1 + \partial_2 u^2|$

- Initial state Event by Event vorticity and divergence fluctuations.
- Amplitude of random vorticity and divergence fluctuations are the same
- In dynamical development viscous corrections are negligible (→ no damping)
- Initial transverse expansion in the middle (±3fm) is neglected (→ no damping)
- High frequency, high wave number fluctuations **may feed** lower wave numbers

How can we see these?

Separation of shape & rotation



Still both rotation and shape influence the DCF so rotation alone is not easy to identify

➔

We can use the work

To reflect an event
CF' := (CF + R[CF])/2
will have no rotation

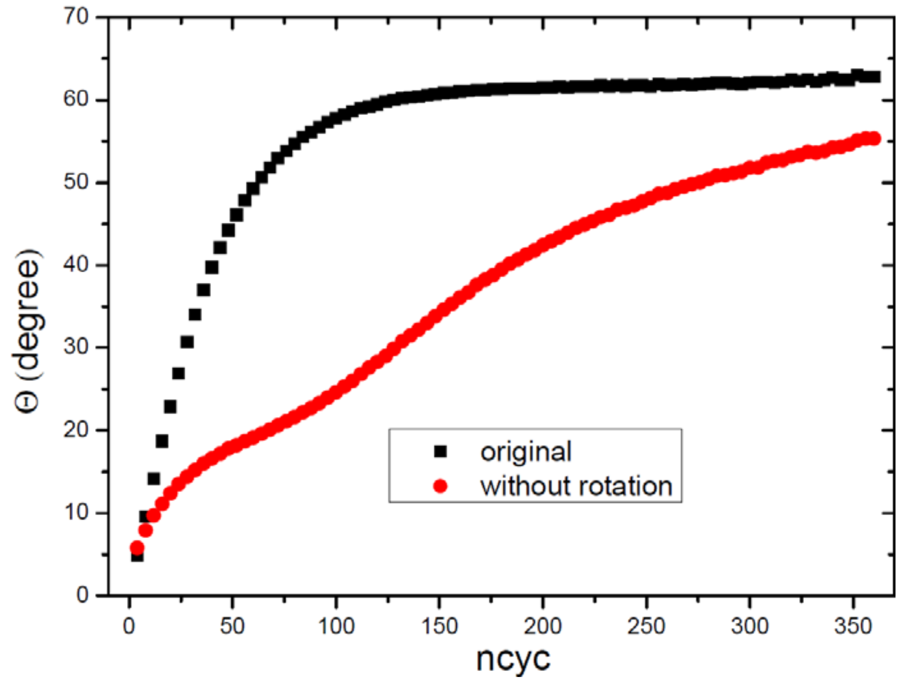
➔

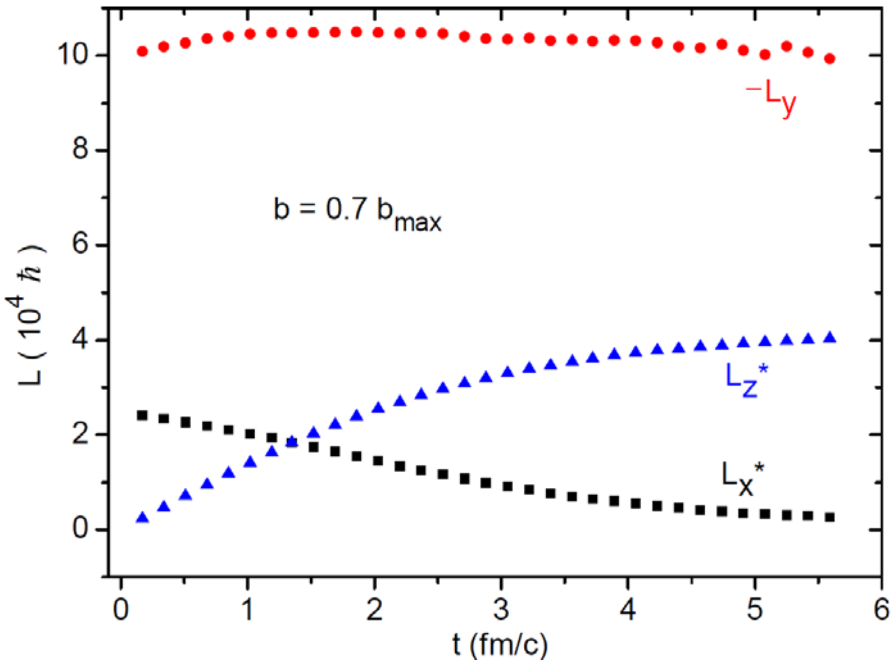
Rotation and shape effects can be separated

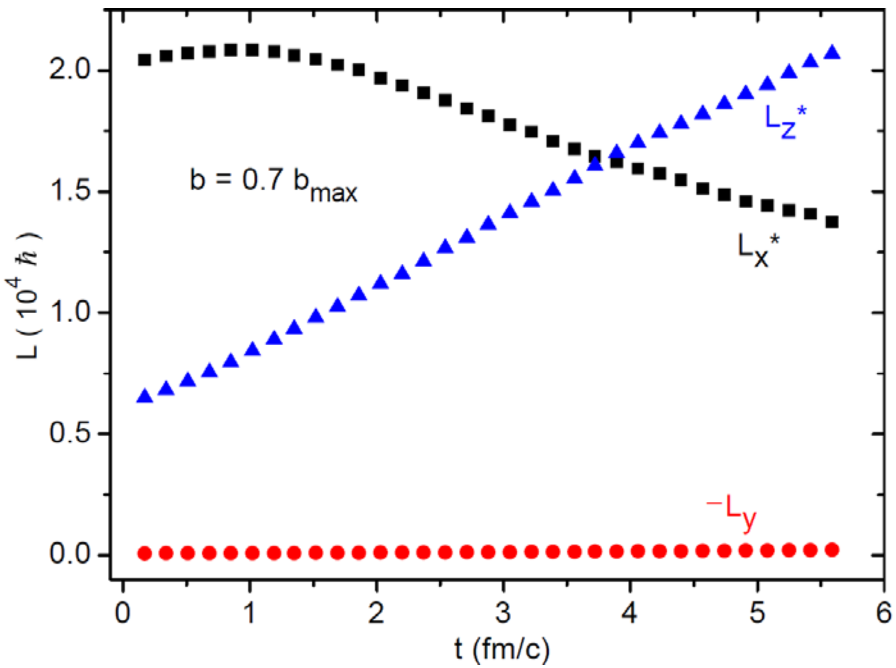
[G. Graef, M. Lisa et al., arXive 1302.3408]

Testing the sensitivity of DHBT

- ❑ Rotation comp. of v is removed
- ❑ Global flow analysis
- ❑ Symmetry axis without rotation→

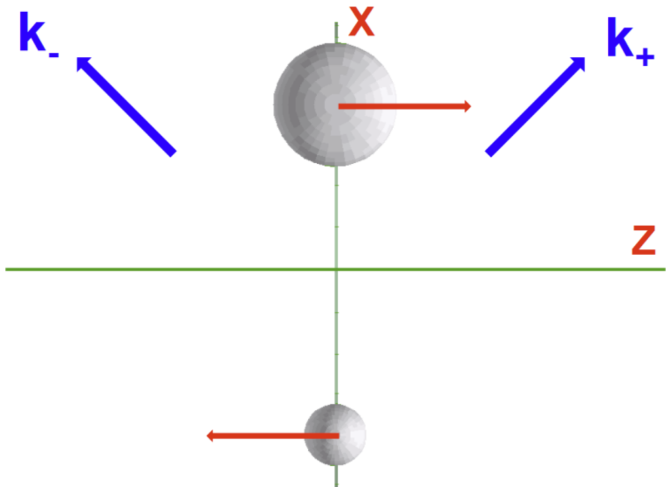


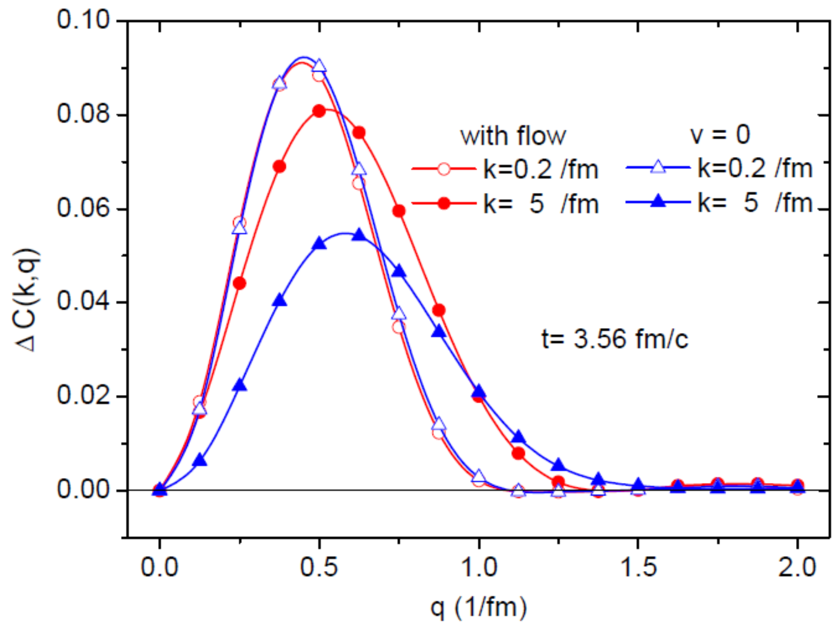




Detecting initial rotation: Two particle correlations, Diff. HBT

$$\Delta C(k_\pm, q_{out}) \equiv C(k_+, q_{out}) - C(k_-, q_{out}) = \frac{4\exp(-R^2q^2)\,\epsilon\sinh\left(\frac{2u_z\,bk}{T_s}\right)\,(1-\epsilon^2)\left[1-\cosh\left(\frac{u_z\,bq}{T_s}\right)\cos\left(aqd_x\right)\right]}{\left[(1+\epsilon^2)\cosh\left(\frac{2u_z\,bk}{T_s}\right)+(1-\epsilon^2)\right]^2 - 4\epsilon^2\sinh^2\left(\frac{2u_z\,bk}{T_s}\right)}.$$





[L.P. Csernai, S. Velle, subm. to PRC]

[L.P. Csernai, S. Velle, D.J. Wang , in prep.]

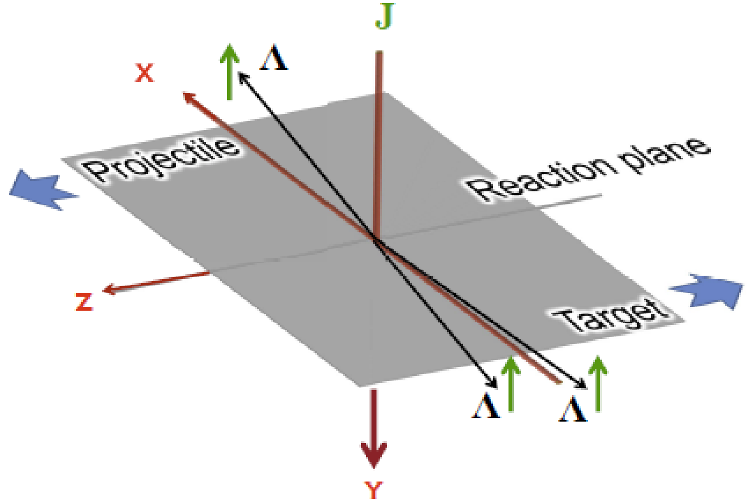
FIG. 3. (color online) The flow velocity dependence of the differential correlation function at the final time.

Detecting rotation: Lambda polarization

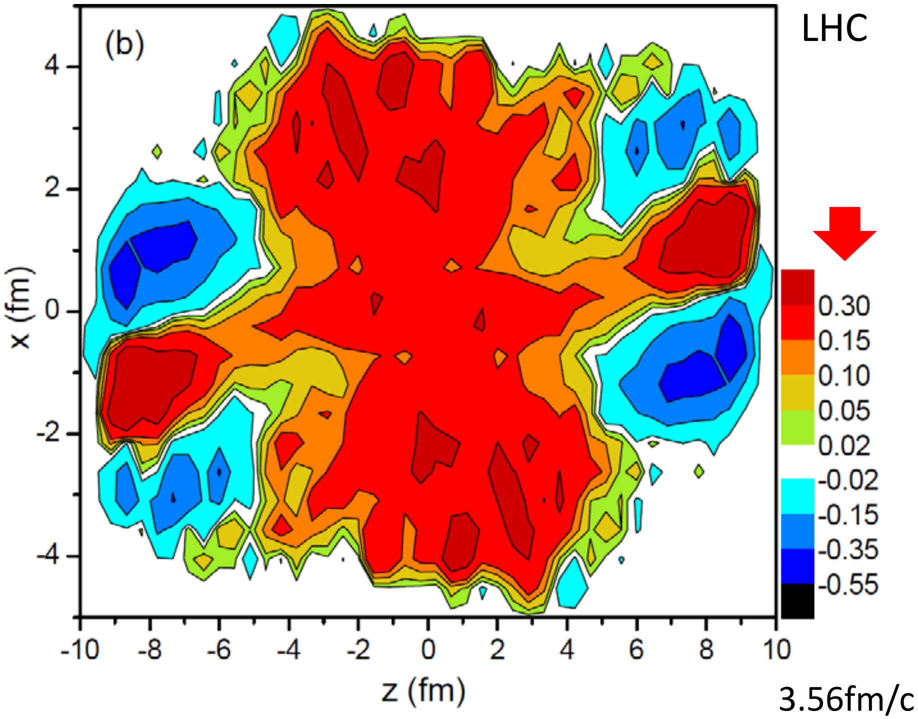
$$\mathbf{\Pi}(p) = \frac{\hbar\varepsilon}{8m} \frac{\int \mathrm{d}V \, n_F \, (\nabla \times \beta)}{\int \mathrm{d}V \, n_F}$$

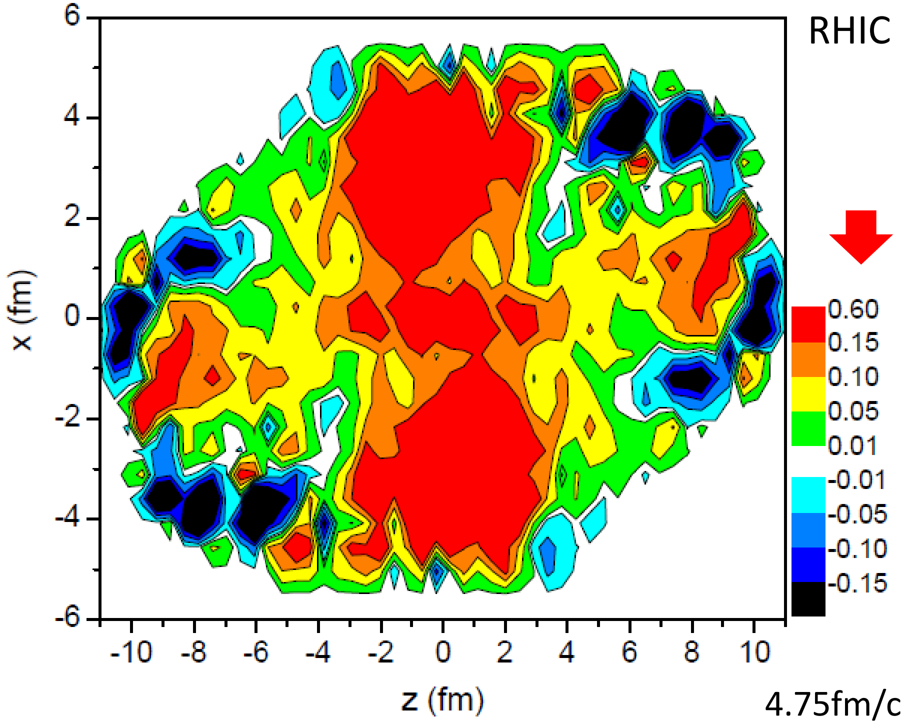
$$\beta^\mu(x) = (1/T(x)) u^\mu(x)$$ ← From hydro

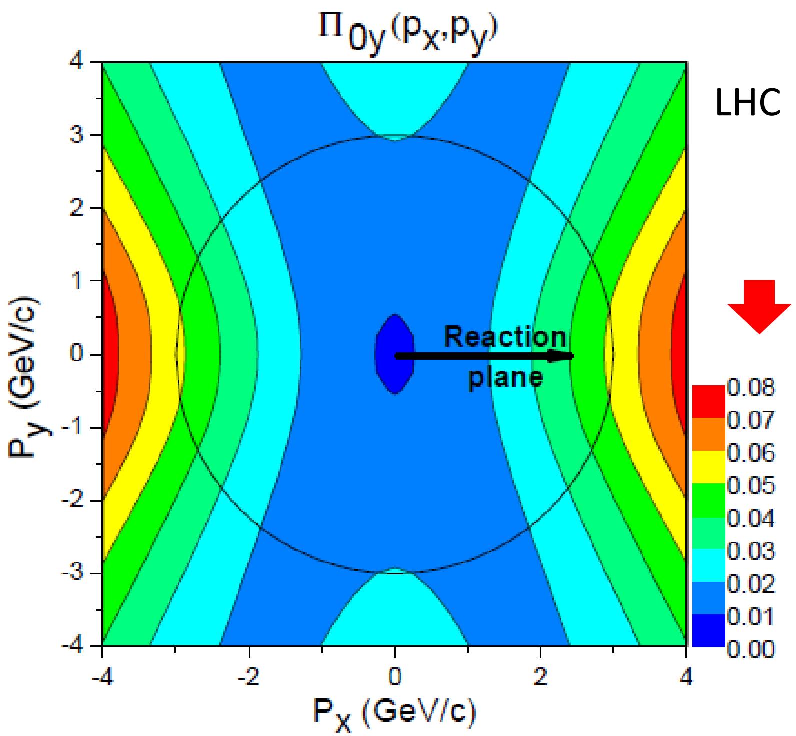
$$\mathbf{\Pi}_0(p) = \mathbf{\Pi}(p) - \frac{\mathbf{p}}{\varepsilon(\varepsilon + m)} \mathbf{\Pi}(p) \cdot \mathbf{p}$$

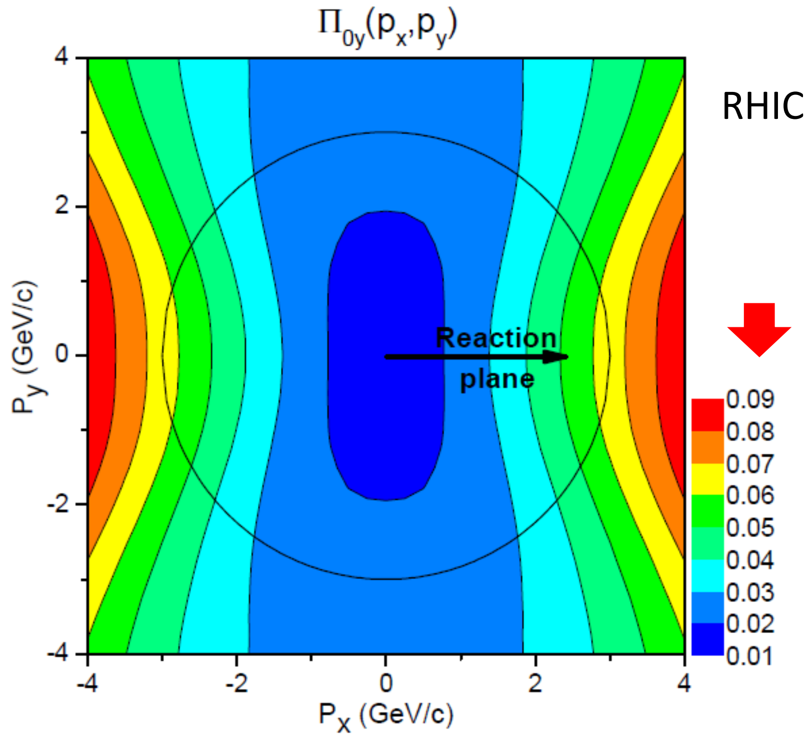


[F. Becattini, L.P. Csernai, D.J. Wang, Phys. Rev. C **88**, 034905 (2013)]









- **The POLARIZATION of Λ and $\bar{\Lambda}$ due to thermal equipartition with local vorticity is slightly stronger at RHIC than at LHC due to the much higher temperatures at LHC.**
- **Although early measurements at RHIC were negative, these were averaged over azimuth! We propose selective measurement in the reaction plane (in the +/- x direction) in the EbE c.m. frame. Statistical error is much reduced now, so significant effect is expected at $p_x \geq 3$ GeV/c.**

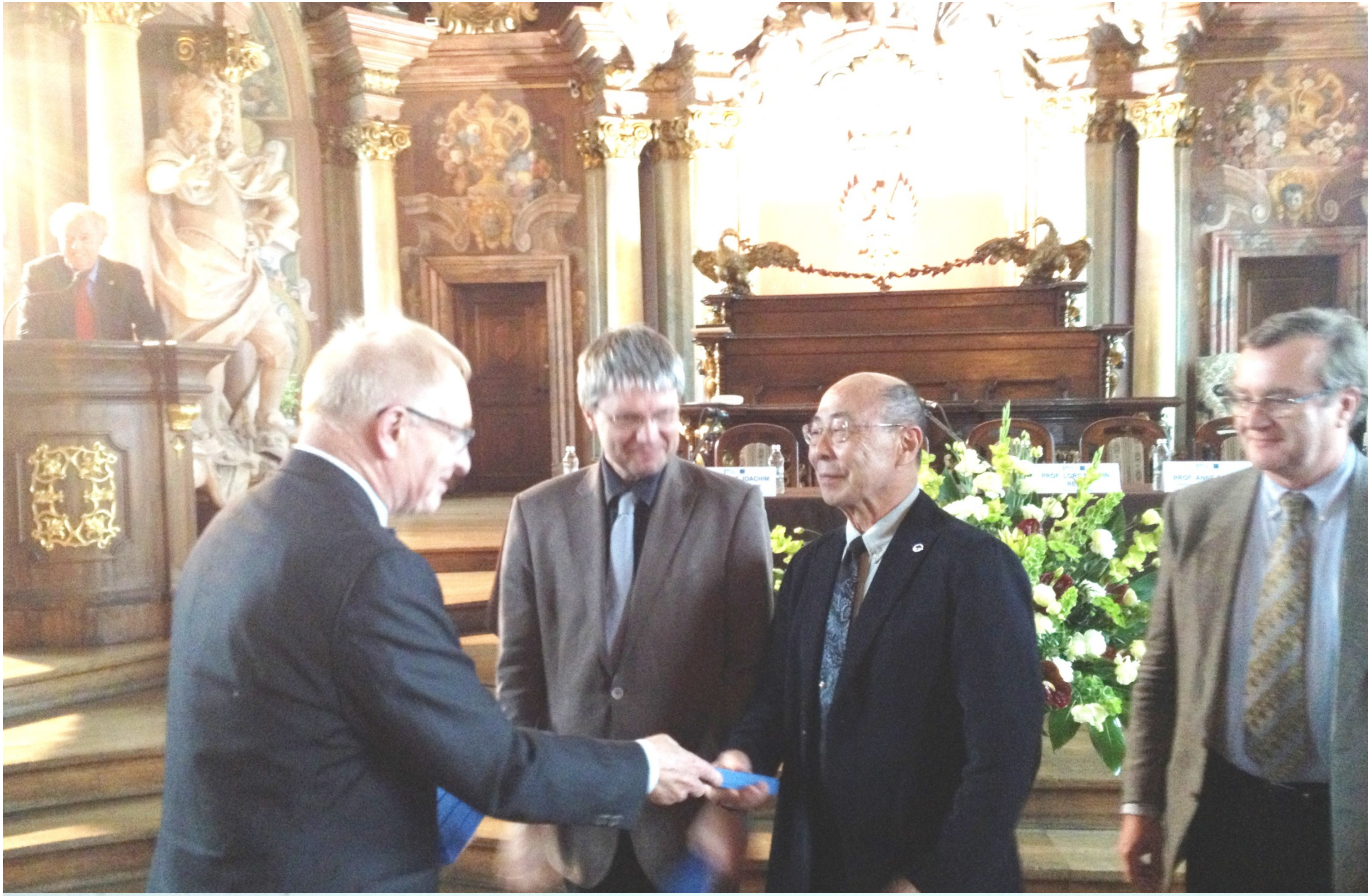
Summary

- FD model: Initial State + **EoS** + Freeze out & Hadronization
- In A+A the I.S. is causing global collective flow
- Consistent I.S. is needed based on a dynamical picture, satisfying causality, etc.
- In peripheral collisions angular momentum is large!
- This leads to **rotation** and if η low, to **turbulence**
- Experimental observation is possible via v_1, HBT and polarization.


Two
months
ago


Reward for the long and hard work.


One week ago



Takeshi KODAMA (Foreign member), Brazil: Federal University of Rio de Janeiro.
Frankfurt. Quantum Chromodynamics. Relativistic Heavy Ion Collisions. Non-equilibrium Dyn
Supernova.